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THE CRYOSTAT FOR THE SSC 6 T MAGNET OPTION*

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ABSTRACT

A design has been developed for a SSC 6T option dipole magnet cryostat. The design criteria that defines the basic parameters and performance requirements are discussed. Details of the single phase assembly, suspension, insulation, thermal shields, vacuum vessels and interconnections are presented. Results of the experimental program in support of the design effort are discussed.

INTRODUCTION

Conceptual designs for a 20 TeV on 20 TeV proton-proton collider, called the Superconducting Super Collider (SSC), have been developed.[1] The SSC incorporates two adjacent, 29 km diameter accelerator rings in a common tunnel. The rings consist of dipole magnets for bending, quadrupole magnets for focusing and special magnets for correction.

MAGNET SYSTEM

The conceptual design of a superconducting dipole magnet suitable for use in the SSC has been developed.[2] This magnet would generate a 6 T field over a 4 cm aperture and have a 16.6 m magnetic length. The magnet design employs collared coils with adjacent cold iron. Approximately 7740 dipoles are required for the two rings.

CRYOGENIC DESIGN

The cryostat features are critical to the SSC design since they must allow proper magnetic function, impose a low refrigeration load, operate with a 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 single phase assembly, thermal shields, insulation, suspension system, vacuum vessel and interconnections. The cross-section is shown in Figure 1. Component design considerations include fluid flow, materials selection, structural performance, displacement, thermal performance and differential thermal contraction. Functional tradeoffs are incorporated to optimize

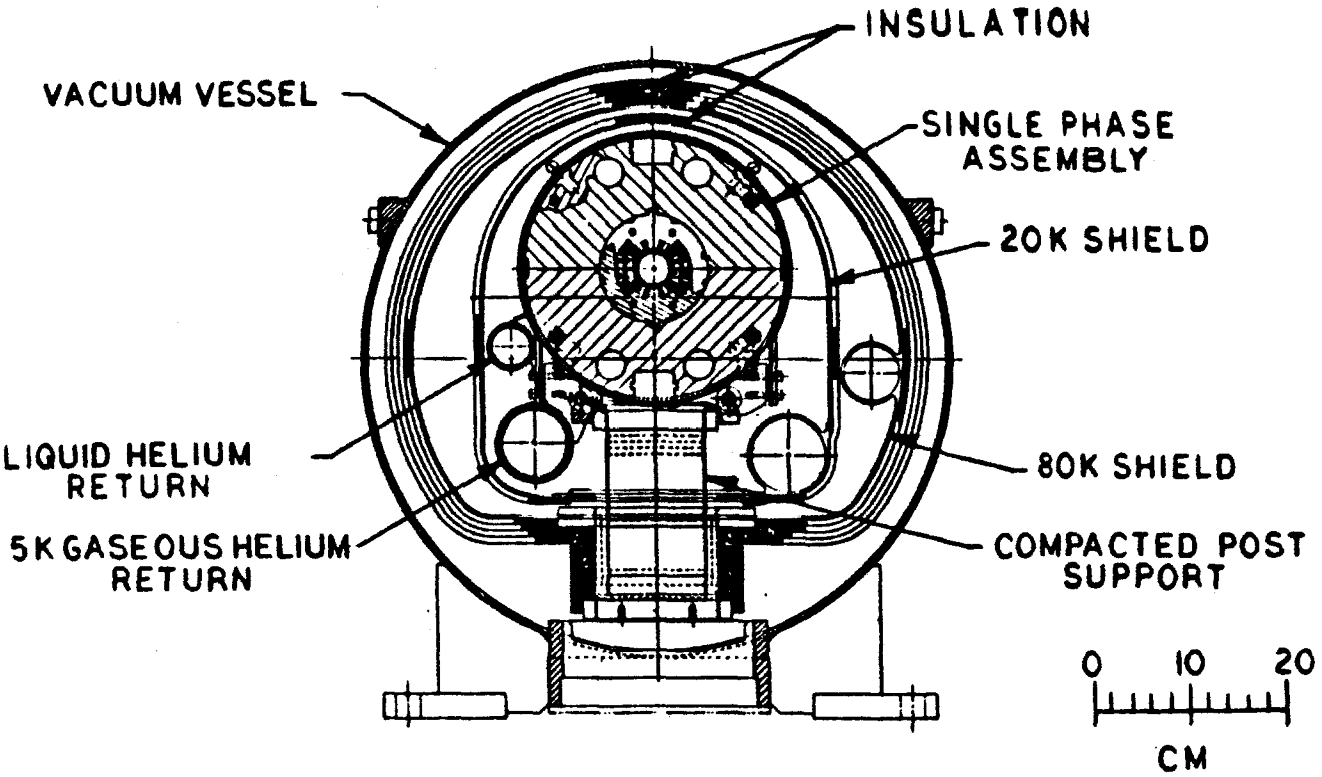

Fig. 1. 6 T magnet cryostat section

the effectiveness of each component as it relates to the overall, long-term performance of the magnet system. The design effort has involved intensive interactions with magnet, cryogenic system and manufacturing designers.

The cryogenic system requires five pipes in the cryostat. The pipes provide services for the single phase helium, liquid helium return, 5 K gaseous helium return, 20 K gaseous helium shield and 80 K liquid nitrogen shield. The 20 K shield temperature was selected to optimize the performance of the refrigeration system.[3]

The heat leak budget per magnet is given in Table 1.

During cooldown, the cryostat will be subjected to an approximate step function (300 K to 4.5 K) cooling profile through the single phase assembly. The maximum allowable time period for a dipole magnet string to be cooled from 300 K to 4.5 K is one day. This results in a 30 minute cooldown for an individual single phase assembly from 300 K to 4.5 K. The individual 20 K shield will be cooled down from 300 K to 20 K in one hour, while the individual 80 K shield will be cooled from 300 K to 80 K in two hours.

CRYOSTAT DESIGN CRITERIA

In a program as dynamic and broad as the SSC, it is often difficult to develop and maintain a set of design objectives and requirements. Once developed, uniform and timely communication within the design community can be a problem. Accordingly, a design criteria has been developed to promote an efficient and effective magnet cryostat design. The criteria

Table 1. Cryostat Heat Leak Budget/Magnet

	Watts At Temperature		
	80K	20K	4K
Radiation	17.2	1.72	.05
Supports	5.0	0.4	.055
Anchor	0.193	.013	.003
Voltage taps	0.1	.01	.01
Ends (junction)	1.0	0.05	.05
Subtotal	23.493	2.193	.168
Contingency	1.507	0.307	.132
TOTAL	25	2.5	0.3

The criteria provides the cryostat designer with a comprehensive reference document that fully defines the functional requirements of the cryostat. The contents of the criteria are given in Table 2.

The criteria document is dynamic in that it can be charged to reflect the content and scope of the magnet program. The criteria are regularly reviewed by a group that represents interests in accelerator design, magnet coil assembly design, cryostat design, cryogenic system design, manufacturing and operational safety. The experience to date with the design criteria has been very good. It has provided a forum for accelerator, magnet, cryostat and cryogenic design personnel to define the design problem and to establish guidelines for the program. Related criteria for the coil assembly, cryogenics, etc., should have a similar positive effect on the individual and integrated efforts.

SINGLE PHASE ASSEMBLY

The single phase assembly cross-section is as shown in Figure 1. The main components are the stainless steel beam tube with correction elements, a two layer $\cos\theta$ coil assembly wound with niobium titanium copper stabilized cable, laminated stainless steel Lorentz force containment collars, laminated steel yoke, warmup heaters and the stainless steel containment skin.

Table 2. Cryostat Design Criteria Contents

- Interfaces
- Tunnel installation
- Magnetic function
- Position control
- Structural loads
- Vacuum system
- Cryogenic
- Design life and operating cycles
- Radiation environment
- Storage/installation environment
- Instrumentation
- Repairs
- Design and analysis
- Material properties
- Suspension system
- Failure mode analysis

The single phase assembly has a 3.28 cm bore, 26.7 cm OD, 16.6 m magnetic length and 3 mm sagitta. The uniformly distributed mass is 4.3 kg cm^{-1} and the total mass is 7250 Kg. The 4.8 mm thick containment skin, considered to be the principle structural element, affords a flexural stiffness of $7.2X10^{6}$ Nm^{2} and a torsional stiffness of $4.4X10^{6}$ Nm^{2}.

The coil assembly is cooled by 4.4 K, 4 ATM single phase liquid helium flowing at 100 gs^{-1}. The flow is divided between the beam tube-coil annulus and cooling passages in the yoke. The return flow is divided between 4.5 K liquid and 5 K gas. The 5 K gas line reduces the pressure drop across the magnet and thus reduces the associated temperature gradient. The 20 K line provides quench buffering.

THERMAL SHIELD

Two thermal shields, operating independently at 20 and 80 K, surround the single phase assembly to absorb the radiant heat flux from warmer regions of the cryostat and provide heat sink stations for the suspension system.

The shields are 6061 T6 aluminum and are fabricated in a combination of ≈3mm thick extruded flow channels and rolled shapes. Aluminum is a material with desirable thermal properties that lends itself to normal manufacturing operations such as extruding, machining, and welding at low cost. Aluminum does not exhibit a brittle low temperature transition and remains strong and ductile at cryogenic temperatures. The low temperature strength is particularly important for the shields which must sustain the loads due to differential thermal motions associated with system cooldown and warmup.

The 5 K liquid and gaseous helium return pipes are supported from the single phase assembly. The 20 K shield is supported by and is thermally anchored to the single phase assembly suspension. The 80 K shield can be reconfigured to provide a symmetrical supplemental flow section to serve as the nitrogen return for a single ring; i.e., p-p, collider.

The shields are supported at five points with an axial anchor at mid-span. Elongated cutouts in the shield mounts provide for relative thermal motion between the shields and the supports. The design allows all shields and cooling channels to contract to their operating lengths, while other parts remain at ambient temperature. During operation, it is planned to cool the single phase assembly and 80 K shield together, followed by the 20 K shield.

A program to study thermal bowing has been developed and carried out as a part of the iron-less $\cos\theta$ SSC magnet development program.[4] A 10 K thermal radiation shield was selected for study. The thermal and structural response of the shield, when subjected to a 100 K 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 100 K.

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

INSULATION

Multilayer insulation is installed between 300 and 80 K and between 80 and 20 K surfaces to reduce radiant heat transfer. Insulation design requirements include low heat transfer, acceptable insulating properties at pressures to 10^{-2} Torr, relative insensitivity to local compressive loads, and low material and installation costs.

The selected insulation system consists of flat, reflective aluminized .0025 cm polyester film radiation shields with .025 cm random oriented fiberglass mat spacers. The system provides 18 reflective layers per cm and is prefabricated in blankets of eleven layers. Four blankets are installed on the 80 K surface and one blanket is installed on the 20 K surface. Prefabricated transition pieces and well defined installation procedures are necessary to eliminate insulation system voids that could significantly increase heat leak.

The polyester substrate and the fiberglass mat should not suffer performance degradations when subjected to the estimated radiation environment of 1×10^{8} RAD over the 20 year machine life. It is assumed that the radiation environment will be controlled by careful accelerator operating procedures; i.e., slow filling, etc.

The cryostat design insulating vacuum is 10^{-6} Torr with the single phase assembly and shields 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[5,6] and 12 m Heat Leak Model,[7,8] of the iron-less, $\cos\theta$ SSC magnet development program.

The radiation heat transfer factors employed for the design were 6.1×10^{-1} $\mathrm{Wm^{-2}}$ to 80 K, 7.5×10^{-2} $\mathrm{Wm^{-2}}$ to 20 K and 2.7×10^{-4} $\mathrm{Wm^{-2}}$ to 4.5 K. The insulation system was easily manufactured and performed well during heat leak measurements at good; i.e., 10^{-6} Torr, and poor; i.e., 10^{-2} Torr, vacuums.

The system was also evaluated from 300 to 80 K in a special test dewar[9] and yielded a mean apparent thermal conductivity of 6×10^{-7} $\mathrm{Wcm^{-1}K^{-1}}$ which corresponds to a radiation heat transfer factor of 5.8×10^{-1} $\mathrm{Wcm^{-1}K^{-1}}$ for a four blanket assembly.

SUSPENSION

The location and long term stability of the single phase assembly absolute position has the highest priority in cryostat design. The cryostat design requires that the maximum deflections of the magnet axis do not exceed the following limitations:

- Deflection relative to suspension points: 0.5 mm
- Maximum allowable variation axis from true position (over machine design life): 1.0 mm

The latter requirement permits suspension static and thermal deflections to be compensated for during installation.

The cryostat is designed to withstand structural accelerations as follow:

- High Level Shipping: Vertical = ±2.0 g, Lateral = ±1.0 g., Axial = ±1.5 g

- Low Level Shipping: Vertical = Lateral = Axial = ±0.5 g

. Handling Loads: = ±5.0 g (This load can be imposed on the cryostat with its axis <u>either</u> horizontal or vertical.)

. Seismic: Vertical = Lateral = Axial = ±0.7 g

The single phase and shield assemblies with their distributed static, dynamic and magnetic loads are supported relative to the vacuum vessel at five points along their length. The number and location of the support points was determined by the analysis of the deflection of the single phase assembly as a beam and the need to minimize the number of support points for reasons of magnet fabrication ease and low heat leak.

The suspension employs reentrant post supports, the details of which are given by Figure 2.[10] The insulating sections are G11CR tubing with metallic interconnections and heat intercepts. All junctions are made by shrink fit techniques. The post is fixed at the 300 K end and incorporates a slide at the 4.5 K end to accommodate the ≈2 cm axial differential contraction between the mid span anchored single phase assembly and the vacuum vessel. The calculated conduction heat leaks for a five support suspension system are 5.2 W to 80 K, 0.5 W to 20 K and 0.1 W to 4.5 K. These heat leaks agree well with the heat leak budget values plus 25% of the total heat leak contingency.

Significant transient bowing of the single phase assembly is not expected due to its structure, location of helium flow paths, and the cooldown and warmup procedures employed. The 20 K and 80 K shields will undergo transient bowing and the shield-post interfaces are designed to permit the relative motions and to provide support.

Post type supports were employed successfully in the iron-less, cosΘ SSC magnet development program. Single tube, pivoted post assemblies were incorporated in the 6 m Magnetic Effects Model (3 posts) and the 12 m Heat Leak Model (5 posts). The posts performed to design, both structurally and thermally. An identical instrumented post assembly was thermally evaluated in a suspension heat leak measurement dewar[11] and showed excellent agreement of predicted and observed performance.

VACUUM VESSEL

The vacuum vessel defines the insulating vacuum space and provides the support connection to the tunnel floor. The vessel will be fabricated

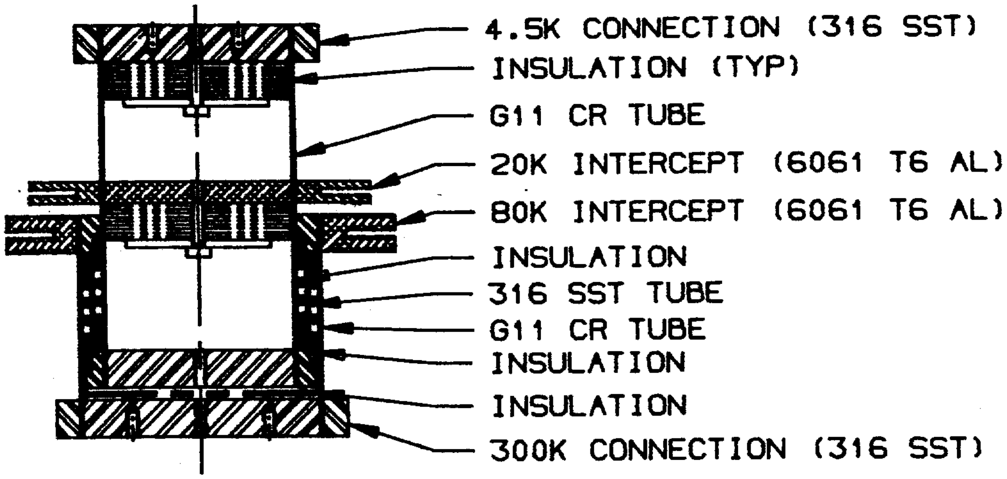

Fig. 2. Compacted post support

as a single piece sub-assembly for reasons of magnet assembly and to permit inspection of vessel welds. The magnet assembly procedure incorporates a slide-in insertion of the completed internal assembly into the vacuum vessel. The support post-vacuum vessel connection provides for the alignment of the internal single phase fiducial system with the vacuum vessel fiducial system. There is no capability for adjustment of the single phase assembly position relative to the vacuum vessel after magnet manufacture.

Since the vessel has no magnetic requirements, candidate materials were steel, stainless steel and aluminum. 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. At present, an AISI 1008 steel is planned. Alloying may be necessary to increase the notch toughness of the material to enable survival of potentially high local stresses due to cooling associated with cryogen or vacuum loss. A detailed failure analysis will determine the need for alloying.

The vacuum vessel is designed for a 5 ATM internal pressure to allow back-pressuring of the cryogenic piping to prevent the loss of valuable cryogens from operationally produced leaks.

INTERCONNECTIONS

Mechanical and electrical interconnections are made at the cryostat ends. The connections are to be straightforward to assemble and disassemble, compact, reliable and low cost.

Cryogenic piping within the cryostat and the interconnection region is designed for an internal pressure at 20 ATM which corresponds to the worst case predicted quench conditions.

All pressure tight connections; i.e., beam tube, single phase, assembly, helium return, and 20 K and 80 K pipes and the vacuum vessel, are circular, and incorporate bellows for assembly and disassembly and to allow for axial thermal contraction. The bellows will be stainless steel and employ transition joints where required. Machine welding will be employed. The beam tube connection, which is surrounded by single phase fluid, employs a double bellows whose internal volume is connected to the insulating vacuum space for leak interception. For piping, two bellows are employed in series to increase the offset tolerance.

Electrical connections, the coil bus in particular, must provide adequate motion allowance, conductor support and insulation, high reliability and low heating due to conductor joints.

CONCLUSIONS

The cryostat design meets the SSC 6T Magnet Option design criteria requirements and can be manufactured for low cost. Confidence in attaining the performance objectives is enhanced by the extensive, related cryostat experimental program for the iron-less, $\cos\theta$ SSC magnet cryostat.

ACKNOWLEDGEMENTS

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