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SUPERCONDUCTING SUPER COLLIDER SECOND GENERATION DIPOLE MAGNET CRYOSTAT DESIGN

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Abstract

The Superconducting Super Collider, a planned colliding beam particle physics research facility, requires ~10,000 superconducting devices for the control of high energy particle beams. The ~7,500 collider ring superconducting dipole magnets require cryostats that are functional, cryogenically efficient, mass producible and cost effective. A second generation cryostat design has been developed utilizing the experiences gained during the construction, installation and operation of several full length first generation dipole magnet models. The nature of the cryostat improvements is presented. Considered are the connections between the magnet cold mass and its supports, cryogenic supports, cold mass axial anchor, thermal shields, insulation, vacuum vessel and interconnections. The details of the improvements are enumerated and the abstracted results of available component and system evaluations are presented.

Introduction

The Superconducting Super Collider (SSC) Magnet Development Program is developing accelerator dipole magnets with successive design iterations. The first iteration[1] is complete with six full length magnet models and a thermal model having been built and tested. This experience along, with the evolving SSC Magnet System Requirements, has resulted in the second generation design which will be employed for the near term ongoing magnetic, thermal, string and accelerated life testing.

Cryostat

Cryostat features are critical to the performance of SSC magnets 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 reliably undergo transport, transient, steady state and upset conditions. The major cryostat components 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 cold mass axial motion during cooldown and warmup, position the magnetic axis and be compatible with a compact cryostat geometry. The connections are attached to the support posts and transfer load to the suspension system. Four of the connections accommodate relative axial motion while the anchor connection restrains the cold mass axially.

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The connection-slide design development utilized the experiences of the initial design and improved performance with regard to cold mass shell welding, cold mass angular position adjustment, dynamic load structural capacity, improved bearing performance, increased simplicity and alignment accuracy.

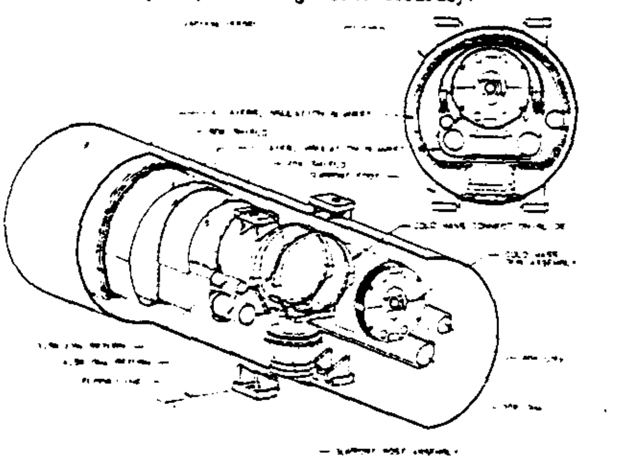

Figure 1. Cryostat assembly major components.

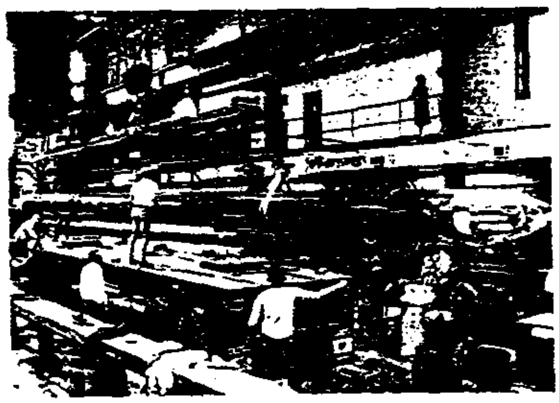

Figure 2. Magnet model loaded for transport.

The connection-slide[2] is shown by Figure 3. Four bearing blocks, containing removable bearing pads, contact the cold mass outer shell and establish its position. The blocks are mounted in upper and lower cradles. The lower cradle is secured to the support post cold end.

To function properly, the cold mass outer skin must be precise in nature relative to its thickness and form and must be installed with intimate contact to the cold mass iron yoke at the bearing contact points. The degree of precision required is dependent on the functional requirements of the skin. If the only functional requirement 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 the 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.

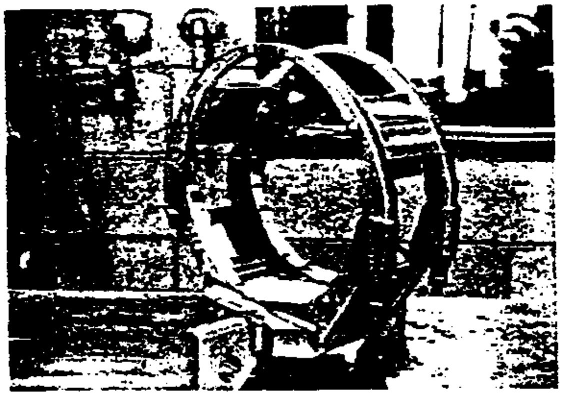

Figure 3. Cold mass connection-slide.

The connection-slides allow cold mass rotational adjustment during magnet assembly. The average vertical magnetic plane is measured and its offset is determined. The cold mass is rotated to compensate for the 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-slide retains the cold mass during transportation and seismic loading. Conical spring washers act as tensioner springs on the bolts which connect the two halves. The spring action maintains uniform loading during thermal cycling and minimizes radial differential thermal contraction effects. The connection has been successfully tested at design loads.

Evaluations of sliding characteristics were performed with a full length model at ambient conditions and with a short model at cryogenic conditions. The evaluation results indicate that the 3.3 mm (0.13 in) cold mass horizontal sagitta has little effect on sliding and cooling to 80 K increases the sliding resistance ~2.5 times ambient. The connection-slides perform acceptably for a number of cycles that greatly exceed the specified twenty cooldown - warmup cycles.

Suspension System

The suspension system resists the structural loads imposed on the cold mass, ensures position stability and insulates the cold mass from the environment.[3]

The suspension system operating stresses must be low enough to avoid material creep with sufficient reserve strength for loads imposed during shipping and handling, seismic events and internally generated axial quench loads. The suspension components are sized for structural requirements and utilize materials that afford a good compromise between mechanical strength and thermal impedance.

Support Post

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 suspension system incorporates a reentrant support post assembly[4] as shown by Figure 4. The second generation post has been modified as a result of a better understanding of the effects of seismic, shipping and handling and axial quench loads. The outer tube is a 178 mm (7 in) OD X 2.77 mm (0.109 in) wall fiberglass reinforced epoxy composite. The inner tube is a 127 mm (5 in) OD X 3.28 mm (0.129 in) wall graphite reinforced epoxy composite. The thicker walls, along with the graphite inner tube, increase the strength and stiffness of the post. The use of graphite partially offsets the increased heat load due to a thicker wall. The change to graphite is appropriate only 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.

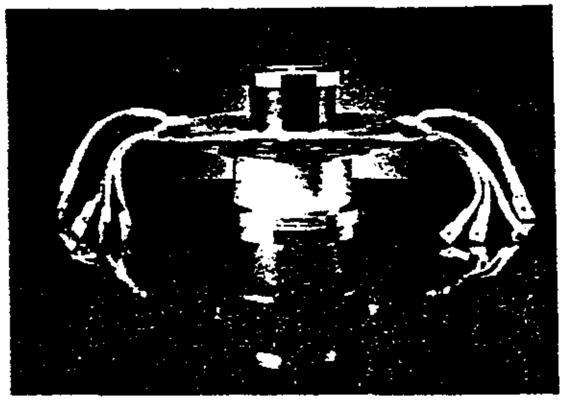

Figure 4. Support post.

The post heat loads have been measured in a heat leak test facility.[5] A heat load to 4.5 K of 0.025 W was measured. This value does not include the effects of the connection-slide. Table 1 lists heat load values.

Table 1. Support Post Heat Loads

Thermal Station	Heat Load (W) Predicted	Heat Load (W) 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. The center post is rigidly attached to the cold mass to establish axial position. Axial thermal contraction of the cold mass assembly requires axial sliding between the cold mass and the four outer posts. Thus, these posts do not participate in axial load restraint. With no other axial restraint, the center post would carry the total axial load. A single post is incapable of handling these loads. Utilizing a stronger center post would impose an intolerable heat load. In order that all five posts be combined to effectively act as a single axial restraint,[6] the cold end of each post is connected with tie bars to that of each adjacent post. Figures 5 and 6 illustrate the post-tie bar anchor system.

The tie bar is a filament wound, graphite reinforced epoxy composite 51 mm (2 in) OD X 6.4 mm (0.25 in) wall X 3.05 m (120 in) long tube. Graphite was chosen for thermal expansion. When cooled from 300 to 4.5 K, the graphite fibers grow while the epoxy shrinks. The net effect can be a tube which changes length by only a small amount when cooled down. The measured shrinkage of a prototype tie bar was 0.025 mm (0.001 in) when cooled to 80 K. Graphite is stiff and thus tends to distribute axial loads between the five support posts more evenly than a less rigid material.

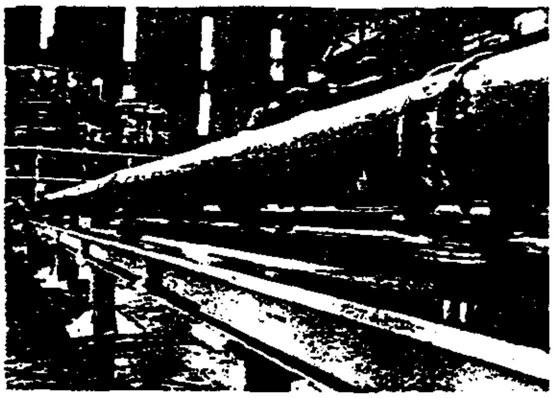

Figure 5. Anchor system with tie bars for axial load sharing.

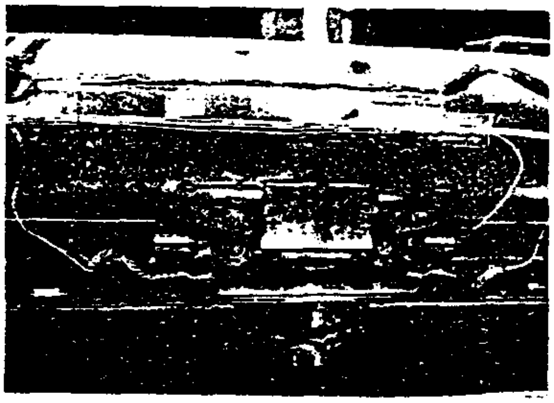

Figure 6. Cold mass center post anchor connection.

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 and thus contribute no conductive heat load. They lie completely inside the thermal shields and thus require no shield penetrations.

Ambient temperature structural testing has been done on a complete post-anchor system. Figure 7 illustrates the deflection at the tops of the five support posts and provides an indication of load sharing between posts. Figure 8 illustrates the cold mass deflection vs. applied load and indicates the integrated anchor stiffness.

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

Two thermal shields intercept radiant heat flux and provide suspension system heat sinks. Extruded aluminum pipes carry the cooling fluids; i.e., helium gas and liquid nitrogen. The shields surround the cold mass and are operated at 20 and 80 K. 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 posts. The post-shield interface permits relative axial motion for shield motion during cooldown and warmup. The shields are thermally connected to the post heat intercept rings by copper cables. The installation of the 20 K shield is shown by Figure 9.

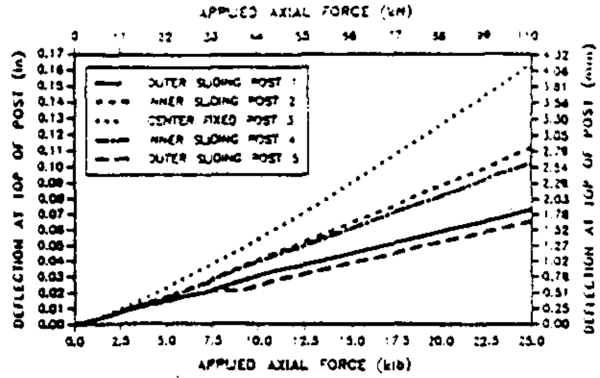

Figure 7. Post - tie bar anchor post deflection vs. load.

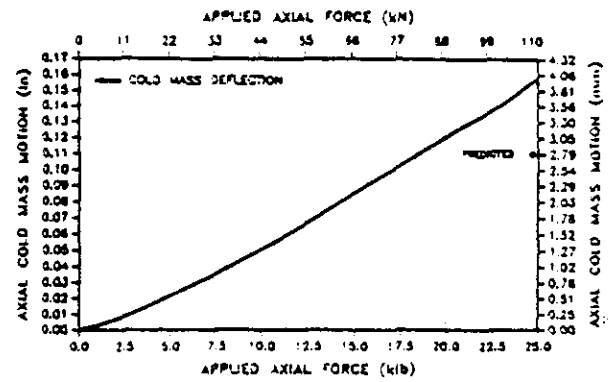

Figure 8. Post - tie bar anchor coldmass deflection vs. load.

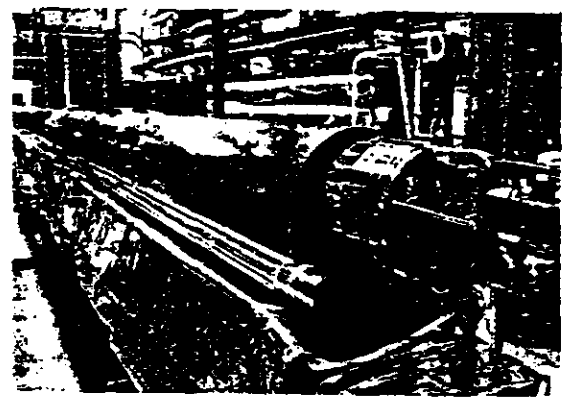

Figure 9. 20 K thermal shield during assembly.

The initial generation shields performed well but were 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 section has two components instead of five, resulting in reduced assembly time and cost. The shields are thinner, resulting in reduced material and forming costs. The heat sink strap lugs are crimped 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. Assembly and fastening is by spot welding rather than fusion welding. The lower shield half is pulled up along the posts from the bottom during assembly instead of being split and welded. The longitudinal bottom weld had poor accessibility and was time-consuming to make and could result in considerable shield distortion.

Predictions and measurements of shield bowing during cooldown and warmup will be made to establish the shield structural integrity and elastic nature of 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 with spacer fabricated and installed as blankets on the cold surfaces.

The second generation blanket materials are a double aluminized polyester film reflective layer with a spunbonded polyester spacer that separates 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 80 K indicated that 59 layers were required to meet the 80 K heat leak budget. Thus, the 80 K shield insulation consists of an assembly of four blankets. The 20 K shield insulation consists of two blankets. Insulation is 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, 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. A single blanket consisting of 5 reflecting layers and 4 spacer layers is employed.

Insulation development continues.[7] The performance of candidate insulation systems between 80 and 4.5 K 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 continue to be refined during long magnet model fabrication.

Vacuum Vessel

The vacuum vessel provides the insulating vacuum required for the control of residual gas conduction heat transfer and transfers the internal structure loads 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 vessel shell is a 610 mm (24 in) OD X 6.4 mm (0.25 in) wall steel tube.

A reinforcing ring is welded to the vacuum vessel at the mounting positions of the internal supports. The 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 shell bottom.[8]

The initial generation vacuum vessel has been incorporated into one short (4.5 m) and six long (16.6 m) 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.

For installation and alignment purposes, the five external supports employed in the first generation cryostat overconstrain the installed position since two external supports are adequate to fix the magnet assembly location. However, two supports are not sufficient to support the cold mass. The cold mass static sag supported at two points is ~12.7 mm (0.5 in). The solution selected was to retain five internal support posts between the cold mass and vacuum vessel and to eliminate three of the five external feet. Figure 10 shows the second generation vacuum vessel. The vessel is built with a vertical precurve to reduce its static deflection when loaded by the magnet 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.

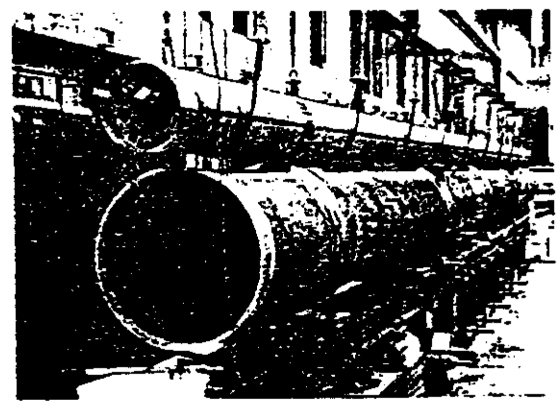

Figure 10. Vacuum vessel assembly during vertical precurve verification measurements.

The vacuum vessel is fabricated from prefabricated, 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 facilitates the vertical precurving of the vacuum vessel assembly.

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

Interconnections

The cryostat interconnection consists of seven pipes, with bellows which accommodate the axial cooldown and warmup motion, that must be connected. All pipes are stainless steel except the steel vacuum shell. All connections will be welded with automatic welding units when installed and will be cut apart with orbital pipe cutters when removed.

The interconnection is developed from the cold mass center outward. 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 conduction. The other side is unattached but overlaps enough for the magnet to contract upon cooldown. Shields are insulated as they are on the body of the magnet. The final connection made is the vacuum shell. An interconnection during assembly is shown by Figure 11.

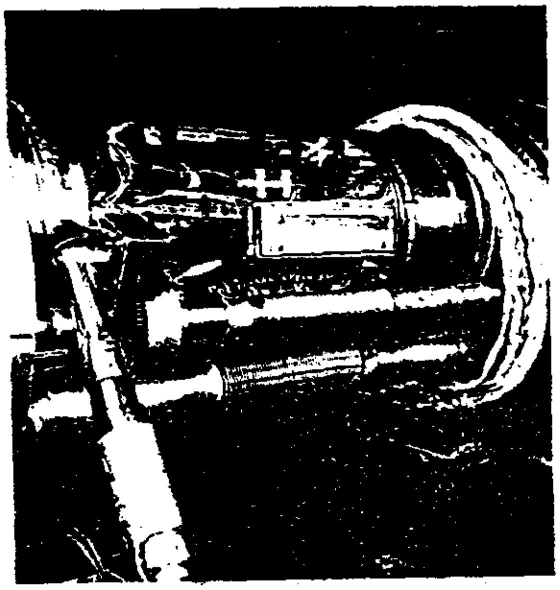

Figure 11. Welding of liquid helium return line.

The second generation interconnection is different from the initial version 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 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 do not need to be removed from one end of the magnet. They become part of the magnet and will only be welded and cut off on one end. This eliminates four welds and four cuts per end. For the helium return and shield pipe connections, a sleeve is used instead of a consumable washer. The 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

Several units of the second generation design will be incorporated into the model magnet program. The initial unit was extensively instrumented to monitor cryostat performance as compared to that predicted and that measured for individual components and subassemblies. Details of the cryostat measurements will be reported later. This design will be employed for the balance of the FY88 and for all of the FY89 model magnet program.

Conclusions

- The second generation SSC dipole magnet cryostat is a logical extension of the successful initial generation 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.

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

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

- A continuing and timely development effort is necessary to support the second generation 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 handling and installation, transportation and seismic loading, vacuum vessel pumpdown, cooldown and warmup, quench, operation in strings and life testing

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