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STRUCTURAL DESIGN AND ANALYSIS FOR A DOUBLE-BAND COLD MASS SUPPORT OF MICE COUPLING MAGNET

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ABSTRACT

The cooling channel of Muon Ionization Cooling Experiment (MICE) consists of eighteen superconducting solenoid coils, which are magnetically hooked together. A pair of coupling magnets operating at 4 K is applied to produce up to 2.6 T magnetic field on the magnet centerline to keep muon beam within the RF cavity windows. The peak magnetic force on the coupling magnet from other magnets in the MICE channel is up to 500 kN in longitudinal direction, and the requirements for magnet center and axis azimuthal angle at 4 K are stringent. A self-centered double-band cold mass support system with intermediate thermal interruption is applied for the coupling magnet. The physical center of the magnet does not change as it is cooled down from 300 K to 4.2 K with this support system. In this paper the design parameters of the support system are discussed. The integral analysis of the support system using FEA method was carried out to determine the tension forces in bands when various loads are applied. The magnet centre displacement and concentricity deviation form the axis of the warm bore are obtained, and the peak tension in support bands is also determined according to the simulation results.

KEYWORDS: MICE coupling magnet, cold mass support, self-centered, double-band, FEA method.

INTRODUCTION

The muon ionization cooling experiment (MICE) will be a demonstration of muon cooling in a configuration of superconducting solenoids and absorbers that may be useful for a neutrino factory [1]. The MICE cooling channel shown in FIGURE 1 contains two

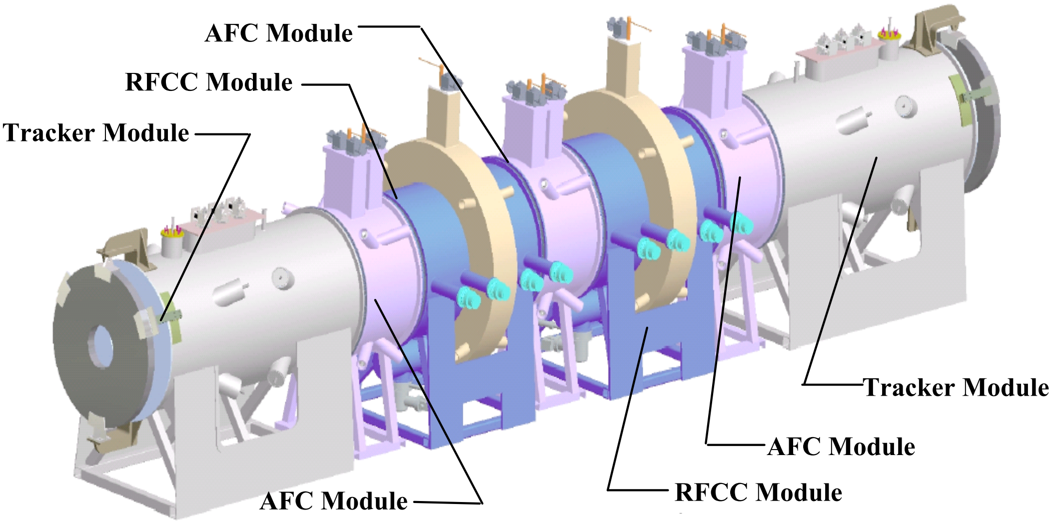

FIGURE 1. A 3D View of the MICE Cooling Channel with spectrometer magnets

tracker modules, three absorber focus coil (AFC) modules that focus and ionize cool the muons in an absorber inside the focusing magnet and two RFCC modules that reaccelerate the muons back to their original longitudinal momentum. The RFCC module comprises a superconducting coupling solenoid magnet mounted around four conventional conducting 201.25 MHz closed RF cavities bounded by thin beryllium windows [2]. The function of the coupling magnet is to produce enough magnetic field up to 2.6 T on the magnet centerline to keep the beam within the iris of the thin RF cavity windows.

The engineering design and fabrication of a pair of coupling magnets are being carried out by the Institute of Cryogenics and Superconductivity Technology (ICST) in Harbin Institute of Technology (HIT) in collaboration with the Lawrence Berkeley National Laboratory (LBNL) [3]. The design of the cold mass supports is one of the key issues for the fabrication of the coupling magnets. This paper presents the design parameters and the structure of the cold mass support for the coupling magnet. The performance of the cold mass support was also analyzed using FEA method.

REQUIREMENTS FOR SUPPORT SYSTEM DESIGN

The MICE coupling coil is a single 285 mm long solenoid wound on a 6061-T6-Al mandrel. The inner radius of the coil is 750 mm and its thickness is 102.5 mm at room temperature. The basic parameters of the coupling coil are listed in TABLE 1. FIGURE 2 is the 3-D view of the MICE coupling magnet [3]. The coupling coil, powered though a pair of copper (upper part of the lead) and HTS (lower part of the lead) power leads, is indirectly cooled by a pair of pulse tube coolers with cooling capacity of 1.5 W at 4.2 K each, though cooling tubes immerged in the cover plate using thermo-siphon principle.

The eighteen MICE superconducting coils in seven modules are magnetically coupled together without iron shields to shield the coils and return the flux. So the coupling magnet will feel large magnetic forces from the other coils in the MICE channel. After the magnet is cooled down and fully charged, the cold mass support must withstand the forces put on the magnet during a quench or a fault as well as when the MICE channel is normally operated besides its weight. According to the calculations using FEA method, the peak magnetic force on the coupling magnets happens when one coupling coil's leads reverses

TABLE 1. The Basic Parameters for MICE and MuCool Coupling Magnets [3]. (In the flip mode, the direction of the field in the focusing magnets changes. In the non-flip mode both coils in the focusing magnet are at the same polarity and the filed direction doesn't flip. As a result the magnet current in the coupling magnet is higher in the flip mode than in the non-flip mode.)

Parameter	**Flip**	**Non-flip**
Coil Length (mm)	285	
Coil Inner Radius (mm)	750	
Coil Thickness (mm)	102.5	
Number of Layers	96	
No. Turns per Layer	166	
Magnet Self Inductance (H)	592.5	
Magnet J (A-mm^{-2})*	114.6	108.1
Magnet Current (A)*	210.1	198.2
Magnet Stored Energy (MJ)*	13.1	11.6
Peak Induction in Coil (T)*	7.4	7.12
Coil Temperature Margin (K)*	~0.79	~1.1

* The Worst case design based on p = 240 MeV/c and _= 420 mm

in the flip mode at 240 MeV/c, and the peak value is up to 416.4 kN, along longitudinal direction towards the channel center [4]. The design longitudinal force on the coupling coil is set as 500 kN considering the contingency, and the design radial force is set as 50 kN considering that the coil cold mass is around 1500 kg.

The cold mass support of the coupling magnet is not only to transmit both the cold mass gravity force and the electromagnetic force from the 4.2 K cold mass to the vacuum vessel of the cryostat at 300 K, but also to withstand the shipping loads from Harbin in China to Fermilab and Berkeley in the US at room temperature. Therefore, the cold mass support for the coupling magnet should meet the following requirements as well [5]: a) The allowable displacements of the coil current center is 1 mm along the longitudinal direction and 0.3 mm along the radial direction. The maximum allowable tilt of the cold mass axis is

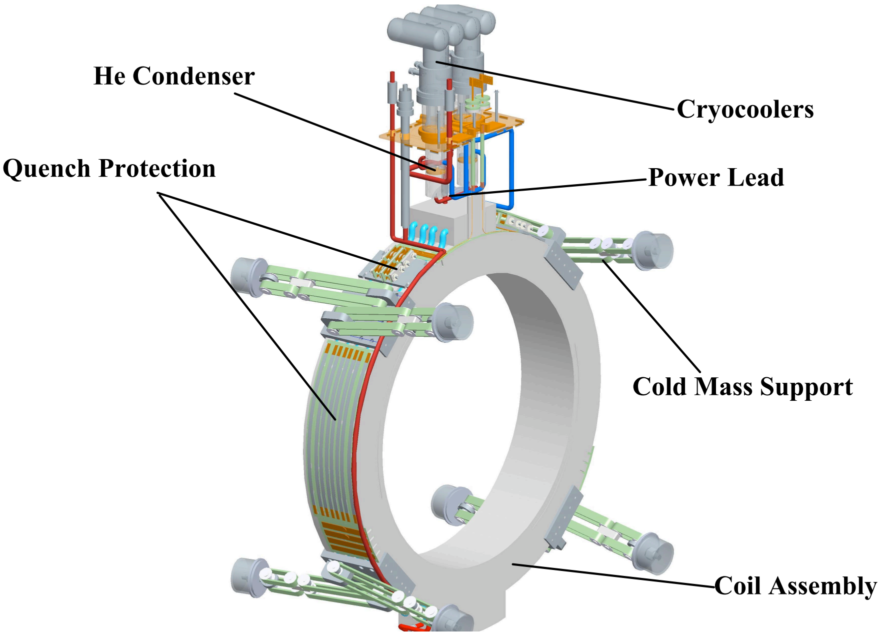

FIGURE 2. A 3-D view of the MICE coupling coil magnet with the double band cold mass supports

less than ±0.001 radian. b) The heat leak along the whole support system to 4 K region should be less than 0.25 W due to the limited cooling capacity of cryocoolers. c) The support should withstand both 500 kN force along longitudinal direction and 50 kN force along the radial direction. The spring constants for the cold mass support system along both longitudinal and radial direction should be greater than $2x10^8$ N-m^{-1}. d) The cold mass support system should withstand the shipping loads during long-distance transportation

PARAMETER AND STRUCTURE OF SUPPORT SYSTEM

A self-centered double band support system shown in FIGURE 2 is applied on the coupling magnet so that the magnet center does not change during the cool-down process from 300 K to 4.2 K. It consists of eight support strap assemblies, four at each end of the magnet. Its warm ends are near the vacuum vessel ends at azimuthal angles of 45, 135, 225, and 315 degrees. The cold ends are at the same angles but off by ±5 degrees toward the mid-plane to avoid space interference. The support system is configured so that it provides rotational restraint. When the magnet is cooled down from 300K to 4K and fully charged, the displacements of support cold ends are obtained by the coupled field FEA analysis on cold mass, which are shown in TABLE 2. The displacements of support ends are closely associated with the pre-stress value in bands.

FIGURE 3 shows the 3-D view of a support strap assembly. Each support strap assembly consists of four oriented fiberglass epoxy (E-Glass) support bands with attachment hardware at each end and an intermediate temperature intercept between the bands. The width, thickness and inner diameter of the band are respectively 40 mm, 8 mm and 50 mm. The intermediate temperature intercept is connected to the thermal shield for cooling through a copper strip. The intermediate temperature is expected to be less than 70 K. The cold clevis and base plate will be fabricated from stainless steel, and bolted to the outer surface of the cold mass. The thermal intercept section between the support bands will be fabricated from stainless steel also. The room temperature end of the support system will be mounted on the vacuum vessel through a stainless steel sleeve.

FEA ANALYSES ON THE COLD MASS SUPPORT PERFORMANCE

Integral Physical Model of Cold Mass Support System

A 3-D Integral FEA model of the cold mass support system was built using ANSYS to verify the self-centered characteristics of the support, to determine the tension forces in

TABLE 2. The Cold Mass Support End Positions at Different Cold Mass Temperatures and Charge States

Warm End angle (degree)	45
Warm End R (mm)	1036.23
Warm End Z (mm)	582.00
Cold End Angle (degree)	50
300K Cold End R (mm)	956.50
300K Cold End Z (mm)	-125.50
4.2K Cold End R (mm)	952.96
4.2K Cold End Z (mm)	-125.04
4.2K & Charged Cold End R (mm)	953.53
4.2K & Charged Cold End Z (mm)	-125.02

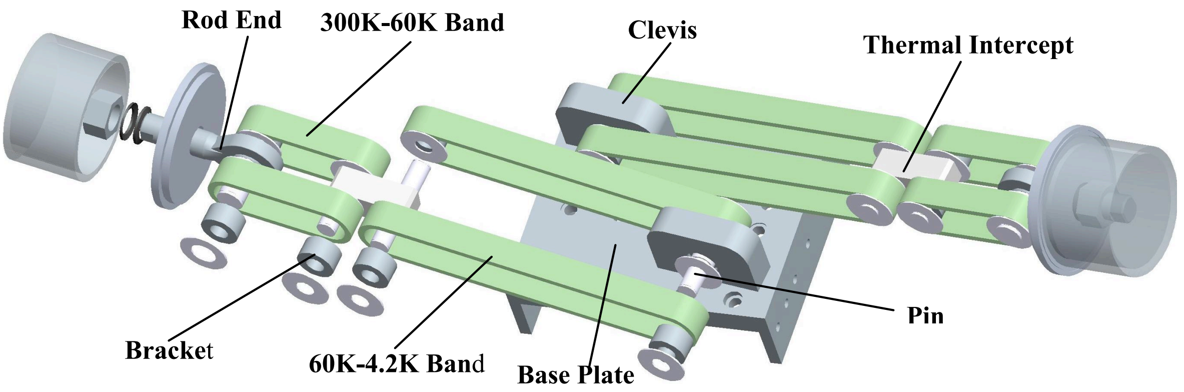

FIGURE 3. The structure of a double band cold mass support assembly

support bands when various loads are applied on the support system and to obtain the magnet center displacement and concentricity deviation form the axis of warm bore as well.

The ANSYS model shown in FIGURE 4 is simplified as the following: a) The support assembly consists of only tension bands, neglecting thermal intercept and rod ends. b) The two tension bands are regarded as a single one with the same cross-section area 1280mm^2 and the mass of tension bands are neglected. c) The cold mass is regarded as a solid rigid column, of which the mass is 1500 kg. The warm ends of support are totally fixed and the displacements of cold ends are coupled with the displacements of corresponding attached points on cold mass.

Verification of Self-centered Characteristic

The following loads are applied on the ANSYS model in FIGURE 4: The pre-stress in eight bands are set uniformly as 23 MPa. The temperature of the cold mass is changed from 300 K to 4 K, and the mean thermal expansion coefficient of the cold mass is 1.1486 x 10^{-5}. The thermal contraction of the bands is not considered, because the contraction only causes the same pre-stress change in bands which does not affect the force and moment equilibrium.

According to the simulation results, the tension in band is reduced by 4.4 MPa due to the thermal contraction of the cold mass, which means that the distance between the cold end and the warm end is reduced. The magnet center displacement is of the order of two microns and the concentricity deviation from warm bore axis is of the order of 10^{-6} radian, which can be neglected. So the cold mass support system of MICE coupling magnet is self-centered during the cooldown from 300 K to 4 K.

Peak Tension in Support Bands

The support system will be sealed by welding caps at the warm ends after the final alignment. Adjustment of the cold mass supports will no longer be possible after sealing, so the pre-tension level in bands at 300 K will affect the pre-tension in bands after cool-down and fully charged. The peak tension in bands in the worse case is directly related to the transportation schemes of the coupling magnet. There are two transportations of the coupling magnet: a) The 2.5 gravity (g) dynamic shipping load at 300 K is taken only by support bands. b) The 2.5g dynamic shipping load along radial direction is taken by special facilities (such as anti-collision nails) in the cryostat other than taken only by the tension bands. When the 2.5g dynamic shipping load at 300 K is afforded only by support bands, the pre-stress at 300 K should be able to keep all the bands from slacking under the shipping load 2.5-g along any direction, and at the same time the corresponding pre-stress

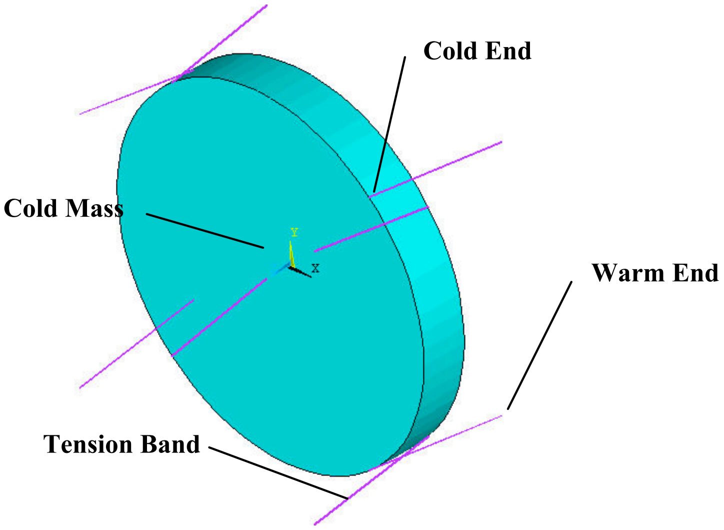

FIGURE 4. The ANSYS model of MICE coupling magnet support system

in the band after cooled down to 4.2 K and fully charged should keep all the bands from slacking under the load both 500 kN along either longitudinal direction and 1-g gravity of the cold mass along the vertical direction. According to the simulation result using the ANSYS model shown in FIGURE 4, the minimum pre-stress allowable is 59 MPa at 300 K, and the magnet center displacements and magnet axis tilt are listed in TABLE 3. The peak force on the support assembly is 221 kN when carrying 500 kN longitudinal force and 1-g gravity of the cold mass. The design force of each support assembly will be as large as 265 kN considering 20% contingency.

When the 2.5g dynamic shipping load along radial direction is taken by special facilities in the cryostat other than only by the tension bands, only the 1-g gravity load along any direction needs to be considered. Because support system dose not have any problem carrying the 2.5g shipping load along longitudinal direction considering that the directions of support bands are almost paralleled with magnet center axis. The load on the support system at 4 K when the system was fully charged is the same as the load for 2.5g warm transportation scheme. The simulation results show that the allowable pre-stress at 300 K is 23 MPa and the peak force on the support assembly is 174.6 kN when carrying 500 kN longitudinal force and 1-g gravity of the cold mass. The design force of each support assembly will be set as 200 kN considering contingency.

TABLE 3 Support Parameters as Function of Transportation Schemes

Parameter		**Transportation Schemes**	
		2.5-g Warm	**1-g Warm**
300 K Pre-stress (MPa)		59	23
4.2 K Cool-down (MPa)		110	74
4.2K & Charging (MPa)		108	72
Peak Tension in Band (MPa)		172.4	136.4
Peak Tension force (N)		2.207×10^5	1.746×10^5
Magnet Center Displacements (mm)	DX	-1.58×10^{-3}	-1.58×10^{-3}
	DY	-2.62	-2.62
	DZ	-0.864	-0.864
Concentricity Deviation from axis (mrad)		0.308	0.308

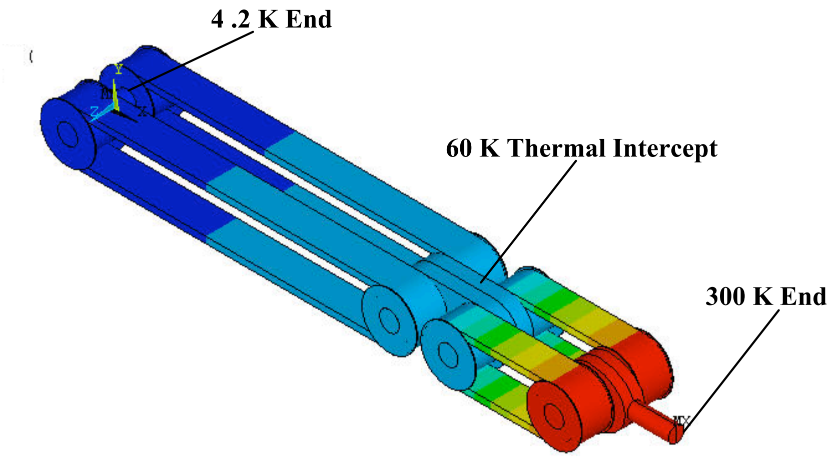

FIGURE 5. Temperature distribution on the cold mass support assembly

Considering the stringent stress margin of both support assembly and vacuum vessel due to the design force with the first transport scheme, the second transportation scheme will be applied for coupling magnet. According to the results in TABLE 3, for both transportation schemes the maximum displacement of the magnet center along both the axial and the horizontal direction meets the position accuracy requirements as shown above. The vertical displacement of the magnet center is 2.62 mm, which can be compensated in advance by tuning the support bands after the temporary support sytem is removed from the cold mass. The maximum tilt of the cold mass axis is 0.308 mrad, which meets the requirement as well.

Thermal and Structural Analysis of the Support Assembly

The thermal and structural analysis of the support assembly was carried out using FEA method. The temperature distribution on the cold mass support assembly is shown in FIGURE 5. The heat leaks based on the properties of G-10 for one cold mass support from 60 K to 4.2 K and 300 K to 60 K are respectively 0.0388 W and 1.19 W. The heat flows down all the eight supports are 0.31 W and 9.52 W respectively. The thermal conductivity of E-Glass is about two thirds of the thermal conductivity of G-10 [6], so the heat leak down the cold mass support system can be less than 0.25 W at 4 K.

Applying the design force 200 kN on the support assembly, the average von Mises stress on the support band is 156 MPa, and the peak stress is 213 MPa occurred on the inner surface of the band around the support pin due to both tension and bending effects of band, which is lower than one-third of tension strength of E-Glass.

CONCLUSION

A self-centered double-band cold mass support system has been designed for the MICE coupling magnet. The self-centering characteristic of the cold mass support was verified because the magnet center displacement was of the order microns and magnet center axis change is of the order of 10^{-6} radian during cool down of the magnet from 300 K to 4 K, which is well within the specified limits. The 2.5g dynamic shipping load along radial direction will be carried by special facilities (such as anti-collision nails) in the cryostat other than only by the tension bands. The design tension force on each cold mass support assembly is about 200 kN considering contingency. The heat leak through all eight cold mass supports to 4 K from 60 K is 0.21 W. The heat leak through all eight cold mass assemblies from 300 K to 60 K is about 6.37 W. The ratio of the heat leak through the cold mass support system to the total available refrigeration from two coolers is about seven percent on both stages.

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REFERENCES

1. Gregoire, G., Ryckewaert, G., Chevalier, L., et al, “MICE and International Muon Ionization Cooling Experiment Technical Reference Document.” Available: http://hep04.phys.itt.edu/cooldemo
2. Li, D., Green, M.A., Virostek, S. P., Zisman, M. S., “Progress on the RF Coupling Module for the MICE Channel,” Proceedings of 2005 Particle Accelerator Conference Knoxville TN, pp 3417, 2005.
3. Institute of Cryogenics and Superconductivity Technology, “Engineering design of MICE/MUCOOL coupling solenoid magnet (2008)”, Harbin Institute of Technology.
4. Wu, H., Wang, L., et al, “A Single-band Cold Mass Support System for MICE Superconducting Coupling Magnet,” Proceedings of ICCR2008 Shanghai in China, 2008, pp 351-355.
5. Lawrence Berkeley National Laboratory, “Technical Agreement about MICE Coupling Magnet”, 2007
6. Green, M. A, Lawrence Berkeley National Laboratory, private communication, May 2007.

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