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# Design and Analysis of a Self-centered Cold Mass Support for the MICE Coupling Magnet

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***Abstract*—The Muon Ionization Cooling Experiment (MICE) consists of eighteen superconducting solenoid coils in seven modules, which are magnetically hooked together since there is no iron to shield the coils and the return flux. The RF coupling coil (RFCC) module consists of a superconducting coupling solenoid mounted around four conventional conducting 201.25 MHz closed RF cavities. The coupling coil will produce up to a 2.2 T magnetic field on the centerline to keep the beam within the RF cavities. The peak magnetic force on the coupling magnet from other magnets in MICE is up to 500 kN in longitudinal direction, which will be transferred to the base of the RF coupling coil (RFCC) module through a cold mass support system. A self-centered double-band cold mass support system with intermediate thermal interruption is applied to the coupling magnet, and the design is introduced in detail in this paper. The thermal and structural analysis on the cold mass support assembly has been carried out using ANSYS. The present design of the cold mass support can satisfy with the stringent requirements for the magnet center and axis azimuthal angle at 4.2 K and fully charged.**

***Index Terms*—Superconducting Magnet, Cold Mass Support, Self-centered, Coupling Coil**

## I. 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 muon cooling channel contains two spectrometer modules to analyze muons and other particles that enter and leave the MICE cooling channel [2], three absorber focus coil (AFC) modules that focus and ionization cool the muons in an absorber inside the focusing magnet [3], and two RF coupling coil (RFCC) modules that reaccelerate the muons back to their original momentum [4]. The RFCC module comprises a superconducting coupling solenoid magnet mounted around four conventional conducting 201.25 MHz closed RF cavities bounding by thin beryllium windows [5]. The coupling coil will produce up to a 2.2 T magnetic field on the centerline to keep the beam within the RF cavities.

The eighteen MICE superconducting coils in seven modules are magnetically coupled together without iron shields to shield the coils and return the flux [6]. The large magnetic force on the coupling magnet from the other magnets in MICE in longitudinal direction will be transferred to the base of RFCC module through a cold mass support system. A self-centered double-band cold mass support system with intermediate thermal interruption is applied for the coupling magnet. The design of the cold mass support is introduced in detail in this paper. The thermal and structural analyses on the cold mass support assembly are presented also.

## II. MICE COUPLING MAGNET

The MICE coupling coil wounded on a 6061-T6-Al mandrel is a single superconducting solenoid, which is fabricated from commercial NbTi conductor with the critical current about 760 A at 5 T and 4.2 K. The basic parameters of the coupling magnet are listed in Table I [7]. Under the flip mode, the field direction generated by the focusing magnets changes different from that under the non-flip mode. The current in the coupling magnet is to be higher in the flip mode than that in the non-flip mode. The coupling coil, powered though a pair of binary power lead, is indirectly cooled by liquid helium flowing in cooling tubing nested in the cover plate of the coil case using thermo-siphon principle [7]. The pulse tube coolers with the cooling capacity of 1.5 W at 4.2 K each will be used..

TABLE I Basic Parameters of Coupling Magnet

| Parameter | Flip Mode | Non-flip Mode |
|---|---|---|
| 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 Current Density (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 $\beta$= 420 mm

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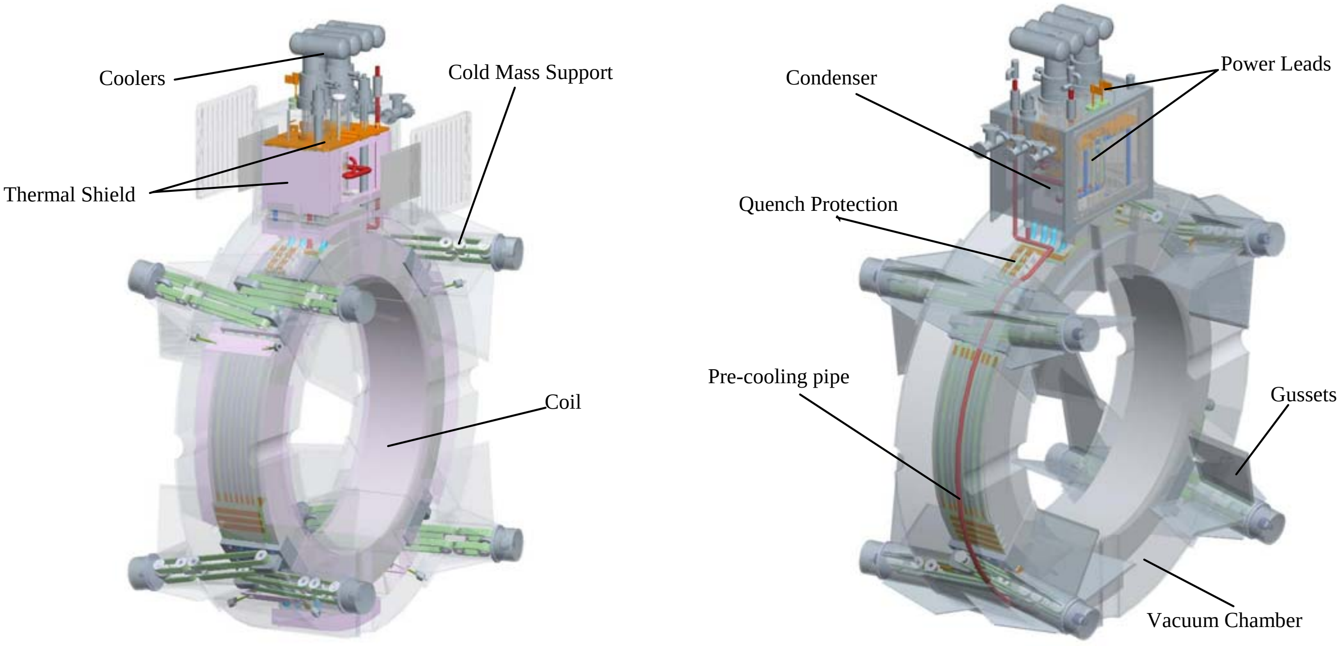

Fig. 1. 3D model of MICE coupling magnet

The coupling magnet consists of the 4.2 K cold mass assembly and the cryostat, as shown in Fig. 1. The 4.2 K cold mass assembly consists of the superconducting coil and its mandrel, quench protection assembly, two LHe vessels and the cooling tubing nested into the cover plate. The total mass is about 1600 kg. The coupling magnet cryostat includes the magnet cooling system, cold mass support system, thermal shield assembly, power leads, vacuum chamber and measurement system.

## III. REQUIREMENTS FOR COLD MASS SUPPORT SYSTEM

### *A. Peak Magnetic Force on the Coupling Magnet*

Since the superconducting magnets in MICE are magnetically coupled together, the coupling magnet will suffer the large magnetic force from the other coils. After the magnet is cooled down and fully charged, its cold mass support system must take on the forces on it during a quench or a fault as well as when the MICE channel is normally operated besides its weight. According to the calculations of the magnetic force using FEA method [8], the magnetic force on the coupling coil during normal operation is 253.2 kN departing from the channel center. The peak magnetic force happens when the power leads of a coupling coil is reversed, and the value is 416.4 kN towards the channel center. So 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 cold mass is 1600 kg.

### *B. Requirements for Support System*

The cold mass support system for the coupling magnet should meet the following requirements [11]: 1) It should withstand both 500 kN force along the longitudinal direction and 50 kN force along the radial direction after fully charged. The spring constants for the cold mass support system along both the longitudinal and the radial direction should be greater than $2\times10^8$ $\mathrm{Nm}^{-1}$. 2) It should withstand the shipping loads during long-distance transportation. 3) The allowable displacements of the coil current center is ±0.5mm along the longitudinal direction and ±0.3 mm along the radial direction. The maximum allowable tilt of the cold mass axis is less than ±0.001 radian. 4) The heat leak along the whole support system to the 4.2 K region should be less than 0.25 W due to the limited cooling capacity of cryo-coolers.

## IV. STRUCTURE OF COLD MASS SUPPORT

### *A. Angles of Cold Mass Support Assembly*

A self-centered double-band cold mass support system shown in Fig. 1 is applied to the coupling magnet so that the magnet center does not change during the cool-down process from 300 K to 4.2 K [9]. It consists of eight identical support strap assemblies, four at each end of the magnet. As shown in Fig. 2, the position coordinates of the cold ends of the supports are at the center of clevis hole on the cold base, and the position coordinates of the warm ends of the supports are at the center of interface between the load cell and the end plate of support sleeve on vacuum chamber. The current center of the coupling magnet is set as the coordinate origin, and the central line of the magnet is set as Z axis. The support warm ends are at azimuthal angles of 45, 135, 225, and 315 degrees on the end plates of the support sleeves on the vacuum chamber, the support cold ends are at the same angles but offset by ±5 degrees. It is configured in order to avoid interference between two opposite support assemblies and provide rotational restraint for 4.2 K cold mass.

### *B. Structure of Cold Mass Support Assembly*

Fig. 2 show the 3-D view of a pair of support assemblies. Each support assembly consists of four oriented fiberglass epoxy (E-Glass) bands, an intermediate temperature interception between the bands, the cold base and the warm end

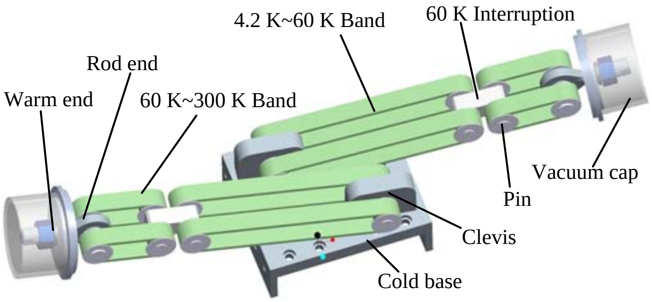

Fig. 2. 3D view of the cold mass support assembly

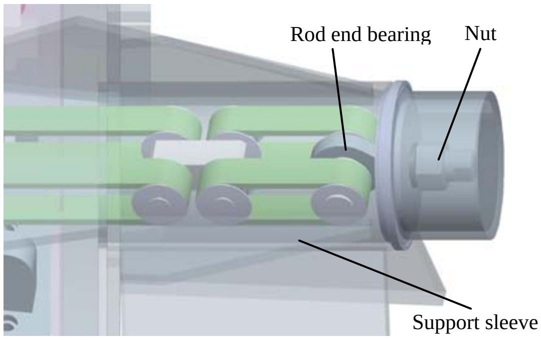

Fig. 3. Structure of the cold mass support warm end

attachment. The intermediate temperature interruption is cooled by heat conduction through a copper strip connected to the thermal shield. The intermediate temperature is expected to be less than 70 K.

The cold end is fixed to the clevis of the cold base through a high strength pin and a bearing. The cold base consists of the stainless steel clevis and the base plate, which is bolted to the outer surface of the cold mass by sixteen stainless steel bolts. The two end plates on the sides of the cold base are accurately fixed to the end plate of the cold mass by pins. The load imposed on the cold mass along the longitudinal direction is transferred to the support bands by the end plate of the cold mass. The load imposed on the cold mass along the radial direction is transferred to the support bands by the pins on the end plates and the bolts on the base plate.

At the warm end the tensile force of support bands is transferred to the vacuum chamber through a rod end bearing and a stainless steel support sleeve, as shown in Fig. 3.

## V. PARAMETERS OF COLD MASS SUPPORT

### A. *Coordinates of Cold Mass Support Ends*

The position changes of support ends are closely associated with the tension in bands, which need accurate calculations. During cool down and charge of the coupling magnet, the positions of the warm ends don’t vary, but the positions of the cold ends change. The FE analysis was carried out to obtain the position changes of the cold ends by solving the electric-magnetic-thermal-structural coupled fields. A 2-D axisymmetric model of the cold mass was built. During cool down process, the cold mass contracts along both the radial and the axial direction. During charge process, the cold mass contracts along the axial direction, and meanwhile expands along the radial direction due to the magnetic force in the coil. The position changes of the cold mass support ends at different phases are listed in TABLE II [10].

TABLE II POSITIONS OF COLD MASS SUPPORT ENDS AT DIFFERENT PHASES

| | |
|---|---|
| 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 |

### B. *Stresses in Support Assembly at Different Phases*

The self-centered characteristic of the support system for MICE coupling magnet was verified in [10]. The present cold mass support system is designed to take on 1-g gravity load along any direction at 300 K and to withstand 500 kN load along the longitudinal direction and its gravity along the vertical direction after cooled down to 4.2 K and fully charged. During shipment at 300 K, the 2.5-g shipment load along the radial direction will be undertaken by specially designed facilities in the cryostat other than by tension bands.

The pre-stress in support bands should be 23 MPa at room temperature after the vacuum chamber is pumped. The corresponding stress in support bands after the coupling magnet is cooled down is 74 MPa. After fully charged, it will be 72 MPa. The peak tension in the support assembly is 174 kN, when the support system suffers both 500 kN longitudinal force and its gravity. Considering the contingency, the design force of the cold mass support assembly is set as 200 kN.

## VI. THERMAL AND STRUCTURAL ANALYSIS ON COLD MASS SUPPORT ASSEMBLY

### A. *Thermal Analysis of Cold Mass Support Assembly*

The temperature distribution along the cold mass support was simulated using ANSYS as shown in Figure 3. The temperature of the support cold end is assumed at 4.2 K, 300 K at the support warm end and 60 K at the thermal interception. The bands are assumed only contact with the outer faces of brackets. The calculated heat leak for one cold mass support from 60 K to 4.2 K is 38.84 mW, and the total heat leak down the eight cold mass supports is about 0.31 W, assuming the bands made of G-10. The calculated heat leak for one cold mass support from 300 K to 60 K is 1.19 W, and the total heat leak is about 9.58 W. The thermal conductivity integral of the oriented fiberglass support band is about two thirds of that of G-10 [12]. So the heat leaks down the cold mass support system to 4.2 K and 60 K are 0.207 W and 6.39 W respectively.

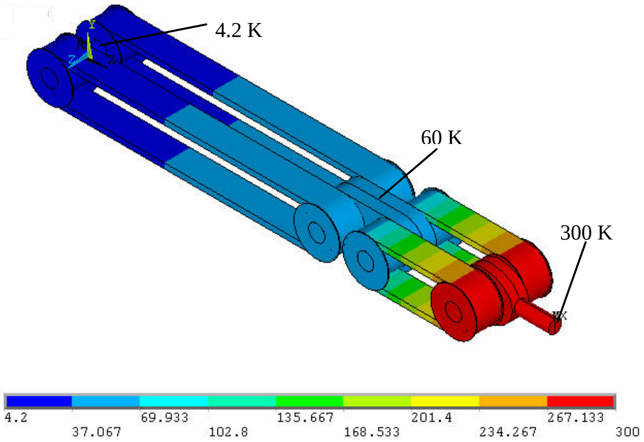

Fig. 4. Temperature distribution on the cold mass support assembly (K)

### B. *Structural Analysis of Cold Mass Support Assembly*

Due to the symmetry, a structural FE model for half of the cold mass support assembly is built using ANSYS. The mechanical properties of the materials at 300 K for the support assembly are used. The following boundary conditions and loads are applied: 1) The warm end at room temperature is completely constrained. 2) Apply symmetry condition on the symmetry plane. 3) Apply the pressure of 131.6 MPa on the area of pin contacting with the cold end bearing, which is corresponding to the design force of 200 kN. 4) The interfaces between support bands and brackets are contact condition.

Because the warm end of the support is fixed, the peak displacement happens at the cold end, which is 3.31 mm under 200 kN force. The spring constant of the support assembly can be calculated using Hooke Law, which is $6.04\times10^{7}$ $\mathrm{Nm}^{-1}$. So the spring constant of the support system is eight times of that value, which is $4.83\times10^{7}$ $\mathrm{Nm}^{-1}$.

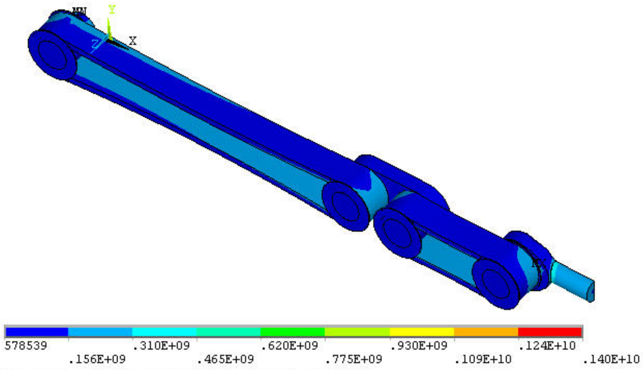

Fig. 5. Von Mises stress on the cold mass support assembly (Pa)

The von Mises stress on the whole support assembly is quite high, partly due to the stress concentration, which is shown in Fig. 5. The stresses at suspicious stress concentration areas are linearized to eliminate the effect of stress concentration. 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 the band, which is lower than one-third of tension strength of E-Glass. The Von Mises stresses on the rod end bearing, the thermal interruption and the pins are at a safe level. So the cold mass support assembly can afford the 200 kN design force.

## VII. CONCLUSION

A self-centered double-band cold mass support system is applied to the coupling magnet so that the magnet center does not change during the cool-down process from 300 K to 4.2 K. Its structure and parameters are discussed in detail. The heat leaks down the cold mass support system to 4.2 K and to 60 K are calculated as 0.207 W and 6.39 W respectively. The spring constant of the support system is $4.83\times10^{7}$ $\mathrm{Nm}^{-1}$. The cold mass support assembly can afford the design force of 200 kN.

## ACKNOWLEDGMENT

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