STRUCTURAL DESIGN AND THERMAL ANALYSIS FOR THERMAL SHIELDS OF THE MICE COUPLING MAGNETS

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ABSTRACT

A superconducting coupling magnet made from copper matrix NbTi conductors operating at 4 K will be used in the Muon Ionization Cooling Experiment (MICE) to produce up to 2.6 T on the magnet centerline to keep the muon beam within the thin RF cavity windows. The coupling magnet is to be cooled by two cryocoolers with a total cooling capacity of 3 W at 4.2 K. In order to keep a certain operating temperature margin, the most important is to reduce the heat leakage imposed on cold surfaces of coil cold mass assembly. An intermediate temperature shield system placed between the coupling coil and warm vacuum chamber is adopted. The shield system consists of upper neck shield, main shields, flexible connections and eight supports, which is to be cooled by the first stage cold heads of two cryocoolers with cooling capacity of 55 W at 60 K each. The maximum temperature difference on the shields should be less than 20 K, so the thermal analyses for the shields with different thicknesses, materials, flexible connections for shields' cooling and structure design for their supports were carried out. 1100 Al is finally adopted and the maximum temperature difference is around 15 K with 4 mm shield thickness. The paper is to present detailed analyses on the shield system design.

KEYWORDS: MICE coupling magnets; Thermal shield; FEA

INTRODUCTION

The Muon Ionization Cooling Experiment (MICE), to be operated at the Rutherford Appleton Laboratory in the UK, will be a demonstration of muon cooling in a configuration of superconducting solenoids and absorbers [1]. The MICE cooling channel consists of alternating three absorber focus coil modules (AFC) and two RF coupling coil modules (RFCC) [2-3]. The superconducting coupling solenoid is mounted around four conventional 201.25 MHz closed RF cavities bounding by thin beryllium windows and is to produce 2.6 T magnetic field to keep the beam from expanding beyond the edge of the RF cavity thin windows [4].

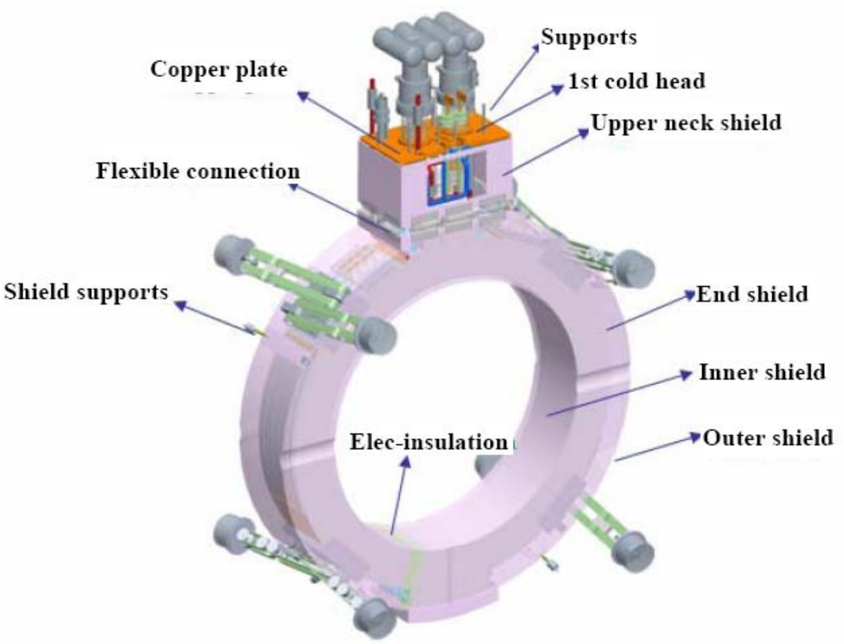


FIGURE 1. 3D view of thermal shields in coupling magnet cryostat.

The coupling coil made of commercial copper matrix NbTi conductor is to be cooled by using two cryocoolers that produce up to 1.5 W at 4.2 K each. The operation temperature margin of the coupling coil at 210 A is only about 0.8 K. Therefore, it is necessary to install intermediate temperature shields between the coil cold mass and the warm vacuum chambers in order to reduce the heat leakage directly from the room temperature to 4.2 K.

The thermal shields are to be cooled by conduction through the copper plates attached to the first-stage cold heads of cryocoolers running at approximately 60 K. The maximum temperature difference on the thermal shields is designed to be less than 20 K so that the hot spot temperature on them should be no larger than 80 K. This paper discusses in detail the thermal analyses of design of the shields in detail.

STRUCTURE OF THERMAL SHIELDS

The thermal shield system consists of an inner shield, an outer shield and two end shields as shown in FIGURE 1. The outer shield is divided into two parts: upper neck part and main part, which are connected together by flexible metal strips to take account into the thermal strain during cooling down. The upper neck part will be welded with the copper plates attached to the first-stage cold heads of the cryocoolers by copper-aluminum transition parts. The upper neck shield and copper plates are supported by the warm top plate of the cryostat with four G-10 supports. The main outer shield, the inner shield and the end shields are slit into two parts by G-10 elec-insulation in order to avoid generation of eddy current during magnet charging, discharging and quench. The main shields around the magnet cold mass will be supported individually by eight tension rods connected to the outer vacuum chamber. To reduce heat leakage, the thermal shields will be insulated with 50~60 layers of multilayer insulation (MLI).

THERMAL ANALYSES ON WALL THICKNESS AND MATERIALS OF THERMAL SHIELDS

The thermal shield system will be cooled through heat conduction by the first-stage cold head of the cryocoolers at around 60 K. In order to keep the hot spot temperature on the shields less than 80 K, the shields should be made from the material

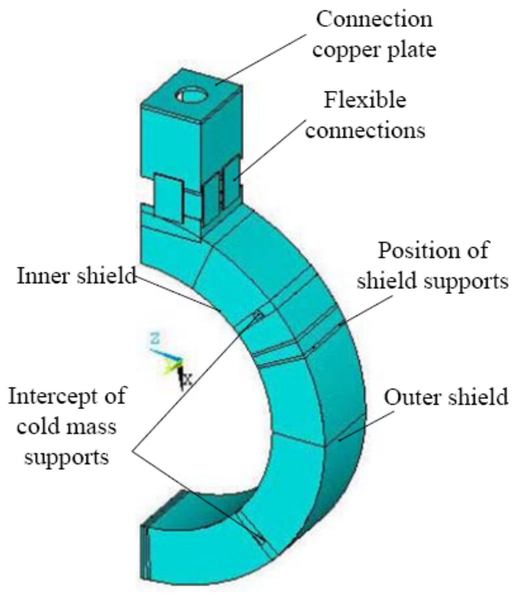
TABLE 1. Heat leakage to the shields at 60 K.

Heat Leakage Source	Heat load (W)
Copper leads	19.30
Cold mass supports	9.9
Radiation heat to 60 K thermal shields	8.7
60 K Intercepts for instrumentation wires	1.0
60 K intercepts for neck tubes	4.823
Heat shield supports	4.0
Upper neck shield supports	0.62

with good thermal conductivity. The heat load from room temperature to the shields includes radiation heat and conduction heat from copper leads, intercepts of various neck tubes and cold mass supports, shields' supports and instrumentation wires. The refrigeration capacity of the first-stage cold head of the cryocooler is 40 W at 40 K, 45 W at 50 K, 55 W at 60 K, respectively [5]. TABLE 1 lists the heat leaks to the shields.

Two kinds of materials, copper and aluminum, may be considered for the thermal shields. Thermal simulation for shields made from the two materials were carried out and compared by FEA method. The thermal shields are considered as symmetric and one half 3-D are modeled as shown in FIGURE 2, The main dimensions of the thermal shields are shown in TABLE 2. The shields and flexible connections in finite element model are made of the copper with RRR of 20 or 1100 aluminum. The connection plate to the cooler and thermal intercepts of the cold mass supports are made of pure copper with RRR of 60. The flexible connections are simplified as straight.

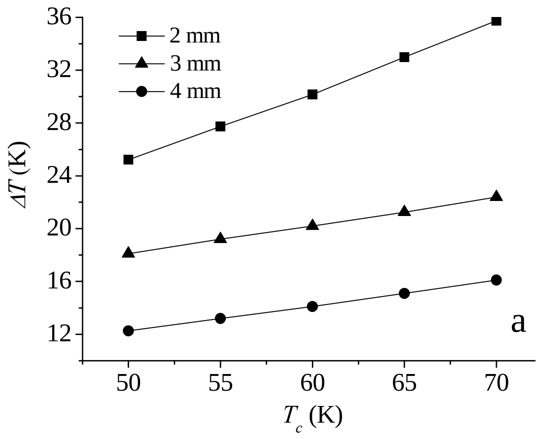
There are five heat load conditions applied on the finite element model: (1) Radiation heat load (half of 8.7 W) applied to all external surfaces of the model; (2) Heat loads from cold mass supports applied to the copper blocks (1.236 W per block); (3) Heat loads from shield supports applied to the position of shield supports (2 W); (4) Heat loads from various intercepts applied to the connection plate. (5) 45 W, 55 W and 60 W of refrigeration capacity put onto the copper plate with the temperature at the copper plate set at 50 K, 60 K and 70 K respectively.



Parameters	Dimensions (mm)
Inner diameter of inner shield	1431
Outer diameter of outer shield	2056
Width of inner and outer shields	389
Height/width/length of neck shield	522/389/920
Width/length/thickness of flexible connection*	1500/150/8

*Width of flexible connection is the total width of all the connections

FIGURE 2. FE Model and the basic dimensions of the components in thermal shields listed in the FE model.



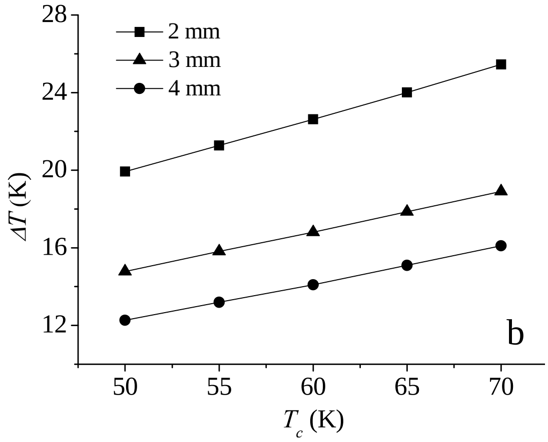


FIGURE 3. ΔT_{max} on the 1100 Aluminum (a) and pure copper (RRR=20) (b) shields with wall thickness.

The temperature difference ΔT on both copper and 1100 Al shields with 4 mm thick is less than 20 K even when the temperature on the connection plate goes up to 70 K. For the 4 mm thick shields, the weight of a copper shield is 338 kg and the weight of an aluminum shield is 102 kg. Considering to keep the weight load imposed on the four vertical G-10 supports connected to the warm top plate of the cryostat as light as possible, the material of thermal shields is selected as 1100 aluminum.

FIGURE 4 shows the temperature distributions on the 1100 aluminum shields with thickness of 3 mm and 4 mm, respectively, when the temperature on the cold connection plate is set at 60 K. The hot temperature on the shields occurs at their bottom due to the symmetric, it is about 75 K with the 4 mm thick and 80 K with the 3 mm thick. Hence, the wall thickness of the aluminum shields is designed as 4 mm.

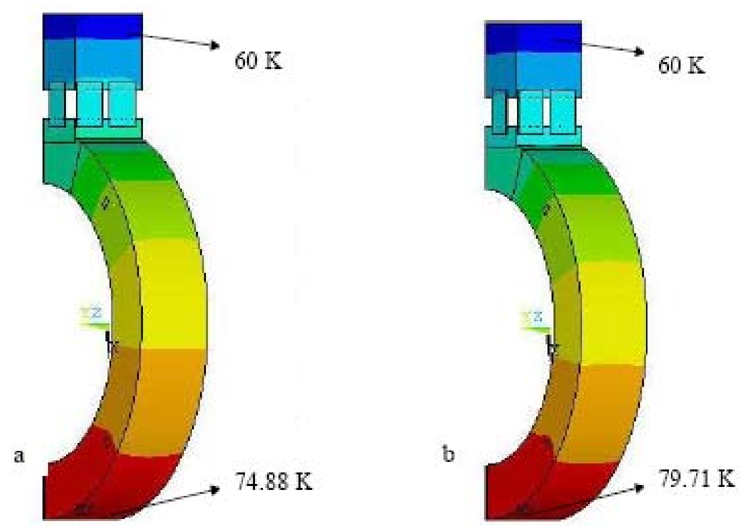


FIGURE 4. Temperature distribution on 4 mm (a) and 3 mm (b) thick shields made of 1100 aluminum.

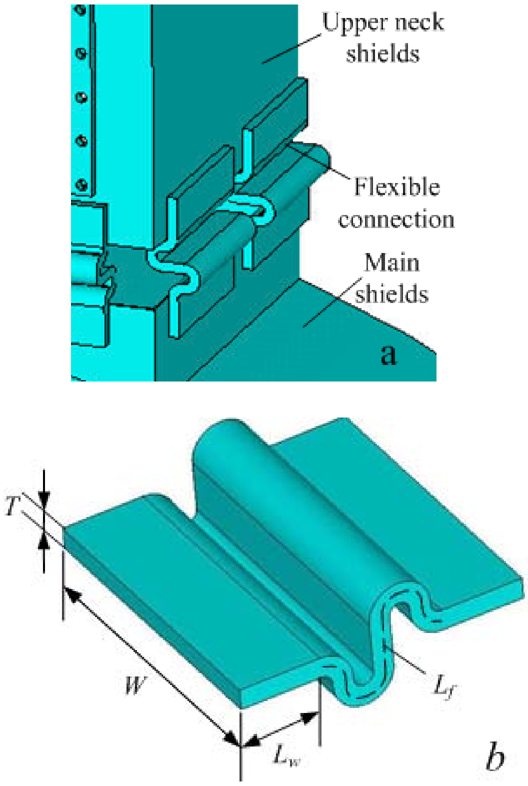


FIGURE 5. Diagram (a) and the dimensions definition (b) of flexible connection.

OPTIMIZATION OF THE DESIGN OF THERMAL SHIELD FLEXIBLE CONNECTIONS

The total weight of the shields made of 4 mm thick aluminum is about of 102 Kg, which is to be supported by eight G-10 rods and eight side supports respectively. During cool down, thermal stress will appear due to contraction of the shields and the connection copper plate. Flexible connection will be used to connect the shields in order to release the thermal stress and protect the cold heads of the cryocooler from destruction. The flexible connection is composed of Al strips with ends welded to the upper neck shield and to the main shield. In order to keep the temperature difference along the strips less than 2 to 2.5 K, the flexible connection design is optimized.

FIGURE 5 shows the flexible connection structure. Each of the flexible connection is cut from a whole board with same shape. *W* is the transverse width of each flexible connection; the total width is the width of entire board. For each flexible connection, it will be fillet welded with the neck or main shields along all the edges of flat parts at both ends. The L_w is the longitudinal length of the flexible connection welded; the L_f is the flexible length of ripple part of one connection. *T* is the thickness of connection.

The temperature difference along the connection flexible part is ΔT_F, which can be calculated using the expression (1):

$$\Delta T_F = Q_L \cdot \frac{L_f}{\lambda \cdot W \cdot T} \tag{1}$$

where λ is the thermal conductivity; Q_L is the heat leakage through connections. For the aluminum shields, the heat leakage is the sum of the first three terms of the heat load defined in the above. The total temperature difference ΔT_t includes the temperature difference along the connection flexible part and the temperature difference of the welds.

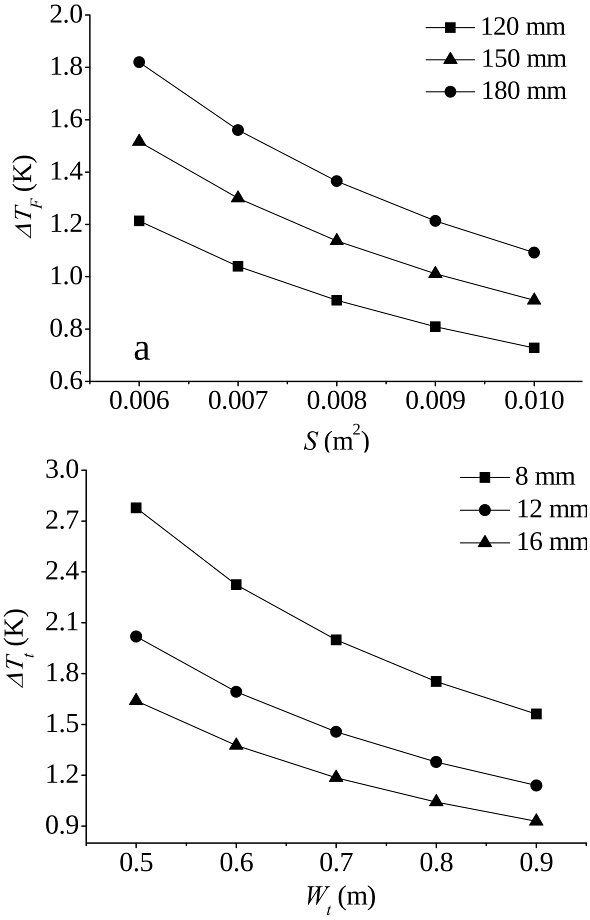


FIGURE 6. Relation between the conduction cross-sectional area S and temperature difference ΔT_F (a) and the relationship between the total width W_t and the total temperature difference ΔT_t of the connection at different thickness of the connection (b).

FIGURE 6a shows the relationship between the conduction cross-sectional area and the temperature difference along the connection flexible part for different lengths of the connection.

FIGURE 6b presents the relationship between the total width and the total temperature difference ΔT_t along the whole connection at different thicknesses of the connection with 40 mm welding length. The length and thickness of the flexible part should be more than 120 mm and less than 150 mm respectively for easy manufacture, therefore the minimum conduction cross-sectional area is 6400 mm^2 and the total width is more than 600 mm.

TABLE 2 lists the optimized dimensions of the flexible connections. For half one shield, the circumference of the neck shields is about 1300 mm, considering the welding gap, it can be welded 24 connections with width of 50 mm, therefore the total width of the flexible connection for half one shield can be 750 mm. The thickness of 8 mm of the flexible connection meets the requirement.

TABLE 2. Dimensions of flexible connection.

Parameters	Value (mm)
Thickness T	8
Welding length L_w	40
Width W	50
Length of flexible strip L_f	150

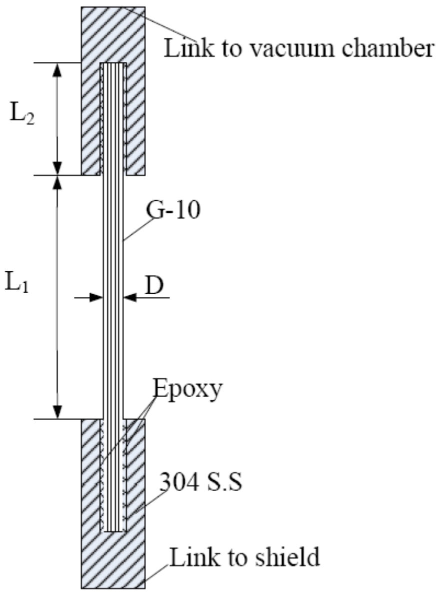


FIGURE 7. Structure of shields supports.

DESIGN OF THE THERMAL SHIELD SUPPORTS

The main shields are to be supported by four pairs of supports as shown in FIGURE 7. First, the shield supports are to withstand shipping loads at room temperature. Secondly, after the shield system is cooled down, they must withstand a certain amount of forces due to shrinkage of the shield system towards the mechanical center besides its weight. Thirdly, the supports should have a low thermal conductivity in order to minimize the conduction heat load. So, the supports mainly consist of an unifilar G-10 stick and two 304 stainless steel sleeves, which are to be glued together by epoxy. The tensile stress applied to the supports is transferred as the shear stress of the epoxy, so the depth of G-10 rod into the stainless steel sleeve is the key factor to affect the maximum allowable tensile force of the supports.

Considering assembly and transportation, the shield supports should withstand shield gravity in both vertical and horizontal direction. During transportation, the shield supports also withstand a dynamic load of 3-g load in the horizontal direction. Because the tensile stress is transferred as the shear stress of the epoxy, the allowable shear stress of epoxy is 13 MPa with a safety margin relative to 30 MPa [6], assuming that the filling rate of epoxy is 0.7, then the maximum allowable force is shown in FIGURE 8 at different diameters. Considering minimizing the heat leakage from the supports, the diameter is desired as small as possible. The G-10 stick with 8 mm diameter used for the shield supports has a heat leakage of 0.38 W, and when the insert depth L_2 is 15 mm

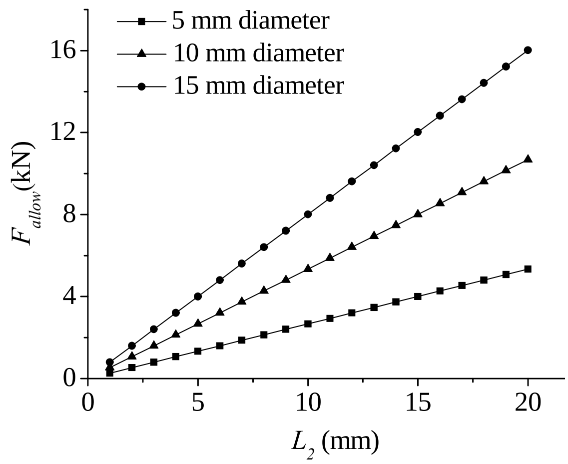


FIGURE 8. Maximum allowable tensile force applied on one support at difference diameter.

at each end, the maximum allowable force can be up to 4 kN, which meets the transportation requirement. Therefore, a diameter of 8 mm was chosen for the G-10 and the total length (including insert depth L_2) of G-10 is 50 mm; the insert depth L_2 at each end is 15 mm.

CONCLUSIONS

Conduction cooled thermal shields made from 1100 aluminum with 4 mm thickness are adopted in the MICE coupling magnet based on the thermal analyses. When the temperature of connection cold plate is 60 K, the hot spot temperature on the shields is 74.8 K, and the maximum temperature difference ΔT_{max} is about 14.8 K. The flexible connections are used in order to release the thermal stress. The temperature difference in the connections is estimated to be below 2 K with a thickness of 8 mm, a total width of 1500 mm and a total length of 230 mm. The composed G-10 and stainless steel supports are designed for shields. Each of the support can withstand 4 kN and have the heat leakage of 0.38 W with the G-10 diameter of 8 mm, the insert glued depth of 15 mm and the total length of 50 mm.

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