MICE Note 219
LBNL-6ttttt

Design of Current Leads for the MICE Coupling Magnet

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ABSTRACT

A pair of superconducting coupling magnets will be part of the Muon Ionization Cooling Experiment (MICE). They were designed and will be constructed by the Institute of Cryogenics and Superconductivity Technology, Harbin Institute of Technology, in collaboration with Lawrence Berkeley National Laboratory. The coupling magnet is to be cooled by using cryocoolers at 4.2K. In order to reduce the heat leak to the 4.2K cold mass from 300 K, a pair of current leads composed of conventional copper leads and high temperature superconductor (HTS) leads will be used to supply current to the magnet. This paper presents the optimization of the conventional conduction-cooled metal leads for the coupling magnet. Analyses on heat transfer down the leads using theoretical method and numerical simulation were carried out. The stray magnetic field around the HTS leads has been calculated and effects of the magnetic field on the performance of the HTS leads has also been analyzed.

INTRODUCTION

The MICE, to be operated at the Rutherford Appleton Laboratory in UK, will provide the first demonstration of the muon ionization cooling technique, which is critical to the success of a future muon-based accelerator system and neutrino factory[1]. One of its key components, the MICE cooling channel, consists of alternating three absorber focus coil module (AFC) and two RF coupling coil module (RFCC). 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. A function of the coupling coil magnetic field is to produce a low muon beam beta function in order to keep the beam from expanding beyond the edge of the RF cavity thin windows[2]. The coupling solenoid will be powered by using a single 300A/±10 V power supply that is connected to the magnet through a single pair of leads that are designed to carry a maximum current of 210A. A pair of binary current leads, composed of copper leads and high temperature superconducting (HTS) leads, are to be used in order to reduce heat leak into the 4.2 K region [3].

The binary leads are conduction-cooled by two-stage cryocoolers [3]. The upper warm end of the coupling coil HTS leads is connected to the cold end of copper lead. And the cold end of HTS lead is connected to a 4.2 K niobium titanium pigtail leading from the coupling coil. Most of heat leak from the copper leads is taken away by the first stage cold head of cryocooler which is connected to both the cold end of copper leads and the warm end of HTS leads. Only a little heat flows into 4K temperature region along the HTS leads by conduction. Because the coupling magnet is not shielded, there is stray magnetic field around the HTS leads. The performance of HTS leads is both a function of the magnetic field and the temperature at the warm end of HTS leads. So the position and orientation of HTS leads will be determined by the stray field at the top end of the HTS leads[4].

This paper presents the optimization of conventional conduction-cooled metal leads for the coupling magnet, and analyses on effects of the magnetic field on the performance of the HTS leads.

DESIGN OF THE CONVENTIONAL COPPER LEADS

Generally, pure copper is used as the material of conventional metal current leads since its thermal and electrical conduction is well. Heat leakage down the copper lead comes from two sources: conducted heat from room temperature and joule heat generated within the lead. The Fourier rate equation shows that conduction heat is proportional to the conduction area and inversely related to the length. The effect of area and length on the joule heat is totally different from the conduction heat. For a given current and the material, there is an optimal relationship for length and area which makes the heat leak minimum.

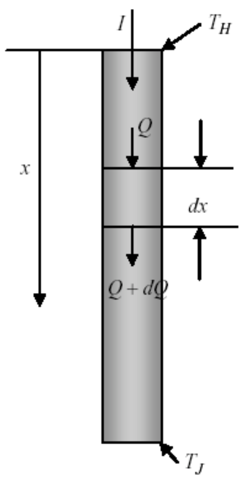

Figure 1. A Schematic of a 1D Conduction Cooled Cu Lead

Figure 1 shows a single conduction-cooled copper lead. The lead carries a current I. The top and bottom of lead are kept at higher temperature T_H and lower temperature T_J. Combine the Fourier rate equation for one dimensional steady heat transfer and energy conservation of principle. The minimum heat leak Q_{opt} at the cold end of lead and the shape factor $(IL/A)_{opt}$ under optimal operation can be described as follows:

$$\frac{Q_{opt}}{I} = \sqrt{2\int_{T_J}^{T_H} k(T)\rho(T)dT} \tag{1}$$

$$\left[\frac{IL}{A}\right]_{opt} = \int_{T_J}^{T_H} \frac{k(T)dT}{\sqrt{2\int_{T_J}^{T_H} k(T)\rho(T)dT}} \tag{2}$$

where: A is the cross-sectional area, L is the length of lead, k(T) is the temperature dependent thermal conductivity of material, and ρ(T) is temperature dependent electrical resistivity of material.

Most of pure metals and alloys obey the Wiedemann-Franz Law (WF) fairly well, i.e. $k(T)\rho(T) = L_O T$, Note that the value of $L_O = 2.45\times10^{-8}$ W-Ω K^{-2} is the Lorentz constant[5]. To apply the WF on the above expressions, then Eq. (1) and Eq. (2) become:

$$\frac{Q_{opt}}{I} = \sqrt{L_O(T_H^2 - T_J^2} \tag{3}$$

$$\left[\frac{IL}{A}\right]_{opt} = \frac{1}{\sqrt{L_O}}\int_{T_J}^{T_H} \frac{k(T)dT}{\sqrt{T_H^2 - T^2}} \tag{4}$$

From Eq. (3), the theoretical minimum heat leak Q_{opt} is almost independent of the materials to be used.

Under the optimal operating condition, the heat leak to the cold end of lead is equal to the joule heat generated in the lead from the energy conservation of principle. Hence, the voltage drop along the lead can be obtained:

$$(\Delta V)_{opt} = \frac{Q_{opt}}{I} \tag{5}$$

The conduction copper lead used for the MICE coupling solenoid can be optimized based on the above equations. Both 210A and 280A of leads are designed. The results for two current leads are listed in Table 1.

Table 1 Theoretical optimized results of copper leads for MICE coupling magnet

Optimized Current *I* (A)	210	280
Temperature Range T_H - T_J (K)	300 - 60	300 - 60
Material	*RRR*=10 Cu	*RRR*=10 Cu
Minimum heat leak per Lead Q_{opt} (W)	9.652	12.869
IL/*A* (A/m)	3.071×10^6	3.071×10^6
Optimized length *L* (mm)	384	384
Cross-sectional area *A* (mm^2)	26.25	35
Voltage drop per Lead at I_{opt} *V* (mV)	46	46

Finite volume method is used to simulate the steady temperature profile of the above 210A current lead. Figure 2 shows the temperature distributions of the 210A current lead when carrying 0A, 210A and 250A. The corresponding heat leak at the bottom of the lead is 5.638W, 9.074W and 11.069W. The heat leak at a current of 210A is consistent with the theoretical calculated result listed in Table 1. When the lead carries a current of 250A, the peak temperature on the lead is about 307A. So the lead can carry a current of 250A safely.

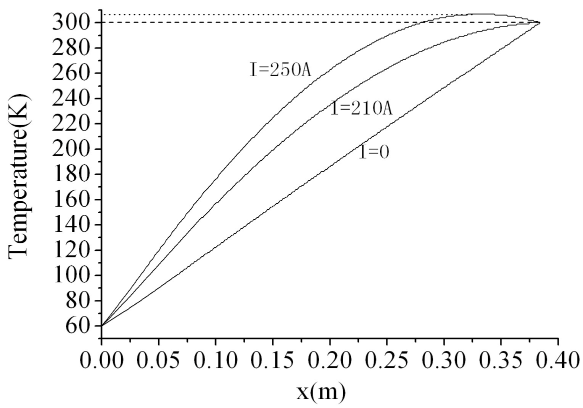

Figure 2. Lead Temperature Profile while the Lead Carries Different Currents

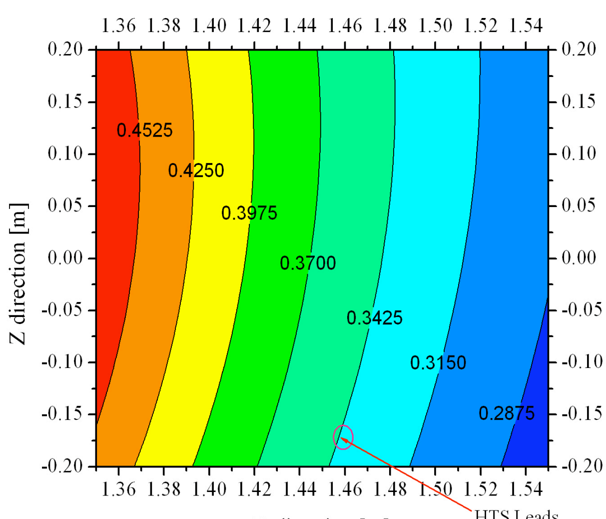

Figure 3. Magnetic field around the HTS leads

PERFORMANCE OF HTS LEADS AND STRAY FIELD

Because the performance of HTS leads is determined by the magnetic field and temperature around the warm end of leads, the position of the current leads with respect to the cold mass is mainly determined by the MICE worst-case magnetic field around the warm end of the HTS leads[4]. The HTS leads to be used for the coupling solenoid magnet are made from the first generation multifilament BSSCO conductor, whose favorable directions are along the lead length and along the conductor flat face[4]. In order to make the leads operate with higher performance, the leads should be positioned so that the magnetic field from the coupling magnet runs in the favorable directions. The lower of the warm end temperature of the HTS lead is, the better of its performance is. For instance, at a magnetic field of 0.4T parallel to flat face, the lead the current capacity is reduced about 20 percent at 64K and 50 percent at 70K[4].

One must calculate the magnetic field around the Magnet in order to determine the location of leads and coolers. The magnetic field around the magnet will be calculated when entire MICE system is operating at the worst-case. Numerical calculation of the magnetic field induced by all MICE solenoid coils is based on Biot-Savart Law [5]. Figure 3 shows the contour plot of stray field around the HTS leads. R is the radial direction respect to the axis of MICE magnet channel and Z is longitudinal direction. The unit for the magnetic field in Figure 3 is Tesla. At the region out of 1.41m in radial direction, the magnetic field is lower than 0.4T. So the warm end of HTS leads could be positioned in that region.

CONCLUSIONS

The copper part of a conduction-cooled binary current lead was optimized and the temperature distribution along the copper lead is simulated. The results show that the lead can operate at the current of up to 250A. The stray magnetic field around the warm end of the HTS leads was calculated. It is suggested that the location of the warm end of the HTS leads should be out of 1.41m in radial direction from the central axis of MICE magnetic channel.

ACKNOWLEDGEMENTS

This work was supported by Funds of cryogenics and superconductivity technology innovation project under "985-2 Plan" of Harbin Institute of Technology. This work was also supported by the Office of Science, US Department of Energy under DOE contract DE-AC02-05CH11231. DOE funding of the US Neutrino Factory Muon Collider Collaboration is greatly appreciated.

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