Title
Thermal Stability Analysis for Superconducting Coupling Coil in MICE

Author
Wu, Hong

Publication Date
2010-06-28

Peer reviewed

Thermal Stability Analysis for Superconducting Coupling Coil in MICE

H. Wu, L. Wang, M. A. Green *Member IEEE*, H. Pan, X. L. Guo

***Abstract*—The superconducting coupling coil to be used in the Muon Ionization Cooling Experiment (MICE) with inner radius of 750 mm, length of 285 mm and thickness of 110.4 mm will be cooled by a pair of 1.5 W at 4.2 K cryo-coolers. When the coupling coil is powered to 210 A, it will produce about 7.3 T peak magnetic field at the conductor and it will have a stored energy of 13 MJ. A key issue for safe operation of the coupling coil is the thermal stability of the coil during a charge and discharge. The magnet and its cooling system are designed for a rapid discharge where the magnet is to be discharged in 5400 seconds. The numerical simulation for the thermal stability of the MICE coupling coil has been done using ANSYS. The analysis results show that the superconducting coupling coil has a good stability and can be charged and discharged safely.**

***Index Terms*—AC loss, HTS lead protection, thermal stability, transient temperature distribution**

I. INTRODUCTION

THE international Muon Ionization Cooling Experiment (MICE) will be a demonstration of muon cooling in a configuration of superconducting magnets and absorbers that may be useful for a neutrino factory [1]. A pair of coupling magnets are applied to produce enough magnetic fields (up to 2.6 T on the magnet centerline) to keep the beam within the iris of thin RF cavity windows [2]. The Institute of Cryogenics and Superconductivity Technology (ICST) in the Harbin Institute of Technology (HIT) in collaboration with the Lawrence Berkeley National Laboratory (LBNL) are in charge of the engineering design and fabrication of the MICE coupling magnet.

The MICE coupling magnet is a medium sized superconducting solenoid magnet indirectly cooled by a pair of small coolers. The thermal stability is one of the key issues for the normal operation and safety of the coupling magnet. The AC losses during charging and discharging added to the static heat leak of cryostat will raise the temperature in the coil, which may cause a quench in the worst case. However, during a power failure the sensible heat of boiled helium can be utilized to protect the HTS leads from quenching.

The AC losses and the transient temperature distribution in the coupling coil during a charge and discharge are analyzed using ANSYS combined with a Fortran program. The protection of HTS leads for MICE coupling magnet during a power failure is discussed also.

Manuscript received 20 October 2009. This work was supported by Funds of cryogenics and superconductivity technology innovation project under “985-2 Plan” of Harbin Institute of Technology, China and by the Office of Science, US Department of Energy under DOE contract DE-AC02-05CH11231.

L. Wang was with the Institute of Cryogenics and Superconductivity Technology, HIT, Harbin 150001, China. She is now with Shanghai Institute of Applied Physics, Shanghai 201204, China (phone: 86-21-33932552, e-mail: wangli_icst@hit.edu.cn).

H. Wu, H. Pan, X. L. Guo are with the Institute of Cryogenics and Superconductive Technology, Harbin Institute of Technology, Harbin 150001, P. R. China (e-mail: hitwuhong@163.com).

M. A. Green, is with the Lawrence Berkeley National Laboratory, Berkeley CA 94720, USA (e-mail: magreen@lbl.gov).

II. THE MICE COUPLING MAGNET AND ITS AC LOSSES

A. The MICE coupling magnet

Table I lists the basic parameters of the MICE coupling coil [3]. The MICE coupling coil is a single 285 mm long superconducting solenoid wound on a 6061-T6 Al mandrel. It is indirectly cooled by a pair of pulse tube coolers each with cooling capacity of 1.5 W at 4.2 K, through cooling tubes in the cover plate using the thermo-siphon principle [4]. The static heat load at 4.2 K from the cryostat is 1.94 W [5]. Fig. 1 shows the coupling coil assembly, which is comprised of the coil mandrel, the insulated conductor, inter-layer insulation, G-10 plates around coil for electrical insulation to ground and the 5356-Al wire banding.

The magnet will be powered to full current 210 A by a 300 A, 10 V power supply through a pair of copper (upper part) and HTS (lower part) power leads. The times needed for charge, discharge, and rapid discharge the magnet are 13950 s (~3.9 hours), 13790 s (~3.8 hours) and 5400 s (~1.5 hours) respectively [5][6].

TABLE I. COUPLING MAGNET SPECIFICATIONS

Parameter	Flip	Non-flip
Coil Length (mm)	285	
Coil Inner Radius (mm)	750	
Coil Thickness (mm)	110.4	
Number of Layers	96	
No. Turns per Layer	166	
Magnet Self Inductance (H)*	591.8	
Magnet J (A mm^{-2})*	106.85	100.76
Magnet Current (A)*	210.1	198.2
Magnet Stored Energy (MJ)*	13.1	11.6
Peak Induction in Coil (T)*	7.3	7.0
Coil Temperature Margin (K)*	~0.8	~1.1

* the worst case design based on p = 240 MeV/c and β= 420 mm

The coupling coil is fabricated from standard MRI magnet conductor with a cooper to superconductor ratio of four. The nominal RRR for the copper is 70. The bare dimension of the coupling coil conductor is 0.95 mm×1.6 mm with round corners of 0.2 mm. The conductor has 222 filaments that is 41 µm diameter and a nominal twist pitch of 19 mm. Using this conductor, the magnet operating margin is expected to be ~0.8 K when the peak field point is 7.3 T on the coil with full current of 210 A and operating temperature of 4.2 K [4].

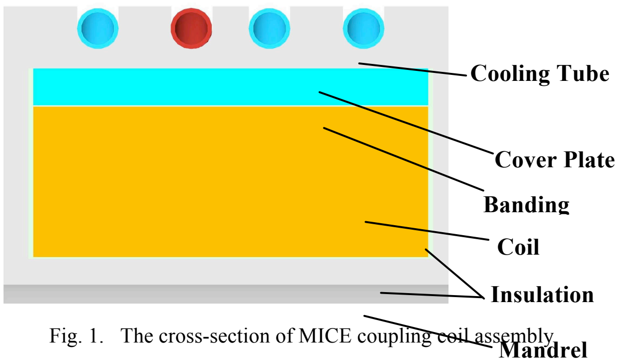

Fig. 1. The cross-section of MICE coupling coil assembly

B. *The AC losses in the coupling coil*

AC losses in the coupling magnet come from three sources: the hysteretic AC loss in superconductor, the coupling loss between filaments in a multi-filament superconductor，and the eddy current loss due to coupling between the coil and the mandrel and support structure. The primary calculation shows that the coupling AC loss is two orders lower than the hysteretic AC loss for the same conductor, which is neglected for MICE coupling coil conductor in all practical purpose [7].

In order to calculate the hysteretic AC loss accurately, the cross-section of the coupling coil is divided into 200 sub-blocks, and the charge, discharge and rapid discharge processes are divided into 100 sub-steps. The critical current density j_c of superconductor is calculated based on the magnetic induction at the center of the sub-block B_B at the midpoint time of Δt. The total hysteretic AC loss produced during the charge and discharge are independent of time. The value is 12.7 kJ, which is obtained by summating the hysteretic AC loss over each sub-block during each sub-step.

The eddy current loss in mandrel is caused by eddy current induced in the mandrel by di/dt. The mutual inductance between coupling coil and the mandrel M is 0.032 H, which is obtained using Finite Element Method (FEM). The coupling coefficient between the coil and the mandrel is 0.905. The effective resistance of the mandrel and banding at 4 K is $2.54\times10^{-6}\,\Omega$. It is assumed that the induced electric potential across the cross-section of the mandrel and banding is uniform. Using the Joule's law, the power of eddy current loss during charge, discharge and rapid discharge are 0.091 W, 0.094 W and 0.61 W respectively.

The total AC loss for the MICE coupling magnet are summarized in Table II. During charge and discharge of the coupling coil, the AC loss added to the static heat load at 4.2 K is nearly 3 W, both of the coolers needed to run at the same time to prevent the helium from venting. During a rapid discharge due to power failure, the total energy released in the coupling magnet due to the AC losses is nearly 15.6 kJ, which can only be removed by boiling away about 6.4 liters liquid helium around the magnet.

TABLE II. THE AC LOSSES IN THE COUPLING COIL

Scheme	Hysteretic Loss (kJ)	Mandrel Loss(kJ)	Total AC Loss (kJ)	Average AC Loss (W)
Charge	12.7	1.27	13.97	1.001
Discharge	12.7	1.30	14.0	1.004
Rapid Discharge	12.7	3.29	16.0	2.96

The transient AC losses in the coupling magnet during charge, discharge and rapid discharge are shown in Fig. 2. At the start of the charge the AC losses together with the static heat load 1.94 W is greater than the cooling capacity. This may vaporize some helium, but later the coolers will re-liquefy the helium vaporized early in the charge due to the decrease of AC losses. The AC loss during discharge process is the almost inverse process of charge. During a rapid discharge due to power failure, the boiling helium around the magnet is the only option for keeping the magnet cold. The sensible heat of the boiled helium can be used to keep the top of HTS leads cold during a rapid discharge. This is discussed in detail later.

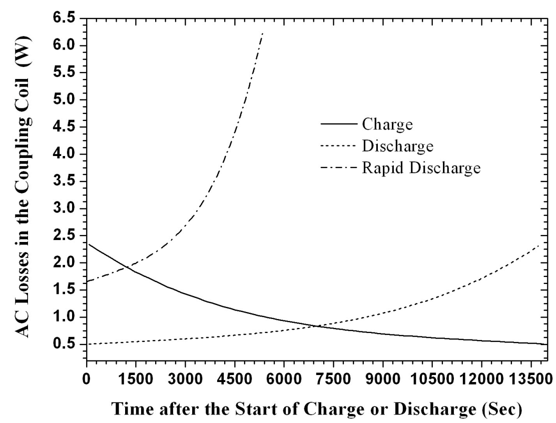

Fig. 2. The total AC loss for the MICE coupling magnet

III. TRANSIENT COUPLING COIL THERMAL SIMULATION

The finite element (FE）thermal simulation on the coupling coil has been performed by general finite element software combined with a Fortran program. The steady state temperature distribution in the coil during normal operation was obtained. The transient temperature distributions in the coil during charge, discharge and rapid discharge were analyzed in detail.

A. *The Finite element Model*

In the thermal analysis, a 2-D axial-symmetric model for half of the coupling coil has been developed to study both the steady temperature distribution during normal operation and transient temperature distribution during charge, discharge and rapid discharge. As shown in Fig. 3, the model includes the coil, the mandrel, the banding, the electric insulation and the cooling tubes. The coil and mandrel including banding are divided into sub-blocks and the charge, discharge and rapid discharge process is divided into100 sub-steps. All parts are glued together in this FE model. The thermal properties of the materials used in the FE models between 4 K and 10 K are referenced in [8], and the properties of the coil are orthotropic.

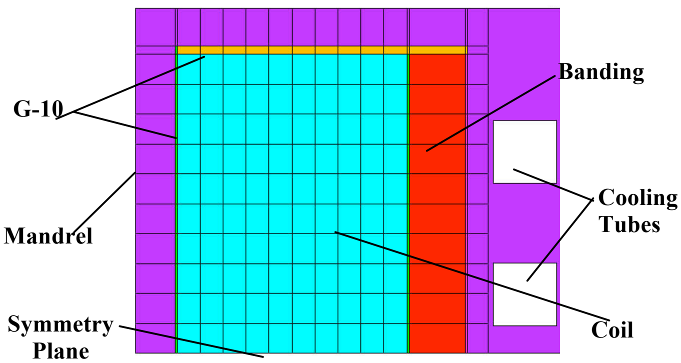

Fig. 3. The 2-D axial symmetric model for half of the coupling magnet

The following assumptions are applied for the model: a) the inner surfaces of cooling tubes are regarded as rectangular ones; b) the heat load on the cold mass from cold mass support is not considered; c) the heat loads on the cold mass from the conductor splices are neglected.

The static operating conditions are: a) the temperature on the inner surface of cooling tubes is set at 4.27 K; b) the symmetry plane is an adiabatic boundary condition; c) a heat flux of 0.2 W/m^2 is applied on the outer surfaces of the cold mass as thermal radiation.

During charge and discharge, the additional dynamic heat loads due to AC losses should be applied on the FE model. At first the hysteretic loss on each sub-block of the coil during each sub-step based on the results generated by the Fortran program is applied. Then the eddy current loss generated in the mandrel on each sub-block is added, which is calculated based on the assumption that the induced electric potential across the cross-section of the mandrel and banding is uniform.

B. Steady temperature distribution in the coil

Because the temperature margin in the coupling magnet is only 0.8 K at its design current in the flip mode at p = 240 MeV/c and β=420 mm, it is important to reduce the temperature drop between the hot spot in the magnet and the inner surface of the cooling tubes. During the steady state before charge or discharge, merely the static heat load is applied on the coupling coil. The temperature distribution on the cold mass is shown in Fig. 4.

The peak temperature is 4.317 K appearing on the middle of inner surface of the mandrel due to its farthest way from the cooling surface and the radiation heat load. The temperature drop between the hot spot in the magnet and the inner surface of the cooling tube is 0.047 K, which is acceptable.

C. Transient temperature distribution in the coil

During charge, discharge and especially rapid discharge the total heat load of the AC losses in the coil and the 1.94 W static heat load is greater than the cooling capacity of two small coolers. They may raise the temperature at the hot point above the critical temperature of local superconductor considering the small temperature margin (0.8 K).

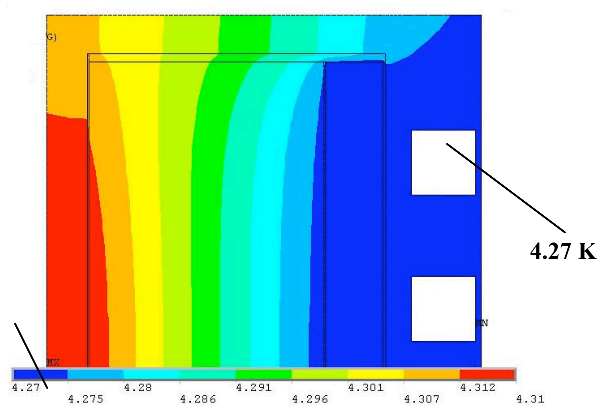

Fig. 4. Steady temperature distribution in the coupling coil

The magnetic filed is proportional to the operation current in the coupling coil, and the peak magnetic field always occurs on the middle inner surface of coupling coil, which is the most possible place to quench during charge, discharge and especially rapid discharge. So the temperature here is needed to fully concern. The temperature profiles at the peak magnetic field point as a function of time during charge, discharge and rapid discharge are shown in Fig. 5.

For charge process, the peak temperature reaches 4.46 K appearing at the beginning of charge due to the large AC loss, which is 2.2 W. It is still safe for the coupling coil, considering the critical temperature on this point at this time is above 9 K due to the nearly zero magnet field and zero current. The critical temperature of the superconductor at the peak induction point will decrease faster than the decrease of temperature here. Meanwhile, it is always higher than the temperature at the peak induction point. At the end of charge, there still has 0.67 K temperature margin, so the coupling coil can be charged safely with 10 volts across the power supply.

During discharge process, the temperature profile is nearly the inverse process of that for charge process, and the minimum temperature margin is 0.66 K at the beginning of discharge. So the coupling coil can be charged safely with -10 volts across the power supply

During rapid discharge process, the temperature rise at the beginning of discharge is 0.14 K due to the low AC loss, the temperature margin has the minimum value 0.59 K. The peak temperature rise is 0.42 K at the end of rapid discharge. The temperature rising rate at the peak magnetic field point is slower than the critical temperature rising rate during most of the fist half discharge process. At the second half discharge process, the temperature at the peak field point rises quickly, but the coupling coil still has large temperature margin since the operation current and magnet field are already rather low.

So the coupling coil can be rapid discharged safely in 5395 seconds with 22 volts across the discharge diodes.

Comparing Fig. 5 and Fig. 2, it can be found that the temperature changes with the AC losses almost without delay. Because the thermal diffusion rate of the magnet is 0.334 m^2/s, which is huge for the AC losses and static heat load. The temperature rise in the coil can be controlled very well by tuning the charging rate, so the temperature rise is not the critical factor to limit the charge and the discharge rate.

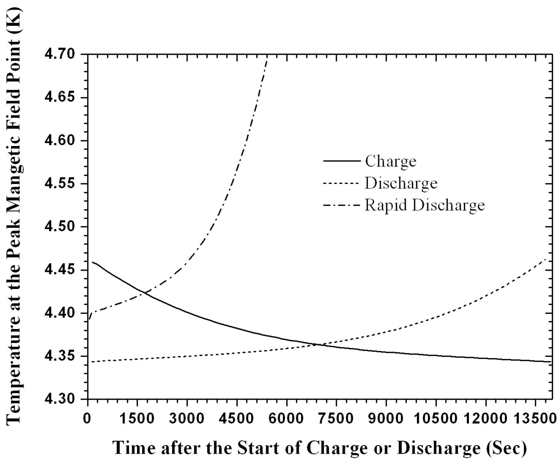

Fig. 5. The temperature at the peak magnetic field point of the magnet

IV. Protection of the HTS Leads

Some failure modes such as a power failure that causes a shutdown of the coolers can cause the upper end of the HTS lead to overheat. The current from the magnet and its leads must be removed rapidly in order to protect the leads from thermal runaway. The extra cooling to prevent the HTS leads from going normal and runaway has to be provided during rapid discharge. Otherwise quenching the magnet will be the only choice. There are three ways to provide this extra cooling: a) use a volume of liquid (or solid) in the cryostat held in reserve; b) use enough solid thermal mass (extra copper or aluminum) as a cold sink; c) Use a small heat exchanger to utilize the sensible heat of the boiled helium from the magnet during rapid discharge. Given the limited space within the magnet cryostat, the last two methods are preferable for the protection of the HTS leads.

A block of copper (or aluminum) connected to the first stage of the cooler can be used to ensure that the HTS lead don't burn out during a rapid discharge of the magnet. The rapid discharge of the magnet will not cause the magnet to quench, as long there is liquid helium around the magnet coils. The heat leaked from the leads during rapid discharge (5400 s) is 104.22 kJ, and the allowable temperature rise of the cold sink during rapid discharge is 5 K. So the recommended amount of metals connected to the first stage of the magnet coolers is ~122 kg for copper or 72 kg for Aluminum. It is difficult to mount a large heat sink into the tight space in the cryostat turret.

During the rapid discharge process, ~10 liters of liquid helium around the magnet will boil off due to AC losses and static heat load at 4.2 K. The boiled helium will go though a coiled heat exchanger attached to the copper around the first stage cold heads of the coolers to keep both the shield and the HTS leads cold. The heat exchanger will be made of copper tubing of 8 mm in inner diameter and 3-4 m in length. The pressure drop along it is about 100 Pa. The designed coil heat exchanger is shown in Fig. 6.

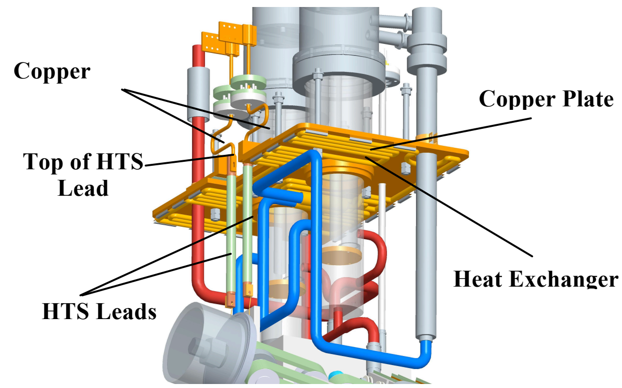

Fig. 6. The coil heat changer for HTS leads protection

V. Conclusion

The AC losses in the coupling coil during a charge and discharge were calculated using FEM, and 6.4 liters helium will be vaporized due to the heating generated by AC losses during rapid discharge. The peak temperature drop between hottest point and cooling tube is 0.047 K for normal operation, which is acceptable. The peak temperature drop reaches 0.47 K for rapid discharge. The coupling magnet can be operated safely during charge and discharge. The temperature change in the coil has almost no delay with the change of AC losses. The coil temperature rise is not the critical factor that limits the charging and discharge rates. A coiled heat exchanger attached to the first stage cold heads of the coolers is designed to protect HTS lead from going normal using the sensible heat of boiled helium during rapid discharge.

References

[1] G. Gregoire, G. Ryckewaert, L. Chevalier, et al, "MICE and international muon ionization cooling experiment technical reference document," http://www.mice.iit.edu, 2001

[2] D. Li, M. A. Green, S. P. Virostek, M. S. Zisman, "Progress on the RF coupling module for the MICE channel," Proceedings of 2005 Particle Accelerator Conference Knoxville TN, pp. 3417, 2005.

[3] L. Wang, F. Y. Xu, H. Wu, et al, "Magnetic and cryogenic design of the MICE coupling solenoid magnet system," *IEEE Transactions on Applied Superconductivity* vo.**19**, No. 3, pp. 1344-1347, 2009.

[4] L. Wang, M. A. Green, F. Y. Xu, et al, "The engineering design of the 1.5m diameter solenoid for the MICE RFCC modules," *IEEE Transactions on Applied Superconductivity* vo.**18**, No. 2, pp. 937, 2008.

[5] Institute of Cryogenics and Superconductivity Technology, "Engineering design of MICE/MUCOOL coupling solenoid magnet," (Unpublished) Harbin Institute of Technology, China, 2008.

[6] M. A. Green, H. Wu, L. Wang, et al, "AC losses in the MICE channel magnets, is this a curse or a blessing?" MICE Note-195, http://www.mice.iit.edu, LBNL-63804, Jan. 2008.

[7] H. Wu, L. Wang, M.A. Green, et al, "AC loss analysis on the superconducting coupling in MICE," Proceedings of ICEC-22, Seoul Korea, pp. 959, 2008.

[8] M. A. Green, and S.Q. Yang, "Heat transfer into and within the 4.4 K region and the 40 K shields of the MICE focusing and coupling magnets," Oxford Physics Department Engineering Note 2, 2004.