Thermal design of BESIII magnet

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This paper presents the thermal analysis of Beijing Spectrometer Magnet (BESIII magnet) which will be used as a superconducting detector magnet in BEPC-II. BEPC-II is an upgrade project to the Beijing Electron Positron Collider (BEPC). BESIII Magnet is cooled by forced flow of two phase helium and the inner winding technique is adopted in the coil winding process. A 3D model of calculation for the magnet was built. The heat load and the temperature distribution of the magnet were analyzed by a finite element method, and the upper limits of several heat leak sources were calculated.

INTRODUCTION

In order to provide an axial magnetic fie1d of 1.0 T over the tracking volume of the third upgraded Beijing Spectrometer (BESIII) in BEPC-II, a superconducting magnet scheme is adopted due to its superior performance and stability during operation. The superconducting magnet is designed to run at 4.5 K and be cooled by forced flow of two phase helium. High purity (>99.99%, RRR>500) aluminum-stabi1ized NbTi/Cu (1:1) supercon-ductor is adopted, and the superconductor is encapsulated inside a restraining cylinder made of aluminum alloy 5083 for reason of radiation transparency and for compatibility of thermal contraction. During coil winding the inner winding technique will be used. A liquid nitrogen thermal shield is designed to minimize the radiation heat load to the superconducting coil. The main structure of BESIII magnet is shown in Figure 1.

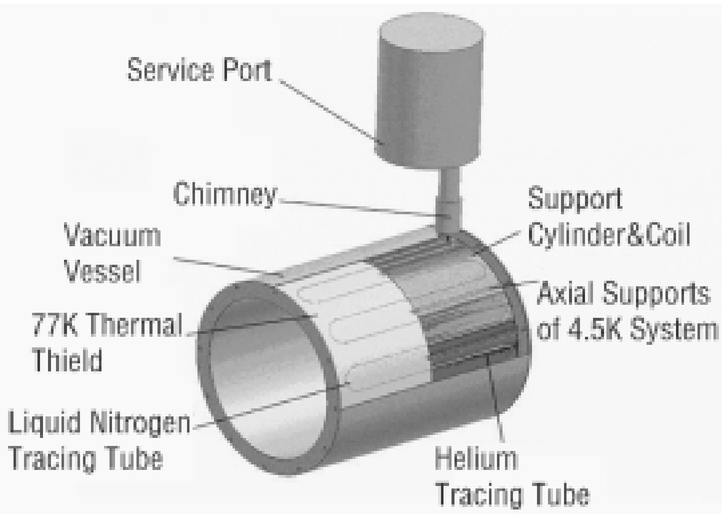

Figure 1 Overall view of BESIII magnet

STATIC HEAT LOAD

There are mainly five kinds of heat loads when BESIII Magnet is in static operating condition: Joule heating of the joint turns, radiation heat leak, heat leak through axial and radial supports, current leads heat leak and measuring wires heat leak. Detail is listed in Table 2 (Heat load in the interface of magnet system and cryogenic system: chimney and service port is also listed here). BESIII superconductor is composed of three long conductors, design data of electric resistance of the joint turn is 10^{-9} Ω. On the outside of the support cylinder and the nitrogen thermal shield, the multilayer superinsulation (S.I) system is used to decrease the radiation heat load. Double side aluminized mylar or polyester film is used. The aluminized mylar is insulated by polyproparene. The design wrapping density is about 50 to 60 layers per inch, and mylar is cut off for every 10 layers. Thus, the design of S.I. system has the effective thermal conductivity and Q/A value as Table 1.

Table 1 Experience data of superinsulation system adopted in BESIII Magnet

Range (K)	Layer (#)	Vacuum Gap (mm)	K (W/m.k)	Q/A (W/ m^2)
300 – 80	50	25.4	8.3 x 10^{-5}	0.6
80 – 4.5	30	19	1.447 x 10^{-5}	0.043

There are totally 24 axial supports and 24 radial supports for the 4.5 K cold mass system and 8 radial supports for nitrogen thermal shield, all these supports are connected to 300 K system directly. Material of these supports is unidirectional fiberglass. Heat load is calculated using following equation:

$$Q = A/L \int K\mathrm{d}T \qquad \text{(a)}$$

Where Q: heat load through supports, A: cross section area of supports, L: length of supports, K: thermal conductivity of suppports and T: temperature of supports. Designed operating current of BESIII Magnet is 3250 A. According to Martin N. Wilson’s book <Supercondcting magnets>, heat leak of optimum current leads is about 1.04 mW/A, using the safe factor of 1.1, we have the current leads heat leak calculated. There are totally about 370 measuring wires (thermometers, strain sensors, heaters and so on) in BESIII Magnet system. Heat load of these wires is also calculated using equation (a).

Table 2 Calculated data of heat loads of BESIII magnet (W)

Items of heat load	77 K system	4.5 K system
Joule heat of the joint turn	/	0.02
Radiation heat leak	44.75	3.50
Heat leak through supports	0.3	0.97
Current leads heat leak	/	7.44
Measuring wires heat leak	5.31	0.83
Heat load in chimney & SP	60	13.43
Total	110.36	26.66
Adopted heat load（×1.5）	165.54	40

MASS FLOW RATE OF HELIUM AND NITROGEN

The 4.5 K cold mass system is cooled by two phase helium forced flow. Considering that too much liquid helium boiling away causes many bubbles in the tracing tube, which may greatly decrease the convective heat transfer coefficient between liquid helium and tracing tube, also according to the operating experience of BELLE Magnet in KEK Japan, vaporization rate of helium is determined to be 20 percent in the magnet. And liquid helium at outlet of magnet should not less than 50 percent. Then the mass flow rate of helium is designed to be 10 g/s, and the pressure should be about 1.25 bar. The radiation thermal shield is cooled by liquid nitrogen and the mass flow rate is designed to be 1.89 g/s

TEMPERATURE DISTRIBUTION

The static temperature distribution of BESIII magnet was calculated with a commercial FE method software-Ansys. A 3D model of the magnet was built. Following assumptions were made in the calculation: There are no contact heat resistances between 4.5 K system and axial&radial supports, superconducting coil is well bond to the support cylinder, and the temperature of the inner surface of helium tracing tube is 4.5 K. Although the first assumption is very different to the fact, but it is a safe consideration. The second assumption is not a safe consideration, but it is a basic request for the operation of the magnet. If the coil is not well bond to the support cylinder, much trouble may occur: temperature of the joint turn will rise, coil temperature will rise, and during quenching, coil temperature will increase to a very high level. Calculated heat transfer temperature difference between two phase helium and tracing tube is about 0.01 K, so the third assumption is also acceptable. Calculating result is shown in Table 3. We still find that with the assumption that the coil is well bond to the support cylinder, the temperature of the joint turn hot point is not high even the joule heating of the joint turn increases 100 times larger than before. But if the coil is not well bond, things will become troubled. Figure 3 presents the detail. In the calculation of radiation heat load, experience data of 0.043 W/m^2 (77 K to 4.5 K) is used, but as everyone is painfully aware, it is the way in which superinsulation system is applied that really makes the difference in heat transfer, the above heat flux data may differ greatly with the real condition. Figure 4 presents the influence of radiation heat load on the main hot points.

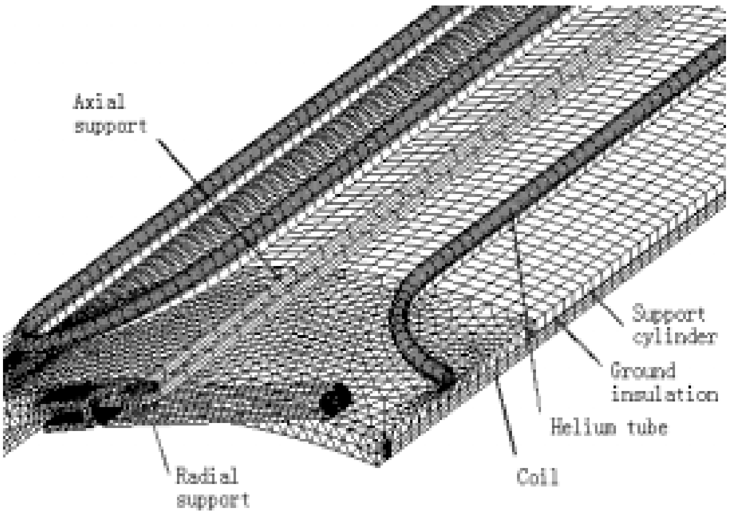

Figure 2 1/12 part 3D model of BESIII magnet

Table 3 The static temperature distribution of BESIII magnet

Items of hot point	Temperature (K)
Hot point due to joint turn joule heat	4.51
Hot point due to radiation heat leak	4.51
Hot point due to axial support heat leak	4.58
Hot point due to radial support heat leak	4.78
Temperature difference due to the welding of the helium tracing tube	0.01
Temperature difference due to the ground plane insulation and turn to turn insulation	0.02
Temperature difference due to the side wall insulation	0.22

DYNAMIC HEAT LOAD

Eddy current loss in support cylinder during the magnet charging/discharging period of 30 minutes was

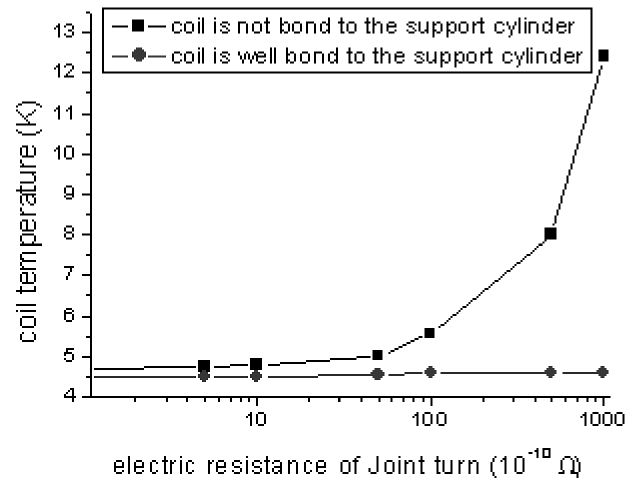

Figure 3 The influence of electric resistance of joint turn on coil temperature

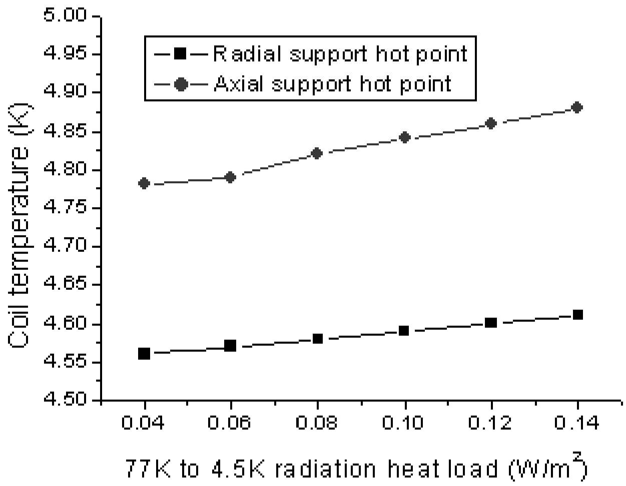

Figure 4 The influence of radiation heat load on the main hot points

calculated by the following equations:

Induced voltage $E = - d\Phi / dt$ (b)

magnet flux $\Phi = SB = S\mu H = S\mu nI / L$ (c)

Dynamic heat load $Q\mathrm{dy} = E^2 / R$ (d)

Where t: Charging/discharging time, S: Cross section area of the support cylinder, n: net turn of the coil, L: Axial length of the coil, R: Electricity resistance of the support cylinder. The calculating result of the dynamic heat load is about 4.95 W. In case of emergency fast ramping, the dynamic heat load would be increased

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SUMMARY

Heat load and temperature distribution of BESIII magnet were analyzed by FE method. The main heat loads are current leads heat load and heat load in chimney and service port, radiation heat load is also an important one. The main hot points are hot points due to radial supports and hot points due to axial supports. Dynamic heat load is about 4.95 W during the magnet charging/discharging period of 30 minutes.

ACKNOWLEDGMENT

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