Stability Study on Cryocooler-Cooled Superconducting Magnets

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***Abstract*—Superconducting magnets cooled by cryocooler, without liquid helium, have been developed in recent years. This kind of magnet system is very easy and convenient to operate. The stability of the magnet depends on the balance between the cryocooler refrigeration capacity and the thermal loads. Based on thermal analysis for the magnet, study has been carried out on the stability of cryocooler-cooled superconducting magnet during current excitation.**

***Index Terms*—Cryocooler, stability, superconducting magnet, thermal analysis.**

I. INTRODUCTION

A cryocooler-cooled superconducting magnet is one of the trends for magnet technology. It benefits from two breakthroughs: the 4K-GM cryocooler and the high-Tc superconducting current lead. Without cryogen, the magnets are easy and convenient for the user to operate. The stability of the magnet depends on the balance between the cryocooler refrigeration capacity and the thermal loads. Many cryocooler-cooled superconducting magnets used at liquid helium temperature or at liquid nitrogen temperature have been constructed [1]–[3]. A stability criterion has been put forward for high temperature superconducting (HTS) magnets [4]. At present, "critical current-margin" stability criterion is commonly used for low temperature superconducting (LTS) magnets. But there are not reports on how much margin should be chosen for LTS. Especially, when the superconducting magnet is charged, ac loss is generated and it causes the coil temperature to rise. The ac loss occurring in superconductors will be one part of the refrigeration loads. It is obvious that this is the most serious case for magnet operation.

Based on thermal analysis and ac loss calculation for the magnet, a stability study has been carried out on a cryocooler-cooled low temperature superconducting magnet. It was found that as soon as the thermal linking mechanism is determined, appropriate operating current and excitation rate have decisive effects on magnet stability.

Manuscript received October 2, 2004. This work was supported by the National Natural Science Foundation of China (NSFC). no. 103 550 011.

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Digital Object Identifier 10.1109/TASC.2005.849245

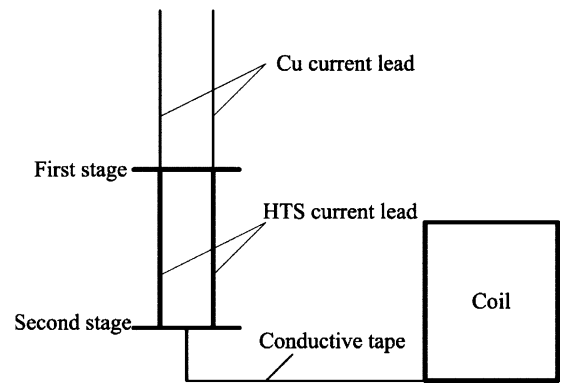

Fig. 1. Thermal linking mechanism of cryocooler-cooled superconducting magnet.

II. ANALYSIS AND MODEL

A. Thermal Sources and Conductive Path

Before the magnet is energized, it must be cooled down. The atmosphere in the adiabatic cryostat should be kept below $1.33\times 10^{-1} - 1.33\times 10^{-2}$ Pa. Residual gas conductivity is negligible under such gas pressure.

The schematic of the thermal linking mechanism is shown in Fig. 1. A two-staged GM refrigerator is applied to the magnet. The refrigeration capacity is 0.5 W at 4.2 K. Copper leads, 100 mm length and 14 mm $\times$ 1.5 mm cross section, are used between room temperature and the warm head of the HTS lead. The warm and cold end of the HTS lead is located between the 1st and 2nd stages of the refrigerator. The first stage of the refrigerator cools the radiation shield, and the second cools the magnet. Heat leakages can be calculated corresponding to the two stages.

The first stage heat loads include the Cu current lead, radiation heat leakage, glass fiber reinforced epoxy sheet (between Cu shield and radiation shield), and joule heat generated in junction resistance.

The second stage heat loads include the HTS current lead conductive heat leakage, radiation heat leakage, glass fiber reinforced epoxy sheet (between radiation shield and magnet), joule heat generated in junction resistance, joule heat generated in measurement wires, and ac loss generated during current excitation. All the heat leakages will be calculated as follows.

Cu current lead heat leakage:

$$\frac{d\left(\frac{k_{cu}(T)dT}{dx}\right)}{dx} + \frac{\rho_{cu}(T)I^2}{A_{cu}^2} = 0 \qquad (1)$$

Where, k_{cu} is the thermal conductivity of copper, T is the temperature of Cu current lead, I is the operating current, ρ_{cu} is the resistivity of copper, A_{cu} is the cross section of copper current lead, x is any point in the current lead. Through numerical calculation, heat leakage at the end of copper current lead can be obtained.

HTS current lead heat leakage:

$$Q = \frac{A_{HTS}}{L_{HTS}} \int_{T_L}^{T_t} k_{HTS}(T)dT \tag{2}$$

Where, Tt is the first stage temperature of the refrigerator, T_L is the second stage temperature. A_{HTS}, L_{HTS} are the cross section and length of HTS current lead. Heat leakage of glass fiber reinforced epoxy sheet can be calculated in the same manner as HTS current lead.

Joule heat generated at junction resistance and measurement wires obeys the ohm law.

B. AC Loss

When the superconducting magnet is energized, ac loss is generated and it causes the coil temperature to rise. In composite superconductors, there are hysteresis losses and coupling losses [5].

The hysteresis power density P_{hy} (in $\mathrm{W/m^3}$) can be calculated:

When $B > B_p$,

$$P_{hy} = \frac{4}{3\pi} J_C \times a_{SC} \times \dot{B} \left[1 + \left(\frac{J_{op}}{J_C} \right)^2 \right] \tag{3}$$

When $B < B_p$,

$$P'_{hy} = P_{hy} \left(\frac{B}{B_P} \right)^2 \tag{4}$$

Where, J_c is the critical current density, a_{SC} is the radius of superconducting filament, $\dot{B}$ is magnetic flux density changing rate, J_{op} is the operating current density, B_p is the magnetic flux density at which full penetration occurs, μ_0 is the magnetic permeability.

$$B_P = \mu_0 J_C a_{SC} \tag{5}$$

Currents that are set up among the interfilamentary copper matrix in a composite superconductor cause coupling loss.

The coupling power density P_c (in $\mathrm{W/m^3}$) is calculated:

$$1P_c = \frac{2\tau}{\mu_0} \dot{B}^2 \tag{6}$$

Where, τ is the time constant of coupled filaments embedded in the matrix.

Because magnetic flux density B is different at various positions in the magnet, P_{hy} is different. The total ac loss Q can be obtained by integrating all the power density in the whole magnet.

$$Q = \int (P_{hy} + P_c) dV \tag{7}$$

TABLE I
PARAMETERS OF SUPERCONDUCTOR

Superconductor		
	Diameter (bare)	Φ 0.8 mm
	Diameter (insulated)	Φ 0.88 mm
	Cu/SC ratio	2.0
	Filament diameter	Φ 100 μm
	Jc at 5T	2500 A/mm^2

TABLE II
PARAMETERS OF MAGNET

Magnet		
	Inner diameter	Φ 100 mm
	Outer diameter	Φ 198 mm
	Height	200 mm
	Maximum field	4.4 T
	Operating current	70 A
	Inductance	9.03 H

Stability analysis is based on the parameters listed in Table I and Table II [6].

Combining steady heat leakage with ac loss, we can obtain the total heat loads that is the basis of our stability investigation.

C. Model

According to the thermal conductivity mechanism for cryocooler-cooled superconducting magnet, the thermal equilibrium equation at the second stage of the refrigerator is as follows:

$$Q_{cool}(T_{head}) = \frac{1}{R}(T_{coil} - T_{head}) + Q_{ge}(T_{head}, I_{op}) \tag{8}$$

Where Q_{cool} is the cryocooler refrigeration capacity, T_{head} is the second stage temperature of the refrigerator, T_{coil} is the magnet temperature, and R is the thermal resistance of conductive strip between the cryocooler and the magnet. It is a function of the strip temperature. Q_{ge} is the steady heat leakage conducted from first stage of the refrigerator. It is a function of the operating current I_{op} and T_{head}.

The thermal equilibrium equation in the magnet is as the following:

$$V\gamma C(T_{coil}) \frac{dT_{coil}}{dt} = Q_{ac}(T_{coil}, \Delta I) + Q_i - \frac{(T_{coil} - T_L)}{R} \tag{9}$$

Where V is the magnet volume, γ is density, C is the volumetric specific heat, t is time, Q_{ac} is the ac loss in the magnet, and it is a function of magnet temperature and excitation rate ΔI. Q_i is the steady heat leakage in the magnet.

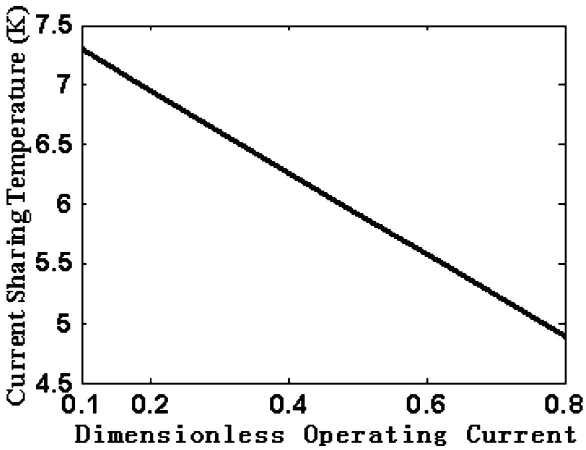

Fig. 2. Relationship between current sharing temperature and dimensionless operating current.

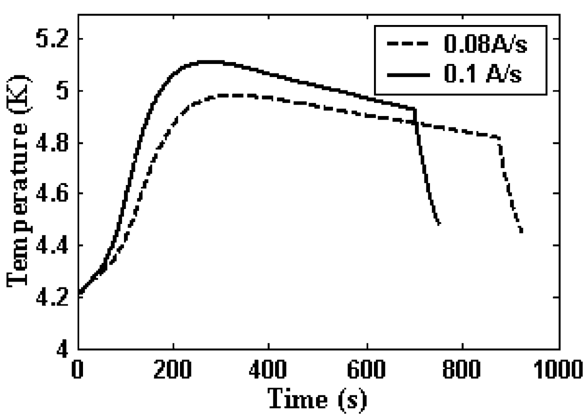

Fig. 3. Temperature distribution in the magnet during current excitation at different charging rate.

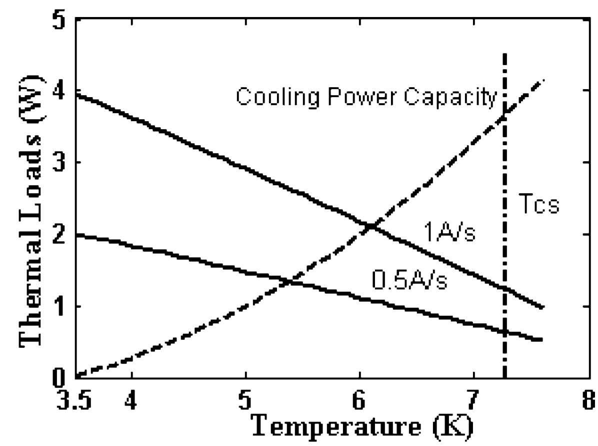

Fig. 4. Thermal balance point at different charging rate. Operating current is 70 A.

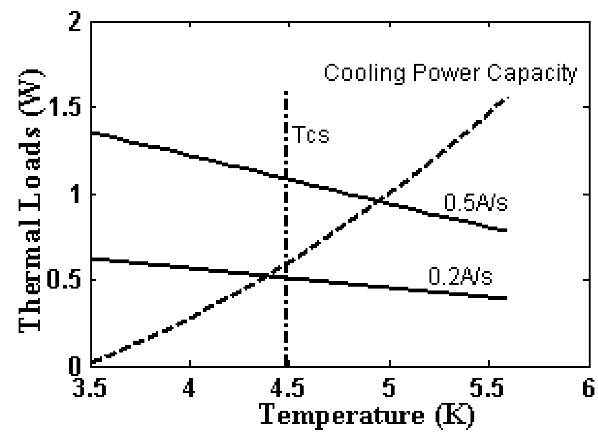

Fig. 5. Thermal balance point at different charging rate. Operating current is 140 A.

Equation (9) is a nonlinear ordinary differential equation. The two above equations are coupling. The value of magnet temperature can be obtained through numerical calculation.

III. Result and Discuss

Operating current I_{op} is determined by the destined central magnetic flux density and the critical characteristics of the superconductor. As soon as I_{op} is determined, current sharing temperature T_{cs} is determined too. Fig. 2 shows the relationship between T_{cs} and dimensionless operating current i, which also can be considered as current margin of the superconducting magnet.

The charging rate of the magnet must be controlled. Otherwise as soon as the magnet temperature is above current sharing temperature, quench will take place. So we have to choose the appropriate ramp rate to stay below the designed coil temperature for magnet operation. The magnet temperature distribution with respect to time at different excitation rates is shown in Fig. 3. The operating current is 70 A. The faster the charging rate, the higher coil temperature is, and the shorter the time for the current to reach the operating point. The coil temperature reaches the maximum value at about 250 s, and then falls smoothly with time. Because the magnetic flux density becomes higher and higher during current excitation, the corresponding critical current descends. It can be seen from (3) that ac loss diminishes. When current excitation is over, there is no ac loss. The curve drops fast at 700 s and 875 s corresponding to 0.1 A/s and 0.08 A/s charging rate. The smaller T_{cs} means the charging rate should be lower in order to keep the magnet stable. The problem is how to select the appropriate operating current and charging rate to avoid instability in the magnet.

Fig. 4 shows the relationship between thermal loads and the refrigerating capacity at different charging rates when I_{op} is 70 A. Because T_{cs} is 7.27 K at 70 A, the crossing point of thermal loads and refrigeration capacity is lower than T_{cs}. When the balanced temperature is above T_{cs}, the magnet will become resistive, and the cryocooler cannot cool down the magnet further during this positive feedback process. The magnet will quench in the end. When the operating current is 140 A, T_{cs} is 4.49 K and the current margin is 0.8. Fig. 5 shows that when the charging rate is 0.5 A/s at 140 A, the magnet is unstable. So there exists the quantitative relationship between operating current and charging rate in order to keep the magnet stable during current excitation. Fig. 6 shows the relationship. The magnet is unstable for operating points up this curve, while stable for operating points down this curve. This curve is useful when the magnet needs fast ramp rate. On one hand, operating current determines the maximum magnetic flux density in

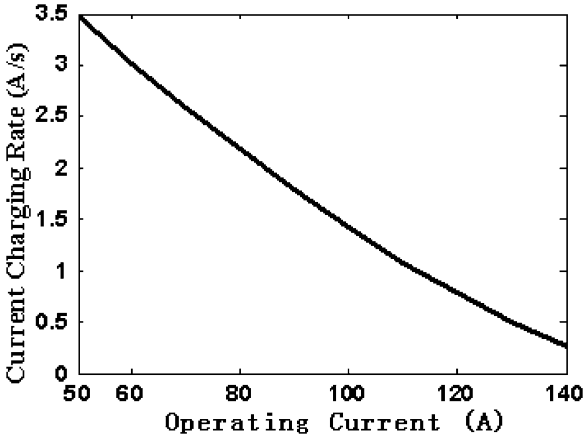

Fig. 6. Relationship between current charging rate and operating current.

the magnet; on the other hand, current margin determines the charging rate. When coil quench occurs, the stored energy is absorbed adiabatically by the coil mass. Assuming that the store energy of 316 J is entirely absorbed only by the heat capacity of the coil mass, the estimated coil temperature is about 30 K.

IV. Conclusion and Next Step

We investigate the stability of cryocooler-cooled low temperature superconducting magnets. As soon as the thermal linking mechanism is formed, appropriate operating current and excitation rate have decisive effects on magnet stability. The quantitative relationship between operating current and charging rate is the stability criterion. We will investigate the optimization of thermal linking in the magnet in order to reduce the steady heat leakage as the following step.

Acknowledgment

The authors would like to thank the whole staff that works at applied superconductivity laboratory, the Institute of Electrical Engineering, Chinese Academy of Sciences.

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