Stability analysis for cryocooled aluminum-stabilized superconducting magnet

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Aluminum-stabilized superconductors have been employed in superconducting magnet, such as SMES and detector magnets etc. The stability and homogeneity of temperature in superconducting magnet fabricated by these kinds of conductors are considerably improved due to the advantage of high RRR and high thermal conductivity at low temperature. Because of current redistribution, there is finite-length normal zone propagation in the conductors during quench. The transient recovery process is affected by the slow current diffusion in the bulky aluminum stabilizer.

INTRODUCTION

For the development of high current density and compact superconducting coils, superconducting wires with low copper superconductor ratio are usually wound in close-packed and epoxy-impregnated formats. It is a simplest way to increase the volume of the copper stabilizer to enhance the coil stability margin. However, it brings some drawbacks such as increase of coil volume and weight, and reduction of coil current density [1]. The great concern here is to increase the coil stability margin while keeping the coil weight as light as possible and the current density as high as possible. To overcome these contradictions, using high purity aluminum stabilizer is a good solution [2]. The development of conductors with high pure aluminum as the super-stabilizer was proposed for such applications of detector magnets for high-energy physics and superconducting magnet storage energy devices. It adopted cryogenics stabilization with coolant. The stability and homogeneity of temperature in superconducting magnet fabricated by these kinds of conductors are considerably improved due to the advantage of high RRR, and high thermal conductivity at low temperature [3]. With the widely use of cryocooler for superconducting magnets, our interest is focused on cryocooled aluminum-stabilized superconducting magnet. A numerical method has been developed to investigate the thermal and electromagnetic behaviors of cryocooled aluminum-stabilized superconducting magnet.

SIMULATION METHOD AND MODEL

The dynamics process in composite superconductors is determined by both temperature and current density distributions. A complete treatment of the problem requires the solution of heat diffusion equation which defines the dynamics of the temperature field, and a set of Maxwell equations which define the dynamics of the current density distribution. The equations are formed by a set of three-dimensional and time-dependent nonlinear equations. We developed a numerical method to investigate the thermal and electromagnetic behaviors of cryocooled aluminum-stabilized superconducting magnet.

The parameters of conductors and superconducting magnet are presented in Table 1. The conductor model used in this analysis is shown in Figure 1.

Table 1 Parameters of conductor and superconducting magnet

Conductor	NbTi/Cu/Al	Magnet	Solenoid
Cable	Φ3. 0 mm	Inner dia.	1.0m
Conductor	Φ15. 0 mm	Outer dia.	1.015m
Cu/SC ratio	1.2	High	0.3m
Al/ NbTi/Cu ratio	23.8	Total turns	20
Current density (in NbTi/Cu)	6×10^8A/m^2	layer	1
External field	6.25T	Current	7.1KA

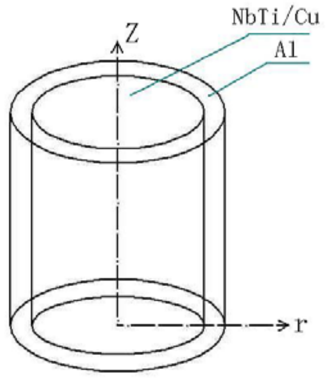

Figure 1 Conductor model

A simulation of 3D quench propagation was done by using a logical coordinate system in which each magnet is transformed into a single long conductor and it is divided into finite-length elements. Due to high thermal conductivity of ultra-purity aluminum and its volumetric ratio is larger in the conductor, uniform temperature distribution over the cross section is assumed. The governing equation of heat conduction is as following:

$$\gamma C(T)\frac{\partial T}{\partial t}=\frac{\partial}{\partial z}\left(k(T)\frac{\partial T}{\partial z}\right)+Q_J+Q_D \tag{1}$$

Where T is temperature, t is time, γ is density, C is specific heat, k is thermal conductivity, Q_J is joule heating density, Q_D is energy density of disturbance.

Basic equation for the current diffusion in stabilizer of aluminum matrix is:

$$\mu_0\frac{\partial J}{\partial t}=\nabla\bullet(\rho(T)\nabla J) \tag{2}$$

Where J is current density, ρ is electrical resistance, μ_0 is permeability of free space.

The initial condition is:

$$\begin{aligned} J(r,z,0)&=J_{op}, \quad (r,z)\in\Omega_{SC} \\ J(r,z,0)&=0, \quad (r,z)\notin\Omega_{SC} \end{aligned} \tag{3}$$

Though current density may be changing, the current through the conduct is constant. The magnetic field derivative produced by the current is zero at the conductor boundary.

$$\frac{\partial J_{SC}}{\partial r}|_{r=0} = \frac{\partial J_{ST}}{\partial r}|_{r=b} = 0 \quad (4)$$

Where b is radius of conductor, ST represents the whole conductor, SC represents the superconducting section.

The conductor in this paper is considered as 'quasi-adiabatic' during the normal zone propagation process. The assumption holds true since a cryocooler delivers cooling only through thermal conduction, therefore the cryocooler's response to a rapid temperature change within the magnet is attenuated [4]. Equation (1) and (2) can be solved by alternating direction implicit (ADI) with globally convergent methods. The nonlinearity of electrical resistance, heat capacity and thermal conductivity are also taken into account.

NUMERICAL SIMULATION RESULTS

The stability of a cryocooled superconducting magnet will be determined by two following factors.

Current Diffusion into the Stabilizer

If any disturbance causes the temperature to rise above the current sharing temperature, current will begin to transfer into the copper and then to the aluminum stabilizer. Because the time constant for the magnetic field diffusion in aluminum stabilizer is relatively long due to the low resistivity of aluminum at low temperature, the slow diffusion of the current will generate joule heat pulse. And the most important, it is much larger than uniform current distribution over the stabilizer cross-section (see Figure 2). The front of normal zone is then propagating while the back is recovering as the current diffuses deeper into the stabilizer and joule heat drops below the helium heat removal rate when the conductor is immersed in the coolant. Thus there is a finite length normal zone propagating in the conductor during the transient process shown in Figure 3.

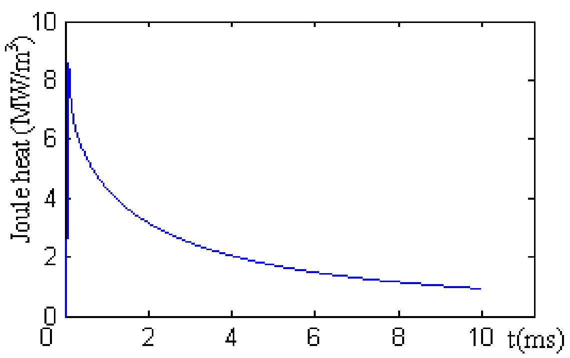

Figure 2 Joule heat during the process

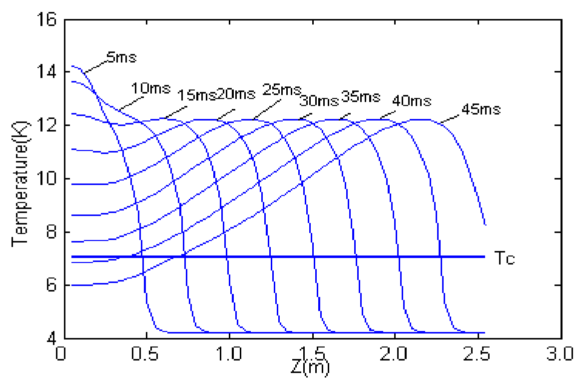

Figure 3 Temperature distributions

But when the conductor is cooled by crycooler, any losses or heat load will be conducted only along the conductor. In this circumstance, there also exists the current diffusion phenomenon (see Figure 4). The relationship between heat generation and thermal conduction determine the conductor stability margin.

Heat Transfer to Neighboring Turns and Layers

In our 'quasi-adiabatic' model, under the disturbance with the length of 0.25 m and duration of 0.25 ms, it was found that any disturbance caused the temperature to reach current sharing temperature will quench in the end (see Figure 5).

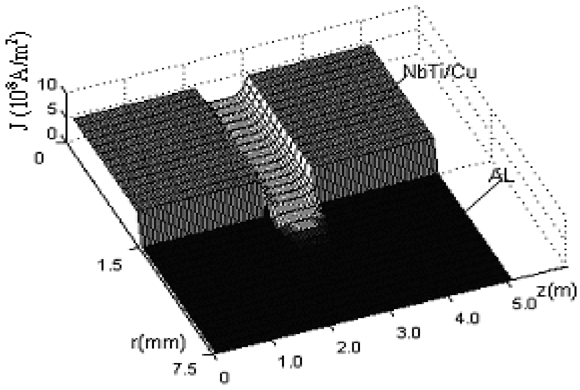

Figure 4 Current distributions with respect to space and time

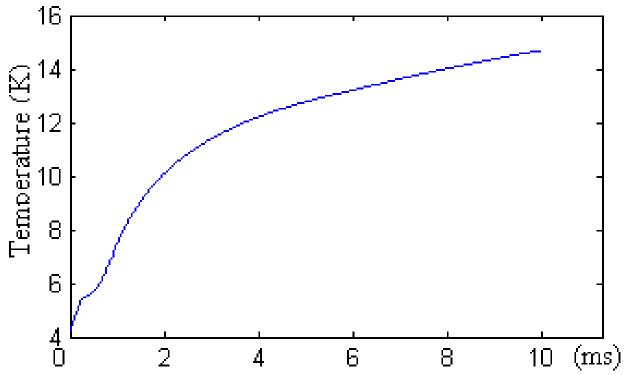

Figure 5 Hot spot temperature in ‘quasi-adiabatic’ model

As for magnet, the thermal conductivity between turns or layers play an important role in magnet stability. The following graphs (see Figure 6 and Figure 7) are the temperature distributions of the magnet with our logical coordinate, in which the whole magnet is transformed into a single long conductor. We can see the heat transfer between turns is much more quickly than that along azimuthal direction.

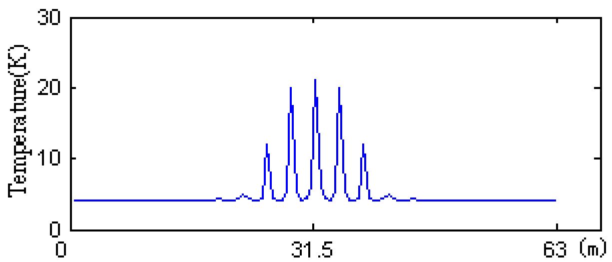

Figure 6 Temperature distribution in the magnet at 15ms during transient process

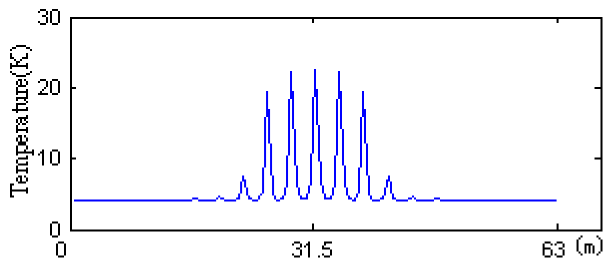

Figure 7 Temperature distribution in the magnet at 20ms during transient process

CONCLUSION

The stability of cryocooled aluminum-stabilized superconductor was investigated by numerical simulation method. It is the most important for cryocooled superconducting magnet to improve the thermal conductivity structure, especially for aluminum-stabilized magnet. We will investigate several kinds of ways that can improve the stability margin and increase the quench propagation velocity as the following step.

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