Influence of Current Diffusion in Superconducting Magnet Fabricated by High Stabilizer Aluminum on Quench Propagation

Qiuliang Wang, Jinliang He, Cheon Seong Yoon, and Keeman Kim

***Abstract*—The development of conductors with an aluminum super-stabilizer was proposed for some applications of accelerator detector magnets for high-energy physics and superconducting magnet storage energy devices. The conductors are designed with the cryogenics stabilization by using a large amount of low resistance aluminum stabilizer. However, it has induced to some new problems. One of these is the effect of the current redistribution between superconducting strands and stabilizer on the quench propagation and stability. In this study, we assume a superconducting magnet to be immersed in liquid helium. A quasi-three-dimensional model is proposed to study thermal diffusion in superconducting magnet and current diffusion is based on the solution of Maxwell's equation. The uniform temperature distribution in the cross-sectional area of conductor is taken into account due to the high thermal conduction of stabilizer and small size compared with the length. An adaptive mesh scheme COLSYS is employed to capture the solution of temperature and current in the front of normal position. The computational model includes nonlinear thermal and electrical characteristics in superconducting strands and aluminum stabilizer and heat transfer of helium. The influence of current re-distribution between stabilizer and superconducting strands on the quench is studied.**

***Index Terms*—Adaptive mesh, current diffusion, normal zone of finite length propagation, quasi-three-dimensional numerical model, quench, stability, superconducting magnet.**

I. Introduction

IT IS ESSENTIAL for the superconducting conductors to be stable against any disturbance during operation, especially, the large-scale superconducting magnet with large inductance and storage. The development of conductors with high pure aluminum as the super-stabilizer was proposed for such applications of accelerator detector magnets for high-energy physics and superconducting magnet storage energy devices. The conductors are designed with the cryogenic stabilization by using a large amount of low resistance aluminum stabilizer. However, it has induced to some new problems. One of these is the effect of the current redistribution between superconducting composite strands and stabilizer on the quench propagation and stability [1], [2].

Although a large aluminum stabilizer can ensure conductor recovery from the normal state after a disturbance, it cannot guarantee the limitation of normal zone propagation. Such a high current large monolithic conductor has a long current diffusion time constant. When the conductor is driven to the party normal state, a large initial Joule generating heat resulting from the early limitation of current to a small cross-sectional area rises the local temperature, transmits heat into the next section and drives it normal state. The front of normal zone is then propagating while the back is recovering as current diffuses deeper into the stabilizer and Joule generating heat drops below the helium heat removal rate. Thus a finite-length normal zone propagation from both ends of the initial normal zone is sweeping the entire conductor. It was found that the conductor has a maximum nonpropagating current, the current above that a normal zone will propagate. The minimum normalizing energy pulse which is defined as the energy required to raise the strand temperature above the current sharing level and the quench energy pulse which is the pulse over which the conductor can not recovery are two important parameters [3].

The formation of the traveling zone was shown to be the results of the high Joule power generated in the stabilizer matrix during the relatively long process of current redistribution between the superconducting strands and the stabilizer. This paper presents a detailed numerical model to study the current diffusion and the influence of current redistribution on the normal zone propagation velocity. First, a single conductor is studied and then a quasi-three-dimensional (3-D) model is employed to simulate the quench propagation in a solenoid-shaped superconducting magnet. An adaptive mesh scheme COLSYS [4] is employed to solve the equations of temperature distribution in conductors.

II. Mathematical Discription of Finite-Length Normal Zone Propagation in Superstabilizer Conductors

A thin-wall superconducting solenoid, which is fabricated by a conductor with an aluminum super-stabilizer, is taken into account. The parameters of magnet and conductors are listed in Table I. Due to the high thermal conduction of pure aluminum, the temperature distribution in the cross section of conductor is assumed to be uniform. Therefore, the one-dimensional (1-D) temperature distribution is considered for the single

Manuscript received July 5, 2001; revised October 25, 2001.

Q. Wang is with the Institute of Electrical Engineering, Academia Sinica China and Samsung Advanced Institute of Technology, Yusong-gu, Taejon-305-380, Korea (e-mail: qiuliangw@hotmail.com).

J. He is with the Department of Electrical Engineering, Tsinghua University, Beijing, China (e-mail: jlhe@emc.eea.tsinghua.edu.cn).

C. S. Yoon is with the Hannam University, Taejon 306-791, Korea (e-mail: csyoon@mail.hannam.ac.kr).

K. Kim is with the Samsung Advanced Institute of Technology, Yusong-gu, Taejon-305-380, Korea.

Publisher Item Identifier S 0018-9464(02)02775-9.

TABLE I
PARAMETERS OF CONDUCTOR AND SUPERCONDUCTING MAGNET

Conductor	NbTi/Cu/AL	Magnet	Solenoid
Cable size (mm)	Φ 3.0	Inner dia.	1.0 m
Conductor size (mm)	Φ15.0	Outer dia	1.015 m
Cu/SC ratio	1.2	High	0.3 m
Operating current	4.6 kA	Insulator	70 μm
Operating field	6.25 T	Operating current	5.0 kA
Operating temperature	4.2 K	Center field	5-6 T

conductor. The heat generated due to the quench flows, not only along the conductor, but also in the transverse direction, through the insulation. Within the solenoid-shaped magnet, this tends to short-circuit the quench propagation along the conductor causing the preheating and birth of normal zones in the adjacent turns. Furthermore, the heat conduction will initiate the quench in the adjacent layers. The heat coupling term is treated as an external heat source. Therefore, the approximation of the heat transfer in the winding package is obtained by substituting each part of conductor and insulation between two conductors with an equivalent slab having the same average extension in the direction normal to heat flux. By the simplification, the heat diffusion in the winding cross section can be regarded as a set of independent 1-D problems. Thus, the 3-D) problem is reduced to 1-D model [5]. The heat transfer coefficient between the turns or layers is calculated by the steady state temperature distribution across the conductor, insulation, and other conductor. The heat transfer coefficient is varied with the average temperature of the cross section of conductor and insulation. The heat transfer coefficient is taken into account including the liquid helium heat transfer if the superconducting magnet contacted with helium. Basic energy equation of thermal diffusion is expressed as below

$$\gamma C(T)\frac{\partial T}{\partial t}=\frac{\partial}{\partial z}\left(k\frac{\partial T}{\partial z}\right)+Q_j+Q_d+\sum_{j=1}\frac{p_j}{A_j}h_j\left(T\left(z_2^m\right)-T\left(z_1^n\right)\right) \quad (1)$$

where z is the axis of the conductor length; t is the time; T is the conductor temperature; k is the average thermal conductivity coefficient of aluminum, copper, and superconductors; γC is the average heat capacity of the conductor; h is the average heat transfer coefficient between the turns of magnet; A is the cross-sectional area of conductors; p is the cooled perimeters of conductors; Q_d is the heat power density, and Q_J is the Joule generating heat. The current transition between the superconductor and copper matrix is very fast after the quench or recovery of the superconductor. On the other hand, the current diffusion in the stabilizer aluminum (Al) is very slow process compared with that in the NbTi–Cu region due to the very low resistivity of the stabilizer. Therefore, the 3-D current diffusion is considered in the stabilizer matrix of aluminum. Basic equation for the current diffusion in stabilizer of aluminum matrix is

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

where J is the current density in the super-stabilizer, ρ is the resistivity, and μ_0 is the magnetic permeability. If the cross sectional area of the conductor is assumed as A, Joule generating heat can be expressed as follows for the NbTi–Cu and stabilizer matrix:

$$Q_j=\frac{\int\int \rho(T)(J(x,y,z))^2\,dA}{A}. \quad (3)$$

Since the electrical resistivity of superconducting strands depends on the temperature of conductor, an linear relation between the resistivity of superconducting strands and temperature is assumed, therefore, and is expressed as

$$\rho_{\rm st}(T,B)=\begin{cases}0, & (T<T_{\rm sh})\\ \frac{\rho_{\rm Cu}(B,T)(1+f)}{f}\,\frac{T-T_{\rm sh}}{T_C-T_b}, & (T_{\rm sh}\le T\le T_C)\\ \frac{\rho_{\rm Cu}(B,T)(1+f)}{f}, & (T>T_C)\end{cases} \quad (5)$$

where T_C and $T_{\rm sh}$ denote the critical temperature and current sharing temperature of superconducting strands; f is the ratio of copper to superconductor in the strands; $\rho_{\rm Cu}$ is the resistivity of the copper; and B is the local magnetic field. The resistivity ρ of the aluminum is determined by

$$\rho_{\rm Al}(T,B)=\rho_0(T)\left(1+\frac{2B^2(1+0.006B)}{4+3B+B^2}\right) \quad (6)$$

where ρ_0 is the resistivity for aluminum for an induction field equal to $0T$. When the superconductor in the superconducting state, the current flows through the superconductor and there is no any current in the stabilizer. The current cannot be diffused. When the superconductor is partially quenched, the current starts to be transited to the stabilizer copper and then it is diffused into the stabilizer matrix of aluminum.

A superconducting magnet subjected to a disturbance shows fast transient process. The heat transfer between the superconducting magnet and liquid helium depends on the temperature difference of the magnet and helium. The helium heat transfer can be expressed according to the experimental result [6]

$$\boldsymbol{q_h}=\begin{cases}1.2\times10^4(\boldsymbol{T}-\boldsymbol{T_b}), & (\boldsymbol{T}-\boldsymbol{T_b}\le 0.58)\\ 1.05\times10^4-6\times10^3(\boldsymbol{T}-\boldsymbol{T_b}), & (0.58<\boldsymbol{T}-\boldsymbol{T_b}\le 1.5)\\ 1.2\times10^3+2.3\times10^2(\boldsymbol{T}-\boldsymbol{T_b}), & (1.5<\boldsymbol{T}-\boldsymbol{T_b})\end{cases} \quad (7)$$

where T_b is the ambient temperature of liquid helium.

Equations (1) and (2) can be solved with the initial and boundary conditions. Equation (1) can be transformed to two ordinary differential equations. It is solved by adaptive mesh solver, COLSYS. Equation (2) is discretized by the finite volume method for the space and Crank–Nicolson scheme is employed to integrate time.

III. NUMERICAL SIMULATION RESULTS

In order to study the dynamic normal zone propagation under the current redistribution between the superconducting strands and super-stabilizer aluminum, we numerically solve (1) and (2). At the first, the single conductor is studied, i.e., the thermal coupling between turn-to-turn is ignored in the magnets. The basic parameters of the conductor are listed in Table I. Fig. 1 shows the hot-spot temperature rise of the conductor versus time

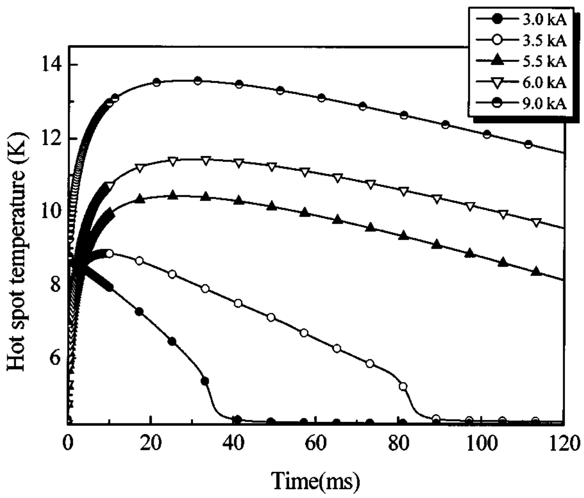

Fig. 1. Hot spot temperature versus time for various operating currents in the single conductor under the disturbance located at the center of conductor.

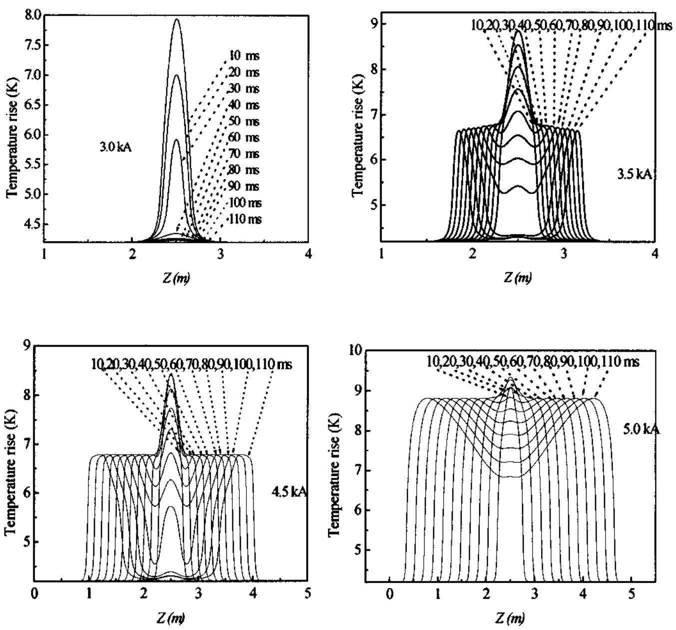

Fig. 2. Temperature distribution with respect to the space coordinate under the various operating currents during the quench of conductor.

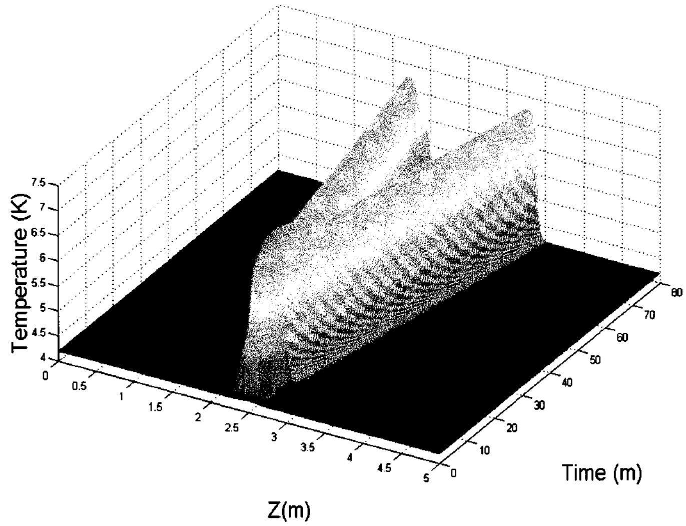

Fig. 3. Temperature distribution versus time and space for the conductors with operating current of 4.5 kA and disturbance located at the center.

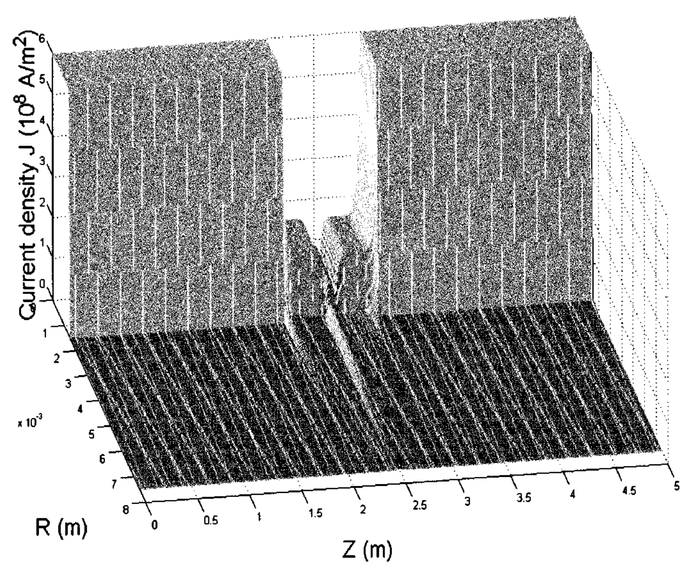

Fig. 4. Profiles of current density distribution with respect to the space and time in conductor with operaing current of 4.5 kA after 40 ms during quench.

for the various operating currents under the disturbance with the length of 0.25 m and duration time of 0.25 ms. From the profiles of the temperature with respect to time, the conductor should be recovered to the superconducting state during the operating currents of 3, 3.5, 5.5, 6, and 9 kA because the hot-spot temperatures are decreasing to the initial temperature of 4.2 K. However, as a matter of fact, the conductor is only recovered during the operating current of 3 kA, and the conductor is in the quench during the operating currents over than 3.5 kA. Therefore, it can not be distinguished whether or not the disturbance leads to the quench of the conductor from the hot-spot temperature profiles [9]. In order to study the quench propagation characteristics, Fig. 2 shows the profiles of temperature distribution with respect to the space. Even though the temperature at the distribution center is decreased, the finite length of normal zone is propagating along the conductor for the operating currents over than 3 kA. The various operating currents have the different normal zone lengths and temperature rises at the normal zones for the same operating conditions and disturbance. Such as the peak temperatures in the normal zone for operating currents of 4.5 and 5 kA are about 7 and 9 K, respectively. The profiles of temperature with respect to the space and time are shown in the Fig. 3 for the operating current of 4.5 kA. It is noticed that the normal zone with the finite length is moving along the conductor from the disturbance center to travel through the whole conductor.

Fig. 4 shows the profiles of current distribution with respect to the space after quench. When the superconducting strand is quenched, the current is shifted to the copper and aluminum from the superconducting core. The diffusion time constant of the current for the round geometry is given by [7], [8]

$$\tau = \frac{1}{2(3.82)^2}\frac{\mu_0}{\rho}R^2 \quad (8)$$

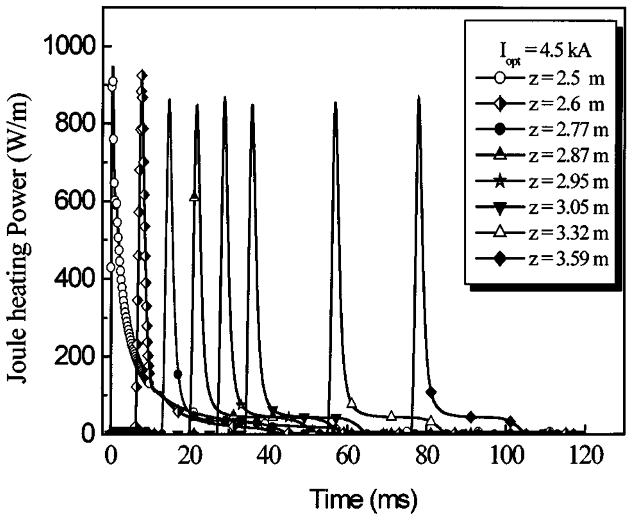

Fig. 5. Joule heating distribution along conductor at various time at the operating current of 4.5 kA after the quench of the conductor.

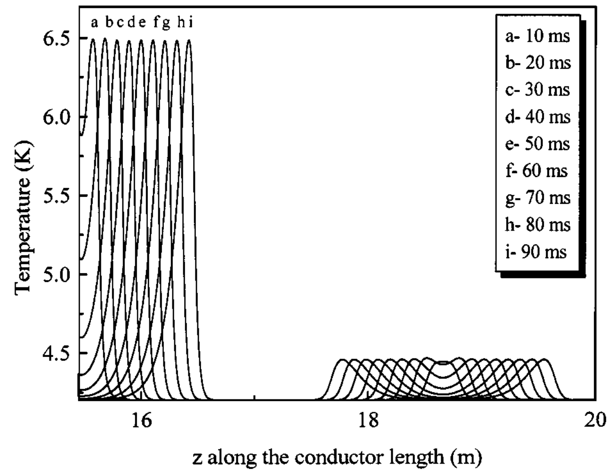

Fig. 6. Profiles of temporary temperature of superconducting magnet for disturbance located at the central point of magnet, disturbance length of 0.25 m and duration of 0.25 ms.

where ρ/μ_0 is the basic magnetic diffusivity constant. R is the radius of conductor. The current is rapidly transformed between copper and superconducting core, but the current is slowly diffused in stabilizer aluminum ($\tau_{\rm al} = 10^3 \tau_{\rm Cu}$). This slow diffusion of current in stabilizer aluminum will generate the sharply increasing peak Joule heating power at the front of normal of superconducting strands. The Joule heating can lead to the finite-length normal zone propagating along the conductor. The profiles of Joule heating power per unit length located at various positions of the conductor are plotted in Fig. 5. The Joule heating is sharply increased while the normal zone is arrived. Because Joule heating power is much over than the helium heat transfer and heat conduction by the conductor, the local temperature rise of conductor is rapidly increased to generate the quench of conductor. With the current diffusion into the stabilizer aluminum, the Joule heating is gradually decreased with respect to time. Therefere, after the normal zone front is through the poisition, the superconducting strand can recover due to that the local generating heat power lower than the transfer of heat power.

The dynamics quench process of the superconducting magnet is studied. The superconducting magnet is immersed in liquid helium. The disturbance is located at the midst of the solenoid. The temporary profiles of temperature in the superconducting magnet by using quasi-3-D model are illustrated in Fig. 6. It shows that the thermal coupling between turns generates to the quench the adjacent turns of quench and current diffussion. The dynamics normal zone propagation region with constant length and constant propagation velocity sweeps the whole the magnet from the disturbance zone center.

IV. Conclusion

A finite-length normal zone propagation in super-stabilizer matrix conductor and magnet has been simulated on the basis of the numerical model. The code provides tools for magnet stability analysis and optimization with consideration of thermal diffusion, current diffusion, nonlinear material on the magnetic field and temperature, and thermal coupling between the layers or turns of superconducting magnets. It can study the dynamic and transient stability in this kind of conductors and magnets. The simulaton shows that the transient recovery of the conductor is affected by the slow current diffusion in the bulky aluminum stabilizer. The slow current diffusion generates the impossiblily to be recovery of the conductor when the conductor is designed on the basis of cryostable design criteria for the operating current over than certain current value.

References

[1] A. V. Gavrilin and Y. M. Eyssa, "Modeling of electromagnetic and thermal diffusion in a large pure aluminum stabilized superconductor under quench," *IEEE Trans. Appl. Superconduct.*, vol. 11, pp. 2599–2602, March 2001.

[2] Y. Lvovsky, J. Waynert, and S. Kral, "Transient stability od SMES monolith conductor with normal stabilizer," *IEEE Trans. Magn.*, vol. 5, pp. 381–384, Feb. 1995.

[3] S. Noguchi and A. Ishiyama, "Transient stability of large aluminum stabilized superconductors," *IEEE Trans. Magn.*, vol. 9, pp. 624–627, Feb. 1999.

[4] U. Ascher, "COLSYS-collocation software for boundary value problems," *ACM Trans. Math. Software*, vol. 7, pp. 223–229, 1981.

[5] Q. Wang, C. S. Yoon, and K. Kim, "Simulation of quench in pancake-shaped superconducting magnet using a quasithree-dimensional model," *Progr. Superconduct.*, vol. 1, no. 1, pp. 125–134, 2000.

[6] N. Amemiya and O. Tsukamoto, "Influence of disturbance characteristics and copper to superconductor ratio on stability," *Adv. Cryogen. Eng.*, vol. 37, p. 323, 1992.

[7] L. Dresser, *Stability of Superconductor*. New York: Plenum, 1995.

[8] A. Lee and R. H. Wads, "Study of current redistribution in an aluminum stabilized superconductor," *Cryogenics*, vol. 32, no. 10, pp. 863–865, 1992.

[9] F. P Juster and J. C. Lottin, "Stability of Al-stabilized conductors for LHC detector magnets," *IEEE Trans. Appl. Superconduct.*, vol. 5, pp. 377–380, Feb. 1995.