SSCL-309

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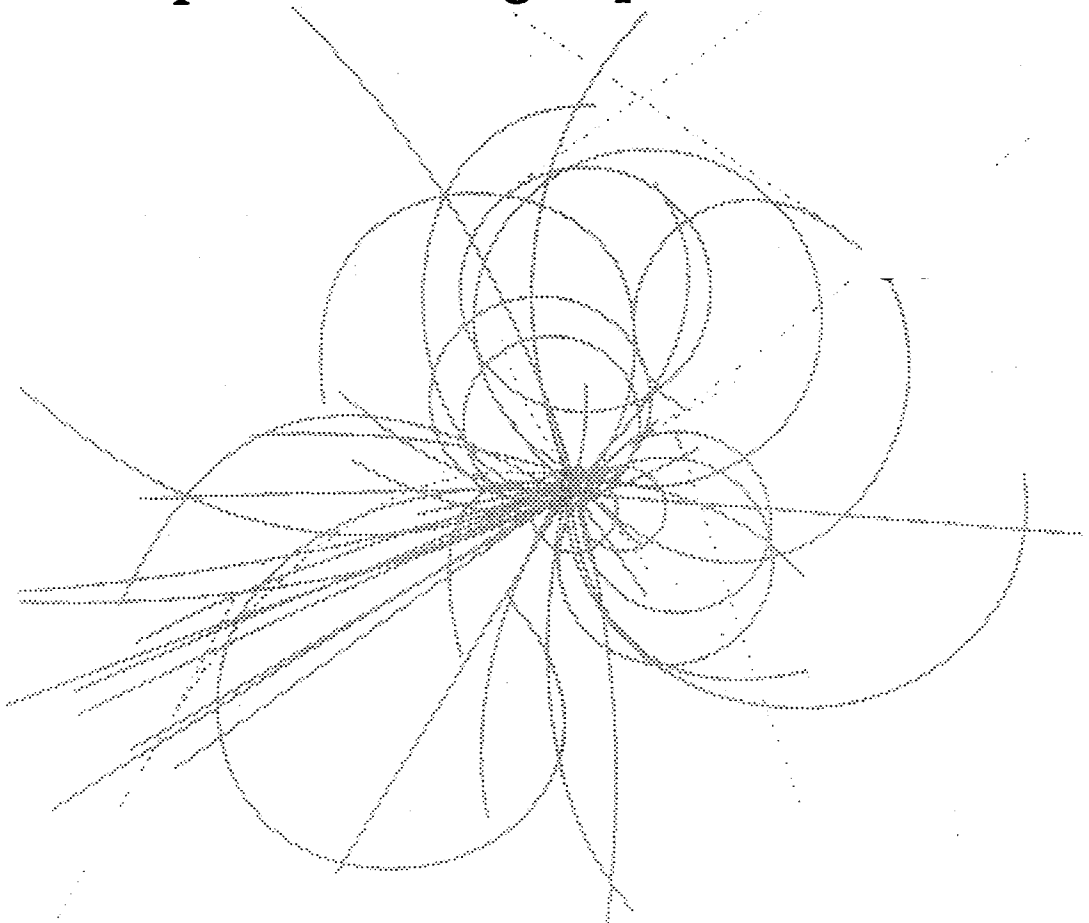

Analytical Approximation to the Turn-To-Turn Quench Propagation

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Abstract

Using a gross approximation for the flow of heat in a one-dimensional model, an analytical expresion is obtained for the turn-to-turn time delay to quench other nearby conductors. This expression agrees qualitatively with the experimental data of the SSC R&D dipole magnets.

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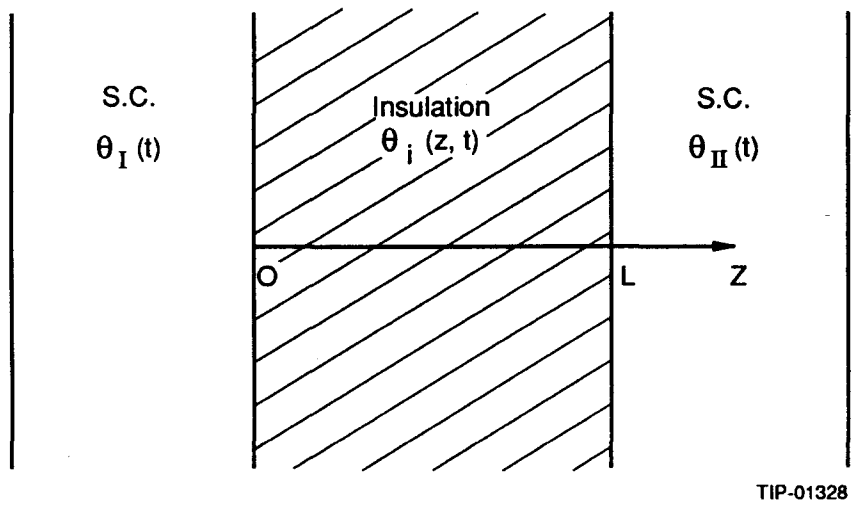

Figure 1. One Dimensional Model. Quench starts in the first conductor and the heat propagates to the second one through the gap of insulation. The temperature at the time $t \leq 0$ is the batch temperature, $\theta_o(\theta_I(\leq 0) = \theta_i(z, \leq 0) = \theta_{II}(\leq 0) = \theta_o)$.

The temperature in the insulation at any time, is given by solving the following equation

$$(\delta c)_i \frac{\partial \theta_i}{\partial t} = -\frac{\partial S}{\partial z} \quad , \tag{3}$$

where S is the flow of heat going into the insulation; $(\delta c)_i = (\delta c)(\theta_i)$ is the density multiplied by the specific heat average over the components of the insulation materials; $k_i = k(\theta_i)$ is the total thermal conductivity of the insulation. Assuming that the change in the heat flowing along z is proportional to the flow of heat and inverslly proportional to the heat source separation, z, the following relation is satisfied

$$\frac{\partial S}{\partial z} = \frac{S}{z} \quad , \tag{4}$$

where the selected sign in accordance with the reference system chosen. Using (4) in (3), the following nonlinear partial differential equation arises

$$(\delta c)_i \frac{\partial \theta_i}{\partial t} + \frac{k_i}{z} \frac{\partial \theta_i}{\partial z} = 0 \tag{5}$$

which can be solved by the Characteristics Method and brings about the solution

$$C_2(\theta_i) - t + \frac{(\delta c)(\theta_i)}{k(\theta_i)} z^2 = 0 \quad , \tag{6}$$

where C_2 is an arbitrary function of the temperature θ_i. Consider that $\theta_I(t)$ is the temperature of the first quenched conductor at the time t, and that the boundary condition,

$$\theta_i(0,t) = \theta_I(t) \quad , \tag{7}$$

is included in the expression (6), then it follows the next solution

$$C_2(\theta_i(t)) = t \quad . \tag{8}$$

Thus, due $\theta_I(t)$ is an increasing function with time; C_2 must be the inverse function of θ_I, that is

$$C_2(s) = \theta_I^{-1}(s) \quad , \tag{9}$$

for any parameter s; in this way, the solution (6) is written in the following implicit form

$$\theta_I^{-1}(\theta_i) - t + \frac{(\delta c)(\theta_i)}{k(\theta_i)} z^2 = 0 \ , \tag{10}$$

or it can be written as the implicit relation

$$\theta_i = \theta_I \left(t - \frac{(\delta c)(\theta_i)}{k(\theta_i)} z^2 \right) \quad . \tag{11}$$

Assume now, that at the end of the insulation, $z = L$, and at the time $t = \tau_2$, the temperature (11) equals the heat generation temperature started in the first conductor, θ_g, then the relation (11) is expressed as

$$\theta_g = \theta_I \left(\tau_2 - \frac{(\delta c)(\theta_g)}{k(\theta_g)} L^2 \right) \quad , \tag{12}$$

but if τ_1 is the time at which the heat generation starts in the first conductor, from the relation (12), it would follow the expression

$$\tau_1 = \tau_2 - \frac{(\delta c)(\theta_g)}{k(\theta_g)} L^2 \quad . \tag{13}$$

Thus, the border of the insulation, $z = L$, will have the temperature θ_g at the time

$$\tau_2 = \tau_1 + \frac{(\delta c)(\theta_g)}{k(\theta_g)} L^2 \quad . \tag{14}$$

Time, τ_1, can then be calculated from

$$(\delta c)_c \frac{d\theta_I}{dt} = \rho J^2 \quad , \tag{15}$$

where ρ is the total resistivity of the conductor materials and J is the current density; $(\delta c)_c$ is the density multiplied by the specific heat averaged over the conductor

materials. The current and the magnetic field are taken as constants during the process. Integrating (15) with the initial condition $\theta_I(0) = \theta_i(z,0) = \theta_o$, the next relation follows

$$\tau_1 = \frac{1}{J^2} \int_{\theta_o}^{\theta_g} \frac{(\delta c)_c}{\rho} d\theta_I \quad . \tag{16}$$

Assuming that the characteristics of both superconducting cables are the same, the turn-to-turn time delay is given by

$$\tau_d = \frac{2}{J^2} \int_{\theta_o}^{\theta_g} \frac{(\delta c)_c}{\rho} d\theta + \frac{(\delta c)(\theta_g)}{k(\theta_g)} L^2 \ . \tag{17}$$

3. RESULTS AND CONCLUSIONS

Figure 2 shows the values obtained using (17) in comparison with some experimental results[4]. For the calculation of (17), the following parameters were assumed

cu : sc =1.6 ,
A = $11.785\times10^{-6}\ m^2$,
θ_o =4.35 K ,
B= $0.8065 + 0.947\times10^{-3} I_o$ T (I_o in Amperes) ,
$\delta_{Kp} = 1.42\times10^3\ Kg/m^3$,
$\delta_{epoxy} \simeq \delta_{Kp}$,
kapton : epoxy = 4:3 ,
L = 1.524×10^{-3} m
and
$\theta_g(B) = \theta_c(B)$ - $(\theta_c(B) - \theta_o) J_o / J_{co}(B)$,

where the critical current temperature, θ_c, and the critical current density, J_{co}, are calculated from known expressions[5]. The expression (17) gives a gross approximation to the experimental turn-to-turn time delay values for transversal quench propagation and could be used cautiously in quench computer simulations. There is a qualitative difference between expression (17) and (2) related to the separation of the conductors and the thermal conductivity. Although expression (13) is consistent with normal diffusion time between two materials[6], caution is advised, because of the possible inconsistency in this gross approach.

Applying the same expression to the turn-to-turn time delay between wedges provides a time delay much smaller than between the insulation. In this case, the one dimensional model is not valid any more. Due to the high thermal conductivity of copper, heat is spread with the same speed in both directions drastically reducing the time delay for quenching the other conductor. However, other sets of experiments carried out in a 4 cm SSC R&D dipole magnet, see refence [7], show that a pure Fourier conduction mechanism (expressions (1) or (17)) for the transversal quench propagation is not enough to understand the transversal quench behavior of these magnets (the turn-to-turn heat propagation is not sequential).

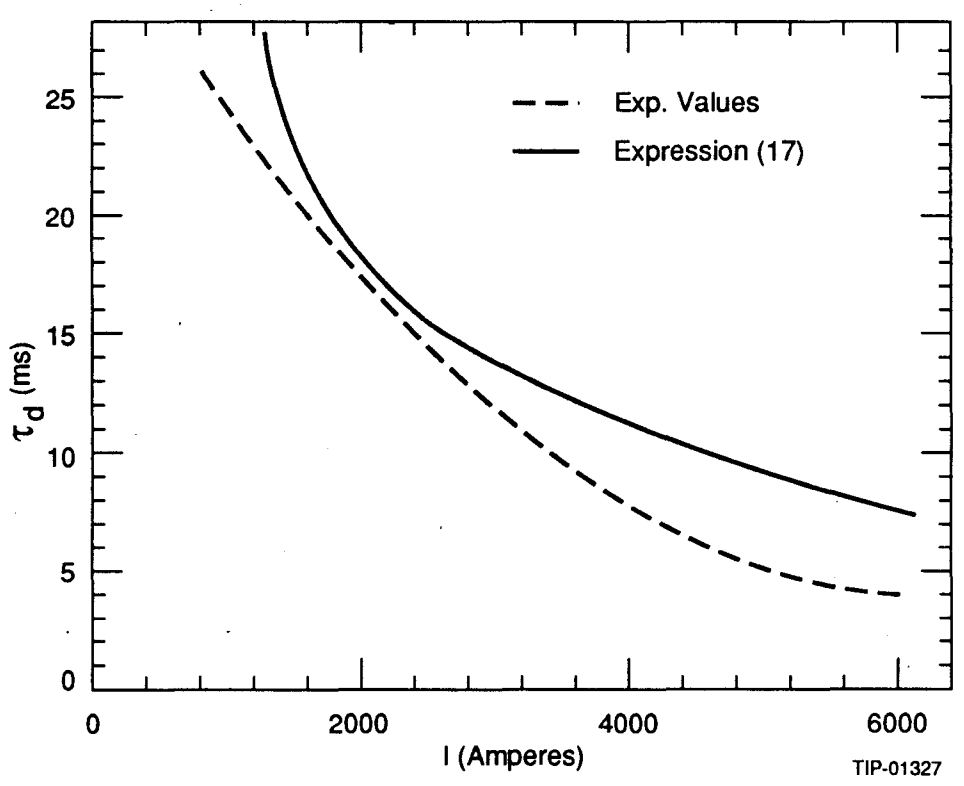

Figure 2. Experimental values for the turn-to-turn time delay in comparison with the expression (17) (continuous line).

Acknowledgement

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REFERENCES

1. G. López and G. Schnitler, SSCL-283, 1990.
2. M. N. Wilson," Superconducting Magnets," Oxford Science Publications, chapter 9, 1983.
3. A. Devred,"Quench Characteristics of Full-Length SSC R&D Dipole Magnets," SSC-234, 1989.
4. W. B. Sampson, Personal communication 1986.
5. G. Morgan and W. B. Sampson,"New Coefficients for a $J_{co}(B)$ analytic form," SSC-N-519, 1986.
6. R. P. Shutt,"Estimates of Pressures and Temperatures Generated During Quenches of SSC Magnets," SSC-N-265, 1986.
7. J. Cortella,"Quench Data Analysis of Magnet DD0012 (Parts I,II and III)," MD-TA-90,91 and 92, 1988.