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# QUENCH BACK IN SUPERCONDUCTING MAGNETS WITH SHORTED SECONDARY CIRCUITS

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While testing a thin superconducting solenoid with a shorted secondary circuit, the coil was observed to become fully normal faster than quench propagation would permit. We call this process "quench back". The quench back was caused by heating in the secondary circuit from current induced from the primary circuit. This paper presents a theoretical expression which can be used to estimate the quench back time in a solenoid with a well coupled secondary circuit. The calculation of quench back time is compared with measurements made on two one-meter diameter solenoid magnets.

## INTRODUCTION: A SIMPLIFIED THEORY FOR THERMAL QUENCH BACK

Since 1975, the Lawrence Berkeley Laboratory (LBL) has built and tested high current density superconducting magnets which use closely coupled shorted secondary circuits as an integral part of the magnet quench protection system [1]. The concept of shorted secondary circuits has permitted LBL to build large solenoid magnets which operate at high current densities and quench safely. The role of shorted secondary circuits in quench protection is as follows: 1) The current shifted from the superconductor to the secondary circuits inductively will reduce the hot spot temperature in the superconductor. 2) The secondary circuits can absorb a substantial amount of the magnet stored energy. 3) The shorted secondary circuits permit some unusual types of external active quench protection to be used (i.e., the varistor resistor) [2]. 4) The shorted secondary circuit causes the whole coil to become normal through "quench back" [3].

The driving of a superconducting coil normal through quench back derives from two sources which are; 1) thermal quench back from heating in the secondary circuit, and 2) magnetic quench back from a.c. loss heating in the superconductor. From our experimental data, thermal quench back seems to be the dominant form of quench back in the solenoid magnets we have tested. This paper presents a theoretical statement of thermal quench back time which is compared with measurements of quench back time in two one-meter diameter solenoids. The theory presented in this paper has been simplified so that a closed form equation of quench back time results.

A theory for thermal quench back and the calculation of quench back time in solenoids is presented in Ref. [4]. Thermal quench back can be characterized by two processes which both contribute to the time delay which is quench back time $t_{QB}$. These are: 1) the time needed to shift current to the secondary circuit and heat it up to a temperature above the superconductor critical temperature $t_Q$ and 2) the time needed to transfer heat across the insulation between the secondary

circuit and the superconductor $t_H$. $t_{QB}$ is approximated by the sum of $t_Q$ and $t_H$.

At low current densities in the superconductor, the thermal quench back time is dominated by the time needed to heat the secondary circuit. The heat transfer time constant becomes important at higher current densities.

In the one-meter diameter thin solenoids used in the LBL tests [1], the quench propagated from layer to layer and half way around the magnet circumference faster than the time to quench back $t_{QB}$. The process of quench propagation in the coil before quench back was for the most part one dimensional.

A closed form expression for $t_Q$ can be developed if some simplifying assumptions are made: 1) There is only one secondary circuit to quench back from. 2) The current in the coil drops very little before quench back. 3) The velocity of quench propagation along the wire $V_L$ does not change with time. 4) The energy dissipated in the coil and its secondaries is small (compared to total stored magnetic energy) before quench back. 5) The coupling is so good that the time constant for rapid current shift to the secondary circuit is small compared to the quench back time. 6) Through most of the time before quench back, the superconducting coil circuit time constant is much greater than the secondary circuit time constant. 7) The primary circuit inductance $L_1$, the secondary circuit inductance $L_2$, and the secondary circuit resistance $R_2$ are constant with time before quench back. Using these assumptions the first quench back time constant $t_Q$ takes the following approximate form:

$$t_Q = \frac{t1}{2} + \left[ \frac{3\ F_2^*}{\left( \frac{L_2\ R_{o1}\ N_1\ \alpha\ V_L\ i_o}{L_1\ R_2\ N_2\ A_{c2}} \right)^2} \right]^{1/3} , \qquad (1)$$

where $F_2^*$ is the current density integral defined by Eq. (3); $i_o$ is the magnet starting current; $N_1$ is the number of turns in the primary circuit; $N_2$ is the number of turns in the secondary circuit; $A_{c2}$ is the cross-sectional area of the secondary circuit; $t_1$ is the time for the quench to propagate half way around the coil; $R_{o1}$ is the resistance constant in the one-dimensional resistance growth equation; $V_L$ is the quench propagation velocity along the wire; and $\alpha$ is the ratio of turn-to-turn quench velocity to quench velocity along the wire.

$R_{o1}$, $\alpha$ and $t_1$ are given by the following expressions:

$$R_{o1} = \frac{2\pi\ a_1 N_1 \rho_1 \left(\frac{r+1}{r}\right)}{\ell_1\ A_{c1}} , \qquad (2a)$$

and for coils with round conductors

$$\alpha = 0.75 \left[ \frac{\rho_1 k_i}{L\ T_c}\ \frac{D_w}{S}\ \frac{r+1}{r} \right]^{1/2} , \qquad (2b)$$

and

$$t_1 = \frac{\pi\ a_1}{V_L} , \qquad (2c)$$

where $a_1$ is the solenoid radius; $\ell_1$ is the superconducting coil length; $\rho_1$ is the resistivity of the matrix material in the

cross-sectional area of the superconductor (includes matrix material); $k_i$ is the thermal conductivity of the insulation between conductor turns; L is the Lorentz number; $T_c$ is the superconductor critical temperature; $D_w$ is the superconducting wire diameter; and S is the thickness of the electrical insulation from turn to turn. Equation (2a) assumes the quench is started at the end of the solenoid coil.

The term $F_2^*$ in Eq. (1) is defined as the integral of current density squared needed to increase the temperature of the secondary circuit from 4.2K to a temperature of about 10K (the superconductor critical temperature). $F_2^*$ is defined as follows [4]:

$$F_2^* = \frac{\Delta H_2}{\rho_2} = \int_0^{t_Q} J_2(t)^2 dt \quad , \tag{3}$$

where $\rho_2$ is the resistivity of the material in the secondary circuit; $\Delta H_2$ is the enthalpy change of the material in the secondary circuit when its temperature is raised from 4.2K to 10K; and $J_2(t)$ is the current density in the secondary circuit as a function of time t.

The equation for the second term in the quench back equation can be stated as follows:

$$t_H = \frac{b\ a\ \Delta H_{SC}}{k_{in}\ \Delta T} + \frac{a^2\ \Delta H_i}{k_{in}\ \Delta T} \quad , \tag{4}$$

where b is the average thickness of one layer of superconductor (for round wire $b \approx \pi D_w/4$); a is the thickness of insulation between the secondary circuit and the superconducting coil; $\Delta H_{SC}$ is the enthalpy change needed to drive the superconductor normal, $\Delta H_i$ is the enthalpy change in the insulation as it is heated; $k_{in}$ is the thermal conductivity of the insulation between the secondary circuit and the superconducting coil; and $\Delta T$ is the temperature change in the secondary circuit needed to cause quench back.

## MEASUREMENT OF QUENCH BACK IN THE A AND B MAGNETS

Thermal quench back was first observed and identified during induced quenches in the A and B, LBL one-meter diameter solenoids [1]. The magnets, which were approximately half a meter long, were built with two layers of 1.0mm diameter superconductor wound on an 1100-0 aluminum bore tube (the shorted secondary circuit). Figure 1 shows the cross-section of the coil. The thickness of insulation between the superconductor and the bore tube was about 0.35mm. Table 1 shows the physical parameters of the A and B solenoid magnets. Included in the table are inductances, resistances, and superconductor parameters. The 1100 aluminum bore tubes were closely coupled to the superconducting coils (about 99 percent coupling). The coil and its secondary circuit were cooled indirectly by forced two phase helium in tubes outside of the coil.

The A and B magnets were instrumented with small coils for inducing quenches at one end of the coil. A normal region just over one centimeter in diameter could be induced in the magnets by discharging a capacitor into the small coils [5]. Quench back was observed by a sharp drop in the coil current, and a sharp increase in the $d\phi/dt$ voltage. Since quenches were induced, the quench back time was easily measured.

Figure 2 shows a plot of $i_1/i_o$ versus time for various induced quenches in the B solenoid magnet. The start and finish of quench

Table 1. Parameters and constants for the A and B magnets.

| | A Magnet | B Magnet |
|---|---|---|
| **Magnet Parameters** | | |
| Coil diameter $2a_1$ (m) | 1.021 | 1.021 |
| Coil length $\ell_1$ (m) | 0.461 | 0.464 |
| Number turns $N_1$ | 835 | 832 |
| Coil inductance $L_1$ (H) | 0.789 | 0.782 |
| Bore tube inductance $L_2$ (H) | $1.04\times10^{-6}$ | $1.04\times10^{-6}$ |
| Bore tube cross-section $A_{c2}$ ($m^2$) | $3.18\times10^{-3}$ | $3.18\times10^{-3}$ |
| Bore tube resistance at 10°K $R_2$ (ohm) | $1.77\times10^{-6}$ | $1.77\times10^{-6}$ |
| **Superconductor Parameters** | | |
| Number of filaments | 2300 | 2700 |
| Conductor diameter $D_w$ (mm) | 0.99 | 1.00 |
| Copper to superconductor ratio r | 1.8 | 1.0 |
| Twist pitch (mm) | 10 | 10 |
| Matrix copper resistivity at 10°K and B=0 $\rho_1$ (ohm m) | $2.39\times10^{-10}$ | $2.83\times10^{-10}$ |
| Conductor cross-section area $A_{c1}$ ($m^2$) | $7.85\times10^{-7}$ | $7.85\times10^{-7}$ |

back are indicated by a circle and an inverted triangle respectively. The measured quench back time for the A and B magnet versus starting current is shown in Fig. 3.

## CALCULATION OF QUENCH BACK TIME AND COMPARISON WITH MEASURED DATA

The value of $F_2^*$ for the secondary circuit from 4.5K to 10K can be calculated from the enthalpy change $\Delta H_2$ for aluminum and $\rho_2$ the resistivity of the 1100 aluminum in the bore tube. Since $\Delta H_2$ = 11600 $Jm^{-3}$ and $\rho_2 = 1.8\times10^{-9}$ Ωm (for RRR=14 aluminum), $F_2^* = \Delta H_2/\rho_2 = 6.44\times10^{12}\ A^2m^{-4}s$. Table 2 shows the value $J_o$ (the starting current density of the superconductor) $\rho_1$, $V_L$, $\alpha$, $R_{o1}$, $t_1$ and $\Delta H_{SC}$ as a function of the current $i_o$ at the start of the quench. In order to calculate the various values given in Tables 2 and 3 the following constants are given: $a_1 = 0.51$ m, $\ell_1 = 0.46$ m, $D_w = 10^{-3}$ m, $S = 1.25\times10^{-4}$ m, $k_i = 0.36\ Wm^{-1}K^{-1}$, $N_2 = 1$, $L = 2.45\times10^{-8}\ \Omega WK^{-2}$, and $T_c = 7K$. The values of r, $N_1$, $A_{c1}$, $A_{c2}$, $L_1$, $L_2$, and $R_1$ can be found in Table 1. Figure 4 shows measured values of $V_L$ as a function matrix current density $J_o$. (Note: $J_o = i_o/A_{c1}$).

Table 3 compares the calculated quench back time $t_{QB}$ with measured quench back time in the A and B solenoid magnets as a function of starting current. The theory agrees reasonably well with measurements of quench back time. For a given current, the quench back time in the A magnet is greater than in the B magnet. The reasons for this are that $R_{o1}$ and $\alpha$ are larger for the B magnet. This reflects the lower copper to superconductor ratio r and the somewhat higher resistivity of the matrix material $\rho_1$ in the superconductor for the B magnet.

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Table 2. The values of various current dependent parameters needed to calculate quench back time in the LBL A and B thin solenoid coils.

| $i_o$ (A) | $J_o$ ($Am^{-2}$) | $\rho_1$* (ohm m) | $V_L$ ($ms^{-1}$) | $\alpha$* | $R_{o1}$* (ohm $m^{-1}$) | tl (s) | $\Delta H_{SC}$ ($Jm^{-3}$) |
|---|---|---|---|---|---|---|---|
| A Magnet | | | | | | | |
| 200 | $2.55\times10^8$ | $2.32\times10^{-10}$ | 3.5 | 0.0189 | 2.75 | 0.458 | 20000 |
| 300 | $3.82\times10^8$ | $2.44\times10^{-10}$ | 6.0 | 0.0191 | 2.81 | 0.267 | 16000 |
| 400 | $5.10\times10^8$ | $2.50\times10^{-10}$ | 8.0 | 0.0193 | 2.83 | 0.200 | 12000 |
| 500 | $6.37\times10^8$ | $2.55\times10^{-10}$ | 12.0 | 0.0195 | 2.94 | 0.146 | 9500 |
| 700 | $8.92\times10^8$ | $2.60\times10^{-10}$ | 26.0 | 0.0198 | 3.00 | 0.062 | 7500 |
| B Magnet | | | | | | | |
| 195 | $2.48\times10^8$ | $2.83\times10^{-10}$ | 3.5 | 0.0230 | 4.02 | 0.458 | 25000 |
| 390 | $4.96\times10^8$ | $2.87\times10^{-10}$ | 7.6 | 0.0233 | 4.16 | 0.211 | 15000 |
| 585 | $7.45\times10^8$ | $2.95\times10^{-10}$ | 16.0 | 0.0236 | 4.26 | 0.100 | 11000 |
| 780 | $9.92\times10^8$ | $3.04\times10^{-10}$ | 29.0 | 0.0239 | 4.33 | 0.055 | 8500 |
| 920 | $11.72\times10^8$ | $3.10\times10^{-10}$ | 35.0 | 0.0241 | 4.40 | 0.046 | 8000 |

*Includes estimated effects of magneto-resistance.

Table 3. Calculated values of $t_Q$, $t_H$, and $t_{QB}$ compared with measured quench back times in the A and B magnets.

| $i_o$ (A) | $J_o$ ($Am^{-2}$) | $t_Q$ (s) | $t_H$ (s) | $t_{QB}$ (s) | $t_{QB}$ measured (s) |
|---|---|---|---|---|---|
| A Magnet | | | | | |
| 200 | $2.55\times10^8$ | 0.930 | 0.029 | 0.959 | 0.74-0.90 |
| 300 | $3.82\times10^8$ | 0.517 | 0.027 | 0.544 | 0.43-0.50 |
| 400 | $5.10\times10^8$ | 0.364 | 0.025 | 0.389 | 0.26-0.31 |
| 500 | $6.37\times10^8$ | 0.237 | 0.023 | 0.260 | 0.16-0.24 |
| 700 | $8.92\times10^8$ | 0.108 | 0.022 | 0.130 | 0.10-0.12 |
| B Magnet | | | | | |
| 195 | $2.48\times10^8$ | 0.703 | 0.032 | 0.735 | 0.56-0.68 |
| 390 | $4.96\times10^8$ | 0.288 | 0.026 | 0.314 | 0.20-0.28 |
| 585 | $7.45\times10^8$ | 0.133 | 0.023 | 0.156 | 0.13-0.17 |
| 780 | $9.92\times10^8$ | 0.073 | 0.022 | 0.095 | 0.09-0.10 |
| 920 | $11.72\times10^8$ | 0.058 | 0.021 | 0.079 | 0.07-0.08 |

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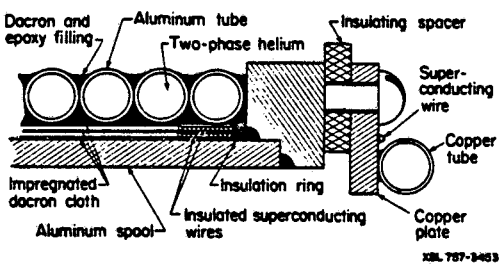


Fig. 1 A cross section of the one meter diameter solenoid magnets

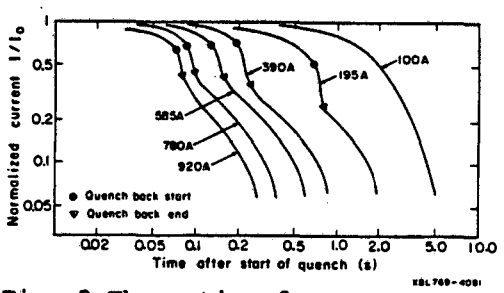


Fig. 2 The ratio of current to starting current vs time for induced quenches in the B magnet

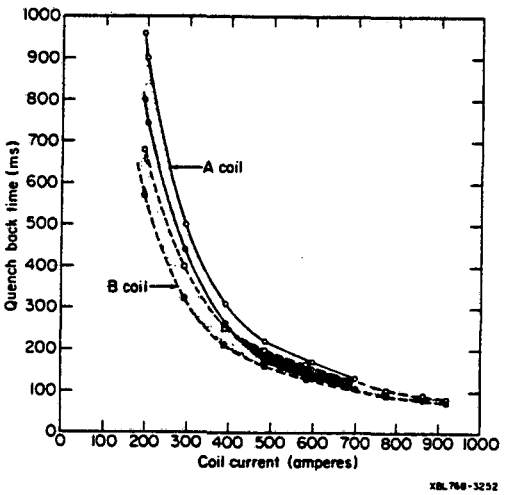


Fig. 3 Quench back time vs starting current in the A and B solenoid magnets

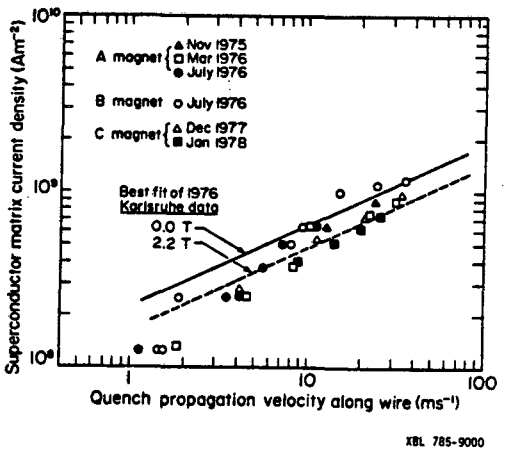


Fig. 4 Measured quench velocities $V_L$ as a function of superconductor matrix current density $J_o$

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