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M.A. Green

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Engineering and Technical Services Division
Lawrence Berkeley Laboratory
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M. A. Green

Engineering and Technical Services Division
Lawrence Berkeley Laboratory
University of California
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ABSTRACT

This report demonstrates the role of quench back in the quench protection of high current density superconducting solenoid magnets with well-coupled shorted secondary circuits. The phenomenon of "quench back" can be used to greatly reduce the size of an external quench protection resistor or even to eliminate the need for an external quench protection system altogether. A comparison is made with conventional magnet quench protection systems with and without a closely coupled secondary circuit.

The Lawrence Berkeley Laboratory (LBL) has been building large superconducting solenoid magnets for high energy physics applications for some years. These magnets have required a minimum amount of material between the inside and outside surfaces of the solenoid. In this application, conventional cryostable[1] magnets are not appropriate. The approach developed at LBL uses high current density superconducting coils which are closely coupled inductively to one or more secondary circuits.[2-4]

Using superconductors at high current densities ($j \geq 2 \times 10^8$ Am^{-2}) requires an understanding of the quench process. When a secondary circuit is involved, an integral part of the quench process is quench back between the secondary circuit and the superconducting coil.[5] Quench back becomes a key element to being able to safely quench large high current density superconducting solenoids which have no external quench protection system.

The quench process in a one-dimensional superconductor can be characterized by the one-dimensional equation[6]:

$$C \frac{\partial T}{\partial t} = \rho j^2 + \frac{\partial}{\partial x} \quad k\left(\frac{\partial T}{\partial x}\right) \qquad (1)$$

where C is the specific heat per unit volume ($Jm^{-3}K^{-1}$); T is temperature (K); t is time (s); ρ is the electrical resistivity of the wire (ohm-m); j is the current density (Am^{-2}); x is the dimension along the wire (m); and k is the thermal conductivity of the wire ($Wm^{-1}K^{-1}$). C, ρ, and k are nonlinear functions of temperature. Equation (1) can be rearranged into the form

$$\frac{\partial F}{\partial t} = j^2 + \frac{1}{\rho}\frac{\partial}{\partial x}\left(\alpha\rho\,\frac{\partial F}{\partial x}\right) \qquad (2)$$

where F is defined as

$$F(T) = \int_0^T \frac{C}{\rho}dT \qquad (3a)$$

and α the thermal diffusivity is

$$\alpha = k/C \qquad (3b)$$

Equation (2), which is nonlinear, can be simplified if certain assumptions are made. The quench process can be divided into three regions; the first two are not important in this analysis. The third is when α is small. (This region occurs at temperatures above 30 K.) When α is neglected, (2) takes the following approximate form:

$$\frac{\partial F}{\partial t} \simeq j^2 \quad . \qquad (4)$$

Equation (4) is the so-called "burnout" equation, which is commonly used in the electronics industry. This equation was applied to superconductors by Maddock and James.[7] When (4) is integrated at the superconductor hot spot (the point of origin of the quench), it takes the following form:

$$F(T_M) = \int_0^{T_M} \frac{C(T)}{\rho(T)}\,dT = \frac{r+1}{r}\,j_0^2 \int_0^t \Xi(t)^2 dt \qquad (5)$$

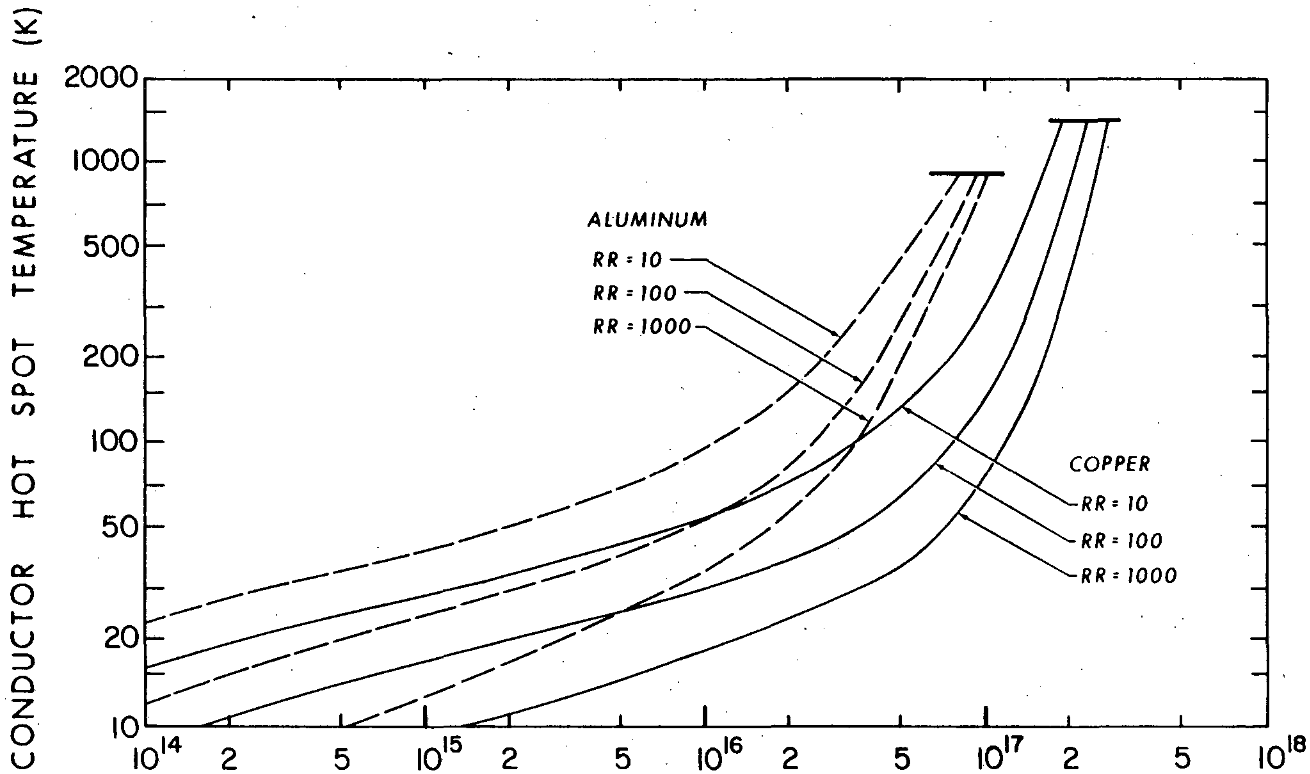
where T_M is the superconductor hot spot temperature (K), and r is the matrix material to superconductor ratio. C and ρ are applied to the superconductor matrix material; j_o is the current density in the superconductor at the start of the quench; and $\Xi(t) = i(t)/i_o$ where i(t) is the coil current during the quench and i_o is the starting current in the coil.

For a superconducting magnet to quench safely, T_M must be 400 K or less. For a typical copper-based high current density superconductor, this means that $F(T_M)$ must be 1.7×10^{17} $A^2m^{-4}s$ or less. (In this case, j and j_o are defined as the current density in the superconductor plus matrix material.) Figure 1 shows $F(T_M)$ as a function of T_M for various residual resistance ratio (RRR) coppers and aluminums.

<u>Safe quenching of magnets without a secondary circuit</u>

It is possible to design a magnet and an accompanying quench protection circuit that is safe against burnout. The most pessimistic assumption one can make is to assume that the superconducting coil has zero resistance (the hot spot occurs in an infinitely small piece of conductor). Thus, the coil energy must be removed by the quench protection circuit shown in Fig. 2. The current decay is represented by:

$$i = i_o e^{-t/\tau_1} \qquad (6)$$



$$F(T) = \int_{T=0}^{THOT} \frac{C(T)}{\rho(T)}\, dT = \frac{r+1}{r} \int J^2(t)\, dt \quad (A^2 m^{-4} s)$$

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Fig. 1 Peak hot spot temperature T_M as a function of $F(T_M)$ for various coppers and aluminums

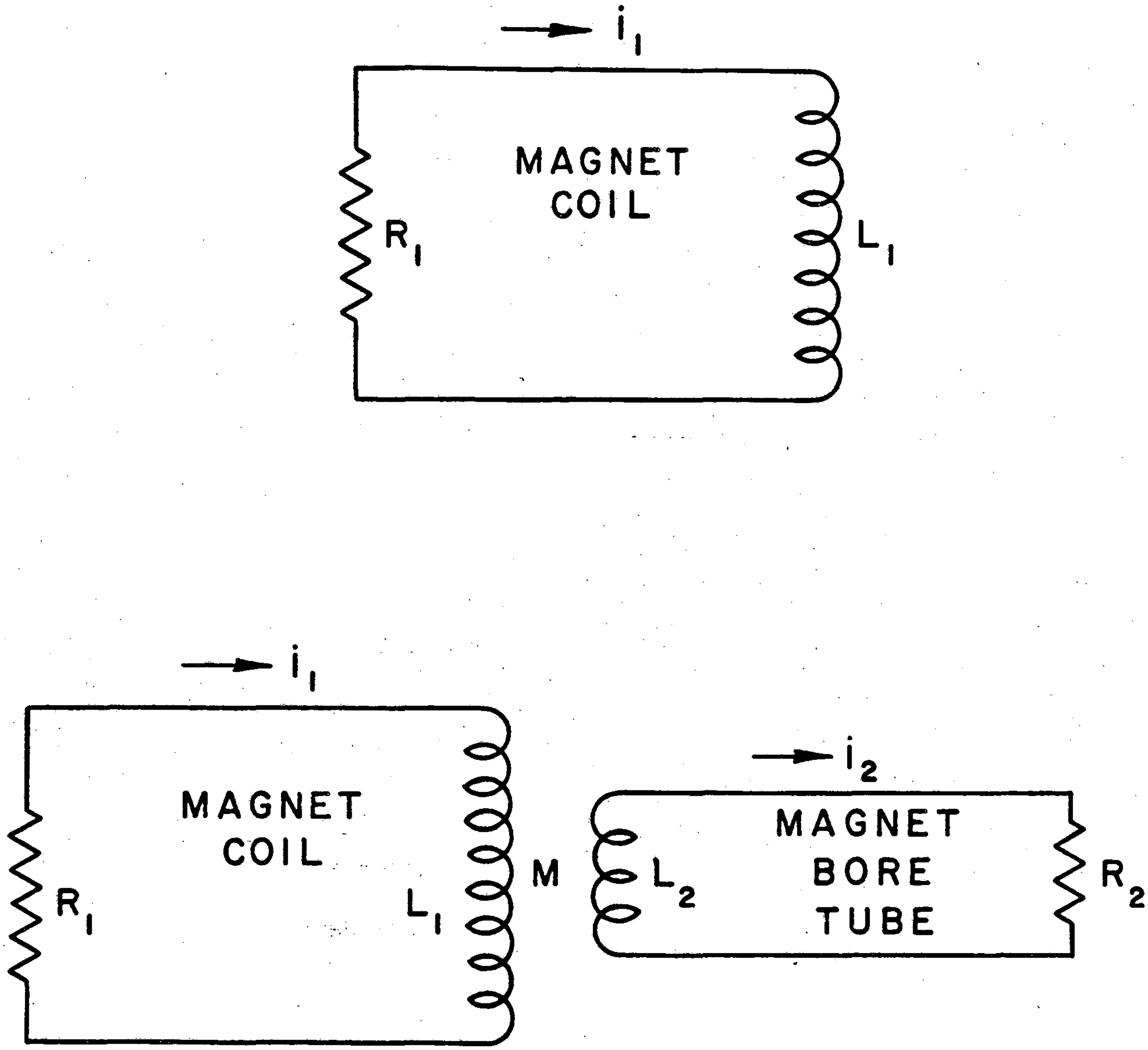

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Fig. 2 Electrical circuit diagrams of superconducting magnets with and without shorted secondary circuits: (a) coil without the bore tube; (b) coil with the bore tube where τ_1, the time constant of the coil circuit (s), is L/R_{ex} with L defined as the coil inductance (H) and R_{ex} as a constant external resistance. (In Fig. 2, R_{ex} is defined as R_1.)

$$F(T_M) \simeq \frac{r+1}{r} j_o^2 \left(\frac{\tau_1}{2} + t_{SO}\right) \tag{7}$$

where j_o is the starting current density in the superconducting matrix and t_{SO} is the time required to detect the quench and switch on the resistor. If a constant resistance is used, the value of this resistance R_{ex} is:

$$R_{ex} \simeq \frac{j_o^2}{2F(T_M)} \frac{r+1}{r} L_1 \tag{8}$$

where L_1 is the coil inductance, j_o is the starting current density in the matrix, $F(T_M)$ is found in Fig. 1, and r is the normal metal to superconductor ratio. The maximum voltage developed across the coil electrical leads is:

$$V_o = i_o R_{ex} \tag{9}$$

where i_o is the starting current.

In general, one wants to limit V_o to some reasonable value. In most superconducting magnets, the product of V_o and i_o has been limited to around 10^6 W. Thus one can define a limit over which one should not operate a magnet. From Fig. 1, one can see that $F(T_M)$

for a copper-based superconducting magnet is about 10^{17}. Thus, the operating limits for superconducting magnets should be set so that

$$E_o j_o^2 = V_o i_o \, F(T_M) \, \frac{r+1}{r} \simeq 10^{23} \tag{10}$$

where E_o is the magnet stored energy (J); j_o is the superconducting matrix current density (Am^{-2}); V_o is the maximum voltage across the quench protection resistor (V); i_o is the starting current (A); and $F(T_M)$ is found in Fig. 1.

In order to make substantial changes in the $E_o j_o^2$ limit given in (10), one must either change the type of external resistor used or employ a secondary circuit. The thyrite resistor or varistor is an external resistor with nonlinear resistance. The resistance is low at high current and high at low current. The resistance of a varistor is characterized by

$$R = R_o(\Xi)^{b-1} \tag{11}$$

with b on the order of 0.2 to 0.25. The starting resistance of the varistor is R_o. The value of $F(T_M)$ in a circuit using a varistor is:

$$F(T_M) \simeq \frac{r+1}{r} \, j_o^2 \left(\frac{\tau_1}{3-b} + t_{SO}\right) \tag{12}$$

where $\tau_1 = L_1/R_o$. As $b \to 0$, the varistor circuit reduces $F(T_M)$ to two-thirds of the value that would be obtained using a constant resistance $R_{ex} = R_o$. This is not an impressive gain.

Safe quenching of magnets with a secondary circuit but no quench back

A closely, inductively coupled low resistance secondary circuit permits one to increase the superconductor current density j_0 for a given stored magnetic energy E_0. The $E_0j_0^2$ limit is no longer a function of quench protection parameters when a secondary circuit is used. (The $E_0j_0^2$ limit is a function of such things as maximum allowable strain in the superconductor).[8]

The well-coupled low resistance secondary circuit will affect the quench process in the following ways:

(1) The secondary circuit behaves as a shorted secondary, which causes a shift in current away from the coil to itself.

(2) The secondary circuit will absorb a substantial amount of the magnet stored energy during the quench process.

(3) Since the time constant for magnetic flux decay is long compared to the time constant for the initial coil current decay, the transient voltages in the magnet coil system are reduced.

(4) A secondary circuit will greatly improve the performance of the varistor resistor and will permit other unusual types of external quench protection systems to be used (e.g. the center tap discharge method[9]).

(5) The secondary circuit causes portions of the coil that otherwise would not do so to go normal by ordinary quench propagation. This phenomenon is called "quench back."

The secondary circuit must be closely coupled, which means that $\varepsilon \leq 0.05$ where $\varepsilon \simeq (1 - M^2/L_1L_2)$. M is the mutual inductance between the superconducting coil, which has a self-inductance L_1, and the secondary circuit, which has a self-inductance L_2. When an ordinary resistor is used for quench protection, the coil circuit time constant τ_1 is defined as L_1/R_{ex} (R_1 in Fig. 2) and the secondary circuit time constant τ_2 is defined as L_2/R_2.

When τ_1 and τ_2, the coil and secondary circuit time constants, respectively, are constant, the current i in the coil has the following time relationship:

$$i = \frac{i_o}{\tau_L - \tau_S}\left[(\tau_1 - \tau_S)e^{-t/\tau_L} + (\tau_L - \tau_1)e^{-t/\tau_S}\right] \tag{13}$$

where, when ε is small,

$$\tau_1 = L_1/R_{ex} \tag{14a}$$

$$\tau_2 = L_2/R_2 \tag{14b}$$

$$\tau_L \simeq \tau_1 + \tau_2 \tag{14c}$$

$$\tau_S \simeq \frac{\varepsilon\tau_1\tau_2}{\tau_1 + \tau_2} \tag{14d}$$

$$\varepsilon \simeq 1 - \frac{M^2}{L_1 L_2} \tag{14e}$$

When τ_1 and τ_2 are constant, the value of $F(T_M)$ takes the following approximate form (no quench back is assumed):

$$F(T_M) = \frac{r+1}{r}\, j_o^2 \left[\frac{\tau_1^2}{2(\tau_1+\tau_2)} + \frac{\tau_S}{2} + t_{SO}\right] . \qquad (15)$$

A comparison of (7) and (15) shows that a low-resistance, well-coupled shorted secondary circuit will reduce $F(T_M)$ and the hot spot temperature considerably. Maddox and James[7] pointed out that if the secondary and primary circuits are made from the same material, the secondary circuit can be combined with the primary circuit to yield a somewhat lower value of T_M (when quench back is not present). If one makes the primary circuit from a copper-based superconductor and the secondary circuit from aluminum, then a lower hot spot temperature T_M will occur for a given superconductor plus secondary circuit mass. (Note: when the aluminum is combined with the primary circuit, a lower value for $F(T_M)$ is required for a given value of T_M.)

If the external resistor is replaced by a varistor resistor, a dramatic reduction in T_M results (when there is no quench back present). The method for calculating T_M is given in Refs. 9 and 10. The varistor resistor required for protection is very small when the secondary circuit is present. The coil energy is deposited in the coil and the secondary circuit rather than in the external resistor. Thyrite resistors are quite expensive, so it is fortunate that only a small amount of the thyrite material (similar to ferrite) is required. The options for external quench protection systems will be compared later.

Before leaving the varistor resistor, we should point out its major disadvantage. When a magnet quenches through a varistor, the voltage across the terminals remains high for some time during a quench. If the terminals are in the cryostat vacuum, the magnet may heat up, releasing frozen gases during this high voltage period. This hazard must be considered when designing coils protected by varistor resistors.

The quench back time required for fail-safe quenching

If the whole superconducting coil turns normal fast enough, the superconductor hot spot temperature T_M will be below its maximum allowable limit. Thus, fail-safe quenching can be achieved. If one can control the quench back time, then one can make the whole coil turn normal fast enough to allow for fail-safe quenching.

The quench back time required for fail-safe quenching, t_{QBR}, is a function of the maximum allowable hot spot temperature T_M, the normal metal to superconductor ratio r, the starting current density j_o over the whole superconductor plus matrix, and the temperature, T_{S1}, that the superconductor would achieve if the entire coil were to turn normal instantaneously.

Using adiabatic theory, one can rewrite (5) so that[11]

$$F(T_M) - F(T_{S1}) = \int_{T_{S1}}^{T_M} \frac{C(T)}{\rho(T)}\, dT = \frac{r+1}{r}\, j_o^2 \int_0^{t_{QBR}} \Xi(t)^2 dt \qquad (16)$$

where F(T) is defined by (3a) and ρ, C, and $\Xi(t)$ are previously defined.

The only assumption which may be applied to (16) is that $\Xi(t) = 1$. This assumes that the current in the conductor does not change until after quench back occurs. (This assumption results in a minimum value for t_{QBR}.) Using (16), one can estimate t_{QBR}:

$$t_{QBR} = \frac{r}{r+1}\left[\frac{F(T_M) - F(T_{S1})}{j_o^2}\right] \tag{17}$$

The temperature T_M can be arbitrarily set, but T_{S1} is a function of the material contained in the superconducting coil and in all of the coupled secondary circuits.

Using a complete theory for quench evolution, T_{S1} can be found by solving the following integral equation for T_{S1}:

$$G_1(T_{S1}) = \int_0^{T_{S1}} \rho(T)C(T)dT = \frac{r}{r+1}\int_0^{\infty} E(t)^2 dt \tag{18}$$

where $\rho(T)$, r, and C(T) are previously defined for the superconductor matrix and E(t) is the electrical field in the superconducting material which has been turned normal. The value of E(t) is very much a function of the various time constants of the secondary and primary circuits as the coil energy is deposited in those windings when the coil quenches.

There are equations similar to (18) that calculate G(T) and T_S for each of the active circuits in the magnet. At the end of the quench, each circuit will have a different temperature T_S, and the thermal energy deposited in all of the circuits must equal the initial energy stored in the magnet. For a magnet with only one well-coupled secondary circuit, the equation of thermal state at the end of the quench takes the following form:

$$E_o = L_1\, i_o^2/2 = V_1[H_1(T_{S1}) - H_1(T_o)] + V_2[H_2(T_{S2}) - H_2(T_o)] \quad (19)$$

where L_1 is the superconducting coil self inductance; i_o is the starting current in the superconducting coil; $H_1(T_{S1})$ is the enthalpy per unit volume of the material in the coil circuit at a temperature T_{S1}; $H_2(T_{S2})$ is the enthalpy per unit volume in the secondary circuit at a temperature T_{S2}. $H_1(T_o)$ and $H_2(T_o)$ are the enthalpies per unit volume of the materials in the two circuits at the initial temperature T_o. V_1 and V_2 are the metal volumes in the two circuits. Calculations of T_{S1} and T_{S2} are not easy to make with only a hand calculator, so simplifying assumptions are often made.

These simplifications are: (1) the temperatures of the coil and secondary circuit are the same at the end of the quench and (2) the structural and insulating material does not absorb any of the energy during the quench. Making these assumptions is not totally satisfactory, but generally the resulting error in T_{S1} is on the conservative side.

Once T_{S1} has been determined, the value of $F(T_{S1})$ can be determined from Fig. 3 for various copper matrix superconductors. Figure 3 gives $F(T_{S1})$ as a function of T_{S1} and the residual resistivity ratio RRR of the matrix material in the superconducting

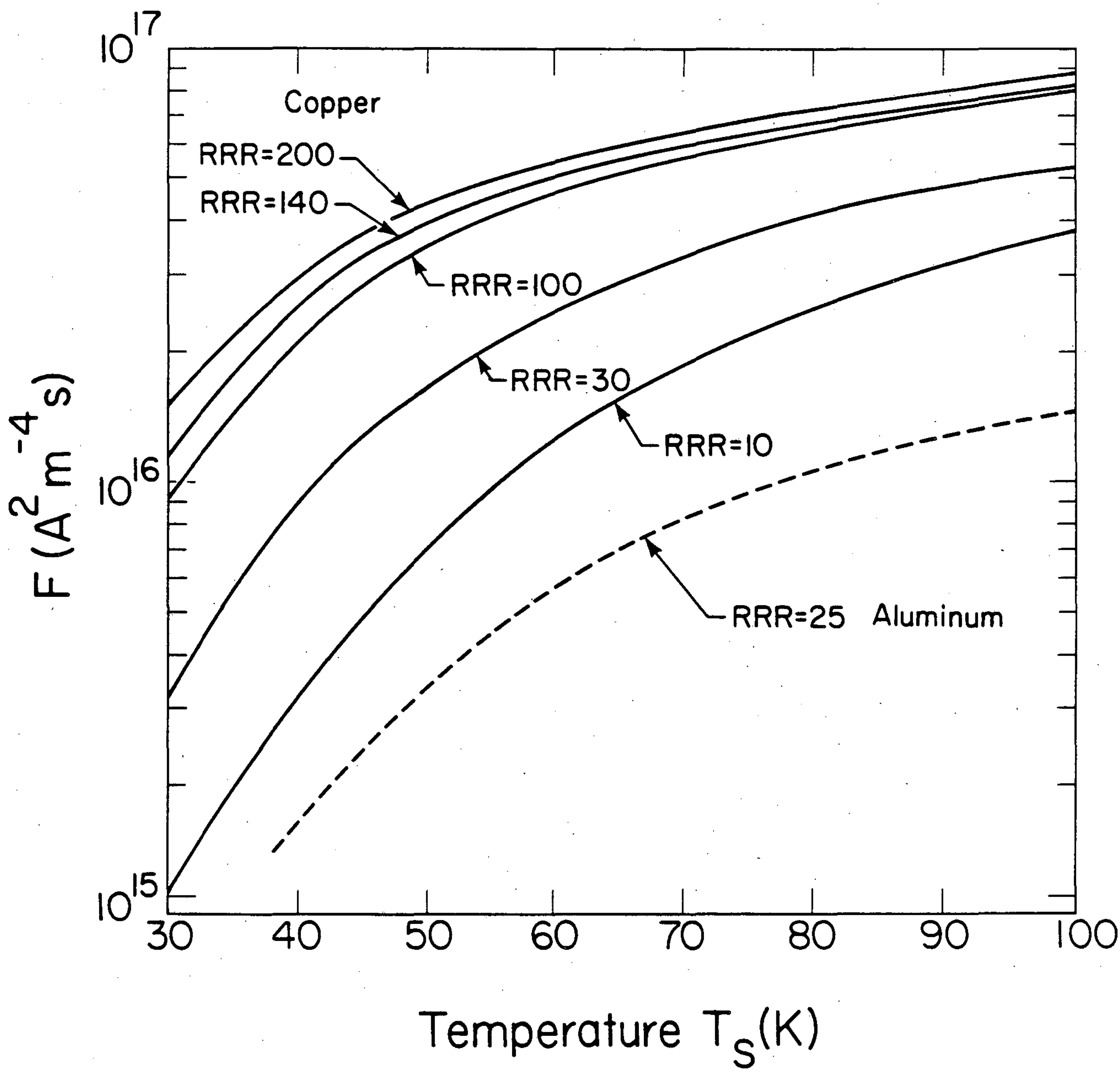

Fig. 3 The value of $F(T_S)$ versus the temperature T_S for coppers of various residual resistance ratios (RRR) and for aluminum (RRR = 25)

wire. Table 1 gives $F(T_M)$ for various RRR at values of T_M = 300 K and T_M = 400 K. It is interesting to note that $F(T_M)-F(T_{S1})$ is nearly constant for all values of residual resistivity ratio from 10 to 1000 as long as $T_{S1} \geq 65$ K. In large coils one should set the value of T_{S1} to 100 K or less. If T_M is set to 300 K and T_{S1} is set to 100 K, $F(T_M)-F(T_{S1}) \simeq 6.7 \times 10^{16}$ $A^2m^{-4}s$ for copper-based superconductors with matrix residual resistivity ratios of 10 to 1000. Increasing T_M from 300 to 400 K will increase $F(T_M)-F(T_{S1})$ by about 25 percent.

<u>The role of quench back in the quench protection of a magnet with an external resistor</u>

Quench protection of a superconducting magnet with a secondary circuit is enhanced if the bore tube can be heated to cause quench back. When quench back is considered, the value of the external resistor R_{ex} can be made smaller than one would calculate using (15). (The development of the theory of quench back is described elsewhere.[5])

For a superconducting magnet with a single secondary circuit, using adiabatic theory, one can define a function F_2^* which is a function of the integral of current density in the secondary circuit squared with time:

$$F_2^* = F_2(T_Q) - F_2(T_o) = \int_0^{t_Q} j_2(t)^2 dt \tag{20}$$

Table 1. Values of $F(T_M)$ for T_M = 300 K and 400 K for copper of various residual resistance ratios (RRR) and for aluminum at RRR = 25

		$F(T_M)$ ($A^2m^{-4}s$)	
Material	RRR	T_M = 300 K	T_M = 400 K
Copper	10	10.5×10^{16}	12.2×10^{16}
Copper	30	11.9×10^{16}	13.6×10^{16}
Copper	100	14.5×10^{16}	16.2×10^{16}
Copper	140	14.8×10^{16}	16.5×10^{16}
Copper	200	15.4×10^{16}	17.1×10^{16}
Aluminium	25	4.0×10^{16}	4.7×10^{16}

where

$$F(T_Q) - F_2(T_o) = \frac{\Delta H_2}{\rho_2} \tag{20a}$$

and

$$j_2(t) = \frac{i_2(t)}{A_{c2}} \tag{20b}$$

where i_2 is the current in the secondary circuit; A_{c2} is the cross-sectional area of the secondary circuit; ΔH_2 is the change in enthalpy per unit volume of the secondary circuit material from T_o to T_Q; ρ_2 is the resistivity of the secondary circuit material (ρ_2 is a constant from 0 to 15 K); T_o is the starting temperature of the secondary circuit; T_Q is the temperature of the secondary circuit that drives the superconducting coil normal through quench back (T_Q is between 10 and 15 K); and t_Q is the time for the secondary to heat up from T_o to T_Q in order to induce quench back.

The current in the secondary circuit for a well-coupled system (ε and τ_s are small) can be approximated by

$$i_2 \simeq \frac{\tau_2}{\tau_1+\tau_2} \frac{N_1}{N_2} i_o \tag{21}$$

where τ_1 and τ_2 are defined by (14a) and (14b); N_1 is the number of turns in the primary circuit (the superconducting coil); N_2 is the number of turns in the secondary circuit from which quench back is induced; and i_o is the starting current in the superconducting coil.

Using (21), one can redefine (20) to the following form:

$$\frac{\Delta H_2}{\rho_2} = \int_0^{t_Q} \left[\frac{\tau_2}{\tau_1 + \tau_2} \; \frac{N_i}{N_2} \; \frac{i_o}{A_{c2}} \right]^2 dt \tag{22}$$

Equation (22) can be solved for t_Q if several assumptions are made as follows:

(1) The current in the primary circuit drops only a little before quench back occurs ($\tau_2 << \tau_1$).

(2) The energy dissipated in the coil and its secondary circuit is small compared to the total magnetic energy in the coil before quench back.

(3) The coupling between the coil circuit and the secondary circuit is good ($t_Q > \tau_s$).

(4) Quench propagation in the coil does not affect quench back (the coil resistance is zero; $R_1 = R_{ex}$).

When (22) is solved for t_Q using these assumptions, the following solution evolves:

$$t_Q \simeq \frac{\Delta H_2}{\rho_2} \left[\frac{\tau_1}{\tau_2} \, \frac{N_2}{N_1} \, \frac{A_{c2}}{i_o} \right]^2 \tag{23}$$

Equation (23) can be solved for R_{ex} directly in the following form:

$$R_{ex} \simeq \left[\frac{L_1}{\tau_2} \, \frac{N_2}{N_1} \, \frac{A_{c2}}{i_o} \right] \left[\frac{\Delta H_2}{\rho_2 t_{QR}} \right]^{1/2} \tag{24}$$

where L_1, τ_2, N_2, N_1, A_{c2}, i_o, ΔH_2, and ρ_2 have been previously defined. t_{QR} is a function of the quench back time required for fail-safe quenching, t_{QBR}, defined by (17). t_{QR} is defined as follows:

$$t_{QR} = t_{QBR} - \left(t_H + \tau_s/2 + t_{SO}\right) \tag{25}$$

where τ_s is defined by (14d); t_{SO} is the time required to detect the quench and switch in the resistance R_{ex}; and t_H is the time associated with heating the superconductor and the insulation between the superconductor and secondary circuit by heat conducted from the secondary circuit.[5] t_H has a value of 0.03–0.04 seconds when the insulation thickness between the superconductor and the secondary circuit is 0.5 mm. When the insulation thickness is increased 1.0 mm, t_H increases to 0.08 to 0.10 seconds.

Before using (24), one should make sure t_H is less than t_{QBR}. One should also check τ_s. If R_{ex} is small (which means τ_1 is large compared to τ_2), $\tau_s = \epsilon\tau_2$. One must check to see that the basic assumptions behind (24) are met before applying the equation. If they are not, one must use (23), substituting $(\tau_1+\tau_2)/\tau_2$ for τ_1/τ_2. The full form for τ_s must also be used. Equations (14a), (14d), and the modified form of (23) can be solved iteratively to yield a minimum value for R_{ex}.

Table 2 presents the parameters of a magnet similar to the Time Projection Chamber (TPC) magnet built by LBL.[12] It is assumed that

Table 2. Parameters of a superconducting magnet and its secondary circuit

Magnet Parameters	
Self inductance, L_1	4.5 H
Number of turns, N_1	1800
Starting current, i_o	2300 A
Starting current density, j_o	6.5×10^8 Am^{-2}
Copper to superconductor ratio, r	1.8
Temperature, T_{s1}	80 K
Hot spot temperature, T_M	400 K
$F(T_M)$ in matrix (RRR = 100)	1.62×10^{17} $A^2m^{-4}s$
Required quench back time, t_{QBR}	0.15 s
Switching time for resistor	0
Secondary Circuit Parameters	
Circuit time constant, L_2/R_2	5 s
Number of turns	1
Secondary circuit cross sectional area, A_{c2}	$3.15 \times 10^{-2} m^2$
Enthalpy change from T_o to T_Q (T_Q = 15 K)	4.9×10^4 J
Secondary circuit resistivity, ρ_2	10^{-9} Ωm
$\varepsilon = 1 - M^2/L_1L_2$	0.01
Heat transfer period, t_H	0.08 s

a 3.3 m long, 9.5 mm thick aluminum bobbin is used as a quench back element. Table 3 compares the starting resistance for various external quench protection resistors R_{ex} and the peak voltage across that resistor for various types of quench protection systems.

Table 3 shows that the addition of a secondary circuit reduces the values of an external ordinary quench protection resistor. The performance of a varistor resistor is enhanced by the secondary circuit. The reduction is even greater when quench back from the secondary circuit is considered. Quench back as an aid to quench protection using an external resistor is planned for the Collider Detector Facility (CDF) thin solenoid at the Fermi National Laboratory in the United States.[13] Quench back, if properly controlled, can be used for safe quenching of magnets without an external resistor.

Controlled quench back as a method of safe quenching without an external quench protection system

The preceding section showed that thermal quench back can reduce the value of an external resistor used for quench protection of a superconducting magnet with a closely coupled secondary circuit. Reference 5 shows that quench back is an important element in the quench protection of two LBL test solenoids with closely coupled circuits and no external quench protection. Quench back was induced by the growing resistance of the coils as the normal region propagated within the superconducting coil.

If a superconducting magnet turns completely normal fast enough (in a time less than t_{QBR}), no external quench protection system is

Table 3. Resistance of an external quench protection resistor and its peak voltage for safe quenching of a magnet with parameters given in Table 2.

Quench Protection System	R_{ex} (Ω)	V_{max} (V)
Magnet coil without a secondary circuit and with a normal resistor (Eq. (8))	9.07	20860
Magnet coil without a secondary circuit but with a varistor resistor, b = 0.2 (Eq. (12))	6.48[b]	14900
Magnet coil with a secondary circuit and a normal resistor, no quench back (Eq. (15))	2.51	5770
Magnet coil with a secondary circuit and a varistor resistor, (b = 0.2), no quench back[a]	0.37[b]	850
Magnet coil with a secondary circuit and a normal resistor and quench back (Eq. (25))	0.29	670

a See Ref. 10 for the method of calculation

b Resistance of the varistor at 2300 A

needed. If the growth of resistance can be controlled and if the current is transferred to the secondary circuit fast enough, fast quench back (where the whole superconducting coil turns normal) can occur such that t_{QB}, the quench back time, is less than t_{QBR}. This section presents the conditions favorable for fast quench and hence for fail-safe quenching without an external quench protection system.

The quench back time for a superconducting magnet with a closely coupled secondary circuit in thermal contact with the superconducting coil can be calculated with the following approximate expression:

$$t_{QB} \simeq t_Q + t_H \tag{26}$$

where t_Q is the period associated with the shift of current from the superconducting coil to the secondary circuit and the heating of the secondary circuit to a temperature T_Q (about 10 K), and t_H is the period associated with heating the superconductor and the insulation between the superconductor and the secondary circuit by heat inducted from the secondary circuit (see (15) in Ref. 5).

t_Q can be calculated using (20) where $j_2(t)$ is defined by (20b), and i_2 is defined by (21). Here τ_1 is not a constant; instead, it starts out at infinity and gets smaller as the resistance of the coil grows. The theory for the growth of the coil resistance is discussed in some detail in Ref. 5. The important thing to understand is whether the quench is predominately three-dimensional, two-dimensional, or one-dimensional. In Ref. 5, expressions for t_Q are developed for thin coil superconducting solenoids (the coil thickness is small compared to the coil radius such that a three-dimensional quench changes to a two-dimensional quench quickly).

The approximate expressions for t_Q developed in Ref. 5 are as follows:

If the normal region propagation within the coil is two-dimensional, the expression for t_Q is:

$$t_Q \approx \left[5F_2^* \left(\frac{L_1 R_2 N_2 A_{c2}}{L_2 R_{02} N_1 \alpha V_L^{\,2} i_o}\right)^2\right]^{1/5} \tag{27}$$

where F_2^* is determined by (20) and (20a) and Table 4. L_1, L_2, N_1, N_2, R_2, i_o, and A_{c2} are previously defined. V_L can be determined by measurement or by the method given in Ref. 14. (Measured normal region propagation velocities along the wire made by LBL are shown in Fig. 4.) α is the ratio of turn-to-turn normal region propagation velocity to the normal region velocity along the wire V_L. The normal region velocity ratio α for a coil with rectangular conductors can be expressed as:

$$\alpha = \left[\frac{\rho_1 k_i}{L\ T_c}\ \frac{a}{S}\,\frac{b'}{b}\ \frac{r+1}{r}\right]^{1/2} \tag{28a}$$

when b'/b is greater than 0.5, and as:

Table 4. Enthalpy of various materials as a function of temperature from 4.5 to 15 K.

Temperature	Enthalpy ($J \cdot m^{-3}$)			
	Aluminum[a]	Copper[a]	Nb–Ti[a]	Epoxy[b]
4.5	1620	1600	8800	9000
5.0	2100	2230	11300	13000
6.0	3270	3830	17200	24000
7.0	4860	6330	24900	40000
8.0	7020	9790	34700	62000
10.0	13200	21400	—	120000
12.0	22400	40100	—	200000
15.0	48600	95200	—	360000

[a]See Reference 10

[b]Estimate

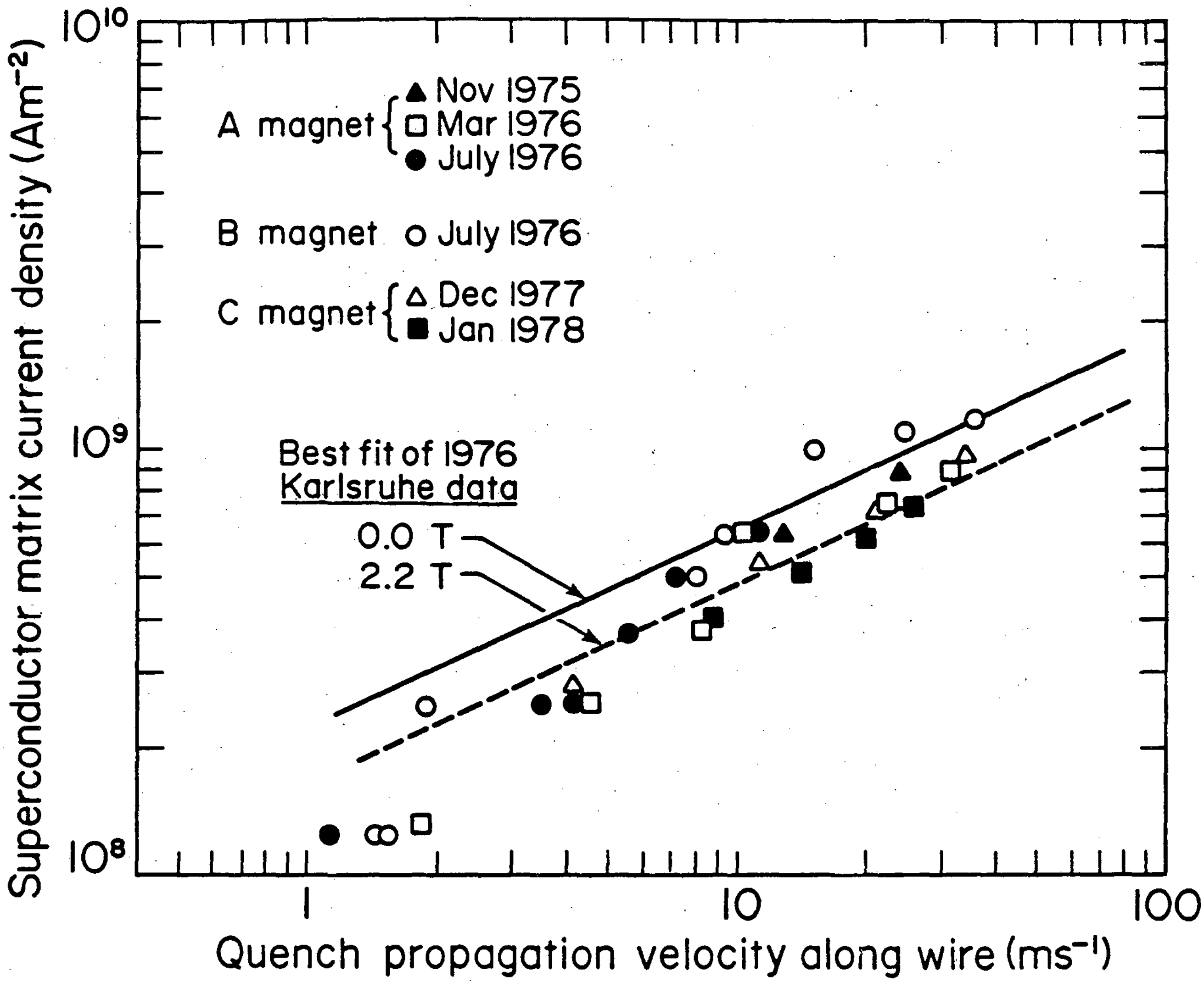

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Fig. 4 Measured normal region propagation velocities along the superconducting wire V_L as a function of superconductor overall current density J_o

$$\alpha \simeq 0.7 \left[\frac{\rho_1 k_i}{L\ T_c} \frac{a}{S} \frac{r+1}{r}\right]^{1/2} \qquad (28b)$$

when b'/b is less than 0.5. k_i is the thermal conductivity of the insulation between turns; ρ_1 is the resistivity of the matrix material in the superconductor; r is the normal metal (matrix material) to superconductor ratio; L is the Lorentz number ($L = 2.45 \times 10^{-8}\ \Omega W K^{-2}$); and T_c is the critical temperature of the superconductor (use $T_c = 7$ K). The values of a, b, b', and S are given as follows: a is the width of the conductor in the turn-to-turn propagation direction; b is the thickness of the conductor; b' is the width of the flat face at the edge of the conductor (b = b' when there are no rounded corners on the rectangular conductor); and S is the thickness of the insulation between turns.

For thin superconducting coils with round conductors, the ratio of turn-to-turn to longitudinal normal region propagation velocity α takes the same form as (28b) except that a is defined as the diameter of the round conductor.

The resistance function R_{02}, which has the units of Ωm^{-2}, takes the following form for a thin solenoid magnet:

$$R_{02} = \frac{N_1 \rho_1}{\ell_1 A_{c1}} \left(\frac{r+1}{r}\right) \qquad (27a)$$

where N_1, ρ_1, and r are previously defined; ℓ_1 is the length of the solenoid ((27a) assumes that the quench propagates from the end of the solenoids; if the quench propagates from the center of the solenoid, R_{02} is doubled); and A_{c1} is the cross-sectional area of the superconductor (matrix material plus superconductor).

If the normal region propagation within the coil is one-dimensional, the approximate solutions for t_Q are:

$$t_Q = \frac{t1}{2} + \left[3F_2^*\left(\frac{L_1R_2N_2A_{c2}}{L_2R_{01}N_1\alpha V_L i_o}\right)^2\right]^{1/3} \tag{29}$$

when t* = t1 (one-dimensional propagation is from turn to turn, as would be the case in a long solenoid), where t* is the shorter of two times t1 or t2, which are defined as follows:

$$t1 = \frac{\pi a_1}{V_L} \tag{30a}$$

and

$$t2 = \frac{\ell_1}{\alpha V_L} \tag{30b}$$

where a_1 is the radius of the solenoid; ℓ_1, α, and V_L have been previously defined.

The resistance function R_{01}, which has the units Ωm^{-2}, is defined for the case where t* = t1 as follows:

$$R_{01} = \frac{2\pi a_1}{\ell_1}\,\frac{N_1\rho_1}{A_{c1}}\,\frac{r+1}{r} \tag{29a}$$

where a_1, ℓ_1, N_1, ρ_1, A_{c1}, and r have been defined previously. A quench started at the center of the coil will have double the value given by (29a).

The second form of one-dimensional propagation occurs when $t^* = t2$ (one-dimensional propagation along the wire, in a short solenoid); t_Q has the following approximation for this case:

$$t_Q \approx \frac{t2}{2} + \left[3F_2^* \left(\frac{L_1 R_2 N_2 A_{c2}}{L_2 R_{01} N_1 V_L i_o} \right)^2 \right]^{1/3} \tag{31}$$

where R_{01} takes the form:

$$R_{01} \approx \frac{2N_1 \rho_1}{A_{c1}} \; \frac{r+1}{r} \tag{31a}$$

where N_1, ρ_1, r and A_{c1} are previously defined.

Equations (27), (29), and (31) can be used to define t_Q for a thin solenoid, but a better understanding of the quench process requires further modification of these equations. If one assumes that a thin solenoid is well coupled to its shorted secondary circuit (ε is small), L_1, L_2, and R_2 are defined as follows:

$$L_1 \approx \frac{\mu_o \; \pi \; a_1^2 \; N_1^2}{\ell_1} \, g_1(a_1, \ell_1) \quad , \tag{32a}$$

$$L_2 \approx \frac{\mu_o \; \pi \; a_2^2 \; N_2^2}{\ell_2} \, g_2(a_2, \ell_2) \quad , \tag{32b}$$

$$R_2 \approx \frac{\rho_2 \; 2\pi \; a_2 \; N_2}{A_{c2}} \quad , \tag{32c}$$

where a_1 is the average radius of the superconducting coil; a_2 is the average radius of the secondary circuit coil; ℓ_1 is the length of the superconducting coil; ℓ_2 is the length of the secondary circuit coil; N_1 is the number of turns in the superconducting coil; N_2 is the number of turns in the shorted secondary; ρ_2 is the resistivity of the secondary circuit material; and A_{c2} is the cross-sectional area of the secondary circuit. $g_1(a_1,\ell_1)$ and $g_2(a_2,\ell_2)$ are geometric factors for the solenoid. (g_1 and g_2 are one when the solenoid is bounded by unsaturated iron poles.) μ_o is the magnetic permeability of vacuum ($\mu_o = 4\pi \times 10^{-7}$ Hm^{-1}).

Since the coupling between the primary and secondary circuit is good, $a_1 \simeq a_2$ and $\ell_1 \simeq \ell_2$. Therefore, the geometric factors g_1 and g_2 are to first order, equal to one another. Thus (30a) and (32b) can be used for L_1 and L_2 in the general case with no iron.

The value of F_2^* is given by (20) and (20a). F_2^* is a function of nothing but ΔH_2 and ρ_2. The turn-to-turn to longitudinal quench velocity ratio α is defined by (28a) and (28b), and R_{02} and R_{01} by (27a), (29a) and (31a). When one makes the appropriate substitutions into (27), (29), and (31), one gets the following forms:

$$t_Q \simeq \left[\frac{200\ \Delta H_2 \rho_2\ LT_c\ a_1^2 \ell_1^{\,2}}{\rho_1^3\ \Gamma\ V_L^4\ j_o^2} \quad \left(\frac{r}{r+1}\right)^3\right]^{1/5} \tag{33}$$

for a two-dimensional quench in a thin solenoid from (27);

$$t_Q \simeq \frac{t1}{2} + \left[\frac{3\Delta H_2 \rho_2\ LT_c \ell_1^{\,2}}{\rho_1^3\ \Gamma\ V_L^{\,2}\ j_o^{\,2}} \quad \left(\frac{r}{r+1}\right)^3\right]^{1/3} \tag{34}$$

when $t^* = t1$, the one-dimensional quench from (30); and

$$t_Q \simeq \frac{t2}{2} + \left[\frac{30\Delta H_2 \ \rho_2 a_1^{\ 2}}{\rho_1^2 \quad V_L^{\ 2} \ j_o^{\ 2}} \quad \left(\frac{r}{r+1}\right)^2\right]^{1/3} \tag{35}$$

when $t^* = t2$, the one-dimensional quench from (31). Note that ΔH_2, ρ_2, L, T_c, a_1, ℓ_1, ρ_1, r, V_L, j_o, t1 and t2 have been previously defined. Γ is the turn-to-turn to longitudinal propagation function, defined as:

$$\Gamma \simeq k_i \ (a/S)(b'/b) \tag{36a}$$

for rectangular conductors with b'/b greater than 0.5 (see (28a)) and

$$\Gamma \simeq 0.5 \ k_i \ (a/S) \tag{36b}$$

for rectangular conductors with b'/b less than 0.5. (Equation (36b) can be applied to round conductors if a is defined as the conductor diameter.)

We find from (33), (34), and (35) that quench back in a solenoid is a function of several variables: (1) ρ_2, the resistivity of the secondary material; (2) ΔH_2, the enthalpy change in the secondary needed to induce quench back; (3) ρ_1, the resistivity of the matrix material in the superconductor; (4) r, the matrix material to superconductor ratio in the conductor; (5) j_o, the starting current density in the conductor, and (6) V_L, the quench velocity along the wire at a current density j_o. (V_L is a function of j_o as well; from Fig. 4, one can use $V_L \simeq 2.65 \times 10^{-15} \ j_o^{\ 1.8}$. See Ref. 16

for Karlsruhe-measured data where V_L has a j_o^2 relationship.) The quench back time t_Q is also a function of various coil geometric factors and, where applicable, it is also a function of Γ, the constant which determines the turn-to-turn quench propagation.

From (17), one can see that t_{QBR} is also a function of r and j_o. The reduction of t_Q which results from increasing j_o and decreasing r is more than compensated for by a reduction in t_{QBR}. Thus, from a practical standpoint, the only functions which can make a change in t_Q without changing t_{QBR} in a given superconducting magnet are ρ_2, ΔH_2, and ρ_1.

Changes in ρ_2 and ΔH_2 go together; ρ_2 and ΔH_2 are functions of the type, not the amount, of material used in the secondary circuit. The amount of material in the secondary circuit or circuits does affect t_{QBR} but not t_{QB}. (The secondary circuit absorbs energy from the magnetic field; therefore, T_{S1} is reduced when the amount of material in the secondary circuit increases.)

One can use two secondary circuits to promote quench back and absorb energy from the magnetic field. One secondary circuit can induce quench back in a magnet (this circuit needs very little material and should be very closely coupled to the superconducting coil), while a second circuit absorbs a substantial portion of the magnet stored energy (which increases t_{QBR}). Such a pair of secondary circuits has been used in the TPC magnet.[12,16,17]

The parameter with the largest effect on quench back time t_{QB} is ρ_1, the resistivity of the superconductor matrix material. If one wants to reduce t_{QB} by reducing t_Q, one can increase ρ_1. This has its price, however, in reduced superconductor adiabatic and dynamic stability. Up to a point, one can compensate for this reduced stability by reducing the superconductor filament size.[18] When ρ_1 is increased substantially, stability must be considered. Unfortunately there are no direct experimental measurements of the effect of ρ_1 on t_{QB}.

The theory for calculating quench back time t_{QB} and the required quench back time for fail-safe quenching t_{QBR} has a number of assumptions, and there is not much experimental data on the effects of changes in parameters such as ΔH_2, ρ_2, and ρ_1. The theory appears to be conservative when compared with experimental data taken at LBL. For example, the A and B solenoid experimental data described in Ref. 5 showed that one can predict the quench back time t_{QB}. One can also predict t_{QBR} and compare it with measured t_{QB} data.

Figure 5 shows the calculated values for t_{QB} and t_{QBR} in the B solenoid built by LBL.[19] The measured quench back time t_{QB} is shown. The open square and triangle shows that the calculated value of the hot spot temperature T_M (based on measurements of the integral of j^2 dt) is less than 300 K. The filled square and triangle show a calculated value of T_M greater than 300 K. In reality the hot spot temperature in B coil did not become higher than 300-400 K because the coil quenched safely at all currents up to 920 A.[19,20] In addition, a later run at the Sandia National Laboratory showed that B coil could be safely quenched at 960 A.[20]

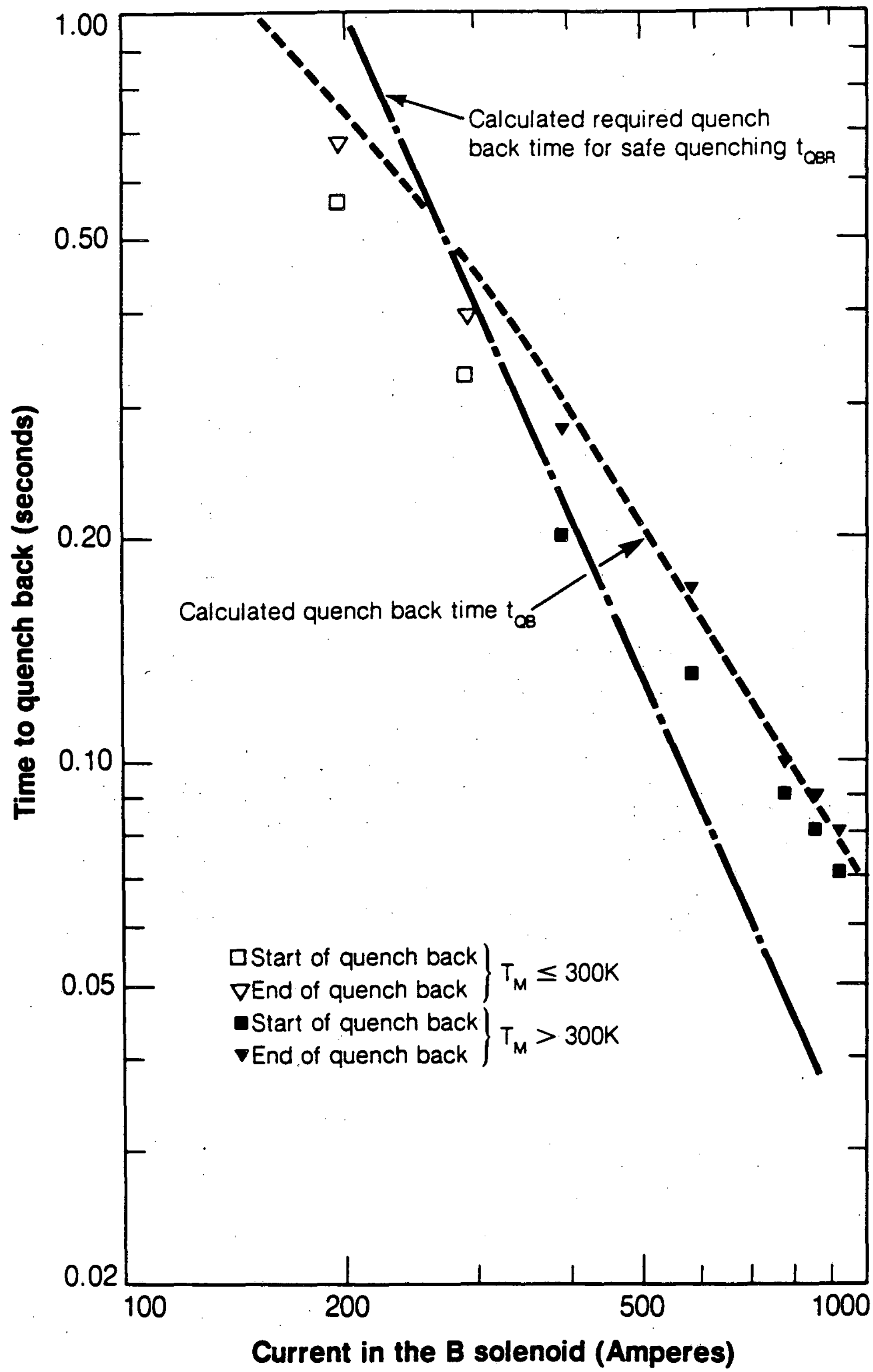

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Fig. 5 Calculated values of t_{QB} and t_{QBR} compared with measured quench back time in the B solenoid (see text) as a function of start current i_o in the solenoid

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AUTHOR

The author is in the Mechanical Department of the Engineering and Technical Services Division of the Lawrence Berkeley Laboratory, Berkeley, California 94720.

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