QUENCHES IN LARGE SUPERCONDUCTING MAGNETS*

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Abstract

The development of large high current density superconducting magnets requires an understanding of the quench process by which the magnet goes normal. A theory which describes the quench process in large superconducting magnets is presented and compared with experimental measurements. The use of the quench theory to improve the design of large high current density superconducting magnets is discussed.

Introduction

The Lawrence Berkeley Laboratory has been developing high current density superconducting solenoid magnets for over two years[1]. The use of superconductors at high current densities ($> 5 \times 10^8$ Am^{-2}) requires an understanding of the quench process. Quenching, the process by which a superconducting magnet goes normal, can be very damaging to a magnet, unless the current in the coil is dropped quickly. The energy which is dissipated into the superconducting coil while the magnet turns normal will tend to be concentrated into the warmest parts of the magnet.

The quench process in a one-dimensional superconductor can be characterized by the following one-dimensional equation[2]

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

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

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

where F is defined as follows:

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

and α the thermal diffusivity is

$$\alpha = \frac{k}{C} \ . \quad (3b)$$

Equation 2 is nonlinear; hence, difficult to solve in a meaningful way. The quench can be divided into three distinct regions. The first region (Region A) is characterized by a low thermal diffusivity. When α is neglected,

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

This equation is used to calculate burnout of a superconducting magnet as described by Tollestrup[3]. The second region (Region B) is dominated by heat transfer and it is a region where the electrical resistivity is a constant. The differential equation describing this region is:

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$$\frac{\partial F}{\partial t} = j^2 + \frac{\partial}{\partial x}\left(\alpha \frac{\partial F}{\partial x}\right) . \quad (5)$$

Equation 5 takes a form similar to the wave equation. From it a characteristic quench velocity can be obtained. The third region (Region C) is characterized by zero resistivity. This region will not enter into the discussions of this paper. The boundary between Region A and Region B occurs at between 20 and 30K. The boundary between Regions B and C occurs at the critical temperature of the superconductor.

The velocity of quench waves. The velocity of normal region propagation can be found from Equation 5. The solution to this equation takes the following form[4]:

$$v < j \left[\frac{\rho_n \alpha_{nc}}{h_{nc}-h_{no}}\right]^{1/2} \quad (6)$$

where ρ_n is the resistivity of the normal metal, α_{nc} is the thermal diffusivity of the normal metal at the critical temperature of the superconductor and $h_{nc}-h_{no}$ is the normal metal enthalpy difference (Jm^{-3}) between the critical temperature of the superconductor and the normal operating temperature. Note the above equation has no direct dependence on r, the ratio of normal metal to superconductor. The form of the velocity equation which LBL is currently using is

$$v \gtrsim 0.6\, j \left[\frac{\rho_n \alpha_{nc}}{h_{nc}-h_{no}}\right]^{1/2} . \quad (7)$$

The preceding equation is dependent on B and j. There is almost no dependence on r. The dependence on current density is about $j^{1.5}$ at low current densities. At high current densities, this becomes a j^2 dependence similar to that observed by Turowski[5]. At higher magnetic inductions, the quench wave moves faster (see Fig. 1).

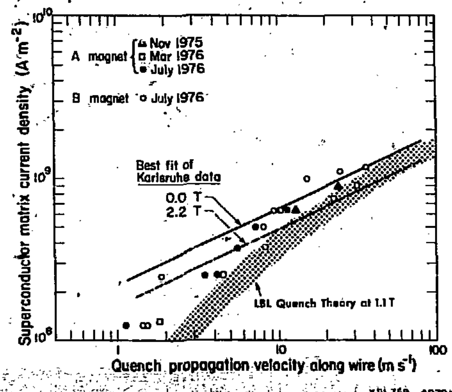

Figure 1. Theoretical and measured quench velocities as a function of superconductor matrix current density.

Figure 1 compares measurements of quench velocity in the LBL thin solenoids with a theoretical curve derived from Equation 7 and with the Karlsruhe measurements made by Turowski. Note that the trend of the measured points follows the shape of the theoretical curve. The theoretical curve shows velocities which are higher than the measurements. This is probably due to the fact that the theory does not take into account either the insulation around the superconductor or the heat transfer out of the system. The Karlsruhe data shows a j^2 dependence; the LBL data does not. The Karlsruhe samples were much better cooled than the LBL magnets; it is likely that good heat transfer to the helium bath accounts for the reduced quench velocities measured by Karlsruhe at low current densities.

Figure 1 shows the quench wave velocity in copper-based superconductors where the copper has a resistance ratio of around 100. Increasing the resistance ratio has only a small effect on the quench velocity. The velocity of quench waves in aluminum-based superconductors is about a factor 3 higher than for copper-based superconductors. A greater dependence on r the normal metal to superconductor ratio is expected.

The increase in resistance of the coil as the quench is propagated causes the coil energy to be dumped. In a single wire $R \approx vR_0t$; in a thin coil (two-dimensional) $R \approx R_0\gamma v^2t^2$; and in a thick (three-dimensional) coil $R \approx R_0\gamma^2v^3t^3$ where t is time, R_0 is a resistance constant, v is the quench velocity along the wire, and γ is the ratio of transverse to longitudinal quench velocities. Increasing the velocity of propagation v and increasing γ all help to increase the resistance faster. One must dump the current fast enough to prevent burnout.

Derivation of the burnout condition. The limit under which burnout of a superconducting magnet may occur can be found by integrating Equation 4:

$$F = \int_0^t j^2 dt . \quad (8)$$

Redefining this slightly, one gets

$$F^*(T) = \int_0^t \frac{C}{\rho_n} dT = \frac{1+r}{r} \int_0^t j^2 dt$$

$$= \frac{1+r}{r} j_0^2 \int_0^t \Xi^2 dt \quad (9)$$

where j_0 is the starting current density in the superconducting matrix and Ξ is the ratio of current i_0. If one defines a limiting temperature which the coil hot spot is permitted to be, one defines a permissible integral of j^2dt.

Figure 2 shows temperature as a function of F*(T) for copper and aluminum of various resistance ratios. F*(T) is determined by the matrix material and its resistance ratio (ratio of resistance at 273K to resistance at 10K). The permissible integral of j^2dt is determined by multiplying F*(T) given in Figure 2 by r/(r+1).

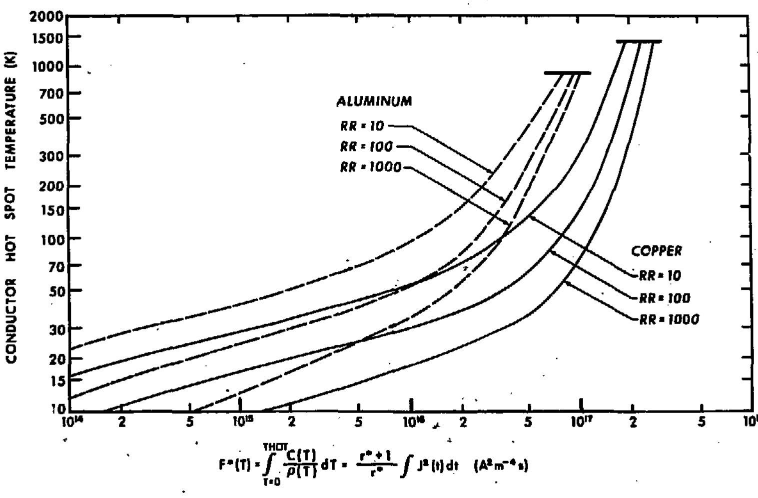

Figure 2. Hot spot temperature vs. F*(T) for copper and aluminum of various resistance ratios.

A safe method of coil testing. One can test a superconducting magnet and avoid burnout by quenching at low currents(6). The integral of j^2dt, which we will define as Δ, is measured. If the product of Δ times $(r+1)/r$ is less than $F^*(T_{max})$, one has not reached burnout. The next safe current at which the magnet can be operated is determined as follows:

$$i_{next} = \left[\frac{F^*(T_{max})r}{\Delta(r+1)}\right]^{1/2} i_o \tag{10}$$

where Δ is the measured integral of j^2dt when the magnet was quenched at a starting current of i_o; r is the normal metal to superconductor ratio and i_{next} is the highest value of current at which safety from burnout can be guaranteed.

This method of quench testing has been used on all of the large high current density superconducting solenoids built at LBL. The value used for T_{max} in all of the LBL tests was 400K.

Safe design of magnets with a single coil. 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 magnet 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 Figure 3. The current decay is represented by:

$$i = i_o e^{-t/\tau} \tag{11}$$

where τ, the time constant of the coil circuit (s), is L/R_{ext} with L defined as inductance (H) while R_{ext} is a constant external resistance.

$$F^*(T_{max}) \simeq \frac{1+r}{r} j_o^2 \left[\frac{\tau}{2} + t_{SO}\right] \tag{12}$$

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 in the resistor. If a constant resistance is used, the value of this resistance R_{ext} is:

$$R_{ext} = \frac{j_o^2}{2F^*(T_{max})} \frac{r+1}{r} L \tag{13}$$

where L is the coil inductance; V_o is the starting current density in the matrix; $F^*(T_{max})$ is found in Figure 2 and r is the normal metal to superconductor ratio. The maximum voltage developed across the coil electrical leads is:

$$V_o = i_o R_{ext} \tag{14}$$

where i_o is the starting current.

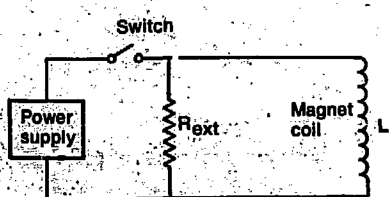

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Figure 3. Quench protection circuit for a simple coil.

In general, one wants to limit V_o to some reasonable value. In most superconducting magnets which have been built, the product of V_o and i_o has been limited to around 10^6W. Thus, one can define a limit over which one should not operate a magnet. From Figure 2, one can see that $F^*(T_{max})$ for copper-based superconducting magnet is about 10^{17}. Thus, the operating limits for superconducting magnets should be set so that

$$E_o j_o^2 = V_o i_o F^*(T_{max}) \frac{r+1}{r} \approx 10^{23} \tag{15}$$

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 $F^*(T_{max})$ is found in Figure 2.

Figure 4 shows the superconductor matrix current density as a function of stored magnetic energy for a number of superconducting magnets which have been built or have been proposed. Note that most of them are near or below the $E_o j_o^2 = 10^{23}$ line. The notable exceptions are the LBL thin solenoid test coils and the proposed TPC solenoid.

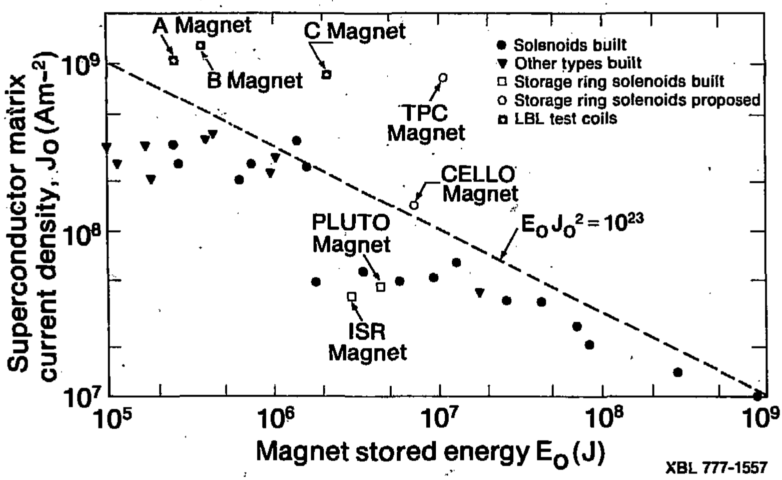

Figure 4. Superconductor matrix current density vs. magnetic stored energy for a number of magnets which have been built or are proposed.

How have such large departures from the $E_o j_o^2 = 10^{23}$ line been achieved? Two methods have been used: (1) the thyrite resistor, and (2) the conductive bore tube.

<u>The thyrite resistor</u>. 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[7]

$$R = R_o(\Xi)^{b-1} \tag{16}$$

with b of the order of 0.2 to 0.25. The starting resistance of the varistor is R_o. The value of $F^*(T_{max})$ in a circuit using a varistor is given as follows:

$$F^*(T_{max}) \approx \frac{r+1}{r} j_o^2 [\frac{\tau_o}{3-h} + t_{so}] \tag{17}$$

where $\tau_o = L_1/R_o$. As $b \to 0$, the varistor circuit reduces $F^*(T_{max})$ to 2/3 the value that would be obtained using a constant resistance $R_{ext} = R_o$. This is not an impressive gain; therefore, the varistor alone does not account for the spectacular gain in the LBL thin magnets.

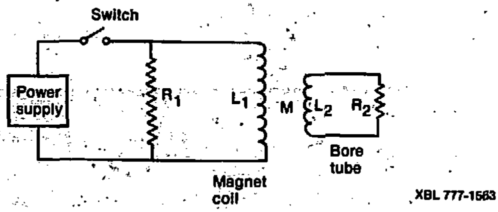

Figure 5. Quench protection circuit for a simple coil with a coupled bore tube.

Magnets with coupled bore tubes. The coupled bore tube is the key to making operation possible well above the $E_o j_o^2 = 10^{23}$ line. The theory of the coupled bore tube is discussed elsewhere[7,8]. This section will just describe its effect. The coupling between the bore tube and the coil must be very good, say $\varepsilon \leq 0.05$ where $\varepsilon = (1-M^2/L_1L_2)$. M is the mutual inductance between the coil and the bore tube, L_1 is the coil inductance and L_2 is the bore tube inductance (see Fig. 5). The resistance of the bore tube R_2 should be low such that $\tau_2 = L_2/R_2$ is greater than $\tau_1 = L_1/R_{ext}$ at all temperatures above 10K. The bore tube is most effective when $\tau_2 \geq 2\tau_1$.

The well-coupled low resistance bore tube will affect the quench process in the following ways:

1) The bore tube behaves as a shorted secondary which causes a shift in current away from the coil to itself.
2) The bore tube 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 greatly reduced.
4) The bore tube causes portions of the coil to go normal which would not do so by ordinary quench propagation. This phenomena is called "quench back".

When τ_1 and τ_2, the coil and bore tube time constants, respectively, are constant, the current i in the coil has the following time relationship;

$$i = \frac{i_o}{\tau_L-\tau_S}\left[(\tau_1-\tau_S)e^{-t/\tau_L} + (\tau_L-\tau_1)e^{-t/\tau_S}\right] \tag{18}$$

where when ε is small

$$\tau_L \approx \tau_1 + \tau_2 \tag{19a}$$

$$\tau_S \approx \frac{\varepsilon\tau_1\tau_2}{\tau_1+\tau_2} \tag{19b}$$

When τ_1 and τ_2 are constant, the value of $F^*(T_{max})$ takes the following approximate form (no quench back is assumed);

$$F^*(T_{max}) \approx \frac{r+1}{r} j_o^2 \left[\frac{\tau_1^2}{2(\tau_1+\tau_2)} + \frac{\tau_S}{2} + t_{SO}\right]. \tag{20}$$

From equation 18, one can see that substantial reductions of $F^*(T_{max})$ can be made. The varistor has a much more dramatic effect when there is a bore tube. Figure 6 shows the current decay of a magnet with and without a conductive bore tube. The constant resistor and the varistor are used. In Figure 6 the bore tube time constant is assumed to be twice the coil circuit time constant. The coupling is very good, $\varepsilon = 0.02$. Table 1 shows $F^*(T_{max})$ and T_{max} for a copper-based conductor with a resistance ratio of 100 and a copper to superconductor ratio r of 1. $j_o = 7 \times 10^8$ Am^{-2}, $\tau_2 = 2$ and the switching time t_{SO} is assumed to be zero.

Table 1 shows the effectiveness of the conductive bore tube particularly when a varistor is employed instead of an ordinary resistor. The behavior shown in Fig. 6 has been measured

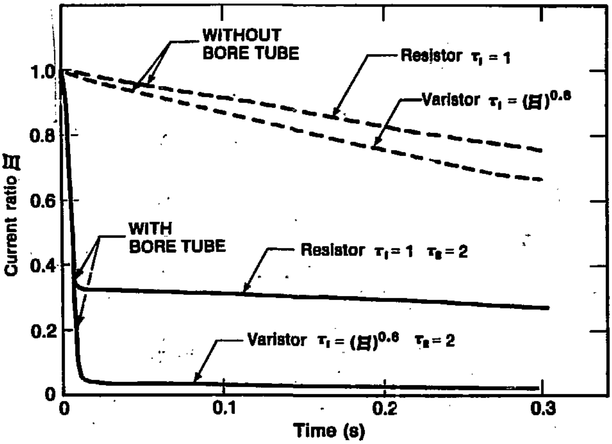

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Figure 6. The current ratio Ξ time for coils being discharged through simple resistors and varistors with and without a closely coupled conductive bore tube.

Table 1. $F^*(T_{max})$ and T_{max} for the four curves given in Figure 6. $j_o = 7 \times 10^8$ Am^{-2}, $t_{SO} = 0$, $\varepsilon = 0.02$, $r = 1$.

bore tube	Type of resistance	$F^*(T_{max})$	T_{max} (K)
No	resistor*	4.9×10^{17}	>1300‡
No	varistor**	3.5×10^{17}	>1300‡
Yes	resistor*	1.6×10^{17}	~350
Yes	varistor**	6.1×10^{15}	~ 28

*$\tau_1 = 1$ ‡copper melts

**$\tau_1 = (\Xi)^{0.8}$

experimentally[9]. Varistors have reduced the current in the LBL thin solenoid magnet by factors of 20 to 30. The integral j^2dt measured during these tests was dominated by $j_o^2t_{SO}$ term. Even though t_{SO} is less than 10 ms, it is a dominant factor in the integral j^2dt measured.

None of the curves shown in Fig. 6 take into consideration quench back from the bore tube. The current flowing in the bore tube will cause the whole magnet to go normal quickly. If the resistance of the bore tube grows fast enough, quench back will occur early enough to permit fail safe coil operation (with no quench protection circuit). Fail safe operation without quench protection has been demonstrated in the LBL test coils at values of $E_oj_o^2 = 6 \times 10^{23}$. Experiments using the varistor quench protection system show that operation at values of $E_oj_o^2 > 10^{25}$ is possible.

Conclusions

Large superconducting magnets operating at high current densities can be built provided one understands the quench process. The basic theory suggests steps that can be taken to make the operation of large superconducting magnets safe. In conclusion the following comments can be made:

1. Quench velocities vary with j and B. There is a j^n dependence on the velocity where N is between 1.5 and 2.1. Quench velocities in aluminum-based superconductors are about a factor of three faster than for copper-based superconductors.

2. Quench protection can be achieved in coils without conductive bore tubes provided $E_o j_o^2 < 10^{23}$ in copper-based coils. In aluminum-based coils $E_o j_o^2 < 3 \times 10^{22}$.

3. The closely coupled conductive bore tube substantially improves the ability of superconducting coils to withstand quenching. Fail safe operation without quench protection has been demonstrated at $E_o j_o^2 = 6 \times 10^{23}$. The use of a good quench protection system should permit copper-based coil operation at $E_o j_o^2 > 10^{25}$.

4. The effectiveness of the thyrite resistor (varistor) quench protection circuit is greatly enchanced by the closely coupled conductive bore tube.

5. Quench back due to current flowing in the conductive bore tube will help protect the coil from burnout.

6. A coil with a quench protection circuit requires quick detection of the quench. The switching time is very important when the coil operates at high current densities.

The quench process is well enough understood so that a large detector solenoid can be built. This magnet will have an $E_o j_o^2 = 8 \times 10^{24}$ (see the TPC magnet in Figure 4)[10].

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