Lawrence Berkeley National Laboratory

Recent Work

Title

QUENCH BACK IN SUPERCONDUCTING MAGNETS WITH SHORTED SECONDARY CIRCUITS

Permalink

<https://escholarship.org/uc/item/01h0v5pw>

Author

Green, M.A.

Publication Date

1982-05-01

Lawrence Berkeley Laboratory

UNIVERSITY OF CALIFORNIA

RECEIVED
LAWRENCE
BERKELEY LABORATORY

Engineering & Technical Services Division

JUL 5 1982

LIBRARY AND
DOCUMENTS SECTION

Presented at the 9th International Cryogenic Engineering
Conference, Kobe, Japan, May 11-14, 1982

QUENCH BACK IN SUPERCONDUCTING MAGNETS WITH SHORTED
SECONDARY CIRCUITS

M.A. Green

May 1982

TWO-WEEK LOAN COPY

*This is a Library Circulating Copy
which may be borrowed for two weeks.
For a personal retention copy, call
Tech. Info. Division, Ext. 6782.*

LBL-14383

DISCLAIMER

This document was prepared as an account of work sponsored by the United States Government. While this document is believed to contain correct information, neither the United States Government nor any agency thereof, nor the Regents of the University of California, nor any of their employees, makes any warranty, express or implied, or assumes any legal responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by its trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof, or the Regents of the University of California. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof or the Regents of the University of California.

QUENCH BACK IN SUPERCONDUCTING MAGNETS WITH SHORTED SECONDARY CIRCUITS

M.A. Green

Mechanical Engineering Dept, Lawrence Berkeley Laboratory,
University of California, Berkeley, California, USA

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_0 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:

$$t_Q = \frac{t_1}{2} + \left[\frac{3 F_2^*}{\left(\frac{L_2 R_{01} N_1 \alpha V_L i_0}{L_1 R_2 N_2 A_{c2}} \right)^2} \right]^{1/3}, \quad (1)$$

where F_2^* is the current density integral defined by Eq. (3); i_0 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_{01} is the resistance constant in the one-dimensional resistance growth equation; V_L is the quench propagation velocity along the wire; and α is the ratio of turn-to-turn quench velocity to quench velocity along the wire.

R_{01} , α and t_1 are given by the following expressions:

$$R_{01} = \frac{2\pi a_1 N_1 \rho_1 \left(\frac{r+1}{r} \right)}{\ell_1 A_{c1}}, \quad (2a)$$

and for coils with round conductors

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

and

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

where a_1 is the solenoid radius; ℓ_1 is the superconducting coil length; ρ_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]:

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

where ρ_2 is the resistivity of the material in the secondary circuit; ΔH_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:

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

where b is the average thickness of one layer of superconductor (for round wire $b = \pi D_w/4$); a is the thickness of insulation between the secondary circuit and the superconducting coil; ΔH_{SC} is the enthalpy change needed to drive the superconductor normal, ΔH_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 ΔT 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_0 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 l_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)	1.04×10^{-6}	1.04×10^{-6}
Bore tube cross-section A_{c2} (m ²)	3.18×10^{-3}	3.18×10^{-3}
Bore tube resistance at 10°K R_2 (ohm)	1.77×10^{-6}	1.77×10^{-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 ρ_1 (ohm m)	2.39×10^{-10}	2.83×10^{-10}
Conductor cross-section area A_{c1} (m ²)	7.85×10^{-7}	7.85×10^{-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 ΔH_2 for aluminum and ρ_2 the resistivity of the 1100 aluminum in the bore tube. Since $\Delta H_2 = 11600 \text{ Jm}^{-3}$ and $\rho_2 = 1.8 \times 10^{-9} \text{ } \Omega\text{m}$ (for RRR=14 aluminum), $F_2^* = \Delta H_2 / \rho_2 = 6.44 \times 10^{12} \text{ A}^2\text{m}^{-4}\text{s}$. Table 2 shows the value J_0 (the starting current density of the superconductor) ρ_1 , V_L , α , R_{01} , t_1 and ΔH_{SC} as a function of the current i_0 at the start of the quench. In order to calculate the various values given in Tables 2 and 3 the following constants are given: $a_1 = 0.51 \text{ m}$, $l_1 = 0.46 \text{ m}$, $D_w = 10^{-3} \text{ m}$, $S = 1.25 \times 10^{-4} \text{ m}$, $k_1 = 0.36 \text{ Wm}^{-1}\text{K}^{-1}$, $N_2 = 1$, $L = 2.45 \times 10^{-8} \text{ } \Omega\text{WK}^{-2}$, and $T_c = 7\text{K}$. 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_0 . (Note: $J_0 = i_0 / A_{c1}$).

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_{01} and α are larger for the B magnet. This reflects the lower copper to superconductor ratio r and the somewhat higher resistivity of the matrix material ρ_1 in the superconductor for the B magnet.

ACKNOWLEDGEMENTS

The author acknowledges the contribution of P.H. Eberhard and R.R. Ross in the development of the theory used to calculate quench back time. Special thanks go to G.H. Gibson, R.G. Smits, and J.D. Taylor in their contribution to the project. This work was supported by the Director,

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	J_o	ρ_1^*	V_L	α^*	R_{ol}^*	t_l	ΔH_{SC}
(A)	(Am ⁻²)	(ohm m)	(ms ⁻¹)		(ohm m ⁻¹)	(s)	(Jm ⁻³)
A Magnet							
200	2.55×10^8	2.32×10^{-10}	3.5	0.0189	2.75	0.458	20000
300	3.82×10^8	2.44×10^{-10}	6.0	0.0191	2.81	0.267	16000
400	5.10×10^8	2.50×10^{-10}	8.0	0.0193	2.83	0.200	12000
500	6.37×10^8	2.55×10^{-10}	12.0	0.0195	2.94	0.146	9500
700	8.92×10^8	2.60×10^{-10}	26.0	0.0198	3.00	0.062	7500
B Magnet							
195	2.48×10^8	2.83×10^{-10}	3.5	0.0230	4.02	0.458	25000
390	4.96×10^8	2.87×10^{-10}	7.6	0.0233	4.16	0.211	15000
585	7.45×10^8	2.95×10^{-10}	16.0	0.0236	4.26	0.100	11000
780	9.92×10^8	3.04×10^{-10}	29.0	0.0239	4.33	0.055	8500
920	11.72×10^8	3.10×10^{-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	J_o	t_Q	t_H	t_{QB}	t_{QB} measured
(A)	(Am ⁻²)	(s)	(s)	(s)	(s)
A Magnet					
200	2.55×10^8	0.930	0.029	0.959	0.74-0.90
300	3.82×10^8	0.517	0.027	0.544	0.43-0.50
400	5.10×10^8	0.364	0.025	0.389	0.26-0.31
500	6.37×10^8	0.237	0.023	0.260	0.16-0.24
700	8.92×10^8	0.108	0.022	0.130	0.10-0.12
B Magnet					
195	2.48×10^8	0.703	0.032	0.735	0.56-0.68
390	4.96×10^8	0.288	0.026	0.314	0.20-0.28
585	7.45×10^8	0.133	0.023	0.156	0.13-0.17
780	9.92×10^8	0.073	0.022	0.095	0.09-0.10
920	11.72×10^8	0.058	0.021	0.079	0.07-0.08

Office of Energy Research, Office of High Energy and Nuclear Physics, Division of High Energy Physics of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

REFERENCES

- 1 Green, M.A., Eberhard, P.H., and Taylor, J.D. "Large High Current Density Superconducting Solenoids for Use in High Energy Physics Experiments," published in Proceedings of the 6th International

Cryogenic Engineering Conference ICEC-6, Grenoble, France, May (1976), LBL-4824.

- 2 Taylor, J.D., et al. "Quench Protection for a 2MJ Magnet," IEEE Transactions on Magnetics MAG-15(1), Lawrence Berkeley Laboratory Report LBL-7576, January (1979).
- 3 Green, M.A. "The Development of Large High Current Density Solenoid Magnets for Use in High Energy Physics Experiments," Doctoral dissertation, University of California, Berkeley, Lawrence Berkeley Laboratory Report LBL-5350, May (1977).
- 4 Green, M.A. "Design Conditions for Fail Safe Quenching of a High Current Density Solenoid with a Shorted Secondary Circuit," LBL Report (to be published).
- 5 Eberhard, P.H., and Taylor, J.D. "A Technique to Induce Quenches," LBL Physics Note 816, February (1976).

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_0

This report was done with support from the Department of Energy. Any conclusions or opinions expressed in this report represent solely those of the author(s) and not necessarily those of The Regents of the University of California, the Lawrence Berkeley Laboratory or the Department of Energy.

Reference to a company or product name does not imply approval or recommendation of the product by the University of California or the U.S. Department of Energy to the exclusion of others that may be suitable.

TECHNICAL INFORMATION DEPARTMENT
LAWRENCE BERKELEY LABORATORY
UNIVERSITY OF CALIFORNIA
BERKELEY, CALIFORNIA 94720