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THE LOCATION OF THE QUENCH ORIGIN IN A SUPERCONDUCTING ACCELERATOR MAGNET

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Abstract

A method of calculating the initial rate of rise of the resistive voltage in a quenching superconducting magnet is described. Comparison of such calculations with data from spontaneously occurring quenches gives the location of the quench origin since the normal state resistance of the conductor is determined by its position in the windings due to the magnetoresistance of the copper matrix. The characteristics of the voltage buildup is used to separate quenches occurring in low field regions, such as the magnet ends, from those starting in the two-dimensional straight section of the coil. The magnitude of $\dot{V}$ is a measure of performance and can be used to determine if the magnet is reaching the maximum current permitted by the conductor parameters.

Introduction

When a superconducting magnet quenches the initial growth of the normal zone is governed by the velocity of propagation along the conductor and the cable resistance. The propagation velocity depends on the peak magnetic field in the conductor cross section and the current at quench. This velocity can be calculated for the current and field conditions in the windings if enough information is available from tests of samples of the conductor. The normal state resistance of a specific turn in the coil is determined by the average field over the conductor and its residual resistivity ratio. Since the average field for the rather large conductors used in accelerator dipoles varies with position in the winding each turn will have a unique value of initial voltage rise for a specific quench current and can be identified. In practice the difference between turns is often small and it is convenient to divide the winding into a few groups of similar turns and identify regions in the coil rather than specific turns. In this paper the rate of rise of voltage observed in spontaneous quenches is compared with that calculated from the conductor properties for a short sample training test experiment and for the SSC prototype magnet designed LLN-002.

Magnetoresistance

The normal state resistance of the cable used in accelerator dipoles and quadrupoles is usually specified by giving the resistance at room temperature (295K) and the residual resistance ratio (RRR), the ratio of the resistance at room temperature to that in liquid helium. In practice the resistance at the critical temperature of NbTi at zero field is used and designated R_{10}. For a typical SSC inner coil conductor R_{295} is 26.2 μΩ/cm and the RRR is 70. Since the increase of resistance with field (magnetoresistance) is greater for high conductivity copper the resistivity approaches the same value at high fields. An improvement in RRR while it does not translate directly into high field conductivity, always results in a net gain. This is illustrated in Fig. 1 where the resistance of the SSC conductor is shown as a function of field for several values of RRR. A similar graph can be easily constructed for other conductors with different copper to superconductor ratios.

Magnetic Field Distribution

The magnet field distribution in the coil determines the average field over the cross section of a turn and hence its resistance. Figure 2 is a field map of the inner layer of the SSC Design D magnet with lines of constant field marked as a fraction of the peak field which occurs in the turn nearest the post. For convenience this layer has been divided into four sections and the average field over the turns in each section computed and indicated in Fig. 2.

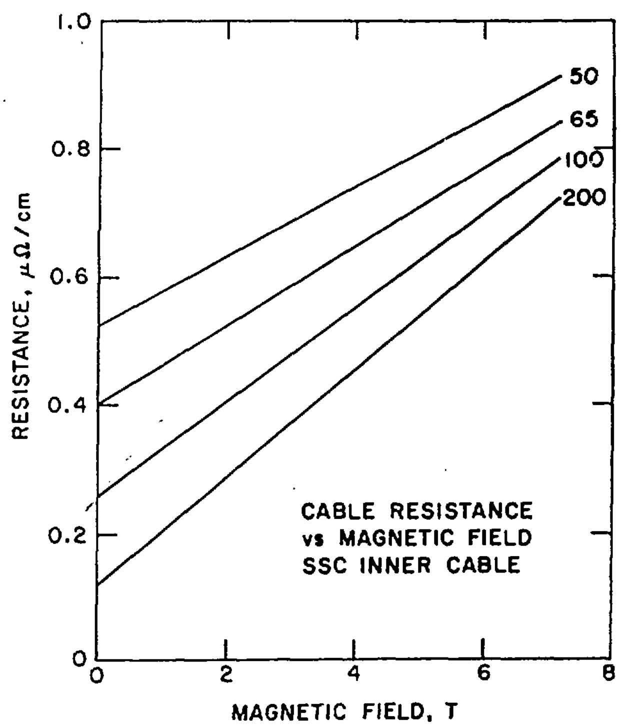

Fig. 1. Cable normal state resistance as a function of magnetic field for various values of the Residual Resistivity Ratio.

The peak field for each conductor is near the inner boundary and is between 90 and 100% of the maximum field. From the information in Figs. 1 and 2 the resistance can be calculated for a representative turn in each of the four groups as a function of current. If the velocity of propagation is known, the rate of rise of voltage can be calculated from the equation;

$$\frac{dV}{dt} = 2IR_I\upsilon \qquad 1$$

where R_I is the resistance per unit length of the conductor at the current I and υ is the longitudinal propagation velocity. The factor two arises from the fact that the normal zone grows in both directions. The rate of change of voltage will only be constant until neighboring turns begin quenching. Because of this and other effects such as "quench speedup" which complicates the situation as the normal zone develops, we have restricted our analysis to the first 10-15 ms of the transition.

Longitudinal Propagation Velocity

The velocity of propagation of the normal front along a superconducting cable can be conveniently represented by the equation,[1]

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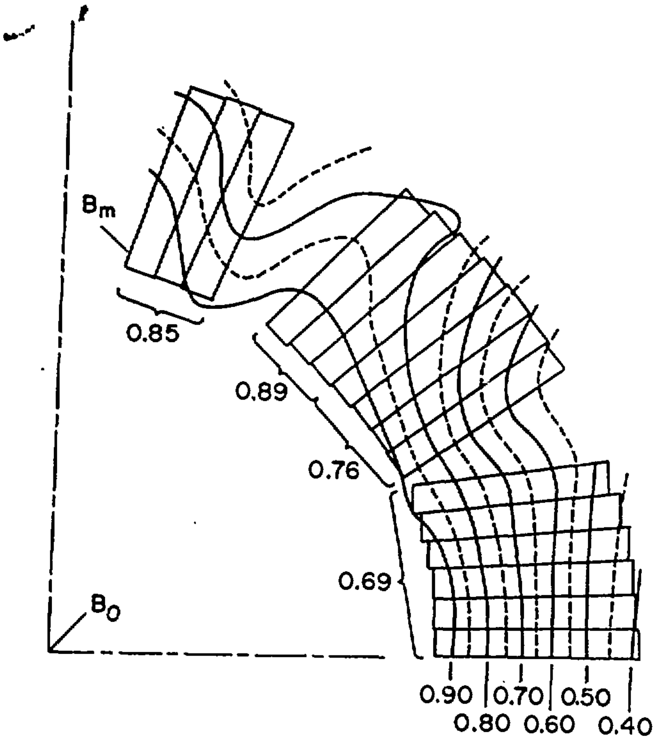

Fig. 2. The field distribution in the inner layer of the SSC design D magnet. The average field over the groups of turns indicated by the brackets is give as a fraction of the peak field.

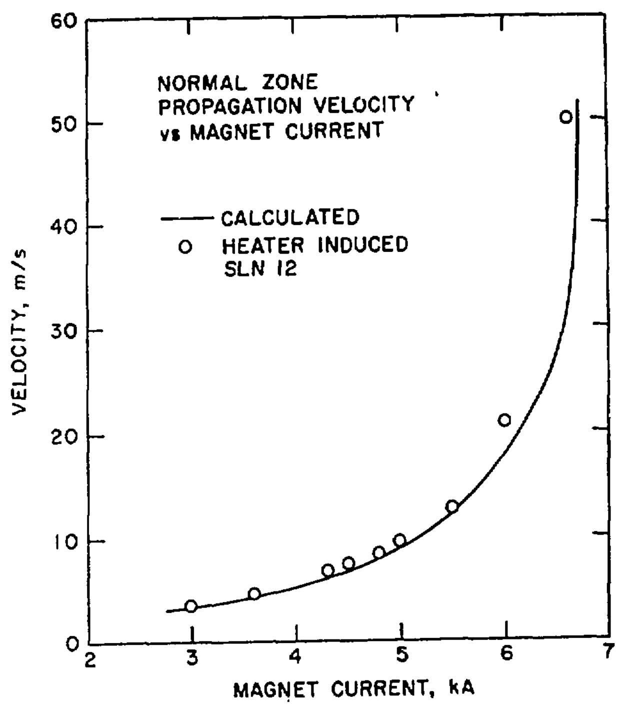

Fig. 3. The longitudinal propagation velocity measured in model magnet SLN12 compared with the velocity calculated from the cable parameters.

$$\upsilon = \frac{I_m}{AC}\sqrt{\frac{\kappa,\rho}{T_o}}\, f(i,\xi) \qquad 2$$

In this expression I_m, is the maximum current attainable at field and is usually referred to as the "quench" current, A is the cross sectional area and C is the heat capacity per unit length including any "trapped" helium. T_o is the excess temperature [i.e. $T_c(H)$-T_{BATH}) and κ and ρ are respectively the thermal conductivity and resistivity of the cable. The function f (i,ξ) gives the shape of the υ vs I curve and is expressed in terms of the reduced current i, ($i = I/I_m$) and the cooling parameter, ξ. The various factors in this expression are determined experimentally by inducing normal zones in test conductors using spot heaters and measuring the velocity directly by time-of-flight between voltage taps. Once sufficient data and experience has been gathered, it is possible to scale the results to other fields and current with considerable accuracy. A key point in being able to predict the voltage buildup in a magnet concerns the propagation velocity in cables which have a large field gradient across their width. In Fig. 3 the velocity calculated from conductor test data is compared with direct velocity measurement in an early SSC model magnet designated SLN12.[2] In this experiment spot heaters on the median plane conductor were used to initiate normal regions whose velocity was measured using voltage taps attached directly to the cable near the spot heater. The excellent agreement between observed and calculated values indicate that the velocity is determined by the peak magnetic field in the cable cross section.

Experimental Results

Short Sample Training

When cable samples are tested for critical current they are examined for stability by repeatedly quenching them until a stable repeatable current is obtained. The number of "training" steps required to reach this "plateau" current depends on the size and configuration of the conductor. In general, cables of very high critical current density or relatively low copper to superconductor ratio exhibit the most training. The growth of resistance and buildup of voltage is the same in this situation as in a magnet and can be predicted by the methods outlined above. Figure 4 shows a comparison of calculated values of $\dot{V}$ with measurements from spontaneous quenches in SSC inner cable 343 at 6 Tesla. The magnitude of $\dot{V}$ indicates how near the conductor is to its limiting current where the propagation velocity is very high and quenches can be initiated by extremely small disturbances. The conventional critical current defined by the resistivity of 10^{-14} Ω meters criterion is shown by the dotted line and corresponds to approximate 40 V/S for this conductor. Because of the small energy input required to initiate a quench in the region above 40 V/S it is unrealistic to expect a magnet to operate at a current equivalent to higher $\dot{V}$ levels. In many cases this $\dot{V}$ = 40 V/S current corresponds to the resistive critical current specified in the usual way. Some conductors, however, may have a "critical current" which is equivalent to a $\dot{V}$ of 100 V/S or higher and clearly beyond the expected level of operation of the magnet. In these cases the current corresponding to a $\dot{V}$ of 40-50 V/S is a better guide to maximum magnet performance.

Prototype Magnet Analysis

The measurement of the resistive component of the voltage in a quenching magnet is complicated by the presence of large inductive voltages. This difficulty is overcome by using a difference signal derived by "bucking" the voltage of one half of the magnet again the other half thereby cancelling the inductive component, a technique usually used for quench detection circuitry. In Fig. 5 the calculated values of $\dot{V}$ for the maximum and minimum locations in the two dimensional cross section are plotted against the magnet current for the SSC prototype magnet described elsewhere in these proceedings.[3] The calculations were based on measurements of the resistance and velocity of the conductor used for the inner coils. Of the first four spontaneous quenches in this magnet those marked 1,

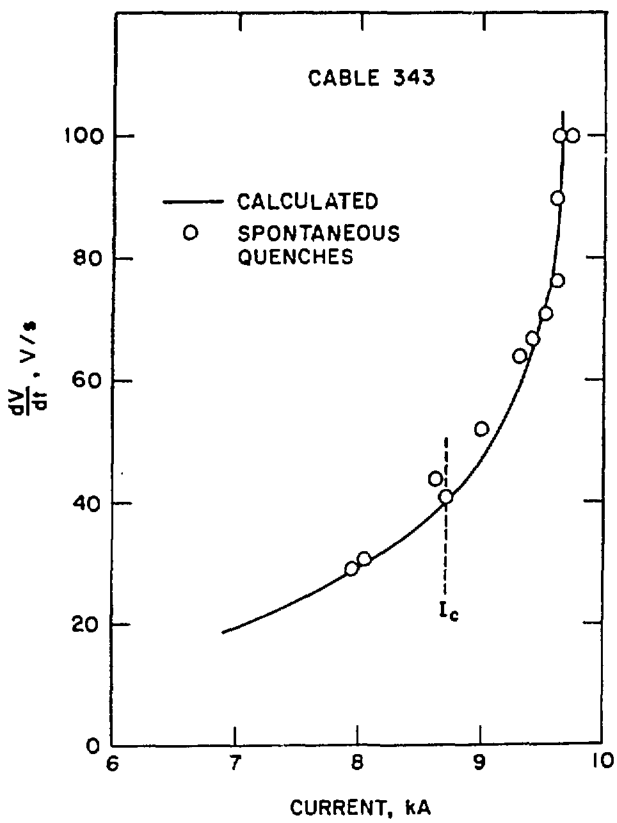

Fig. 4. A comparison of $\dot{V}$ observed during spontaneous quenches with that calculated from conductor parameters.

3 and 4 must be occurring near the peak field region while quench 2 is probably on the median plane. The calculation appears to underestimate $\dot{V}$ for the peak field region possibly due to averaging over groups of turns. Quenches induced on the median plane by spot heaters are in good agreement with calculation. The events labeled 16 and 19 are in liquid helium and the magnet may be somewhat colder than the nominal 4.6K temperature used in the calculations. The group 37-40 consist of one (37) which is a median plane quench and three (38, 39 and 40) which are clearly much too low to correspond to any conditions in the two dimensional region of the coil and must originate in low field region at the coil ends.

Conclusions

Direct observations of the rate of voltage rise due to normal zone propagation can be used to locate the point of origin of a quench in a superconducting magnet and indicate how close the coil is operating to the limits set by cable parameters. Improvements in magnet instrumentation should make it possible to identify the turn where the quench starts and help in diagnosing causes for poor magnet performance. More detailed measurements of the conductor properties are also needed to improve the calculations.

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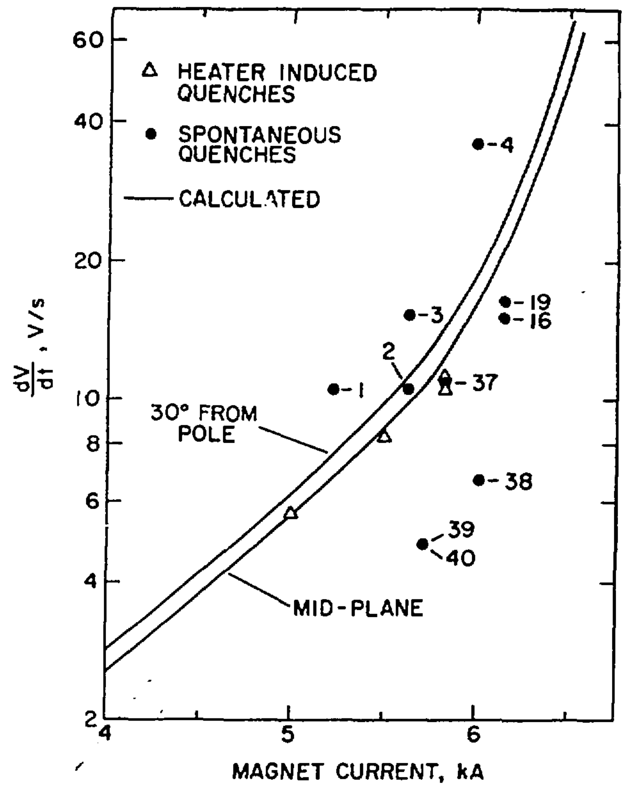

Fig. 5. Calculated values of dV/dt as a function of current for SSC prototype magnet LLN002. The numbered points are spontaneously occurring quench events.

References

[1] A. K. Ghosh et al., "Quench Propagation Across the Copper Wedges In SSC Dipoles", Applied Superconductivity Conference, Baltimore, MD (1986).

[2] G. Ganetis and A. G. Prodell, "Results from Heater-Induced Quenches of a 4.5 m Reference Design D Dipole for the SSC", Applied Superconductivity Conference, Baltimore, MD (1986).

[3] B. C. Brown et al., "Tests of Prototype SSC Magnets", these proceedings (paper I-1).