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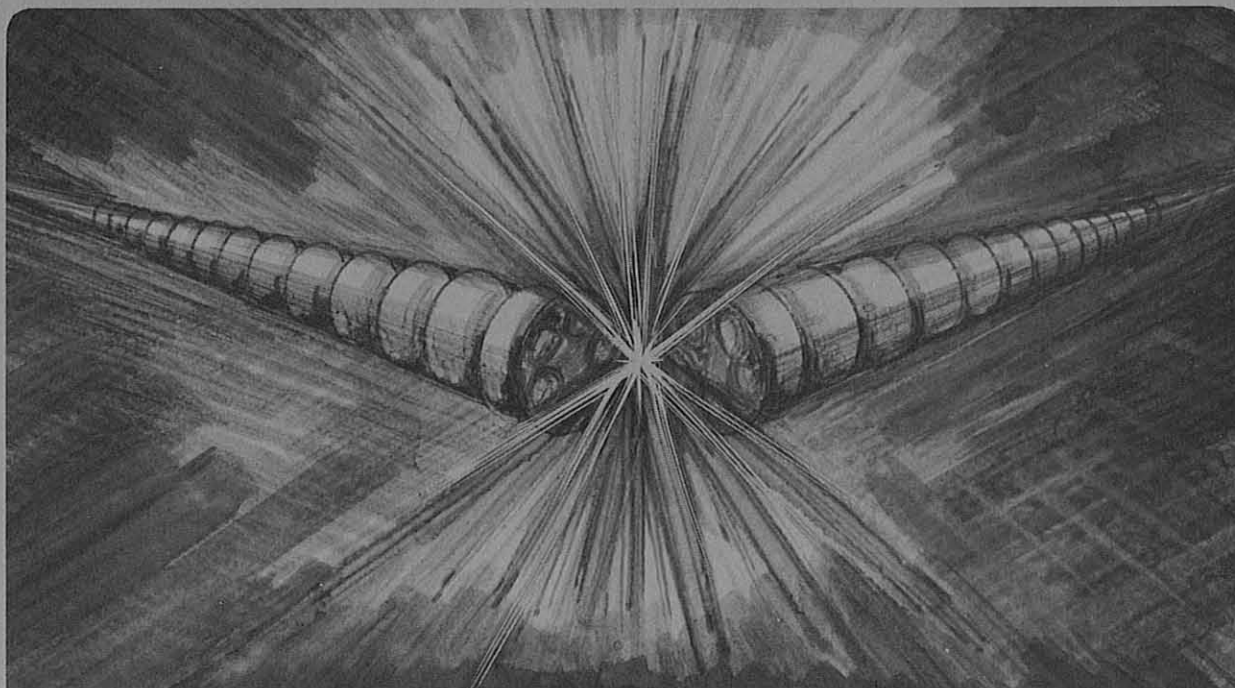
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W.V. Hassenzahl

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HEATER INDUCED QUENCHES IN SSC MODEL DIPOLES*

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Abstract

A 1-m long SSC dipole constructed at the Lawrence Berkeley Laboratory was subjected to a series of heater induced quenches to determine: axial quench propagation velocities, transverse quench propagation, and conductor temperature rise. Quenches were produced by 3 heaters at different locations in the magnet and at several currents. The results of these studies are described and are compared to previously published theoretical studies of quenches on the SSC dipoles. These results are shown to be in agreement with the calculations of the program "QUENCH", which includes an increase of the quench velocity during the first few milliseconds of the quench.

Introduction

Superconducting 1-m long model magnets of the type proposed for the Superconducting Super Collider have been constructed with two layers of copper stabilized NbTi cable. A typical coil is shown in cross section in Fig. 1. The conductor and the magnets are described in detail in other reports.¹⁻⁵ In operation it is anticipated that the 16-m long SSC dipoles will undergo quenches, transitions from the superconducting to normal state, due to a variety of causes including beam loss and temperature excursions. In

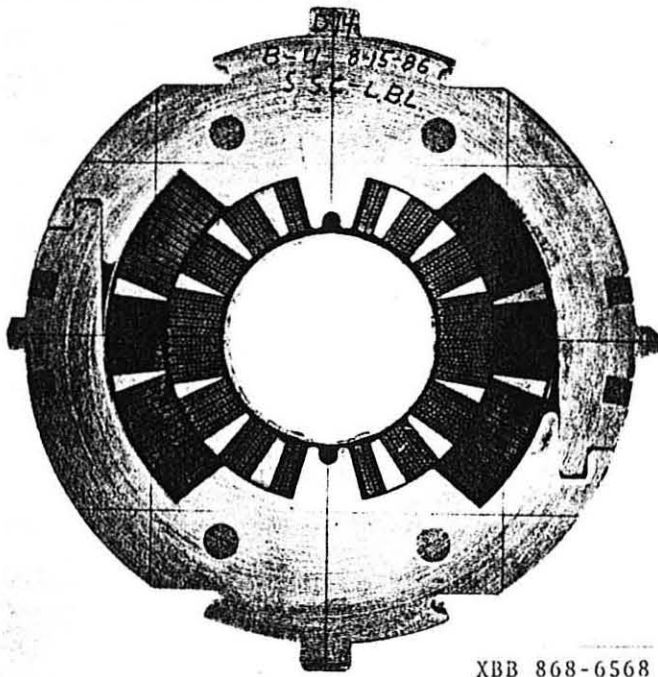


Fig. 1. Cross section of two layer SSC model Dipole D-14B-4

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addition, these magnets may be tested at very high currents, (or near the critical current limit) during certification and/or preconditioning. To insure the safety of these magnets it is necessary to understand both the possible and the likely evolution of quenches that start at various places in the coil.

To be in a position to predict this performance we installed several heaters on one of the 1-m long SSC model magnets, D-12C-7, and studied quench development at several currents. Because this model is different from the final SSC dipoles in several regards, the application of the results determined here in predicting the performance of 16 m long SSC production dipoles requires several adjustments.

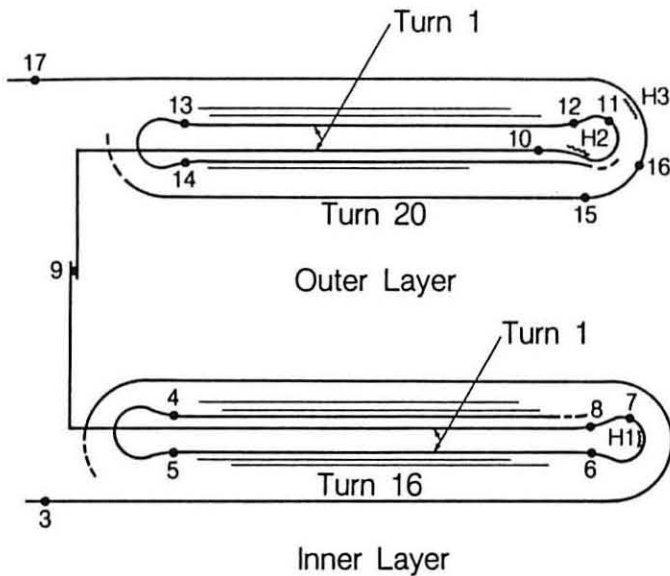
- Critical current of NbTi -- This characteristic of the superconductor is continuously improving, and at a given temperature and field it may be 20 to 30% higher in SSC magnets than in D-12C-7.
- Operating temperature -- The tests were at ~4.3 K whereas the SSC will operate at a higher temperature -- this partly compensates for the better NbTi. However the SSC magnets may also be quenched at lower temperatures and higher currents.
- Magnet length -- The rapid decay of current in D-12C-7 due to the normal resistive region is initially 16 times faster than that in a full length dipole and the increased dB/dt in the model may increase the quench propagation velocity.
- Ends -- The D-12 series of magnets had flared ends to accommodate the bending of the rather stiff cable and to reduce peak field. In later models and in the present SSC design³ this type of end has been abandoned as it does not appear necessary. In the results discussed here, the low fields at the ends affect (reduce) the local propagation velocities.
- Wedge transit time -- It is not possible to measure propagation across a wedge in one of these magnets because the transit time is of about the same magnitude as the time to reach the ends of the 70 cm straight sections and return along the other side.

Knowing that these differences or limitations exist it is more or less straightforward to extrapolate to the performance of the full length SSC dipoles, but of course quench tests of the 16 m dipoles will be required to assure confidence in their safety.

Three types of results are described here. The first is axial (along the conductor) quench propagation, the second is conductor temperature rise and the third is transverse (turn-to-turn) propagation. In the first and second the experimental results are compared to the values estimated in the program QUENCH.⁶

Experimental Procedure

Voltage taps were installed at several locations within the coils of D12C7 as shown in Fig. 2. This distribution is typical, though not identical, to that used in most of our model dipoles; only one half of the coil is shown, the voltage taps in the other half were about the same, except those just adjacent to the heaters were not used. In addition, 3



XBL 869 10150

Fig. 2. Voltage tap and heater arrangement for SSC model dipole D-12C-7.

heaters were installed on this magnet. Their positions are also shown in Fig. 2. The lengths between some of the voltage tap pairs are given in Table I.

TABLE I
Lengths between voltage tap pairs in the 1-m long
SSC model dipole D-12C-7

Voltage Taps	Channel #	Location (layer)	Separation (cm)
4-5	7	inner	24.31
5-6	8	inner	74.78
7-8	10	inner	4.85
11-12	14	outer	5.0
12-13	15	outer	74.80
13-14	16	outer	5.0

The outputs of pairs of voltage taps were amplified, or for the full coils, attenuated, by isolation amplifiers and then passed to a 5 kHz, 32 channel data acquisition system. The voltages were continuously monitored and stored in a cyclic buffer that was constantly being erased and written over. The buffer could store about 0.5 s of data and was set up to save only the data taken from 0.3 s before to about 0.2 s after a quench trigger.

During typical tests a quench detection and energy extraction system is employed. The magnetic energy in the coil is usually extracted in ~0.1 s. In normal operation the detection and response process requires about 20 ms, that is, the extraction resistor is commuted into the circuit and the power supply demand signal is reduced to zero within 20 ms of the time an observable voltage appears on the coils. To measure the quench velocity and temperature rise it was necessary to defeat the energy dump system. This was accomplished by introducing a delay between quench detection and the firing of the extraction system. The delay time was variable, but lasted between 0.05 and 0.2 s. For the longer times, essentially all the magnetic energy is deposited in the magnet before the extraction circuit is fired. In essence, this means the magnet is passively safe,

however, we continue to use the extraction circuit to reduce helium boiloff and to speed up the tests.

Longitudinal Quench Velocities

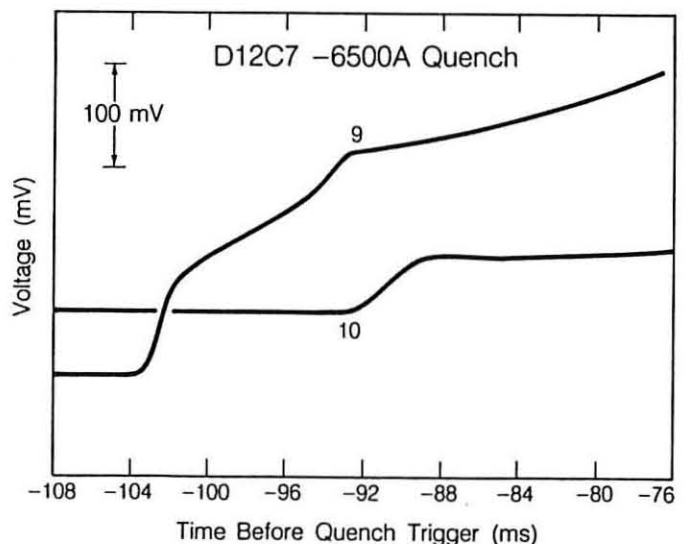
The quench velocity along a conductor can be calculated from the relationship⁶

$$v_q = \frac{I}{C} \sqrt{\frac{k\rho}{\theta_c}} \sqrt{\frac{(\theta_m - 2\theta_c)}{(\theta_m(\theta_m - \theta_c))^{1/2}}}$$

where I is the current, C is the effective specific heat of the conductor, k is the thermal conductivity, ρ is the resistivity, θ_m is the difference between the peak conductor temperature in the normal region and the bath temperature, and θ_c is the difference between the critical temperature and the bath temperature. Clearly the value of v_q increases to an asymptotic value during a quench, as θ_m increases.

In general, all of these quantities, except C , are known quite well. The uncertainty in C is associated with the cooling effect of the evaporation of the helium in the windings. If this component is not well known, but is fixed for measurements at one current then a prediction should be possible for other currents. In fact a model was developed some time ago to estimate this contribution in an earlier set of cable magnets and the contribution is used here without further modification. The contribution of the helium to the specific heat is assumed to be in the temperature range up to about 15 K and the effective volume of helium in the winding to be 5%.

Two methods exist to measure longitudinal velocities. The first is a simple time of flight between two voltage taps separated by a known distance. The second is to calculate the velocity from voltage buildup in a large region in which only a small portion is going normal. The former is easy, but to get good results, requires many voltage taps. The latter is very difficult, requires a knowledge of $\rho(T, B)$, but requires few voltage taps.



XBL 869 10151

Fig. 3. A 6500 A quench in layer 1 of SSC model magnet D-12C-7.

TABLE II
Typical Velocities for Quenches

Current	Layer	Field	Measured Velocity m/s	Calculated* Velocity m/s
6000	outer	low (end)	13	12
6500	outer	low (end)	14	14
4500	outer	intermediate	15	10
4500	outer	high	19	15
6000	outer	intermediate	29	25
6000	outer	high	54	45
6500	outer	intermediate	36	35
6500	outer	high	63	55
4500	inner	low	10	8
4500	inner	high	13	12
6000	inner	low	22	12
6000	inner	high	39	40
6500	inner	low	16	15
6500	inner	high	56	45

*from the program quench.

It is the former that is used here primarily, but the second technique is useful as a check. The voltages generated on channels 9 & 10 (see Table I) during a 6500 A quench are shown in Fig. 3. (The time is given with respect to an arbitrary zero, which is the time the extraction circuit fired.) At the beginning of the plot, ~ -104 ms, the quench starts in region 9 and propagates in 2 directions. At -102 ms it reaches one end of region 9 and passes on. It still travels in the other direction until it passes into channel 10 at ~ -93 ms. The voltage continues to increase in channel 9 because the resistance rises as the conductor heats up; the current has changed little. The time to traverse region 10 is only 3 ms and, since, this section is 4.85 cm long, the velocity is 16.2 m/s.

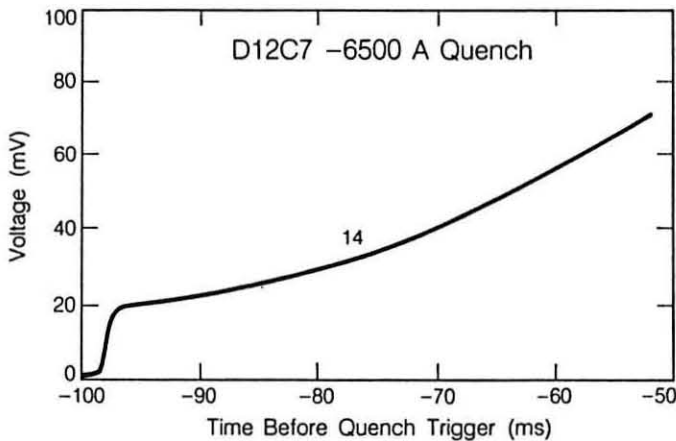
The velocities determined in this way for several quench currents and heater initiation points are given in Table II. For comparison the velocities that are calculated by the program QUENCH based on the previously described specific heats etc. are also included in Table II. The results

are quite comparable though there is some variation. It is difficult to estimate the errors in the velocity measurement, but both the measurement and the calculation are probably accurate to $\pm 20\%$.

Temperature Rise During a Quench

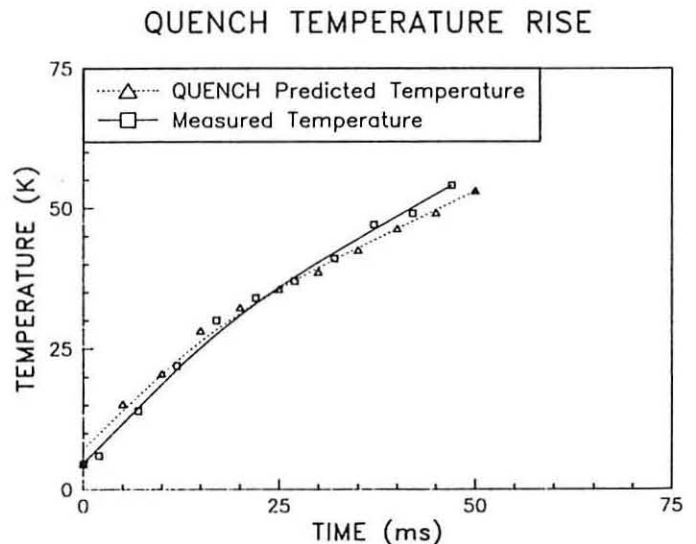
The temperature rise during a quench can be calculated quite easily from a knowledge of the specific heat and resistivity. The former varies with temperature and latter depends on both temperature and field. The variation, though strong, is quite well known and is incorporated in QUENCH and other such quench analysis programs.

It is, however, difficult to measure the temperature because it changes so quickly and it is hard to get a probe into the magnet. In the data from some of the heater induced quenches it is possible to observe a voltage rise in a region over a very long (≈ 60 ms) period. Because the



XBL 869-10152

Fig. 4. A 6500 A quench in layer 2 of SSC model magnet D-12C-7. The voltage rise after -97 ms shows the temperature increase of this 5 cm long section.



XBL 869-3553

Fig. 5. Temperature rise, T vs. t for the 6500A shown in Fig. 4.

current and thus the magnetic field changes very little during this time, the average temperature of a length of conductor can be estimated from the observed voltage and the known variation of resistance with temperature and field.⁷ Thus the conductor itself becomes a thermometer, and temperature lag and thermal contact are no longer concerns. The data plotted in Figs. 4 and 5 are for a quench at 6500 A in a 5 cm length of conductor, Channel 14. The second curve in Fig. 5 is the predicted peak temperature from the program QUENCH. There are several reasons why the curves could be different. The most likely is a misrepresentation in the program QUENCH of the resistance of the conductor.

Transverse Quench Propagation

Only a few of the heater induced quenches of magnet D-12C-7 gave interpretable data for the turn-to-turn quench propagation. Detailed data on this effect is described by Prodell.⁸ However, in some of our quenches at high current, the transition across many turns was observed. This time corresponds to a turn-to-turn transit time of about 4 ms. This value is consistent with the asymptotic value given by Prodell and is exactly the value predicted by QUENCH based on relative longitudinal and transverse thermal conductivities. It is similar to values measured in spontaneous quenches in others coils.⁹

Conclusions

The measurements of axial and transverse quench propagation and temperature rise in 1-m long model SSC dipoles are in quite good agreement with calculations. This gives some confidence in using the calculational tools to predict the development of quenches in magnets such as full length SSC dipoles.

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