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INVESTIGATION OF HEATER-INDUCED QUENCHES IN A FULL-LENGTH SSC R&D DIPOLE

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ABSTRACT

A 17-m-long SSC R&D dipole magnet instrumented with quench heaters and numerous voltage taps has been tested. These voltage taps enable (1) accurate localization of the quench start, (2) detailed studies of quench development, and (3) determination of coil temperature rise during a quench. The hot-spot temperature is determined by measuring the resistance of the conductor in the vicinity of the heater and is plotted versus number of MIITs. Measured temperatures are are found to be in good agreement with predictions based on the assumption that the conductor is heated adiabatically. Finally, a limit to be imposed on the number of MIITs to operate the magnet safely is determined.

INTRODUCTION

A primary concern when building a 17-m-long superconducting dipole magnet is protection of its coil during a quench: How fast will the quench propagate? How much energy will be dissipated in the coil? How hot will the conductor get?

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The first two questions were addressed in a previous paper,[1] which presented statistical studies of propagation velocities and of the number of MIITs* over the several long SSC dipole prototypes tested in the last two years.[2,3] Even though the quenches developed much faster than was ever seen or predicted before, the mechanism was reproducible from magnet to magnet,[1] depending only on the fraction of short sample. We also established a neat correlation between the number of MIITs and the inverse of the propagation velocity, illustrating the benefit of this fast quench development in reducing the overall energy dissipated in the coil. This paper addresses the third question and establishes the correlation between the number of MIITs and the maximum temperature reached by the conductor during a quench, also called the *hot-spot* temperature.

The temperature increase during a quench is central to the issue of safety. The temperature has to be limited to avoid failure of the Kapton insulation and degradation of the superconductor critical current. These effects both occur at a temperature of about 1000 K.[4] The SSC prototypes are currently operated with a maximum allowance of 800 K.

MEASURING THE HOT-SPOT TEMPERATURE

The best way to measure the temperature of a copper-stabilized conductor is to use the conductor itself as a temperature sensor. The resistivity of copper, ρ_{Cu}, is a well-tabulated function of three parameters: the copper residual-resistivity ratio, RRR; the temperature, T; and the magnetic field, B.[5] Let us consider a length L of conductor, carrying a current I. Once it has switched to the normal resistive state, the conductor sample exhibits an apparent resistance R_a

$$R_a = \frac{U}{I},$$

where U is the voltage across the sample. If the copper RRR and the magnetic field are known, an estimation of the conductor temperature, T, assumed to be uniform along the length L of the sample, is obtained by solving the implicit equation in T

$$\rho_{Cu}\,(\mathrm{RRR},T,B) = \frac{r_{CuS}}{1+r_{CuS}}\,\frac{R_a S}{L}, \qquad (1)$$

where r_{CuS} is the copper-to-superconductor ratio, and S is the conductor cross-sectional area. Monitoring U and I during a quench then enables us to determine the temporal evolution of T.

Since we are interested in the hot-spot temperature, we have to monitor a voltage across a length of conductor surrounding the hot spot. Under normal conditions, the maximum temperature of a quenching coil is reached at the point where the quench originated. The quench start locations are not known in advance for spontaneous quenches, but they are well defined for spot-heater induced quenches. A simple experiment is to equip a magnet coil with spot heaters closely surrounded by two voltage taps. This has been done on a few full-length SSC dipole prototypes, including DD0017, which we will now discuss.

Figure 1 shows a cross section of the Brookhaven-design collared coil. The coil consists of four separately wound parts joined during assembly: two inner (upper and lower) and two outer (upper and lower) quarter coils. The inner quarter coils contain sixteen turns and three copper wedges; the outer quarter coils contain twenty turns and only one wedge. (Turns are counted starting from the midplane of the coil.) The characteristics of the inner- and outer-layer cables wound in DD0017 are given in Table 1.

TABLE 1.
Selected DD0017 Cable Characteristics

Quarter Coil	S(m^2)	r_{CuS}	RRR
Lower inner	11.79 10^{-6}	1.59	81
Lower outer	9.89 10^{-6}	1.62	83

*Between 10 and 295 K.

To establish the temperature-versus-MIITs correlations, the coil was equipped with six sets (spot heater + two voltage taps): two on the pole turn and two on the midplane turn of the lower inner quarter coil (one about 2 m from each end), and two on the pole turn of the lower outer coil (one at each end, in the middle of the curved sections). The length L between the two voltage taps is 25.4 cm for the inner-coil spot-heaters and 11.5 cm for the outer-coil spot-heaters. The RRR measurements provided in Table 1 were

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*The number of MIITs is the integral over time t

$$\mathrm{MIITs} = \frac{1}{10^6}\int_{\infty}^{0} dt\, I^2(t)\,, \qquad (\mathrm{A}^2\mathrm{sec})$$

where I is the current.

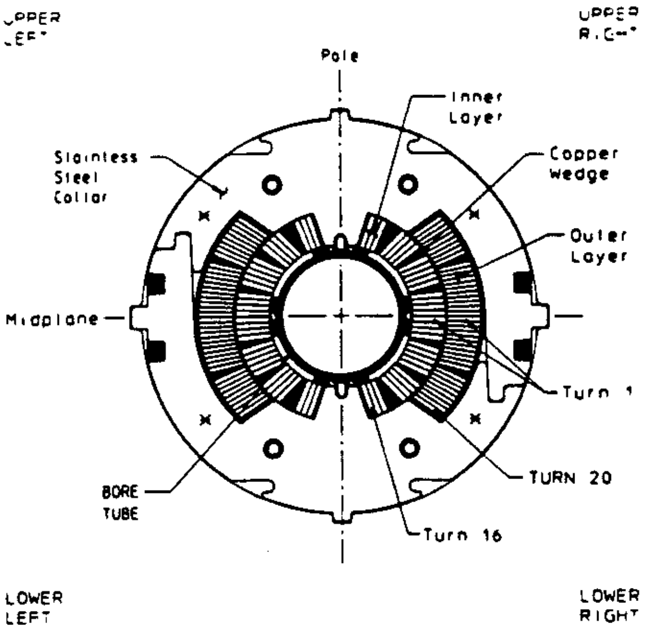

Figure 1. SSC Dipole cross section (C358).

made after testing, by warming up the whole magnet to a temperature of 12–13 K and circulating a current of about 10 A. The measurements were highly reproducible from one set of spot-heater taps to another. The magnetic field on the conductor, of course, depends on the coil turn and layer, and on the current. Numerical computations of the transfer functions $B = f(I)$ for the turns of interest are given in Table 2.

TABLE 2.
Transfer functions for the turns of interest

Inner coil turn 16	$B = 0.7505 + 0.9470\ 10^{-3} I$
Inner coil turn 1	$B = 0.7183 + 0.9064\ 10^{-3} I$
Outer coil turn 20	$B = 0.6266 + 0.7555\ 10^{-3} I$

An important part of magnet DD0017 testing was devoted to spot-heater quenching, varying the current at quench, and successively firing different heaters. Figures 2 and 3 show typical records of the current I and the voltage U monitored during a quench induced at 6500 A by one of the inner-coil turn-1 heaters. The apparent resistance can then be calculated for any time, and the temperature can be estimated by solving Eq. (1), where the correct value of B for the given value of I has been introduced. The time, t_n, result is plotted as a continuous curve in Figure 4. As expected, it appears that after about 300 milliseconds the temperature reaches a kind of plateau. (The undulation for times greater than 400 milliseconds can be attributed to calculation errors, since current and voltage then are both fairly small.) This plateau value defines the maximum temperature, $T_{\max}$, reached by the coil during the quench. In our example, the number of MIITs is 7.39 and the maximum temperature is 157 K.

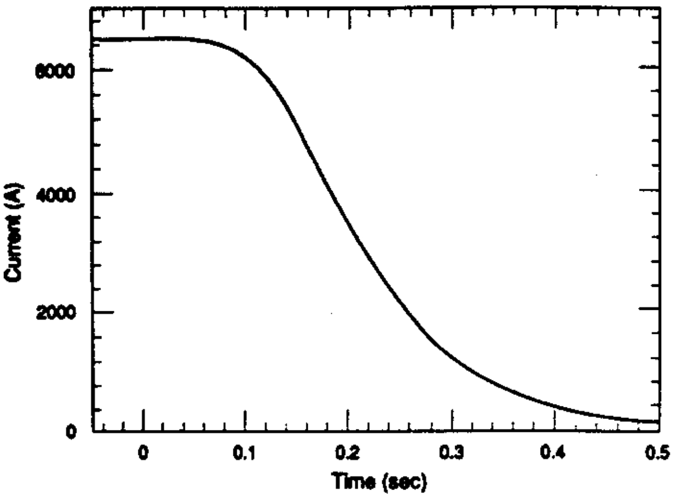

Figure 2. Current decay during a quench induced at 6500 A on turn 1 of the inner coil.

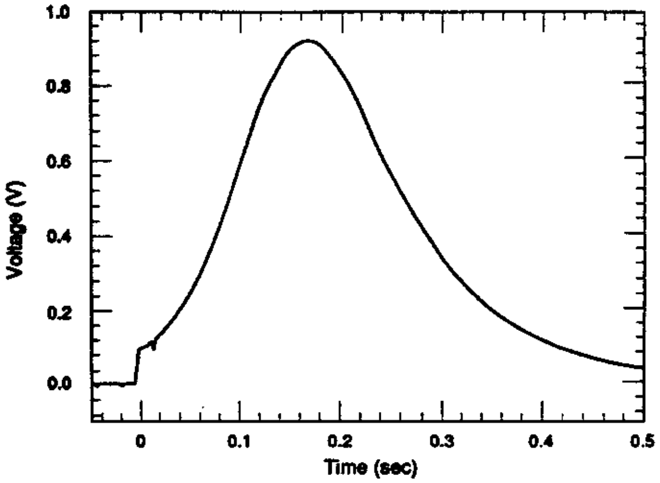

Figure 3. Voltage evolution across the spot-heater taps during a quench induced at 6500 A on turn 1 of the inner-coil.

The continuous curve of Figure 5 shows the result of the temperature computation for a quench induced at 6500 A on turn 20 of the outer coil. The shape of the curve is similar to Figure 4: after about 250 milliseconds, the temperature reaches a very stable plateau. Nevertheless, the value of this plateau is much higher than for the inner layer. At the same current as in the previous example, the number of MIITs is 8.39, and the maximum temperature is 289 K. The higher value of MIITs tells us that the quench propagates slower in the outer coil than in the inner coil, which is understandable because the field on the outer layer is much less than the field on the inner layer. More MIITs give, of course, a higher temperature. Also contributing to the higher temperature is the fact that the outer-layer conductor has about 15 percent less copper than the inner layer conductor, but, as it carries the same current, it dissipates 22.5 percent more Joule power. The interesting conclusion of this comparison is that, from the safety point of view, the limiting conductor is in the outer layer.

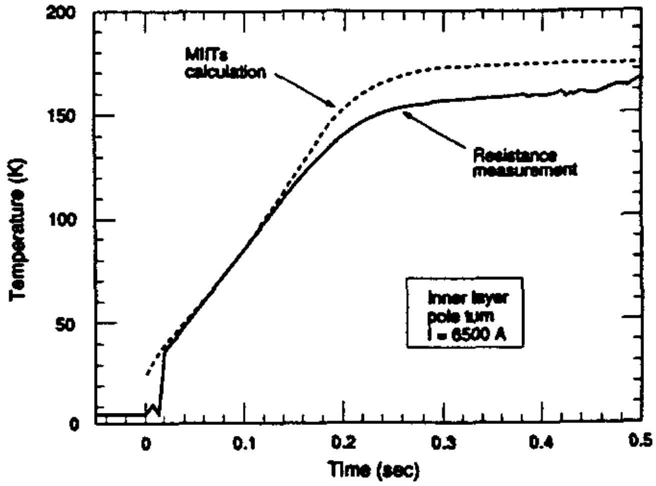

Figure 4. Evolution of the hot-spot temperature during a quench induced at 6500 A on turn 1 of the inner coil.

In Figure 6 we have plotted, as a function of the number of MIITs, the maximum temperatures measured for all the spot-heater quenches induced in DD0017. This plot confirms that for a given number of MIITs the temperature rise is higher for an induced quench in the outer-coil than for an induced quench in the inner coil (about 100 K more for MIITs between 8 and 9). It also appears that, for quenches in the inner coil, pole-turn and midplane-turn induced quenches are indistinguishable. This tells us that the 4 percent lower field on the turn-1 conductor does not greatly affect the overall power dissipation seen by this conductor as compared with that seen in the pole turn. (There is indeed a slight difference in the number of MIITs as a function of current for these two spot-heater locations—at a given current, the number of MIITs produced by a turn-1 induced quench is a few percent higher than for a turn-16 induced quench—showing that the propagation of a quench initiated in the midplane turn is presumably slower than the propagation of a quench initiated in the pole turn.) Nonetheless, the main conclusion that can be drawn from Figure 6 is that for both conductor layers the temperature rise during a quench remains well below the limit of 800 K and that the safety of the magnet coil is ensured for MIITs numbers less than 9.

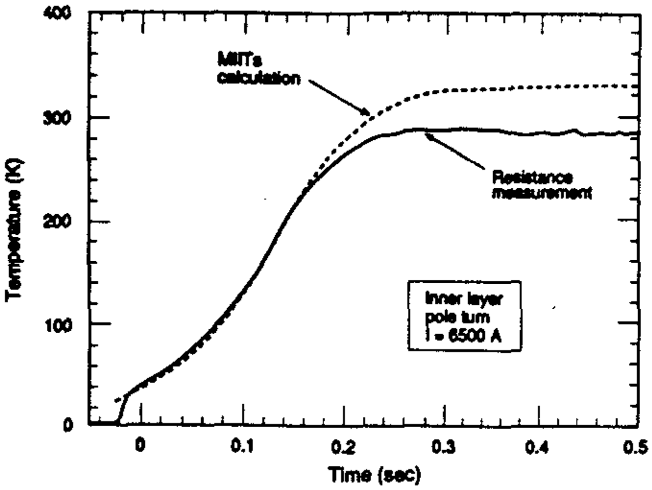

Figure 5. Evolution of the hot-spot temperature during a quench induced at 6500 A on the outer coil turn 20.

PREDICTIONS AND MEASUREMENTS COMPARED

To analytically predict the correlation of temperature-MIITs, we write the heat-balance equation for a small volume of conductor near the hot spot

$$C(T)\frac{\partial T}{\partial t} = \frac{1+r_{\text{CuS}}}{r_{\text{CuS}}}\rho_{\text{Cu}}(\text{RRR},T,B)\left(\frac{I}{S}\right)^2 - H(t), \qquad (2)$$

where C is the specific heat per unit volume of conductor and H is the power transferred to the surrounding medium, either by thermal conduction along the conductor or to the conductor insulation and the helium. An overestimation of the hot-spot temperature is given by neglecting H, e.g., by considering that the conductor near the hot spot behaves adiabatically,[6] and by assuming that the magnetic field remains constant, equals to its value B_0 at $t = 0$. Integrating Eq. (2) over time yields an implicit equation in $T_{\max}$

$$\int_{T_{\max}}^{T_0} dT \frac{r_{\text{CuS}}}{1+r_{\text{CuS}}} \frac{C(T)}{\rho_{\text{Cu}}(\text{RRR},T,B_0)} = \cdots$$

$$\frac{1}{10^6}\int_{\infty}^{0} dt\, I^2(t) = \text{MIITs}, \qquad (3)$$

where T_0 is the initial temperature. In fact, since we know I as a function of t, we can solve Eq. (3) for each value of time and thus predict the temporal evolution of the hot-spot temperature.

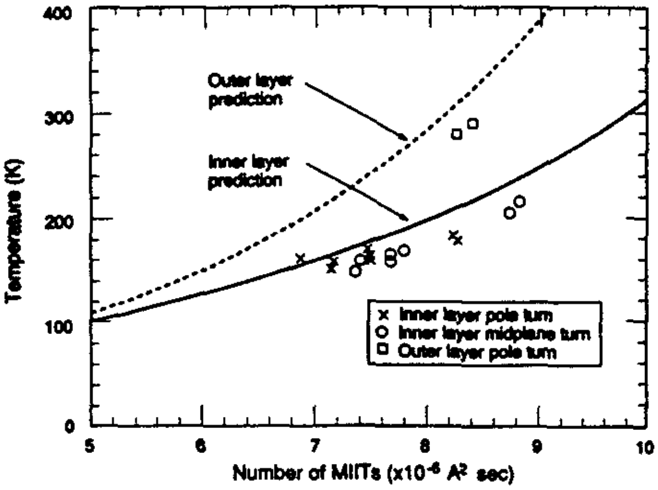

Figure 6. Temperature-versus-MIITs correlations

The dashed curves in Figures 4 and 5 show two examples of computation compared with the measured temperatures already presented. For the induced quench in the inner layer, B_0 has been chosen to be constant, equal to 7 T. The outer-layer computation requires more care. As the outer-layer spot-heaters are located at the ends of the coil, in the middle of the turn-20 curved sections, they sit outside of the iron yoke and see a very reduced field. In our computation, we have thus chosen to take $B_0 = 0$. In both cases, predictions and measurements are in good agreement. This implies that the hypothesis of justified, at least at the observed time scale. In other words, the amount of heat transferred to the surrounding media is small compared with the Joule heating, or the time required by the heat to be transferred to (or to be diffused through) the surrounding medium is large compared with 300 milliseconds. (The existence of a plateau in the temporal evolution of the temperature was already a clue that H could be neglected.)

With more confidence in our hypotheses, we return to Figure 6. The continuous and dashed curves are the temperature-versus-MIITs correlations, for the inner- and the outer-layer spot-conductors, as predicted by Eq. (3), using the same values of B_0 as above. The data points and the analytical predictions are in fairly good agreement. Equation (3) thus furnishes a reliable basis for predicting temperature-versus-MIITs correlations. Such agreements between hot-spot temperature measurements and predictions have also been seen on a short HERA model dipole.[7]

To conclude our safety analysis, it just remains to determine how the limit of 800 K on the peak temperature translates into a MIITs number. Iterations of Eq. (3) give 14 for the inner-coil turn-16 conductor (with $B_0 = 7$ T) and 10 for the outer-coil turn 20 (with $B_0 = 5.6$ T). A limit of 10 on the number of MIITs thus ensures that the conductor never gets higher than 800 K, wherever the quench occurs.

CONCLUSION

The use of spot heaters with two close voltage taps has enabled us to accurately measure the coil temperature increase during a quench. The measurements appear in good agreement with estimations assuming adiabatic heating of the conductor. We extrapolated that the number of MIITs has to be limited to ten to limit the peak temperature to 800 K.

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