Presented at the 1986 Applied Superconductivity Conference Baltimore, Maryland September 28-October 3, 1986

CONF-860914--26

BNL 38855

RESULTS FROM HEATER-INDUCED QUENCHES OF A 4.5 m REFERENCE DESIGN D DIPOLE FOR THE SSC

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BNL--38855

DE87 003474

Abstract

Quench studies were performed using a 4.5 m long Reference Design D, SSC dipole to determine the temperature rise of the magnet conductor during a quench by measuring the resistance of the conductor cable in the immediate vicinity of the quench. The single bore magnet was wound with improved NbTi conductor in a 2-layer cosine θ coil configuration of 4.0 cm inner diameter. Eight pairs of voltage taps were installed at various locations on the right side of the inner coil of the magnet. "Spot" heaters were centrally located between the voltage taps of 4 of these pairs on the midplane turn of the inner coil to initiate magnet quenches. A redundant array of voltage taps and heaters was also installed on the left side of the inner coil. The resistance of the conductor was obtained from observations of the current and voltage during a magnet quench. The temperature of the conductor was then determined by comparing its resistance to an R vs T curve appropriate for the conductor. The quantity $\int I^2 dt$ and the temperature, T, are presented as a function of current, and the maximum conductor temperature is shown as a function of $\int I^2 dt$. Measured longitudinal and azimuthal quench propagation velocities are also presented as a function of magnet current, and the temperatures at several locations on the inner magnet coil are plotted as a function of the time after a quench was initiated.

Introduction

This paper reports on tests conducted with a 4.5 m long superconducting dipole built to the specifications of the SSC Reference Design D, the design selected for the proposed SSC. This magnet was wound with improved "high homogeneity" NbTi conductor in a 2-layer cosine θ coil configuration of 4.0 cm inner diameter. The inner and outer layers of the magnet were powered in series. The temperature of the liquid helium bath in which the magnet was suspended was also decreased from 4.5 to 2.6 K during the course of these tests to increase the magnet current at which the heater quenches could be initiated.

Experimental Arrangement

The parameters of the conductor with which the magnet was wound are given in Table 1.

Table 1. Conductor Parameters for the 4.5 m SSC Dipole

Multifilamentary Wire

	Inner Coil	Outer Coil
Superconductor	Nb wt. 46.5% Ti	
Diameter	0.808 mm	0.638 mm
Filament Diameter	23 microns	18 microns
No. of Filaments	457	480
Cu to SC Ratio	1.7 to 1	1.7 to 1

Table 1. (continued)

Cabled Conductor

Width (bare)	9.4 mm	9.8 mm
Mean Thickness (bare)	1.47 mm	1.17 mm
Keystone Angle	1.67°	1.34°
No. of Wires	23	30
Insulation Thickness		
Kapton	0.0254 mm	0.0254 mm
Fiberglass-epoxy	0.1016 mm	0.1016 mm

Eight pairs of voltage taps were installed at locations on the right side of the inner coil of the magnet as shown in Fig. 1.

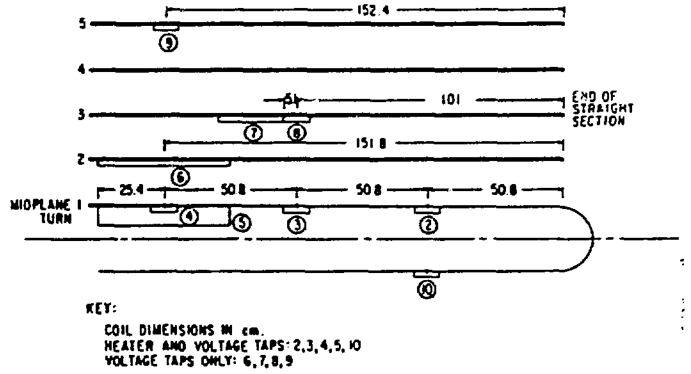

Figure 1. Location of Heaters and Voltage Taps on the Inner Magnet Coil.

"Spot" heaters to initiate magnet quenches were centrally located between the voltage taps of 4 of these pairs on the midplane turn of the inner coil as indicated in Fig. 1 and one of the redundant array of heaters and voltage taps installed on the left side of the inner coil is also shown in Fig. 1 at location 10. Each heater consisted of a 0.0635 mm thick strip of stainless steel with an overall length of 30.5 mm and a width of 7.62 mm with the width reduced to 2.54 mm over the 17.8 mm long center section of the heater. By varying the voltage from 5.0 to 7.5 V, about 1 to 2 J of energy could be delivered to the heater in approximately 60 millisec. The heaters were wrapped with one layer of 0.0508 mm thick Kapton and positioned against the inner surface of the insulated midplane turn of the inner coil. The voltage taps at locations 2, 3, 4, 8, 9 and 10 were separated by nominally 10.2 cm, those at locations 5 and 6 by 50.8 cm, and those at location 7 by 24.8 cm. The leads from each pair of voltage taps were twisted to minimize any induced voltage in the voltage signal due to a change in the magnetic field.

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* Work supported by the U. S. Department of Energy.
Manuscript received by September 30, 1986

Experimental Results

To obtain the highest temperature to which the conductor could be raised by a heater-induced magnet quench, the first heater quenches were made at a constant bath temperature of 4.5 K at different values of magnet current to determine the current, I_m, at which $\int I^2 dt$ was a maximum. The curve of $\int I^2 dt$ vs I for quenches induced by heater 4, whose location is indicated in Fig. 1, is shown in Fig. 2.

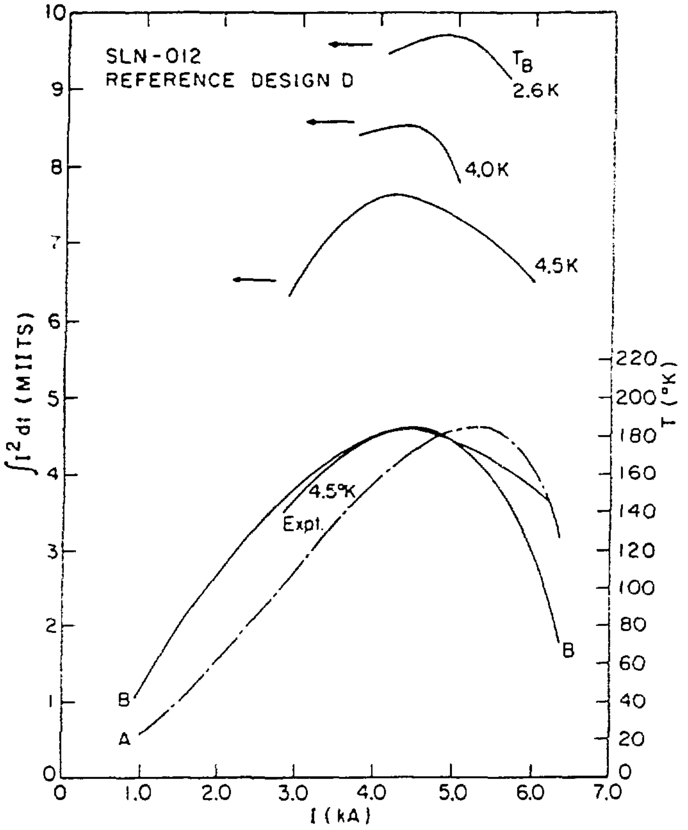

Figure 2. $\int I^2 dt$ at 4.5, 4.0 and 2.6 K and Conductor Temperature, T, vs I.

From this curve it was determined that $\int I^2 dt$ was a maximum when I_m was about 64% of the non-heater induced quench current, I_q, of the magnet at 4.5 K. Similar curves, shown in Fig. 2, were obtained at helium bath temperatures of 4.0 K and 2.6 K to verify that the relationship, $I_m = 0.64\, Iq$, was maintained as the bath temperature was reduced and the quench current, Iq, increased. A plot is also drawn in Fig. 2 of the maximum temperature to which a section of conductor cable was raised as a function of magnet current at a helium bath temperature of 4.5 K when a quench was initiated by the heater at location 4. The profile of this plot follows very closely that of the curve of $\int I^2 dt$ vs magnet current, indicating that at the higher magnet currents the quench velocities are increasing rapidly.

The temperature rise of the conductor cable during a heater-induced quench was measured by monitoring the magnet current and voltage across the section of the cable where the heater was fired. The resistance of this length of cable was calculated from which the average temperature of the length of cable between the appropriate voltage taps was determined by using an R vs T calibration curve. A correction to obtain the "hot spot" temperature was then made. From the trace of the voltage across the section of cable where the heater was fired as a function of time and knowledge of the magnet current the slope $d(\int I^2 dt)/dR$ may be obtained. The voltage trace shows that when the heater is fired the voltage and thus the resistance increase rapidly as the quench propagates away from the heater toward the voltage taps as both ρ and ℓ are increasing in the relationship, $R = \rho\ell/A$. The slope changes when the normal quench fronts reach the voltage taps since ℓ is now constant between the taps and R is a function only of ρ. For each heater quench the time from the beginning of the quench to the time when the entire length between voltage taps is resistive can be measured from such traces. Half this time multiplied by I^2 gives $\Delta\int I^2 dt$, the difference in $\int I^2 dt$ between the hot spot and the half-length between voltage taps which, to first approximation, is the position corresponding to Tave. R is then corrected by adding ΔR where $\Delta R = \Delta\int I^2 dt/d(\int I^2 dt)/dR$ and with this addition the hot spot temperature is found. The correction to the conductor temperature for these tests amounted to an increase of approximately 10 K.

The curve in Fig. 3 illustrates the temperature rise of the section of the conductor where a heater quench was initiated as a function of $\int I^2 dt$. The measurements made when the heaters at locations 2, 3 and 4 were fired were all closely clustered along this curve. The highest corrected temperature measured in these studies was 295 K at a helium bath temperature of 2.6 K.

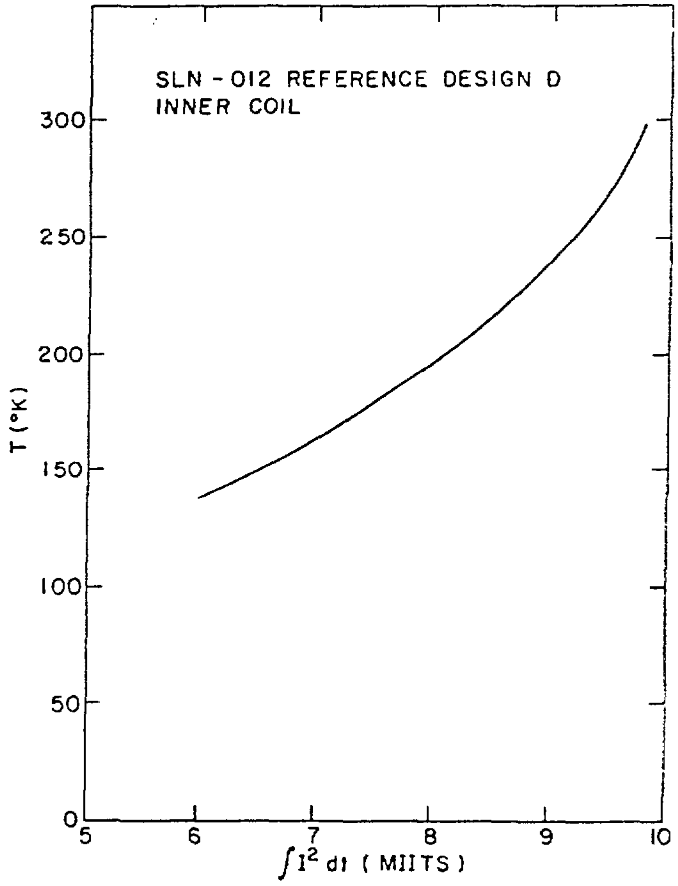

Figure 3. Conductor Temperature, T, vs $\int I^2 dt$.

Observations of the voltage vs. time traces for the several pairs of voltage taps also yielded information from which velocities could be calculated. In addition, measurements were made of longitudinal and azimuthal quench velocities by determining the distance between pairs of voltage taps and recording the time when a voltage signal would appear at the several pairs of taps after a heater quench had been initiated at a particular location. Figure 4 shows plots of longitudinal quench velocities as a function of magnet current between locations 3 and 2, and 4 and 3 on the midplane turn when the heater at 4 was used to initiate the quench.

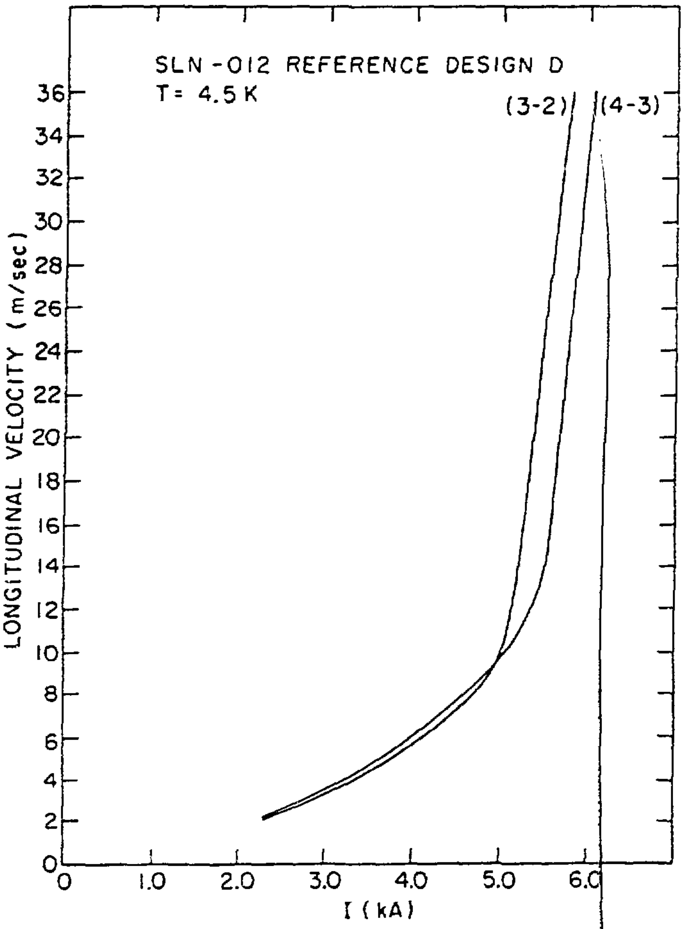

Figure 4. Longitudinal Quench Velocities vs. I at 4.5 K.

The curves illustrate how rapidly the longitudinal quench velocity increases with increasing magnet current at the higher current levels. The longitudinal quench velocities along the midplane turn obtained by these measurements do not give clear evidence of an acceleration component. Any indication of such a component, from a limited number of measurements, appears only at magnet currents above about 5.0 kA. At magnet currents below 5.0 kA, the measured velocities in every case but one show a small deceleration component. Three measurements made of the velocity from location 2 to 10 around the end of the magnet at 2.6 K and magnet currents of 5.5, 5.0 and 4.5 kA yield velocities less than those from location 4 to 3 when heater 4 was fired.

The azimuthal quench velocities between the first and second turns, locations 4 and 6 and the second and fifth turns, locations 6 and 9, obtained when heater 4 was used are shown as a function of magnet current in Fig. 5.

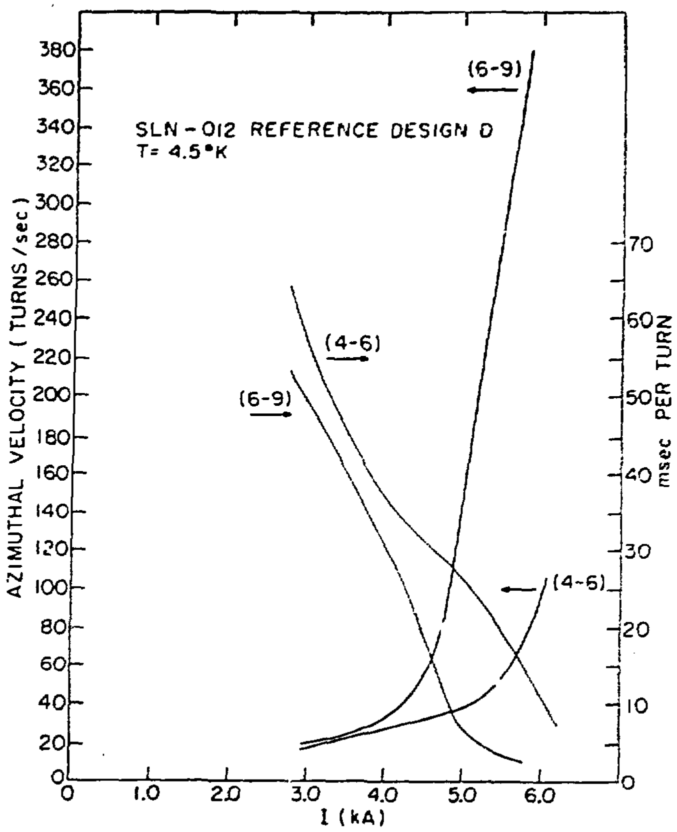

Figure 5. Azimuthal Quench Velocities vs I at 4.5 K.

The azimuthal quench velocities increase rapidly with magnet current and it is this rapid increase together with that of the longitudinal velocities which cause both $\int I^2 dt$ and T to peak and then begin to decrease as the magnet current increases as mentioned above. A comparison of the azimuthal velocities determined from these measurements indicates the presence of an acceleration component which increases rapidly above a magnet current of about 4.0 kA as the magnet current increases.

The effect of the dependence of the azimuthal and longitudinal quench velocities on the magnet current can be illustrated by describing the early partial profile of the quench front in several ranges of magnet current. Referring to Fig. 1, using heater 4 to initiate a magnet quench, voltage signals are recorded at locations 4, 5 and 6 for all magnet currents before signals are seen at any of the other locations. The sequence in which signals appear at these other locations changes with magnet current. At magnet currents above 5.0 kA, the quench front reaches location 9 on the fifth turn before it travels longitudinally to location 3. At magnet currents between 4.8 and 4.9 kA and still using heater 4, the quench front propagates longitudinally to location 3 and next reaches 9. At magnet currents from 4.5 to 4.7 kA, the quench front propagates to location 3, then to 7, and then to 9. For magnet currents from 3.0 to 4.3 kA, the quench front reaches locations 3, 7, 8 and 9 in order. At all magnet currents, the quench front propagates longitudinally to location 2 and then 10 after having reached all other indicated positions. Generally then at high magnet currents the profile of the quench front shows a peak azimuthally (5 turns) and a relatively narrow base longitudinally with the profile changing as the magnet current is decreased. Fig. 6 shows a plot of the azimuthal velocity from location 4 to 6 vs the longitudinal velocity from location 4 to 3 for a range of magnet currents when the heater at 4 is used to initiate a quench.

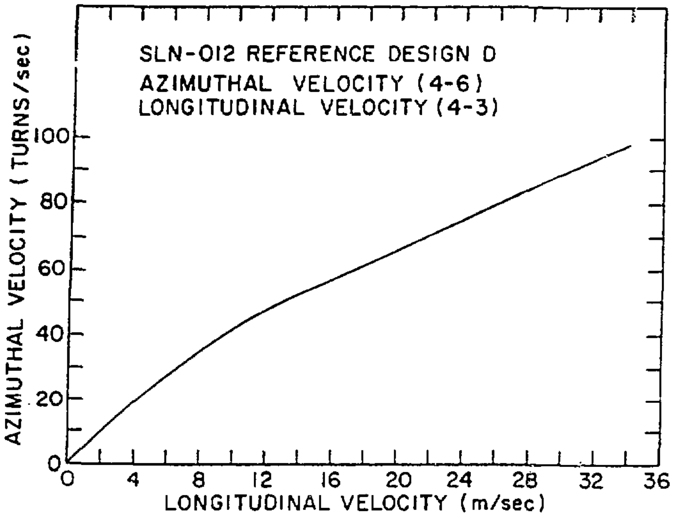

Figure 6. Azimuthal Quench Velocity vs Longitudinal Quench Velocity for Magnet Currents up to 6.0 kA.

Figure 7 shows the temperature profiles as a function of time at the several locations designated by the number next to each curve when the heater at 4 was used to initiate a quench.

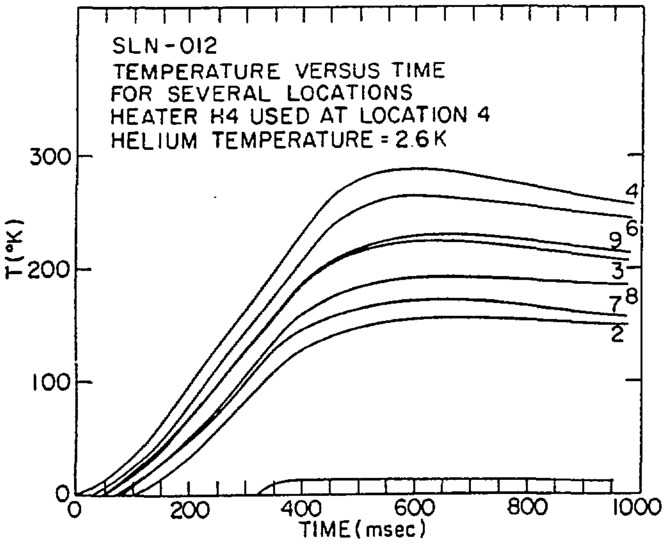

Figure 7. Temperatures After a Quench vs Time for the Several Locations on the Inner Magnet Coil.

Figure 8 shows curves of the magnet current and the quantity $\int I^2 dt$ as a function of time when the heater at 4 was used to initiate a quench. The quench front reaches all locations except 10 before there is any significant decrease in magnet current and reaches location 10 after the current has decreased by about 15%.

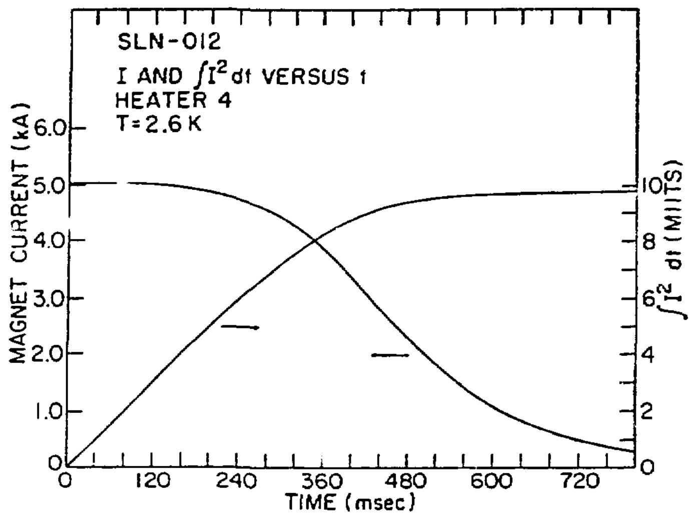

Figure 8. Magnet Current and $\int I^2 dt$ vs. Time after a Quench Was Initiated.

As mentioned above, at a helium bath temperature of 4.5 K, the quantity $\int I^2 dt$ and the temperature, T, to which the conductor was raised during a quench reached maximum at a magnet current that was about 64% of the non-heater induced quench current, Iq, for the inner coil of the magnet. Earlier calculations have indicated that T is a maximum at I = 0.8Iq which follows from the dependence of T on I in the relationship:

$$T = A' \left\{ \frac{E_{max} I^4 (I_q - I)}{I_q^2} \right\}^{2/5}$$

It is interesting to note that a different dependence of T on I, for example:

$$T = A' \left\{ \frac{E_{max} I^2 (I_q - I)}{I_q^2} \right\}^{2/3}$$

gives T as a maximum at $I = 0.67 I_q$. Curves for these two relationships normalized to the experimental data, are shown in Fig. 1, the curve for the first relationship designated by A, and that for the second by B.

DISCLAIMER