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

RESULTS USING ACTIVE QUENCH PROTECTION STRIP HEATERS ON A REFERENCE DESIGN D SSC DIPOLE MAGNET*

G. Ganetis and A. Prodell
Brookhaven National Laboratory
Upton, New York 11973

BNL--38856

DE87 003211

Abstract

Measurements were made with a Reference Design D SSC dipole magnet to study the quench behavior of the magnet when active quench protections trip heaters were used to initiate quenches. The magnet has a 2-layer cosine θ coil configuration with a bore diameter of 4 cm and a length of 4.5 m. The strip heaters, their arrangement and installation are described. Three strip heaters individually and in combinations were used during these studies in the first series of which the magnet current was set at that value for which the quantity $\int I^2 dt$ was maximum. A capacitor was discharged through the strip heater with the charging voltage being increased progressively until a magnet quench was inititated. The time interval between when the voltage was applied to the strip heater and when the magnet quench began was measured as was the time required for the voltage across the magnet coil that had quenched to reach 3V. These times and the quantity $\int I^2 dt$ are presented for several values of charging voltage for different heaters and combinations of heaters. Curves of these times and $\int I^2 dt$ as a function of magnet current at constant capacitance and voltage are also shown.

Introduction

Studies were conducted of the quench behavior of a 4.5 m long Reference Design D SSC dipole magnet using active quench protection strip heaters to initiate quenches. This magnet was wound in a 2-layer cosine θ coil configuration with a 4.0 cm inner diameter using improved NbTi conductor and with the inner and outer coils connected in series. The magnet was suspended in a liquid helium bath whose temperature was maintained at 4.4 K and for these studies the magnet current was set at 4.95 kA, the current at which the quantity $\int I^2 dt$ was a maximum for this magnet.

Experimental Arrangement

Four strip heaters were installed on the magnet, one in each quadrant along the length of the outside surface of each coil-half of the outer two coils of the magnet. Each strip heater as designed by J. G. Cottingham [1] and shown schematically in Fig. 1 consisted of a stainless steel strip with a number of cutouts, the strip serving both as the current connection between heaters as well as being the heater in the cutout sections. Twelve cutout or heater sections were equally spaced along each of the four heater strips. For the strip shown in Fig. 1, at 4.4K the resistance of each heater section is approximately 0.105 ohms and the resistance of the connecting stainless steel strip is about 1.08 x 10^{-3} ohms per centimeter of strip. A complete description of this type of strip heater, its properties and parameters is given in reference 1. As shown in Fig. 1, the strip heaters were placed over the coil insulation and held in position with additional insulation wrapping and by the magnet coil collars.

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

Three strip heaters and combinations of these heaters were used during the tests.

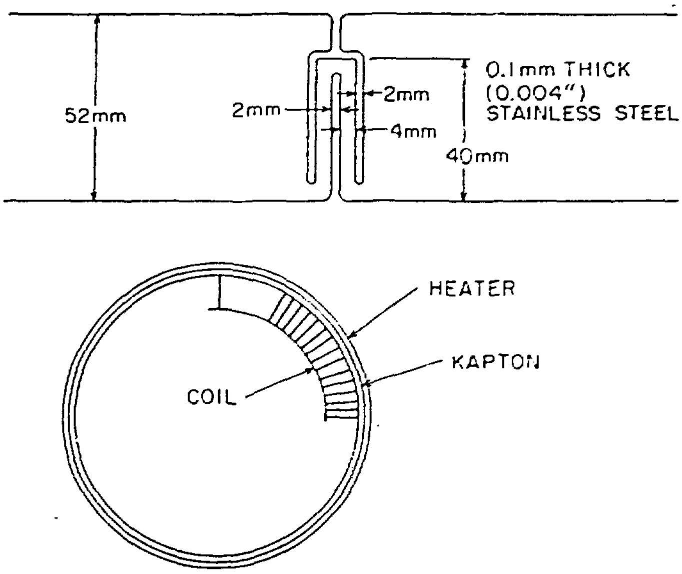
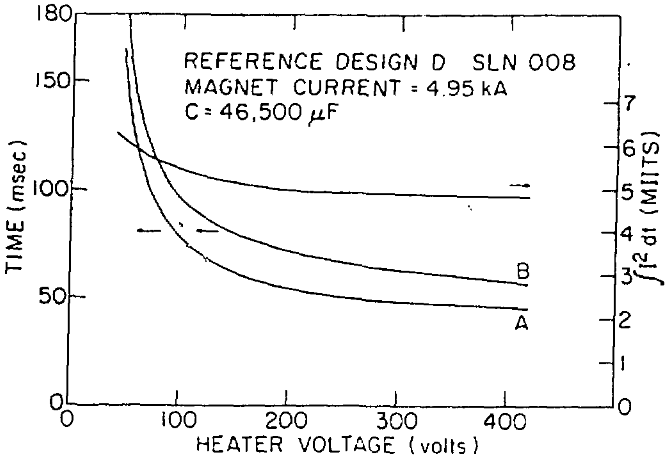


Figure 1. Schematic of strip heater showing placement on magnet coil.

For the first series of tests, the magnet current was set at 4.95 kA, the current at which $\int I^2 dt$ was a maximum, and a capacitor bank with a capacitance of 0.0465 farads was charged and then discharged through a strip heater with the charging voltage being increased progressively until a magnet quench was initiated. The time interval between when the voltage was applied to the strip heater and when the magnet quench was initiated was measured as was the time interval between when the voltage was applied to the strip heater and when the voltage across the magnet coil that had quenched reached 3 V. After the lowest charging voltage at which a quench could be initiated was determined, the "threshold voltage", the voltage was increased in a number of steps until no substantial change in the times being measured was observed.

Experimental Results

Figures 2 and 3 show plots of the times measured as a function of the voltage applied to the strip heater when heaters 1 and 3 were fired sing- ly. The quantity $\int I^2 dt$ is also plotted as a function of the applied voltage in each case. It is apparent that the times measured decrease rapidly at first as the voltage is increased from the threshold voltage to values in the range of 250 to 300 V beyond which range the rate of decrease is much smaller and the times approach a constant value. A similar statement may be made about the $\int I^2 dt$ versus heater voltage curves. Neglecting cooling, at the threshold voltage of 60 V and a capacitance of 0.0465 farads, the temperature of the heater sections of the strip rises to about 130 K and the temperature of the connecting strip to about 20 K when the capacitor bank is discharged through the strip heater.



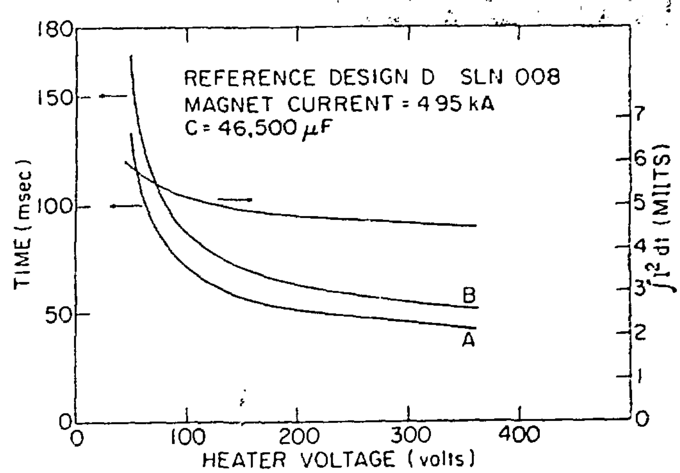


Figure 2. Strip Heater 1: Times and $\int I^2 dt$ vs. Heater Voltage.
Curve A: Time [Heater Voltage Applied - Quench Initiated].
Curve B: Time [Heater Voltage Applied - Ouench Voltage = 3 V].

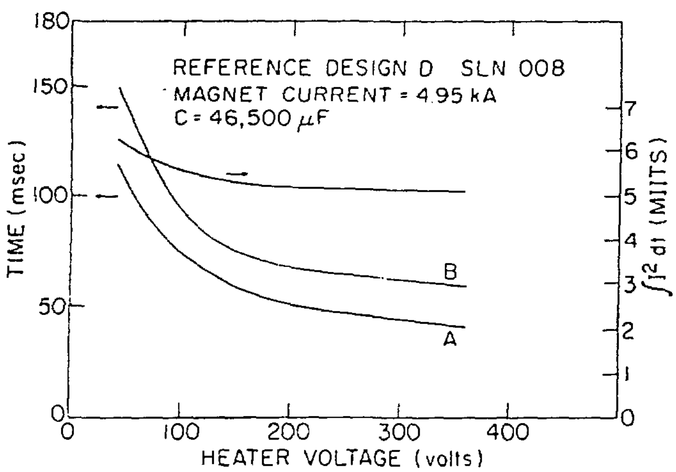


Figure 3. Strip Heater 3: Times and $\int I^2 dt$ vs, Heater Voltage.
Curve A: Time [Heater Voltage Applied - Ouench Initiated].
Curve B: Time [Heater Voltage Applied - Quench Voltage = 3 V].

Figure 4 shows the curves obtained when voltage was applied to heaters 1 and 3 connected in parallel.

Figure 4: Strip Heaters 1 and 3: Times and $\int I^2 dt$ vs. Heater Voltage.
Curve A: Time [Heater Voltage Applied - Quench Initiated].
Curve B: Time [Heater Voltage Applied - Ouench Voltage = 3 V].

Although the curve for the times between heater voltage applied and quench initiated is similar to those for the single strip heaters, the times between quench initiated and a quench voltage of 3 V were smaller than those for the single heater tests as expected since more of the magnet conductor is driven resistive in a given time by two heater strips as compared to one. This last statement is illustrated also by a comparison of the $\int I^2 dt$ versus heater voltage curves for two heater strips with the curve for a one heater strip case. When voltage was applied to two heater strips the quantity $\int I^2 dt$ was less at the various voltages than when only one heater strip was used to initiate quenches.

Figure 5 shows the curves plotted when voltage was applied to heaters 1, 2 and 3 connected in parallel. Because of instrumentation constraints, the voltages measured across the coil sections where quenches were initiated by the three heaters were not additive and so there is no significant difference between the times plotted for these curves and those for the case of two heaters in parallel. However, it can be noted that the values of $\int I^2 dt$ in Fig. 5 are less than those in Fig. 4 at the various voltages used in these tests.

Curves of magnet current versus time and $\int I^2 dt$ versus time are plotted in Fig. 6 for the three cases

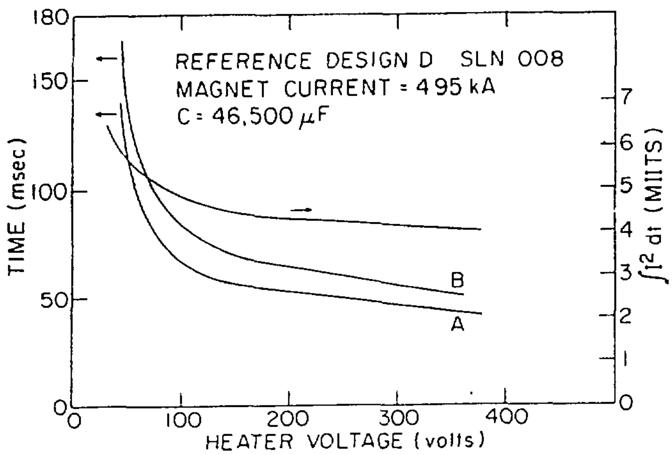


Figure 5. Strip Heaters 1, 2 and 3: Times and $\int I^2 dt$ vs. Heater Voltage.
Curve A: Time [Heater Voltage Applied - Quench Initiated].
Curve B: Time [Heater Voltage Applied - Quench voltage = 3 V].

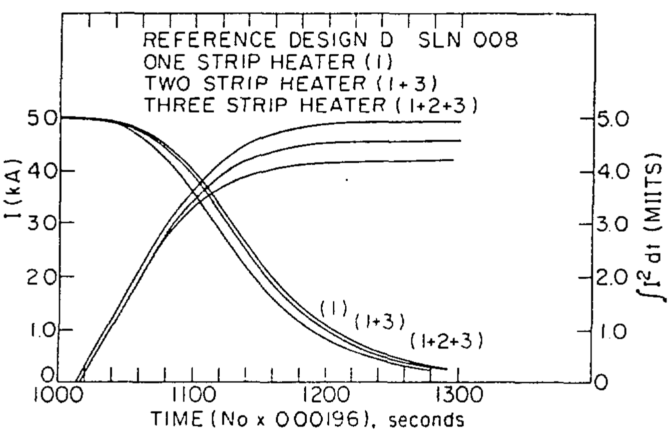


Figure 6. Magnet Current and $\int I^2 dt$ vs. Time when 1, 2 and 3 strip heaters are powered.

where one, two and three strip heaters are powered using a capacitance of 0.0465 farads and a voltage of 275 V. As expected, the time constant of the current decay decreases as the number of heaters used increases, indicating that more of the magnet conductor becomes resistive as more heaters are brought into play. The effect of the greater resistance and shorter time constant on $\int I^2 dt$ is noticeable, the use of three heaters reducing the value of $\int I^2 dt$ by about 14 percent below that measured when one heater was used.

The curves shown in Fig. 7 are from measurements made by varying the capacitance while setting the charging voltage each time at 275 V using one heater strip. The magnet current for each of these quenches was 4.95 kA. As can be seen from this figure the times become dependent on the capacitance and therefore the energy discharged in the heater only at low values of the capacitance.

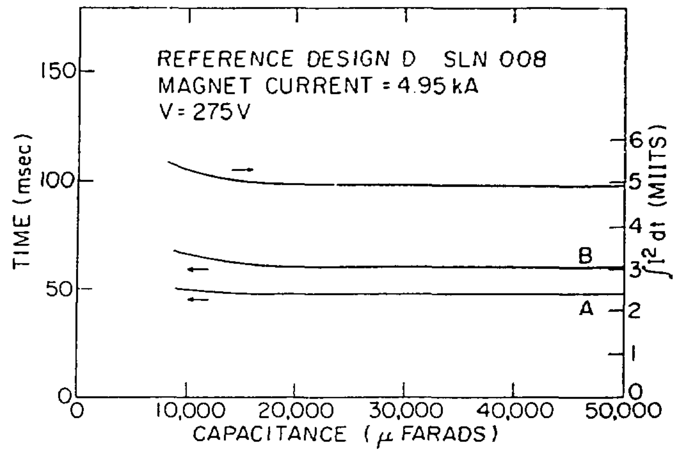


Figure 7. Strip Heater 1: Times and $\int I^2 dt$ vs. Capacitance.
Curve A: Time [Heater Voltage Applied - Quench Initiated].
Curve B: Time [Heater Voltage Applied - Quench Voltage = 3 V].

These tests indicate that the times to initiate a quench and to achieve a quench voltage of 3 V are strongly dependent on the voltage applied to the strip heater for the lower values of the applied voltage with this dependence weakening as the value of the voltage is increased. Presumably this dependence is related to the power level applied to or the initial "kick" given to the heater. The heater acts like a fuse but once a quench has been initiated the heating effects are rapidly dominated by the magnet discharging through the increasingly resistive conductor. The figures also show that the time interval between the initiation of a quench and the quench voltage reaching 3 V approaches a constant limiting value as the strip heater voltage is increased which value probably depends primarily on the quench front velocities which in turn are dependent on the magnet current.

Figure 8 shows plots of time and $\int I^2 dt$ as a function of magnet curent with a capacitance of 0.0465 farads and a voltage of 275 V being used to energize strip heater 1 for each of several magnet currents. The time interval between the heater voltage applied and quench initiated decreases as the magnet current is increased because the thermal margin of the conductor decreases as the magnet current approaches the "natural" quench current. The interval between the two time curves also decreases with increasing magnet current, an indication that the time between the initiation of a quench and a measured quench voltage of 3 V is dependent on the current and on the quench front velocities which are increasing as the magnet current increases.

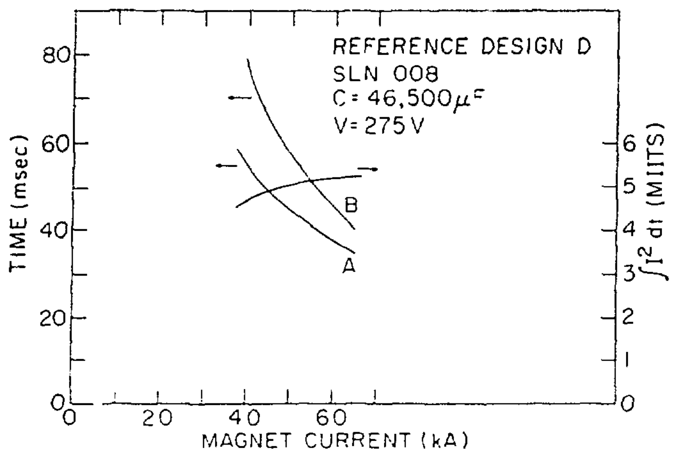


Figure 8. Strip Heater 1: Times and $\int I^2 dt$ vs. Magnet Current.
Curve A: Time [Heater Voltage Applied - Quench Initiated].
Curve B: Time [Heater Voltage Applied - Quench Voltage = 3 V].

References:

1. J. G. Cottingham, "Quench Protection Heater for SSC Magnets", SSC-MD-8, BNL, 1984.