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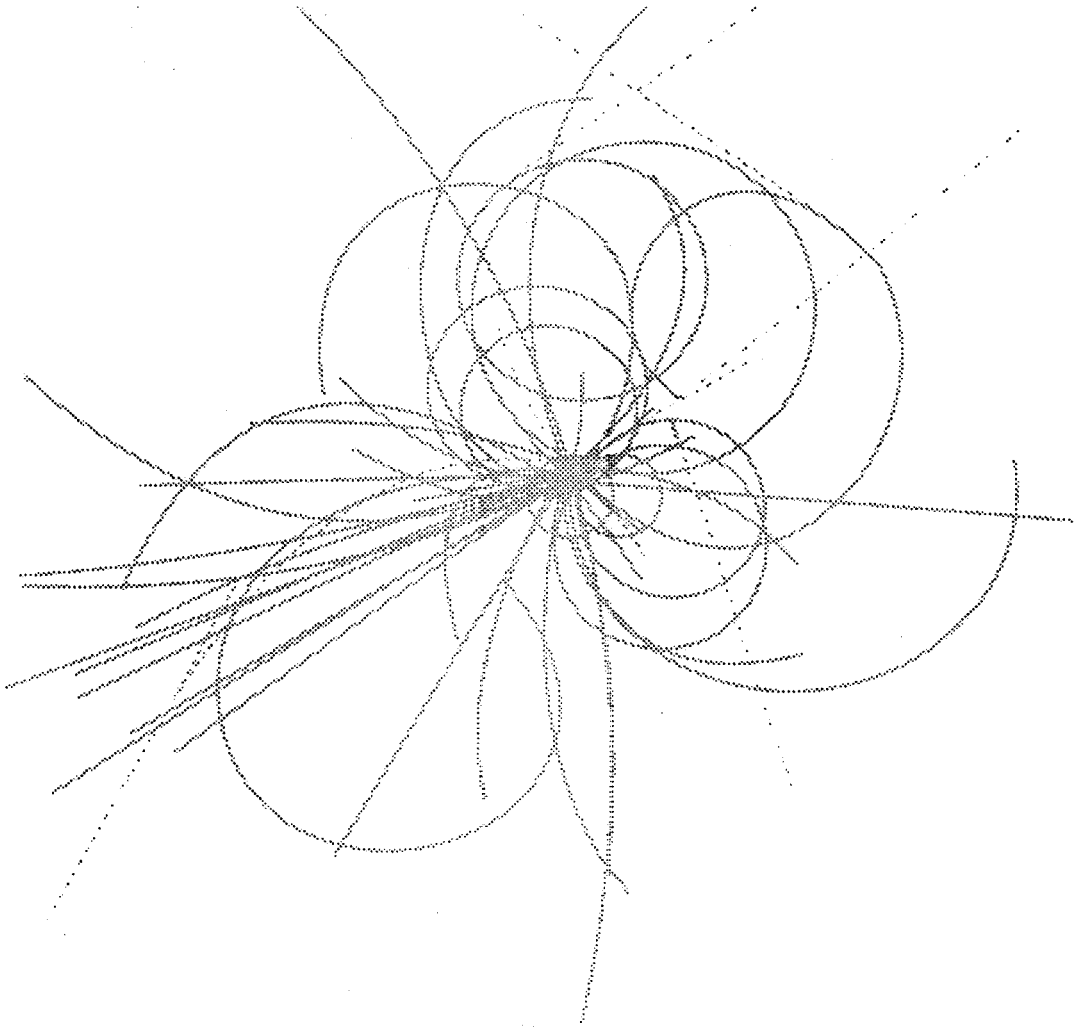

# Quench Simulation Studies of TAC Jelly Roll Superferric Dipole Corrector Elements for the SSC

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* Operated by the Universities Research Association, Inc., for the U.S. Department of Energy under Contract No. DE-AC02-89ER40486.

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## Abstract

Using the computer program SSC-DTAC-T, which is a modification of the quench computer program SSC-RR to model Jelly Roll coils, the quench behavior of the dipole corrector element (TAC design with Jelly Roll winding) is studied. The simulations are made as a function of the length of the magnet, the copper-to-superconducting ratio, and the thickness of insulation surrounding the wires. The magnet is self-protected with all listed considerations. In addition, this implies that other corrector multipoles (quadrupole, sextupole, octupole, etc.), which use the same conductor winding technique, are self-protected. A passive protection system should work for these elements.

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## 1.0 INTRODUCTION

Quench simulation of superconducting (s.c.) magnets has been a very important guide to design s.c. magnets and the associated quench protection system. The goal of the simulation is to understand and predict the quench behavior of a s.c. magnet. Also, to study quench effects with changes of some parameters of interest for its design, such as the type of s.c. wire, spacing between wires, coil configuration, etc. Although the complete goal is not possible to achieve with any computer simulation, as the real phenomenon implies the solution of many nonlinear coupled partial differential equations with very complicated boundary and initial conditions (nonlinear heat equation for each conductor, nonlinear time-depending heat transfer equation for He, nonlinear electric circuit equation, and nonlinear hydrodynamic equation for the motion of He). A good approximation has been obtained by computer gross model simulations.[1,2] In addition, these model simulations quickly extracts basic information for a confident magnet design and quench protection system (hot-spot temperature and peak voltage between normal zone and s.c. zone).

The quench simulation program SSC-DTAC-T is a modification of the SSC-RR program used to study the active and passive protection system for the SSC R&D main dipole magnet. The quench model uses the following adiabatic quench velocity expression[3]

$$v_q = \frac{J_{co}\sqrt{L_o}}{\gamma(\delta c)_m} \frac{q}{\sqrt{1 - q + \delta\theta/(\theta_c - \theta_o)}}, \tag{1}$$

where $J_{co}$ is the critical current density at the bath temperature, $\theta_o$; $L_o = 2.45 \times 10^{-8}\, W\Omega K^{-2}$ is the Lorentz number; $\gamma$ is the copper-to-s.c. ratio; $\theta_c$ is the critical temperature at zero current; $q$ is the fraction of the critical current density; $\delta\theta$ is a small shift in the generating temperature,

$$\theta_g = \theta_c - (\theta_c - \theta_o)q\,, \tag{2}$$

and $(\delta c)_m$ is the average in the product of the density, $\delta$, times the specific heat, $c$, of the metal components in the conductor. The temperature for each wire, $\theta$, is estimated through the solution of the equation

$$(\delta c)\frac{d\theta}{dt} = \rho J^2\,, \tag{3}$$

where $\rho$ is the total resistivity of the conductor, $J$ is the current density flowing in the conductor, $t$ is the time, and $(\delta c)$ is the average in the product of the density times

the specific heat of all the components of the conductor. The thermal conductivity is ignored in the above expression since the quench velocity is higher than the diffusivity velocity. The conductivity is considered in the temperature profile along the conductor. The heat transfer to He is not taken into account since it has a small effect on the quench characteristics.

The voltage between the normal zone and the s.c. zone in the magnet is estimated by the following expression

$$V = R_Q I\,(1 - M/L) + M V_{cs}/L\,, \tag{4}$$

where $R_Q$ is the total quench resistance in the coil (normal zone), $I$ is the current, $V_{cs}$ is the voltage across the magnet, $L$ is the magnet self inductance, and $M$ is the mutual inductance between the part of the coil formed by normal zone and the other part of the coil which is still s.c. (it is proportional to the square of the number of turns that are normals). During the quench evolution, $M/L$ and $MV_{cs}/L$ have normally very small value compared with $I$ and $R_Q I$ respectively. The transverse quench propagation is estimated using correction factors[4] (thickness of insulation and operational current) in the experimental values used in Reference 2.

The hot-spot temperature, the highest temperature reached in the coil during a quench (normally it is located where the quench first appears), gives information about the safe situation of the magnet in a quench. Some threshold limits are: degradation of the Kapton,[5] about 500 K; the melting point of solder (depends very much of the type), degradation of critical current density,[6] about 1000 K; and the copper melting point, about 1385 K.

The peak voltage between the normal zone and the s.c. zone (very approximately the peak quench resistance voltage) gives information about the safe situation of the magnet with respect internal break-down voltages. This threshold limit needs to be measured, and it should include the possible ionized behavior created by the radiation damage in the coil (a reference value of about $40MV/m$ [7] for two electrodes in vacuum and in high magnetic field is quite dubious).

The hot-spot temperature and the peak voltage in the coil are the two main parameters that will be studied in the quench analysis of the superferric corrector dipole magnet for the SSC.

## 2.0 COIL-CONDUCTOR CHARACTERISTICS AND QUENCH SIMULATION

The cross section of the superferric corrector dipole is shown in Figure 1. The half-coil is made up of six double-layers having 33 s.c. wires per layer. In each double-layer, one

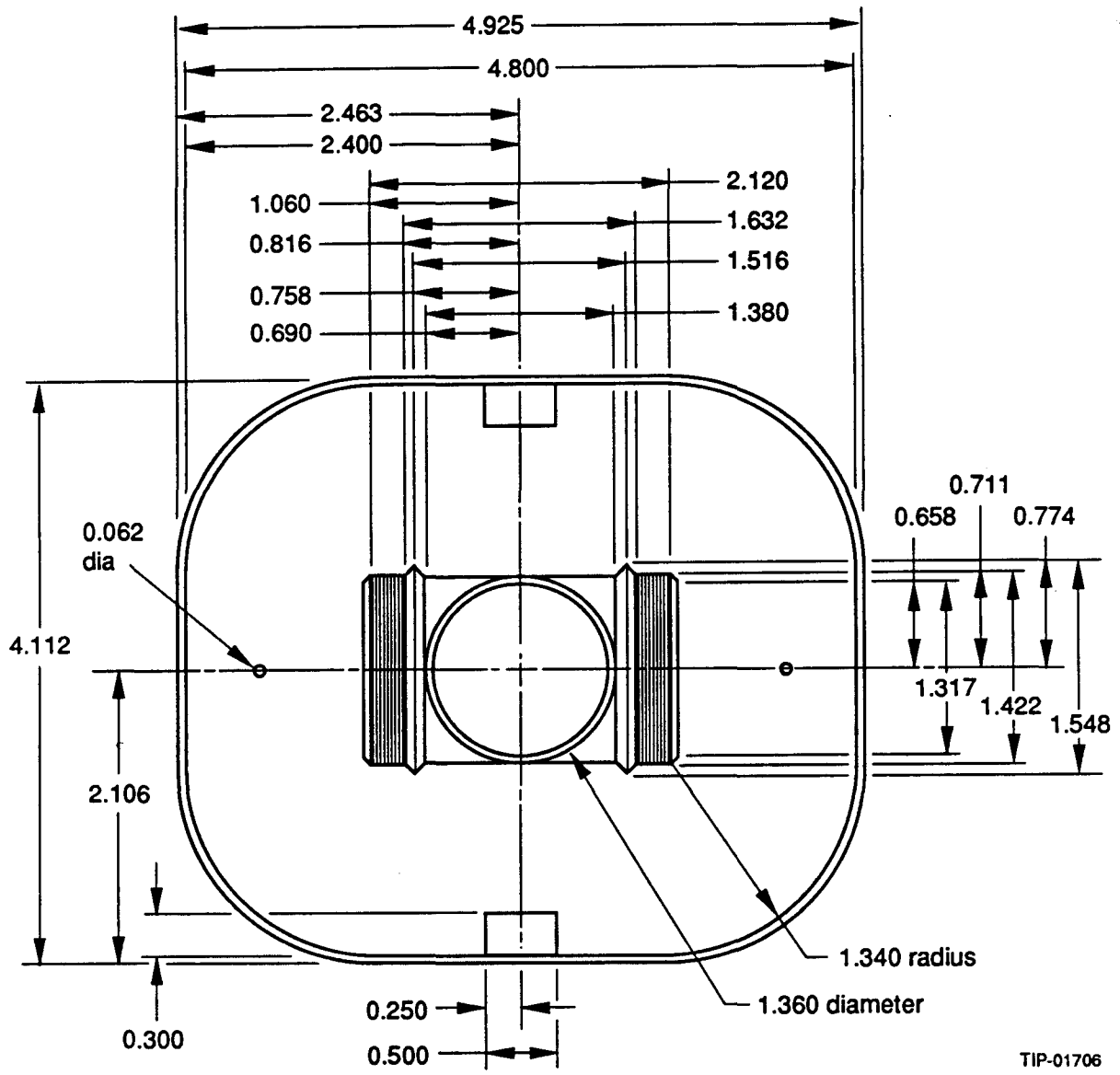


Figure 1. Cross Section of the Superferric Corrector Dipole Magnet (in inches).

wire touches only two neighbor wires (except the end wires), as it is shown in Figure 2 where its nominal parameters are given. In this figure, $\tau_1$ represents the wire-to-wire time delay quench propagation, and $\tau_2$ represents the double-layer to double-layer time delay quench propagation.

A passive protection system model has been chosen to analyze the quench behavior of this magnet (the active protection system will be discussed later). The circuit model is shown in Figure 3. The turn-on voltage, for the diode to conduct current, was chosen as 0.6 volts (assuming a cold diode). However, the quench behavior does not depend critically on this value, and the results will be essentially unchanged even for turn-on voltages a little

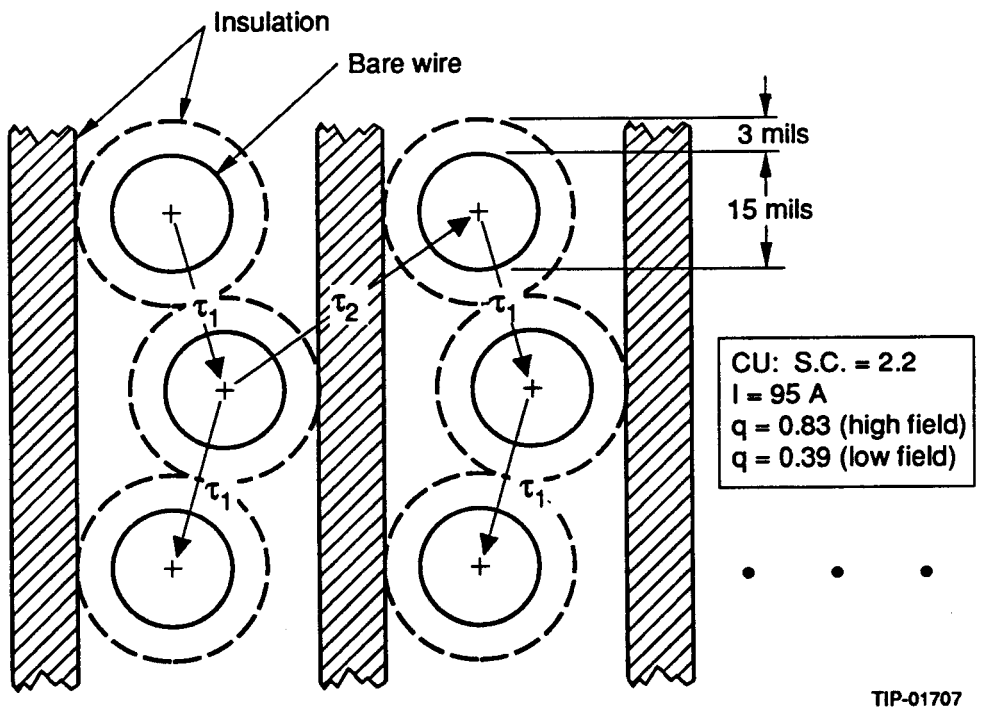


Figure 2. Sketch of Two Double-Layers Wire Array (not to scale).

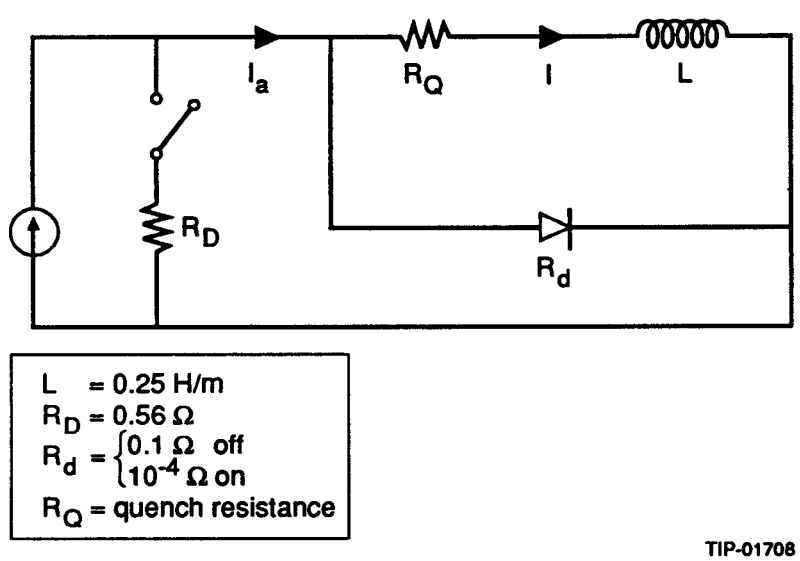


Figure 3. Circuit Model.

bit higher than of 2.0 volts (warm diode). The quench behavior does not depend on either the value chosen for the circuit dump resistance $R_D$. $R_Q$ represents the time-depending total quench resistance.

For a nominal 1 m-long superferric corrector dipole, Figure 4 to Figure 8 show the evolution of some quench parameters when the quench appears in the wire with the highest magnetic field (first top wire of the first layer), "High Field Case." Figure 4 shows the evolution of the current in the dipole during a quench and its falling-off characteristic time, 0.075 sec. Figure 5 shows the change in time of the normal zone, the s.c. zone voltage in a quench event and its peak voltage of approximately 681 volts. Figure 6 shows the evolution of the temperature on the first top conductor of the first layer and its hot-spot temperature which is approximately 64 K. Figure 7 shows the temperature evolution of the first wire quenched in the second layer, and the time at which this conductor quenches which is 4 msec. Figure 8 shows the voltage across the magnet during a quench, and the time at which the diode decouples the magnet from the circuit (0.6 volts), 40 msec. The maximum adiabatic quench velocity was about 13 m/sec, for this case, and the number of wires that were driven normal in the first double-layer was sixteen; furthermore, eight wires of the second double-layer were driven normal.

For the "Low Field Case," the quench appears in the first top wire of the last layer. Figure 9 shows the evolution of its temperature and the hot-spot temperature, 61 K. The characteristic time for the current to fall off was 0.08 sec, and the peak voltage was 593 volts. In addition, its maximum adiabatic quench velocity was 9.5 m/sec, and the number of wires driven normal was similar to the above case.

Figures 10, 11, and 12 show the hot-spot temperature, the peak voltage, and the maximum adiabatic quench velocity when the copper-to-s.c. ratio changes, keeping the amount of s.c. the same. Adding more copper to the wire making it wider. The hot-spot temperature decreases since the density of heat generated decreases. The peak voltage decreases because the quench resistance decreases when the cross section area of the wire increases. The maximum adiabatic quench velocity first decreases, since it depends inversely on the copper-to-s.c. ratio (see expression (1)), but at high values of Cu : s.c., it does not change much because $\gamma(\delta c)_m$ is dominated by the fraction of s.c. at low temperatures. The length of the magnet was 1 m, and the thickness of wire insulation was 3 mils. This analysis was made for the high field case.

Figures 13 and 14 show the hot-spot temperature and the peak voltage as a function of the length of the superferric dipole magnet for the high field case. The maximum adiabatic quench velocity was 13 m/sec.

Figures 15 and 16 show the variation on the hot-spot temperature and the peak voltage with respect to the thickness of insulation which covers the wire, $KP_{\text{thickness}}$, for the high

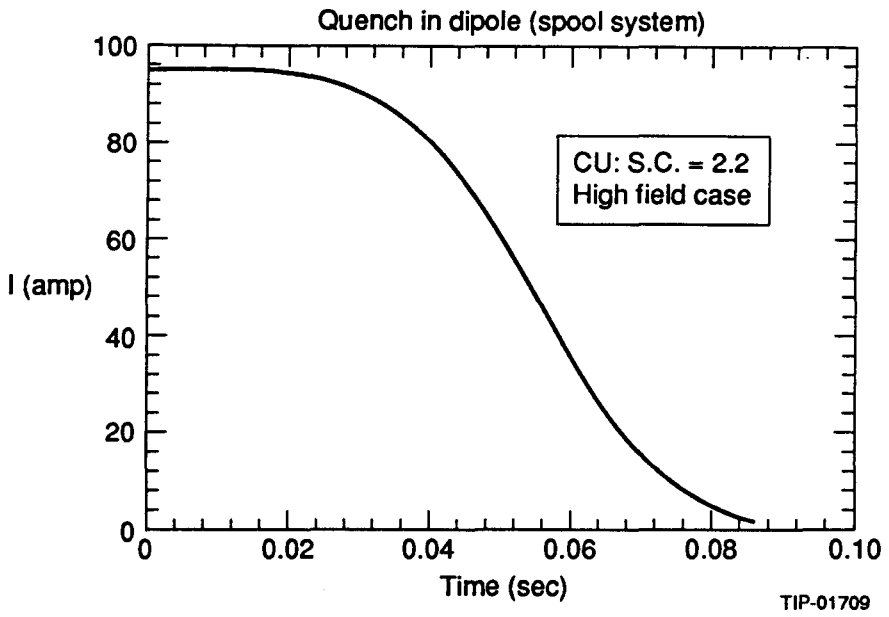


Figure 4. Current Evolution During a Quench.

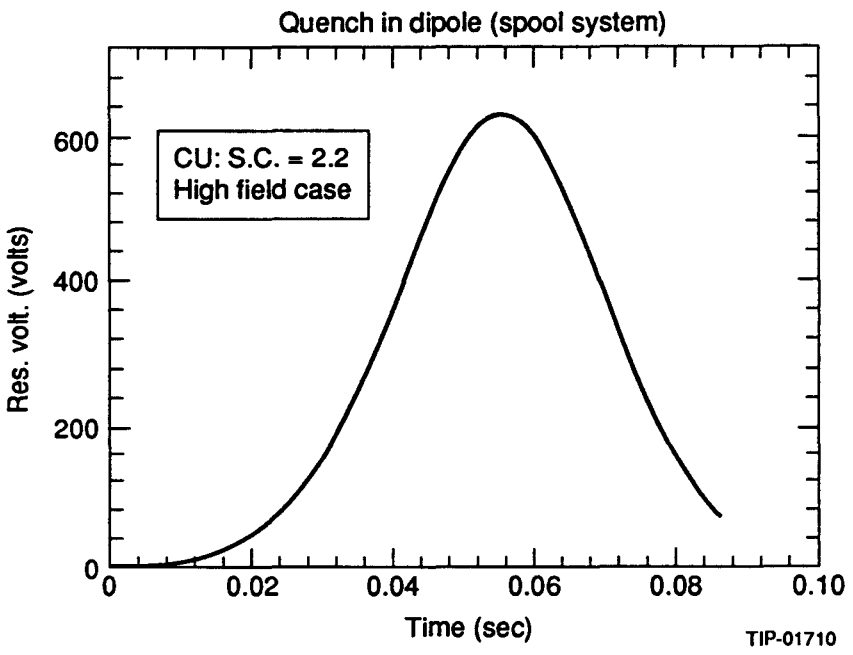


Figure 5. Quench Resistance Voltage During a Quench.

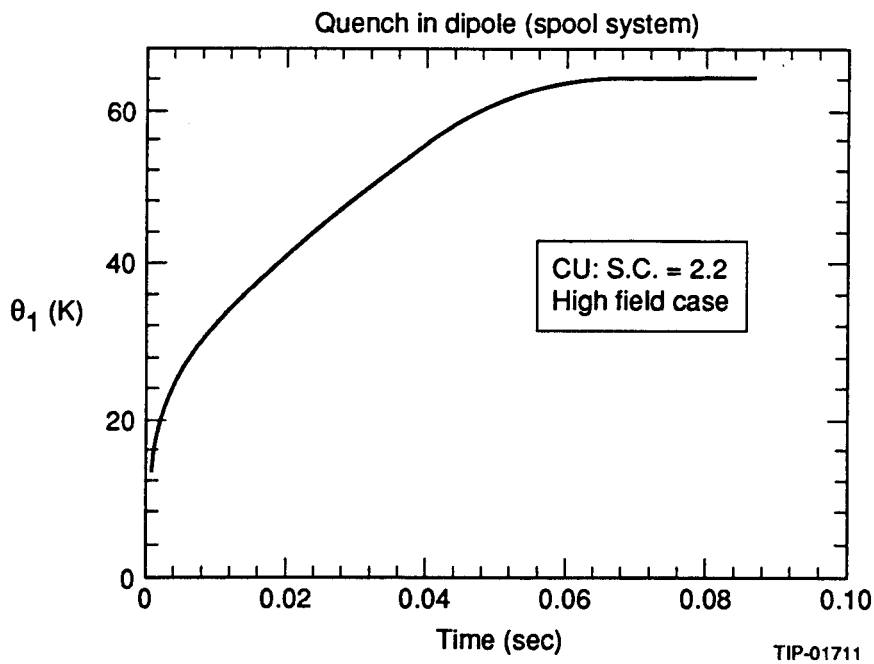


Figure 6. Temperature in the First Conductor Quenched.

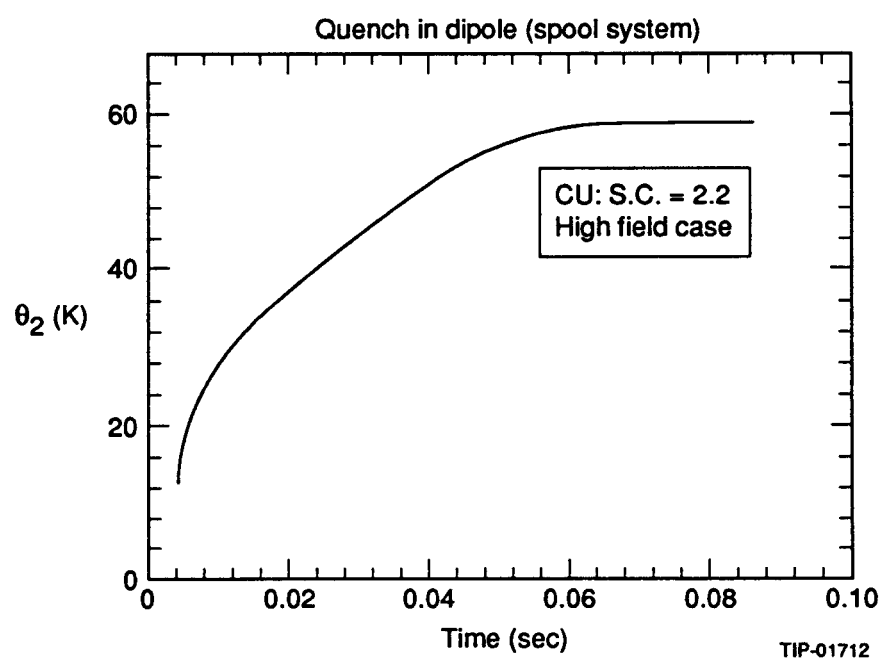


Figure 7. Temperature Rise in the Second Conductor Quenched.

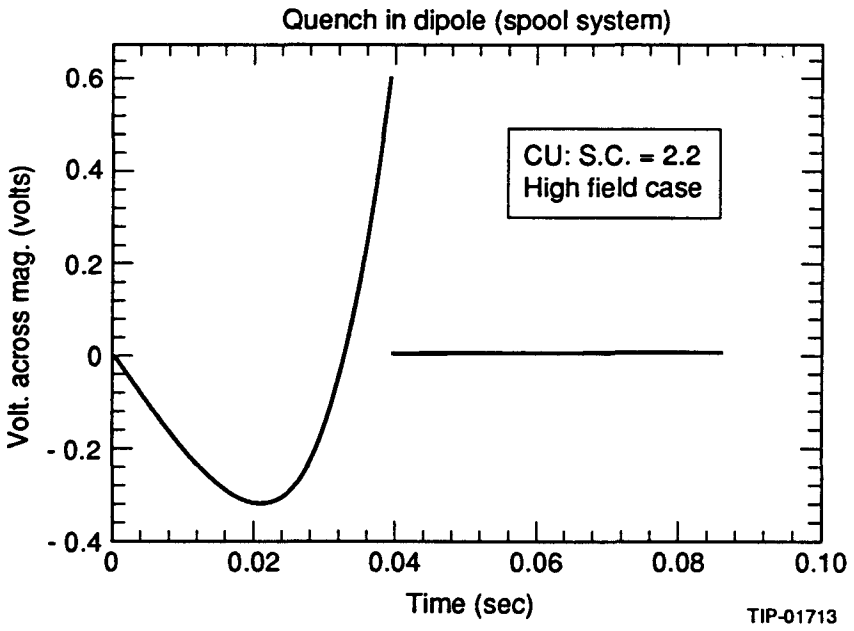


Figure 8. Voltage Across the Magnet During a Quench.

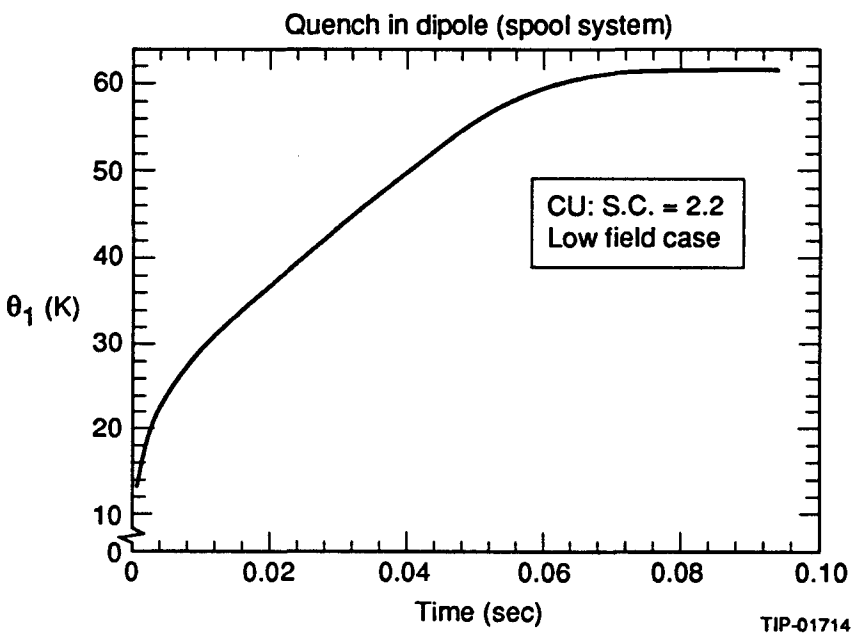


Figure 9. Temperature Rise in the First Conductor Quenched (Low Field Case).

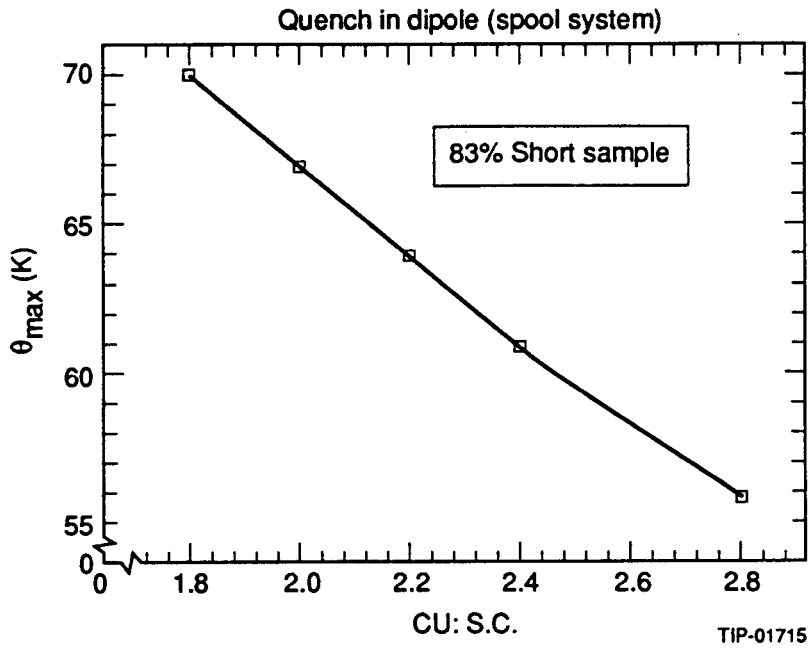


Figure 10. Hot-Spot Temperature as a Function of the Copper-to-s.c. Ratio.

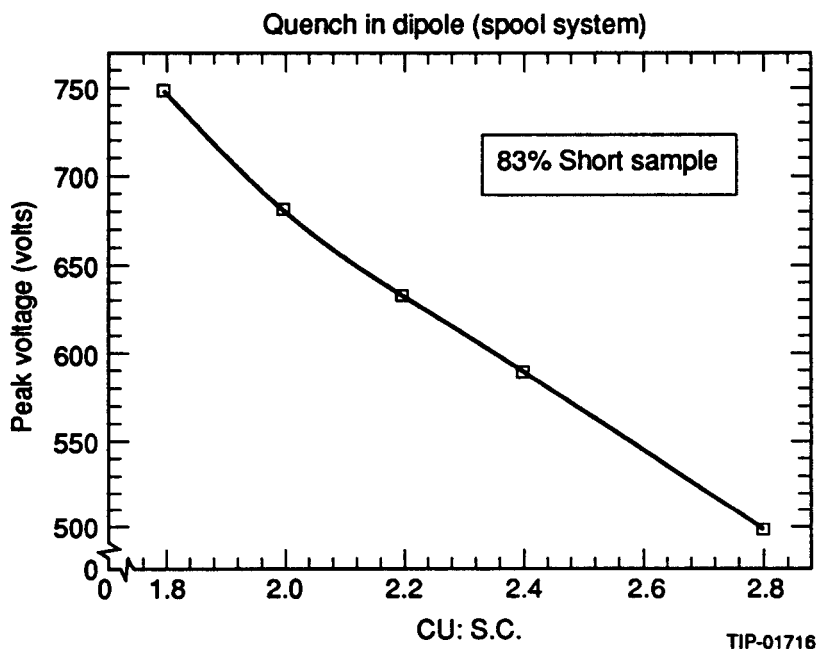


Figure 11. Peak Voltage as a Function of the Copper-to-s.c. Ratio.

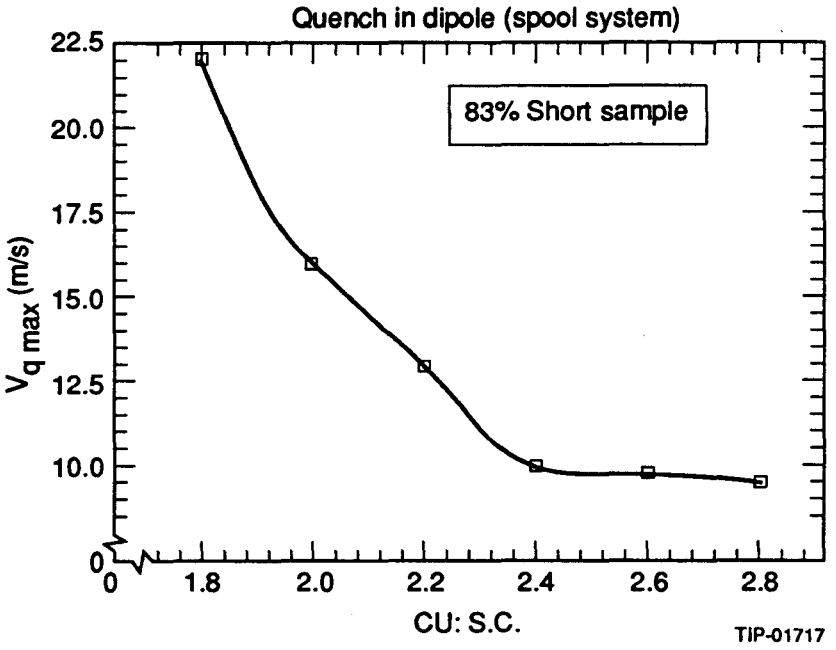


Figure 12. Maximum Adiabatic Quench Velocity as a Function of the Copper-to-s.c. Ratio.

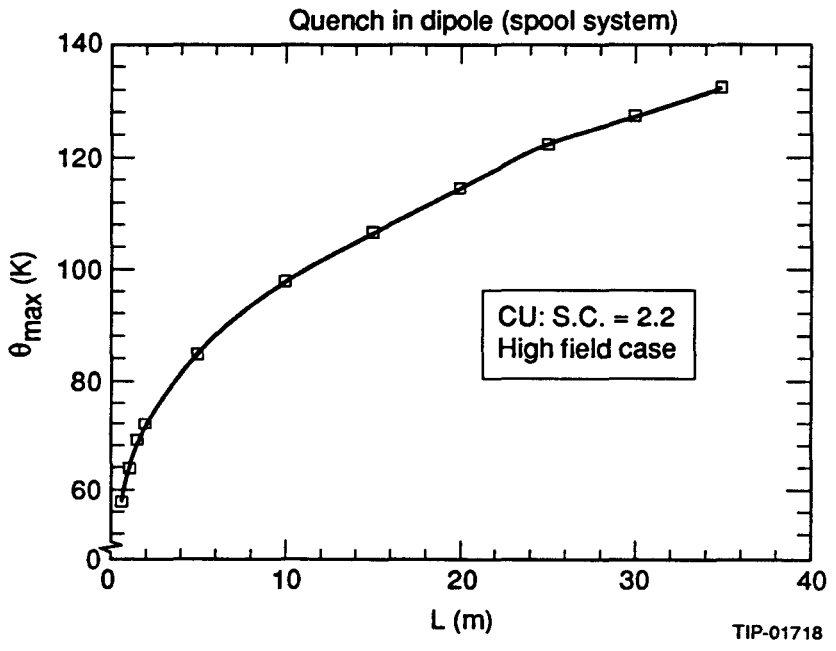


Figure 13. Hot-Spot Temperature as a Function of the Magnet Length.

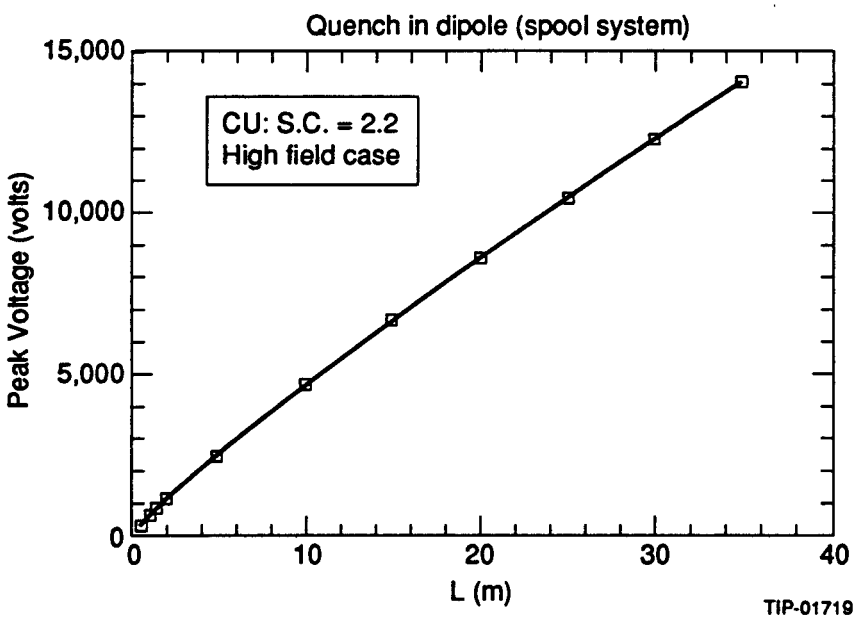


Figure 14. Peak Voltage Dependency on the Length of the Magnet.

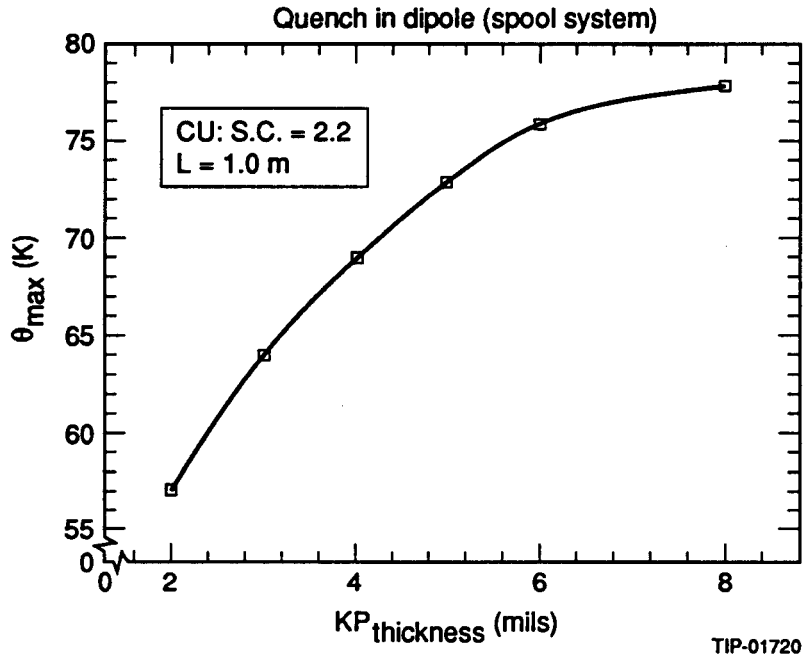


Figure 15. Hot-Spot Temperature Dependency on the Thickness of Wire Insulation.

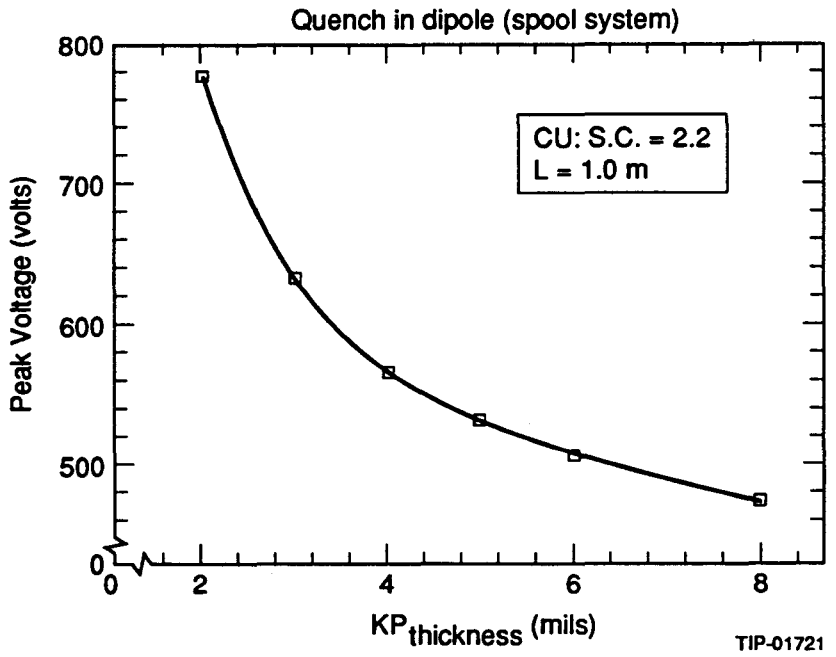


Figure 16. Peak Voltage Dependency on the Thickness of Wire Insulation.

field case ($v_q$ = 13 m/sec). The number of conductors that become normal, decreases rapidly after 4 mils of insulation thickness, this brings about the flatness in Figure 15.

## 3.0 IMPLICATIONS AND OBSERVATIONS OF THE DIPOLE QUENCH ANALYSIS

The above quench analysis point out the fact that the superferric corrector dipole magnet is widely self-protected. Since each individual magnet has a separated power supply, a passive protection system (for self redundancy, two parallel cold or warm diodes) is the most likely protection option for this magnet. If cold diodes are selected, radiation damage in the diodes and, consequently, in the magnet quench behavior are not important at least for the first 50 years of operation of the SSC.[2,8,9] An active protection system (heaters) may not be an appropriate quench protection system since the time for the heaters to induce other quenches must be brief, probably less than 20 msec. It is important to notice that, the time the quench is detected (with voltage taps across the magnet) to the time the current has fallen off, is only about 40 msec. The analysis made of the magnet quench behavior with respect the magnet length, copper-to-s.c. ratio, and wire thickness insulation points out the fact this magnet can change many of its parameters freely without affecting its safe quench behavior.

Since the type of conductor, as shown in Figure 2, is the same for other superferric Jelly Roll multipole corrector magnets (quadrupole, sextupole, octupole, etc.), and the

stored energy of these other elements is lower than the superferric corrector dipole, these multipoles are even safer than the dipole is. Even more, this allows one to take a pessimistic point of view to study the quench protection system for these other magnets.

Assume that the stored energy per unit length of the superferric corrector p-multipole is that of the superferric corrector dipole. To have $N$ focussing p-multipole of length $l_p$ connected in series, as it is shown in Figure 17, is equivalent to having a single long p-multipole corrector of effective length $Nl_p$ (from the quench point of view). The question of having a safe quench protection system for the p-multipoles corrector is reduced to that of having a safe long p-corrector in a quench event. Then, it is possible to use Figure 13 to study the quench protection system for a set of p-multipoles connected in series to a single power supply. This equivalence is justifiable in this case since the quench velocity is not high and the time for the current to fall off is brief.

In a typical SSC arc sector there are 96 Spool devices. Assume that the arc sector has a set of 96 focussing-defocussing p-multipole corrector elements in alternating pattern; although the number of octupoles and decapoles planned are less than 96. If all the focussing (48) superferric p-multipole corrector are connected in series, the estimated hot-spot temperature from Figure 13 are written in Table 1.

Table 1. Expected Hot-Spot Temperatures.

| p-multipole | $l_p$ (m) | $L_{\text{effective}}$ (m) | $\theta_{\text{max}}$ (K) |
|---|---|---|---|
| Quadrupole | 0.5 | 24.0 | 120 |
| Sextupole | 0.7 | 33.6 | 130 |
| Octupole | 0.3 | 14.4 | 105 |
| Decapole | 0.1 | 4.8 | 82 |

This result means that it is possible to connect all the focussing (defocussing) corrector p-multipoles in series and to have a passive protection system (two parallel cold or warm diodes) for them, is shown in Figure 17. The pessimistic maximum temperature expected in a quench, about 130 K, permits enough security margin to the passive protection system.

Figure 18 shows the time for the current to fall off in a quench event, of the superferric corrector dipole magnet, as a function of its longitudinal length. This time is very brief, even for a 35 m long dipole, about 0.15 sec. That is, for 48 focussing (defocussing) p-multipoles connected in series, the stored energy will fall off in less than 150 msec in a quench event. So, if an active protection system (heaters) is implemented here, the time

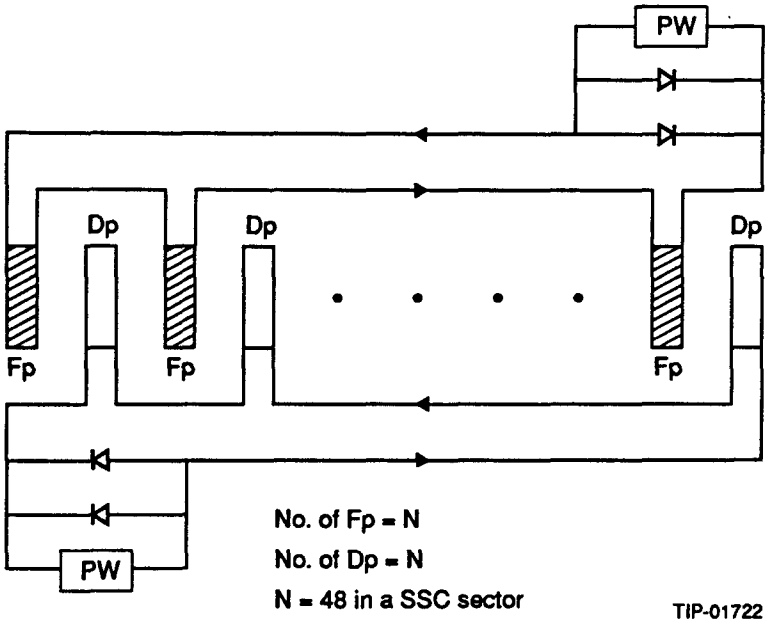


Figure 17. Passive Protection System for the p-multipoles Connected in Series.

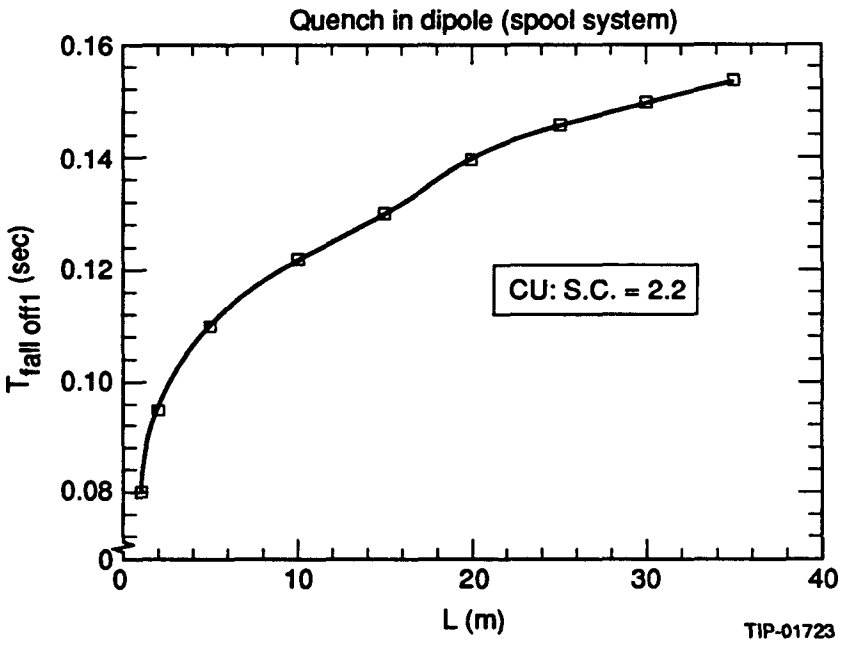


Figure 18. Magnetic Field Falling-off Characteristic Time in a Quench Event as a Function of the Length of the Magnet.

for the heaters to induce other quenches (after detecting the first quench), must be quite brief (less than 40 msec) in order for the heaters to distribute effectively the stored energy among the other p-multipoles in sector and to reduce the hot-spot temperature (that does not need to be reduced since this one is too low).

Finally, it is necessary to point out that quenches of lower current corresponds to lower hot-spot temperatures in this case (see Reference 2, simulation on 50 mm aperture SSC R&D main dipole magnet).

## 4.0 CONCLUSION

The modification of the SSC-RR computer program (SSC-DTAC-T) allowed to study the quench behavior of the superferric corrector dipole for the SSC. This magnet is self-protected in a quench event even under changes in their nominal parameters like length, copper-to-s.c. ratio, and thickness of insulation which surrounds the wires. This conclusion can be extended to the other superferric Jelly Roll correction multipoles. A passive protection system is the most likely protection system for these magnets. One power supply per corrector dipole (beam dynamic correction requirement) and one power supply per focussing (defocussing) corrector p-multipole per sector with two parallel bypass diodes (cold or warm) are safe passive quench protection systems resulting from the above analysis. An active protection system (heaters) is not required because the characteristic time for the current to fall off is quite brief, and the magnets are self-protected.

Finally, a more confident simulation can be obtained if the turn-to-turn time delay between wires could be obtained experimentally.

## ACKNOWLEDGEMENT

I wish to thank Dr. S. Stampke for his useful discussions and Dr. R. Schwitters, Dr. Don Edwards, for their support at the SSC Laboratory.

## REFERENCES


1. M.N. Wilson, *Superconducting Magnets*, Oxford Science Publications, Chapter 9, 1983.
2. G. López and G. Snitchler, *Study of Passive and Active Protection System for the SSC R&D Dipole Magnet*, SSCL-283, June 1990.
3. G. López, *Divergent Quench Velocity Expression*, SSCL-266, April 1990.
4. G. López, *Analytical Approximation to the Turn-to-Turn Quench Propagation*, SSCL-309, September 1990.
5. R. Doherty, *Electrical Eng. Times*, Nov. 14, 1988.
6. Letter from A. Devred and R. Stiening to Tom Kirk, LBL, Nov. 29, 1988.
7. D. Wolgest, LBL communication to TAC, 1986. From LBL-design data J.O. Turner, May 1980.
8. J. Zeigler and R. Carcagno, *Lifetime of Passive Quench Protection Diodes in the SSC*, SSC-N-610, Superconducting Super Collider Laboratory, Dallas, Texas (1989).
9. W.B. Sampson and A.J. Stevens, *Radiation Exposure of Bypass Diodes*, BNL-422, 1983.