SSCL-593

Superconducting Super Collider Laboratory

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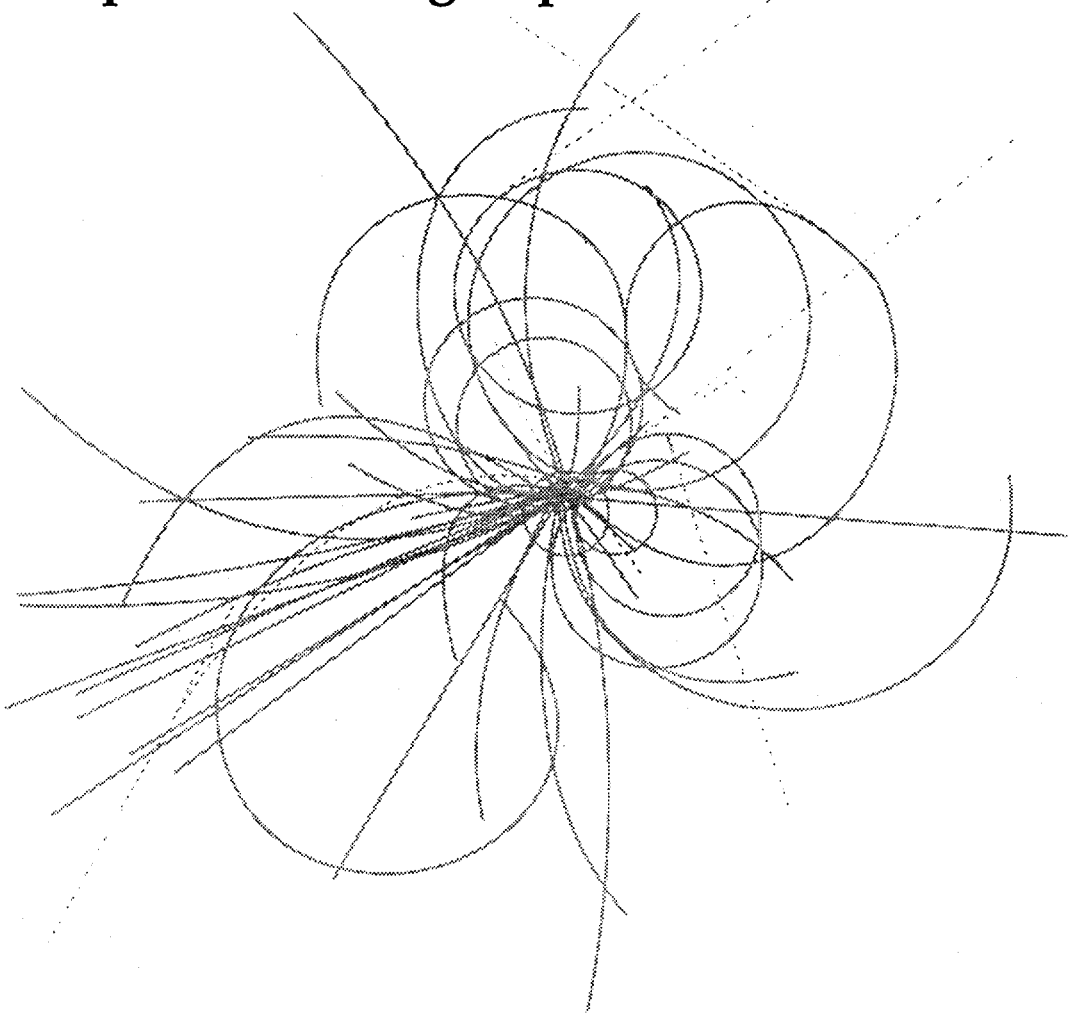

Quench Simulation for the 40-mm-Aperture Collider Quadrupole Magnet for the SSC

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Abstract

Using the computer program SSCQ-RR, which is a modification of the program SSC-RR, the quench propagation in a 40-mm-aperture Collider Quadrupole Magnet (CQM) at an initial current of 6500 A is studied. Single quadrupole passive protection is analyzed. The active protection system is examined when this magnet is connected in series with a given number of 50-mm-aperture dipole magnets. The result of the single CQM passive protection simulations agrees with the experimental observation that the CQM is self-protected. The results of the active protection system simulations show that the original Site-Specific Conceptual Design Review (SCDR) active protection system is completely safe with or without heaters in the quadrupole, providing that the heater time delay τ_h is less than 150 ms.

1.0 INTRODUCTION

Preliminary simulations of the quench protection system for the Superconducting Super Collider (SSC)[1] took into consideration only the Collider Dipole Magnets (CDM). These simulations were made with the program SSC-RR, which calculates the longitudinal quench velocity for each conductor in the coil using the adiabatic quench velocity expression[2]

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

where J_{co} is the magnetic field-dependent critical current density at the bath temperature θ_o, $L_o = 2.45 \times 10^{-8}\ W\Omega K^{-2}$ is the Lorentz number, γ is the copper to superconductor (s.c.) ratio, θ_c is the critical temperature at zero current, q is ratio of the operation current density to the critical current density, $\delta\theta$ is a small shift in the generating temperature, $\theta_g = \theta_c - (\theta_c - \theta_o)q$, and $(\delta C)_m$ is the average of the product of the density δ times the specific heat C of the metal components in the conductor. The temperature θ for each conductor is estimated through the solution of the equation

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

where ρ is the total resistivity of the conductor, J is the current density flowing in the conductor, t is the time, and (δc) is the average of the product of the density times the specific heat of all the components of the conductor. The thermal conductivity of the conductor is not considered in Eq. (2) since the quench velocity is much higher than the thermal diffusion velocity. However, this thermal conductivity effect is taken into consideration when calculating the temperature profile along the conductor.[3] The heat transfer to the helium is not included because it has only a small effect on the quench characteristics. The transverse quench propagation is estimated using the experimental values (current dependence) from Reference 1. The voltage between the normal zone and the s.c. zone in the magnet is approximated by the following expression:

$$V = R_Q I(1 - M/L) + MV_{cs}/L , \tag{3}$$

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 the normal zone and the other part of the coil that is still superconducting.

The hot-spot temperature, the highest temperature reached in the coil during a quench (which normally is located where the quench first appears), is the most important parameter affecting magnet safety. The peak voltage between the normal zone and s.c. zone

(approximately the peak quench resistive voltage) is the other important parameter when internal breakdown voltages are considered. The characteristics of the Collider Quadrupole Magnet (CQM) and CDM can be found in Reference 4. Figure 1 shows the cross section of these magnets. It is clear that the magnetic field in the conductor must be considered to calculate the quench velocity and resistance developed. In what follows, the analysis of a single CQM (passively protected) and one CQM with several CDMs connected in series and actively protected will be presented. In the active protection system, CDMs will have heaters but the CQM does not have a heater.

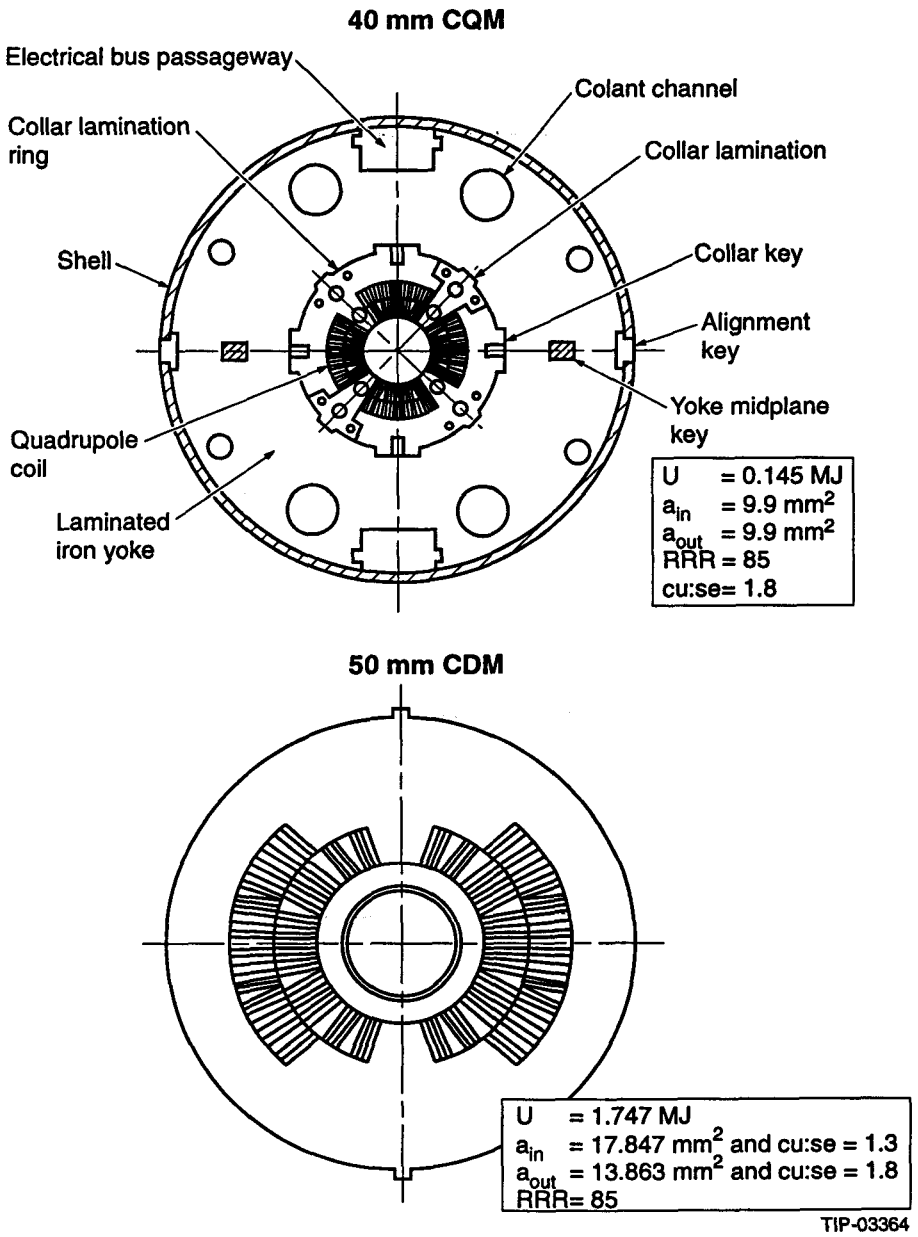

Figure 1. Cross Sectional View of the CQM and CDM.

2.0 PASSIVE PROTECTION SYSTEM FOR ONE CQM

Figure 2 shows the model for the electric circuit. The initial current is 6500 A. The inner-coil quench appears in the last conductor from the midplane (by symmetry only a quarter of the coil is considered) after the copper wedge in conductor 8. The quench propagates all the way down across the wedge and upward across the insulator layer between the inner and outer coils. The first conductor quenching in the outer coil will be the one closest to inner conductor 8, which is conductor 13. In the outer-coil case, the quench starts at conductor 13 and propagates all the way down and into the inner coil, quenching conductor 8 first.

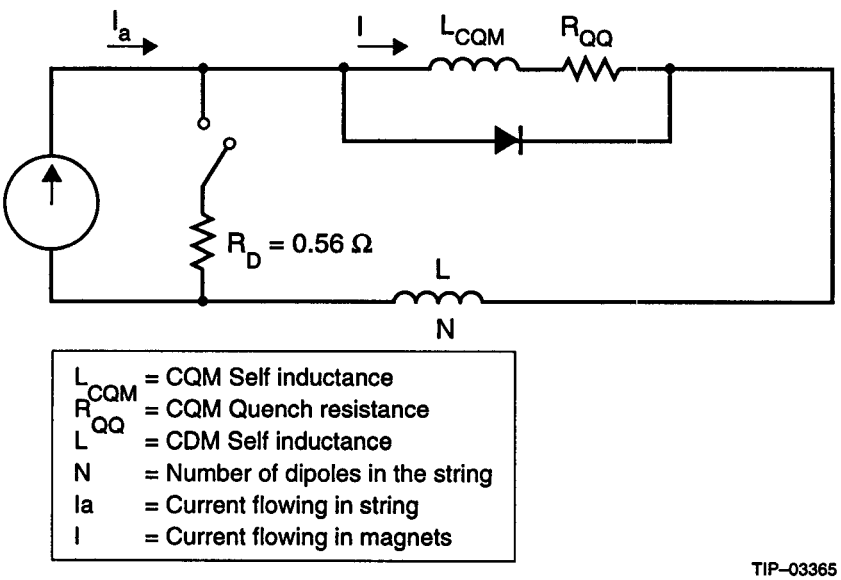

Figure 2. Passive Protection System Circuit Model.

Figures 3 and 4 show the temperature evolution of these conductors for the inner- and outer-coil quench. Figures 5, 6, 7, and 8 show the evolution of the current, the total quench resistance, the peak voltage developed, and the voltage across the magnet. As Figures 3 and 4 clearly indicate, the CQM is a self-protected magnet. (The hot-spot temperature is less than 170 K.)

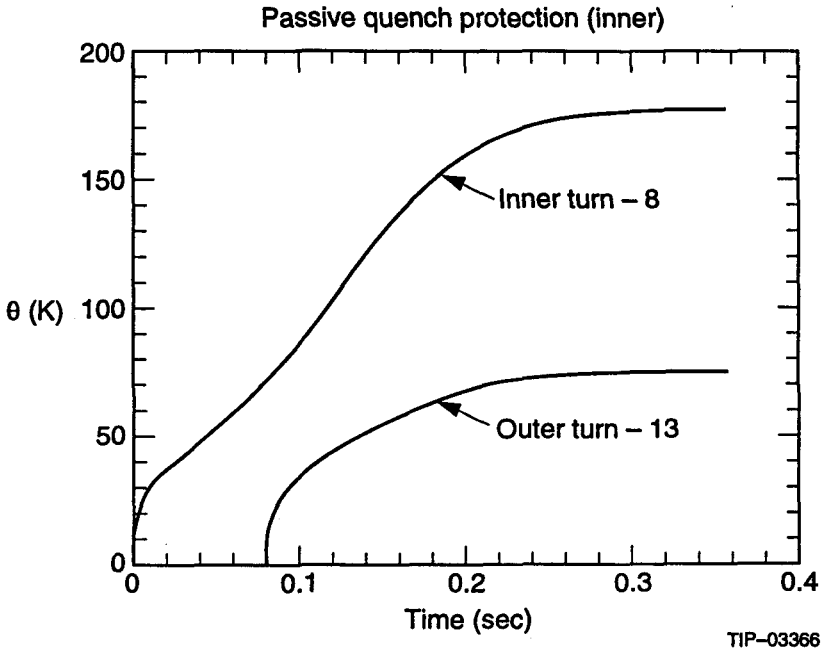

Figure 3. Evolution of the Hot-spot Temperature in the Inner Coil (1) and Outer Coil (2). Quench Starts in the Inner Coil.

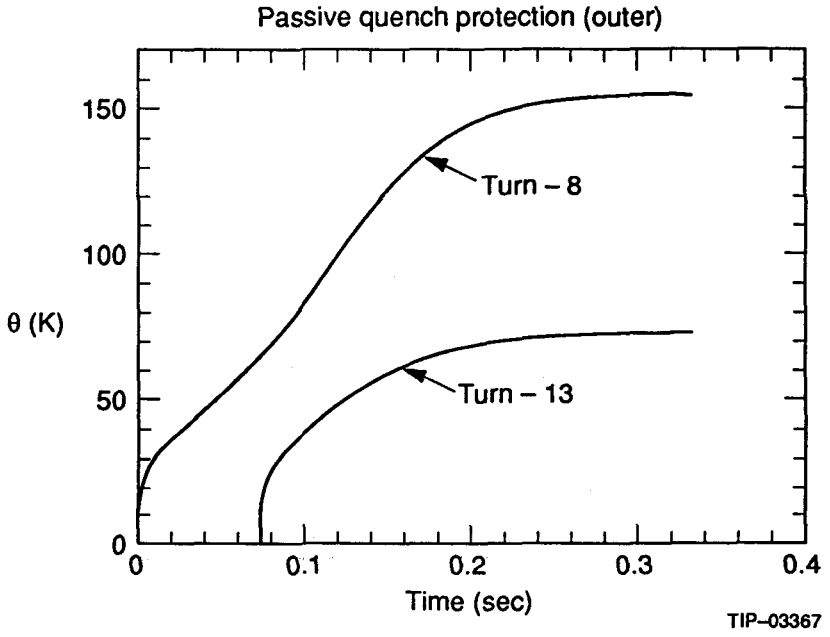

Figure 4. Evolution of the Hot-spot Temperature in the Outer Coil (2) and Inner Coil (1). Quench Starts in the Outer Coil.

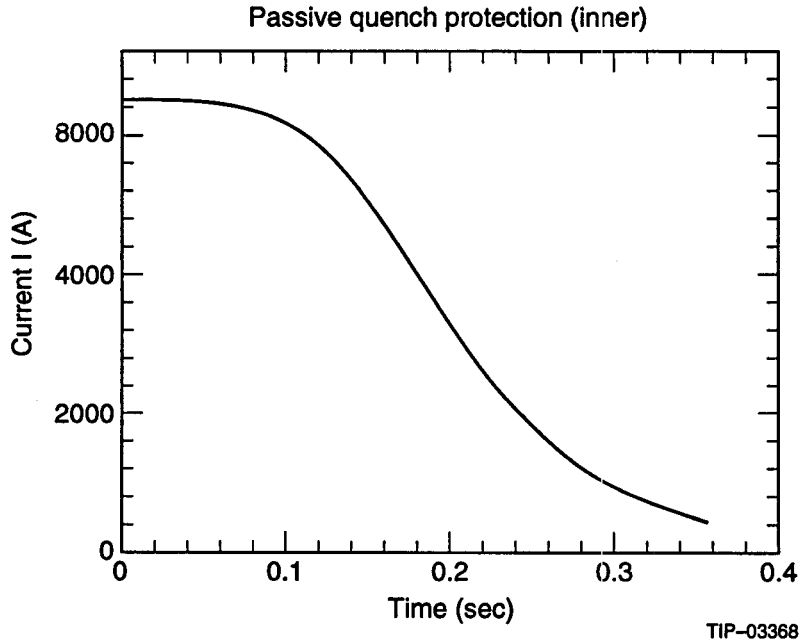

Figure 5. Decay of the Current during a Quench.

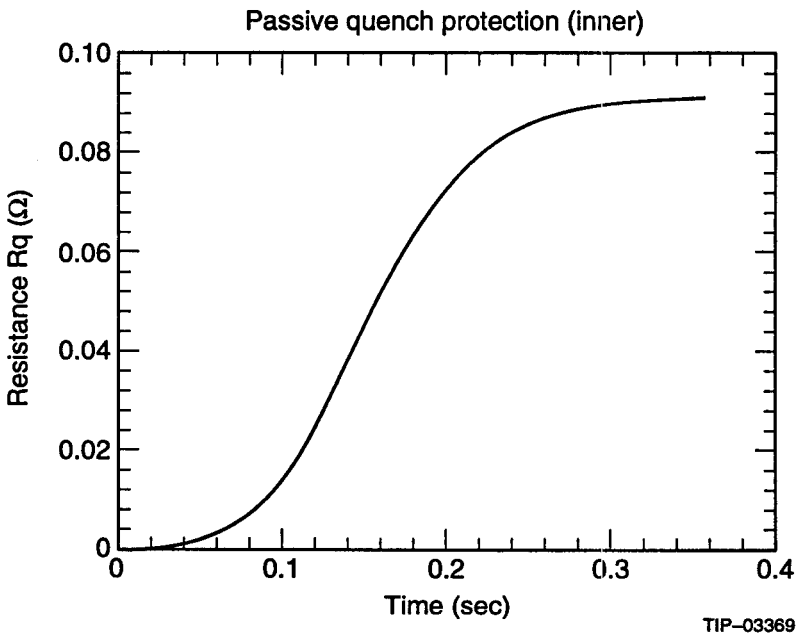

Figure 6. Total Resistance Developed during the Quench.

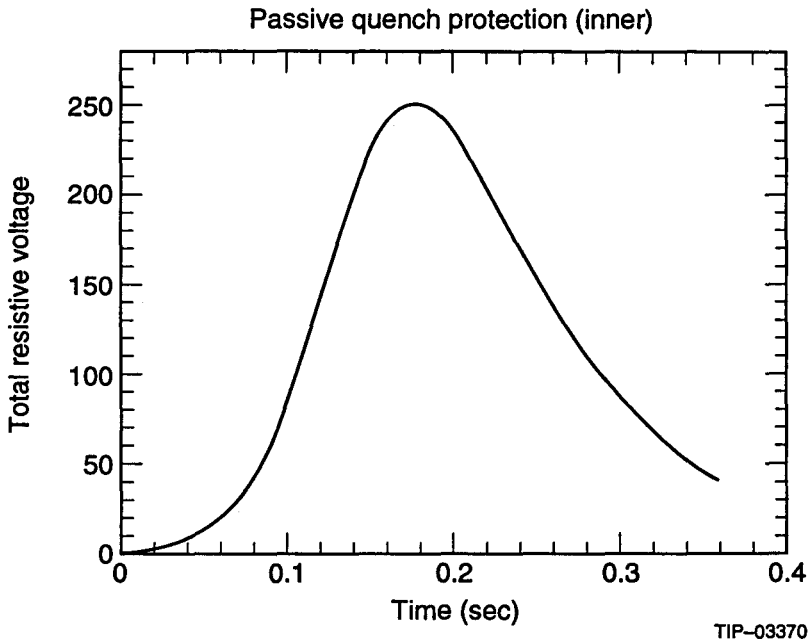

Figure 7. Quench Resistance Voltage during the Quench.

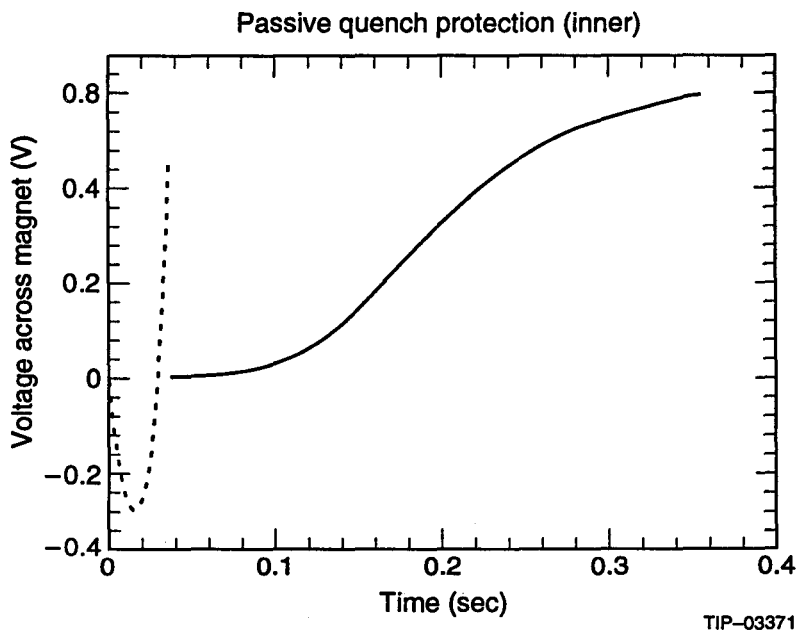

Figure 8. Voltage Across the Magnet during the Quench.

3.0 ACTIVE PROTECTION SYSTEM FOR ONE CQM IN SERIES WITH CDMS

Figure 9 shows the model for the electric circuit. The initial current here is also 6500 A. Since the difference in temperature for the inner- and outer-coil quenches is not significant, the inner-coil quench case will be the only one presented here. After the CQM quench initiates, the heaters induce a CDM quench at time "*bypass* $-$ *time* $+ \tau_h$" at a single point (worst-case heater performance) on each conductor of the dipole outer coils. The quench velocity on these magnets and all the quench characteristics (temperature, peak voltage, resistance, *etc.*) are then calculated. Figures 10 and 11 summarize the evolution of the temperature in the CQM and the total quench resistance for several dipoles connected in series with a quadrupole. At first inspection of Figure 11 one might think that the contribution of the quadrupole to the total resistance in the system is negligible (see Figure 6 for a plot of CQM resistance). However, Figure 12 shows that when the quadrupole is connected in series with dipoles, the longer current-decay time results in a higher and more uniform temperature in the CQM, bringing about a higher total resistance. This fact is very important for a correct estimation of the quench behavior of the system. An underestimation of this resistance may result in the design of an unnecessarily complicated quench protection system.

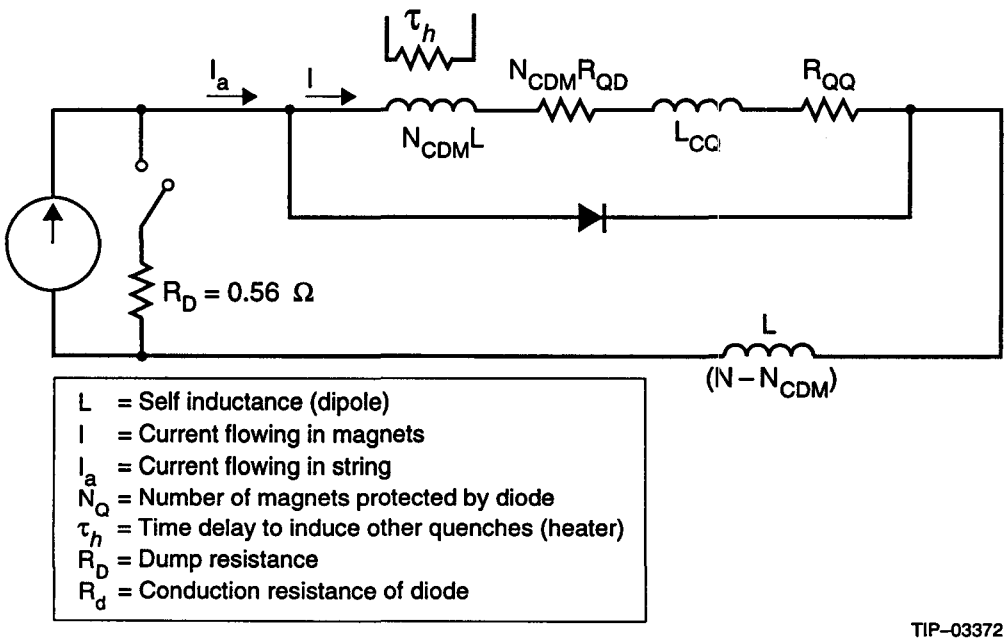

Figure 9. Circuit Model for the Active Protection System.

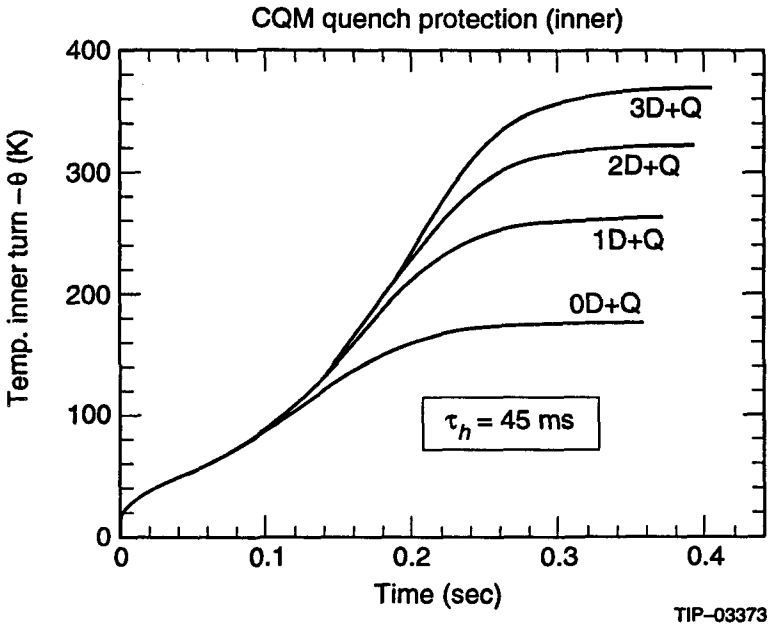

Figure 10. CQM Hot-spot Temperature Evolution for Various CDMs Connected in Series.

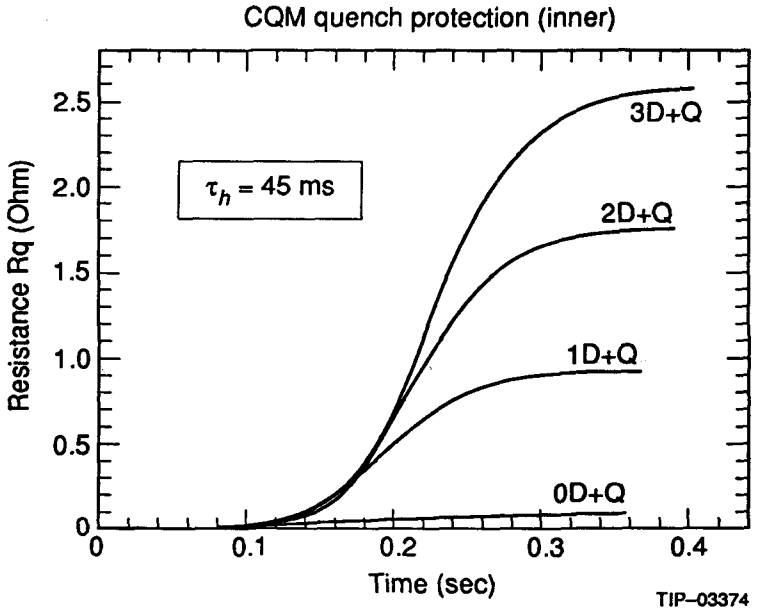

Figure 11. Total Quench Resistance Developed in the System CQM+CDMs.

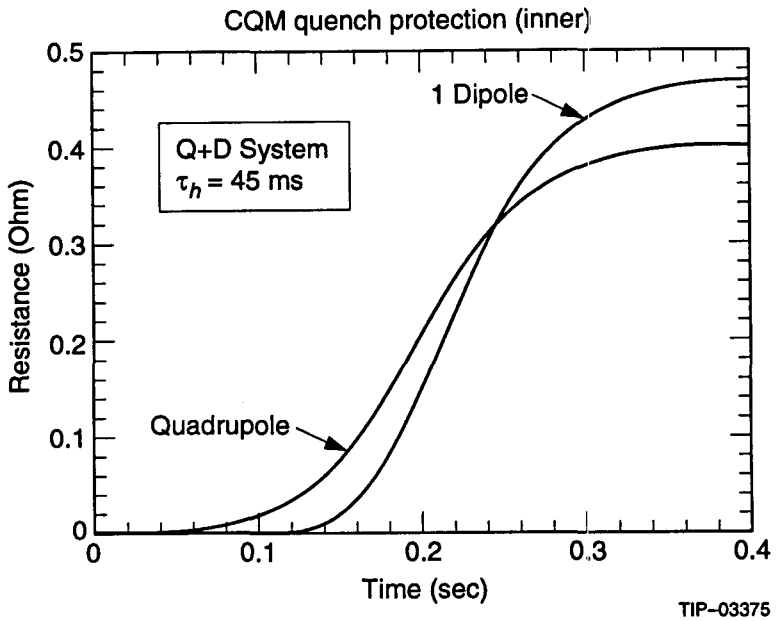

Figure 12. Total Resistance Developed in the CQM and CDM in the System CQM+CDM During a Quench in the CQM.

In the preceding calculations the heater time delay for the dipole magnets has been set to $\tau_h = 45$ ms. Figures 13(a) and 13(b) show the hot-spot temperature and the number of MIITS developed in the quadrupole magnet for several CDMs connected in series and for three heater delay times. As can be see in this figure, even for a heater delay time of about $\tau_h = 150$ ms, the hot-spot temperature for the configuration D+D+Q will be about 400 K.

The case for a dipole quench in the system can be seen in Reference 1. The presence of the quadrupole in this case is irrelevant since its stored energy is one order of magnitude lower, and most of the stored energy is dissipated in the dipoles (mainly in the one where the quench appeared first).

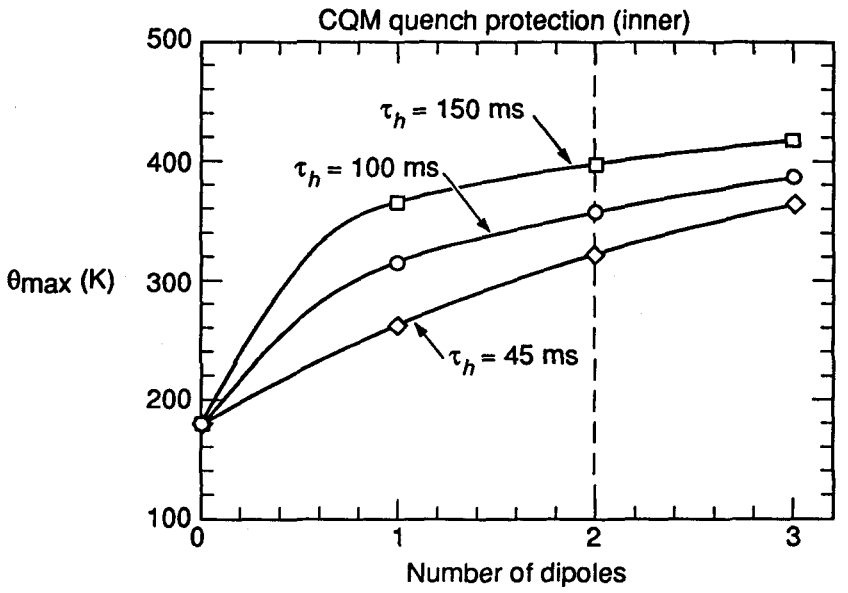

Figure 13a. CQM Hot-spot Temperature for Several CDMs.

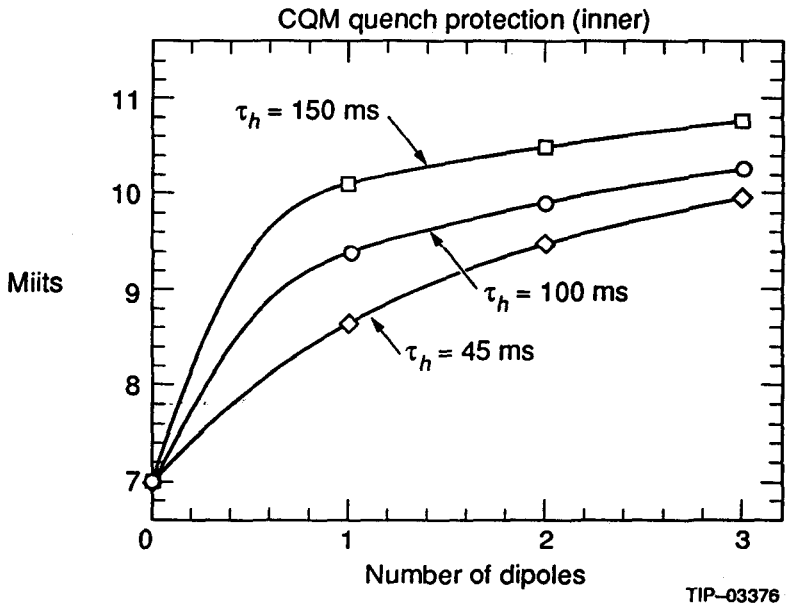

Figure 13b. CQM Number of MIITS for Several CDMs.

4.0 SUMMARY AND COMMENTS

Passive protection system simulations agree with the experimental results that indicate the 40-mm-aperture quadrupole magnet for the Collider is self-protected. Active protection system simulations suggest that the schemes as shown in Figure 14 are safe quench-protection schemes. Accelerator System String Test (ASST) experiments could test the most reliable option for the SSC. The simulations assume that the heaters cause a quench at a single point of each conductor of the outer CDM coil, then the quench propagates according to the longitudinal quench velocity, the time delay for transverse propagation, the magnetic field, *etc.* Actually, the heaters will be capable of quenching a large portion of the outer coil simultaneously. Hence, the assumption made here should reflect the worst-case scenario.

Recall that the heater time delay τ_h in the simulation is in addition to the approximately 80 ms of delay from the start of the quench in the quadrupole (see Figure 15). This is the time required for current in the system (Ds+Q) to bypass the magnets, and it is assumed in the simulations that at this time the quench is detected. Therefore, the total time delay safe limit, after the start of quench in the quadrupole, is about 80 ms + 150 ms = 230 ms.

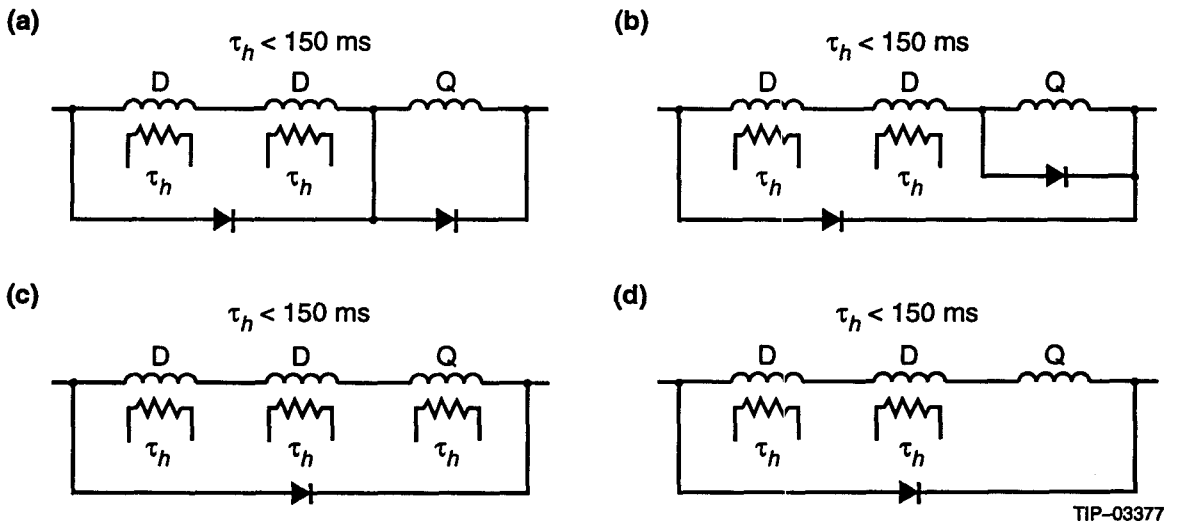

Figure 14. Safe Active Quench Protection Schemes: a) Two safety leads scheme (warm diodes). b) One safety lead and one "minor" CQM safety lead scheme. ("minor" CQM safety lead can be avoided using one cold diode) c) Original SCDR quench protection scheme. d) Model proposed in the simulations.

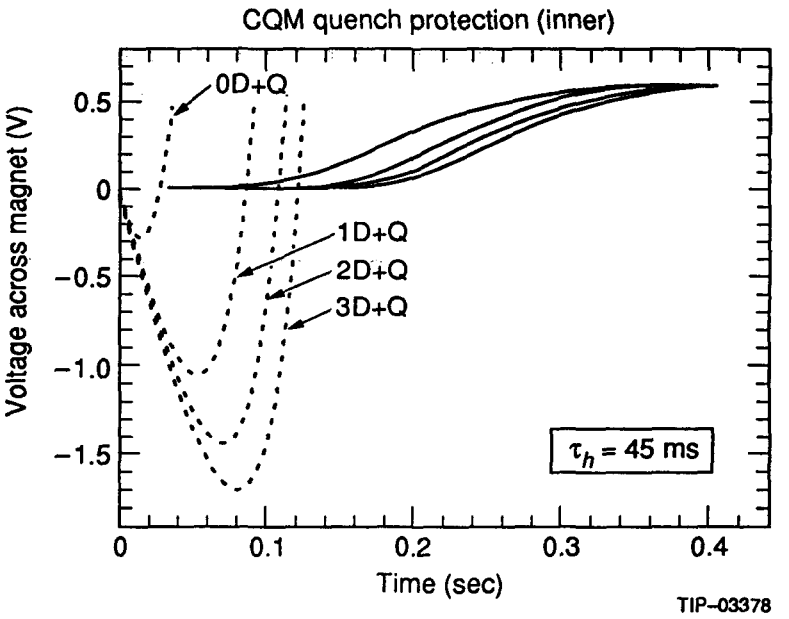

Figure 15. Voltage Across the System CQM+CDMs.

ACKNOWLEDGEMENTS

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