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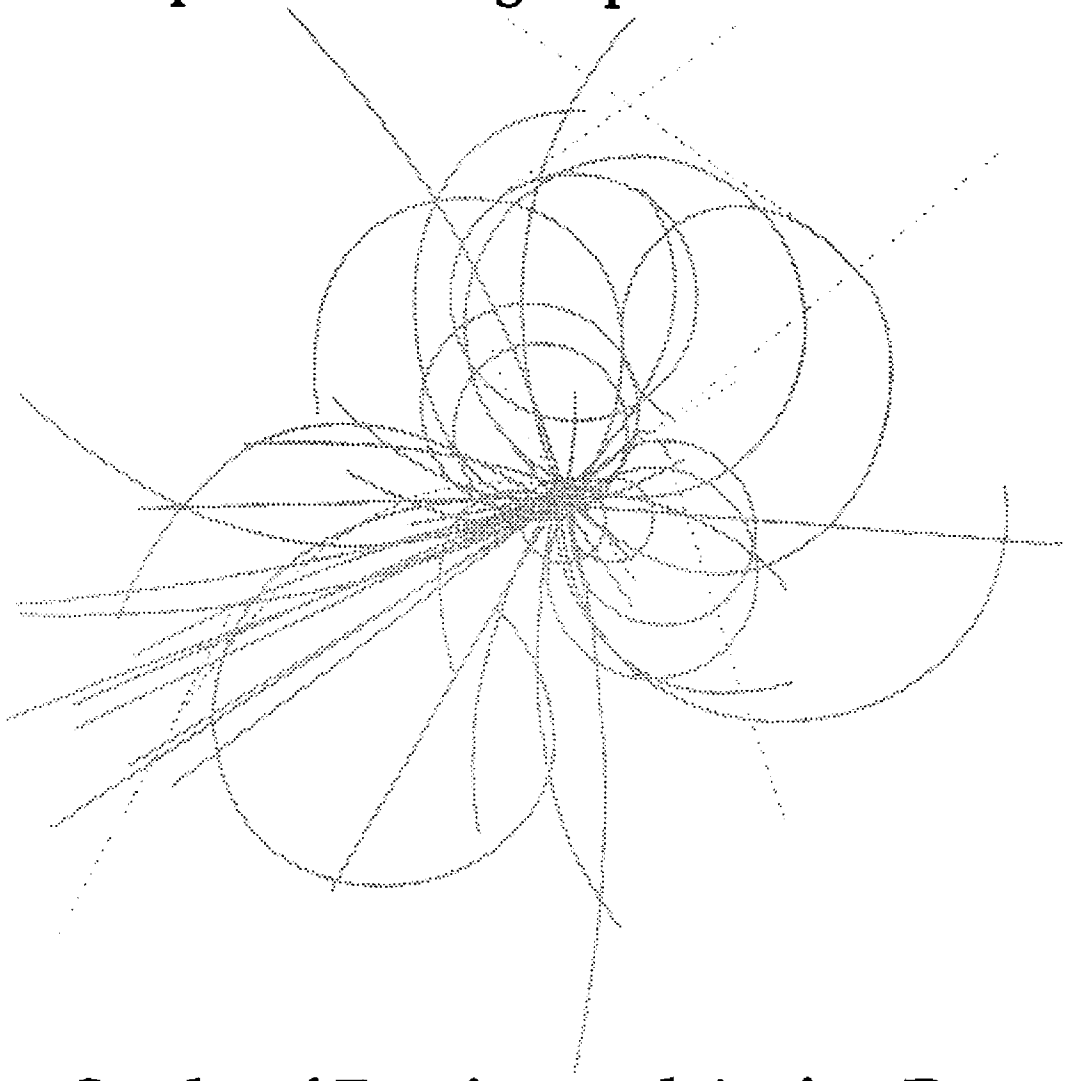
Superconducting Super Collider Laboratory



Study of Passive and Active Protection System for the SSC R&D Dipole Magnet

G. López and G. Snitchler

June 1990

1. INTRODUCTION

The protection system of the SSC R&D superconducting dipole magnet is one of the most important parameters under consideration for the SSC accelerator. It influences the performance, cost, and reliability of the accelerator. The main idea in the protection system is to have a device (diode, SCR) operating at ambient or low temperatures which reroutes the stored energy of many magnets connected in series from the number of magnets protected by such a device, once a quench appears in one these magnets. If this device does not need other systems (heaters) to protect the magnets then it can be stated that it is a "Passive Protection System," otherwise it must be stated that it is an "Active Protection System."

As of this time, the only superconducting accelerator working in the world is the Tevatron at Fermilab, with a Warm-SCR Active Protection System(1). Plans for the *Large Hadron Collider* (HERA) superconducting accelerator include a Cold-Diode Passive Protection System as the main scheme and an Active Protection System as an auxiliary element in case of a main unit failure(2). The selection of the protection system depends upon whether the magnets are self protected in a quench event. This is known in the test experiments and/or through simulations of the magnet behavior. For the 40 mm SSC R&D dipole magnet, there have been many experiments(3) indicating that this magnet is self protected, but these experiments have been without a clear understanding concerning the quench behavior of this magnet.

This report states the simulations were carried out for the SSC R&D dipole magnet using the programs SSC*. These programs were developed at the Texas Accelerator Center and were used to predict the quench behavior of the 35 m long superferric magnet(4). The 35 m long superferric magnet was successfully tested. New features incorporated in the programs are a new expression for the axial quench velocity, which correctly fits the experimental values, and allows us to track the quench evolution for each conductor independently, and the phe-

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G. Lopez and G. Snitchler

Superconducting Super Collider Laboratory†
2550 Beckleymeade Ave.
Dallas, TX 75237

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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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G. López and G. Snitchler
Superconducting Super Collider Laboratory*
Accelerator Division
2550 Beckleymeade Avenue
Dallas, TX 75237

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ABSTRACT

A comparative study of Passive versus Active Protection Systems is made using the computer programs SSC*, designed especially for this proposal. These programs track the quench evolution of each conductor independently, the axial quench velocity is given by a modified expression which correctly fits the experimental data, the phenomenological turn-to-turn transversal quench propagation is considered as an input parameter of the programs. The results of the simulations for a 40 mm dipole indicate that a single dipole is widely self-protected, which suggests that a Cold Diode Passive Protection System is a safe method to protect the magnet (no heaters are needed), and also that two or three magnets (Conceptual Design) will be a safe Active Protection System if the heater-time-delay to cause other quenching is sufficiently brief ($\tau_h < 50$ ms). Assuming the same turn-to-turn quench propagation for the 50 mm SSC R&D Dipole Magnet, the predictions for this magnet will have much lower axial quench velocity and the above results will be still valid for this new magnet.

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nomenological turn-to-turn time delay quench propagation for this magnet. In this paper, only the Diode Protection System will be considered.

2. DIODE PROTECTION SYSTEM

The study of quench protection using diodes can be divided into the following forms:

$$\text{(a) Passive Protection System} \begin{cases} \text{Warm Diode} \\ \text{Cold Diode} \end{cases}$$

and

$$\text{(b) Active Protection System} \begin{cases} \text{Warm Diode} \\ \text{Cold Diode} \end{cases}$$

The turn-on voltage (V_o) to enable the cold diode to begin conducting current is approximately three times higher than the warm diode. The first observation to make is that the quench characteristics of the magnet (maximum temperature in the coil and peak voltage between normal zone and superconducting (s.c.) zone) do not depend critically on the turn-on voltage. The reason for this, is that after several milliseconds of starting the quench, the quench resistance grows faster than the inductive voltage does, consequently voltage across the magnet reaches the turn-on voltage very quickly. This observation implies that, from the quench point of view, there is no difference in having a warm or cold diode and there is no difference in having one, two or three diodes connected in series. The turn-on voltage was set to 0.6 Volts (V_o = 0.6 Volts) for simulations, and for a single diode to protect the magnets. Assume that the quench propagates axially with the field-depending quench velocity derived in Ref. 5; the transverse quench propagation is sequentially determined by the phenomenological turn-to-turn and between-wedges time delay for quenching[6,7] as shown in the Figure 1. The self inductance is field depending as shown in Figure 2. The quench are located at the inner turn 16 (inner pole turn), for the inner case, and in the outer turn 20 (outer pole turn), for the outer case, shown in Figure 3, where the characteristics of the conductors are shown. Batch temperature is taken as 4.35 K ($\theta_o = 4.35\ K$).

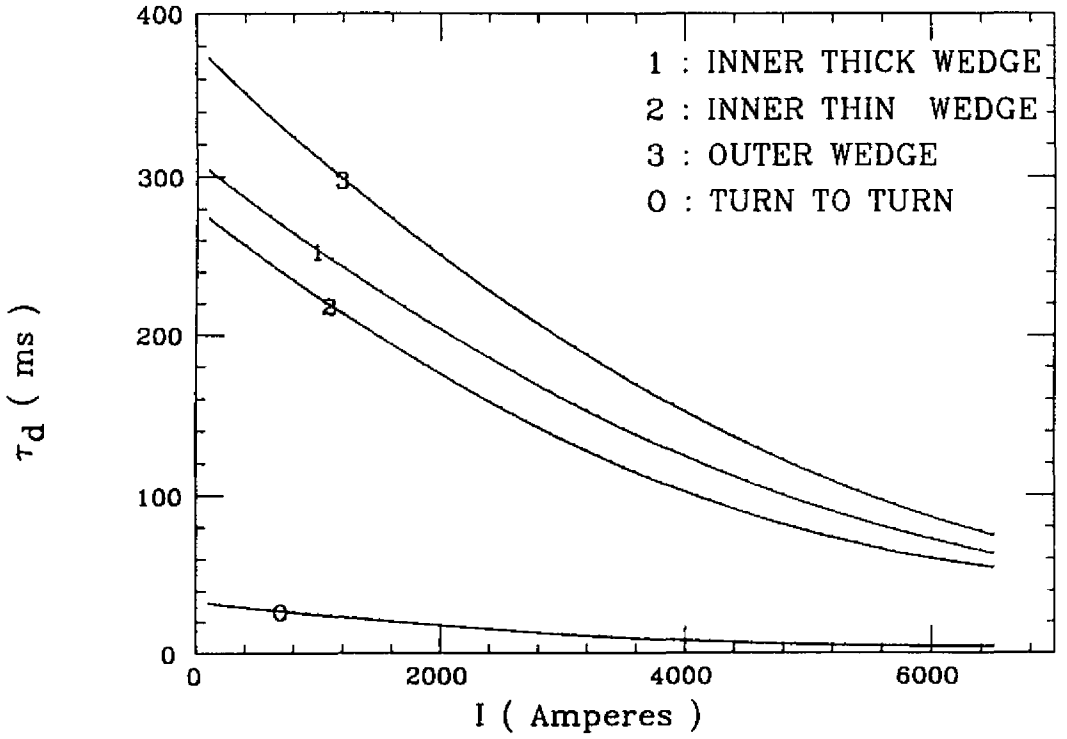

Figure 1. Time delay turn-to-turn and between wedges.

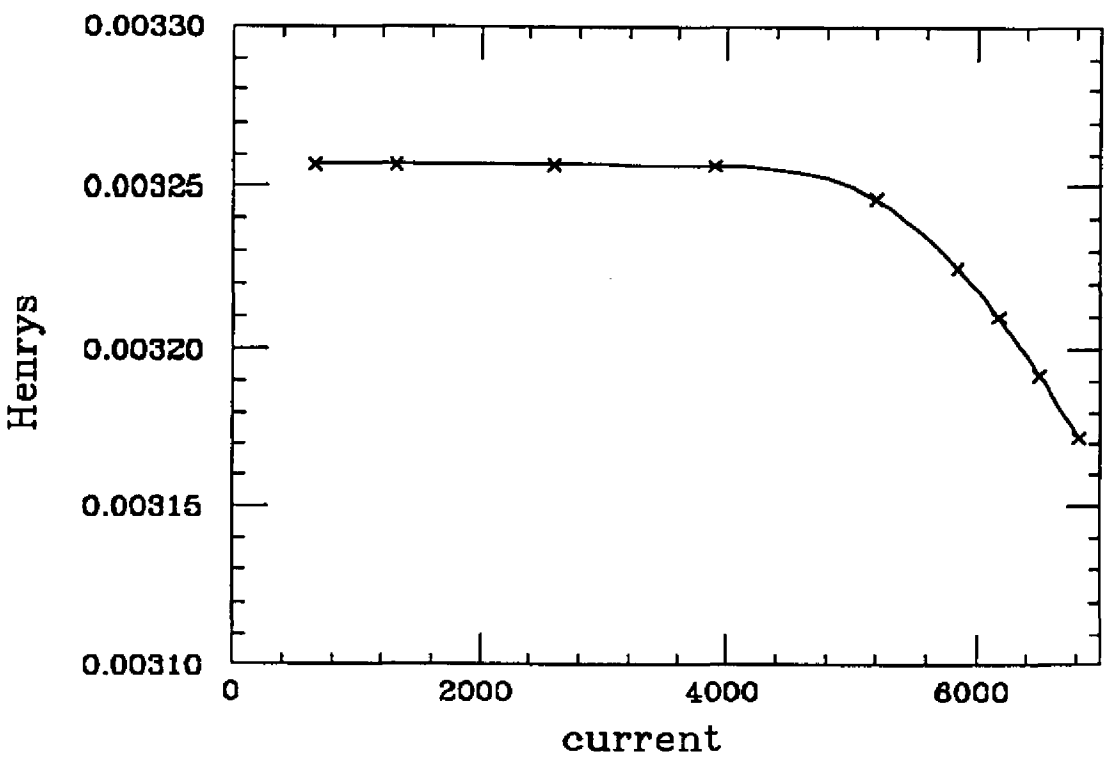

Figure 2. Self-inductance field depending.

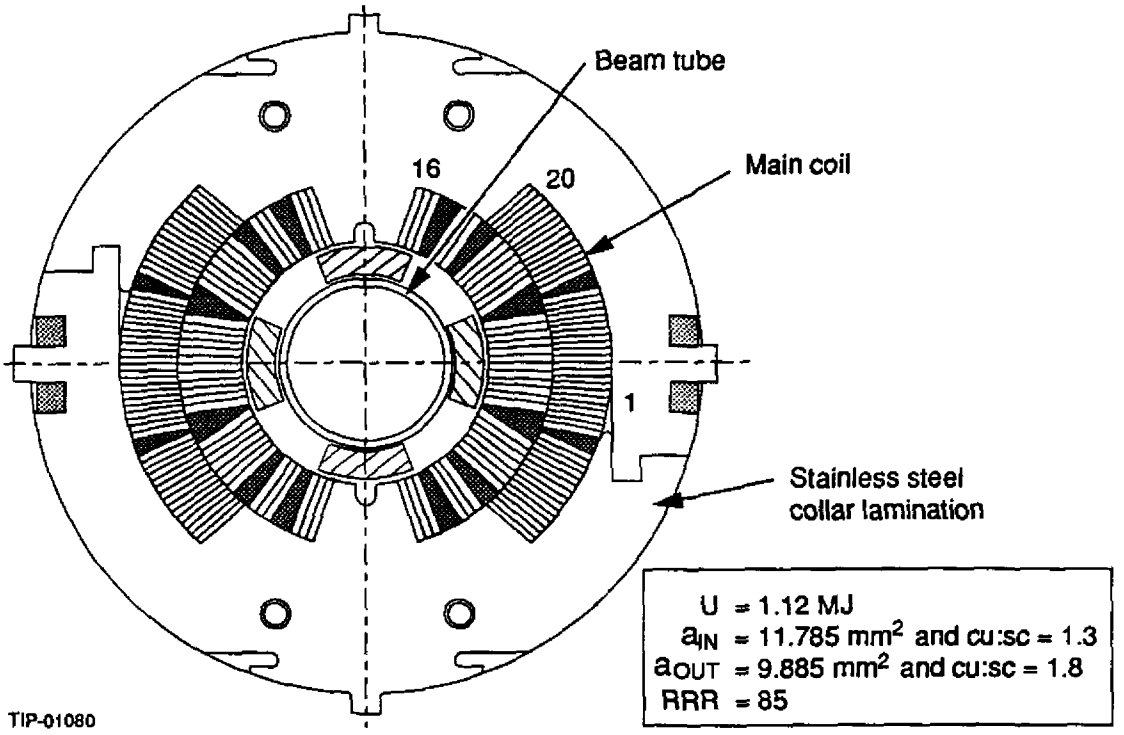

Figure 3. Coil cross section of the 40 mm SSC R&D dipole magnet and conductors characteristics.

The circuit model for active (heaters) or passive protection system is shown in Figure 4, with definitions of the parameters involved. The time delay to activate the dump resistance (R_D) and to turn off the power supply was set equal to zero with respect to the quench detection (voltage across the magnet is 0.6 Volts). Quench characteristics of the magnet do not depend critically on these parameters because of the decoupling made by the bypass diode of the remaining magnets in the ring. In the active protection system, assume that the heaters are located between the outer coil and the collar, and they induce quenching in the outer coil turns at the same time, τ_h.

Typical information obtained by the simulation is time evolution of current inside the magnet, the potential difference between normal zone and the s.c. zone, the voltage across the magnet, the temperature rise where quench appeared, and

the temperature rise of the first-turn quench in the other coil. These evolutions are shown in Figures 5 through 9 for the inner case with a single magnet using a passive protection system. The profile, of the maximum temperatures in the inner and outer coil, with respect the initial quench, is shown in Figure 10.

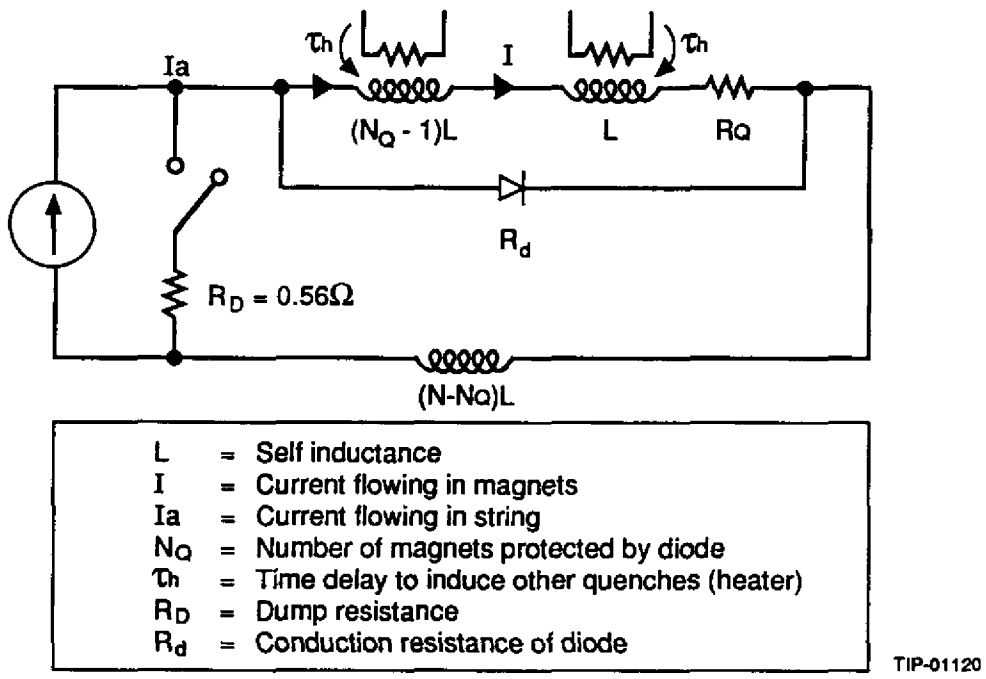

Figure 4. Circuit model. L is the self inductance, I is the current flowing in the magnet, I_a is the current flowing in the whole string, N_Q is the number of magnets protected by the diode, τ_h is the time delay to induce other quenches (heater), R_D is the dump resistance, and R_d is the conduction-resistance of the diode.

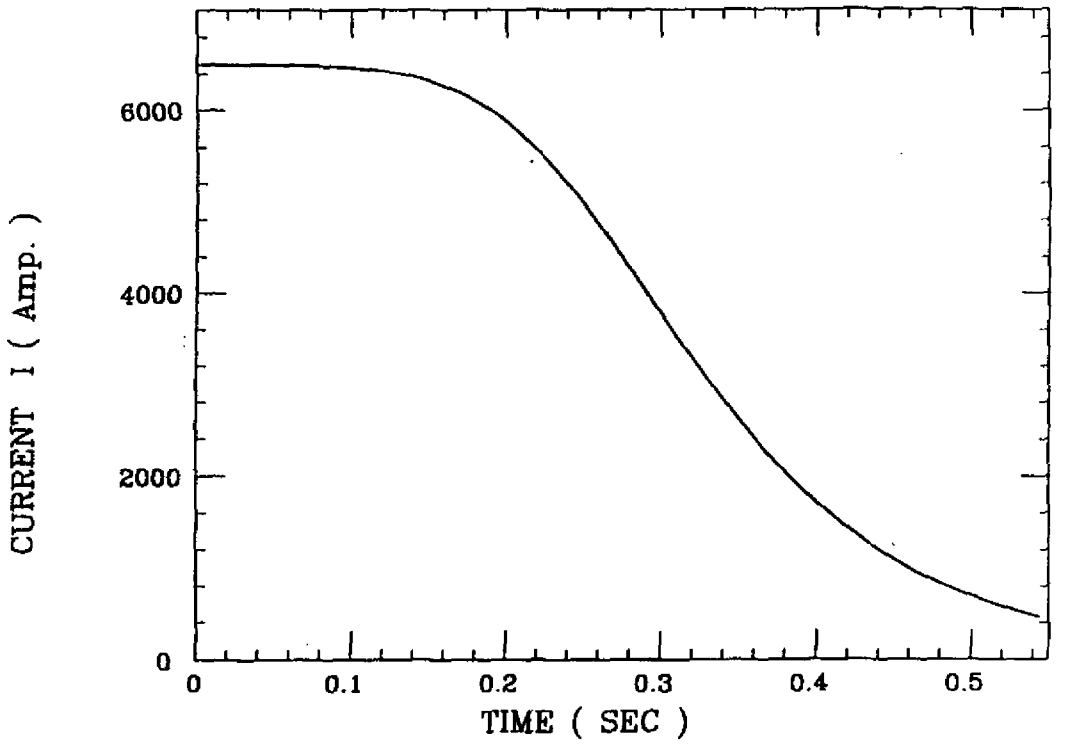

Figure 5. Single 40 mm magnet. Current evolution.

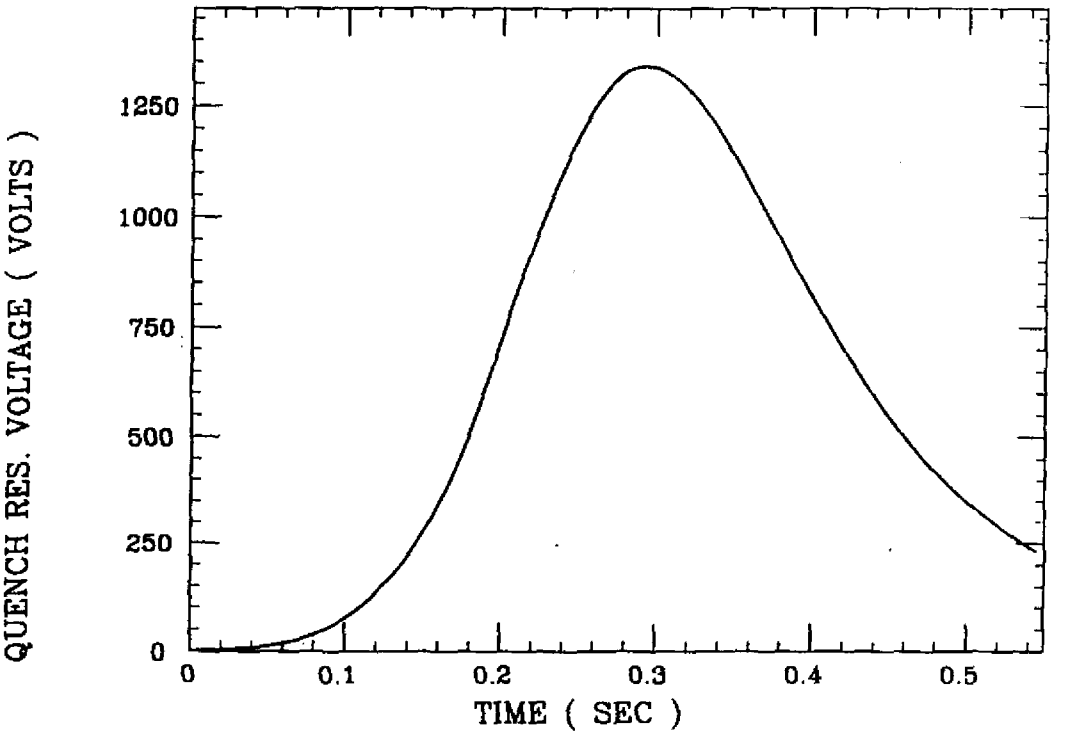

Figure 6. Single 40 mm magnet. Quench-resistance voltage evolution.

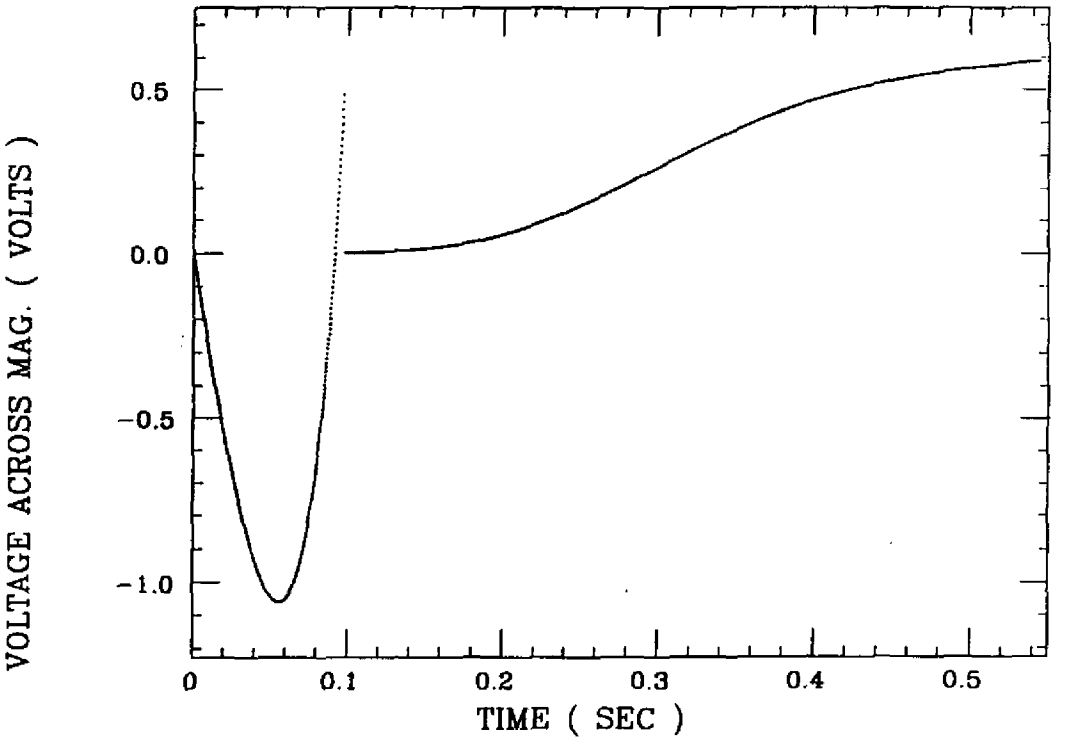

Figure 7. Single 40 mm magnet. Voltage across the magnet evolution.

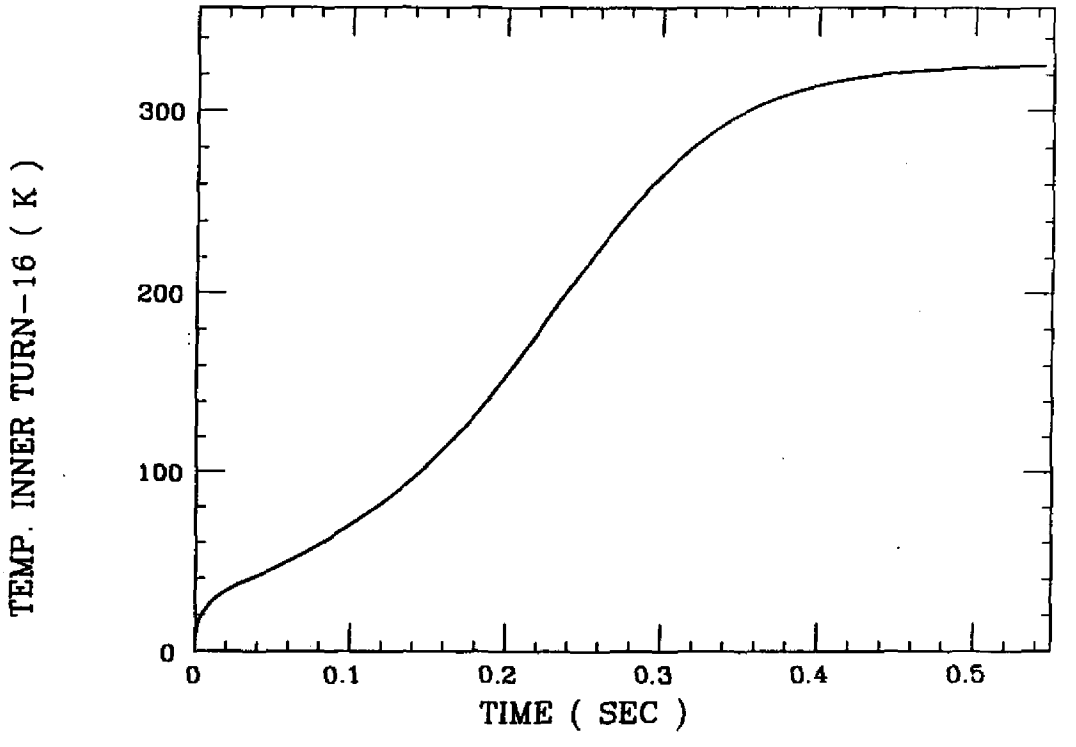

Figure 8. Single 40 mm magnet. Inner turn-16 temperature evolution.

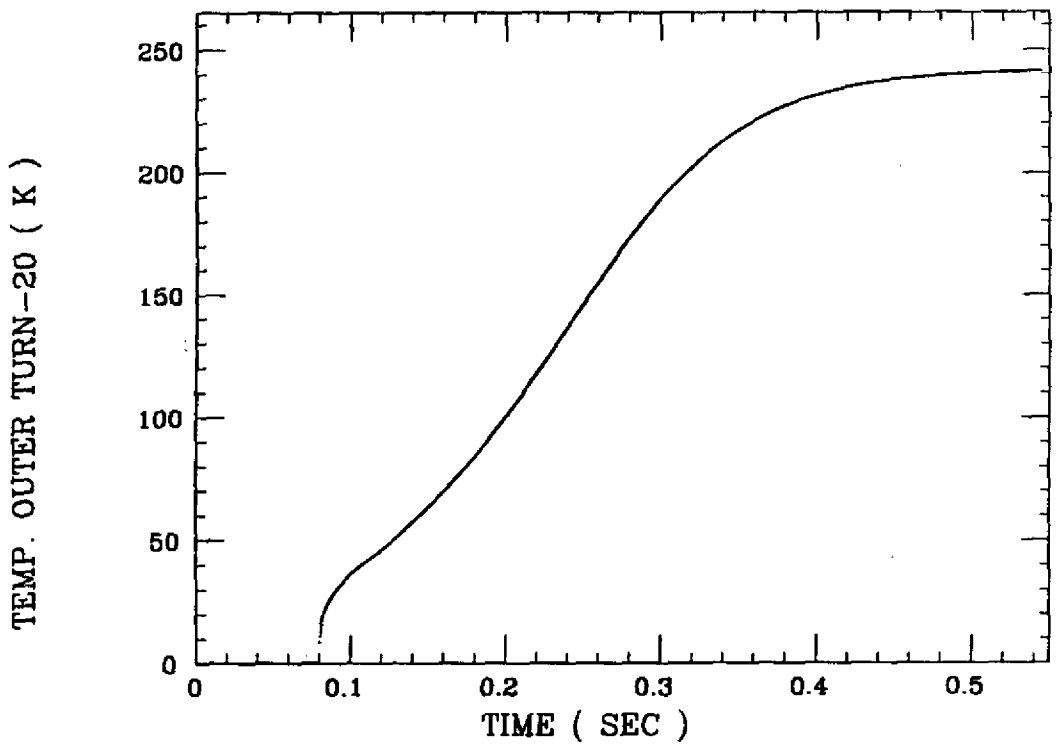

Figure 9. Single 40 mm magnet. Outer turn-20 temperature evolution.

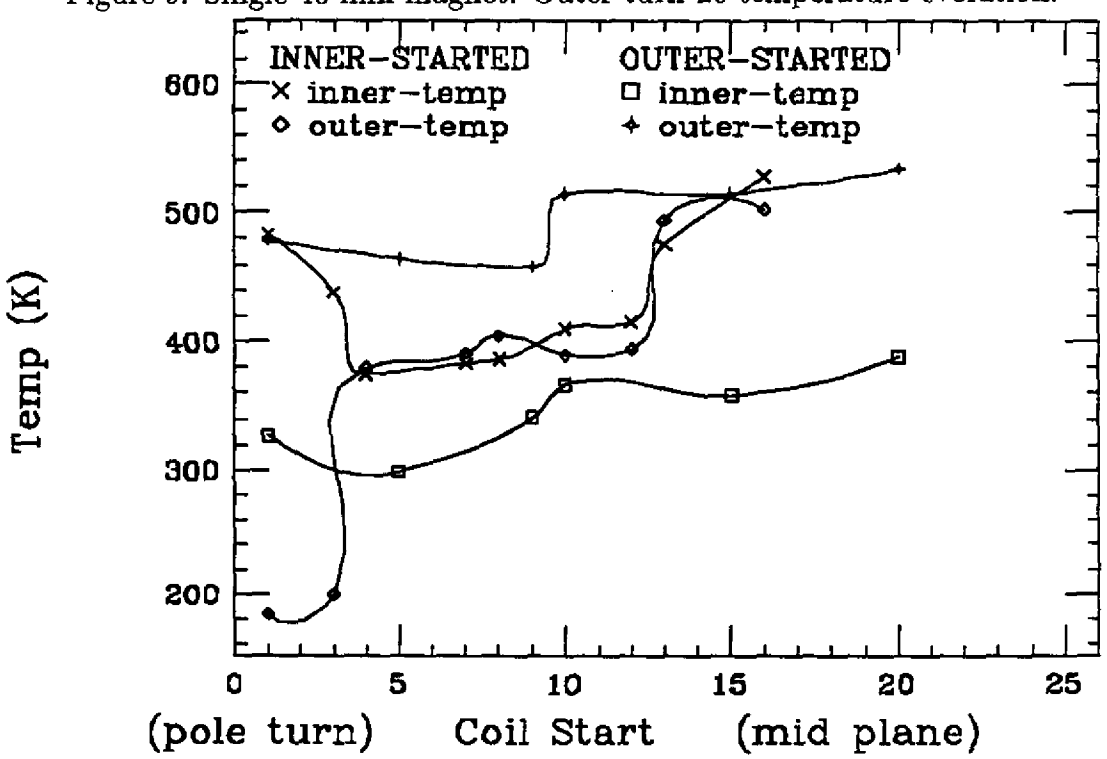

Figure 10. Single 40 mm magnet. Temperature profile.

3. PASSIVE AND ACTIVE PROTECTION FOR 40 mm DIPOLE MAGNET

To contrast protection schemes, quench simulations were modeled for passive and active protection systems. In Figure 11, the maximum temperature attained is presented during a quench, as a function of the number of magnets. These results are based on the time delays shown in Fig. 1.

The evolution of the current for several initial currents is shown in Figure 12. Lower initial currents decay slower due to the smaller axial quench velocities, slower transversal quench propagation, and lower self inductance. Figure 13 shows the relationship between current and axial quench velocity. The maximum temperature increases as the stored energy increases, but it decreases as the quench velocity increases rapidly. In Figure 14, the increases in the maximum temperature corresponds to the increases of the stored energy, until the quench velocity increases rapidly in the non-linear region near J_c. In these simulations, the quench started at the pole-turn in the inner coil. But, if the quench starts at the pole-turn in the outer coil, the maximum temperatures, as a function of the number of magnets, are a little higher than the above cases, as shown in Figure 15, and the same happens as a function of the initial current, as in Figure 16.

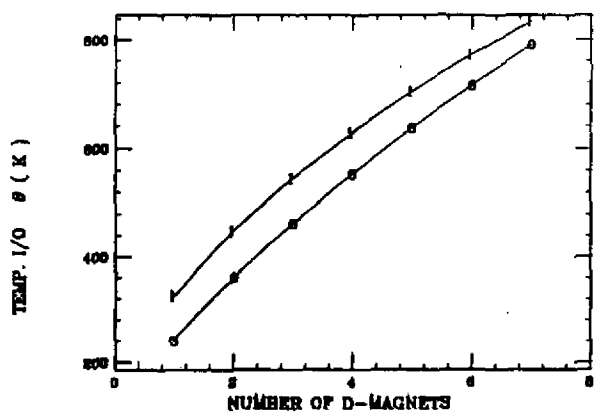

Figure 11. Inner turn-16 and outer turn-20 maximum (pole turns) temperatures as a function of the number of magnets protected by the diode (N_Q) for the 40 mm dipole magnet.

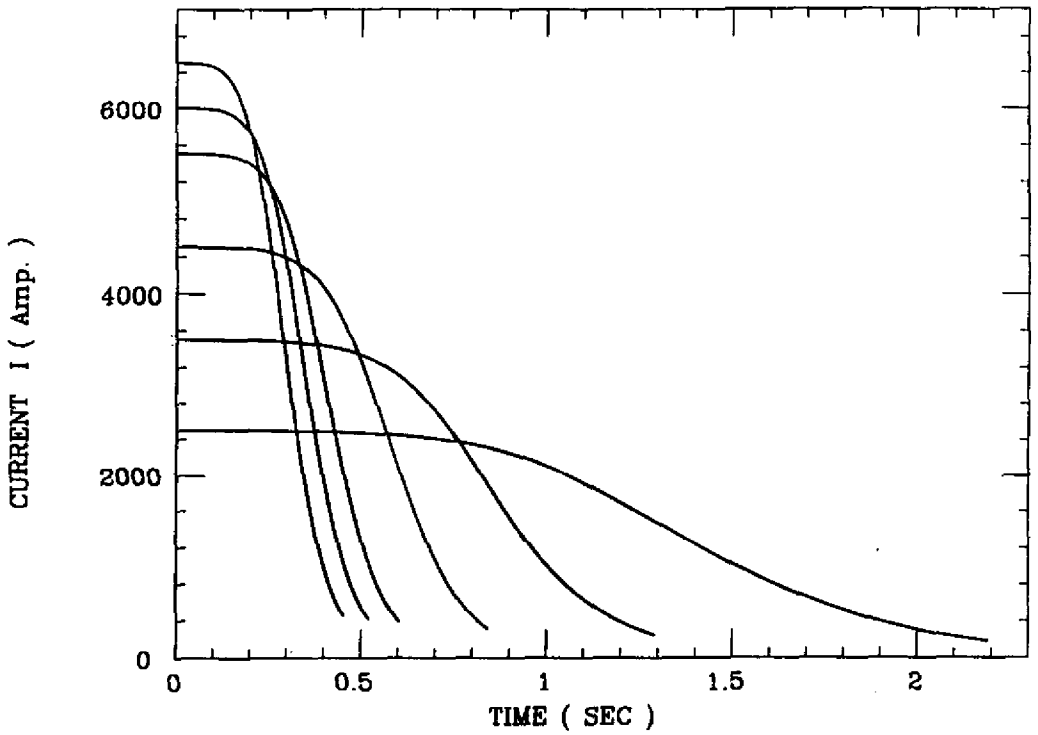

Figure 12. Single 40 mm magnet. Current evolution as a function of the initial currents.

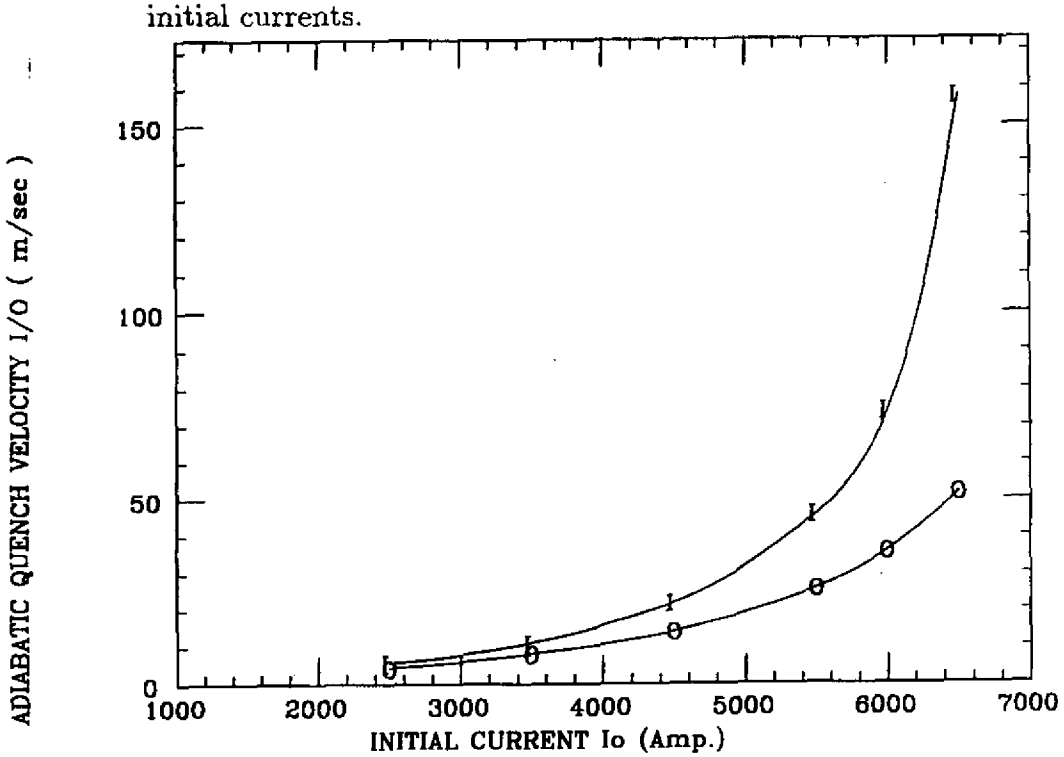

Figure 13. Single 40 mm magnet. Inner turn-16 and outer turn-20 maximum quench velocity as a function of the initial current.

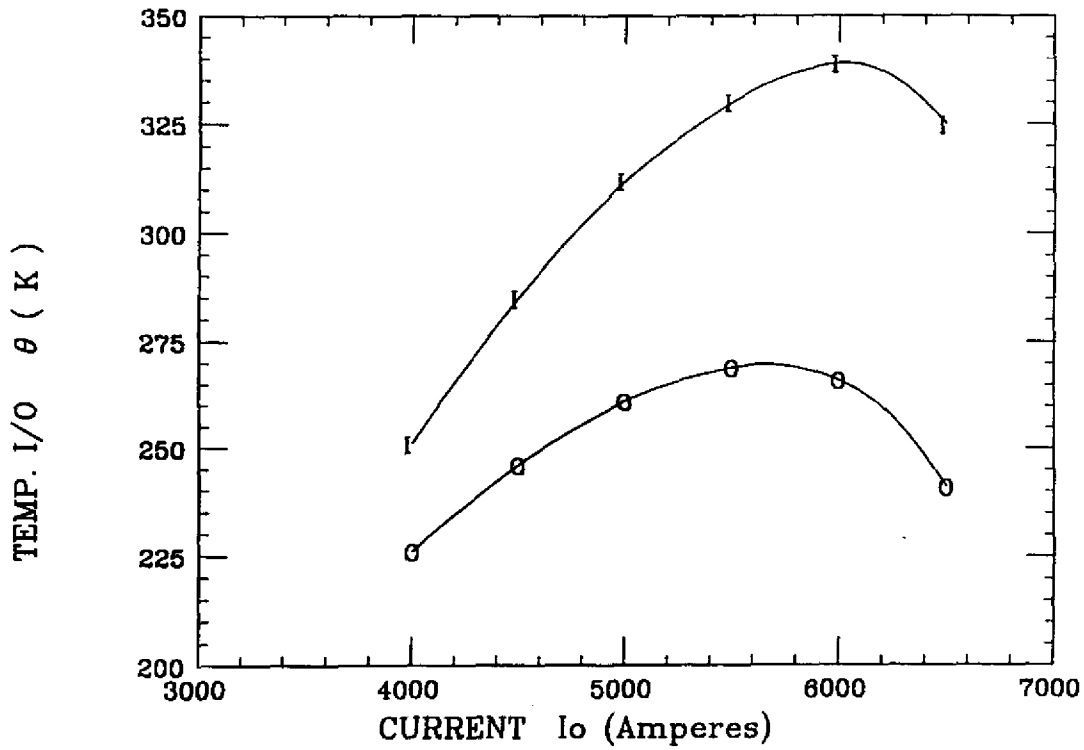

Figure 14. Single 40 mm magnet. Inner turn-16 and outer turn-20 temperatures as a function of the initial current (quench starts in the inner).

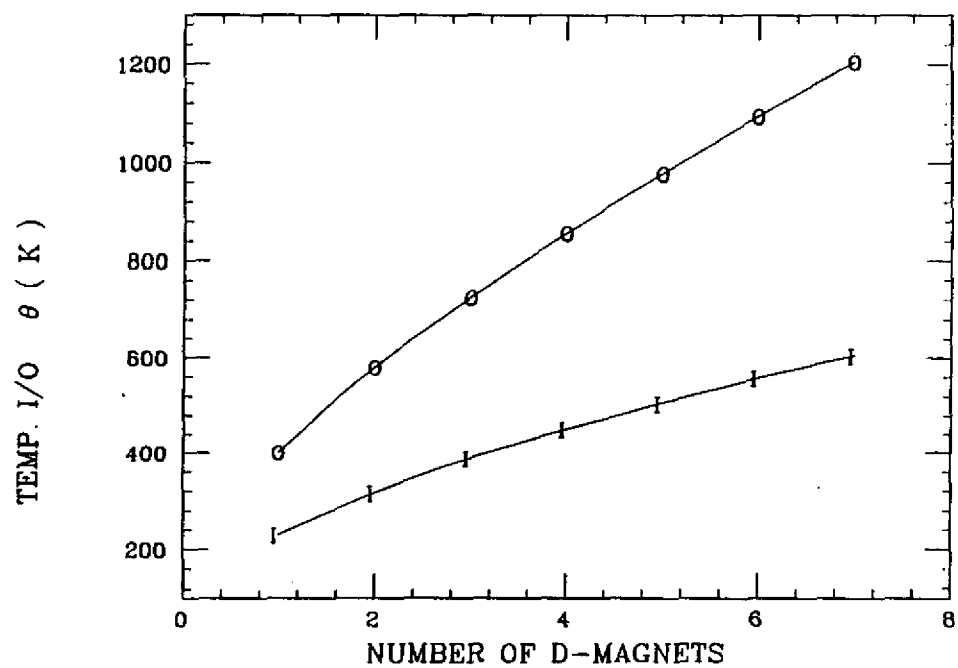

Figure 15. Maximum inner-turn-16 and outer-turn-20 temperatures as a function of the number of magnets protected by the diode (N_Q) for the 40 mm dipole magnet.

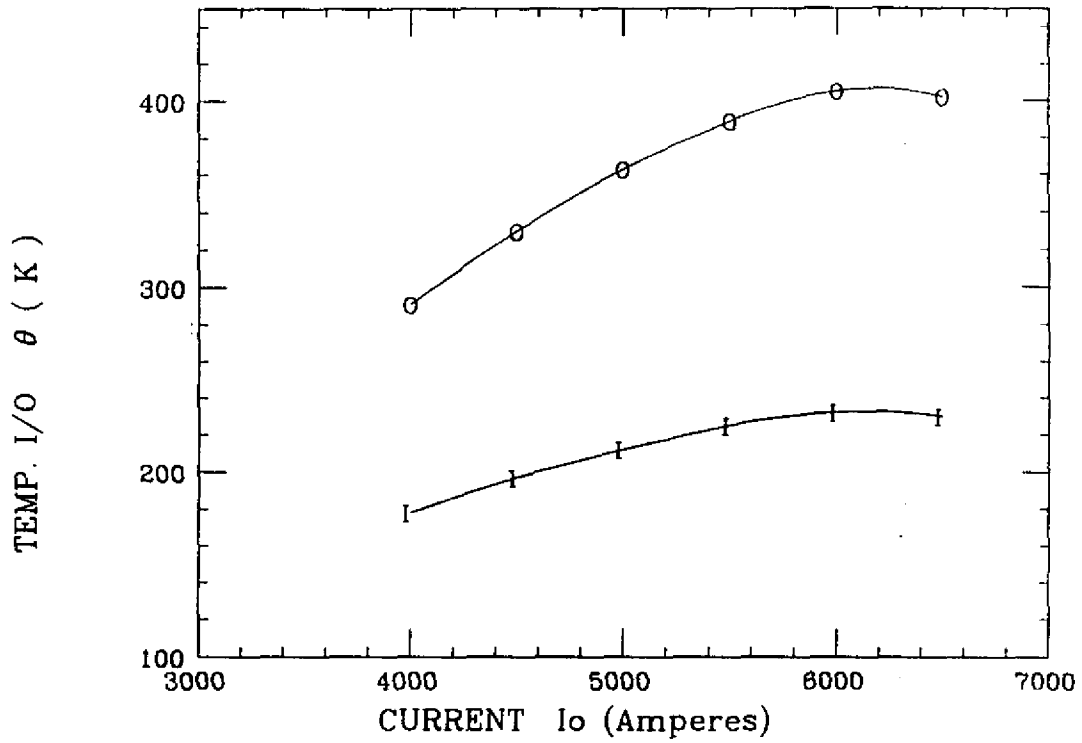

Figure 16. Single 40 mm magnet. Inner turn-16 and outer turn-20 temperatures as a function of the initial current (quench starts in the outer).

The cases above correspond to a passive protection system. Now, using an active protection system, when quench starts at the pole-turn in the inner coil, the maximum temperatures, as a function of the initial current are shown in Figure 17. In Figure 18, these temperatures are shown as a function of the number of magnets for different heater-induce-quenching time delays (τ_h), and Figure 19 shows the peak resistance voltage between normal zone and s.c. zone reached inside the magnet.

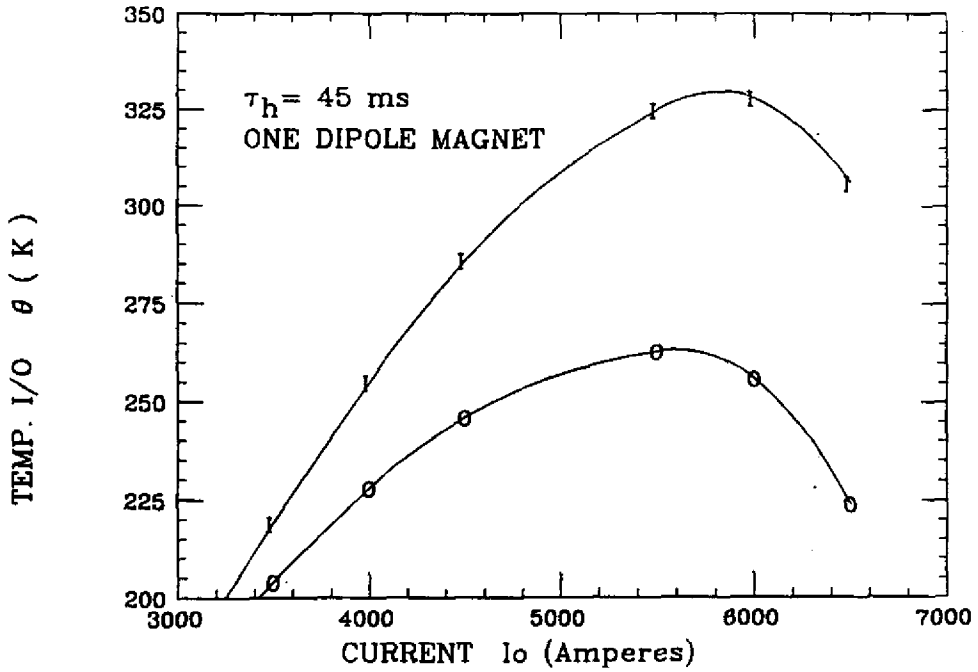

Figure 17. Single 40 mm magnet. Inner turn-16 and outer turn-20 maximum temperatures as a function of the initial current and for a heater-induced-quenching time delay of 45 ms.

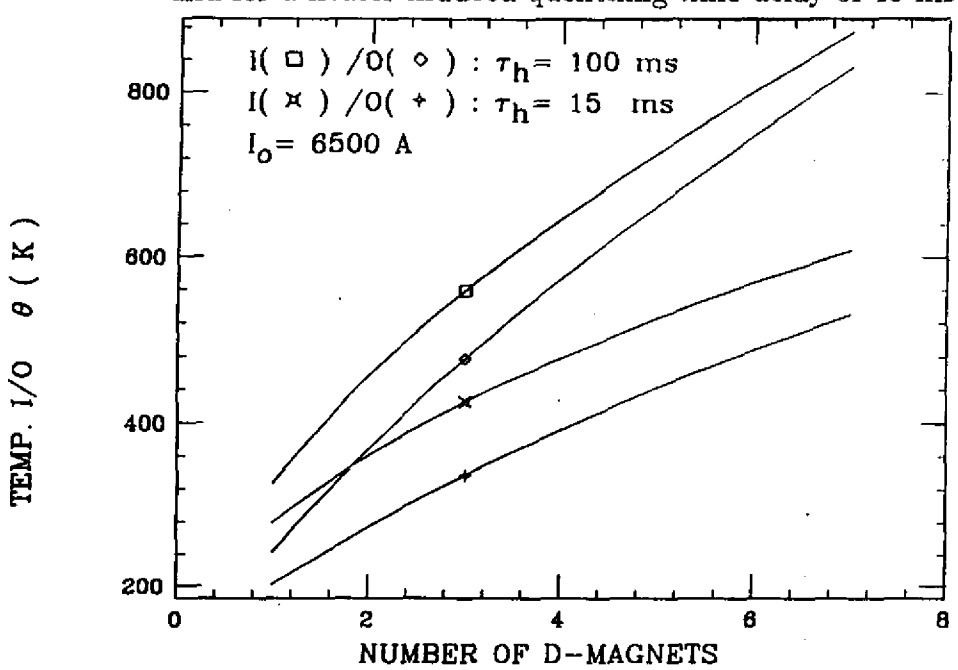

Figure 18. Maximum inner-turn-16 and outer-turn-20 temperatures as a function of the number of magnets protected (N_Q) and for two different heater-induced-quenching time delays in the 40 mm dipole magnet.

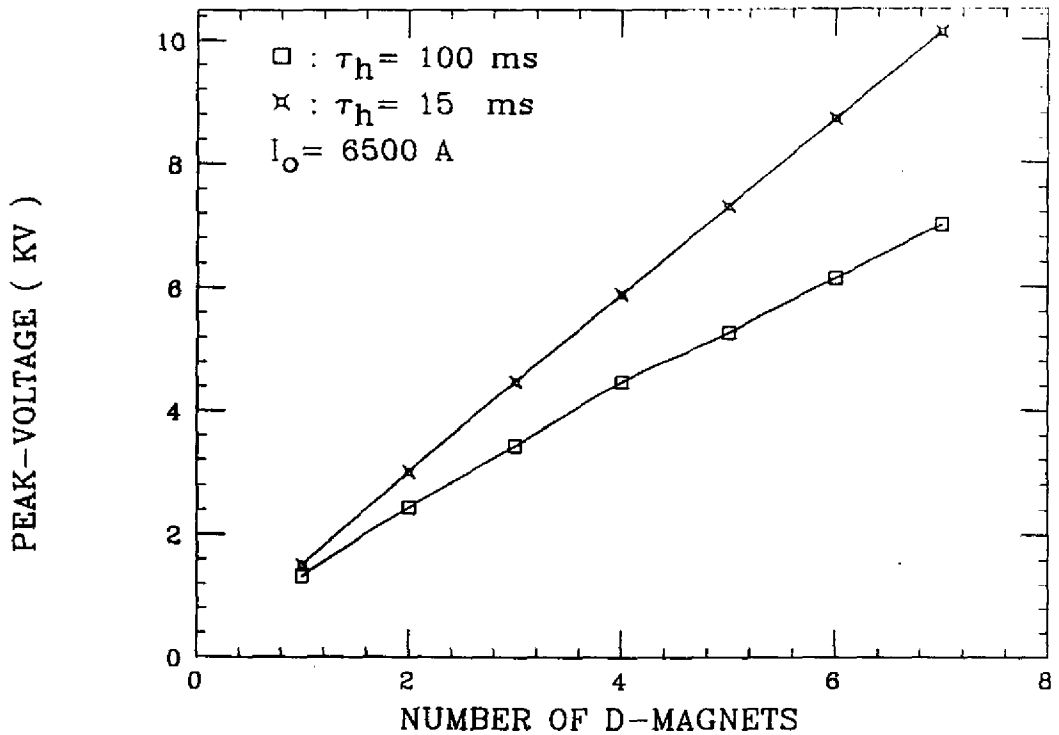

Figure 19. Peak quench resistance voltage as a function of the number of magnets protected by the diode (N_Q) for the 40 mm dipole magnet.

4. PASSIVE AND ACTIVE PROTECTION FOR THE 50 mm DIPOLE MAGNET

The cross section of this magnet, and the characteristics of its conductors are shown in Figure 20. The turn-to-turn time delay is taken as before (optimistic point of view), the time delay between wedges is also taken as before (pessimistic point of view) and the transversal quench propagation proceeds sequentially. The effect of radiation damage in the diode is considered in this magnet. One of the effects is to reduce the turn-on voltage of the diode[8], and as it was pointed out already this one does not have a qualitative alteration in the quench characteristics of the magnet. The other effect is to increase its conduction resistance[9]. The possibility of working at a lower temperature and higher field is also studied.

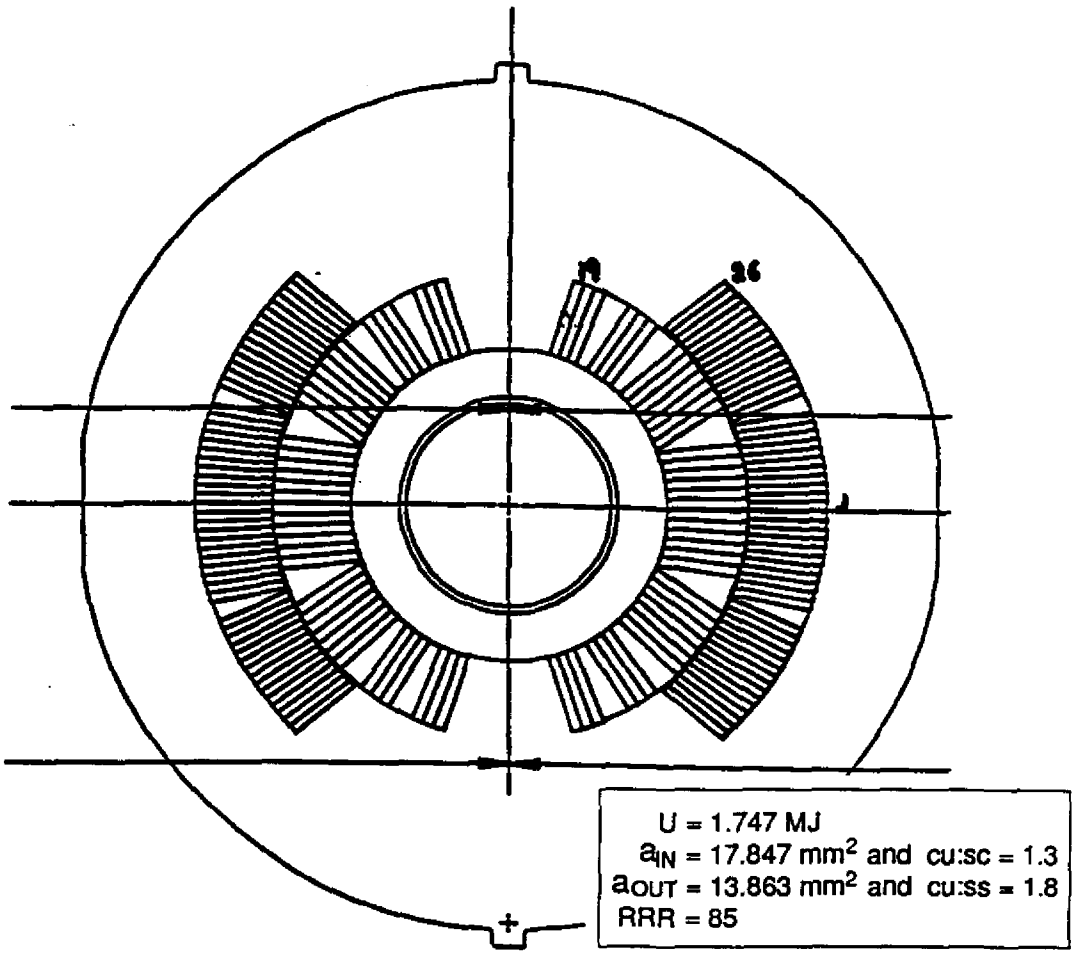

Figure 20. Coil cross section of the 50 mm SSC R&D dipole magnet.

The maximum temperature profile in the inner and outer coil as a function of the initial quench is shown in Figure 21. The variation of the adiabatic axial quench velocity as a function of the initial current for the inner and outer pole turns, are shown in Figure 22. The maximum temperatures are shown in Figure 23 as a function of the initial current, and in Figure 24 as a function of the number of magnets. In these cases the quench started in the inner coil. When the quench starts at the pole-turn in the outer coil, the maximum temperatures, as a function of the number of magnets, are shown in Figure 25. In both cases, the effect of radiation damage in the diode was studied and the results are shown in Figures 26 and 27, where the maximum temperatures are given as a function of the damaged-conduction resistance. The quench result for the magnet working at lower batch temperature ($\theta_o = 3.4\ K$), with a higher magnetic field ($B_o \simeq 7.6\ T$),

is shown in Figure 28, where maximum temperatures are given as a function of the number of magnets.

The above cases were made, considering a passive protection system for the magnet. The results for an active protection system can be seen in Figures 29 and 30, where maximum temperatures are given as a function of the number of magnets and for several heater-induce-quenching time delays (τ_h).

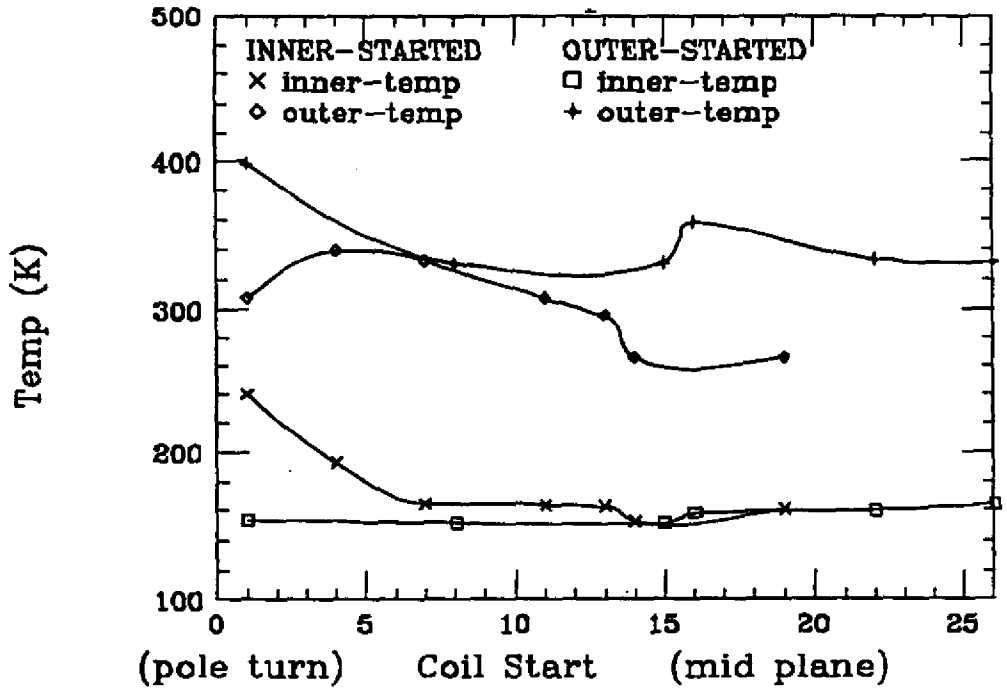

Figure 21. Maximum temperature profile for a single 50 mm SSC R&D dipole magnet.

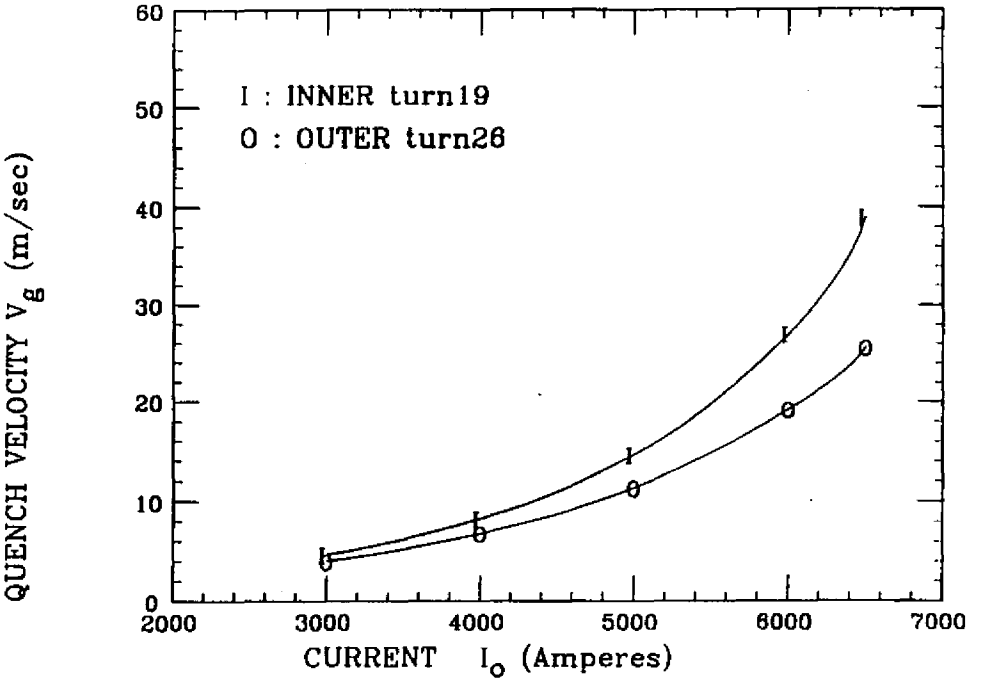

Figure 22. Single 50 mm magnet. Maximum quench velocity expected.

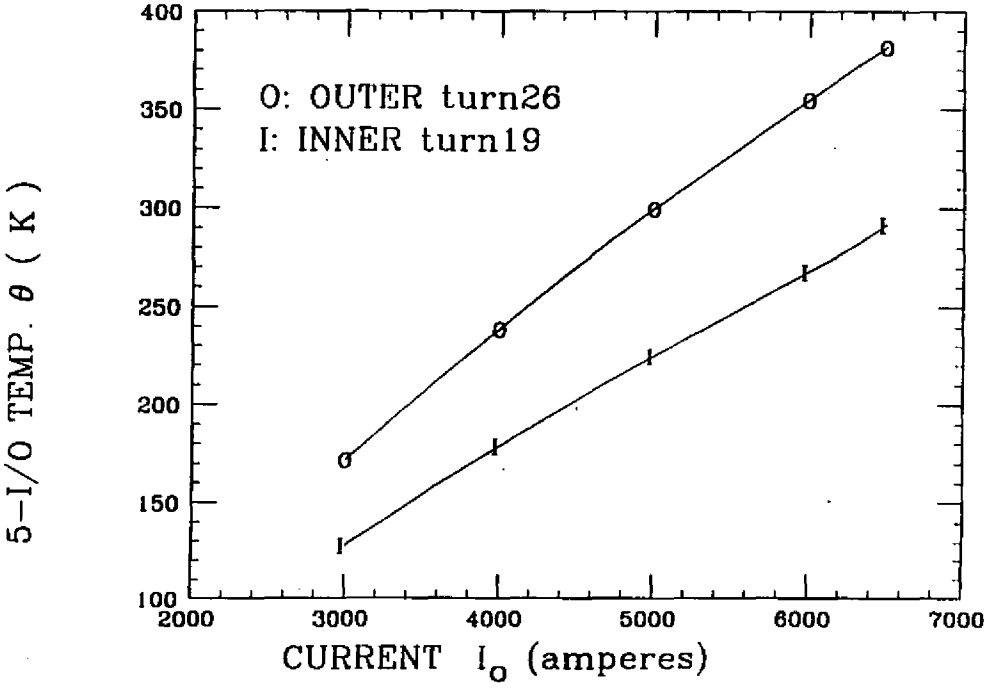

Figure 23. Single 50 mm magnet. Maximum temperature as a function of the initial current.

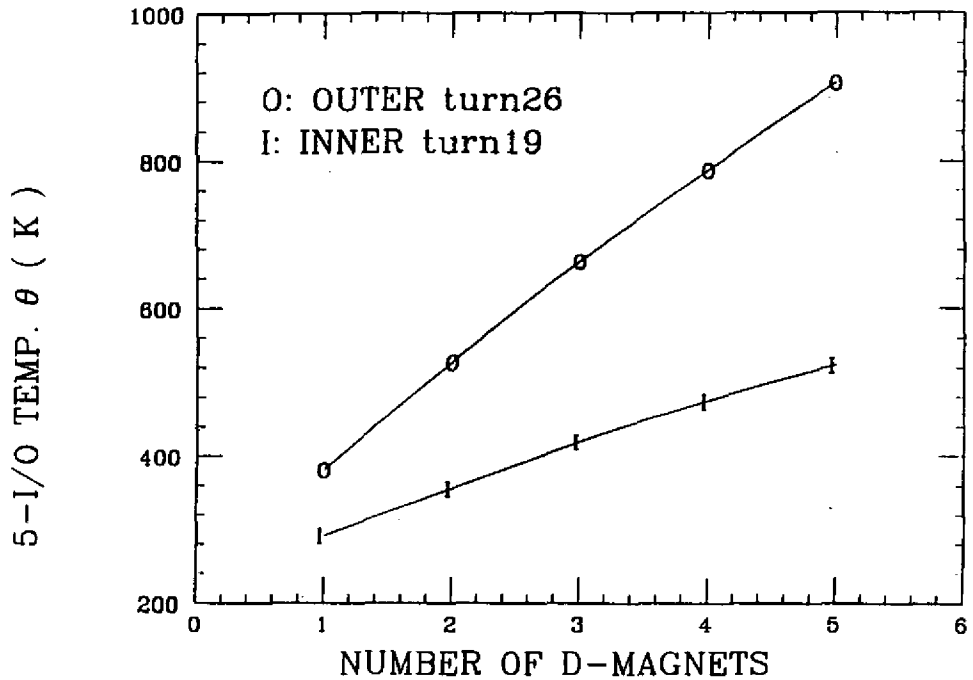

Figure 24. Maximum temperature as a function of the number of magnets (N_Q). Quench appears in the inner coil of the 50 mm SSC R&D dipole magnet.

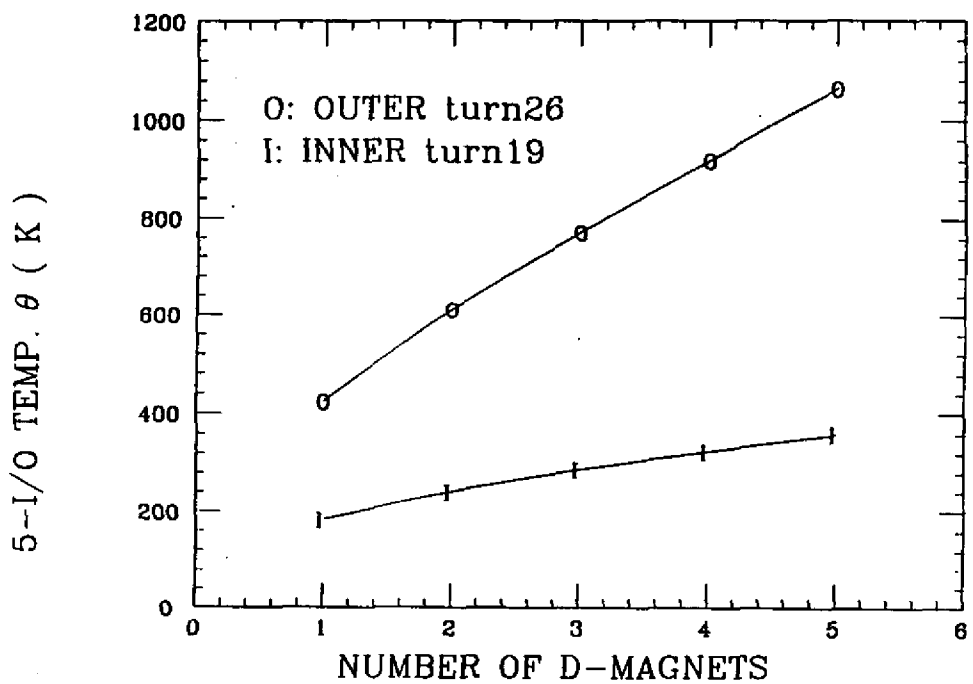

Figure 25. Maximum temperature as a function of the number of magnets (N_Q). Quench appears in the outer coil of the 50 mm SSC R&D dipole magnet.

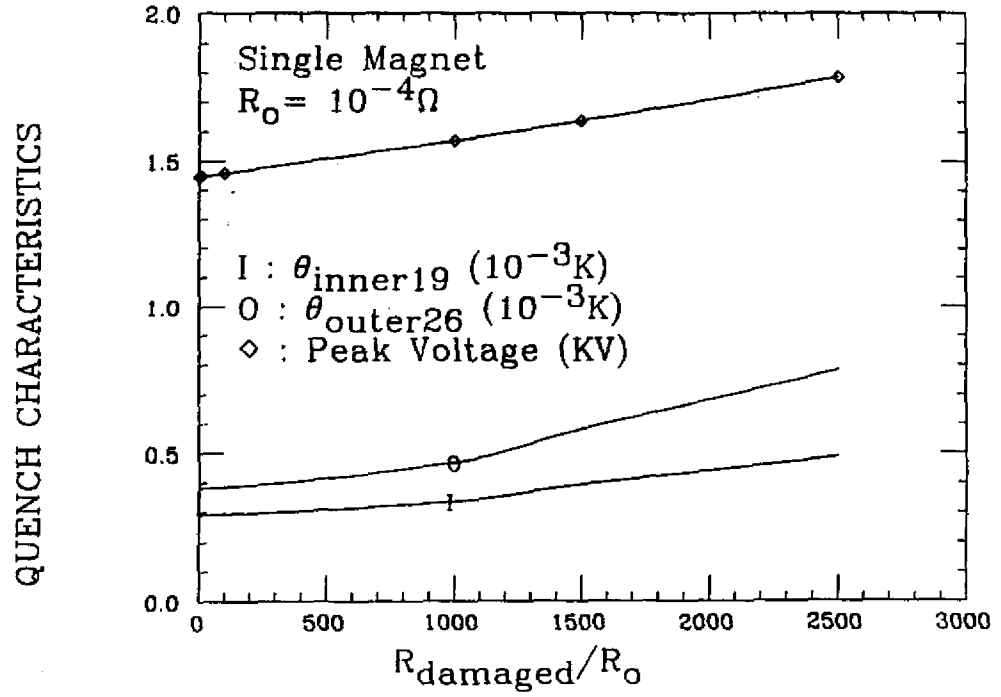

Figure 26. Maximum temperatures and peak voltage reached as a function of the bypass-diode-resistance damaged by radiation. Quench appears in the inner coil of the 50 mm SSC R&D dipole magnet.

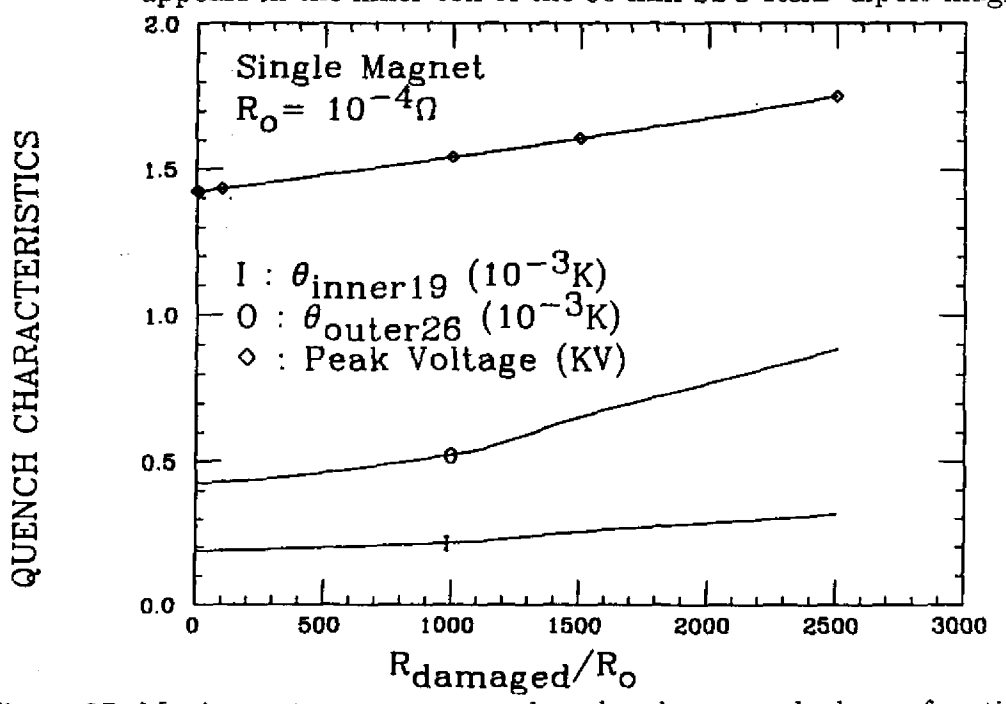

Figure 27. Maximum temperatures and peak voltage reached as a function of the bypass-diode-resistance damaged by radiation. Quench appears in the outer coil of the 50 mm SSC R&D dipole magnet.

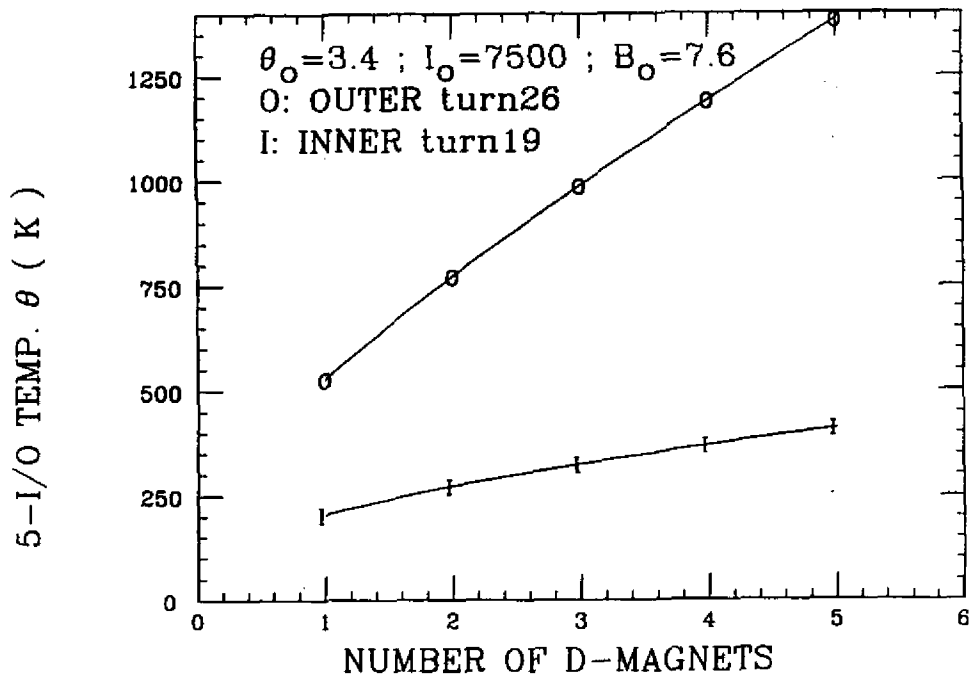

Figure 28. Maximum temperature as a function of the number of magnets (N_Q), but a lower temperature and higher field in the 50 mm SSC R&D dipole magnet.

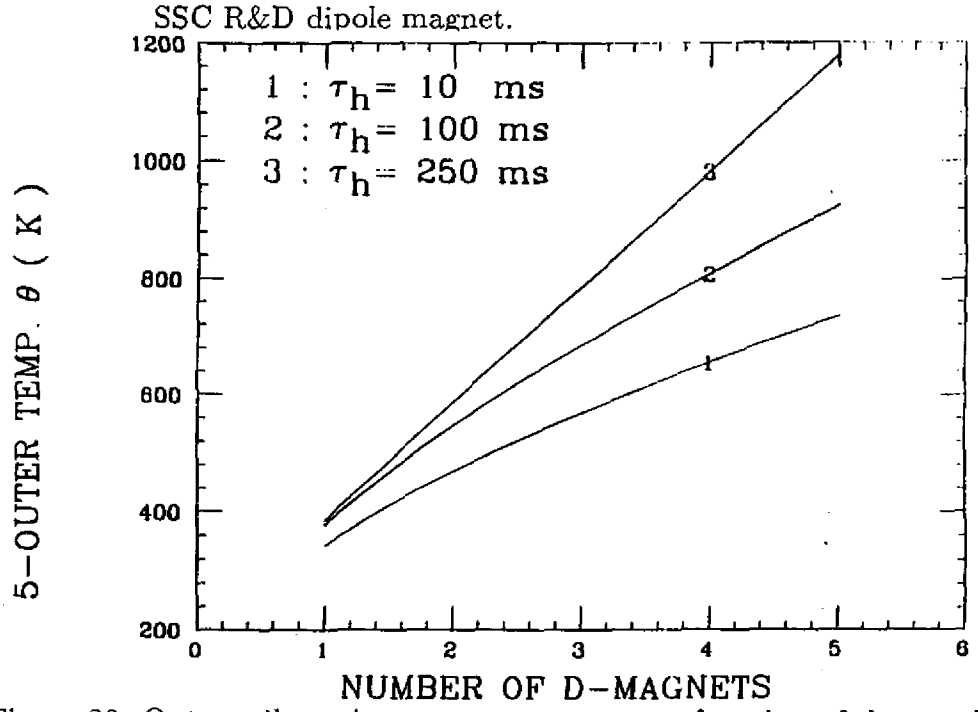

Figure 29. Outer coil maximum temperature as a function of the number of magnets (N_Q) and for several time delays for heater to induce other quenches. Quench appears in the inner coil of the SSC R&D dipole magnet.

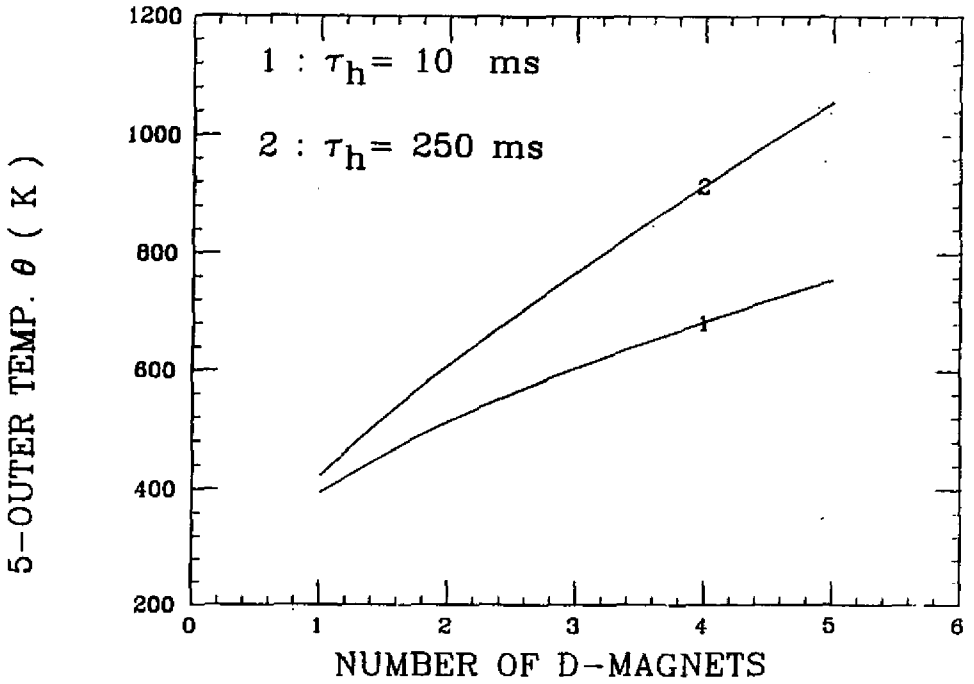

Figure 30. Outer coil maximum temperature as a function of the number of magnets (N_Q) and for several time delays for heater to induce other quenches. Quench appears in the outer coil of the 50 mm SSC R&D dipole magnet.

5. CONCLUSIONS

From experiments made in the 40 mm SSC R&D dipole magnets and from the results shown in Figs. 10 and 11, we know that this magnet is self protected when the bath temperature is 4.35 K, but from Figs. 14 and 17 is expected that this magnet has problems working a lower temperature because its maximum temperature occurs a lower current. These same figures represent qualitatively the experimental behavior observed in this magnet with respect the initial current, we do not expect an exact agreement because of the considerations made to study this complicated phenomenon, but the approximation is good enough

to be taken account seriously. Let us summarize the approximations made in the simulations and the results obtained:

Main approximations :

i) Quench proceeds sequentially (using the experimental data of the Fig. 1). This implies an overestimation in the maximum temperature at high field with respect to the experimental values as it is shown in Figure 31. The nonsequential transversal quench propagation is not clearly understood.

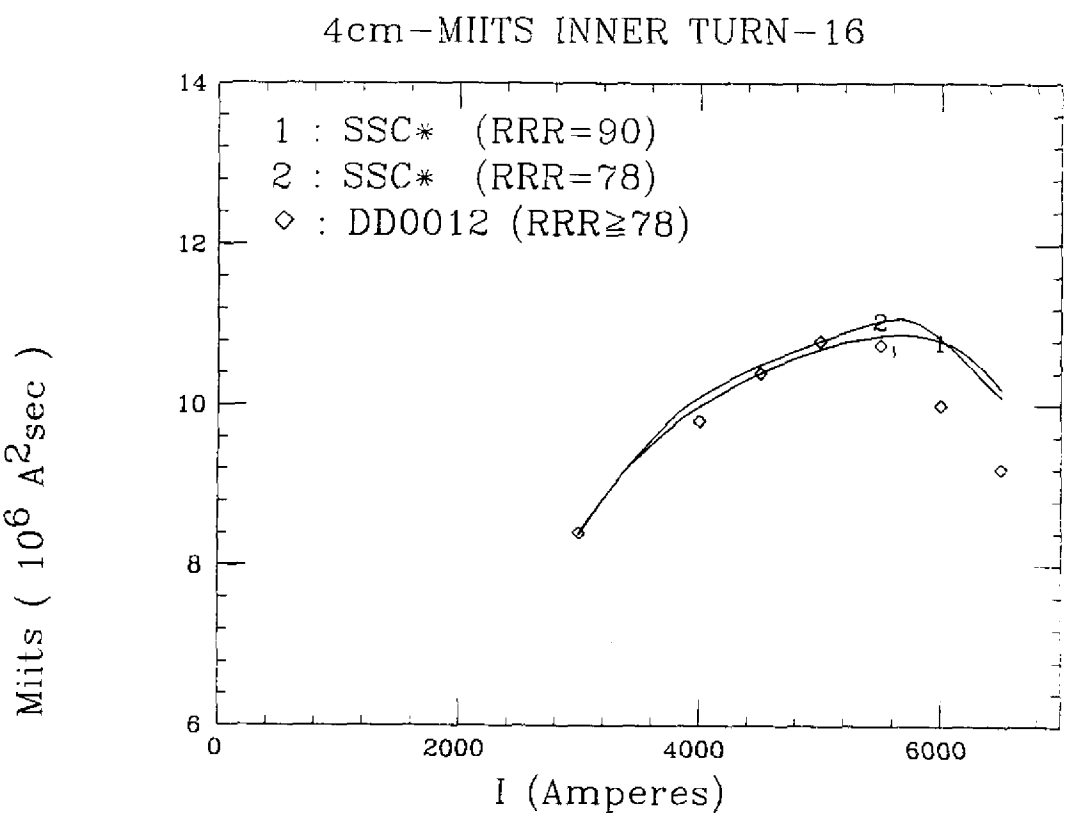

Figure 31.

ii) Simultaneous quenches (experimental fact) are not taken account.

iii) The heater-induced-quenching time delay, τ_h, represents the time delay to fire the heater plus the time delay for the heaters to cause other quenches. Heaters are located at the outer face of the outer coil and all of the turns quench at the same time (optimistic assumption).

A. Results from the Passive Protection System study:

i) A single dipole magnet is safe protected with wide margin (Figs. 5 to 17 and Fig. 20 to 28).

ii) A single magnet protected by a Cold Diode minimizes the number of current-leads, therefore, the cooling power required in the SSC ring.

iii) Heaters are not needed as an auxiliary protection system (Figs. 17, 18, 19, 29, and 30).

iv) The 50 mm SSC R&D dipole magnet is expected to have its highest temperature at the highest field in a quench event (Fig. 23), and to work well (Fig. 28) at lower batch temperatures ($\theta_o = 3.4\ K$) and higher magnetic field ($B_o = 7.6\ T$). It is not expected to have a qualitative change in its quench behavior, at least in the first 50 years of operation of the SSC[8,9], because of the radiation damage in the diode (Figs. 26 and 27).

v) Comment: A failure in the cold diode implies to open the cryostat to replace the diode or the magnet (if this one is damaged in a quench event).

B. Results from the Active Protection System study:

i) Two or three dipoles per diode (Conceptual Design) is safe selection for an active protection system if the heater-induce- quenching time delay, τ_h, is less than 50 ms (Figs. 18, 19 and 29), independently whether we have warm or cold diode.

ii) Comment: A failure in the above heater-induce-quenching time delay, τ_h, implies degradation of the insulation or the s.c. cable, and eventually, the replacement of the magnet. The peak voltage between the normal zone and s.c. zone can be higher than 4 kV (Fig. 19) in a quench event, this may require special attention. Experimental measurements of the turn-to-turn and between wedges quench propagation are needed in the 50 mm SSC R&D dipole magnet to have a better estimation in the results.

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