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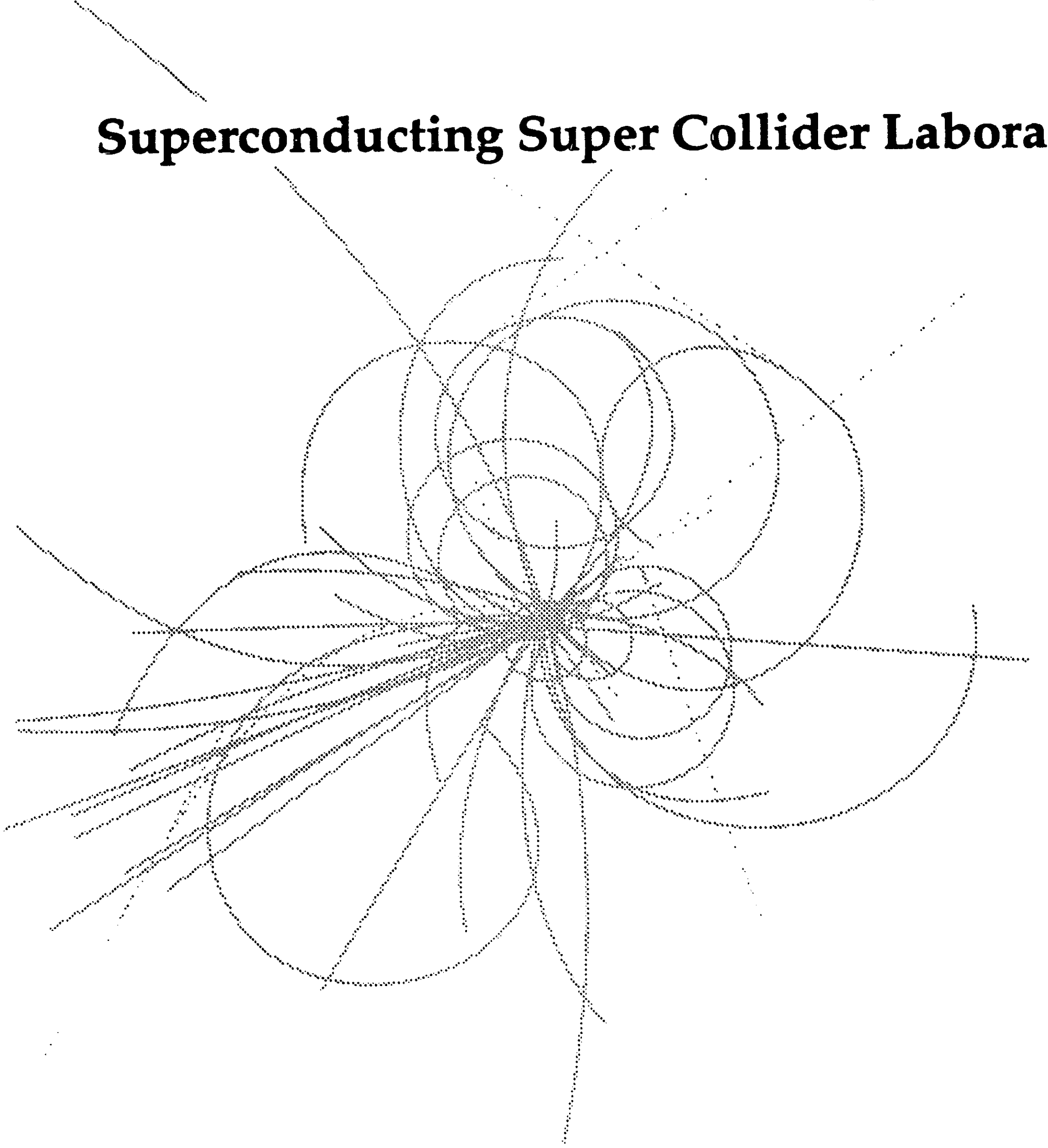

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QUENCH PROPAGATION IN THE SSC DIPOLE MAGNETS

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Abstract

The effects of quench propagation are modeled in 40mm and 50mm diameter collider dipole magnet designs. A comparative study of the cold diode (passive) and quench heater (active) protection schemes will be presented. The SSCQ modeling program accurately simulates the axial quench velocity and uses phenomenological time delays for turn-to-turn transverse propagation. The axial quench velocity is field dependent and consequently, each conductor's quench profile is tracked separately. No symmetry constraints are employed and the distribution of the temperatures along the conductor differs from the adiabatic approximation. A single magnet has a wide margin of self protection which suggests that passive protection schemes must be considered.

Introduction

In the current configuration, the aperture size of the long SSC collider dipole magnets (CDM) has been changed from 40mm to 50mm. While the test results in long 40mm CDM test magnets reveal that the observed fast quench velocities provide excellent quench protection, the remaining concern is that if the 50mm magnets propagate significantly slower than the 40mm design there could be difficulty in designing a protection scheme. Currently, there is no explanation for the unusually fast quench velocities in the long 40mm CDM magnets.

The unexplained quench propagation velocities only occur in long 40mm SSC dipole magnets which are 17m in length. The quench velocity governs the resistance development in the coil which in turn governs the current decay. A rapid current decay implies a lower maximum temperature and is usually represented in terms of the integral of I^2 over all time after initiation of the quench and is refered to as MIITS. The number of MIITS must be limited to protect the materials and the integrity of the cold mass. In the current long 40mm SSC dipole magnets, the plateau quench normal zone appears to propagate with extremely fast velocities, near 140m/s on the inner pole-turn cable. In contrast, the plateau quench velocities in short SSC dipole magnets, 1.8m in length, are near 80 meters/second[1] which is the thermal conductive propagation limit.[2] Recent experimental evidence suggests that the quench velocities accelerate from 100m/s to 150m/s if the quench propagates down the full length of the magnet.[3]

A preliminary model of quench events in long 40mm dipole magnets is based on an empirical approach. The adiabatic quench velocities are normally expressed in terms of current density fraction-of-short-sample, q. The adiabatic quench velocity expression can be modified to fit experimental data from 40mm long magnet test data. Test magnet turn-to-turn azimuthal propagation test delays and inner-outer coil times delays are employed to predict maximum temperatures in the coil.

There is a pressing need to predict the performance of the impending long 50mm dipole magnets. The first long prototype should be completed in the fall of 1991. The long 40mm magnet model has been extended to the 50mm design assuming the longitudinal quench velocity and all azimuthal and inner-outer coil time delays have the same dependence of q. This model is used to predict active and passive protection schemes and their effectiveness to moderate maximum temperatures developed in a quench event.

Quench Model

The preliminary quench model for the 40mm designs has been completed. Since the limit of thermal conduction quench velocities in SSC dipole magnets is approximately 80 meters/second, an empirical technique is employed to approximate the faster quench velocities and the temperature profile in SCC long dipole magnets. The standard quench velocity expression is

$$U_{as} = \frac{J_o}{\delta C_s}\sqrt{\frac{k\rho}{(\theta_s-\theta_o)}} \qquad (1)$$

where J_0 is the current density, δC_s is the density times the heat capacity, k is the copper thermal conductivity, ρ is resistivity, θ_0 is the batch temperature, and θ_s is the temperature that the heat generation step function turns on.[4] θ_s is usually approximated by $\theta_s=(\theta_g+\theta_c)/2$ where θ_g is the current sharing temperature, θ_c is the critical temperature. This expression is modified such that the quench velocity matches near short sample quenches.

$$\theta_s^* = \theta_g + \delta\theta(q) \qquad (2)$$

where θ_s^* is the adjusted heat generation step function which is then inserted in equation 1 to produce V_{ag}, the adjusted quench velocity. The term $\delta\theta(q)$ is a fit parameter such that V_{ag} matches test magnet data. In figure 1, the adiabatic and adjusted quench velocities are plotted against test magnet quench data.

The quench temperature profile of each conductor is tracked, and temperature and B-field dependent material properties determine the quench velocities, based on V_{ag}. Maximum temperatures are presented in table 1 and are a factor of 2 higher than experimental data. This model differs from test conditions in that all turn-to-turn time delays are assumed to be maintained and all conductors go normal sequentially. Also, this single model did not contain a heater firing representation and that the inner coil copper-to-superconductor ratio is $\lambda=1.3$. The only hot-spot experimental data available was on a magnet with $\lambda=1.6$ and the heaters were fired with no time delay. An additional model using $\lambda=1.6$ produced a hot spot temperature approximately 100K lower than the model results presented in the table. Other test results suggest this test data had a reduced peak temperature, approximately 50K lower, due to the heater firing.[5] There are several adjustments which can be made to refine this preliminary model. Also, there is a need for more hot-spot temperature measurements based on more recent magnet designs which are closer to the 40mm design baseline.

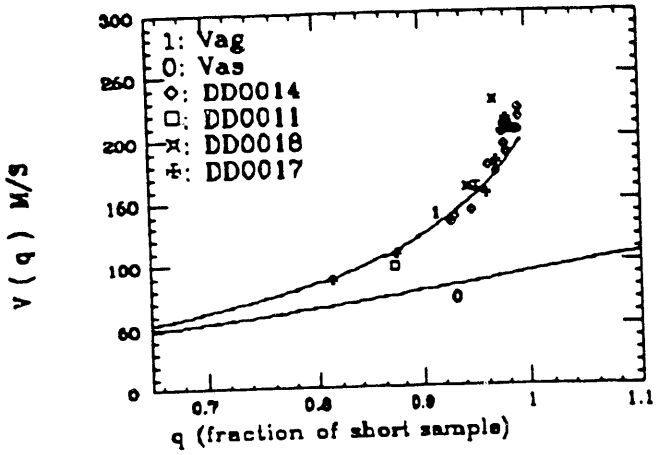

Fig. 1- Adjusted vs. adiabatic quench velocities

This technique may yield uncertainties in predicting the behavior of a new design because the quench velocities are not well understood; however, it can suggest relative design performance. Unfortunately, this technique is empirical and does not represent any physical process. Comparative models can only be made by scaling the anomalously accelerated propagation as a function of q.

Table 1	40mm baseline	DD0017†	50mm baseline
Cu:S.C. ratio inner	1.3	1.6	1.5
Cu:S.C. ratio outer	1.8	1.8	1.8
inner cable area	11.79		15.37
outer cable area	9.89		11.87
Stored Energy:	1.2MJ	1.2MJ	1.57MJ
	Model	Expt.	Model
Max temperature	390	157	310
MIITS	9.64	7.39	19.5
†40mm test magnet, Reference 5.			

This model predicts that the 50mm design will experience peak temperatures half that of the 40mm design. This approximately agrees with simple adiabatic "MIITS" approximations using empirical fits to experimental data which concludes that the 50mm design can sustain 20 MIITS before reaching 800K vs. 12 MIITS in the 40mm design.[6] The major protection difference in these designs is the 30/20% increase in cross-sectional area in the inner/outer conductor as seen in Table 1. Using an empirical model, a relative comparison of 40mm vs. 50mm designs suggests that the 50mm design will be easier to protect and obtain lower maximum temperatures.

Active Protection Models

This model has been adapted to model magnet protection in active and passive schemes. The active protection system may include up to five long SSC dipole magnets and a quadrupole magnet which are isolated from the sector power supply by a warm diode. The passive protection system would isolate an individual magnet with a cold diode under the assumption that a single magnet is "self protected" and no heaters are needed to protect it. In both schemes, the non-quenching sector magnets are ramped down in approximately 30 seconds.

If an active protection system is employed to protect a half-cell of magnets, the stored energy of some or all of the 6 magnets must be distributed between all magnets in the half-cell. The current protection baseline states that the half-cell will be divided into two active protection sub-groups each separated from the sector by a warm diode. Each magnet has active two outer-pole-turn strip heaters. Each strip heater contains twenty-four heater pads which forces ten cables into a normal state down the length of the magnet. In the event of a quench, the warm diode will isolate the 3 magnets.

A modification of the model described previously was used to model a quench event in a series circuit of magnets. A string of magnets in series was modeled with one heater firing on both sides of the magnet to emulate the active protection scheme. The heater time delays represent both voltage detection and systemic time delays in firing the heaters. The heater trigger specification is 0.5 volts across the magnet. In figure 2, the results of several total time delays are presented. These results demonstrate that there is a clear maximum acceptable time delay before firing the heaters to protect the half-cell. This one heater model provides a pessimistic view of quench development in the outer coil. The baseline configuration has 24 heaters in series on each side of the magnet and improved models based on 24 heaters would yield more optimistic results.

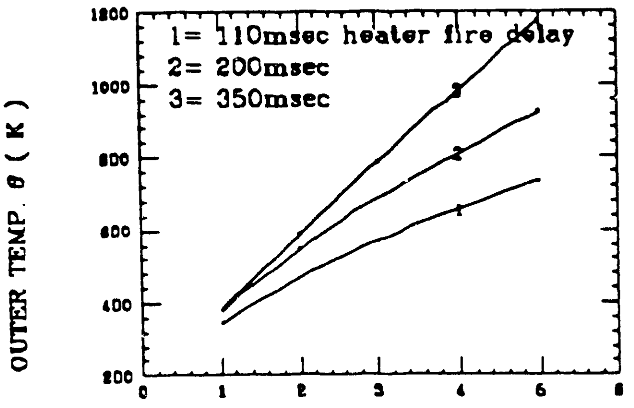

Fig. 2 - Hot Spot Temperatures

The second technique involves using the resistance development from magnet test data to predict string performance. This is a simple and more accurate model which is based on the current vs. time data from test magnets. A resistance vs. time profile is calculated and it reproduces the inductance-resistance (LR) circuit current vs. time profile. By using a time dependent model of the resistivity development during spontaneous and heater induced quenches, one can develop a new current profile for a series of magnets and predict MIITS for the spontaneously quenching magnet assuming the inductance is known. This is not completely accurate because resistivity would develop faster in the case of higher time delays with more stored energy. The case chosen was developed from current vs. time test data from a near short-sample quench for the test magnet DD0027. The only safety-heater induced quench test data occurring near short sample was a 6600amp quench found in DD0019 and this current vs. time profile was almost identical to the resistivity development in the spontaneous 6800 amp quench in DD0027.

Using the resistance profile from the previously mentioned spontaneous DD0027 quench for spontaneous, $R_s(t)$, and heater induced quenches, $R_h(t)$, a LR circuit was modeled based on the inductance of N magnets where (N-1) magnets had a firing time delay modeled by offsetting the resistance development for (N-1) magnets. The current profile is

$$I=I_0 \ \mathrm{Exp}[\ -t(\ R_s(t) + (N-1)R_h(t+d))\ /\ (NL)\ ] \quad (3)$$

where d is the time delay and I_0 is the initial current. In figure 3, the MIITS performance is plotted in relationship to heater firing delay times and the number of dipole magnets in the string. As the firing time increases, the spontaneously quenching magnet continues to heat-up due to the stored energy of all the magnets in series. 8 MIITS corresponds to a hot-spot temperature of 200K and 12 MIITS corresponds to 800K for a 40mm inner coil. The 800K number has not been observed, it is only derived from the adiabatic approximation.

Qualitatively, the two models agree that active protection is feasible. The following results suggest that if a quench can be detected and the heaters fire in 40-100msec, the half cell would be properly protected.

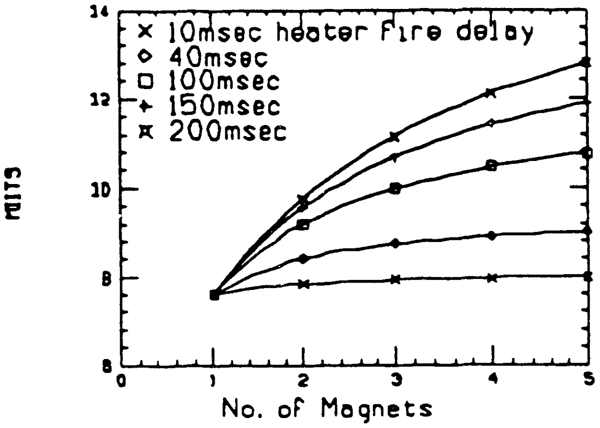

Fig. 3 - Active Protection 40mm MIITS

Conclusions

Empirical passive protection models predict that the 50mm magnets are more protected than the current 40mm test magnets. The 50mm design is more protected because the reduction of the current density in copper slows down the resistivity development and power dissipation; however, lower current densities also slow down the quench velocities and these models may not accurately predict quench velocities in untested magnet designs.

The resistive development active protection model predicts with proper quench detection that an active protection system will also provide adequate magnet protection. The models strongly depend on test data from the 40mm design. The heat development and quench event will develop slower in the 50mm design facilitating more margin for heater reaction time; however, higher Jc margin slows down heater reaction. This also implies that fast acting heaters could further reduce peak temperatures. Also, active protection may provide the best protection for outer coil quenches which tend to have slower quench velocities.

The planned long sample tests and more complete models will yield more information for 50mm long magnet half-cell protection. Hopefully, these tests and models will be completed in time to impact the long 50mm dipole magnet program. More complete test data and corresponding models must be developed to accurately describe the near sonic velocities in the long SSC dipoles. The current paradigm includes a helium hydraulic quench event either in the annular space or inside the cable insulation. Long sample tests and more complete models are under development.

References

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