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

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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 quite well self-protected under all of these considerations. In addition, this implies that the other corrector multipoles (quadrupole, sextupole, octupole, etc.) which use the same conductor winding technique are self-protected. A passive protection system is likely to work for these elements.

I. Introduction

Quench simulation of superconducting (s.c.) magnets has been a very important guide in the design s.c. magnets and their associated quench protection system. The goal of the simulation is to understand and predict the quench behavior of a s.c. magnet as well as to study the quench effects under changes of some parameters of interest for its design (e.g., like the type of s.c. wire, spacing between wires, coil configuration, etc.). Although the complete goal is not possible to achieve for any computer simulation because of the given complexity of the phenomenon, very reasonable approximation has been obtained by computer gross model [1, 2]. In addition, these model simulations allow one to quickly extract 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 which was used to study the active and passive protection system for the Superconducting Super Collider (SSC) R&D main dipole magnet. The quench model uses the following adiabatic quench velocity expression [3]:

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

where J_{co} is the 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 s.c. ratio; θ_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, $\theta_g = \theta_c - (\theta_c - \theta_o)\ q$; and $(\delta c)_m$ is the average in the product of the density, δ, times the specific heat, c, of the metal components in the conductor. The temperature for each wire, θ, is estimated through the solution of the equation

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

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 in the product of the density times the specific heat of all the components of the conductor. The thermal conductivity term is ignored in the above expression because the quench velocity is higher than the diffusivity velocity. The conductivity is estimated in the temperature profile along the the conductor. The heat transfer to He is not taken into account because 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

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

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 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 values compared with 1 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, about 500 K; the melting point of solder (depends very much on the type), and degradation of critical current density, about 1000 K.

The peak voltage between the normal zone and the s.c. zone (very approximately the peak quench resistance

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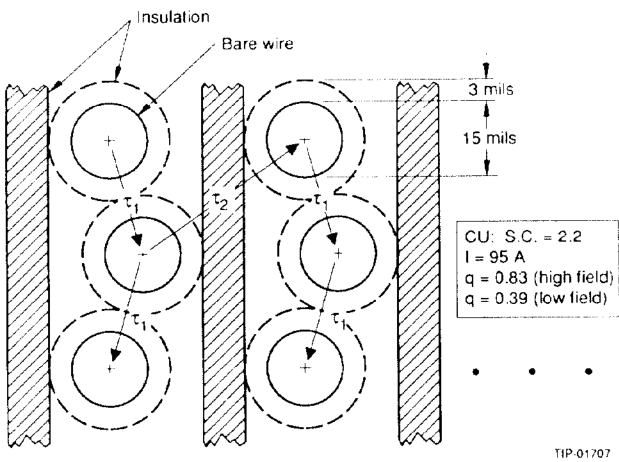

Figure 1: Sketch of Two Double Layers Wire Array.

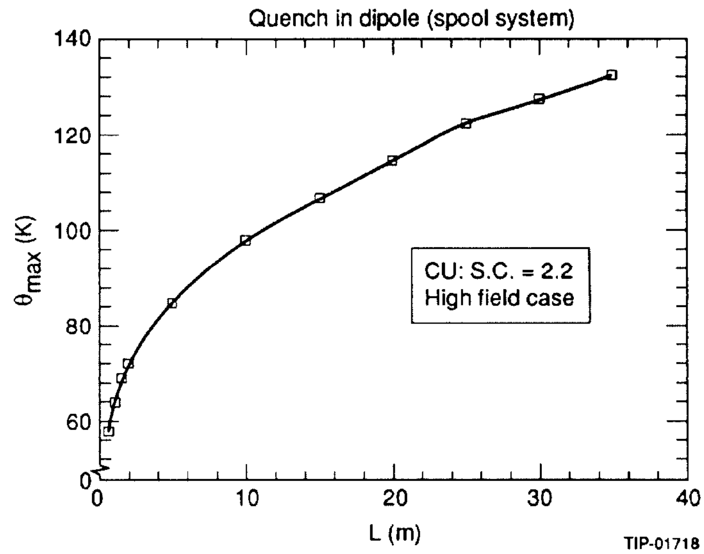

Figure 2: Hot-Spot temperature.

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 40 MV/m [5] 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.

II. Quench Simulation

The superferric corrector dipole half coil is made up of six double layers having 33 s.c. wires per layer. In each double layer, one wire touches only two neighbor wires (except the end wires), as shown in Figure 1, where its nominal parameters are given. In this figure, τ_1 represents the wire to wire time delay quench propagation, and τ_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 on). The turn-on voltage for the diode to conduct current was chosen as 0.6 V (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 bit higher than 2.0 V (warm diode). Nor does the quench behavior depend on the value chosen for the circuit dump resistance R_D. R_Q represents the time-depending total quench resistance. The results of the simulations are summarized above.

For a nominal 1-m-long superferric corrector dipole and a thickness of wire insulation of 3 mils, the magnet is quite self-protected in a quench event happening at low or high field wire. The maximum hot-spot temperature is 64 K and the internal peak voltage is 600 V. The maximum adiabatic quench velocity is about 13 m/s, and the time for the current to fall off is about 70 msec. Increasing the thickness of wire insulator increases the hot-spot temperature, but it remains in the safe region as long as this thickness is not higher than 0.254 mm. When the copper to s.c. ratio changes, keeping the amount of s.c. the same (i.e., adding more copper to the wire making it wider), the hot-spot temperature and the peak voltage decrease since the density of heat generated and cable resistance decrease.

Figure 2 shows the hot-spot temperature as a function of the length of the superferric dipole magnet. For a safe inner peak voltage, the length of this magnet must not be higher than 10 m.

III. Observations And Implications

The above quench analysis points out the fact that the superferric corrector dipole magnet is widely self-protected. Since each individual magnet has a separate 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, 6]. 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 quite brief, probably less than 20 msec. It is important to mention that from 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 to the magnet length, copper to s.c. ratio, and wire thickness insulation points out that this magnet can change many of its parameters freely without affecting its safe quench behavior.

Since the type of conductor is the same for other superferric Jelly Roll multipole corrector magnets (quadrupole, sextupole, octupole, etc.) and their stored energy 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. Having N focusing p-multipole of length l_p connected in series 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 2 to study the quench protection system for a set of p-multipoles connected in series to a single power supply. This eqivalence is justifiable in this case since the quench velocity is not high, and the time for the current to fall off is brief.

There are 96 spool devices in a typical SSC arc sector. Assume that the arc sector has a set of 96 focusing-defocusing p-multipole corrector elements in alternating pattern, although the number of octupoles and decapoles planned is less than 96. If all the focusing (48) superferric p-multipole corrector are connected in series, the estimated hot-spot temperature from Figure 2 are as shown in Table 1.

Table 1. Expected Hot-Spot Temperatures

p-multipole	L_p(m)	L_{eff}(m)	θ_{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 focusing (defocusing) corrector p-multipoles in series and to have a passive protection system (two parallel cold or warm diodes) for them. The pessimistic maximum temperature expected in a quench, about 130 K, permits enough security margin to the passive protection system. 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 is very brief even for a 35-m-long dipole (about 0.15 sec). That is, for 48 focusing (defocusing) 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 is implemented here, the time for the heaters to induce other quenches 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. It is necessary to point out that quenches of a lower current correspond to lower hot-spot temperatures in this case (see Reference 2, simulation on 50 mm aperture SSC R&D main dipole magnet).

IV. Conclusions

Modification of the SSC-RR computer program (SSC-DTAC-T) allows study of the quench behavior of the superferric corrector dipole for the SSC. This magnet is self protected in a quench event even under changes in 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. An active protection system (heaters) is not needed 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.

V. Acknowledgements

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VI. References

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