SSC Dipole Quench Protection Heater Test Results

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Abstract

There presently is a need to increase the resistance of the quench protection heaters for SSC dipole magnets to be of the order of 15-20 Ohms. This need is derived from system characteristics related to the quench protection heater power supply performance and cost. A quench heater is fired after the detection of a small part of the coil becoming normally resistive. It is essential for safe operation of the collider to minimize the time interval between the two events of firing of the quench heater and the entire magnet coil becoming normally resistive. It is also necessary to maximize the volume of the coil becoming normally resistive in order to minimize the discharge time of the magnet. This paper presents results of tests of a redesigned quench protection heater for SSC dipole magnets.

I. INTRODUCTION

The current design of quench protection heater for SSC dipole magnets consists of a number of spot like heaters connected together in series on a long strip which is attached to the outer surface of the outer coil. The heater strip is electrically insulated from the coil by 2 layers of Kapton film. There are four heater strips in dipole magnets for quench protection. Pairs of heater strips are placed in opposite quadrants and wired together in parallel for single magnet tests and in series for collider operation. A single pair of heater strips will be sufficient for magnet protection. The second pair is to provide a level of redundancy in the system. The design of the heater is shown in Figure 1. At 12 equally spaced intervals the strip is cut away to produce the S-shaped pattern shown in the figure. Upon detection of a quench a capacitor bank style heater firing unit (HFU) is discharged producing a large temperature gradient across the Kapton insulation between the heater and the coil. That part of the coil under each heater pad is driven normally resistive, the quench is then propagated throughout the rest of the coil at the quench propagation velocity of the conductor. The resistance of the heater strip at 4K is (1.5 +/- 0.3) Ohms. In the magnet test set-up the resistance of the heater strip is comparable to the parasitic resistance of the leads connecting the heater strip to the HFU, as much energy is deposited into the leads as into the heater. For operation in the collider, a large gauge cable is required to meet performance requirements, but this approach is costly. As an alternative, the majority of the power could be deposited into the heater by increasing the resistance of the strip. Furthermore the current flowing for the same power deposited into the heater will be reduced easing power supply internal losses and connection requirements. A quench protection heater has been designed according to the criteria and analyses presented in [1]. The heater is shown in Figure 2. It consists of a complete strip of stainless steel 1.27 cm in width and 25.0 μm in thickness. The heater is partially copper plated leaving 12 regions of stainless steel each 60.0 cm long which perform the heating of the coil. The resistance of this heater is 12.4 ohms at 4K. It is convenient that this heater design is very similar to those used at the Tevatron and later at DESY, and that there has been considerable experience with them. The tests results obtained with the redesigned heater, and a comparison with the existing heater is presented below.

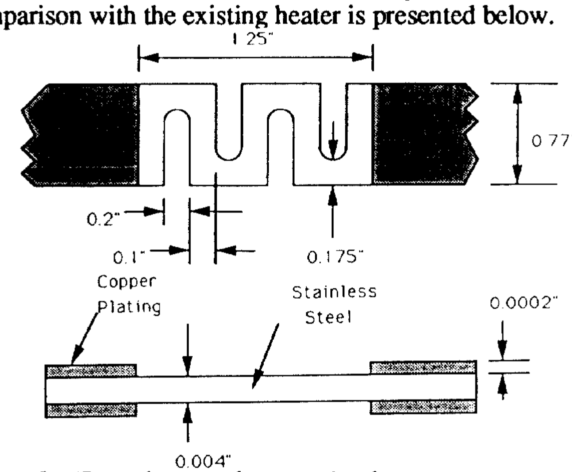

Figure 1. "B" sytle quench protection heater.

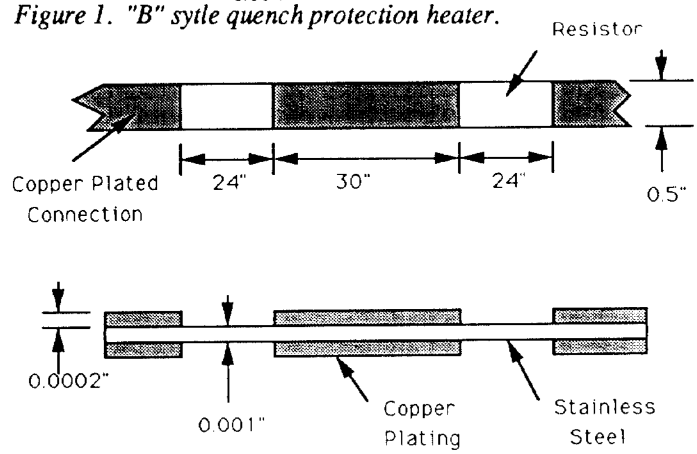

Figure 2. "S" style quench protection heater.

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Short Magnet and Full length Magnet Test Goals: Short test magnets are constructed to test new design features of magnets to reduce cost and time to produce test results. These magnets are typically between 1.0 m and 2.0 m in length. Full length ("long") magnets are then built after the design has been verified. Quench heaters have been tested in the same way. The protection of a magnet is accomplished by limiting the maximum temperature of the conductor to less than 800K at which temperature the superconducting properties of the cable are degraded. This may also be expressed as limiting the MIITs to experienced by the coil, where MIITs = $1/10^6 \int i^2$ dt. The number of MIITs is easily measured during magnet tests. For "DD" series long 40mm aperture SSC dipole outer coils, characterized by a 1.7:1 Cu:Sc ratio, 800K has an equivalence of 10 MIITs. Although MIITs values can be obtained from short magnet tests, it is difficult to scale up the data to represent the figure for a long magnet, due to the higher quench propagation velocities observed in long magnets. Furthermore the cryogenic conditions of test are different for long and short magnets. In order to perform short magnet tests before a full length heater would be tested, a figure of merit was required. The accumulation of MIITs by a magnet coil is the combination of 2 delays and a propagation time: (a) the delay between detection of a quench and the firing of the HFU (b) the time for the quench protection heater to rise in temperature and for the heat to be conducted to the coil and produce a normally resistive region and (c) the time for the normal region to propagate throughout the entire coil. Of these item (b) is a candidate for short magnet tests, since item (a) is function of the quench detection system and item (c) is a function of the size of the magnet and the cryogenic conditions. A time *T_fn* is defined, which represents the time interval between firing of the HFU and the first detection of a resistive voltage between upper and lower coil voltage taps. This is the figure of merit used in the short magnet tests. For long magnet tests, a full set of operating parameters can be explored, i.e varying the applied heater power to determine its influence on *T_fn*, the measurement of magnet MIITs and the measurement of MIITs following a spontaneous quench of the magnet. Both long and short magnet tests were performed at Fermi National Accelerator Laboratory.

II. SHORT MAGNET RESULTS

A 1.0 m long 40mm aperture dipole magnet DS0323,was equipped with the existing "B" style and the redesigned "S" style heater. Only one strip of each style was used for the initial tests. The energy deposited into the heaters was scaled from long magnet tests in the ratio of the collared lengths of the magnet. Each heater was fired individually at 3 magnet currents between 2000 and 6500 Amperes, the time *T_fn* was recorded in each case. The results are shown in Figure 3. The plots shows that at lower current the magnet coil is first made resistive by the "S" style heater while at higher currents the opposite is true. The mechanism for this is not yet understood and will be further investigated, since it has relevance to long magnet protection. The aim of this test was simply to show that the "S" style heater could provide times *T_fn* comparable to the existing heater. The analyses presented in [1] show that the "S" style heater operates at a lower peak temperature than the "B" style. It is therefore possible to increase the energy deposited in the heater significantly in order to reduce *T_fn*, without the risk of damaged insulation and its consequences. A second short magnet DS0315, was equipped with two "S" style heaters and the measurements of *T_fn* repeated at several magnet currents and also at several heater energies. The results are shown in Figure 4. In long magnet tests the energy applied to the heater is adjusted until *T_fn* = 200 ms at a magnet current of 2000 Amperes. Lower times will represent a fewer number of magnet MIITs. It can be seen that with the "S"style heater at higher energies, times of 58 ms are possible.

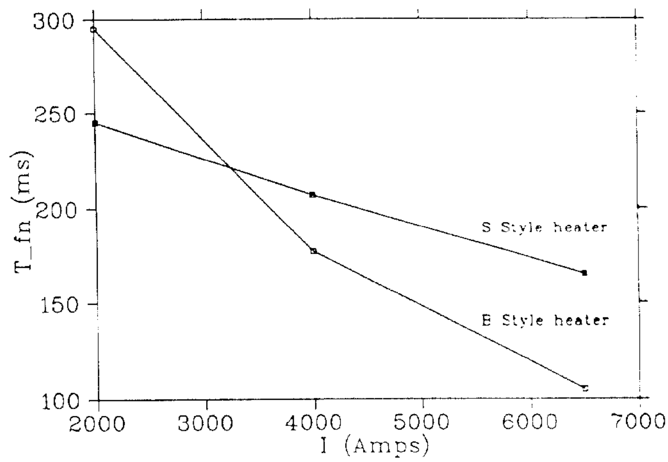

Figure 3. Heater response times for "B" style and "S" style single quench protection heaters fired individually as a function of magnet current.

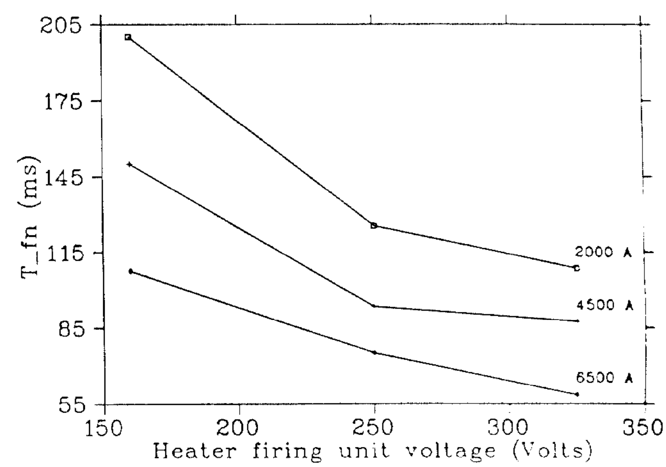

Figure 4. Heater response time T_fn as a function of magnet currentand heater power supply voltage for two "S" style quench protection heaters in opposite quadrants fired together.

III. LONG MAGNET TESTS

Following short magnet tests, two heaters of each style were installed in a long 40mm dipole DC0306. Using a magnet current of 2000A the energy deposited into each heater was varied and the magnet quenched until T_fn = 200 ms for each heater. It has been shown that the MIITs experienced by the coil has a maximum value when the magnet current is approximately 0.6 times the critical current of the cable. In this case this figure is approximately 5000 Amperes. At this level of current the time T_fn for the "B" style heater is 100 ms, the heater is producing a lower T_fn than the "S" style, this was shown above in Figure 3. The energy applied to the "S" style heater was increased until its T_fn value was also 100 ms and the test continued. The resulting MIITs data for the two current levels is shown in Table 1.

Table 1

Style	T_fn (s)	MIITs	Current (A)
"S"	0.21	2.88	2000
"B"	0.19	3.00	2000
"S"	0.11	7.46	5000
"B"	0.10	7.64	5000

Table 1. MIITs recorded for long magnet DC0306 for "S" and "B" style quench protection heaters.

For the data in Table 1. The capacitance value of the HFU was left fixed for both heater types. Since the "S" style heater is several times the resistance of the "B" style the circuit RC time constant is much longer for this heater (190 ms vs 65 ms). The energy is therefore deposited at a lower rate than the "B" style. In order to compare the heater performance using more equal discharge times, half the capacitors in the HFU were removed and the "S"style heater test was repeated. The results are shown in Table 2.

Table 2

Current (A)	T_fn (s)	Capacitance (mF)	RC time (ms)	MIITs
2000	0.21	28.8	190	2.88
2000	0.18	15.2	100	2.82
5000	0.11	28.8	190	7.46
5000	0.11	15.2	100	7.61

Table 2. MIITs data for full size dipole DC0306 using "S" style heaters with different circuit time constants.

The data shows that there is little effect on the number of magnet MIITs as the capacitance is halved. In the collider it is planned to wire sets of three heaters in parallel and to provide the energy to them via a single HFU channel. The result from above can be used to advantage since the energy supplied to a number of heaters can be increased by increasing the number of capacitors in the HFU. The effect of the increased circuit time constant does not appear to affect the protection if the HFU capacitance is increased by a factor of two.

In the collider the protection heaters will be fired after the detection of a spontaneous magnet quench. This extra delay will result in a higher number of MIITs. To investigate this the effect a spontaneous quench was modelled by firing a spot heater mounted on the magnet coil. Upon detection of the quench the protection system fired the quench protection heaters. The tests was performed individually for both styles of heater, the results are shown in Table 3.

Table 3

Style	T_fn (s)	MIITs
"S"	0.11	7.92
"B"	0.11	8.15

Table 3. Comparison of magnet MIITs for "S" and "B" styler heaters at maximum MIITs current, following a spot heater induced quench.

IV. SUMMARY AND CONCLUSIONS

The re-designed heater has a similar performance to the existing heater in terms of its ability to protect a long 40mm magnet. It meets the system requirements of increased resistance by using a smaller cross sectional area and a larger active length. This results in a larger area of heater which has advantages as will be described below, but does result in higher powers being required from the HFU. The implication of increased cost is mitigated somewhat since lower gauge connection cable is made possible. The magnet program for SSC will continue with an increased aperture dipole magnet. The 50mm dipole is characterized by higher operating margin and slower quench propagation velocities. A consequence is that higher energies will be required to be deposited in the quench heaters to initiate a quench in the same T_fn. By recording the current and voltage applied to the heaters. it is possible to determine the resistance, and via a look up table, the approximate temperature of the heater during the discharge. Measurements show that the redesigned heater operates at a lower temperature, significant increases in the applied energy are possible in order to produce a small T_fn without risk to the magnet insulation. It can be seen form the data that at the lower currents, when the quench propagation velocity within the conductor is slower, that the "S" style heater provides a larger margin of improvement. This is due to the larger active area of the heater which forces 40% of the axial length of the coil to be normally resistive at time T_n. The discharge of the magnet coil is proportional to exp(L/R) and the "S" style heater has the effect of maximizing R at T_n at lower currents. The 50mm dipoles will also be characterized by slower quench propagation velocities and the design of the "S" style heater will be used to advantage here.

V. REFERENCES

[1] C. Haddock, B. Aksel, R. Jayakumar, G. Snitchler, "SSC Dipole Quench Protection Heater Development" To be presented at the 12th International Conference on Magnet Technology, Lenningrad USSR, June 1991.