Quench Protection Studies of LHC Interaction Region Quadrupoles at Fermilab

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Abstract-- High gradient quadrupoles are being developed by the US-LHC Accelerator Project for the LHC interaction region inner triplets. Protection strip heaters are the primary means of protecting these magnets against excessively high coil temperatures and coil voltage to ground as a result of a spontaneous quench. The main objective of the quench protection R&D program is to optimize the heater performance within the constraints of the LHC heater power supply and quench detection system. The results of these studies on several two meter long models magnets are presented.

I. Introduction

The four CERN LHC interaction regions will consist of high gradient quadrupoles from KEK and the US-LHC accelerator project. The US magnets will be combined into a cryogenic element consisting of two 5.5 m quadrupoles connected in series, operating at a peak field gradient of 215 T/m and corresponding excitation current of approximately 12 kA. The quench protection strategy for these magnets is to utilize strip heaters energized by external heater power supplies. Upon quench detection the leads of the magnet element will be effectively shorted together and the stored energy dissipated within the magnet. The prompt and symmetric onset of resistive voltage due to the heaters is essential to minimizing the peak coil temperature and minimizing the resistive-inductive voltage imbalances which can generate large voltages to ground. This paper reports the quench protection studies performed in the 1.9 m model magnet program.

Details of the baseline magnet design have been described elsewhere[1]. The cross section of the 70 mm aperture coil is shown in Figure 1. As seen, these cold iron superconducting quadrupoles consist of eight coils positioned in a two-layer cos(2θ) coil geometry. The coils are electrically connected in series through inner coil pole turn to outer coil pole turn splices in each quadrant and through midplane turn quadrant to quadrant splices.

The outer coils are made of 46 strand NbTi Rutherford cable. For magnets up to HGQ06, the inner coil consists of 38 strand Rutherford cable. For HGQ07 the number of inner strands was reduced to 37 to lower the cable compaction with no change in the short sample current[2]. The strands are 0.808 mm (0.648 mm) in diameter for the

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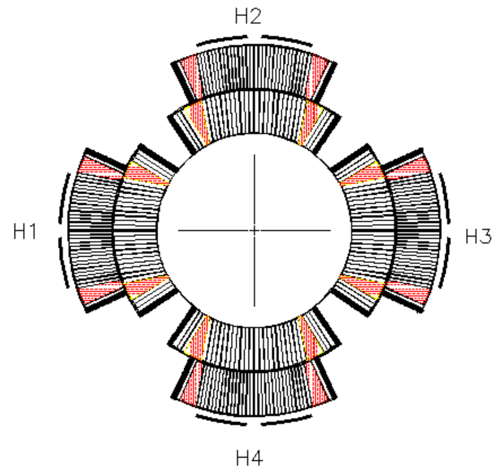

Fig. 1. Coil Cross section. Coil aperture is 70 mm. Azimuthal location of quench protection heaters (H1-H4) are shown.

inner (outer) coil; both contain 6 μM NbTi filaments. The cable is wrapped with Kapton tape with either epoxy or polyimide adhesive. The Kapton insulated coil is insulated from the stainless steel collars with four layers of Kapton forming the ground plane.

Magnets have been equipped with two possible layers of protection heaters. Inter layer heaters are located between the inner and outer coils, while the outer layer heaters are placed between the collars and the outer layer. Each layer consists of 4 heaters whose azimuthal positions are shown in Figure 1. The geometry of the heater is that of a "racetrack" covering approximately 12 turns of one side of two azimuthally adjacent coils. Thus the parallel or series connection of two “opposite heaters” (H1&H3 or H2 & H4) in a given layer provides protection to all four magnet quadrants. It is envisioned in the LHC quench protection system [3] that the two heaters strings will be powered by independent power supplies for protection redundancy.

The results of heater studies on the first two model magnets, HGQ01 and HGQ02, have been previously reported [4,5]. Using a spot heater to induce quenches in the inner layer pole turn it was shown that the magnets could be adequately protected with stainless steel heaters. In particular, the peak voltages were low (less than 200 Volts when extrapolated up to a full scale magnet) and the quench integral predicted a peak coil temperature that was less than 200K using an adiabatic (temperature change governed only by ohmic heat generation and the heat

TABLE I.
STRIP HEATERS IN RECENT HIGH GRADIENT QUADUPOLE MODELS

Magnet	Position	Element (all 25 μm thick)	Insulation
HGQ03 & HGQ05	Inter	Stainless steel 15.9mm wide	325uM
	Outer	15.9 mm wide with copper plating 38 mm etched areas at 114 mm intervals.	350uM
HGQ06	Inter	None	N/A
	Outer	12.7 mm wide with copper plating 610 mm etched areas at 1930 mm intervals.	250uM
HGQ07	Inter	None	N/A
	Outer	22.2 mm wide with copper plating 610 mm etched areas at 1930 mm intervals.	250uM

capacity of the cable) model. One circuit of "opposite heaters" from either the inter layer or outer layer was all that was required. This result prompted our decision to only use the easier-to-install outer heater starting with HGQ06.

The adiabatic model did not predict a comfortable temperature margin for quenches originating in the outer coil pole turn or outer coil midplane. Furthermore, approximately 900 Volts would be required for the heater power supply to protect a full scale ~6 meter long magnet with the stainless steel strip heaters. The nominal setting for the heater supplies in the LHC protection scheme will be 700 Volts with a 7 mF capacitance. Reduction of the heater suppply voltage is possible by longitudinally distributing the resistance by plating the stainless steel with copper [6].

Thus the remaining goals for our program are to 1) make direct measurement of the peak temperature in both the outer and inner coils in both the pole and midplane turns and in the process show that the outer coils are protected from excessive temperatures and 2) test heaters with various longitudinal patterns of resistance. Additionally, we have performed tests on the widths of the heaters. We also reduced the amount of insulation between the heaters and the coils, starting with HGQ006. A summary of the heater configurations is given in Table I.

II. TEST PROGRAM

The tests were performed between October 1998-September 1999 at the Fermilab Technical Division Vertical Magnet Test Facility [7]. VMTF utilizes a vertical Dewar designed to operate with superfluid and normal helium at 1.1 atmosphere. Magnet current is supplied by a 16 kA DC power system with an energy extraction circuit (dump resistor). The strip heater and spot heater voltage is supplied by a 450 V Heater Firing Unit (HFU). The capacitance of the system can be set in 4.8 mF increments up to 19.2 mF. The cold resistance of a stainless steel heater of width 15.9 mm is about 5.5 ohms. The stainless steel heaters were typically operated in parallel, while the distributed resistance heaters were operated in series. The

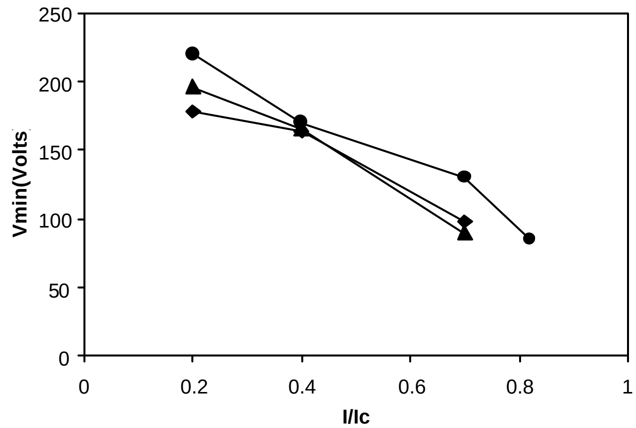

Fig. 2. Minimum voltage per heater circuit to initiate a quench vs. normalized excitation current: (Circles) outer layer stainless steel strip heaters in parallel, (diamond) HGQ06 in series, (triangles)HGQ07 in series

RC time constant for the former tests was 40 mS while for the latter tests the time constant was set to approximately 80 mS. The 80 ms time constant was chosen because this is the value in LHC operation, using a 7 mF capacitor bank and two full length heaters connected in series with a 33 percent stainless steel/copper distribution.

III. RESULTS AND DISCUSSION

A. Heater Performance

Heater performance is characterized by Vmin, the minimum voltage (or energy) required to initiate a quench, t_{fn}, the time between quench heater firing and resistive voltage initiation, and the MIIT's, the time integral of the square of the quench integral normalized to 10^6.

Vmin level determines the voltage requirements for the heater power supplies. Figure 2 shows the measured Vmin for stainless steel heaters in parallel and the series circuit of the distributed resistance heaters in HGQ06 and HGQ07. The latter two heaters have a similar ratio of stainless steel to total area (approximately 33 percent). As shown, the voltage for the distributed heaters is slightly reduced relative to that for the stainless steel heaters. The HGQ07 voltage reduction would be more significant if the heaters had the same widths. In fact the peak power surface densities at these Vmin voltages are comparable. The voltage savings is not as significant as one would expect for the narrower HGQ06 heater. A possible explanation for this is that the HGQ06 heater primarily covers turns near the low field midplane and thus requires a larger power density to be effective.

The t_{fn} is a good measure of the heaters efficacy. Low values of t_{fn} result in lower quench integrals which in turn translates into lower coil peak temperatures. As shown in Figure 3, the 15.9 mm wide stainless steel strip heaters at a peak power density of 40 W/cm^2 yielded t_{fn} values lower than 60 ms over the measured range of currents, reaching a value of 20 ms at 0.8 I/Ic. A similar result was achieved with the HGQ07 22 mm wide distributed heater at the test value of 55 W/cm^2. Additional data points taken at 0.4 I/Ic 20 and 37 W/cm^2 yield a slightly larger t_{fn}. The

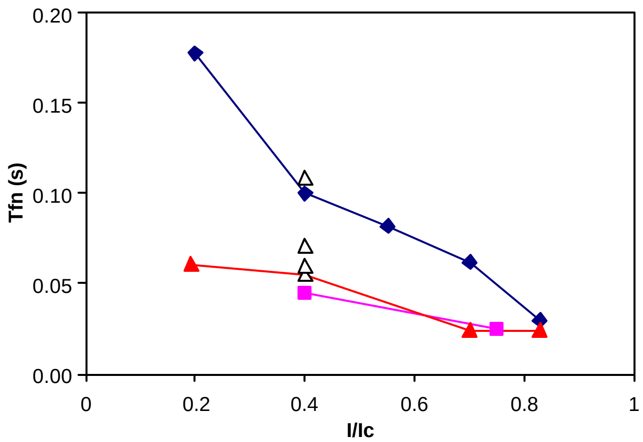

Fig. 3. t_{fn} for heaters as a function of normalized current: (squares)stainless steel heaters with peak power 40 W/cm^2, (diamonds) 12.5 mm wide distributed heaters at 20 W/cm^2, (solid triangles) 22 mm wide heaters at 55 W/cm^2, (open triangles) 22 mm wide distributed heater in order of increasing t_{fn} 55,37,21,10 W/cm^2.

narrower width heater in HGQ06 when operating at a lower peak power of 20 W/cm^2 yielded a relatively high t_{fn} at low currents (at I/Ic=0.4 HGQ07 achieved this t_{fn} at half the peak power) but had an acceptably low t_{fn} of 30 ms at 0.8 I/Ic This effect is again likely related to the area coverage of the HG006 heater strips. This longer t_{fn} results in slightly higher peak coil temperatures at lower currents.

Finally we compare the relative effectiveness of the distributed resistance heaters for HGQ06 and HGQ07. The quench integral attributed to the strip heater resistance growth is shown in Figure 4. Since the quench integral starts from the time of resistive growth in the heaters it does not reflect the t_{fn} contribution to the quench. A comparison of the quench integrals show that the wider HGQ07 heater is more effective at limiting the MIIT's, as expected.

For HGQ06, we considered the scenario of attaching two adjacent heaters in series for protection (for example H1 in series with H2). In this configuration, the same number of turns are covered as with the "opposite" heaters, but the resistance distribution is no longer symmetric (there will be one coil quadrant with no quench protection). The adjacent vs. opposite heater pairing are equally effective in limiting quenches, which indicates that the contribution of the quench integral due to longitudinal quench propagation around the magnet ends is not significant.

B. Peak Voltage

The peak voltage is defined as the highest voltage measured from any of the eight coil leads relative to the magnet leads. This voltage develops because of coil to coil variation in t_{fn} and coil to coil differences in RRR. The design goal for these magnets was to limit this voltage to 1000 V for a full scale magnet [8]. As previously shown[5] and verified again (see figure 5), the measured voltages to ground are low: less than 30 Volts for 1.9 meter magnets. Extrapolating to a full scale magnet with two

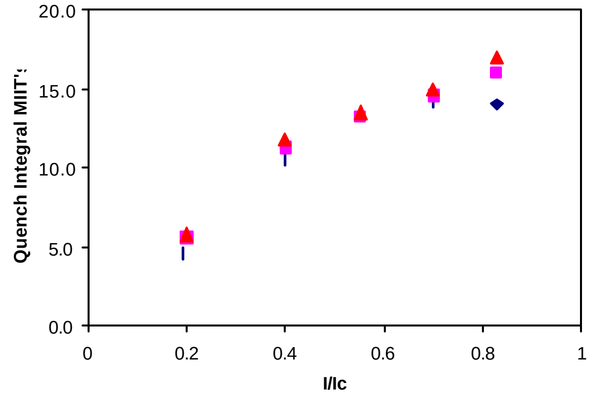

Fig. 4. Quench integral vs. normalized excitation current for strip heater induced quenches: 22.5 mm wide heater (diamonds), 12.5 mm wide heater (square), 12.5 mm heater using adjacent heater (triangle)

redundant heater circuits, the voltage is will not exceed 200 volts. The results for the "adjacent" heater configuration is also included in Figure 5. Even under this case, with no heater protection in one quadrant, the peak voltage is less than 120 volts, which would translate to less than 400 volts for a full scale magnet.

Using these data, one can attempt to model the effects of having two 5.5 meter long magnets connected in series, using as input the measured resistance and inductive voltage growth from the heater induced quenches. We varied the starting time of the resistance growth within the measured t_{fn}. We also studied the possibility of a resistive voltage imbalance between the two magnets due to a 100 % difference in the conductor RRR. We estimate that the peak voltage growth would not increase by more than a factor of two under these conditions thus still producing an acceptably low voltage.

C. Peak Coil Temperature

The peak coil temperature, assumed to be the origin of the spontaneous quench is estimated in two ways. First, the temperature can be simply related to the time integral of the square of the excitation current (quench integral), using an adiabatic temperature model. The other method is to

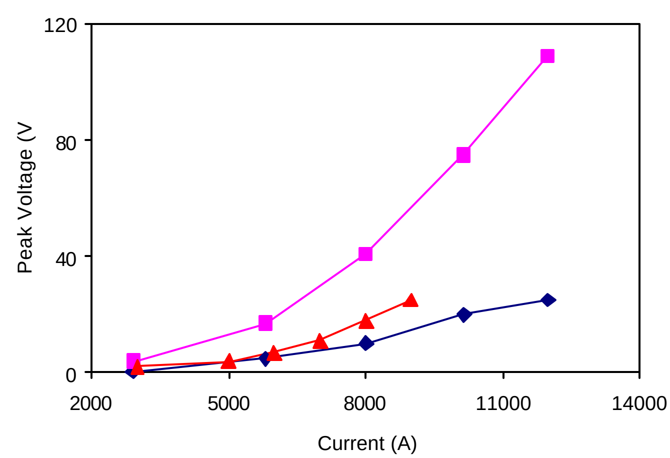

Fig. 5. Peak voltage as a function of excitation current: (triangles) stainless steel heaters, (diamonds) distributed heaters, (squares) adjacent heaters in series.

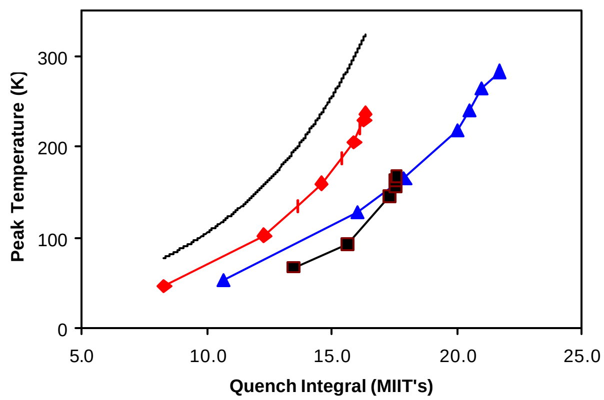

Fig. 6. Measured peak temperature vs. the MIIT's: Diamonds: outer coil pole turn, triangle outer coil midplane turn, squares inner coil pole turn. The adiabatic prediction for one of the curves (outer pole turn) is shown.

measure directly the cable resistance adjacent to a spot heater. The measured resistivity, dominated by the resistance of the copper is then directly related to the cable's local temperature. The design for the magnet was to limit this peak temperature to less then 400K [8].

Figure 6 shows the measured peak temperature as a function MIIT's. The spot heaters for these tests are located in three locations, 1) the pole turn of the inner coil, 2) the pole turn of the outer coil, and 3) the outer coil midplane turn in the end of the magnet. In all cases, increasing MIIT's represent higher excitation currents and therefore high magneto-resistance at the onset of the quench. In general the inner cable has a lower peak temperature vs. MIIT's curve since the inner cable has more copper and superconductor. For the outer cable, the pole turn temperature is higher than the midplane temperature for a given MIIT's due to the pole turn being in a higher field region. This explains the greater sensitivity of the pole turns to heat generation. In all cases the shape of these curves is well predicted by the adiabatic calculation. As expected, the scale of the adiabatic prediction is more pessimistic.

Finally, the peak temperature is plotted directly against the peak excitation current, as shown in Figure 7. For

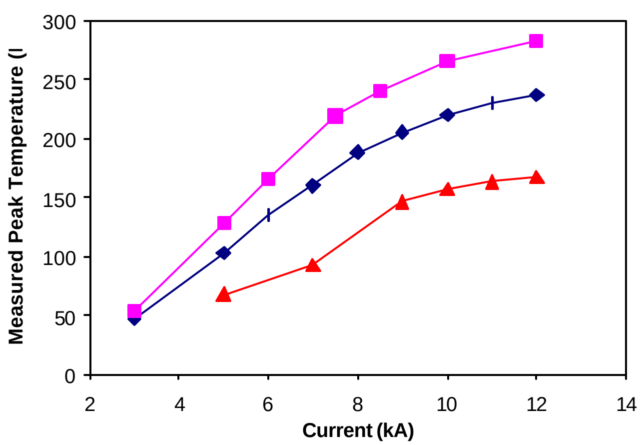

Fig. 7. Measured peak temperature vs. excitation current from spot heater induced quenches: pole turn inner (triangle),pole turn outer (diamond), midplane outer (square).

quenches originating in the inner coil, the peak temperature is approximately 150 K. For the outer pole turn, the peak temperature for quenches in the 12 kA operating range is less than 250 K. Finally, the peak temperature for outer midplane turns is measured to be less than 300 K.

Note that the inner coil direct measurements were made with the 38 strand conductor. One would expect a slightly higher peak temperature with the 37 strand conductor due to the decrease in the copper and superconductor. Using our adiabatic calculations to scale, the peak temperature is predicted to increase by approximately 10 percent to 165 K.

IV. Conclusion

Strip heaters have been shown to be effective in protecting the high gradient quadrupole magnets from excessive peak temperatures and peak voltages to ground. Only one circuit (two heaters) in either the outer or inter layer is required. The direct measurement of the peak temperature shows that the magnet will not reach a temperature higher than 300K and the coil voltage to ground should not exceed 200 V for a full scale magnet. Distributed resistance heaters are effective in reducing the heater power supply voltage while still providing adequate quench protection. Further optimization studies on the heater geomtries will continue in the remaining 2 magnets in the model program.

Acknowledgment

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