Quench Protection Studies of Short Model High Gradient Quadrupoles

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***Abstract*—High gradient quadrupoles (HGQ) being developed for the CERN Large Hadron Collider (LHC) interaction regions will rely on strip heaters for quench protection. Tests were performed on strip heaters in two locations on 1.9 meter model quadrupoles to study heater response times from strip heater induced quenches and quench velocities and peak temperatures from spot heater induced quenches. The results for the two heater locations are presented and compared to prediction.**

I. Introduction

The design of the four interaction regions of the CERN LHC requires 70 mm single aperture quadrupoles with operating gradients in excess of 200 T/m. It is important that these magnets operating in superfluid are protected from excessively high coil temperatures and voltage to ground in the event of a spontaneous or beam induced quenches. Spontaneous quenches are likely to occur in the magnet high field regions, i.e. in conductor near the magnet pole, while beam induced quenches will occur near the magnet midplane.

As part of the Fermilab high gradient quadrupole development and test program, strip heaters were placed in the highly instrumented short R&D models. The performance of these heaters are studied through spontaneous training quenches as well as through strip heater and spot heater induced quenches. The results of these tests will be used to decide the type, number and location of strip heaters in the full length production magnets.

II. Magnet Description

The magnets (HGQ01 and HGQ02) for this study are 1.9 m long quadrupoles. Details of the baseline design have been described elsewhere[2], [3]. These cold iron superconducting quadrupoles have two-layer $\cos(2\theta)$ coils with 70 mm diameter bores.

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The inner (outer) coils are made from 38 (46) NbTi strand Rutherford cable. The strands are 0.808 mm (0.648 mm) in diameter for the inner (outer) coil; both contain 6 μm NbTi filaments. The inner cable is insulated with a 50% overlap wrap of 25 μm Kapton tape followed by a wrap of 50 μm Kapton tape with 2 mm gaps between turns to increase the liquid helium wetted surface. The first insulation wrap of the outer cable is the same as for the inner cable. The second layer is 50% overlap wrap of 25 μm Kapton in HGQ01 and a butt-wrap of 50 μm Kapton in HGQ02. In both coils, the outer Kapton layer is coated on one side with 3M 2290 epoxy in HGQ01 and with QIX polyimide adhesive in HGQ02. In each quadrant the inner-outer coil splice is made radially beyond the magnet lead end through a pole turn to pole turn transition.

The coils are supported in the body and the non-lead end by free-standing stainless steel collars. The coil lead end and the inner-outer coil splice are clamped with a 4 piece G-10 collet assembly enclosed in a tapered aluminum cylinder. Iron yoke laminations surround the collared coil and a welded 8 mm thick stainless steel skin surrounds the yoke. At both ends 50 mm thick stainless steel endplates are welded to the skin to provide support for longitudinal Lorentz forces.

Both HGQ01 and HGQ02 were protected with inner strip heaters. The heater design was based on previous studies [4] [5]. The heaters are 25μm thick, 15.9 mm wide, stainless steel strips sandwiched in two layers of 25μm thick Kapton film, and located radially between the inner and outer coil. They are separated from both coils by two layers of 125 μm and 75 μm Kapton sheets. The heaters cover approximately 10 turns of the inner coil and 12 turns of the outer coil for all octants. For HGQ02 additional outer strip heaters of the same design were installed on the outer surface of the outer coil. The outer strip heaters are separated from the outer coils by two layers of 125 μm and 75 μm Kapton sheets. The cold resistance of the heaters are approximately 5 Ω.

In addition, HGQ02 has spot heaters covering a 2.5 cm length of conductor installed in two positions for studying quench propagation and peak temperatures. The inner spot heater is located on the inner conductor portion of the inner-outer coil transition region, approximately 3 cm from the inner pole turn straight section and well within the body field of the magnet. The outer spot heater is located on the midplane coil lead.

Both magnets are instrumented with 96 voltage taps, distributed primarily over the inner and outer pole turn, inner-outer transition and inner coil wedges.

III. Experimental Procedure

0HGQ01 was tested in February-March of 1998 and HGQ02 was tested in June of 1998 at the at the Fermilab Technical Division vertical magnet test facility (VMTF)[6]. VMTF utilizes a vertical dewar designed to operate with superfluid and normal helium at 1.1 atmosphere. Magnet current is supplied with a 16 kA DC power system with an energy extraction circuit (dump resistor). Strip heater and spot heater voltage was supplied by a 14 mF capacitance, 450V maximum voltage Heater Firing Unit (HFU). During our tests two strip heaters were typically connected in parallel. The system resistance was low relative to the strip heater resistance such that 92 percent of the HFU energy was deposited into the heaters.

The test program for both magnets consisted of quench training and magnetic field measurements in addition to the magnet protection studies. The results of the training and magnetic measurement studies are presented elsewhere [7], [8].

The goals of the quench protection studies were to measure the effectiveness of the strip heaters in the two radial locations by measuring the minimum voltage for heater firing, heater delay times, the peak voltages and temperatures as a result of quenches. Quench velocities were also measured which will be useful in understanding the propagation of the resistive voltage growth.

Data were collected from quenches initiated from "strip heater induced" and "spot heater induced" quenches. The strip heater quenches were used to study the time delay, t_{fn} between protection heater current initiation and the presence of a detectable quench voltage in the outer coils as a function of various heater, HFU and magnet parameters. An important parameter is the minimum heater voltage required to induce a quench (V_{min}). This voltage, and the subsequent t_{fn} have design implications for the LHC quench detection and HFU hardware. The start time of a quench was determined by tracing back the voltage rise in the coil to the last digitized data point which was below the 2σ noise level.

The spot heater induced quenches were used to study peak voltages, quench integral and quench velocities. The spot heaters were fired using a dedicated HFU, the heater voltage set to twice the minimum quench initiation voltage. The quench detection threshold was set to 300 mV. Upon quench detection, the power supply was promptly turned off, the strip heaters fired promptly and the dump extraction circuit was delayed 1 second to allow the magnet to dissipate its stored energy.

IV. Results and Discussion

A. Strip Heater Performance

First, the minimum HFU voltage required to quench the magnet as a function of excitation was determined. We expect the required voltage to decrease monotonically with increasing excitation current, as the conductor operating point becomes closer to the critical surface. This trend is observed in Fig. 1 where the minimum HFU voltage required to quench the magnet is plotted as a function of the normalized magnet current. From this one can conclude that, setting the HFU voltage to a minimum of 250V will insure that a quench, can always be initiated for $I/I_c > 0.2$.

For a full length (∼6 m) production magnet, a 900 V power supply would be required. This voltage is feasible for the power supply system and poses no voltage breakdown risk to the magnet. However, to reduce the HFU voltage and power consumption we will test in future magnets new heater designs with longitudinally distributed resistance.

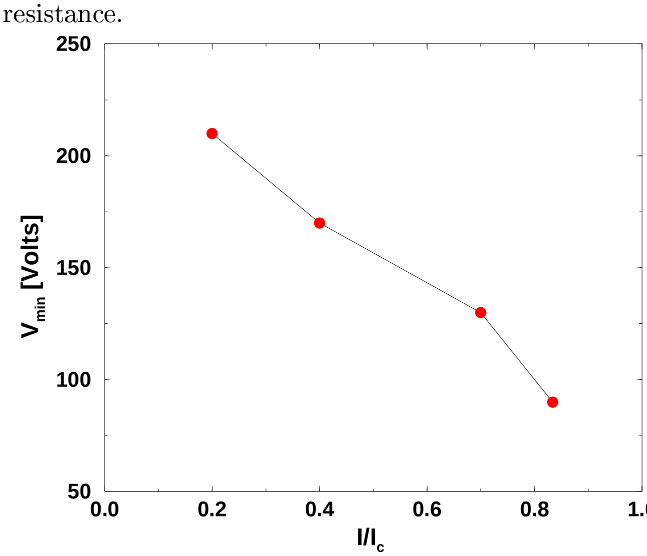

Fig. 1. Heater induced quenches. Minimum heater voltage to quench the magnet vs. normalized current at quench.

Having established the minimum heater voltage, the heater response time t_{fn} (Fig. 2) is measured as a function of I/I_c at fixed HFU voltages for inner and outer strip heaters. As shown, there is essentially no difference in the heater response for HGQ01 inner strip heaters from 250V-400V. There is as well good agreement between HGQ01 and HGQ02 inner strip heaters. HGQ02 inner strip vs. outer strip heaters show no difference in response indicating they are equally effective in initiating quenches.

It is interesting to further compare the performance of the inter layer and outer layer heater. The t_{fn} for both inner and outer heater is set by the resistive growth in the outer coil. We observe that for the inner strip heater, the t_{fn} contribution from the inner coil is retarded relative to the outer coil, despite the fact that the inner coil is in a higher magnetic field. This delay is likely due to the inner coil cooling channels which increase the liquid helium wetted surface between the inner strip heater and the inner coil. The inter and outer heaters have comparable t_{fn} for the outer coil because the heater insulations are nearly identical and the magnetic field across the outer coil conductor is fairly uniform in the vicinity of the heaters.

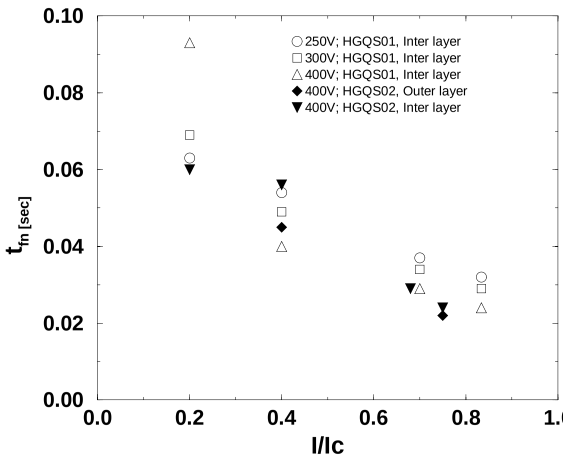

Fig. 2. t_{fn} is plotted as a function of I/I_c at a fixed HFU voltages.

B. Peak Voltage

High voltages can develop as a consequence of the magnet quench and subsequent heater protection. This effect was studied during the spot heater induced quench program. The peak voltage is defined as the maximum measured voltage across any inner or outer coil during the quench. The results are shown in Fig. 3 for quenches induced with the inner spot heater and protected with either the inner or outer strip heaters. The peak voltage generated with the inter strip heater is roughly a factor of 2 lower than the outer strip heater. The lower peak voltage observed with the inner strip heater is likely due to the better distribution of resistive voltage to both inner and outer coils. In the case of the inner strip heater, the peak voltage was less than 30 volts at 11kA; a simple extrapolation of the voltage for a full length production magnet at critical current of the short sample gives a peak voltage of less than 200 volts, in good agreement with expectations [9].

C. Quench Integral

The quench integral in MIITs ($10^6 A^2 s$) is plotted in Fig. 4 as a function of the applied current for quenches induced with the inner spot heaters and protected either with the outer (solid symbols) or inner (open symbol) strip heaters. There are three family of curves; the upper set represents the quench integral with a starting time at the onset of the spot heater induced resistive voltage, the middle set are the quench integral with a starting time corresponding to the 300 mV quench detection, and the lower set represents the quench integral from the onset of voltage growth in the outer coil due to the strip

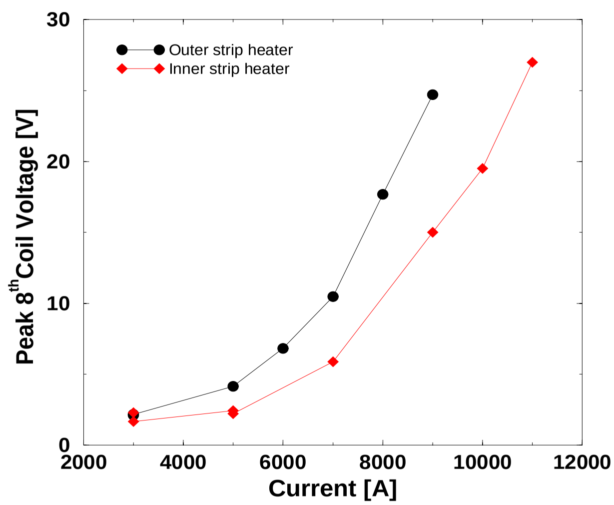

Fig. 3. Measured Peak Coil voltage is plotted as a function of the magnet current.

heaters. The full quench integral has a peak value of about 19 MIIT's using either protection heater. This corresponds to a inner coil peak temperature of about 200K [9]. Therefore the quench protection system is capable of protecting the magnet for inner coil quenches. The inner strip heaters are slightly more effective than the outer strip heaters. For these spot heaters, the quench detection delay time is a significant contribution to the overall MIITs budget.

For these magnets it was not possible to measure the MIIT's from an outer pole turn quench. The quench detection contribution to the MIITs is expected to be much smaller due to the increased cable resistance and the faster quench velocity (as shown below).

Studies using the outer spot heater has been performed and presented elsewhere [10]. We observed 15 MIITs at 5 kA excitation current which corresponds to 300 K. Approximately 8 of the 15 units of MIIT's are attributed to quench detection due to the slow quench propagation from the spot heater to the magnet midplane and then through the magnet. The large quench integral and subsequent temperature at such a low current indicates that for the production magnets the leads need to be properly stabilized against the event of a lead quench.

As for quenches in the magnet midplane during accelerator operation, most likely due to beam heating, the resistive voltages will be rapidly generated and the quench integral will be much lower. In future magnets, we plan to install spot heaters near the pole turn and midplane of the outer coil to obtain a more direct measurement of the magnet quench integral and peak temperature.

V. Quench Propagation Velocities

The quench propagation velocity was determined using a "time of flight" technique. The basic idea of this technique is to determine the time needed for the quench to propagate between voltage taps separated by a known

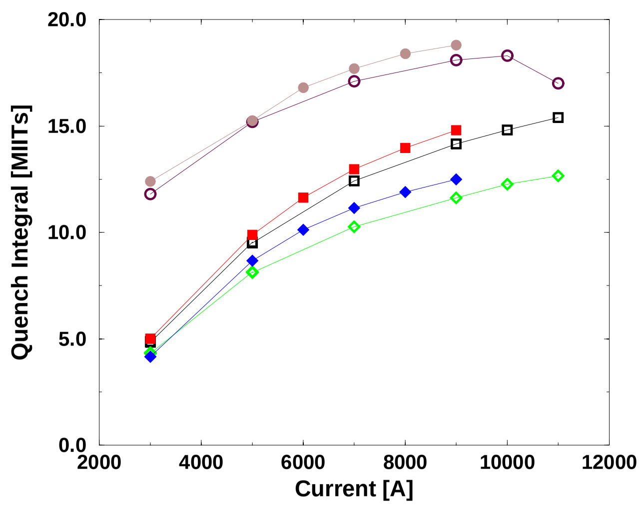

Fig. 4. Quench integral vs. magnet current for spot heater induced quenches. Magnet protected with inner (open symbol) or outer strip heater (solid symbol), circle symbol: quench integral from time of spot heater quench initiation, square symbol: quench integral from quench detection time, diamonds: quench integral from strip heater voltage onset.

distance. The start time of a quench in a voltage tap segment was determined by tracing back the voltage rise in the segment to the last point 2σ below the noise. The difference between this start time and the start time of the adjacent segment was used to determine the velocity. In some cases, the change in slope of the segment where the quench was initiated was used to indicate that the quench had moved to an adjacent segment rather than using the start time of the adjacent segment itself.

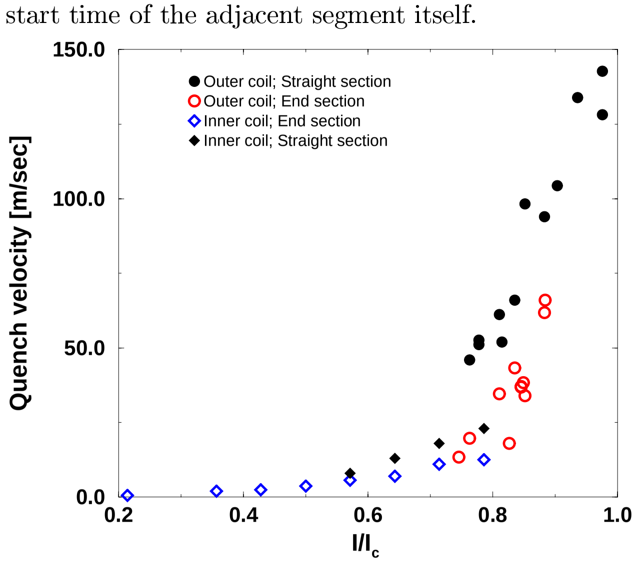

Fig. 5. Quench propagation velocity as a function of I/I_c.

Both spontaneous and spot heater induced quenches were used to measure quench propagation velocities.

Quench propagation velocity as a function of the normalized current (I/I_c) is plotted in Fig. 5, for pole turn inner and outer coil quenches. From Fig. 5 one observes the expected increase in quench velocity with increasing excitation current, with the large increase as the current approaches short sample critical current. The quenches in the end region are systematically slower than those in straight section at the same excitation current. This is expected as the ends are in a lower magnetic field. The quench velocity in the outer coil is also higher than in the inner coil.

VI. Conclusion

Quench protection tests have been performed on two high gradient quadurpole models. Both the inner and the outer layer strip heaters are capable of initiating quenches with acceptable values of HFU voltage, t_{fn} and peak voltage. The inner pole turn of one magnet was instrumented with a spot heater. Studies using this heater indicate that the inner conductor peak temperature during a quench is low (200 K) using either set of strip heaters. Quenches initiated from the outer coil midplane show that the coil leads need to be stabilized. The leads will be stabilized in future magnets.

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