QUENCH PROTECTION OF SC QUADRUPOLE MAGNETS

S. Feher, R. Bossert, J. DiMarco, D. Mitchell, M.J. Lamm, P.J. Limon, P. Mazur,
F. Nobrega, D. Orris, J.P. Ozelis, J.B. Strait, J.C. Tompkins, A.V. Zlobin,
Fermi National Accelerator Laboratory*, P.O. Box 500, Batavia, IL 60510, USA
A.D. McInturff, Lawrence Berkeley National Laboratory*, Berkeley, CA USA

Abstract

The high gradient quadrupole (HGQ) being developed for the LHC interaction regions by the collaboration of FNAL/LBNL/BNL[1], relies on the use of quench protection heaters. As part of the HGQ R&D program at Fermilab, Tevatron low-β quadrupoles installed with quench protection heaters were tested in normal and superfluid helium. This paper focuses on heater operation time delay and quench propagation velocity measurements since these are important input parameters for designing the quench protection system of the HGQ.

1 INTRODUCTION

The energy stored in a superconducting (SC) accelerator magnet is dissipated after a quench in the normal zones, heating the coil and generating a turn to turn and coil to ground voltage drop. The propagation velocity of the normal zone is usually low relative to the heating rate of the cable and the cable temperature will rise so high that it will damage the cable. Quench heaters are used to protect the SC magnet by greatly increasing the coil normal zone thus allowing the energy to be dissipated over a larger conductor volume making the protection to be less dependent on the quench propagation velocity. Such heaters will be required for the HGQ.

Without overheating the cable or developing too high voltages, the ellapsed time between the quench origin and the start time of the stored energy dissipation in the heater quenched part of the coil is usually quite short, for HGQ this value is in the order of a few millisecond[2]. This time depends mainly on the quench propagation velocity and the time delay of the heater operation. The study of these important parameters in normal and superfluid helium as part of the HGQ R&D program has been started at Fermilab on low-β (LBQ) quadrupoles[3, 4]. This paper presents experimental results on a LBQ (R54002) heater operation time delay and quench propagation velocity.

2 MAGNET DESCRIPTION

The magnet R54002 for this study is a modified 1.4 m long Tevatron low-β quadrupole. Details of the baseline design have been described elsewhere[5, 6]. This cold iron superconducting quadrupole has two layer coils with a 76 mm diameter bore. There are copper wedges in the inner coils whose primary purpose is to minimize the geometric 12- and 20-pole harmonics. Four inner to outer coil splices are located in the magnet lead end radially beyond the outer coil and are made through pre-formed solder-filled cable originating from the lead end pole turn.

The inner and outer coils are made from 36 strand Rutherford cable. The strands are 0.528 mm in diameter and contain 13 μm filaments. The cable insulation is made of 25μm thick and 9.53 mm wide Kapton tape covered both side with B-stage epoxy. Kapton tape is wrapped with 67% overlap forming three layer of insulation with total thickness of 75μm and 1-1.5 mm gaps in the outer insulation layer.

The coils are supported in the body by aluminum collars. The coil lead and return ends are clamped with a 4 piece G-10 collet assembly enclosed in a tapered cylindrical can. Iron yoke laminations surround the coil in the body region, and stainless steel laminations surround the end region cylindrical can. A welded stainless steel skin surrounds the yoke.

The quench protection heaters are 25μm thick and 12.5 mm wide stainless steel strips and are located radially beyond the outer coil, in the middle of four layers of 125 μm Kapton sheets. One heater covers approximately 12 turns of two midplane-adjacent outer coils. This is accomplished by running the heater longitudinally along the body of the magnet and making appropriate folds on the heater in the magnet return end region. Two heaters oriented 180 degrees apart provide coverage for one side of each of the four outer coils. The resistance of the heater for coils A and B was 5.5 Ω, and that for C and D was 5.0 Ω. The system resistance (including cabling from the Strip Heater Firing Unit (SHFU) to the magnet) was 3.0 Ω , which means that $\sim$85.5 % of the SHFU voltage was deposited directly to the heaters.

The 69 voltage taps that instrumented R54002 allowed for localization and determination of propagation velocity for most quenches. Magnet was tested at the Fermilab Technical Division horizontal test facility[7].

3 HEATER TIME DELAY

The heater time delay (t_{fn}) is the time from protection heater current initiation to the presence of a detectable quench voltage in the outer coils. Figure 1 shows the time diagram of the heater and magnet voltage and an example of the t_{fn} determination.

The heater time delay as a function of voltage applied to heaters is shown in Figure 2. As one can see, at the lower heater energies (close to V_{min}) the t_{fn} increases rapidly

---

[*] Supported by the U.S. Department of Energy

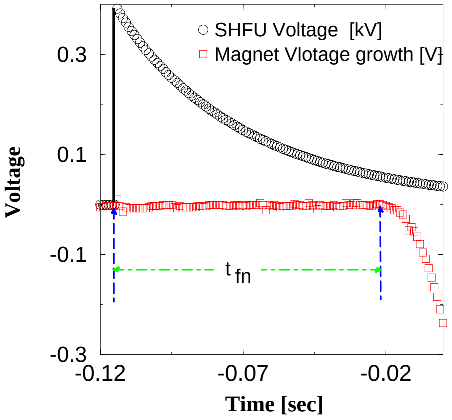

Figure 1: Heater and magnet voltage vs. time.

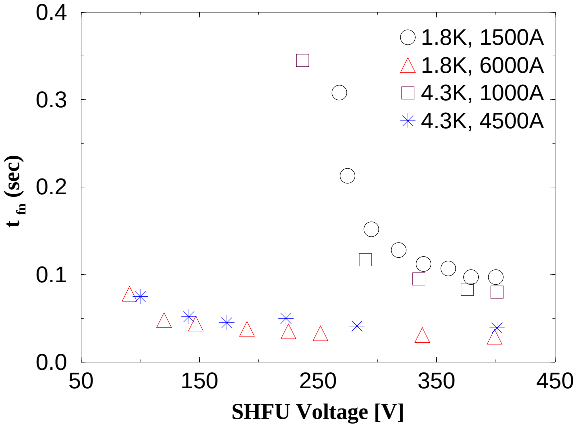

Figure 2: t_{fn} vs. the heater voltage.

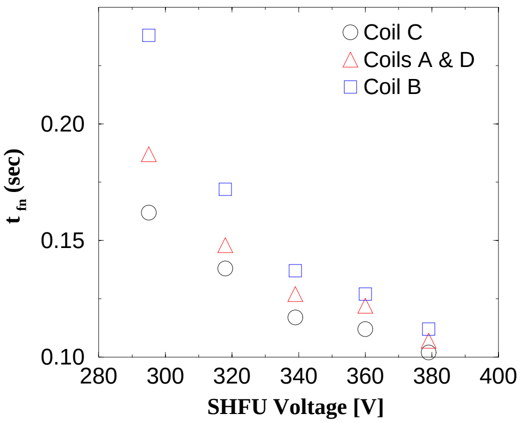

Figure 3: t_{fn} is plotted for each of the four coils in contact with the heaters vs. SHFU voltage at $I/I_c = 0.2$

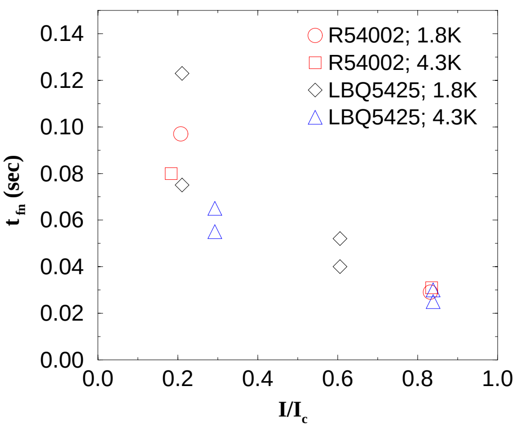

Figure 4: t_{fn} as function of I/I_c. R5425 is a previously tested Tevatron low-β quadrupole[4].

while at higher energies t_{fn} levels off. At sufficiently large SHFU voltage ($>$ 300 V), t_{fn} does not change significantly with changes in SHFU voltage and magnet operating temperature.

In Figure 3 we plotted t_{fn} for each of the four coils in contact with the heaters as a function of the SHFU voltage. These data are at 1.8K He bath temperature and 1500A magnet current. At low SHFU voltages, the coils show quite a large absolute spread in their t_{fn} values. It could be indicative of small differences in the magnet construction favoring the quenching of some coils over others. At larger SHFU voltages this spread decreases and all four coils quench with similar t_{fn}. Therefore to avoid an unreasonably large spread of the individual coil t_{fn} values, the SHFU voltage should be set sufficiently high with respect to the coil which has the largest t_{fn}.

In Figure 4 heater time delay is plotted as a function of normalized current (I/I_c) at a fixed and relatively high SHFU voltage. The I_c used in the plots for current normalization, correspond to the expected short sample limit of the magnet (5400A @ 4.3K and 7150A @ 1.8K)[3]. It shows an order of magnitude decrease of the heater time delay as magnet current approaches the critical value. At operating currents 10-15% below the I_c the time delay becomes rather small, less than 20-30 ms. This suggests that the heater time delay does not depend significantly on the magnet operation temperature. The penetration of superfluid helium in the coil (if it indeed takes place) does not affect the value of the heater time delay at high operating currents.

4 QUENCH PROPAGATION VELOCITY

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 distance. Figure 5 shows the signals collected with voltage taps during a magnet spontaneous quench. The start time of a quench in a voltage tap segment was determined by tracing back the voltage rise in the segment to the first point 3σ above the

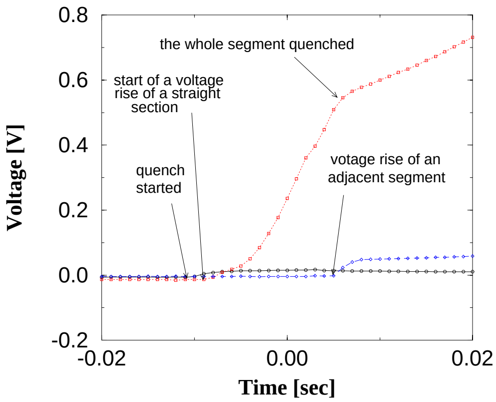

Figure 5: Voltage rise diagram.

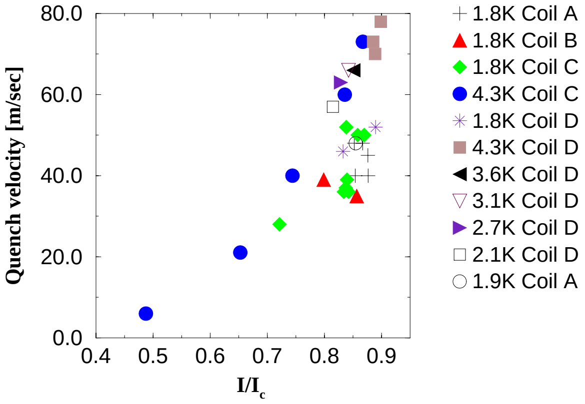

Figure 6: Quench velocity as a function of I/I_c.

noise. In some cases the end time was determined by the change of the slope of the voltage growth in the segment where the quench was initiated, rather than the difference between the start times in adjacent segments.

Longitudinal quench propagation velocity as a function of the normalized current (I/I_c) is plotted in Figure 6. It is increasing with the magnet operating current and 15% below the magnet critical current it is already quite high, more than 60 m/sec. From Figure 6 one can conclude that the longitudinal quench propagation velocity as a function of the normalized current does not change with temperature in the interval between 2.1-4.3K. However, dramatically lower values were observed at superfluid helium temperatures between 1.8-1.9K. This effect might be explained by the better cooling condition of the cable in superfluid He.

Quenches which occurred close to voltage tap located near the pole turn of the coil could be used to measure turn to turn quench propagation velocity using the voltage taps on the next turn. The turn to turn quench propagation times as a function of the normalized current at quench are shown in Figure 7. The turn to turn quench propagation time decreases as the operating current aproaching the magnet critical current. The experimental data obtained at relatively high normalized current ($I/I_c \sim 0.8 - 0.85$) indicate that turn to turn quench propagation time monotonically decreases as the temperature is droping from 4.3K to 1.8K.

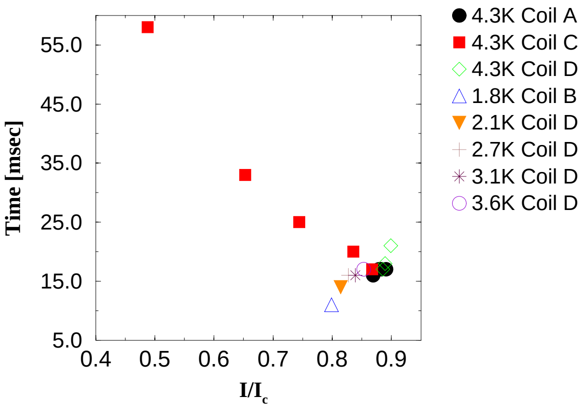

Figure 7: Turn to turn quench propagation time as a function of the normalized current at quench.

5 CONCLUSIONS

It was observed that at sufficiently large heater energies the heater time delay does not change significantly with changes in the applied heater energy and magnet operating temperature. Significantly lower longitudinal quench propagation velocity was observed for quenches taken at 1.8-1.9K temperature range relative to those taken at 2.1-4.3K. At fixed normalized current value the turn to turn quench propagation velocity however increases as the temperature decreases from 4.3 to 1.8K.

6 REFERENCES

[1] R. Bossert et. al., ”Development of a High Gradient Quadrupole for the LHC Interaction Regions”, ASC’96, Pittsburg (1996).

[2] A.V. Zlobin,”Quench Protection of a High Gradient Quadrupole for the LHC Interaction Regions”, ASC’96, Pittsburg (1996).

[3] R. Bossert et. al., ”Test of Fermilab Low-β Quadrupoles”, ASC’96, Pittsburg (1996).

[4] A. Lietzke et. al., ”Superfluid Performance of Tevatron IR Quad Heaters”, ASC’96, Pittsburg (1996).

[5] “D0 Low-β Quadrupole Requirements and Specifications #10,” Fermilab Technical Support Section Internal Document, February 15, 1990.

[6] A.D. McInturff et. al.,”The Fermilab Collider D0 Low-β Sustem”, EPAC, Rome, Italy, Vol.2, p.1264, June 1988.

[7] J. Strait et. al.,”Fermilab R&D Test Facility for SSC Magnets”, Supercollider 1, p. 61 (1989).