TEST RESULTS OF SHORT MODEL QUADRUPOLES FOR THE LHC LOW-BETA INSERTIONS*

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Abstract

A quadrupole is being developed for the LHC low-β insertions by Fermilab and LBNL. A series of short model magnets is being built to optimize the design and refine assembly methods. This paper presents results of two short model magnet tests performed in normal and superfluid helium, summarizing the quench and mechanical performance of the short model magnets. Results on quench protection heater studies are also presented.

1 INTRODUCTION

The magnets (HGQ01 and HGQ02) for this study are 1.9 m long quadrupoles. Details of the baseline design have been described elsewhere[1, 2]. These cold iron superconducting quadrupoles have two-layer cos(2θ) coils with 70 mm diameter bores.

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. The end parts are made of G10 for HGQ01, and of Ultem for HGQ02.

The coils are supported in the body and the non-lead end by free-standing stainless steel collars. The coil lead end is 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.

Azimuthal prestress (measured to within 3 MPa) of HGQ01 at room temperature for inner (outer) coils was 67 (71) MPa. For HGQ02 the average azimuthal prestress was 76 (94) MPa for the inner (outer) coil. Longitudinal end prestress (measured to within 0.5 kN) for HGQ01 was 1.3 kN per quadrant. Between the test cycles the longitudinal end preload for HGQ01 was increased to 26.7 kN per quadrant. HGQ02 longitudinal preload for the lead end was 11.1 kN per quadrant and for the non-lead end it was 7.6 kN per quadrant.

Both HGQ01 and HGQ02 were protected with quench heaters. 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 heaters were installed on the outer surface of the outer coil. In addition, HGQ02 has spot heaters installed at the pole turn and midplane region close to the lead end of the magnet.

Both magnets are instrumented with 96 voltage taps. Pole turns and turns around wedges are each instrumented with four voltage taps, located close to the end section of the coil. This arrangement allows us to distinguish between coil end and straight section quenches.

2 MECHANICAL AND QUENCH PERFORMANCE

These magnets were tested at the Fermilab vertical magnet test facility (VMTF)[3]. VMTF is designed to operate with superfluid helium (at 1.9K) as well as normal helium at 1.1 atmosphere. HGQ01 was tested twice: in February and in March of 1998. HGQ02 was tested in June of 1998.

Coil azimuthal stresses and longitudinal end force measurements were made on each excitation cycle. These data indicate that the azimuthal support of the coils is adequate for both magnets HGQ01 and HGQ02. (See Figure 1.) No unloading of the coils was observed at the highest operating currents reached by these two magnets; it further appears that positive coil stress would be maintained at maximum field gradient. Indeed, few quenches originated in the collared coil part of both magnets. (See Table 2.)

Figure 2 shows a typical longitudinal coil force measurement for magnet HGQ01. No end force was observed at the non-lead end below 7000 A, indicating that the coil had shrunk more with cool-down than the cold mass shell. The slope of end force with current represents

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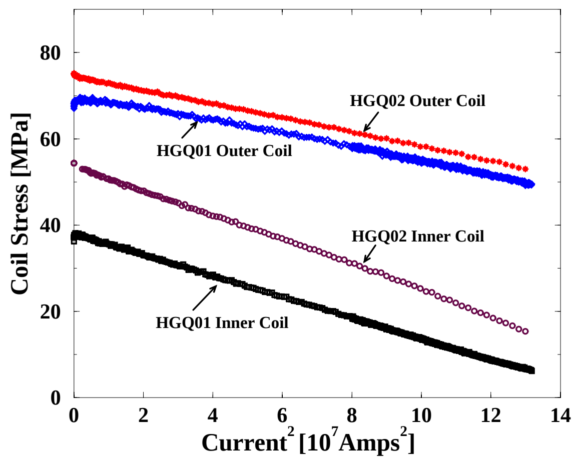

Figure 1: Azimuthal coil stress change due to Lorentz forces as measured by strain gauges.

about 20% of the calculated Lorentz force. For the second cryogenic test cycle, additional longitudinal load was applied to the coils to compensate for the cool-down loss. This additional load was sufficient to produce coil-end plate contact even at zero excitation current.

The room temperature longitudinal end force applied to HGQ02 was intermediate between that applied for the two test cycles of HGQ01. It was observed that this end preload was insufficient to maintain coil-end plate contact in all quadrants at zero or low currents. Further, the current threshold for the observation of positive end force decreased with successive excitation cycles indicating irreversible longitudinal motion of the coils has occurred.

Data for coil azimuthal and longitudinal stress/force dynamics under various operating conditions are summarized in Table 1.

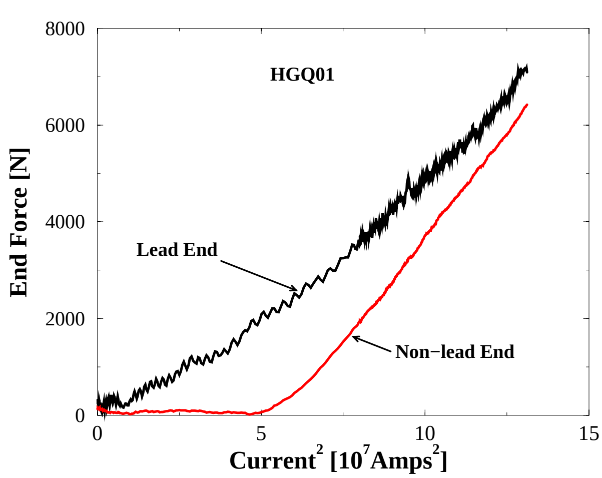

Figure 2: A typical longitudinal coil force measurement.

Table 1: Mechanical Performance of HGQ Coils

	unit	HGQ01	HGQ02
Inner Coil Cool-down Stress Change	MPa	30-32	11-13
Outer Coil Cool-down Stress Change	MPa	13-14	3-10
Inner Coil Lorentz Loss (azimuthal)	MPa/A^2	2.8x10^{-7}	3.0x10^{-7}
Outer Coil Lorentz Loss (azimuthal)	MPa/A^2	1.3x10^{-7}	1.4x10^{-7}
Lead End Longitudinal Lorentz Force	N/A^2	1.0x10^{-4}	8.2x10^{-5}
Non-lead End Longitudinal Lorentz Force	N/A^2	9.7x10^{-5}	8.2x10^{-5}

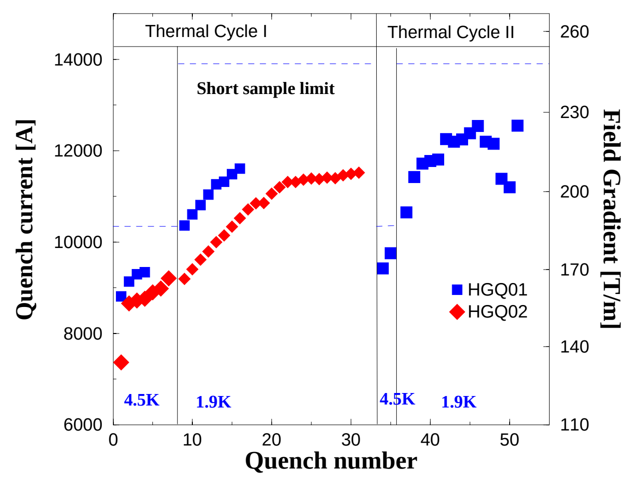

Figure 3: Quench training history.

The training histories for the magnets are presented in Figure 3. At 4.5 K HGQ01 achieved 8776 A on the first quench and three additional quenches increased the quench current to 9342 A, about 15% below the critical current. Then HGQ01 was quenched 8 times at 1.9K with a monotonic quench current increase of 100–300 A per quench. As at 4.5 K, the quench current at 1.9K ceased to increase significantly even though it was below the predicted short sample limit of 13900 A. After a thermal cycle to 300 K, the magnet was quenched twice at 4.5 K with both quenches below the short sample limit. The magnet was cooled to 1.9 K and quenched 15 more times. It reached a peak gradient of 219 T/m, but then exhibited erratic behavior. No significant improvement in quench performance was observed due to the increase of the end preload on the second cool-down.

At 4.5 K HGQ02 achieved 7366 A on its first quench. Then HGQ02 was quenched six more times at 4.5 K. At 1.9 K HGQ02 achieved 9191 A on the first quench and required 23 quenches to reach its plateau of 11500A, corresponding to 207 T/m. During the quench training program for both magnets a dump resistor extracted about 50% of the stored energy.

Quench locations for both magnets are summarized in Table 2. HGQ01 quenches were dominantly at several locations in the outer body-end transition regions. Most of the HGQ02 quenches were at one specific location in the inner end, beyond the body-end transition region.

Table 2: Quench origin

Quench location	HGQ01	HGQ02
Outer coil; Lead End	9	2
Inner coil; Lead End	1	4
Outer coil; Non-Lead End	21	2
Inner coil; Non-Lead End	4	17
Outer coil; Straight Section	3	1
Inner coil; Straight Section	2	1

Measurements of the outer coil ends performed later on similar coils suggested that coils in HGQ01 had insufficient azimuthal preload. Therefore we increased the azimuthal outer coil end preload of HGQ02. Compared to magnet HGQ01, the quench locations in HGQ02 changed from the outer coil to the inner coil and from the collared coil - end transition region to a region closer to the end of the coil. Detailed mapping of the end section of subsequently fabricated coils revealed an uneven coil size distribution along the length of the end. This again suggests that azimuthal end preload of the inner coil is not uniformly sufficient even in HGQ02.

3 QUENCH PROTECTION STUDY

The quench protection scheme for these magnets will rely on the use of protection heaters. Heater operation time delay (t_{fn}) and quench propagation velocities are important input parameters for designing the quench protection heaters. These parameters were extensively studied [5, 6] as part of the HGQ R&D program using Fermilab Low-β quadrupoles and are also part of the HGQ01 and HGQ02 test plan.

To test directly the magnet quench protection scheme, spot heater induced quenches were taken with the dump circuit set to allow the magnet to absorb its stored energy. Inner and outer coil spot heaters initiated quenches and both outer and interlayer heaters protected the magnet. The quench integral in MIITs ($10^6 A^2 s$) is plotted in Figure 4 as a function of the applied current. The quench integral has a peak value of about 19 MIITs for inner coil quenches, corresponding to a peak temperature of about 200K [4]. Therefore the quench protection system is capable of protecting the magnet for inner coil quenches. The interlayer heaters are slightly more effective than the outer heaters. Outer midplane spot heater induced quenches generated 15.3 MIITs at 5000 A. This corresponds to a peak temperature of 300 K [4], preventing the repetition of these tests

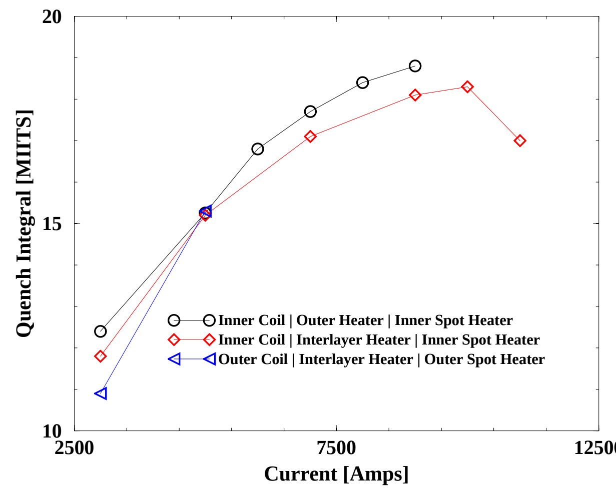

Figure 4: Quench integral vs. magnet current

at higher currents. The quench protection of the outer coil requires additional study and further optimization.

4 CONCLUSIONS

Two LHC High Gradient Quadrupole short model magnets were tested. Both magnets achieved field gradients higher than that required in the LHC under collision condition; however, their quench performance is not yet satisfactory. The quench currents appears to be mechanically limited. Although the body preload is adequate, the end azimuthal and/or longitudinal preload seems to be insufficient to prevent conductor motion. Quench protection heater studies showed that the magnet can be protected for inner coil quenches; however, outer coil quench protection will require further study.

5 REFERENCES

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