Quench Behavior of Quadrupole Model Magnets for the LHC Inner Triplets at Fermilab

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***Abstract*—The US-LHC Accelerator Project is responsible for the design and production of inner triplet high gradient quadrupoles for installation in the LHC Interaction Region. The quadrupoles are required to deliver a nominal field gradient of 215T/m in a 70mm bore, and operate in superfluid helium. As part of the magnet development program, a series of 2m model magnets have been built and tested at Fermilab, with each magnet being tested over several thermal cycles. This paper summarizes the quench performance and analysis of the model magnets tested, including quench training, and the ramp rate and temperature dependence of the magnet quench current.**

I. Introduction

The magnets being developed for the LHC Interaction Region inner triplets are 2m long cold iron superconducting quadrupoles with 70 mm diameter bores. They consist of two-layer $cos(2\theta)$ coils made of Rutherford NbTi cable supported in the body by free-standing stainless steel collars.

To date seven model magnets have been built and six of them have been tested as part of the magnet development program [1] at Fermilab. The first three model magnets achieved field gradients higher than that required in the LHC under collision condition; however, their quench performance was not satisfactory. They exhibited long and slow quench training [2] and also significant retraining was observed on HGQ03.

To improve the quench performance of the model magnets, several design and manufacturing modifications were implemented. Details of the baseline design and the design optimization are described elsewhere [3] [5].

Significant improvement in magnet training was achieved in HGQ05, and HGQ06 and HGQ07 were built with incremental design changes (see Table I).

Manuscript received September 29 , 1999.
This work was supported by the U.S. Department of Energy

TABLE I
HGQ Magnet Design Features

	HGQ05	HGQ06	HGQ07
Inner Cable	38 strand Right Lay	38 strand Left Lay	37 strand Left Lay
Outer Cable	46 strand Left Lay	46 strand Left Lay	46 strand Left Lay
Cable insulation	Kapton Epoxy	Kapton Polyimide	Kapton Polyimide
Inner Coil Target size	additional 0.225 mm	additional 0.175 mm	additional 0.2 mm
Inner Coil modulus	8 GPa	9.5 GPa	8.5 GPa
Outer Coil Target size	additional 0.15 mm	additional 0.175 mm	additional 0.2 mm
Outer Coil modulus	11 GPa	9.5 GPa	8.5 GPa
End Part Config.	4 block design	5 block design	5 block design
End Part Material	G10	G11	G11
End longitudinal loading	2000 lbs. per bullet [a]	2000 lbs. per bullet	No end load [b]

[a]Thermal Cycle 3 – no end load at the return end of the magnet.
[b]Thermal Cycle 3 – end load to be applied at both ends of the magnet.

II. Test Results

The magnets for this study were tested at the Fermilab vertical magnet test facility (VMTF) [9]. All of the magnets were tested at normal helium temperature first, then cooled down to 1.9K. After training the magnet with spontaneous quenches (20A/sec ramp rate), ramp rate dependence studies were performed, followed by quench protection heater studies and magnetic measurements (including cleansing quenches at 10000A). The thermal cycle was then finished with temperature dependence studies. HGQ05 went through three, HGQ06 and HGQ07 (to date) through two thermal cycles. Between thermal cycle two and three, return end longitudinal preload for HGQ05 was reduced to zero. During training of the magnets about 70% of the stored energy was extracted and dissipated into an external dump resistor. Fig. 1 shows the quench history for HGQ05, HGQ06, and HGQ07 to date.

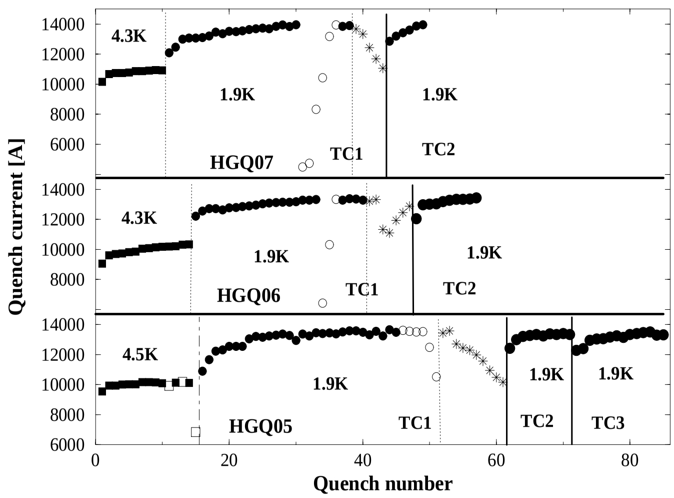

Fig. 1. Quench history of three LHC model magnets (heater and cleansing quenches not shown). The training quenches were taken at the nominal 20A/sec ramp rate. The open circles and open squares represent ramp rate dependence, and the stars represent temperature dependence quenches.

A. Quench Training

The magnet training results are presented in Figs. 2-4. At normal helium temperature, after short training, HGQ05 and HGQ07 reached the estimated critical current value of the conductor based on critical current measurements of a short sample of the cable (short sample limit). The quench current of HGQ006 at 4.3K after quenching the magnet 15 times was five percent below the short sample limit.

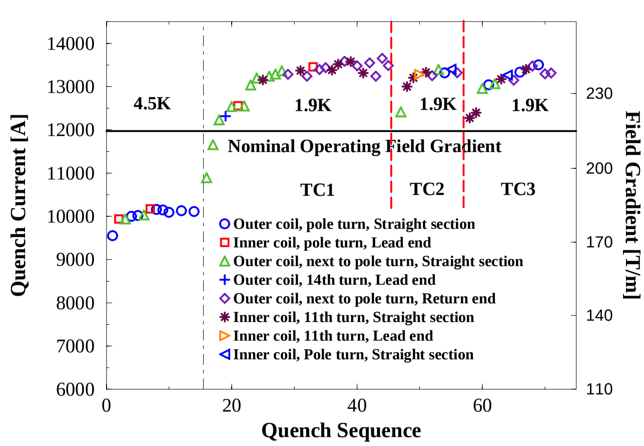

Fig. 2. Quench training of HGQ05.

The first quench at 1.9K for HGQ06 and HGQ07, and the third quench of HGQ05, was higher than the required nominal field gradient value. All three magnets partly remembered their training after the first thermal circle, and had their first quench at greater than 215 T/m field gradient value (see Table II).

Table III summarizes the quench locations. Most of the quenches for HGQ05 were outer coil quenches while

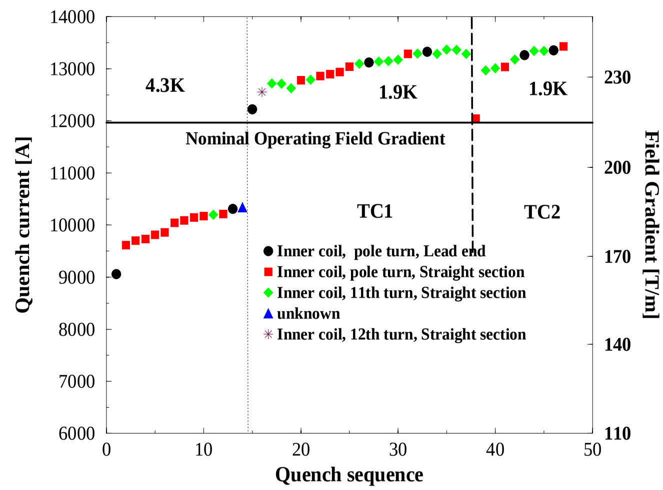

Fig. 3. Quench training of HGQ06.

for none HGQ06, and only two for HGQ07, occurred in the outer coil. This was expected: HGQ05 outer cable short sample limit was 3% lower than that of the inner cable, while HGQ06 and HGQ07 inner and outer cable short sample limits were identical to a tenth of a percent. However, it was unexpected that twice as many quenches occurred at the wedge than in the pole region when the quench current was above 13000A (see reference [3] for description of the magnet cross section).

In Table III we also divided the quench locations into two groups: body and end regions. The body of the magnet terminates where end cans take over support of the coil from the collar laminations. Although HGQ05 had many end quenches, it was not surprising since the magnet end and the body had very similar short sample limits.

The quench current values at 1.9K, normalized to the short sample limits, are shown in Fig. 5. All three magnets reached 90% of their short sample limit within ten quenches.The magnets appear to be mechanically limited for HGQ05 and HGQ07 at 97%, and for HGQ06 at 92%, of their short sample limit. Although strain gauge measurements [8] did not indicate any unloading of the coils

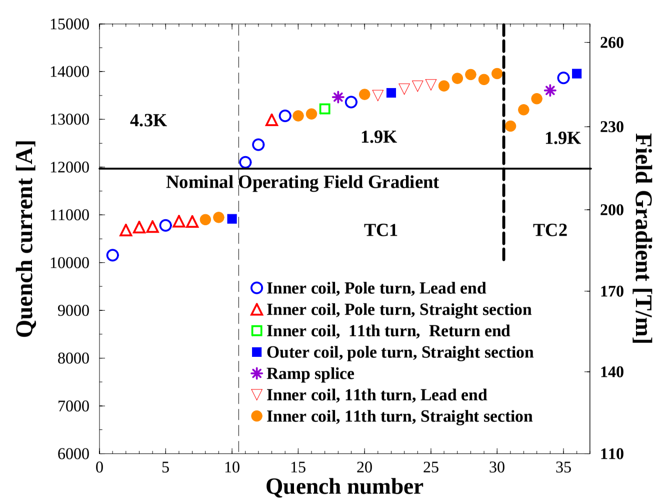

Fig. 4. Quench training of HGQ07.

TABLE II
QUENCH PERFORMANCE SUMMARY

	$I_q^{first}[A]$ TC1	Quenches $\leq 215T/m$	$I_q^{first}[A]$ TC2	Quenches $\leq 215T/m$
HGQ05	10896	2	12417	0
HGQ06	12224	0	12044	0
HGQ06	12101	0	12855	0

TABLE III
QUENCH LOCATION SUMMARY(AT 1.9K)

	HGQ05		HGQ06		HGQ07	
	Pole	Wedge	Pole	Wedge	Pole	Wedge
Inner Body	2	13	9	19	1	11
Inner End	2	1	5	0	5	5
Outer Body	4	14	0	0	2	0
Outer End	0	16	0	0	0	0

even at the very high Lorentz force levels, these magnets might still be sensitive to preload. Turns next to the wedge toward the midplane have non-radial alignment which might require greater pre-compression to prevent them from moving. HGQ06 has less preload in the inner coil than the others which might explain its lower plateau.

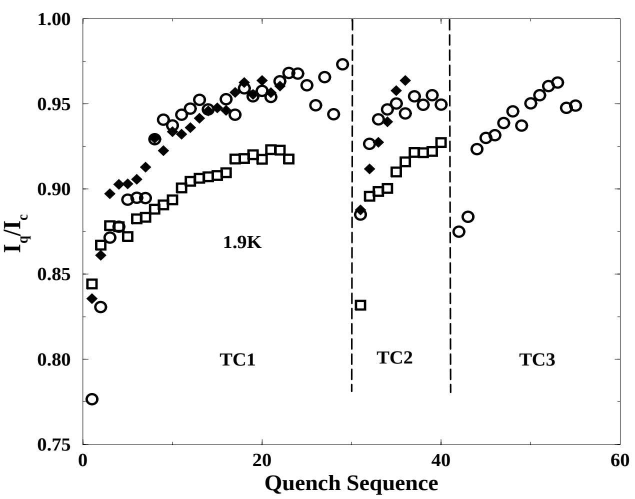

Fig. 5. Quench training history is plotted in normalized current values. Open circles correspond to HGQ05, open squares to HGQ06 and solid diamonds to HGQ07.

B. Quench Current Temperature Dependence

Quench current as a function of the helium bath temperature is plotted in Fig. 6. There was a monotonic decrease of quench current with increasing temperature for all three magnets. For HGQ05, quenches between 2.2-3.0K originated in the outer coil near one of the inter-layer splices. High resistive heating and restricted cable cooling conditions might have been responsible for the reduction of HGQ05 quench current with respect to its short sample limit. Splice cooling conditions were improved for HGQ06 and HGQ07, and indeed no quenches occurred in the splices around the lambda temperature.

The operating point for the high luminosity Interaction Region magnets is 205 T/m, but the temperature at the midplane of the coil is expected to be larger than that of low luminosity IR magnets (which operate at 215 T/m) due to higher beam losses. Under this condition the temperature margin for HGQ06 and HGQ07 is about 2.1K.

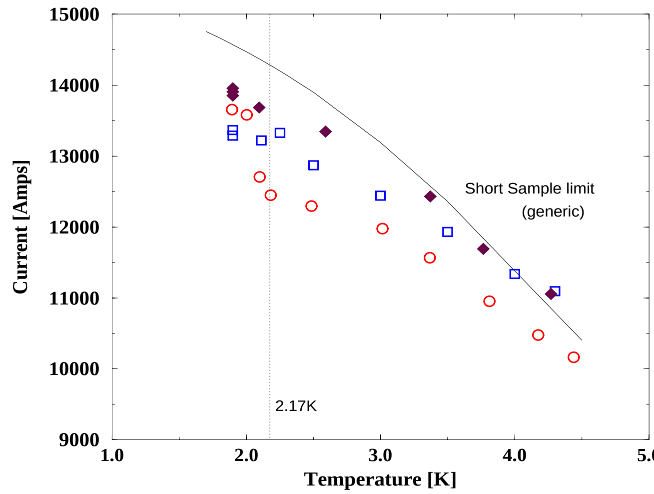

Fig. 6. Quench current temperature dependence. Circles correspond to HGQ05, squares to HGQ06 and diamonds to HGQ07.

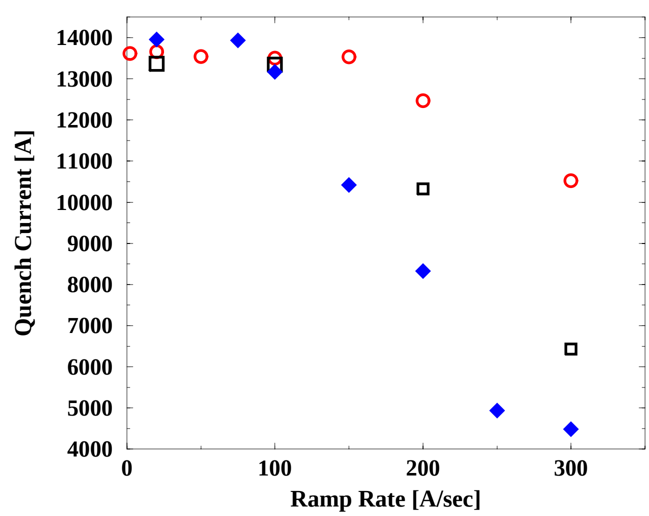

Fig. 7. Quench current ramp rate dependence. Circles correspond to HGQ05, squares to HGQ06 and diamonds to HGQ07.

C. Quench Current Ramp Rate Dependence.

Fig. 7 shows the dependence of the magnet quench current vs. ramp rate for HGQ05, HGQ06, and HGQ07. HGQ05 ramp rate sensitivity was similar to HGQ01 - HGQ03 [5]. However both HGQ06 and HGQ07 showed much lower quench current values at high ramp rates(see Table IV). While high ramp rate quenches for HGQ05 were at the inter-layer splices, for HGQ06 and HGQ07 they appeared in the midplane turn of the coil. The high ramp rate sensitivity shows direct correlation with AC loss measurements. Further analysis revealed that the interstrand resistances significantly decreased for both HGQ06 and HGQ07 inner cable due to the curing temperature and curing pressure increase.

TABLE IV
RAMP RATE SENSITIVITY

	Coil curing cycle		$I_q(300A/s)$
	Temperature	Pressure	A
HGQ05	135 C	High	10519
HGQ06	190 C	High	6433
HGQ07	190 C	High	4487

III. Conclusions

We have presented results from recent tests at Fermilab of the latest model magnets developed for the inner triplet LHC Interaction Regions. The last three model high gradient quadrupoles show satisfactory and reproducible quench performance. They quickly reached their operating gradient and exceeded their operating gradient before quenching after the first thermal cycle. Although none of the magnets achieved their short sample limit at 1.9K, the quench plateaus for all of them were well above the nominal operating current. Two thirds of the quenches were in coil turns next to the wedge. Measurements of the temperature dependence indicate an operating margin of 2.1K at 205 T/m. At less than 100 A/sec ramp rate the quench currents are well above the operating current and show no sensitivity to ramp rate. High curing temperature and pressure resulted in lower interstrand resistance, higher AC losses, and lower quench performance at high ramp rates.

Acknowledgment

The authors would like to thank the staff of the Fermilab Technical Division for their contributions to this work.

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