CHAPTER 7. Quench Performance

1. Introduction.

Magnet design and fabrication procedures have to be adequate for manufacturing reliable and reproducible magnets. A good performing magnet has sufficient current, current ramp rate and temperature margin around the required nominal field gradient. Magnet tests were important for the R&D phase of the short model magnet project, since the results were used to optimize the magnet design and fabrication procedure to obtain the required magnet performance. The goals of the quench tests were to study:

- magnet training including first quench current value, quench locations, number of quench to reach magnet short sample limit, critical current short sample limit and magnet retraining. Acceptable training was defined that the number of quenches at 1.9 K required to reach field gradient of 230 T/m to be low (in the order of 10-20) and after warming up the magnet to room temperature and cooling down to 1.9 K again the magnet will reach 220 T/m field gradient before the first quench occur.
- ramp rate sensitivity. Although the nominal ramp rate at LHC is low ~10 A/s, the ramp rate dependence study can reveal important information about heat deposition (eddy current effects in the cable) and coil cooling conditions. This study was also used to verify that the temperature margin is sufficient to operate the magnet in high radiation environment where the heat deposition in the coils is large.
- quench current temperature dependence. It gives information about the critical current short sample limit, magnet mechanical and temperature margin.
- optimization of the production test plan and schedule without any sacrifice to obtain all necessary information about magnet performance. This has a direct impact on the project cost.

Model magnet design and fabrication features are discussed in Chapters 1-4. All models have been tested at the Fermilab Vertical Magnet Test Facility (VMTF) [1] in normal and super-fluid liquid Helium in the temperature range of 1.8K-4.5K. During quench performance studies about 70% of the stored energy were extracted and dissipated in external dump resistor. Each model magnet was instrumented with voltage taps to determine the origin of each quench in the coil

2. Magnet training.

The training histories are summarized in Figure 1. Models HGQ01-HGQ07 were trained in normal and superfluid helium environment while HGQ08 and HGQ09 were trained only in superfluid helium. HGQ05 and HGQ07 went through three test cycles, the

rest of the magnet were warmed up only once to room temperature before they were tested again in liquid helium.

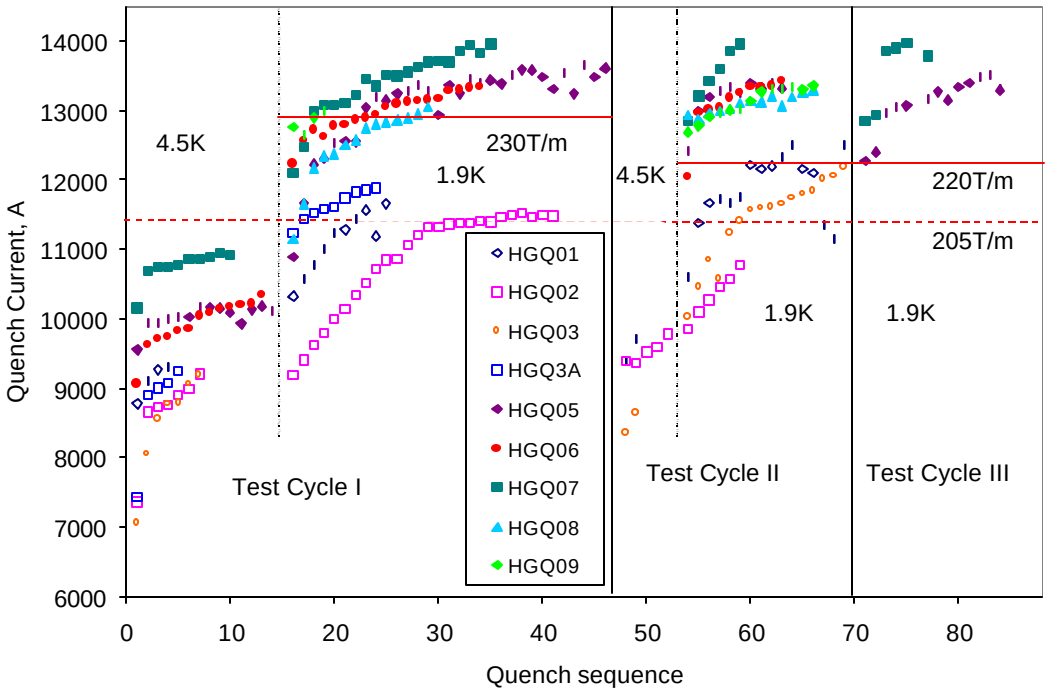

Figure.1 Quench training history for HGQ01-09. Horizontal dashed line corresponds to 205 T/m field gradient. The solid line at the first test cycle corresponds to 230 T/m field gradient which was the value to be reached during training the magnet at the first test cycle. The solid line at the second thermal cycle corresponds to 220 T/m field gradient.

A. HGQ01-04

Primary goals for building the first four model magnets were to test the quench performance of the baseline design and designs where external coil splices were replaced with internal splices and also where G10 for coil end parts were replaced with Ultem.

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 was used to extract about 70% of the stored energy.

HGQ03 was tested with free ends in TCI and then with collar-yoke interference provided by longitudinal shims.

Quench locations for HGQ01-03 are summarized in Table.

Characteristic quench locations:

HGQ01: Outer coil at body-end transition.
- Inner coil ends: 2%(LE)+10%(RE)
- Outer coil ends: 23%(LE)+53%(RE)
- Inner coil body: 5%
- Outer coil body: 7%

HGQ02: Inner coil, curved part of end in large current block.
- Inner coil ends: 20%(LE)+59%(RE)
- Outer coil ends: 6%(LE)+9%(RE)
- Inner coil body: 3%
- Outer coil body: 3%

HGQ03 and HGQ03A: Inner coil body-end transition.
-Inner coil body-end transition (67%).
-Inner coil end (13%).
-Inner coil straight section (13%).
-Outer coil end (8%).

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 (see Chapter. Coil). This again suggests that azimuthal end preload of the inner coil is not uniformly sufficient even in HGQ02.

Quench performance for the HGQ01-03 short models are summarized in Table 1. First quench currents at 4.5 K and 1.9 K as well as number of quenches required to reach 205 T/m are presented.

Table 1: Quench performance summary

Model Number	Iq1(4.5K), A	Iq1(1.9K), A	N(<205T/m)
HGQ01	8776	10327	8
HGQ02	7365	9191	23
HGQ03	7057	10019	7
HGQ03A	7438	11228	1

All three magnets achieved field gradients higher than that required in the LHC under collision condition; however, their quench performance was not 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.

Analysis of HGQ01-03 results showed that the observed poor quench performance was associated with several manufacturing and design details, such as insufficient and non-uniform coil end and end-body transition prestress, low coil end rigidity, a significant difference of thermal contraction for the Ultem spacers and conductor in the coil, longitudinal instability of the collar structure. Since HGQ04 design was similar to HGQ03 the fabrication of this model has been stopped. In spite of the fact that quench performance of these models was not perfect, the results were sufficient to make the decision choosing the internal splice configuration for the next model magnets.

B. HGQ05-09

Starting from HGQ05 a set of design and manufacturing modifications were implemented to address issues which were considered to be the causes for poor quench performance of previous model magnets. The most important changes relative to the base-line design are:

- Use of G10/G11 as end part material
- Cure of inner coil at higher pressure, resulting in a higher inner layer elasticity modulus and more uniform inner/outer coil mechanical properties
- A continuous body/end transition, including elimination of key extension
- Welded 75mm collar packs with pole filler pieces
- Aluminum end can assemblies over both ends
- Attachment of the end cans to the end plate, which ensures contact between the coil ends and end plates as well as stretches the coil straight section after cool-down

New inner cable and new end design starting from HGQ06

Stabrite coated cable used in HGQ008 allowed us to use HGQ08 as a thermal model to study the coil cooling conditions. Magnet HGQ09 was the last short model magnet and the goal for building this magnet was to produce the best magnet performance parameters for this magnet design. New test plan was introduced for HGQ08 and HGQ09 tests. The first test cycle procedure was close to the production magnets' test plan. All R&D studies have been performed during the second test cycle.

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.

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 cycle, and had their first quench at greater than 215 T/m field gradient value.

Table 2 summarizes the quench locations. Most of the quenches for HGQ05 were outer coil quenches while none for 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 for description of the magnet cross section).

Table2. Quench location summary

	HGQ05		HGQ06		HGQ07		HGQ08		HGQ09	
	pole	wedge	pole	wedge	pole	wedge	pole	wedge	pole	wedge
Inner body	2	13	9	19	1	11	4	10	3	7
Inner end	2	1	5	0	5	5	1	0	1	0
Outer body	4	14	0	0	2	0	1	8	1	2
Outer end	0	16	0	0	0	0	0	0	0	1

In Table 2 the quench locations were also divided 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.

All three magnets reached 90% of their short sample limit within ten quenches, but even 30 quenches were not sufficient for them to reach the short sample limit. 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 did not indicate any unloading of the coils 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.

Quench performance in first thermal cycle for the HGQ short models is summarized in Table 3. First quench currents at 4.5 K and 1.9 K as well as number of quenches required to reach nominal field gradient of 205 T/m and are presented.

Table 3. Quench performance summary

Model Number	Iq1(4.5K), A	Iq1(1.9K), A		N(<205 T/m)	N(<230 T/m)
		TCI	TCII		
HGQ05	9553	10896	12417	1	7
HGQ06	9056	12224	12044	0	8
HGQ07	10155	12101	12855	0	2
HGQ08	-	11145	12939	1	12
HGQ09	-	12760	12688	0	3

The location of quenches varies somewhat from magnet to magnet. For HGQ05, initial training was dominantly in the outer coil body, near a longitudinal break in the coil wedge, and in a lower prestress region of the coil. In HGQ06, the prestress on the outer coil was raised slightly, and that on the inner coil lowered slightly. All quenches in HGQ06 are in the inner coil body, with many located in turn 11, just below the wedge. As a result, the prestress target in HGQ07 was raised on both the inner and outer coils to 70-75MPa, and the initial quenches in HGQ07 are located in the inner coil pole turn. This magnet reaches 230T/m much more quickly than either HGQ05 or HGQ06. Around 235-240 T/m, well above the operating gradient, the quench locations in both HGQ05

and HGQ07 start to vary, and quenches next to the inner coil wedge start to appear. At this force level, we believe the mechanical discontinuity introduced by the wedge is sufficient that the continued adequate compression of the coil is difficult.

AC loss measurements and eddy current effect in field harmonics indicated that interstrand resistance in cable in HGQ06-07 has been reduced dramatically during coil curing at high temperature and high pressure required to reach high elasticity modulus in the coil. According to the theoretical predictions the reduction of interstrand resistance in the cable improves cable stability that could improve also magnet quench performance. It was expected that the reduction of the inner cable packing factor in HGQ07 with 37 strand cable will also improve inner cable stability by increasing the fraction of superfluid helium inside the cable. However, test results show that there is no distinguished change in magnet quench performance for HGQ06-07 was observed.

HGQ07 has been tested without longitudinal end support on the return end and without coil restraint. Test results for this magnet show that there is no positive correlation between magnet end restraint and quench performance of these magnets.

Test results of HGQ05-07 have demonstrated that the training problem for this magnet design is practically solved. The problem of reduction of eddy current effects and magnet performance reproducibility was solved with last two short models.

Although it took eight quenches to train HGQ08 above 230T/m, at the second test cycle the first quench current was as high as the last quench current value at the first test cycle showing no retraining effect due to thermal cycling the magnet. At the fourth quench the field gradient of HGQ09 was already higher than 230 T/m and it also showed very little retraining at the second test cycle. It was the first time that the magnets were trained at 1.9K first rather than training them at 4.5K then training them again at 1.9K. Comparing 1.9K quench training of HGQ08-09 with HGQ05-07 no difference can be observed which means previous quench history at lower Lorentz force level has no affect on quench training. HGQ08 cable was coated with stabrite which could increase the cable stability. Also no improvement in quench current has been observed for HGQ08 relative to HGQ05-09. Most of the quenches for both magnets were close to the wedges, which means they have the same mechanical limitation as the others.

After the HGQ06-09 were trained the magnets were quenched several times using spot heaters to initiate the quench and no external resistor was used to extract the stored energy. The magnets were protected by using strip heaters only so the stored energy was dissipated by the magnet. After these heater induced quenches we quenched few times the magnet and no quench current degradation was observed.

3. Ramp rate sensitivity

The dependence of quench current with current ramp rate for HGQ01-09 at 1.9 K is shown in Figure 2. One can see two regions on this curve: flat, ramp rate independent region at low current ramp rates and region with monotonic decrease of quench current with the increase of current ramp rate.

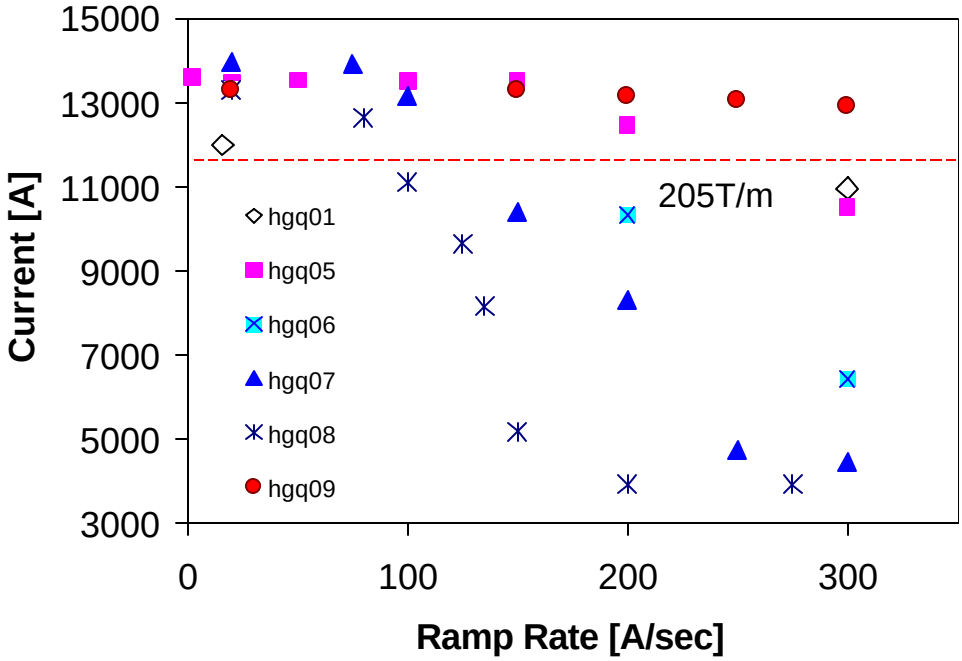

Figure 2. HGQ01-09 quench current ramp rate dependence.

Summary of magnet ramp rate sensitivity and coil curing temperature is reported in Table 4.

Table 4. Ramp rate sensitivity

Model Number	Inner coil curing		Strand coating	AC loss @100A/s J/cycle	Ic(300 A/s), A
	Temperature, ^{O}C	Pressure, MPa			
HGQ01	135	20	No	-	10965
HGQ02	190	20	No	210	11335
HGQ03	195	20	No	234	11298
HGQ05	130	80	No		10519
HGQ06	190	80	No	589	6433
HGQ07	190	80	No		4487
HGQ08	190	80	Stabrite	4538	3941
HGQ09	190/135	20/80	No		12946

For ramp rates less than 100 A/s, the magnet quench current is well above the nominal operating current of 12 kA corresponding to a field gradient of 215 T/m. All quenches at lower ramp rates took place in the coil pole regions exposed to the highest field. At higher ramp rates the quenches in HGQ01-05 were located in the splice region. Since the high ramp rate quenches are observed near the inter layer splices, the probable explanation for this ramp rate dependence is the combination of AC losses and cooling conditions in the solder-filled splice cable.

In HGQ06-08, the high ramp rate quenches originated in the midplane turns, related to the low cable interstrand resistance, a result of the 190 C high pressure cure used on

HGQ06-07 coils and stabrite cable in HGQ08. AC loss and magnetic measurements confirmed the presence of the large eddy current component in those magnets.

4. Temperature dependence and short sample limit

The dependance of quench current vs. temperature for HGQ01-09 is presented in Figure 3. This dependence was measured after the completion of magnet test at 1.9 K. Solid line shows the generic short sample limit for this magnet design calculated based on the SSC strand parameters.

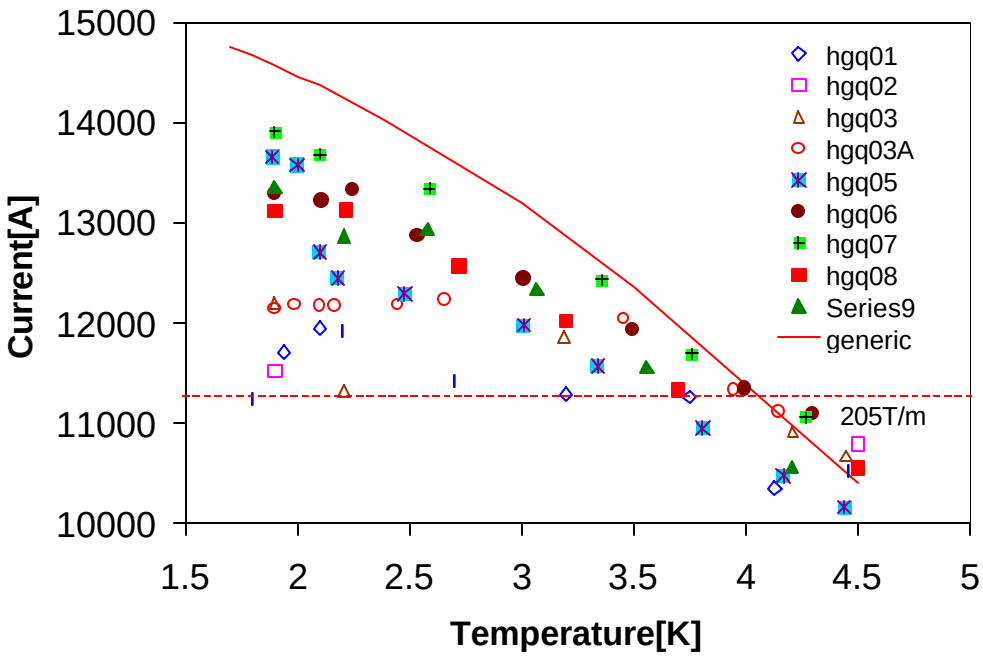

Figure 3. Temperature dependence of HGQ01-09 quench current.

The measured and calculated quench currents at 4.5 and 1.9 K are reported in Table 5.

Table 5. Quench current @ 1.9 K and 4.5 K

Model number	Ic(1.9K), kA		Ic(4.2-4.5K), kA	
	Measured	Calculated	Measured	Calculated
HGQ01	12.6	14.02	10.5	10.32
HGQ02	11.5	14.39	10.7	10.49
HGQ03	12.2	14.38	10.6	10.48
HGQ05	13.7	14.03	10.1	10.23
HGQ06	13.3	14.48	11.1	10.93
HGQ07	13.9	14.48	11.1	10.93
HGQ08	13.1	13.93	10.6	10.17
HGQ09	13.4		10.6	

After training at 1.9 K all magnets reached their short sample limit at 4.5 K. With nominal superconductor parameters the temperature margin at nominal operation current for this design is about 2.3 K. Quench current as a function of the helium bath temperature is plotted in Figure3. There was a monotonic decrease of quench current with increasing temperature for all three magnets. For HGQ05, quenches between 2.2-3.0 K 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 - HGQ09, 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 higher 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 HGQ06-09 is about 1.8 K.

5. Summary

Test results of the short model quadrupole magnets developed for the inner triplet LHC Interaction Regions are presented. Quench performance of the last five model high gradient quadrupoles were satisfactory for LHC operations. Their quench performance were similar leading to a conclusion that the production procedure is well controlled. All four magnet 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, quench plateaus for all of them were well above the nominal operating current. Two thirds of quenches were in coil turns next to the wedge. Measurements of the temperature dependence indicate an operating margin of 1.8 K at 205 T/m. The magnet quench currents at current ramp rate less than 100 A/s are well above the operating current and show no sensitivity to current ramp rate.

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