FIELD QUALITY OF THE LHC INNER TRIPLET QUADRUPOLES BEING FABRICATED AT FERMILAB *

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Abstract

Fermilab, as part of the US-LHC Accelerator Project, has designed and is producing superconducting low-beta quadrupole magnets for the Large Hadron Collider (LHC). These 70 mm bore, 5.5 m long magnets operate in superfluid helium at 1.9 K with a maximum operating gradient of 214 T/m. Two quadrupoles, combined with a dipole orbit corrector, form a single LQXB cryogenic assembly, the Q2 optical element of the final focus triplets in the LHC interaction regions. Field quality was measured at room temperature during fabrication of the cold masses as well as at superfluid helium temperature in two thermal cycles for the first LQXB cryogenic assembly. Integral cold measurements were made with a 7.1 m long rotating coil and with a 0.8 m long rotating coil at 8 axial positions and in a range of currents. In addition to the magnetic measurements, this paper reports on the quench performance of the cold masses and on the measurements of their internal alignment.

1 INTRODUCTION

Superconducting low-beta quadrupole magnets (MQXB) for the Large Hadron Collider have been fabricated at Fermilab. These magnets are required to provide a maximum operating gradient of 214 T/m over a 70 mm coil bore, and to operate in superfluid helium at 1.9K [1]. Two 5.5 m long MQXB magnets are combined with a dipole orbit corrector (MCBX) to form a single cryogenic assembly (LQXB).

To date half of cold MQXB masses have been built. Four of them (MQXB01-04) were selected for assembling in the first two LQXB cryogenic units. In this paper we present the results of the warm field measurements of magnets MQXB01-09 in the production stage. The quench performance and field measurements of the first LQXB01 (MQXB01-02 quadrupoles) are described as well. A comparison with the results from the model magnet program [2] and the full scale prototype [3] is included. The results of the relative alignment of the first two cold masses inside the LQXB cryogenic assembly are also presented, including warm to cold correlations.

2 QUENCH PERFORMANCE

LQXB01 was tested at Fermilab Magnet Test Facility in superfluid helium at LHC operational temperature at 1.9 K in two thermal cycles (TC1 and TC2). Figure 1 summarizes the quench performance for the HGQ05-09 model magnets [2] together with the result from the prototype MQXP01 [3]. The outstanding performance of the first two MQXB01-02 magnets is pointed out by the large squares and the triangle around the horizontal solid line. MQXB01 achieved 230 T/m without any training. MQXB02 needed one training quench to reach the acceptance criteria of 230 T/m. Also it is important to note that magnets do not need to be retrained on TC2.

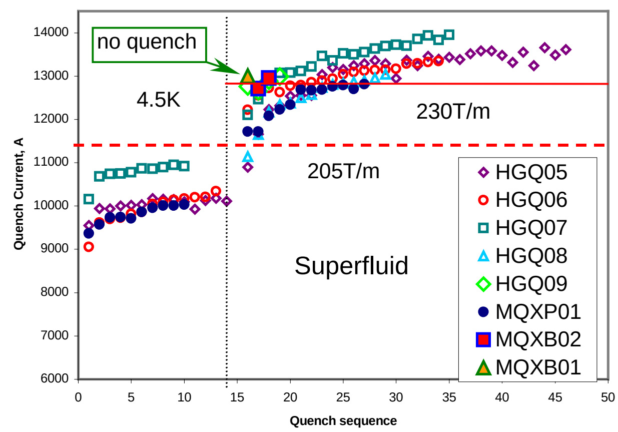

Figure 1: Quench training history for the model magnets HGQ05-09 and first prototype MQXP01. The horizontal dashed line corresponds to 205 T/m field gradient. The solid line corresponds to 230 T/m field gradient which is the acceptance criteria for MQXB magnets

3 MAGNETIC MEASUREMENTS

4.1 Measurement system

Magnetic measurements were performed using a horizontal drive rotating coil system. A long drive shaft, assembled from 1.5 m sections, is used to transfer the rotation to the probe. The shaft sections are supported in gates. They are controlled by photo-eyes and cycled open-closed by pneumatic cylinders when the probe is inserted or extracted from the magnet. Details on the magnetic measurements readout system are reported elsewhere [3].

The probes used have a tangential winding for measurement of higher order harmonics as well as specific dipole and quadrupole windings for measurement of the lowest order components of the field. The warm

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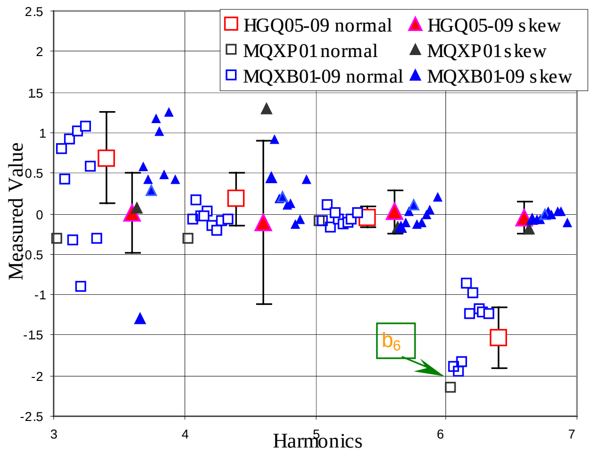

Figure 2: Measured collared coil harmonics in the body of MQXB01 through MQXB09. The large squares and triangles represent the average harmonics derived from the model magnet program. The error bars are one sigma. The arrow points at a systematically larger dodecapole than in the model magnets.

measurements are made with a coil of 31.8 mm nominal radius and 91.2 cm long. For the cold measurements we used two probes. The integral harmonics are obtained using a 7.1 m long rotating coil assembled from three independent probes connected in series. In addition to the integral measurements a DC cold scan was done with a 81 cm long probe.

4.2 Results of the warm measurements

In the process of production of every MQXB magnet two measurements are performed to ensure magnet quality. In the first one an integral z-scan of the collared coil is executed. This measurement checks the quality of the coil assembly and of the collaring process.

The second z-scan is done after yoking is complete. The measurement probe is placed at the same z-positions as for the collared measurements. This allows us to compare the harmonic changes due to the process of the yoking.

Fig. 2 shows the harmonics up to the dodecapole for the average of the last five HGQ model magnets, for the MQXP01 prototype, and for the MQXB01-09 production cold masses after. An acceptable but systematic deviation from the average harmonics of short model magnet tests is observed in the normal dodecapole for the first three cold masses MQXB01-03 (Fig.2).

The similar result for b_6 is obtained for the yoked cold masses. A performed accelerator simulation pointed to the possibility that in some configuration b_6 could be too large to be compensated with the available corrector strength. An effort was made into the production to decrease the normal dodecapole deviation. The result of the field calculation was implemented first in the MQXB04 cold mass [4]. 50 µm of Kapton insulation were removed from the midplane of each inner coil octant, and 25 µm were added to each inner pole. This caused each inner coil octant to be shifted toward the midplane by 25-50 µm. A decrease of 1 unit in b_6 is

Table 1: Integral field harmonics (in units at 17 mm) in MQXB01-02 at 11.9 kA field (214 T/m) compared to the acceptance criteria defined in Reference table v.3.2 [2]

n	Reference table v.3.2	MQXB 01	02	Reference table v.3.2	MQXB 01	02
	$<b_n>\pm\delta(b_n)$	b_n	b_n	$<a_n>\pm\delta(a_n)$	a_n	a_n
3	0.00±1.66	0.75	0.15	0.00±1.34	-0.82	-0.88
4	0.00±1.25	0.64	-0.65	0.00±1.29	-0.06	0.29
5	0.00±0.65	0.09	-0.24	0.00±0.65	-0.47	-0.13
6	0.21±0.97	-0.37	-0.23	-0.03±0.19	-0.02	0.10
7	0.00±0.12	-0.02	-0.05	0.00±0.10	-0.02	-0.02
8	0.00±0.08	0.02	0.01	0.00±0.05	0.02	-0.01
9	0.00±0.04	0.04	0.02	0.00±0.04	-0.03	-0.03
10	-0.01±0.04	-0.01	-0.02	0.00±0.04	-0.04	-0.04

observed which is somewhat larger than the expected 0.85 units from the field calculation. Following the result of the warm measurements the shim pattern was slightly modified in MQXB05 to decrease the change. This shim pattern was used in the production of MQXB07-09.

4.3 Cold measurements.

Harmonic measurements in the superconducting state have been performed on the MQXB01-02 cold masses connected in a single cryogenic unit LQXB01 at 1.9 K. The integral harmonics at 11923 A (214 T/m) are presented in Table 1. They are compared with the field quality values from the reference table v3.2 [2] which are derived from the model magnet program. The uncertainties assigned to the reference means, $<b_n>$ and $<a_n>$ in Table 1, correspond to $\delta(b_n,a_n) = d(b_n,a_n) + 3\sigma(b_n,a_n)$, where d and σ are the uncertainties in mean and standard deviation respectively. One may conclude that the magnet harmonics are inside the accelerator required limits.

To check for possible dynamic effects during the injection plateau, measurements were performed with an accelerator cycle similar to the one used in the LHC arc dipole tests [4]. The duration of the plateau is 15 min at 669 A (12.3 T/m). The decay and snap-back of the normal dodecapole at for MQXB01-02 is presented in Fig.3. The average decay amplitude is 0.55 units after 15 min. followed by the snap-back time of ~8.5 s.

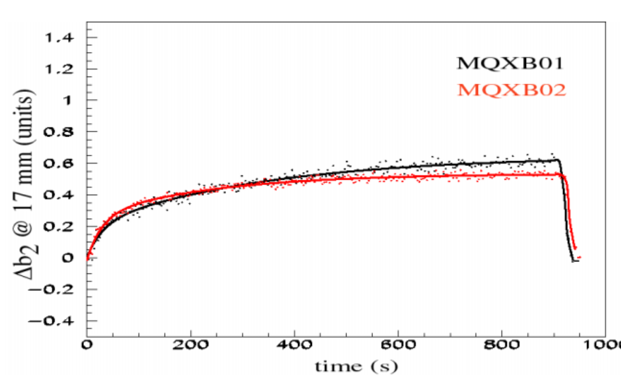

Figure 3: Decay and snap-back of the dodecapole component for a plateau at injection of 15 min.

Table 2: Hysteresis width (in units) of the dodecapole at 6kA.

Ramp Rate A/s	HGQ models					MQXB	
	05	06	07	08	09	01	02
10	-0.1	0.2	0.1	0.1	-0.1	-0.3	0.1
40	-0.1	1.1	0.6	0.7	-0.1	-0.4	-0.3
80	-0.1	2.1	1.1	1.5	-0.1	-0.6	-0.4

Current loops at 10, 40 and 80 A/s for MQXB01-02 have been performed. Table 3 summarizes the width ($b_6^{up\ ramp}$ - $b_6^{down\ ramp}$) of the dodecapole hysteresis at 6 kA. One can conclude that MOXB01-02 have a similar behavior to the model magnets and that the Eddy current contribution to b_6 is relatively small.

The integral quadrupole field over the 5.5 m magnetic length was measured with a single stretched wire system (SSW) [5] and found to be 101.07±0.02 T/kA at injection and 98.86 ±0.02 T/kA at collision.

4 ALIGNMENT OF THE COLD MASSES FOR LQXB

Alignment measurements of the LQXB magnets consist of measuring the average magnetic axis of the two cold-mass system and transferring its location to the external fiducials. The survey data are reported to CERN and will be used in the absolute positioning of the LQXB assembly with respect to the LHC beamline axis.

The relative alignment of the MQXB cold masses inside the LQXB was carefully monitored for changes during TC1 and TC2 on the cold test stand using SSW. Table 3 summarizes, in chronological order, measurements performed in TC1 and TC2 at 4.5 K as well as warm measurements between the thermal cycles. The average ΔX, ΔY center offsets, the yaw, pitch and roll angles of MQXB01-02 are presented relative to the final alignment measurement labeled “cold TC2”, when the magnetic centers of the cold masses are positioned on x,y=0,0.

Based on the TC1 results, small mechanical adjustments were made between the “After TC1” and “Before TC2”, using the adjustment logs of the cold mass supports. The cold mass positions changed predictably with changes of the logs. The changes seen during the thermal cycles, warm-cold-warm, are reproducible, for each TC, and similar in TC1 and TC2 despite the mechanical adjustments between them.

Table 3: Measured changes in average ΔX, ΔY center offsets, yaw, pitch and roll angles relative to the cold TC2 measurement

Measu-rement	Magnet	ΔX (mm)	ΔY (mm)	Yaw (mrad)	Pitch (mrad)	Roll (mrad)
Before TC1	01	-0.32	0.88	0.05	-0.15	-0.37
	02	-0.16	0.60	-0.04	0.03	0.47
Cold TC1	01	-0.36	0.54	0.06	-0.03	-0.33
	02	0.03	0.14	0.08	-0.06	0.47
After TC1	01	-0.29	0.65	0.07	-0.17	-0.36
	02	-0.06	036	-0.05	0.07	0.56
Before TC2	01	0.06	0.25	0.16	-0.30	-0.56
	02	-0.08	0.38	-0.05	0.07	0.33
Cold TC2	01	0.0	0.0	0.20	-0.27	-0.50
	02	0.0	0.0	0.03	-0.04	0.50
After TC2	01	0.16	0.15	0.14	-0.33	-0.55
	02	-0.01	0.26	-0.07	0.10	0.44

The final cold SSW measurement, labeled “Cold TC2”, confirmed that the relative yaw, pitch and roll angles between the MQXB01-02 cold masses are within alignment tolerances required from the accelerator beam optic studies [6].

5 CONCLUSIONS

The first LQXB cryogenic unit for the LHC interaction region has been tested.

Both magnets in the LQXB01 cryogenic assembly showed outstanding quench performance. They reached the acceptance criterion of 230 T/m with minimal training quenches.

The quality assurance warm magnetic measurements after collaring and yoking of the cold masses were described. As a whole the field harmonics are quite small and consistent with those measured in the last five short model magnets and in the first full scale prototype

Cold magnetic measurements were performed on the MQXB01-02 cold masses assembled in the cryogenic unit (LQXB01). Integral field are quite small and they are consistent with the acceptance criteria. The effect of the cable Eddy currents is small and similar to that seen in the model magnets. The decay and snap-back at injection plateau was studied and the average change in b_6 was found to be relatively small (0.55 units after 15 min).

The alignment of the first two cold masses inside LQXB01 assembly has been completed. Field alignment measurements, performed with the SSW system, confirmed that the placement errors of the cold masses are within the required limits.

6 REFERENCES

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