MAGNETIC FIELD MEASUREMENTS OF THE LHC INNER TRIPLET QUADRUPOLES PRODUCED AT FERMILAB *

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Abstract

Production of 18 superconducting low-beta quadrupoles (MQXB) for the LHC is well advanced. These 5.5 m long magnets are designed to operate at 1.9 K with a peak field gradient of 215 T/m in 70 mm aperture. Two MQXB cold masses with a dipole orbit corrector between them form a single cryogenic unit (LQXB) which is the Q2 optical element of the final focus triplets in the LHC interaction regions. A program of magnetic field quality and alignment measurements of the cold masses is performed at room temperature during magnet fabrication and of the LQXB assembly as well as at superfluid helium temperature. Results of these measurements are summarized in this paper.

INTRODUCTION

High gradient quadruoles are required for the interaction regions of the Large Hadron Collider. These magnets, arranged as the final focus triplet (Q1, Q2, Q3), have to provide a maximum operating gradient of 215 T/m over a 70 mm coil bore, at 1.9K in superfluid helium [1].

Half of these superconducting low-beta quadrupoles (MQXB) for the interaction regions are provided by Fermilab. The other half were produced by KEK [2] and the final assembly, including the cryostating of the all magnets, is ongoing at Fermilab.

To date 15 of the cold MQXB masses have been built. Ten of them (MQXB01-06, 08, 10-12) were selected for the assembly of the first five LQXB01-05 cryogenic units. Four of LQXB have been cold tested, LQXB05 is currently undergoing testing.

In this paper we present the results of the warm field production measurements of MQXB01-15. The quench performance of LQXB01-04 is summarized and the results from cold magnetic measurements are discussed as well. The outcome of the relative alignment of the cold masses inside the LQXB cryogenic assemblies is also presented, including warm to cold correlations.

MEASUREMENT SYSTEMS

Magnetic measurements were performed at the Fermilab Magnet Test Facility. The measurement setup uses a horizontal drive rotating coil system with a long drive shaft, assembled from independent sections. The probes utilized have tangential windings for measurement of higher order harmonics as well as specific dipole and quadrupole windings for detection of the lowest order field components. Details on the magnetic measurements readout system have been reported elsewhere [3].

The test stand is instrumented with a series of 'quench antenna' panels mounted on the inner surface of the warm finger. These panels contain multipole windings the sensitive to the sextupole and octupole components of the field. The signals from these windings allow determination of the quench location and direction in the azimuthal plane as described in [4].

Alignment and integral strength measurements are performed with a Single Stretched Wire (SSW) system [6].

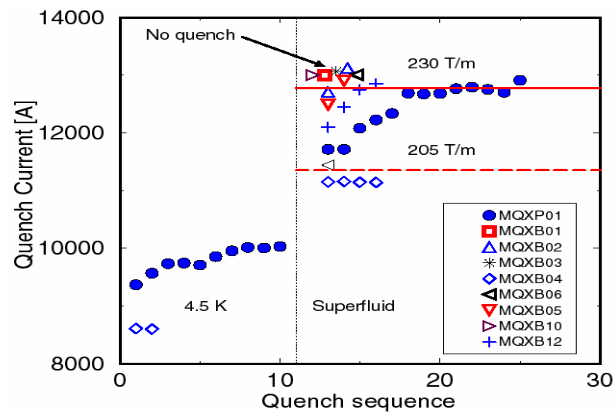

Figure 1: Quench training history plot for the first prototype MQXP01 and 8 production MQXB magnets. The solid line corresponds to 230 T/m field gradient which is the acceptance criteria for MQXB magnets. Seven of the production magnets reached 230 T/m with minimal or no training.

QUENCH PERFORMANCE

LQXB01-04 were tested in superfluid helium at the LHC operational temperature of 1.9K. Figure 1 summarizes the quench performance for the MQXB magnets together with the result from the prototype MQXP01 [3]. Five of the six magnets tested showed outstanding quench performance. They achieved the acceptance limit of 230 T/m without any, or minimal (one quench), training, Also it is important to note that the first two magnets (MQXB01-02) were tested in a second thermal cycle and reached the required 220 T/m gradient without retraining.

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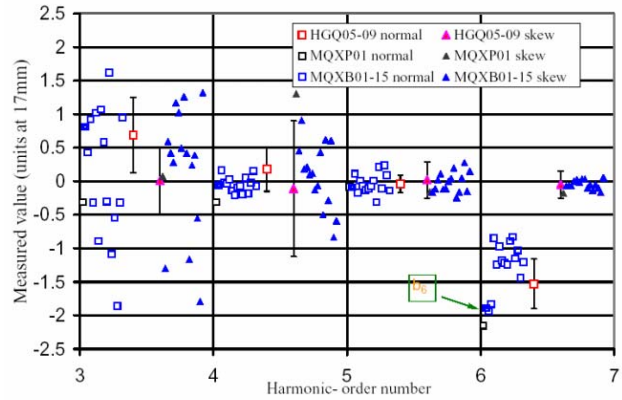

Figure 2: Measured collared coil harmonics (in units at 17 mm) in the body of MQXB01 through MQXB15. The large squares and triangles represent the average harmonics derived from the model magnet program.

One of the magnets did not pass the acceptance criteria. MQXB04 quenched at 11152A, 200A below the required 205 T/m operating field gradient value (Fig. 1, quenches are represented with diamonds). After four quenches without any increase in current, the magnet was rejected.

The analysis of quench antenna data indicated that all the quenches occurred in the same coil quadrant of the magnet. MQXB04 was disassembled and dissected. The suspect portion of the coil was sent to the BNL cable test facility for additional investigation. However none of the tests performed revealed any problem with the conductor. More information about the quench performance of MQXB04 is reported in [5].

MAGNETIC MEASUREMENTS

3.1 Results of the Warm Measurements

To ensure quality in the production of MQXB cold masses two integral z-scan measurements are performed. The first measurement is executed after the coil is collared. It checks the quality of the coil assembly and the harmonics variation in the body.

The second z-scan follows the yoking process. The rotating coil probe is placed at the same z-positions as for the collared coil measurements. This allows us to determine harmonic changes due to the addition of the yoke and the welding process.

The low order harmonics (up to the dodecapole) for the average of the last five HGQ model magnets (the error bars represent one sigma deviation), for the MQXP01 prototype, and for the MQXB01-15 production cold masses are shown in fig2. An acceptable but systematic deviation from the average of short model magnet tests is observed deviation [3].

A shift of 0.85 units of b_6 was predicted by the calculation, and one unit was observed. Following the result from warm measurement of MQXB04, the shim

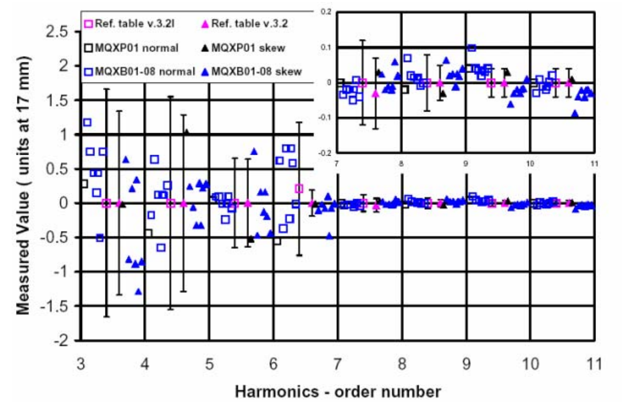

Figure. 3. Integral field harmonics (in units at 17 mm) in MQXB01-03 at 11.9 kA current (214 T/m) compared with the acceptance criteria defined in Ref. Table v.3.2. The insert shows the high order harmonics.

pattern was modified in MQXB05 and fixed for the production of MQXB06 and later.

3.2 Cold Measurements

The final quality assurance magnetic measurements were performed at superfluid helium temperature (~1.9K) on the MQXB cold masses assembled in cryogenic units LQXB01-04 (except for rejected assembly, MQXB04). The integral field harmonics at 11923 A (215 T/m), up to order 10, are presented in Fig 3. They are compared with the reference values v3.2 that were derived from the latter stage of the model magnet program. The errors assigned to the reference means (see Fig.3 points with error bars), 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 at the LHC operating current the magnet harmonics are within limits.

The integral quadrupole strength over the 5.5 m MQXB magnetic length was measured with SSW and the results are summarized in Table 1. The average strengths are found to be 202.18±0.04 T/kA at injection and 198.21 ±0.10 T/kA at collision.

A well-known problem for the LHC superconducting magnets is the decay and subsequent snap back of field components at the injection plateau. To characterize this effect in the MQXB quadrupoles, we performed measurements with an accelerator cycle similar to the one used in the LHC arc dipole tests. The duration of the plateau is 15 min at 669 A (12.3 T/m). The average decay amplitude is 0.55 units after 15 min. followed by the snap-back time of ~8.5 sec.

Table 1: Measured integral strength in LQXB01,03,04

LHC operation	Integral Strength T/kA		
	LQXB01	LQXB03	LQXB04
injection	202.14	202.22	202.20
collision	197.72	197.97	197.94

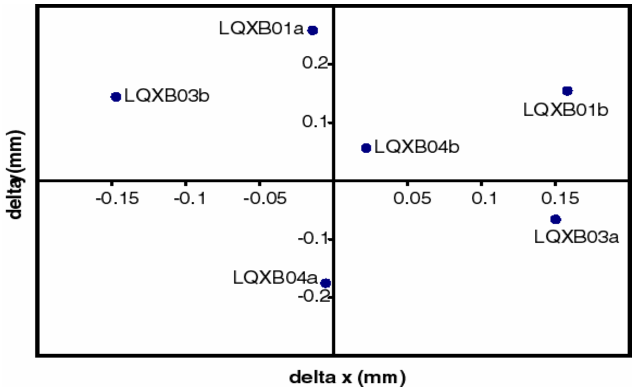

Figure 4: Δy vs. Δx for average warm to cold motion of centers of the cold masses inside LQXB.

ALIGNMENT OF THE COLD MASSES IN LQXB

Alignment measurements of the LQXB assemblies provide important information for positioning the quadrupoles on the LHC beamline axis. They 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 they are electronically logged in the LHC magnet database.

Relative alignment of the MQXB cold masses was carefully monitored for changes using SSW during LQXB production. After complete assembly, further internal adjustments were made, with the magnet mounted on the test stand, via lugs accessible through vacuum ports on the cryostat. The Q2a/b alignment was measured warm and cold during each thermal cycle. Yaw and pitch angles for Q2a/b magnets with respect to their magnetic axes, and their average roll angle are summarized in Table 3. Motion in the average centers from warm to cold is presented in Fig.4. Substantial changes are observed both in pitch/yaw angles and average centers during thermal cycle; these are reproducible. Note that alignment adjustments made warm on LQXB01 using the lugs resulted in corresponding cold changes [3]: this would indicate that, if needed, lug adjustment could be employed to further improve alignment based on warm measurements . The final cold alignment measurements indicate these LQXB magnets are acceptable from the viewpoint of accelerator beam optic studies [7].

Table 3: Warm and cold yaw, pitch and average roll angle (Q2a/ and Q2B). (note that 0.1mrad yaw/pitch corresponds to 0.55mm over the 5.5m magnet length)

Measu-rement/ magnet	Yaw (mrad) Q2a	Pitch (mrad) Q2a	Yaw (mrad) Q2b	Pitch (mrad) Q2b	Ave. Roll (mrad)
Cold/01	0.03	-0.04	0.20	-0.27	0.0
Warm/01	-0.07	0.10	0.14	-0.33	-0.06
Cold/03	-0.52	0.23	0.05	0.20	0.0
Warm/03	-0.38	0.13	0.08	0.06	0.08
Cold/04	-0.07	-0.09	-0.04	-0.10	-0.0
Warm/04	-0.10	-0.01	0.02	-0.15	-0.03

CONCLUSIONS

Fifteen of a total of eighteen superconducting low-beta quadrupole cold masses for LHC have been produced. The quality assurance warm magnetic measurements after collaring and yoking of these cold masses are within specifications established by the last five short model magnets and the first full scale prototype [3].

Four LQXB cryogenic units for the LHC interaction region have been tested in superfluid helium. Seven of eight cold masses showed outstanding quench performance. They achieved the acceptance limit of 230 T/m with minimal or no training quenches. However, MQXB04 plateau-ed below the required 205 T/m operating limit. The quench results indicated the possibility of localized conductor damage.

Cold magnetic measurements were performed on the MQXB cold masses assembled in the LQXB cryogenic units. At collision, the integral field harmonics are quite small and they are consistent with the acceptance criteria. An additional study of dynamics effects was made at the injection plateau current. The decay and snap-back after 15min injection showed an average change in b_6 of 0.7 units and consistent decay times of ~8.5s.

The relative alignment of MQXB magnets inside LQXB assemblies has been performed. Final cold SSW measurements confirmed that the placement errors of the cold masses are within required limits.

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