PRODUCTION AND TEST OF THE FIRST LQXB INNER TRIPLET QUADRUPOLE AT FERMILAB*

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Abstract

Fermilab, in collaboration with LBNL and BNL, has developed a quadrupole (MQXB) for installation in the interaction region inner triplets of the LHC. This magnet is required to have an operating gradient of 215 T/m across a 70 mm coil bore, and to operate in superfluid helium at 1.9K. Two 5.5 m long MQXB magnets are combined with a dipole orbit corrector to form a single cryogenic unit (LQXB). This paper discusses the construction and test of the first full-scale production-quality LQXB.

1 INTRODUCTION

Superconducting low-beta quadrupole magnets for the Large Hadron Collider have been developed by the US-LHC Accelerator Project. These 70 mm bore 5.5 m long quadrupole magnets are designed to operate in superfluid helium at 1.9 K with a nominal field gradient of 215 T/m as part of the final focusing triplets in the interaction regions [1] (Fig.1). Half of these MQX quadrupoles for the inner triplets will be built at Fermilab. The other half will be built by Toshiba and tested at KEK [2]. Following a series of 2 m model magnets (HGQ) [3] in 1998-2000 and a full scale cryostated prototype (MQXP01) [4] in 2001, a production process has been started. Warm magnetic field measurements of the first cold masses have been performed. In this paper we present the status of the production process and the first results of the warm magnetic measurement, including a comparison with the measurements from the model magnets and the prototype. Finally, the relative alignment of the cold masses was determined and the results are also presented.

2 MAGNET DESIGN

The MQXB design, developed in collaboration with LBNL and BNL, is based on four two-layered coils connected in series. The coils are surrounded by stainless steel collars and iron yoked laminations. The azimuthal cross section (Fig. 2) is the same as in the model magnet HGQ09 [3] and the first prototype MQXP01 [4].

The magnets utilize two keystone Rutherford-type cables made of 37 NbTi strands for the inner cable and 46 for the outer one, respectively. Both cables have the same

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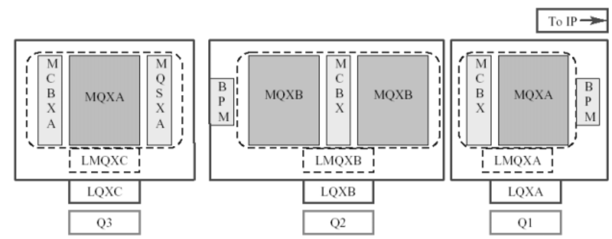

Fig. 1. Schematic of the LHC focusing inner triplet system. The LQXB magnet is the middle element in the triplet

radial width of 15.4 mm but different mid-thickness of 1.465 (1.146) mm for the inner (outer) layer cable, and are insulated with Kapton tape. Each of the four coils consists of 14 (16) turns in the inner (outer) layer.

More design details of the magnet models are reported elsewhere [3,4,5].

3 LQXB PRODUCTION

To date four cold masses (MQXB01-04) have been built. Two of them (MQXB01-02) were selected for assembling the first full LQXB cryogenic unit. During the production processes of collaring and yoking of these masses, the outside diameters were strictly controlled. For the collared coils, the average deflection is around 0.2 mm, comparable with the results from the latest model magnets. The twist in the assembly of the cold masses after welding the skin and the end plates is checked not to

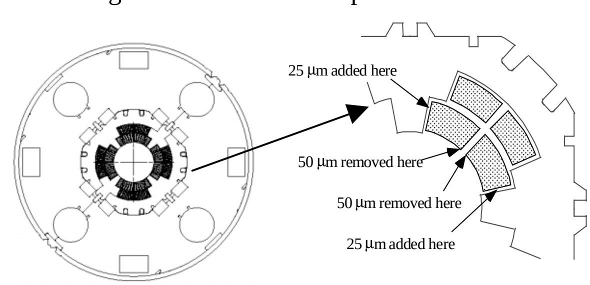

Fig. 2. Left: cold mass cross-section. The coil bore diameter is 70 mm. Right: illustration of the coil shimming which was done to correct b6.

exceed the maximum allowed twist of 0.2 mrad/m. An average twist of 0.18 mrad/m and of 0.01 mrad/m was measured for MQXB01-02.

The process of assembling the first LQXB cryogenic unit, which will form the Q2 optical element, is well underway. In addition, the unit includes a CERN supplied MCBX steering dipole corrector mounted between MQXB01-02 (Fig. 1). We expect the assembly to be completed shortly, and to be cold tested during the summer.

4 MAGNETIC MEASUREMENTS

4.1 Measurement system

Magnetic measurements presented in this paper 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 opened-closed by pneumatic cylinders when the probe is inserted or extracted to the magnet.

The probe use has 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 measurements are made with a coil of 31.8 mm nominal radius and 91.2 cm long.

We use Metrolab PDIs (model 5035) to read the coil winding voltages. An HP3458 DVM is used to monitor the magnet current. PDIs and DVM are triggered by an angular encoder connected to the probe shaft. The encoder synchronizes the simultaneous measurements of field and current. To center the probe in the magnet we use "feed down" of the quadrupole to the dipole signal.

4.2 Field quality analysis from warm measurements

All results will be reported according to the conventions that the field is represented in terms of harmonics coefficients defined by the multipole series expansion

$$B_y + iB_x = B_2 10^{-4} \sum_{n=1}^{\infty} (b_n + ia_n) \left(\frac{x+iy}{r_o} \right)^{n-1}$$

where B_x and B_y are the field components in the Cartesian coordinates, b_n and a_n are the 2n-pole coefficients at the reference radius r_0 of 17 mm (b_2 is normalized to 10^4). The coordinate system is defined in [5].

In the production stage of every MQXB magnet two different quality assurance magnetic measurements are performed. In the first one an integral z-scan of the collared coil is performed. This measurement checks the quality of coil production 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 to compare the harmonic changes due to welding of the laminations and of the skin of the cold masses.

Table 1 shows the harmonics up to the dodecapole for the average of the last 4 HGQ model magnets, MQXP01 and the first four MQXB01-04 cold masses after the collaring process. One can see, a moderate deviation from the average harmonics of short model tests is observed in the normal dodecapole (MQXB01-03).

The similar result is presented in Table 2 for the yoked cold masses. As a whole, there is good agreement between the average harmonics from the HGQ measurements and the harmonics for the first four MQXB cold masses.

An effort was made to correct for the normal dodecapole deviation. Using the ROXIE code [6] an optimization for additional shims was done. The result of the optimization was implemented in the MQXB04 cold mass. 50 μm of Kapton insulation were removed from the midplane of each inner coil octant, and 25 μm were added to each inner pole (Fig. 2). This caused each inner coil octant to be shifted toward the midplane by 25-50 μm. It also resulted in a slight decrease in the preload. A decrease in half of b_6 is observed.

The result from the integral z-scans was utilized for the determination of the magnetic center of the cold masses. An accuracy of 1.5-2.0 mm (including the transfer to external fiducials) on the cold mass skin was achieved. This accuracy is determined primarily by the contribution of the mechanical survey.

A single stretched wire system (SSW) [7] was used to confirm the position of the MQXB01-02 magnetic centers. The flux measured in a counter directional movement of the wire stage A and B (fig. 3) depends on the longitudinal position of the magnetic center with

Table 1: Measured harmonics of the collared coil

n	HGQ	MQXP	MQXB			
	05-09	01	01	02	03	04
b_3	0.69±0.56	-0.31	0.81	0.43	0.92	-0.32
b_4	0.18±0.33	-0.31	-0.06	0.16	-0.02	-0.03
b_5	-0.04±0.13	-0.08	-0.09	0.11	-0.17	0.01
b_6	-1.53±0.37	-2.15	-1.89	-1.94	-1.83	-0.85
a_3	0.01±0.50	0.07	-1.30	0.59	0.42	0.28
a_4	-0.11±1.01	1.30	0.45	0.91	0.18	0.21
a_5	0.02±0.27	-0.16	-0.16	-0.11	0.02	0.11
a_6	-0.05±0.20	-0.18	-0.07	-0.07	-0.07	0.00

Table 2: Measured harmonics of the yoked cold mass

n	HGQ	MQXP	MQXB			
	05-09	01	01	02	03	04
b_3	0.69±0.53	0.21	1.35	0.16	0.82	0.21
b_4	0.10±0.35	0.32	0.07	0.05	-0.01	0.04
b_5	-0.03±0.12	-0.27	-0.16	0.09	-0.04	-0.11
b_6	-1.33±0.49	-1.58	-1.62	-1.73	-1.52	-0.69
a_3	-0.02±0.49	-0.43	-0.92	0.62	-1.06	0.37
a_4	-0.20±0.84	1.34	0.46	0.88	-0.22	-0.42
a_5	0.03±0.16	0.08	-0.11	-0.08	-0.20	-0.02
a_6	-0.11±0.20	-0.31	-0.07	-0.08	-0.08	0.00

respect to the stages. The accuracy of the procedure is on the order of 3-5 mm including the mechanical survey.

The longitudinal positions of the MQXB magnetic centers measured by the rotating coil and SSW systems are in good agreement within an average difference of 2 mm.

5 ALIGNMENT OF THE COLD MASSES FOR LQXB

As shown in Fig. 1 the two cold masses of MQXB quadrupoles will be placed in a single cryostat. The absolute alignment of the LQXB unit with respect to the LHC beamline axes will be determined during the magnet installation. However the relative alignment of the MQXB cold masses inside the LQXB will be fixed (the two cold masses have to be welded together) in the production process at Fermilab and must be carefully monitored.

Relative alignment was accomplished in four steps (Tab. 3). A special stand, shown schematically in Fig. 3, was built to perform this alignment. In the first step MQXB02 was placed on the stand and its roll angle was zeroed with a gravity μ-level. This sub-procedure was repeated for MQXB01 keeping the distance between the magnetic centers at the specified nominal value of 6519.6 mm. Next the alignment measurement was performed with SSW. The average X, Y offsets, the lead end (LE) and non-lead end (NLE) X, Y offsets and roll angle of MQXB02 relative to MQXB01 are presented in Tab. 3 (Step 1).

Table 3: Measured changes in X, Y and roll angle of MQXB01 relative to the field axis of the MQXB02. The steps are described in the text.

Step	X-center (mm)			Y-center (mm)			Roll (mrad)
	LE	NLE	Ave	LE	NLE	Ave	
1	-1.79	-1.69	-1.74	-0.61	-0.51	-0.56	0.13
2	-1.06	-0.85	-0.95	-0.67	-0.50	-0.58	0.13
3	-0.01	0.14	0.07	-0.06	0.05	-0.01	0.42
4	-0.09	0.20	0.06	-0.11	-0.03	-0.07	0.00

Steps 2 and 3 included fine mechanical adjustments using the stand's fixtures and additional shims. The results from the SSW after Step 3 showed that the average relative displacements of LE and NLE are smaller than 0.07 mm. This mechanical alignment introduced an additional roll angle of 0.29 mrad.

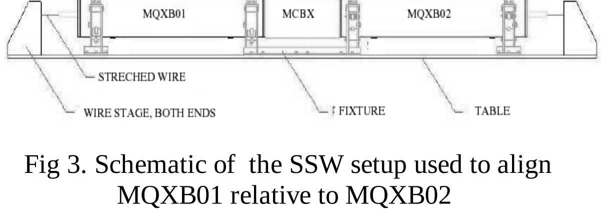

Fig 3. Schematic of the SSW setup used to align MQXB01 relative to MQXB02

In the Step 4 MQXB01 was rolled to compensate for the relative angle between the magnetic axes. The final SSW measurement (Step 4, Table 2) confirmed that the transverse displacements and relative roll angle between the MQXB01-02 cold masses are well within alignment tolerances of 0.5 mm and 1 mrad respectively [8].

6 CONCLUSIONS AND FUTURE PLANS

The first LQXB cryogenic unit for the LHC interaction region is under construction and test.

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 four short model magnets and the first full length prototype, except for the normal dodecapole, where a moderate deviation was observed. This problem was corrected in the MQXB04 cold mass.

The relative alignment of the first two cold masses has been completed. Field alignment measurements, performed with the SSW system, confirmed that the placement of the cold masses in the first LQXB assembly is more accurate than required.

The second dipole corrector MCBX recently arrived at Fermilab and the next LQXB will be assembled as soon as the first one is completed. In addition to the LQXB units, Fermilab is also responsible for the completion of the LQXA (Q1) and LQXC (Q3) cryogenic-assemblies (Fig. 1). The main quadrupoles in these assemblies are the MQXA magnets, designed by KEK and built by Toshiba in Japan [2]. The first MQXA successfully arrived at Fermilab and assembly of this magnet into the LQXA cryogenic unit will start in late this year.

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