TEST RESULTS OF FERMILAB-BUILT QUADRUPOLES FOR THE LHC INTERACTION REGIONS *

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Abstract

As part of the US LHC Accelerator Project, Fermilab is nearing the completion of the Q2 optical elements for the LHC interaction region final focus. Each Q2 element (LQXB) consists of two identical high gradient quadrupoles (MQXB) with a dipole orbit corrector (MCBX). This paper summarizes the test results for the LQXB/MQXB program including quench performance, magnetic measurements and alignment, and gives the status of production and delivery of the LQXB magnets to the LHC.

OVERVIEW

The final focus for the LHC interaction regions is provided by a single aperture quad triplet optical configuration shown schematically in Fig. 1. In total, nine LQXA-B-C elements are required for the four LHC interaction regions including one set of spares. Fermilab is responsible for the assembly of these cryogenic elements with contributions from KEK, CERN, as well as corrector magnets from European industry. Fermilab is building the high gradient quadrupoles (MQXB) for the LQXB element, while KEK is responsible for the MQXA element utilized in the LQXA and LQXC [1]. The MQXA/B magnets are both 70 mm aperture quadrupoles with a peak operating gradient of 215 T/m.

The Fermilab MQXB program started in 1998 with the construction and test of nine 2-meter model magnets [2] followed by a full scale prototype MQXB magnet (MQXP01) which was successfully tested in superfluid in a single magnet cryostat [3].

For the LQXB, two 5.5 m long MQXB quadrupoles are bussed in series to form a single focusing unit. Details of the LQXB production have been discussed elsewhere [4]. The two MQXB magnets are joined together by a 1 meter long stainless steel ring which is welded to the MQXB return end plates. This ring, along with the magnet outer shell plus end domes forms the LQXB helium vessel. Once welded, the relative alignment of the two cold masses is largely set, although small adjustments can be made through the cryostat support structure [5].

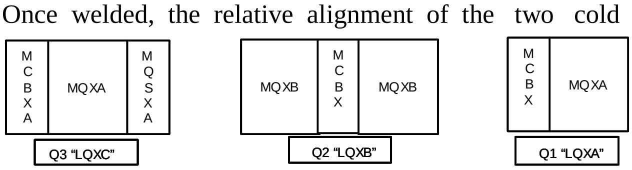

Figure 1: Schematic of LHC insertion regions. MQXA/B are high gradient quadrupoles. MCBX is a nested horizontal/vertical dipole orbit corrector. MCBXA contains additional higher order correctors. MQSXA is a skew quadrupole corrector.

Prior to shipment to CERN, all LQXB elements are tested in superfluid helium at the Fermilab magnet test facility. The critical test performance parameters are magnetic field quality, internal alignment of the MQXB elements and translation of the cold magnetic axis to external fiducials, reliable operation at the peak operating gradient of 215 T/m and protection against excessively high coil temperatures and voltage to ground in the event of a spontaneous quench.

MAGNETIC MEASUREMENTS

Magnetic field measurements were performed during various stages of the magnet construction as a measure of construction quality control. For the completed LQXB the integral harmonics and field strength are measured at the operating and injection gradients.

Cold field harmonics are measured using a rotating harmonics coil in an anti-cryostat in the LQXB bore. The system consists of a 0.8 m long probe, with a tangential coil for higher order harmonics, and dipole and quadrupole windings sensitive to the lower order harmonics. The probe is connected to a rotating shaft which is precisely positioned longitudinally in 8 locations throughout the length of the MQXB. The measured fields are combined together to form the integral field. Each MQXB is measured separately, with the integral field of the series'd connected LQXB computed from the individual MQXB magnets. The results are shown in Fig. 2 for the measured values and compared to target values established during the model magnet program [6]. The harmonics are within target values.

Finally, the integral field strength of the two MQXB magnets connected in series is measured using the Single Stretched Wire System (SSW) [7].

ALIGNMENT

The primary goal of the alignment measurement is to determine the average magnetic field axis of the MQXB pair and relate this to external fiducials on the LQXB cryostat. These external fiducials will then be used to relate the magnetic axis to the CERN accelerator coordinate system. The magnetic axis is determined using the SSW System. Typically the magnet axis, relative to the SSW platform can be determined to within 25 μm. Relating the magnet axis to the external fiducials through a laser tracker system has a typical RMS measurement error of approximately 75 μm.

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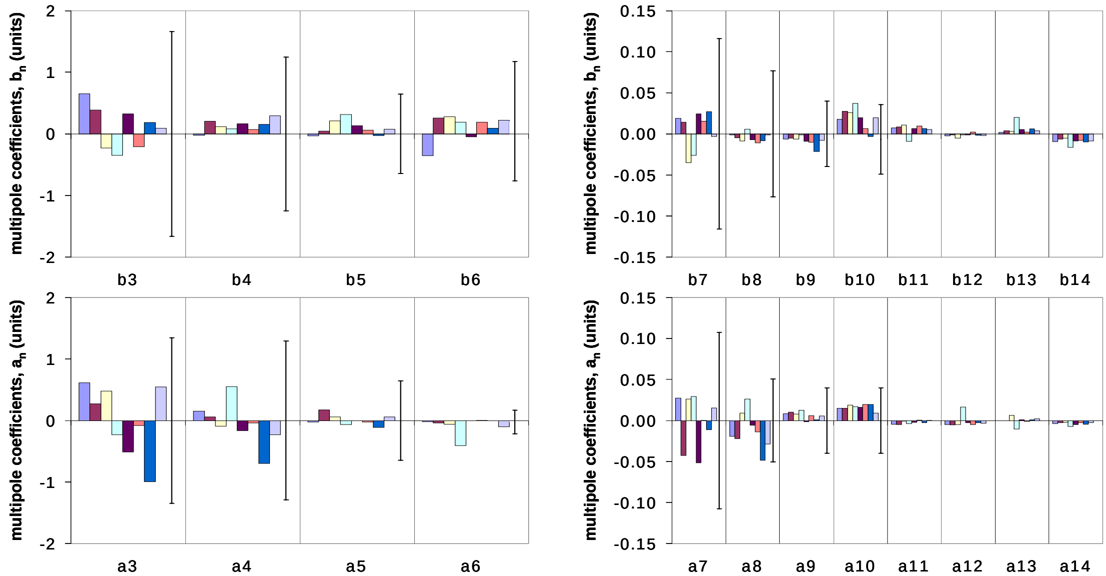

Figure 2: Measured multiple components of the LQXB quadrupoles at collision energy in units of 10^{-4} at R_{ref} of 17 mm, compared with target values (error bars).

SSW measurement of the magnetic axis is performed prior to cool down, at liquid helium temperatures, and again at room temperature. For a subset of the LQXB, measurements were taken on subsequent thermal cycles. After one thermal cycle, it is observed that there is an approximately 300 μm settling of the cold mass in the cryostat. Magnets exhibited an additional settling of approximately 100 μm on a second thermal cycle. Progressively smaller (<100 μm) settling was observed on further cooldowns.

Additional measurements were performed to determine the relative orientation of the two MQXB magnets in pitch, roll and yaw angle. The average pitch, yaw and roll angles are shown in Table 1. These values are consistent with recommended alignment values [8].

The axis of the beam tube is determined using a "geo mole" system supplied by CERN. The mole is a cylinder with an alignment target mounted to one front face. This target is precisely registered to the transverse geometric center of the beam tube. In 1 cm longitudinally intervals, the target location is recorded relative to the external cryostat fiducials through a laser tracker.

Finally the magnetic and beam tube axis is measured again after shipment to CERN, using the CERN measurement systems as well as a Fermilab supplied SSW system. A systematic shift in the LQXB magnetic axis with respect to the external fiducials is observed, typically 100-200 μm in the downward vertical direction. This shift is most likely due to settling during the transit to CERN from Fermilab.

Table 1: Average Relative Rotation Misalignments for LQXB Production Magnets

	Average	RMS
Roll (mrad)	0.40	0.28
Pitch (mrad)	0.22	0.17
Yaw (mrad)	0.22	0.24

QUENCH PERFORMANCE

Within the LQXB, each MQXB was independently quenching trained at 1.9K until it reached 230 T/m. For the first two LQXB and the prototype MQXP01, a second thermal cycle was performed to demonstrate that LQXB could reach 220T/m without quench. Since no retraining was observed in these production magnets, the full scale prototype, or in several 2 meter models, this 2nd thermal cycle was dropped from the test program. Similarly, a thorough program of quench protection tests was performed on the first Q2 assembly LQXB01, the prototype MQXP01, and several magnets in the model program. Magnets were quenched by firing the quench protection heaters at the operating gradient without the aid of an extraction circuit. These tests showed that the MQXB coils have an acceptably low peak temperature and low voltage to ground as the result of a quench [9]. Subsequently, in order to save helium and reduce the quench recovery time, all magnet quenches were performed with an energy extraction circuit which absorbed approximately one half of the store energy at full field.

The results of the quench tests are shown in Fig. 3. In many cases the magnets reached the test gradient goal of 230 T/m without quenching. In almost every case, the MQXB magnet reached the 230 T/m goal in no more than 4 quenches. However in two cases the MQXB failed to reach the operating gradient of 205 T/m (MQXB04 and MQXB14). In the case of MQXB04, LQXB02 was disassembled and MQXB03 was paired with another magnet, MQXB13, to make LQXB08. MQXB04 coils were not reused. For MQXB14, the magnet was rebuilt by replacing coils from the limited quadrant with new coils. Unfortunately, the rebuilt magnet only performed slightly better; its quench performance improved by only 100 Amperes with quenches in another of the original coils.

The cause of these failures is not fully understood. A quench antenna system, built into the test stand anti-cryostat, provided information on quench location for these production magnets [10]. The quench locations for MQXB04 and MQXB14 are very near the inner/outer splice at the lead end pole, and further analysis to better localize the quench origin, in radius and azimuth, is under way. For a given temperature and ramp rate, the quench current and antenna signal development are very repeatable, and exhibits temperature dependence suggestive of a conductor limitation. Extensive ramp rate tests were performed at 4.5 K. At very low ramp rates (0.5 to 5 A/s) there is a significant increase in the quench current of several hundred Amperes relative to the nominal ramp rate of 20 A/s.

Several conjectures to explain the limited quench performance are being investigated. Thermal limitations caused by splice heating and/or poor cooling conditions seem unlikely, but cannot yet be ruled out. Another hypothesis is that current distribution among the strands is non-uniform, due to poor coupling within the inner/outer splice; this could lead some strands to reach the critical surface (at the high field point) well below the expected magnet current. At the splice interface, the inner and outer cable strands are nearly parallel, and there is a possibility that solder flow within the splice fixture may not be uniform. More tests are planned to further explore this hypothesis.

PROJECT STATUS

The production and tests of MQXB magnets for the LQXB are nearly complete. Eight LQXB elements have been successfully built. Tests show that these magnets meet the field and alignment requirements for LHC operation. However the LQXB07 field gradient is inadequately low. Two approaches to repairing LQXB07 are being pursued in parallel. The prototype MQXP01, which reached 230 T/m, is being rebuilt for use in LQXB07. The second approach is to rebuild MQBX14, with an emphasis on improving the splice quality. In both cases the single MQXB would be tested in the prototype cryostat to verify that magnet can operate to the target field gradient, prior to LQXB07 reassembly.

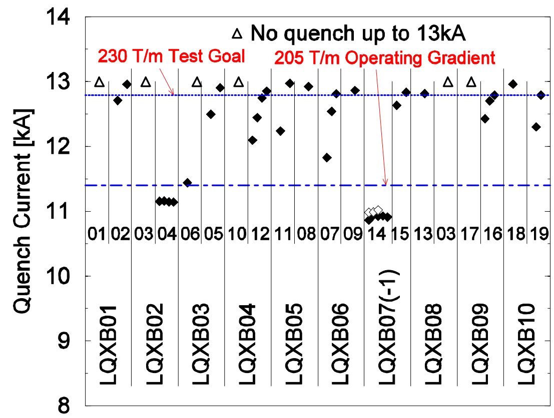

Figure 3: Training History of MQXB quadrupoles. For LQXB07, open symbols are quenches from the rebuild of MQXB14.

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