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Field Measurement of Fermilab-Built Quadrupole Magnets for the LHC Interaction Regions

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Abstract—**Superconducting low-beta quadrupole magnets for the interaction regions of the Large Hadron Collider have been developed by the US-LHC Accelerator Project. These 70 mm bore 5.5 m quadrupole magnets are intended to operate in superfluid helium at 1.9 K with a nominal field gradient of 215 T/m. Fabrication and testing of these magnets has begun at Fermilab. Magnetic field measurements of the first magnets produced are described and compared with results from prototype magnets as well as with requirements set by machine performance studies.**

Index Terms—**Magnetic fields, quadrupole, superconductivity.**

I. Introduction

TO ACHIEVE a luminosity of 10^{34} $cm^{-2}s^{-1}$ at the LHC, special quadrupole magnets are required for the final focusing triplets in the interaction region [1]. These magnets must provide a field gradient of 215 T/m over a 70 mm bore with good field quality due to large and rapidly varying values of the β-function in the interaction region. Of the inner triplet quadrupoles, half (MQXB) will be built at Fermilab with the remainder built at KEK. A short model magnet program to validate the design of the MQXB and construction techniques was completed in 2000. A full scale prototype (MQXP01) of an MQXB cold mass was tested last summer. During testing, an extensive program of field harmonics measurements was executed. To date 5 MQXB have been constructed. The first two have been assembled in their joint cryostat. Cold testing is expected to begin shortly. In this paper we present results of field measurements of these magnets.

II. Magnet Design

The MQXB design, developed by a Fermilab-LBNL collaboration, is based on four two-layer coils connected in series, surrounded by stainless steel collar and iron yoke laminations. The magnet cross-section is shown in Fig. 1. Details of the design evolution and improvements in field quality during the course of the model magnet program can be found in [2].

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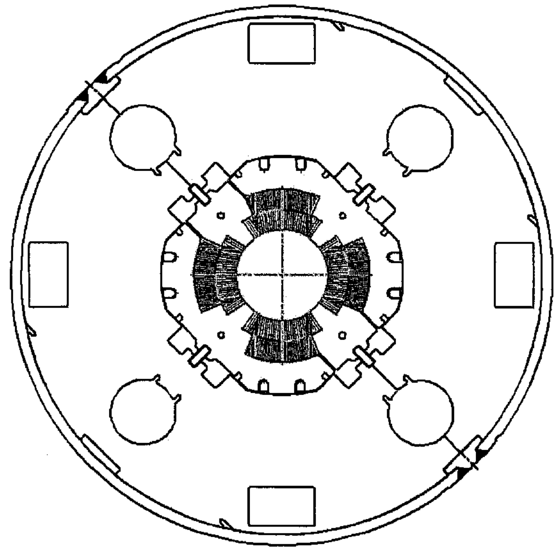

Fig. 1. Magnet cross-section. The coil bore diameter is 70 mm and the skin outside diameter 416 mm.

III. Field Harmonics Measurement System

Magnetic measurements presented in this paper were performed using a variety of rotating coils. Probes used have a tangential winding sensitive to harmonics of all orders as well as dedicated dipole and quadrupole windings for measurement of the lowest order components of the field. These windings also allow for bucking the large dipole and quadrupole components in the tangential winding signal. Most measurements presented in this paper were made with a 3 section integral coil of 41 mm nominal diameter and overall length 7.1 m. The active length of each section as well as the interconnection region between sections is an integral multiple of the 0.114 m cable winding pitch length of the MQXB magnet. Warm measurements made for quality control during magnet production were taken with a 64 mm diameter coil of 0.9 m length. Warm measurements made for quality control during production of model magnets and prototype were taken with a 25 mm diameter coil of 1 m length with an integrated drive system ("mole").

The readout system used for model magnet measurements as well as the mole was described in [2]. A new readout system for production measurements has been constructed. Coil winding voltages are read using METROLAB Model 5035 integrators. One integrator is required for each winding of the probe. Windings in the separate sections of the integral probe are connected in series. An HP 3458 digital volt meter is used to monitor

TABLE I

MEASURED HARMONICS OF THE MAGNET AT 6 kA

	HGQ					MQX
n	05	06	07	08	09	P01
b_3	0.72	0.25	0.18	0.61	0.71	0.28
b_4	0.00	0.09	0.01	-0.12	-0.05	-0.44
b_5	-0.04	-0.11	-0.04	-0.01	0.08	0.04
b_6	-0.30	-0.05	-0.45	-0.06	-0.28	-0.55
b_7	0.01	-0.03	0.02	-0.01	0.06	0.00
b_8	0.00	0.00	0.00	0.00	-0.01	-0.02
b_9	0.00	0.00	-0.01	0.00	0.00	0.04
b_{10}	0.01	0.00	-0.02	-0.01	-0.01	0.00
a_3	0.12	-0.27	0.41	-0.01	0.35	-0.02
a_4	0.19	-0.31	-0.50	-0.43	0.31	1.03
a_5	0.05	-0.07	-0.24	0.12	-0.14	-0.52
a_6	-0.03	-0.05	-0.10	-0.03	0.04	-0.01
a_7	0.01	0.00	0.07	0.00	0.02	0.03
a_8	0.00	0.00	0.01	-0.01	0.01	-0.03
a_9	0.00	0.00	0.01	-0.01	0.00	0.02
a_{10}	0.00	0.00	0.00	0.00	0.00	0.01

magnet current. Integrators and DVM are triggered simultaneously by an angular encoder on the probe shaft, synchronizing measurements of field and current. Feed down of the quadrupole signal to the dipole is used to center the probe in the magnet. A horizontal drive system allows for longitudinal scans of the production magnets on either the warm measurement stand or the cold test stand.

IV. FIELD QUALITY ANALYSIS

In the straight section of the magnet, the field is represented in terms of harmonic coefficients defined by the power series expansion

$$B_y + iB_x = B_2 10^{-4} \sum_{n=1}^{\infty} (b_n + ia_n) \left(\frac{x + iy}{r_0} \right)^{n-1} \quad (1)$$

where B_x and B_y are the transverse field components, B_2 is the quadrupole field strength, b_n and a_n are the 2 n-pole coefficients ($b_2 = 10^4$) at the LHC reference radius r_o of 17 mm. All field harmonics in this paper are given in these units of 10^{-4} normalized to the main field. The coordinate system for magnetic measurement is defined in [3].

A. Results From Cold Testing of MQXP01

Many field measurements from cold testing of the prototype magnet were published in [4]. Field quality was comparable to those of the later model magnets even though these were the first coils produced with the new tooling needed for 5.5 m magnet production. Table I shows the measured harmonics up to the 20-pole for the last 5 model magnets and the MQXP01. We compare to the last 5 model magnets (HGQ05-09) as field harmonics in these magnets of the series were consistently small after steady improvement in field quality in the first few model magnets due to better coil production techniques. The largest harmonic in the prototype is 1 unit of skew octupole, much smaller than the several units of low order harmonics seen in the first few model magnets. Similar examples of 0.5 to 1 unit of low order harmonics were observed in the later model magnets. Note that the comparison in Table I is between measurements in the straight section of the model magnets and integral measurements of the prototype magnet. We comment on this below.

TABLE II

CALCULATED AND MEASURED HARMONICS OF THE MAGNET END REGIONS

	HGQ					MQX	
	06	07	08	09		P01	
harmonic		lead end			ret.	lead	ret.
b_6, calc.		3.5			0.1	3.5	0.1
b_6, meas.	3.1	3.1	3.1	3.0	-0.6	3.1	-2.1
b_{10}, calc.		-0.1			-0.1	-0.1	-0.1
b_{10}, meas.	-0.1	-0.1	-0.0	-0.1	-0.1	-0.2	-0.5

A comparison of measured harmonics in the magnet ends is given in Table II for HGQ06-9 and the MQXP01. These magnets all have the same end design. Calculations of the harmonics based on this design are also given in the table. As in the magnet straight section, the multipole components in the end regions are expressed in units of 10^{-4} of the quadrupole field. Measurements in the lead end of the 5 magnets are within 0.1 unit of each other. We have return end measurements at 1.9 K for only two magnets. The b_6 in HGQ09 is small and shows the same difference between measured and calculated values of 0.4–0.5 units as the lead end. This is believed to be due to local shims in the magnet end region not included in the calculation. The measurement in the prototype magnet is larger. It should be noted that, although the value is large, the contribution to the integral field is still small (-0.1 unit). Furthermore the uncertainty on this measurement is also much larger (0.7 units) as the value is found from the difference of measurements made by the integral probe in two different longitudinal positions. Cold tests of the first two production cold masses should clarify the situation. We plan to make a direct measurement of both end regions using the same 1 m probe used for the model magnet measurements having constructed additional drive shaft sections since testing of the prototype magnet that will allow us to do so.

With regards to cable eddy currents and magnetization, we summarize the situation as follows. Coils for MQXP01 were cured using the curing cycle introduced during production of the last model magnet (HGQ09) after large eddy current effects due low crossover resistance attributed to elevated temperatures during one step of the curing cycle were seen in HGQ06-08 [2], [3]. Magnetic measurements made during ramping at different ramp rates show that the effects of cable eddy current on measured harmonics are small [4]. Production coils are cured as for MQXP01 and HGQ09. We expect to confirm similar small eddy current effects during cold testing of the production magnets. Injection field in the MQXB ranges from 12.3 to 14.1 T/m due to the different β^* in the various interaction regions. At these low field levels, persistent currents give an additional contribution to the allowed harmonics. The average additional b_6 measured at the lowest injection field in the model magnets was -1.6 units (RMS 0.6). The additional b_6 measured in MQXP01 is -0.8 units, slightly smaller in magnitude than in any of the model magnets. Note that with respect to accelerator performance, smaller is better. We will continue to characterize the field at injection during cold testing of the production magnets, but we expect the effects of persistent current on the allowed harmonics to be similarly small.

TABLE III
COMPARISON OF ALLOWED HARMONICS IN MODEL MAGNET AND PROTOTYPE BODY

	HGQ05-9		MQXP01
n	$<b_n>$	$\sigma(b_n)$	b_n
6	-0.23	0.17	-0.86
10	-0.01	0.01	-0.06

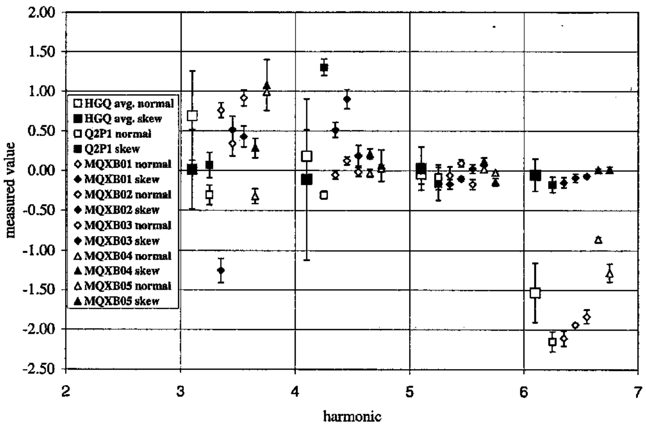

Fig. 2. Summary of collared coil measurements. Error bars for the 5 model magnet ensemble are the standard deviation (σ) of the distribution of measured harmonics. Values for individual magnets are the average over the 5 independent and nonoverlapping measurements in the magnet straight section. The error bars are taken as $\sigma/\sqrt{(n)}$.

B. Warm Measurements of Production Magnets

We have already noted that the comparison given in Table I is between measurements in the straight section of the model magnets and integral measurements of the prototype magnet. Deconvolution of measurements made by the integral probe in MQXP01 at different longitudinal positions give a body b_6 somewhat more negative than that seen in the model magnets (Table III). Warm measurements of the first few production magnets and the prototype show a systematically larger b_6 than in the model magnets of approximately 0.5 units (Fig. 2). The $\langle b_6 \rangle$ of the model magnets was very close to the ideal target since when combined with the end fields the resulting integral magnet value was -0.004 units. Based on this systematic difference, the decision was made prior to winding of coils for MQXB04 to tune the b_6 by changing the shim patterns in the coils. Inner coils had 25 μm of shim added at the pole and 50 removed at the midplane. Field calculations predicted that this would reduce the b_6 by 0.75–0.95 units depending on the details of how the two current blocks involved deformed. Measurements of the collared coil showed a change in the normal dodecapole of 1.2 units, somewhat larger than desired. We thus modified the shim pattern slightly in MQXB05 to reduce the change. For these coils we took 25 μm out at the midplane and added 25 at the pole. This produced a measured change in b_6 of 0.7 units compared to the expected 0.45. Taking into account the systematic shift between collared coil and final magnet at operating temperature and current, we would expect a body b_6 in this magnet of -0.01, closer to those of the later model magnets. It can also be seen from Fig. 2 that the change in the shim pattern has caused no dramatic increase in low order unallowed harmonics. Pending the outcome of further measurements of these magnets during cold testing, we plan to continue shimming coils as we did MQXB05.

V. CONCLUSIONS

A full length prototype of MQXB magnets for the LHC interaction region has been constructed and tested. Integral and end field harmonics of the prototype are quite small and consistent with those measured in later magnets in the short models of this design. Cable eddy current effects are small. The effect of the magnetization on the field is similar to that seen in previous models. Five production magnets have been constructed. Measurements of the first three confirmed a systematic shift in the normal dodecapole between model magnets and prototype. Modifications to the coil shimming pattern in MQXB04 and 05 appear to have successfully reduced this shift, and we plan to proceed with the modified shim configuration pending cold testing of these magnets.

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