FIELD QUALITY OF THE LOW-BETA QUADRUPOLE MAGNETS, MQXA, FOR THE LHC-IR

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Abstract

KEK has constructed five low-beta quadrupole magnets, MQXA, for the LHC interaction regions and the magnetic field measurements of three of them have been completed. The magnets produce a field gradient of 215 T/m, with a variation of less than 0.05 %. The major error field in the magnet straight section is b_4. The average and the standard deviation of b_4 are 1.24 *units* and 0.06 *units*. The other components are all less than 0.25 *units*.

1 INTRODUCTION

In the framework of the collaboration program between CERN and KEK, KEK is constructing 18 low-beta quadrupole magnets, MQXA[1], for the LHC interaction regions. As a result of the measurement of five 1m-model magnets[2] and two prototypes[3], it has been confirmed that the MQXA magnet works to generate a field gradient of up to 215 T/m at the accelerator flat top, and has an effective magnetic length of 6.37 m. Magnetic field measurements of all magnets will be performed at 1.9 K in a vertical cryostat. Up to April 2002, the measurements have been made on the first three magnets. The production and the field measurement of the magnets are in progress, and in this conference we will report the results of systematic field measurements and the reproducibility of field geometry of the early part of the production run.

2 FIELD MEASUREMENT

The field measurements are performed with a 600 mm long harmonic coil in a warm bore of a vertical anti-cryostat[4]. The nominal coil radius is 21 mm, and the measured multipole components are transferred to the values on the reference radius of 17 mm.

The multipole components are defined by the following equation,

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

where B_2 is the quadrupole strength, R_{ref} is the reference radius. b_n and a_n are the normal and skew $2n$-pole coefficients. These coefficients are expressed in *units*, which are normalised with respect to B_2 and scaled by a factor 10,000.

For the operation of the LHC accelerator, the following measurements are scheduled for all magnets at 1.9 K:

(1) Integral field measurement - The harmonic coil is moved 300 mm stepwise inside the warm tube, and the field mapping is performed. The measurement begins 1 hour later after reaching the target current in order to reduce the effect of the field change with time. The scheduled currents are 0.39 kA (injection porch), 2.0 kA, 3.2 kA, 6.1 kA, 6.6 kA and 7.2 kA (flat top) during the ramp-up branch. From the field profile along the magnet axis, the integral field is calculated for the straight section and the both ends.

(2) Magnetic field as a function of current – The magnetic field at the magnet center is measured for 23 different currents during both the ramp-up and ramp-down branches. Before the measurement, the magnet is pre-cycled up to 7395 A, corresponding to the field gradient of 220.9 T/m. The ramp rate of the current was 10 A/s during all measurements. The magnetic field is measured 4 minutes after reaching the target current.

(3) Magnetic field change with time – The change of the magnetic field with time is measured at the magnet center for 0.39 kA and 7.2 kA.

3 FIELD PERFORMANCE OF MQXA

3.1 Field Gradient and Magnetic Length

Table 1 gives the field gradient, *G*, and the magnetic length, *L*, of the three magnets at the excitation current, *I*= 7228 A. *G* is the integrated value in the magnet straight section. For this current, the three magnets reached the field gradient of 216 T/m. The differences of *G* and *L* between the three magnets are less than 0.1 T/m and 1 mm, which correspond to 5×10^{-4} and 2×10^{-4} of the average. The profile of *G* in the magnet straight section is shown in Fig. 1. In this section, MQXA-02 has a largest change of *G* along the magnet axis. The *G* of MQXA-02 increased by 0.16 T/m from the lead end to the return end. The variation corresponds to 7×10^{-4} of *G*. The current dependence of *G* is shown with the transfer function, *T=G/I*, in Fig. 2. The fine dependence shown by the solid line was measured at the magnet center, and the integrated values in the straight section are designated by symbols for 6 currents. The dependence of *T* due to the magnetic saturation in the iron yoke begins beyond 2 kA for the three magnets. For this dependence, the integrated

Table 1: Field gradient and magnetic length at 7228A

Magnet No.	*G*, T/m	*L*, mm
MQXA-01	216.12	6368.4
MQXA-02	216.22	6368.4
MQXA-03	216.19	6367.4

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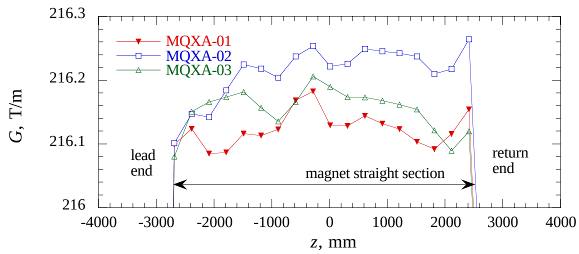

Figure 1: Field gradient profile along magnet axis

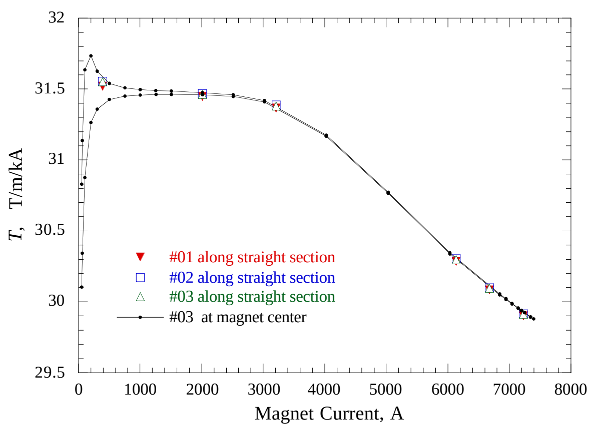

Figure 2: Transfer function vs. excitation current

values are slightly different from the T at the magnet center, but the difference is less than 0.02 T/m, except for the current of 390 A.

3.2 Multipole Components in the Straight Section

The multipole coefficients in the magnet straight section of the three magnets are summarised in Table 2. The coefficients are defined in the coordinate viewed from the lead end. These coefficients are averages of the measured values along the magnet axis. In the table, the measured magnetic length, L, is also given, too. The averages and the standard deviations of the coefficients between the three magnets are described in Table 3. From these results, the amplitudes of multipole coefficients of higher order than the *12-th* pole are less than 0.02 *units*. In the initial design of MQXA, b_{10} was considered to be too large for the beam optics; it was, however, reduced successfully by optimizing the magnet cross section[5]. The b_4 coefficients of the three magnets are systematically large values from 1.19 to 1.30 *units*. The b_4 is mainly introduced from the oval deformation of the two iron-yoke halves by the keying process[6]. The standard deviation of b_4 is 0.06 units, and the variation due to the construction error is quite small. In the prototype and the 1m-model magnets, b_6 was systematically –0.85 *units* different from the design value[4]. The origin of the difference is still being studied, however, we decided to add the pole shim of 0.1mm in order to cancel b_6 and optimize the pre-stress in the coil. This reduced b_6 to 0.18 *units* on average for the three magnets.

Table 2: Multipole coefficients in the straight section at the reference radius of 17mm and 7228A (216T/m), *units*

L mm	MQXA-01 5400.9		MQXA-02 5400.9		MQXA-03 5401.0	
n	a_n	b_n	a_n	b_n	a_n	b_n
3	0.24	0.15	-0.15	0.75	-0.03	-0.18
4	-0.13	1.19	0.21	1.22	-0.35	1.30
5	0.03	0.06	0.10	-0.07	-0.02	-0.03
6	-0.01	0.13	-0.04	0.20	-0.04	0.22
7	-0.00	-0.01	0.00	0.01	0.01	-0.01
8	-0.00	0.01	0.01	0.02	-0.02	0.01
9	-0.00	0.00	0.01	-0.01	-0.00	0.00
10	0.00	-0.00	-0.01	0.01	-0.00	0.00

Table 3: Average multipole coefficients and the standard deviations of the three magnets, *units*

	Average		Standard Dev.	
n	a_n	b_n	σa_n	σb_n
3	0.02	0.24	0.20	0.47
4	-0.09	1.24	0.28	0.06
5	0.04	-0.02	0.06	0.07
6	-0.03	0.18	0.02	0.05
7	0.00	-0.00	0.01	0.01
8	-0.00	0.01	0.01	0.00
9	0.00	-0.00	0.00	0.01
10	-0.00	0.00	0.01	0.00

3.3 Multipole Components in the Coil Ends

Tables 4 and 5 present summaries of the integral multipole coefficients in the ends. The coefficients in the lead and return ends are calculated with respect to B_2 for L of 625 mm to 627 mm and for L of 341 mm, respectively. At the lead end, the major error fields are b_4 and b_6. The averages of b_4 and b_6 of three magnets are 2.09 *units* and 2.67 *units*, respectively. Since b_6 in the straight section is only 0.18 *units*, the integral B_6 at the lead end is comparable to that of the straight section. The standard deviation of b_6 in the lead end is 0.14 *units*, and the variation from magnet to magnet is small. The b_4 is due to the magnet oval deformation, the same as in the straight section, and the coil configuration at the lead end, which has mirror symmetry on the mid-plane. The standard deviation of b_4 between the three magnets is 0.48 *units*. The multipole components of higher order than the *14-th* pole are less than 0.13 *units*.

At the return end, the average and the standard deviation of b_6 are –0.42 *units* and 0.13 *units*, respectively. The b_4 coefficient is at the same level as the straight section.

Table 4: Multipole coefficients at lead end (7228A), *units*

L mm	MQXA-01 626.3		MQXA-02 626.8		MQXA-03 625.4	
n	a_n	b_n	a_n	b_n	a_n	b_n
3	0.50	0.03	0.30	-0.41	0.65	0.12
4	0.56	2.51	0.62	1.67	-0.45	2.08
5	0.16	-0.21	-0.42	-0.44	-0.33	0.05
6	-0.02	2.56	-0.01	2.82	0.08	2.61
7	0.04	0.01	0.01	-0.02	0.02	-0.01
8	0.03	0.13	0.00	0.11	-0.01	0.12
9	-0.01	0.02	0.02	0.01	0.00	-0.00
10	-0.00	-0.05	-0.01	-0.06	0.00	-0.06

Table 5: Multipole coefficients at return end (7228A), *units*

L mm	MQXA-01 341.1		MQXA-02 340.7		MQXA-03 341.0	
n	a_n	b_n	a_n	b_n	a_n	b_n
3	-0.24	1.11	1.57	0.05	0.89	0.61
4	0.66	0.60	-0.06	1.26	-0.04	1.22
5	-0.09	-0.16	0.25	0.09	0.21	-0.13
6	-0.02	-0.56	0.01	-0.31	-0.08	-0.38
7	0.01	-0.00	-0.01	0.02	0.01	0.00
8	-0.02	0.01	-0.01	0.02	-0.01	0.02
9	-0.02	-0.03	0.03	0.01	0.02	-0.02
10	-0.01	-0.09	-0.00	-0.09	-0.01	-0.08

3.4 Multipole Components as a function of current

Fig. 3 shows the typical results for b_4, b_6 and b_{10}. The solid curves were measured at the magnet center of MQXA-03, and the averages of b_4, b_6 and b_{10} in the straight section are shown by symbols, too. The b_6 and b_{10} coefficients show hysteresis between the ramp-up and ramp-down branches by the magnetization of the superconductor, as shown in Figs. 3 (b) and (c). The differences of b_6 and b_{10} in the straight section between the three magnets are within 0.1 *units* at the excitation current from 2 kA to 7.2 kA. Concerning to the current dependence of b_6 and b_{10}, the variation from magnet to magnet is quite small, too.

While b_4 did not exhibit hysteresis between the ramp-up and ramp-down branches, the change with the excitation current was observed in three magnets. The b_4 coefficient has a linear relation with the square of current from 2 kA to 7.2 kA, and the b_4 change is considered to be produced by deformation due to the electro-magnetic force. For MQXA-03, the average b_4 in the straight section is greater by about 0.1 *units* than for the other two magnets. However, the behaviour of b_4 with the excitation current is same from 2 kA to 7.2 kA.

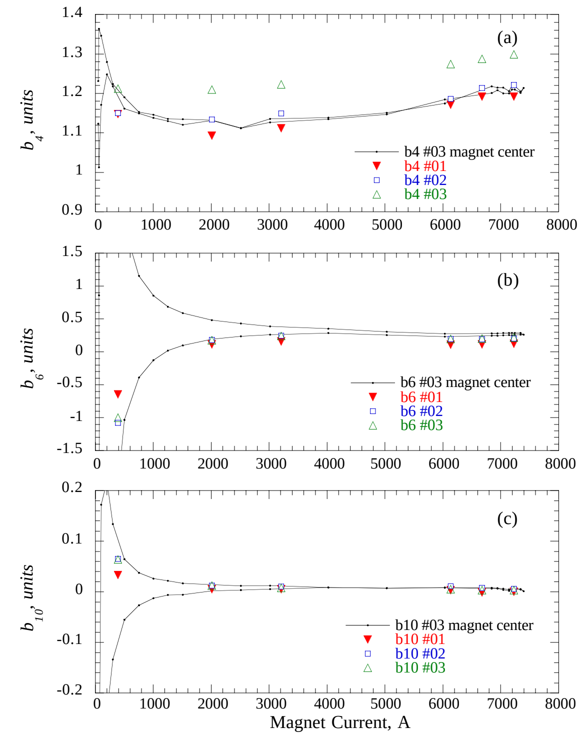

Figure 3: b_4, b_6 and b_{10} as a function of current

4 CONCLUSION

Up to April 2002, the first three production MQXA magnets for the LHC-IR have been tested. These magnets reached the field gradient of 215 T/m, and the variations of the field gradient and the magnetic length from magnet to magnet were within 5×10^{-4}. As for the field errors, b_4 was the major component and the integral b_4 in the magnet straight section was 1.24 *units*. The b_6 coefficient was reduced to 0.18 *units* by introducing pole shims of 0.1 mm. All other harmonics were well below the requirement.

5 ACKNOWLEDGEMENT

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