FIELD QUALITY OF THE LHC-IR 1-M MODEL QUADRUPOLE MAGNETS DEVELOPED AT KEK

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Abstract

KEK has constructed five model magnets in a R&D program of the MQXA quadrupole for the LHC interaction region. The last three magnets have a same cross section, which will be applied to the real MQXA magnets. The reproducibility of the magnetic field of these three magnets was studied by the field measurements. The standard deviation and the mean value of the field gradients at 7.3 kA were 0.2 T/m and 219.6 T/m. The multipole components of the three magnets satisfied the accelerator requirement.

1 INTRODUCTION

As part of the collaboration program between CERN and KEK for the Large Hadron Collider (LHC), KEK has constructed five model quadrupole magnets for the MQXA [1]. These magnets were designed to generate a field gradient of 240 T/m at a temperature of 1.9K. The first two magnets were designed to have b_6 of 0.07 units and b_{10} of –0.013 units at the radius of 10 mm, respectively. However, subsequent studies of the beam optics showed that b_{10} needed to be reduced. Therefore, the cross section of the 3rd magnet was redesigned, and b_6 and b_{10} were reduced to 0.134 units and 0.001 units at the radius of 17 mm[2]. After construction of the 3rd magnet, the magnetic field measurements were performed and it was confirmed that b_{10} of the 3rd magnet was reduced to 0.03 units[3]. The 4th and 5th magnets, which have the same cross section as the 3rd magnet, were constructed to study the repeatability of the magnetic field. The 4th and the 5th magnets were constructed by KEK and Toshiba Corp., respectively. In this paper, the quality and the reproducibility of the magnetic field of the last three magnets are discussed.

2 FIELD MEASUREMENT SYSTEM

The 3rd magnet was measured with two harmonic coils[4], whose lengths are 200 mm and 25 mm. The nominal radii of the harmonic coils are 22 mm. The 4th and 5th magnets were measured with 600 mm long and 25 mm long harmonic coils which were constructed for the 6.6 m long MQXA magnets. The nominal coil radii are 21 mm. These four harmonic coils were calibrated with the same conventional dipole, quadrupole and sextupole magnets[5]. The harmonic coils are used in a warm bore of a vertical anti-cryostat, and are moved along the magnet axis in order to measure the field profile along the magnet axis. A DCCT obtained from CERN was used to measure the magnet current during the test of the 4th and 5th magnets while another DCCT had been used for the 3rd magnet. Therefore, the currents of the 3rd magnet were adjusted to the CERN-DCCT. The coordinate system used in this analysis is the same as that of CERN[6].

3 FIELD PERFORMANCE

3.1 Field Gradient and Effective Magnetic Length

The field gradient, *G*, and the effective magnetic length, *L*, of the three magnets are summarized in Table 1. They were measured at 7345A. The average field gradient was 219.6 T/m, and the standard deviation was 0.2 T/m. This deviation is 9.1×10^{-4} of the average value and it corresponds to the inner radius change of less than 30 μm[7]. The standard deviation of *L* between three magnets is 1.3 mm. The profiles of the quadrupole coefficients, b_2, along the magnet axis are shown in Fig. 1. The component b_2 is normalized by the quadrupole component at each magnet center. The difference of *L* came from both ends. In the lead end, $Z < -250$mm, b_2 of the 3rd magnet is apparently higher than the other magnets. The maximum difference between the 3rd and the 5th magnets reached 30 units. In the return end, $Z > 365$mm, b_2 in the 3rd magnet is larger than the other magnets.

In Fig. 2, the changes of the transfer functions and the standard deviations with the magnet current are shown. From 1.5 kA to 7.3 kA of the magnet current, the standard deviations stay in the range from 0.027 to 0.029

Table 1: Field gradients and effective lengths @ 7345 A

Magnet No.	*G* , T/m	*L* , m
# 3	219.8	1.1081
# 4	219.6	1.1065
# 5	219.4	1.1055

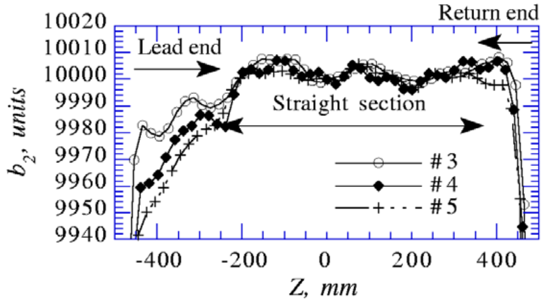

Figure 1: b_2 profiles along the magnet axis. The position, $Z = 0$ mm, corresponds to the magnet center.

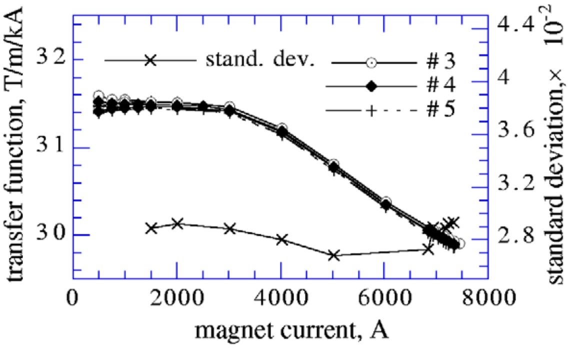

Figure 2: Transfer functions and the standard deviations with the magnet current.

T/m/kA. The magnetic effects of the iron yokes on the quadrupole component of three magnets are almost same.

3.2 Multipole Components in the Straight Section

The multipole coefficients in the straight section are summarized in Table 2. They were measured by the 200 mm long harmonic coil for the 3rd magnet and the 600 mm long harmonic coil for the 4th and the 5th magnets. The multipole coefficients are calculated at the reference radius of 17mm. The averages and the standard deviations of the multipole coefficients of the three magnets are summarized in Table 3.

As for b_6 and b_{10}, the averages of three magnets are –0.77 units and 0.02 units, respectively. The average b_6 has the difference of –0.90 units from the design value while the b_{10} is quite close to the design value. In the 1st and 2nd magnets, the same kind of the difference in b_6 was observed. Field calculation study[7] showed that the azimuthal coil displacement to the pole surface with quadrupole symmetry could explain the difference in b_6. The calculated movement of the coil to explain this difference is 0.03 degree. The standard deviations of b_6 and b_{10} are 0.05 units and 0.01 units, respectively. These small standard deviations mean these magnets have good reproducibility of b_6 and b_{10}.

The component b_4 is introduced from the oval deformation of the two half iron-yoke by the keying process[8]. From the mechanical calculation, the average b_4 of 0.72 units corresponds to the inward deformation of 80 μm in the coils and the yokes on the horizontal mid-plane. The standard deviation of b_4 is 0.34 units, and that is equivalent to the coil deformation of 37 μm.

The reference error table[9] for the magnet straight section of the MQXA are shown in Table 4. They are estimated from the field calculation[2] and the measured field quality of the 1st to the 3rd magnets. The measured average multipole coefficients of the three magnets are close to the systematic errors, except for b_3. The standard deviations of the multipole components are within the random errors in Table 4.

Table 2: Multipole coefficients in the straight section at the reference radius of 17 mm and 7345A, units

	#3		#4		#5	
n	a_n	b_n	a_n	b_n	a_n	b_n
3	-0.44	0.20	0.37	-1.38	0.56	-1.21
4	0.22	0.43	0.03	1.09	-0.49	0.64
5	-0.08	0.11	0.10	0.12	0.22	-0.02
6	-0.04	-0.72	0.20	-0.77	0.00	-0.81
7	0.00	-0.01	0.04	-0.07	0.05	-0.03
8	0.01	0.00	0.00	0.03	-0.03	0.01
9	-0.00	-0.00	0.01	0.01	0.00	0.01
10	0.00	0.03	0.01	0.03	0.00	0.00

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

	average		Standard deviation	
n	a_n	b_n	A_n	b_n
3	0.16	-0.80	0.53	0.87
4	-0.08	0.72	0.37	0.34
5	0.08	0.07	0.15	0.08
6	0.05	-0.77	0.13	0.05
7	0.03	-0.04	0.03	0.03
8	-0.00	0.01	0.02	0.01
9	0.00	0.01	0.00	0.01
10	0.01	0.02	0.01	0.01

Table 4: Reference error field in the straight section, units

	design		systematic errors		random errors	
n	a_n	b_n	a_n	b_n	a_n	b_n
3	0.0	0.0	0.50	0.50	0.99	0.99
4	0.0	0.0	0.27	0.67	0.54	0.54
5	0.0	0.0	0.13	0.13	0.26	0.26
6	0.0	0.134	0.07	0.94	0.13	0.48
7	0.0	0.0	0.03	0.03	0.06	0.06
8	0.0	0.0	0.02	0.02	0.03	0.03
9	0.0	0.0	0.01	0.01	0.02	0.02
10	0.0	0.001	0.01	0.06	0.01	0.04

3.3 Multipole Components in Coil Ends

The field profile along the magnet axis was measured by the 25 mm long harmonic coil. In Fig. 3, b_6 profiles along the magnet axis are shown as a typical measured result. Three magnets show the same profile of b_6 in both ends.

The integral multipole components in the both ends are

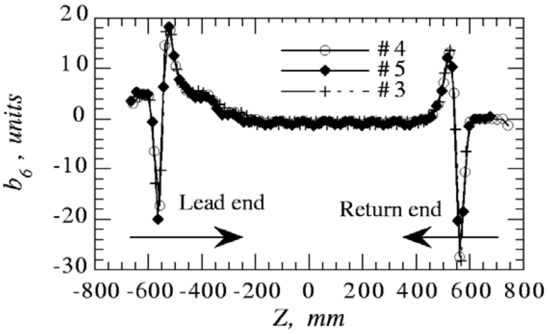

Figure 3: b_6 profile along the magnet axis.

listed in Tables 5 and 6. The averages and the standard deviations of these integral multipole coefficients are shown in Tables 7 and 8. As mentioned in the section 3.1, the integral b_2 along the 3rd magnet ends is larger than the other magnets. The summation of the standard deviations of b_2 in both ends is 14.37 units•m. This value is equivalent to the magnetic length of 1.437 mm, and it is almost same as the standard deviation of the whole effective magnetic length, 1.3 mm.

The measured averages of integral b_6 in the lead and return ends are 1.53 and –0.28 units•m, respectively. Compared to the design values of 1.44 units•m for the lead end and –0.1 units•m for the return end, the measured values are very close to the design value.

The integral b_4 in the lead end is calculated to be 1.11 units•m. This is introduced from the geometry of the lead end. The 4th and 5th magnets show a good consistency to the design while the 3rd magnet has 0.14 units•m.

From the standard deviation point of view, the multipole components are quite reproducible except for the sextupole component. The maximum standard deviation is the integral a_3, 0.65 units•m. This is equivalent to 10^{-5} to the integral quadrupole component of the full length MQXA magnet.

Table 5: Integral multipole coefficient in the lead end

	#3, units•m		#4, units•m		#5, units•m	
n	Int.a_n	Int.b_n	Int.a_n	Int.b_n	Int.a_n	Int.b_n
2	0.	3037	0.	3026	0.	3022
3	-0.41	0.78	-0.60	0.12	0.61	0.72
4	-0.01	0.14	-0.05	0.98	-0.05	1.04
5	-0.04	0.07	-0.07	0.24	0.20	0.34
6	-0.00	1.51	-0.05	1.56	0.06	1.52
7	-0.01	0.01	-0.01	0.07	0.07	0.10
8	0.00	0.05	-0.01	0.09	0.02	0.09
9	-0.00	0.01	0.00	0.01	0.02	0.03
10	-0.00	-0.04	-0.01	0.02	0.03	-0.04

Table 6: Integral multipole coefficient in the return end

	#3, units•m		#4, units•m		#5, units•m	
n	Int.a_n	Int.b_n	Int.a_n	Int.b_n	Int.a_n	Int.b_n
2	0.	1895	0.	1888	0.	1881
3	-0.84	-0.32	-0.09	-0.74	-0.13	-0.70
4	-0.03	0.04	-0.14	0.17	-0.12	0.04
5	-0.02	0.04	0.08	-0.10	0.01	-0.13
6	-0.02	-0.22	0.04	-0.31	-0.05	-0.32
7	0.00	-0.01	0.01	0.00	0.01	-0.00
8	0.00	0.00	-0.02	-0.00	-0.00	-0.00
9	-0.00	-0.00	-0.00	0.01	-0.02	0.01
10	-0.00	-0.03	0.01	-0.04	0.05	-0.03

Table 7: Average multipole component and the standard deviation in the lead end

	Average		Stand. Dev.	
n	Int.a_n	Int.b_n	Int.a_n	Int.b_n
2	0.0	3028.3	0.0	7.55
3	-0.13	0.54	0.65	0.37
4	-0.04	0.72	0.02	0.50
5	0.03	0.22	0.15	0.14
6	0.00	1.53	0.06	0.02
7	0.01	0.06	0.05	0.05
8	0.00	0.08	0.01	0.02
9	0.01	0.02	0.01	0.01
10	0.01	-0.02	0.02	0.03

Table 8: Average multipole components and the standard deviation in the return end

	Average		Stand. Dev.	
n	Int.a_n	Int.b_n	Int.a_n	Int.b_n
2	0.0	1887.8	0.0	6.82
3	-0.36	-0.58	0.42	0.23
4	-0.10	0.09	0.06	0.07
5	0.02	-0.06	0.05	0.09
6	-0.01	-0.28	0.04	0.06
7	0.01	-0.00	0.01	0.01
8	-0.01	-0.00	0.01	0.00
9	-0.01	0.01	0.01	0.01
10	0.02	-0.04	0.03	0.01

4 CONCLUSION

Five 1-m model quadrupole magnets for the LHC-MQXA have been constructed. The last three magnets have a same magnet cross-section, and the reproducibility of the field was confirmed.

The multipole components of three magnets were acceptable for the LHC-IR optics.

5 ACKNOWLEDGEMENT

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