THE FIELD QUALITY OF THE 1-METER MODEL KEK-LHC LOW-β QUADRUPOLE MAGNETS

Y. Ajima, T. Nakamoto, T. Ogitsu, N. Ohuchi , M. Qiu, T. Shintomi,
K. Tsuchiya, and A. Yamamoto, KEK, Tsukuba, Japan

Abstract

Two 1-m model magnets of the KEK-LHC low-β quadrupole magnet were constructed and tested. The two magnets reached a field gradient of more than 240T/m. Magnetic field measurements were performed with two kinds of harmonic coils. In this paper, the field qualities of the straight section and the end regions are reported and compared with the calculations.

1 INTRODUCTION

KEK has made two 1-m model magnets for the R&D of the LHC low-β quadrupole magnets [1, 2]. The first magnet (No.1-a) had additional shims at the pole surfaces of the coils to keep the pre-stress in the coil at 55MPa in the azimuthal direction. The thickness of the shims was 0.2mm for the inner two layers and 0.1mm for the outer two layers, respectively. Iron yokes almost covered the straight section, and the length was 599mm. Due to the additional shims, the magnet had a b_6 of 1.25units in calculations. The multipole components of the magnet are summarized in Tab. 1.

Table 1: Calculated multipole components of No.1-a, No.1-b and No. 2 in the straight section (units).

Multipole	No.1-a	No.1-b & 2
b_6	+1.25	-0.20
b_{10}	-0.89	-0.84

The second magnet (No.2) was fabricated as designed. There were no additional shims. Therefore, the calculated multipole components are different from those of the No.1-a magnet. Especially the b_6 shows a large difference of 1.45units. The straight section and the ramp area of the magnet were covered with iron yokes.

The first magnet was re-assembled to remove the additional shims (No.1-b). Therefore, the calculated field characteristics in the straight section are the same as the No.2 magnet. The whole magnet is covered with iron yokes.

The calculation of the magnet return end for the No.1-b has been completed using ROXIE, and the results are summarized in Tab. 2. The definition of each section for the KEK magnet is shown in Fig. 1.

2 FIELD MEASUREMENT SYSTEM

The field measurements were performed by two harmonic coils. One is 200mm long, and it is used for measuring the field profile along the magnet length [3]. The other is 25mm long. It was designed to see the fine structure of the field profile in the end regions. The radii of the both harmonic coils are 22mm. The harmonic coils consist of seven windings: a tangential winding, three dipole windings and three quadrupole windings. The inductive voltages of the windings are measured by integrators (Metrolab PDI 5025). The harmonic coils are supported in the warm tube in the magnet bore, and their temperatures are kept at room temperature by dry nitrogen gas.

In the 200mm harmonic coil, a radial coil is installed. It is used for measuring the field gradient. It is one turn coil, and the length and the radius are 200mm and 22mm, respectively.

The measurements are performed in a vertical cryostat. The harmonic coils are moved vertically, and the position of the harmonic coil is measured by a magnetic scale. The revolution speed of the harmonic coils is 0.208Hz. The azimuthal position is measured by an angular encoder.

Table 2: Calculated multipole components along the return end (units·meter).

Multipole	
b_2	+1658.6
b_6	+1.329
b_{10}	-0.128

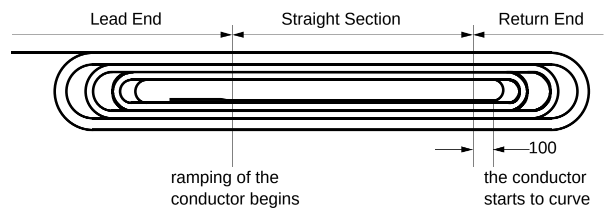

Figure 1: Definition of the lead end, straight section and return end of the 1-m model magnet.

3 FIELD MEASUREMENT RESULTS

3.1 *Multipole components as a function of position*

The harmonic coils were moved longitudinally be a constant amount d_z, and at each position, the measurements of ten rotations were performed with a constant current (Z-scan measurement). The summary of the measurements is shown in Tab. 3. The No.1-a magnet was only measured by the 200mm long harmonic coil. The No.2 and No.1-b magnets were measured by the both harmonic coils. The field

Table 3: Summary of Z-scan measurement.

Magnet	No.1-a	No.2	No.1-b
Harmonic coil	200	200	200
Current (A)	7000	7000/6400	7200
d_z (mm)	100	100	200
Harmonic coil	NA	25	25
Current (A)	NA	20	20
Harmonic coil	NA	NA	410
d_z (mm)	NA	NA	200

profiles along the No.1-b magnet, which were obtained by the 25mm long harmonic coil, are shown in Figs. 2 - 5.

In Fig. 3, the b_4 mainly comes from the lead end, it is negligible in the return end. In the both ends, the b_6 shows a large peaks of over 30units. The peaks are induced by the geometry of the ends and this is explained by the 3-D calculation. In Fig. 5, the b_{10} comes almost entirely from the straight section.

The multipole components along the straight section are summarized in Tab. 4. The data of the No.1-a magnet were obtained by the measurements of the 200mm long harmonic coil, and the No.2 and the No.1-b magnets were obtained by the 25mm long harmonic coil. The multipole coefficients were re-calculated at the radius of 17mm. The data in the table are plotted in Figs.6 and 7. In Fig. 7, the allowed multipoles, which are the design, are shown by arrows with he measurements. The b_6 and b_{10} of the magnets have offsets to the calculations, which are -0.6 to -1.5units for the b_6 and -0.1 to -0.15units for the b_{10}.

The multipole components along the magnet ends are summarized in tables 5 and 6. The coefficients are normalized by the quadrupole components at the straight section.

The lead end was measured for the No.1-a and the No.1-b magnets, and the return end was measured for the No.2 and the No.1-b magnets. In the lead end, large multipole components are b_4, b_5 and b_6. The values will be compared to the calculations. In the return end, the multipole components are calculated as shown in Tab. 2. Both the No.2 and No.1-b magnets show a good agreement to the calculation for b_6 and b_{10}. The No.2 magnet has a b_5 of -1.05 units·m while it is -0.03 for the No.1-b magnet.

Table 4: Multipole components along the straight section.

Magnet	No.1-a	No.2	No.1-b
Multipole	a_n/b_n (units)	a_n/b_n (units)	a_n/b_n (units)
3	-0.32/-1.60	1.55/-1.70	-0.55/-1.52
4	0.85/-1.12	-0.71/-1.34	0.49/-0.80
5	-0.27/-0.02	-0.56/-0.08	-0.37/-0.01
6	0.06/-0.04	-0.38/-1.67	0.53/-0.82
7	-0.02/0.02	0.13/0.05	-0.07/0.01
8	0.00/-0.05	-0.05/-0.30	0.02/-0.02
9	0.22/0.00	0.09/0.26	0.00/-0.01
10	-0.08/-1.01	0.01/-0.90	0.04/-0.93

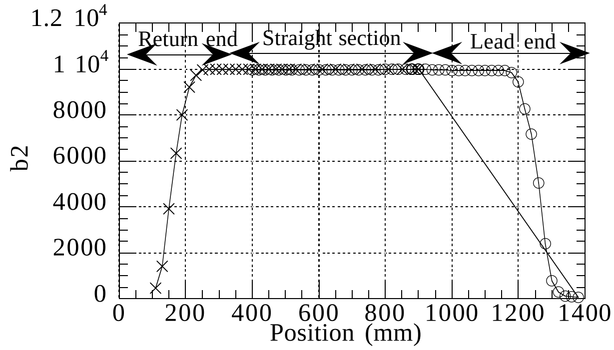

Figure 2: b_2 profile along the No.1-b magnet.

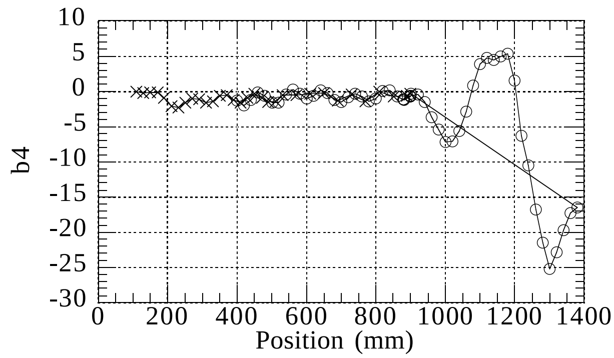

Figure 3: b_4 profile along the No.1-b magnet.

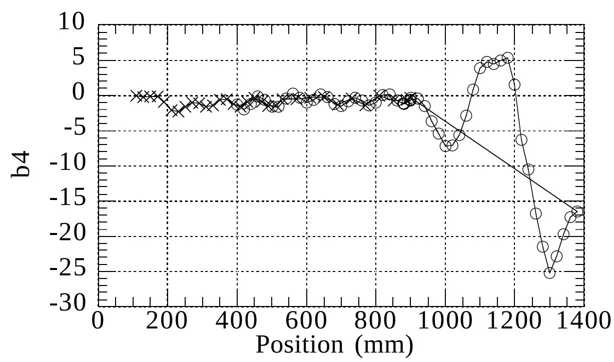

Figure 4: b_6 profile along the No.1-b magnet.

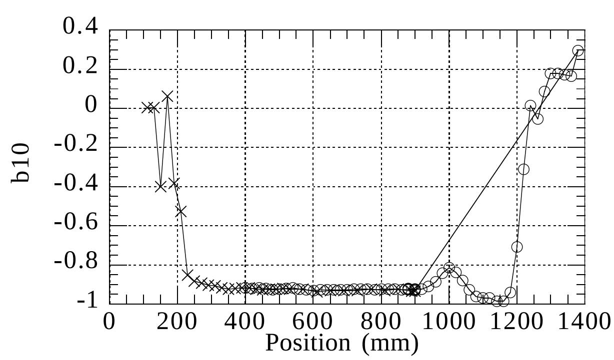

Figure 5: b_{10} profile along the No.1-b magnet.

The No.1-b magnet was measured at the injection stage by the 200mm long harmonic coil. The field quality at the magnet center is summarized in Tab. 7. The b_6 shows a difference of -1.9units from that at 7200A. This is due to the magnetization of the superconductor. The effect on b_{10} is small, and the difference is -0.05units.

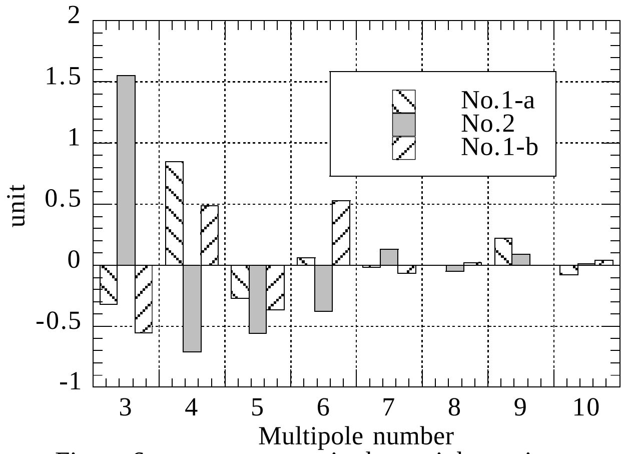

Figure 6: a_n components in the straight section.

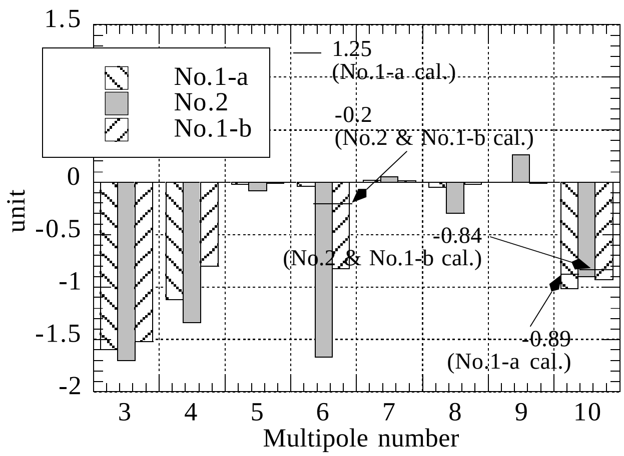

Figure 7: b_n components in the straight section.

3.2 Current dependence of a multipole field

The current dependence of the multipole components was measured at the magnet center with the 200mm long harmonic coil while stopping the current ramp. Before the measurements the magnet current was cycled from 50A to 7200A four times due to Z-scan measurements. The measurement scheme is shown in Fig. 8. In the scheme, we quenched the magnet at 7603A in order to measure the effect of the quench on the multipole components. After the quench, the measurements were performed at magnet currents of 410A and 7200A during up- and down-ramping.

In Figs. 9 to 12, the measured values of b_3 through b_6 are shown. The open circle symbols correspond to the measurements of the first cycle, and the cross symbols correspond to the measurements after the quench. As seen in Fig. 12, the b_6 has a hysteresis of 6units at the injection stage. The b_3 shows a change with magnet current, and the value of the change is -0.4units from 2000A to 7200A.

In the first cycle after the quench, large differences between pre- and post-quench multipole values were measured at 410A. The differences of b_4 and b_6 are -1.1 and -0.6units respectively. The differences became smaller with cycling the magnet current, and the multipole coefficients became close to the values before the quench. At 7200A, the quench effects on the multipoles were negligible.

Table 5: Multipole components along the lead end.

Magnet Multipole	No.1-a a_n/b_n (units·meter)	No.1-b a_n/b_n (units·meter)
2	0.00/2975	0.00/3077
3	0.14/0.31	-0.01/-0.07
4	0.15/-1.92	-0.02/-3.10
5	-0.39/-1.24	0.20/-0.06
6	0.05/2.10	0.04/2.47
7	-0.02/-0.04	-0.02/0.01
8	-0.04/0.02	0.02/0.04
9	0.08/0.21	0.02/0.00
10	-0.02/-0.27	0.01/-0.22

Table 6: Multipole components along the return end.

Magnet Multipole	No.1-a a_n/b_n (units·meter)	No.1-b a_n/b_n (units·meter)
2	0.00/1690	0.00/1693
3	0.22/0.19	-0.14/0.07
4	-0.03/0.18	-0.18/-0.24
5	0.02/-1.05	0.01/-0.03
6	-0.07/1.00	-0.05/1.03
7	0.02/-0.04	-0.01/-0.01
8	0.01/-0.11	-0.01/-0.01
9	0.04/-0.18	0.00/-0.00
10	0.00/-0.13	0.01/-0.12

Table 7: Multipole components at the injection stage.

Magnet Multipole	No.1-b a_n/b_n (units)
3	-0.25/-0.24
4	-0.74/0.18
5	-0.27/0.15
6	-0.07/-2.74
7	-0.12/0.17
8	0.18/0.01
9	-0.04/-0.03
10	-0.07/-0.98

4 SUMMARY

The field quality of the two 1-m model magnets can be summarized as follows:

Straight section

- The sextupole and octupole components are -1.6 to 1.7units.
- The b_6 has an offset of -0.6 to -1.5units to the design.
- The b_{10} has an offset of -0.1 to -0.15 units. In the No.3 magnet, b_{10} is designed to be 0.001units while the previous magnets have the b_{10} of -0.84units. The b_{10} is expected to be within 0.1units.

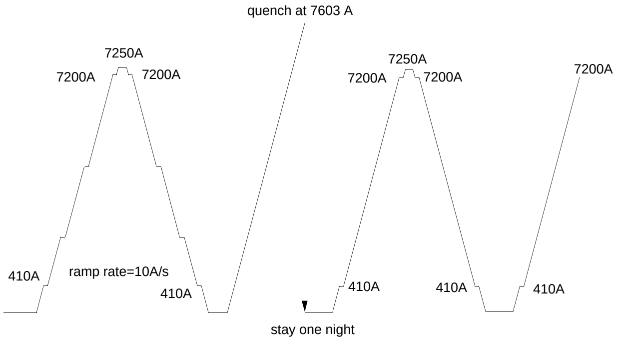

Figure 8: The measurement scheme of the current dependence.

Return end

- The allowed multipoles are almost consistent with the design.
- In the new design, the b_6 and b_{10} are 0.003 and -0.037units m, respectively.

Lead end

- Compared to the return end, the b_4 and b_6 are relatively large. This is due to the wiring of the conductor out of the coil. The wiring position of the conductor will be re-designed.

Current dependence

- The b_6 has a hysteresis of 6units at the injection stage.
- In the first ramp after the quench, the sextupole to the dodecupole components show differences of 1unit to the values before quench at the injection stage.

5 REFERENCES

[1] A. Yamamoto, K. Tsuchiya, et al. "Design study of a Superconducting Insertion Quadrupole Magnet for the Large Hadron Collider", IEEE Trans. Applied Superconductivity, Vol. 7, No. 2, pp. 747-750 (1997).

[2] T. Nakamoto, et al, "Quench and Mechanical Behavior of an Insertion Quadrupole Model for LHC", presented in ASC-98, Palm Desert, (1998).

[3] N. Ohuchi, et al, "Magnetic Field Measurements of a 1-m Long Model Quadrupole Magnet for the LHC Interaction Region", presented in ASC-98, Palm Desert, (1998).

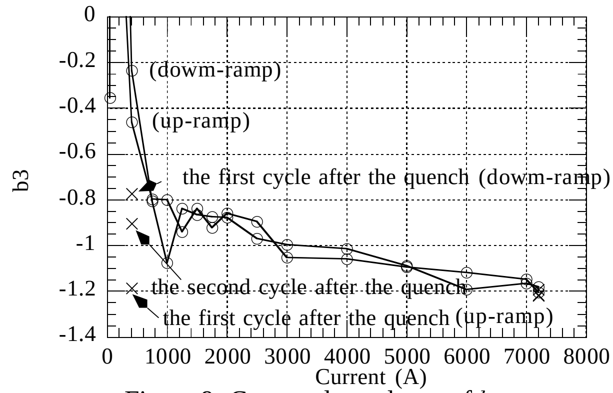

Figure 9: Current dependence of b_3.

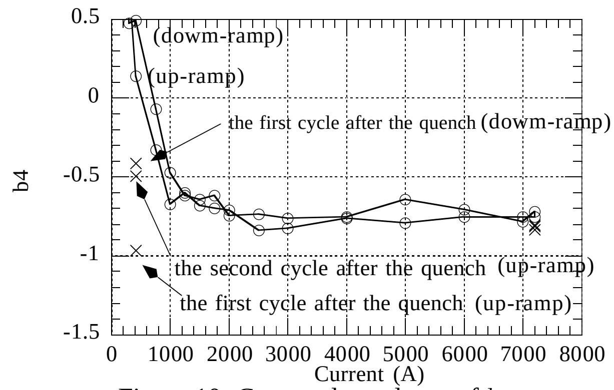

Figure 10: Current dependence of b_4.

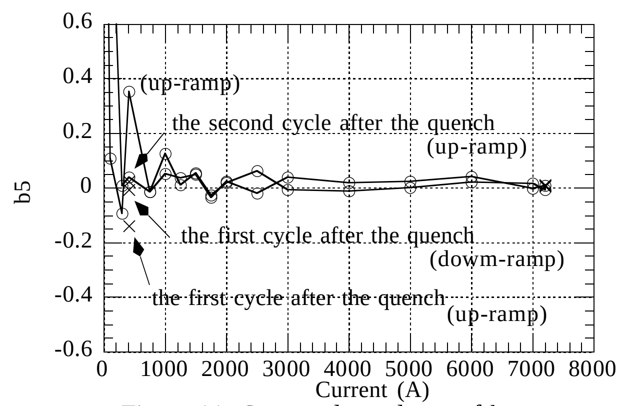

Figure 11: Current dependence of b_5.

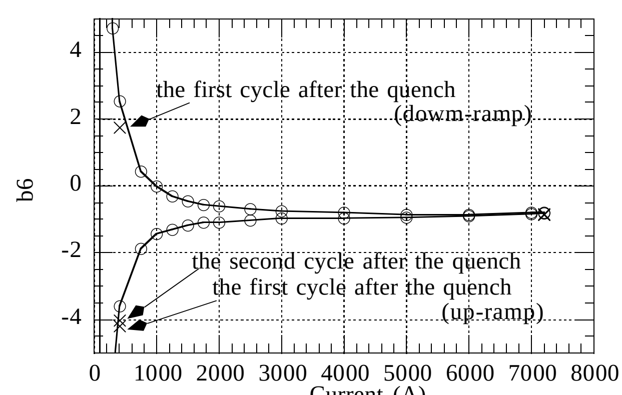

Figure 12: Current dependence of b_6.