# FIELD MEASUREMENTS OF 1-M MODEL QUADRUPOLE MAGNETS FOR THE LHC-IR

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## Abstract

Three 1 meter model quadrupole magnets have been constructed as a R&D program of the MQXA quadrupole magnets for the LHC interaction region. After the field measurements of the first two magnets, the third magnet was redesigned to reduce the $b_{10}$ of the magnet body to less than 0.1 units. The field measurements showed that the $b_{10}$ of the third magnet was improved to be 0.03 units while the previous two magnets had $b_{10}$ of -0.9 units.

## 1 INTRODUCTION

KEK has constructed three 1 meter models of the MQXA quadrupole magnet for the LHC interaction region as part of the collaboration program with CERN[1,2]. The magnets were designed to be operated at a field gradient of 215 T/m. The magnets consist of 4 layer coils and the bore diameter of the magnets is 70 mm. The first two magnets, No.1 and No.2, were constructed with a basically same cross section in the magnet body. In the design, $b_6$ and $b_{10}$ were 0.175 units and -0.975 units, respectively. The No.1a magnet had additional shims to keep the pre-stress larger than 55 MPa in the azimuthal direction. After the tests, the shims were removed and the magnet was reassembled (No.1b). The length of the iron yokes along the magnet length is different between these magnets. The field quality of these magnets has been measured and reported[3]. From the results and the beam optics at the LHC interaction region, $b_{10}$ in the body of the MQXA magnet was required to be less than 0.1 units. Therefore, the No.3 magnet was redesigned so that $b_{10}$ in the magnet body was 0.001 units and the integral $b_6$ in the return end was -0.1 units•m[4,6]. The design values of the three magnets are summarized in Table 1 and 2.

In this paper, we describe the field measurement results of the No.3 magnet, compared with the previous two magnets.

Table 1: Calculation in the body at r = 17mm, units.

|          | No. 1a | No. 1b and 2 | No. 3  |
|----------|--------|--------------|--------|
| $b_6$    | 1.081  | 0.175        | -0.002 |
| $b_{10}$ | -0.994 | -0.975       | 0.004  |

Table 2: Calculation in the ends at r = 17mm, units•m.

|              | No. 1 and No. 2 | | No. 3 | |
|--------------|--------|--------|--------|--------|
|              | return | lead   | return | lead   |
| Int.$b_6$    | 1.32   | 2.87   | -0.10  | 1.44   |
| Int.$b_{10}$ | -0.13  | -0.21  | -0.03  | 0.02   |

## 2 FIELD MEASUREMENT SYSTEM

The measurements were performed with two harmonic coils[5], with lengths of 200 mm and 25 mm. The radii of the harmonic coils are 22 mm. The harmonic coils consist of 7 windings: one tangential winding, 3 dipole windings and 3 quadrupole windings. The dipole and quadrupole windings are used for analog and digital bucking processes. The harmonic coil is installed in a warm bore of a vertical anti-cryostat, and these two harmonic coils are moved along the magnet axis in order to measure the field profile along the magnet length. Especially, with the 25 mm long harmonic coil, we can measure a fine field profile along the magnet length. The revolution speed of the coils is 0.208 Hz.

## 3 FIELD MEASUREMENTS

### 3.1 Transfer Function

The transfer functions were measured by the 200 mm long harmonic coil at the magnet center. The measured results are shown in Fig. 1. The measured transfer functions of the No.1a and No.2 were 31.68 and 31.65 T/m/kA at 7 kA, respectively. The No.1b magnet was fully covered with iron yokes along the magnet length. The transfer function was 31.73 T/m/kA at 7 kA. The No.3 magnet has a different coil cross section and is also fully covered with iron yokes. The transfer function is 30.33 T/m/kA at 7 kA. The difference of the transfer function of the No.3 magnet to the No.1b was 4.3 %. The No.3 magnet reached the maximum operation field gradient of 215 T/m at the 7089A.
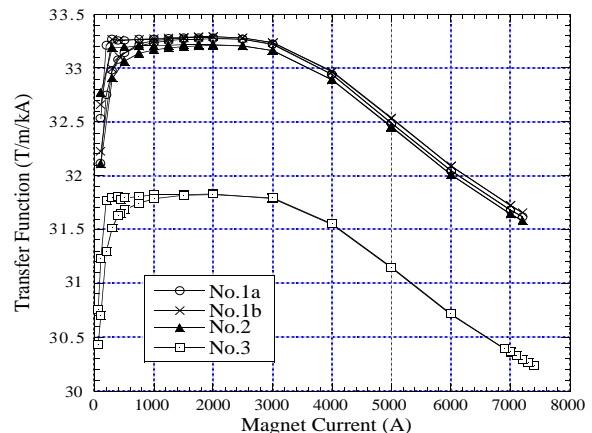


Figure 1: Transfer functions of three magnets.

## 3.2 Field Quality

Figs. 2 and 3 show the $b_6$ and $b_{10}$ profiles of the No.1b and 3 magnets. The measurements were performed by the 25 mm long harmonic coil, and they were taken every 20 mm. The abscissa of the plots gives the position along the magnet axis, where zero corresponds to the magnet center.

The field quality was measured at 7200 A and 7300 A for the No.1b and No.3 magnets, respectively. In the design of the No.3 magnet, the $b_{10}$ in the magnet body was improved to 0.004 units from -0.975 units in the previous two magnets. As shown in Fig. 3, the $b_{10}$ of the No.3 magnet was 0.03 units while it was -0.93 units for the No.1b magnet. We have successfully reduced the $b_{10}$ in accordance with the requirement by the beam optics in the LHC interaction region.

The field quality in the magnet body of the three magnets are summarized in Figs. 4 and 5. The improvement of $b_{10}$ is apparent. The $b_6$ of the three magnets has a negative offset from the design values. The average offset of three magnets is -1.16 units. The offset of the No.3 magnet is -0.71 units. The sextupole component is easily induced by the asymmetric coil assembly. The amplitude of the sextupole component in the No.3 magnet was 0.48 units. The amplitudes for No.1a, b and 2 are 1.65, 1.69 and 2.37 units, respectively. From these data, we can say that the construction of the No.3 magnet was better controlled than the other magnets. The effects of the coil deformations on the field quality are discussed in [6]. The multipole coefficients of the No.3 magnet after warming
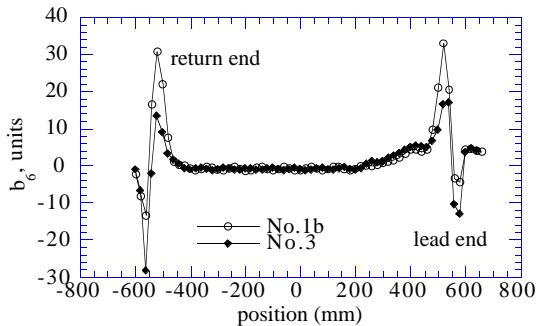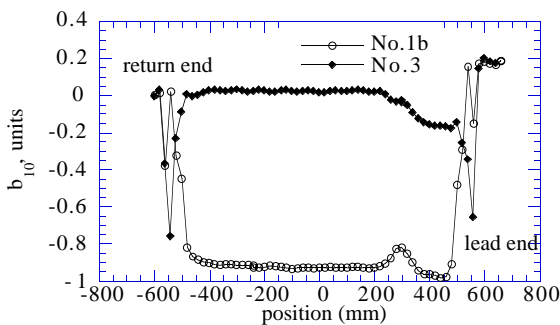


Figure 2: $b_6$ profile along the magnet length.



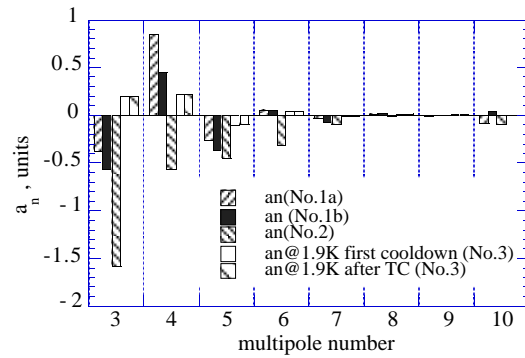Figure 3: $b_{10}$ profile along the magnet length.



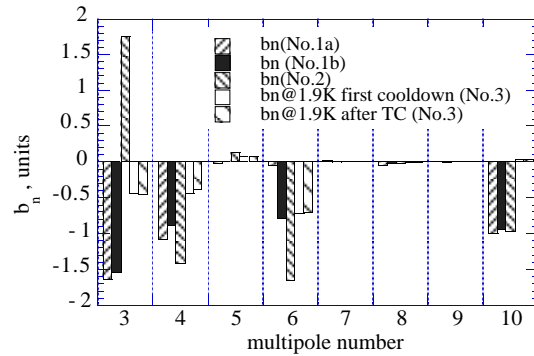Figure 4: $a_n$ in the magnet body of the three magnets.



Figure 5: $b_n$ in the magnet body of the three magnets.

the magnet up to room temperature and cooling down to 1.9 K (thermal cycle) are shown in the same figures: the changes are negligible.

In the No.3 magnet, the integral $b_6$ in the return end was also improved by redesigning the axial position of coil blocks in the end, and the value was reduced to -0.1 units•m in the design. As seen in Fig. 2, the $b_6$ profile along the return end of the No.3 magnet shows a shift of peaks in the negative direction, compared with the profile of the No.1b magnet. In the lead end, the integral $b_6$ is 1.44 units•m since the lead end includes the transitions of the conductor from the lower layer coil to the upper layer coil. In Table 3, the measured integral multipole coefficients in both ends are summarized. The integral $b_6$ in both ends of the No.3 magnet was close to the design value. As a result, the integral $b_6$ was decreased by 1 units•m from the No.1b magnet.

Table 3: Measured integral multipole coefficients in the ends at r = 17 mm, units•m.

| | No. 1b | | No. 3 | |
| --- | --- | --- | --- | --- |
| n | return | lead | return | lead |
| | $a_n, b_n$ | $a_n, b_n$ | $a_n, b_n$ | $a_n, b_n$ |
| 2 | 0, 1693. | 0, 3077. | 0, 1895. | 0, 3037. |
| 3 | -0.1, 0.1 | -0.0, -0.1 | -0.3, -0.8 | 0.8, -0.4 |
| 4 | -0.2, 0.2 | -0.0, -3.1 | -0.0, -0.0 | -0.0, -0.1 |
| 5 | 0.0, -0.0 | 0.2, -0.1 | -0.0, 0.0 | -0.1, 0.0 |
| 6 | -0.1, 1.0 | 0.0, 2.5 | 0.0, -0.2 | 0.0, 1.5 |
| 10 | 0.0, -0.1 | 0.0, -0.2 | 0.0, -0.0 | 0.0, -0.0 |

## 3.3 Current Dependence of Field Harmonics

The current dependence of the multipole components was measured at the magnet center with the 200 mm long harmonic coil. Fig. 6 shows this dependence of the $b_6$. To compare the dependence between three magnets, the $b_6$ which was induced from the geometrical shape of the coil was excluded from the measured values. The geometrical $b_6$ was estimated by averaging the measured values at 1000 A while ramping the current up and down. The values and the hysteresis at 1000A are summarized in Tables 4 and 5. The No.3 magnet shows a different behavior from the other magnets since the magnet cross section and the used conductor are different. The measured hysteresis is in good agreement with the calculation. The No.1b and 2 magnets have the same cross section and conductor. These magnets show a very similar behavior below 4000 A, however, they behave in different ways at higher currents. A possible explanation for this difference is a low pre-stress of the No.1b magnet, 30 MPa, in room temperature. With this low pre-stress, the coils might be deformed by an electro-magnetic force at high current.

Fig. 7 shows the current dependence of $b_{10}$. The No.1 and No.2 magnets have an apparent influence of the iron yoke saturation over 3000 A. The saturation effect on the No.3 magnet is almost negligible because the geometrical $b_{10}$ is much smaller than the other magnets.
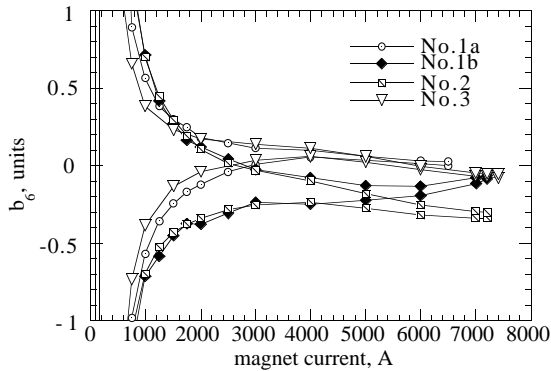
Table 4: Geometrical $b_6$ and $b_{10}$ at 1000A, units.

|          | No.1a | No.1b | No.2  | No.3  |
|----------|-------|-------|-------|-------|
| $b_6$    | -0.01 | -0.73 | -1.47 | -0.72 |
| $b_{10}$ | -0.97 | -0.96 | -0.93 | 0.02  |

Table 5: Measured and calculated hysteresis of $b_6$ and $b_{10}$ at 1000A, units.

| No. | $b_6$, meas. | $b_6$, cal. | $b_{10}$, meas. | $b_{10}$, cal. |
|-----|--------------|-------------|------------------|-----------------|
| 1a  | 1.13         | 1.34        | 0.003            | 0.006           |
| 1b  | 1.43         | 1.35        | 0.006            | 0.007           |
| 2   | 1.39         | 1.43        | 0.013            | 0.007           |
| 3   | 0.77         | 0.87        | 0.040            | 0.032           |

## 4 CONCLUSION

Three one meter model quadrupole magnets for the LHC-MQXA have been developed and tested in KEK. From the magnetic field quality and the requirement of the first two magnet, the cross section of the third magnet was redesigned in order to decrease the amplitude of $b_{10}$ within 0.1 units. By field measurements of the third magnet, it was confirmed that the $b_{10}$ was successfully reduced to 0.03 units.

In the return end, the coil geometry was redesigned to an integral $b_6$ of -0.1 units•m. The measured integral $b_6$ in both ends was improved by 1 units•m.

## 5 ACKNOWLEDGMENT

Figure 6: Current dependence of the $b_6$.
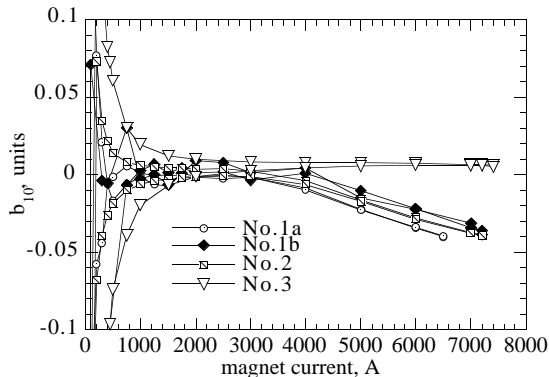


Figure 7: Current dependence of the $b_{10}$.

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