STATUS OF LHC LOW-β QUADRUPOLE MAGNETS, MQXA, AT KEK

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Abstract

KEK has developed a superconducting quadrupole magnet, MQXA, for the LHC interaction region. This magnet is required to generate an operating field gradient of 215 T/m in the magnet bore of 70 mm and have an effective magnetic length of 6.37 m. For the accelerator operation, sixteen MQXA magnets will be installed in total for four interaction regions, and the cold tests of ten MQXA magnets of them have been completed. These ten magnets had good quench performance and satisfactory field quality for the requirement of beam optics. This paper describes the production quality and the magnet performance of the MQXA magnets.

INTRODUCTION

Under the cooperative program between CERN and KEK, KEK has developed a superconducting low-beta quadrupole magnet, MQXA, for the LHC interaction region [1], and KEK will provide eighteen MQXA magnets in total, including two spare magnets. These MQXA magnets will operate in the final focus system (low-β triplet) with the MQXB magnets developed by FNAL [2]. The MQXA magnets are designed to have a magnet bore of 70 mm and generate an operating field gradient of 215 T/m along the effective magnetic length of 6.37 m in the superfluid helium at 1.9K [3, 4]. As the peculiar points in this design, the magnet has a four-layer coil configuration with current grading, however, mechanically the magnet has a two-layer coil configuration. The horizontal split iron yokes have a function of mechanical support against the electro-magnetic force. The main parameters are summarized in Table 1.

After the R&D studies with two full-scale proto-type magnets [5], the series production of MQXA was launched in 2001 [6]. Presently, the construction of eleven MQXA magnets was completed and ten of these magnets were tested at 1.9 K. We report the production and performance of these ten MQXA magnets in this paper.

PRODUCTION

Coil Size Control

In order to minimize the difference from magnet to magnet in the mechanical characteristics and field quality, the dimension of each coil is controlled during the curing process. To confirm manufacturing quality in this process, the coil sizes were measured at six points along the straight section for each octant of the inner or outer two layer coils. In Figs. 1 (a) and (b), the average coil sizes of MQXA-1 to 10 under the pressure of 53MPa are shown. The error bars correspond to the standard deviation of 1σ for the 48 measured values. The coil size is described by the deviation from the design dimension. The coil sizes of the inner layers varied from –74 μm for MQXA-5 to –5 μm for MQXA-10, and the standard deviation of 1σ for ten magnets is 23 μm. For each magnet, the deviation of 1σ is in the range from 15 μm to 23 μm. For the outer layers, the variations of the coil size are smaller than those of the inner layers. The 1σ for ten magnets is 7 μm. The 1σ in each magnet is in the same range as the inner layers. The 1σ of the measured Young's moduli for ten magnets are 0.11 GPa and 0.22 GPa for the inner and outer layers, respectively. From those measured results, the variations are within the production tolerance, and the ten magnets showed a good reproducibility.

Table 1: Main Parameters of LHC-MQXA

Field gradient=215T/m	Coil
Current=7149A	inner radius=35mm
Peak field=8.63 T	outer radius=81.3mm
Load line ratio	Yoke
inner=80%	inner radius=92mm
outer=78%	outer radius=235mm
Stored energy=352kJ/m	Yoke length=6.51m
Inductance=13.8mH/m	Effect. mag. length=6.37m

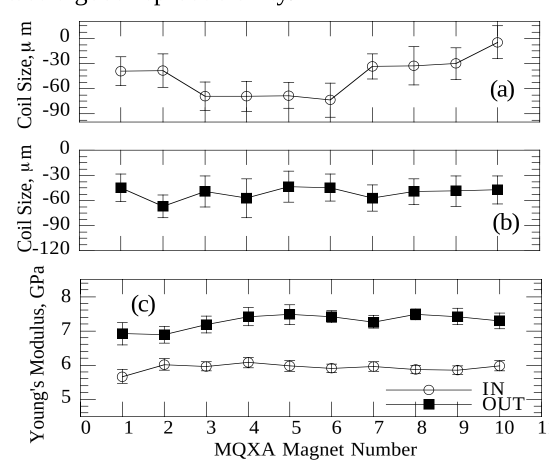

Figure 1: Coil size (a,b) and Young's Modulus (c) of MQXA-1 to 10.

Cold Mass Geometry

The deformation (bending) of the magnet cold mass was measured after welding the magnet-shell, and before and after the cold test. In Fig. 2, the deformations after the cold test are shown. The magnets were aligned on the supports at the axial positions of plus and minus 2100 mm

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for these measurements. In the early MQXA magnets, the large vertical deformations from 0.8 mm to 1.1 mm were measured. Presently, it is understood that these deformations were induced by welding caps of the holes on the shell for the assembly and the magnet sag. In the recent magnets, the welding scheme was improved and this vertical deformation was reduced. The horizontal deformations of ten magnets were within plus or minus 0.3 mm. These deformations were within the mechanical tolerance.

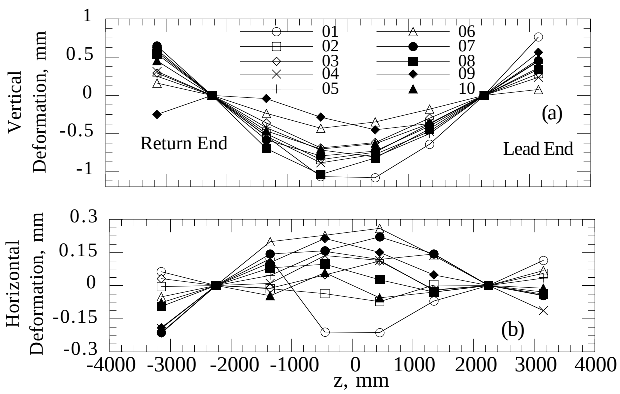

Figure 2: Vertical (a) and horizontal deformations (b) of ten magnets. The position of z=0 mm corresponds to the magnet center.

QUENCH PERFORMANCE

In order to evaluate the quench performance of the magnets, all magnets are scheduled to be tested at 1.9 K in the vertical cryostat at KEK. The test scheme is as follows: (1) Training quench up to 230 T/m with a ramp-rate of 10 A/s. (2)Full energy dump test at 215 T/m (LHC operating point) induced by a quench protection heater. (3)Re-excitation up to 220 T/m without a quench.

Fig. 3 shows the training quench history of MQXA-1 to 10. All magnets reached 230 T/m after their training quenches. For these ten magnets, the total number of quenches was 72 times including the quenches during the second thermal cycle. The ratios of the quench locations are 60%, 28% and 11% in the lead end, the return end and the straight section, respectively. Fig. 4 shows the distribution of the quench locations for each magnet. From the MQXA-1 to MQXA-7, the locations of the quench origin concentrated in the both ends, especially in lead end. However, the MQXA-10 showed different characteristics, i.e. four quenches in the magnet straight section, the largest number of training quench (during the first thermal cycle) and the lowest current at the first quench. We will watch this quench behavior for the successive magnets.

In the full energy dump test at 215 T/m, it was confirmed that the measured MIITs ranged from 11.1 to 11.5 and the coil temperature was less than 350 K in the adiabatic assumption. After this dump test, all magnets were energized to 220 T/m without a quench.

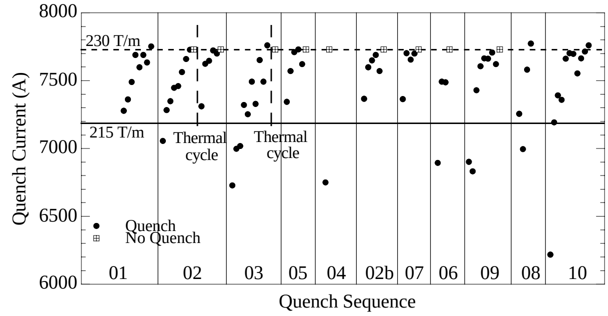

Figure 3: The training history of the MQXA-1 to 10.

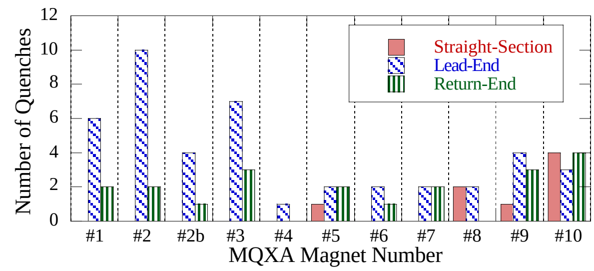

Figure 4: Distribution of the quench location.

MAGNETIC FIELD PERFORMANCE

Field Gradient and Effective Magnetic Length

The magnetic field measurements were performed using a 600 mm long harmonic coil of which nominal coil radius was 21 mm [7]. In order to obtain the integral magnetic field, the harmonic coil was moved stepwise along the magnet length, *z*-scan measurements, in a warm bore of a vertical anti-cryostat. For six excitation currents, the *z*-scan measurements were performed. The measured field gradient, G, and the effective magnetic length, L_{EFF}, were summarized in Table 2. G and L_{EFF} are the average of ten magnets and 1σ is its standard deviation. The G values of 12.366T/m and 216.24 T/m are close to the field gradients at the injection porch and the flat top of the accelerator cycle, respectively. Four data between these two currents were taken to obtain the current dependence of G. For each current, 1σ was in the level of 3×10^{-4} with respect to each field gradient. The effective magnetic lengths were in the range of from 6.365 m to 6.3686 m and 1σ was less than 1 mm. From these results, the differences from magnet to magnet in G and L_{EFF} are quite small for these magnets.

Table 2: Field Gradient and Effective Magnetic Length

I	G, T/m		L_{EFF}, m	
kA	average	1σ	average	1σ
0.392	12.366	0.004	6.3650	0.0008
2.011	63.278	0.016	6.3648	0.0008
3.208	100.68	0.026	6.3647	0.0007
6.134	185.87	0.049	6.3676	0.0008
6.677	200.97	0.047	6.3681	0.0008
7.228	216.24	0.058	6.3686	0.0008

Field Quality

The measured error field components are described as the multipole coefficients on the reference radius of 17mm by Eq. 1,

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

where B_2 is the quadrupole strength, R_{ref} is the reference radius. The coefficients 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 production of MQXA magnets, the reference error components at 215 T/m were defined from the R&D studies with five 1m-model magnets and field calculations. The reference systematic and random error components are shown in Table 3. For the MQXA-1 to 10 magnets, the error components in the straight section of 5.4 m at the current of 7.228 kA are shown in Table 4. In this sec-tion, the averaged b_4 was 1.23 *units*, and it was beyond the systematic error in Table 3. This b_4 is still controllable in the beam optics because the b_4 corrector, which will be installed in the triplet system, has a capacity to cancel two times larger b_4 than 1.23 *units*. The other harmonic com-ponents was in very low values compared to the sys-tematic errors in Table 3. Especially, averaged b_6 was 0.16 *units* while the allowed systematic b_6 error was 0.94 *units*.

Table 3: Reference Error Field for MQXA

n	b_n design	b_n sys. err.	b_n rand. err.	a_n design	a_n sys. err.	a_n rand. err.
*Straight Section (L_{eff}=5.8 m)						
3	0.0	0.50	0.99	0.0	0.50	0.99
4	0.0	0.67	0.54	0.0	0.27	0.54
5	0.0	0.13	0.26	0.0	0.13	0.26
6	+0.134	0.94	0.48	0.0	0.07	0.13
7	0.0	0.03	0.06	0.0	0.03	0.06
8	0.0	0.02	0.03	0.0	0.03	0.03
9	0.0	0.01	0.02	0.0	0.01	0.02
10	+0.001	0.06	0.03	0.0	0.01	0.01
*Lead End (L_{eff}=0.31 m)						
6	4.65	0.25	0.12	0.0	0.03	0.03
10	-0.129	0.03	0.03	0.0	0.03	0.03
*Return End (L_{eff}=0.19 m)						
6	-0.53	0.42	0.20	0.0	0.05	0.05
10	-0.16	0.05	0.05	0.0	0.05	0.05

Table 4: Multipole Coefficients in Straight Section

n	b_n average	b_n 1σ	a_n average	a_n 1σ
3	0.03	0.36	0.22	0.36
4	1.23	0.12	-0.07	0.36
5	-0.00	0.04	0.02	0.05
6	0.16	0.10	-0.04	0.03
7	-0.00	0.01	-0.00	0.01
8	0.01	0.00	0.00	0.01
9	-0.00	0.01	-0.00	0.00
10	-0.01	0.01	-0.01	0.00

Table 5: Multipole Coefficients in Ends

n	*Lead End* ave. b_n	1σ	ave. a_n	1σ	*Return End* ave. b_n	1σ	ave. a_n	1σ
3	0.08	0.45	0.86	0.64	-0.02	1.47	-0.01	1.18
4	2.13	0.24	0.04	0.48	1.12	0.24	0.20	0.28
5	0.00	0.26	-0.16	0.22	-0.01	0.19	0.06	0.17
6	2.66	0.13	0.09	0.06	-0.49	0.12	-0.06	0.04
7	-0.02	0.02	0.03	0.02	0.00	0.01	-0.01	0.02
8	0.12	0.01	0.00	0.02	0.01	0.01	-0.00	0.01
9	-0.00	0.01	0.00	0.01	-0.00	0.02	0.00	0.02
10	-0.06	0.01	-0.00	0.01	-0.09	0.01	-0.00	0.01

The variations from magnet to magnet in the multipole components were very small, and 1σ of each multipole coefficient was within the range of the random error.

The multipole components in both ends at the current of 7.228kA are summarized in Table 5. From the constraint of the measurement system, the measured effective lengths for the lead end and the return end are 0.63m and 0.34m, respectively, and they are different from the values in Table 3. In the both ends, the large multipole components are b_4 and b_6. In the lead end, b_6 of 2.66 *units* is almost same as the design value for this effective magnetic length. The coefficient b_4 of 2.13 *units* corresponds to the integrated b_4 of 1.34 *units*•m, and the value is one fifth of b_4 in the straight section. It can be cancelled by the corrector. In the return end, b_6 is slightly larger than the design in the negative sign. Since b_6 in the straight section and the lead end has a positive sign, b_6 in the return end reduces the integral b_6 in the whole magnet.

CONCLUSION

The ten production MQXA magnets for the LHC interaction regions were manufactured and tested at 1.9 K. All magnets reached 230 T/m after the training quenches, and they were re-excited up to 220 T/m without a quench following the full energy dump at 215 T/m.

The variations, 1 σ, of the field gradient and the magnetic length were 3×10^{-4} with respect to their gradient and less than 1mm, respectively. As for the field errors, b_4 was the major component and the integral b_4 in the straight section was 1.23 units. The b_4 was still within a capacity of the b_4 corrector. All other harmonics were satisfactory below the beam optics requirements.

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