DEVELOPMENT OF LHC LOW-β QUADRUPOLE MAGNETS AT KEK

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Abstract

Development of low-β quadrupole magnets for the LHC beam interaction regions has been carried out. The magnet is designed with a field gradient of 240 T/m in a coil aperture of 70 mm, and is to be operated at ≤ 215 T/m with absorption of beam loss heating. Three 1-m models with the final design have been developed and tested with satisfying requirements of field quality and training characteristics. A full-scale (6.3-m) prototype has been developed, and is being tested. Progress of the LHC low-β quadrupole development at KEK is reported.

1 INTRODUCTION

Development of low-β quadrupole magnets for beam interaction regions at LHC has been carried out at KEK as a CERN-US-Japan co-operation program for the LHC project [1 - 3]. The 7 TeV proton beam is focused at four beam interaction regions by using the low-β quadrupoles "inner triplet" consisting of Q1, Q2a, Q2b, and Q3 as illustrated in Fig. 1. KEK provides 16 magnet cold masses, MQXA, consisting of Q1 and Q3. Those are combined with MQXB, which consists of Q2a and Q2b being developed at Fermilab and are assembled into common cryostats also being developed at Fermilab [4]. The MQXA quadrupole is designed with a field gradient of 240 T/m in a coil aperture of 70 mm [5 - 8], and is operated at a field gradient of ≤ 215 T/m while absorbing a beam-loss heating of ~ 5 W/m in pressurized superfluid helium at 1.9 K. R&D works have been carried out with1-m models and full-scale (6.3 m) prototypes. Based on the previous work of the 1-m models, #1 and #2, cross sectional design of the coil was further optimized to satisfy the field quality required from beam dynamics. Three 1-m models and a full-scale prototype have been successfully developed. Figure 2 shows the full-scale prototype being tested at KEK at room temperature prior to the cold test at 1.9 K. This report describes progress of the 1-m models, and the full-scale prototype.

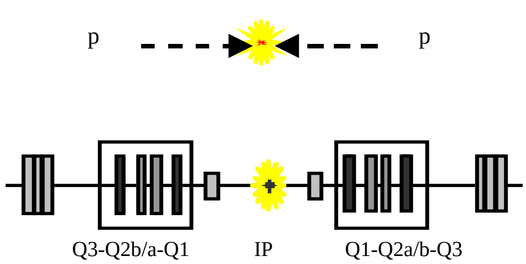

Fig. 1. Schematic layout of LHC low-β inner triplet.

Fig. 2. A prototype of LHC low-β quadrupole (MQXA) in field measurement at room temperature at KEK.

2 MAGNET DESIGN

The general magnet design features:

- four-layer coils with NbTi/Cu Rutherford-cables,
- two-shell coil structure in assembly,
- four-split thin collars made of non-magnetic steel,
- horizontally split iron yoke with keying.

The design aims at a precise and stable structure, which is established during the assembly, at room temperature. Design parameters are summarized in Table 1 and further design details are given in [5 – 8].

Table 1: Design parameters of LHC low-β quadrupole (MQXA).

	Design	Operation (max)
Field gradient	240 T/m	215 T/m max.
Peak magnetic field	9.6 T	8.6 T
Current	8057 A	7150 A
Coil inner radius	35 mm	
Cold mass outer radius	245 mm	
Magnetic length	6.3 m	
Stored energy	~ 2.8 MJ	~ 2.2 MJ

3 DEVELOPMENT OF MODEL MAGNETS

Based on the finalized design, three 1-m models and a full-scale prototype have been developed. Cross-

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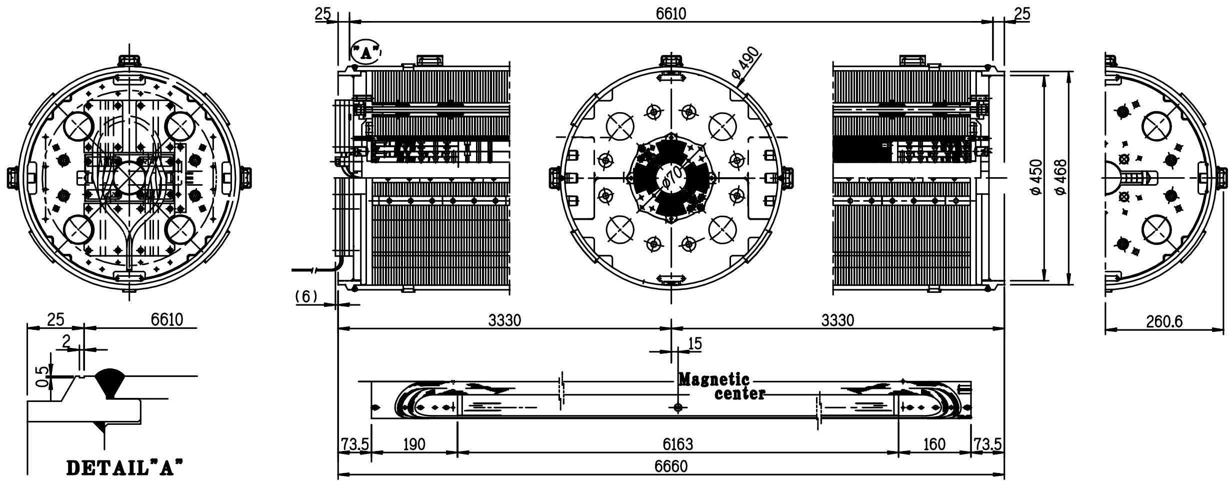

Fig. 3. Cross sections of the LHC low-β quadrupole, MQXA, being developed at KEK.

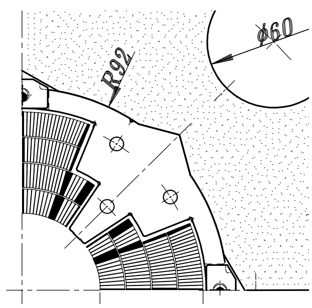

Fig. 4. Coil cross section.

sectional views of the full-scale prototype and the quadruant coil cross section are shown in Fig.3, and Fig. 4, respectively. The 1-m models #3 and #4 were developed at KEK and, at the same time, the technology was transferred to the production magnet fabricator, Toshiba. The 1-m model #5 and the prototype have been manufactured by Toshiba. The reference multipole harmonics, in version 4, for the MQXA magnet are summarized in Table 2. For each harmonic component, values of the mean $<b_n>$, uncertainty $d(b_n)$ in the mean and standard deviation $\sigma(b_n)$ are listed.

Table 2. Reference harmonics for MQXA.

n	$<b_n>$	$d(b_n)$	$\sigma(b_n)$	$<a_n>$	$d(a_n)$	$\sigma(a_n)$
• *Straight section (5.8 m)*						
3	0.0	0.5	0.99	0.0	0.5	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	0.02	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 (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 (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

4 PERFORMANCE OF MODEL MAGNETS

Figure 4 shows training characteristics of the1-m models and the full-scaled prototype. The maximum operational field gradient of 215 T/m was achieved in the first or within a few training quenches [9, 10]. The training was performed to reach 230 T/m in the first thermal cycle test. Model #3 reached a maximum gradient of 245 T/m in the third test cycle. The averaged transfer function in the 1-m models was 29.90 T/m/kA at 7.345 kA with standard deviation of 0.029 T/m/kA. This suggests a relative dimensional accuracy of 0.03 mm consistent with an expected mechanical tolerance of < 0.05 mm. Table 3 gives measured harmonics for the 1-m models and the first prototype [11, 12]. All harmonics measured in the straight section stay within the reference harmonics as shown in Fig. 6. A systematic deviation of ~ 0.8 units was observed in b_6, and it could be explained with a combination of radial and azimuthal deviation of the coil size and position [7]. The integrated magnetic length was measured to be 6.37 m as the breakdown given in Table 3. The straightness and the tilting of the coil axis was

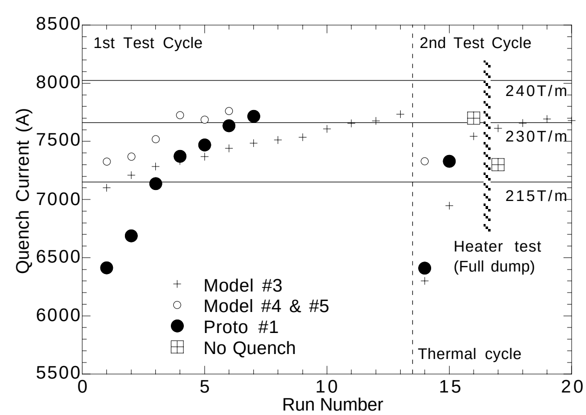

Fig. 5. Training characteristics of MQXA 1-m models and a prototype. 1-m models #4-#5 tested in series connection.

measured to be 0.3 mm and 0.87 mrad. / 6 m, respectively [13].

Table 3. Measured harmonics at 220 T/m (@ 7.3 kA).

	1m-#3	1m-#4	1m-#5	Prototype	Average	<σ>
• Straight section (5.88 m)						
b_3	0.2	-1.38	-1.21	-0.24	-0.76	0.541
b_4	0.43	1.09	0.64	0.90	0.77	0.25
b_5	0.11	0.12	-0.02	0.07	0.07	0.021
b_6	-0.72	-0.77	-0.81	-0.56	-0.72	0.095
b_7	-0.01	-0.07	-0.03	0.02	-0.023	0.025
b_8	0.00	0.03	0.01	0.01	0.013	0.009
b_9	-0.00	0.01	0.01	-0.00	0.005	0.004
b_{10}	0.03	0.03	0.00	0.01	0.018	0.013
a_3	-0.44	0.37	0.56	0.68	0.29	0.25
a_4	0.22	0.03	-0.49	-0.52	-0.19	0.32
a_5	-0.08	0.10	0.22	-0.02	0.055	0.11
a_6	-0.04	0.20	0.00	-0.06	0.025	0.10
a_7	0.00	0.04	0.05	0.00	0.023	0.023
a_8	0.01	0.00	-0.03	-0.01	-0.008	0.015
a_9	-0.00	0.01	0.00	-0.00	0.003	0.004
a_{10}	0.00	0.01	0.00	0.00	0.003	0.004
• Lead end (0.30 m)						
b_6	5.03	5.20	5.07	TBD	5.10	0.073
b_{10} -	-0.13	0.07	-0.13	TBD	-0.023	0.071
• Return end (0.19 m)						
b_6	-1.16	-1.63	-1.68	TBD	-1.49	0.24
b_{10} -	-0.16	-0.21	-0.16	TBD	-0.18	0.024

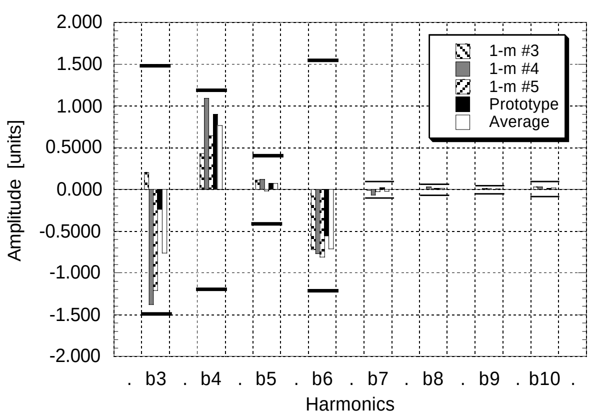

Fig. 6. Measured harmonics in the 1-m models and the prototype. The top and bottom bars indicate envelope of the reference harmonics including the systematic errors, uncertainty, and standard deviation.

5 MAGNET PRODUCTION

Magnet production has been recently started, and 16 magnets are to be completed by early 2004. Prior to the production, a fine tuning of the coil positioning has been made with adding a pole shim thickness of 0.1 mm in order to optimize the pre-stress in the coil and to reduce the systematic shift of the multipole, b_6. All the production magnets will be tested at KEK, and shipped to Fermilab to be assembled with the cryostat.

6 SUMMARY

Development of the LHC low-β quadrupole model magnets has been carried out at KEK. With the final design, three 1-m models and a full-scale prototype have been successfully developed and tested. This series magnet production has begun and is to be completed in three yeas. All the magnets are to be tested at KEK prior to shipping to Fermilab for the inner triplet assembly into the cryostat.

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