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Progress of LHC Low-β Quadrupole Magnets at KEK

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Abstract **Development of the LHC low-β insertion quadrupole magnet is in progress at KEK since 1995 as a cooperative program between CERN and KEK. Five 1-m short model magnets have been fabricated and three of them have been tested. From the various test results of the first two models, the coil configuration was further optimized to reduce the higher magnetic field harmonic coefficients. The cold test of the third model showed satisfactory performances of the field harmonics. After this R&D work, we are on a stage for fabrication of two prototype magnets which have the same scale as the production magnets. The status of the R&D for the LHC low-beta insertion quadrupole magnet at KEK is described.**

Index Terms**--LHC, R&D, status report, superconducting low-beta quadrupole magnet**

INTRODUCTION

A cooperative program between CERN and KEK to develop the LHC low beta insertion quadrupole magnets has been carried out since 1995. These magnets will be operated at a field gradient between 205 and 215T/m in an aperture of 70mm in diameter. The LHC requires 32 magnets as inner triplets at 4 interaction points. KEK will provide 16 magnets which have an effective length of 6.3m and FNAL will do others with a length of 5.5m. They will be installed into cryostats at FNAL and be combined to each other as the inner triplet at CERN. The magnet is operated with high magnetic field (8.6T at the nominal operation), with good field quality and in an environment of continuous irradiation due to lost particles and showers. In order to bridge over these severe conditions, we have carefully designed and developed the magnets with trial fabrication of models. Total five model magnets have been constructed and three were tested. The assembly of the last two has been completed for the tests. This paper reports the status of the LHC low beta insertion quadrupole magnets at KEK.

DESIGN CONCEPT AND PROGRESS

To realize the nominal field gradient of 215T/m reliably, the following design guidelines were introduced [1]:

- the designed field gradient of 240T/m with I_d/I_c of 91% and the nominal operation with I_{op}/I_c of 80%,
- four layer coil configuration with current grading,
- mechanically two layer coil configuration,
- thin and four split collar for pre-assembling, and
- mechanical confinement and dimensionally controllable structure with horizontally split iron yoke.

According to the concept, the 2D electromagnetic design (straight section) and the coil end design have been carried out using ROXIE developed at CERN and OPERA-2D. The design works were confirmed with cable rigidity test and a 20cm long mechanical cross-section model test [2]. From 1997 to October 1998, the first two 1-m model magnets were fabricated and tested. After training quench tests, field measurements and quench protection heater tests, model #01 was disassembled and reassembled twice with small modifications for several surveys (these are identified as #01a and #01b). The second model followed the original design to check the reproducibility by using the modified cables in thickness from the survey of the coil size.

The training performances of the first two models including modified ones were satisfactory for our test criterion. However, the field measurements showed larger harmonics in b_6 and b_{10} than the revised reference values from beam dynamics survey [3].

In order to reduce the b_6 and b_{10} components, the 2D coil cross-section and the coil end distributions were further optimized by using analytical formula, ROXIE and OPERA-2D [4]. The main modifications of the new design are as follows:

- the cable mid-thicknesses for the inner and outer coils were slightly increased from the original design to keep the design coil sizes under the necessary pre-stresses,
- one turn was removed in each 1st and 2nd layer windings,
- the 1st layer winding was divided into two blocks,
- the pole angles and the wedge sizes of the inner windings were optimized keeping the pole angles for the outer windings unchanged,
- the dimensions of the collar and yoke were unchanged, and
- the coil ends were optimized to reduce the integrated b_6 and b_{10} along the magnet axis.

After those optimizations, three models #03 - #05 have been fabricated. Model #03 was tested for quench performance [5], field quality [6] and magnet protection [7]. The other two models #04 and #05 are ready for tests.

The history of the model magnet development is shown in Table I.

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TABLE I

VARIOUS CONDITIONS OF MODEL MAGNETS

			#01	#01a	#02	#01b	#03	#04	#05
No. of turns/pole ($1^{st}/2^{nd}/3^{rd}/4^{th}$)			13/5+12/15/18	←	←	←	4+8/4+12/15/18	←	←
No. of wedges/pole			0/1/0/0	←	←	←	1/1/0/0/	←	←
Current @ 240T/m		[A]	7,677	←	←	←	8,057	←	←
Cable mid thickness		[mm]	1.469/1.330	←	1.484/1.337	1.469/1.330	1.486/1.338	←	←
Cable keystone angle		[°]	2.343/1.351	←	2.34/1.396	2.343/1.351	2.31/1.36	←	←
Inductance @ 240T/m		[mH/m]	14.4	←	←	←	13.6	←	←
Extra shims	Inner	[mm]	0.2	0.2	0	←	←	←	←
	Outer	[mm]	0.1	0.1	0	←	←	←	←
Pole shoe			G10	←	Brass	←	←	←	←
Iron yoke length		[mm]	600	←	850	1200	←	←	←
Axial tension/pole			no	12kN	←	←	←	←	←
Cylinder			shrinkage fit	←	←	half shell with welding		←	←
Epoxy resin on insulation		[µm]	20	←	10	20	10	←	←
Pre-stress	Inner	[MPa]	66	na	45	25	30	37	41
at assembly	Outer	[MPa]	61	na	41	35	42	58	47
Superconducting cable fabricated by			Hitachi	←	←	←	Sumitomo	←	←
Magnet fabricated by			KEK	←	←	←	KEK/Toshiba	KEK	Toshiba
Year of completion			Nov. 1997	Apr. 1998	Oct. 1998	Nov. 1998	Sep. 1999	Jun. 2000	Aug. 2000

The parameters of the magnet and the cables for the new design are given in Table II and III, respectively, and the magnet cross-section is shown in Fig. 1.

FABRICATION ACCURACIES

In order to obtain the required field quality, it is important to control the coil sizes precisely. The coil size and coil rigidity of each completed coil were measured at several points along the axis as summarized in Table IV. According to the progress of the model development, the coil size control has been well established.

The coil is tightly fixed with the precisely stamped 4-split collar and the horizontally split yoke. The coil fabrication accuracy also depends on the stamping accuracy of the collar and the yoke. The accuracy was confirmed to be within a level of 25µm.

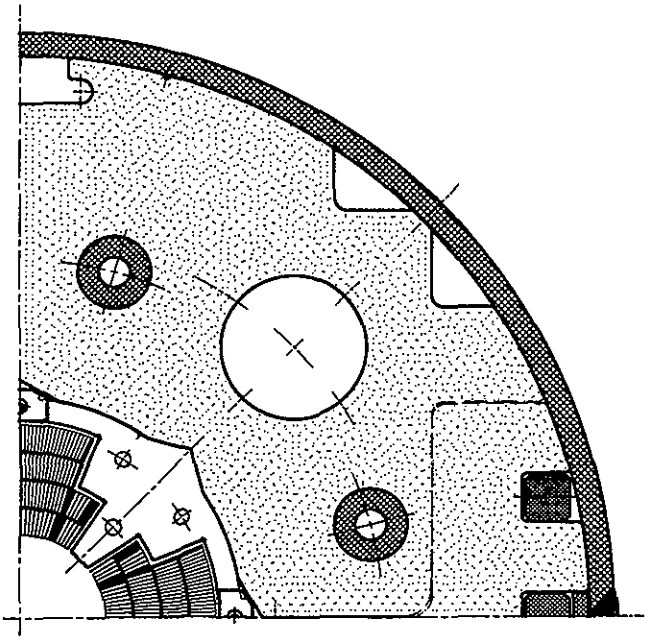

Fig. 1 One quadrant cross-section of the LHC low-beta insertion quadrupole magnet.

TABLE II

PARAMETERS OF LHC INSERTION QUADRUPOLE MODELS #03 - #05

		Design	Operation
Field gradient		240 T/m	215 T/m max.
Current at warm		8057 A	7149 A max.
Peak magnetic field	Outer coil	9.62	8.6
	Inner coil	8.41	7.3
Load line ratio	Inner cable	91 %	80 %
at 1.9K, 240T/m	Outer cable	88 %	78 %
Coil inner radius		35 mm	
Coil outer radius		81.3 mm	
Coil straight section length		900 mm	
Coil overall length		1230 mm	
Coil turns per pole	1^{st}, 2^{nd}, 3^{rd} & 4^{th} layers	4+8, 4+12, 15, 18	
Yoke inner radius		92 mm	
Yoke outer radius		235 mm	
Cylinder outer radius		245 mm	
Stored energy at design gradient		442 kJ/m	
Inductance at design gradient		13.6 mH/m	
Transfer function w/o saturation		31.69 T/m/kA	
Saturation at design gradient		7 %	

TABLE III

PARAMETERS OF SUPERCONDUCTING CABLES FOR MODELS #03 - #05

		[unit]	inner	outer
Strand	Diameter	[mm]	0.815±0.003	0.735±0.003
	Nb-Ti balance	[w%]	47 - 53	47 - 53
	Cu/SC raito		1.2	1.9
	Filament diameter	[µm]	10	10
	Twist pitch (S)	[mm]	20±2	20±2
	Spacing b/w filaments	[mm]	1.7	1.7
	Surface condition		Sn-5Ag	Sn-5Ag
	J_c in Nb-Ti after cabling	[A/mm^2]		
	@ 9T, 1.9K		2,397	2,433
	@ 10 T, 1.9K		1,846	1,887
	@ 11 T, 1.9K		1,284	1,303
Cable	Width	[mm]	11.00	11.00
	Minor thickness	[mm]	(1.264)	(1.199)
	Middle thickness	[mm]	1.487±0.006	1.340±0.006
	Major thickness	[mm]	(1.710)	(1.463)
	Keystone angle	[deg]	2.309	1.319
	Cabling pitch (Z)	[mm]	90±10	90±10
	Number of strands		27	30
	Critical current	[kA]		
	@ 9T, 1.9K		15.35	10.80
	@ 10 T, 1.9K		11.83	8.35
	@ 11 T, 1.9K		8.17	5.75
	RRR of copper		163	224
	Insulation (polyimide)	Inside	25µm thick half lap	
		Outside	50µm thick 67% coverage with 10µm thick B-stage epoxy	

TABLE IV

COIL SIZE AND COIL RIGIDITY DEVIATIONS OF MODEL #03 - #05 AT 53 MPa

Model	Inner		Outer	
Size				
	δl (μm)	1σ (μm)	δl (μm)	1σ (μm)
#03	89	16	145	28
#04	33	18	100	19
#05	4	13	9	15
Rigidity				
	E_{av} (GPa)	1σ (GPa)	E_{av} (GPa)	1σ (GPa)
#03	6.49	0.47	7.08	0.32
#04	8.41	0.32	8.09	0.44
#05	7.48	0.22	9.17	0.55

QUENCH PERFORMANCES

Three model magnets, #01 to #03, were tested for training performances, field qualities, quench protection, and temperature margin against heating-up by scattered beam.

The criterion of acceptance for quench performances of the production magnets is as follows;

- training quench should reach 105% (~226T/m) of the nominal operation,
- full energy dump test with confirmation of no damage after the training test, and
- thermal cycle test without degradation.

The model #01 showed two quenches under the nominal operation and came over 105% at the third quench. The first quench of model #02 was over the nominal operation current and after two quenches the current was over 105%. The modified model #01b, which is fully covered with iron yoke, quenched over 105% at the first excitation. The optimized model #03, which was tested recently, also showed good quench performances as the previous ones. Summary of these training histories is shown in Fig. 2.

Models #02 and #03 showed degradations after the first thermal cycle test. We repeated these tests and obtained the good training memory in the further thermal cycles as shown in Fig. 2. Finally, we concluded that they had good memory for thermal cycles.

The quench location has been studied for each model. For models #01 and #02, most of the quenches occurred at the pole turns in the straight sections of the first and second layers where the magnetic field is highest, and they scattered in the four quadrant coils. On the contrary, for model #01b which is fully covered with iron yoke, most quenches took place at the first pole turn in the magnet ends and it may be understood with the magnetic field enhanced there. It is, however, noticed that the lower coil pre-stresses of this model by removing additional pole shims did not negatively influence the quench performance. Model #03, which is also fully covered with iron, quenched mostly at the 4th layer of every quadrant even though the first quench is over 215T/m [5].

The quench protection tests with measurements of temperature rise and induced voltages in the coils have been carried out for these models to be safe enough after quench [7], [8]. From these tests and simulation works, we have confidence for protecting the magnets.

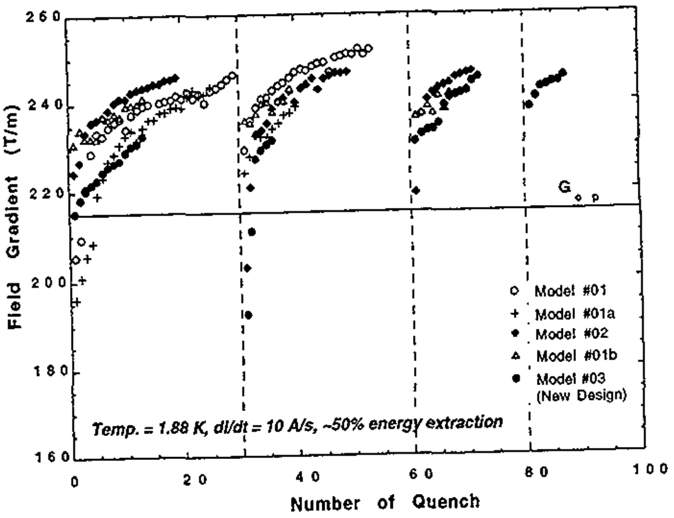

Fig. 2 The training history of the LHC low-beta insertion quadrupole model magnets including reassembled ones.

MAGNETIC FIELD QUALITY

The magnetic field measurement of the first two models, #01 and #02 including modification of #01 magnet by reassembling, were carried out [9]. The field harmonics of these models are summarized in Table V with the improved model #03 [6]. Model #01a, which had extra pole shims, showed much smaller b_6 in the straight section compared with those of models #01b and #02. The calculated b_6 including the extra shims, however, is 1.23 units and then the difference might be caused by some coil deformation or displacement. Models #01b and #02 have shown the same tendency probably by the same reason.

The other harmonic coefficient b_{10} was also relatively large for the models with the previous coil configuration. The measured harmonic coefficient b_{10}, however, agrees well with the calculated one.

TABLE V(a)

MULTIPOLE COEFFICIENTS ALONG STRAIGHT SECTION (UNITS: 10^{-4})

Model	No. 01a		No. 01b		No. 02		No. 03	
n	a_n	b_n	a_n	b_n	a_n	b_n	a_n	b_n
3	-0.32	-1.60	-0.57	-1.55	-1.55	1.62	0.20	-0.44
4	0.85	-1.12	0.45	-0.88	-0.65	-1.34	0.22	-0.43
5	-0.27	-0.02	-0.37	0.00	-0.55	-0.15	-0.11	0.08
6	0.06	-0.04	0.05	-0.79	-0.37	-1.62	0.04	-0.72
		(1.23)		(0.32)		(0.32)		(0.15)
10	-0.09	-1.01	0.04	-0.93	0.01	-0.90	0.00	0.03
		(-1.00)		(-0.98)		(-0.98)		(0.001)

(calculated)

TABLE V(b)

INTEGRAL MULTIPOLE COEFFICIENTS AT ENDS (UNITS • M)

Model	No. 01b				No. 02		No. 03			
	lead end		return end		return end		lead end		return end	
n	A_n	B_n	A_n	B_n	A_n	B_n	A_n	B_n	A_n	B_n
2	0.0	3077	0.0	1693	0.0	1690	0.0	3037	0.0	1895
3	-0.01	-0.07	-0.14	0.07	-0.22	-0.19	0.78	-0.41	-0.32	-0.84
4	-0.02	-3.10	-0.18	-0.24	-0.03	0.18	-0.01	-0.14	-0.03	-0.04
5	0.20	-0.06	0.01	-0.03	-0.02	1.05	-0.07	0.04	-0.04	0.02
6	0.04	2.47	-0.05	1.03	-0.07	1.00	0.00	1.51	0.02	-0.22
10	0.01	-0.22	0.01	-0.12	0.00	-0.13	0.00	-0.04	0.00	-0.03

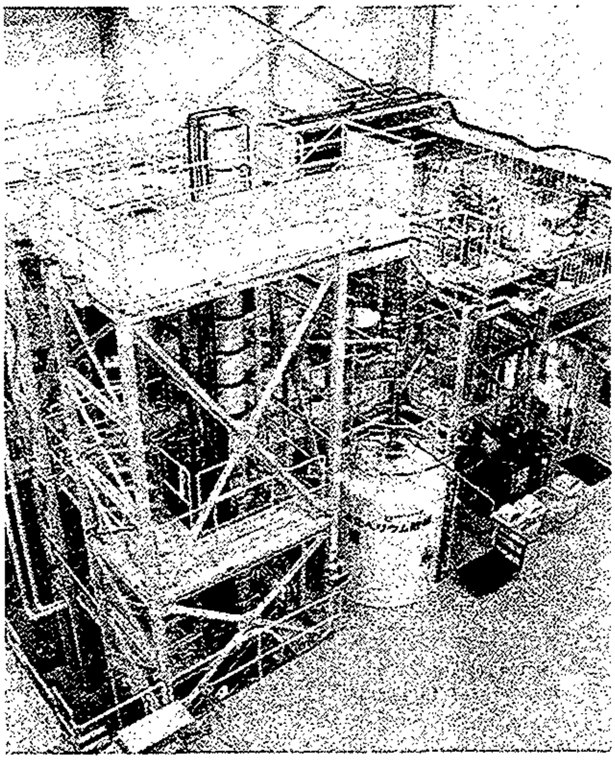

Fig. 3 Newly built test facility for the production magnets.

After the magnetic field measurements were carried out for the first two models, the coil configuration was re-optimized to reduce the harmonics to be 0.15 and 0.001 for b_6 and b_{10}, respectively. In model #03, although the measured coefficient b_{10} becomes small as expected, there is still a difference of ~ 1 unit in b_6. In the simulation to reproduce the measured harmonics [10], the followings may be suggested: (1) the displacement may be 21μm for #03 if the measured harmonics are caused by the azimuthal displacements of the coil blocks only, and (2) the displacement may be 30μm if it is caused by the radial displacement. The reproducibility of the field quality will be confirmed by further measurements of models #04 and #05.

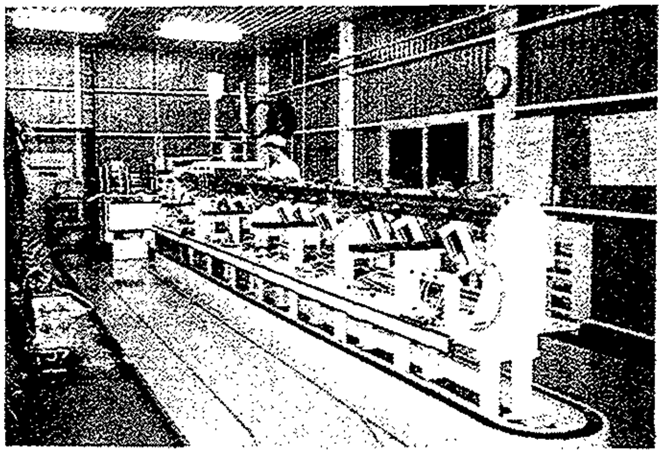

Fig. 4 Coil winding of the first prototype in progress.

SUMMARY AND FUTHER SCHEDULE

The R&Ds with the five short model magnets have been carried out for the LHC low-β insertion quadrupole magnets. The satisfactory results of the quench performances have been obtained and the field quality has also been improved according to the progress of the model works. With model #03, which was fabricated in cooperation of KEK and Toshiba Corp., the technologies for the magnet production were transferred to the company which is the fabricator for the prototypes and production magnets. Model #04, which was fabricated at KEK, is intended to check the reproducibility and model #05, which was done by Toshiba, to confirm the technology transfer. These magnets will be tested soon together at a newly built test facility as shown in Fig. 3. The coil winding of the first prototype is in progress (Fig. 4). This magnet is to be completed in November and to be tested after series tests of the last two short models. The production of the practical magnets will start in 2001.

REFERENCES

[1] A. Yamamoto, K. Tsuchiya, N. Higashi, T. Nakamoto, T. Ogitsu, N. Ohuchi, T. Shintomi, A. Terashima, G. Kirby, R. Ostojic, and T. M. Taylor, Design study of a superconducting insertion quadrupole magnet for the Large Hadron Collider, *IEEE Trans. Appl. Superconductivity*, vol.7, pp. 747 - 750, 1997.

[2] G. A. Kirby, R. Ostojic, T. M. Taylor, I. Vanenkov, T. Nakamoto, A. Terashima, N. Higashi, H. Higashi, H. Kawamata, Y. Ogitsu, T. Shintomi, K. Tanaka, K. Tsuchiya, and A. Yamamoto, Mechanical design and characteristics of a superconducting insertion quadrupole model magnet for the Large Hadron Collider, *Proc. of MT-15*, Beijing, China, pp. 63 - 66, 1998.

[3] J. Strait, personal communication, 1999.

[4] K. Tsuchiya, T. Nakamoto, A. Yamamoto, T. Ogitsu, N. Ohuchi, M. Qiu, and T. Shintomi, Magnetic design of a low-β quadrupole magnet for the LHC interaction regions, *IEEE Trans. on Applied Superconductivity*, vol. 10, pp. 135 —138, 2000.

[5] T. Nakamoto, A. Yamamoto, K. Tsuchiya, E. Burkhardt, N. Higashi, N. Kimura, T. Ogitsu, N. Ohuchi, T. Shintomi, and A. Terashima, Quench performance and mechanical behaviour of 1-m model magnet for the LHC low-beta quadrupoles at KEK, to be presented in this conference, 1LH09, ASC2000.

[6] N. Ohuchi, Y. Ajima, T. Nakamoto, T. Ogitsu, M. Qiu, R. Ruber, T. Shintomi, K. Tsuchiya, and A. Yamamoto, Field measurements of 1-m model quadrupole magnets for the LHC-IR, *Proc. of EPAC*, Vienna, 2000, submitted for publication.

[7] E. Burkhardt, A. Yamamoto, T. Nakamoto, T. Ogitsu, T. Shintomi, and K. Tsuchiya, Quench protection heater studies for the 3rd 1-m model magnet for the KEK low-beta quadrupoles for LHC, to be presented in this conference, 1LH05, ASC2000.

[8] E. E. Burkhardt, A. Yamamoto, T. Nakamot, T. Ogitsu, T. Shintomi, and K. Tsuchiya, Quench protection heater studies for the 3rd 1-m model magnet for the KEK low-beta quadrupoles for LHC, *IEEE Trans. on Applied Superconductivity*, vol. 10, pp. 681 - 684, 2000.

[9] N. Ohuchi, Y. Ajima, M. Qiu, T. Nakamoto, T. Ogitsu, T. Shintomi, K. Tsuchiya, and A. Yamamoto, Field quality of two 1-m model magnets for LHC low-β quadrupole magnets, *IEEE Trans. on Applied Superconductivity*, vol. 10, pp. 139 —142, 2000.

[10] K. Tsuchiya, R. Ruber, T. Nakamoto, T. Ogitsu, N. Ohuchi, M. Qiu, T. Shintomi, A. Terashima, and A. Yamamoto, Field analysis of LHC insertion quadrupole model magnets at KEK, *Proc. of EPAC*, Vienna, 2000, submitted for publication.