DEVELOPMENT AND TEST RESULTS OF A LOW-β QUADRUPOLE MODEL FOR THE LARGE HADRON COLLIDER

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Abstract

A 1-m model of the high gradient 70 mm aperture superconducting low-β quadrupoles for the Large Hadron Collider (LHC) has been developed. A field gradient of 250 T/m at 1.9 K has been achieved with a peak field of 10 T in the coil. This paper describes development of the first model magnet and presents the test results.

1 INTRODUCTION

A cooperative program between KEK and CERN to develop low-β insertion quadrupole magnets for the LHC has been carried out. The magnet was designed for a field gradient of 240 T/m at 1.9 K in a coil aperture of 70 mm. This should satisfy long term operational conditions with field gradients of 200 to 220 T/m at 1.9 K, with absorbing heat due to lost particles and showers from the colliding beams.

Development of 1-m long model magnets is being carried out to establish needed technologies prior to a full scale magnet production to be started in 2001. The first 1-m model magnet has been completed and tested. This paper describes the development and test results.

2 MAGNET DEVELOPMENT

2.1 General Magnet Design

The magnet design was optimized with the following guidelines [1-4].

- NbTi superconductor and 1 atm He-II at 1.9 K,
- Design field gradient of 240 T/m at I/Ic = 92 %,
- 4-layer coils with current grading and two shell structure,
- 4-fold symmetric high-Mn steel collars for pre-assembly,
- 2-way split iron yoke for magnetic flux return and mechanical support structure.

The main parameters of the magnet are given in Table 1. A cross section of the model magnet is shown in Fig. 1.

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Table 1: Main parameters of low-β quadrupole model

Field gradient (G)	240 T/m
Current	7,677 A
Peak field in coil @I/Ic=92 %	9.64 Tesla
Coil inner radius/ Magnet outer radius	35 / 250 mm
Stored energy	425 kJ/m
Forces per octant, ΣFx / ΣFy	1.40 / -1.67 MN/m

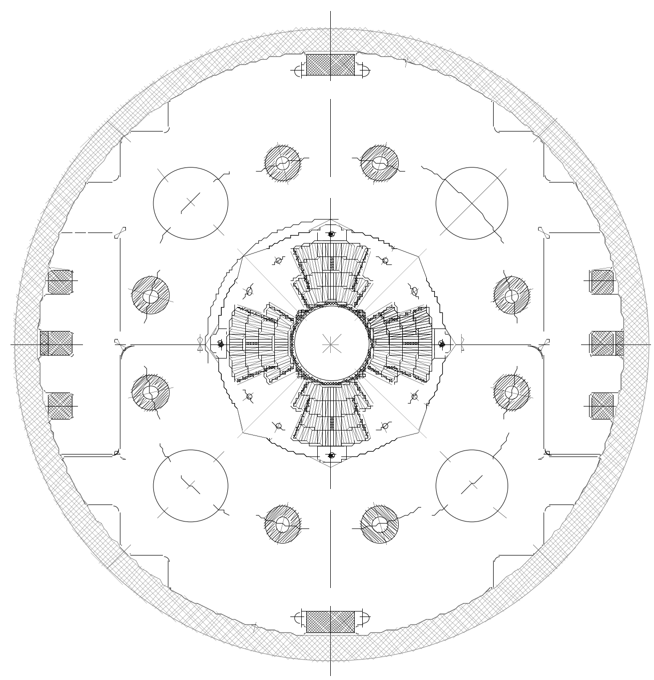

Fig. 1: Cross section of the first low-β quadrupole model.

2.2 Magnet Fabrication [3-4]

The superconducting cables with compacted strands of 10 μm NbTi filaments stabilized by Cu (RRR = 70) and coated with Ag-Sn were fabricated by Hitachi Cable Co. Ltd. The cable was insulated with polyimide half-overlapped film as the first layer and a film with epoxy-resin with a gap wrap to improve heat transfer through the insulation as the second layer. The four-layer coil was fabricated with two sets of "double pancake coils", and was assembled together and re-cured at 125 C. The overall curing time was 10 hours. Placed in the vertical position, the four coils (poles) were pre-assembled with low prestress, four-fold spacer-collars made of high-Mn steel.

The collared coil was assembled in the horizontal position with a vertically split iron yoke consisting of soft-iron laminations. The coil was placed between the top and bottom halves of the yoke laminations and was pressed vertically. A rigid structure was achieved by using interlocking keys on both sides. The coil pre-stress generated during magnet fabrication is summarized in Table 2. Both coil ends were placed in high-Mn steel laminations to reduce the magnetic field and force. The magnet assembly was completed with an outer shrink-fit support cylinder.

Table 2. Coil prestress in fabrication.

	1st & 2nd	3rd & 4th layers
Coil Rigidity	7.2 GPa	5.7 GPa
Prestress after collaring	≤ 5 MPa	≤ 5 MPa
Prestress after yoking	70 MPa	50 MPa

3 TEST RESULTS

3.1 Training and Field Gradient

The first model reached the maximum current of 8,007 A (250 T/m) after a series of training quenches as shown in Fig. 2. The magnet was first tested at 4.5 K. In the first quench, it reached 5935 A (188 T/m) or 96 % Ic at 4.5 K. After cool-down to 1.9 K, the training started at 6,432 A (203 T/m). The magnet reached the design current of 7,677 A (240 T/m) on the 20th training quench. Three fast ramp-rate tests were made, and a quench current of 7,175 A (225 T/m) was observed at 200 A/s. The training was interrupted with a thermal cycle up to 300 K. The magnet was re-cooled down directly to 1.9 K, and the re-training started at 7,243 A (227 T/m). The magnet reached the maximum quench current of 8,007 A (250 T/m) on the 23rd quench.

Quench origin and propagation characteristics were measured by using voltage taps. The origins were

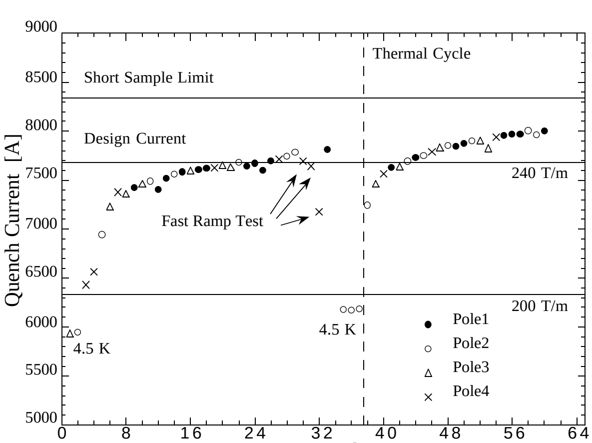

Fig. 2. Training history of the first low-β quad-model.

Table 3. Quench locations

Pole	1	(end)	2	(end)	3	(end)	4	(end)
1st layer	17	(0)	7	(3)	9	(1)	5	(0)
2nd layer	1	(1)	10	(3)	3	(1)	3	(0)
3/4th layer	1	(0)	0		0		0	

distributed as summarized in Table 3. Most of the quenches started at (or near) the pole-turn in the straight section of the 1st/2nd layer where the field was highest.

Figure 3 shows the load line and short sample data as function of current. At the maximum quench current of 8,007 A (250 T/m), the peak field at the conductor is 10 T, at 95 % Ic. The magnetic field was monitored by a Hall-sensor installed at a location of R = 40.5 mm, θ = 45 deg. in the collar-lamination. The measured field (closed circles) agreed with the field computation (solid line) obtained by OPERA/PE2D within an accuracy of 0.5 %. The magnetic field at R = 10 mm is also shown.

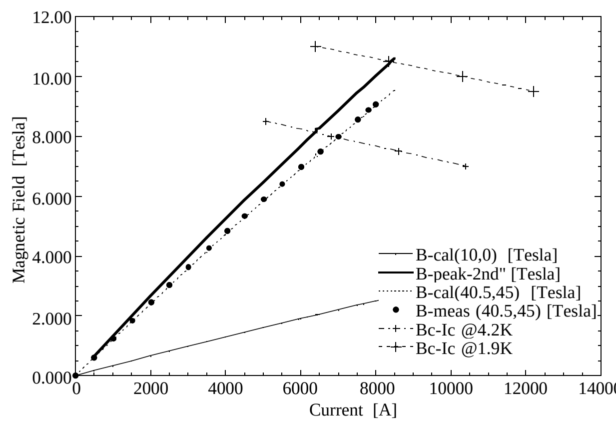

Fig. 3. Magnetic field as function of current.

Figure 4 shows mechanical stress changes in the coil and yoke as function of current-square during an excitation up to 8,007 A (250 T/m). The azimuthal stress change in the coil was measured with capacitance gauges [5], which show that the coil prestress still remain at ≤250 T/m. The rigid yoke structure was monitored with conventional

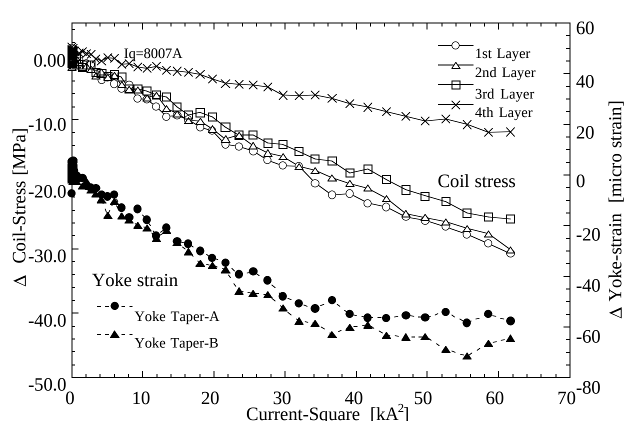

Fig. 4. Azimuthal stress in coil, and vertical strain in mating yoke as function of I^2.

strain gauges installed at the mating surface between the top and bottom half yokes. The result shows that contact is confirmed with negative (compressed) strain.

3.2 Re-training after Re-assembling

After the first series of training tests, the magnet was fully re-assembled and the influence of the modification on training were studied. The re-assembled magnet was identical to the original one except that additional axial pre-tensioning of 15 kN/pole was applied in the coil straight section by using expansion-bolts installed in a collar section. The re-assembled magnet showed similar training as the original one in the first test. The axial pre-tensioning was not effective to reduce the present training. Cracking of epoxy-resin could be generally a pat of reasons, but should not be a primary reason, at least, in the re-assembled magnet well trained. The crack-ing of the epoxy-resin should be well processed in the first series of training, and its may not be recovered and repeatable in the same place. Further systematic study is being carried out.

3.3 Fast Ramp Tests

Fast ramp-rate tests were carried out to measure AC losses in the coil and to simulate coil heating due to beam losses in the coil. The AC loss was measured during a continuous excitation between 2,400 - 7,050 A with ramp rates of +/-100 to 150 A/s, without quenching. Figure 5 shows measured power dissipation into the coil; 4.9 W at 100 A/s, 7.0 W at 130 A/s, and 8.8 W at 150 A/s. The AC power-loss was converted to energy-loss per cycle as shown with a linear plot as function of ramp-rate. The magnetization loss in the superconductor was obtained from the off-set of the line extrapolated from the measure-ment. The coupling current losses, consisting of intra-strand and inter-strand couplings, was obtained from the slope of the line. As a result for the total AC loss of 8.8 W, magnetization loss of 4.5 W, intra-strand coupling loss of 0.3 W, and inter-strand coupling loss of 4.0 W were obtained (assuming a contact resistance of 20 $\mu\Omega$ between strands), in reasonable agreements in comparison with other measurements [6]. Based on these results, the energy-loss density has a peak of 2.5 mW/cm^3 in

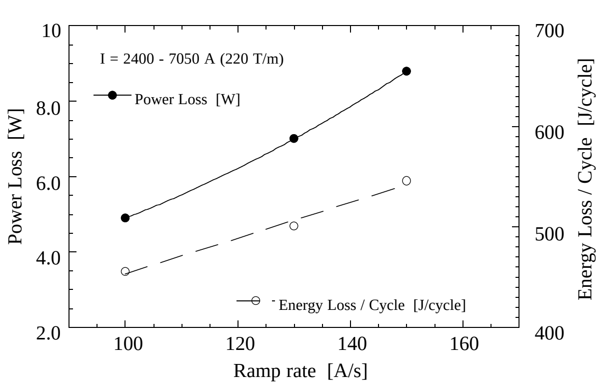

Fig. 5. AC loss measured as function of the ramp rate.

the mid-turn and decreases to 1.5 mW/cm^3 at the pole turn of the first layer. The results, summarized in Table 4, suggest that the fast ramp-rate test has been successful to absorve a energy of 8.8 W without quenching and it suggests possible magnet operation with heating due to particle loss of < 5 W/m, at a field gradient of ≤ 220 T/m without quench. [7-8].

Table 4: Energy dissipation in the fast ramp test.

Field Gradient @ ≤ 7,050 A		≤220 T/m
AC loss @ 150 A/s		8.8 W
		{Mid. - Pole}
Loss density;	1st-layer	2.5 - 1.5 mW/cm^3
	2nd layer	3.5 - 1.3 mW/cm^3

4 CONCLUSION

The first low-β quadrupole model magnet has been successfully tested. It reached a gradient of 250 T/m at a load line ratio of 95 % at 1.9 K with training quenches that were mostly at the pole turns in the coil straight section. The magnet structure, using two-split yoke, functioned as expected, and the azimuthal prestress given by the shell was maintained at 250 T/m, as expected.

A power dissipation of 8.8 W induced in the coil by fast ramping was absorbed without quenching at 220 T/m. It suggests possible operation of the low-β quadrupoles under a presentely estimated beam-loss of < 5 W/m.

The field quality in terms of higher order harmonics is to be evaluated. Further model magnet development will be carried out prior to production of full-scale low-β quadrupoles for the LHC interaction regions.

REFERENCES

[1] R. Ostojic, T.M. Taylor and S. Weisz, "Systems layout of the low-β insertions for the LHC experiments", Proc. PAC'97, Vancouver, (1997), LHC Project Report 129.

[2] A. Yamamoto et al, "Design study of a Superconducting Insertion Quadrupole Magnet for the Large Hadron Collider", IEEE Trans. A.S, Vol. 7, No. 2, (1997) p. 747.

[3] A. Yamamoto et al., "Development of a Superconducting Insertion Quadrupole Model Magnet for the Large Hadron Collider", Proc, MT-15 (1997).

[4] G. Kirby et al., "Mechanical design and characteristics of a superconducting insertion quadrupole model magnet for the Large Hadron Collider", Proc. MT-15 (1997).

[5] I. Vanenkov, "Using capacitive force transducers for measuring stresses in superconducting magnet coils for the LHC" CERN/LHC Note 96-14, (1996).

[6] T. Ogitsu, et al., “Influence of inter-strand coupling current on field quality of superconducting accelerator magnets”, Paricle Accelerators,, Vo. 57 (1997) p. 215.

[7] N. Mokhov and J. Strait, "Optimization of the LHC Interaction Region with Respect to Beam-Energy Deposition", Proc. EPAC'96, Sitges, (1996) p.386.

[8] S. Kato et al., “Beam-induced energy deposition in a LHC Quadrupole Magnet”, KEK report 98-2.