KEK Preprint 96-107
September 1996
A

Design Study of a Superconducting Insertion Quadrupole Magnet for the Large Hadron Collider

A. YAMAMOTO, K. TSUCHIYA, N. HIGASHI, T. NAKAMOTO, T. OGITSU, N. OHUCHI,
T. SHINTOMI, A. TERASHIMA, G. KIRBY, R. OSTOJIC and T.M. TAYLOR

*Presented at 1996 Applied Superconductivity Conference,
Pittsburgh, U.S.A., August 25 - 30, 1996.*

National Laboratory for High Energy Physics, 1996

KEK Reports are available from:

Technical Information & Library
National Laboratory for High Energy Physics
1-1 Oho, Tsukuba-shi
Ibaraki-ken, 305
JAPAN

Phone: 0298-64-5136
Telex: 3652-534 (Domestic)
(0)3652-534 (International)
Fax: 0298-64-4604
Cable: KEK OHO
E-mail: Library@kekvax.kek.jp (Internet Address)
Internet: http://www.kek.jp

Design Study of a Superconducting Insertion Quadrupole Magnet for The Large Hadron Collider

A. Yamamoto, K. Tsuchiya, N. Higashi, T. Nakamoto T. Ogitsu, N. Ohuchi, T. Shintomi, and A. Terashima
National Laboratory for High Energy Physics (KEK), Tsukuba, Ibaraki, 305, Japan

G. Kirby*, R. Ostojic, and T. M. Taylor
European Laboratory for Particle Physics (CERN), 23 Geneve, CH-1211, Switzerland

Abstract---The conceptual design study of a high gradient superconducting insertion quadrupole magnet has been carried out in collaboration between KEK and CERN for the Large Hadron Collider (LHC) to be built at CERN. A model magnet design has been optimized to provide a nominal design field gradient of 240 T/m with a bore aperture of 70 mm and an operational field gradient of 225 T/m at 1.9 K under radiation environment with a beam energy deposit of several watts per meter in the superconducting coils. The design and its optimization process are discussed.

I. INTRODUCTION

A cooperative program to develop low-β insertion quadrupole magnets has been established between KEK and CERN as part of the Japanese contribution to the LHC accelerator project being carried out at CERN [1]. KEK will provide half of 32 quadrupole magnets required for the inner triplets. These quadrupoles are key components to provide strongly focused high energy proton beams and to realize high luminosity beam collisions for physics experiments. The main design goal for the magnet is to provide a design field gradient of 240 T/m in a coil aperture of 70 mm diameter and the nominal operational field gradient of 225 T/m at 1.9 K with a superconductor load line ratio of 85 % to the critical current. The lost particles and showers from the colliding beams will deposit a power of several watts per meter into the coil windings. The design optimization has been made based on the use of NbTi superconductor cooled with pressurized superfluid helium at 1.9 K. In this paper, we describe the conceptual design of the magnet, including the design optimization process and the proposed model magnet development program.

II. DEVELOPMENT PLAN OF MODEL MAGNETS

In the R&D program following previous studies [2-3], 3 - 4 short insertion quadrupole model magnets will be developed to establish necessary technology especially in the straight section and the coil end design. Based on this experience, two full length (about 6 m) prototype magnets are to be developed to establish the production technology. The short model magnets are being developed in the period of 1995 - 97, and the full size prototypes from 1998 to 99. Series production will start in 2,000.

III. MODEL MAGNET DESIGN

A. General design approach

To realize the field gradient of 225 T/m reliably in a long term operation under high beam spray loss level of several watts per meter (or a few mW/cm^3), the following design guide lines are incorporated.

- NbTi superconductor used at 1.9 K in pressurized superfluid helium,
- Io / Ic of 92 % at 240 T/m and 85 % at 225 T/m along the load line in design and in operation, respectively,
- Safety design in terms of T-peak <<300 K after quench,
- 4 layer coils with current grading,
- High-Mn steel, 4-split collar for preassembly,
- Horizontally split yoke, with its two functions:
  (i) magnetic return iron yoke, and
  (ii) coil prestressing and dimensional control.

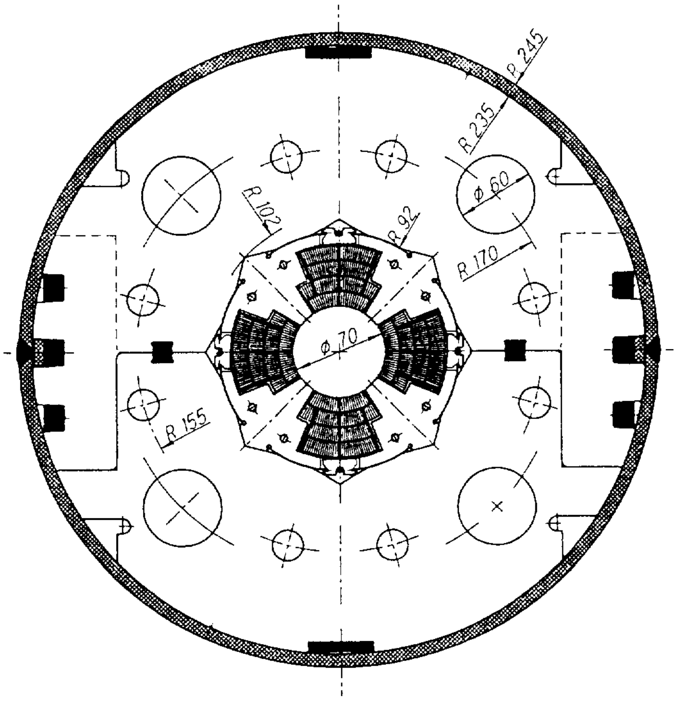

Fig. 1. Cross section of the insertion quadrupole model.

Manuscript received Aug. 26, 1996.

*Visiting Scientist at KEK supported by Japan Soc. for the Promotion of Science.

TABLE I.
DESIGN PARAMETERS OF THE INSERTION QUADRUPOLE MODEL.

	Unit	Design	Operation
Nominal gradient (G_0)	[T/m]	240	225
Nominal current	[A]	7,677	7,164
Peak field in winding	[T]	9.64	9.04
Load line ratio at 1.9K			
inner cable	[%]	92	86
outer cable	[%]	87	81
Coil inner radius	[mm]	35	
Coil outer radius	[mm]	81.1	
Coil straight length	[mm]	900	
Coil overall length	[mm]	1200	
No of turns per pole			
1st layer coil	[turns]	13	
2nd layer coil	[turns]	12+5	
3rd layer coil	[turns]	15	
4th layer coil	[turns]	18	
Yoke inner radius	[mm]	92	
Yoke outer radius	[mm]	235	
Multipole components ($b_n=B_n/B_2$ @ r=10mm)			
$b_6 \times 10^{-6}$		7.0	7.1
$b_{10} \times 10^{-6}$		-1.3	-1.3
Stored energy	[kJ/m]	425	374
Inductance	[mH/m]	14.4	14.6
Resultant of magnetic forces per pole (octant)			
ΣFx	[kN/m]	1400	1250
ΣFy	[kN/m]	- 1670	-1460

B. 2D coil design (straight section)

The coil design in the straight section has been optimized according to the following guidelines;

- Graded 4 layer coil with a reasonably smaller operational current (< 10,000 A) resulting in a cable width of 11 mm,
- Conductor optimization with Cu/S ratio of 1.2/ 1.9 in inner/outer coil from a view point of MIITs resulting in a coil peak temperature of << 300 K after quench,
- Iron yoke as close the coil as possible, resulting in an inner yoke radius of 92 mm with a collar minimum thickness of approximately 10 mm.

A general cross section of the first model magnet is shown in Fig. 1, and the main design parameters are given in Table I. The enlarged coil cross section is shown in Fig. 2, and superconductor parameters are given in Table II. The cable width of 11 mm has been optimized to realize the field gradient of 225 T/m at the load line ratio of approximately 85 %, as shown in Fig. 3 and Fig. 4. Higher order harmonics have been minimized to optimize the coil angle in each layer and grading of the current density in the inner and outer layers. The optimization has been carried out, independently, by using a program which uses analytic expressions for computing the field harmonics of sector coils, and also by using the program ROXIE [4] developed at CERN, and consistent results have been obtained. The effect of iron saturation has been evaluated by using OPERA-2D program (developed by Vector Fields).

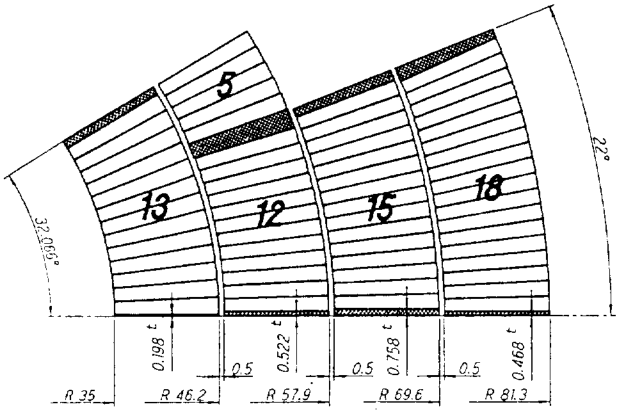

Fig. 2. Coil cross section of the insertion quadrupole model.

TABLE II.
DESIGN PARAMETERS OF SUPERCONDUCTING CABLE.

	unit	inner	outer
Strand:			
Diameter	[mm]	0.815 ±0.005	0.735 ±0.005
Cu/Sc ratio		1.2 ± 0.1	1.9 ± 0.1
Filament dia.	[mm]	10	10
Twist pitch	[mm]	16 ± 1.5	15 ±1.5
RRR of Cu		> 130	> 130
Surface condition		coated with Sn-5Ag	coated with Sn-5Ag
Current density of NbTi [A/mm^2]			
@ 1.9K, 9T		> 2100	> 2100
@ 1.9K, 10T		> 1600	> 1600
@ 1.9K, 11T		> 950	> 950
Cable			
Width	[mm]	11.00 ± 0.01	11.00 ± 0.01
Minor thickness	[mm]	1.243	1.199
Middle thickness	[mm]	1.470 ± 0.006	1.331 ± 0.006
Major thickness	[mm]	1.697	1.463
Keystone angle	[deg.]	2.363 ± 0.05	1.373 ± 0.05
Cabling pitch	[mm]	90	90
Number of strands		27	30
Critical current	[A]		
@ 1.9K, 9T		> 13250	> 9150
@ 1.9K, 10T		> 10100	> 7000
@ 1.9K, 11T		> 6000	> 4150
Insulation		25 µm Upilex tape 50 % overlapped+ 50 µm Upilex tape with 25 µm epoxy helical wound with 2 mm gap.	

C. Coil end design

The coil end design has been optimized with consideration to the following points: peak fields, integrated harmonics through the end, stress in the cable due to bend radius, and access for fixing bolts to hold the end spacers on the winding mandrel during coil winding. The ROXIE program has been used to design the ends. The full 3D coil can be modeled (see Fig. 5). The ends were optimized to minimize the integrated harmonics by moving the eleven end blocks in the 'Z' direction back and forth, shown in Fig. 6.

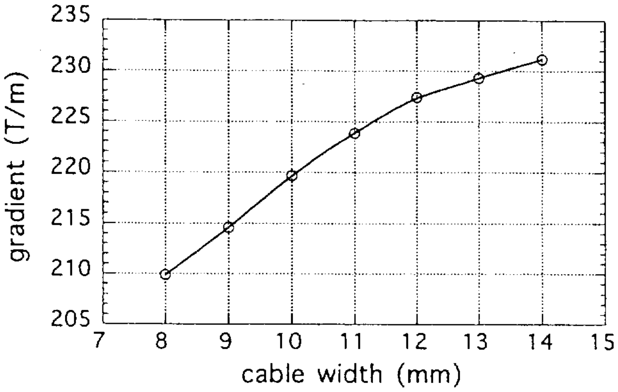

Fig. 3. Cable width dependence on field gradient at a load line condition of 85 % .

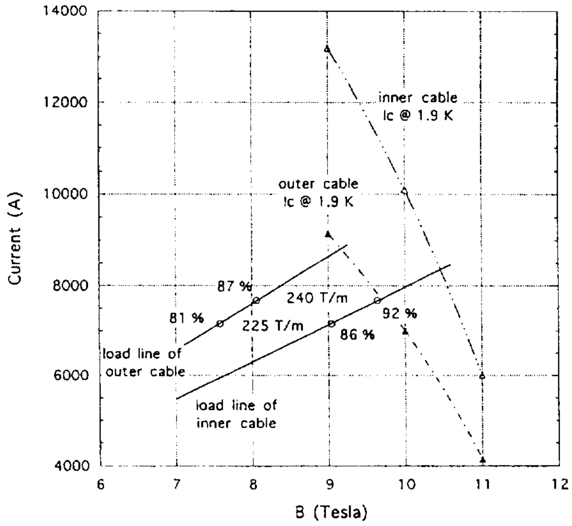

Fig. 4. Expected conductor performance along load lines.

A limit was placed on this movement to allow space for the fixing bolts. There are many solutions to the shape of curved section of coil end. We chose shapes that tried to maximize the bend radius and conform to a constant perimeter. ROXIE generates a Computer Numerical Control (CNC) file that was read by the CNC machining center and a set of end spacers for winding test have been machined. The test coil winding will soon be made to check the fitness of the end spacers.

D. Mechanical Design

The mechanical design of the magnet is based on the following considerations;

- Preassembly of the coil by using thin High-Mn steel collars, without high prestress in the coil,
- Full prestressing of the coil by using the 2-split iron yoke assembly with keys to fix the yoke assemblies together[5],
- Rigid and well fixed structure at room temperature.

1) Cable rigidity test: In order to optimize the coil dimensions and mechanical characteristics, preliminary coil modulus measurement have been made by using a dummy

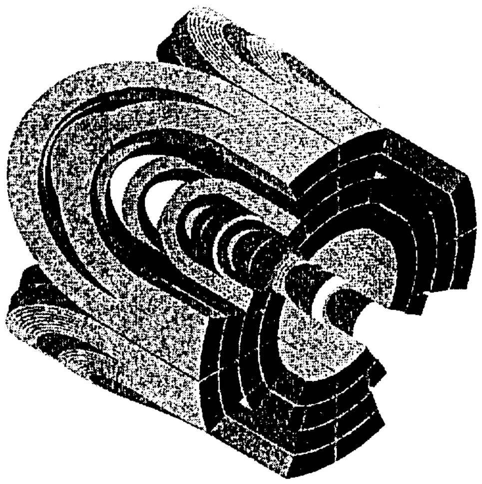

Fig. 5. The coil end view (by ROXIE)

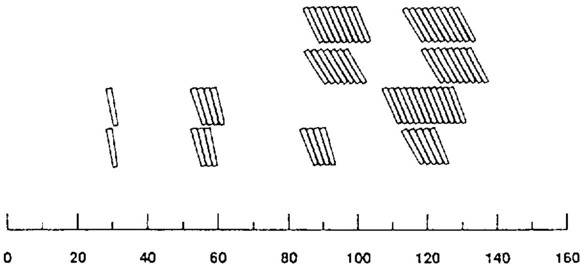

Fig. 6. Cross section of the coil end (by ROXIE).

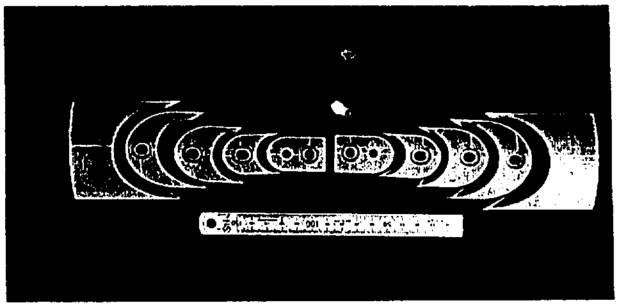

Fig. 7. Coil end spacers made by using ROXIE output data transfered to a CNC machine at KEK.

cable. Fig. 8 shows the test results with a schematic sketch of the experimental apparatus. A test stack of 16 insulated turns was prepared. This stack was cured at a pressure of 50 MPa and a temperature of 130 deg. C for more than 2 hours to cure the epoxy coating on the outer layer of insulation. Ten preliminary test cycles were made to make the system stable up to 100 MPa, and then the measurements were carried out, as shown in Fig. 8. Point 'A' is placed at the pressure at which the cable dimensions were originally measured. This gives a starting point for coil size estimations. The average rising modulus between points A & B is 8,200 MPa. The initial falling modulus is 47,900 MPa between points B & C, and the average falling modulus between points C & D is 17,000 MPa. We repeated the test for a sample with no insulation so that we could obtain the compressed insulation thickness at the working pressure of 55 MPa. The nominal 0.1 mm thick insulation is compressed to 0.096 mm and the 1.470 mm thick cable decreases to 1.466 mm.

2) Coil Prestress: Fig. 9 shows an expected trend for the coil prestress, based on the cable rigidity measurements. The coils are collared at low pressure. We expect a maximum pressure of 17 MPa reducing to about 5 MPa when the collaring press is released. The collared coil assembly is then placed into the two part iron yoke and the top and bottom yokes are then forced together under the 15 MN/m press. This increases the coil pressure to about 100 MPa. At this point a total of six keys are placed into the yoke key slots to hold the gap between the two yoke halves together. When the Yoking press is released we expect to lose some pressure due to relaxing in the structure. After yoking, the gap in the iron is closed with some pressure in the mating faces. This places the collared coil assembly in a symmetric cavity in the yoke, at a pressure of about 80 to 90 MPa. As the assembly is cooled the iron yoke contracts less than the coil assembly and the resulting loss in pressure is about 35 MPa. As the magnet is energized, the redistribution of forces in the coil reduces the pole stress by a further 35 MPa. The coil position is not affected leaving 10 to 20 MPa in the coil at full field.

3) 10 cm long 2D cross section test: Prior to the magnet fabrication, a 10 cm long 2D cross sectional model test will be carried out. We will use a Capacitance Sheet-Pressure-Transducer (CSPT), recently developed at CERN, to measure the change in prestress during: collaring, yoking, placing the keys, and cooling. The CSPT's are 0.5 mm thick sheets that can measure up to 200 MPa and be placed between the coil and collar shims [6].

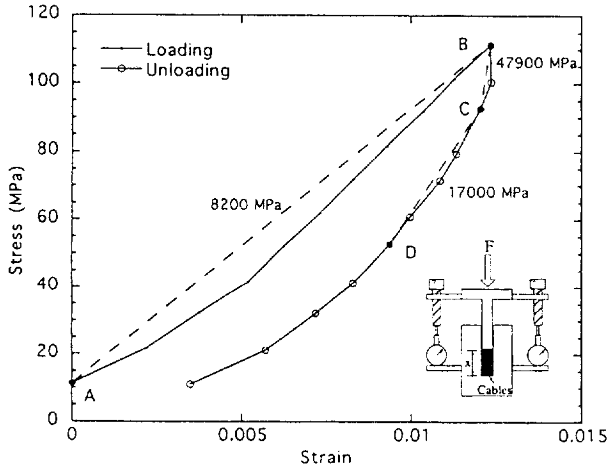

Fig. 8. The coil rigidity measurement.

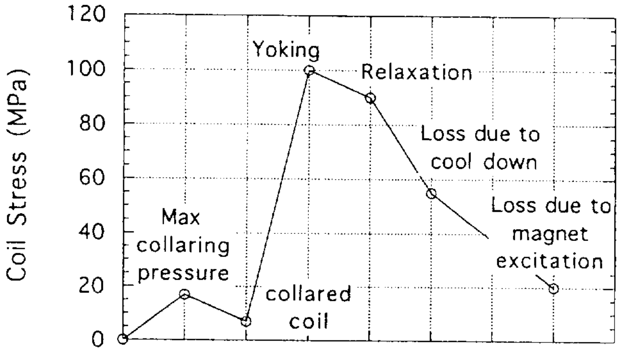

Fig. 9. Expected trend (changes) of the prestress in the coils according to the magnet assembly, cool down and excitation.

IV. SUMMARY

A conceptual design of an insertion quadrupole model magnet has been made with the following design approach,

- 225 T/m operating field gradient.
- NbTi conductor at 1.9 K, Io/Ic = 85 % in operation,
- 4 layer graded coil with 11 mm wide Rutherford cables,
- High Mn-steel 4-split collar, 2 part yoke that provides the prestress for the coils.

The first 1 m short model magnet is being developed, and will be tested at KEK. During the next 3 years, the design should be advanced to a full length prototype.

ACKNOWLEDGMENTS

The authors would like to thank Dr. S. Russenschuck for his help in using the ROXIE program. The KEK workshop (mechanical engineering center) and cryogenics center are also appreciated for their professional support and cooperation.

REFERENCES

[1] The Large Hadron Collider Conceptual Design Report, CERN/AC/95-05 (LHC), 1995,
[2] R. Ostojic and T.M.Taylor, "Conceptual Design of a 70 mm Aperture Quadrupole for the LHC Insertions", IEEE Trans. Appl. Superconductivity, 3 (1993) pp 761-764.
[3]R. Ostojic T.M. Taylor and G.A. Kirby, "Design and Construction of a One-Metre Model of the 70 mm Aperture Quadrupole for the LHC Low-beta Insertions", IEEE Trans. Magn., 30 (1994) pp 1750-1753.
[4] S. Russenschuck, "A computer program for the Design of superconducting accelerator magnets" to be published in Proc. of ACES'95, CERN LHC Note 354, (1995).
[5] P. Wanderer et al., "Construction and Testing of Arc Dipoles and Quadrupoles for the Relativistic Heavy Ion Collider (RHIC) at BNL", Proc. of the 1995 Int. Conf. Particle Accelerators, Dallas, 1995.
[6] I. Vanenkov, A. Ijspeert, and G. Kirby, CERN, private communication, 1996.