Design study of a superconducting dipole model magnet for the Large Hadron Collider

Shuma Kawabata*, Akira Yamamoto+, Hiroshi Yamaoka+ and Hiromi Hirabayashi*+

*Department of Accelerator Science**
The Graduate University for Advanced Studies
1-1 Oho, Tsukuba, Ibaraki-ken, 305, Japan

National Laboratory for High Energy Physics(KEK)+
1-1 Oho, Tsukuba, Ibaraki-ken, 305, Japan

Abstract

Design study of a 10 tesla twin aperture superconducting dipole magnet has been carried out as a research and development project for future high energy accelerators. On the basis of this design study, Nb.Ti/Cu superconducting cables with high key-stone angles have been developed as key elements to realize the 10 tesla dipole magnet. In order to study effects of iron saturation on field quality in beam bores, permeability in the iron yoke has been experimentally verified up to 6 tesla and the results have been fed back into the design study. The design study and progress of the technical research and development will be reported.

Introduction

The Large Hadron Collider project (LHC) at CERN is expected to be one of the most advanced superconducting particle accelerators in coming decade and 10 tesla twin aperture dipole magnets are inevitably required as key elements to provide 2 x 8 TeV proton-proton collisions in the existing LEP accelerator tunnel[1,2]. Recently, an accelerator research collaboration has been established between CERN and KEK. Based on this agreement, the development of a 10 tesla twin aperture dipole model magnet has been initiated at KEK since 1989[3].

In this study, we have aimed to design the coil as symmetric and simple as possible in mechanical and electrical design. Progress of the design study and R & D works to fabricate the test dipole magnet is described in the following sections.

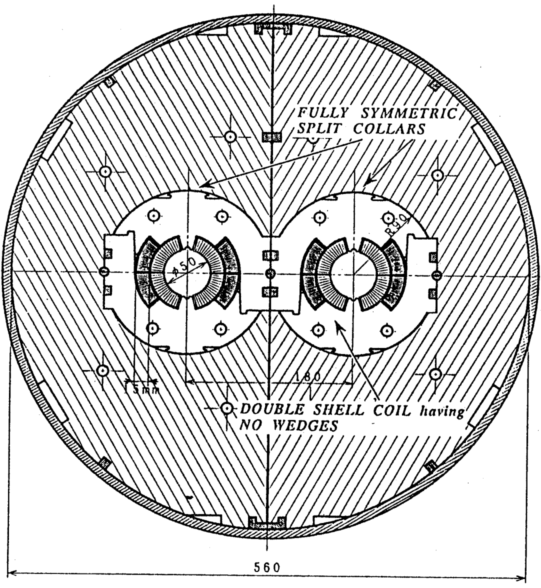

Fig. 1 Cross section of the 10 tesla twin aperture dipole model magnet being developed at KEK.

Design optimization

Figure 1 shows a general cross section of the 10 tesla twin aperture dipole magnet being developed at KEK and configuration of its magnetic flux lines is shown in Fig. 2. Two coils with a bore diameter of 50 mm are located with a beam bore separation of 180 mm and the coils are supported by individual collaring structure made of hybrid metallic laminations.

This design has the following features :

(1) Double shell coil configuration having no wedges and
(2) Fully symmetric split collaring structure.

To realize such a magnet, the following new technical parameters are required :

(1) High keystone angle of 4.6 degrees in the inner coil cable,
(2) Cable width of 15 mm in each coil,
(3) Outer radius of 90 mm in split collars(boundary to iron).

Major design parameters of this magnet are summarized in Table 1.

Magnetic field quality

The magnetic field in the twin aperture dipole magnet has been evaluated with the program ANSYS and POISSON. The maximum field in the coil appears at the inner top end of each inner and outer coil and it has been computed to be 10.2 tesla and 8.0 tesla in the inner coil and the outer coil, respectively.

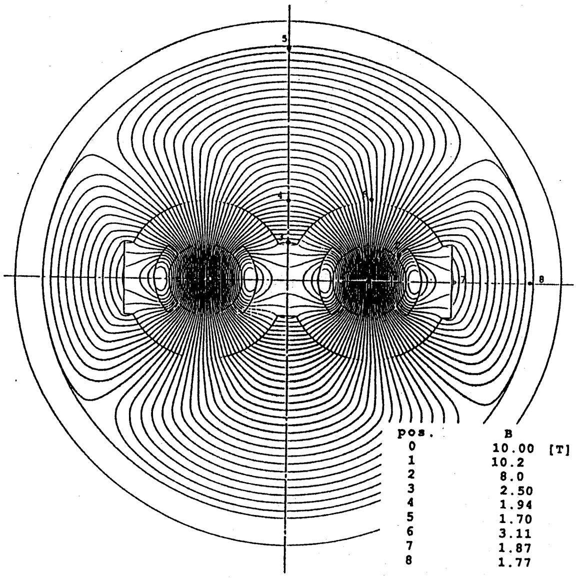

Fig. 2 Configuration of magnetic flux lines.

Table 1
Main parameters of the 10 tesla twin aperture dipole model

Bo (2K)	10 T	
Io	12,720 A	
Stored Energy	666 kJ/m	
Coil aperture radius	25 mm	
Collar outer radius	90 mm	
Iron yoke outer radius	280 mm	
Separation b / w twin bore	180 mm	
	(Inn. coil)	(Out. coil)
#Turns in half coil	16	24
Bmax	10.2 T	8.0 T
J (ov.al.)	322.6 A/mm^2	578.0 A/mm^2
J / Jc	91.5 %	87.5 %
Magnetic force		
Fx	218 tonf/m	
Fy (inn / out)	-30.7 tonf/m	-87.1 tonf/m
Field useful aperture (ANSYS)		
x (dB/B<1x10^{-4})	10 - 18 mm	
Multipole Components (POISSON)		
(b_n/B_0 @ r=10 mm)	(at 1.4 T)	(at 10 T)
b3:	- 4.6 x 10^{-5}	5.4 x 10^{-5}
b5:	- 1.1 x 10^{-5}	- 2.3 x 10^{-5}
b7:	5.8 x 10^{-6}	- 1.0 x 10^{-5}
b9:	- 1.3 x 10^{-6}	- 2.2 x 10^{-5}
b2:	1.3 x 10^{-5}	- 6.2 x 10^{-6}
b4:	7.1 x 10^{-6}	1.4 x 10^{-5}
b6:	1.3 x 10^{-5}	3.6 x 10^{-5}
b8:	1.7 x 10^{-5}	4.7 x 10^{-5}

The higher order multipole components have been calculated with a reference radius of 10 mm. Results of the calculation at central fields of 1.4 tesla and 10 tesla are given in Table 1. All the multipole components are in the level less than 1 x 10^{-4}.

Figure 3 shows the field distribution computed by ANSYS in the median plane according to the field excitation up to 10 tesla. It has been understood that a field uniformity of dB/B=±1 x 10^{-4} can be achieved in a region of x<±10 - 18 mm depending on the excitation level.

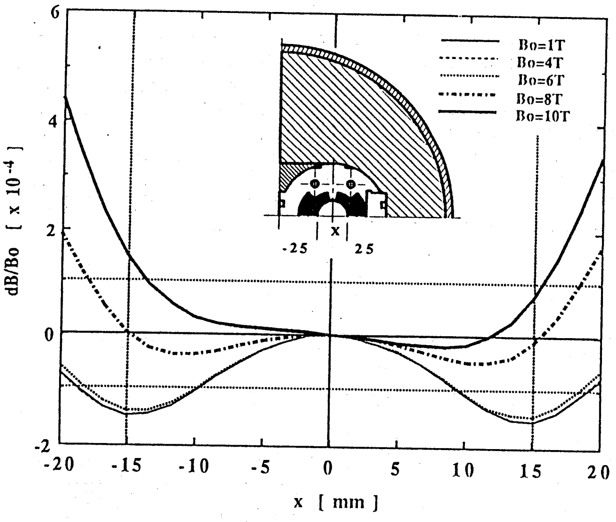

Fig. 3 Field distribution on the median plane depending on magnet excitation. The field distribution is identical below 6 tesla because of no iron saturation.

Effect of iron saturation

The maximum field in the iron yoke has been calculated to be 3.1 tesla at B_0=10 tesla. The effect of iron saturation in the yoke has been evaluated with ANSYS based on iron magnetic permeability data originally measured with the iron for the TOPAZ magnet$^{4)}$. The ratio of B/I is 0.7985 tesla/kA at B_0=1.0 tesla and 0.7862 tesla/kA at 10 tesla, respectively. Therefore, the saturation effect of iron should be about 1.5% at 10 tesla in terms of the central magnetic field.

In order to verify the effect of the iron saturation, we have made a precise experiment to measure the permeability of iron at liquid helium temperature (4.2 K). In this experiment, we have developed an original experimental technique to reinforce the magnetomotive force by using superconducting wire to apply large primary current (ampere-turns) in the coil surrounding toroidal iron core samples. By using this technique, the permeability measurements has been realized up to 6 tesla in the iron. Figure 4 shows the measured permeability at 4.2 K compared with the existing data and extrapolation. In a re-calculation using the measured permeability, it is found that the quadrupole component is very sensitive to the iron magnetic characteristic. The results of the calculation are summarized in Table 2.

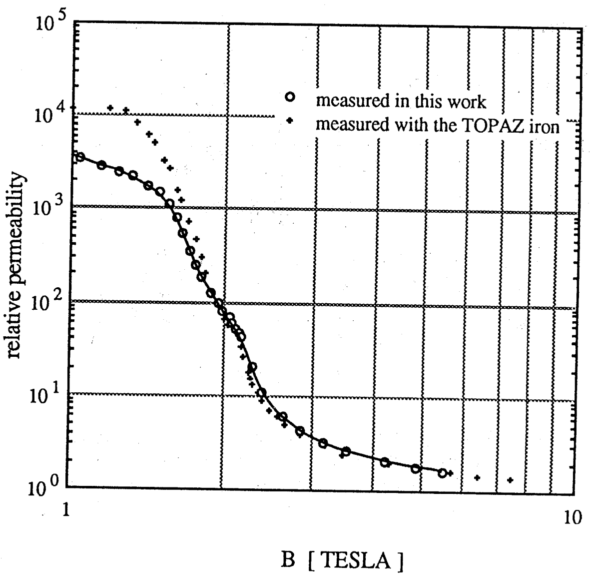

Fig. 4 Measured permeability in iron at 4.2 K.

Table 2
Results of harmonic analysis by POISSON program
(b_n/B_0 at r=10 mm, B_0=10 T)

Permeability	Data measurd with the TOPAZ iron	Measured data
Multipole component :		
b3:	5.4 x 10^{-5}	4.9 x 10^{-5}
b5:	- 2.3 x 10^{-5}	- 2.3 x 10^{-5}
b7:	- 1.0 x 10^{-5}	- 0.9 x 10^{-5}
b9:	- 2.2 x 10^{-5}	- 1.9 x 10^{-5}
b2:	- 6.2 x 10^{-6}	- 1.6 x 10^{-5}
b4:	1.4 x 10^{-5}	1.3 x 10^{-5}
b6:	3.6 x 10^{-5}	3.4 x 10^{-5}
b8:	4.7 x 10^{-5}	4.8 x 10^{-5}

Status of technical development

Development of the superconducting cable has been recently completed. The critical current of superconductor strand has been measured at temperatures of 4.2 K, 2.0 K and 1.8 K. The results are shown in Fig. 5 in comparison with the design values given in Table 3. The critical current have reached up to 80-100 % level compared with the design goals and the magnet should be able to reach 10 tesla with a load line ratio of 96 % if we may expect no reduction of the critical current during coil fabrication.

The first coil-winding practice has been successful and a collaring test has been also successful. It is planned to assemble the first main coil into the iron yoke with single aperture, as shown in Fig. 6, to evaluate the coil performance before the final assembly of the two-in-one magnet. The twin aperture dipole is planned to be fabricated in next year.

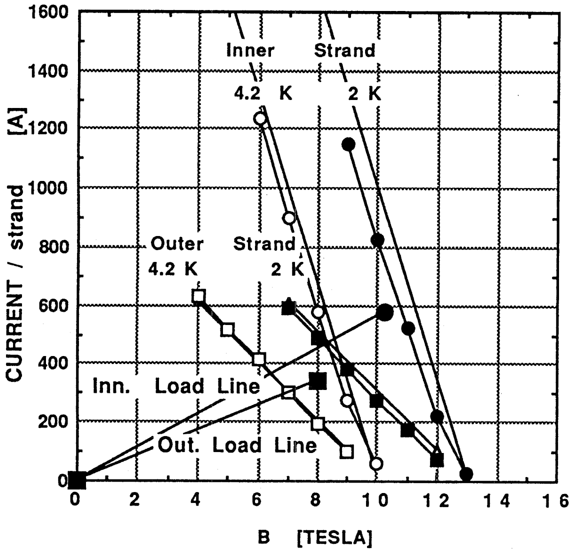

Fig. 5 Measured critical current of NbTi/Cu /strand as a function of the magnetic field at temperatures of 4.2 K and 2.0 K. The solid lines are design values (goals) and circles and squares are measured values.

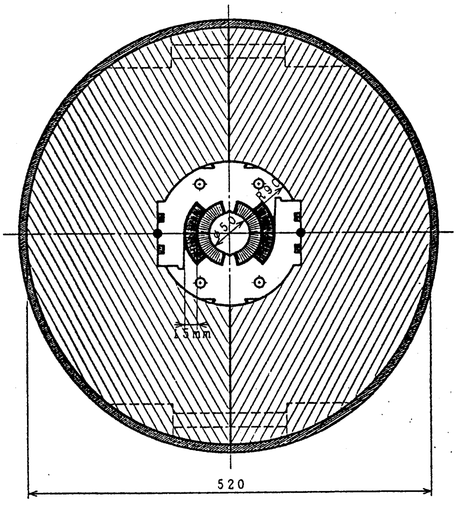

Fig. 6 Cross section of the single aperture dipole model

Table 3
Main parameters of superconductor for the
10 tesla dipole model

Items		Inner	Outer
Cable			
Width	[mm]	15	15
Thickness - in	[mm]	1.884	1.100
- out	[mm]	3.093	1.554
Keystone	[deg]	4.614	1.735
Cable PT	[mm]	110	110
#Strands		22	37
Pk. Fact.	[%]	> 90	> 90
B_{op_max}	[T]	10.2	8.0
I_{op}	[A]	12,720	12,720
J (over - all)	[A / mm^2]	322.6	578.0
J (cable)	[A / mm^2]	340.7	638.9
Strand			
Diameter	[mm]	1.39	0.79
Cu / Sc		1.6	1.8
Fil. dia.	[μm]	6	6
J (strand)	[A / mm^2]	381.3	684.0
J (Nb.Ti)	[A / mm^2]	990.7	1915.0
J / Jc (1.1)	[%]	91.5	87.5

Summary

Design study of a high field superconducting magnet for the LHC project has been carried out. We aimed to design and to fabricate a 10 tesla twin aperture dipole magnet with mechanical configuration as simple and symmetric as possible to provide favorable field quality in the two-in-one magnet and to make sure the large scale production in future. We introduced the our own design concepts of (i)double shell coil consisting of high keystone cables with no wedges and (ii) fully symmetric split collar design.

Our design may satisfy basic requirements for the LHC accelerator dipole in two-in-one configuration with favorable characteristics in terms of the field uniformity and the operational current. The higher order multipole components are reasonably small enough in the coil design with the double shell coil design. The main coil winding is being started and the twin aperture magnet is expected to be finished in next year.

Acknowledgement

The authors would express their sincere appreciation to Dr. T. Tortshanoff at CERN for his help in evaluation of field quality . They would thank Dr. G. Brianti, Associate Director of CERN and Drs. R. Perin and D. Leroy of CERN for their valuable discussions and encouragements. They would thank Prof. H. Sugawara, Director General of KEK, Prof. S. Iwata, Director of Physics Department of KEK, and Prof. Y. Kimura, Director of Accelerator Department of KEK, for their continuous encouragements during this work.

Reference

1. G. Brianti, K. Hubner, "The Large Hadron Collider in the LEP tunnel", CERN-87-05 (1987).
2. R. Perin, " The superconducting magnet system for the LHC", IEEE MAG-27, No.2, *1990 Appl. Super. Conf. Snowmass* (1991) p.1735.
3. H. Hirabayashi, A. Yamamoto, S.Kawabata, G. Brianti, D. Leroy and R. Perin, "Design study of a superconducting dipole model magnet for the Large Hadron Collider", IEEE MAG-27, No.2, *1990 Appl. Super. Conf. Snowmass* (1991) p.159.
4. Nippon Steel Corporation technical report, "Electrical steel plate N-SMIP-1 of Nippon Steel", August (1989).