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Akira Yamamoto, Hiromi Hirabayashi and Hiroshi Yamaoka

National Laboratory for High Energy Physics (KEK); 1-1 Oho, Tsukuba, Ibaraki, 305, Japan
Shuma Kawabata

Kagoshima University; 1-21-40 Korimoto, Kagoshima, 890, Japan

Giorgio Brianti, Daniel Leroy, Romeo Perin and Louis Walckiers

CERN; 23 Geneve, CH-1211, Switzerland

Masafumi Hirano and Susumu Ito

Toshiba Corporation; 2-4, Suehirocho, Tsurumi-ku, Yokohama, 230, Japan

Itaru Inoue and Masaru Ikeda

The Furukawa Electric Co. Ltd; 500 Kiyotaki, Nikko, Tochigi, 321-14, Japan

Masayoshi Kondo

Nippon Steel Corporation; 2-6-3 Ote-machi., Chiyoda-ku, Tokyo, 100-71, Japan

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Abstract--- Development of high field dipole model magnets for future high energy accelerators has been carried out as a part of the cooperative accelerator R&D program between CERN and KEK. A single aperture dipole model magnet was completed and tested. The magnet reached 8.0 T at 4.3 K and 9.87 T at 1.8 K. A twin aperture dipole model magnet with identical coil design is being assembled. Progress of the development and test results are described in this report.

I. INTRODUCTION

The Large Hadron Collider (LHC) project is planned at CERN as the primary future high energy accelerator project [1] and high field twin aperture dipole magnets will play an important role to realize 2×7.7 TeV proton-proton collision in the existing LEP accelerator tunnel at CERN. [2]

A cooperative R&D effort to develop the high field twin aperture dipole magnet has been carried out between CERN & KEK since 1989, as a part of the joint research program for future high energy accelerator technology. Based on R&D experience at CERN for the high field magnet, an alternate 10 T dipole magnet design has been proposed at KEK [3,4,5] and development of two model magnets has been carried out; a single aperture model magnet and a twin aperture model magnet with identical coil and collar design. The single aperture model magnet was fabricated in order to evaluate the coil design and performance quickly before the twin aperture model magnet fabrication. It was tested at 4.3 K in Japan and tested at 1.8 K at CERN. The twin aperture dipole is being assembled to be tested. Progress of the model magnet development described in the following sections.

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Fig. 1. Cross sections of (a) single aperture and (b) twin aperture 10 T dipole models being developed at KEK.

II. DEVELOPMENT OF THE MAGNET

A. General Design

Design of the KEK 10 T twin aperture dipole magnet has aimed to have simplicity and symmetry in the magnet configuration under boundary conditions fixed by CERN. The following design modification has been incorporated into the KEK 10 T twin aperture model magnet:

- a pair of fully symmetric collaring structure split at the center of two beam axes,
- double shell coil configuration consisting of highly key-stoned superconducting cables without wedges,
- use of new hybrid (YUS/Al) material in collar lamination to optimize mechanical stiffness and thermal contraction.

Figures 1 (a) and (b) show cross sectional views of the single and the twin aperture model magnets being developed at KEK with the same collared coil design. It is clearly understood that the two-in-one configuration is very effective to save space for the magnets. Main parameters of the model magnets are given in Tab. 1.

Table 1. Design parameters of the 10 T model magnets.

	Single ap.	Twin ap.
Bo	10 T	10 T
Io	12720 A	12,720 A
Stored energy	310 kJ/m	666 kJ/m
Dimensions:		
Coil aperture radius	25 mm	25 mm
Collar outer radius	90 mm	90 mm
Iron yoke outer radius	260 mm	280 mm
Separation b/w beam axis	---	180 mm
Magnet total length	1180 mm	1180 mm

B. Superconductor Development

The highly key-stoned compacted strand cable has been developed with design parameters given in Tab. 2. The major design guidelines for the superconductor are as follows:

- $J_{op} = 1150 \text{ A/mm}^2$ at 11.2 T, 2.0 K in NbTi superconductor with an operational safety margin of 8 % along the load line,
- large cable ($I_{op}=12720 \text{ A}$) and fine filament size (6 μm),
- high key-stone angle of 4.6 degree in the inner cable and possible minimum bending radius of 7 mm,
- mechanical and electrical stability under an electromagnetic force of 100 MPa.

As a result of the development, a critical current density of 867 A/mm^2 in NbTi after cabling was achieved at 8 T, 4.2 K, corresponding to the same current density at 11 T, 1.8 K, in the inner cable strand as given in Table 3. Based on this result, it was expected to reach 10 T at 1.8 K with an operational margin of a few percent along the load line ratio at 1.8 K in the present magnet design.

Table 2. Design parameters of the superconductor and coil for the 10 T model magnet.

		Inner	Outer
Strand:			
Diameter	[mm]	1.39	0.79
Cu / SC		1.6	1.8
Filament dia.	[μm]	6	6
J-op (strand)	[A/mm^2]	381	684
J-op (NbTi)	[A/mm^2]	991	1915
Cable:			
Width	[mm]	15	15
Thickness	[mm]	1.884/3.093	1.100/1.554
Keystone angle	[deg]	4.614	1.735
Cable pitch	[mm]	110	110
Number of strands		22	37
J-op (cable)	[A/mm^2]	341	639
Packing factor	[%]	>90	>90
Coil:			
Number of turns / half coil		16	24
J-op (over all)	[A/mm^2]	322.6	578.0
J-op/Jc (load line) [%]		91.5	87.5
B-op max	[T]	10.2	8.0
I-op	[A]	12,720	12,720
Mag. force: ΣF_x	[MN/m]		2140
ΣF_y	[MN/m]	-301	-854

Table 3. Measured superconductor performance.

B [T]	Jc in NbTi [A/m^2]	
4.2 K (1.8K)	(Inner cable)	(Outer cable)
Before cabling:		
6 (9)	2020	2280
7 (10)	1455	1645
8 (11)	910	1040
After Cabling		
6 (9)	1925	2125
7 (10)	1397	1535
8 (11)	867	981

C. Hybrid Collar Development

A hybrid collar lamination consisting of high Mn steel (YUS130) and aluminum alloy (A3003) has been developed to optimize properties of thermal contraction (300-1.8K), magnetic permeability, μ , and mechanical strength in collar. This hybrid material may minimize the specific magnetic permeability to be 1.002 or less in comparison with that of 1.02 in stainless steel at 4.2 K as summarized in Tab. 4. This hybrid collar material may contribute to eliminate a sextupole component induced by magnetic property in collar with keeping mechanical stiffness and thermal contraction as same as that in the stainless steel collar. [5]

Table 4. Properties of hybrid collaring lamination in comparison with stainless steel.

Item	Unit	Coil	SUS316L	Hybrid
Material			Ni/Cr/Fe	Hi-Mn st./Al
Ratio				1.27/1
Y.S.	[MPa]		350	320
U.S.	[MPa]		650	550
Elongation	[%]		48	51
Young's mod. [GPa]		15	180	140
μ at 300K			1.002	<1.001
at 4K			1.02	<1.002
Thermal contr. [%] (300 K - 4.2 K)		0.30	0.31	0.30

D. Magnet Fabrication

The single aperture model magnet was fabricated, in advance to fabrication of the twin aperture model dipole. The single aperture coil was successfully wound with highly key-stoned cables, was collared with the hybrid lamination and was assembled into solid iron yoke. Finally the yoke was assembled with an outer support cylinder made of stainless steel by using shrink-fit technique. Figure 2 shows a picture of the single aperture model magnet completed. Fabrication of the twin aperture model magnet is in progress. A pair of coils have been completed and the collaring is in progress. The collared coil will be assembled with laminated iron yoke and stainless steel support cylinder.

III. TEST OF THE SINGLE APERTURE MAGNET

The first cool-down and excitation test of the single aperture model magnet was carried out in Japan. The magnet was cooled-down to 4.3 K in a vertical position and was successfully excited up to a short sample limit of 8.0 T after three quenches as shown in Fig. 3. Then, the magnet was warmed up and transported to CERN to be tested at 1.8 K.

The test at CERN was carried out also in a vertical position. The magnet was tested again at 4.3 K to observe effects of thermal cycling and transportation from KEK to CERN. The training behavior was similar to the result of the first test in Japan. The re-training behavior was observed. The test at 1.8 K was followed and the magnet reached 9.87 T in maximum after 25 quenches at 1.8 K as shown in Fig. 3. In the training test, the ramp rate was 2 A/s. The most of the quenches were initiated at the axial end of the coil according to voltage tap measurement and a sophisticated inductive measurement recently developed at CERN. [6] The load line ratio achieved in the single aperture magnet is shown in Fig. 4.

A series of test with higher ramp rates was carried out between di/dt of 240 A/s and 560 A/s with an initial offset current of 2884 A in most cases. Figure 5 shows the ramp rate dependence on the quench current. The magnet reached 9.57 T with $di/dt=240$ A/s. As a result, this magnet accepted much higher ramping rate than magnets developed by others.[7] The experimental data is being evaluated to study this interesting behavior.

Fig. 2. Single aperture 10 T dipole model magnet completed.

Fig.3. Quench history of the KEK single aperture 10 T dipole model magnet.

IV. SUMMARY AND DISCUSSION

A single aperture 10 T dipole magnet has been developed as a cooperative R&D effort between CERN and KEK for future high energy particle accelerator technology. The single aperture dipole magnet was tested at 4.3 K and 1.8 K and the following behaviors have been observed:

Fig. 4. Quench characteristics along the load line for the single aperture model magnet.

1. The magnet reached a short sample limit of 8.0 T at 4.3 K after a few quenches.
2. The magnet reached 9.87 T at 1.8 K after twenty-five quenches at 1.8 K.
3. The quenches were mostly initiated at the axial coil end.
4. After a thermal cycling at CERN without transportation, the training memory was mostly kept and the magnet reached 9.5 T in one quench.
5. The magnet accepted a high ramp rate of $dI/dT=240$ A/s corresponding to about $dB/dT=10$ T/min to reach 9.57 T before quenching.

The quenches at the short sample limit at 4.3 K are detected as expected in the straight part of the winding. Except two quenches at the beginning of the training at 1.8 K, all the others are detected to be in the ends. For one third of them, voltage tap measurements indicate that the transition is initiated at the same time in the inner and the outer layer. A longitudinal sliding between the two layers is there suspected. Most of the training quenches are following spikes seen on the voltage taps and on the pick-up coils which are a signature for a structural movement. The magnet did not reach the short sample limit at 1.8 K. We consider that the magnet quenches due to mechanical weakness in the coil structure. This result will be reflected on the twin aperture dipole magnet to be assembled.

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Fig. 5. Ramp rate dependence on the quench current in the single aperture model magnet.

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