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***Abstract*---A twin aperture dipole magnet has been developed with a feature of symmetric, separate coil/collar design in a R&D cooperation between CERN and KEK towards the LHC project. The magnet reached 8.1 T at 4.2 K and 9.6 T at 1.8 K in the training test. Development of the magnet and test results are discussed. Design study of a new 56 mm φ twin aperture dipole is also discussed.**

I. INTRODUCTION

A research and development program on high field superconducting magnets towards the Large Hadron Collider (LHC) to be built at CERN has been carried out, as a cooperative R&D effort between CERN and KEK, since 1989 [1]-[3]. In this program, a twin aperture dipole magnet with a feature of symmetric, separate coil/collar configuration has been developed [4]-[5]. As the first step, a 50 mm φ single aperture dipole (MSAKEK#1) was developed and the magnet performance was evaluated. The magnet reached 8.0 T at 4.3 K and reached 9.9 T at 1.8 K after training. A 50 mm φ twin aperture dipole (MTAKEK) was fabricated with identical coil/collar design and with additional improvement on prestress in the coil. The magnet was fabricated in cooperation amongst KEK, Toshiba Corporation and The Furukawa Electric Co. Ltd. Fig. 1 shows outlook of the twin aperture dipole completed. The magnet was tested at KEK/Toshiba and at CERN and it reached 8.2 T at 4.3 K and 9.6 T at 1.9 K, respectively. Results of the training test showed that all quenches observed were initiated at coil ends mostly due to mechanical disturbance. The second single aperture dipole (MSAKEK#2) is being fabricated with much effort to support the coil ends tightly. The magnet test is planned to be carried out at KEK in early next year.

Since the LHC machine design and the major magnet parameters were changed in last year [6], a new series of development on the dipole has been started. A new model with a beam aperture enlarged to 56 mm φ and an operational field of 8.65 T is being designed. A few single aperture dipoles and a twin aperture dipole are to be developed. Progress of the development and design study for further R&D plans are described in the following sections.

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II. DEVELOPMENT OF THE MAGNET

The twin aperture dipole model magnet was designed and developed with the following technical approaches;

- Fully symmetric separate coil/collaring structure,
- Double shell coil configuration with no-wedges,
- Use of hybrid (YUS/Al) collar to optimize thermal contraction with less residual permeability.
- Vertical split iron yoke and stainless steel outer cylinder.

Main parameters of the twin aperture magnet are given in Table I. Design and performance of the superconductor are described in [4]-[5].

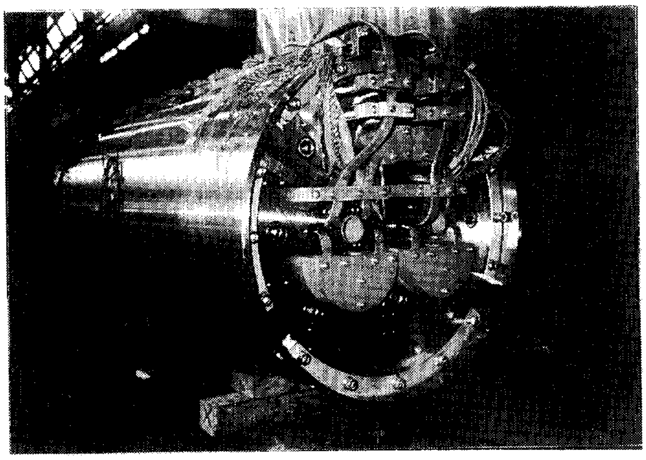

Fig. 1. Outlook of the twin aperture dipole (MTAKEK).

TABLE I
DESIGN PARAMETERS OF THE TWIN APERTURE DIPOLE MODEL MAGNET (MTAKEK)

Bo		10 T
Io		12,720 A
Stored energy		666 kJ/m
Dimensions:		
Coil aperture radius		25 mm
Collar outer radius		90 mm
Iron yoke outer radius		280 mm
Separation b/w beam axis		180 mm
Magnet length		1180 mm
	[inner]	[outer]
Number of turns / half coil	16	24
B-max.	10.2 T	8.0 T
J (over all)	323	578 A/mm^2
J (cable)	341	639 A/mm^2
J (NbTi)	991	1915 A/mm^2
B-op max.	10.2 T	8.0 T
Magnetic force: ΣFx		2.140 MN/m
ΣFy	-30[illegible]	-0.854 MN/m

III. TEST RESULTS

The twin-aperture dipole was first tested at 4.2 K at Toshiba/KEK and the magnet reached 8.2 T after 6 quenches. The second test was carried out at 4.2 K and 1.9 K at CERN. At 1.9 K, The magnet reached 9.6 T after 22 quenches. Fig. 2 shows training behaviour of the magnet.

The origin of training quenches was observed by means of "pick-up coils" technique [7]-[9]. All quenches were initialized at the coil ends, mainly in the outer coil. Results of the quench localization anaysis are summarized in Table II. No quenches were observed at the straight section and this fact can be understood taking into account the stress measurements performed with the help of beam-transducers located at top end of the inner and the outer coils. Fig. 3 shows the linear relationship between measured strains and the square of the excitation current. No major change of the prestress during cool-down is assumed, in this figure, because the same level of thermal contraction may be expected both in the hybrid-collar(High-Mn/Al) and the coil itself. It is clear that initial prestress is high enough and remains at high fields. Its stability with respect to training quenches was also observed.

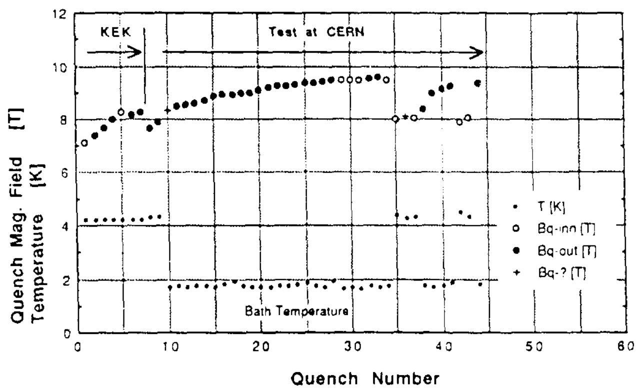

Fig. 2. Training of the twin-aperture dipole (MTAKEK)

TABLE II
QUENCH LOCATIONS DURING TRAINING QUENCHES

Total quench numbers	30
Number of quenches analyzed	27
Spike type	93 %
Outer layer	93 %
Outer layer 1st turn (most inner, end)	67 %
Connection end	67 %
Non-connection end	33 %
Straight section	0 %

Results of the fast ramping test indicate that AC loss is much smaller than that of the other magnets [10]. The possible reasons of much smaller inter-strand loss in the MTAKEK design are smaller width of the cable (15 mm instead of 17 mm), smaller cable pitch (110 mm instead of 117-130 mm) and larger key-stone angle (high contact resistance in the middle of the cable) in comparison with other model dipole. A high ramp excitation with 340 A/s (0.26 T/s) quenched the magnet at 9.14 T [10]. Summary of field quality measurements is given in Table III. Excitation dependence of the sextupole components is shown in Fig. 4.

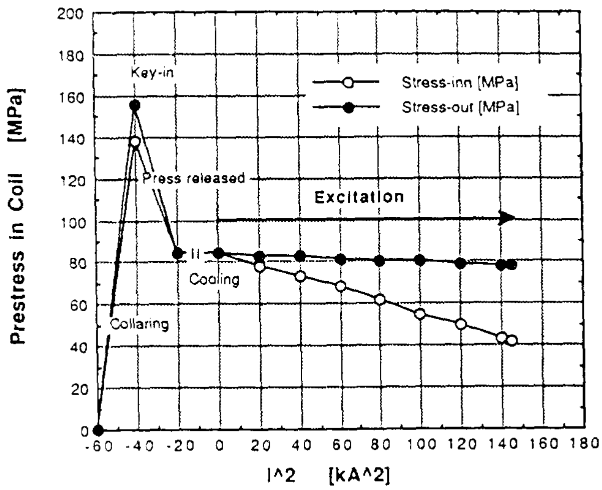

Fig. 3. Prestress at coil-top in fabrication, cooling and excitation.

TABLE III
MEASURED HARMONICS IN MTAKEK(@ R =1 7MM)

bn	Normal	Skew	(Design guide)
2	-1.93 E-4	-0.88 E-4	
3	-20.36	-1.27	8.67 E-4
4	-0.51	-0.28	
5	-1.27	+0.14	3.3
6	+0.08	+0.53	
7	+4.31	+0.27	3.1
8	-0.31	-0.76	
9	-3.83	-0.37	1.7

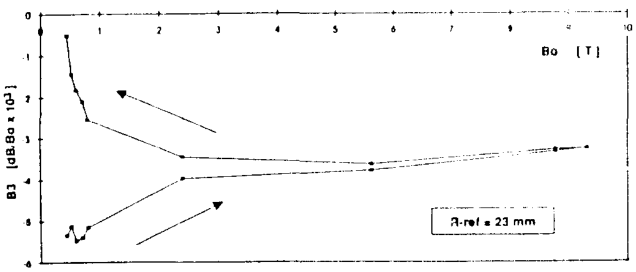

Fig. 4. Excitation dependence of the sextupole component.

IV. FURTHER R&D PLAN

A. Improvement of Coil-End in 2nd Single Aperture Model

In order to reduce training at the coil end, the following improvement is being made. The effect will be evaluated soon in the second single aperture dipole (MSAKEK#2) being fabricated.

- Re-positioning of the coil-end block to eliminate axial separation force between coil-end blocks.
- Individual coil winding of the inner coil and the outer coil and assembling together after curing,
- Replacing the magnetic yoke with non-magnetic "void" at the coil end to reduce the peak field.

B. New Dipole Design with 56 mm Aperture

General Design: According to the re-consideration of the LHC machine and magnet design, the magnet aperture and the operational field were changed to 56 mm and to 8.65 T, respectively[2]-[5]. Design study of a 56 mm ϕ twin aperture dipole magnet (MTA56KEK) is being carried out with complementary approach, in mechanical design, to the effort at CERN, as follows:

- Symmetric, separate collars made of non-magnetic steel with an outer radius of 90 mm,
- Horizontally split iron yoke with an outer radius of 280 mm,
- Five-block coil with a coil inner radius of 56 mm, similar to the CERN coil design,

It is intended to make the twin aperture dipole design as simple as possible with aiming at more reliable quality control in large scale production. Main parameters of the 56 mm ϕ twin aperture dipole (MTA56KEK) are given in Table IV and the cross sectional view is shown in Fig. 5.

Selection of Material for Collar: A systematic study has been made to select an optimum non-magnetic steel to be used in the split collar. Two candidates of stainless steel (SUS316) and high-Mn steel, 28 %-Mn, KHMN [11], have been investigated. Using stainless steel, electro-magnetic force may be fully supported by collar with remaining open gap between outside of collar and inside iron yoke boundary. A feature is that the coil/collar structure may be mechanically independent from the outer iron structure with respect to support electromagnetic force. A disadvantage is larger coil deformation with a level of 90 μm at outer radius of the collar and 120 μm at the coil mean radius, respectively. The use of high-Mn steel (28 % Mn)

TABLE IV
DESIGN PARAMETERS OF THE 56 MM ϕ TWIN APERTURE DIPOLE (MTA56KEK)

Dimensions:			
Coil aperture radius			28 mm
Conductor width			2 x 15 mm
Collar outer radius (IR of Yoke)			90 mm
Beam axis separation			180 mm
Coil straight section			800 mm
Iron yoke length			600 m
Void length at coil-end			2 x 300 mm
Total magnet length			1200 mm
Magnetic field			8.65 T
Current I			11,537 A
Load line ratio			< 90 %
# turns in inner shell			2 x 15
outer shell			2 x 26
Electromagnetic force	Sigma-Fx		1,785 MN/m
	Sigma-Fy		-855 MN/m
Field Quality (@ ref. radius = 17 mm)			
Bo		[0.76 T]	[8.65 T]
b2		-1.88 E-5	-1.53 E-4
b3		-2.28 E-4	+2.46 E-4
b4		+9.76 E-8	--6.71 E-6
b5		-6.38 E-5	+6.66 E-5
b6		-1.65 E-8	-3.49 E-7
b7		-1.42 E-5	-1.42 E-5
b8		-2.25 E-8	-1.91 E-7
b9		-7.32 E-6	-6.41 E-6

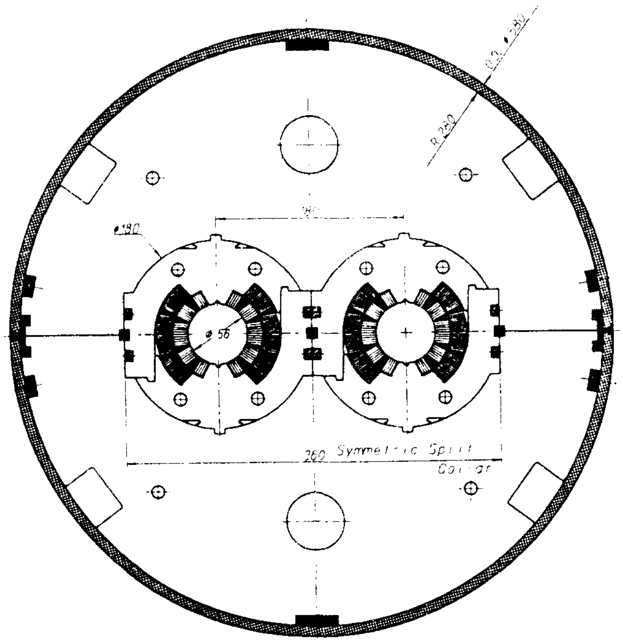

Fig. 5 Cross section of 56mmϕ twin aperture dipole (MTA56KEK)

TABLE V.
EFFECT OF COLLAR MATERIAL ON THE MAGNET OPERATIONAL CONDITIONS*

	Stainless St.	High-Mn St.
Thermal shrinkage (300 K > 1.9 K)	0.309 %	0.17 %
Typ. prestress (inner) aft. collaring	66 MPa	66 MPa
Typ. prestress (Inner) aft. cool-down	68 MPa	54 MPa
Coil prestress change aft. cool-down	no reduction	12MPa
Remaining prestress (Inner) @8.65 T	38 MPa	27 MPa
Collar/Yoke contact. aft. cool-down	Gap=0.1 mm	Gap closed
Collar/Yoke contact at 8.65 T	Gap=0.016 mm	Gap closed
Force (ΣFx) supported in collar	100 %	64 %
Deform. of half collar width(8.65T)	0.09 mm	0.03 mm
Deform. of mean coil radius(8.65T)	0.12 mm	0.06 mm

*The calculation was mad by using ANSYS code.

enables much stiffer mechanical structure in connection to the iron yoke contacting to the collar outer edge at any time. It makes the coil deformation minimum at a level of 30 μm at the outer edge of the collar and 60 μm at the coil mean radius, respectively. On the other hand, reduction of coil prestress is estimated to be in a level of 12MPa after cool-down of the magnet, although it might be acceptable because of a lower field of 8.65 T than that of 10T in the previous design. As a starting point, high-Mn steel has been considered as the primary candidate to be used in the new dipole magnet development. Table V gives a summary of the comparisons between stainless steel and high-Mn steel in terms of effect of collar material on magnet operation; cool down and excitation.

Horizontally Split Iron Yoke with High-Mn Steel Collar: The horizontally split yoke configuration may be convenient for large scale assembly of the magnet. This option may be optimized by using high-Mn steel collars, and it has the following advantages:

- Simple structure and easier assembly with less requirements on tolerances,
- No inclined gap required between two half yokes,
- No strong mating force required between horizontally split yoke.

R&D Plan for 56 mm ϕ Twin Aperture Dipole: Development of the 56 mm ϕ twin aperture dipole will be carried out in two steps. Three single aperture dipoles (MSA56KEK) will be developed to optimize the coil design with some feed back from the previous magnets. The development of the 56 mmϕ twin aperture dipole will be carried out with identical coil design. Since the coil/collar design may be identical, it may be possible to re-assembled two single aperture coils to one twin aperture dipole magnet .

IV. SUMMARY

Development of twin aperture dipole magnets for the Large Hadron Collider have been carried out as a cooperative accelerator R&D program between CERN and KEK. A 50 mm ϕ twin aperture dipole having a feature of symmetric, separate coil/collar configuration has been developed. The magnet reached 9.6 T at 1.8 K after training at the coil ends. A systematic effort to improve the coil end configuration is being carried out.

According to the new LHC machine design recently revised, a new magnet R&D program has been started to develop a 56 mm ϕ twin aperture dipole model magnet. The magnet design is being carried out with symmetric, separate collar made of high-Mn steel in combination with horizontally split yoke.

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