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Akira Yamamoto et al.*
G. Brianti, D. Leroy, R. Perin

A single aperture dipole magnet has been developed with a design magnetic field of 10 tesla by using NbTi/Cu conductor to be operated at 1.8 K in pressurized superfluid helium. The magnet features double shell coil design by using high key-stone Rutherford cable and compact non-magnetic steel collars to be extended to split/symmetric coil/collar design in twin aperture dipoles. A design central magnetic field of 10 tesla has been successfully achieved in excitation at 1.95 K in pressurized superfluid helium. Test results of the magnet with a summary of the design and fabrication will be presented.

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Test Results of a Single Aperture 10 Tesla Dipole Model Magnet for the Large Hadron Collider

Akira Yamamoto, Takakazu Shintomi, Nobuhiro Kimura, Yoshikuni Doi, Tomiyoshi Haruyama, Norio Higashi,
Hiromi Hirabayashi,* Hiroshi Kawamata, Seog-whan Kim, Takamitsu M. Kobayashi, Yasuhiro Makida,
Toru Ogitsu, Norihito Ohuchi, Ken-ichi Tanaka, Akio Terashima, Kiyosumi Tsuchiya and Hiroshi Yamaoka
National Laboratory for High Energy Physics (KEK), Tsukuba, Ibaraki, 305, Japan

Giorgio Brianti, Daniel Leroy, and Romeo Perin
CERN, Geneva, CH-1211, Switzerland,

Shoichi Mizumaki
Dept. of Accelerator Science, The Graduate University for Advanced Studies, Tsukuba, Ibaraki, 305, Japan

Shuichi Kato
Kyushu University, Fukuoka, 812, Japan

Kenji Makishima, Tomohumi Orikasa, Tomoaki Maeto, Akira Tanaka
Toshiba Corporation, Tsurumi, Yokohama, 230, Japan

Abstract -- A single aperture dipole magnet has been developed with a design magnetic field of 10 tesla by using Nb-Ti/Cu conductor to be operated at 1.8 K in pressurized super fluid helium. The magnet features double shell coil design by using high key-stone Rutherford cable and compact non-magnetic steel collars to be extended to split/symmetric coil/collar design in twin aperture dipoles. A design central magnetic field of 10 tesla has been successfully achieved in excitation at 1.95 K in pressurized superfluid helium. Test results of the magnet with a summary of the design and fabrication will be presented.

I. INTRODUCTION

A research and development program on high field superconducting magnets has been carried out, as a cooperative R&D program between CERN and KEK, since 1989, towards the Large Hadron Collider (LHC) at CERN[1]-[4]. As a technical approach, a twin aperture dipole magnet featured with symmetric, separate coil/collar design has been developed [5]. As the first step, a 50 mm ϕ single aperture dipole was developed and the magnet reached 9.9 tesla at 1.8 K [6]. A 50 mm ϕ twin aperture dipole was fabricated with the same coil/collar design and with improvement on prestress in the coil. It reached 9.6 tesla at 1.9 K [7]. As results of the training test, all quenches observed were induced at coil ends and mostly due to mechanical disturbance. Based on those experiences, the second single aperture dipole (MSA50-KEK#2) was developed with intention to improve the coil end structure and to reduce the magnetic field at the coil end. Main parameters of the magnet are summarized in Table 1 and a cross section of the magnet is shown in Fig. 1. The second single aperture dipole magnet has successfully reached 10.3 tesla. The improved magnet design and test results are described in the following chapters.

TABLE I
PARAMETERS OF THE SINGLE APERTURE DIPOLE MODEL MAGNET

<u>General</u>				
Bo			10 T	
Io			12,720 A	
Inductance			3.5 mH	
Dimensions:				
Coil aperture radius			25 mm	
Collar outer radius			90 mm	
Iron yoke outer radius			260 mm	
Magnet length			1200 mm	
<u>Coil</u>				
Number of turns / half coil			16	24
B-max.	[tesla]		10.2	8.0
J (NbTi)	[A/mm ²]		991	1915
Magnetic force:	ΣF_x	[MN/m]		2.140
	ΣF_y	[MN/m]	-301	-0.854
<u>Superconductor</u>				
Cables				
Width	[mm]		15	15
Thickness	max.	[mm]	3.093	1.554
	min.	[mm]	1.884	1.100
Keystone angle	[deg]		4.614	1.735
Cable pitch	[mm]		110	110
Number of strands			22	37
Packing factor	[%]		>90	>90
Jop (cable)	[A/mm ²]		341	639
B-op peak	[T]		10.2	8.0
Ic (10.5T, 2K)	[A]		13100	13100
Strand:				
Diameter	[mm]		1.39	0.79
Cu / SC			1.6	1.8
Filament dia.	[mm]		6	6
J (NbTi)	[A/mm ²]		991	1915
<u>Conductor Performance (measured)</u>				
Jc(Nb-Ti) after cabling				
4.2 K (1.8K)				
6 T (9T)	[A/mm ²]		1980	2150
7 T (10T)	[A/mm ²]		1490	1540
8 T (11T)	[A/mm ²]		980	1000

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Akira Yamamoto, e-mail akira@kek.vax.kek.jp, fax 81-298-64-7831, tel 81-298-64-5408,

*Present Address, Fusion Science Laboratory, Toki, Gifu, Japan

Fig. 1. Cross-section of the single aperture model dipole.

II. IMPROVEMENTS OF THE COIL END DESIGN

Based on the experience and test results of the previous model dipoles, the following improvements have been made in order to minimize the number of training quenches.

TABLE II
NEW COIL-END DESIGN COMPARED WITH THE PREVIOUS DESIGN.

	Previous design	New design
Axial position for coil-end starting:		
Inner coil	0.3 m	0.3 m
Outer coil	0.3 m	0.36 m
Number of turns in each block:		
Inner coil	2+3+5+6	4+2+4+6
Outer coil	12+12	6+7+11
Peak field without iron yoke:		
Inner coil	9.1 tesla	9.3 tesla
Outer coil	8.1	7.6
Magnetic force (x / y / z; MN):		
Inner coil	32.6 / 0.36 / 23.1	40.0 / -8.2 / 33.4
Outer coil	16.9 / 38.6 / 36.8	22.1 / 22.2 / 27.9
Axial force balance among end-blocks [MN]:		
Inner coil (4 blocks)	2.2+4.8+11.3+4.8	5.7+3.9+9.5+14.3
Outer coil (2->3 bl.k)	28.6+8.2	13.4+10.8+3.7

- Re-optimization of the coil-end-structure; to minimize the peak field, and to enhance self attractive force between end blocks for improvement of the mechanical stability,
- Non-magnetic steel yoke (void) at the coil end; to reduce the peak field,
- Separate inner- and outer-coil winding; to verify accuracy and tightness of the coil-end shape,
- Pre-tensioning of the coil in axial direction by using pre-tensioning bolts embedded in the collar; to minimize the axial coil movement.

Figure 2 shows the new coil-end configuration. Table 2 gives the new design parameters compared with the previous design. In the new design, inner and outer coil-end positions

Fig. 2. New coil-end design and axial pre-tensioning scheme.

● : Location of voltage taps.

are axially separated from each other. It enables to reduce the peak field at the coil end, to equalize axial stress in the conductor, and to ensure the self mechanical stability.

III. TESTS AND RESULTS

The magnet was pre-cooled down to 80 K by using LN2 and then cooled down to 4.2 K by using LHe. Excitation tests were made first at 4.4 K, and the magnet reached almost the critical current ($I_q/I_c > 98\%$) in the first quench. The magnet was cooled down to 1.95 K at one atmospheric pressure and the excitation tests were continued in two series with an interval as a thermal cycling test. Fig. 3 shows characteristics of training quenches. The magnet reached 10 tesla after 13 quenches at 1.95 K and finally reached the maximum field of 10.3 tesla ($@I_q/I_c \geq 99\%$) at 1.95 K. The training was not so well memorized after a thermal cycle up to room temperature. A possible reason in relation with LN2 pre-cooling could be uncontrollable, high thermal stress/deformation during pre-cooling. In the second test, the magnet reached maximum field of 10.15 tesla after 10 quenches. The quench current was less stable in the second test and some degradation was observed after reaching the maximum field.

Quench origins and propagations were observed mainly by using voltage taps located at the coil ends as indicated in Fig. 2. The major training quenches occurred at the same spot in the straight part, 15 cm from the axial center, of the top-turn of the lower outer coil. No quench-evidence was observed around the voltage taps located at the coil ends. A quench induced at 9.7 tesla might be initiated at the inner coil end and it propagated in the volume close to the coil median plane; beyond 5th turn of the inner coil. The quench locations during training tests are summarized in Table 3. A quench velocity of 180m/s was measured in the outer coil at the quench current of 12870 A.

Fig. 4 shows remaining azimuthal prestress measured at the coil top-end during the magnet fabrication, cool-down and excitation. The prestress in the inner coil behaved as

TABLE III
QUENCH LOCATIONS DURING TRAINING QUENCHES AT 1.9 K

Location detected		1st test	2nd test
# training quenches		21	11
Upper inner (+)	6th - 16th turns	7	1
	6th - 16th turn, End		1
Upper outer		0	0
Lower outer	1st-2nd turn, Straight sect.	13	9
Lower inner (-)		1	

expected. A reasonable prestress of 25 MPa remained at the full excitation and the prestress was recovered to the initial value at $I = 0$ A. Mechanics for the inner coil seems to work well. On the contrary the prestress at the top of the outer coil behaved differently. The prestress level during excitation did not decrease but remained high. The quench, however, happened mainly at the top turn of the straight part in the lower outer coil. Friction effect at the radial outer coil boundary to the collar structure could explain this experimental result.

The fast ramp test was carried out to study the AC loss effect on the quench current. The test was made by varying the ramp rate from 20 A/s to 600 A/s. There was no significant effect on the quench current even when the ramp test was started at $I = 3,000$ A. Fig. 5 shows measured ramp dependence of the quench current.

A heat load due to the AC loss was measured in a continuous ramping between 0 A and 1,000 A with a ramp rate of 400 A/s. The magnet and helium-bath temperatures were measured during ramping up/down. A temperature rise to 2.05 K from an initial temperature of 1.94 K was measured in the fast ramp test. The heat load was obtained from the temperature difference of 0.21 K, which was converted to a heat load of 9.8 W by using the calibrated heat (temperature) balance between the refrigeration capacity and the electrical heater power input into the superfluid helium system as shown in Fig. 6.

Fig. 3. Training characteristics of the second model dipole.

Fig. 4. Trend of the remaining prestress at the azimuthal coil-top during a period of the magnet fabrication, cool-down and excitation.

Figure 5. Quench current as a function of the ramp rate.

IV. CONCLUSION

The second (#2) single aperture 10 tesla dipole magnet has been developed. Re-optimization of the coil-end structure was focused to eliminate a number of training quenches. Three major improvements have been made in (i) peak field reduction at the outer coil end, (ii) naturally stable and attractive force condition between the sub-divided coil end blocks, and (iii) axial prestress, in tension, generated in the coil.

The magnet has been successfully tested up to the maximum central field of 10.3 tesla ($@I_q/I_c \geq 99\%$) at 1.95 K. The design magnetic field of 10 tesla was achieved after 13 training quenches at 1.95 K. Major training quenches occurred at the same spot at the straight section in the top-turn of the lower-outer coil. The inner coil quenches occurred beyond 9.5 T and they were initiated close to median plane and possibly around at the axial coil end.

As a conclusion, the coil end design has been systematically improved in the second single aperture dipole magnet and the magnetic field of 10 tesla has been successfully achieved

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Fig. 6. Temperature balance during a fast ramp test at 400 A/s. The AC loss of 10 W was obtained by using the temperature balance curve as a function of electrical heater power input into the superfluid helium bath.

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