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T. SHINTOMI, A. YAMAMOTO, Y. DOI, T. HARUYAMA, N. HIGASHI, H. KAWAMATA,
S.W. KIM, N. KIMURA, V. KOVACHEV, T. NAKAMOTO, N. OHUCHI, T. OGITSU,
K. TANAKA, A. TERASHIMA, K. TSUCHIYA, R. PERIN, D. LEROY, S. KATO,
K. MAKISHIMA, T. ORIKASA and A. TANAKA

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Development of a 56 mm Aperture Superconducting Dipole Model Magnet for LHC

T. Shintomi, A. Yamamoto, Y. Doi, T. Haruyama, N. Higashi, H. Kawamata, S.W. Kim, N. Kimura,
V. Kovachev,* T. Nakamoto, N. Ohuchi, T. Ogitsu, K. Tanaka, A. Terashima, and K. Tsuchiya
National Laboratory for High Energy Physics (KEK), 1-1 Oho, Tsukuba, Ibaraki 305, Japan

R. Perin and D. Leroy
European Laboratory for Particle Physics (CERN), 1211 Geneva 23, Switzerland

S. Kato
Kyushu University, 6-10-1 Hakozaki, Higashi-ku, Fukuoka 812, Japan

K. Makishima, T. Orikasa, and A. Tanaka
Toshiba Corporation, 2-4 Suehiro-cho, Tsurumi, Yokohama, Kanagawa 230, Japan

Abstract—A 56 mm single aperture superconducting dipole model magnet, which is one of the frame works of the LHC collaboration between KEK and CERN, has been developed. A central field of 8.65 T is provided at a load line ratio of 90 % with a 5 block coil wound with NbTi superconducting cables. The magnet has a straight section of 0.8 m and a total length of 1.2 m. The distinctive features of the magnet are a magnetically symmetrical configuration being applicable to the twin aperture magnet and mechanical consideration sharing the magnetic forces with a high Mn steel collar and a horizontally split iron yoke. The magnet showed almost no training at 4.4 K. The first quench current at 1.8 K was 91 % of the short sample I_c and the magnet reached a central magnetic field of 8.8 T. Finally it could be excited with the current of more than 99 % of the short sample limit which corresponds to a central field of 9.63 T.

aperture model was fabricated. The main features which are a complementary approach to the CERN R&D are as follows:

- Symmetric, separate collar made of non-magnetic steel with an outer radius of 90 mm,
- Horizontally split iron yoke with an outer radius of 260 mm, and
- Five block coil with a coil inner radius of 28 mm that is essentially the same as the CERN coil disposition.

This single aperture design can be easily applied to the twin aperture dipole magnet without any modification in the collared coil. This symmetrical and horizontal split yoke configuration has an advantage of a simple structure and easier assembly with less requirements on tolerances.

The main parameters are shown in Table I.

I. INTRODUCTION

The R&D of the LHC main superconducting dipole magnet have been carried out as one of the projects within the frame work of the LHC collaboration between KEK and CERN [1]. This R&D is complementary to the work at CERN. A 56 mm single aperture dipole model magnet has been developed. The magnet has the same 5 block coil configuration as the CERN design wound with NbTi superconducting cables to be operated in superfluid helium at 1.9 K and a central field of 8.65 T at a load line ratio of 90 %. This magnet has the following features: a magnetically symmetric configuration intended to be applied to the twin aperture magnet, mechanical consideration using a high manganese steel collar, and a horizontally split iron yoke. It has a straight section of 0.8 m in a total length of 1.2 m. The magnetic forces are supported partly by the collar and partly by the yoke. The end sections follows the design adopted for the previous 50 mm aperture dipole magnet developed at KEK [2]. The magnet design, fabrication, and performance test will be reported in this paper.

II. MODEL MAGNET DESIGN

1) *Design concept*: According to the previous design concept of the twin aperture dipole magnet [1], a single

TABLE I
MAIN PARAMETERS OF 56 MM APERTURE MODEL DIPOLE MAGNET

General			
Central field	[T]	8.65	
Operational current	[A]	11,537	
Collar outer radius	[mm]	89.5	
Yoke outer radius	[mm]	260.0	
Magnet physical length	[mm]	1,200	
Length of straight s.s.	[mm]	800	
Yoke length	[mm]	600	
Outer cylinder thickness	[mm]	15	
Self inductance	[mH/m]	4.4	
Stored energy	[kJ/m]	290	
Mag. force	ΣF_x [kN/m]	1,800	
(1/4 coil)	ΣF_y [kN/m]	-160	
	ΣF_z [kN/m]	-690	
Coil			
Number of turns		Inner 2×15	Outer 2×26
Coil peak field	[T]	9.0	7.6
J_0 w/o insulation	[A/mm ²]	407	523
J_0/J_c	[%]	~ 88	~ 85
Coil inner radius	[mm]	28.09	44.09
Coil outer radius	[mm]	43.09	59.09
Superconductor			
Cables			
Dimension	Width [mm]	15 + 0/-0.03	15 + 0/-0.03
	Mid thickness [mm]	1.89 ± 0.01	1.47 ± 0.01
Keystone angle	[°]	1.30 ± 0.05	1.00 ± 0.05
Number of strands		28	36
Twist pitch	[mm]	110 ± 5 (S)	95 ± 5 (Z)
I_c @ 1.9 K	[A]	> 13,750 @ 10 T	> 12,950 @ 9 T
Strand			
Superconductor		Nb-Ti/Cu	Nb-Ti/Cu
Strand diameter	[mm]	1.065 ± 0.003	0.825 ± 0.003
Cu/SC ratio		≥ 1.6	≥ 1.9
Filament diameter	[μm]	7 ± 0.5	7 ± 0.5
RRR of Cu		> 80	> 80
Twist pitch	[mm]	25 ± 3 (Z)	25 ± 3 (S)

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* Visiting professor from Bulgarian Academy of Science

Fig. 1 Cross section of the model magnet. The coil is collared with high-Mn steel, which is surrounded by horizontally split iron yoke. Instrumented pressure gauges, voltage taps and temperature sensors are not shown.

2) *High-Mn collar design*: Two candidates of non-magnetic steel, SUS-316 and high-Mn steel, have been considered for the design by a systematic study. We adopt the high-Mn steel, 28 % Mn, KHMN [3], in this model magnet because it has a similar thermal contraction coefficient and then the magnet has a stiffer mechanical structure in connection to the iron yoke contacting mechanically to the collar outer edge since room temperature assembly. This means also the small coil deformation of around 60 μm which is smaller than that in case of SUS-316 at the coil mean radius. On the other hand, this has a disadvantage of larger reduction of the coil prestress estimated to be in a level of 12 MPa after cooling-down. The collar should contact rigidly with the yoke at the room temperature. The gap is filled with a 0.5 mm thick steel plate to test the high-Mn collar configuration. When the plate is removed, we can simulate mechanically the collar configuration which may happen in the SUS-316 collar.

3) *Coil end design*: The same concept as the previous single 50 mm aperture model magnet which has shown no quench at the end sections [2] was adopted for the coil end design. The features are as follows:

- Re-optimization of the coil end structure to minimize the local peak field and to enhance self attractive force between end blocks,
- Non-magnetic steel yoke at the coil end to reduce the local peak field, and
- Pre-tensioning of the coil in axial direction using pre-tensioning bolts embedded in the collar.

The end sections of the inner- and outer-coils are distributed into 4 and 2 blocks, respectively, as shown in Fig. 1. Their positions are axially separated from each other to reduce the peak field at the coil ends to equalize axial stress in the conductor and to ensure the mechanical self-stability. All the blocks in the inner- and outer-coils are distributed to be compressed each other by the integrated magnetic forces.

III. FABRICATION OF THE MAGNET

The inner- and outer- coils were separately wound and cured with the temperature of 130°C for 4 hours under the pressure of about 65 MPa. The two coils were connected at the straight section in the first turn of the outer coil layer. The length of the splice is 100 mm. Carbon-glass temperature sensors were installed into each splice fixture made by GFRP.

The coil prestresses were carefully adjusted to have a larger value on the inner coil than the outer coil, because of the larger reduction of pressure on the inner coil during cooling-down and excitation. After collaring the maximum prestresses of the inner- and outer-coils are 72 and 68 MPa, respectively. A modified collar was used for the splice section and the transition from the inner coil to the outer coil.

Fig. 2 Model dipole magnet ready for performance test. A 1.8 K heat exchanger is by the magnet.

Another feature is the use of the pretensioning bolts installed into coil packs to elongate the coil axially and to fix the end sections tightly. We applied an extension force of 3 tons for each coil. As the coil is cooled, we expect the extension force to increase. The total force may be enough, so that the axial fixing stress is not lost due to the magnetic forces.

The yoke inner half width may be kept under 90.0 mm and 0.5 mm larger than the collar outer half width. The measured and well controlled size of the yoke opening was 90.00 to 90.04 mm. The collar half width was measured as 89.52 to 89.55 mm wide. This is a little bit larger than the design value caused by the prestress deformation. We filled the gap between the collar and the yoke with a 0.4 mm thick plate. The yoke of 0.6 m long and the axial end voids of 0.3 m long were attached. The yoke outer radius of the assembled magnet was controlled within ± 0.07 mm. The cylinder was put on the assembled yoke by a shrinkage fit method as the final process.

The completed magnet ready for test is shown in Fig. 2.

IV. TESTS AND RESULTS

The magnet was cooled by using a refrigerator which has the capacity of 300 W at 4.2 K [4] to carry out the performance test at 4.4 K and 1.8 K. Forty quenches have been carried out including seven quenches at 4.4 K and four in the fast ramp tests at 1.8 K. Almost all the quench tests have been performed with a ramp rate of 10 to 20 A/s except for the fast ramp tests (200 or 400 A/s).

Fig. 3 Training curves at 4.4 and 1.8 K with quench locations.

At 4.4 K the first quench reached 98 % of the short sample critical current of the superconducting cable. The successive quenches occurred at the critical current. This was confirmed by the other quenches at 4.4 K after the training test at 1.8 K as shown in Fig. 3. The first quench was located at the straight section of the first turn in the upper

coil. The rest of the quenches occurred at the same position in the straight section of the first pole turn in the lower coil.

After the completion of the training quench at 4.4 K, the magnet was cool down to 1.8 K as shown in the figure. In the first quench, the magnet was excited with a current of 11,778 A which is 91 % of the short sample critical current and reached a central magnetic field of 8.8 T at 1.8 K. Finally it reached the maximum current of 12,934 A which corresponds to more than 99 % of the short sample critical current and to a central field of 9.63 tesla after 27 training quenches at 1.8 K.

At the beginning of the training quench, quenches occurred at a middle turn of the inner coil. The quench locations moved to the straight section of the first and second pole turns or the first turn in the same inner coil.

The quench locations moved from the near pole turns to other turns close to the mid-plane during the fast ramp rate excitations. The ramp rate dependence of the magnet was measured by exciting with ramp rates of 200 and 400 A/s. The degradation is almost linear for $(di/dt)^2$ and was only 8 % at a ramp rate of 400 A/s.

TABLE II
PRESTRESS CHANGE DURING AND AFTER ASSEMBLING (MPa)

Process	Inner coil	Outer coil
Collaring	94	103
After collaring	71.5	68.0
Yoking	68.8	65.5
Shrinkage fit (6 days)	68.0	65.5
10 days after collaring	59.8	58.3
16 days after collaring	59.2	57.6
Cool-down	28.0	32.9

Fig. 4 Coil prestress release behaviors for the inner- and outer- coils during excitation.

Mechanical measurement has been performed continuously from the collaring process through the excitation test using beam type gauges. Just after releasing a collaring

press, the prestresses were 72 and 68 MPa in the inner- and outer-coils, respectively. The values were almost unchanged by yoking, and increased about 2 MPa as a result of shrinkage fitting the outer cylinder over the magnet. The pressure relaxation was around 12 MPa for the inner coil and 10 MPa for the outer coil after the first 10 days, and almost saturated afterwards.

The prestress behaviors during assembling and excitation test are given in Table 2 and Fig. 5, respectively. The inner coil seemed to lose the prestress at around 11,000 A. On the contrary, the outer coil had still maintained prestress at the full excitation.

V. DISCUSSION

1) *Quench locations:* At 1.8 K, almost all the quenches occurred in the straight section in the inner coil at one side, called the lower one, except for two training quenches and those during the fast ramp tests. The first six and other four quenches occurred in the third or forth turn of the lower inner coil. We could not identify the quench locations because of not having enough voltage taps, except for the first and second pole turns. The other quenches except for three occurred at the first pole turns. The quench locations at the first turn were 13 cm apart from the transition and were identified almost at the identical position within 4 cm. We can consider that the quenches occurred at the same position. Half of these quenches occurred simultaneously in the first and second pole turns. From these analysis, this magnet may have a mechanically local weak point through the loss of prestresses. This is consistent with the fact that the prestresses in the inner coil were lost at around 11,000 A as in Fig. 4.

Fig. 5 Longitudinal and transverse quench velocity measured in the inner coil as a function of normalized current.

2) *Prestress behavior:* The release of the prestresses in the inner- and outer-coils by cooling were around 31.2 and 24.7 MPa, respectively. These values are a little bit larger than ones predicted by calculations [5]. Although the behavior of the prestress release by excitation is quite reasonable as seen in Fig. 4, the more careful optimization to the inner coil

should be paid. The prestress release is relatively large just after the collaring and this should be considered at the collaring by compromising with the insulation breakage.

3) *Propagation velocity:* We have measured the longitudinal and transverse propagation velocities as shown in Fig. 5. The horizontal axis is normalized by the quench current limit of the inner cable. We assumed the quench current limit of the magnet as follows: at 4.4 K the achieved quench current limit of the magnet from the training quench is 4 % higher than the measured one for sampled strands from the cable, and then the limit at 1.8 K may be 4 % higher than the measured short sample limit on the same analogy. Two kinds of the longitudinal propagation velocities in the cases of the first pole-turn quench and the first and second pole-turns quench are shown in the figure. From the results, it can be seen that the simultaneous quench of the adjacent turns does not accelerate the propagation of normal zone.

VI. CONCLUSIONS

From this R&D, we have concluded the followings:

- The magnet performed well and reached the central field of 8.8 tesla which was beyond the design operational field at the first quench and finally up to 99 % of the short sample critical current at 1.9 K,
- The magnet still shows gradual training at 1.9 K in contrast with the behavior at 4.4 K,
- The high-Mn steel symmetric collar with the horizontally split yoke well functioned with sharing the magnetic forces,
- Longitudinal tension in the coil using pretensioning bolts between collar packs worked well resulting in no quench at the end sections, and
- The magnet has a mechanically local weak point probably in relation with the lost prestresses in higher excitation current.

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