DESIGN AND FABRICATION OF MODULE COIL AS AN R&D PROGRAM FOR LARGE HELICAL DEVICE

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Abstract

A twisted solenoid coil (named Module Coil or TOKI-MC) has been designed and fabricated in order to study the mechanical property of the Large Helical Device (LHD). One of the most important R&D items of the LHD is the mechanical behavior of helical coils under the large electromagnetic force. The TOKI-MC was wound obliquely on the 3D-machined elliptical bobbin with the maximum torsional rate of 36 degrees/m at the inner most conductor. The maximum field in the coil is 7.7T with the operating current of 20kA, the average current density of 40A/mm^2, and the stored energy of 11MJ. The TOKI-MC can simulate electromagnetic force, conductor torsional rate, magnetic field, operating current, and current density of the LHD superconducting helical coils. The design and test results of the conductor and the design and fabrication of the coil are described.

Introduction

The Large Helical Device (LHD) is a fully superconducting heliotron/torsatron type fusion experimental device[1]. The LHD project was proposed in 1986 as the next main fusion experiment program of joint universities in Japan. The National Institute for Fusion Science (NIFS) is a new laboratory established in 1989 to pursue this project. We have been developing various superconducting conductors and R&D coils[2,3] in order to design and construct the superconducting helical coils and poloidal coils for the LHD. The present design parameters of the LHD helical coils are; the major radius of 3.9m, the minor radius of 0.975m, the coil number of 2, the toroidal pitch number of 10, the toroidal magnetic field of 3T (in the first phase) and 4T (in the final phase), and the stored magnetic energy of 0.9GJ (in the first phase) and 1.6GJ (in the final phase).

The TOKI-MC is one of the R&D coils for LHD, which can simulate electromagnetic force, conductor torsional rate, magnetic field, operating current, and current density of the LHD superconducting helical coils.

Structure of TOKI-MC

Basic design

From the fabrication point of view, one of the most important features of the LHD helical coils is the difficulty of its twisted helical windings. In order to simulate this twisted windings, the TOKI-MC is wound on an elliptical bobbin whose axis is inclined 15 degrees to the rotational axis of winding table. The profile of the TOKI-MC is shown in Fig. 1. The winding parameters of the LHD helical coils about the torsional rate and the radius of curvature are shown in Fig. 2 and those of the TOKI-MC are shown in Fig. 3. The maximum torsional rate of the Module coil (36 degrees/m) is less than the average torsional rate of the LHD helical coils (39 degrees/m), but the minimum radius of curvature of the Module coil (0.4m) is much smaller than that of the LHD (1.47m). Therefore the total effect of the twisted winding on the conductor can be considered almost the same.

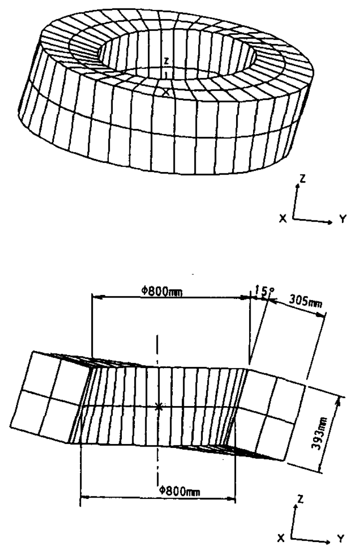

Figure 1. Profile of TOKI-MC

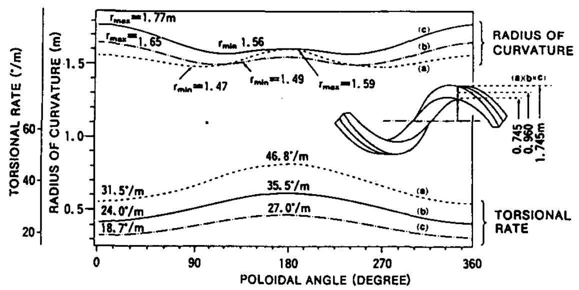

Figure 2. Winding Parameters of the LHD helical coils

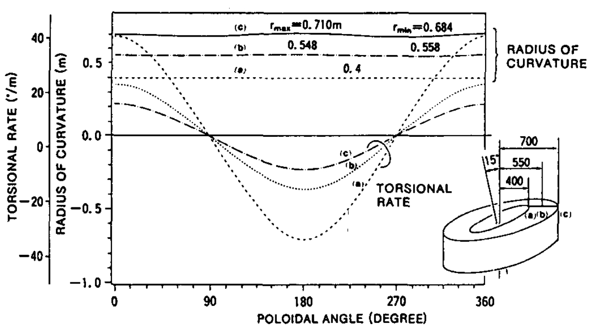

Figure 3. Winding Parameters of the TOKI-MC

In the helical coils, because of the twisted helical windings, the coils are loaded by the electromagnetic force of about 10MN/m (B=4T in the final phase) in both normal direction and bi-normal direction of winding locus as shown in Fig. 4. The magnetic force of the TOKI-MC are shown in Fig. 5. The maximum hoop force in normal

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direction is 9.53 MN/m and the overturning force in bi-normal direction is 2.63 MN/m. The overturning force of the TOKI-MC is not so large as that of the helical coils but the hoop force and total force are almost the same as those of the helical coils. The maximum magnetic field of the TOKI-MC (7.7T) is almost the same as that of the LHD helical coils (7.2T in the first phase).

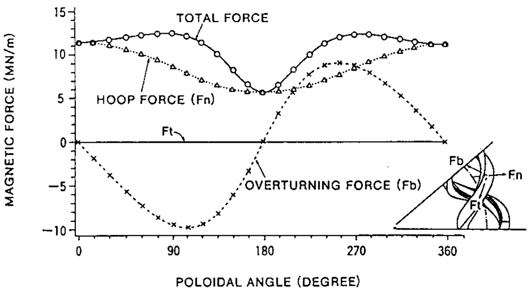

Figure 4. Electromagnetic force of the LHD helical coils

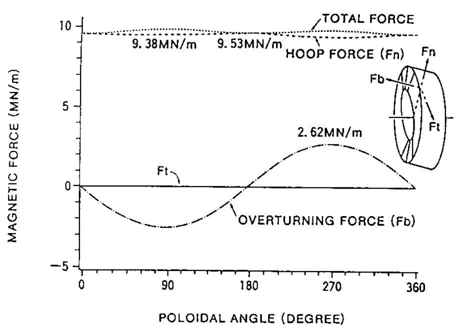

Figure 5. Electromagnetic force of the TOKI-MC

<u>Coil configuration</u>

Major parameters of the TOKI-MC are listed in Tab. 1. The maximum magnetic field of the TOKI-MC (7.7T) is almost the same as that of the LHD helical coils (7.2T in the first phase). Figure 6 shows the coil configuration. The coil was wound on an elliptical bobbin and covered with the 3D-machined stainless-steel coil case. Figure 7 shows the coil case bobbin. Thickness of insulation spacers in the winding and that of ground insulation spacers are 3mm and 10mm, respectively. Cooling channels of the winding are formed by these winding spacers as shown in Fig. 8.

Table 1. Main parameters of the TOKI-MC

Operating Current	20 kA
Winding current density	40 A/mm^2
Inner radius	0.4 m
Outer radius	0.7 m
Coil height	0.4 m
Maximum magnetic field	7.7 [*] T
Inductance	54 mH
Cooling surface ratio	50 %
Stored energy	11 MJ
Number of turns	238
	(17 turns/layer X 14 layers)
Cross sectional dimensions of winding	394 mm X 305 mm (in axial dir.)X(in radial dir.)
Length of conductor	840 m
Maximum conductor torsional rate	36 degrees/m
Number of conductor joints	6
Cooling method	Pool boiling
Mass of winding without coil case	2400 kg
Mass of TOKI-MC with coil case	5100 kg

*: This value is maximum magnetic filed at the conductor surface. Maximum magnetic field in the conductor including self field is 8.1T.

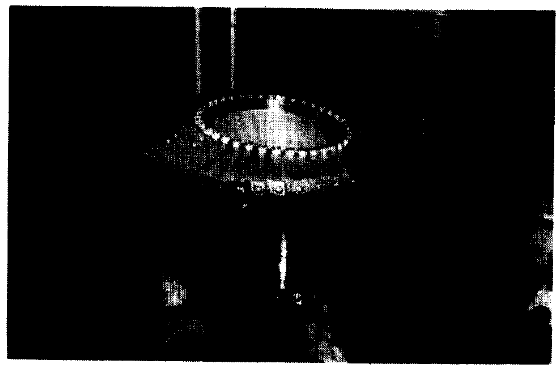

Figure 7. Photograph of the coil case bobbin

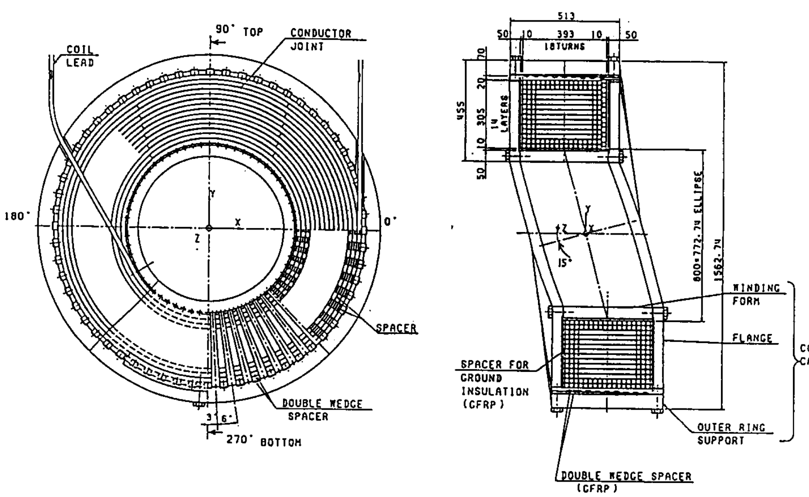

Figure 6. Cross sectional views of the TOKI-MC

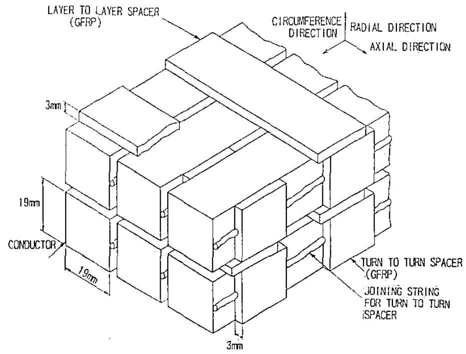

Figure 8. Winding structure in the coil

Schematic diagram of the coil and cryostat is shown in Fig. 9. The coil is immersed in liquid helium bath, but the windings is covered with the thick stainless-steel coil case. Therefore the windings are cooled with liquid helium in the cooling channel penetrated from bottom holes of the coil case. The coil is usually cooled with static pool boiling helium and it also can be cooled with quasi-forced flow of liquid helium from inlet bottom holes to an outlet top hole of the coil case in order to improve the thermal stability.

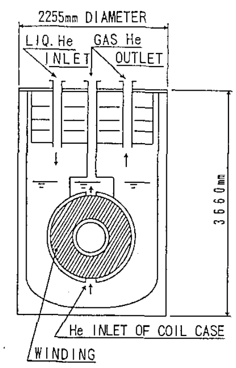

Figure 9. Schematic diagram of the coil and cryostat

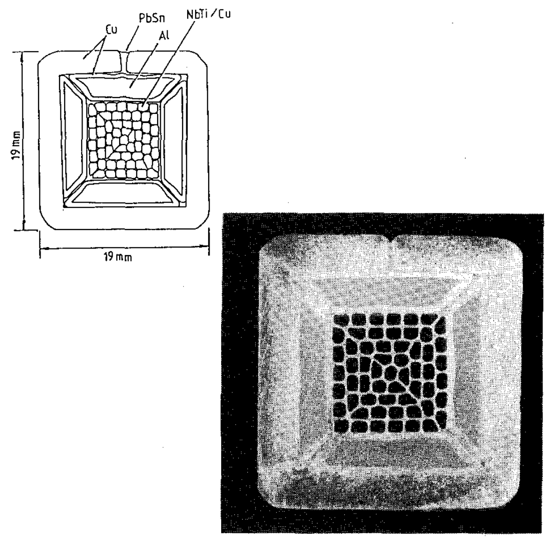

Figure 10. Cross-sectional view of conductor

Table 2. Main parameters of the conductor

Operating current (at 8.2T, 4.2K)	20 kA
Critical current (at 8T, 4.2K)	34.7 kA
Conductor dimension	19.0 mm × 19.0 mm
Overall current density	55.4 A/mm^2
Superconducting material	NbTi
Strand diameter	1.22 mm
Filament diameter	25 μm
Cu/SC ratio of strand	1.0
Critical current density of NbTi (8T)	950 A/mm^2
Number of strands	58
Twist pitch of strand (Twist dir.)	17 mm (Left)
Twist pitch of cable (Twist dir.)	125 mm (Right)
	Same direction for all strands
Stabilizer	5N-Aluminum
Sheath	Half-hard copper
Surface treatment	Copper oxide (2 μm)

Conductor design

The conductor of TOKI-MC is one of the candidate conductors for the LHD in its actual scale. This conductor was specially designed for the LHD considering about the mechanical toughness, the stability, and the manufacturing feasibility. The cross-sectional view of the conductor is shown in Fig. 10 and main parameters are listed in Tab. 2. The conductor consists of NbTi/Cu compacted cable at the conductor center, copper-clad pure aluminum stabilizer, and half-hard copper sheath. These conductor elements are soldered together. The surface of the conductor is coated with copper oxide for good heat flux characteristics in liquid helium bath. The conductor was fabricated by Sumitomo Electric Industries, Ltd., using a specially developed production line. The conductor was designed to satisfy Maddock's stability criterion. Aluminum of 5N purity is employed as a stabilizer and shows the resistivity less than $4\times10^{-11}\ \Omega\cdot m$ (at 8.0T, 4.2K).

Internal structure of the conductor was designed in order to bear large electromagnetic forces of the TOKI-MC and the LHD helical coils. Soft pieces in the conductor are strengthened; the highly compacted strands cable, the copper-clad pure aluminum. Lastly the conductor is covered with the half-hard copper sheath as a mechanical enclosure. he stress distribution in the winding of TOKI-MC under the electromagnetic force was calculated numerically by the finite element method. The maximum compressive stress is observed in not radial direction but axial direction (refer to the coordinate of Fig. 8) and the stress components at this point are 36.6 MPa in the circumferential direction, -23.5 MPa in the axial direction, and -9.1 MPa in the radial direction. Then the stress distribution in the conductor was also calculated using the above stress values. The calculated FE model of the 1/4 cross section of the conductor is shown in Fig. 11. The maximum stresses for each part of the conductor (copper sheath, copper clad of aluminum, aluminum, and superconducting cable) are listed in Tab. 3.

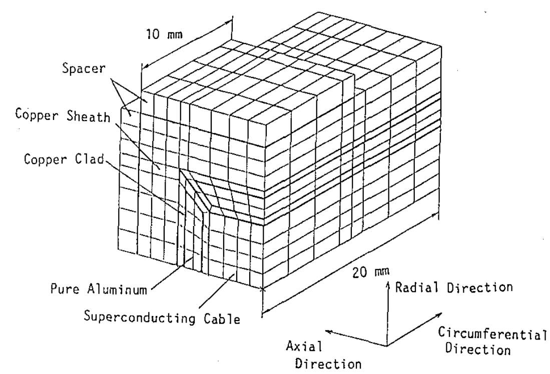

Figure 11. FE model for the conductor

Table 3. Maximum stresses in the conductor

Maximum stress (MPa)	σ_M	σ_X	σ_Y	σ_Z
Copper sheath	134.4	-65.7	-86.5	84.9
Copper clad of aluminum	157.9	-39.7	-117.7	94.9
Aluminum	89.4	-39.0	-67.0	45.4
Superconducting cable	46.5	17.6	-30.3	26.0

Where σ_M is von Mises equivalent stress, σ_X is Radial stress component, σ_Y is axial stress component, and σ_Z is circumferential stress component.

The maximum von Mises equivalent stress of the aluminum (89.4 MPa) is greater than the 0.2% proof stress of 4N-aluminum (73MPa). However, the maximum stress is local value in restricted area and the aluminum is cladded with copper whose maximum stress (157.9 MPa) is less than 0.2% proof stress of copper (182 MPa). Furthermore the conductor is covered with copper sheath whose maximum stress (134.4 MPa) is also less than the 0.2% proof stress.

Conductor test

Critical current of the conductor was measured to be over 30 kA at the maximum magnetic field of 8.2 T (including conductor self-field). The critical current of the conductor is reduced by the conductor self field. The conductor has a multilayered superconducting cable without transposition (one center strand and four layered strands). So the self field and the critical current of each strand are different corresponding to the strand position.

Figure 12 shows the measured quench current of the conductor versus the bias magnetic field. Where the dotted line shows the critical current of the conductor without self field, the solid line is the critical current considering self field at each position of stand, the chain line is the critical current supposing that all strands have the same critical current which is defined by the maximum self field, and the circle points show the measured quench current. The measure quench currents agree with the solid line. It means that the different current can flow for each strand up to the critical current of each strand corresponding to the strand position.

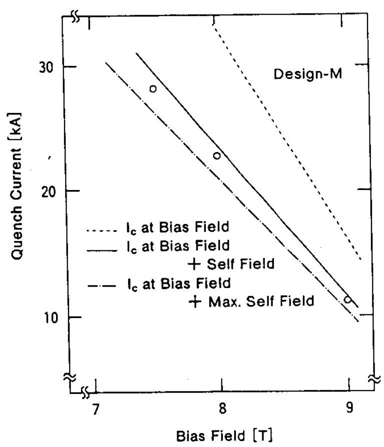

Figure 12. Critical current of the conductor

Coil fabrication

A winding machine system is shown in Fig. 13. The coil is wound as described below.

1) A conductor part in the length of half turn of the winding is twisted by the 6 head twisting machine in stationary situation.
2) Conductor is reeled and wound on the bobbin.
3) Turn to turn spacers with epoxy-glass paste are inserted between conductor.
4) After winding one layer, layer-to-layer spacers are placed on the winding with epoxy-glass paste between the winding and spacers.

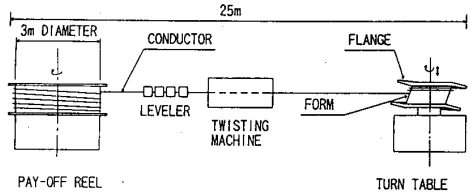

Figure 13. Winding machine system

The conductors are joined by solder at every other transition point between layers in lap length of 400 mm. This joint configuration showed to have 3.0×10^{-9} Ω resistance with a verification test sample. The measured resistance is almost the same as the result of the calculation assuming that the contact ratio between conductor is 50%.

Conclusion

As an R&D of the LHD helical coils, the TOKI-MC, which simulates the torsional rate of the conductor of the LHD helical coils, has been designed and constructed. Valuable items of information on LHD design and fabrication are obtained through the design and construction of the TOKI-MC. One of the candidate conductors for the LHD is applied to the TOKI-MC in its actual scale. The conductor was designed considering about the mechanical toughness, the stability, and the manufacturing feasibility and has been fabricated using a specially developed production line. The critical current of conductor was measured and agrees with the design value considering the effect of self field at the position of each strand. We are doing the excitation test of the TOKI-MC at the end of FY 1990. Feasibility of basic concept of a candidate design of the LHD helical coils will be examined by operation of the TOKI-MC

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