Design and fabrication of forced-flow coils as an R&D program for Large Helical Device

DESIGN AND FABRICATION OF FORCED-FLOW COILS AS AN R&D PROGRAM FOR LARGE HELICAL DEVICE

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Abstract

As research and development of helical field coil and poloidal field coil for Large Helical Device (LHD), two forced-flow cooled NbTi superconducting coils (TOKI-TF, PF) have been designed and fabricated. The helical coil (TOKI-TF) is a 1/4 scale model of LHD. It has the major radius of 0.9 m, the minor radius of 0.25 m and pitch number of 4. Nominal current and maximum field were designed to be 8 kA and 2.8 T, respectively. Another coil (TOKI-PF) was fabricated for the demonstration of LHD poloidal field coils. It consists of two double-pancakes with the inner radius of 0.6 m and the outer radius of 0.82 m. Nominal current of 25 kA simulates that of LHD poloidal field coils. Cable-in-conduit type conductors were used for the both coils. The test facility was also constructed with a vacuum vessel, liquid nitrogen shield, 30 kA power leads, a heat exchanger, cryogenic supports and others. In this paper, design concepts and details will be presented.

Introduction

The Large Helical Device (LHD) is a heliotron/torsatron type fusion experimental device and the seven-year project to construct the LHD started in FY1990[1~3]. Before starting the machine construction, various R&D programs such as superconducting conductors and magnets, a vacuum vessel, heating and diagnostic facilities have been carried out since FY1988.

Superconducting magnet systems are needed for developing a steady state fusion reactor. The R&D of superconducting magnets which consist of helical and poloidal field coils is one of the major objectives for this project. Manufacturing of two forced-flow cooled coils which are named TOKI-TF and -PF has been completed as a part of R&D programs in FY1989 and they are scheduled to be tested in superconducting magnet test facilities which is now under construction in Toki-city near Nagoya. The TOKI-TF and -PF coils simulates the helical and poloidal coils, respectively. The main objectives of these R&D coils are to investigate fabricability, stability, mechanical stiffness, electromagnetic and hydraulic characteristics, and quench protection of the LHD coil system using forced-flow cooled superconductors. It is noted that the TOKI-TF is the first helical coil in forced-flow cooled coils.

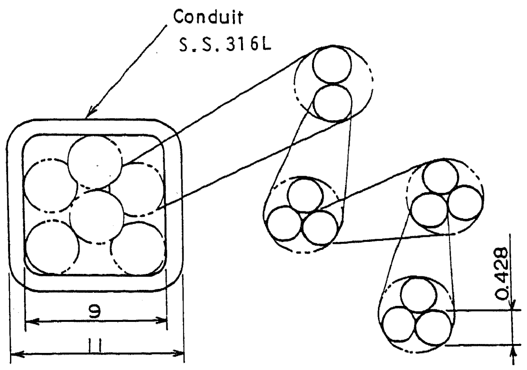
In the current design of LHD, pool-cooling has been adopted as a cooling method of the helical coils. The R&Ds of forced-flow cooled helical coil must, however, be kept on in the long term. From this point of view, not only a pool-cooled helical coil, TOKI-HB[4] but also the forced-flow cooled helical coil, TOKI-TF, was decided to be fabricated. One of severe requirements for the helical coil is high accuracy for magnetic field. For example, the required accuracy is about 1×10^{-4} in regard to global field. Not only careful coil winding but also extreme accuracy for machining and assembling are, therefore, necessary. The mechanical stiffness of the coil is also needed to reduce deformation by electro-magnetic force.

Forced-flow cooling method is proposed for the poloidal coils. The poloidal coils must make field changing of 0.02 T/s in the plasma in order to control it. The field changing up to 0.5 T/sec is required to the poloidal coils. The TOKI-PF coil is, therefore, planned to be tested in a pulse operation.

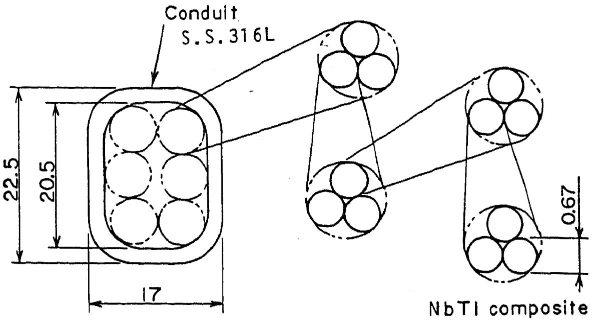
In this paper, design concepts and details of these two coils will be reported. The overview of a test facility for the forced-flow coils will also be presented.

Conductors

Cable-in-conduit type NbTi conductors were used in the both coils. Cross-sectional views and characteristics are shown in Fig. 1 and Table 1, respectively. Conduit thickness of the both conductors was designed to be 1.0 mm considering pressure rise up to 3 MPa due to quench and electro-magnetic force. The exterior surface of conductor was completely insulated by a layer of half-lapped Glass-Kapton-Glass tapes, which allows a dump voltage of 1 kV. The insulation thicknesses of TOKI-TF and -PF are 1 and 2.5 mm, respectively. The void fraction was designed to be 40 % for the both conductors. In regard to the TOKI-PF, CuNi was added into strands and the strands are insulated with formval of 10μm in thickness in order to reduce coupling losses between filaments or strands. The coupling time constant was estimated to be 2.2 msec.



(a) TOKI-TF



(b) TOKI-PF

Figure 1. Cable layouts of conductors

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Table. 1 Specifications of conductors

Parameter	Unit	TOKI-TF	TOKI-PF
Type of conductor		Cable-in-conduit Forced-Flow	
Material		NbTi	
Critical current	kA	16 at 4T	50 at 7T
Conduit dimension	mm	11x11	17x22.5
thickness	mm	1.0	1.0
Void fraction		0.4	0.4
Strand diameter	mm	0.428	0.67
Number of strands		324	480
NbTi:Cu:CuNi ratio		1:4.8	1:1.6:0.5
Stability margin	mJ/cm^3	699	449

Table. 2 Specifications of TOKI-TF and TOKI-PF

Parameter	Unit	TOKI-TF	TOKI-PF
Configuration		helical	double-pancake
Major radius	mm	900	-
Minor radius	mm	250	-
Inner radius	mm	-	600
Outer radius	mm	-	820
Field period:m		4	-
Multipolarity:l		1	-
Operating current	kA	8.08	25.6
Average current density	A/mm^2	47.6	43.6
Maximum field	T	2.77	2.76
Inductance	mH	41.1	3.18
Stored energy	MJ	1.34	1.04

TOKI-TF Coil

Coil Design

Top and cross-sectional views of the TOKI-TF coil are shown in Fig. 2. The TOKI-TF is a helical coil with the toroidal pitch number of 4. The specifications are listed in Table 2. The major radius of 0.9 m corresponds to a 1/4 scale model of the LHD. The winding cross section is 129×129 mm^2. The nominal current of 8 kA and the maximum field of 2.77 T are about 1/3 of those of LHD (I_{op}=20~25kA, B_{max}=7.2T). In spite of these scale-downs, the average current density in the winding is set to be 47.6 A/mm^2 for nominal operation, which is as high as that of LHD.

The TOKI-TF has ten cooling paths into which supercritical helium (SHE) flows. Each layer corresponds to each path with the average length of 8.5 m. The design mass flow rate is 1 g/s for each path with the pressure of 1 MPa. The support structures (a coil case and torus beams) are also cooled by SHE with the total flow rate of 10 g/sec.

Support Structures

The conductors were wound in a coil case in order to fix the coil shape and to support the coil against the electro-magnetic force. Calculated distributions of the electro-magnetic force are shown in Fig. 3. For the helical coil, the force is applied in not only the radial direction but also the circumferential and axial directions. The torus beams joining the coil case contribute toward supporting the over-turning force. The core ring in Fig. 2 was temporarily used for supporting the coil during machining the case and winding the conductors, and took off after manufacturing. These configurations are similar to the LHD support system regardless of cooling method.

As designing the support structures, deformation of the coil is important in view of field accuracy. The structural analysis indicated that the

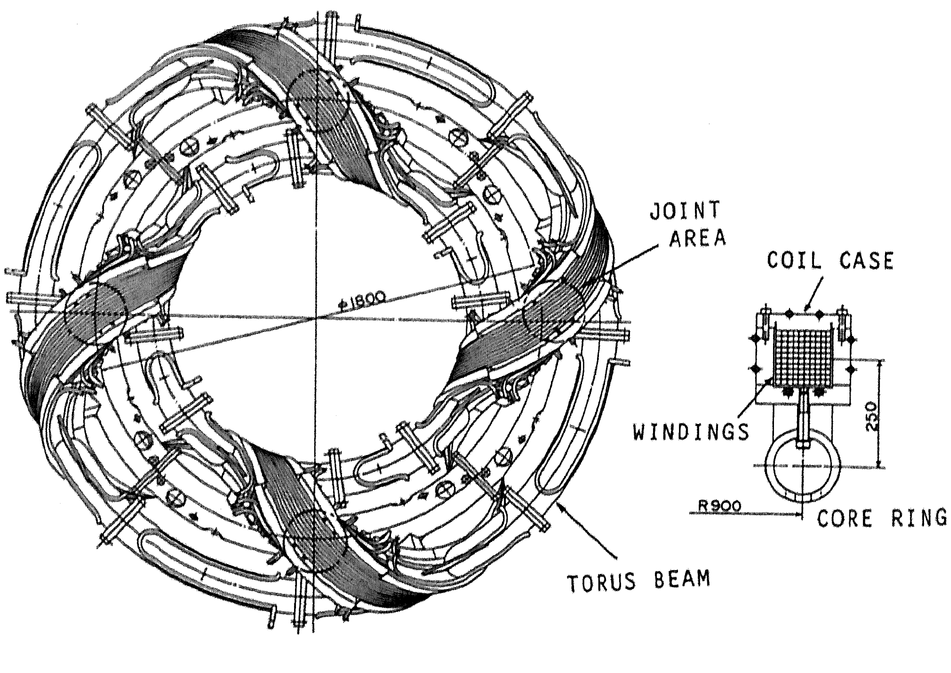

Figure 2. Top and cross-sectional views of TOKI-TF

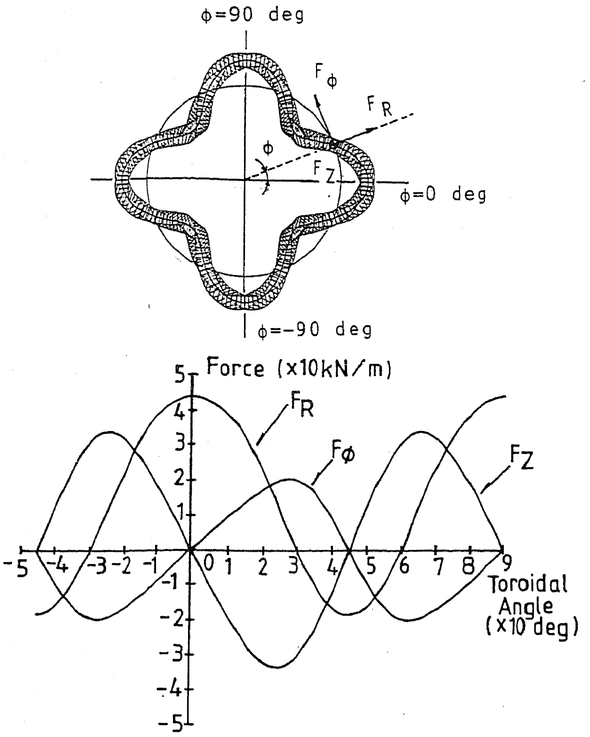

Figure 3. Electro-magnetic force in TOKI-TF winding

maximum deformation is less than 0.3 mm. This value is within acceptable accuracy. During manufacturing of the coil case, the finishing dimensions with the specified accuracy of 5×10^{-4} are required. The case was made with numerically controlled machining process after assembling and welding the parts (the bottom and side slabs). The top parts of the case were, finally, not assembled by welding but with bolts. The irregular deformation due to the weld could be reduced by the above process.

Coil Winding and Conductor Joints

Unlike a conventional ring coil, the bending and twisting angles of the conductor depend on the spatial position. For TOKI-TF, the roller bending method with twisting capability was employed in the winding machine. The forming head could be moved in the toroidal direction and the bent and twisted conductor was paid out from the head into the coil case. The spatial and angular parameters were controlled by a computer system.

The conductors were electrically connected in series between layers after completing the winging process. Thus the TOKI-TF has nine joints. In order to reduce the local error field due to the joints, they were distributed into four locations as shown in Fig. 2. In the joints, superconducting strands were connected using ultra-sonic welding method. Conductivity of the connected part was improved by 5 times compared with conventional soldering. Fig. 4 shows the procedure of ultra-sonic welding.

TOKI-PF Coil

Top and cross-sectional views of TOKI-PF coil are shown in Fig. 5 and the major specifications are listed in Table 2. It consists of two double-pancakes and has the inner radius of 0.6 m and the outer radius of 0.82 m. The nominal current of 25 kA simulates that of the LHD poloidal field coils (20∿35 kA). The maximum field was calculated to be 2.76 T in a single operation. In the next step, a bias field magnet is planned to be mounted with the coil because the maximum field of LHD poloidal coils are 5∿7 T. The conductor was, therefore, designed assuming that it is used in the field of 7 T.

The winding were not encased in the coil case unlike the TOKI-TF and the electro-magnetic force is supported by the conductor itself. In this case, the maximum stress in the S.S.316L conduit was calculated to be approximately 300 MPa, and this value also simulates that of the LHD poloidal field coil.

Number of cooling paths is 4. The SHE will flow from the inner turns to the outer turns because the maximum field is generated at the inner turns. The design mass flow rate is 4 g/s for each path with the pressure of 1 MPa.

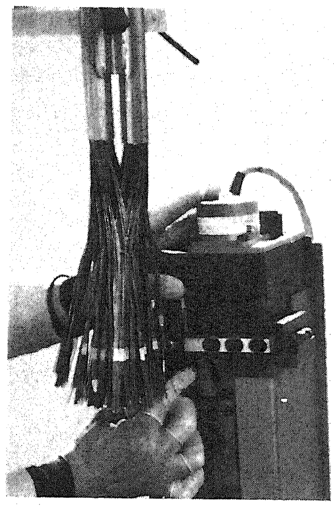

Figure 4. Procedure of ultra-sonic welding in conductor joint

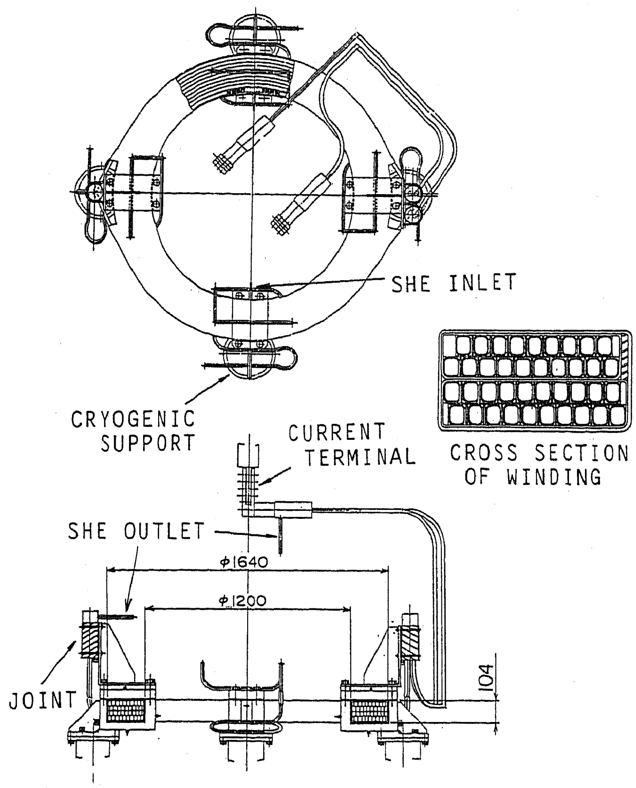

Figure 5. Top and cross-sectional views of TOKI-PF

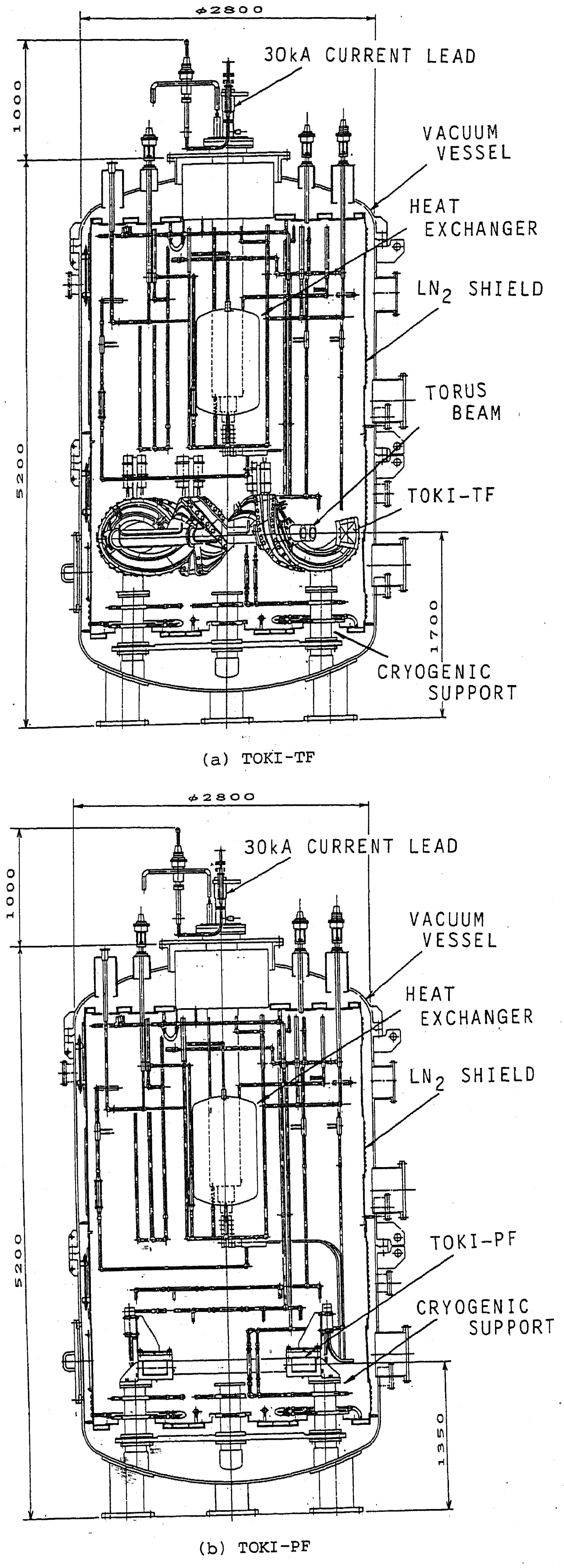

Figure 6. Configurations of the test facility

Test facility

Each coil will be set in the cryostat which is composed of a vacuum vessel, liquid nitrogen shield, 30 kA power leads, a SHE heat exchanger, cryogenic supports and others. Figure 6 shows configurations of the test facility in which each coil is set. The vacuum vessel has a diameter of 2.8 m, height of 6.0 m and weight of 15 ton. When exchanging the coil, the vessel can be divided into two parts.

The power leads, the SHE heat exchanger, various valves and pipes are set in the upper part of the vessel. The vapor-cooled power leads have liquid helium tanks. The heat leak from the transfer line up to 50 W can be compensated by the heat exchanger. The sub-cooling is also possible using the heat exchanger.

Each coil is laid on four cryogenic support posts made of GFRP and S.S.316 in the lower part of the vessel. The support has 20 K and 80 K heat intercepts, and a slide mechanism in the 300 K regime. The support can slide in the only major radius direction using guides. Considering the error field, the coil must be uniformly deformed during cool-down, warm-up and excitation. Such a slide is expected to have an effect on the uniform deformation.

Conclusions

The two forced-flow cooled coils and their test facility have been designed and fabricated as a part of R&Ds for LHD construction, and the confidence in construction of the LHD using forced-flow cooled conductors was obtained. The TOKI-TF helical coil was designed to have high mechanical stiffness and high field accuracy. The TOKI-PF pancake coil can simulate the poloidal field coil of the LHD in regard to reliability of 25 kA cable-in-conduit type conductor and stress of the conduit during quench and excitation. In the test facility, both coils can be tested under similar conditions to superconducting coil system of LHD. Finally, the coils are expected to be tested within FY1990, and the experience in manufacturing and test results will be utilized for constructing the LHD.

References

1. O. Motojima, J. Yamamoto, K. Yamazaki, N. Ohyabu, T. Mito, M. Takeo, S. Morimoto, M. Fujiwara and A. Iiyoshi, "Project of Large Helical Device for Currentless Steady Experiment", Proc. MT-11, 777-782, 1989.

2. S. Morimoto, O. Motojima, J. Yamamoto, N. Ohyabu, K. Yamazaki, et al., "Design Study of the Superconducting Large Helical Device", Proc. 16th Symp. on Fusion Technology (SOFT 16), London 1990, to be published.

3. O. Motojima and LHD Design Group, "Design status of Superconducting Large Helical Device", presented at this conference.

4. N. Yanagi, K. Takahata, T. Mito, J. Yamamoto, O. Motojima and LHD Design Group, "Design and Fabrication of Pool Cooled Helical Coil as an R&D Program for Large Helical Device", presented at this conference.