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journal or publication title	IEEE Transactions on Magnetism
volume	Vol.27
number	Issue 2 Part4
page range	pp.2357-2360
year	1991-03-01
URL	http://hdl.handle.net/10655/3793

doi: 10.1109/20.133691

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

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Abstract

A pool cooled NbTi superconducting helical coil system (named TOKI-HB) has been fabricated as one of the research and development programs for Large Helical Device (LHD). The main purpose of the construction of this device is to build an entire pool cooled superconducting helical coil system which is large enough to be extrapolable to LHD. The helical coil has the major radius of 0.8m and the minor radius of 0.2m with helical pitch number, m , of 3. Operating current of 8.9kA produces maximum magnetic field of 0.75T at the geometrical center of the poloidal cross section and 3T at the coil surface. In this paper basic design concepts of TOKI-HB device is described together with some issues on the fabrication.

Introduction

The seven year project of the construction of Large Helical Device (LHD) has started this year at newly organized National Institute for Fusion Science (NIFS) in Japan. LHD is a heliotron/torsatron type fusion experimental device in which currentless several keV plasmas can be confined only by the external coil system. The size and the magnetic field will be almost twice as large as the existing helical devices; major radius, R , is 3.9m, the minor radius of the helical coil, a_c , is 0.975m, toroidal magnetic field at the plasma center, B_0 , is $3 \sim 4\text{T}^{1,2,3}$. The coil system of LHD consists of two helical coils and 6 (3-pairs) poloidal coils and the all coils will be superconducting. The physical design of LHD is almost complete and the hardware design is now under promotion. The construction of LHD will be complete in 1997 at Toki site of NIFS in Toki city. In order to design and fabricate the superconducting coil system of LHD which has the large stored magnetic energy of $0.9 \sim 1.6\text{GJ}$, various research and developments on superconducting magnet technology are necessary.

One of the R&D coils constructed in 1989 for this purpose is the TOKI-HB coil. The major radius of TOKI-HB is 0.8m, about 1/5 of that of LHD, which is considered to be large enough to be extrapolable to LHD. The cooling method of the helical coils of LHD is presently planned to be pool cooling. A pool cooled superconducting helical coil named KYOTO-SC which is a 1/10 model of LHD had been fabricated and tested in 1989 at Kyoto University⁴. TOKI-HB coil is the next step pool cooled helical coil toward LHD. It is to be mentioned that a forced-flow cooled helical coil named TOKI-TF has also been fabricated in 1990 which is a 1/4 model of LHD. The detail discussion of the design and the fabrication of TOKI-TF coil can be found in Ref.5.

Entire System of TOKI-HB

One of the characteristics of the design of TOKI-HB device is that the entire system simulates that of LHD. Figure 1 shows a top and a side view of TOKI-HB device. The helical coil is contained in a cryostat which simulates that of LHD. The windings of the helical coil are covered with a stainless-steel coil case which sustains large electromagnetic force and contains liquid helium to cool the conductors.

Figure 1. (a) A top view and (b) a side view of TOKI-HB

Manuscript received September 24, 1990

Besides the cryostat is a control dewar which delivers liquid helium into the main coils system. Vapour-cooled current leads are equipped in this control dewar and the helical coil is connected with the current leads through superconducting bus-lines. Between the main cryostat and the control dewar is a bridge in which transfer tubes of liquid helium and superconducting bus-lines are installed.

There are several ports on the cryostat and also on the liquid Nitrogen shield through which various diagnostic systems can be installed. The helical coil is wound on a stainless-steel hollow torus which is used as a guide for the helical winding. The interior of this torus (the minor radius of the inner surface is 120mm) will be used for magnetic field measurements and ports are also prepared on this torus corresponding to those on the cryostat. This structure of the cryostat and the hollow torus simulates the structure of LHD, although in LHD, the hollow torus corresponds to the vacuum vessel in which hot plasmas are confined and the ports are mainly used for diagnostic systems for plasma. By taking this structural design, cooling characteristics and cryogenic stability of helical systems can be investigated. It is also to be noticed that TOKI-HB device has two pools of liquid helium in the control dewar so that the helical coil can be cooled with quasi-forced flow of liquid helium by pressurizing one pool which is connected to the bottom inlet of the cooling channel of the helical coil. This cooling method is considered to improve the thermal stability of the coil compared with the ordinary static pool boiling of liquid helium.

Helical coil of TOKI-HB

Winding Law

The helical coil of TOKI-HB has been wound on the stainless steel torus so that its center satisfies the winding law which is expressed by the following equation.

$$\theta = m/l\phi + \alpha \sin(m/l\phi)$$

Figure 2. A schematic plan view of the $m = 3$ helical coil. Contour lines express the strain values due to the electromagnetic force calculated by finite element method. The arrows indicate the maximum strain and stress points.

Table 1: Main parameters of TOKI-HB coil

Items	Unit	Parameter
Major radius	m	0.8
Minor radius	m	0.2
Winding rule		$\ell = 1, m = 3$
Magnetomotive force	MAT	1
Operating current	A	8930
Number of turns		112
Inductance	H	0.048
Stored energy	MJ	1.9
Maximum field (center)	T	0.75
Maximum field (coil)	T	3
Stability parameter		0.67

where θ is a poloidal angle and ϕ is a toroidal angle, respectively. ℓ is the pole number of the helical coil which takes 1 for TOKI-HB and 2 for LHD. m is the toroidal pitch number of the helical coil and it takes 3 for TOKI-HB and 10 for LHD. α is a pitch modulation parameter which takes 0 for TOKI-HB and 0.1 for LHD. The schematic shape of the helical coil is shown in Fig.2. and the main parameters of the coil are listed in Tab.1.

Electromagnetic Force on the Coil

One of the most difficult problems about the mechanical structure of LHD is how to sustain the large electromagnetic force. In addition to ordinary hoop force, overturning force also exerts on helical shaped coils. Both types of force will reach almost 10MN/m in the helical coils of LHD⁶. Investigation of mechanical strength of helical coils against electromagnetic force is one of the objectives of TOKI-HB. From this view point electromagnetic force generated by the helical coil of TOKI-HB has been numerically calculated. And strain values due to this electromagnetic force have also been calculated by a finite element method. It was assumed that the electromagnetic force exerts only on the coil case which is made of stainless-steel (S.S.304) of 20mm thickness. The results of the calculation is shown in Fig.2; the maximum strain occurs at the top plate of the helical coil in the outboard side of the torus as indicated by the arrows. This strain value corresponds to von Mises equivalent stress of 78MPa which is considered to be much less than the maximum acceptable value of about 200MPa of S.S.304 at room temperature.

Coil Fabrication

It is well known that in helical systems high accuracy of magnetic field is required in order to generate clear magnetic surfaces in the plasma confining region. As for LHD, the error field must be less than 10^{-4} for global modes and 5×10^{-4} for local modes. Considering this severe requirements of accurate magnetic field, bifilar winding method was adopted for TOKI-HB which is considered to minimize error fields from the feeders. Figure 3 shows the schematic structure of the winding method for the case of 8 turns $\times$ 6 layers. The conductors are connected by using solder at every transition point between each layers.

The helical coil of TOKI-HB is consisted of 8 turns $\times$ 14 layers as shown in Fig.4. The conductor of aspect ratio of 0.5 was wound by using a specifically designed winding machine. It is to be noticed that winding process of the helical coil with high spatial accuracy is one of the most important items of this R&D program. The stainless-steel hollow torus was first manufactured

by numerically controlled machining process. After the mechanical process, insulating layers were formed. The overall accuracy of this torus is less than $\pm 0.1\text{mm}$. Upon this torus stainless-steel side boards of the coil case were attached and the conductors were wound between these side boards. The side boards have many holes through which the positions of the conductors are fixed by using FRP spacers with bolts. The spatial accuracy of the positions of the conductors was checked after the winding process for each layer with a specifically equipped shovel gauge. This measurement shows the accuracy of less than $\pm 1.5\text{mm}$ is satisfied in both the radial and the transverse direction. After the winding was complete the top plate of the coil case was welded.

Figure 3. Schematic structure of bifilar winding method of the helical coil

Figure 4. Cross section of the helical coil

The helical coil and the hollow torus are sustained from the bottom of the cryostat by three (120° apart) cryogenic supports made of GFRP and stainless-steel 304. These supports are designed so that they can tilt only in the major radial direction and the shrink due to cooling down is expected to be uniform, which minimizes the global error field.

Conductor of TOKI-HB

Pool-cooled type NbTi conductor was used for the helical coil of TOKI-HB. Figure 5 shows the cross section of the conductor and some specific parameters of the conductor are listed

Table 2: Main parameters of the conductor

Items	Unit	Parameter
Material		NbTi
Critical current (at 3T, 4.2K)	A	17580
Conductor dimension	mm	16.0×8.0
Strand diameter	mm	0.84
Number of strands		30
Twist pitch of strand	mm	100
Filament diameter	μm	22.6
Number of filaments		708
Twist pitch of filament	mm	20

in Tab.2. The conductor consists of NbTi/Cu compacted cables and a copper-clad pure aluminum stabilizer which are contained in a half-hard copper sheath and soldered together. The aspect ratio of the conductor is 0.5. The critical current of the conductor is calculated to be 17580A at the magnetic field of 3T with the temperature of 4.2K. The nominal current of 8930A generates the magnetic field of 3T at the coil surface, therefore, the operation point is set at 67% of the critical current, which guarantees good cryogenic stability of the coil.

Figure 5. Cross section of the conductor

Experimental Plan

TOKI-HB coil is scheduled to be tested at the superconducting magnet test facilities⁷ which is now under construction at Toki site. When the construction of the facility is complete in late 1990, various R&D programs about superconducting magnet technology will start; such as conductor tests, mechanical tests, and tests of three R&D coils including TOKI-HB.

In order to investigate the cooling characteristics and the cryogenic stability of the helical coil various sensors are distributed in the helical coil such as voltage taps, temperature sensors, and strain gauges. Heaters are also installed at the conductor surface in order to generate normal conductivity zone for the investigation of the cryogenic stability of the coil.

In addition to the above sensors which are attached to the coil itself, magnetic sensors such as Hall detectors and pick-up coils will be installed in the interior of the hollow stainless-steel torus. By measuring the three dimensional magnetic field and comparing the observed values with the calculated ones, final accuracy of the magnetic field can be checked. As for the measurement of deformation due to the cooling down, resistive position sensors are also distributed around the helical coil.

Summary

A pool cooled superconducting helical device, TOKI-HB, has been designed and fabricated as one of the R&D programs for Large Helical Device. The helical coil of TOKI-HB is a 1/5 model of LHD and the structural design of TOKI-HB system simulates that of LHD. Cooling down characteristics, cryogenic stability, stress due to electromagnetic force, and accuracy of the required magnetic field will be investigated in the superconducting magnet test facilities which is now under construction at Toki site.

Acknowledgments

The authors are very grateful to Prof. Iiyoshi for his encouragements. Special thanks are given to many workers of Hitachi Ltd. for their great help.

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