Plan for Testing High-Current Superconductors for Fusion Reactors with A 15 T Test Facility*)

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Fusion power plants need larger scale and higher field superconducting magnets than the ITER magnets. Therefore, higher current superconductors with high strength against strong electromagnetic forces are needed. In order to examine the superconducting properties of such large conductors in real conditions, we are preparing a new test facility that is equipped with a solenoid coil of the highest field of 13 T with the bore of 0.7 m, a pair of temperature-variable current leads, and a vacuum chamber for conductor samples. The highest field can be increased to 15 T by installing an additional coil with the cold bore of 0.6 m. Since the inlet temperature of the samples can be varied from 4.4 K to 50 K, it is possible to examine properties of advanced conductors at actual operating temperatures including high-temperature superconductors. We propose coil-shaped conductor samples instead of straight samples in order to apply electromagnetic hoop forces on the conductors to realize the real condition. A reference design of a sample for a cable-in-conduit conductor is provided.

Keywords: cable-in-conduit conductor, high magnetic field, Nb_3Sn, superconducting magnet, test facility

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1. Introduction

High field and high current superconductors are needed for future fusion reactors. Degradation of critical currents of superconductors by electromagnetic forces was observed in the Nb_3Sn conductors for the ITER-TF and CS coils [1]. Degradation should be more serious in the higher field magnets. Therefore, high field test facilities are necessary to examine the conductors for fusion reactors in real conditions. Large compressive strain is induced in Nb_3Sn strands in cable-in-conduit (CIC) conductors because of smaller thermal contraction of Nb_3Sn than the conduit from the heat treatment at 900 K to 1,000 K for production of A15 phase. Then, the hoop force on the conductor is considered to improve the critical current by reduction of the compressive strain in the superconductor. In addition, the hoop force is expected to suppress the degradation of the critical currents observed in straight samples for the ITER-TF and CS coils, in which buckling and cracking of the Nb_3Sn strands occurred in the high field region [2]. It is considered that the longitudinal slippage of the strands against the conduit is induced by large variation of the background field along the conductor and that the slippage accelerates the failures.

We propose coil-shaped conductor samples instead of straight samples in order to apply electromagnetic hoop forces on the conductors. The outer dimension of the conductors of 100 kA class is considered to be close to 50 mm. According to the achievements [3, 4], the minimum bending radius of CIC conductors is preferred to be longer than 5 times the outer dimension to prevent large deformation of the cross-section. Therefore, the necessary bore for the conductor samples of 100 kA class is longer than 0.6 m. Considering reuse of the existing cryostat, we select a pool-cooled solenoid coil as the external field coil to attain a large bore with the restricted outer diameter. At present, a solenoid coil of the highest field of 13 T with the cold bore of 0.7 m is being manufactured. The highest field can be increased to 15 T by installing an additional coil with the cold bore of 0.6 m. We are preparing a new test facility that is equipped with the coil, temperature-variable current leads and a vacuum chamber for conductor samples. In this paper the concept of the new test facility, the design of conductor samples, and testing conditions are discussed.

2. External Field Coil

In order to reduce the outer diameter of the external field coil with a fixed inner diameter by increasing the coil current density, a pool-cooled and closely wound coil is selected, and cylindrical supports with high strength are adopted. The design concept and the criteria of the coil are as follows: (1) Two grades of conductors, NbTi and Nb_3Sn are adopted for outer and inner coils, respectively. The highest field in the outer coil is lower than 7 T for NbTi conductor to attain the high current density. (2) An exter-

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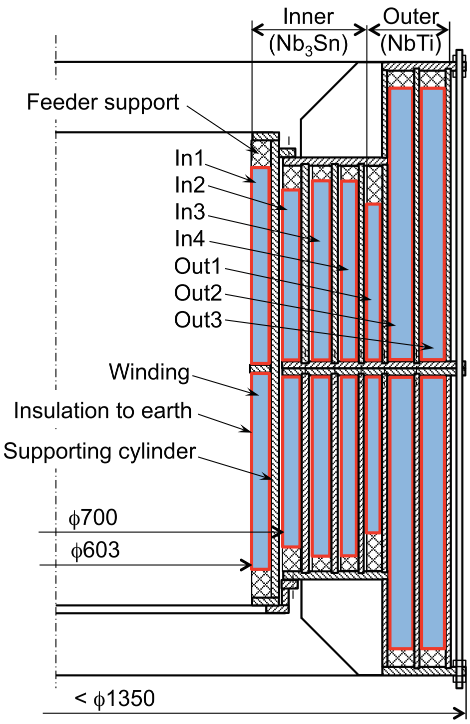

Fig. 1 Layout of the 15 T - 0.6 m external field coil.

Table 1 Major parameters of the external field coil with the innermost coil block, In1 (without In1).

	Inner coil	Outer coil
Superconductor	Nb_3 Sn	NbTi
Maximum field, B_{max} (T)	15.0 (13.0)	6.85 (6.73)
Stored energy (MJ)	16.4 (12.0)	23.8 (22.5)
Self inductance (H)	28.8 (18.0)	54.2
Mutual inductance (H)	27.9 (22.9)	←
Temperature (K)	4.4	4.4
Critical current at B_{max}, I_c (A)	1275 (1807)	3175 (3322)
I_{op}/I_c on the load line (%)	86.8 (76.7)	71.9 (70.7)
Temperature margin (K)	2.21 (3.65)	1.50 (1.56)
Cu/SC ratio (-)	0.9	2.4
Winding inner diameter (m)	0.606 (0.702)	0.957
Winding outer diameter (m)	0.933	1.176
Winding length (m)	0.60	0.97
Magnetomotive force (MA)	5.83 (4.29)	6.53 (6.57)
Turn number	7659 (5612)	8584
Operating current, I_{op} (A)	761 (765)	761 (765)
Conductor width (bare) (mm)	3.2	4.0
Conductor height (bare) (mm)	2.1	2.0
Conductor cross-section (mm^2)	6.51	7.79
Layer insulation (mm)	0.2	0.1
Ground insulation (mm)	>0.8	>0.8
Cross-section per turn (mm^2)	8.17	8.61
Coil current density (A/mm^2)	93.1 (93.6)	88.4 (88.9)
Conductor length (km)	18.5 (14.2)	29.2
Dump resistance (ohm)	8.0 (5.6)	6.0 (5.6)
Voltage between layers (V)	149 (138)	131 (122)
Weight (tons)	2.1 (1.6)	2.9

nal resistor is adopted for the quench protection. The hot spot temperature is lower than 250 K. (3) Shut-off voltage between layers is lower than 150 V to adopt thin ceramic insulation for Nb_3Sn conductors. (4) Temperature margins of Nb_3Sn and NbTi conductors are larger than 2.0 K and 1.0 K, respectively. (5) Hoop stress of supporting cylinders made of SUS316 is lower than 600 MPa. (6) Tensile strain of Nb_3Sn by the electromagnetic force is less than 0.35% to maintain high critical currents [5].

Two rectangular monolithic conductors of Nb_3Sn and NbTi are selected from commercial lineups for the early construction. Since the large current is preferred to reduce the shut-off voltage, the largest conductors in the lineups are selected. The copper ratio of the Nb_3Sn conductor is set at 0.9 to attain the temperature margin of more than 2 K at 15 T at the operation current of 761 A. In order to reduce the shut-off voltage, the copper ratio of the NbTi conductor is set at 2.4, and the dumping time constant of the outer coil is elongated than the inner coil.

As shown in Fig. 1, the halves of inner and outer coils are divided into four and three blocks, respectively. All the blocks are supported by own supporting cylinders, the thicknesses of which are 15 mm, 14 mm, 11 mm, 7 mm, 6 mm, 7 mm, and 8 mm from the inside. The length of the innermost block of the outer coil, Out1 is shortened to suppress the highest field lower than the next block, Out2. The layer/turn numbers of the coil blocks are 12/89, 12/78, 12/83, 12/83, 10/58, 16/116, and 16/116 from the inside. The turn numbers of coil blocks are optimized to minimize the total number of drums of conductors. The final design is listed in Table 1. The total magnetic stored energy is 34.5 MJ and 40.2 MJ for the highest field of 13 T without In1 and 15 T with In1, respectively. The total weight of the assembly is estimated at 6 tons including the integration supports.

3. Setup of Test Facility

Precise measurements of critical currents or current sharing temperatures are needed for the evaluation of the degradation of superconductors. Then, we are preparing a new test facility that is equipped with a pair of temperature-variable current leads and a sample case inside the external field coil, as shown in Fig. 2. The sample is hungered from the current leads with copper busbars, and the assembly is installed in the sample case that is evacuated for thermal insulation. The nominal sample current is 50 kA because the current feeder lines are connected to two 25 kA unit banks of the existing power supply that consists of three 25 kA unit banks [6, 7]. Therefore, sample current can be increased up to 75 kA by installation of additional current feeder lines.

The planned cooling flow of the facility is shown in Fig. 3. The conductor sample and the current leads for the sample are cooled with pressurized gaseous helium, the supply temperature of which is variable from 4.4 K to 50 K by mixing the supercritical helium at 4.4 K and gaseous helium at medium temperature [8]. The external field coil is cooled with liquid helium, and its current leads are cooled with helium vapor. From the experiences for the existing 9 T split coil, the weight of which is 3 tons, it will take one week to cool down the external field coil and more than four weeks to warm up. Therefore, the samples are designed to be cooled down and warmed up independently from the external field coil. After finishing a test of a sample, the liquid helium in the cryostat is fully evaporated. After that, the sample can be extracted by filling helium gas in the sample case, and a new sample can be installed subsequently. Then, the necessary testing period for one sample is expected within two weeks that include installation of 2 days, cool-down of 4 days, testing of 4 days, and warm-up of 4 days.

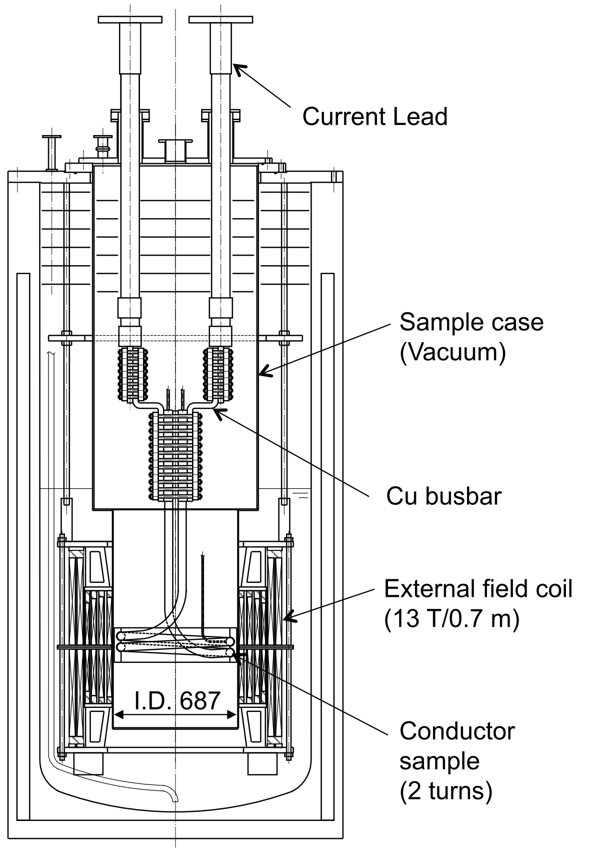

Fig. 2 Setup of the new test facility with the 13 T - 0.7 m external field coil and a conductor sample.

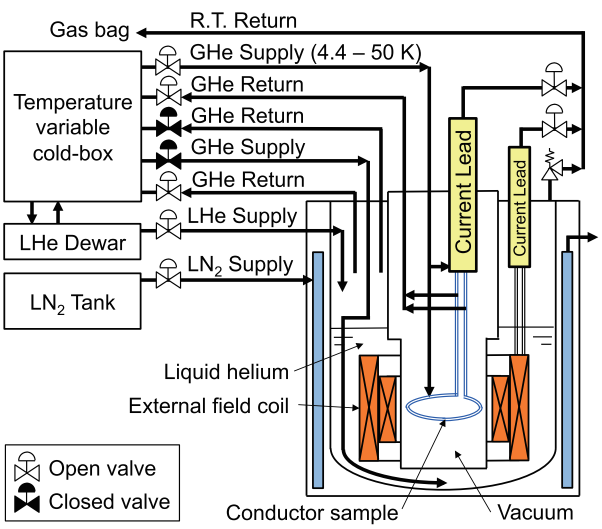

Fig. 3 Cooling flow diagram of the new test facility. The status of valves is at the steady-state operation. Temperature controlled gaseous helium is used for cool-down and warm-up of the external field coil.

4. Design of Test Samples

Figure 4 shows a reference design of a coil-shaped conductor sample. The ITER-TF conductor is considered here. In order to withstand the electromagnetic force by itself, the conductor is supported by a rigid outer supporting ring, as well as the two feeders are firmly clamped to each other to cancel the force. The preferred turn number of the sample is two or higher to apply uniform tension by the electromagnetic force on the strands in the testing region.The necessary thickness of the supporting ring, t_{SS} is given approximately by

$$t_{SS} = (IB_0a_0/S_m - A_{conduit})/L, \tag{1}$$

where I, B_0, a_0, S_m, $A_{conduit}$, and L are the sample current, external field at the sample, bending radius of the sample, allowable stress, cross-sectional area of the conduit, and winding pitch length of the conductor.

The parameters of the reference design for the case of 50 kA at 13 T are listed in Table 2. Considering the strength of the conduit of the CIC conductor, the thickness of the outer supporting ring can be reduced. We propose a screw-shaped groove to enlarge the occupied area of the ring with a fixed outer diameter, as shown in Fig. 4. Before the heat treatment for production of Nb_3Sn, the sample is inserted in the groove of the ring with being rotated. Ceramic electrical insulation is lapped on the conductor. The structure of the terminal is planned to be similar to the ITER conductors [9]. The Nb_3Sn strands are compacted and clamped with a copper plate and a stainless steel plate before the heat treatment. Since the electromagnetic force

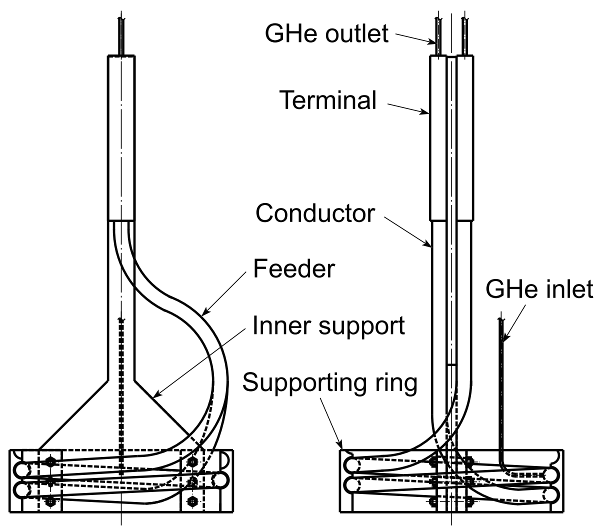

Fig. 4 A reference design of conductor samples.

Table 2 Refernce design of a CIC conductor sample.

	Reference design
Conduit outer diameter (mm)	43.4
Conduit thickness (mm)	1.6
Sample current, I (kA)	50
External field at the sample , B_0 (T)	13.0
Bending radius of the sample, a_0 (mm)	300
Allowable stress, S_m (MPa)	600
Necessary cross-section of support (mm^2)	325.0
Cross-section of the conduit (mm^2)	210.1
Winding pitch length, L (mm)	60
Necessary thickness of Ring support, t_{SS} (mm)	1.9
Diameter of the ring support (mm)	649
Self field (T)	0.50
Self inductance (μH)	3.9
Weight (kg)	280

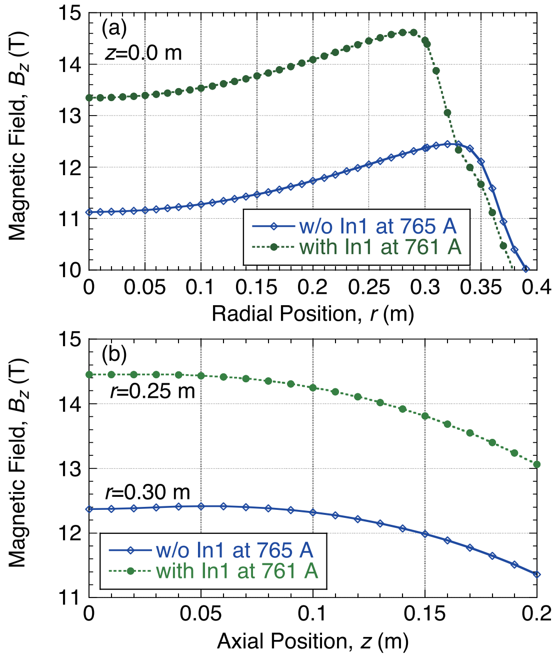

Fig. 5 Magnetic field distribution in the middle plane (a) and at the radius of 0.25 m and 0.3 m (b).

on the vertically bent section in the feeder induces the overturning force, the supporting ring is fixed from the inside with an inner support that prevents the rotation of the ring, as shown in Fig. 4.

The magnetic field distributions in the middle horizontal plane and at the radius of the sample are shown in Figs. 5 (a) and 5 (b), respectively. In the case of the highest field of 13.0 T without In1, the central field is 11.12 T at the operation current of 765 A, and the field at the sample position, where is the radius of 0.30 m, is 12.41 T. Since the self-field of the sample is ±0.5 T for the conductor shown in Table 2, the highest field in the sample is almost 13.0 T. In the case of the highest field of 15.0 T with In1, the central field is 13.34 T at the operation current of 761 A, and the field at the sample position, where is the radius of 0.25 m, is 14.45 T.

Since the vertical magnetic field, B_z is gradually higher and higher toward the inner surface of the external field coil, the off-centering of the conductor sample induces the horizontal force. In the case of small off-centering by Δx in x-direction, the radius of the shifted conductor sample is given by $a_0 + \Delta x \cdot \cos\theta$, and the off-centering force, F_x is given by

$$\begin{aligned} F_x &= \int_0^{2\pi} I \cdot B_z\,(a_0 + \Delta x \cdot \cos\theta)\cos\theta \cdot a_0 \mathrm{d}\theta \\ &= \int_0^{2\pi} I\left(B_0 + \frac{\mathrm{d}B_z}{\mathrm{d}r}\Delta x \cdot \cos\theta\right)\cos\theta \cdot a_0 \mathrm{d}\theta \\ &= \pi a_0 I \frac{\mathrm{d}B_z}{\mathrm{d}r}\Delta x, \end{aligned} \tag{2}$$

where θ and r are the angle from x-axis and radius from the center. In the case of the highest field of 13.0 T, $\mathrm{d}B_z/\mathrm{d}r$ at $r = 0.3$ m is 5.2 T/m. Then, the off-centering of 1 mm induces the horizontal force of 47.1 N for the sample current of 50 kA. The off-centering force is sufficiently smaller than the main hoop force. In order to reduce the net horizontal force on the conductor sample, it is important to optimize the route and figure of the two feeders.

5. Summary

In order to examine the superconducting properties of high-current conductors for fusion power plants in real conditions, we are preparing a new test facility that consists of a solenoid coil of the highest field of 13 T with the bore of 0.7 m, a pair of temperature-variable current leads and a vacuum chamber for conductor samples. The highest field can be increased to 15 T by installing an additional coil with the cold bore of 0.6 m. The nominal sample current is 50 kA, and the inlet temperature of the samples can be varied from 4.4 K to 50 K. Since the conductor sample is cooled independently, the necessary testing period for one sample is expected within two weeks. A reference design of a coil-shaped conductor sample is proposed. A two-turn conductor is inserted in a supporting ring to withstand large electromagnetic force by itself, and the two feeders are firmly clamped to each other to cancel the force.

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[1] A. Devred *et al.*, IEEE Trans. Appl. Supercond. **23**, 6001208 (2013).
[2] T. Hemmi *et al.*, IEEE Trans. Appl. Supercond. **22**, 4803305 (2012).
[3] K. Kizu *et al.*, Fusion Eng. Des. **82**, 1493 (2007).
[4] K. Kizu *et al.*, Fusion Eng. Des. **84**, 1058 (2009).
[5] K. Kasaba *et al.*, Cryogenics **41**, 9 (2001).
[6] J. Yamamoto *et al.*, Fusion Eng. Des. **20**, 147 (1993).
[7] S. Yamada *et al.*, Fusion Eng. Des. **20**, 201 (1993).
[8] S. Hamaguchi, S. Hamaguchi, A. Iwamoto *et al.*, Proc. of ITC24, P6-11 (to be published).
[9] N. Koizumi, K. Matsui and K. Okuno, Cryogenics **50**, 129 (2010).