Development of an Indirectly Cooled Superconductor for the LHD Fusion Reactor FFHR*)

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A 100-kA indirectly cooled superconductor has been designed and optimized for the heliotron fusion power reactor FFHR. A doubly transposed Rutherford cable composed of 216 Nb_3Sn superconducting wires is embedded in an aluminum-alloy jacket with a high filling factor. Additional high purity aluminum strips around the cable reduce the hotspot temperature to 150 K. The final design has a rectangular cross section that is 100 mm wide and 25 mm high, which will achieve an operating current of 100 kA at a current density of 40 A/mm^2. A prototype of the conductor was developed to demonstrate the fabrication process. The prototype has the same configuration as the design, except that the aluminum strips are eliminated.

Keywords: heliotron fusion reactor, indirectly cooled superconductor, Nb_3Sn superconductor, Rutherford cable, aluminum-alloy jacket, friction stir welding

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1. Introduction

Heliotron power reactors have competitive advantages for steady-state operation because they employ a currentless plasma. These advantages are demonstrated by the Large Helical Device (LHD) that uses a superconducting magnet for experiments begun in 1998 [1]. Based on outputs from the LHD, design studies of FFHR demonstration reactors have been performed. The state-of-the-art FFHR-d1 model has a major radius of 15.6 m, a toroidal field of 4.7 T, and a fusion power of 3.0 GW [2, 3]. Details of the operating scenario, core plasma, blanket, superconducting magnet, fuel cycle, and heating device have been published previously [3]. In the design studies, technologies were considered that are expected to be developed in the near future. For the superconducting magnet, an indirect cooling method was proposed that is commonly used in accelerator magnets, as an alternative to pool cooling or forced-flow cooling [4]. The use of indirect cooling enables a simple coil structure to be used.

To date, large-scale Nb_3Sn conductors have been developed that include a Rutherford cable and an aluminum-alloy jacket [4–7]. A Rutherford cable avoids irregular current distributions due to coupling currents, because all the strands are regularly transposed. An aluminum-alloy jacket not only supports the electromagnetic force, it also diffuses the heat generated by the nuclear heating in the conductor because the thermal conductivity of the aluminum alloy is thirty times higher than that of stainless steel [8]. The manufacturing process is unique in that the jacketing process is performed after a reaction heat treatment of the Nb_3Sn cable. We term it a "react-and-jacket" process. This process improves the critical current I_c because the compressive strain induced in the Nb_3Sn filaments by thermal contraction of the jacket is reduced. Measurements of I_c using a subscale prototype conductor verify the improvement [6].

The research shows that an indirectly cooled superconducting magnet is feasible in principle, although several issues remain. The present paper presents a specific design for the conductor. A prototype is developed using Nb_3Sn wires to demonstrate the feasibility of the design.

2. Design Conditions

The major parameters of the helical coil are listed in Table 1. The maximum magnetic field of 11.9 T allows the common Nb_3Sn superconductor to be used. The cross-sectional area of the coil is determined to be 1.47 m^2 based on the magnetomotive force and the current density. The conductor size has been changed from the previous 50 mm × 50 mm [4] to 102 mm × 27 mm with a 1 mm-thick insulator, because a Rutherford cable typically has a flattened shape. The total number of turns is 360, so that

Table 1 Major parameters of the helical coil.

Major radius	15.6 m
Minor radius	3.9 m
Number of helical coils	2
Coil length at the coil center	157 m
Maximum magnetic field	11.9 T
Current density	25 A/mm^2
Magnetomotive force	36.66 MA
Magnetic stored energy	160 GJ

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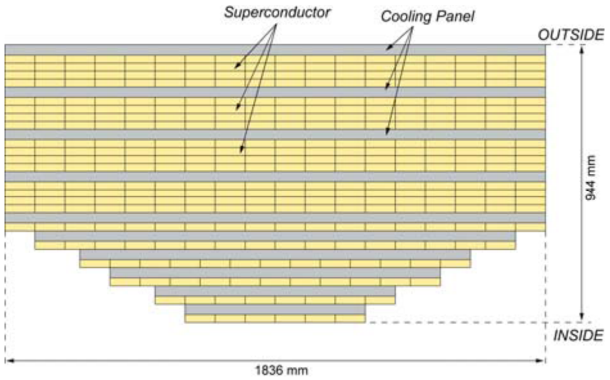

Fig. 1 Structure of the helical coil.

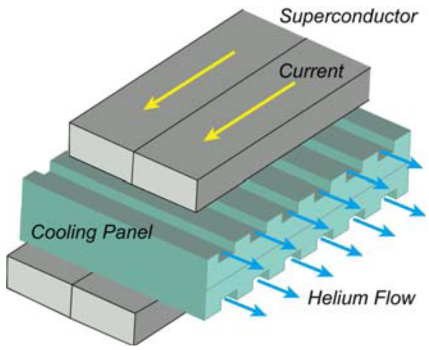

Fig. 2 Method of cooling the windings.

the operating current is 102 kA. The corresponding current density is 40.8 A/mm^2. The mean radius of curvature of the conductor is calculated to be 6.2 m based on the major and minor radii of the coil.

3. Structure of the Helical Coil

Figure 1 depicts the alignment of the conductors and 35-mm-thick cooling panels made of stainless steel. Cooling channels, through which helium coolant flows, are embedded in the panels as shown in Fig. 2. Although groove channels are indicated in the figure, one could alternatively embed cooling pipes in the panel. The inner conductors are cooled positively, that is, the panels contact all of the conductors, because the nuclear heating generates the most heat on the inside. The alignment of the panels depends on the detailed distribution of nuclear heat. The cooling panels also support the electromagnetic force. Therefore, it is necessary to calculate the stress and strain distributions [5].

4. Conductor Design

Figure 3 schematically shows a cross section of the conductor optimized for FFHR-d1. It has a critical current of approximately 200 kA at 12 T, double the operating current of 100 kA. Table 2 lists its specifications. The Rutherford cable consists of 216 (6 × 36) Nb_3Sn wires with diameters of 1.6 mm, along with 36 copper wires. The heat-treated cable and low-melting-point metal fillers are embedded in an aluminum-alloy jacket with a high filling factor. Two 2-mm-thick strips made of high-purity aluminum reduce the hotspot temperature during a quench. A zero-dimensional calculation suggests that the temperature can be kept less than 150 K for a current decay time constant of 20 s. The two jacket halves are bonded by friction stir welding (FSW) which does not damage the cable [9]. Using Nb_3Sn wires with a non-copper critical current density of 1000 A/mm^2 leads to a critical current of 200 kA.

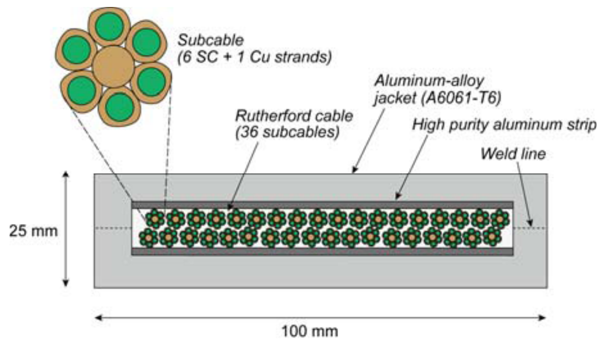

Fig. 3 Schematic of the conductor for FFHR.

Table 2 Conductor specifications.

Operating current	100 kA at 12 T
Operating temperature	4.5 K
Superconducting material	Nb_3Sn
Current density	40 A/mm^2
Conductor dimensions	100 mm × 25 mm
Cable space	84 mm × 8.4 mm
Superconducting (SC) strand diameter	1.6 mm
Number of SC strands	216
Copper ratio in SC strands	1.0
Cable type	Rutherford
Cabling pattern	(6SC+1Cu) × 36
Filled material	Low-melting-point metal
Aluminum strip thickness	2 mm × 2
Jacket material	Aluminum alloy A6061-T6
Welding method of jacket	Friction Stir Welding (FSW)
Critical current (Target)	200 kA at 12 T

5. Estimate of the Strain Effect

The coil is fabricated by a react-and-wind process, that is, it is wound after a reaction heat treatment of the Nb_3Sn superconductor. The react-and-wind process is superior to the conventional wind-and-react process because it does not require a large furnace for the heat treatment, which needs to hold the entire helical coil. However, bending strains due to the winding need to be carefully controlled to prevent degrading I_c because Nb_3Sn is a strain-sensitive material.

The bending strain ε_b only depends on the distance y

Table 3 Estimation of the strain effect on the I_c degradation.

	Maximum intrinsic strain (%)	I_c degradation, $I_{c,con}/(216I_{c,st})$
Thermal	-0.43	0.81
Thermal+Bending	-0.50	0.73

from the neutral axis according to

$$\varepsilon_b = y/r_b, \tag{1}$$

where r_b is the bending radius. When the neutral axis is the midline of the conductor and the radius is 6.2 m, which is the average curvature of the helical coil, the maximum bending strains in the superconducting strands are 0.068% at $y = 4.2$ mm, which is half of the thickness of cable space. (The cable is assumed to be heat treated without bending. Heat treatment with proper bending can reduce the maximum bending strain.) Meanwhile, the intrinsic thermal strain when cooling from the reaction temperature of about 1000 K down to the operating temperature near 5 K is calculated to be −0.43% (where the sign indicates compression) by the rule of mixtures [6]. As a consequence, the bending strain is not a serious problem because its maximum value is only 15% of the thermal strain.

The I_c degradation at 12 T and 5 K was estimated using the empirical formula proposed by Godeke *et al.* [10]. The results are listed in Table 3. The degradation factor is the ratio of I_c for the conductor ($I_{c,con}$) to the product of the number of strands and I_c for a single strand ($216I_{c,st}$). The critical current of the conductor is determined by the critical current density at its most highly strained point [7]. The value $I_{c,st}$ is a fundamental specification parameter for the conductor because it can be measured before cabling and jacketing. The sum of the thermal and bending strains reduces I_c by 27% compared with $216I_{c,st}$. This degradation can be much smaller than that of conventional conductors, such as cable-in-conduit conductors [11]. However, the design of the conductor must take into account the strain effect. The torsional deformation during winding may also be important but it has not been determined.

6. Estimate of the Temperature Rise

The nuclear heating causes the temperature of the conductor to increase. Although that heat is removed by the cooling panel, the temperature gradient due to the thermal flux causes a temperature rise in the conductor. The temperature increase is estimated for the conditions shown in Fig. 4. A conductor with a 1-mm-thick insulator is cooled only along one side. The temperature increases in the insulator and conductor (ΔT_1 and ΔT_2, respectively) are estimated from the one-dimensional heat conduction equation as

$$\Delta T_1 = \frac{Qdt}{\lambda}, \tag{2}$$

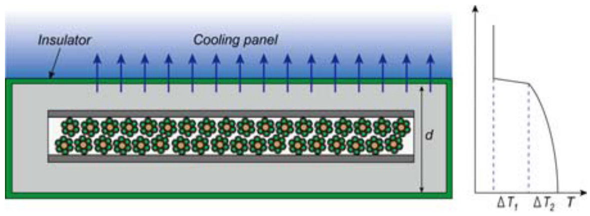

Fig. 4 Conditions for the estimation of the temperature rise.

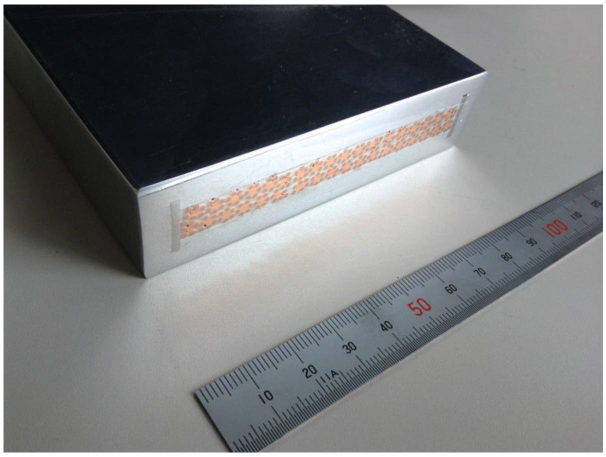

Fig. 5 Photograph of the prototype.

and

$$\Delta T_2 = \frac{Qd^2}{2\lambda}, \tag{3}$$

where Q is the heat generation per unit volume, d is the thickness of the conductor, t is the thickness of the insulator, and λ is the thermal conductivity. The heat generation in the insulator is neglected. When $Q = 500\,\mathrm{W/m^3}$, $d = 0.025$ m, $t = 0.001$ m, and $\lambda = 0.05$ W/m·K, ΔT_1 is calculated to be 0.25 K. The value of λ corresponds to the conductivity of epoxy resigns and glass-fiber-reinforced plastics [8]. At the same time, ΔT_2 may be considerably smaller than ΔT_1 because the conductivities of the component metals are higher than 10 W/m·K. For example, the conductivities of aluminum-alloy A6061-T1, copper at 12 T with RRR = 200, and high-purity aluminum at 10 T with RRR = 1000 are 12, 200, and 2000 W/m·K, respectively [8]. Even if λ is as low as 10 W/m·K, Eq. (3) implies $\Delta T_2 = 0.016$ K. As a result, this cooling method can limit the temperature increase to at most 0.3 K, sufficiently small for proper operation of the superconducting coil. An empirical formula suggests that an increase of 0.3 K corresponds to an I_c degradation of merely 7%.

7. Development of a Prototype Conductor

We developed a prototype of the conductor to demonstrate the fabrication process. Figures 5 and 6 are a photograph and a diagram of it. The prototype has the same

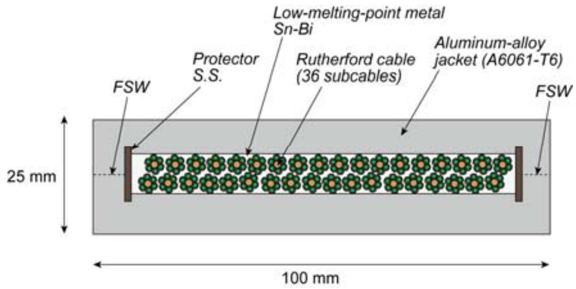

Fig. 6 Schematic of the prototype.

configuration as the design conductor, except that the aluminum strips are eliminated and the cable consists of three parallel Rutherford cables (12 subcables in 3 rows). The protector made of stainless steel guards against frictional heat during FSW. A Sn-Bi low-melting-point metal was used as the filler. Overhaul inspections were performed, including I_c measurements of the strands. The development of the prototype revealed no serious problems during the fabrication process.

8. Conclusions

Specific design studies on a superconductor for a FFHR helical coil have been performed using an indirect cooling method. The Rutherford cable and the aluminum-alloy jacket enable a high operating current of 100 kA at a current density of 40 A/mm^2. This performance can be achieved even if critical current degradation occurs due to a strain effect and a temperature rise. The development of a prototype successfully demonstrates the fabrication process of the design.

We are presently developing a strand having a high critical current, corresponding to a non-copper critical current density of 1000 A/mm^2, and optimizing the indirect cooling process.

Acknowledgements

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[1] O. Motojima *et al.*, Fusion Eng. Des. **81**, 2277 (2006).
[2] T. Goto *et al.*, Plasma Fusion Res. **7**, 2405084 (2012).
[3] A. Sagara *et al.*, Fusion Eng. Des. **87**, 594 (2012).
[4] K. Takahata *et al.*, Fusion Eng. Des. **82**, 1487 (2007).
[5] H. Tamura *et al.*, Plasma Fusion Res. **5**, S1035 (2010).
[6] K. Takahata *et al.*, Cryogenics **51**, 397 (2011).
[7] K. Takahata *et al.*, Plasma Fusion Res. **8**, 245008 (2013).
[8] CryoComp Version 5.1, Eckels Engineeing Inc.
[9] M. Sugimoto *et al.*, IEEE Appl. Super. **22**, 4802905 (2012).
[10] A. Godeke *et al.*, Supercond. Sci. Technol. **19**, R100 (2006).
[11] D. Ciazynski, Fusion Eng. Des. **82**, 488 (2007).