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$_3$Sn 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.

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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$_3$Sn 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$_3$Sn 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$_3$Sn 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$_3$Sn 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$_3$Sn 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 $\times$ 50 mm [4] to 102 mm $\times$ 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>
<thead>
<tr>
<th>Table 1</th>
<th>Major parameters of the helical coil.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Major radius</td>
<td>15.6 m</td>
</tr>
<tr>
<td>Minor radius</td>
<td>3.9 m</td>
</tr>
<tr>
<td>Number of helical coils</td>
<td>2</td>
</tr>
<tr>
<td>Coil length at the coil center</td>
<td>157 m</td>
</tr>
<tr>
<td>Maximum magnetic field</td>
<td>11.9 T</td>
</tr>
<tr>
<td>Current density</td>
<td>25 A/mm$^2$</td>
</tr>
<tr>
<td>Magnetomotive force</td>
<td>36.66 MA</td>
</tr>
<tr>
<td>Magnetic stored energy</td>
<td>160 GJ</td>
</tr>
</tbody>
</table>

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the operating current is 102 kA. The corresponding current
density is 40.8 A/mm². 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. Cool-
ing channels, through which helium coolant flows, are em-
bedded 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 pan-
els 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 cur-
rent of 100 kA. Table 2 lists its specifications. The Ruther-
ford cable consists of 216 (6 × 36) Nb₃Sn wires with di-
meters of 1.6 mm, along with 36 copper wires. The heat-
treated cable and low-melting-point metal fillers are em-
bdeded in an aluminum-alloy jacket with a high filling fac-
tor. 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]. Us-
ing Nb₃Sn wires with a non-copper critical current density
of 1000 A/mm² leads to a critical current of 200 kA.

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
Nb₃Sn superconductor. The react-and-wind process is su-
perior 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, bend-
ing strains due to the winding need to be carefully con-
trolled to prevent degrading $I_c$ because Nb₃Sn is a strain-
sensitive material.

The bending strain $\varepsilon_b$ only depends on the distance $y$
Table 3  Estimation of the strain effect on the $I_c$ degradation.

<table>
<thead>
<tr>
<th>Strain Effect</th>
<th>$I_c$ Degradation, $I_{c,con}/(216I_{c,st})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal</td>
<td>-0.43</td>
</tr>
<tr>
<td>Thermal+Bending</td>
<td>0.81</td>
</tr>
</tbody>
</table>

from the neutral axis according to

$$e_b = \frac{y}{r_b},$$  \hspace{1cm} (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 216$I_{c,st}$. 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 ($\Delta T_1$ and $\Delta T_2$, respectively) are estimated from the one-dimensional heat conduction equation as

$$\Delta T_1 = \frac{Qd}{\lambda t},$$  \hspace{1cm} (2)

where $Q$ is the heat generation per unit volume, $d$ is the thickness of the conductor, $t$ is the thickness of the insulator, and $\lambda$ is the thermal conductivity. The heat generation in the insulator is neglected. When $Q = 500 \text{ W/m}^3$, $d = 0.025 \text{ m}$, $t = 0.001 \text{ m}$, and $\lambda = 0.05 \text{ W/m} \cdot \text{K}$, $\Delta T_1$ is calculated to be 0.25 K. The value of $\lambda$ corresponds to the conductivity of epoxy resins and glass-fiber-reinforced plastics [8]. At the same time, $\Delta T_2$ may be considerably smaller than $\Delta T_1$ 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 $\lambda$ 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
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.

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