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HAL Id: jpa-00223688
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Submitted on 1 Jan 1984

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DEVELOPMENT OF A FORCED COOLED D-SHAPED SUPERCONDUCTING COIL


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Résumé
Une bobine supraconductrice à refroidissement forcé dans l'hélium supercritique a été fabriquée en vue de développer une bobine à champ toroidal de 12T. Celle-ci est bobinée avec des conducteurs tubulaires et sera testée à 10 kA à un champ d'environ 10T.

Abstract
A forced cooled D-shaped superconducting test coil by supercritical helium was made for the purpose of developing 12T toroidal field coil. The coil is wound with cable-in-conduit conductors and will be tested at 10 kA operating current at about 10T field.

1. Introduction
A fusion experimental reactor will require superconducting toroidal field coils which have a very large D-shape bore with its maximum field around 12T. A forced-cooling coil by supercritical helium is considered one of the probable candidates from the structural and cryogenic standpoint to meet the above requirement. Supercritical helium flow is forced through the so-called cable-in-conduit conductor.

The cable-in-conduit conductor which has the capability of critical current 15 kA at the field of 12T was developed. The critical current was studied against various bending strains. The mechanical properties of conduit: 304L SS and 316L SS were studied on unwelded and welded part after or before the heat treatment of 700°C in 100 hours. The calculated stability margin for the designed conductor is 350 mJ/cc under the condition of 4 k inlet temperature and 3 g/s mass flow/1/. The coil manufacturing technologies were developed with dummy conductors prior to winding a test coil. Any of above fundamental research and development showed promising results.

The test D-shape coil consists of 2 pancakes, each 6 turns and has the coil inner bore of 71.5 cm times 87.3 cm. The lower portion of the test coil is sandwiched by small background split coils. The operating current of the test coil is 10 kA and its maximum resultant field is 10T. The supercritical helium is supplied to the coil from a helium refrigerator.

2. Cable-in-Conduit Nb₃Sn Superconductor

2-1 Characteristics
The cable conductor has advantage for the cryogenic stability because of its large wetted perimeter/2/. The cable conductor is capsulated in a conduit and then the Nb₃Sn reacts at 700°C and for 100 h, before winding the coil. The cable-in-conduit conductor is

Article published online by EDP Sciences and available at http://dx.doi.org/10.1051/jphyscol:1984133
designed to satisfy the stability at operating current of 10 kA at 12T on the hydraulic condition of 1 MPa, 4.5 k and 0.01 kg/s supercritical helium. The cross section of the conductor fabricated is shown in Fig. 1, and the main characteristics are listed in Table 1. The material of the conduit, which mainly supports the mechanical force, is made of SUS 316L considering the mechanical strength before and after the heat treatment to produce Nb3Sn.

2-2 Critical Current
The reduced size conductors are used for estimating the critical current at various bending strains instead of measuring the critical current of the final conductor at 12T. The reduced size conductor has 3x6 composites in conduit and are reacted at the same condition as the final conductor, where the void fraction is changed from 30% to 50%. The composite used is the same size as that of the final conductor. The results are shown in Fig. 2, where measured critical current of a composite is plotted for the comparison. The cable-in-conduit conductor with 50% void fraction behaves like a composite against the bending strain, while the conductors with void fraction below 40% behave like compacted composites. This comes from that composites in the conduit may be bound as the void fraction decreases. On the other hand, the critical current at the 30% void fraction deteriorates even though no bending is applied. This may stem from the same reason as the monolithic Nb3Sn conductor/3/.

3. Stability of Forced Cooled Coil
Prior to construction of the final coil, a small coil with 4 m length was used for studying the stability of the coil cooled by the supercritical helium. The conductor used has 3x3x6(54) composites in a conduit of 5.79 mm I.D. The composite has NbTi superconductor of 0.61 mm O.D. which is the same as the real conductor. High frequency heating was employed to generate the normal zone in the coil. The heating power to lead the coil quench was measured at the conditions that the mass flow rate, heating length and the operation current are changed. The main results are as follows: (i) heating energy to lead the coil quench is approximately in proportion to 2.2th power of mass flow rate, (ii) the quench energy for longer heating length is smaller than that for shorter one.

4. Test coil and facility
D-shaped Nb3Sn coil encased in round stainless steel case was installed in thermally shielded vacuum vessel with a pair of background split solenoids and 4.2 k liquid helium bath contained with heat exchanger (Fig. 3). Refrigeration and forced flow helium are supplied by a TCF-100 Sulzer Brothers refrigerator which possesses supercritical helium supply circuit and refrigeration capacity of 200 W at 4.6 k.

Nb3Sn coil itself was wound in a double pancake 1.09 m high and 0.94 m wide using 45 m length and 12 turns of conductor. Conductor was wound tightly and insulated with resin pre-impregnated glass fiber tape and strengthened by interleaving stainless steel tape 0.5 mm thick against hoop stress. D-shaped coil was set in round stainless case using fiber glass spacer to resist magnetic force and to expose the cooling surface of coil and case for cooling. Background coils clamped across bottom section of the test coil generate 9T and superposed field of about 10T is attained by excitation of the test coil. Induction heating coil was wound around the conductor of 1/3 length of the most inside turn of the half pancake for recovery current test. D coil was encased in coil case and welded in lip seal after bolted.

Subcooled forced flow helium passed through the heat exchanger
in liquid helium bath is supplied to coil at openings of conductor conduit near connections between power leads and conductor. Gas cooled leads are cooled by boiled off atmospheric helium in liquid helium bath. Power leads liquid helium bath and 9T background coils were assembled on test coil with other miscellaneous pipes and installed in vacuum vessel (Fig. 4). Simplified flow diagram of helium cooling system is illustrated schematically (Fig. 5).

Supercritical helium passed through Nb3Sn coil is supplied to 4k base, then returns to refrigerator. On the other hand, low pressure helium stream from refrigerator is branched away three streams to cool the D coil, background coils and liquid helium bath, then returns to refrigerator again in single stream.

In steady state operation, while supercritical stream is supplied to D coil continuously liquid helium for 4 k bath and 9T background coils is supplied periodically from 1000 l dewar because of impossibility of mixed mode operation of liquefaction and supercritical helium supply. Refrigerator can produce supercritical helium of 16 atm max. pressure 20 g/s flow rate and 200 W refrigeration at 4.8 k.

Conclusion

The principal fundamental technologies required for a 12T forced cooled D-shaped superconducting coil by supercritical helium were developed. The D-shaped coil wound with cable-in-conduit conductors is to be tested at 10 kA operating current at about 10T field.

References


Table 1. Main conductor characteristics

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum Field</td>
<td>12 T</td>
</tr>
<tr>
<td>Operating Current</td>
<td>10 KA</td>
</tr>
<tr>
<td>Critical Current</td>
<td>15 KA at 12 T</td>
</tr>
<tr>
<td>Overall Dimensions</td>
<td>18.3 x 15.7 mm²</td>
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<tr>
<td>Conduit Thickness</td>
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<tr>
<td>Void Fraction</td>
<td>33 %</td>
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<tr>
<td>Cable Configuration</td>
<td>6 x 3⁴ (486 composites)</td>
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<tr>
<td>Composite Diameter</td>
<td>0.61 mm</td>
</tr>
<tr>
<td>Cu / Non Cu Ratio</td>
<td>2.8 : 1</td>
</tr>
<tr>
<td>Composite Material</td>
<td>Nb₃Sn / Cu</td>
</tr>
</tbody>
</table>

Fig. 1. Cross section of the conductor

Fig. 2. Critical current as a function of bending strain
Fig. 3. Assembled test coil and test facility

Fig. 4. Test facility

Fig. 5. Schematic flow diagram of cooling system