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A 50 mm BORE, 13 TESLA SUPERCONDUCTING MAGNET EMPLOYING A PREREACTED MULTIFILAMENTARY Nb$_3$Sn CONDUCTOR

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Résumé - Après la construction de deux aimants hybrides, nous envisageons la construction d'un troisième aimant hybride pouvant produire un champ de l'ordre de 30 T. Un conducteur Nb$_3$Sn multifilamentaire préréagi sera utilisé pour la partie 12 T du système. Dans une première étape du projet, nous avons réalisé et testé un aimant constitué de 14 doubles galettes de ce type de conducteur, placé dans une bobine de renfort en Nb-Ti.
Les résultats satisfaisants des essais, qui ont permis de produire un champ de 13,4 T, laissent augurer de très bonnes perspectives pour le projet 30 T.

Abstract - Following the construction of two hybrid magnets, we intend to build up a third hybrid magnet which will produce about 30 T. A prereacted multifilamentary Nb$_3$Sn conductor will be employed for the 12 T superconducting part of the Hybrid. As a first step for the project, we have designed, constructed and tested a magnet which consists of 14 double-pancakes made of a prereacted multifilamentary Nb$_3$Sn conductor and a back up coil made of a Nb-Ti conductor. The satisfactory results of the test on the magnet, in which we succeeded to produce 13.4 T, have given us very bright prospects for the 30 T hybrid magnet project.

I - INTRODUCTION

We have constructed two hybrid magnet systems/1/ with 52 and 32 mm diameter room temperature clear bore and succeeded to generate 20.6 and 20.5 T, respectively. Succeeding to these hybrids, we have designed a new powerful one which can generate more than 30 T by a combination of 8 MW water-cooled magnet. As already mentioned in /1/, we employ a prereacted multifilamentary Nb$_3$Sn superconductor for a 12 T superconducting part of the hybrid.

So far most of high field multifilamentary Nb$_3$Sn superconducting magnets employed "react after wind" method. By use of this technique we can make a magnet with a maximum field up to 10 - 15 T. But one of defects in this method is that we cannot use this technique for the intermediate or large scale superconducting magnet larger than about 1 m and with a stored energy more than about 1 MJ. So far a prereacted conductor has been employed in the case of a large superconducting magnet such as one for fusion researches. The maximum available field by this method is, however, 10 to 11 T up to now/2/. Therefore, this technique cannot be used for a high field magnet with a stored energy more than 20 MJ like our superconducting back up magnet in the 30 T hybrid. Thus it is needed to develop the technique to use a prereacted conductor for a high field, large stored energy magnet.

As a first step of the 30 T hybrid magnet project we have designed, constructed and tested a small but high field magnet employing a prereacted multifilamentary Nb$_3$Sn conductor which can generate more than 13 T.

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We have succeeded to generate 13.4 T at the center of the test magnet. In this paper we report the details of design, construction and testing on this first step magnet.

II - IMPROVEMENT AND PREPARATION OF THE CONDUCTOR

As can be seen in Fig. 1, the critical current density $J_c$ decreases very fast around the magnetic field region 11 - 13 T in an ordinary multifilamentary Nb$_3$Sn conductor developed up to now. In order to improve the characteristics of $J_c$ in the high field region, 0.2 wt.% Ti was added in the bronze matrix. It is expected that this Ti addition also improves the characteristics in the stress effect. After an advanced reaction heat treatment (700 °C, 10 days) and this Ti addition in the bronze matrix, the $J_c$ characteristics were very much improved at high field region, as can be seen also in Fig. 1.

After an optimized heat treatment, an advanced tape conductor was obtained. XMA results on the multifilamentary tape are shown in Fig. 2. It is noticed in this figure that almost all the Ti atoms which were added into the bronze matrix have selectively diffused into the Nb$_3$Sn compound. It is believed that the grain size of Nb$_3$Sn becomes very fine due to the incorporation of Ti in the bronze matrix and the very long reaction heating (10 days) at the relatively low temperature (700 °C), and thus $J_c$ grows very remarkable.

As the inner diameter of the test coil is 58 mm, and in order to restrict the strain level less than 0.5 %, we selected the conductor form as a tape of 0.25 x 5 mm. A cross-sectional photograph of a 1/3 part of the tape conductor is shown in Fig. 3. Due to the final rolling process, each fine-multi core has also elliptic cross section as can be seen in this photograph. Nb is used as a barrier. A monolithic multifilamentary NbTi conductor is employed for the back up coil. Table 1 shows the specifications of employed superconductors.

Table 1: Specifications of conductors

<table>
<thead>
<tr>
<th>INNER</th>
<th>OUTER</th>
</tr>
</thead>
<tbody>
<tr>
<td>Section A</td>
<td>Section B</td>
</tr>
<tr>
<td>S.C. material</td>
<td>mf-Nb$_3$Sn (Ti matrix)</td>
</tr>
<tr>
<td>Dimensions (mm)</td>
<td>0.25x5</td>
</tr>
<tr>
<td>Number of filaments</td>
<td>751</td>
</tr>
<tr>
<td>Equivalent diameter of filaments (µm)</td>
<td>17</td>
</tr>
<tr>
<td>Twist pitch (mm)</td>
<td>180</td>
</tr>
<tr>
<td>Cu/Cu$_3$N$_4$/Cu/NbTi</td>
<td>0.33</td>
</tr>
<tr>
<td>Resistance ratio</td>
<td>80</td>
</tr>
</tbody>
</table>

$J_c$ (A) | 153 | 800 | 695 | 650 | 569 | 147 | 9.3 | 9.37 | 8.37 | 8.37 |

Fig. 3 Cross-sectional photograph of Nb$_3$Sn conductor
III - DESIGN AND CONSTRUCTION OF THE MAGNET

Schematic draw of the magnet and specifications of the coil are shown in Fig. 4 and Table 2, respectively. The inner coil consists of 14 double-pancakes wound with a pre-reacted multifilamentary Nb₃Sn tape and generates 4.5 T at 142.5 A. The outer coil is a normal solenoid wound with 4 kinds of multifilamentary NbTi wires, or it is graded in 4 sections and generates a back up field of 8.5 T at 458.5 A. These coils are separately charged by two power supplies which are described in the next section. 14 double-pancakes wound with pre-reacted Nb₃Sn tape were stacked and then assembled concentrically in the outer NbTi back up coil.

IV - POWER SUPPLIES AND CRYOSTAT

Two power supplies for inner and outer coil have a maximum current of 150 and 500 A, respectively, and stability of them are both 10⁻⁶ within 3 hours. The cryostat is a conventional stainless steel bucket type Dewar which was set in a pit of 1.8 m deep. Power leads for outer NbTi coil are He gas-cooled type while ones for inner Nb₃Sn coil are standard copper rods. The liquid He storage capacity is 50 l above the magnet in a height of 50 cm. Evaporation rate of the liquid He is about 3 l/hr at zero current and about 6 l/hr at the rated current.

The magnetoresistance probe made of commercial copper wire wound non-inductively in the center of the magnet was calibrated with a Hall generator (Copal Co.) which had been calibrated by NMR technique in the Copal company.

V - TESTING

The load line of the magnet is shown in Fig. 5. As can be seen in this figure, the outer NbTi coil could generate 8.68 T after two times training. Under the back up of this field, inner Nb₃Sn coil generated 4.74 T and quenched at 13.42 T in total field. The recorder chart of this operation is shown in Fig. 6. The maximum experienced field of the conductor is about 13.65 T.

The magnetic field distribution was measured as shown in Fig. 7 by use of the Copal Hall generator. The agreement with the calculated results is very good and homogeneity near the magnet center is about 0.5 % / 25 DSV.

It was checked whether there is a significant hysteresis or not by use of the built-in magnetoresistance probe. The results of hysteresis measurements are shown in Fig. 8. It turned out that the hysteresis is very small.
as expected since multifilamentary conductors were employed in this magnet. The residual magnetic field is thought to be smaller than 0.05 T at the center of the magnet.

It takes only about 15 minutes to charge up from zero to the maximum field. This short charge-up time is also another advantage of the multifilamentary conductors employed. In addition to these advantages, the effective bore of 50 mm diameter is large enough and relatively small magnet weight of 194 kg makes the cool down from room temperature to liquid helium temperature very easy, so that the magnet is very much suitable for various experiments of development research.

Though the purpose of this test magnet construction was a research and development for the 30 T hybrid magnet project, this magnet is now opened for shared use since it has many advantages mentioned above.

VI - SUMMARY

1. A test magnet employing a prereacted multifilamentary Nb₃Sn tape conductor was designed, constructed and tested as a first step of our 30 T hybrid magnet project.
2. In order to improve the J characteristics at high field region, Ti was added in the bronze matrix and advanced reaction heat treatment was tried.
3. The satisfactory results on this test magnet not only gave us very bright prospects for the 30 T hybrid magnet project but also established the technique to use a prereacted conductor which is essential for the development of very large scale, high field magnet with large stored energy such as one for fusion researches.

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