UPGRADE OF THE SULTAN SUPERCONDUCTING
TEST FACILITY TO 12 TESLA BY THREE A-15
COILS

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UPGRADE OF THE SULTAN SUPERCONDUCTING TEST FACILITY TO 12 TESLA BY THREE A-15 COILS


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Résumé - Le développement des bobines internes en matériau supraconducteur A-15 pour la station d'essai SULTAN est exposé.

Abstract - The development of A-15 insert coils for the superconductor test facility SULTAN is outlined.

The first construction phase of the SULTAN test facility was recently completed (1). Its main component at present is a niobium-titanium magnet system, providing a background field of 8 T at a free inner bore of 1.05 m for testing experimental conductors. The three collaborating laboratories, SIN-Villigen, ENEA-Frascati and ECN-Petten, started design and development work for an insert magnet system, which will increase the background field to 12 T at 58 cm accessible diameter. This second phase project, which is planned for the period 1983-1986, is part of the European fusion technology programme and has been granted preferential support by the European Commission.

I - COIL DESIGN

The construction of the 12 T insert coil system in itself, is planned to be an intermediate step towards the 40 kA critical current conductors needed for the toroidal field coils of next step fusion reactor experiments, as for example INTOR (2). This aim led to the adoption of a number of advanced design principles:

- application of the "react and wind" technique
- internal forced flow cooling with supercritical helium
- high operating current (5 kA).

The system will consist of three coils of identical size and performance but based on different approaches to conductor development, which will result in a sufficiently wide technology assessment for the eventual selection and upgrading to INTOR size. Each partner will make one, which adds a spirit of technical competition to the project. The suspension system will allow assembly in any sequence and testing coils separately and in combination.

The dimensions are shown in Fig.1. Table 1 gives the main coil data. The computed field distribution is included in Fig.1. The total SULTAN magnet system will have a stored energy of 75 MJ of which 20 MJ is contributed by the 12 T insert. The tangential Lorentz force at the innerside of the magnet will be 19.7 kN. As there will be negligible compression between the layers, the stress level will be uniform in radial direction.

The coils will be wound layer-wise from a single 700 m length to avoid conductor joints. Another advantage is the possibility of feeding the inner layer at \( B_{\text{max}} \) with helium of lowest temperature.

The three coils will be connected in series, both electrical and in the cooling circuit, which has two heat exchangers between coils. The supercritical helium conditions are: 3.5 g/s massflow rate, 1.0 MPa inlet pressure and 0.4 MPa outlet. The pressure drop over the coils is: 0.20 MPa (ECN), 0.18 MPa (SIN) and 0.22 MPa (ENEA). The in- and outlet temperatures are 4.4 K and 5.0 K.
II - CONDUCTOR DESIGN

The conductor concepts - shown in Fig.2 - are all three based on a flat superconducting cable, in order to keep the bending strain in acceptable range. Other common aspects are internal cooling channels, use of copper stabilizers for heat transfer and quench protection and stainless steel 316 LN for mechanical strength. In detail the designs are essential different, providing together in their development and application a broad basis for evaluation of materials, fabrication processes, reinforcement and stabilization techniques. The conductor design data are listed in Table 2. They will be subject to changes as dictated by the individual development programmes - which started this year - and corresponding sample performance tests in the Stage I SULTAN facility.

Fig.1. Dimensions (in cm) and field of the complete SULTAN magnet system.

III - SIN CONDUCTOR DEVELOPMENT

The fabrication of the composite conductor is divided in five operations:
- manufacturing of the basic strand
- production of the flat cable
- reaction of the cable
- production of the conventional components
- conductor assembly and joining.

SIN will use Nb3Sn multifilament wire of the external tin diffusion type, developed by SIN and BBC (3). The 0.125 mm diameter basic strand is electroplated with tin. It contains 300 niobium filaments of approximately 3 μm diameter in a copper matrix. The 1729 strand cable will be produced in three stages. The first stage is of 6 on 1 configuration. The second stage consist of 19 primary cables of 0.35 mm. The third level is obtained by twisting 13 second level subcables and compacting to a flat cross section. All cabling is performed by twisting in the same direction. A compaction of 65% has to be obtained; a task still requiring development work.

The cable will be heat treated in inert atmosphere on a spool. Graphite foil will be used between layers to prevent sticking. The tin plating diffuses into the copper matrix and reacts with the niobium filaments to form Nb3Sn. The overall critical current density - measured on single strands and first level cables - is 385 A/mm² at 5 K and 12.2 T. The operating current of 5280 A for the magnet coil means a design current density of 250 A/mm² or 65% of the critical value.

Table 1. Parameters of the 12 Tesla SULTAN magnet coils

<table>
<thead>
<tr>
<th>Parameter</th>
<th>ENEA</th>
<th>ECN</th>
<th>SIN</th>
</tr>
</thead>
<tbody>
<tr>
<td>outer diameter [cm]</td>
<td>100</td>
<td>idem</td>
<td>idem</td>
</tr>
<tr>
<td>inner diameter [cm]</td>
<td>61</td>
<td>idem</td>
<td>idem</td>
</tr>
<tr>
<td>height [cm]</td>
<td>30</td>
<td>idem</td>
<td>idem</td>
</tr>
<tr>
<td>N. of layers</td>
<td>21</td>
<td>23</td>
<td>19</td>
</tr>
<tr>
<td>N. of turns per layer</td>
<td>13</td>
<td>12</td>
<td>15</td>
</tr>
<tr>
<td>conductor length [m]</td>
<td>693</td>
<td>702</td>
<td>723</td>
</tr>
<tr>
<td>operating current [A]</td>
<td>5280</td>
<td>idem</td>
<td>idem</td>
</tr>
<tr>
<td>current density [A/mm²]</td>
<td>26.8</td>
<td>25.1</td>
<td>25.1</td>
</tr>
<tr>
<td>max. field on conductor [T]</td>
<td>12.2</td>
<td>idem</td>
<td>idem</td>
</tr>
<tr>
<td>type of superconductor</td>
<td>Nb3Al</td>
<td>Nb3Sn</td>
<td>Nb3Sn</td>
</tr>
<tr>
<td>weight</td>
<td>about 1100 kg each</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
The most critical operation will be the joining of the reacted cable with the copper tube, copper stabilizers and stainless steel strips in a continuous process. It requires systematic research on soldering and brazing. Special tooling has to be developed and tested for continuous operation.

IV - ENEA CONDUCTOR DEVELOPMENT

The ENEA conductor concept is based on a Rutherford cable of Nb$_3$Al multifilament wire. A production method for this unique type of strands was developed by ENEA and the Italian industry LMI (4). Starting point is the assembly of an extrusion billet of copper matrix containing niobium-aluminium cores. The cores consist of a sandwich of niobium and aluminium foils wrapped around a central pure copper rod. After extrusion and wire drawing, the product is heated to form the A-15 intermetallic compound in the filaments. The critical current density over the filaments is 520 A/mm$^2$. The present development of wire for the SULTAN-project is aiming at a copper fraction of 50% and filament diameter of 70 µm for dynamic and adiabatic stabilization respectively.

The composite conductor will be realized according the following procedure:
- production of a copper U-profile with four channels for cooling
- insertion of cable and copper strip in the U-profile
- drawing through an appropriate die in order to get a good compaction
- heat treatment to react the wire to Nb$_3$Al and to obtain sufficient thermal contact between the copper components by diffusion bonding.

V - ECN CONDUCTOR DEVELOPMENT

The conductor will be based on a Rutherford cable of 38 strands of 0.85 mm diameter. The wire will be made by the ECN powder technique (5). Its principle is the use of a pure copper matrix and niobium tubes filled with NbSn$_2$ powder as cores. The fabrication technology has been developed by ECN and Holec. A recently optimized product will be used, containing 36 filaments and 60 vol.% of copper for intrinsic stabilization (6). The overall critical current density is 450 A/mm$^2$ at 12.2 T at 4.2 K. A 0.85 reduction factor is estimated for the temperature increase to 5 K. The design critical current for the cable is 8250 A. The ratio of operating to critical current will be 0.64.

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Fig. 2. Conductors to be used for SULTAN A-15 coils.

The critical current degradation of the strands has been measured for bending and axial loading separately. At 12.2 T, both impose limits of 0.4% strain (7). The strain of the composite conductor due to Lorentz forces will be limited to 0.1% by using cold worked copper for the stabilizer strips ($E=1.4\times10^{11}$ N/m$^2$). The maximum bending strain is limited to 0.3% by the $d/D$ ratio.

By reacting the cable on a spool of 1.2 m diameter, the bending strain at winding will be partially compensated.
The further steps in the production of the composite conductor of ECN are:
- reacting the cable at 675°C for 48 h in argon atmosphere
- solder filling the cable and solder joining with the two stabilizer strips
- the stainless steel casing will have to be welded leaktight, for which continuous
two side laser welding has been selected.

Table 2. Conductor design data

<table>
<thead>
<tr>
<th></th>
<th>SIN</th>
<th>ECN</th>
<th>ENEA</th>
</tr>
</thead>
<tbody>
<tr>
<td>I, at 12.2 T and 5 K [A]</td>
<td>8130</td>
<td>8250</td>
<td>7540</td>
</tr>
<tr>
<td>width [mm]</td>
<td>20.4</td>
<td>25.0</td>
<td>21.4</td>
</tr>
<tr>
<td>height [mm]</td>
<td>10.3</td>
<td>8.4</td>
<td>9.2</td>
</tr>
<tr>
<td>cross section [mm²]</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>cable</td>
<td>33</td>
<td>27</td>
<td>37</td>
</tr>
<tr>
<td>copper</td>
<td>93</td>
<td>89</td>
<td>82</td>
</tr>
<tr>
<td>stainless steel</td>
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<td>42</td>
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<td>cooling channels</td>
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<td>20</td>
</tr>
<tr>
<td>insulation</td>
<td>21</td>
<td>25</td>
<td>29</td>
</tr>
<tr>
<td>superconductor</td>
<td>Nb₃Sn</td>
<td>Nb₃Sn</td>
<td>Nb₃Al</td>
</tr>
<tr>
<td>n. of wires in cable</td>
<td>1729</td>
<td>38</td>
<td></td>
</tr>
<tr>
<td>wire diameter [mm]</td>
<td>0.125</td>
<td>0.85</td>
<td>not yet</td>
</tr>
<tr>
<td>n. of filaments in wire</td>
<td>300</td>
<td>36</td>
<td>determined</td>
</tr>
<tr>
<td>fraction of copper in wire [%]</td>
<td>0</td>
<td>60</td>
<td>50</td>
</tr>
</tbody>
</table>

REFERENCES