Design features and microstructure of the commercially produced high Jc internal tin Nb$_3$Sn strands with one common diffusion barrier

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**Nb₃Sn strands produced by bronze and internal tin methods**

(In Russia: Development - Bochvar Institute; Production – [UMZ plant] - ChMZ plant)

1975 First bronze strands

1975 First Internal Tin strands

361 filaments

650 filaments

2 Components: Nb + Bronze (Cu-Sn)

3 Components: Nb + Cu + Sn

**Commerially produced Nb₃Sn strands**

ChMZ plant, Glazov, 2009-2015

ChMZ plant, Glazov, 2016-2017

Bronze ITER type

Nb₃Sn wire \( J_c = 850 \, \text{A/mm}^2 \)

IT ITER type

Nb₃Sn wire \( J_c = 1000 \, \text{A/mm}^2 \)

IT LHC-FCC type Nb₃Sn wires with common and separated barriers \( J_c \) (non Cu; 12 T) up to 2500 A/mm²

10.04.2018

FCC week 2018 - Amsterdam
The FCC challenges for internal tin strands

FCC Nb$_3$Sn performance targets

- $J_c$ (16 T, 4.2 K) > 1500 A/mm$^2$
- M (1 T, 4.2 K) < 150 mT ($D_{fil}$ < 20 µm)
- RRR > 150
- UL > 5 km
- Cost(15 T, 4.2 K) < 5 USD/kA m

All single parameters are in reach, their combination is the challenge!

Experimentally attained $J_c$ value in RF
Design of Nb$_3$Sn High Jc Internal Tin strands for FCC

- **Separated diffusion barriers around each subelements**
  - 85 monoelements
  - $D_{eff}$ in the order of 50 µm

- **Single common diffusion barrier**
  - 55 split sub-elements (equivalent to 270 effective filaments)
  - $D_{eff}$ in the order of 25 µm

- **Target performance:**
  - $D_{fil} \approx N$ (subelements)

- **Graph:**
  - Up to 32% of non Cu area will be occupied by unreacted Nb for 20 µm subelements (assuming 4 µm average thickness)

- **Points:**
  - Increase of the number of subelements leads to the corresponding increase of the technological drawbacks connected with the large free surface between subelements enhancement and large preliminary plastic deformation before assembling of the final billet
  - **Difficult to maintain initial RRR >150** for strands with separated diffusion barriers around each subelements

10.04.2018
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Internal tin strand production scheme

Particular feature of IT strands – large cold plastic deformation by drawing without intermediate heat treatments (problems – formation of metallurgical bonding; texture formation)
Basic design parameters of IT strands with one common diffusion barrier designed for HI-LU specifications

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Common Ta barrier</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strand diameter, mm</td>
<td>0.7</td>
</tr>
<tr>
<td>Cu/non Cu</td>
<td>1,20</td>
</tr>
<tr>
<td>Nb fraction within barrier, % vol.</td>
<td>≈41 %</td>
</tr>
<tr>
<td>Nb$_3$Sn fraction in non Cu area after HT, %vol.</td>
<td>46 %</td>
</tr>
<tr>
<td>D subelement, μm</td>
<td>70.5</td>
</tr>
<tr>
<td>Subelement spacing, μm</td>
<td>2.68</td>
</tr>
<tr>
<td>D filament, μm</td>
<td>2.7</td>
</tr>
<tr>
<td>Cu thickness between Nb filaments, μm</td>
<td>0.3</td>
</tr>
<tr>
<td>Ti doping (artificial; in Nb filaments), at%</td>
<td>1.74</td>
</tr>
</tbody>
</table>

The artificial doping by Ti has been done by insertion of the plurality of NbTi rods in the Nb filaments.
Deformation of IT strand’s components without intermediate heat treatments

<table>
<thead>
<tr>
<th>Common barrier</th>
<th>Distributed barriers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nb inside subelements</td>
<td>InAo/A = 11-12</td>
</tr>
<tr>
<td>Nb (Ta) in diffusion barrier</td>
<td>InAo/A = 8 - 9</td>
</tr>
</tbody>
</table>

60 mm in dia Composite outer tube consists of stabilizing Cu, strengthening Cu-Nb layer, Nb diffusion barrier, Ta dividing inserts, technological Cu

Hexagonal composite rod (subelement) consists of axial Sn alloy rod, 6 sectors composed by the Nb(Ti) doped filaments embedded into Cu matrix and separated by the Cu layers

2 mm in dia final design composite wire consists of 37 subelements 37 tin sources, 222 Cu-Nb sectors

Different stages of IT strand manufacture
The Nb barrier should be optimized with 20 Ta rods for subdividing the circular Nb$_3$Sn layer. The thickness could be diminished due to positive role of Cu-Nb strengthening layer adjacent to Nb barrier.

The preliminary design assumes the thickness of Nb barrier around 8 µm.

The 4-5 µm of Nb barrier should be reacted with the formation of the Nb3Sn phase. The volume fraction of diffusion barrier will be around 2.5% from non-Cu area.

The strand after reaction heat treatment with several intermediate stages 220 C + 370 + 570 C + (660-700 C)
The microstructure of IT strands (common barrier)

The microstructure of Nb3Sn layers in highly bridged macrofilaments has to be optimized in the further R&D.

Increase of last stage heat treatment’s (660°C) duration акцъ 25 р еще 100 р
The microstructure of IT strands (common barrier)

Each sector of Nb filaments forms a macrofilament as a result of reaction of Nb and Sn with formation of Nb₃Sn phase (last stage heat treatment temperature – 700 C)
The microstructure of IT strands (common barrier)

<table>
<thead>
<tr>
<th>Element</th>
<th>Weight %</th>
<th>Atomic %</th>
<th>Net Int.</th>
<th>Error %</th>
<th>Kratio</th>
<th>Z</th>
<th>R</th>
<th>A</th>
<th>F</th>
</tr>
</thead>
<tbody>
<tr>
<td>NbL</td>
<td>57.59</td>
<td>53.56</td>
<td>11448.70</td>
<td>2.98</td>
<td>0.4988</td>
<td>0.9949</td>
<td>1.0122</td>
<td>0.8614</td>
<td>1.0107</td>
</tr>
<tr>
<td>SnL</td>
<td>18.26</td>
<td>13.29</td>
<td>2223.70</td>
<td>5.05</td>
<td>0.1426</td>
<td>0.9315</td>
<td>1.0575</td>
<td>0.8216</td>
<td>1.0210</td>
</tr>
<tr>
<td>TiK</td>
<td>0.65</td>
<td>1.18</td>
<td>144.90</td>
<td>22.30</td>
<td>0.0059</td>
<td>1.1160</td>
<td>0.9083</td>
<td>0.7848</td>
<td>1.0297</td>
</tr>
<tr>
<td>CuK</td>
<td>23.50</td>
<td>31.96</td>
<td>2300.60</td>
<td>3.70</td>
<td>0.2644</td>
<td>1.0785</td>
<td>0.9587</td>
<td>0.9615</td>
<td>1.0848</td>
</tr>
</tbody>
</table>

Element Weight % Atomic % Net Int. Error % Kratio Z R A F

<table>
<thead>
<tr>
<th>Nb</th>
<th>Cu</th>
<th>Sn</th>
<th>Nb</th>
<th>Cu</th>
<th>Sn</th>
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Heat treatment of Internal Tin Nb$_3$Sn Strands

[Graphs and diagrams related to heat treatment and phase transitions in Nb$_3$Sn alloys are shown.]
Superconducting properties of IT strands Tc - Jc

Voltage-temperature characteristics of the wires investigated after h.t.

#3- 210 °C/50 h+400 °C/50 h_665 °C/100 h

in comparison with ITER wire
(bronze route, h.t. cycle B)

Critical temperature of IT strands are higher than of bronze processed
Superconducting properties of IT strands

Etching out outer Cu and outer diffusion barrier led to increase of the Tc caused by the relaxation of the internal stresses

\[ y = -4.3893x + 121.28 \]

\[ R^2 = 0.9997 \]
SUMMARY

- The separation of the Nb filaments inside the subelements could be effectively realized by the introduction of the layers of copper based plates.
- The formation of Nb3Sn “macrofilaments” with complete reaction of Nb filaments has been observed.
- Nonuniformity of the grains microstructure in the Nb3Sn “macrofilaments” has been found with columnar grains that is characteristic for solid state reaction altogether with the large equaxed grains in the boundaries regions between former Nb filaments.
- The optimization of the heat treatment regimes with the accent on the intermediate 570 C stage is in progress.
- The attainment of the FCC strand’s specifications is challenging, still requires intensive R&D works but seems to be realistic.