ELECTROMECHANICAL PROPERTIES OF SUPERCONDUCTORS FOR DOE FUSION APPLICATIONS

J.W. Ekin
S.L. Bray
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W.L. Bahn

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Electromechanical Properties of Superconductors for DOE Fusion Applications

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The electrical performance of many superconducting materials is strongly dependent on mechanical load. This report presents electromechanical data on a broad range of high-magnetic-field superconductors. The conductors that were studied fall into three general categories: candidate conductors, experimental conductors, and reference conductors. Research on candidate conductors for fusion applications provides screening data for superconductor selection as well as engineering data for magnet design and performance analysis. The effect of axial tensile strain on critical-current density was measured for several Nb3Sn candidate conductors including the US-DPC (United States Demonstration Poloidal Coil) cable strand and an ITER (International Thermonuclear Experimental Reactor) candidate conductor. Also, data are presented on promising experimental superconductors that have strong potential for fusion applications. Axial strain measurements were made on a V3Ga tape conductor that has good performance at magnetic fields up to 20 T. Axial strain data are also presented for three experimental Nb3Sn conductors that contain dispersion hardened copper reinforcement for increased tensile strength. Finally, electromechanical characteristics were measured for three different Nb3Sn reference conductors from the first and second VAMAS (Versailles Project on Advanced Materials and Standards) international Nb3Sn critical-current round robins. Published papers containing key results, including the first measurement of the transverse stress effect in Nb3Sn, the effect of stress concentration at cable-strand crossovers, and electromechanical characteristics of Nb3Al, are included throughout the report.

Key words: axial stress effect; electromechanical; fusion; Nb3Al; Nb3Sn; stress effect; superconductor; transverse stress effect; V3Ga
Executive Summary

This report presents the results of work done for the U. S. Department of Energy, Office of Fusion Energy, during the period 1986-1993, under interagency agreement No. DE-AL01-84ER52113.

Within the windings of an energized superconducting magnet, the Lorentz force can produce large stresses that increase with magnet size and field. These stresses can significantly degrade the performance of the magnet through a reduction in the superconductor's critical-current density ($J_c$). There are two dominant stress components, a tensile stress that is aligned with the wire's longitudinal axis (axial stress) and a compressive stress that is perpendicular to its axis (transverse stress).

Presently, the most common conductor material used in high-field (>10 T) superconducting magnet designs is Nb$_3$Sn. The $J_c$ of Nb$_3$Sn is highly sensitive to its stress state. Consequently, it is the internal stress state of the magnet windings, rather than the $J_c$ of the unstressed superconductor, that determines the design limits for large high-field magnets. Electromechanical measurements of Nb$_3$Sn candidate conductors for ITER (International Thermonuclear Experimental Reactor) provide screening data for superconductor selection as well as engineering data for magnet design and performance analysis. Data are presented on several Nb$_3$Sn candidate conductors.

As new magnet designs call for larger coils and higher fields, stresses must be limited by structural reinforcement of the magnet windings. Control of the stress, which accumulates radially within the windings, requires distributed reinforcement. Aside from complicating the design and increasing the cost of the magnet, additional internal reinforcement limits the superconductor packing fraction and, thus, reduces the magnetic field. At present, the determining factors of the amount of reinforcement are not just structural, but dominated by the stress sensitivity of Nb$_3$Sn. Consequently, a superconductor less sensitive to stress than the existing high-field conductors, but comparable in $J_c$, could significantly extend the present magnet design limits. Data are presented on five experimental conductors that have strong potential for fusion applications with lowered stress sensitivity—V$_3$Ga, Nb$_3$Al, and Nb$_3$Sn superconductors with dispersion hardened copper.

The consistency of interlaboratory $J_c$ measurements of Nb$_3$Sn superconductors is typically much lower than for NbTi. This is largely due to stress effects, which are much smaller for NbTi. Since measurement inconsistency implies uncertainty in the engineering data for these conductors, it directly impacts DOE magnet designs. In response to this situation, two studies on $J_c$ measurements of Nb$_3$Sn, the first and second VAMAS (Versailles Project on Advanced Materials and Standards) international Nb$_3$Sn critical-current round robins, have been conducted. NIST participated in both of these studies, providing electromechanical data on the superconductors. The results of these measurements are presented in the Appendices.

The report has three main sections: Electromechanical Characteristics of Nb$_3$Sn Superconductors, Electromechanical Characteristics of Experimental High-Field Superconductors, and the Appendices. Within each main section, the data are presented in two formats: published papers, which present comprehensive results, and unpublished data on specific conductors.
The first section contains papers reporting seminal measurements of the transverse stress effect in Nb3Sn, a comparison of transverse stress effects in bronze-process and internal-tin Nb3Sn conductors, and the effect of concentrated transverse stress at cable-strand crossover points. Key results from these publications show that the effect of transverse stress on the $J_c$ of Nb3Sn is much greater than that of axial stress, that anisotropy in stress sensitivity is not a peculiarity associated with a specific Nb3Sn processing method, and that transverse stress data from measurements of single wires subjected to uniform stress are applicable in modeling the concentrated stress at strand crossover points in superconducting cables. Also, complete sets of axial stress data are presented for the US-DPC (United States Demonstration Poloidal Coil) Nb3Sn cable strand, the LLNL (Lawrence Livermore National Laboratory) cable-test strand, and an ITER (International Thermonuclear Experimental Reactor) candidate conductor.

The section on experimental superconductors includes a paper on stress effects in Nb3Al, where this superconducting compound was shown to be significantly less sensitive to both axial and transverse stress than Nb3Sn. Like Nb3Sn, the Nb3Al conductor was more sensitive to transverse stress than axial stress. This demonstrates that the anisotropy, which was first observed in Nb3Sn, is not associated with a particular processing method or even a particular material, but is much more general. Axial stress data are also presented for a V3Ga tape conductor that has good performance at magnetic fields up to 20 T and for three experimental Nb3Sn conductors that contain dispersion hardened copper reinforcement for increased tensile strength.

In addition to the VAMAS publications and data, the Appendices contain an excerpt from the Concise Encyclopedia of Magnetic & Superconducting Materials entitled "Superconductor Specification" and a paper on the development of an internal-tin Nb3Sn conductor for fusion applications, which is processed using hot isostatic pressure (HIP) to double its intrinsic irreversible strain limit.

Unless otherwise noted, the critical-current measurement accuracy is $\pm 2\%$. Axial strains were determined within $\pm 0.02\%$, and transverse loads were determined within $\pm 1\%$. 

Conference papers and reprints removed for separate cycling at
US-DPC Nb$_3$Sn Cable Strand

A complete set of axial strain data was obtained for the critical current of the US-DPC cable strand at magnetic fields from 10 T to 24 T. The conductor specifications are shown in Table 1, and the measured data are shown in Table 2. The data are presented graphically in Figs. 1-4. The $I_C$ and $J_C$ values are based on an electric field criterion ($E_C$) of 2 $\mu$V/cm. The results show a zero-strain 12 T value of $J_C$ (referred to the noncopper area) which was 0.54 GA/m$^2$ and a peak (strain-free) $J_C$ value of 0.62 GA/m$^2$. The irreversible strain limit was reasonably high, 0.82%, and the compressive prestrain was 0.38%. The sample did not fracture until 1.31% strain.

Table 1. US-DPC Nb$_3$Sn conductor specifications.

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
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<tbody>
<tr>
<td>Wire diameter</td>
<td>0.78 mm</td>
</tr>
<tr>
<td>Stabilizing Copper</td>
<td>54 vol.%</td>
</tr>
<tr>
<td>Noncopper</td>
<td>46 vol.%</td>
</tr>
<tr>
<td>Nb Filament</td>
<td>22.9 vol.%</td>
</tr>
<tr>
<td>Copper</td>
<td>48.7 vol.%</td>
</tr>
<tr>
<td>Tin</td>
<td>15.8 vol.%</td>
</tr>
<tr>
<td>Vanadium</td>
<td>12.6 vol.%</td>
</tr>
<tr>
<td>Local Cu:Nb Ratio</td>
<td>1.7:1</td>
</tr>
<tr>
<td>Filament Size</td>
<td>3 $\mu$m</td>
</tr>
<tr>
<td>Filament Composition</td>
<td>Nb-1 wt.% Ti</td>
</tr>
<tr>
<td>Subelements</td>
<td>18</td>
</tr>
<tr>
<td>Twist Pitch</td>
<td>2 twists per inch</td>
</tr>
</tbody>
</table>
Table 2. High-field critical current of US-DPC Nb$_3$Sn sample CRE 1087 B4H21 as a function of axial tensile strain applied at 4 K.

<table>
<thead>
<tr>
<th>$E$ (%)</th>
<th>$E_0$ (%)</th>
<th>$I_c$ (Ampere)</th>
<th>Field (Tesla)</th>
<th>$J_c$ (G/N m$^{-2}$)</th>
<th>$J_{cB}$ (G/N m$^{-3}$)</th>
<th>$I_c/I_{cm}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.00</td>
<td>-38</td>
<td>183.460</td>
<td>10.00</td>
<td>0.819</td>
<td>8.190</td>
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<td>121.140</td>
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<td>64.90</td>
<td>12.00</td>
<td>0.541</td>
<td>4.679</td>
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<tr>
<td>74.870</td>
<td></td>
<td>3.030</td>
<td>14.00</td>
<td>0.334</td>
<td>1.591</td>
<td></td>
</tr>
<tr>
<td>42.423</td>
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<td>0.644</td>
<td>16.00</td>
<td>0.189</td>
<td>0.032</td>
<td></td>
</tr>
<tr>
<td>19.799</td>
<td></td>
<td>0.356</td>
<td>18.00</td>
<td>0.088</td>
<td>0.017</td>
<td></td>
</tr>
<tr>
<td>7.209</td>
<td></td>
<td>0.169</td>
<td>20.00</td>
<td>0.088</td>
<td>0.008</td>
<td></td>
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<tr>
<td>3.753</td>
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<td>0.058</td>
<td>21.00</td>
<td>0.003</td>
<td>0.003</td>
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<tr>
<td>1.724</td>
<td></td>
<td>0.058</td>
<td>22.00</td>
<td>0.003</td>
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<td>23.00</td>
<td>0.003</td>
<td>0.003</td>
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<tr>
<td>0.18</td>
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<td>197.230</td>
<td>10.00</td>
<td>0.880</td>
<td>8.805</td>
<td></td>
</tr>
<tr>
<td>134.810</td>
<td></td>
<td>7.222</td>
<td>12.00</td>
<td>0.602</td>
<td>0.954</td>
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<td>0.23</td>
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<td>0.618</td>
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<td></td>
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<td>12.00</td>
<td>0.631</td>
<td>7.568</td>
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<tr>
<td>0.41</td>
<td>0.03</td>
<td>140.020</td>
<td>12.00</td>
<td>0.625</td>
<td>7.501</td>
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<tr>
<td>90.757</td>
<td></td>
<td>5.672</td>
<td>14.00</td>
<td>0.405</td>
<td>3.812</td>
<td></td>
</tr>
<tr>
<td>53.369</td>
<td></td>
<td>2.221</td>
<td>16.00</td>
<td>0.230</td>
<td>2.221</td>
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</tr>
<tr>
<td>27.644</td>
<td></td>
<td>1.029</td>
<td>18.00</td>
<td>0.123</td>
<td>0.051</td>
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<td>11.528</td>
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<td>0.632</td>
<td>20.00</td>
<td>0.088</td>
<td>0.030</td>
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<tr>
<td>6.746</td>
<td></td>
<td>0.344</td>
<td>21.00</td>
<td>0.016</td>
<td>0.016</td>
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<tr>
<td>3.503</td>
<td></td>
<td>0.162</td>
<td>22.00</td>
<td>0.007</td>
<td>0.007</td>
<td></td>
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<tr>
<td>1.581</td>
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<td>0.058</td>
<td>23.00</td>
<td>0.002</td>
<td>0.002</td>
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<tr>
<td>0.538</td>
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<td>24.00</td>
<td>0.002</td>
<td>0.002</td>
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<tr>
<td>0.52</td>
<td>0.14</td>
<td>132.150</td>
<td>12.00</td>
<td>0.590</td>
<td>7.080</td>
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<td>0.63</td>
<td>0.25</td>
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<td>0.72</td>
<td>0.34</td>
<td>103.970</td>
<td>12.00</td>
<td>0.464</td>
<td>5.570</td>
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<tr>
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<td>140.880</td>
<td>12.00</td>
<td>0.629</td>
<td>7.547</td>
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<td>0.40</td>
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<td>135.650</td>
<td>12.00</td>
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<td>0.52</td>
<td>75.108</td>
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<td>0.335</td>
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<td>0.45</td>
<td>0.07</td>
<td>127.270</td>
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<td>0.96</td>
<td>0.58</td>
<td>60.134</td>
<td>12.00</td>
<td>0.268</td>
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33
Table 2 cont'd

<table>
<thead>
<tr>
<th>E (%)</th>
<th>E_0 (%)</th>
<th>I_c (Ampères)</th>
<th>Field (Tesla)</th>
<th>J_c (GA/m²)</th>
<th>J_c B (GN/m³)</th>
<th>I_c/I_c m</th>
</tr>
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<tbody>
<tr>
<td>0.49</td>
<td>0.11</td>
<td>116.870</td>
<td>12.00</td>
<td>0.522</td>
<td>6.261</td>
<td>0.8273</td>
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<tr>
<td>1.07</td>
<td>0.69</td>
<td>40.730</td>
<td>12.00</td>
<td>0.182</td>
<td>2.182</td>
<td>0.2883</td>
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<td>0.53</td>
<td>0.15</td>
<td>94.625</td>
<td>12.00</td>
<td>0.422</td>
<td>5.069</td>
<td>0.6699</td>
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<td>1.17</td>
<td>0.79</td>
<td>24.363</td>
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<td>1.305</td>
<td>0.1725</td>
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<td>0.58</td>
<td>0.20</td>
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<td>1.27</td>
<td>0.89</td>
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<td>12.00</td>
<td>0.050</td>
<td>0.603</td>
<td>0.0796</td>
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<td>0.56</td>
<td>0.28</td>
<td>34.885</td>
<td>12.00</td>
<td>0.156</td>
<td>1.869</td>
<td>0.2470</td>
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Figure 1. Effect of axial tensile strain on the critical current of US-DPC Nb$_3$Sn sample CRE 1087 B4H21 at 4 K and several magnetic fields.
Figure 2. Effect of magnetic field on the critical current density of US-DPC Nb$_3$Sn sample CRE 1087 B4H21 at 4 K.
Figure 3. \((J_C \times B^{0.5})^{0.5}\) as a function of magnetic field for US-DPC Nb_3Sn sample CRE 1087 B4H21 at 0.01% and 0.23% strain.
Figure 4. Effect of magnetic field on $n^{th}$ power of US-DPC Nb$_3$Sn sample CRE 1087 B4H21 at 4 K.
Nb₃Sn LLNL Cable Test Strand

Axial strain characterization was completed for a Nb₃Sn conductor from Lawrence Livermore National Lab used in a transverse stress test of a cable-in-conduit conductor. The effect of axial strain on the critical current of the LLNL Nb₃Sn test strand was measured at magnetic fields from 8 T to 22 T. The conductor specifications are shown in Table 3, and the measured data are shown in Table 4. The data are presented graphically in Figs. 5 through 7. The $I_C$ and $J_C$ values are based on an electric field criterion ($E_C$) of 2 μV/cm. The zero-strain 12 T value of $J_C$ (referred to the noncopper area) was measured to be 0.36 GA/m² and the peak (strain-free) $J_C$ at 12 T was 0.39 GA/m². The irreversible strain limit was quite high, 1.0% strain, and the compressive prestrain was relatively low at 0.27%. Fracture strain was 1.10%.

Table 3. LLNL Nb₃Sn cable test strand specifications.

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
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<tbody>
<tr>
<td>Wire Diameter</td>
<td>0.533 mm</td>
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<tr>
<td>Local Cu:Nb Ratio</td>
<td>1.0:1.0</td>
</tr>
<tr>
<td>Copper Stabilizer</td>
<td>50%</td>
</tr>
<tr>
<td>7 Subelements</td>
<td></td>
</tr>
<tr>
<td>Filament Composition</td>
<td>1.2 wt.% Ti</td>
</tr>
<tr>
<td>Filament Dia.</td>
<td>~4 μm</td>
</tr>
<tr>
<td>Nb Diffusion Barrier with Cu Interlayers</td>
<td></td>
</tr>
</tbody>
</table>
Table 4. High-field critical current of LLNL Nb3Sn cable test strand.

<table>
<thead>
<tr>
<th>E (%)</th>
<th>Eo (%)</th>
<th>Ic (Ampere)</th>
<th>Field (Tesla)</th>
<th>Jc (6A/m$^2$)</th>
<th>JcB (6N/m$^3$)</th>
<th>Ic/Icm</th>
</tr>
</thead>
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<tr>
<td>0.00</td>
<td>-.27</td>
<td>145.290</td>
<td>8.00</td>
<td>0.650</td>
<td>5.201</td>
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</tr>
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<td></td>
<td>110.270</td>
<td>10.00</td>
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<td>12.00</td>
<td>0.350</td>
<td>4.325</td>
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<td>53.920</td>
<td>14.00</td>
<td>0.241</td>
<td>3.378</td>
<td>0.8841</td>
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<td>32.595</td>
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Figure 5. Effect of axial tensile strain on the critical current of LLNL Nb$_3$Sn cable test strand at 4 K and several magnetic fields.
Figure 6. Effect of magnetic field on the critical current density of LLNL Nb₃Sn cable test strand at 4 K.
Figure 7. Effect of magnetic field on the $n^{th}$ power of LLNL Nb$_3$Sn cable test strand at 4 K.
**Nb₃Sn ITER Candidate Conductor**

An internal-tin-process Nb₃Sn conductor, which is a prototype for the International Thermonuclear Experimental Reactor (ITER), was tested. The axial strain measurements were made over a range of magnetic fields from 15 to 25 T. The conductor specifications are given in Table 5, and the measured data are presented in Table 6 and Figs. 8 through 10. The $I_C$ and $J_C$ values are based on an electric field criterion ($E_C$) of 2 μV/cm. The results show a zero-strain 15 T value of $I_C$ (referred to the noncopper area) which was 0.50 GA/m² and a peak (strain-free) $J_C$ value of 0.55 GA/m². The irreversible strain limit was reasonably high, 0.92%, and the compressive prestrain was 0.28%. The sample did not fracture until 1.09% strain.

Table 5. ITER conductor specifications.

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Table 6. High-field critical current of Nb$_3$Sn ITER candidate conductor as a function of axial tensile strain applied at 4 K.

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<td>0.719</td>
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<td>0.808</td>
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<tr>
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</table>
Figure 8. Effect of axial tensile strain on the critical current of the ITER Nb$_3$Sn candidate conductor at 4 K and several magnetic fields.
Figure 9. Effect of magnetic field on the critical current density of the ITER candidate conductor at 4 K.
Figure 10. Effect of magnetic field on the $n^{th}$ power of the ITER candidate conductor at 4 K.
Nb$_3$Sn Conductors Reinforced with Dispersion-Hardened Copper (DHC) Alloy

The axial strain characteristics of a group of three similar experimental Nb$_3$Sn superconductors were measured over a broad range of magnetic fields. All three conductors were manufactured using the internal-tin process, and a dispersion-hardened-copper (DHC) reinforcement was used in each conductor for increased tensile strength. The first conductor has two concentric rings of stabilizing copper surrounding the noncopper core, which contains the internal tin. The inner ring is pure copper and the outer ring is DHC. The copper stabilizer makes up 72% of the conductor’s total volume. Both of the other conductors have an internal-tin ring surrounding their cores and 56% external copper stabilizer. One of the conductors uses pure copper for the stabilizer and DHC for the core’s matrix; the other conductor has the opposite configuration, a pure-copper matrix and DHC stabilizer. All three conductors have tantalum diffusion barriers between core and stabilizer. The conductor specifications are given in Tables 7 through 9. The $I_c$ and $J_c$ values are based on an electric field criterion ($E_c$) of 2 μV/cm.

The measured data for the tin-core conductor are presented in Table 10 and in Figs. 11 through 13. The large prestrain ($\epsilon_m=0.55\%$) for this conductor is caused by the high copper fraction, 72%. The $I_c$ doubles at 12 T between $\epsilon=0$ and $\epsilon=\epsilon_m$ because of the large value of $\epsilon_m$. The noncopper peak $I_c$ ($\epsilon=\epsilon_m$) at 12 T is 850 A/mm$^2$.

The measured data for the tin-ring conductors are presented in Tables 11 and 12 and in Figs. 14 through 19. The lower copper-stabilizer fraction (56%) results in a smaller prestrain for both conductors ($\epsilon_m=0.3\%$). The noncopper peak $J_c$ ($\epsilon=\epsilon_m$) at 12 T is 1120 A/mm$^2$ for the pure-copper stabilized conductor and 1030 A/mm$^2$ for the DHC stabilized conductor. The low-field n-value for the pure-copper stabilized wire is ~30 and ~20 for the other wire. This difference is probably associated with the smaller filament diameter for the DHC stabilized conductor (1.7 μm compared to 3 μm).

Table 7. DHC reinforced tin-core Nb$_3$Sn conductor specifications.

<table>
<thead>
<tr>
<th>Wire Diameter</th>
<th>0.389 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>DHC (outside)</td>
<td>33%</td>
</tr>
<tr>
<td>Copper Stabilizer</td>
<td>39%</td>
</tr>
<tr>
<td>Noncopper Core</td>
<td>28%</td>
</tr>
<tr>
<td>Nb in Core</td>
<td>~31%</td>
</tr>
<tr>
<td>Ta Barrier</td>
<td>3.8%</td>
</tr>
<tr>
<td>Filament No.</td>
<td>37 x 894 = 33078</td>
</tr>
<tr>
<td>Filament Dia.</td>
<td>0.6 μm @ 0.389 mm dia.</td>
</tr>
<tr>
<td>Local Cu:Nb Ratio</td>
<td>0.8:1</td>
</tr>
</tbody>
</table>
Table 8. Conductor specifications for DHC reinforced tin-ring $\text{Nb}_3\text{Sn}$ wire with pure-copper stabilizer.

<table>
<thead>
<tr>
<th>Component</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wire Diameter</td>
<td>0.267 mm</td>
</tr>
<tr>
<td>Noncopper Core</td>
<td>44%</td>
</tr>
<tr>
<td>DHC Core</td>
<td></td>
</tr>
<tr>
<td>Pure Copper Stabilizer</td>
<td>56%</td>
</tr>
<tr>
<td>Ta Barrier</td>
<td>8%</td>
</tr>
<tr>
<td>Nb-1.3 wt.% Ti</td>
<td>~8%</td>
</tr>
<tr>
<td>Filament No.</td>
<td>624</td>
</tr>
<tr>
<td>Filament Dia.</td>
<td>~3 μm</td>
</tr>
<tr>
<td>Local Cu:Nb Ratio</td>
<td>1:1</td>
</tr>
</tbody>
</table>

Table 9. Conductor specifications for DHC reinforced tin-ring $\text{Nb}_3\text{Sn}$ with DHC stabilizer.

<table>
<thead>
<tr>
<th>Component</th>
<th>Specification</th>
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<tbody>
<tr>
<td>Wire Diameter</td>
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<tr>
<td>Local Cu:Nb Ratio</td>
<td>0.8:1</td>
</tr>
<tr>
<td>Noncopper Core</td>
<td>44%</td>
</tr>
<tr>
<td>DHC Stabilizer (outside)</td>
<td>56%</td>
</tr>
<tr>
<td>Ta Barrier</td>
<td>8%</td>
</tr>
<tr>
<td>Nb-1.3 wt.% Ti</td>
<td>13.5%</td>
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<tr>
<td>Filament No.</td>
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<tr>
<td>Filament Dia.</td>
<td>~1.7 μm</td>
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Table 10. High-field critical current of copper-alloy reinforced tin-core Nb$_3$Sn as a function of axial tensile strain applied at 4 K.

<table>
<thead>
<tr>
<th>E (%)</th>
<th>Eo (%)</th>
<th>Ic (Amperes)</th>
<th>Field (Tesla)</th>
<th>Jc (GA/m$^2$)</th>
<th>JcB (GN/m$^3$)</th>
<th>Ic/Icm</th>
</tr>
</thead>
<tbody>
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<td>0.00</td>
<td>-.55</td>
<td>74.630</td>
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Figure 11. Effect of axial tensile strain on the critical current of DHC reinforced Nb$_3$Sn conductor at 4 K and several magnetic fields.
Figure 12. Effect of magnetic field on the critical current density of DHC reinforced Nb₃Sn conductor at 4 K.
Figure 13. Effect of magnetic field on the $n^{th}$ power of DHC reinforced Nb$_3$Sn conductor at 4 K.
Table 11. High-field critical current of DHC reinforced tin-ring Nb$_3$Sn with pure copper stabilizer as a function of axial tensile strain applied at 4 K.

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<th>E (%)</th>
<th>Eo (%)</th>
<th>Field (T)</th>
<th>Ic (A)</th>
<th>Jc (MA/m$^2$)</th>
<th>Ic/Icm</th>
<th>n value</th>
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Figure 14. Effect of axial tensile strain on the critical current of DHC reinforced Nb$_3$Sn conductor at 4 K and several magnetic fields.
Figure 15. Effect of magnetic field on the critical current density of DHC reinforced Nb$_3$Sn conductor at 4 K.
Figure 16. Effect of magnetic field on the $n^{th}$ power of DHC reinforced Nb$_3$Sn conductor at 4 K.
Table 12. High-field critical current of DHC reinforced tin-ring Nb$_3$Sn with DHC stabilizer as a function of axial tensile strain applied at 4 K.

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Figure 17. Effect of axial tensile strain on the critical current of DHC reinforced Nb$_3$Sn conductor at 4 K and several magnetic fields.

DHC Reinforced Nb$_3$Sn Tin Ring, DHC Stabilizer

$E_c = 2 \mu V/cm$

$\varepsilon_m = 0.3\%$

$\varepsilon_{irrev} = 1.1\%$
Figure 18. Effect of magnetic field on the critical current density of DHC reinforced Nb$_3$Sn conductor at 4 K.
Figure 19. Effect of magnetic field on the $n^{th}$ power of DHC reinforced Nb$_3$Sn conductor at 4 K.
V$_3$Ga Tape

We also tested an experimental high-field V$_3$Ga tape conductor manufactured in Japan, which is not available from US manufacturers. The conductor specifications are shown in Table 13. The complete set of $J_C$ vs. strain data at magnetic fields from 10 T to 19.65 T is given in Table 14, and the data are presented graphically in Figs. 20 through 22. The $I_C$ and $J_C$ values are based on an electric field criterion ($E_C$) of 2 $\mu$V/cm. This material has good $J_C$ properties out to 20 T and is a viable candidate material for extending superconducting magnets to this field range. The results show a peak (strain-free) $J_C$ that is high and nearly constant out to 20 T. The initial prestrain, however, is very low, only about 0.05%, and the irreversible strain limit is only 0.2%.

Table 13. V$_3$Ga tape specifications.

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<th>In-Situ Process</th>
<th>Cross-Sectional Dimensions</th>
<th>4 mm x 150 $\mu$m</th>
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<td>Superconductor Area</td>
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Table 14. High-field critical current of V$_3$Ga tape.

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<th>$E$ (%)</th>
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<th>$I_c$ (Ampere)</th>
<th>Field (Tesla)</th>
<th>$J_c$ (G/cm$^2$)</th>
<th>$J_{cB}$ (G/cm$^3$)</th>
<th>$I_c/I_c m$</th>
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Figure 20. Effect of axial tensile strain on the critical current of $V_3$Ga tape at 4 K and several magnetic fields.
Figure 21. Effect of magnetic field on the critical current density of $V_3Ga$ tape at 4 K.
Figure 22. Effect of magnetic field on the $n^{th}$ power of $V_3Ga$ tape at 4 K.
VAMAS Nb$_3$Sn Test Conductor

A bronze-process Nb$_3$Sn conductor was measured as part of the second VAMAS (Versailles Project on Advanced Materials and Standards) international critical-current round robin. The conductor specifications are given in Table 15. The critical current was measured as a function of magnetic field and axial tensile strain. The measured data are presented in Table 16 and in Figs. 23 and 24. The $I_c$ and $J_c$ values are based on an electric field criterion ($E_c$) of 1 $\mu$V/cm. In the first VAMAS round robin tests, differences in the test specimens' axial strain, caused by variations in the thermal contraction of different test fixtures, was a major source of interlaboratory variation in the critical-current data. Consequently, electromechanical characterization of the test specimen is important for data interpretation and error analysis. In the second round robin, the test apparatus and procedure were more rigidly specified. This increased experimental control reduced the critical-current variation by a factor of 3.5. The results of our measurements will be published in the final VAMAS report.

Table 15. VAMAS Nb$_3$Sn test conductor specifications.

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<th>Value</th>
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<td>Filament No.</td>
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Table 16. High-field critical current of VAMAS Nb₃Sn test conductor as a function of axial tensile strain applied at 4 K.

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<th>E₀ (%)</th>
<th>FIELD (T)</th>
<th>Jc (A)</th>
<th>Jc (MA/m²)</th>
<th>Ic/Icmax</th>
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Figure 23. Effect of axial tensile strain on the critical current of the VAMAS Nb$_3$Sn test conductor at 4 K and several magnetic fields.

Figure 24. Effect of magnetic field on the critical current density of the VAMAS test conductor at 4 K.