Investigation of the strain limit of Sumitomo Type HT-NX conductor and its impact on high field coil design

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Outline

1. Initial assumptions
2. Tests and findings
3. Design limits for coils
4. High-field insert coil design
5. Conclusions and next steps
1.1 Initial Assumptions - Conductor

A composite material:

Brittle superconductor filaments

Contained in a ductile matrix

Reinforced by high strength laminations

K. Kinoshita, WAMHTS1, Hamburg, May 2014
1.2 Initial Assumptions - Stress and Strain

Linear, elastic properties

Solenoid coil with self-supporting turns

B, R ~ constant through turn

\[ \epsilon_{\downarrow t} = \epsilon_{\downarrow w} + \epsilon_{\downarrow n} \]

\[ \epsilon_{\downarrow h} = \frac{BIR}{AE} \]

\[ \epsilon_{\downarrow w} = \frac{t}{2R} \]
2. Tests and findings

2.1 Tensile tests (77 K, self-field)

2.2 Double-bend tests (77 K, self-field)

2.3 Single-bend tests (77 K, self-field)

2.4 Single-turn coils with layer transition features (77 K, self-field)

2.5 Layer-wound coils (4 K, 17 T)

2.6 Barrel samples (4 K, 31 T)

Confirm SEI results

Each test is more ‘coil-like’ than predecessor
2.1 Tensile tests

100 m sample of SEI prototype conductor: Type HT-XX
Tensile tests at NHMFL by Walsh, McRae show improved results

<table>
<thead>
<tr>
<th>Specimen</th>
<th>UTS</th>
<th>Strain at failure</th>
<th>Elastic modulus</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type H</td>
<td>136</td>
<td>0.20</td>
<td>62</td>
</tr>
<tr>
<td>Reinforcement</td>
<td>1750</td>
<td>0.77</td>
<td>225</td>
</tr>
<tr>
<td>HT-XX</td>
<td>516</td>
<td>0.57</td>
<td>91</td>
</tr>
</tbody>
</table>

\[ \Delta Ic(\epsilon) = -7.5\% / \% \]

\[ E_{\text{secant}} = \frac{516 \text{ MPa}}{0.57\%} = 91 \text{ GPa} \]
2.2-3 Bend tests

Conductor samples are bent around G-10 mandrels of decreasing diameter from 3” to 1”

Samples are bent around mandrel, straightened, bent on opposite side for double bend straightened again, and then mounted to G-10

Samples are tested for Ic along length at 77 K

![Image of bend test samples]

![Graph showing critical current vs. bend diameter]

- **Conductor Ic(Bself,77K) ~ 190 A**
- **Double-bend** shows degradation below 38 mm
- **Single-bend** remains intact to 25 mm
2.4 Single-turn coils

Conductor samples are wound onto G-10 formers in diameters from 3” to 7/8”

Two sample configurations were made:
(1) Helical windings to mock up coil interior turns
(2) Helical + s-bend windings to mock up layer transition end turn

Samples were tested for $I_c(B_{self}, 77 \text{ K})$

7/8” and 1” samples not tested - Laminations broke during soldering

Kajita, et al. – Sophia, RIKEN, MT-24
2.5 Layer-wound coils

3 coils, each with 4 layers, 5 turns, 1 splice

Coil 1
51 mm
Limited by winding strain

Coil 2
83 mm
Limited by Ic

Coil 3
114 mm
Limited by hoop strain
2.5 Layer-wound coils

MagLab Cell 4: 17 T, 4.2 K

51 mm coil
I_c(17 T, 4 K) = 593 A

83 mm coil I
Premature failure
I = 325 A

83 mm coil II
I_c(17 T, 4 K) = 542 A

500 cycles
186-489 A

114 mm coil
Tested to failure
I(ε_limit) = 675 A
2.6 Barrel tests

Sample 1
15 T magnet

Sample 2
31 T magnet

Barrel 1
31.2 T magnet

Barrel 2
31.2 T magnet
## Summary of tests

<table>
<thead>
<tr>
<th>Test</th>
<th>R</th>
<th>T</th>
<th>B</th>
<th>Ic</th>
<th>σ hoop</th>
<th>ε hoop</th>
<th>Filaments</th>
<th>Laminations</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>mm</td>
<td>K</td>
<td>T</td>
<td>A</td>
<td>MPa</td>
<td>%</td>
<td>%</td>
<td>%</td>
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<td></td>
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<tr>
<td>Double-bend</td>
<td>15.9</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>0.57</td>
<td>0.57</td>
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<td>Single-bend</td>
<td>12.7</td>
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<td>0.63</td>
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<td>1.25&quot; helix</td>
<td>15.9</td>
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<td></td>
<td>0.50</td>
<td>0.82</td>
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<tr>
<td>1.25&quot; helix + s-bend</td>
<td>15.9</td>
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<td></td>
<td>0.50</td>
<td>0.88</td>
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<tr>
<td>2&quot; coil</td>
<td>25.4</td>
<td>17</td>
<td></td>
<td></td>
<td>593</td>
<td>219</td>
<td>0.31</td>
<td>0.55</td>
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<tr>
<td>3.25&quot; coil</td>
<td>41.3</td>
<td>17</td>
<td></td>
<td></td>
<td>542</td>
<td>325</td>
<td>0.19</td>
<td>0.55</td>
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<tr>
<td>3.25&quot; coil 2 fatigue</td>
<td>41.3</td>
<td>17</td>
<td></td>
<td></td>
<td>489</td>
<td>293</td>
<td>0.19</td>
<td>0.51</td>
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<tr>
<td>4.5&quot; coil</td>
<td>57.2</td>
<td>17</td>
<td></td>
<td></td>
<td>675</td>
<td>561</td>
<td>0.14</td>
<td>0.75</td>
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<tr>
<td>Barrel sample 1</td>
<td>18.5</td>
<td>31</td>
<td></td>
<td></td>
<td>492</td>
<td>242</td>
<td>0.43</td>
<td>0.70</td>
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<tr>
<td>Barrel sample 2</td>
<td>18.5</td>
<td>31.2</td>
<td></td>
<td></td>
<td>505</td>
<td>249</td>
<td>0.43</td>
<td>0.70</td>
</tr>
</tbody>
</table>

**Tensile measurements underestimate the strain limit**
2. Summary of tests

![Graph showing strain vs. radius for different coils and bend types.

- **Single Bends and Single Turn Coils**: Marked with green circles.
- **Barrels**: Marked with blue squares.
- **Coil 1**: Marked with red triangles.
- **Coil 2**: Marked with black diamonds.
- **Coil 3**: Marked with red circles.

Key labels:
- **Strain (mm/mm)**
- **R (mm)**
- **77 K**
- **4 K**
- **Coil limit**
- **Tensile test limit**
3. Design limits for coils: Strain limit load line

\[ \epsilon_{\text{limit}} = \epsilon_{\text{wind}} + \epsilon_{\text{hoop}} \]

\[ \epsilon_{\text{limit}} = \frac{t}{2R} + B_\parallel IR/AE \]

\[ I_{\text{strain}} = AE[\epsilon_{\text{limit}} - \frac{t}{2R}] / B_\parallel R \]
Stress-strain model refinements

Original model
- Self-supporting coil (dry)
- Elastic, linear
- Isotropic modulus, Poisson’s ratio (rule of mixtures)
- Peak hoop stress at \((r = a_2, z = 0)\)

1st refinement
- Monolithic coil – body forces shared through composite windings (potted)
- Elastic, linear
- Isotropic modulus, Poisson’s ratio (rule of mixtures)
- Peak hoop stress at \((r = a_1, z = 0)\)
- Wilson 4.1, Iwasa 3.6.2

2nd refinement
- Monolithic coil
- Orthotropic properties of composite \((E_r, E_z, E_\theta, \nu_r, \nu_z, \nu_\theta)\)
- Generalized Plane Strain (Markiewicz, Dixon) or FE analysis
- External reinforcement possible
Stress-strain model refinements

Series-parallel properties from insulated conductor unit cell $E,G,\nu,\alpha$
Stress-strain model refinements

Generalized plane strain / FE analysis

<table>
<thead>
<tr>
<th></th>
<th>$E$ (GPa)</th>
<th>$G$ (GPa)</th>
<th>$\nu$</th>
<th>$\alpha$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conductor</td>
<td>66</td>
<td>25</td>
<td>0.33</td>
<td>*</td>
</tr>
<tr>
<td>Laminations</td>
<td>224</td>
<td>87</td>
<td>0.39</td>
<td>*</td>
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<tr>
<td>Solder</td>
<td>50</td>
<td>18</td>
<td>0.38</td>
<td>*</td>
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<tr>
<td>Insulation</td>
<td>6</td>
<td>2</td>
<td>0.34</td>
<td></td>
</tr>
</tbody>
</table>

$E_r$ 26 $G_{iz}$ 32 $\nu_{iz}$ 0.33 *

$E_{iz}$ 84 $G_{zr}$ 27 $\nu_{zr}$ 0.33 *

$E_z$ 71 $G_{r0}$ 10 $\nu_{or}$ 0.32 *

$\epsilon_{\downarrow r}(r), \epsilon_{\downarrow \theta}(r), \epsilon_{\downarrow z}(r)$

$\sigma_{\downarrow r}(r), \sigma_{\downarrow \theta}(r), \sigma_{\downarrow z}(r)$
Design criteria

1. Use IMPDAHMA coil set – 16 T background field

2. $B_{\downarrow 0} \sim 24 \, T \, (\sim 1 \, GHz)$

3. $\Delta B/B_{\downarrow 0} < 1 \, ppm \, on \, 1 \, cm \, DSV$

4. $max(\epsilon_{total}) \leq 0.8\%$

5. $I_{\downarrow op}/I_{\downarrow c} \leq 0.8$

6. Insulated HT-NX wire – best available now
$Ic(B_{self}, 77 \, K) = 180 \, A$
4. High field insert coil design

Configure insert coil

Iterate until converged within design criteria

Stress in windings

Strain in windings

B in 1 cm DSV

B in windings

Ic in windings

(BJR)

(BJR/E)
4. High field insert coil design

- **Strain on windings at coil midplane**
  - \( \epsilon_{\text{total}} \)
  - \( \epsilon_{\text{wind}} \)
  - \( \epsilon_{\text{hoop}} \)

- **Load lines**
  - \( I_{c(B\parallel)} \)
  - \( I_{c(B\perp)} \)
  - \( I_{\text{op}} \)
  - Load lines for different field strengths

- **Design limit**
  - Indicated on the strain graph for dry and potted coils
5. Conclusions and next steps

1. Tensile and double-bend measurements underestimate the strain limit for coils

2. Analysis of coil composite part of design cycle

3. Splice development

4. Quench analysis, protection system design

5. Thick test coils in 16 T background (Q2 ‘16)

6. NMR insert coil (Q3 ‘16)
Thank you

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