Thin Large-Diameter Layer-Wound YBCO Coils at High Hoop Stress

Presented by H.W. Weijers

Collaborators
all NHMFL

SuperPower

ISS 2009, Tsukuba, Nov 3, 2009
Outline

• Introduction
• Recent developments
• 32 T magnet project
• Recent coil test results
• Discussion
• Summary
Definitions

\[ J_e = \frac{I}{\text{(conductor area)}} \]

\[ J_{ave} = \frac{N \cdot I}{\text{(winding area)}} \]

\[ J_{ave} = \lambda \cdot J_e \]

\[ \lambda = \text{fill factor} \]
Benchmarks

• For 4 to 5 cm bore magnets

• 25 T: $J_{\text{ave}} \sim 100 \text{ A/mm}^2$, $\sigma_{\text{max}} \sim 200 \text{ Mpa}$

• 30 T: $J_{\text{ave}} \sim 200 \text{ A/mm}^2$, $\sigma_{\text{max}} > 400 \text{ MPa}$
  for reasonably compact magnet

• Stress goes up significantly for larger diameters

Cross-section of an imaginary 25 T magnet based on NHMFL 21 T NMR magnet
**HTS insert coil trends**

<table>
<thead>
<tr>
<th>year</th>
<th>( B_{A+B_{HTS}=B_{total}} ) [T]</th>
<th>( J_{ave} ) [A/mm²]</th>
<th>Stress [MPa] ( J_eB_AxR_{max} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>2003</td>
<td>20+5=25 T (tape)</td>
<td>89</td>
<td>175</td>
</tr>
<tr>
<td>2008</td>
<td>20+2=22 T (wire)</td>
<td>92</td>
<td>109</td>
</tr>
<tr>
<td>2008</td>
<td>31+1=31 T (wire)</td>
<td>80</td>
<td>89</td>
</tr>
</tbody>
</table>

- Bi-2212
- \( \phi 168 \) mm OD
# HTS insert coil trends

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<th>2009</th>
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<td></td>
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<td>B_{A}+B_{HTS}=B_{total} [T]</td>
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<td>19+7.8=26.8 T</td>
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<td>379</td>
</tr>
<tr>
<td>2008</td>
<td>31+2.8=33.8 T</td>
<td>439</td>
<td>324</td>
</tr>
<tr>
<td>2009</td>
<td>20+7.2=27.2</td>
<td>211</td>
<td>314</td>
</tr>
<tr>
<td>2009</td>
<td>20+0.1=20.1</td>
<td>300</td>
<td>~670</td>
</tr>
</tbody>
</table>

- **ReBCO**: Breakthrough in $J_{ave}$ and stress tolerance

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*Bi-2212\[φ 168 \text{ mm OD}]*
HTS insert coil trends

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<tr>
<th>year</th>
<th>$B_{A}+B_{HTS} = B_{total}$ [T]</th>
<th>$J_{ave}$ [A/mm²]</th>
<th>Stress [MPa] $J_{e} \times B_{A} \times R_{max}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2003</td>
<td>20+5=25 20+2=22</td>
<td>89</td>
<td>175</td>
</tr>
<tr>
<td>2008 BSCCO</td>
<td>31+1=31</td>
<td>92</td>
<td>109</td>
</tr>
<tr>
<td>2007 YBCO-SP</td>
<td>19+7.8=26.8</td>
<td>259</td>
<td>379</td>
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<td>211</td>
<td>314</td>
</tr>
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<td>2009 YBCO-NHMFL (stress test)</td>
<td>20+0.1=20.1</td>
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</tr>
</tbody>
</table>

open symbols: BSCCO
solid symbols: ReBCO
Circles: $J_{ave}$
Triangles: Central Field

peak central magnetic field trend
peak $J_{ave}$ trend
NHMFL HTS insert projects

- 32 T YBCO+LTS research magnet
- 25 T magnet with 7 T Bi-2212 insert
### 32 T Magnet Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total field</td>
<td>32 T</td>
</tr>
<tr>
<td>Field inner YBCO coils</td>
<td>17 T</td>
</tr>
<tr>
<td>Field outer LTS coils</td>
<td>15 T</td>
</tr>
<tr>
<td>Cold inner bore</td>
<td>32 mm</td>
</tr>
<tr>
<td>Uniformity</td>
<td>$5 \times 10^{-4}$ 1 cm DSV</td>
</tr>
<tr>
<td>Current</td>
<td>186 A</td>
</tr>
<tr>
<td>Inductance</td>
<td>436 H</td>
</tr>
<tr>
<td>Stored Energy</td>
<td>7.54 MJ</td>
</tr>
</tbody>
</table>

Tentative: pancake winding for inner coil, layer winding for 2 larger HTS coils

User magnet for NHMFL milliKelvin facility
32 T YBCO Coil Parameters

<table>
<thead>
<tr>
<th>YBCO coil</th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inner radius (mm)</td>
<td>20</td>
<td>47</td>
<td>77</td>
</tr>
<tr>
<td>Outer radius (mm)</td>
<td>42</td>
<td>71</td>
<td>101</td>
</tr>
<tr>
<td>Coil length (mm)</td>
<td>144</td>
<td>240</td>
<td>340</td>
</tr>
<tr>
<td>Field increment (T)</td>
<td>5.7</td>
<td>5.7</td>
<td>5.6</td>
</tr>
<tr>
<td>$J_{\text{ave}}$ (A/mm$^2$)</td>
<td>225</td>
<td>211</td>
<td>211</td>
</tr>
<tr>
<td>Current density copper (A/mm$^2$)</td>
<td>426</td>
<td>426</td>
<td>426</td>
</tr>
<tr>
<td>Maximum stress (MPa)</td>
<td>305</td>
<td>400</td>
<td>435</td>
</tr>
<tr>
<td>Conductor length (km)</td>
<td>0.75</td>
<td>2.4</td>
<td>5.2</td>
</tr>
</tbody>
</table>

The proposal design is intended to be compact and yet practical in stress and copper content for protection.
32 T YBCO R&D topics

- Short sample → coil properties?
- Quench protection
  - Amount Cu needed
  - Heaters
- Terminals
- Joints
- Insulation
- ......
YBCO Test Coils and 32 T YBCO Coils

Images are to scale, dimensions in mm
YBCO Test Coils and 32 T YBCO Coils

- Homogeneous stress distribution:
  - Self-supporting windings
  - Special terminals to avoid winding reinforcement

- ~1.5 mm thick, 25 mm tall windings

- Standard SP4050 except:
  - 30 um Cu plating
  - More Cu than standard

- Layer wound, epoxy impregnated

- Instrumented with multiple V-taps, strain gages

3 built
YBCO stress coil 1

- Varnish insulation
- No degradation until 714 MPa (20 T, 204 A)
- Quench at 760 MPa
  - Localized damage near terminal
- Strain gages indicate
  - $E \sim 165$ GPa
  - Gauge bonding failure between 0.05 and 0.3%
- Conductor-Varnish-epoxy combination leads to some flaking at ID and OD
YBCO Stress coil 1

Ramp rate

Current [A]

time [sec]

0 500 1000 1500 2000

ramp rate [A/s]

0 0.20 0.00 -0.20 -0.40 -0.60 -0.80 -1.00 -1.20

250
200
150
100
50
0
-50
-100
-150
-200

0 50 100 150 200 250

Current [A]
YBCO Stress coil 1

- Omitting negative voltages from down ramps

First run at 20T

Spikes only occur on first run

Inductive voltage

outer joint onset ~204 A, whole coil onset ~215 A
ratio: 95%

• Only local damage
• Loss mechanism
YBCO stress coil 2

- Now strain gages mounted with STYCAST 1266
- $I_c > 620$ A at self-field
- Minor damage at outer terminal at 190 MPa
- At 16 T and 560 MPa half a turn at OD delaminates
  - 0.46 to 0.54% hoop strain measured
- Still $I_{\text{quench}}$ of 492 A
  at self-field

Graph shows many load-unload cycles

Plastic deformation
YBCO stress coil 3

- Paper and glass fiber string insulation
  - No flaking or debonding observed
  - Onset of transition at 615 A, $I_{\text{Quench}} = 683$ A
- Self-field
YBCO stress coil 3

- **Paper and glass fiber string insulation**
  - No flaking or debonding observed
- **Self-field**
  - Onset of transition at 615 A, \(I_{Quench} = 683\) A
- **Unprotected quench at 1 T**: -40% \(I_c\)
- **At 465 MPa (10 T)**: minor degradation near outer terminal (only) -4% \(I_c\)
- **No further degradation to 760 MPa**: irreversible strain level of conductor has not been reached yet.
YBCO stress coil 3

- Paper and glass fiber string insulation
  - No flaking or debonding observed
- Self-field
  - Onset of transition at 615 A, $I_{Quench} = 683$ A
- Unprotected quench at 1 T: -40% $I_c$
- At 465 MPa (10 T): minor degradation near outer terminal (only) -4% $I_c$
- No further degradation to 760 MPa: irreversible strain level of conductor has not been reached yet.
- Coil exhibits quench training
- $J_{ave} \sim 300$ A/mm² at 20T
Discussion

- 32 T user magnet funded
- Very high $J_{\text{ave}} > 30 \, \text{T} (> 460 \, \text{A/mm}^2 \text{ in small coil})$
  - Without reaching conductor limits
Discussion

- 32 T user magnet funded
- Very high $J_{ave} > 30$ T ($> 460$ A/mm$^2$ in small coil)
  - Without reaching conductor limits
- Large diameter stress coils
  - Have not reached conductor limits at 760 MPa, 0.6% strain,
    $J_{ave} = 300$ A/mm$^2$ at 20 T
    - Terminals on thin coils that provide minimal reinforcement of
      windings are difficult
  - Compares favorably with benchmark and design $J_{ave}$ and $\sigma$
    - Need to account for larger field angle (~20°) in user magnet
Discussion

- 32 T user magnet funded
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    - Terminals on thin coils that provide minimal reinforcement of windings are difficult
  - Compares favorably with benchmark and design $J_{\text{ave}}$ and $\sigma$
    - Need to account for larger field angle (~20°) in user magnet
- Repeated (protected) quenches do not affect $J_e$
  - Also at self-field
- Magnet technology in relatively early stage
Summary

• 32 T YBCO user magnet project
• Broader supporting R&D at NHMFL
  - (Starting research on HTS NMR and multi-kA cables)
• Breakthrough developments in last few years
• REBCO CC
  - Stress tolerance and $J_{ave}$ for 30 T+
Summary

• 32 T YBCO user magnet project
• Broader supporting R&D at NHMFL
  – (Starting research on HTS NMR and multi-kA cables)
• Breakthrough developments in last few years
• REBCO CC
  – Stress tolerance and $J_{ave}$ for $30^+ T$
• Much made possible by collaborations
  – Primarily SuperPower
• $30^+T$ HTS+LTS magnets viable
High field test coil

- SuperPower SP4050 conductor
  - $I_c$ (self-field, 77 K) = 129 A
- Pancake coil with soldered joints
- Glass fiber overbanding for structure
- Dry wound
  - Allow for pancake replacement
- Varnish turn-turn insulation + G-10 disks
- 24.6 mm ID, 36.8 mm OD, 46 mm high
- 10 pancakes, 380 turns total, 36 m conductor
- Tested in 31 T resistive magnet

With overbanding (later more added)
High field test coil

- SuperPower SP4050 conductor
  - \( I_c(\text{self-field, 77 K}) = 129 \, \text{A} \)
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- Operated to 325 A, 33.8 T (\( \Delta B=2.8 \, \text{T} \))
  - Limited by mechanical effects and
  - lack of cooling: trapped gas at \( B \times dB/dz > 2100 \, \text{T}^2/\text{m} \)
    - \( T > 4 \, \text{K} \), operating in superfluid helium didn't help avoiding this