HTS magnets: ready for applications or not?

From the viewpoint of 30+T magnets

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NHMFL
Applications of high-field HTS magnets

• Research magnets
• NMR magnets
• Scattering magnets
• HEP
  – Dipoles
  – Muon cooling
• Very high field hybrids

Multi-kA cable preferred
What does it take?

- Current density in windings
- Manageable stress levels

Key enabling parameters
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- Current density in windings
- Manageable stress levels
- Stability against disturbance
- Protection against quench and other fault conditions
- AC-loss/ ramping losses
- Magnetic field quality

Key enabling parameters
What does it take?

- Current density in windings
- Manageable stress levels
- Stability against disturbance
- Protection against quench and other fault conditions
- AC-loss/ramping losses
- Magnetic field quality
- Joints, terminals, insulation
- Fabrication technology
- Reliability

Desirable: Flexible architecture (I), wind-as-is
What does it take?

- For 4 to 5 cm bore magnets
  - 25 T: $J_{ave} \sim 100 \, A/mm^2$, $\sigma_{max} \sim 200 \, MPa$
  - 30 T: $J_{ave} \sim 200 \, A/mm^2$, $\sigma_{max} > 400 \, MPa$
    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
## Conductor comparison

<table>
<thead>
<tr>
<th>Property</th>
<th>Comments</th>
<th>YBCO</th>
<th>Bi-2223</th>
<th>Bi-2212</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Strength</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Current density</td>
<td>for 25 T</td>
<td>++</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td></td>
<td>for 25 T</td>
<td>++</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td><strong>Strength</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Current density</td>
<td>for <em>compact</em> 30 T</td>
<td>+</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>for <em>compact</em> 30 T</td>
<td>+</td>
<td>+/-</td>
<td>-</td>
</tr>
<tr>
<td><strong>Piece length</strong></td>
<td></td>
<td>+/-</td>
<td>++</td>
<td>+</td>
</tr>
<tr>
<td><strong>Reproducibility</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>batch-batch $I_c$</td>
<td></td>
<td>+/-</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>size/shape</td>
<td></td>
<td>?</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>transverse resistivity</td>
<td></td>
<td>?</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>anisotropy 4K, 30 T</td>
<td></td>
<td>+/-</td>
<td>+/-</td>
<td>++</td>
</tr>
<tr>
<td><strong>Flexible architecture</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>stabilizer amount</td>
<td></td>
<td>+</td>
<td>-</td>
<td>+/-</td>
</tr>
<tr>
<td>strength/reinforcement</td>
<td></td>
<td>+</td>
<td>+</td>
<td>-</td>
</tr>
<tr>
<td>width/diameter</td>
<td></td>
<td>+</td>
<td>-</td>
<td>+/-</td>
</tr>
<tr>
<td><strong>AC loss</strong></td>
<td></td>
<td>+/-</td>
<td>+</td>
<td>?</td>
</tr>
</tbody>
</table>

All have something (most), none have everything proven for 30+T right now.
Trends

- **ReBCO**: Breakthrough in $J_{\text{ave}}$ and stress tolerance
  - Sufficient for $30^+T$ ($\sim 4$ to 5 cm bore)
- **Bi-2223** commercial product
  - Most experience, including demonstration NMR
  - Considered for 1 GHz+ NMR
- **Bi-2212** wire has replaced Bi-2212 tape
  - Much progress despite limited funding, including coils tested $> 30T$
    - 300 m lengths available
    - Leakage dramatically reduced to (near) zero
  - Is the only round wire HTS conductor
  - $J_e$ sufficient for 25 T
  - Potential for $J_e$ increase
Ready for market? (modest bore solenoids)

• 25 T magnets: Bi-2223 yes, Bi-2212 close

• 30 T magnets: Bi-2223 marginal, 2212 lacking $J_e$

• YBCO: + best $J_e$ and strength
  suitable for 25 and 30 T
  + flexible architecture
  - Reproducibility/predictability beyond $J_e$: TBD
    • Fast conductor development is double-edged (not magnet pull)
    • Lengths available
  - Lack of broad experience

Hopefully very soon
What's missing for the other applications?

(beyond working out usual magnet technology details)
What’s missing for the other applications?

(beyond working out usual magnet technology details)

- High current cables !!
  - 4 K, > 20 T
  - 5, 10 , 20 kA, +
That’s it

Thank you for your attention
Ready for Market?
30 T solenoid magnets

• YBCO coated conductor
  - Has strength and current density ++
  - Piece lengths are a bit short (many joints) ~~
  - Reproducibility
    • Properties within a batch, batch-batch ?
      - Not just magnetization $J_c$: size/shape, transverse resistivity, anisotropy at 4 K, 15-30 T +
    • Conductor is developing (improving) fast -
      - What you test today is not what you buy tomorrow
  
• Customizability
  • Width, stabilizer thickness, substrate/reinforcement are (in principle) relatively easily modified without changing the sensitive parts of production √

• AC loss
  • Seems acceptable for DC magnet +
Ready for Market?
30 T solenoid magnets

- **Bi-2223 conductor**
  - Has strength and current density for 25 T
    - 30 T magnet will not be compact
  - Piece lengths are acceptable
- **Reproducibility**
  - Properties within a batch, batch-batch
    - Not just magnetization $J_c$: size/shape, transverse resistivity, anisotropy at 4 K, 15-30 T
  - Conductor design has stabilized
    - What you test today is what you buy tomorrow
- **Customizability**
  - Laminated reinforcement is relatively easily modified without changing the sensitive parts of production
    - But not width, stabilizer amount,
  - AC loss: solid state NMR possible
Ready for Market?
30 T solenoid magnets

- Bi-2212 conductor
  - Has strength and current density for 25 T
    - 30 T magnet will not be compact
  - Piece lengths are acceptable
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    - Properties within a batch, batch-batch
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  - Customizability
    - Conductor design is relatively easily modified without changing the sensitive parts of production
      - But not diameter, stabilizer amount, reinforcement
  - AC loss: solid state NMR possible
# 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] $J_eB_AR_{max}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2003</td>
<td>20+5=25 T (tape)</td>
<td>89</td>
<td>175</td>
</tr>
<tr>
<td></td>
<td>20+2=22 T (wire)</td>
<td>92</td>
<td>109</td>
</tr>
<tr>
<td></td>
<td>31+1=31 T (wire)</td>
<td>80</td>
<td>89</td>
</tr>
<tr>
<td>2007</td>
<td>19+7.8=26.8 T</td>
<td>259</td>
<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>
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*Bi-2212*  
φ 168 mm OD
HTS insert coil trends

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<tr>
<th>Year</th>
<th>BSCCO</th>
<th>YBCO-SP</th>
<th>YBCO-NHMFL</th>
<th>YBCO-SP (stress test)</th>
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- $B_{A} + B_{HTS} = B_{total}$
- $J_{ave}$ [A/mm$^2$]
- Stress [MPa] $J_{ave} \times B_{A} \times R_{max}$

- Open symbols: BSCCO
- Solid symbols: ReBCO
- Circles: $J_{ave}$
- Triangles: Central Field

**Peak central magnetic field trend**

- Bi-2212
- YBCO SP 2007 87 mm OD
- Bi-2212
- YBCO SP 2007 87 mm OD

- $\phi$ 163 mm OD
- $\phi$ 39 mm OD
- $\phi$ 38 mm OD

- 2003: BSCCO
  - 20+5=25 T (tape)
  - 20+2=22 T (wire)
- 2008: BSCCO
  - 31+1=31 T (wire)
  - 31+2.8=33.8 T
- 2007: YBCO-SP
  - 19+7.8=26.8 T
- 2008: YBCO-NHMFL
  - 31+2.8=33.8 T
- 2009: YBCO-SP
  - 20+7.2=27.2
- 2009: YBCO-NHMFL (stress test)
  - 20+0.1= 20.1

- 2003: 89, 175
- 2008: 92, 109
- 2007: 259, 379
- 2008: 439, 324
- 2009: 211, 314
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