Bi-2212 Coil Technology Development Efforts at the National High Magnetic Field Laboratory

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Part 1. 
Introduction of Bi-2212 Conductor to “Magnet Developers”

The Inside view from an ex-NI REBCO man to a Bi-2212 man
1. High and homogeneous $J_E(B)$

2. Great architectural wire and size design flexibility

3. Low magnetization: no screening current field concerns

4. Long length capability

**PIT Process is cheap without complex Bi-2223 processing**

Candidates for "30 T NMR"
We need more experiments and studies.

(D. Davis, Wed-Af-Or13-03)

5. Bi-2212 Superconducting Joint

6. Lower Tc, Easier to Protect

Bi-2212 for Magnets; Pros

Comparison of REBCO and Bi-2223 inner coil performance for high-resolution NMR magnet

<table>
<thead>
<tr>
<th>REBCO</th>
<th>Bi-2223</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hoop stress tolerance</td>
<td>Very high (e.g. 469 MPa [12])</td>
</tr>
<tr>
<td>Screening current to interfere with obtaining field homogeneity and stability</td>
<td>Large (e.g. 1.51 ppm/°C) [5])</td>
</tr>
<tr>
<td>Degradation due to electromagnetic force</td>
<td>Frequently [3,9,10,12]</td>
</tr>
</tbody>
</table>

5. Bi-2212 Racetrack Coil (tested at LBNL)

Critical current (A) vs Magnetic field (T)

Irreversibility Field (T) vs Temperature (K)

Quench current (A) vs Quench No.
Bi-2212 for Magnets; Cons

**HTS Conductors Mechanical Properties**

<table>
<thead>
<tr>
<th>Conductor</th>
<th>$\varepsilon_{\text{critical}}$ [%]</th>
<th>$\sigma_{\text{critical}}$ [MPa]</th>
<th>$E_{\text{ave}}$ [GPa]</th>
<th>Winding strain?</th>
<th>Critical Bend dia. [mm]</th>
<th>Price [$/m$]</th>
<th>Reacted?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bi-2223</td>
<td>~ 0.20</td>
<td>130</td>
<td>65</td>
<td>Yes</td>
<td>80</td>
<td>-</td>
<td>Yes</td>
</tr>
<tr>
<td>Reinforced 2223</td>
<td>~ 0.50</td>
<td>400</td>
<td>91</td>
<td>Yes</td>
<td>40</td>
<td>30~40</td>
<td>Yes</td>
</tr>
<tr>
<td>YBCO</td>
<td>~ 0.45</td>
<td>550</td>
<td>122</td>
<td>Yes</td>
<td>11</td>
<td>40~50</td>
<td>Yes</td>
</tr>
<tr>
<td>Bi-2212 (OP)</td>
<td>~ 0.50</td>
<td>160</td>
<td>32</td>
<td>No</td>
<td>&lt; 10</td>
<td>100~120</td>
<td>No</td>
</tr>
<tr>
<td>Reinforced 2212</td>
<td>~ 0.40</td>
<td>325</td>
<td>&gt; 70</td>
<td>No</td>
<td>&lt; 10</td>
<td>TBD</td>
<td>No</td>
</tr>
</tbody>
</table>

**Price breakdown of Bi-2233 and Bi-2212**

<table>
<thead>
<tr>
<th></th>
<th></th>
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<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Bi-2223 HT</td>
<td>Silver</td>
<td>~$5.3/m</td>
<td>PIT</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>~$35/m</td>
</tr>
<tr>
<td>Bi-2212</td>
<td>Silver</td>
<td>~$4.2/m</td>
<td>PIT</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>~$110/m</td>
</tr>
</tbody>
</table>

* calculated by simple conductor volume, density, and unit price of $0.52/g (2019.07)

...But Bi-2212 is still a lab-scale product that has much opportunity to reduce costs BELOW Bi-2223 in mass production.

1. Low modulus → requires strong reinforcement
2. Price
   ...like other HTS conductors

Reinforcement technologies used for HTS magnets
Left: YBCO coil with SS cowind (NHMFL)
Right: Bi-2223 standard (top) and reinforced (bottom)

[2,3,8,9]

Reinforcement technologies used for HTS magnets

1. Complex Heat treatment, but no more than Bi-2223 (E. Bosque, Wed-Mo-PL4-03)
What’s Our Inside View?

- “Hybrid” of Nb\textsubscript{3}Sn and Bi-2223
  - in common: multifilamentary architecture
  - like Nb\textsubscript{3}Sn: wind-and-react, round wire
  - like Bi-2223: silver matrix, similar HT, reinforced for magnet application

- Three big advantages
  - Long length capability: > 1 km spool
  - Low magnetization and negligible SCF
  - Low enthalpy margin makes protection much easier than for REBCO

- Its three principal disadvantages are engineering challenges.
  - Low modulus, price, and complex heat treatment
  - Bi-2223 already conquered similar problems.
Part 2.
NHMFL’s Effort for Bi-2212 Coil Technology

What we have done to improve Bi-2212 coil’s performance
Coil Development at NHMFL

- **Bi-2212 coil development at ASC**
  - Major R&D activities are carried out internally.
  - Both material and system groups are in ASC.
  - Two main investments: Furnace and Testbed magnet

  (E. Bosque, Wed-Mo-Pl4-03)

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**Bi-2212 Coil Development Work Flow**

- Conductor evaluation
  - Short sample $I_c(B)$, $I_c(\varepsilon)$
  - Microscope
  - SC joint
  - HT optimization
- Coil design
  - Parts design
  - Stress
  - Field quality
- Bobbin oxidization
- Wire insulation
  - TiO$_2$ coating
  - Braid insulation
- Winding
- Organic burn-off
- OPHT
- Impregnation
- Overbanding
- Magnet Assembly
- Operation (Test)
  - Microscope
  - HT optimization
  - Parts design
- Evaluation

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**Bi-2212 Coils**

- Deltech
  - $\Phi$ 130 mm
  - L 450 mm
  - Since 2014
- Renegade
  - $\Phi$ 250 mm
  - L 1000 mm
  - Ready in 2020
- Cryogenic LTS Magnet
  - (14 T / $\Phi$ 160 mm)
Improvement of Conductor: $J_E(B)$ and Strength

**SRW (Strengthened Rectangular Wire) by SMS, Alex Otto**

- **Cross-section of SRW**
- **SRW Stress Test Coil**
- **$J_E(\varepsilon)$ and $J_E(\sigma)$ of SRW Samples**

New powders broke the old Nexans powder’s record.
(great success supported by DOE-HEP MDP collaboration.)

Test Coil snapped at ~175 MPa

**Notes on the SRW test coil**
- The coil didn’t quench up to 495 A at 5 T.
- Short sample Ic at 5 T: 527 A
- Calculated BJR stress at the failure was ~175 MPa, while the stress created from the conductor was ~ 275 MPa.

(E. Bosque, Tue-Mo-Or8-08)
Insulation of Conductor: Two-Stage Process

- Improved Insulation Quality
  - 2014.12 w/o top coat
  - 2016.03 with top coat

- In-house insulation facility (top) and diameter measurement (bottom)

- Ag droplets extrusion through TiO₂ coating

- TiO₂ + Mullite braid: reliable, thermally resilient, and chemically compatible Insulation

- 25 µm TiO₂ coating

- (Thickness: 100 ~ 230 µm)
Coil Winding

- Coil winding technique has been modified to improve winding pack uniformity and to apply reinforcement co-winding.
Impregnation (VPI)

Cross sections of Pup-3 (2nd trial of VPI using NHMFL61)

Cross sections of a Test coil (impregnated in epoxy bath)

Filling near bottom flange: no void

Current Vacuum Pressure Impregnation Process Setup (revised from the setup in 2015 for better epoxy fill)
Part 3.
Progress of Bi-2212 Test Coils
Two Test Coils for Bi-2212 Coil R&D
1. Riky: Large bore + Thin Coil ← reinforcement technique
2. Pup: Small bore + Thick Coil ← high field insert

Specifications

<table>
<thead>
<tr>
<th>Specifications</th>
<th>Pup</th>
<th>Riky</th>
</tr>
</thead>
<tbody>
<tr>
<td>ID ; OD ; Height [mm]</td>
<td>44.0 ; 83.3 ; ~ 25.0</td>
<td>118.0 ; 127.0 ; 12.5</td>
</tr>
<tr>
<td>Turn ; Layer (Total)</td>
<td>~ 20 ; 18 (350)</td>
<td>10 ; 4 (38)</td>
</tr>
<tr>
<td>Magnet constant</td>
<td>6.58 mT/A</td>
<td>0.39 mT/A</td>
</tr>
<tr>
<td>Conductor length</td>
<td>&gt; 70 m</td>
<td>15 m</td>
</tr>
<tr>
<td>Test bed</td>
<td>14 T Cryogenic Magnet</td>
<td>8 T Cryomagnetic Magnet</td>
</tr>
<tr>
<td></td>
<td>(LHe cooled)</td>
<td>(Cryogen free)</td>
</tr>
<tr>
<td>$B_{J R}$ (I_{op} = 300 A)</td>
<td>137 MPa</td>
<td>226 MPa</td>
</tr>
</tbody>
</table>

Features and Purpose

<table>
<thead>
<tr>
<th></th>
<th>Pup</th>
<th>Riky</th>
</tr>
</thead>
<tbody>
<tr>
<td>High field insert coil</td>
<td></td>
<td>Stress test coil</td>
</tr>
<tr>
<td>Hard to make</td>
<td></td>
<td>Easy to make</td>
</tr>
<tr>
<td>Expensive to test</td>
<td></td>
<td>Cheap to test</td>
</tr>
<tr>
<td>Real Stress ≠ BJR</td>
<td></td>
<td>Real Stress ≈ BJR</td>
</tr>
</tbody>
</table>
# Progress of the Pup Coils

![Graph showing progress of Pup Coils](image)

- **Pups consistently advanced Bi-2212 coil technology.**
- **Cryo-1 and 2: from Cryomagnetics, Inc.** *(S. Minter, Mon-Mo-Or2-05)*
- **Pup-7: a new champion.** *(E. Bosque, Tue-Mo-Or8-08)*
- **New powders are beneficial to coil technology.**
- **Pup-7 also recorded the highest stress and strain.**

## Table: Coils Specifications

<table>
<thead>
<tr>
<th>Test Date</th>
<th>Wire Diameter [mm]</th>
<th>PMM #</th>
<th>Powder</th>
<th>Architecture</th>
<th>ID ; OD ; Height [mm]</th>
<th>Total Turns</th>
<th>Max. ( I_{op} ) (( B_{ext} ))</th>
<th>Max. ( J_E )</th>
<th>Total Field at Max ( J_E )</th>
<th>Max. ( BJ_{E-R} ) stress</th>
<th>Max. Stress</th>
<th>Max. Strain</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jun 2015</td>
<td>( \Phi 1.3 )</td>
<td>PMM131203-2</td>
<td>Lot 82 (Nexans)</td>
<td>121 x 18</td>
<td>44.6 ; 91.6 ; 20.3</td>
<td>270</td>
<td>230 A (17 T)</td>
<td>190 A/mm²</td>
<td>18.00 T</td>
<td>140 MPa</td>
<td>69 MPa</td>
<td>0.22 %</td>
</tr>
<tr>
<td>Feb 2018</td>
<td>( \Phi 1.0 )</td>
<td>PMM140606</td>
<td>Lot 82 (Nexans)</td>
<td>55 x 18</td>
<td>44.6 ; 86.6 ; 22.8</td>
<td>370</td>
<td>215 A (8 T)</td>
<td>299 A/mm²</td>
<td>9.48 T</td>
<td>99.2 MPa</td>
<td>65.7 MPa</td>
<td>0.26 %</td>
</tr>
<tr>
<td>Feb 2019</td>
<td>( \Phi 1.0 )</td>
<td>PMM160909-b</td>
<td>Lot 87 (Nexans)</td>
<td>121 x 18</td>
<td>44.5 ; 86.2 ; 25.5</td>
<td>333</td>
<td>245 A (14 T)</td>
<td>342 A/mm²</td>
<td>15.5 T</td>
<td>199 MPa</td>
<td>74.8 MPa</td>
<td>0.26 %</td>
</tr>
<tr>
<td>Mar 2019</td>
<td>( \Phi 0.9 )</td>
<td>PMM181004-2</td>
<td>LXB-43 (nGimat)</td>
<td>55 x 18</td>
<td>40.6 ; 70.5 ; 45.0</td>
<td>504</td>
<td>201 A (12 T)</td>
<td>316 A/mm²</td>
<td>13.8 T</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Mar 2019</td>
<td>( \Phi 0.8 )</td>
<td>PMM181004-1</td>
<td>LXB-43 (nGimat)</td>
<td>55 x 18</td>
<td>40.5 ; 68.5 ; 53.8</td>
<td>712</td>
<td>191 A (14 T)</td>
<td>417 A/mm²</td>
<td>16.2 T</td>
<td>191 MPa</td>
<td>-</td>
<td>0.27 %</td>
</tr>
<tr>
<td>Jun 2019</td>
<td>( \Phi 1.0 )</td>
<td>PMM180410-1</td>
<td>LXB-116 (nGimat)</td>
<td>85 x 18</td>
<td>44.6 ; 84 ; 25.2</td>
<td>334</td>
<td>345.8 A (14 T)</td>
<td>440.3 A/mm²</td>
<td>16.25 T</td>
<td>278 MPa</td>
<td>-</td>
<td>0.39 %</td>
</tr>
</tbody>
</table>

*not calculated because it is less than Cryo-2.
Part 4.
Future of Bi-2212 Coil Development

Pup-8
27.5 T Design / 40 T Design
What’s Next? Pup-8

- Pup-8 design was fully modified and designed to generate higher field.

<table>
<thead>
<tr>
<th>Specs.</th>
<th>Pup-7</th>
<th>Pup-8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wire</td>
<td>PMM180410-1 (nGimat)</td>
<td>Φ 1.0 mm (bare) / Φ 1.2 mm (ins.)</td>
</tr>
<tr>
<td>ID ; OD ; Height [mm]</td>
<td>44.6 ; 84 ; 25.2</td>
<td>44.5 ; 115.9 ; 40.1</td>
</tr>
<tr>
<td>Turn ; Layer (Total)</td>
<td>19 ; 18 (334)</td>
<td>30 ; 28 (859)</td>
</tr>
<tr>
<td>Conductor length [m]</td>
<td>~ 70</td>
<td>~ 216</td>
</tr>
<tr>
<td>Magnet constant [mT/A]</td>
<td>6.21</td>
<td>12.49</td>
</tr>
<tr>
<td>Inductance [mH]</td>
<td>5.92</td>
<td>39.2</td>
</tr>
<tr>
<td>Overband</td>
<td>Metal strip</td>
<td>TBD</td>
</tr>
<tr>
<td>Status</td>
<td>Tested (+ 2.3 T)</td>
<td>Heat Treated</td>
</tr>
</tbody>
</table>

Pup-8 (after OPHT)
### Design based on current equipments

- **Cryogenic 14 T / 160 mm Magnet**
- **Deltech** (Φ 130 mm hot zone)

### Bi2212
- **Type:** HT-NX
- **Coil 1**
  - **Conductor:** Bi2212
  - **a₁, a₂, 2b [mm]:** 23.0, 48.6, 149.5
  - **Layer x Turn:** 20 x 115
  - **Self field [T]:** 6.88
  - **Length [m]:** 496
  - **Innerbands:** 2
  - **Strain at Iₗₗ [%]:** 0.41
- **Coil 2**
  - **Conductor:** Bi2212
  - **a₁, a₂, 2b [mm]:** 51.0, 58.0, 296.0
  - **Layer x Turn:** 26 x 62
  - **Self field [T]:** 2.54
  - **Length [m]:** 564
- **Coil 3**
  - **Conductor:** Bi2212
  - **a₁, a₂, 2b [mm]:** 67.0, 79.0, 296.0
  - **Layer x Turn:** 44 x 62
  - **Self field [T]:** 4.11
  - **Length [m]:** 1285

### Bi2223
- **Size [mm]:** W4.6 x Thk0.36
- **Powder:** nGimat record

### Design based on future equipment

- **15 T / 260 mm Magnet** (similar to NHMFL’s 32 T outsert)
- **Renegade** (Φ 250 mm hot zone)

### Bi2212+15 T
- **BSCCO + Cryogenic 27.5 T**
- **Φ 40 mm**
References


Thank you for Listening!