Application of Bi-2212 in Prototype Wind-and-React Accelerator Magnets

Lawrence Berkeley National Laboratory

SWCC Showa Cable Systems Co., Ltd.

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Motivation

Magnetic field records in dipole magnets

- Nb$_3$Sn
- NbTi

Lietzke 2003?

New material

Leroy 1998
Intrinsic limitations NbTi and Nb$_3$Sn

Field – temperature limitations and achieved dipole fields

- **NbTi (optimized wire & magnet)**
  - 10.5 T @ 1.8 K
  - 80% of $H_{c2}^*(1.8 \text{ K})$

- **Nb$_3$Sn**
  - 16 T @ 4.5 K
  - 65% of $H_{c2}^*(4.5 \text{ K})$
  - 80% of $H_{c2}^*(4.2 \text{ K})$?
    - 20 T
  - 80% of $H_{c2}^*(1.8 \text{ K})$?
    - 22 T

- Why does Nb$_3$Sn achieve “only” 65% of $H_{c2}^*$?
Practical limitations NbTi and Nb$_3$Sn

**NbTi**
- Pinning optimized ($\alpha$-Ti)
  - $\sim$1 pinning cite/vortex
  - $F_p \propto h(1 - h)$

**Nb$_3$Sn**
- Insufficient pinning centers (grain size $\sim$150 nm)
  - Collective pinning
  - $F_p \propto h^{0.5}(1 - h)^2$
  - Reduced high field efficiency

- Practical dipole limitation is 17 – 18 T
  - Gain with improved pinning is “only” 2 – 3 T

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**Diagram:***

- NbTi: Bottura, TAS 10 (2000)
How to approach 20 T and higher

A switch to a new material is inevitable! (Even if Nb$_3$Sn pinning can be improved)

Material choices for very high field dipoles

![Graph showing current density vs. applied field for different materials](image)

- K.R. Marken, MRS meeting 2006
- High field current carrying capacity: YBCO, Bi-2212, and Bi-2223

**Dipoles: High current, low inductance Rutherford cables ➔ Bi-2212**
Bi-2212 round wire

- **NbTi** $H_{c2}^*(0) \approx 14.5$ T  $\Rightarrow$ Dipoles = 10.5 T
- **Nb$_3$Sn** $H_{c2}^*(0) \approx 28$ T  $\Rightarrow$ Dipole limit $\approx 18$ T

Dipoles achieve $\sim 2/3$ of $H_{c2}^*(0)$
- Beyond Nb$_3$Sn is 20 – 25 T
- $H_{c2}^*(0)$ required is 40 T minimum

![Normalized pinning force vs. Applied field](image)

- Trociewitz, NHMFL report 2005

Rutherford cables

- 85 T @ 4.2 K?

- Trociewitz, NHMFL report 2005
Technological challenges – 1

Challenges: Godeke et al., *TAS 17* (2007)

<table>
<thead>
<tr>
<th>Material</th>
<th>Dipole limit</th>
<th>Reaction</th>
</tr>
</thead>
<tbody>
<tr>
<td>NbTi</td>
<td>10.5 T</td>
<td>Ductile: R&amp;W</td>
</tr>
<tr>
<td>Nb₃Sn</td>
<td>17–18 T (Fₚ↑: 22 T)</td>
<td>~ 675°C in Ar/Vacuum</td>
</tr>
<tr>
<td>Bi–2212</td>
<td>Stress limited</td>
<td>~ 890°C in O₂ (± 2°C)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Material</th>
<th>Insulation</th>
<th>Construction</th>
<th>Quench propagation</th>
</tr>
</thead>
<tbody>
<tr>
<td>NbTi</td>
<td>Polyimide</td>
<td>Stainless Steel</td>
<td>&gt; 20 ms⁻¹</td>
</tr>
<tr>
<td>Nb₃Sn</td>
<td>S/R–Glass</td>
<td>Stainless Steel</td>
<td>~ 20 ms⁻¹</td>
</tr>
<tr>
<td>Bi–2212</td>
<td>Ceramic</td>
<td>Super alloy</td>
<td>~ 0.04 ms⁻¹</td>
</tr>
</tbody>
</table>

Solutions

- Chemically compatible
- Mechanically compatible
- Quench development
- Heat treatment optimization
- Oxygen flow during reaction
Technological challenges – II

Strain issues, longitudinal
- Irreversible $J_c$ reduction
- Thermal contraction matching

Strain issues, transverse
- 60 MPa transverse load limit?
- Early generation cable
- Additional measurements
- Stress management

Data from Bi-2212 tapes around 1995

-75%/

Intrinsic axial strain in Bi-2212

Ten Haken, ToM 32 (1996)

Dietderich, TAS 11 (2001)
Technological challenges – III

### Insulation options
- Fiber based sleeve / tape: OK?
- Metal – Oxides: X?
- Fiber / binder paper: OK?
- Sol – gel coatings: X?
- Plasma spray coatings: OK?

### Fiber based
- S/R Glass (Nb₃Sn)
  - Chem = X (B₂O₃), Temperature = X
- Al₂O₃/SiO₂/B₂O₃ (various combinations)
  - Chem = X (B₂O₃)
- Pure (>99.97%) SiO₂
  - Chem = X (Contaminations)
- Al₂O₃/SiO₂ 72/28
  - OK (?)
- Pure (>99%) Al₂O₃
  - Chem = OK, sleeve = X, cloth OK

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**Table 1.** Potential and observed reactivity between test oxides used in this study and BSCCO constituent oxides. Data from published phase diagrams are given as follows: C indicates systems with known binary compounds; SS indicates that a solid solution forms that has at least a few at. % solubility at 900°C; X indicates no compound or solid solution forms; NPD indicates no phase diagram was found in the literature. The observed reactivity of the test oxides with BSCCO cations by solid-state diffusion through the Ag sheath is defined s follows: U is a non-reactive oxide; R is a reactive oxide and the compound or solid solution that formed is shown; Ag indicates an oxide that reacts with the Ag sheath.

<table>
<thead>
<tr>
<th>Test oxide</th>
<th>BSCCO constituent oxides</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Bi₂O₃</td>
</tr>
<tr>
<td>Ca₂ZrO₆</td>
<td>C</td>
</tr>
<tr>
<td>SrZrO₆</td>
<td>C</td>
</tr>
<tr>
<td>SiO₂-based</td>
<td>—</td>
</tr>
</tbody>
</table>

*The phase diagrams for Ca₂ZrO₆ or SrZrO₆ and each of the BSCCO oxides are not available. The possibility of chemical reactions occurring is based on CaO or SrO from the zirconate reacting with each constituent BSCCO oxide.

*b The same compounds could form as with pure SiO₂ plus additional compounds could form under reactions with other oxides in the glass.

*c Data are not reported for the CeO₂, Zr₂O₅, NiO, and MgO-rich side of the Bi₂O₃–MO₃ phase diagram.

W&R Bi-2212 magnet program

- **2x6 turn stand-alone**: 2.6 T
- **Bi-2212 common coil**
- **Bi-2212 dipole**: 5.8 T

- **2x19 turn stand-alone**: 4.9 T
- **Bi-2212 – Nb₃Sn hybrid dipole**: 6.6 T

- **Bi-2212 – Nb₃Sn hybrid dipole**: 8.5/9.9 T
Magnetic fields and forces

<table>
<thead>
<tr>
<th>Layout</th>
<th>Turns</th>
<th>$\mu_0 H [T]$</th>
<th>$I_{ss} [A]$</th>
<th>$L [mH]$</th>
<th>$P_x [MPa]$</th>
<th>$P_y [MPa]$</th>
<th>$P_z [MPa]$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bi–2212 stand alone</td>
<td>2 × 6</td>
<td>2.6</td>
<td>6213</td>
<td>0.036</td>
<td>1.1</td>
<td>0</td>
<td>1.9</td>
</tr>
<tr>
<td>Bi–2212 stand alone</td>
<td>2 × 19</td>
<td>4.9</td>
<td>5179</td>
<td>0.25</td>
<td>9.7</td>
<td>0</td>
<td>9.4</td>
</tr>
<tr>
<td>Bi–2212 common coil(a)</td>
<td>2 × 19</td>
<td>5.8</td>
<td>4948</td>
<td>0.28</td>
<td>27</td>
<td>7.5</td>
<td>15</td>
</tr>
<tr>
<td>Bi–2212 dipole(a)</td>
<td>2 × 19</td>
<td>6.6</td>
<td>4777</td>
<td>1.2</td>
<td>1.6</td>
<td>14</td>
<td>3.2</td>
</tr>
<tr>
<td>1× Bi–2212 / 2× Nb$_3$Sn hybrid dipole(ab)</td>
<td>2 × 19 (Bi–2212)</td>
<td>8.5</td>
<td>4595</td>
<td>2.4</td>
<td>34</td>
<td>0</td>
<td>20</td>
</tr>
<tr>
<td>2 × 20 (×2 Nb$_3$Sn)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1× Bi–2212 / 2× Nb$_3$Sn hybrid dipole(ac)</td>
<td>2 × 19 (Bi–2212)</td>
<td>9.9</td>
<td>4486 (Bi–2212)</td>
<td>4.4</td>
<td>34</td>
<td>0</td>
<td>20</td>
</tr>
<tr>
<td>2 × 20 (×2 Nb$_3$Sn)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\(a\) With an iron insert inside the Bi–2212 subscale island
\(b\) Bi–2212 and Nb$_3$Sn in series connected and Bi–2212 limited
\(c\) Bi–2212 and Nb$_3$Sn driven independently

Dietderich, TAS 11 (2001)

~ 5000 A
Subscale coil manufacture

- Strand ➔ Cable
- $\text{Al}_2\text{O}_3/\text{SiO}_2$ Sleeve ➔ Sizing removal ➔ on cable
- Wind coil on INCONEL alloy 600 island
- Enclose with Alloy 600 heat treatment package
- Ship to Showa for heat treatment
8 coils manufactured

<table>
<thead>
<tr>
<th>Coil ID</th>
<th>Cable</th>
<th>Insulation</th>
<th>Sizing</th>
</tr>
</thead>
<tbody>
<tr>
<td>HTS-SC01</td>
<td>Ag-alloy dummy</td>
<td>Pure SiO₂</td>
<td>Present</td>
</tr>
<tr>
<td>HTS-SC02</td>
<td>Ag dummy</td>
<td>Pure SiO₂</td>
<td>Present</td>
</tr>
<tr>
<td>HTS-SC03</td>
<td>Untwisted Showa strand</td>
<td>Al₂O₃/SiO₂</td>
<td>Present</td>
</tr>
<tr>
<td>HTS-SC04</td>
<td>Untwisted OST strand</td>
<td>Al₂O₃/SiO₂</td>
<td>Present</td>
</tr>
<tr>
<td>HTS-SC05</td>
<td>Twisted Showa strand</td>
<td>Al₂O₃/SiO₂</td>
<td>600°C/1h*</td>
</tr>
</tbody>
</table>

* Sizing removal reaction on insulation prior to insulating the cable

Twisted Showa strand – Al₂O₃/SiO₂ – Cleaned @ 825°C/4h

- HTS-SC07
- HTS-SC09
- HTS-SC11

Various degrees of confinement

HT optimization
Heat treatment optimizations

- Dummy coil, and dummy coil with wires and cable sections

\[ \Delta T = \pm 1^\circ C \]

Criterion:
\[ 1 \mu V/cm \]

\[ I_c(\text{end to end}) = 381 A \]

\[ V = 45 \text{mm (1 pitch)} \]

\[ 64 K, \text{ self-field} \]
Leakage occurred
- Not at the leads
- But inside the package
- More severe at straight sections
  - Better confined

Leakage is **absent** in HT optimizations and insulated “free” wires and cables
Leakage: EDX on colored insulation

- From lightest off-white through yellow, brown, and black
  - Mainly increasing Cu

C most probably arises from C tape for sample mounting
Origin of leakage?

Non-confined wires and cables exhibit no leakage
  - Chemical compatibility is apparently OK

Confined winding pack exhibits leakage
  - Mechanical
    - Cable expansion during heat treatment
    - Ag-alloy expansion larger than INCONEL alloy 600
      - Both are presently not accounted for
  - Oxygen household in package (too little lowers melt $T$)
    - Remaining sizing $\Rightarrow$ Oxygen depletion through burn-off
      - 0.4 gram sizing on 7 m insulated cable
      - Organic sizing $\Rightarrow$ assume 50% H and 50% C plus $O_2 \Rightarrow H_2O$ and $CO_2$
      - Requires about 1.2 gram $O_2 \Rightarrow 2$ L/h (1 atm, 300K)
    - No remaining sizing $\Rightarrow$ insufficient $O_2$ flow
  - Free $Cr_2O_3$? (E. Hellstrom)
Test: Free versus confined cables

- Load structure to simulate winding pack with single cable

- Free vs. confined ➔ clear difference
Summary

- Progress in W&R Bi-2212 accelerator magnet technology
  - 8 subscale coils manufactured
    - Three in HT with varying degree of confinement
  - \( \text{Al}_2\text{O}_3/\text{SiO}_2 \) 72%/28% insulation with 80 \( \mu \text{m} \) wall thickness
    - Sizing removed before application to cable \( \Rightarrow \text{Nb}_3\text{Sn} \)?
    - Chemically compatible if not confined in Inconel package
  - Inconel alloy 600 package
    - Favorable thermal contraction

- Coils exhibit leakage
  - Due to confinement
  - Mechanical and/or Oxygen related?
    - Chemical might also still be an issue inside a package
  - Solvable