Title
To Crack or Not to Crack: Strain in High Temperature Superconductors

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Author
Godeke, Arno

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To Crack or Not to Crack: Strain in High Temperature Superconductors

Arno Godeke
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With kind contributions from

Najib Cheggour (NIST)
Danko van der Laan (NIST)
Shlomo Caspi (LBNL)

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Motivation

Magnetic field records in dipole magnets

- Bi-2212
- Nb₃Sn
- Lietzke 2003?
- NbTi
- Leroy 1998
How do Nb$_3$Sn magnets work?

Example: LARP Quad TQS01
- Ti-6Al-4V poles
- 8 W&R cos $\Theta$ coils
- 90 mm bore, > 220 T/m

Reversible strain!

Caspi, MT20: 4LX03 (2007)
Why do Nb$_3$Sn magnets work?

Reversible axial strain dependence

Reversible means:
- $\Delta \varepsilon \Rightarrow \Delta N(E_F), \Delta \lambda_{ep}$
- $\Delta T_c$ and $\Delta H_{c2}$
- $\Delta J_c$
- Slope depends on $H$ and $T$

Godeke, *SuST* 19 2006
How can magnets fail?

‘Preliminary’ $J_c$ collapse
- Irreversible
- Crack formation

Axial strain tests IT wire:

Bend tests IT wire:


This workshop!
Limitations of NbTi and Nb$_3$Sn

- Nb$_3$Sn dipoles are limited to 17 – 18 T
  - Provided that strain can be handled

A switch to Bi-2212 is inevitable: $\mu_0 H_{c2}^*(4.2 \text{ K}) \approx 85 \text{ T}$
Towards new magnetic field records

Bi-2212 W&R subscale magnet program

<table>
<thead>
<tr>
<th>Material</th>
<th>Reaction</th>
<th>Insulation</th>
<th>Quench</th>
</tr>
</thead>
<tbody>
<tr>
<td>NbTi</td>
<td>Ductile R&amp;W</td>
<td>Polyimide</td>
<td>&gt; 20 ms⁻¹</td>
</tr>
<tr>
<td>Nb₃Sn</td>
<td>675°C Ar/Vacuum</td>
<td>S/R glass</td>
<td>~ 20 ms⁻¹</td>
</tr>
<tr>
<td>Bi-2212</td>
<td>890±2°C O₂</td>
<td>Ceramic</td>
<td>&lt; 0.05 ms⁻¹</td>
</tr>
</tbody>
</table>

**Table: Wind-and-React Bi-2212 subscale coil test configurations**

<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 × Nb₃Sn hybrid dipole(^b)(^c)</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 Nb₃Sn)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
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<td>1 × Bi-2212 / 2 × Nb₃Sn hybrid dipole(^b)(^c)</td>
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<td>9.9</td>
<td>4486 (Bi-2212)</td>
<td></td>
<td>34</td>
<td>0</td>
<td>20</td>
</tr>
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</tr>
</tbody>
</table>
Typical axial tensile behavior in Bi-2212

Axial strain dependence early (~1993) 2212 tapes

- Independent of \( H \) and \( T \)
- **Always** irreversible
  - Crack formation
- \( J_c \) collapse point depends on pre-strain

\[ \text{Pre-strain} \quad 0.2 - 0.4\% \]

\( J_c \) collapse

Generalized axial strain behavior in Bi-2212

3 regions

I and III
- $J_c$ collapses
- Significant cracks

II
- Quasi constant
  - (Still irreversible)
- Quasi-elastic behavior
- Small cracks?
- Length corresponds to pre-strain

Fig. 1. The normalised critical current as a function of the axial strain. Measured on different samples for compressive and tensile strains (measured at 4.2 K and 8 or 16 T).

A model for axial strain behavior in Bi-2212

Model...

...and measurement

All axial compressive strain irreversibly reduces $J_c$

Ten Haken, *ToM* 32 (1996)
Repetitive ‘low’ strain variations

- All strain irreversible

Fig. 5. The $I_c$ versus strain in two samples of conductor A. First a cyclic deformation between 0 and 0.28% axial strain and then between 0 and -0.28% strain. The solid and dotted line follows the measuring sequence. The solid lines indicate two sequential $I_c$ measurements and a dotted line is used when one or more strain cycles are skipped.

Ten Haken, TAS, 1997
Are these ‘cracks’ real...? (~1996)

Axial strain measurement on Bi-2212 tapes:
- With strain gauge
  - Direct
- With X-ray
  - Indirect
Are these ‘cracks’ real…? (~1996)

Apply external axial strain
- Shift in $2\Theta$ for 0020 peak
  - Proportional to strain in $c$ direction (if elastic)
  - $\varepsilon_y = -\nu_y \varepsilon_z \propto -2\Theta$

Yes, these cracks are real (~1996)

Strain behavior

- c-axis compression with axial tensile strain
  - Elastic up to +0.2% axial
    - $\varepsilon_z \propto 2\Theta$
  - Cracks above +0.2% axial

At $J_c(\varepsilon_{\text{axial}})$ plateau
- $c$-axis deformation proportional to $\varepsilon_{\text{axial}}$
- Elastic behavior

Outside $J_c(\varepsilon_{\text{axial}})$ plateau
- $c$-axis is constant
- Elastic behavior disappears
- Crack formation

Ten Haken, PhysC, 1996
MOI on strained HTS: Cracks

Unstrained Bi-2212

Strained Bi-2212

Filament
Filament + pinhole
Filament

Strained Bi-2223

MOI and $J_c$ on strained HTS: Cracks

Magnets made from HTS?

How are we supposed to set new magnetic field records with HTS materials that break into pieces under load?
IGC Bi-2212 round wire, 7x61 filaments
Courtesy of Najib Cheggour – NIST

∅ 0.81 mm; Non optimized HT

∅ 0.81 mm; Optimized HT

Rise!
Curvature!
Showa Bi-2212 round wire
Courtesy of Najib Cheggour – NIST

∅ 0.57 mm; 19x37 filaments; Non optimized HT

∅ 0.82 mm; 7x127 fil; Optimized HT

Modern wires appear much better than 1st generation tapes

Rise and curvature!
What we need!

- Very much like Nb$_3$Sn
- No crack behavior
  - (but electronic in origin…?)

See:

- Van der Laan, *APL* 90 (2007)
- Talk this workshop

Could we get this in a wire…?
Summary

- (Accelerator) Magnet community prefers reversible strain behavior
  - Though we could work around some irreversible reduction
    - NMR type HTS insert magnets at NHMFL

- Crack formation dominates in (early generations) HTS tapes

- Latest generation wires appears much more promising

- YBCO rocks! (but for accelerator magnets we need wires…)
Spare slides on transverse pressure
A quick note on transverse pressure…

On short tape samples
- Worrying?

On cables
- OK!
  - Sensitive to proper experiment

Fig. 4 The relative current density as a function of the transverse pressure at 4.2 K.

Ten Haken, TAS 3 (1993)

Unpublished ~1993
Transverse pressure on Bi-2212 tapes

From the ‘House of Horrors’… ➤ Very discouraging!

Ten Haken, TAS, 1993; PhD thesis, 1994

Figure 6.16: The normalised critical-current reduction of the Bi-2212 tape conductor (T-19) subjected to a transversal pressure, measured on the $F_{c} / B$ transverse press. The measured $I_c(\sigma_t)$ is compared with two lines representing the calculated $I_c$ versus pressure dependence for two different Young’s moduli ($E_{eff} = 20$ and $3.5$ GPa).
Transverse pressure on Bi-2212 cables

Better than tapes…
- …but insufficient?
- Limited to 60 MPa broad face load?

Fig. 3. Variation of the critical current (4 T, 4 K) with stress for a cable loaded on the broad face of the cable.

Fig. 4. Variation of the critical current (self-field, 4 K) with stress for a cable loaded on the edge of the cable.

Dietderich, TAS, 2001