## Title
Materials for Very High Field Dipole Magnets



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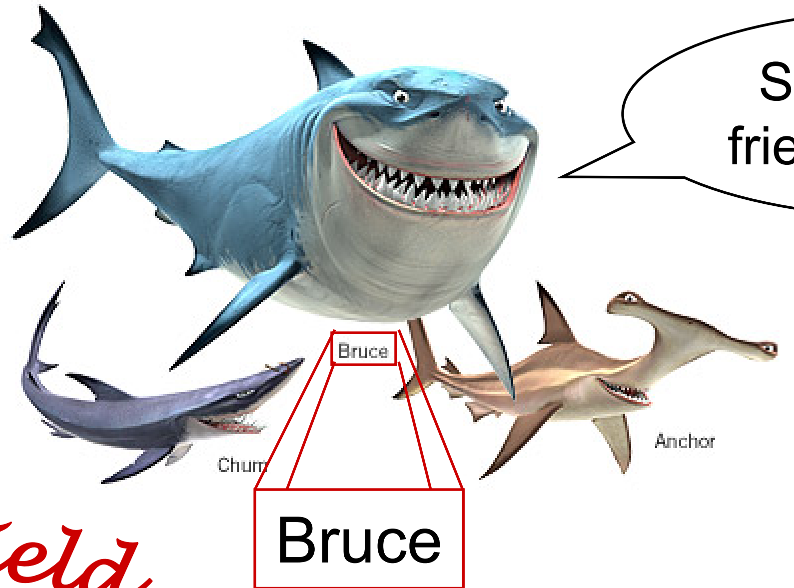
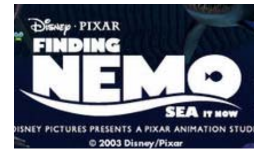
# High Temperature Superconductors for Very High Field Dipole Magnets

*A. Godeke, D.R. Dietderich, S.O. Prestemon, and G. Sabbi*

**LTSW07 – South Lake Tahoe, CA**
**October 30, 2007**

*Funded by the US Department of Energy under contract No. DE-AC02-05CH11231*




Field

# High ~~Temperature~~ Superconductors for Very High Field Dipole Magnets

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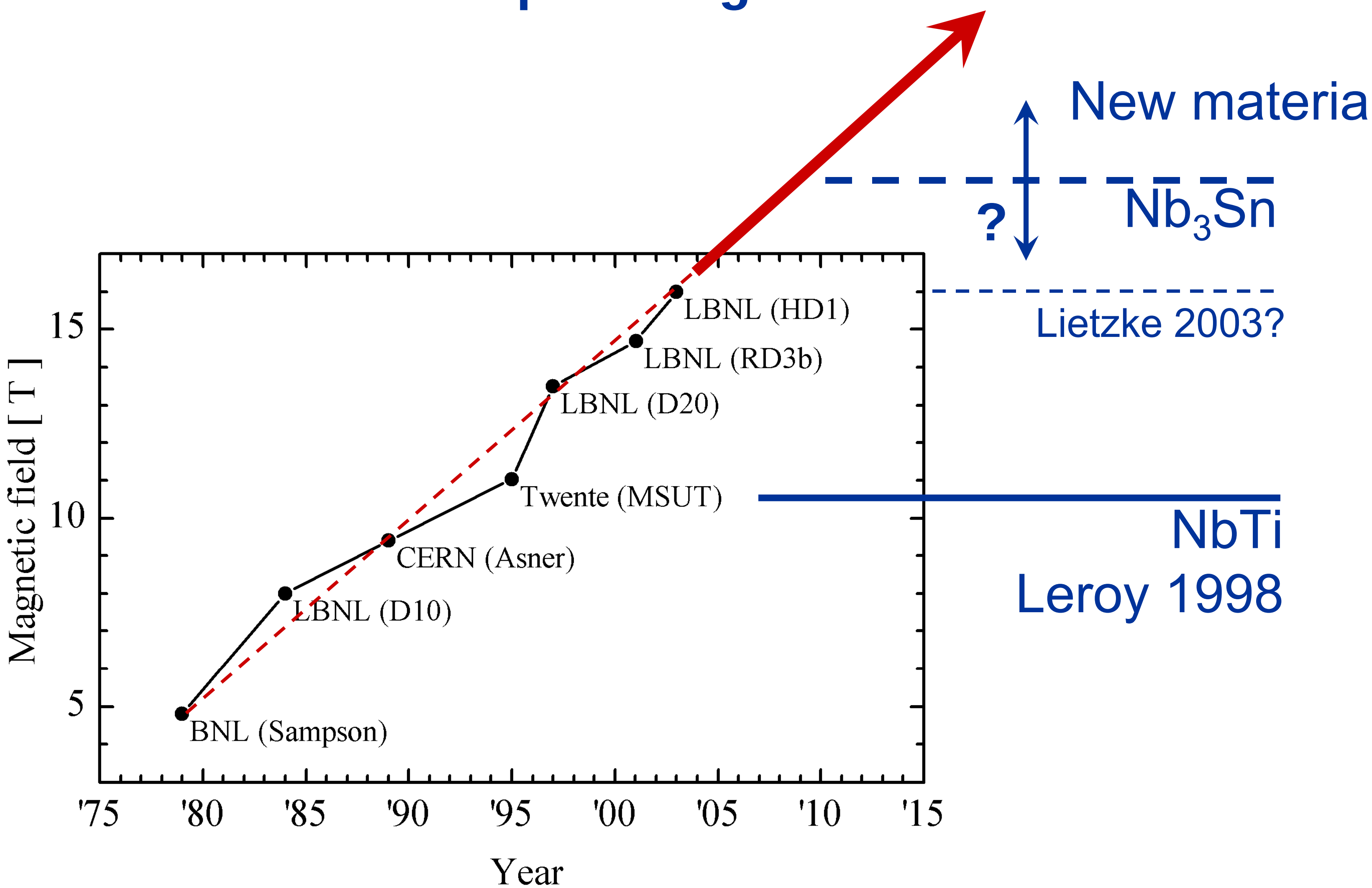
# Motivation

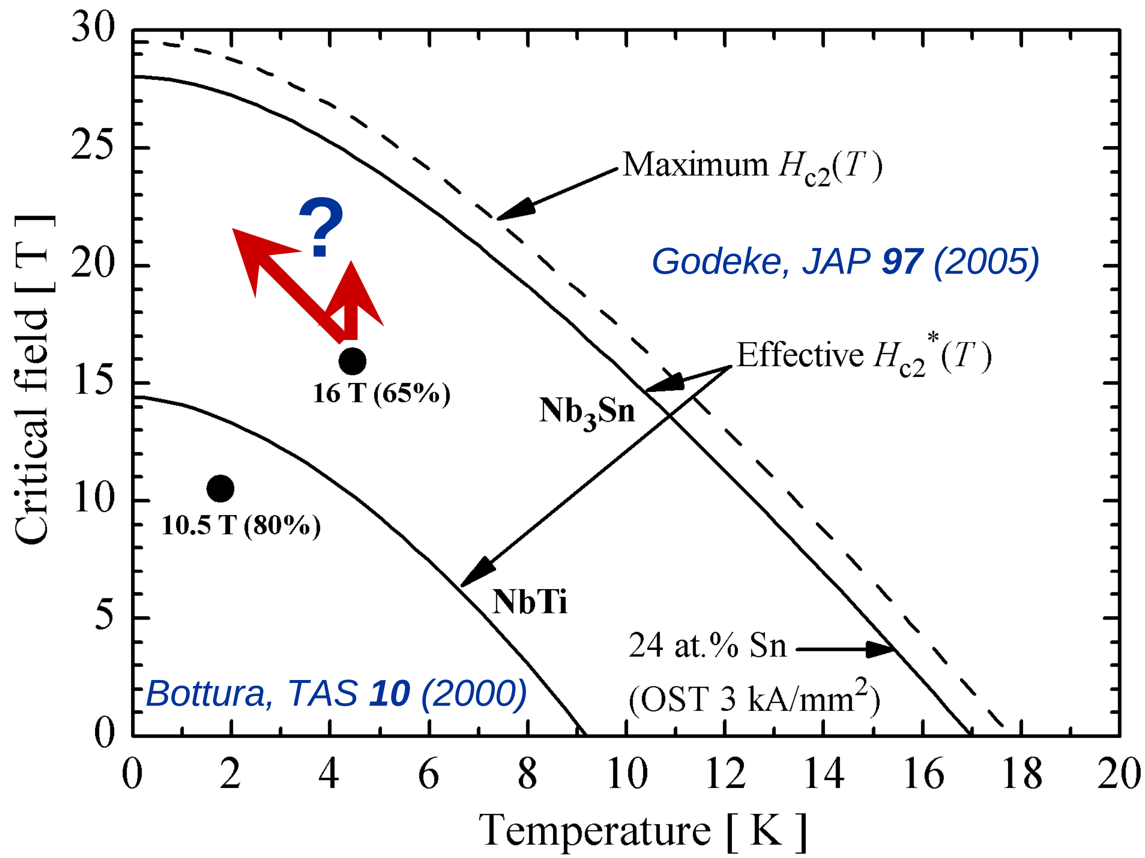
## Magnetic field records in dipole magnets



# Intrinsic limitations in NbTi and $Nb_3Sn$

## Field – temperature limitations and achieved dipole fields

- NbTi
  - 10.5 T @ 1.8 K
  - 80% of $H_{c2}$*(1.8 K)
- $Nb_3Sn$
  - 16 T @ 4.5 K
  - 65% of $H_{c2}$*(4.5 K)
  - 80% of $H_{c2}$*(4.2 K)?
    - 20 T
  - 80% of $H_{c2}$*(1.8 K)?
    - 22 T
- Why does $Nb_3Sn$ achieve "only" 65% of $H_{c2}$*?



# Practical limitations in NbTi and $Nb_3Sn$

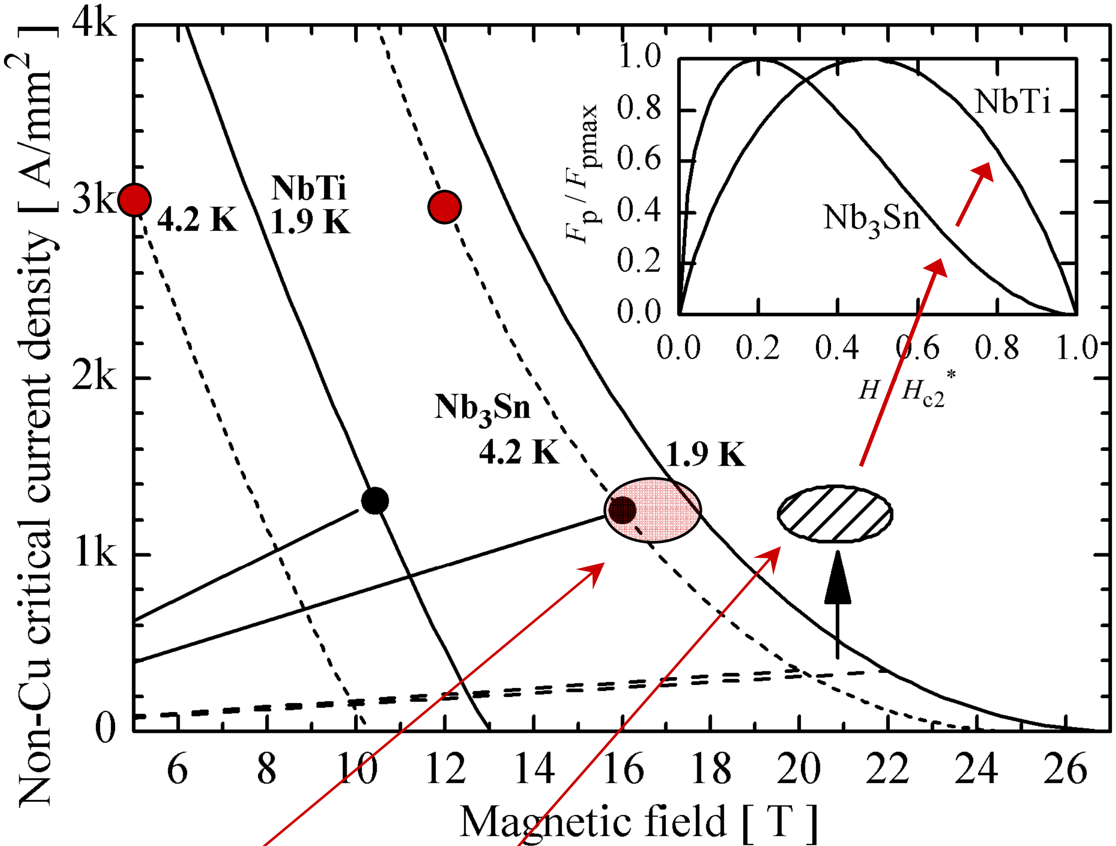
## NbTi

- Pinning optimized (α-Ti)
  - ~1 pinning cite/vortex
  - $F_p \propto h(1 - h)$

## $Nb_3Sn$

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

NbTi: *Bottura, TAS **10** (2000)*
$Nb_3Sn$: *Godeke, SuST **19** (2006)*

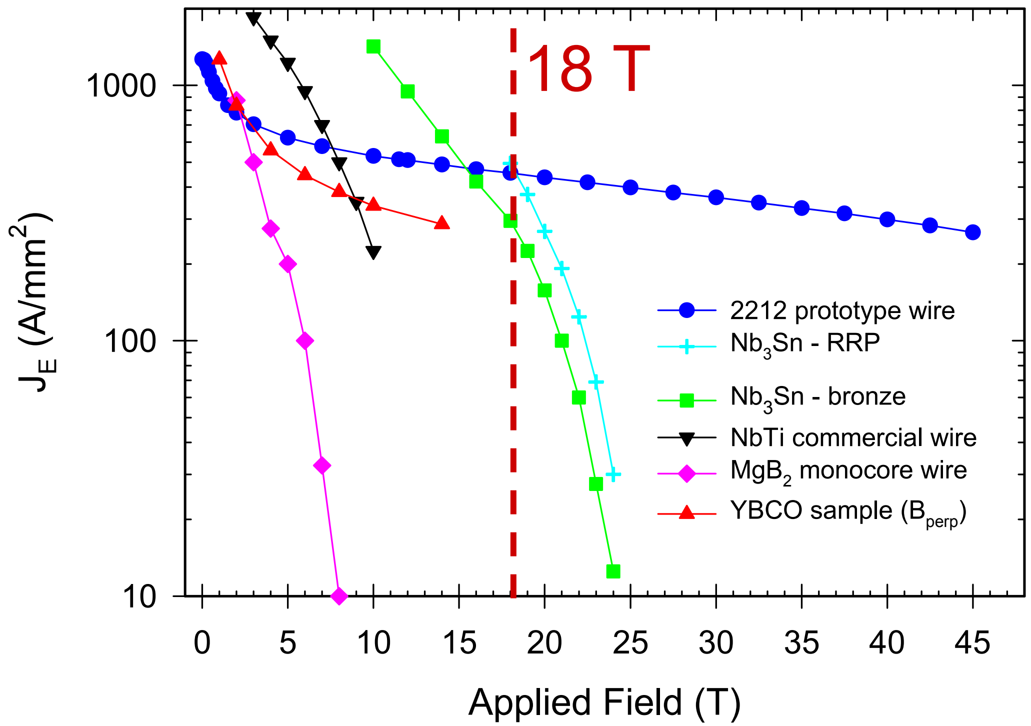



- Practical dipole limitation is 17 – 18 T
  - Gain with improved pinning is “only” 2 – 3 T

# How to approach 20 T and higher

**A switch to a new material is inevitable!** **(Even if $Nb_3Sn$ pinning can be improved)**

## Material choices for very high field dipoles




- K.R. Marken, MRS meeting 2006

- High field current carrying capacity: YBCO, Bi-2212, and 2223

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

# Approaching 20 T in dipole magnets

## Conductor specifications

- Short term (to become of interest)
  - *Effective* $H_{c2}$
  - *Engineering* current density
  - A *wire, filaments/subelements,* low resistive matrix
  - Brittle ➔ *W&R* process
  - *Homogeneous* $J_E$ over a certain *length*

- Long term (what is actually needed)
  - Transposed filaments
  - Cabling enabled
  - Reversible strain dependence, withstand *P_|_*
  - N-value
  - Minimum piece length
  - Price

# Effective $H_{c2}$*(0) above 40 T

## NbTi

- $H_{c2}$*(0) ≈ 14.5 T ➔ Dipole record = 10.5 T

## $Nb_3Sn$

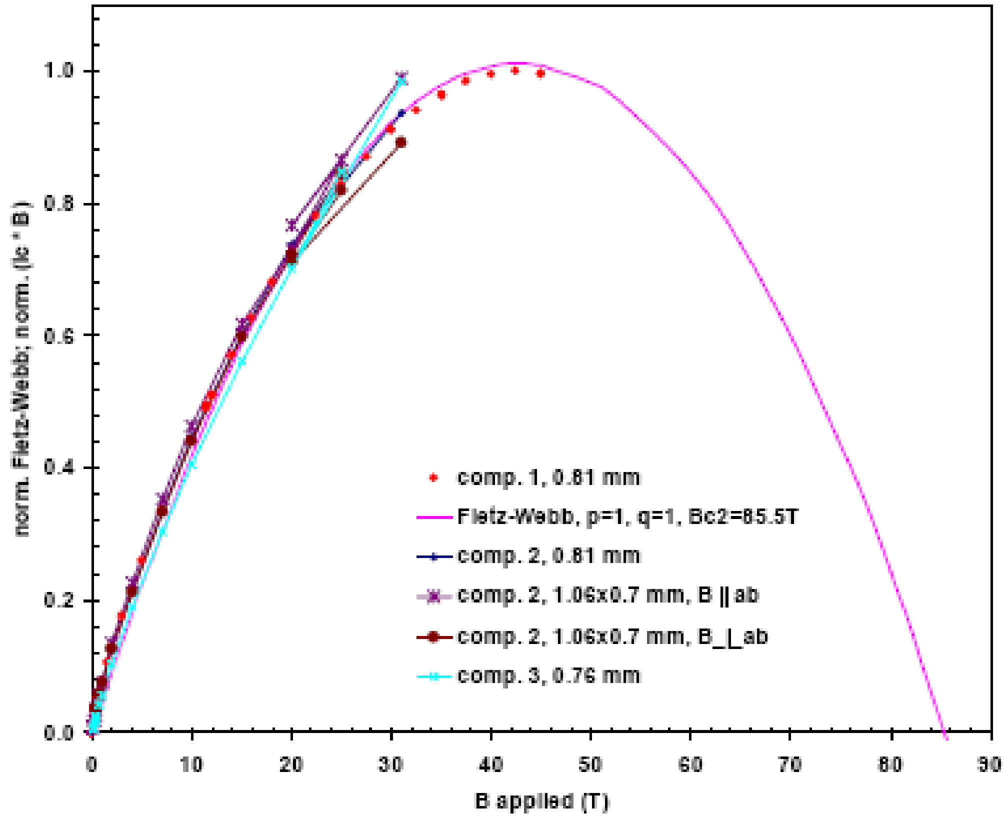
- $H_{c2}$*(0) ≈ 28 T ➔ Dipole limit ≈ 18 T

## Dipoles achieve ~ 2/3 of $H_{c2}$*(0)

- Beyond $Nb_3Sn$ is 20 – 25 T
- $H_{c2}$*(0) required is 40 T minimum

## Trociewitz, 2005 NHMFL report

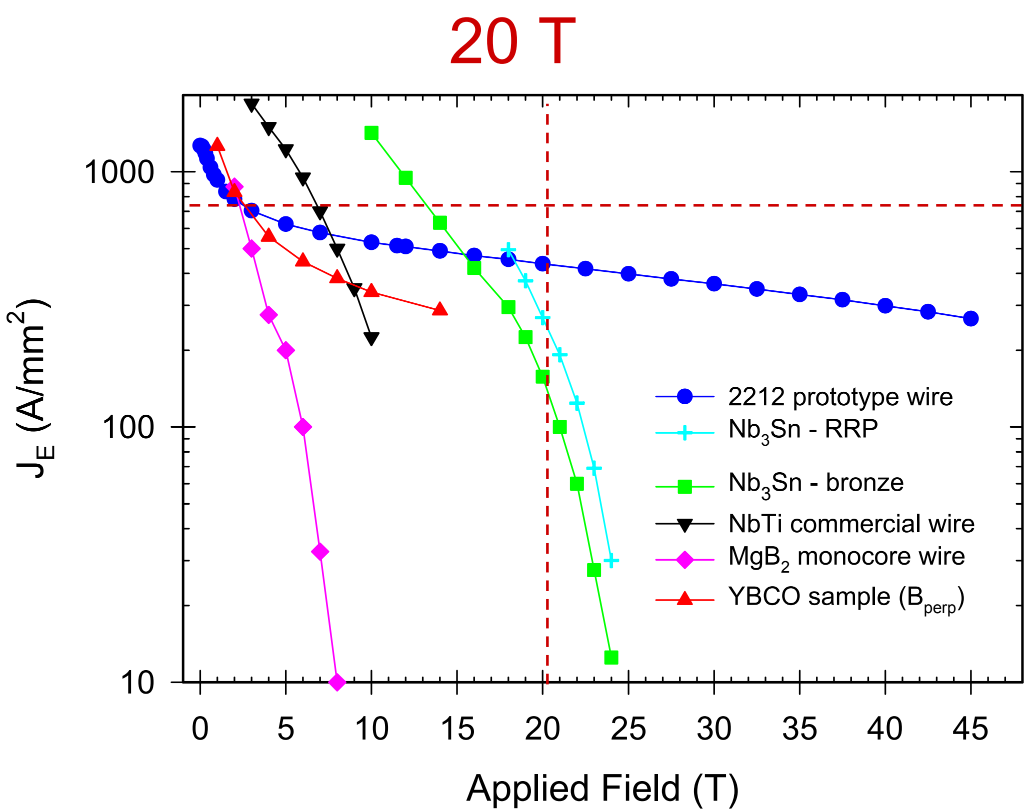
- $H_{c2}$*(4.2 K) ~ 85 T in Bi-2212
- Very “NbTi-like” pinning curve (**?**)



# $J_E$ > 750 Amm$^{-2}$ at 20 T, 4.2 K

## Existing Bi-2212 RW

- 25% of cross-section is superconductor
- How much of this 25% carries current? (3%, 5%,..?)

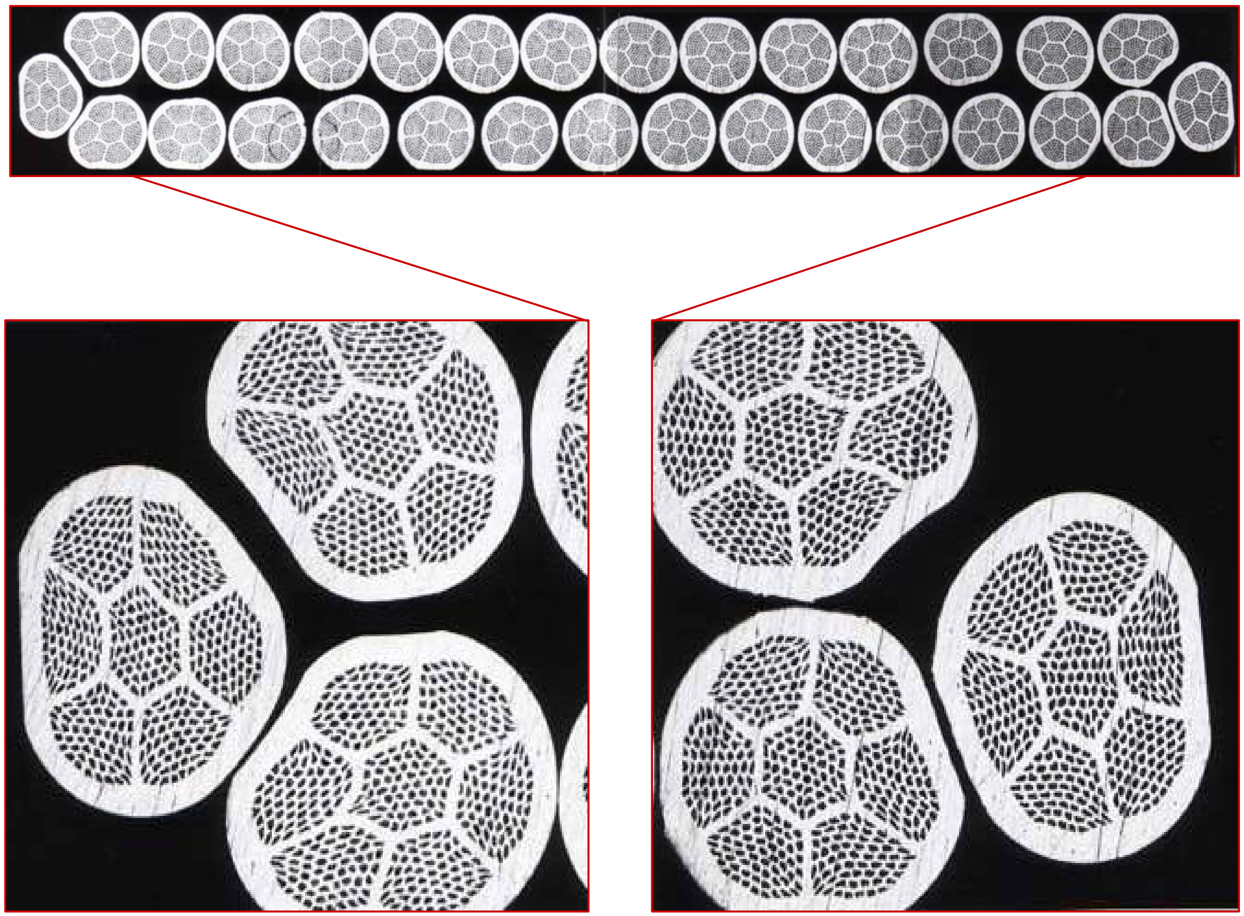



750 Amm$^{-2}$
(~ +50%)

# Cabling enabled

## Cabled Bi-2212 RW

- Cabling OK

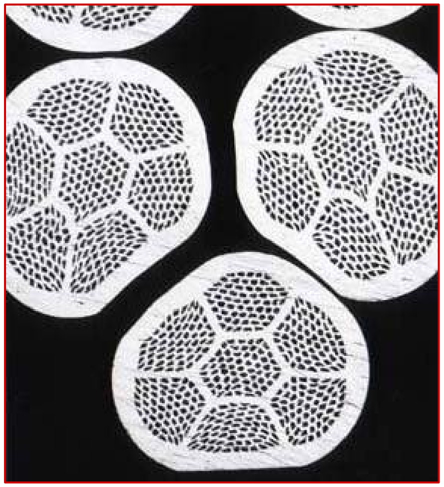


# Filaments / subelements, matrix

**Smallest SC volume ➔ 'intrinsic' stability**

- Filaments sinter together (…*but form an open web*)
  - Subelement diameter
  - Typical guide diameter $Nb_3Sn$ is 40 μm
- Exact value depends on thermodynamics
- 100 μm subelement seems for now reasonable target

- 800 μm wire



**Ag (alloy) matrix ➔ 'dynamic' stability**

- Rho(300 K) < 2 μΩcm
- RRR > 50 (measurement??)
- Stable electric field > $10^{-4}$ $Vm^{-1}$ ?

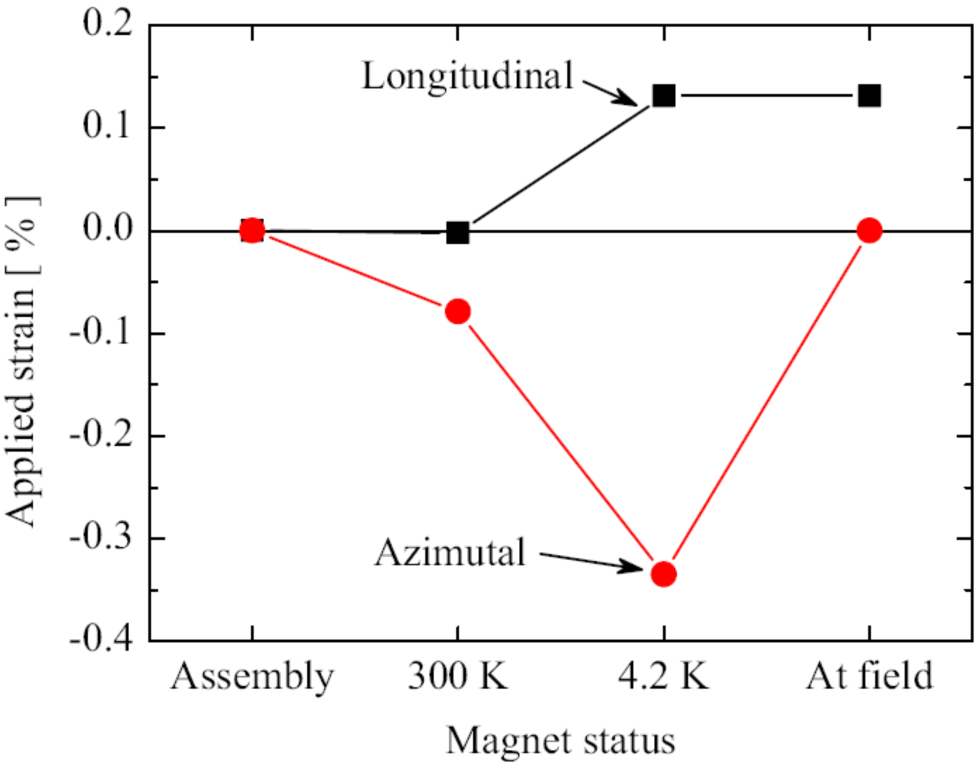
} Discussion point

**Transposition ➔ *J* uniformity**

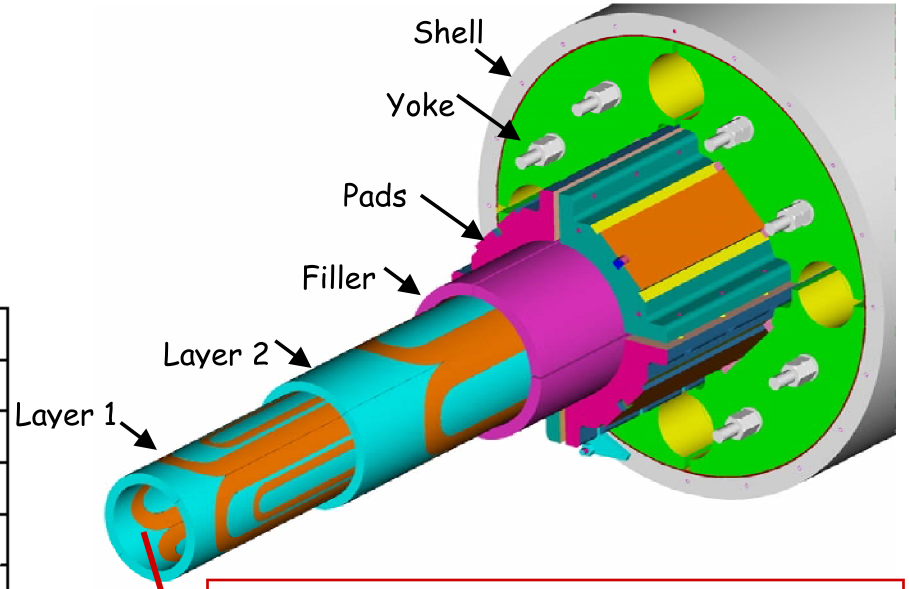
- 20 – 40 mm twist pitch in 0.8 mm wire

## Example: LARP Quad TQS01

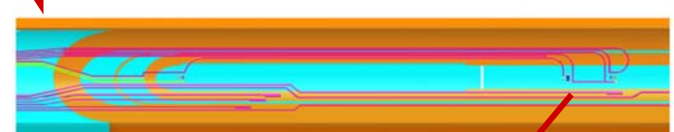
- Ti-6Al-4V poles
- 8 W&R cos Θ coils
- 90 mm bore, > 220 T/m




**Reversible strain!**




Caspi, *MT20: 4LX03 (2007)*



# A model for axial strain in Bi-2212 tapes

## Model…

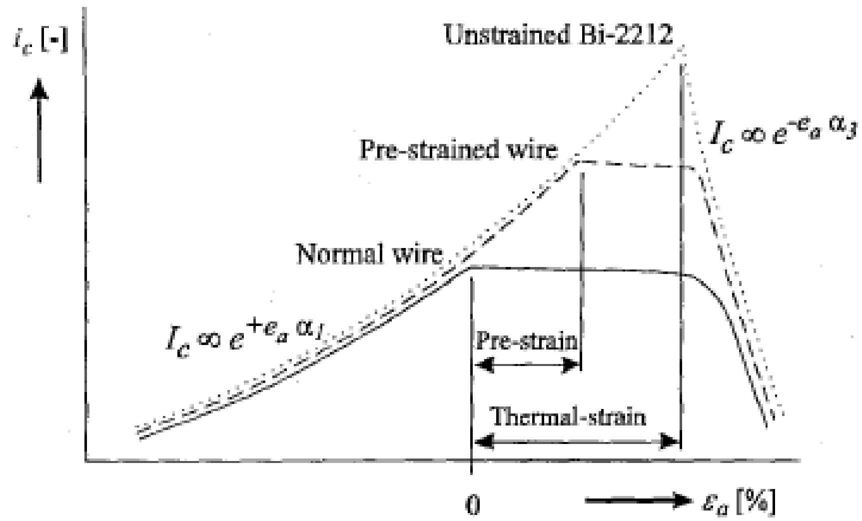
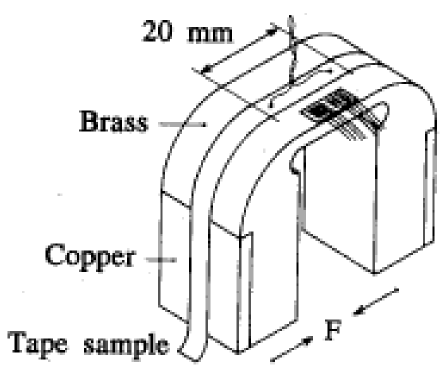



Fig. 2. The proposed description for the $I_c(\varepsilon_a)$ dependence of Bi-2212.




## …and measurement

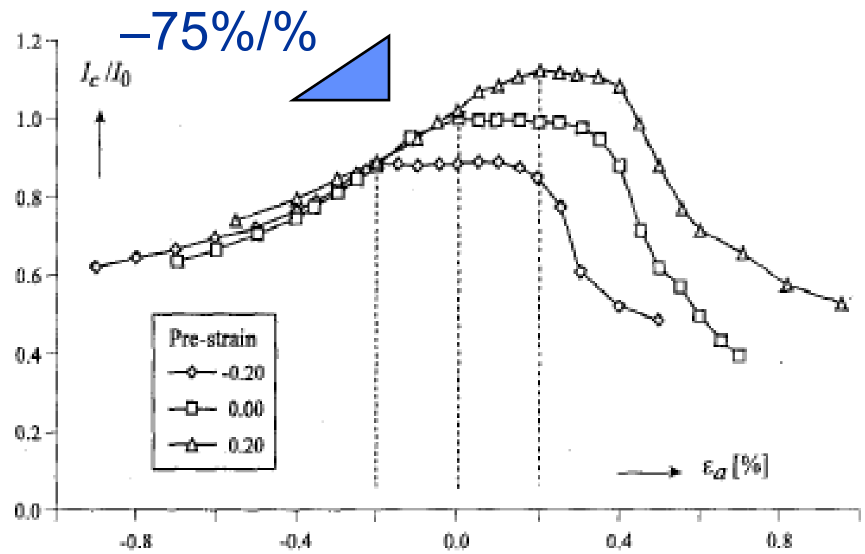



Fig. 3. The normalised critical current as a function of the axial strain measured on three pairs of pre-strained samples (measured at 4.2 K and 16 T).

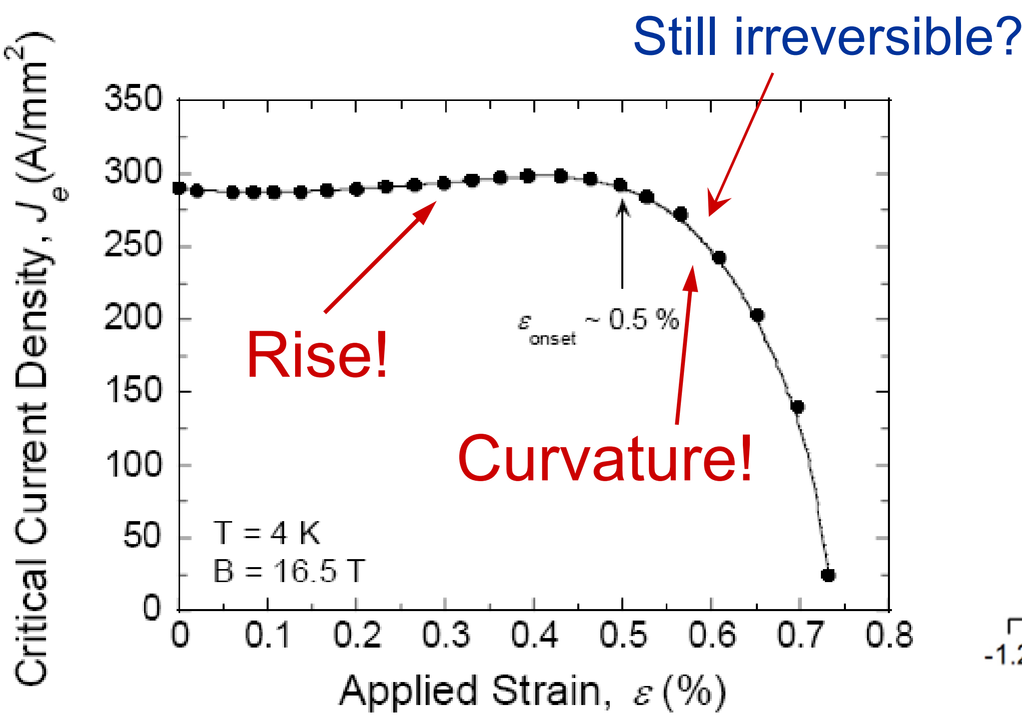
- Ten Haken, *ToM* **32** (1996)

- All axial compressive strain irreversibly reduces $J_c$

# Is there hope for 2212 wires?

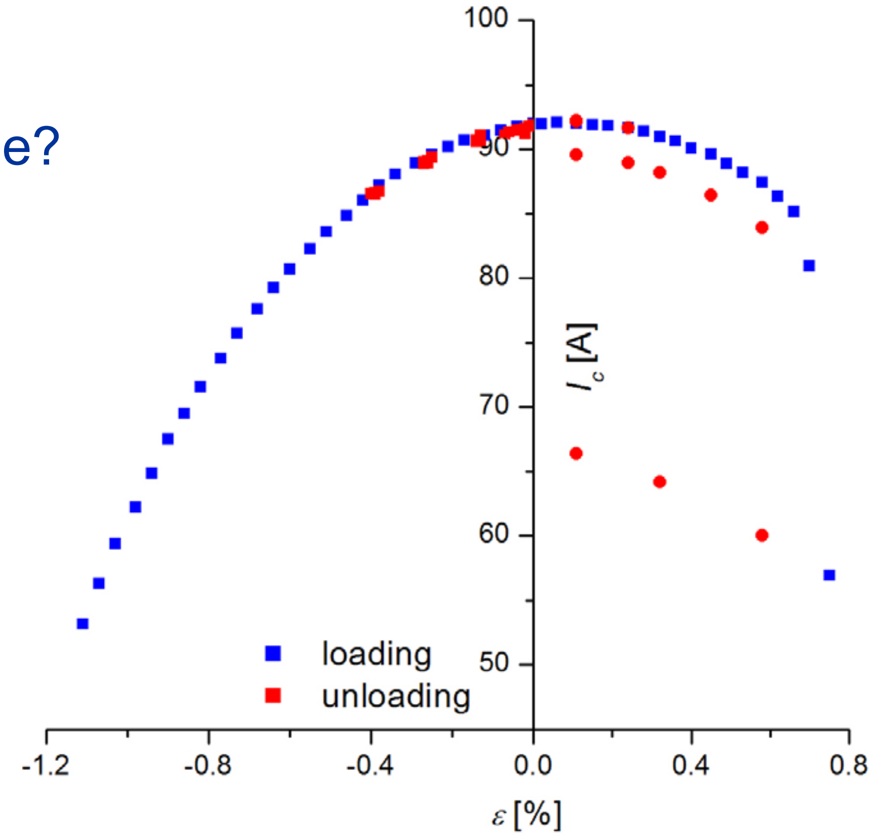
## IGC Bi-2212 round wire

- ∅ 0.81 mm; Optimized HT
- 7x61 filaments




- Courtesy of Najib Cheggour

## SuperPower MOCVD-IBAD YBCO



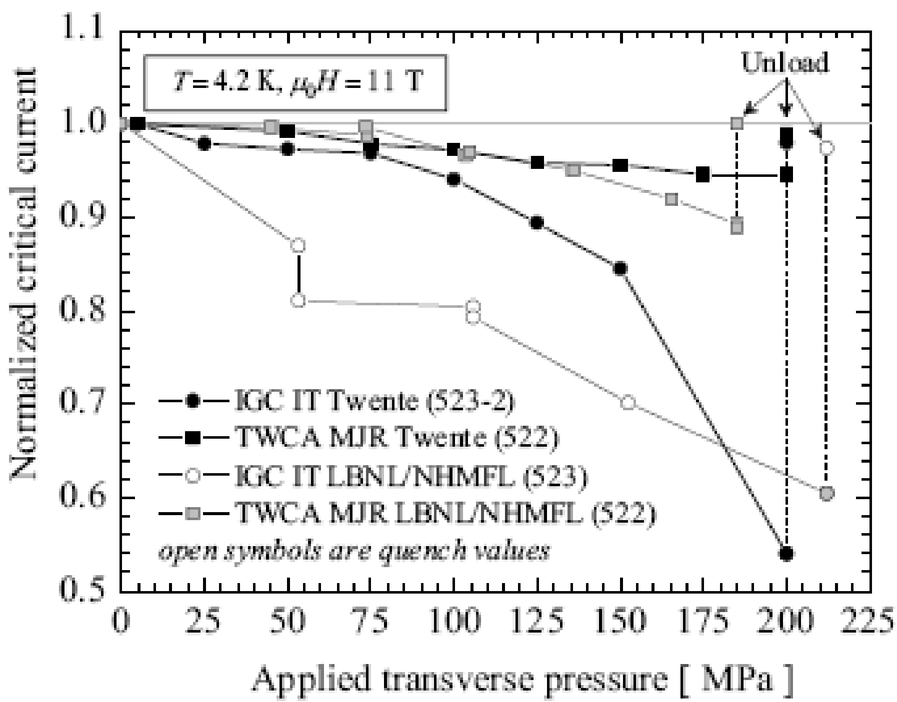

- Courtesy of Danko van der Laan

MAGNETIC TECHNOLOGY DIVISION
BOULDER, COLORADO

# Transverse pressure on cables

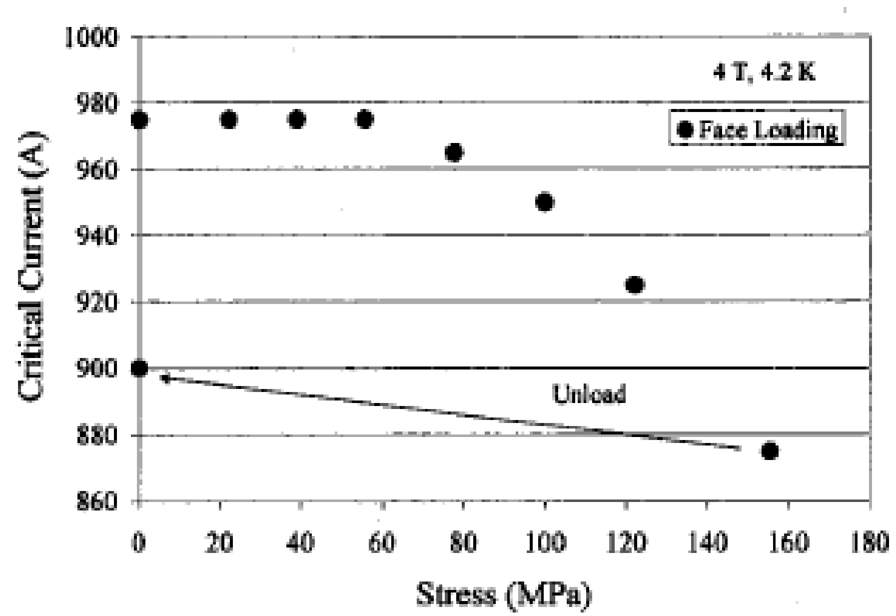
## $Nb_3Sn$: LBNL – D20 cable results

- Twente
- LBNL @ NHMFL



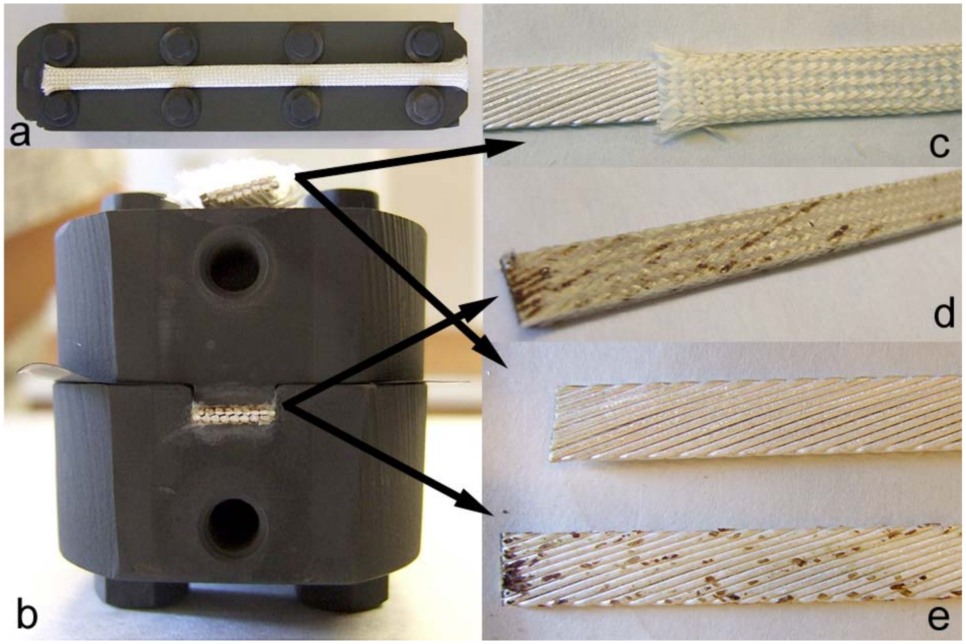

## Bi-2212

- LBNL @ NHMFL
- One measurement
- ~2000 generation wire




➡ Dietderich, *TAS* **11** (2001)

# W&R compatibility




**Confinement causes leakage**

- Unconfined cable pristine after HT
- Confined sample shows leakage

**LBNL coil reacted at Showa**

- Closed package HT
- $O_2$, chemical, mechanical, Cr ?

- $Al_2O_3/SiO_2$ 72%/28% insulation, 80 µm wall thickness
- Insulation pre-heat cleaned
- Alloy 600 package

# N-value, piece length, price

## N-value

- 20 at 20 T, 4.2 K

## Piece length and homogeneity

- Compromise between present billet size and magnet needs
- 2 km with $J_E$ variation within ± 5%

## Price

- Available 40 $/kAm at 20 T and 4.2 K
- Target ➔ 20 $/kAm at 20 T and 4.2 K

# Summary

## Round Wire conductor needs for very high field magnets

Table 1: Bi-2212 conductor development goals for magnet applications (Phase I)

| | |
|---|---|
| Effective zero Kelvin upper critical field | ≥ 40 T |
| 20 T, 4.2 K engineering current density | ≥ 750 A $mm^{-2}$ |
| Filament / sub-element size | ≤ 100 μm |
| Matrix resistivity at 300 K<br>Matrix RRR<br>Stable electric field along wire | 2 μΩcm<br>50<br>≤ $10^{-4}$ V/m |
| Leakage during partial melt reaction | Absent |
| Engineering current density inhomogeneity along wire length | ≤ 5% |

Table 2 Bi-2212 conductor development goals for magnet applications (Phase II)

| | |
|---|---|
| Wire twist pitch (0.8 – 1 mm wire) | 20 – 40 mm |
| Allowable wire $J_E$ reduction due to cabling | ≤ 10% |
| Reversible longitudinal strain regime relative to free wire cooldown state | ± 0.5% |
| Transverse Rutherford cable load resulting in 10% $I_c$ reduction | ≥ 100 MPa |
| n-value at 20 T and 4.2 K | ≥ 20 |
| Piece length | ≥ 2 km |
| Price (based on 20 T, 4.2 K performance) | 20 $/kA m |