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

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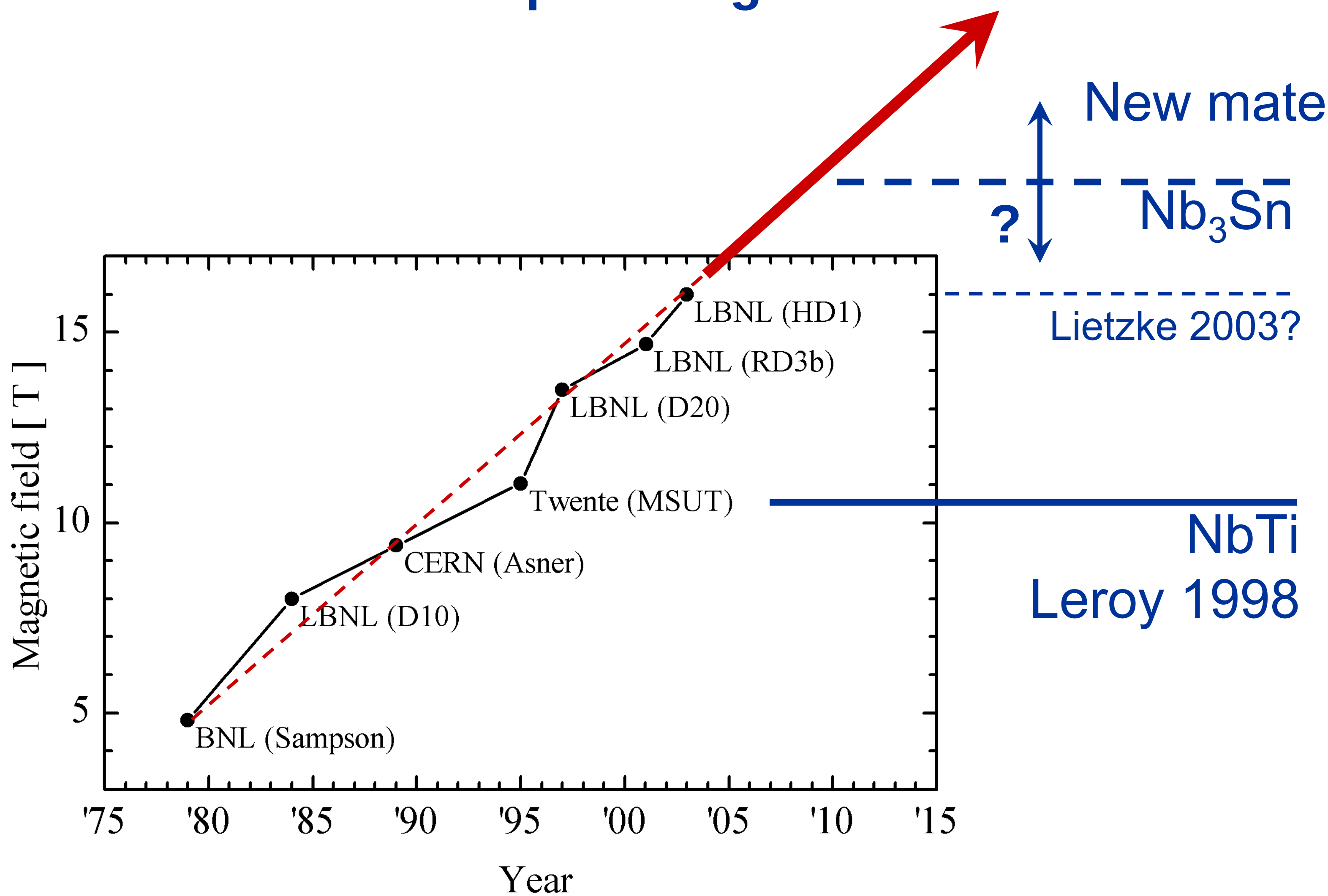
Motivation

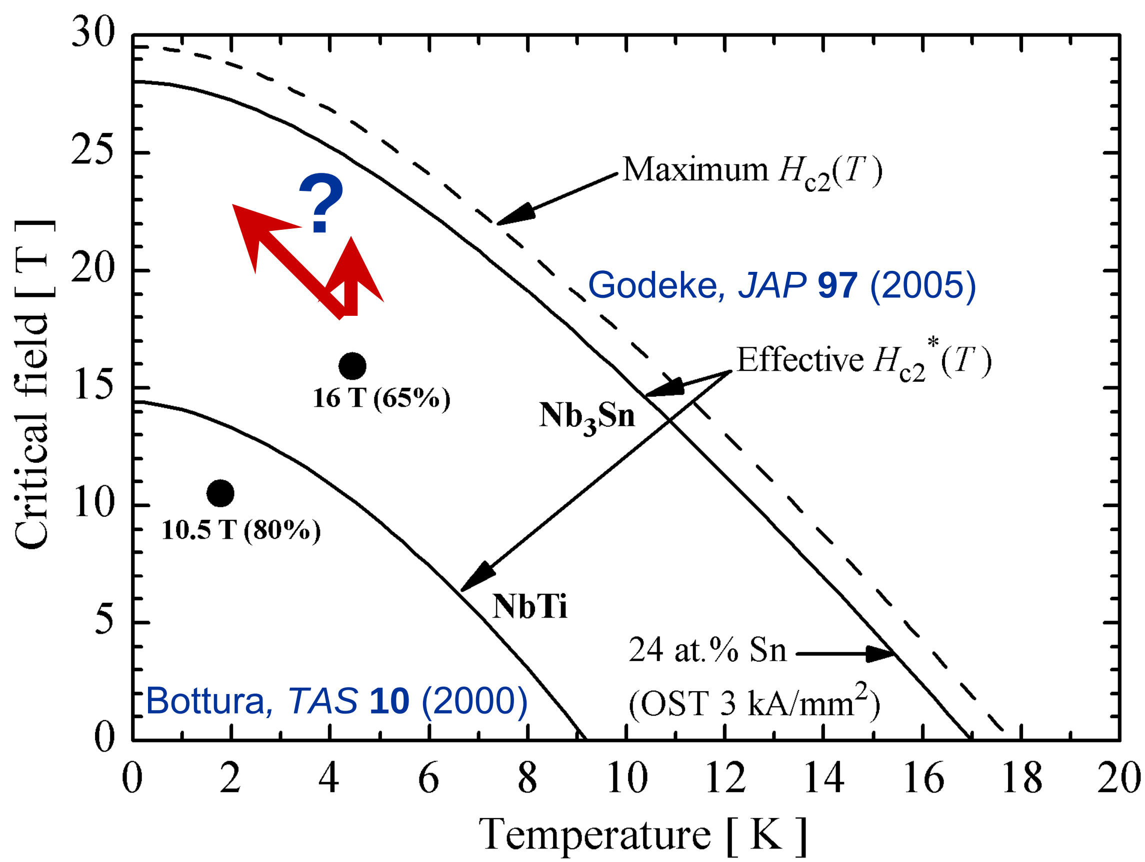
Magnetic field records in dipole magnets



Intrinsic limitations NbTi and Nb_3Sn

Field – temperature limitations and achieved dipole fields

- NbTi (optimized wire & magnet)
  - 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 NbTi and Nb_3Sn

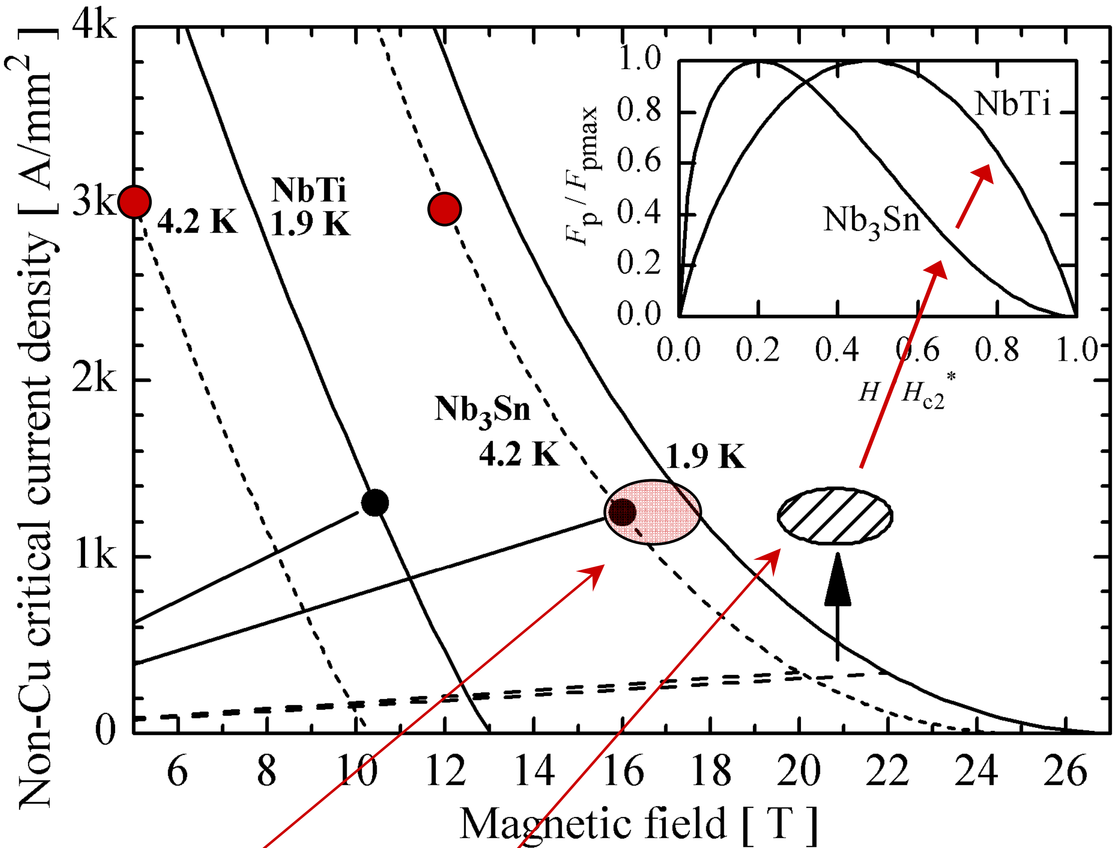
NbTi

- 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)

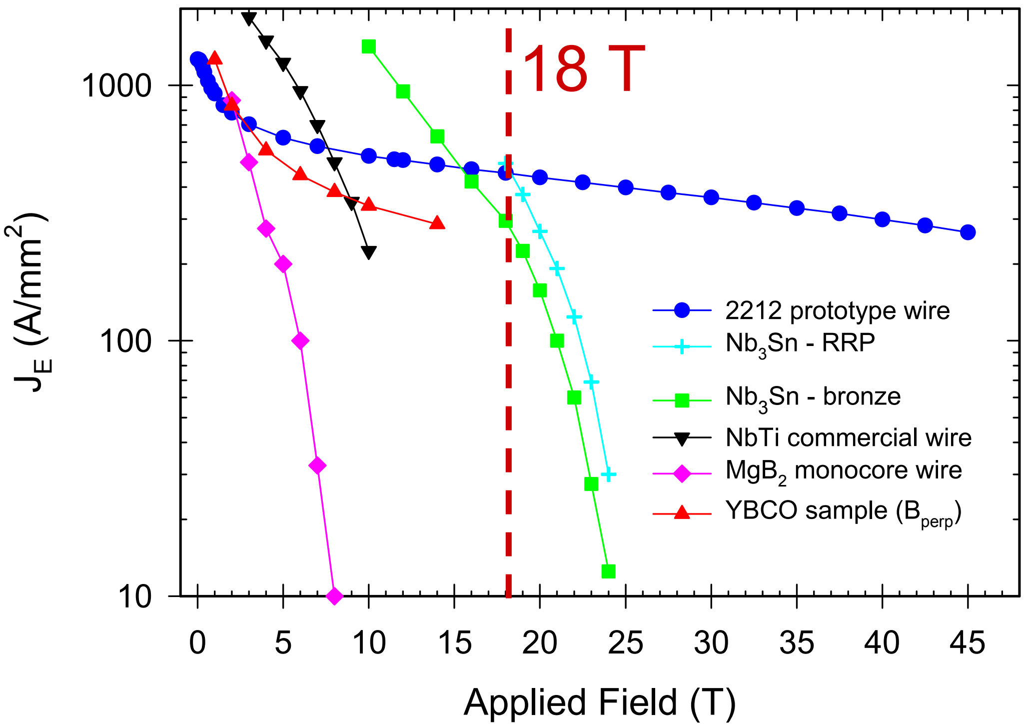


- Practical dipole limitation is 17 – 18 T
  - Gain with improved pinning is “only” 2 – 3 T

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 Bi-2223

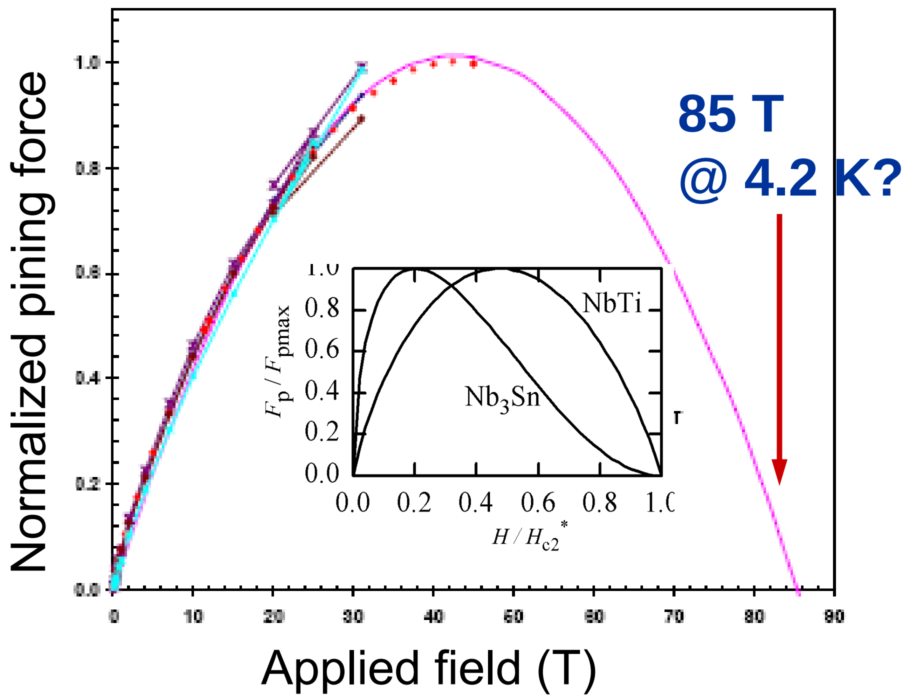
Dipoles: High current, low inductance Rutherford cables → Bi-2212

Bi-2212 round wire

- **NbTi** $H_{c2}^*(0) \approx 14.5$ T ➔ Dipoles = 10.5 T
- **Nb_3Sn** $H_{c2}^*(0) \approx 28$ T ➔ Dipole limit ≈ 18 T

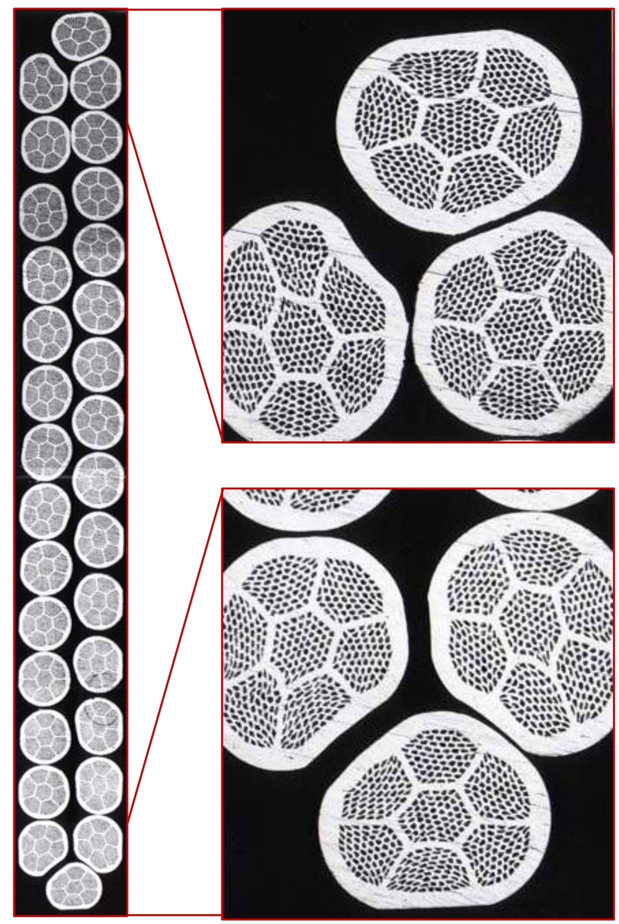
Dipoles achieve ~ 2/3 of $H_{c2}^*(0)$

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



- Trociewitz, NHMFL report 2005

- Rutherford cables



Technological challenges – I

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

Material	Dipole limit	Reaction
NbTi	10.5 T	Ductile: R&W
Nb_3Sn	17–18 T (F_p ↑: 22 T)	$\sim$ 675°C in Ar/Vacuum
Bi–2212	Stress limited	$\sim$ 890°C in O_2 (± 2°C)

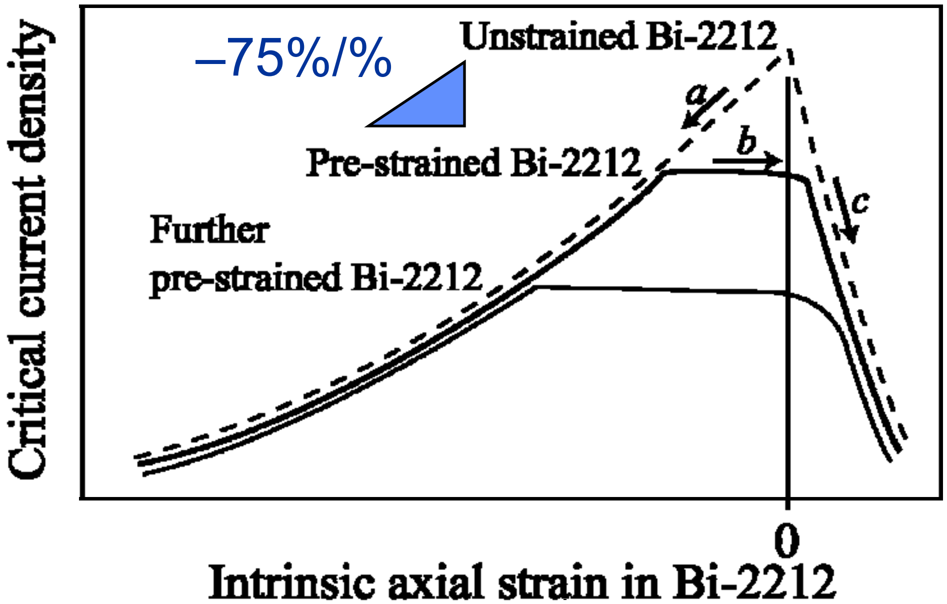
Material	Insulation	Construction	Quench propagation
NbTi	Polyimide	Stainless Steel	$> 20\ ms^{-1}$
Nb_3Sn	S/R–Glass	Stainless Steel	$\sim 20\ ms^{-1}$
Bi–2212	Ceramic	Super alloy	$\sim 0.04\ ms^{-1}$

- Solutions
  - Chemically compatible
  - Mechanically compatible
  - Quench development
  - Heat treatment optimization
  - Oxygen flow during reaction

Technological challenges – II

Strain issues, longitudinal

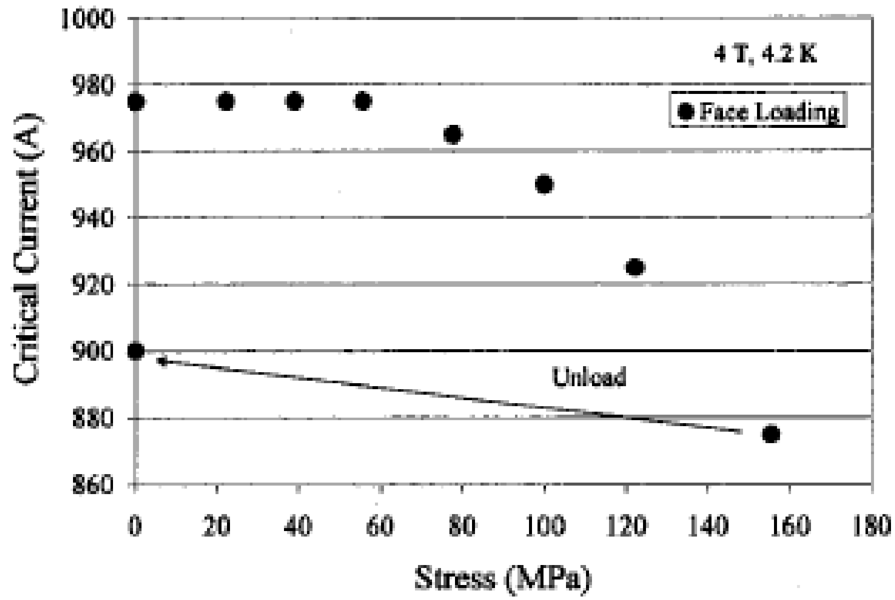
- Irreversible J_c reduction
  - Thermal contraction matching
- Data from Bi-2212 tapes around 1995



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

Strain issues, transverse

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



*Dietderich, TAS **11** (2001)*

Technological challenges – III

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.

	BSCCO constituent oxides				
Test oxide	Bi_2O_3	SrO	CaO	CuO	Reactivity
Al_2O_3	C [7]	C [7]	C [7]	C [8]	U
CeO_2	— [7][c]	C [9]	SS [10]	X [11]	U
SiO_2 (pure)	C [7]	C [7]	C [7]	X [8]	U
Y_2O_3	C [10]	C [10]	C [12]	C [11]	U
ZrO_2	— [7][c]	C [13]	C [7]	X [8]	U
$CaZrO_3$ [a]	C	C	C	C	U
$SrZrO_3$ [a]	C	C	C	C	U
Fe_2O_3	C [7]	C [14]	C [7]	C [7]	R–$CuFe_2O_4$
NiO	— [7][c]	NPD	SS [7]	SS [14]	R–Ni(Cu)O
MgO	— [7][c]	X [9]	SS [7]	C [9]	R–Mg(Cu)O
Cr_2O_3	C [12]	C [15]	C [7]	C [12]	Ag
SiO_2-based glass[b]	—	—	—	—	Ag

[a] The phase diagrams for $CaZrO_3$ or $SrZrO_3$ 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 SiO_2 plus additional compounds could from reactions with other oxides in the glass.

[c] Data are not reported for the CeO_2, ZrO_2, NiO, and MgO-rich side of the Bi_2O_3–MO_y phase diagram.

Wesolowski, *SuST* **18** (2005)

Insulation options

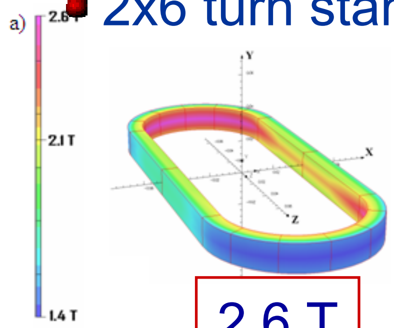
- Fiber based sleeve / tape OK?
- Metal – Oxides X?
- Fiber / binder paper OK?
- Sol – gel coatings X?
- Plasma spray coatings OK?

Fiber based

- S/R Glass (Nb_3Sn)
  - Chem = X (B_2O_3), Temperature = X
- $Al_2O_3/SiO_2/B_2O_3$ (various combinations)
  - Chem = X (B_2O_3)
- Pure (>99.97%) SiO_2
  - Chem = X (Contaminations)
- Al_2O_3/SiO_2 72/28
  - OK (?)
- Pure (>99%) Al_2O_3
  - Chem = OK, sleeve = X, cloth OK

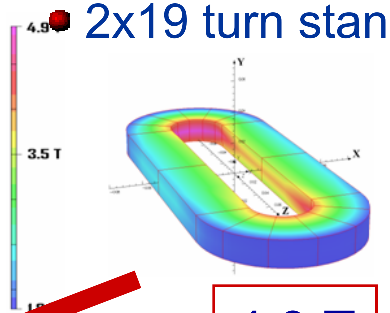
W&R Bi-2212 magnet program

- 2x6 turn stand-alone

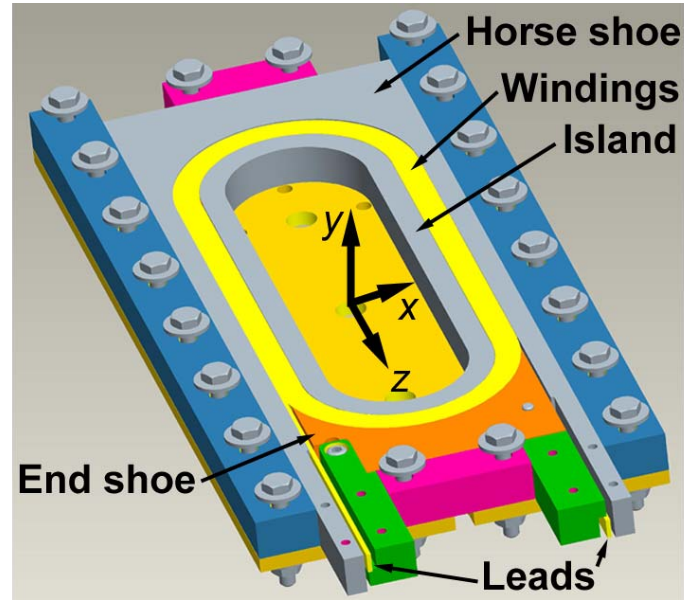


2.6 T

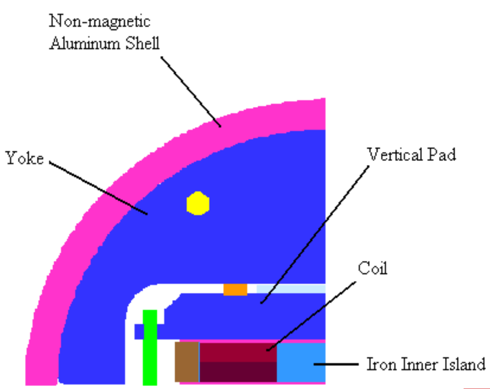
- 2x19 turn stand-alone

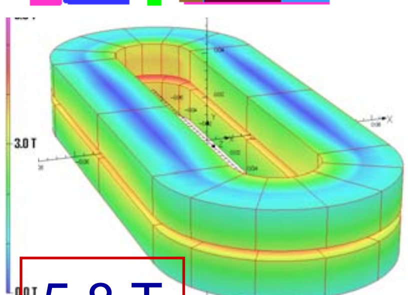


4.9 T



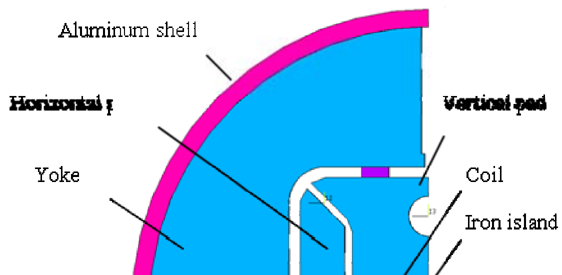
- Bi-2212 common coil

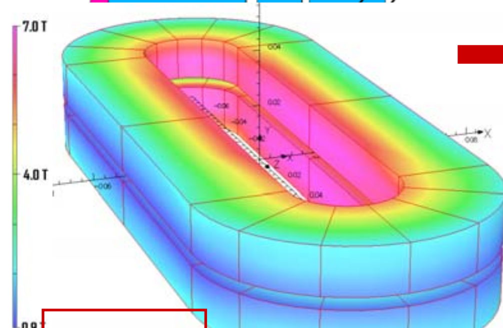




5.8 T

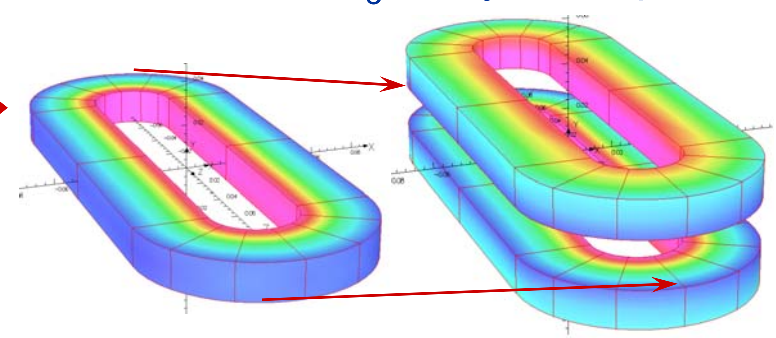
- Bi-2212 dipole





6.6 T

- Bi-2212 – Nb_3Sn hybrid dipole



Bi-2212 | 8.5/9.9 T | Nb_3Sn x2

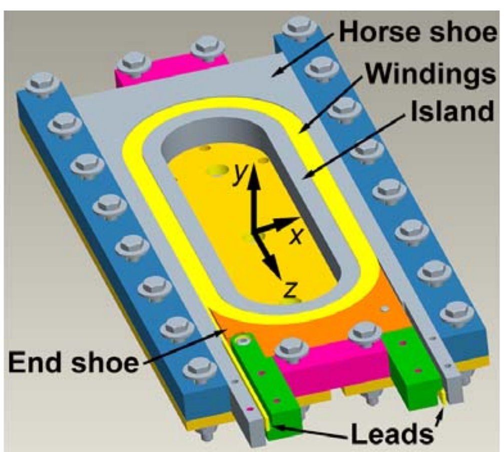
Magnetic fields and forces

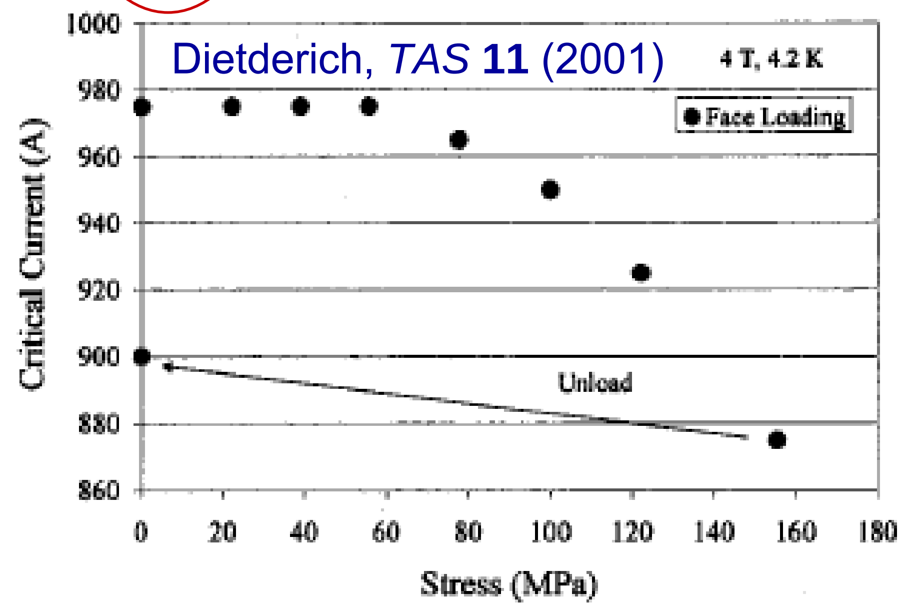
~ 5000 A

Wɪɴᴅ-ᴀɴᴅ-Rᴇᴀᴄᴛ Bɪ–2212 ꜱᴜʙꜱᴄᴀʟᴇ ᴄᴏɪʟ ᴛᴇꜱᴛ ᴄᴏɴꜰɪɢᴜʀᴀᴛɪᴏɴꜱ

Layout	Turns	$\mu_0 H$ [T]	I_{ss} [A]	L [mH]	P_x [MPa]	P_y [MPa]	P_z [MPa]
Bi–2212 stand alone	2 × 6	2.6	6213	0.036	1.1	0	1.9
Bi–2212 stand alone	2 × 19	4.9	5179	0.25	9.7	0	9.4
Bi–2212 common coil[a]	2 × 19	5.8	4948	0.28	27	7.5	15
Bi–2212 dipole[a]	2 × 19	6.6	4777	1.2	1.6	14	3.2
1× Bi–2212 / 2× Nb_3Sn hybrid dipole[ab]	2 × 19 (Bi–2212) 2 × 20 (×2 Nb_3Sn)	8.5	4595	2.4	34	0	20
1× Bi–2212 / 2× Nb_3Sn hybrid dipole[ac]	2 × 19 (Bi–2212) 2 × 20 (×2 Nb_3Sn)	9.9	4486 (Bi–2212) 6112 (Nb_3Sn)				

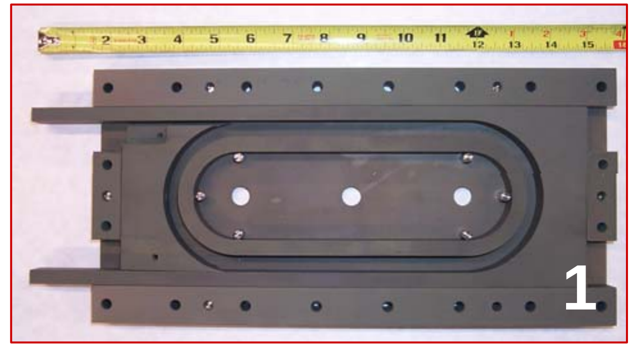
[a] With an iron insert inside the Bi–2212 subscale island
[b] Bi–2212 and Nb_3Sn in series connected and Bi–2212 limited
[c] Bi–2212 and Nb_3Sn driven independently

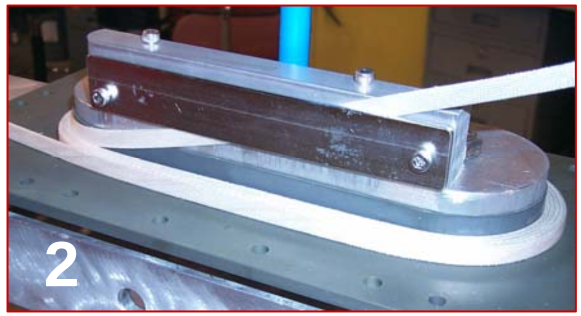


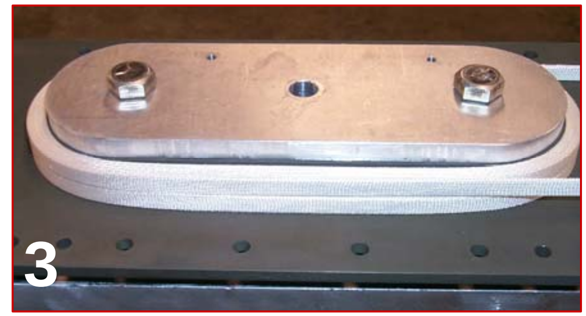


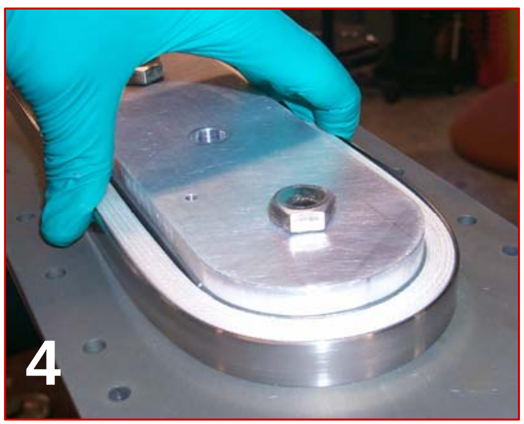
Subscale coil manufacture

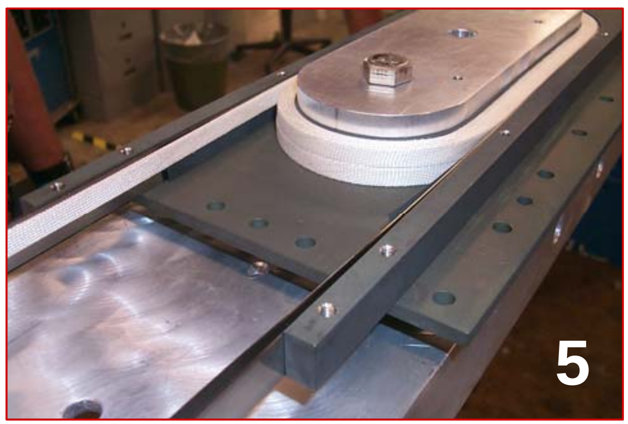
- Strand➔ Cable
- Al_2O_3/SiO_2 Sleeve➔ Sizing removal➔ on cable
- Wind coil on INCONEL alloy 600 island
- Enclose with Alloy 600 heat treatment package
- Ship to Showa for heat treatment











Manufactured subscale coils

8 coils manufactured

WIND-AND-REACT BI–2212 SUBSCALE COILS

Coil ID	Cable	Insulation	Sizing
HTS-SC01	Ag-alloy dummy	Pure SiO_2	Present
HTS-SC02	Ag dummy	Pure SiO_2	Present
HTS-SC03	Untwisted Showa strand	Al_2O_3/SiO_2	Present
HTS-SC04	Untwisted OST strand	Al_2O_3/SiO_2	Present
HTS-SC05	Twisted Showa strand	Al_2O_3/SiO_2	600°C/1h*

* Sizing removal reaction on insulation prior to insulating the cable

HT optimization (HTS-SC01, HTS-SC02)

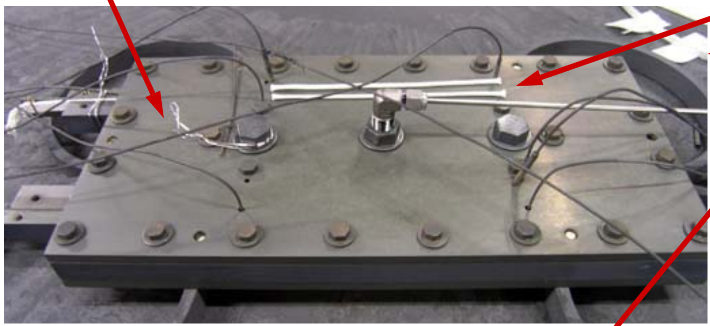
Twisted Showa strand – Al_2O_3/SiO_2 – Cleaned @ 825°C/4h

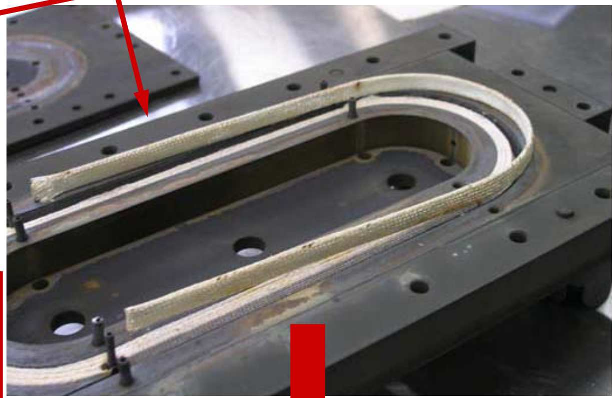
- HTS-SC07
- HTS-SC09
- HTS-SC11

Various degrees of confinement

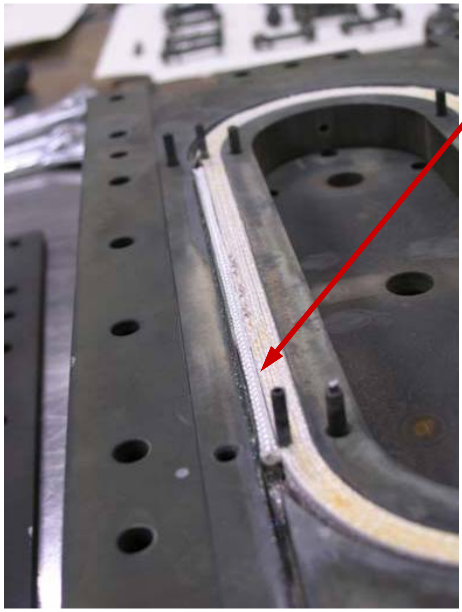
Heat treatment optimizations

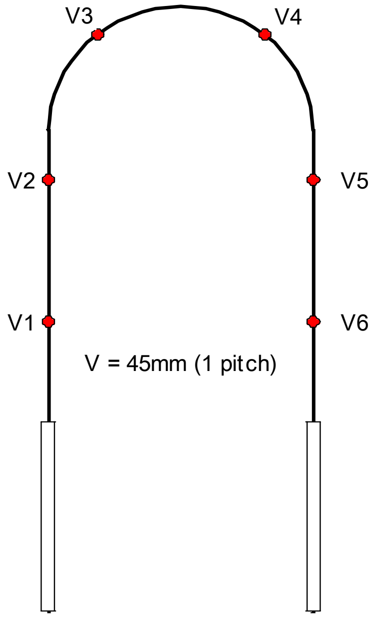
- Dummy coil, and dummy coil with wires and cable sections

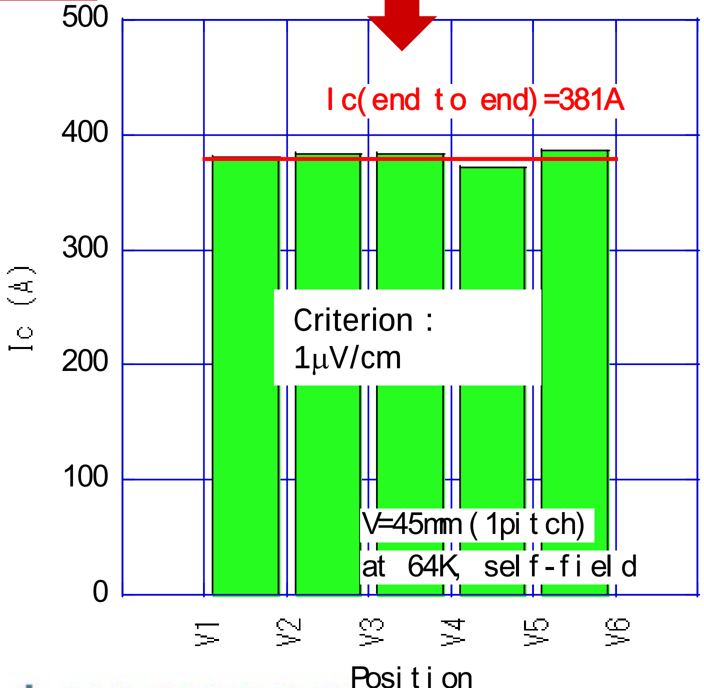




$\Delta T = \pm 1°C$





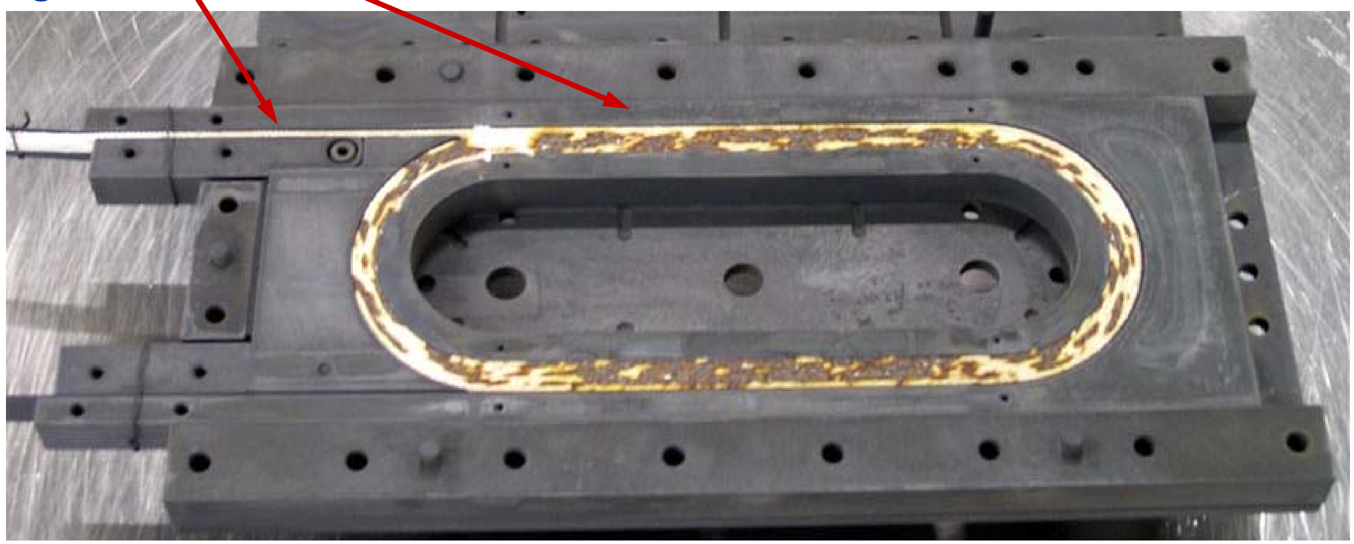


Subscale coil after HT

Leakage occurred

- Not at the leads

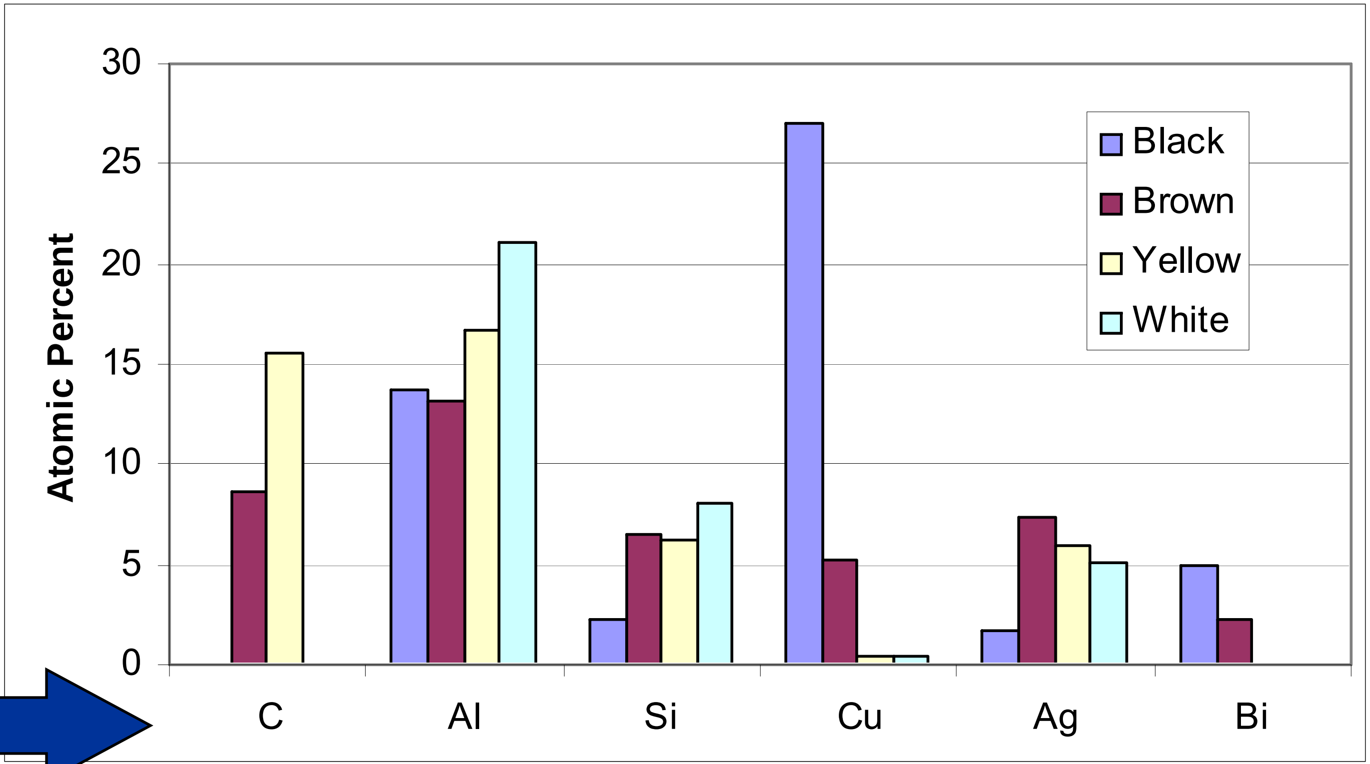
- But inside the package
- More severe at straight sections
  - Better confined



- 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

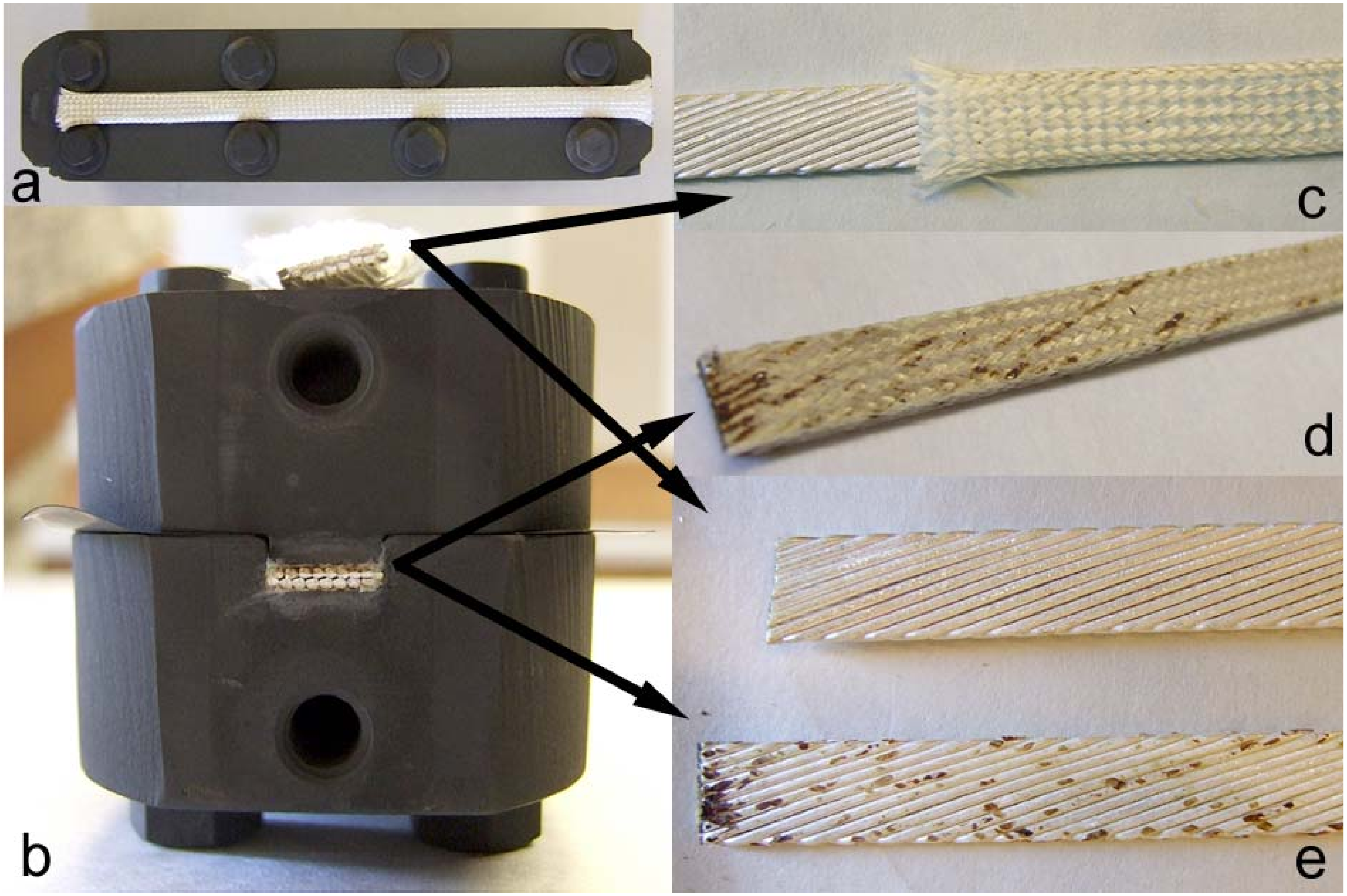
- Chemical compatibility is apparently OK

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 ➔ Oxygen depletion through burn-off
    - 0.4 gram sizing on 7 m insulated cable
    - Organic sizing ➔ assume 50% H and 50% C plus O_2 ➔ H_2O and CO_2
    - Requires about 1.2 gram O_2 ➔ 2 L/h (1 atm, 300K)
  - No remaining sizing ➔ 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
- Al_2O_3/SiO_2 72%/28% insulation with 80 μm wall thickness
  - Sizing removed before application to cable ➔ Nb_3Sn?
  - 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