

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

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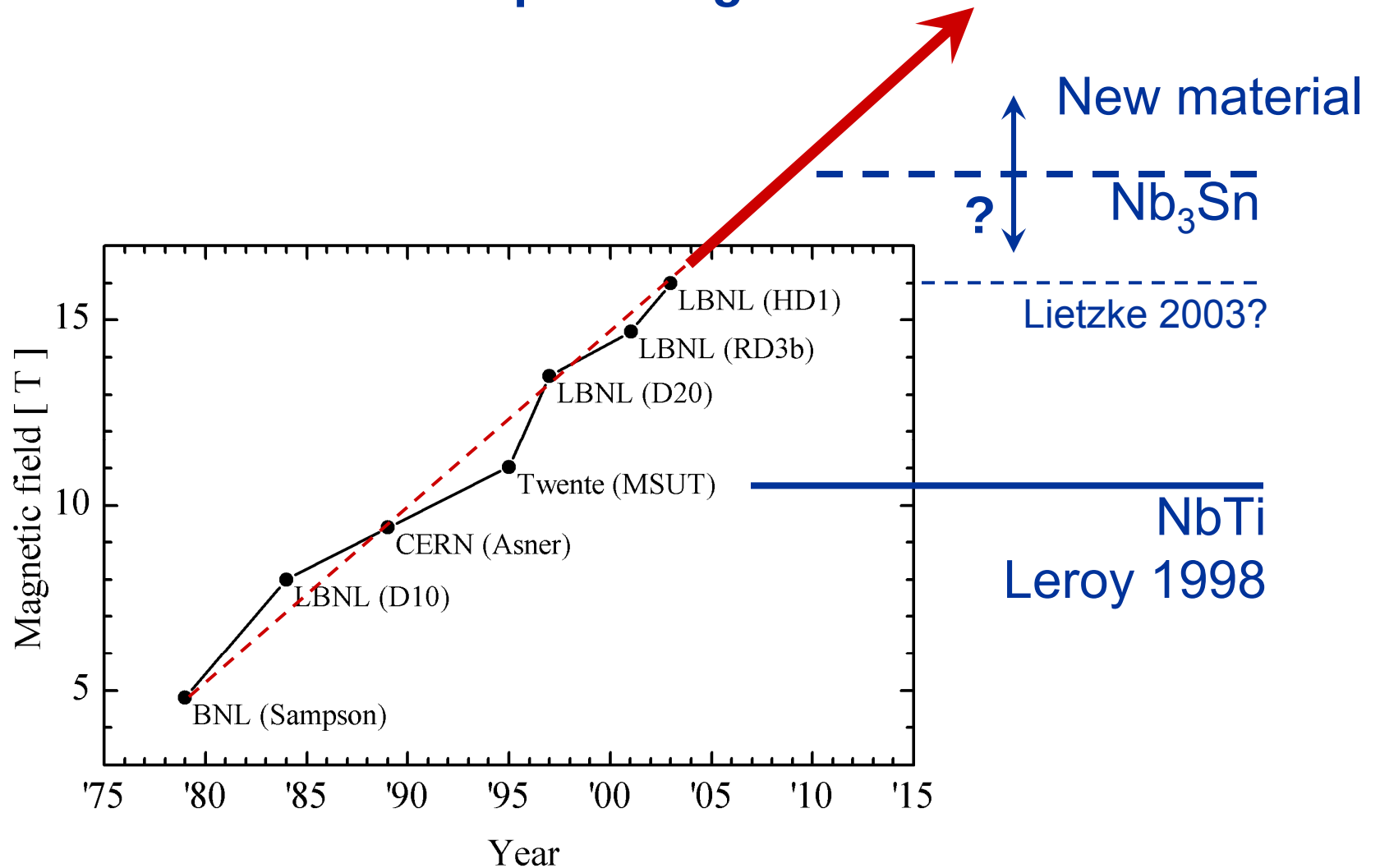
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Magnetic field records in dipole magnets



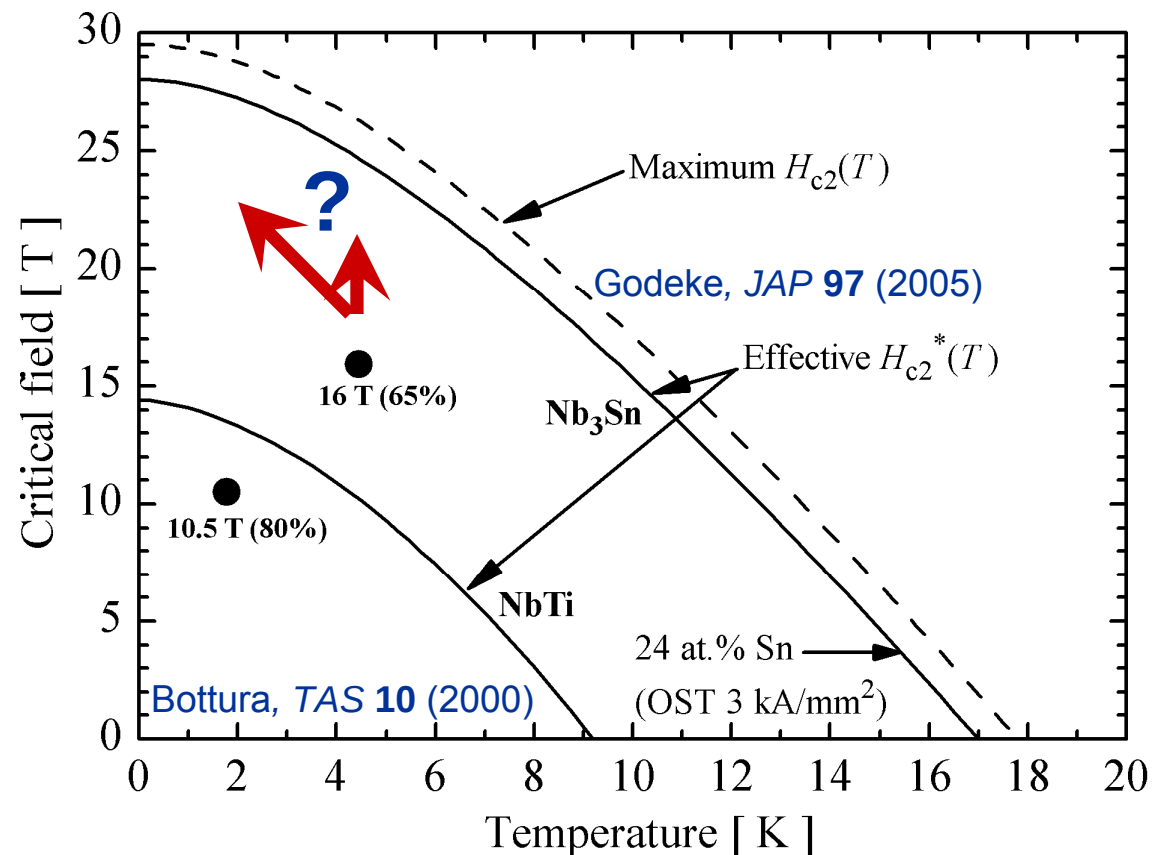
Field – temperature limitations and achieved dipole fields

■ NbTi (optimized wire & magnet)

- ➔ 10.5 T @ 1.8 K
- ➔ 80% of $H_{c2}^*(1.8 \text{ K})$

■ Nb₃Sn

- ➔ 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 Nb₃Sn achieve “only” 65% of H_{c2}^* ?

NbTi

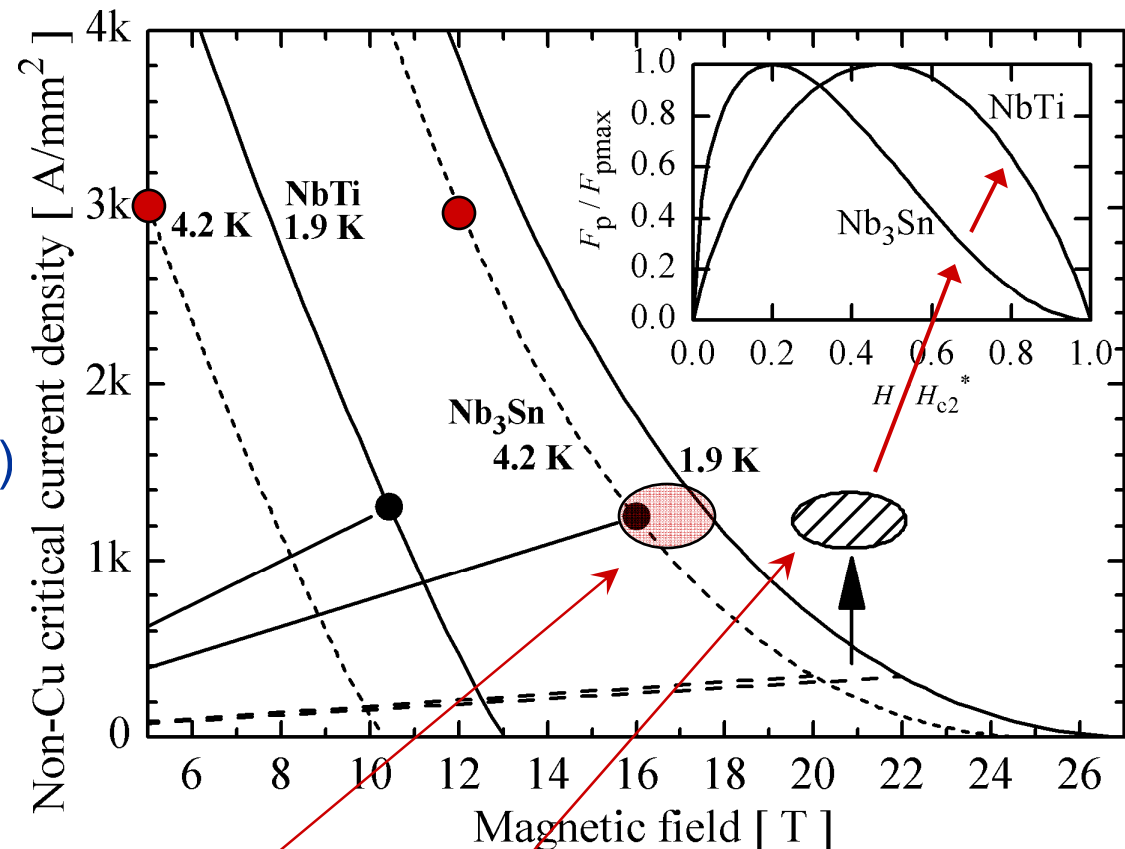
- Pinning optimized (α -Ti)
 - ➡ ~1 pinning cite/vortex
 - ➡ $F_p \propto h(1 - h)$

NbTi: Bottura, *TAS* **10** (2000)

Nb₃Sn: Godeke, *SuST* **19** (2006)

Nb₃Sn

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

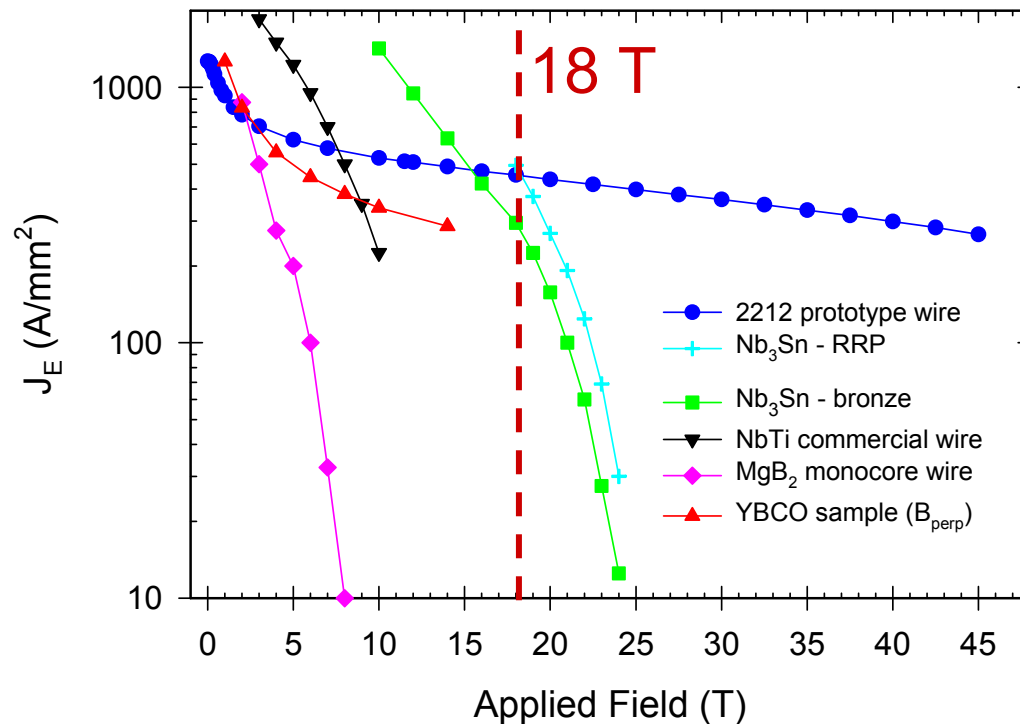


- Practical dipole limitation is 17 – 18 T
 - ➡ Gain with improved pinning is “only” 2 – 3 T

How to approach 20 T and higher

A switch to a new material is inevitable! (Even if Nb₃Sn 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

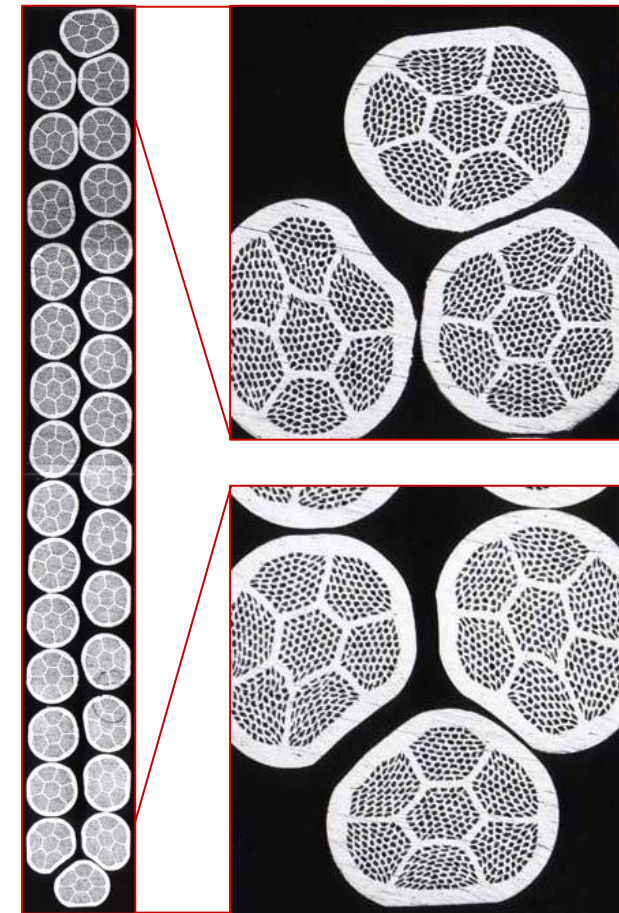
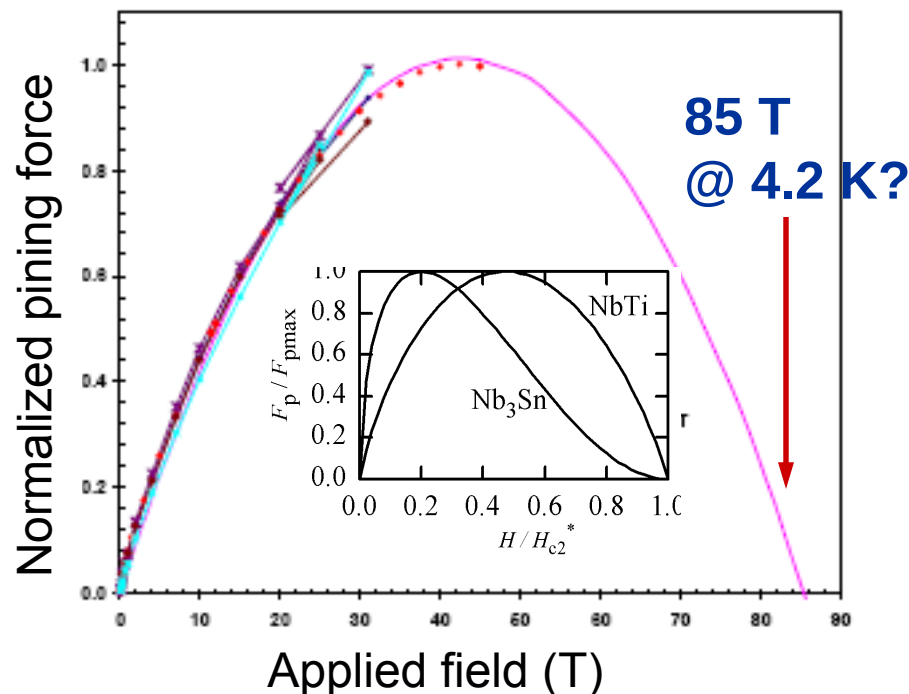
Bi-2212 round wire

- **NbTi** $H_{c2}^*(0) \approx 14.5 \text{ T} \rightarrow$ Dipoles = 10.5 T
- **Nb₃Sn** $H_{c2}^*(0) \approx 28 \text{ T} \rightarrow$ Dipole limit $\approx 18 \text{ T}$

- Rutherford cables

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

- Beyond Nb₃Sn is 20 – 25 T
- $H_{c2}^*(0)$ required is 40 T minimum



- Trociewitz, NIMF report 2005

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

Material	Dipole limit	Reaction
NbTi	10.5 T	Ductile: R&W
Nb ₃ Sn	17–18 T ($F_p \uparrow$: 22 T)	$\sim 675^\circ\text{C}$ in Ar/Vacuum
Bi-2212	Stress limited	$\sim 890^\circ\text{C}$ in O ₂ ($\pm 2^\circ\text{C}$)

Material	Insulation	Construction	Quench propagation
NbTi	Polyimide	Stainless Steel	$> 20 \text{ ms}^{-1}$
Nb ₃ Sn	S/R-Glass	Stainless Steel	$\sim 20 \text{ ms}^{-1}$
Bi-2212	Ceramic	Super alloy	$\sim 0.04 \text{ ms}^{-1}$

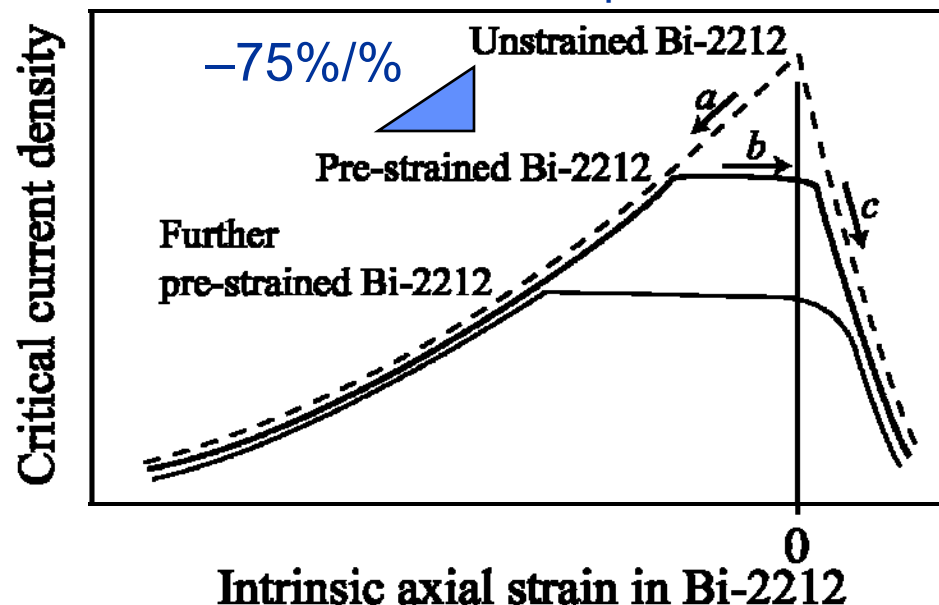
- Solutions

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

Strain issues, longitudinal

- Irreversible J_c reduction
 - ➔ Thermal contraction matching

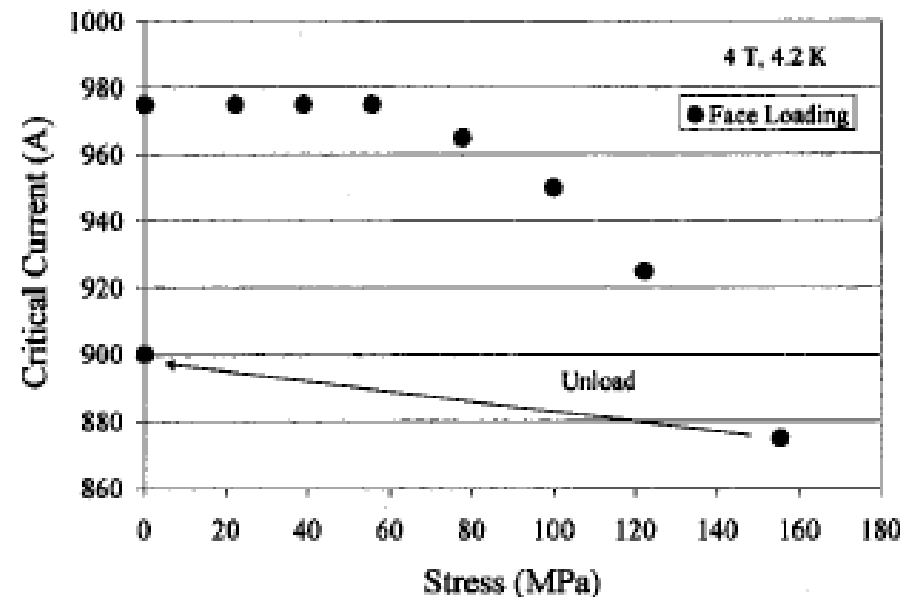
- Data from Bi-2212 tapes around 1995



Ten Haken, ToM 32 (1996)

Strain issues, transverse

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



Dietderich, TAS 11 (2001)

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 as 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.

Test oxide	BSCCO constituent oxides				Reactivity
	Bi ₂ O ₃	SrO	CaO	CuO	
Al ₂ O 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 ₂ O 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 ₂ O ₃	C [7]	C [14]	C [7]	C [7]	R-CuFe ₂ O 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 ₂ O ₃	C [12]	C [15]	C [7]	C [12]	Ag
SiO ₂ -based glass ^b	—	—	—	—	Ag

^a The phase diagrams for CaZrO₃ or SrZrO₃ 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 from reactions with other oxides in the glass.

^c Data are not reported for the CeO₂, ZrO₂, NiO, and MgO-rich side of the Bi₂O₃-MO_y phase diagram.

Wesolowski, *SuST 18* (2005)

Insulation options

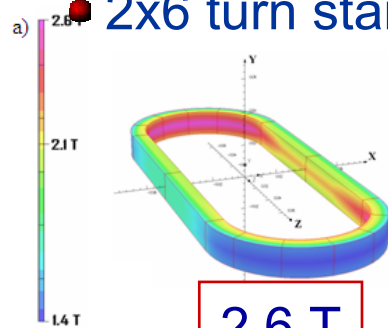
- Fiber based sleeve / tape OK?
- Metal – Oxides X?
- Fiber / binder paper OK?
- Sol – gel coatings X?
- Plasma spray coatings OK?

Fiber based

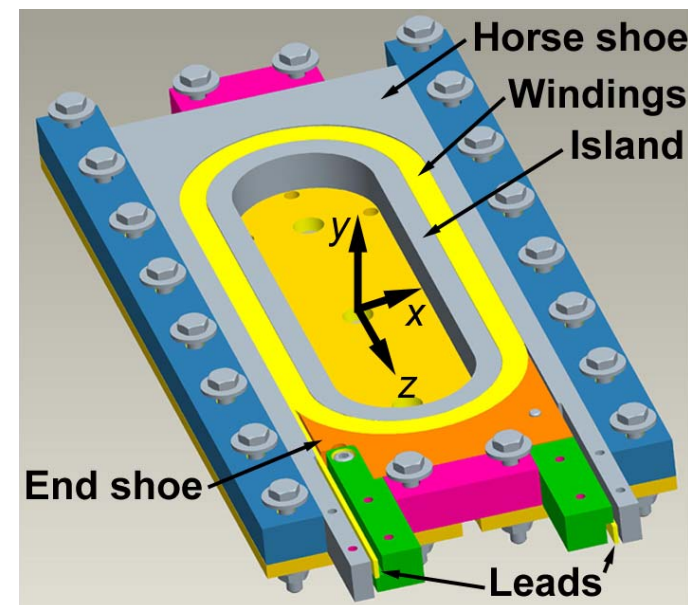
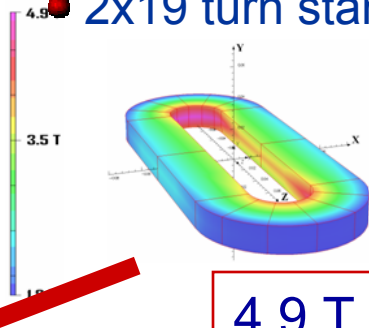
- S/R Glass (Nb₃Sn)
 - ➔ Chem = X (B₂O₃), Temperature = X
- Al₂O₃/SiO₂/B₂O₃ (various combinations)
 - ➔ Chem = X (B₂O₃)
- Pure (>99.97%) SiO₂
 - ➔ Chem = X (Contaminations)
- Al₂O₃/SiO₂ 72/28
 - ➔ OK (?)
- Pure (>99%) Al₂O₃
 - ➔ Chem = OK, sleeve = X, cloth OK

W&R Bi-2212 magnet program

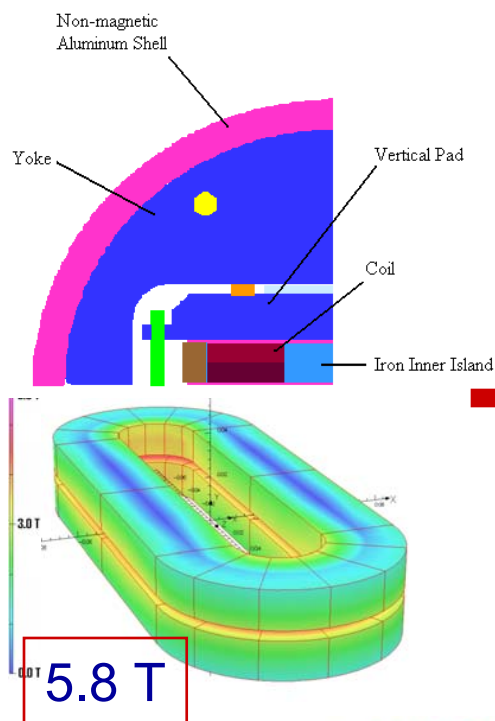
2x6 turn stand-alone



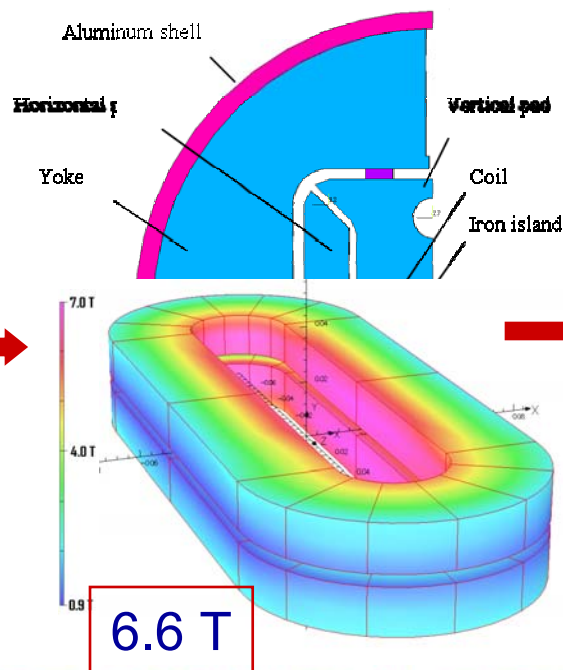
2x19 turn stand-alone



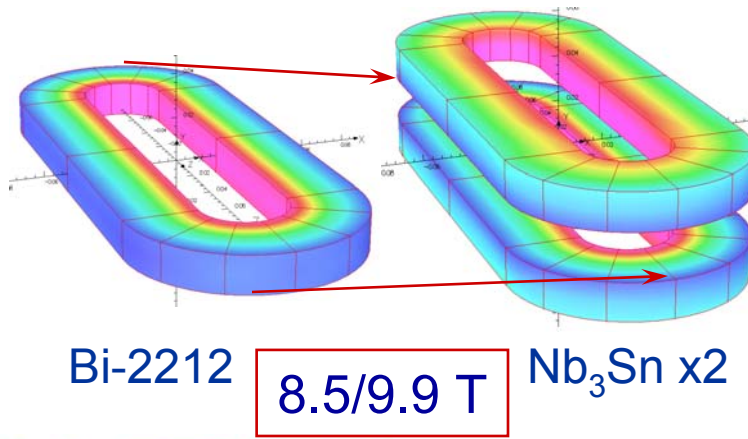
Bi-2212 common coil



Bi-2212 dipole



Bi-2212 – Nb₃Sn hybrid dipole



Magnetic fields and forces

~ 5000 A

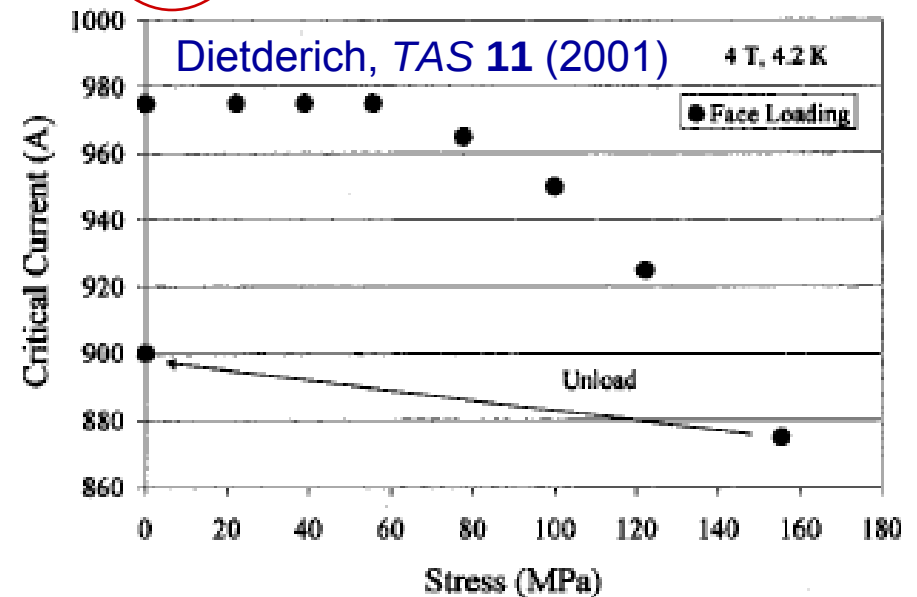
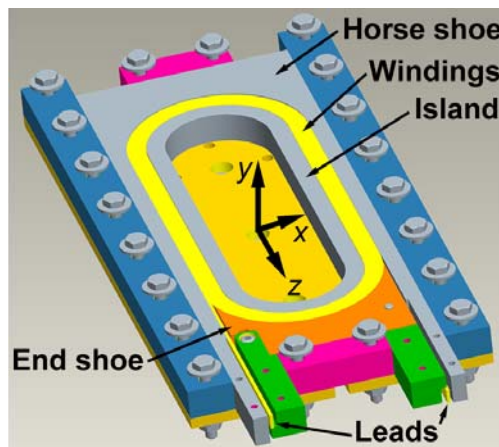
WIND-AND-REACT BI-2212 SUBSCALE COIL TEST CONFIGURATIONS

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 $\times$ Bi-2212 / 2 $\times$ Nb ₃ Sn hybrid dipole ^{ab}	2 $\times$ 19 (Bi-2212) 2 $\times$ 20 ($\times 2$ Nb ₃ Sn)	8.5	4595	2.4	34	0	20
1 $\times$ Bi-2212 / 2 $\times$ Nb ₃ Sn hybrid dipole ^{ac}	2 $\times$ 19 (Bi-2212) 2 $\times$ 20 ($\times 2$ Nb ₃ Sn)	9.9	4486 (Bi-2212) 6112 (Nb ₃ Sn)				

^a With an iron insert inside the Bi-2212 subscale island

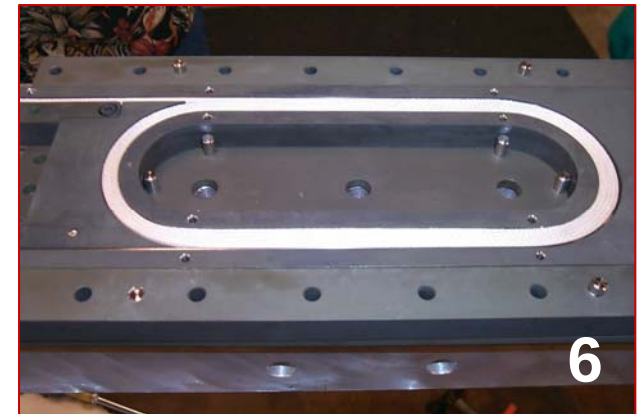
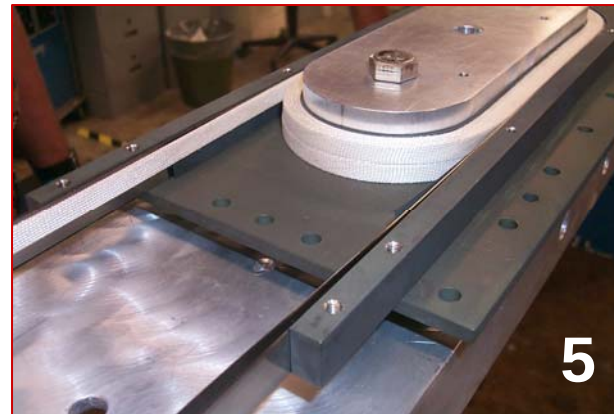
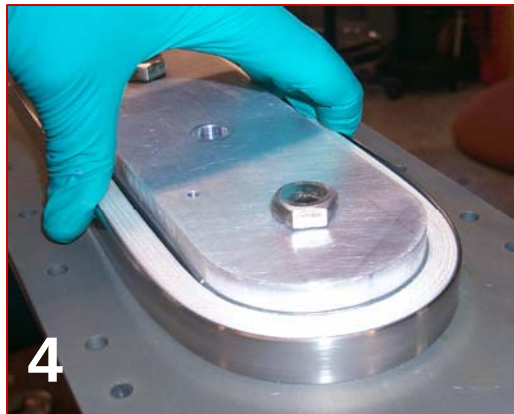
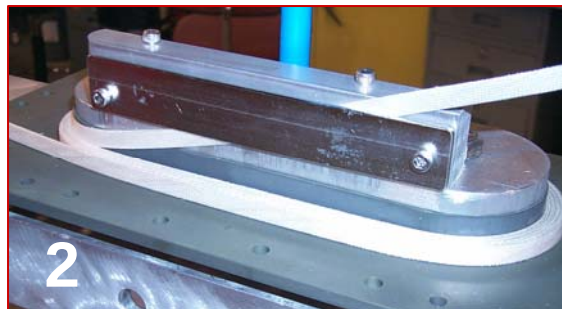
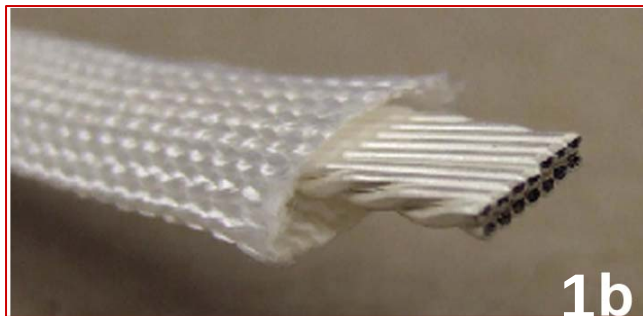
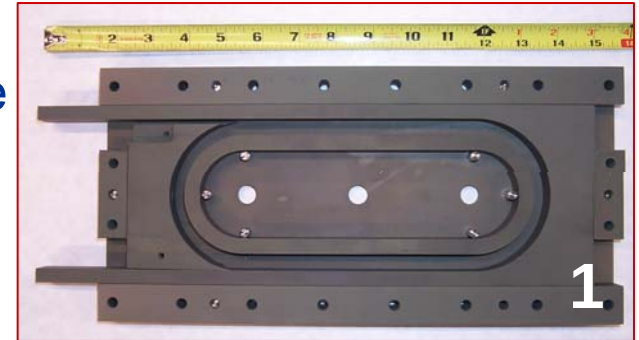
^b Bi-2212 and Nb₃Sn in series connected and Bi-2212 limited

^c Bi-2212 and Nb₃Sn driven independently



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

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 ₂ O ₃ /SiO ₂	Present
HTS-SC04	Untwisted OST strand	Al ₂ O ₃ /SiO ₂	Present
HTS-SC05	Twisted Showa strand	Al ₂ O ₃ /SiO ₂	600°C/1h*

} HT optimization

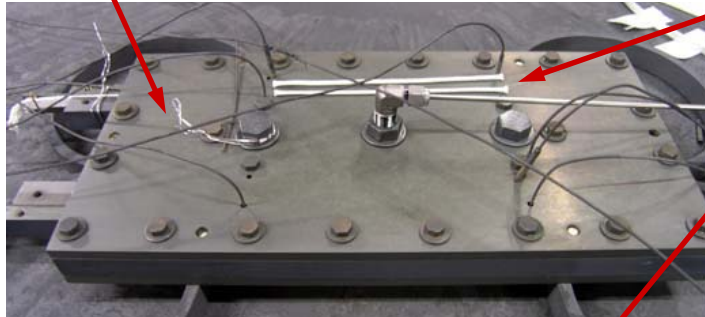
* Sizing removal reaction on insulation prior to insulating the cable

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

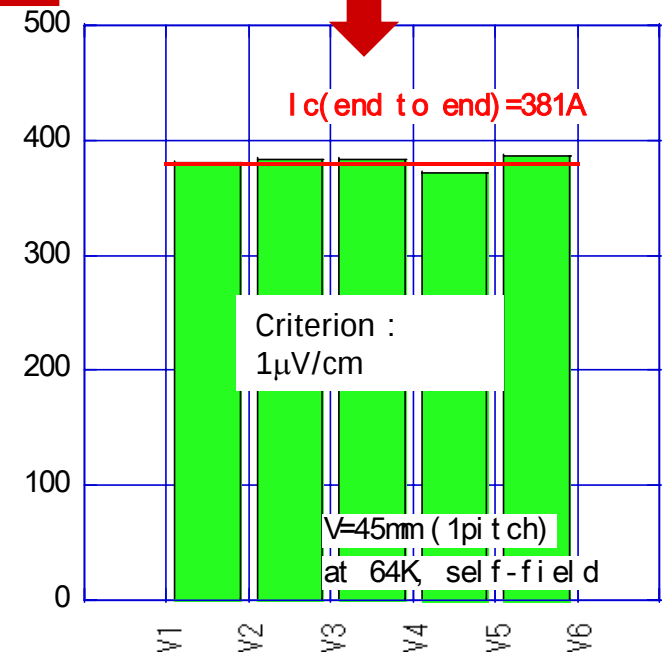
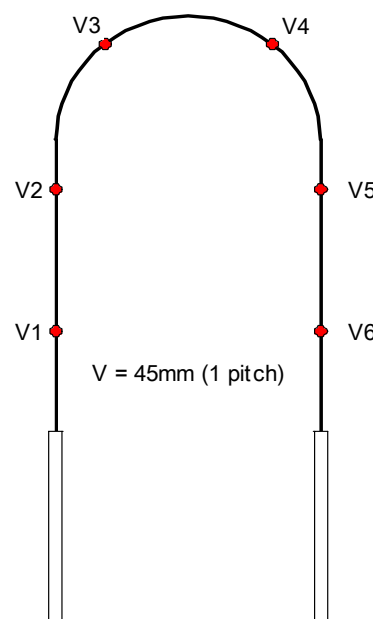
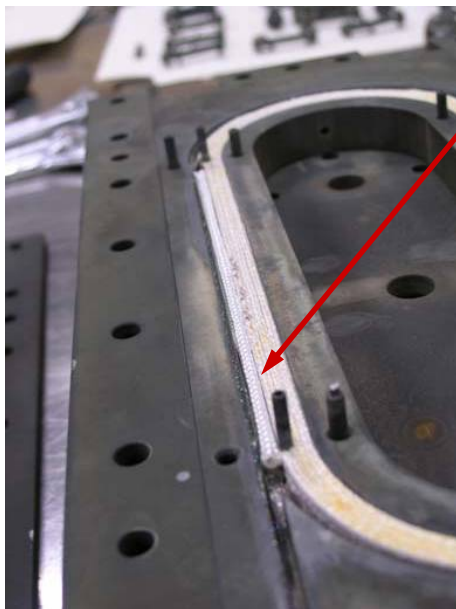
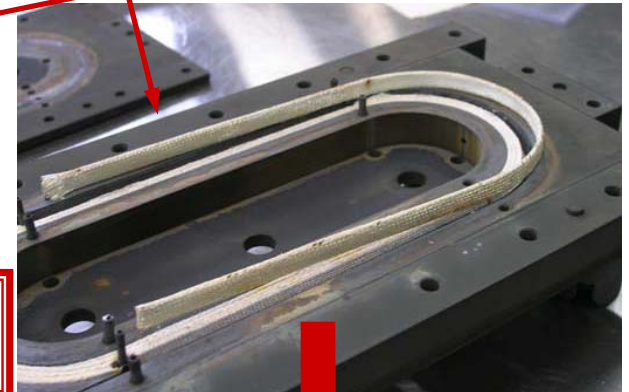
- HTS-SC07
- HTS-SC09
- HTS-SC11

} Various degrees
of confinement

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



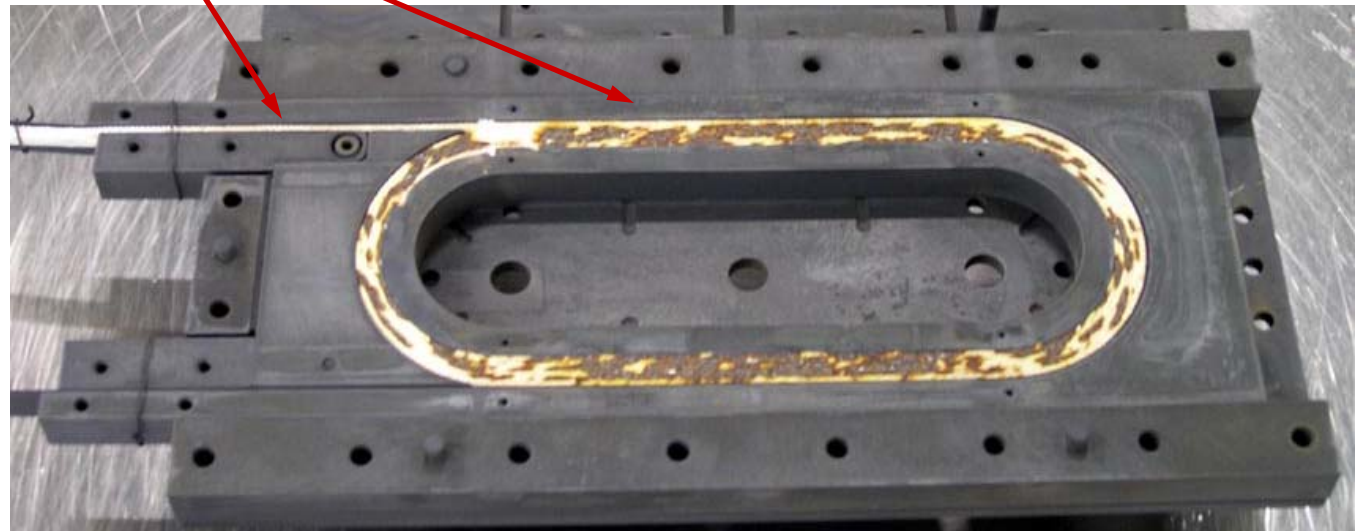
$$\Delta T = \pm 1^{\circ}\text{C}$$



Subscale coil after HT

Leakage occurred

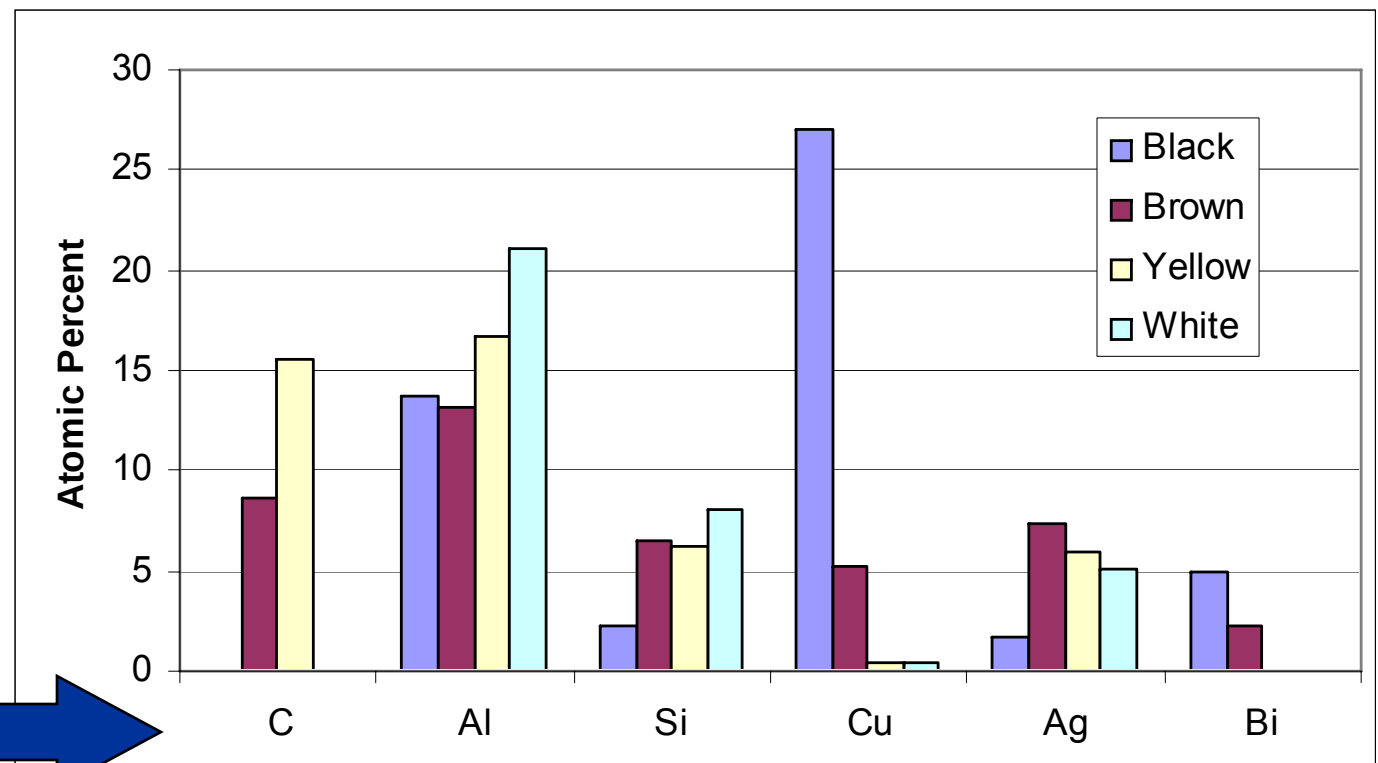
- Not at the leads
- But inside the package
- More severe at straight sections
 - ➡ Better confined



- 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

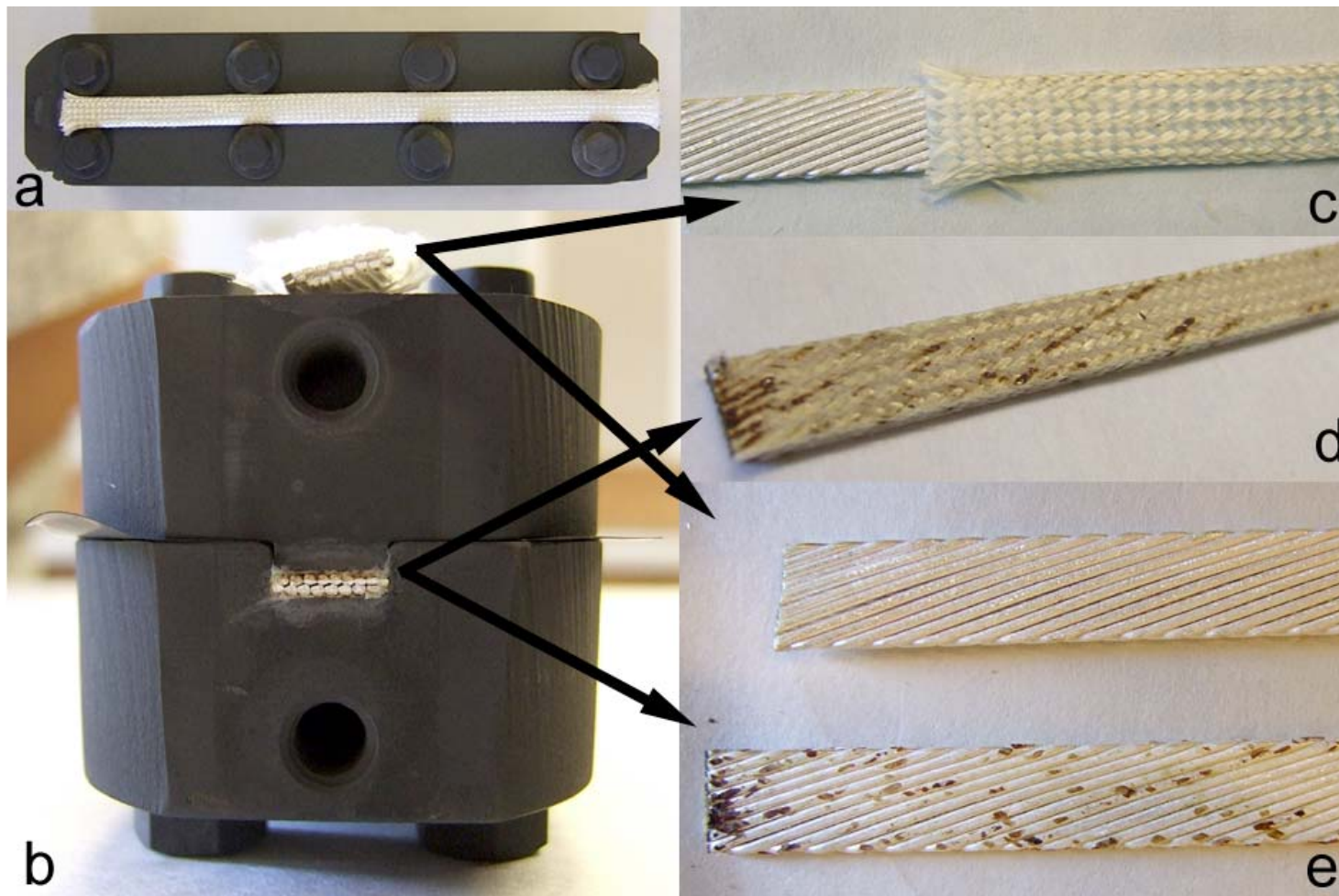
- ➡ Chemical compatibility is apparently OK

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

- 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 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