Development of Wind & React Bi-2212 Accelerator Magnet Technology

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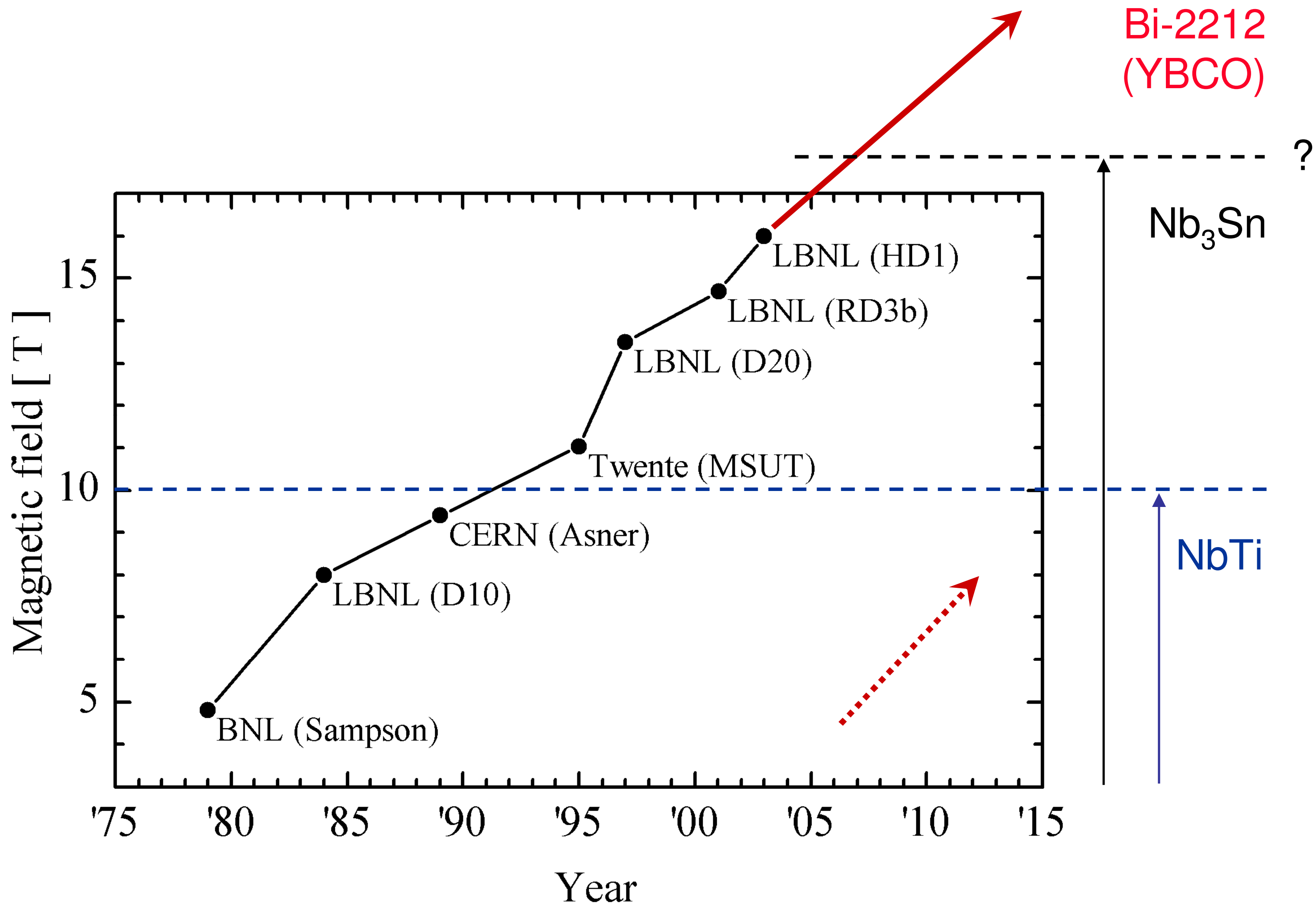
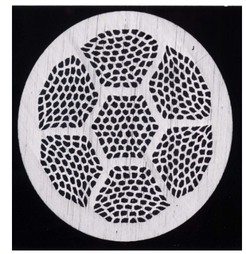
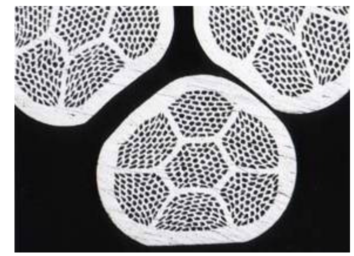
Progress in Maximum Dipole Field



Bi-2212 Program Motivation & Goals

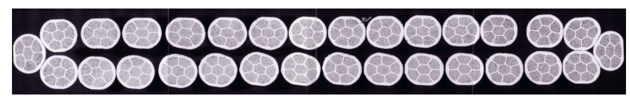
HD1 & HD2 operate close to the limits of Nb_3Sn





R&D plan to approach a 20 T dipole field:

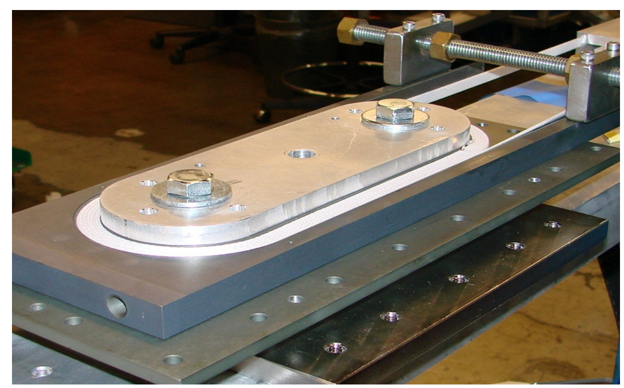
- Fine-tune Nb_3Sn performance to its full potential
- Introduce design features for high-field coil inserts
- Develop Bi-2212 W&R Technology:
  - *Cabling parameters and winding procedures*
  - *Heat treatment of large thermal masses*
  - *Optimization of HT (temperature, oxygen flow)*
  - *Chemical compatibility (insulation, structure)*



Cable fabrication

Progress to date:

- Established work plan and collaborations
- Investigated design and materials issues
- Fabrication/test of first HTS wind-and-react coils



Bi-2212 Coil Winding

Technology Challenges for Bi-2212

Material	NbTi	Nb_3Sn	Bi-2212
Dipole Limit	10-11 T	16-17 T	Stress limited
Reaction	Ductile	~675^{0}C in Air/Vacuum	~890^{0}C in O_2 (±2^{0}C)
Wire axial compression	N/A	Reversible	Irreversible?
Cable transverse stress	N/A	< 200 MPa	60 MPa?
Insulation	Polymide	S/E Glass	Ceramic
Construction	G-10, stainless...	Bronze, Stainless	Super alloy
Quench propagation	>20m/s	~20 m/s	0.1 m/s?

R&D Issues and Plans

Material studies:

- *Support vendors on conductor/material development*
- *Investigate insulations, coil and structural materials*
- *Rutherford cable fabrication, characterization, and testing*

Coil technology development:

- *Fabrication procedures and tooling*
- *Heat treatment optimization*
- *Coil instrumentation*

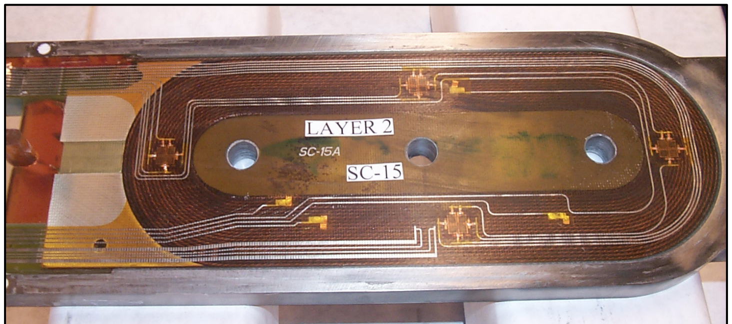
Mechanical and magnetic performance:

- *Investigate various field / force conditions*

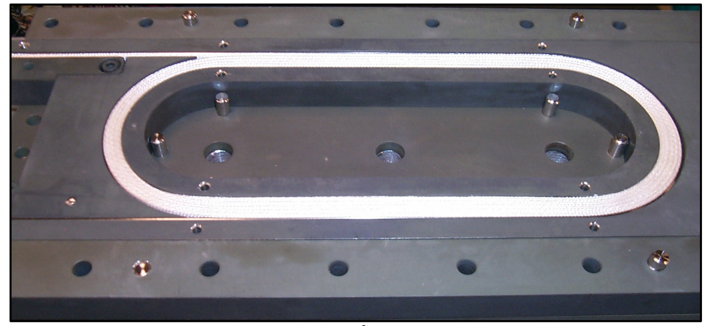
Quench protection:

- *Quench detection and propagation*
- *Protection analysis and system design*

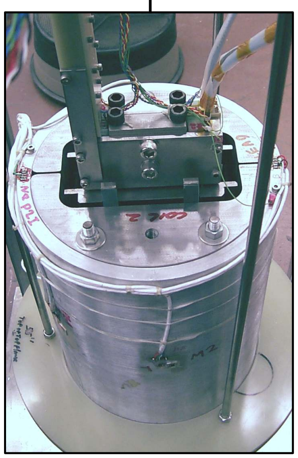
Sub-scale Coils and Structures



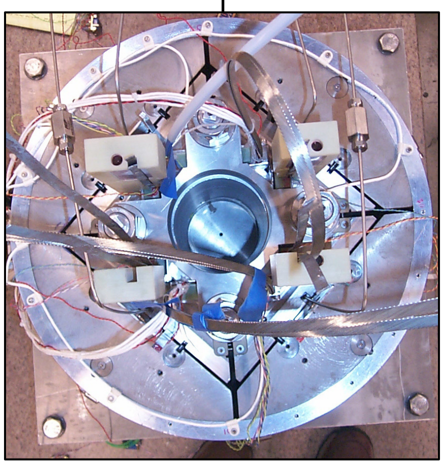
Nb$_3$Sn



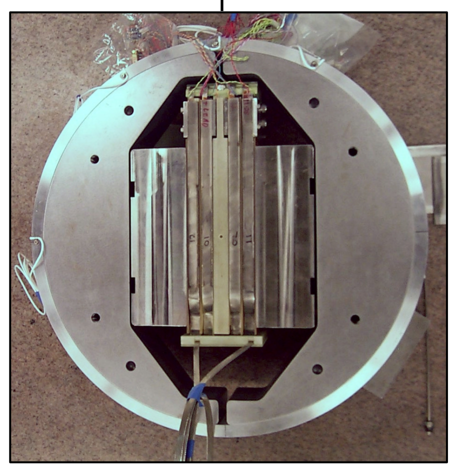
Bi-2212



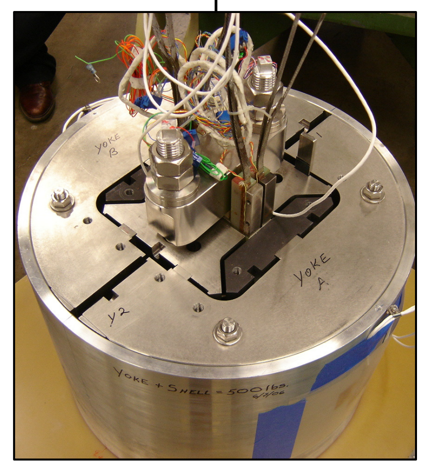
SM
Low field
Low stress



SQ
High stored energy
High Axial forces



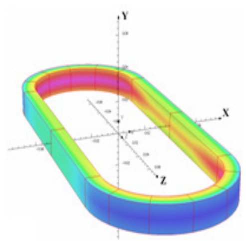
NMR
4-coil layout
High field



SD
High field
High stress

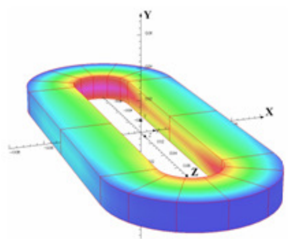
Test Configurations

6-turns



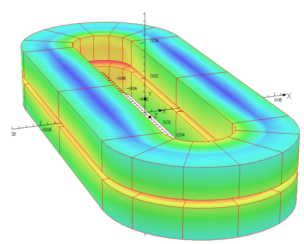
2-3 T

19-turns



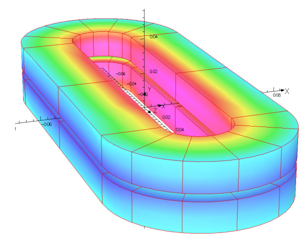
4-5 T

Common coil



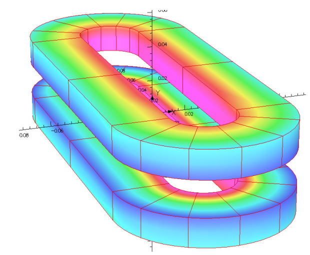
5-6 T

Block



6-7 T

Hybrid



8-10 T

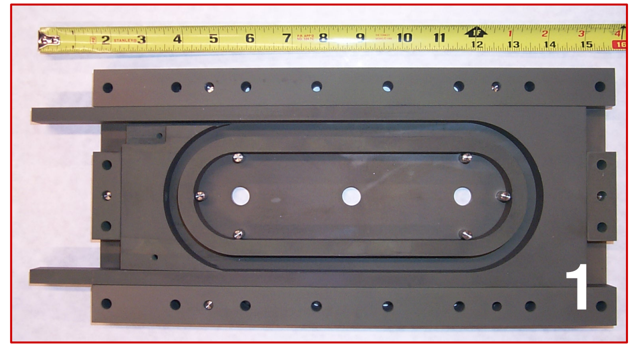
WIND-AND-REACT BI–2212 SUBSCALE COIL TEST CONFIGURATIONS

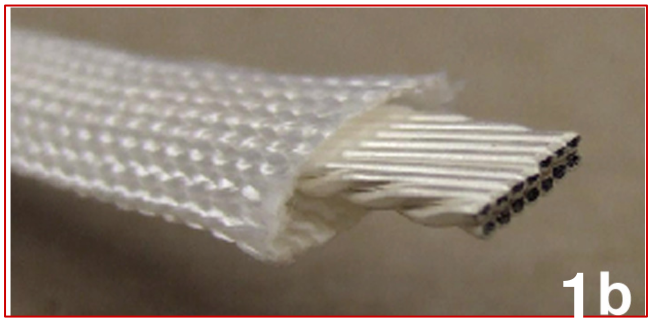
Layout	Turns	$\mu_0 H$ [T]	I_{ss} [A]	L [mH]	P_x [MPa]	P_y [MPa]	P_z [MPa]
Bi–2212 stand alone	2×6	2.6	6213	0.036	1.1	0	1.9
Bi–2212 stand alone	2×19	4.9	5179	0.25	9.7	0	9.4
Bi–2212 common coil[a]	2×19	5.8	4948	0.28	27	7.5	15
Bi–2212 dipole[a]	2×19	6.6	4777	1.2	1.6	14	3.2
1× Bi–2212 / 2× Nb_3Sn hybrid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

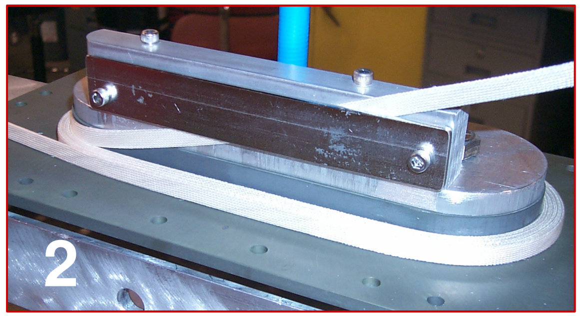
[a] With an iron insert inside the Bi–2212 subscale island
[b] Bi–2212 and Nb_3Sn in series connected and Bi–2212 limited
[c] Bi–2212 and Nb_3Sn driven independently

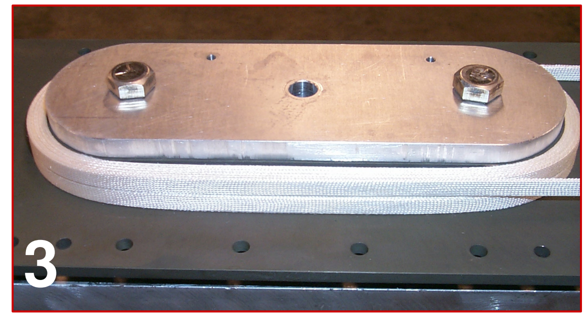
Sub-scale Coil Manufacture

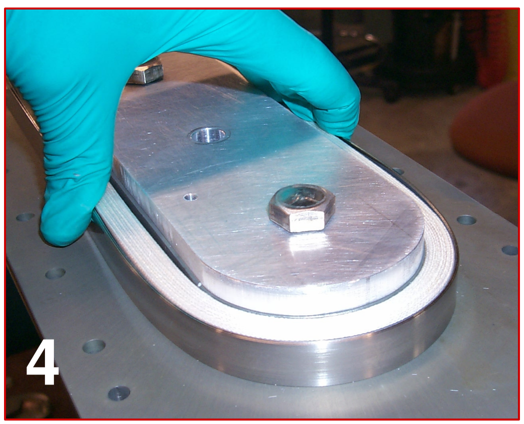
- Remove sizing on alumina-silica sleeve
- Fabricate and insulate cable
- Wind coil on INCONEL alloy 600 island
- Enclose with Alloy 600 heat treatment package
- Ship to wire manufacturer for heat treatment

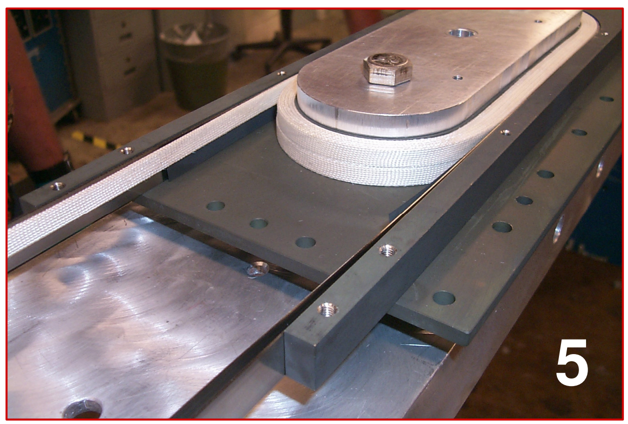


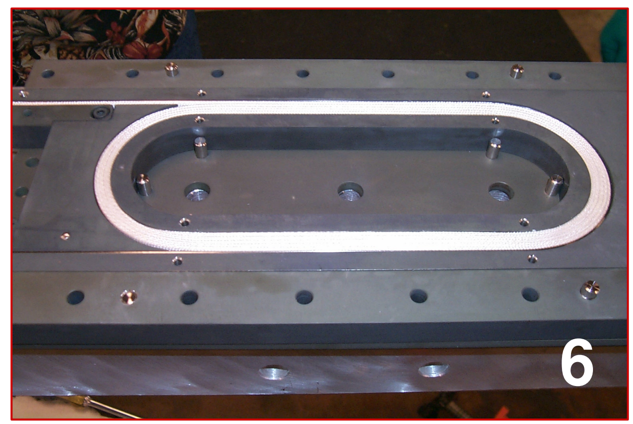






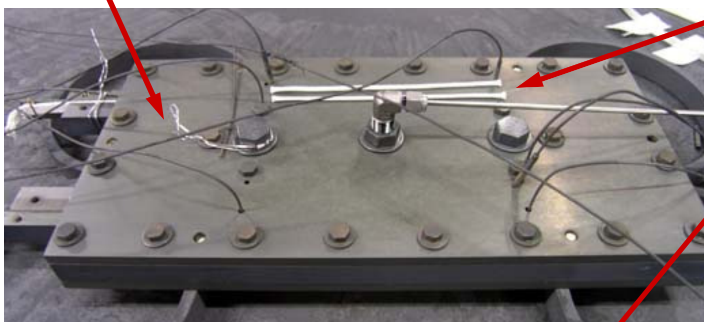


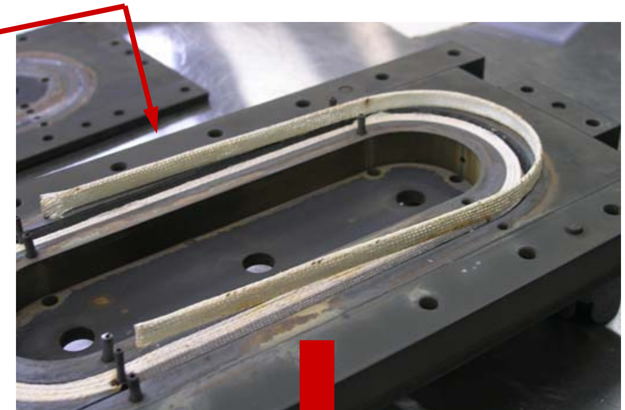




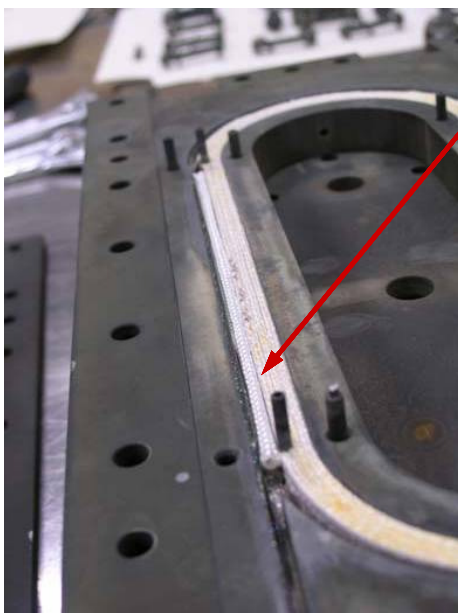
Heat Treatment Studies at Showa

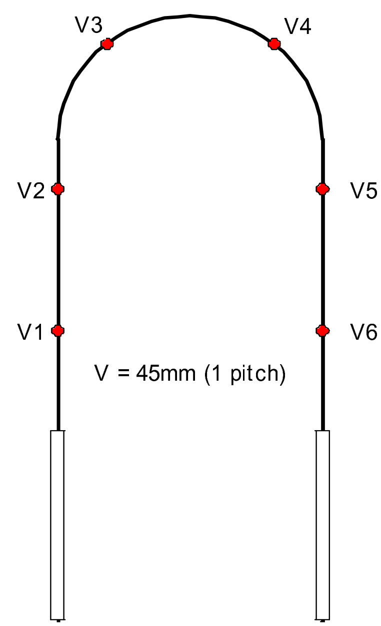
Dummy coil, and dummy coil with wires and cable sections

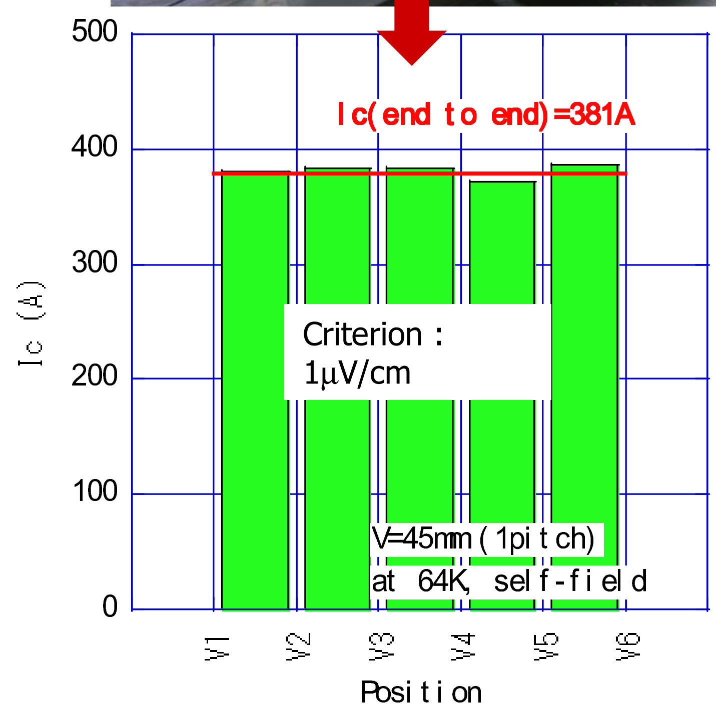




Achieved
$\Delta T = \pm 1$ °C

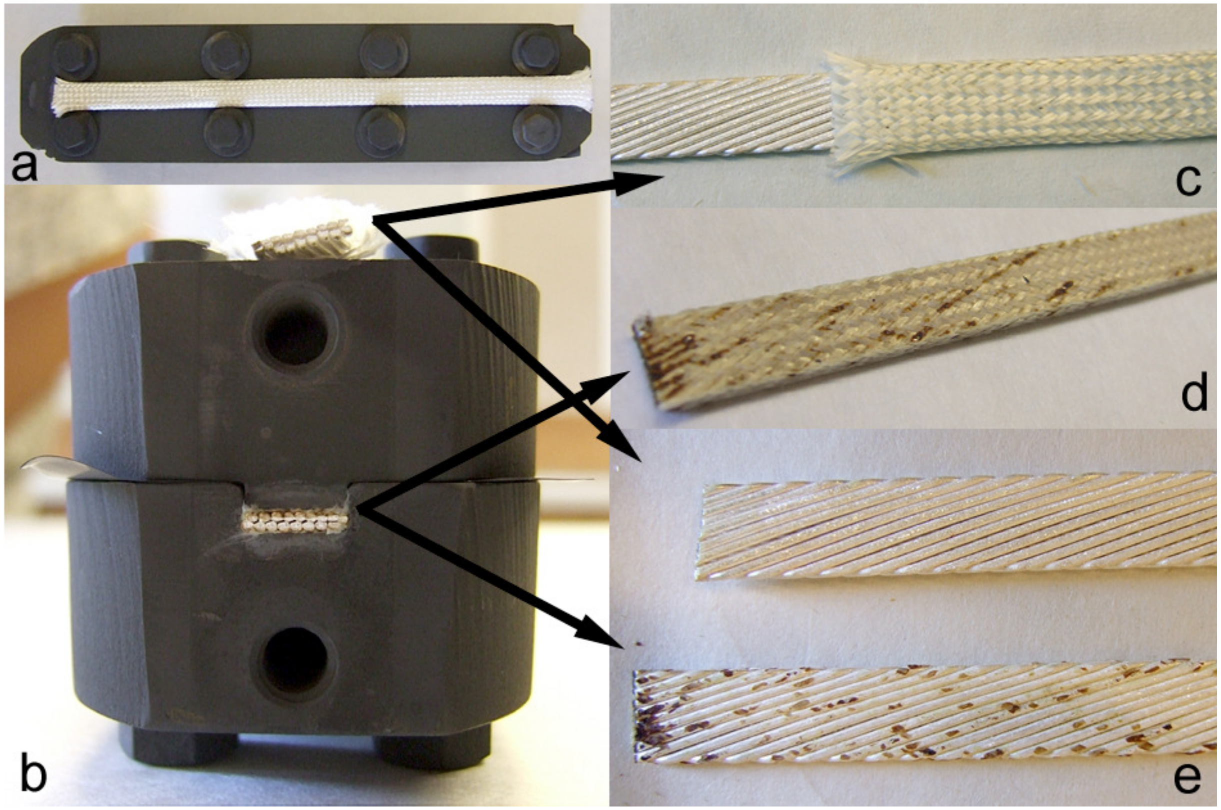






Heat Treatment Studies at LBNL

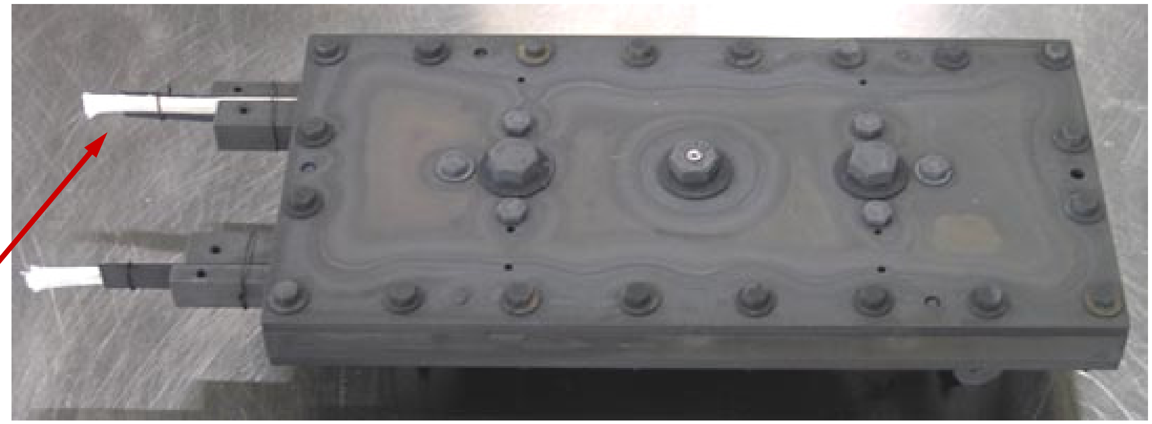
Load structure to simulate winding pack with single cable



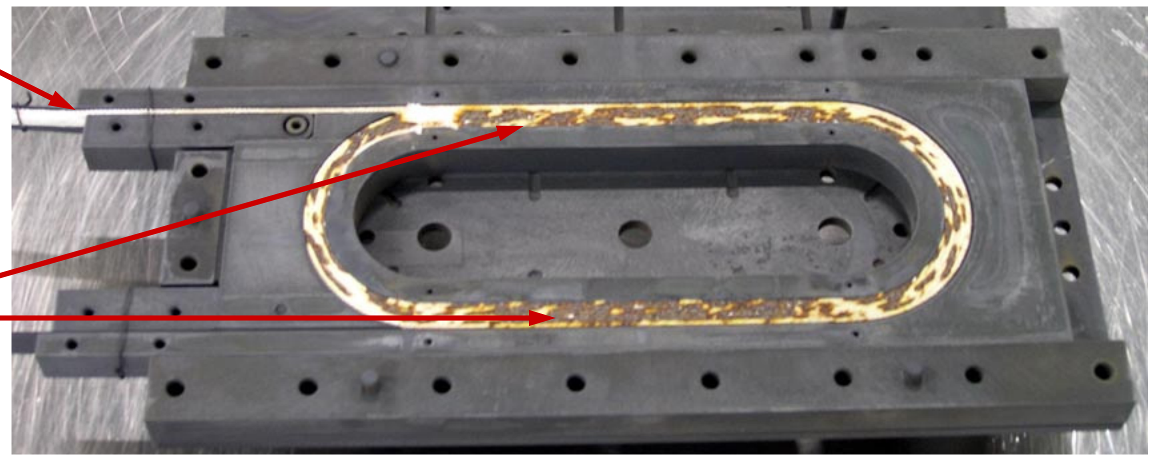
Clear difference found between free and confined condition
Note: no gas flow is provided by the clamping fixture

Leakage during Coil Heat Treatment

Bi-2212 leakage in the coil package during HT



Not at the leads



More severe at straight sections
More confined?

Leakage is *absent* in HT optimizations and insulated free wires and cables
OST wire (SC-04) exhibited less leakage, but HT cycle needs verification

Origin of Bi-2212 Leakage

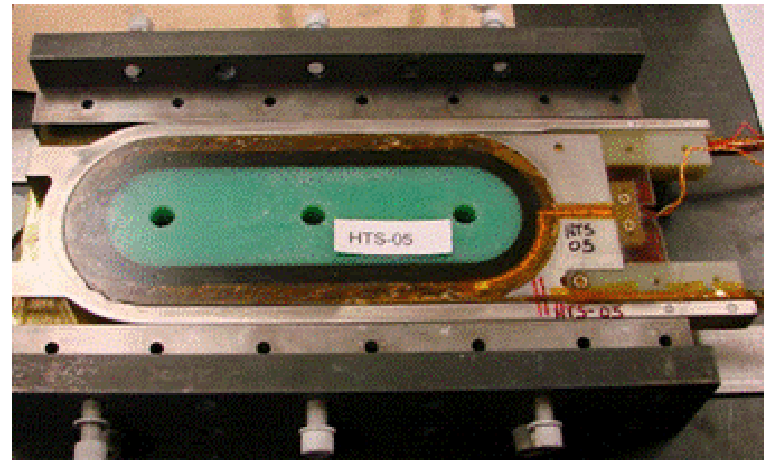
- Non-confined wires and cables exhibit no leakage
- Confined winding pack exhibits leakage – candidate causes:
  - Mechanical
    - Cable expansion during heat treatment
    - Ag-alloy expansion larger than INCONEL alloy 600
      - Both are presently not accounted for
  - Oxygen environment in package (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 O2 ➔ H2O&CO2
      - Requires about 1.2 gram O2 ➔ 2 L/h (1 atm, 300K)
    - No remaining sizing ➔ insufficient O2 flow
  - Chemical compatibility: ok in unconstrained state; need further verification in confined state where components are in closer contact
  - Other?

HTS Sub-scale Coil Series

Coil ID	Cable	Insulation	Sizing	Confinement
HTS-SC01	Ag dummy SCC	Pure SiO_2	Present	Full
HTS-SC02	Ag dummy OST	Pure SiO_2	Present	Full
HTS-SC03	Untwisted SCC	Al_2O_3/SiO_2	Present	Full
HTS-SC04	Untwisted OST	Al_2O_3/SiO_2	Present	Full
HTS-SC05	Twisted SCC	Al_2O_3/SiO_2	600°C/1hr	Full
HTS-SC07	Twisted SCC	Al_2O_3/SiO_2	825°C/4hr	Low (X&Y)
HTS-SC09	Twisted SCC	Al_2O_3/SiO_2	825°C/4hr	Low (X)
HTS-SC11	Twisted SCC	Al_2O_3/SiO_2	825°C/4hr	Low (Y)

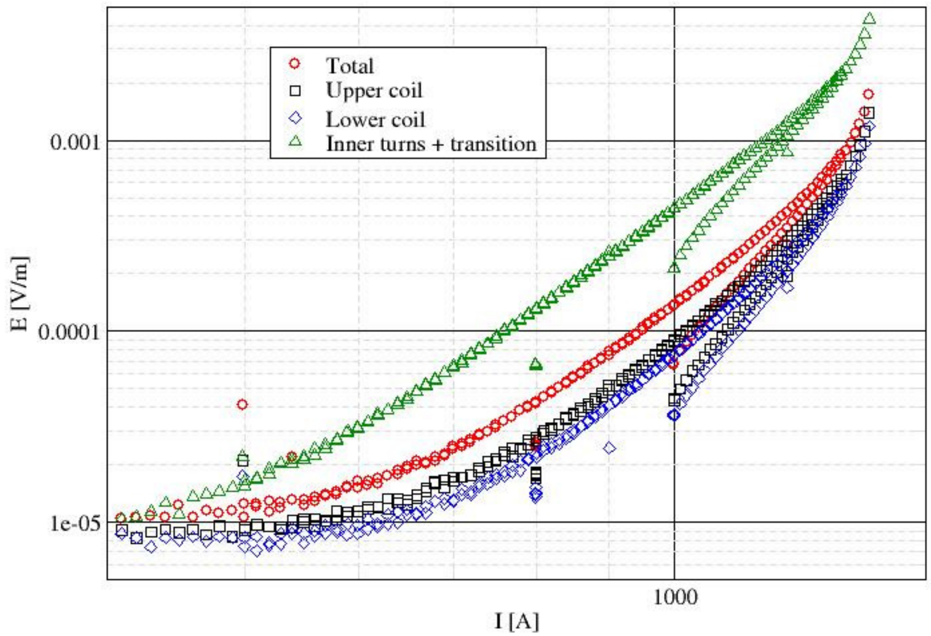
Sub-scale Coil Testing

- Significant leakage observed in coils
- Coils are nevertheless not shorted
- Proceed to testing and further analysis
- Develop capabilities (V-taps, leads)
- Vacuum impregnation of coil
- Test coil at 4.2K



- Testing performed in short-sample test facility
- Simpler, faster setup than main magnet test facility
- 200MHz data acquisition for (short) window about trigger signal
- Triggered by quench detection signal
- Quench detection via differential voltage across coil “halves”
- Allows good signal to noise (eliminates PS fluctuations)
- Quench signal shuts down power supply; no additional protection

First Coil Test Results (HTS-05)



Clean, reproducible and reversible V-I transition

Low N-value (~6)

Thermal "runaway" occurs slowly - no actual quench generated

- Transition occurs at much lower current than witness sample suggested
- I_c ~ 800A, expecting several kA
- Comparison based on 65K witness sample test results scaled to 4.2K
- No leakage observed on witness sample
- Next steps: test of coil #4 (OST) and #7-9-11 (SCC)

Acknowledgement

SWCC GROUP

- Bi-2212 wire design and fabrication
- Definition of the R&D plan
- Heat Treatment optimization (coil #1)
- Heat treatment of coil #3, #5, #7, #9, #11
- Strand and cable Ic measurements
- Chemical compatibility studies
- Investigations of the causes of leakage

OXFORD INSTRUMENTS

- Bi-2212 wire design and fabrication
- Heat Treatment optimization (coil #2)
- Heat treatment of coil #4
- Chemical compatibility studies

The Applied Superconductivity Center
National High Magnetic Field Laboratory
Florida State University

- Heat treatment cycle optimization
- Conductor and materials studies
- Chemical compatibility studies

Summary

Cable optimization and fabrication using both OST and Showa strands

- *Builds on LBNL experience from production of Showa SMES cable*

8 subscale coils manufactured using different conductor and confinement

- *Short sample HT tests also performed simulating coil environment*

Investigated and selected insulation (Al_2O_3/SiO_2, 80 μm thickness)

- *Chemically compatible if not confined in Inconel package*

Coils exhibit leakage

- *Due to confinement? Mechanical and/or Oxygen related?*
- *Chemical might also still be an issue inside a package*
- *Based on experience so far, we think leakage problem is solvable*

Coil testing setup operational, first test on HTS coil performed

Reduced Jc performance when compared to measured witness samples

$\Rightarrow$ *leakage likely contributor*

Can protect small coils – noise level low, stored energy small