Recent Bi2212 and YBCO Coil Tests in High Fields

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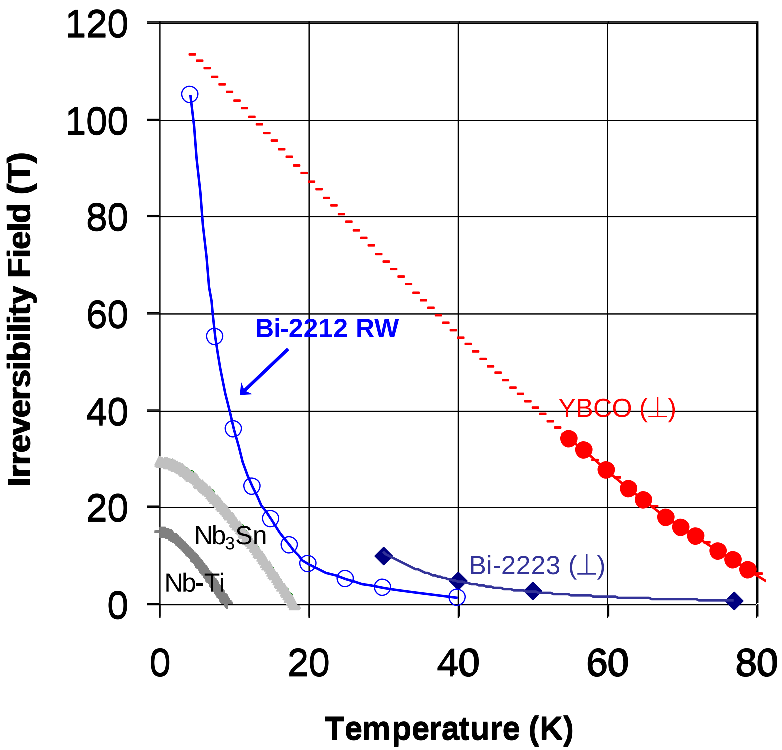
NHMFL, FSU

EuCARD – AccNet Mini-Workshop on a “High-Energy LHC”, HE-LHC’10

14-16 October 2010, Villa Bighi, MALTA

Why HTS Conductor Technology?

- **LHC has pushed Nb-Ti to its limits**
  - 8.5 T in main ring magnets and 10.5 T at 2 K in special magnets
- **LARP is pushing Nb_3Sn to its limits for LHC Phase I upgrades**
  - 16 T at 4.5 K (LBNL) and 230 T/m at 1.9 K LARP quadrupole
- **Bruker has just achieved 1 GHz (23.5 T at ~1.8 K) in a Nb-Ti/Nb_3Sn NMR magnet**
- **HTS widens field of potential high field applications, however imposes new restrictions:**
  - Mechanical, stress
  - Quench
  - A young and still developing conductor technology due to materials' complexity



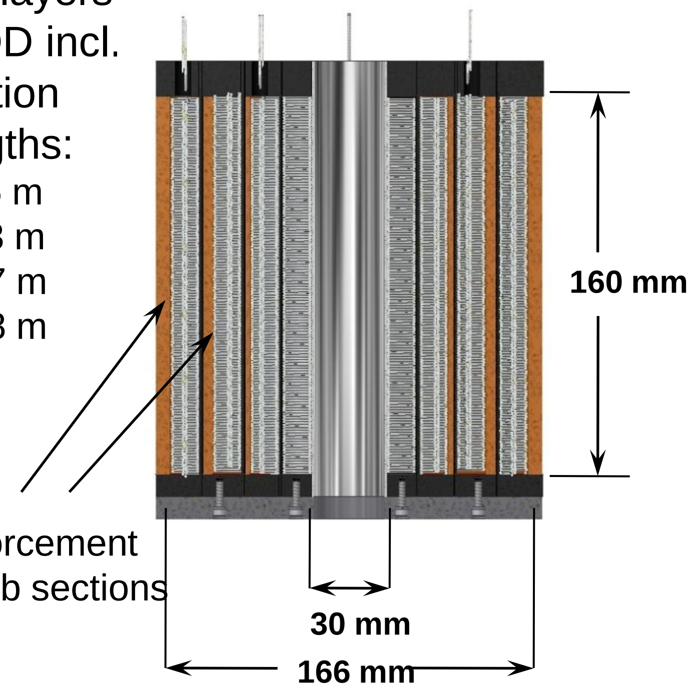
Nb_3Sn appears limited to ~18 T in saddle magnets and ~ 24 T in solenoid magnets

High Field Solenoid with Bi2212

- FSU goal: high-field solenoid to reach 7 T stable field increment in 18 T background field
- R&D needed with a focus on conductor to further increase J_w ;two main approaches:
  - Increase conductor I_c in coils; heat-treatment, conductor architecture, minimize adverse chemical interactions, (previous conductor leakage issue solved at manufacturer)
  - Increase packing factor of winding pack
    - reduce conductor insulation thickness
    - Strengthen alloy of matrix material

- each shell: 10 layers
- 1.3 mm wire OD incl. 0.3 mm insulation
- conductor lengths:
  - shell A: 186 m
  - shell B: 303 m
  - shell C: 437 m
  - shell D: 588 m

total ~ 1.5 km



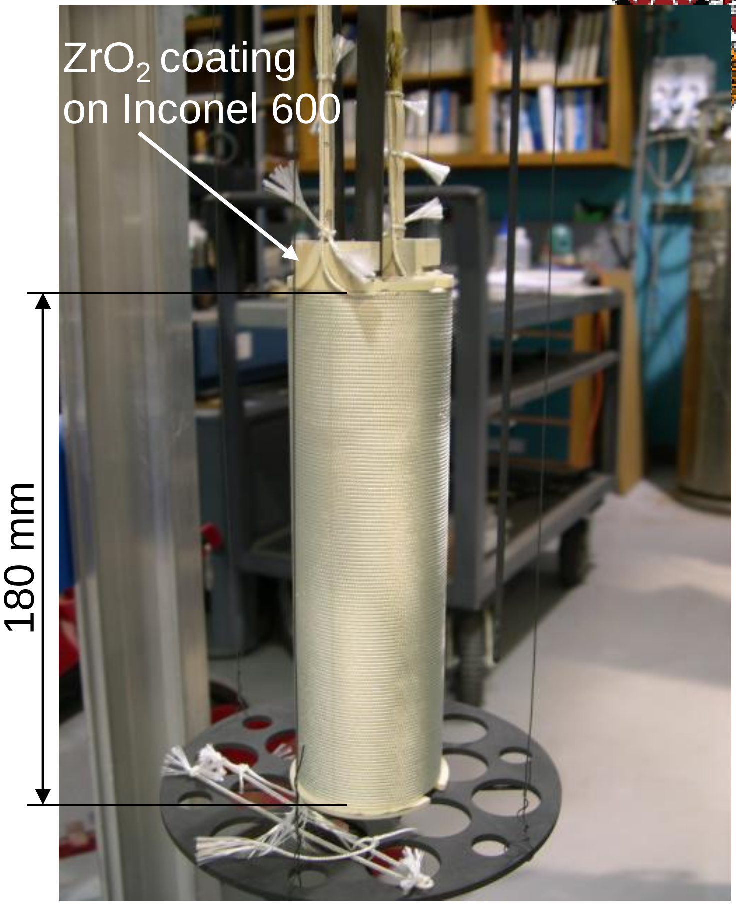
Small Bi-2212 Round Wire Test Coils on Inconel600

Both coils: "regular" HT, no visible leaks

Coil specs:
- 10 layers/750 turns, L ~ 3 mH
- ID = 15 mm, OD = 38 mm
- height = 100 mm
- conductor length ~66 m

- ΔB = 1.1 T at 31 T
- winding J_w = 80 A/mm^2 at 31 T
- (90 – 70 A/mm^2 in previous 5 T magnet at 20 T)
- no mechanical degradation

- **first HTS wire-wound coil to go beyond 30 T (32.1 T in 31 T background)**



Coil specs:
- 10 layers/135 turns, L = 14.9 mH
- ID = 32.4 mm, OD = 57.4 mm
- height = 180 mm
- conductor length ~220 m

- **Field generation: 2.3 T at s.f. and 1.2 T at 20 T, early transition driven by innermost layer**

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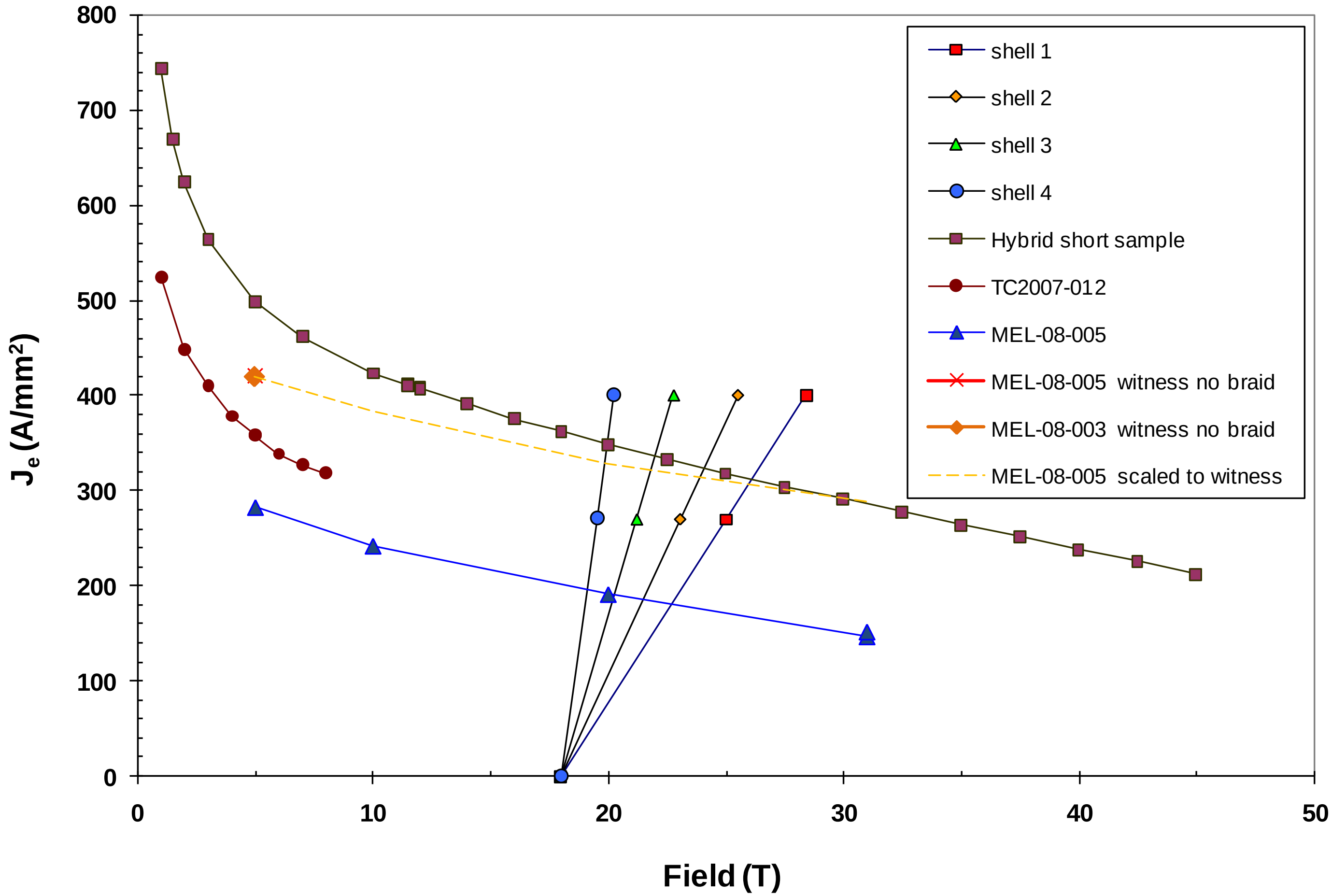
7 T Conductor Requirements



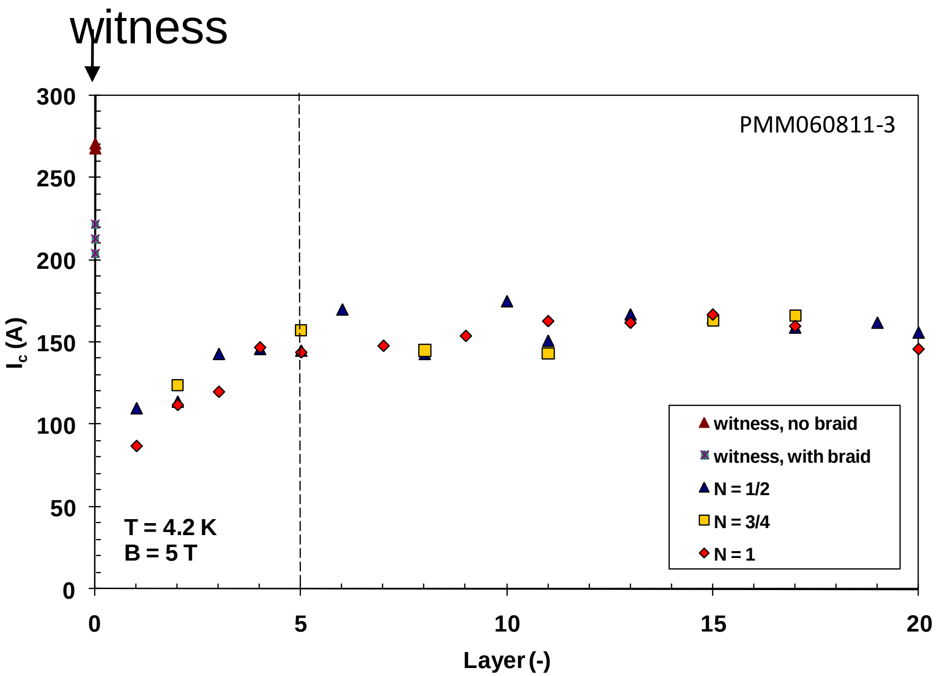
- J_e needed at assumed packing density loss of 0.5 due to large thickness of braid insulation
- to reach 25 T we need to raise J_e by developing thinner insulation OR raise J_c
- for 30 T and beyond we need to do both

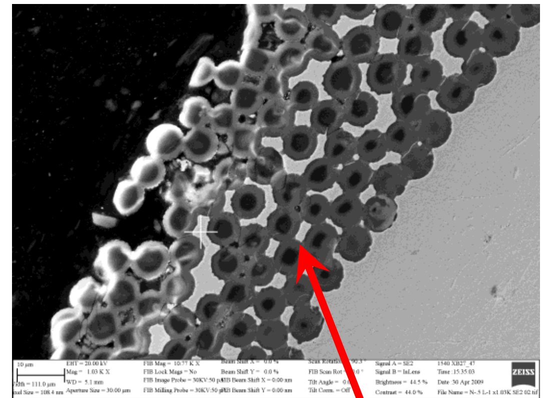
Conditions Impacting Coil Performance

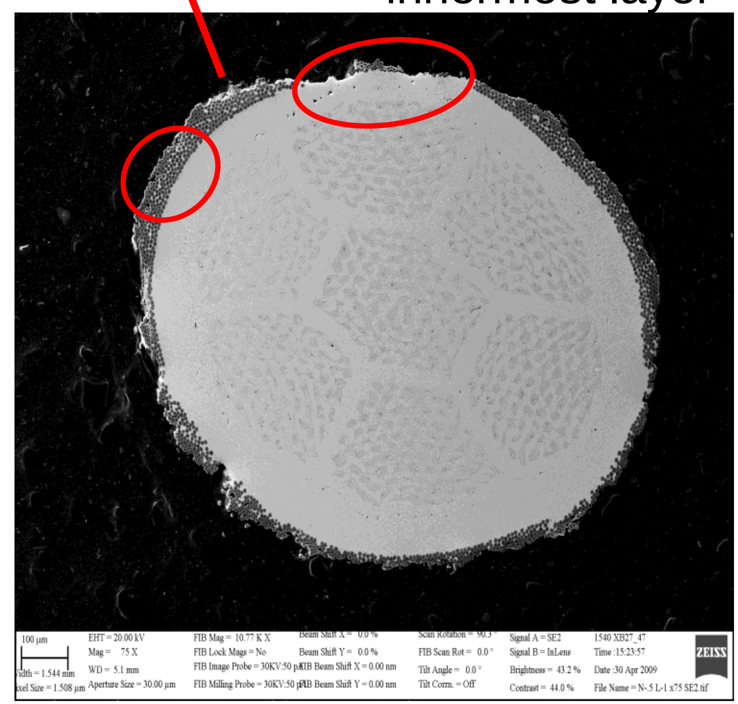
- Conductor leakage (largely solved by manufacturer)
- Chemical interactions with other materials
  - insulation
  - structural materials
- Thermal processing of winding pack
- Conductor properties
  - heat treatment parameters – what really is needed?
  - Sheath alloys – can stronger sheaths be made?
  - Powder compositions – can vortex pinning be enhanced?

All topics currently addressed within VHFSMC tasks

Understand Winding Pack Uniformity





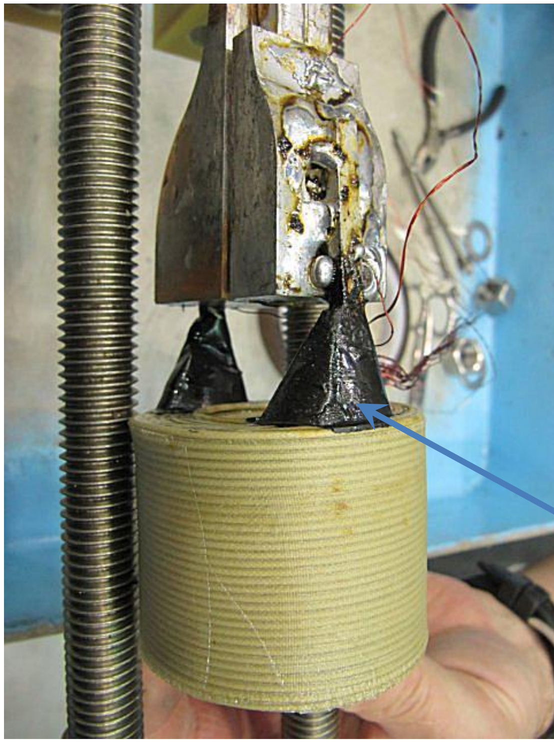


- Ag in between and inside aluminosilicate fibers
- Ag dissolves into braid, erodes matrix
- deformation of innermost layer

- dissected coil reveals homogeneous (but low) performance across 15 layers
- witness samples show consistently higher I_c
- Average losses:
  - Witness braid *vs.* no braid = 21%
  - Coil *vs.* witness no braid = 41%
  - Coil vs. witness with braid = 26%

Jiang, Myers

Bore-tube-free Test Coils



- Pre-annealed at 620 C for 1h with collapsible alumina bore tube in place to eliminate bending stress
- eliminate deformation and I_c variation on innermost layers
- eliminate chemical interactions with conductor
- reduce thermal mass
- Epoxy reinforced terminal structures mechanically coupled to the coil

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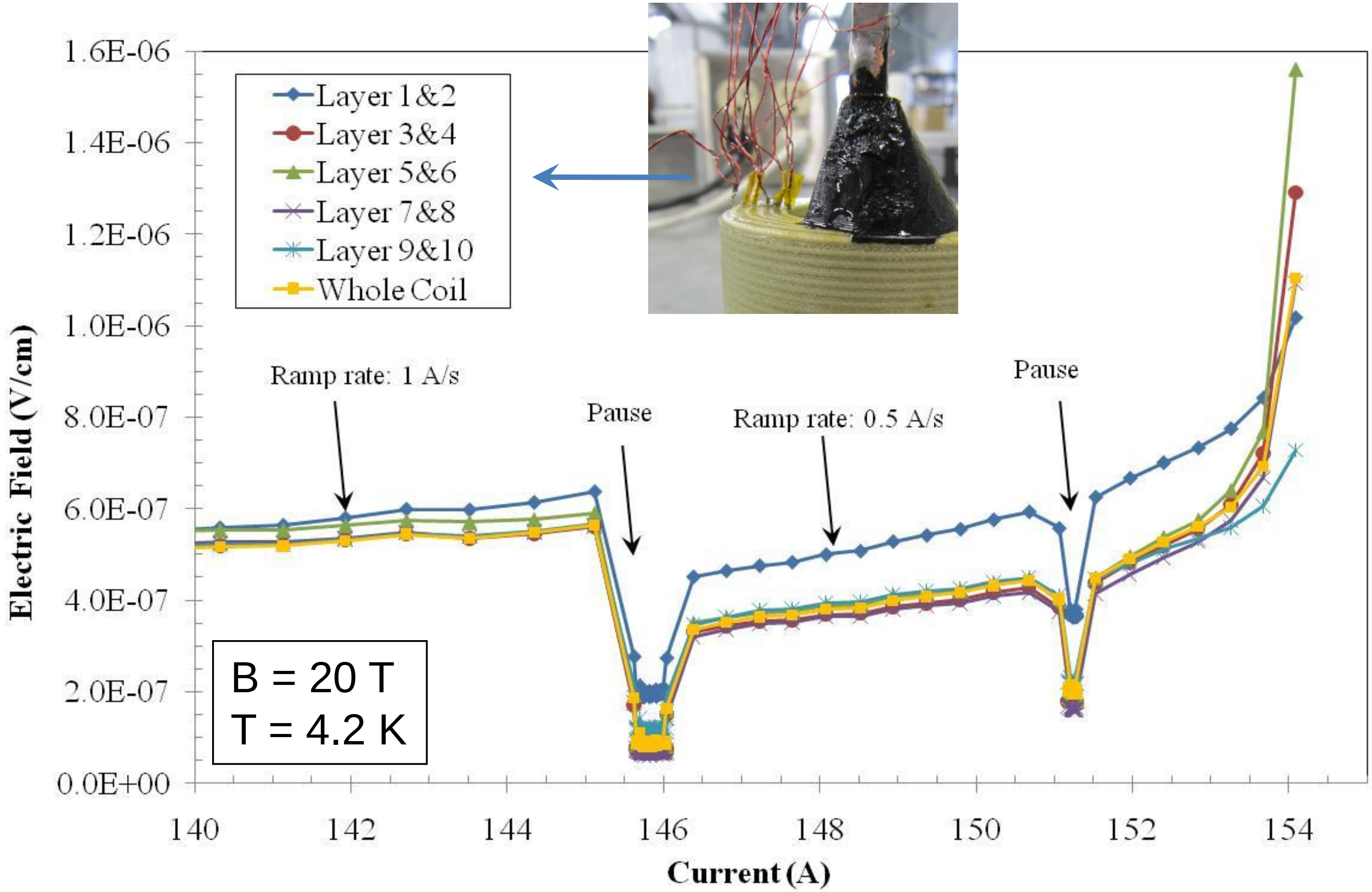
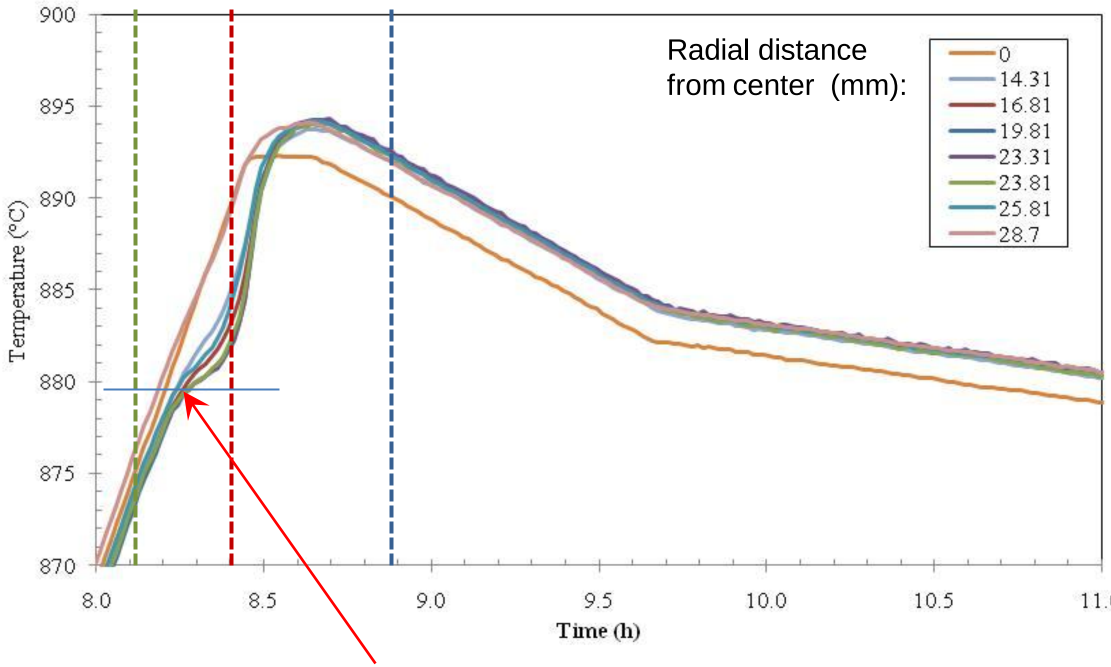
Successful Operation in 20 T

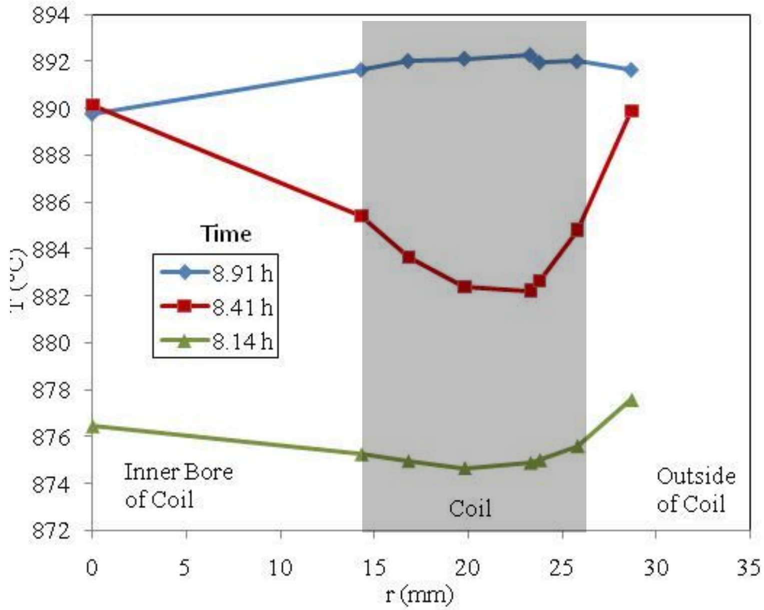


- uniform transition throughout coil
- suitable test bed for further coil processing experiments

How Uniformly Can Coils be Processed?

• monitor potential temperature variations during the H.T. of coils.
• Inserted a number of thermocouples at various radii





• Bi-2212 appears to melt just below 880°C and remains in the melt for more than 2 hours

• Largest temperature variation is only about 3 °C and occurs during the melting of Bi-2212.

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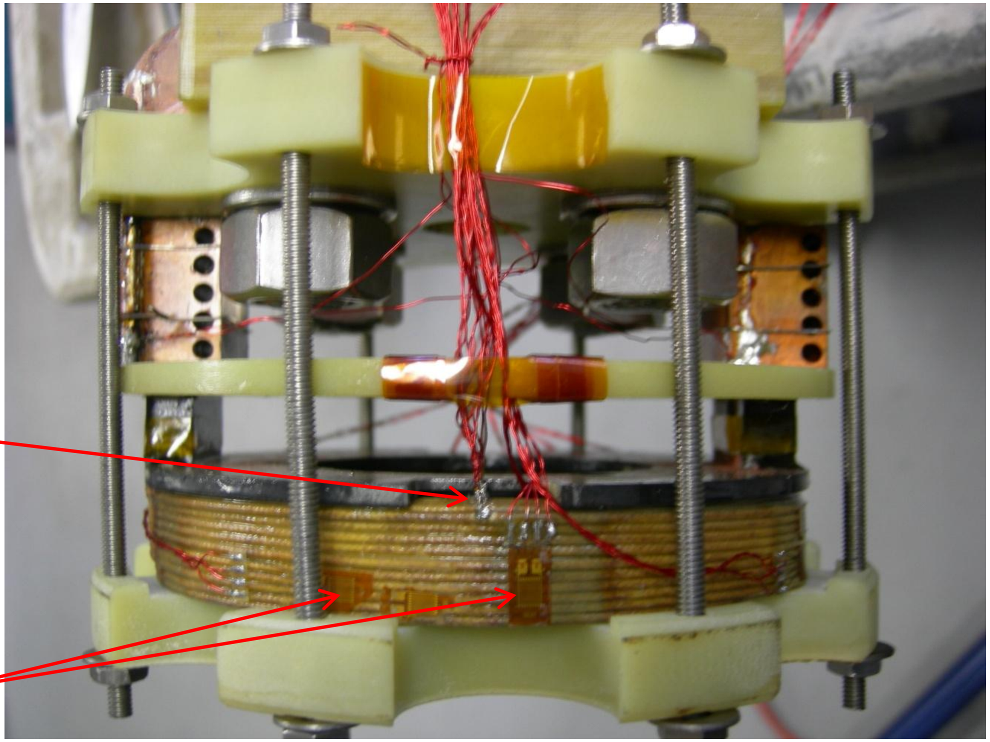
Large OD Hoop Stress Test Coil

Coil specifications:

- 1.03 mm OD wire (PMM070413-4)
- ID = 92.5 mm
- OD = 118.5 mm
- 10 layers, 10 turns
- Bore tube less
- epoxy impregnated
- $\Delta B \sim 0.2$ T at 20 T

Voltage Taps

Strain gauges



- Coil dimensions represent section of type “C” coil of 7 T design

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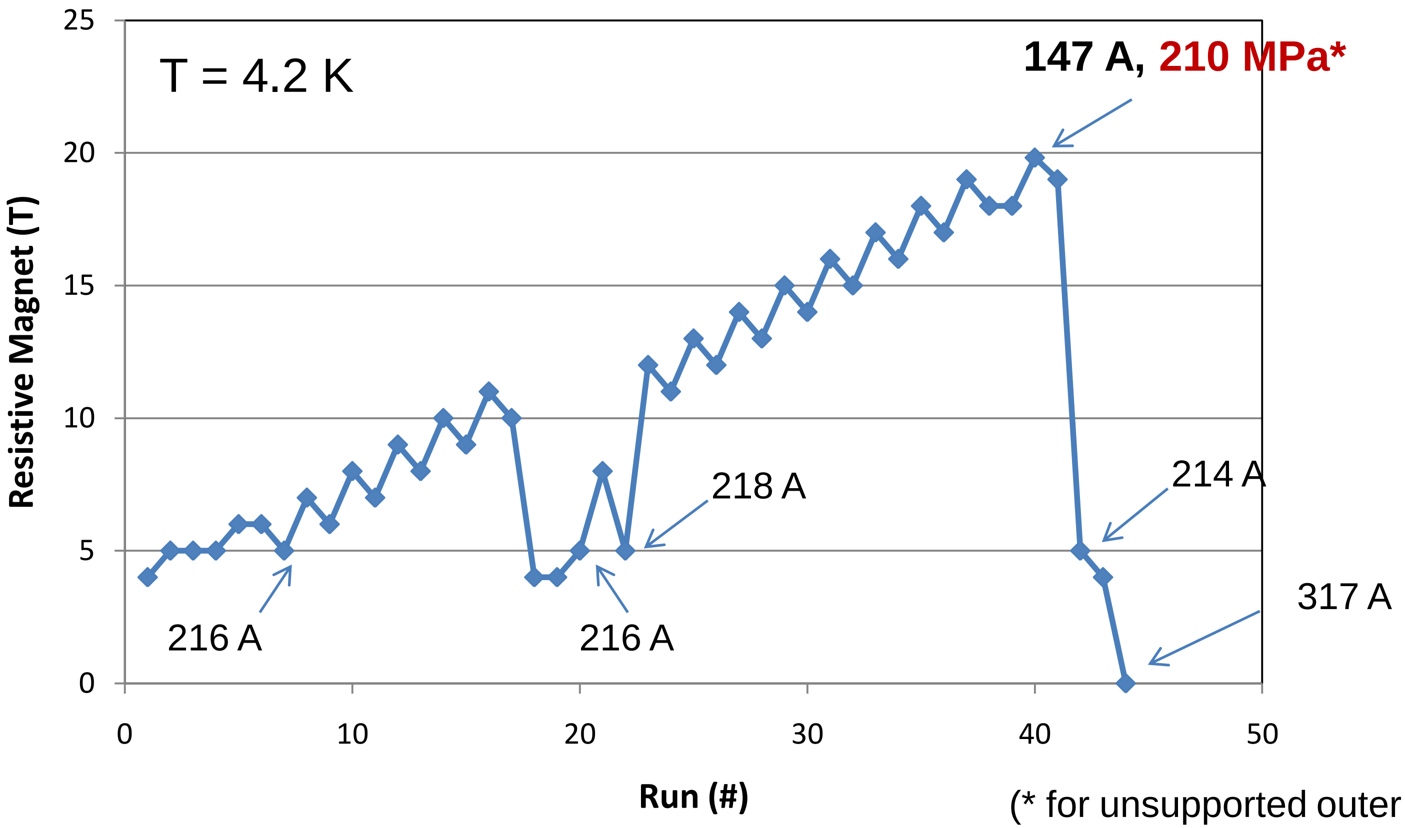
Degradation-free Test in 20 T



(* for unsupported outer turn, σ_{coil} ~ 91 MPa, ε ~ 0.15%)

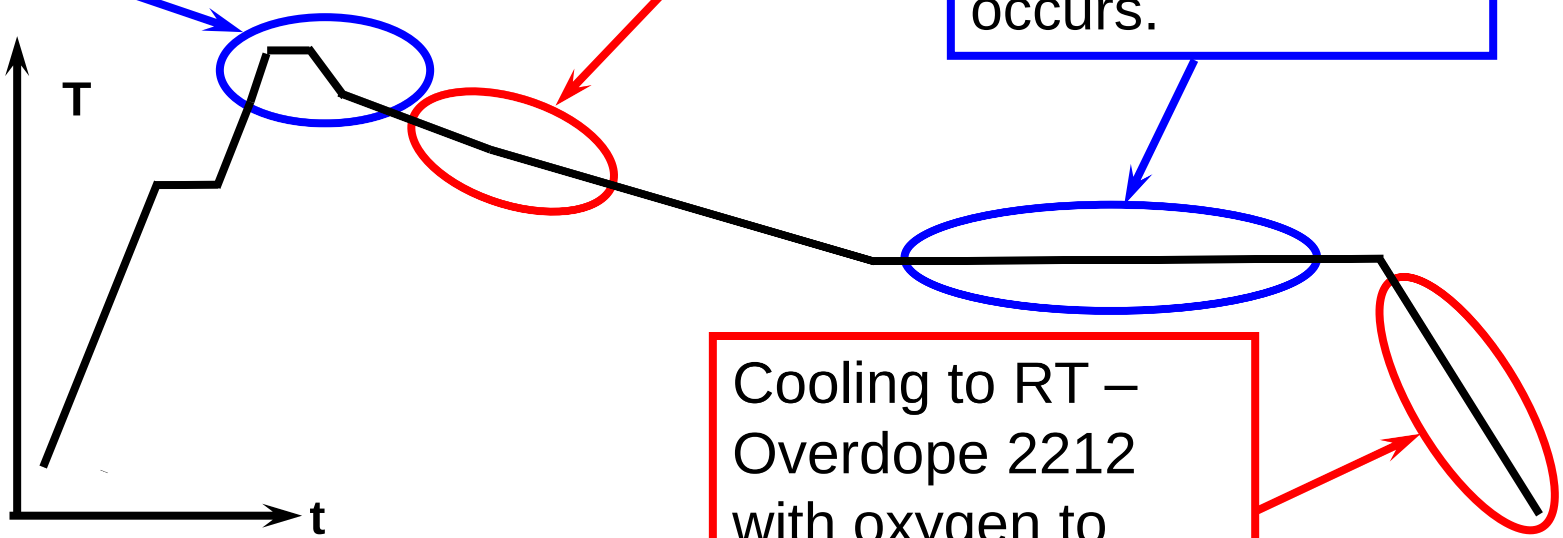
- Coil did not degrade at I_c(20T), effective load sharing by epoxy impregantion
- I_c of bare witness at 5 T = 361 A

What is the Dominant Current Limiting Mechanism in 2212?

Melt region – Why does J_c vary with T_{max}? Or is it t_{max}?
- Bubbles form
- Cu-loss to sheath

2212 formation region – How to form more, better connected 2212?

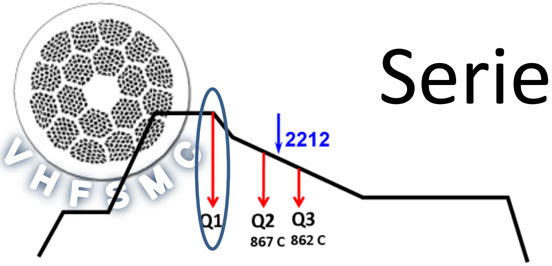
Annealing step – necessary to increase J_c, but do not know what occurs.

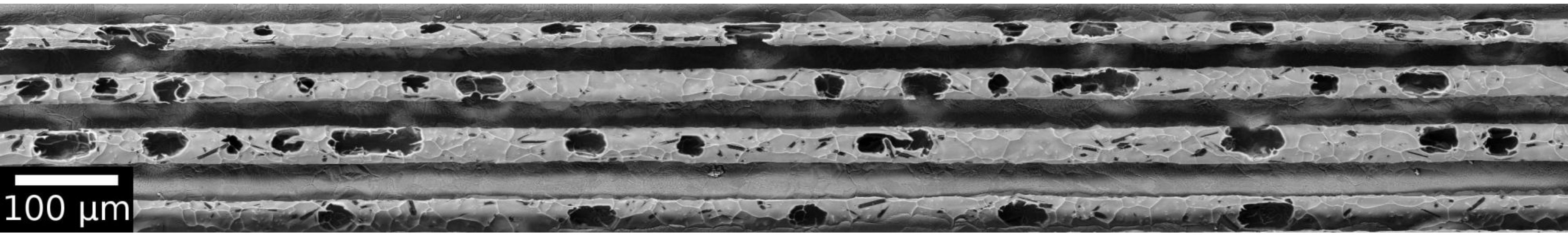


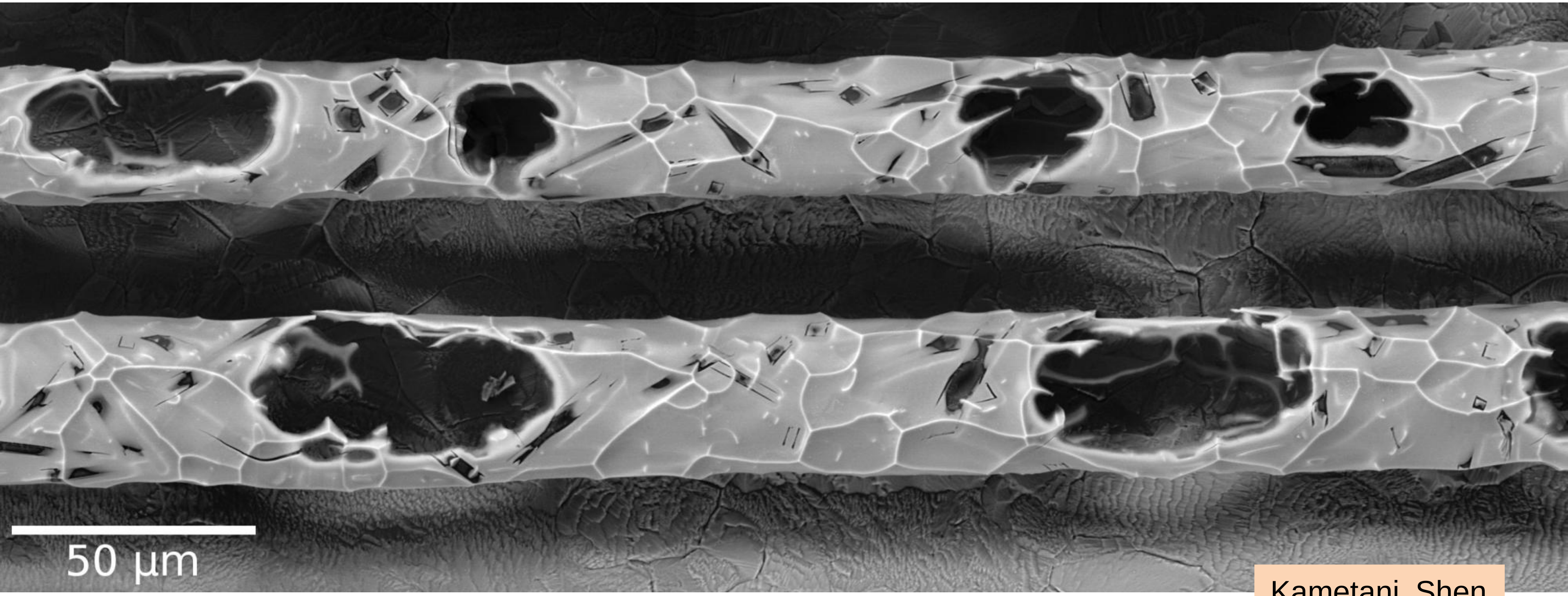
Cooling to RT – Overdope 2212 with oxygen to increase pinning and J_c.

- "regular" HT schedule

Series of Quench Experiments: Large Bubbles Present

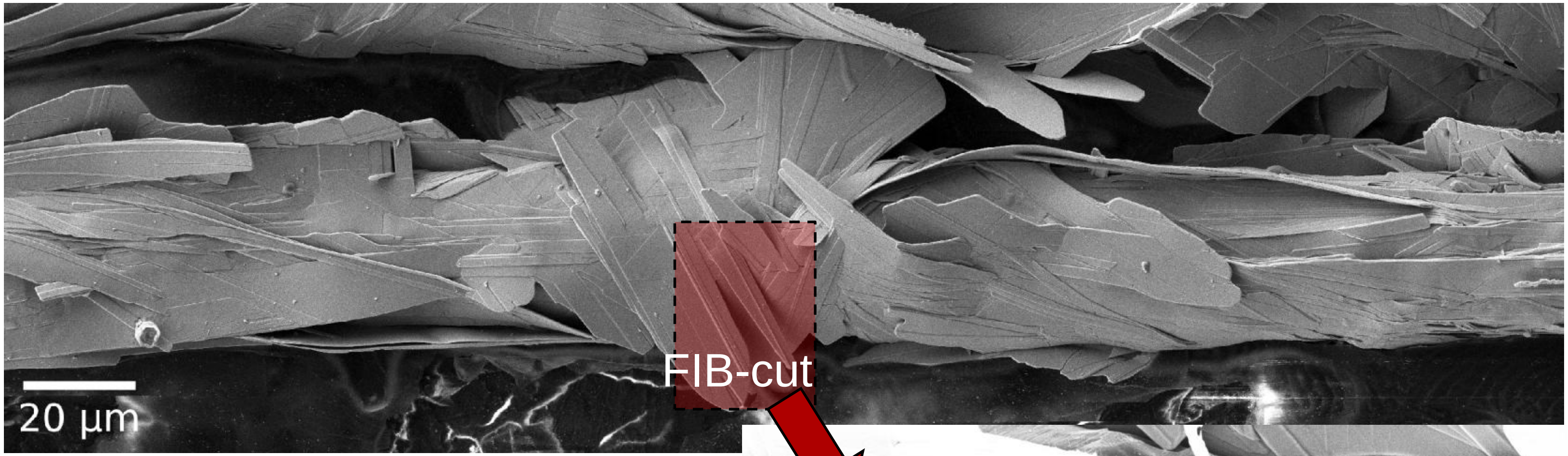


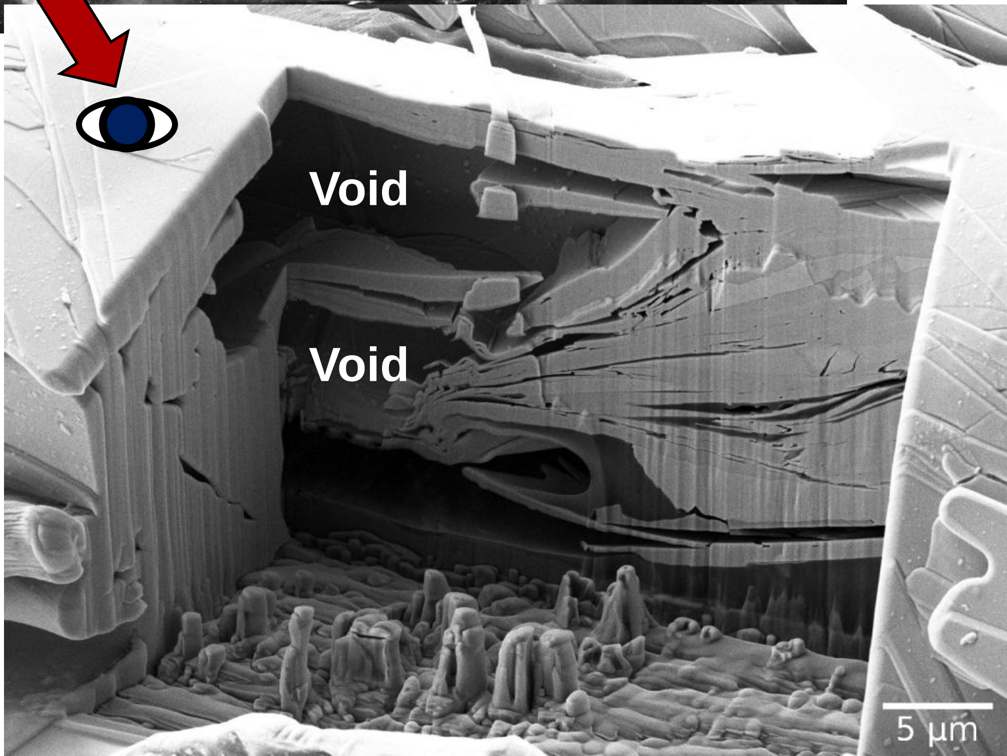




Kametani, Shen

Large Voids in Filaments Remain even in Fully-Processed Wire





Large voids stay present in the filaments - reduce cross-sectional area for current flow

Kametani

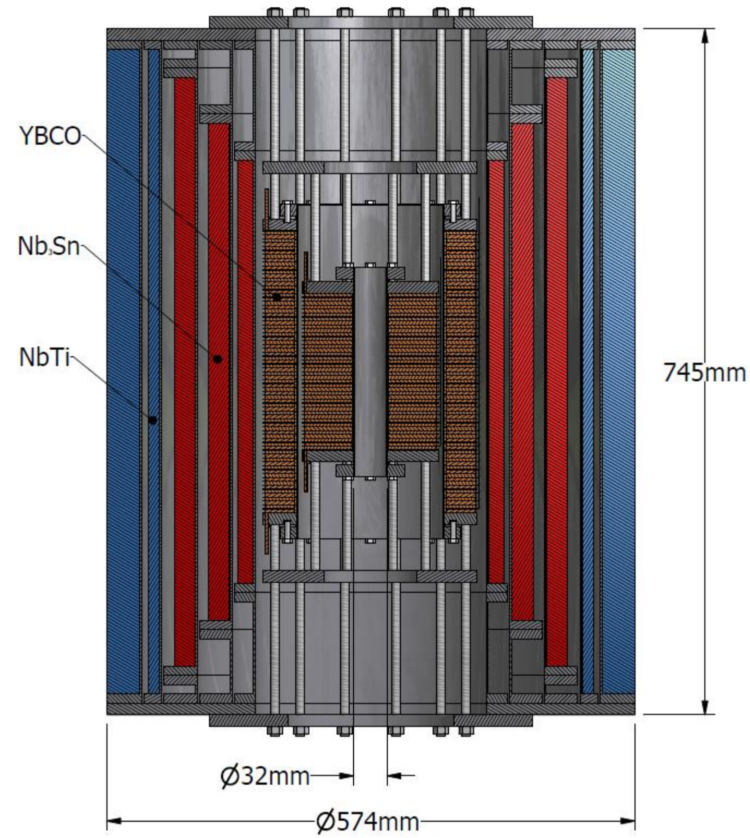
Conclusions – Bi2212

- Magnet pull driver of R&D on conductor and coils
  - Single wire with multi-hundred amp conductors (LBNL, FNAL)
  - Cables to make multi-kiloamp conductors
- Significant progress made on conductor level and understanding of Bi2212 round wire processing
- High field capable conductor, 250 - 300 m typical batch lengths available
- Mechanically robust conductor within winding pack
- Available critical current densities still an issue, however several issues have been identified
- Sustained interaction with R&D collaborators and industry through VHFSMC

32 T All S/C Magnet Project

- Goal: User high field magnet to replace 16 T LTS magnet at NHMFL

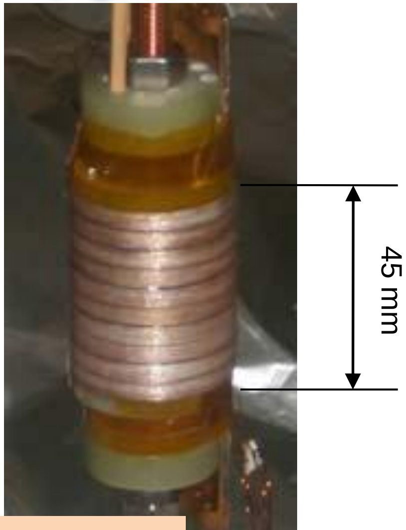
Total field	32 T
Field inner YBCO coils	17 T
Field outer LTS coils	15 T
Cold inner bore	32 mm
Uniformity	$5x10^{-4}$,1 cm dsv
Current	186 A
Inductance	436 H
Stored Energy	7.54 MJ
Total length YBCO	8 km
Maximum stress (MPa)	435 (outer YBCO shell)



Markiewicz

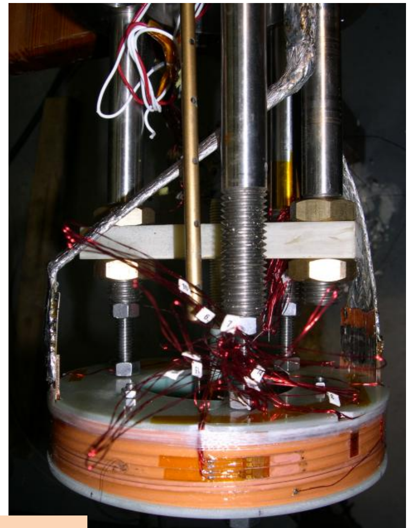
YBCO Coil Technology

Initial tests with YBCO tape very promising:



Markiewicz

- **10 single pancake coils**
- **ΔB = 2.8 T at 31 T**



Trociewitz

5 turns/12 layers, 4 mm wide varnish insulated

- ID = 159.7 mm
- OD = 163.2 mm
- glass fiber width = 0.5 mm, epoxy impregnated

no external reinforcement

- ΔB = 0.1 T at 20 T (central field)
- At nominal 0.115 mm conductor thickness,
  - **217 A =: 760 MPa**

Layer winding (LW) or pancakes (PC)?

LW:

+ continuous winding pack, small amount of resistive joints, terminals on top of coil

- Available batch lengths, conductor homogeneity over long lengths, bending strain issues?

PC:

+ flexibility, replaceable units in case of performance variations

- large amount of resistive joints, loss of packing density due to radial built in joint area, terminals top and bottom

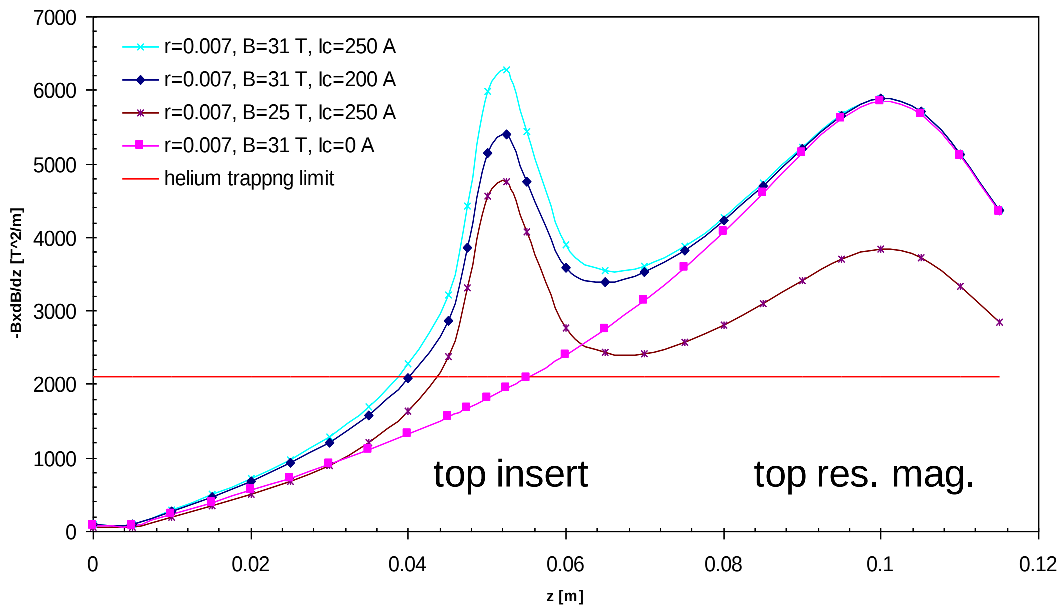
Reality check: typical conductor batch lengths are on the order of ~100 - 150 m, PC approach not suitable for high homogeneity magnets

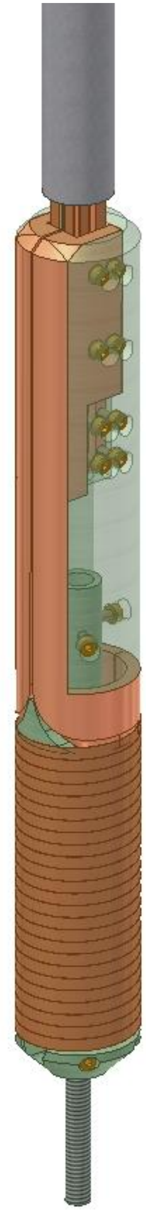
High Field Insert Coils, Reaching toward 40 T

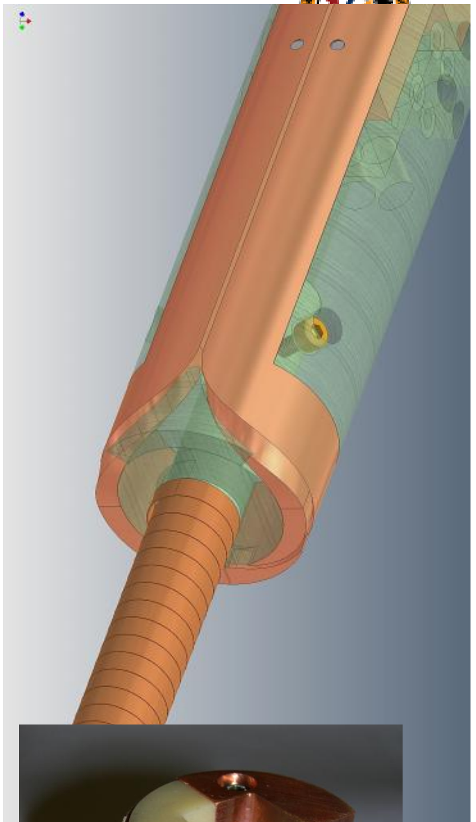
Explore limits of current YBCO technology

Intermediate goals:

- explore **layer winding**, significantly reduce amount of resistive joints in coils
- layer-wound insert coil to generate high field increment in 31 T background
- Previous high field test coil failed at terminals
- New terminal concept: **Twist-bend junction**
  - Move resistive part of terminal joint away from winding pack and high <u>*M*</u>**grad* <u>*B*</u> area; critical: varying field orientation angle



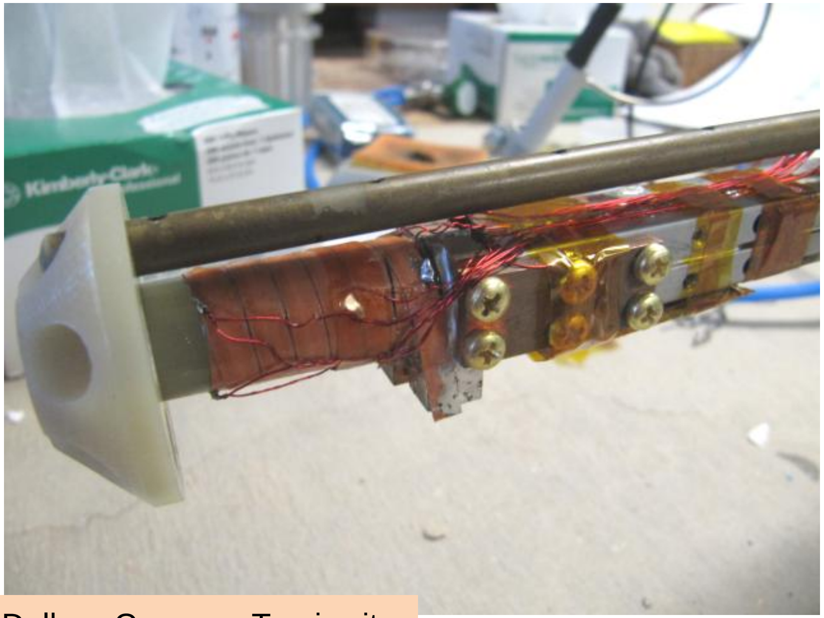




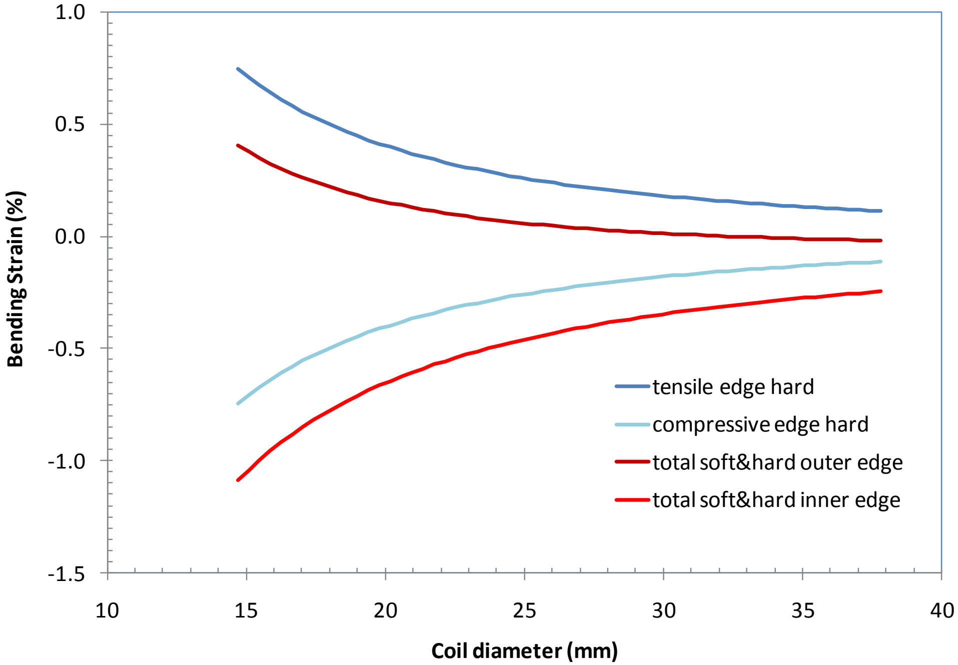
Termination test piece

Small YBCO Spiral

In-field Transport at 77 K and 4.2 K



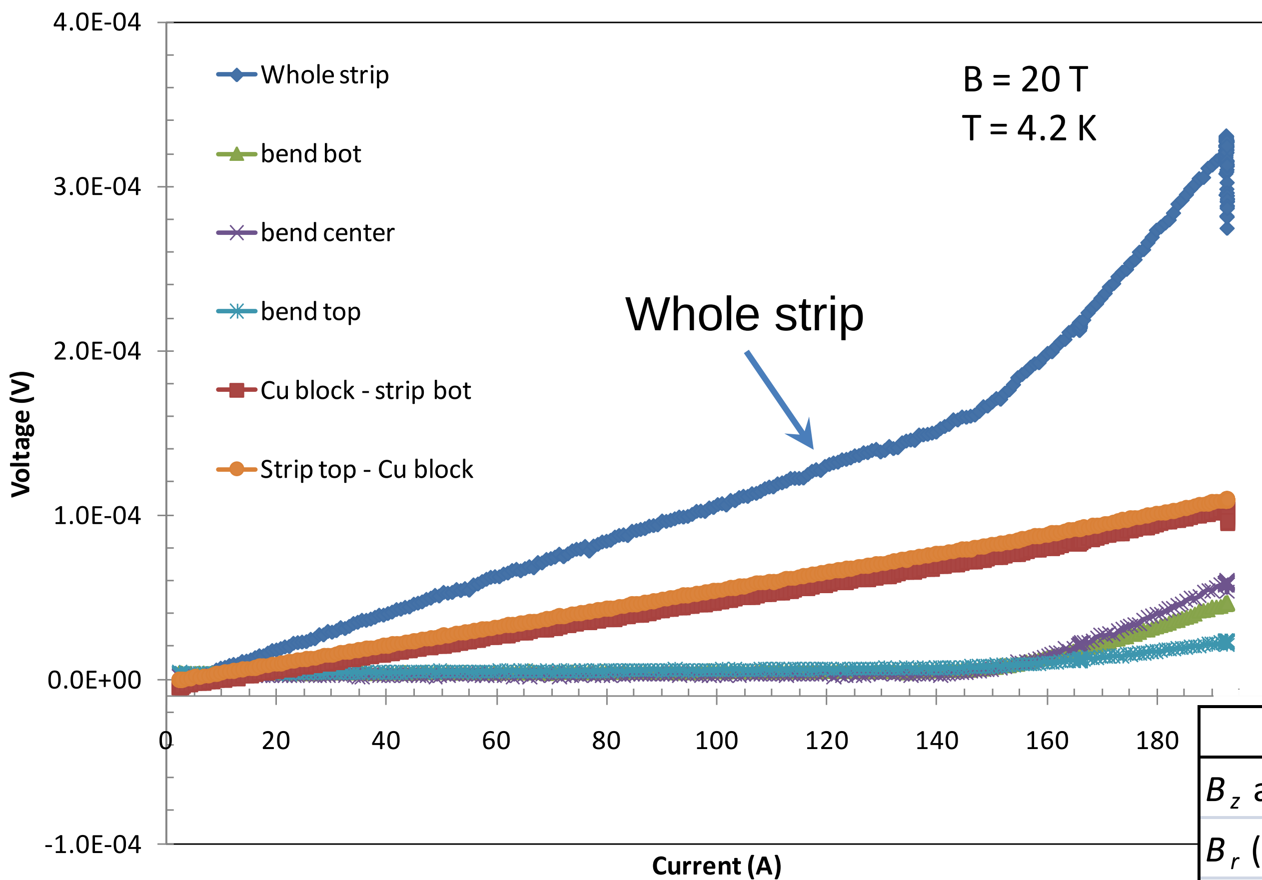
Dalban-Canassy, Trociewitz

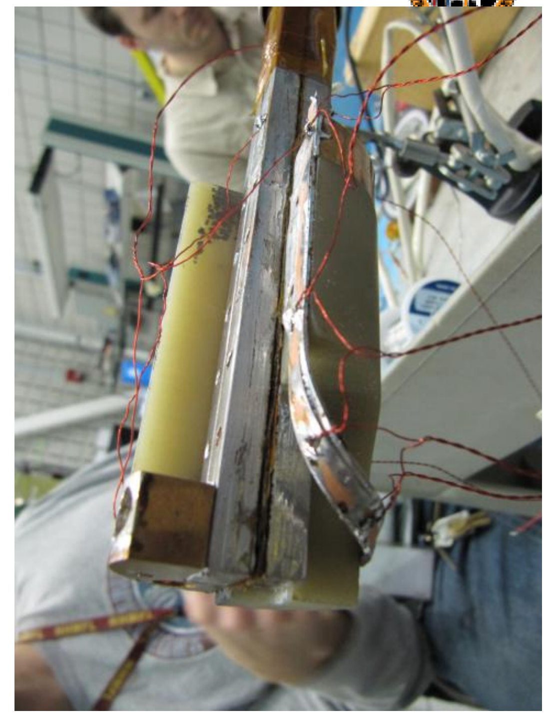


- "Standard" conductor (SP15), varnish coated: 2 layers, 1 hard bent, 11 turns, ID = 14.35 mm
- Monitored V-taps: outer layer, inner layer, hard bent, terminals, lead-lead
- Coil reached close to spec. I_c of short sample at 77 K
- At 4.2 K and 20 T current reached ~400 A (~310 MPa) before trip of protection circuit on outer terminal (design current for HTS insert in 32 T magnet: 186 A)
- Coil did not show any signs of degradation, no difference visible between performance of layers a and hard bent

(D.C. van der Laan, "$YBa_2Cu_3O_{7-\delta}$ coated conductor cabling for low ac-loss and high-field magnet applications", Supercond.Sci.Technol. 22 (2009))

V(I) Curves Twist-bend Section





	c.f.	off center
B_z appl. (T)	20	13
B_r (T)	0	0.54
	I_c (A)	I_c (A)
bend top	152	242
bend center	146	230
bend bottom	148	237
whole section	154	245
I_{op}	192	292

- Section ran without thermal run off for several minutes at I_{op}

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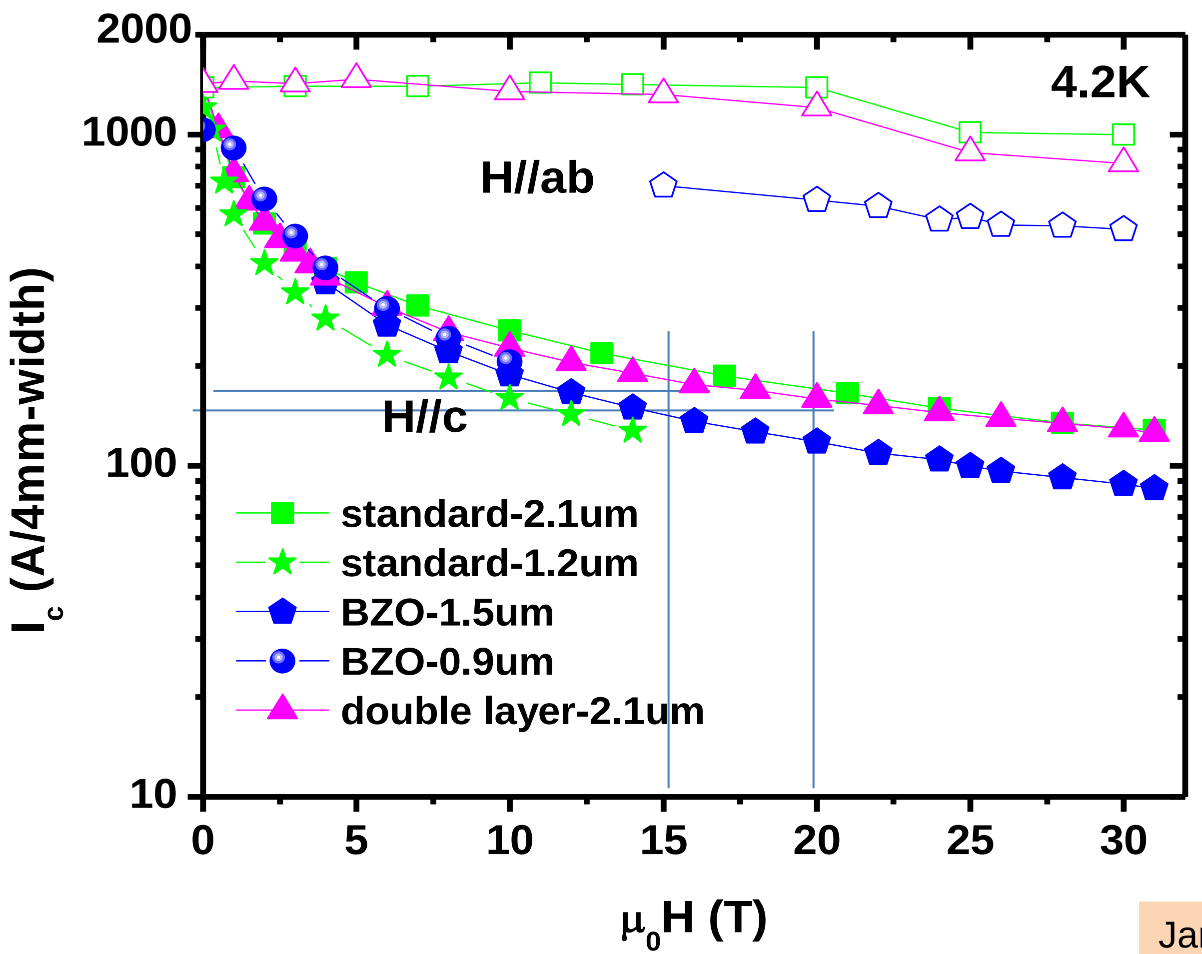
$I_c(B,\varphi)$ Short Sample Comparison

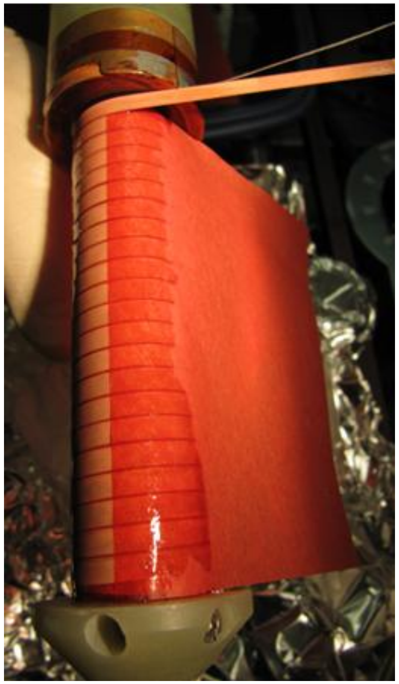


Jaroszinski, Xu

- Experiments reproduce short sample results for $B||c$

YBCO High Field Layer–wound Test Coils Y10-02 and Y10-03

	coil1 (Y10-2)	coil2 (Y10-3)
tape width (mm)	4.00	4.02
glas fiber width (mm)	0.40	0.40
bare tape thickness (um)	160.00	95.00
interlayer (um)	35.00	35.00
total tape thickness (um)	195.00	130.00
r1 (mm)	7.15	7.15
r2 (mm)	19.00	18.25
h (mm)	100.00	100.00
turns/layer (-)	21.50	20.90
turns total (-)	1291.00	1470.00
no of layers (-)	60.00	70.00
total conductor length (m)	112.00	119.50



- Epoxy wet layer-wound coil using “standard” YBCO tape
- Inter-layer spacing using 35 μm thick silk paper, glass thread for turn-turn insulation

Projected coil performance:

- At I_{op} = 327 A (previous run, within expected I_c range), ΔB = 4.5 T (or 0.014 T/A)
- L = 8.2 mH, E = 0.45 kJ

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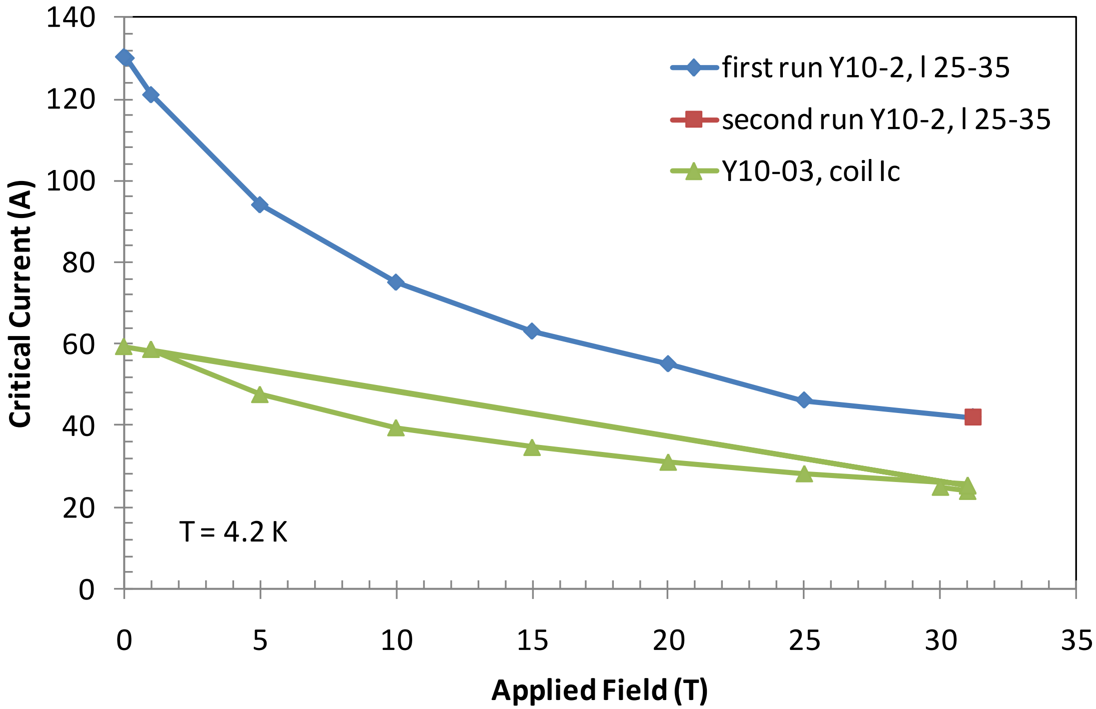
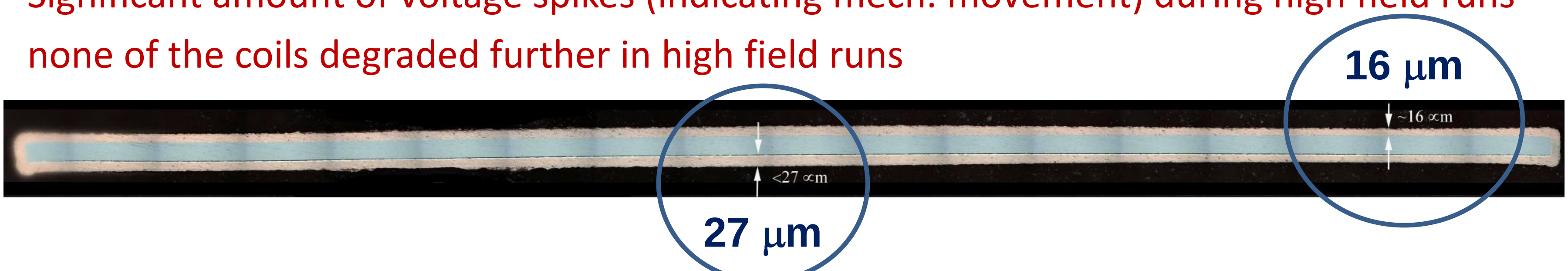
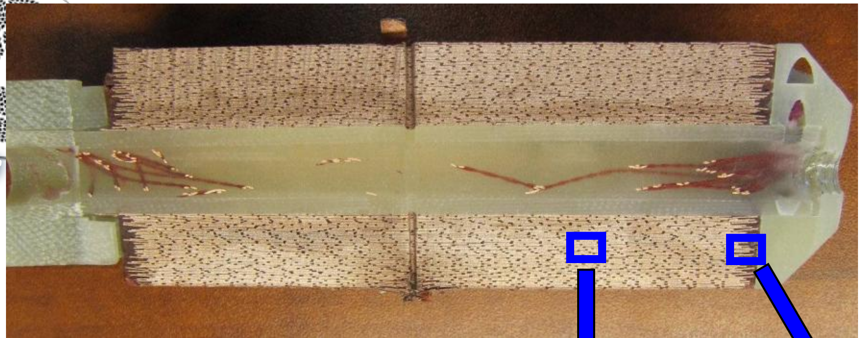
I_c *(B)* of Coils Y10-02 and Y10-03

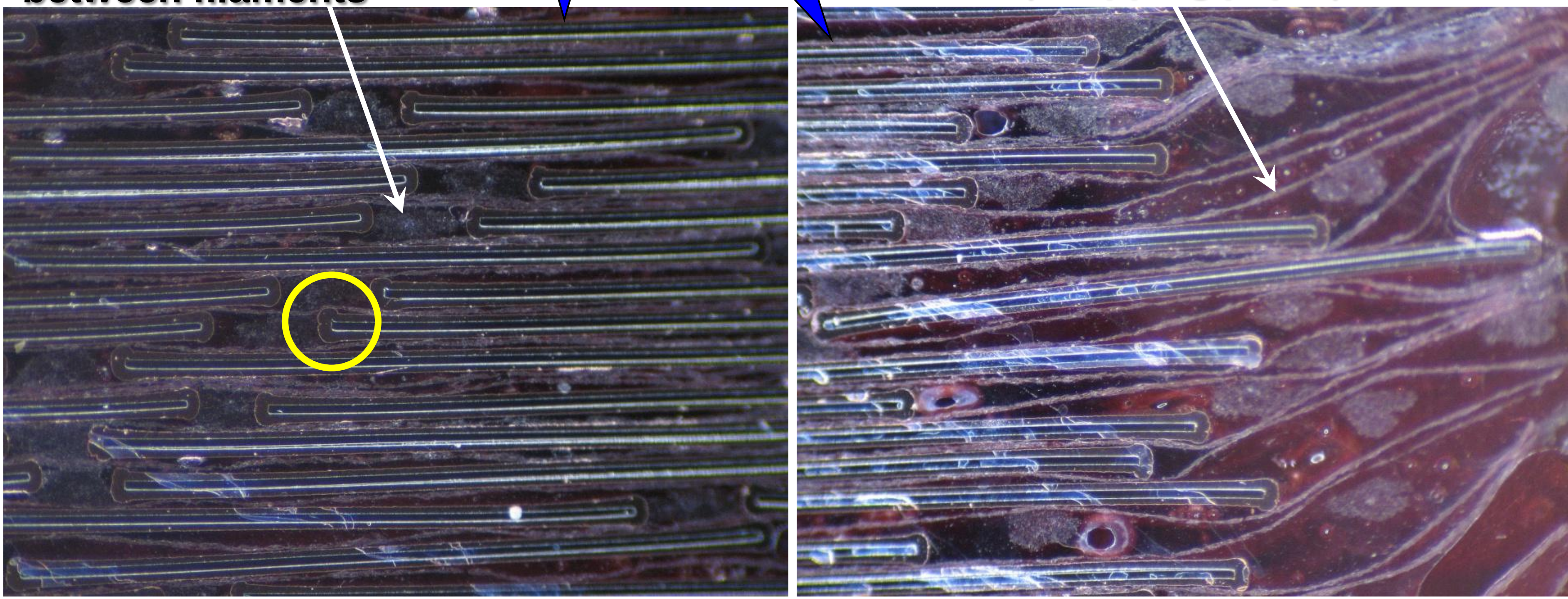


- Significant performance difference between Y10-02 and Y10-03
- Early transition in various layers (no systematic *r*-dependence), already visible in 77 K s.f.
- No transitions on terminals
- Significant amount of voltage spikes (indicating mech. movement) during high field runs
- none of the coils degraded further in high field runs



Deconstructed YBCO Coil Shows Some Challenges





- ~30 - 70 μm layer spacing due to "dog-boning" of conductor (35 μm nominal thickness)
- Packing density ~69 %
- **No visible cracking of the epoxy**

Conclusions - YBCO

- **YBCO is still a pilot plant product**
- Initial testing of coil at LN_2 applying slow cool down (~1.5 h from RT to 77 K) revealed issues within coil layers that showed later in 4.2 K runs
- Large occurrence of spikes at high B-I indicate mechanical movement
- Results indicate that coil degradation occurs during cool-down and may be related to conductor delamination due to thermal contraction of the epoxy-conductor composite
- Layer wound coils are possible; tolerate wide range of tensile stress/strain without significant amount of degradation; longer conductor batches highly desirable
- Need to carefully consider mechanical coupling in winding pack