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Considerations for Quenching HTS Coils

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Outline

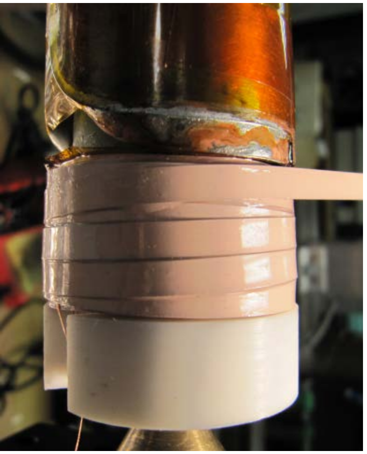
- Our experience in REBCO coils
  - The path to 35.4 T
  - 32 T user magnet
  - Food for thoughts on REBCO
- Our experience in Bi2212 coils
  - The path to 33.8 T
  - Food for thoughts on Bi2212
- Summary

OUR EXPERIENCE IN REBCO COILS

- **Path to 35.4T => Layer wound (LW) coil for very high field – NMR demonstration coils**
- 32T magnet => Double Pancake (DP) user magnet, LTS outsert, HTS insert

Mechanical Decoupling as a Solution to Delamination

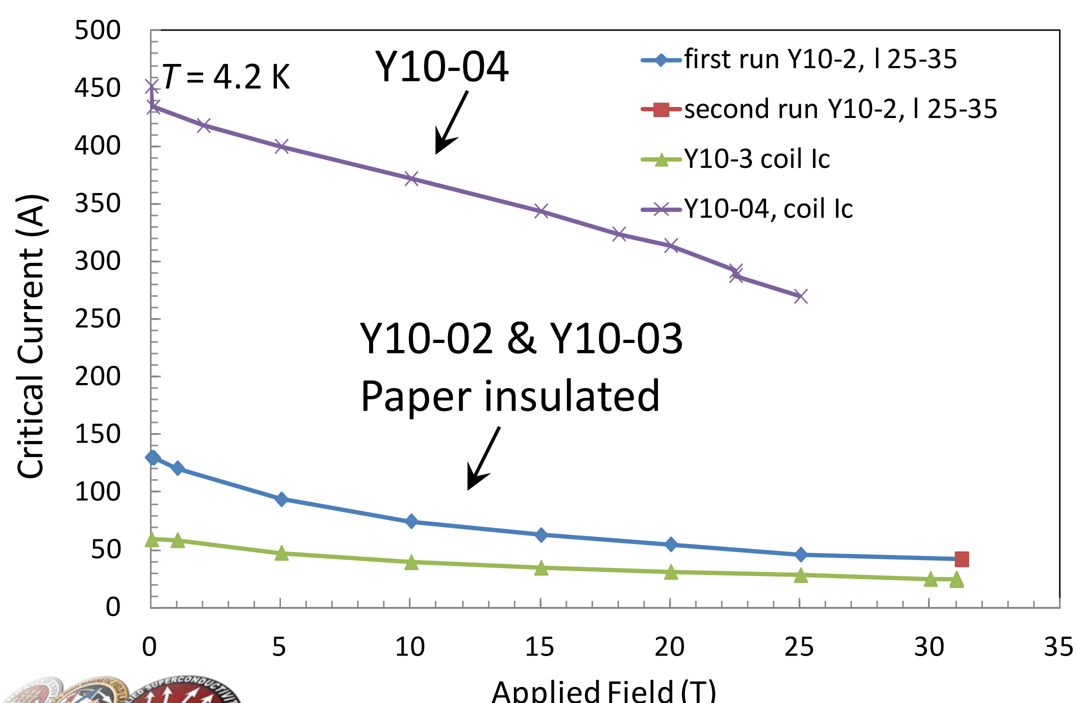
Test Coil Y10-04



- **Layer-wound** coil
- **Wet-wound** coil, i.e. impregnated
- **Conductor insulated** with Polyester heat shrink tubing from Advanced Polymers, Inc. (avoid delamination)

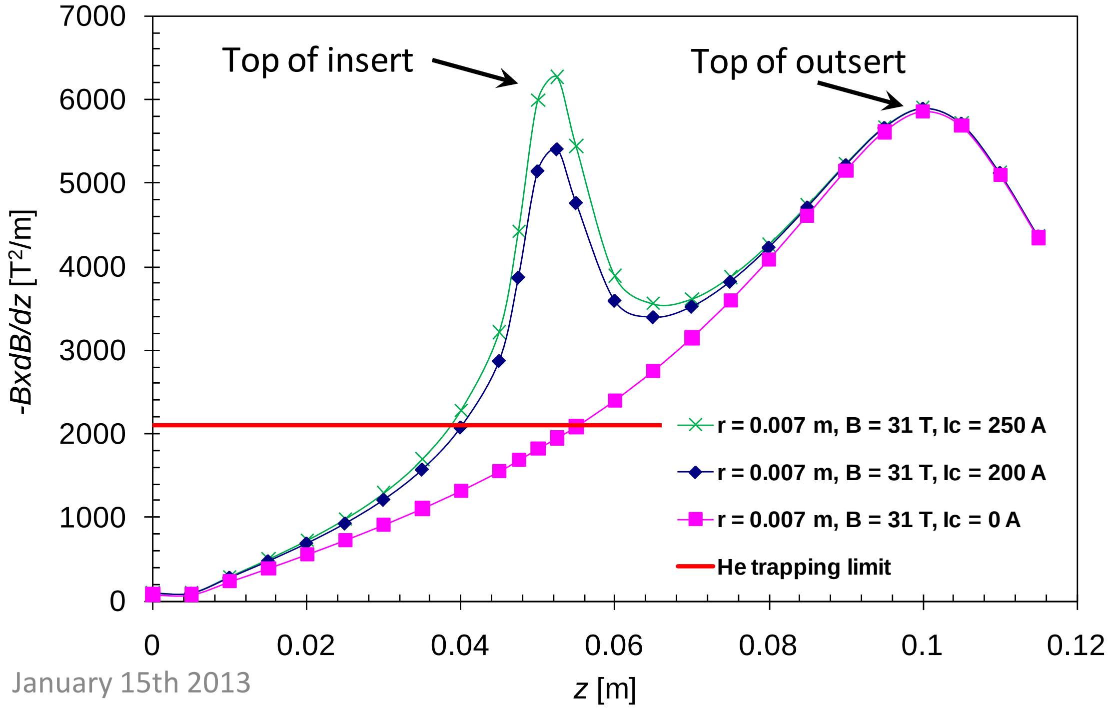
=> **NMR geared activities**: Avoid current redistribution seen in non-insulated dry-wound coils and its impact on field stability

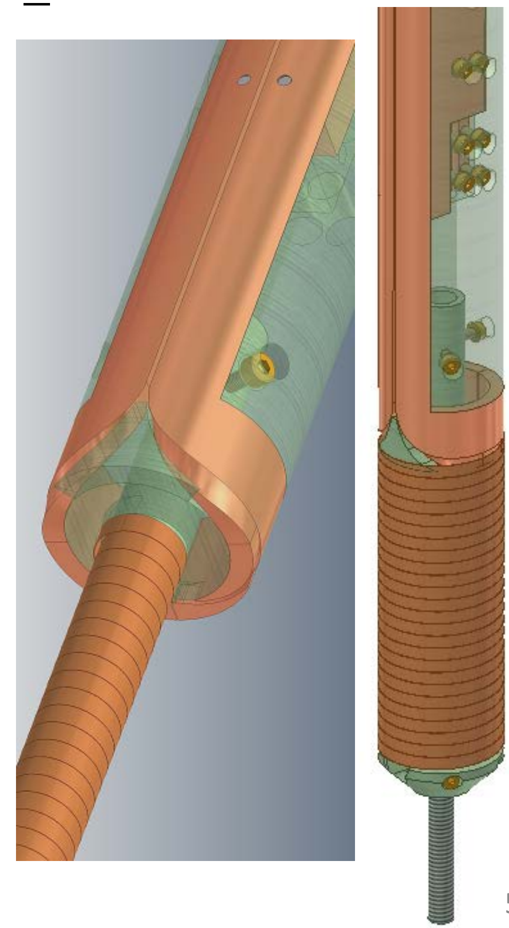
- Coil reproduced short sample values taking effective field angle into account
- Rapid cool-down to 77 K (thermal shock) reproduced previous 77 K data and did not degrade coil
- **Decoupling works** but it comes at a cost: thermal conductivity (300 K)
  - Cu, Ag ~400 W/mK
  - Ceramics: ~ 1 W/mK
  - Plastics: ~ 0.1 – 0.4 W/mK



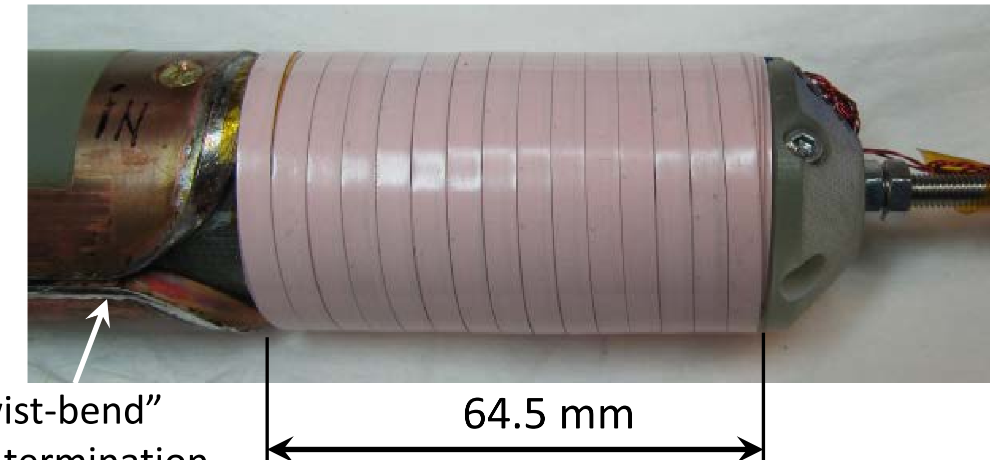
He Gas Bubble Trapping
=> New Terminal Design

- Early high field test coil failed at terminals
- **Helium gas bubble** trapping above $\underline{B}.\nabla\underline{B} > 21\ T^2/cm$
- New terminal concept: **Twist-bend junction**
  - Move terminal joint away from winding pack and high $\underline{B}.\nabla\underline{B}$ area
  - Use copper conduction cooling
  - Compact design
  - Longer less resistive joints





REBCO LW High Field Coil

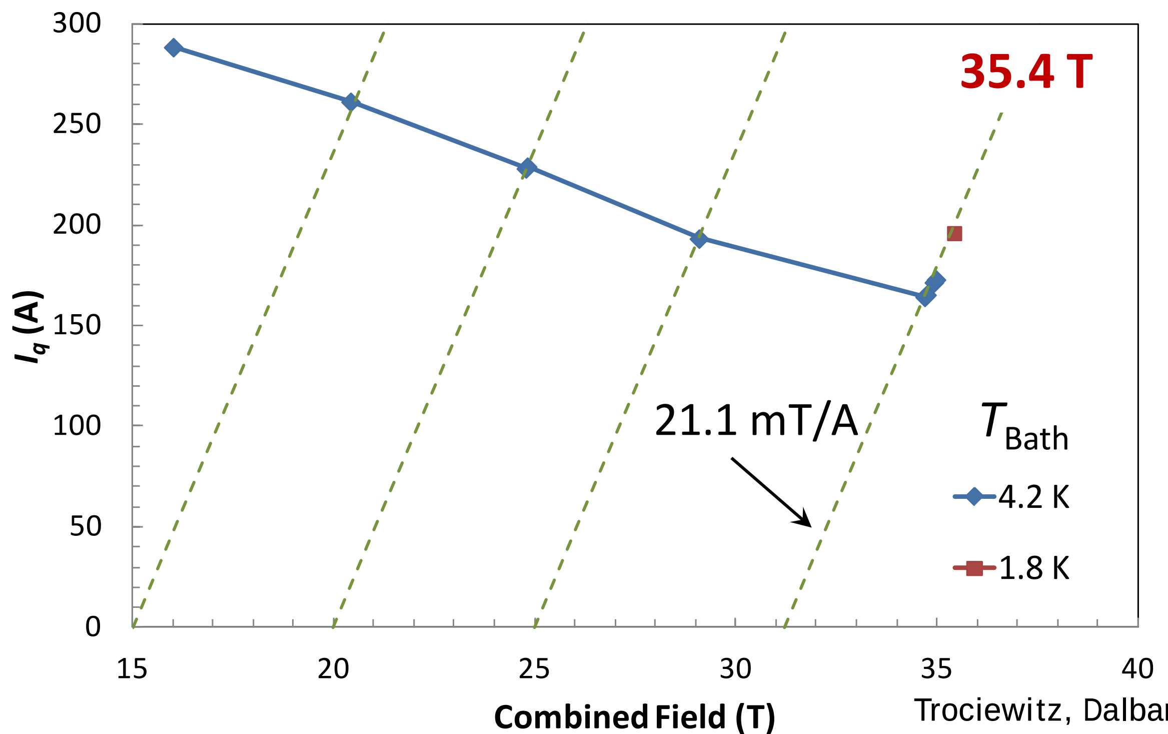


- Wet layer-wound, epoxy filled
- No splices
- Thin walled polyester heat- shrink tube insulated conductor
- Coil instrumented with array of voltage taps every 5 – 10 layers

Conductor & Coil			EM Properties	
Cond. Width [mm]:	4.02		Operating Current [A]:	200
Cond. Thickness [mm]:	0.096		Je (Engineering) [A/mm^2]:	518.24
			Jw (Winding) [A/mm^2]:	308.93
Inner Radius [mm]:	7.16		B(0,0) [mT]:	4221.01
Outer Radius [mm]:	18.92		Coil Constant (0,0) [mT/A]:	21.11
Height [mm]:	64.52		L [mH]:	8.90
Layers [-]:	80		Total Field Energy [J]:	187.92
turns/Layer [-]:	14.65			
turns total [-]:	1172			
Cond. Length [m]:	96.03			

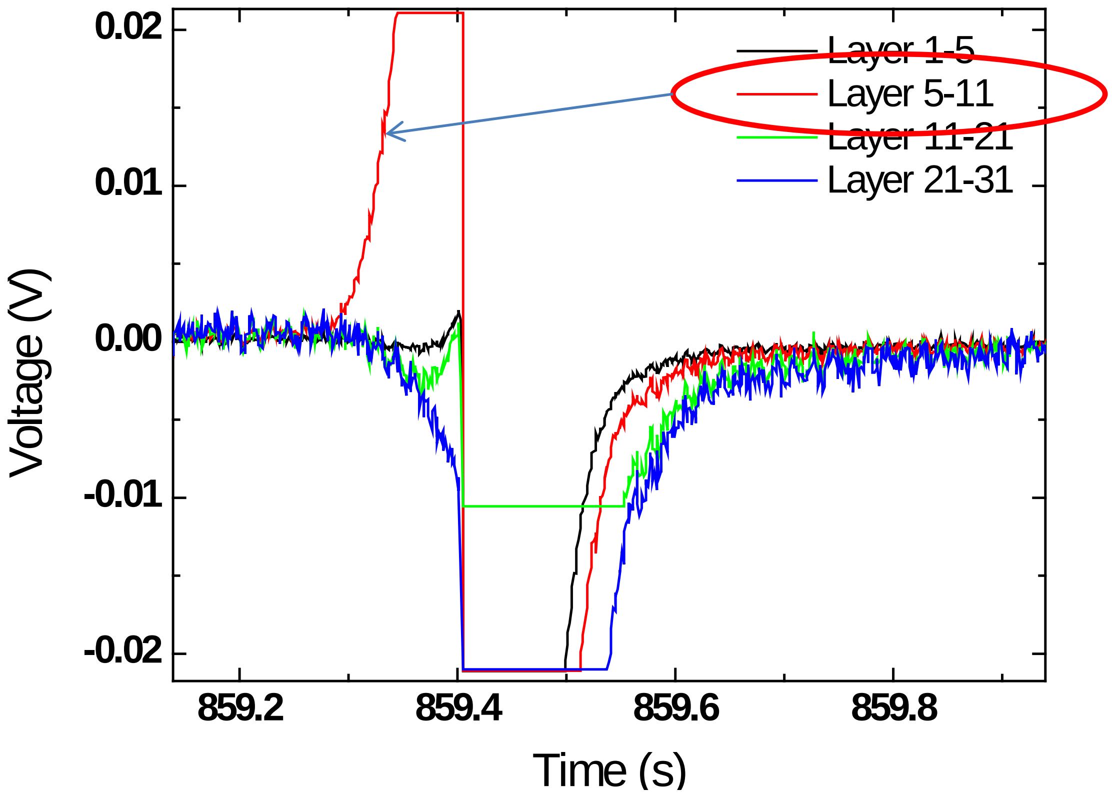
Field Generation and Coil Load Line

- **4.2 T field increment achieved in 31.2 T background field**
- **No coil degradation**
- **Introducing layer decoupling during coil manufacturing, bypasses transverse stress weakness**
- **Stress levels >340 MPa and conductor current density J_e ~500 A/mm^2 are possible**



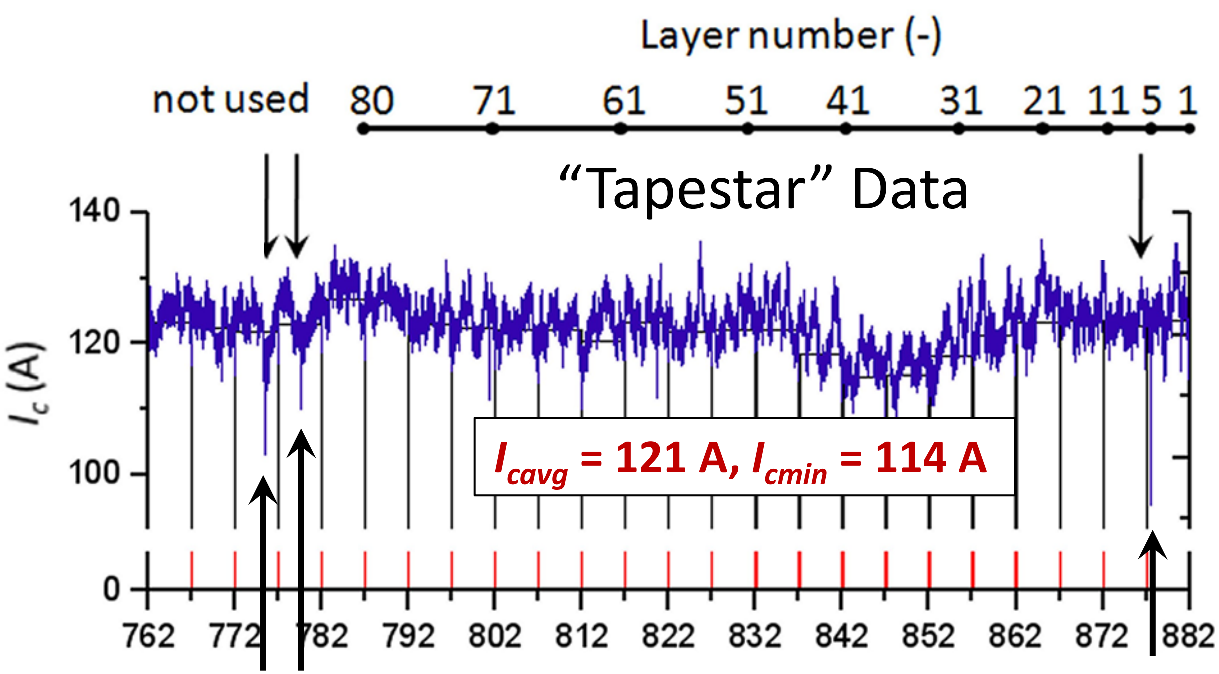
Trociewitz, Dalban-Canassy, Hilton et al. Appl. Phys. Lett. **99**, 2011

How Does the Coil Behave During Quench?



- **Layers 5-11 transition very early on (not theoretically the lowest I_c in the coil)**
- **Quench propagates into neighboring layers soon after**

How do Coil and Conductor Properties Compare?



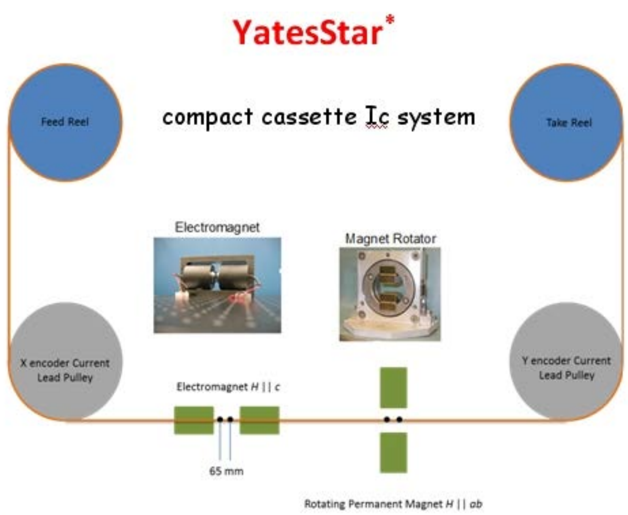
Spikes not detected with LANL Continuous I_c testing ("YatesStar")

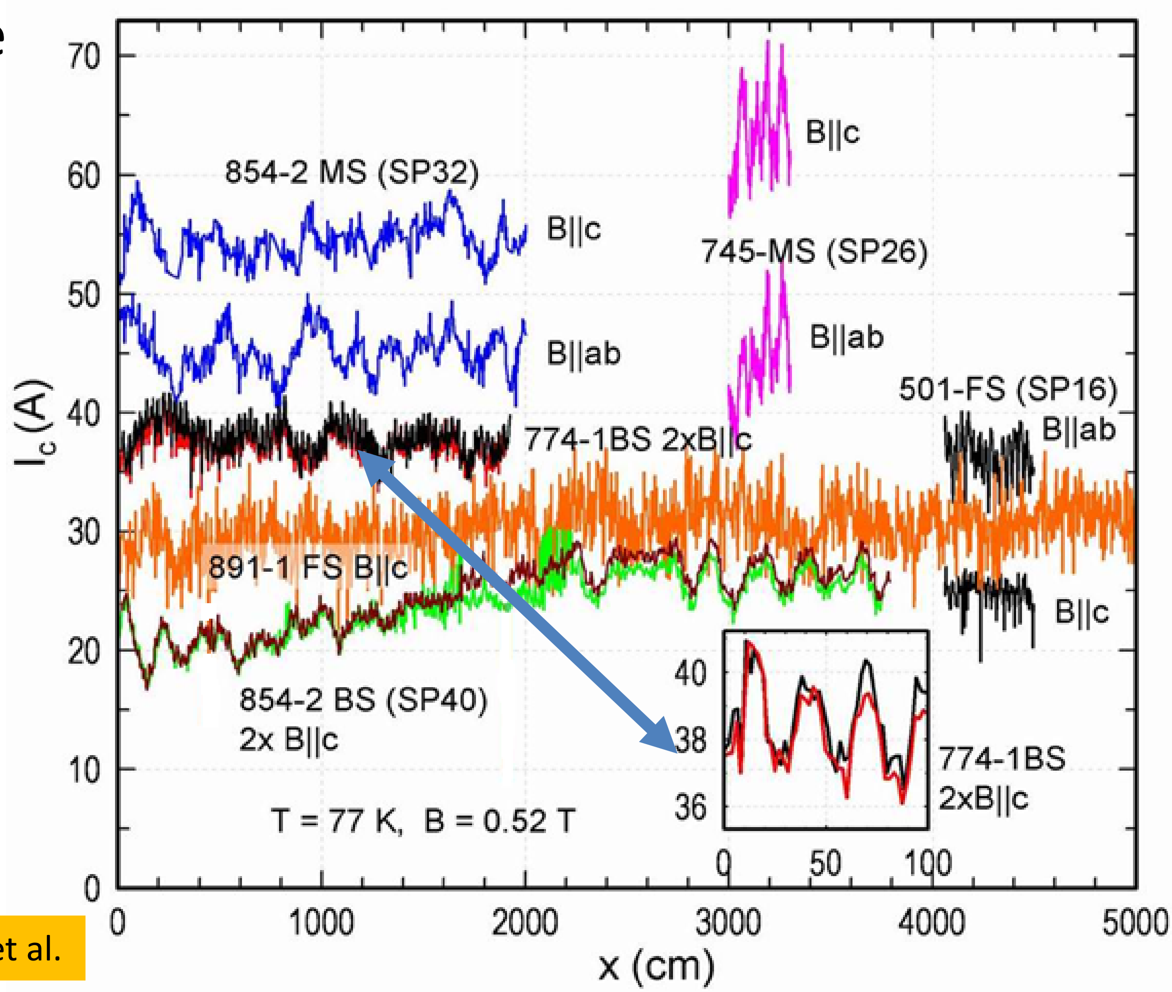
Spike Occurs within layers 5 - 11

- **Very high field magnets are possible -> NHMFL 32 T all s/c magnet project (uses ~10 km of conductor for 17 T REBCO section) => extensive testing needed**
- **Large long length inhomogeneities may cause sudden catastrophic coil failure during quench and need to be understood and best eliminated**

Reel-to-reel I_c measurements @ 77 K

- Different tapes, rich "zoology", no defects!
- Periodicity due to knife
- High reproducibility





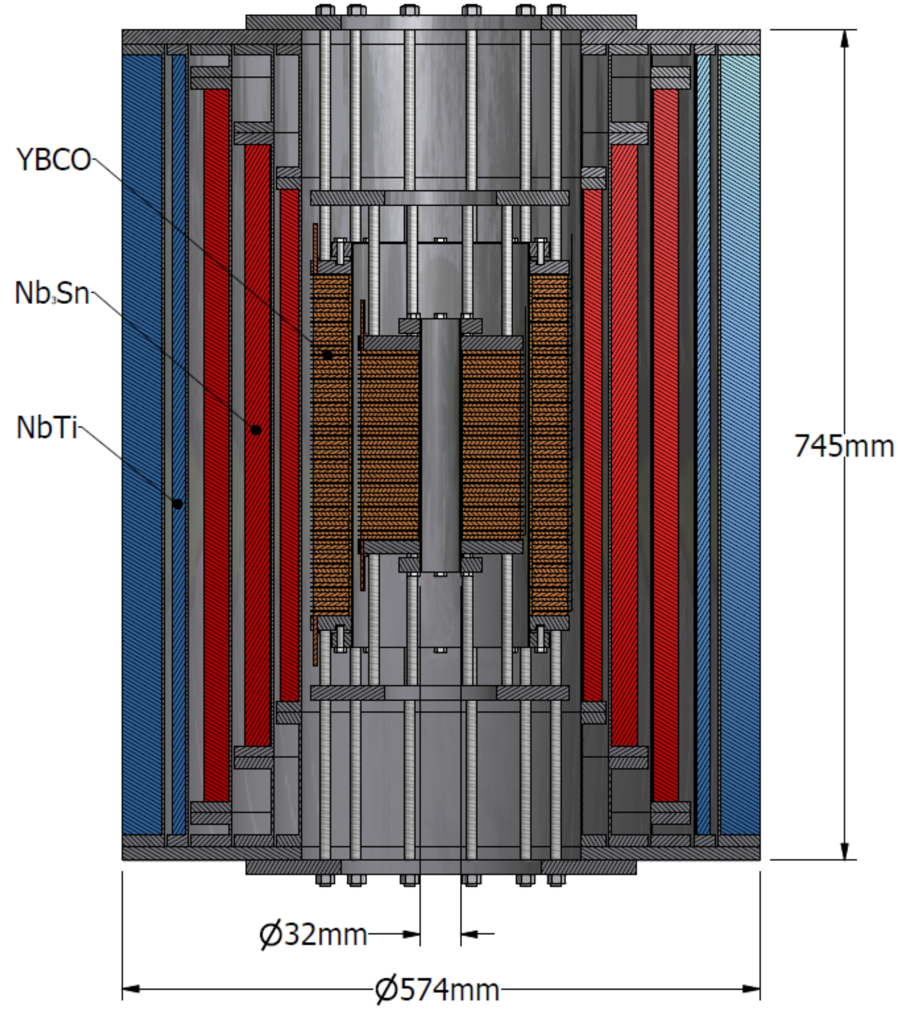
Sinclair, Jaroszynski et al.

OUR EXPERIENCE IN REBCO COILS

- HTS R&D program => Layer wound (LW) coil for very high field – NMR demonstration
- **32T magnet => Double Pancake (DP) user magnet, LTS outsert, HTS insert**

32 T All Superconducting User Magnet

Total Field	32 T
Field inner YBCO coils	17 T
Field outer LTS coils	15 T
Cold inner bore	32 mm
Current	172 A
Inductance	619 H
Stored energy	9.15MJ
Uniformity (1 cm DSV)	500 ppm
Dilution refrigerator	< 20 mK



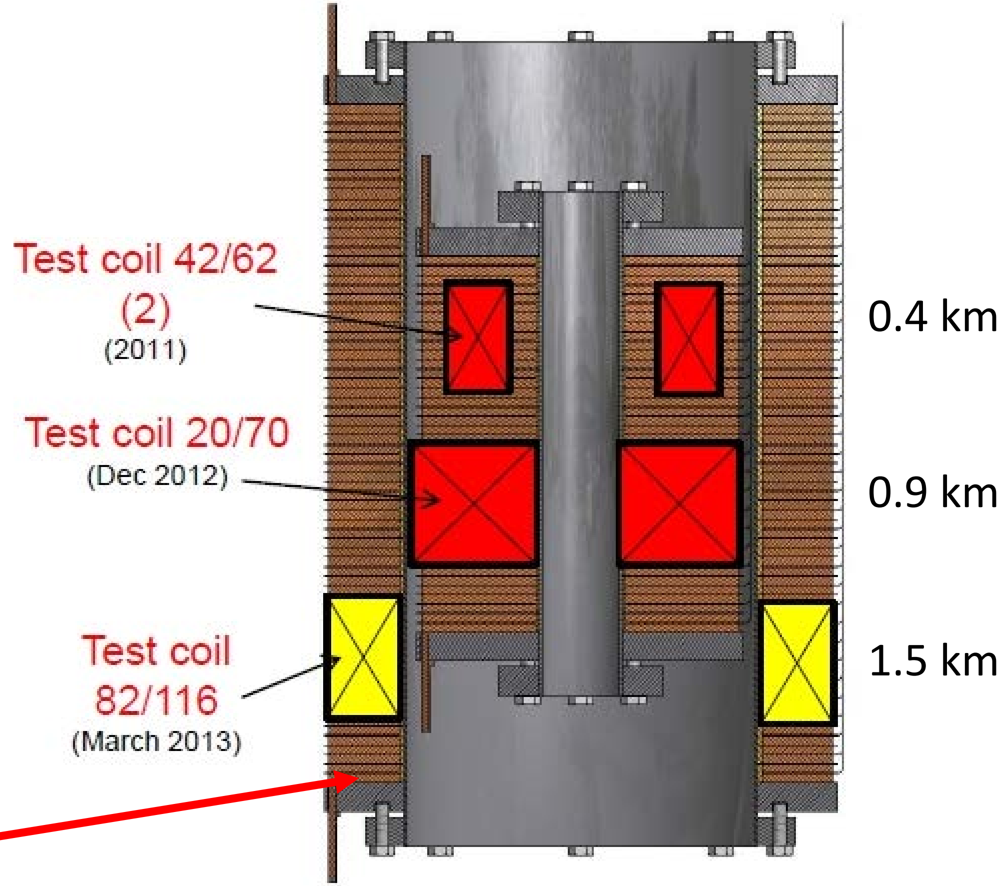
Project Manager: Huub Weijers
Principal Investigator: Denis Markiewicz
Co-PI's: David Larbalestier, Steven Julian

32 T All Superconducting User Magnet

- Outer magnet
  - 15 T, 250 mm bore, Nb3Sn/NbTi
  - Commercially supplied
- Inner coils
  - 17 T, 34 mm bore YBCO coils
  - In-house development
    - Coil winding technology
    - Joint technology
    - Insulation technology
    - Quench analysis and protection
    - Extensive component testing
    - YBCO characterization and quality check

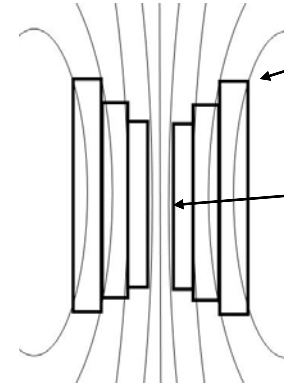
YBCO Coils for 32 T

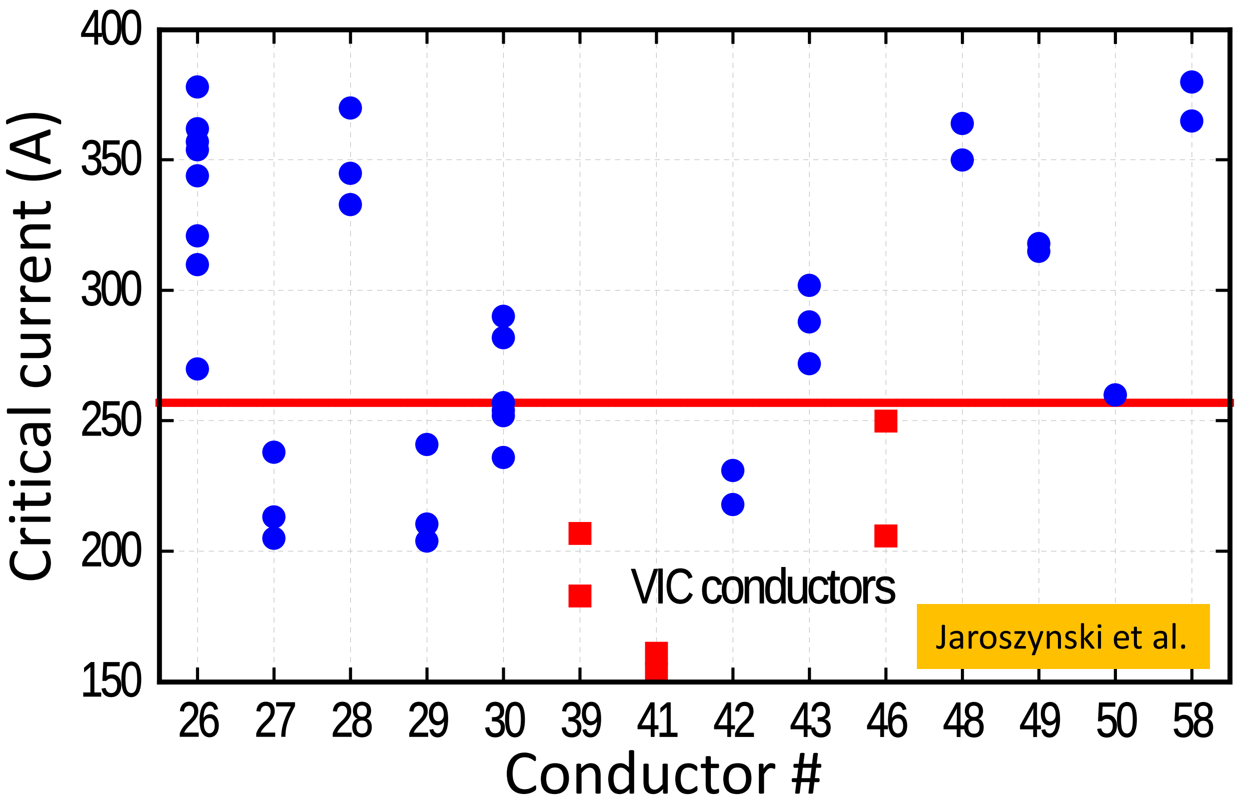
Total ≈ 10 km conductor



CRITICAL POINT
16 T, 18 deg off ab plane

Tests @ 18 deg off ab, 4.2 K, 16 T

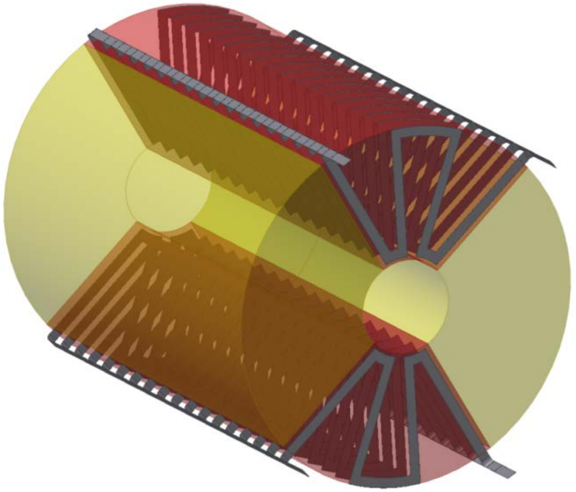




- **Again significant variations between conductors**
- **Some conductors do not meet criteria at 18 deg off !!! => grading envisioned**

32 T Quench Protection Scheme

- Low quench propagation velocities, especially azimuthally and axially
- Passive protection methods are ineffective
- Active protection system with distributed heaters embedded in spacers between modules
- Performance of protection heaters being assessed: distribution, operation power, number of heaters in coil…



Distributed heater concept

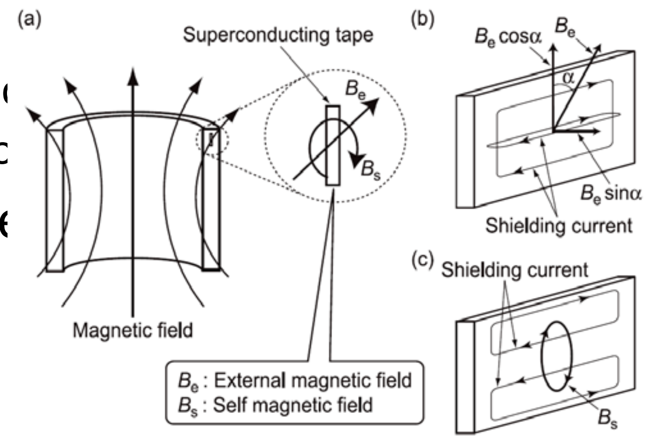
Test coil heater spacer

32 T heater spacer

Food for Thoughts YBCO (1)

- Long length inhomogeneity may be/become an issue
  - What is the most sensitive zone in the magnet?
  - Where can a quench potentially occur?
    - At the lowest I_c according to the design (B an
    - At the lowest I_c driven by conductor defects c
- Screening currents may change the pictur
  - Potential to severely reduce coil Ic
  - Impact of coil stability (Yanagisawa)
- Conductor geometry
  - Anisotropic: much lower I_{op}/I_c where B along ab plane => harder to protect against quench
  - Physical geometry (layering, single filament) may lead to harder current redistribution in case of quench
- 77 K tests <u>cannot</u> be used to predict 4.2 K performance, but systematic LHe tests may become a show stopper in large systems

Amemiya (2008)



Food for Thoughts YBCO (2)

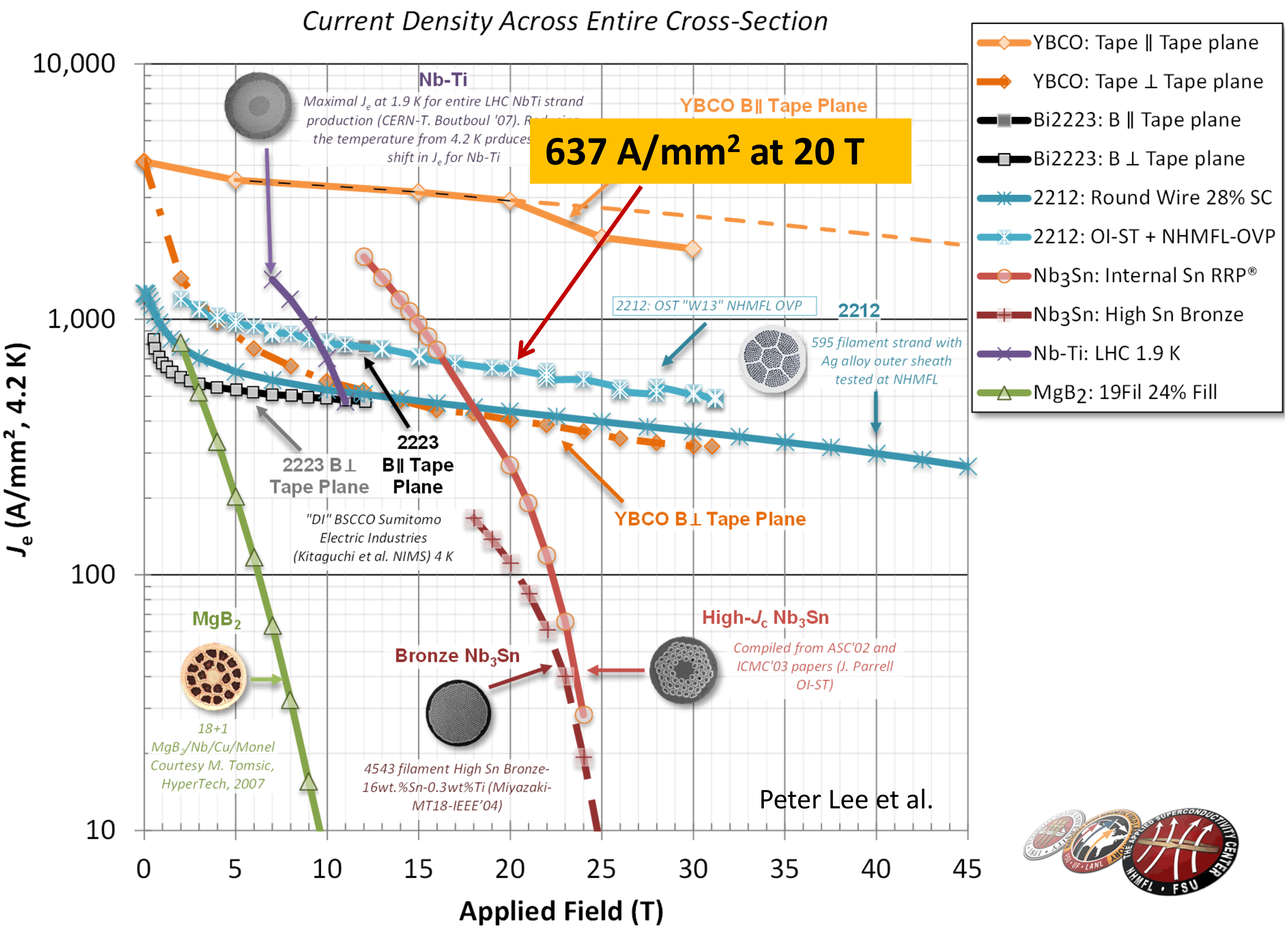
- Coated conductors in impregnated coils require an insulation
  - High mechanical and thermal integrity
  - Faster ramping than non insulated coils
  - Necessity of a thin highly thermally conductive insulation
  - High sensitivity to defects (single strand)
- He bubble trapping in large $\underline{B}.\nabla\underline{B}$ regions = special terminal:
  - Regular right angle = resistive section in bubble region
  - Pig tails do not work physically with YBCO
  - Twist bent may limit the I_c , due to the conductor-field orientation in the twist
- Cabling technology is still fairly limited => limiting large magnet capabilities

OUR EXPERIENCE IN BI2212 COILS

- Old coils showed overall low transport properties
- OP process => Current Bi2212 J_e comparable to YBCO J_e with B // c-axis
- Recent test: 2.6 T increment in 31.2 T background

Increasing J_w for Bi2212 Coils?

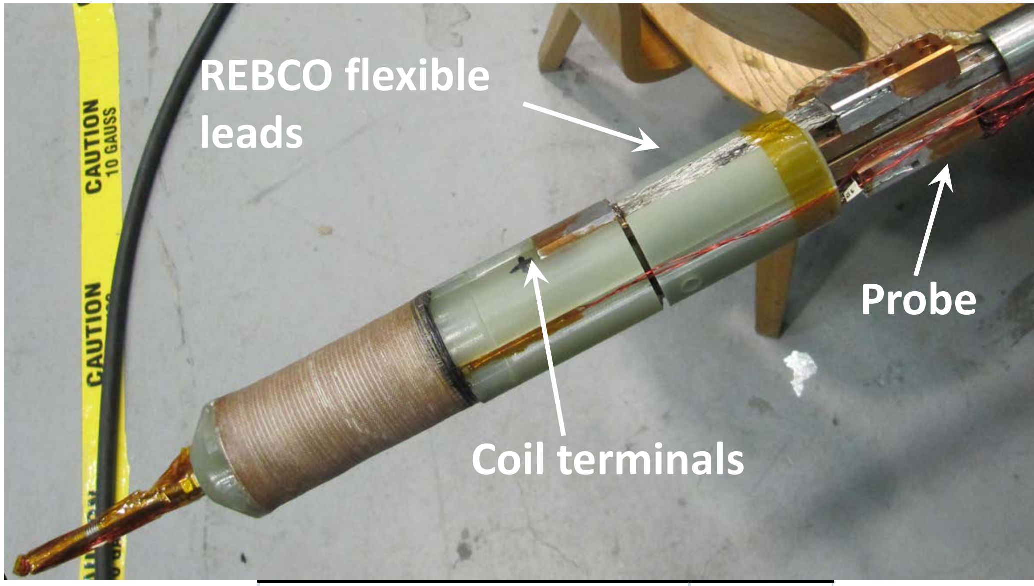
- New densification process yielding J_e similar to YBCO along c-axis direction
- Development of thin insulation => nGimat, in-house development: 10 x thinner than conventional
- Densification of coils => changes the geometry => importance of epoxy for integrity
- Long length homogeneity still under question but expected to be much better than before densification


Current Density Across Entire Cross-Section
YBCO: Tape ∥ Tape plane
YBCO: Tape ⊥ Tape plane
Bi2223: B ∥ Tape plane
Bi2223: B ⊥ Tape plane
2212: Round Wire 28% SC
2212: OI-ST + NHMFL-OVP
Nb3Sn: Internal Sn RRP®
Nb3Sn: High Sn Bronze
Nb-Ti: LHC 1.9 K
MgB2: 19Fil 24% Fill
Nb-Ti
Maximal Je at 1.9 K for entire LHC NbTi strand production (CERN-T. Boutboul '07). Reducing the temperature from 4.2 K prduces a shift in Je for Nb-Ti
YBCO B∥ Tape Plane
637 A/mm² at 20 T
2212: OST "W13" NHMFL OVP
2212
595 filament strand with Ag alloy outer sheath tested at NHMFL
2223 B⊥ Tape Plane
2223 B∥ Tape Plane
"DI" BSCCO Sumitomo Electric Industries (Kitaguchi et al. NIMS) 4 K
YBCO B⊥ Tape Plane
MgB2
18+1 MgB2/Nb/Cu/Monel Courtesy M. Tomsic, HyperTech, 2007
Bronze Nb3Sn
4543 filament High Sn Bronze-16wt.%Sn-0.3wt%Ti (Miyazaki-MT18-IEEE'04)
High-Jc Nb3Sn
Compiled from ASC'02 and ICMC'03 papers (J. Parrell OI-ST)
Peter Lee et al.
10,000
1,000
100
10
Je (A/mm², 4.2 K)
0
5
10
15
20
25
30
35
40
45
Applied Field (T)

Bi2212 Coil for OPHT and 31 T Test

- Coil as built (as designed): 47 (50) turns, 8 (8) layers, 36.35 (37.38) mm OD
- 2 innovations to drive $J_w >> 100$ A/mm^2
  - OP process
  - Thin insulation (15 μm)
- Insulation (TiO_2-PPC) requires a preliminary heat treatment to burn out the organics
- Then "standard" HT in 10 bar OP O_2-Ar gas mixture (1 bar O_2 partial pressure)

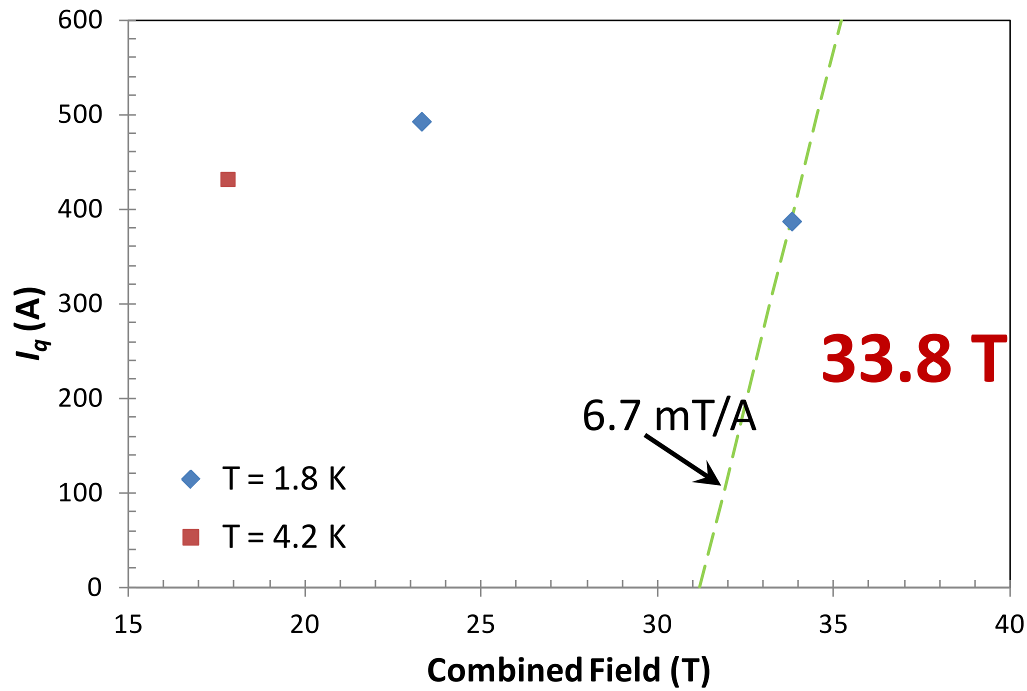
Configuration for 31 T test:



Wire dia. (mm):	1.40
nGimat Insulation (mm):	0.015
Turn-turn non-tightness (mm):	0.085
layer-layer tightness (mm):	-0.065
Inner Radius (a1) (mm):	7.25
Outer Radius (a2) (mm):	18.17
Height (2b) (mm):	71.21
Radial Layers (-):	8
Turnss/Layer (-):	47
Total turns (-):	376
Conductor Length (m):	30.03

Field Generation and Coil Load Line

- 2.6 T Field increment achieved in 31.2 T background field (I_q = 388 A, J_w = 187 A/mm^2)
- Slight degradation on inner terminal after 4.2 K runs
- Lower I_c on terminal due to space restriction in reaction furnace + He bubble
- Total of about 20 in-field runs at ramp rates varying from 2.5 – 50 A/s
- Potential for much higher I_c in coils: J_e = 252 A/mm^2 vs. 637 A/mm^2 in short sample



Food for Thoughts Bi2212

- Bi2212 is back in the game!
- Multi-filamentary round wire conductor
  - Provides “easy” current path around defects
  - Filaments surrounded by Ag: better current transfer compared to YBCO
  - Isotropic conductor
  - No or less screening currents
- Conductor mechanically fragile
- OP Wind and React process rather cumbersome
- Long length inhomogeneity still unknown with new processes though expected to be decreased
- Conductor not useable above 20-30 K or so

No quench issues so far !

- Small coils
- Highly instrumented
- Slow transition of HTS

=> Controlled quenches with external dump resistor

- Won’t be the same for larger magnets !

Summary

- REBCO
  - Insulation crucial in single strand => avoid delamination
  - I_c non-uniformity problematic =>What is the I_c of the coil?
  - Conductor geometry => single filament and anisotropic
  - Screening currents in high radial field regions => Influence on coil I_c map and field quality
  - Limited cabling capability
- Bi2212
  - New Over-Pressure process allows unprecedented J_e very close to values observed in REBCO
  - Insulation instrumental to increase J_w
  - Multi-filamentary with all-around Ag matrix: good current transfer around defects, better longitudinal and potentially transverse quench propagation
  - Mechanically weak conductor
  - Rutherford cabling capability potentially applicable

THANK YOU !