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Materials Science & Engineering

Status of HTS Magnets
and the conductors they depend upon

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North Carolina State University

EuCARD - HE-LHC'10 AccNet

mini-workshop on a “High-Energy LHC”

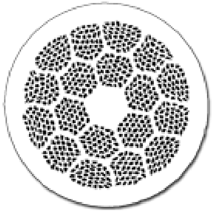
14 October 2010

Malta

Schwartz Research Group

Five undergraduates, seven PhD students, two post-docs, two Research Professors (one Visiting) … and me

With openings for PhD students and a post-doc interested in HTS materials & technology



In partial collaboration with the Very High Field Superconducting Magnet Collaboration (VHFSMC)

(a collaboration focused on Bi2212 R&D)

Fermilab

The Applied Superconductivity Center NHMFL • FSU

National High Magnetic Field Laboratory FSU • UF • LANL

Florida State University 1851

Los Alamos
NATIONAL LABORATORY
EST. 1943

BROOKHAVEN
NATIONAL LABORATORY

nc state
ENGINEERING

NIST

BERKELEY LAB

AFRD
ACCELERATOR & FUSION
RESEARCH DIVISION

TEXAS A&M
UNIVERSITY

Other key collaborators

- Supercon Inc.
- Muons Inc.
- American Superconductor Corporation
- SuperPower Inc.
- GE R&D
- nGimat
- ***We’re always open to new partnerships***

Outline

- Motivation for HTS magnets
- The conductors
- Magnet challenges and reasons for hope
- Potential “game changers”
- Conclusions

Why use HTS for magnets?

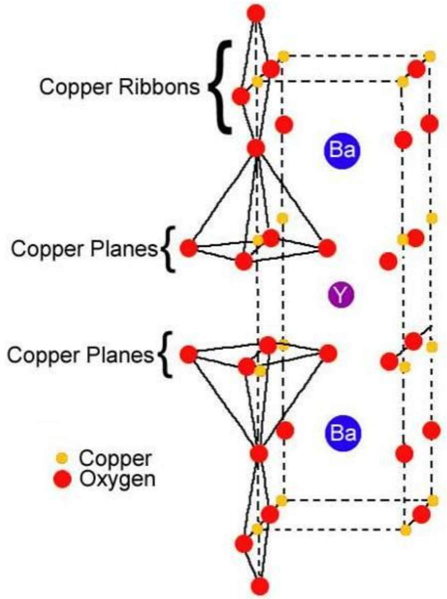
Magnet engineering issues: LTS versus HTS

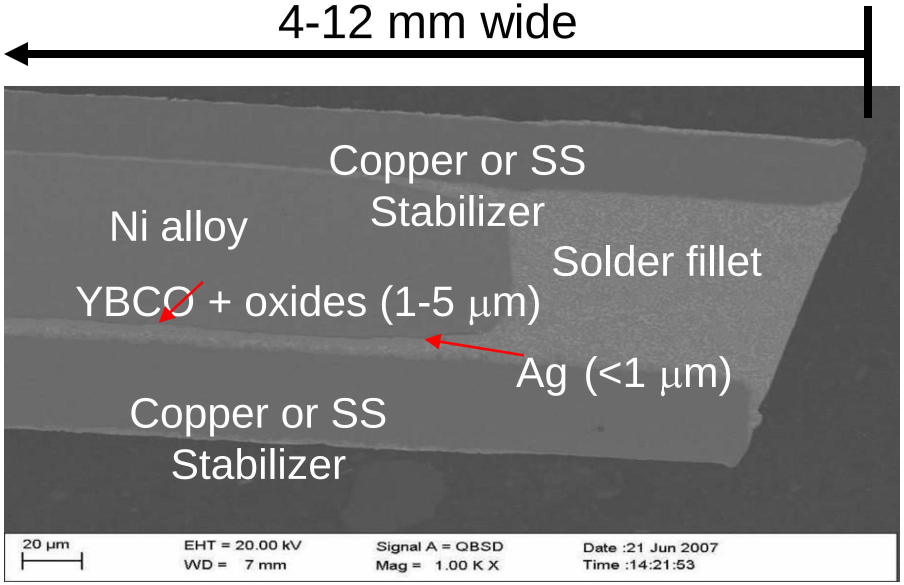
- Conductor $J_c(B,T)$, n-value, homogeneity
- Conductor I_c- strain
- Conductor scale-up
- Conductor cost
- Conductor availability
- Packaging (insulation & reinforcement)
- Coil manufacturing
- Stability, quench detection, quench protection
- Application specific issues field profile, homogeneity, heat load, radiation resistance
- Overall materials complexity

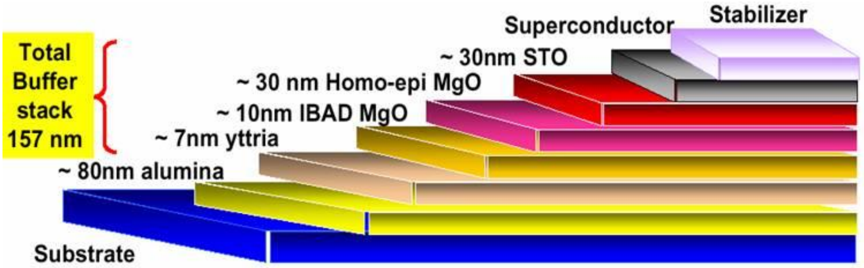
HTS is an enabling technology, not replacement technology

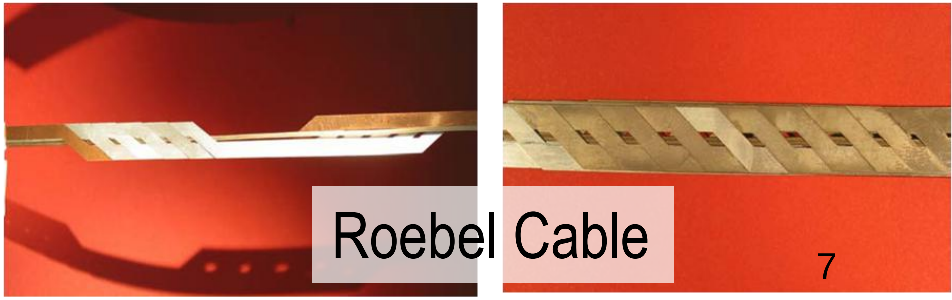
Emerging conductor: RE-Ba-Cu-O coated conductor

- Formed by thin-film deposition processes
- Specialized buffer layers required
  - Transmit/provide textured template
  - Chemical barrier between YBCO and Ni
- *Biaxial* texture required
- Wide, thin tapes only
- Anisotropic EM properties

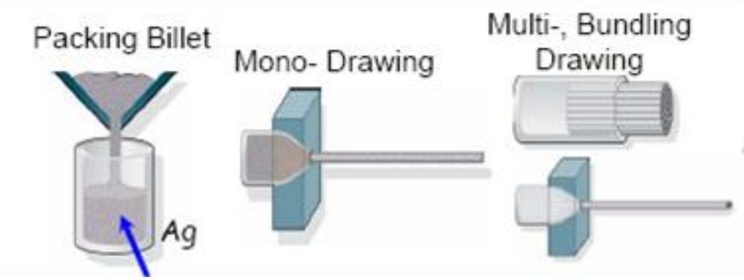




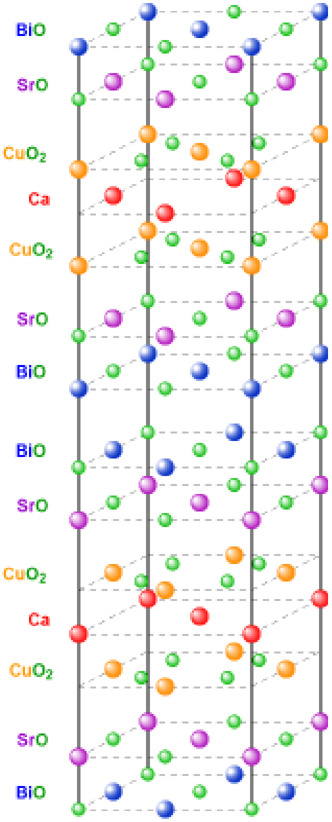


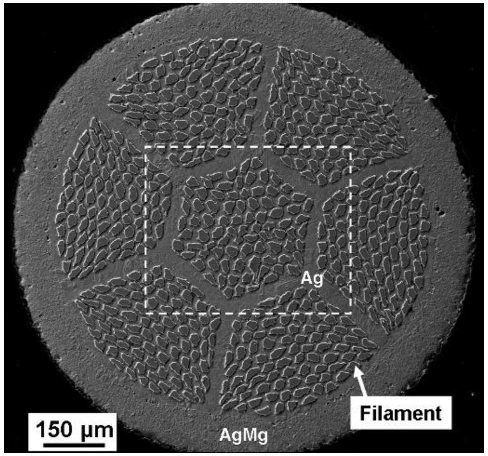

Roebel Cable

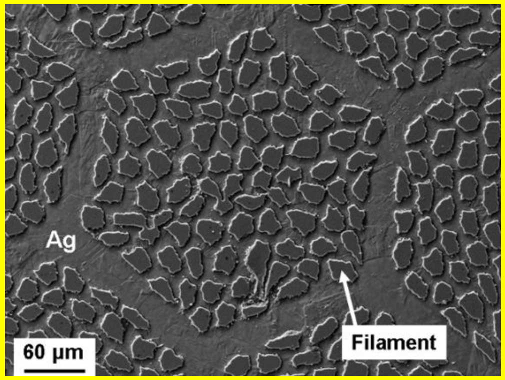
Emerging conductor: $Bi_2Sr_2CaCu_2O_x$



- Formed by “powder-in-tube” process
- Requires Ag/AgX matrix
- *Uniaxial* texture essential (?)
- Micaceous due to double Bi-O layer
- *Only HTS round wire option*
- *Only HTS conductor w/isotropic EM behavior*







Bi2212 Cable courtesy E. Barzi, FNAL

Bi2212 versus (RE)BCO

What are the main differences?

- Bi2212
  - Round wire, ~30% fill factor
  - Isotropic
  - Cabled (relatively) easily
  - Weak, plastic matrix
  - Not well understood microstructure-property relationships
  - Wind & react magnets; highly sensitive to heat treatment
  - Readily scalable process
  - High field only potential market
- (RE)BCO
  - Wide, thin tape, ~1% fill factor
  - Anisotropic
  - Roebel cable option
  - Strong Ni-alloy matrix
  - Highly engineered microstructure (nanostructure)
  - React & wind magnets
  - Scale-up involves challenges
  - High temperature primary market driving development

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Some high field HTS inserts

Year	Conductor	$B + \Delta B = B_{net}$ (T)	J (A/mm^2)	Stress (MPa) (J_exBxR)	
2003	Bi2212	20 + 5 = 25 T	89	175	NHMFL + OST
2008		20 + 2 = 22 T	92	109	NHMFL/ASC
2008		31 + 1 = 32 T	80	89	NHMFL/ASC
2007	YBCO	19 + 7.8 = 26.8 T	259	382	SuperPower
2008	YBCO	31 + 2.8 = 33.8 T	460	324	NHMFL/ASC
2009	YBCO	20 + 7.2 = 27.2 T	211	314	SuperPower
2009	YBCO	20 + 0.1 = 20.1 T	241	611	NHMFL/ASC

HTS magnets moving forward

- *Numerous active HTS magnet programs around the world!*
- In US alone, funded projects include:
  - NHMFL (NSF): 32 T YBCO user magnet
    - 15 T LTS + 17 T YBCO
  - MIT (NIH): 30 T, 1.3 GHz NMR
    - 700 MHz LTS + 600 MHz Bi2223/YBCO
  - ABB (ARPA-E): 24 T, 3 MJ YBCO magnet for energy storage
    - Largest industrial project yet!
  - VHFSMC is focused on Bi2212 technology
- And at NIMS, Japan
  - 1.03 GHz NMR magnet
    - 20.6 T LTS + 2.6 T Bi2223

Magnet pull…

- Magnet pull let’s us (re)think
  - **Conductor issues … *the building blocks***
  - Coil manufacturing … *putting the pieces together*
  - Mechanical behavior … *JxB is high*
  - Quench behavior … *and so is* $E \sim B^2$
  - Additional important issues … on which we’ve only begun
    - Joints
    - Irradiation effects

Conductor materials issues

could fill the whole day…

- Primary (RE)BCO R&D:
  - Scale-up
  - Cost
  - Anisotropy as a function of temperature (nanoscale engineering)
  - Thickness dependence … as a route to higher I_c … and lower $/A
- Primary Bi2212 R&D:
  - Fundamental structure - property (- processing)
    - why does Bi2212 carry current?
  - Densification
  - Role of oxygen
  - Heat treatment peak-temperature sensitivity
  - Heat treatment optimization
  - *… lots of materials science…*

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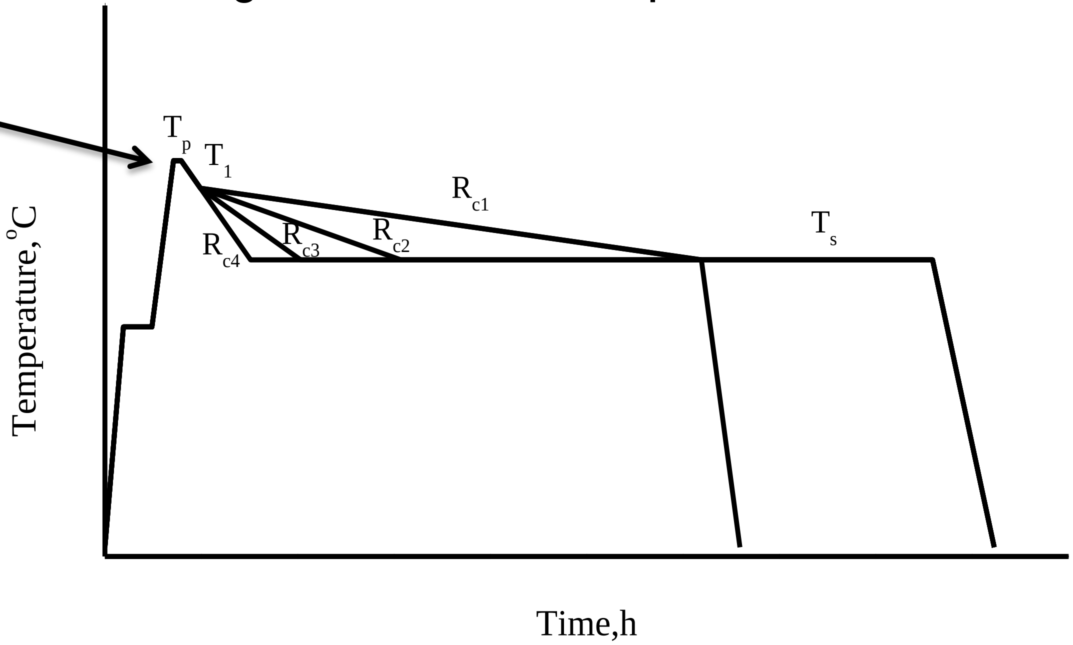
Coil manufacturing: Bi2212

- Wind & react magnet issues, but with O_2 and a sensitive conductor
  - Heat treatment uniformity for large magnets
  - Presence of insulation reduces wire performance
  - Conductor leakage in coils lowers performance further



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From short samples to coils

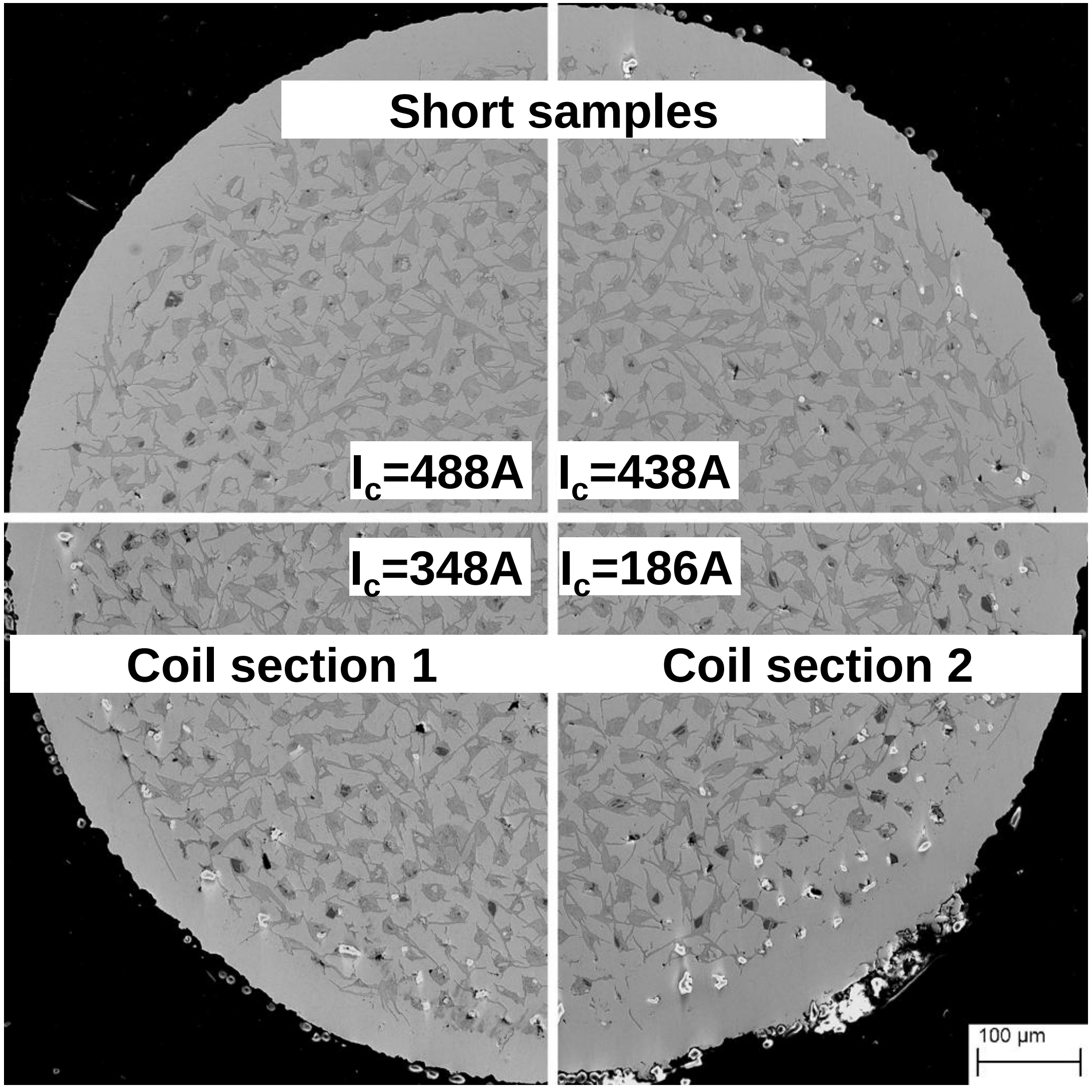
CF- Light; AEC-Black

Element	*CF (at%)*	*AEC (at%)*
SrL	53.87	30.90
CaK	17.88	13.19
CuK	0.57	54.73
BiL	27.68	01.18

- With insulation, more CF phase observed at the outer filaments
- For cut coil sections, more filaments wicked away

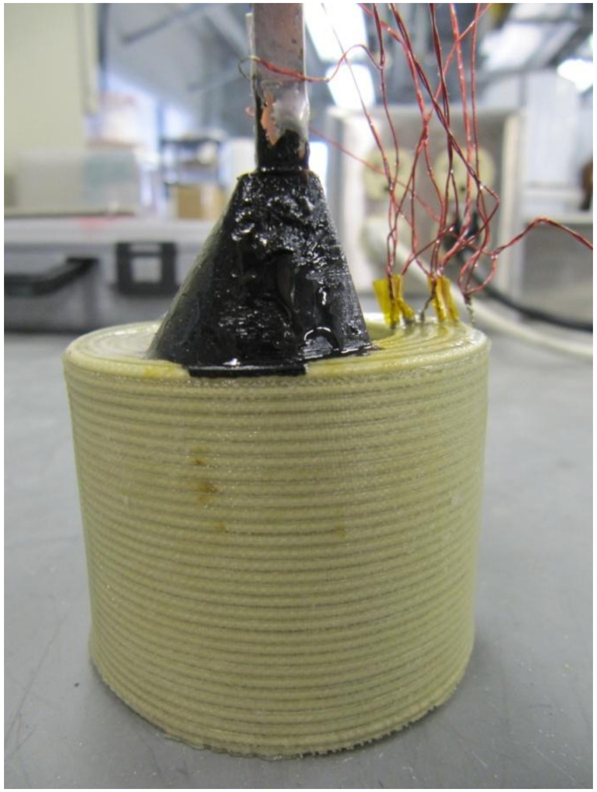
X.T. Liu

Without insulation **With insulation**



Solutions on the horizon?

- Optical-fiber based distributed sensor to detect equilibrium T-profile
- Oxford Instruments may have learned to avoid leakage (albeit with lower short sample J_c)
- Oxygen pre-annealing reduces inhomogeneities within coils
- Change the insulation…
- … or add additional Cu



Magnet pull…

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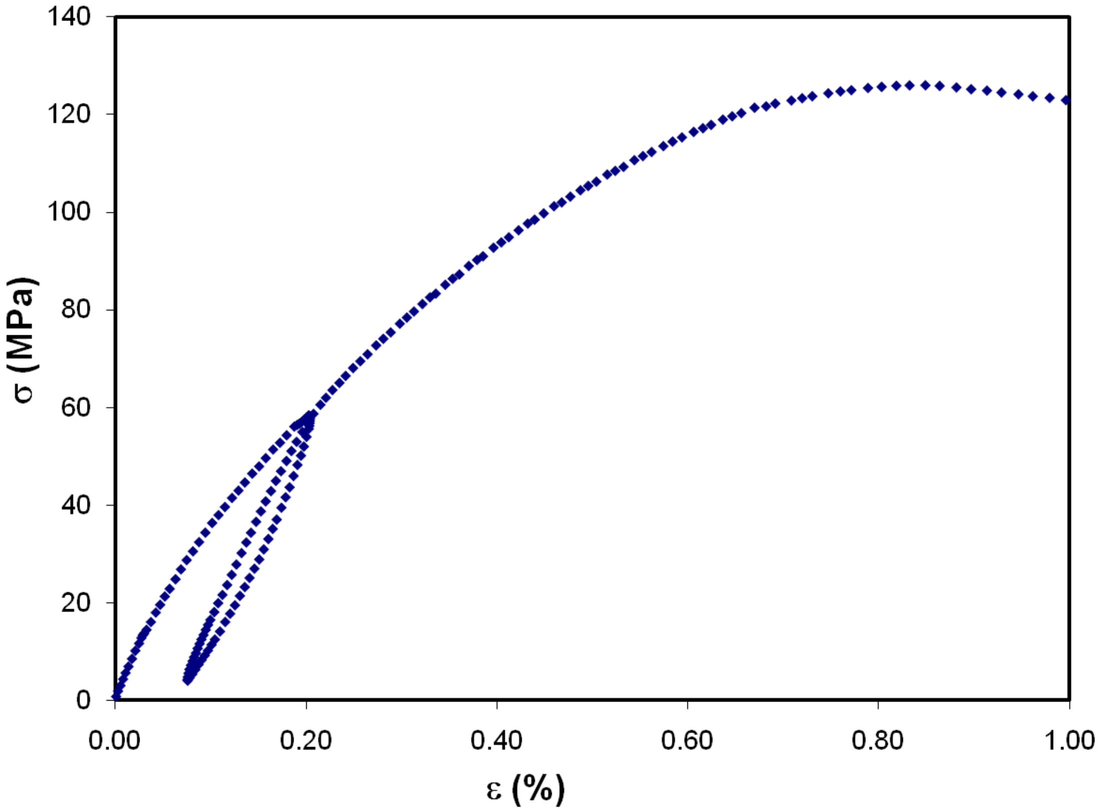
Bi2212 electro-mechanical behavior

- Bi2212 wire is mechanically irreversible, weak, and *non-uniform*
- Weak matrix with a brittle ceramics “fiber” as functional element
  - Brittle materials often best-studied using statistical approaches



Weibull statistical analysis of electromechanical behavior

Three-parameter Weibull distribution function:

$$F(x;\alpha,\beta,\gamma) = 1 - e^{-\left(\frac{x-\gamma}{\alpha}\right)^{\beta}} \quad : \alpha \geq 0, \beta \geq 0, \gamma \geq 0 \text{.......... ....}(1)$$

where α, β and γ are scale, shape and location parameters respectively. Rearranging and taking double logarithms we get:

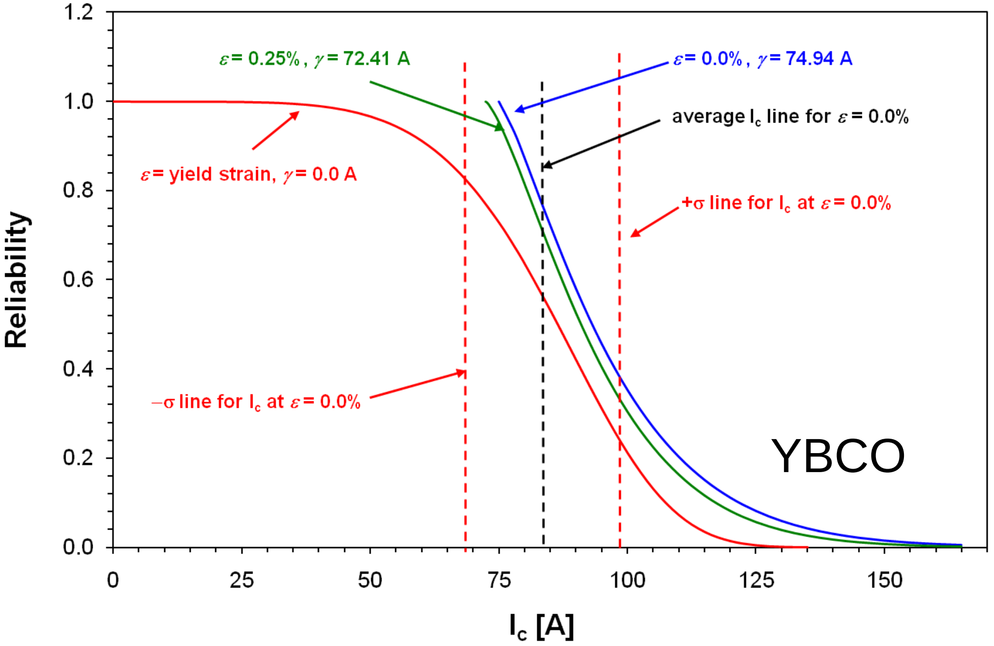
$$\ln\left[\ln\left\{\frac{1}{1-F(x;\alpha,\beta,\gamma)}\right\}\right] = \beta\ln(x-\gamma) - \beta\ln(\alpha) \text{......... ....}(2)$$

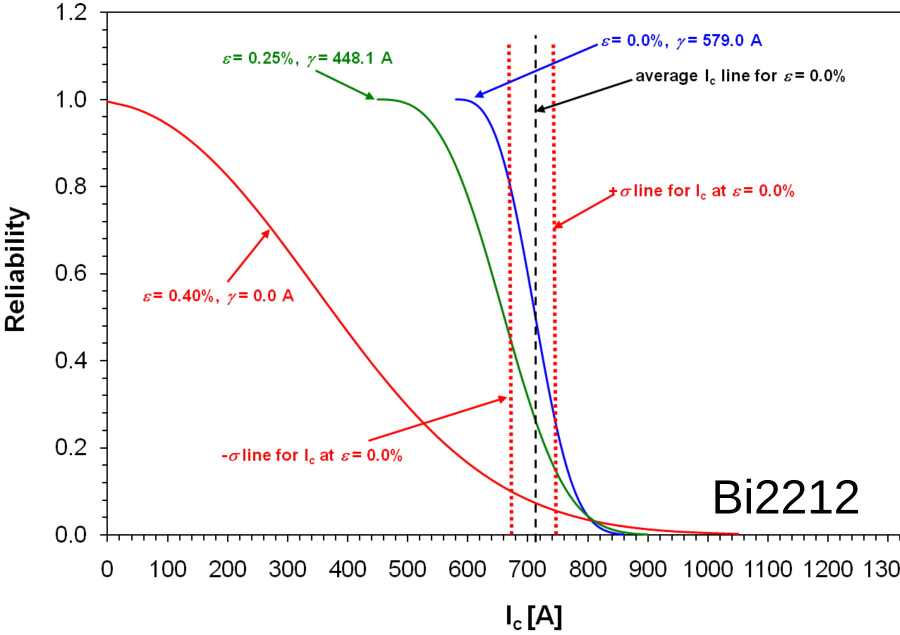
The function $F(x;\alpha,\beta,\gamma)$ is estimated from the experimental data by formula below:

$$F(x_{(i)};\alpha,\beta,\gamma) = \frac{i-0.3}{(n+0.4)} \text{.......... ....}(3)$$

- Measure: yield stress, Young modulus, I_c at strains ranging from ε=0% to yield
- I_c test condition: 4.2 K, self-field for Bi2212; 77 K, self-field for YBCO
- Electric field criterion: 1 μV/cm
- 25 samples tested for each strain value

Bi2212 RW versus YBCO Weibull reliability curves





- γ(ε) = zero-margin design limit
- YBCO: indicative of metallic behavior at low/intermediate strain; ceramic-like at high strain
- Bi2212: inhomogeneous, defect-dominated behavior; high current tail in high strain curve may indicate a strain-resistant “backbone”
- Mbaruku et al., SuST **23** 115014 (2010)

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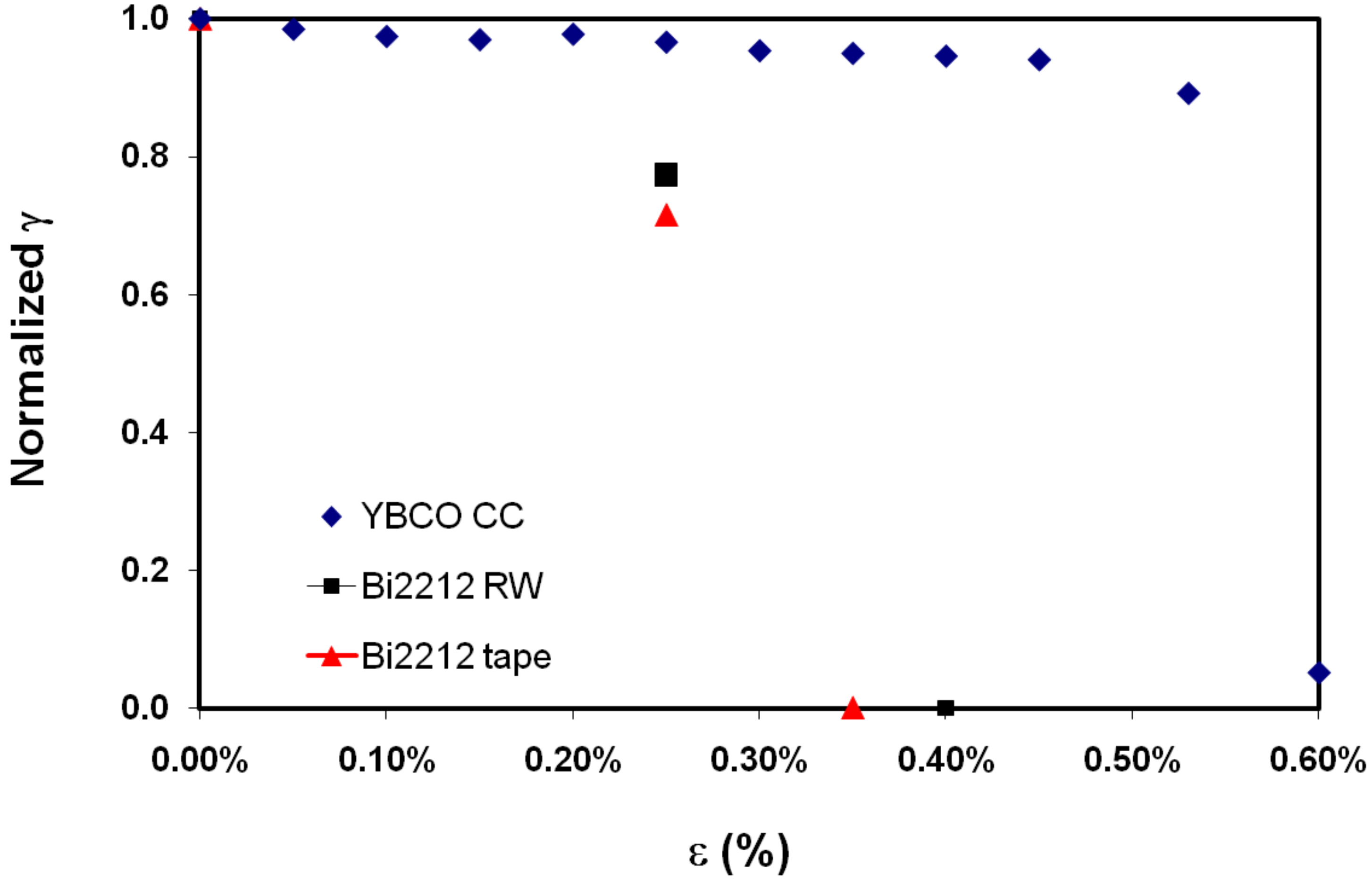
What do the Weibull results mean for magnets?



ε_c model may not be best for present-day Bi2212 wires

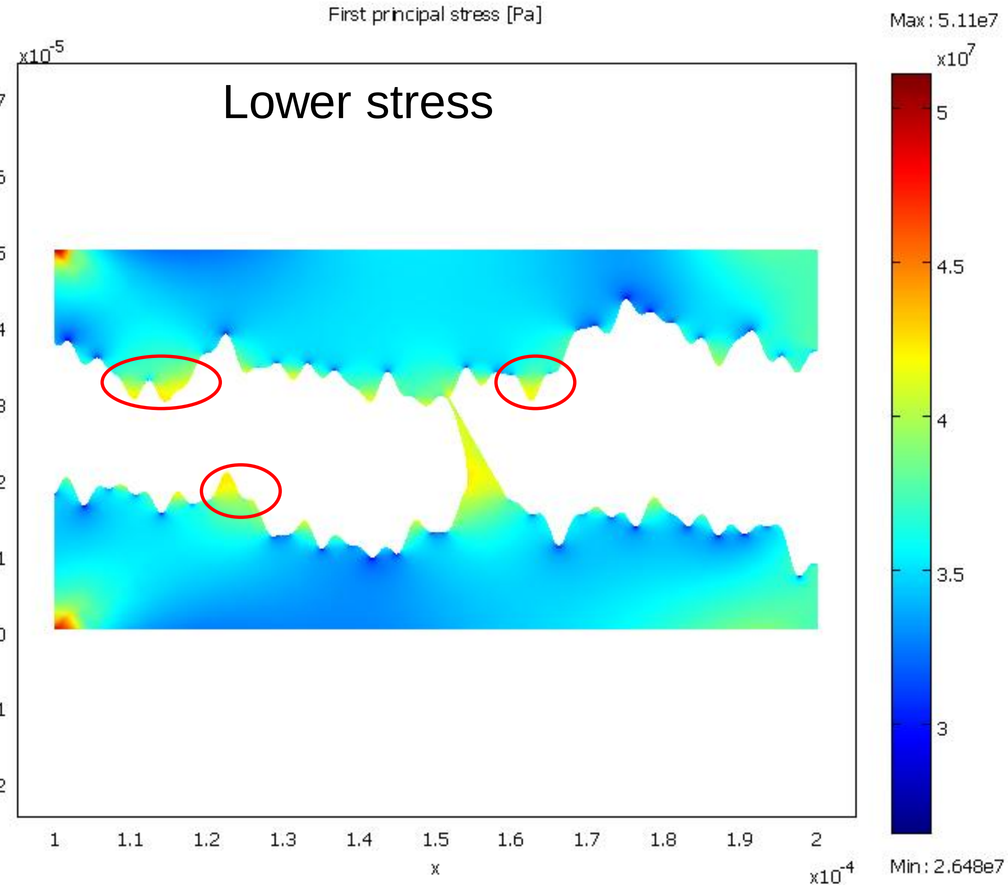
Bi2212 electro-mechanical behavior

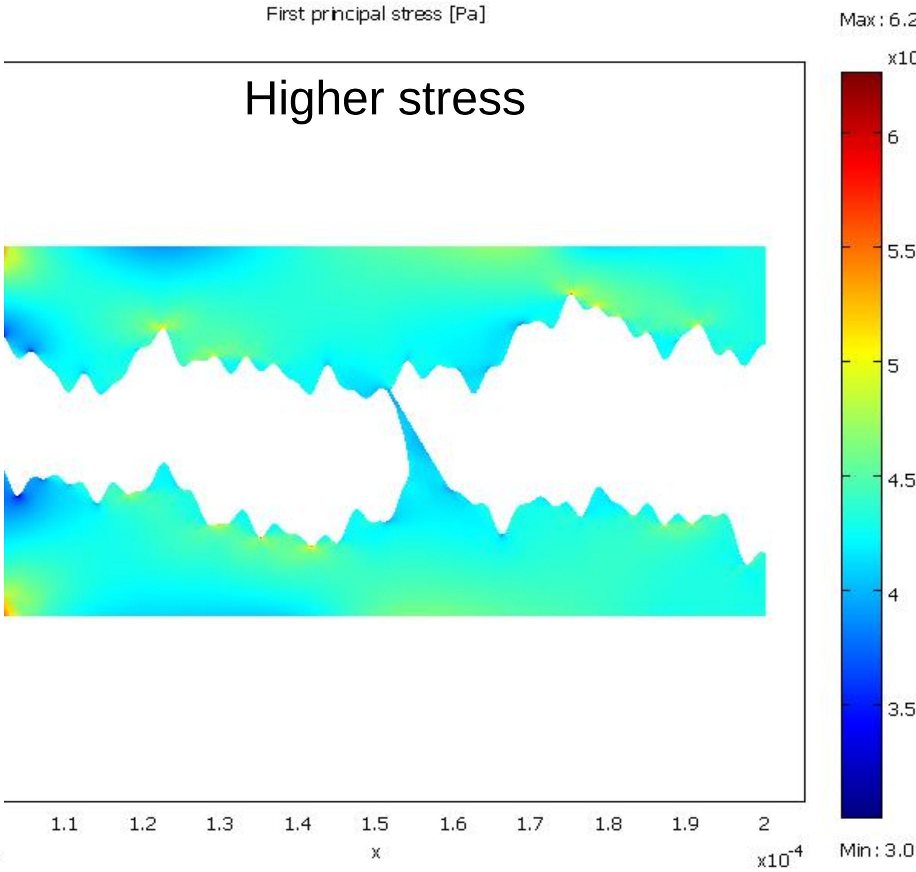
is it the end of the story?

- Does Bi2212 strong, reversible backbone imply potential for significant improvements?
- Can we engineering the Ag matrix significantly better?
- Can we understand what’s happening at the microscopic level?
  - *will higher* J_c *also lead to more strain-resistance?*
  - *microstructurally-driven fractal analysis of localized stress concentrations says yes!*

Fractal-based stress-concentration results

Stress concentrations in bridges not dominant





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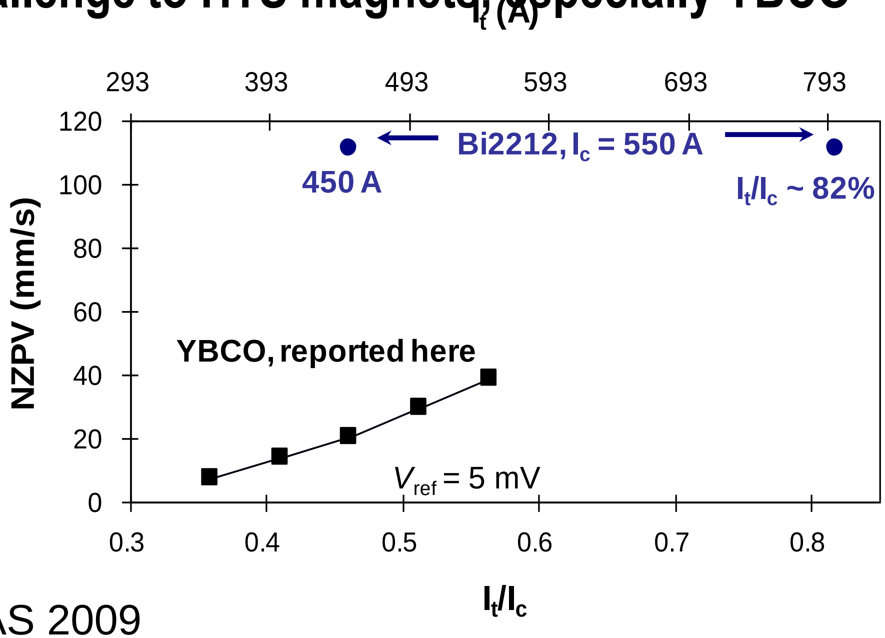
    - ***Focus on (RE)BCO***
  - Additional important issues … on which we’ve only begun
    - Joints
    - Irradiation effects

HTS magnet quench protection

- Protection in HTS qualitatively similar to LTS; requires
  - Detection → typically depends on propagation
  - Understanding of failure limits
    - Does NON-catastrophic quenching effect electromechanical behavior?
  - Protective response
- Some simple truths remain true
  - High field → high energy
  - High J_E → high energy density

HTS magnet quench protection

- Protection in HTS ***quantitatively*** very different from LTS
  - Propagation is very slow
  - But perhaps temperature rise is slow too?
  - It's primarily the ***localization*** of the problem … traditional detection has limited spatial resolution; is it sufficient?
- ***The key is to limit the local growth of the temperature (gradient) relative to our ability to detect***
- **A key remaining challenge to HTS magnets, especially YBCO**



Song & Schwartz, IEEE TAS 2009

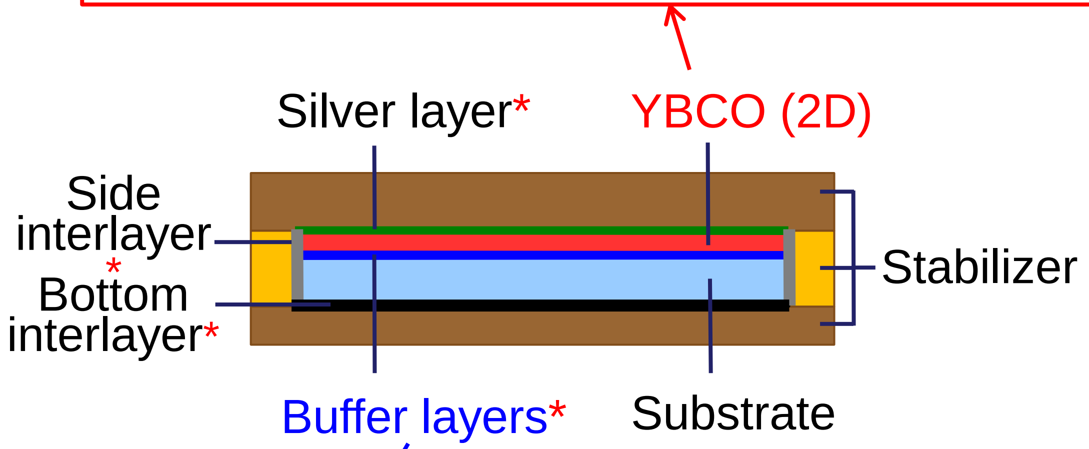
Possible solutions

attacking the problem at both ends

- Distributed (co-wound) optical fiber sensor to give fast, localized detection
  - Spatial resolution approaches wavelength of light!
  - Data overwhelm!
  - In practice, this “data problem” → trade-off between temporal and spatial resolutions
  - Is it sufficiently intimate with the conductor?
- Can a 3D “propagation” mode reduce the local temperature (gradient)?
  - *Thermally-conducting electrical insulators under development*
- Have we even quantified the problem accurately?
  - Multiscale modeling attacking the problem

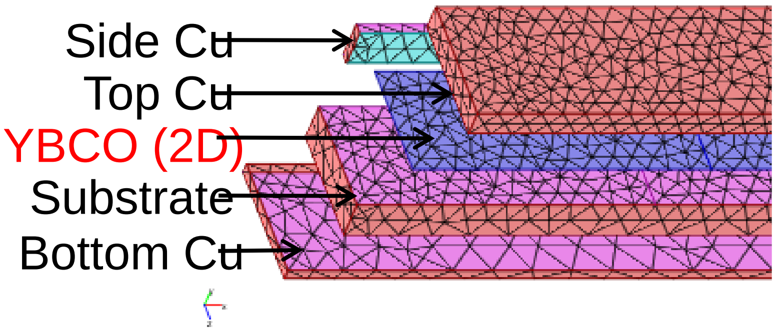
Multiscale (3D/2D) tape model

$$d_y \rho_y(\tilde{T})\, C_y(\tilde{T}) \frac{\partial \tilde{T}}{\partial t} - d_y \nabla_t \cdot \left(K_y(\tilde{T}) \nabla_t \tilde{T}\right) = d_y Q(\tilde{T}) + \frac{K_s}{d_s}\left(T_{cu}^{-} - T^{+}\right) + \frac{K_b}{d_b}\left(T_{ni}^{+} - T^{-}\right)$$



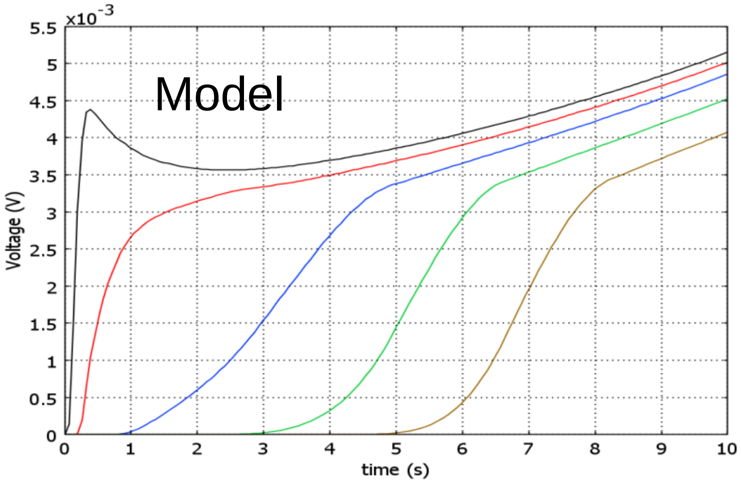
* Not meshed

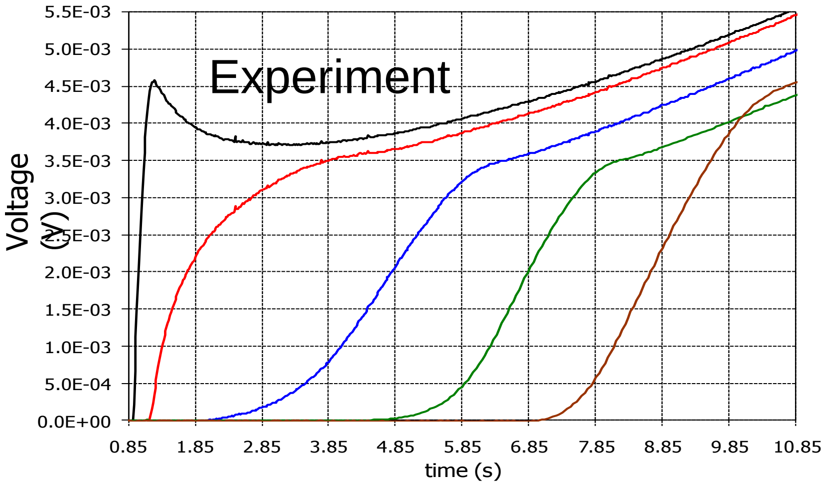
$$-K_{ni} \nabla T \cdot \mathbf{n}\Big|_{\Gamma_{ni}^{+}} = \frac{K_b}{d_b}\left(T^{-} - T_{ni}^{+}\right) + d_b \sigma_b \left[\left(\frac{(V_{ni}^{+} - V^{-})}{d_b}\right)^2 + \nabla_t V_{ni}^{+}{}^{2}\right] - d_b \rho_b C_b \frac{\partial T}{\partial t} + d_b \nabla_t \cdot \left(K_b(T) \nabla_t T\right)$$

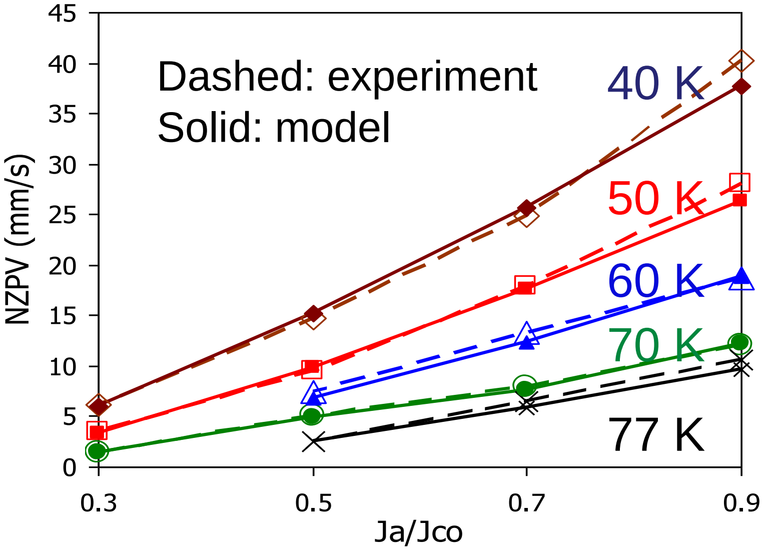


Chan et al., *IEEE Tranactions on Applied Superconductivity* in press

Experimental Validation







X. Wang *et al.*, *J. Applied Physics* 2007

W. K. Chan et al., *IEEE Transactions on Applied Superconductivity* in press

Using the model to engineering better conductors for quench protection

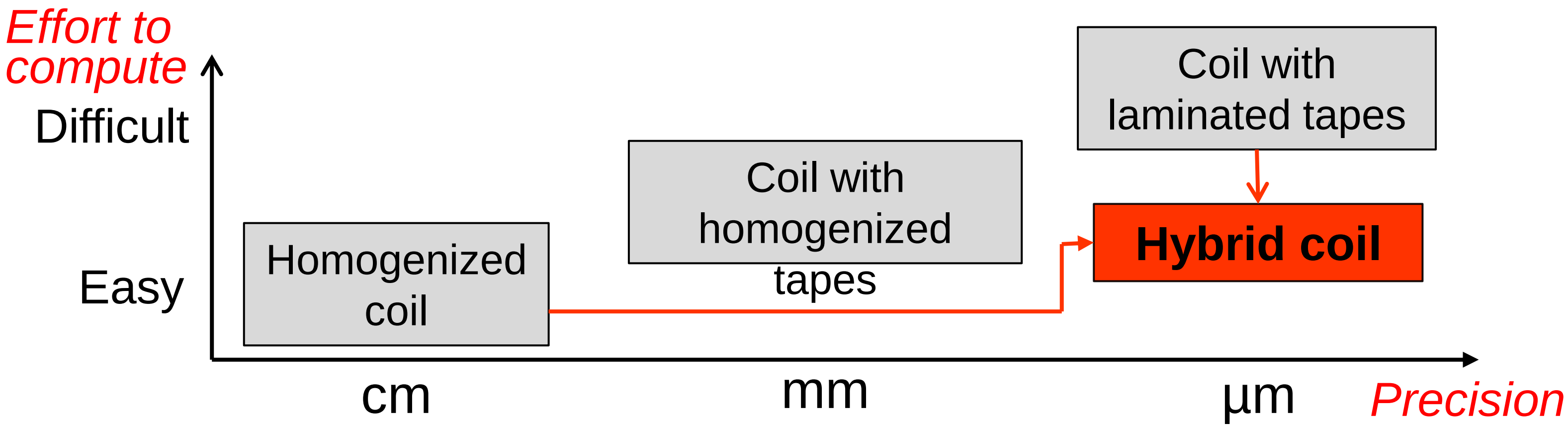
YBCO thickness (um)	~MQE density (W/m^3)	NZPV (cm/s)	T @ V2, 4 mV (K)
1.4	1.16e9	2.00	121.0
2.8	0.845e9	4.22	170.0

Cu thickness (um)	~MQE density (W/m^3)	NZPV (cm/s)	T @ V2, 4 mV (K)
25	0.6e9	2.53	146.5
37	1.16e9	2.00	121.0
50	1.45e9	1.75	104.0

Stabilizer material	~MQE density (W/m^3)	NZPV (cm/s)	T @ V2, 4 mV (K)
Cu	1.16e9	1.78	121.0
Brass (UNS 22000)	0.3e9	3.18	226.0

Buffer conductivities ρ (S/m)/κ (W/m-K)	~MQE density (W/m^3)	NZPV (cm/s)	T @ V2, 4 mV (K)
1 / 1	1.16e9	2.00	121.0
5e7 / 250	1.16e9	2.00	121.0

Embed conductor model into a hybrid 3D coil model



Effort to compute

Difficult

Easy

Homogenized coil

Coil with homogenized tapes

Coil with laminated tapes

Hybrid coil

cm

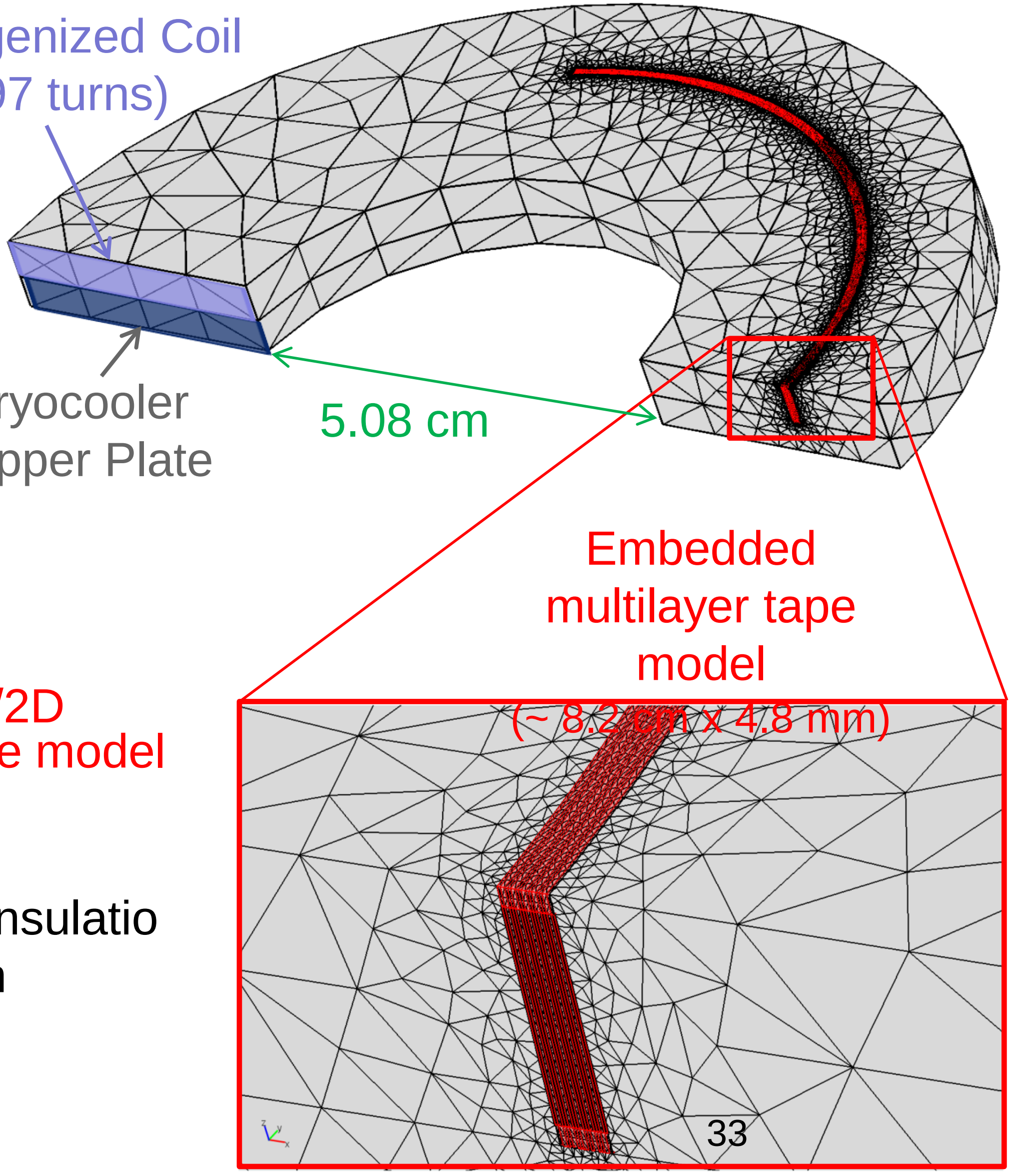
mm

µm

Precision

- Homogenized coil model *embedded* with localized multilayer tape model
  - Obtain global, macroscopic and local, microscopic data without building globally complicated, expensive-to-compute coil model
- Localized multilayer tape model is the center building block
  - Precise quench details at µm scale down to each layer within a tape.
  - Estimate lump parameters and effective material properties for coil model.
- Coil model provides background magnetic field and acts as heat mass and magnetic energy storage.

Compare coil model with experimental data

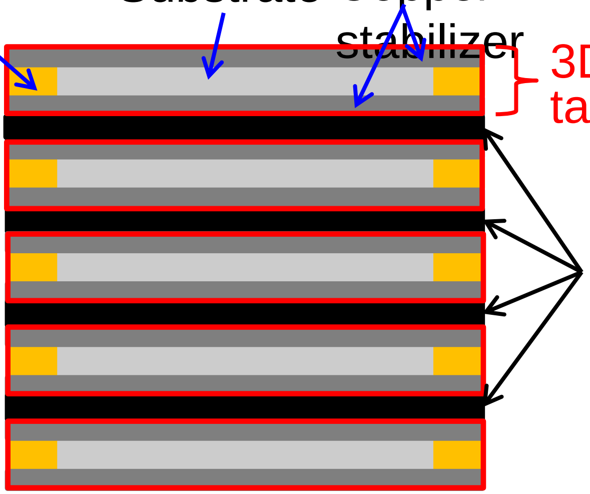


Homogenized Coil
(= 97 turns)

Cryocooler
Copper Plate

5.08 cm

Embedded
multilayer tape
model
(~ 8.2 cm x 4.8 mm)



Side
stabilizer

Substrate

Copper
stabilizer

3D/2D
tape model

Turn 62

Turn 61

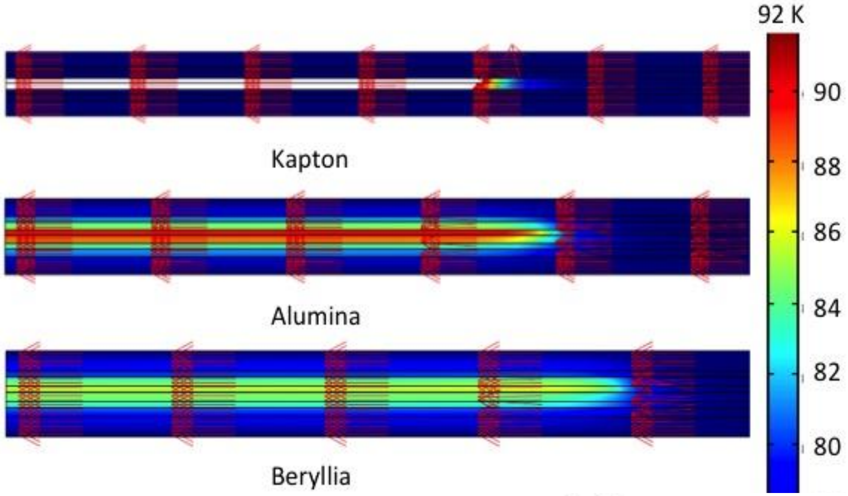
Turn 60
+
heater

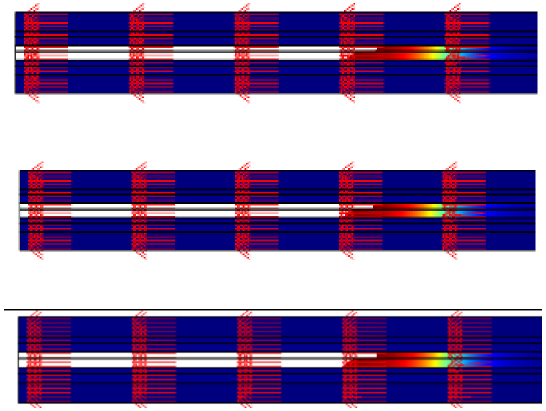
Turn 59

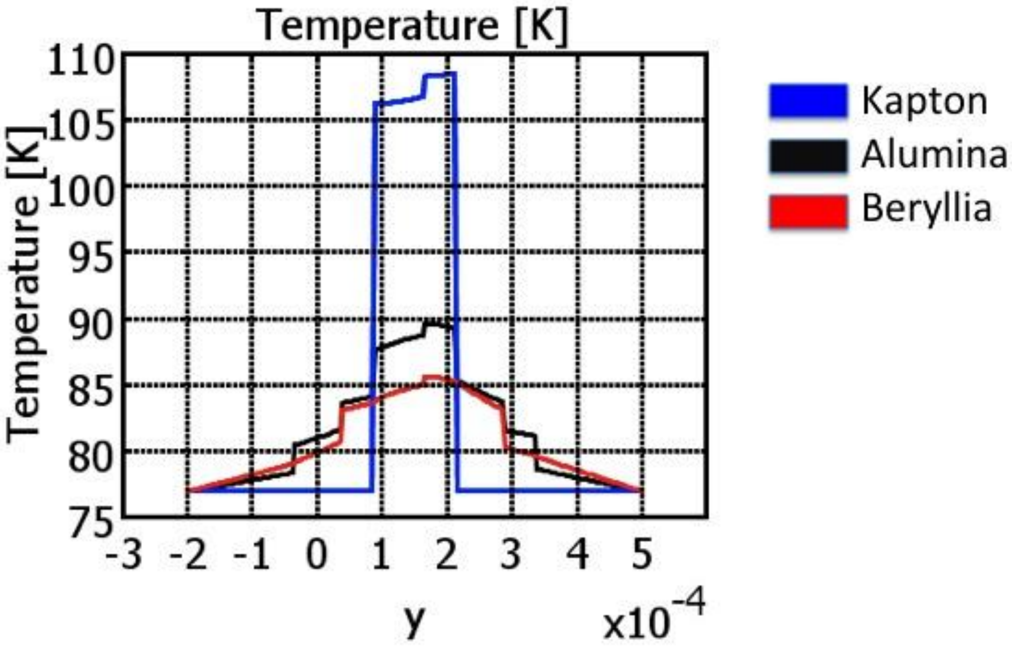
Turn 58

Insulation

Thermally conducting insulation might just work!







Other important technology issues

- Joints – little has been done for either Bi2212 or (RE)BCO
- Irradiation … we know that the MQE is very large
  - Some beginning results on neutron irradiation of YBCO are coming thanks to ITER but not enough to be conclusive
  - Ag renders Bi2212 irradiation studies more difficult
  - Conceivably IR magnets could operate at higher temperature than 4.2 K if irradiation tolerance is sufficient … T_{op} would be an optimization issue

Potential “game changers”

- YBCO
  - High performance round wire would probably eliminate Bi2212 immediately
  - Low cost processing
- Bi2212
  - 100% dense filaments
    - Impact on $J_c(B)$?
    - Impact on $J_c(\varepsilon)$ and $\gamma(\varepsilon)$?
  - Alternative mechanisms to *significantly* improve mechanical behavior of cables

Conclusions

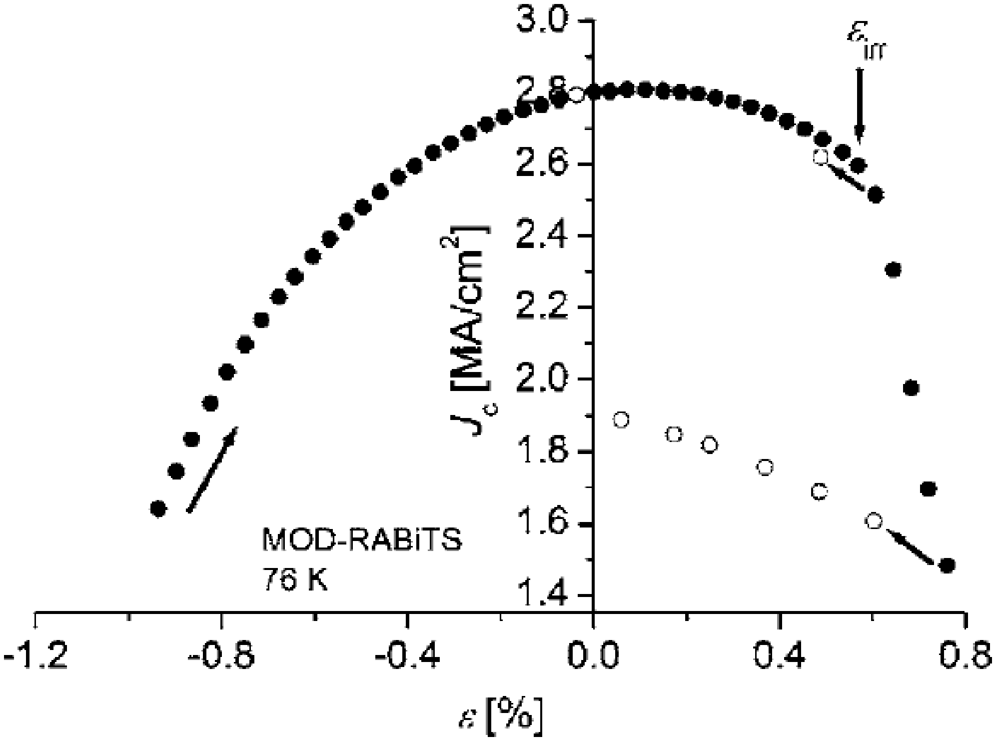
- HTS magnets are progressing
- Bi2212 and YBCO magnets have vastly different limitations and challenges
- Solutions include
  - some “LTS extrapolations”
  - some “out of the box” approaches
- At present it’s a staircase, but there are potential elevators
- Materials community getting away from “if we make a conductor, applications will come”
- Magnet community should not view conductor as a “fixed” product
- Applications pull is THE necessary driving force
  - YBCO: applications aplenty, though not all R&D relevant for high field magnets
  - Bi2212: high energy physics and NMR are only two players in the game

Coil manufacturing: (RE)BCO

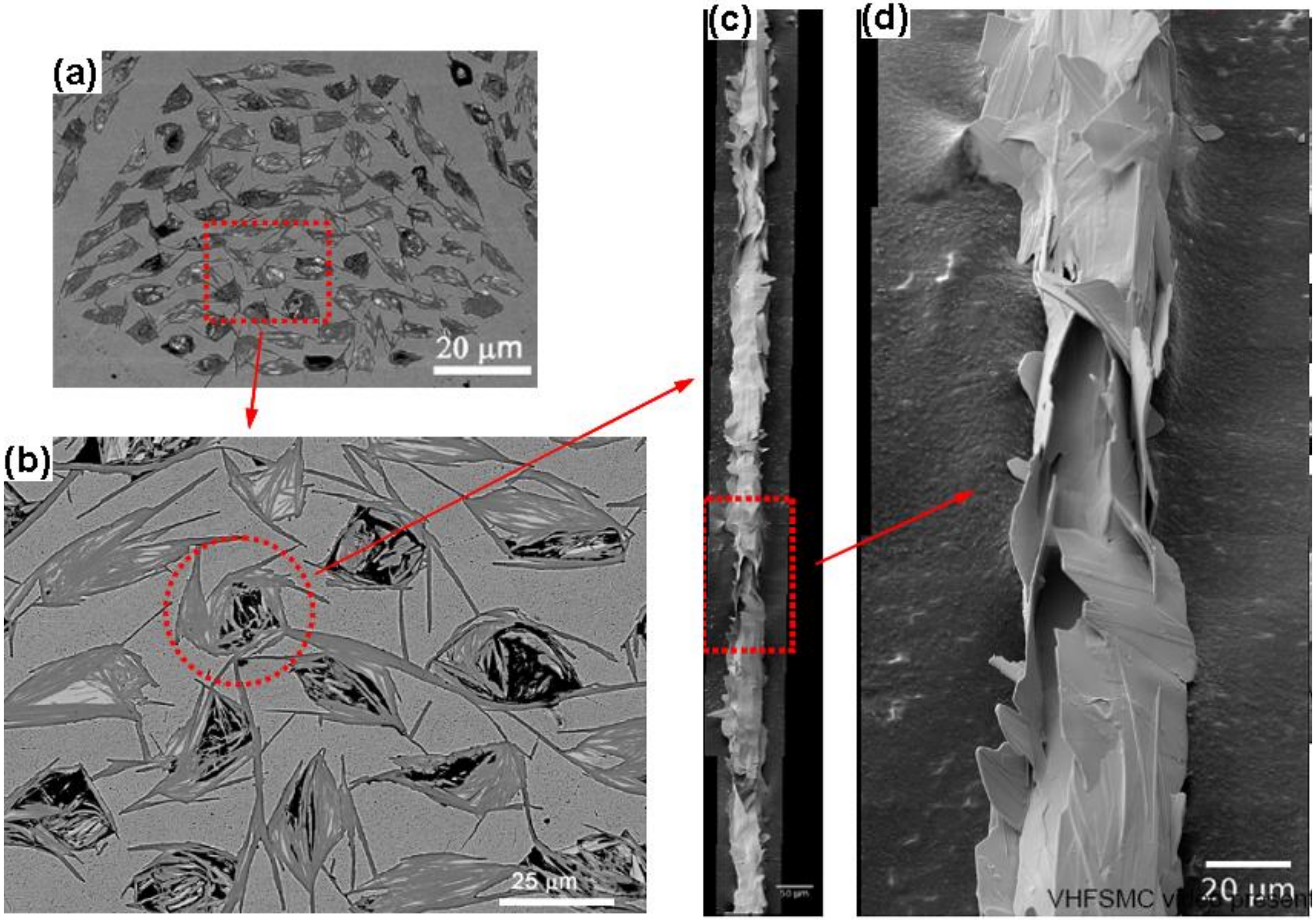
- (RE)BCO
  - Bending strain is a minor factor
  - Lack of cables (Roebel simply not tested for magnet applications)
  - Anisotropy issues (ends of a solenoid)
  - Winding direction reversals (solenoids)
  - *Mostly "conventional" R&W magnet issues with a tape conductor*

YBCO electro-mechanical behavior

- YBCO is reversible and strong
  - van der Laan & Ekin, APL 2007
- Hastelloy substrate gives excellent behavior!



Hi-res image of an individual filament



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Digitize the filament image for fractal analysis