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Key Obstacles to Bi2212 and REBCO Coils, Including but Not Exclusively Quenching

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Workshop on High Temperature Superconducting Magnets for Muon Colliders

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SCHWARTZ GROUP

Department of Materials Science and Engineering

Outline … *from the Workshop Charge*

- "YBCO, Bi2212 … what needs to be improved"
  - Are there pathways for improvements?
- Quenching … "What are the quench characteristics? … How quickly can we detect?"

- Detection → beyond voltage!
- Enhanced propagation → 3D normal zones!
- Understand failure → in order to prevent it

- Conclusions

"YBCO, Bi2212, … *what needs to be improved?*"

- Bi2212 (>22 yrs of PIT)
  - Is porosity intrinsic to PIT?
  - Are non-Bi2212 phases intrinsic to peritectic melting?
  - Narrow temperature window challenge *in large systems*
  - Lack of strain tolerance
    - Are 100%-dense, 100%-phase pure filaments the answer?
    - AgX needs a better "X"
  - Lack of powder source
- Magnetization
- Quench challenges

- YBCO (>15 yrs of CCs)
  - Can we manage the high J_c?
    - Very different J(x,y)
    - Particularly in light of drop-outs
  - High J_e cable? What price?
  - Can high current cable bend?
  - Joining (conductors & cables)
- Magnetization
- Quench challenges

An ***ignored challenge*** for HTS conductors

Martin Wilson, MT-22, 2011:

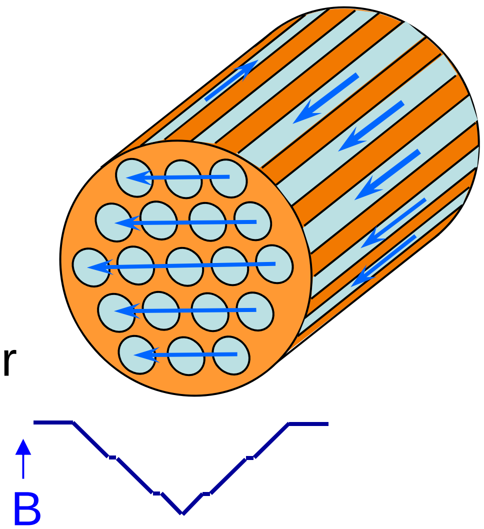
1969: Filamentary composite wires

- *Low Magnetization*

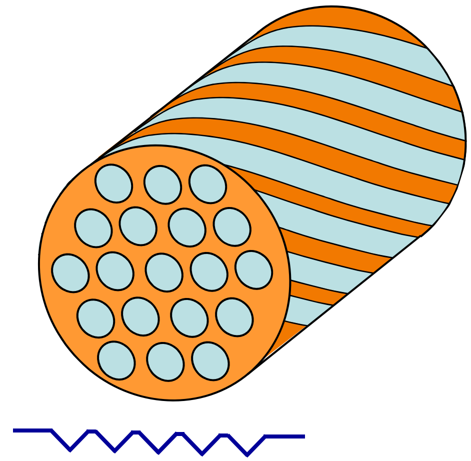
  needed where field quality is important, eg accelerator magnets, NMR spectrometers

- *Twisting is essential*

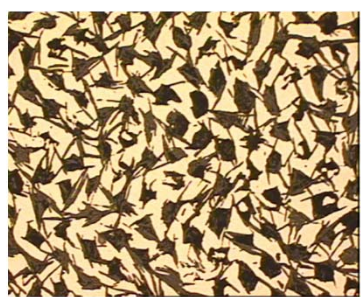
untwisted filaments are magnetically coupled and behave together like a solid wire



twisted filaments are magnetically decoupled and behave like separate entities



Note the Bi2212 microstructure

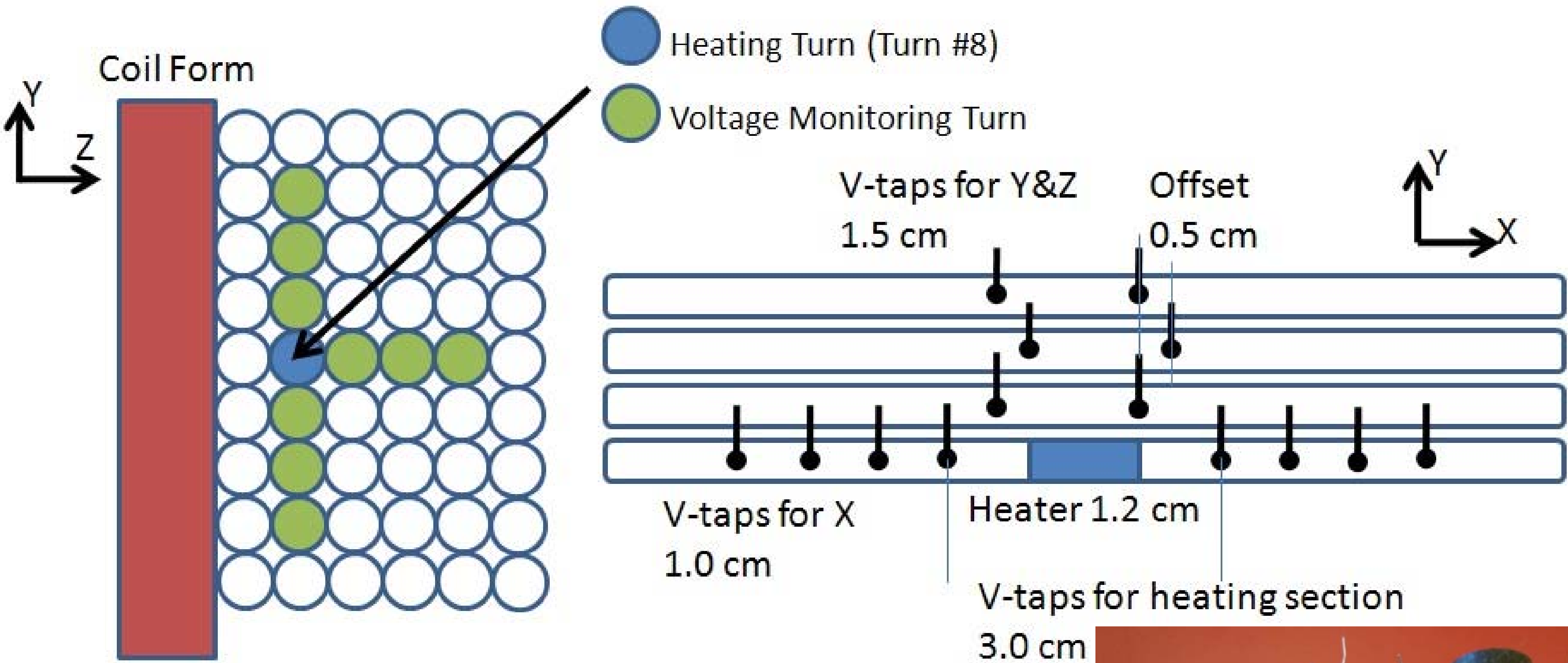


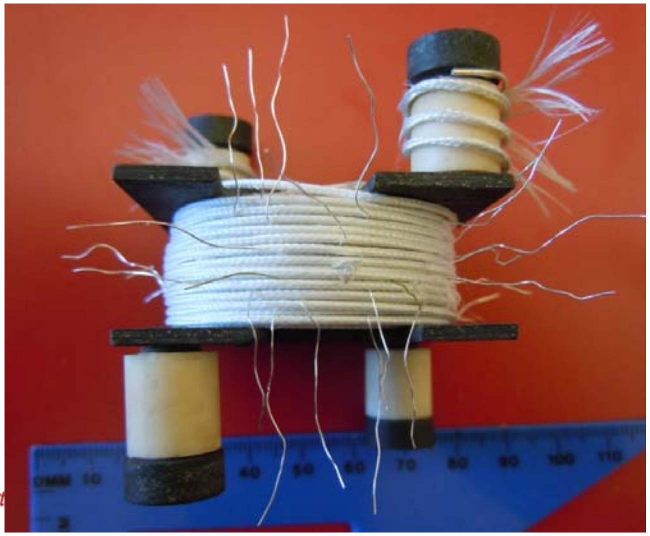
Two aspects to quench protection

- Detection
  - while there's still time to act
  - without false positives
- Action
  - before conductor is degraded
  - must know *causes* and *onsets* of degradation
- Can high field magnets survive a high energy (density) quench?
- Degradation likely very different between REBCO and Bi2212

- These are two distinct yet intertwined topics
- Core problems are *slow propagation* and *ceramic carrier*

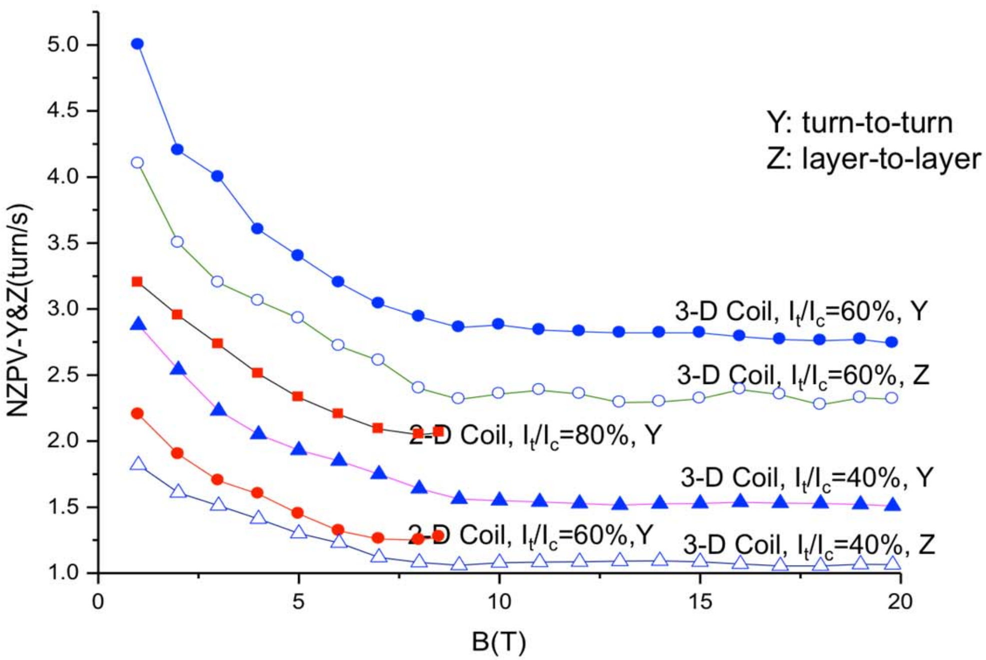
Does high field improve propagation?

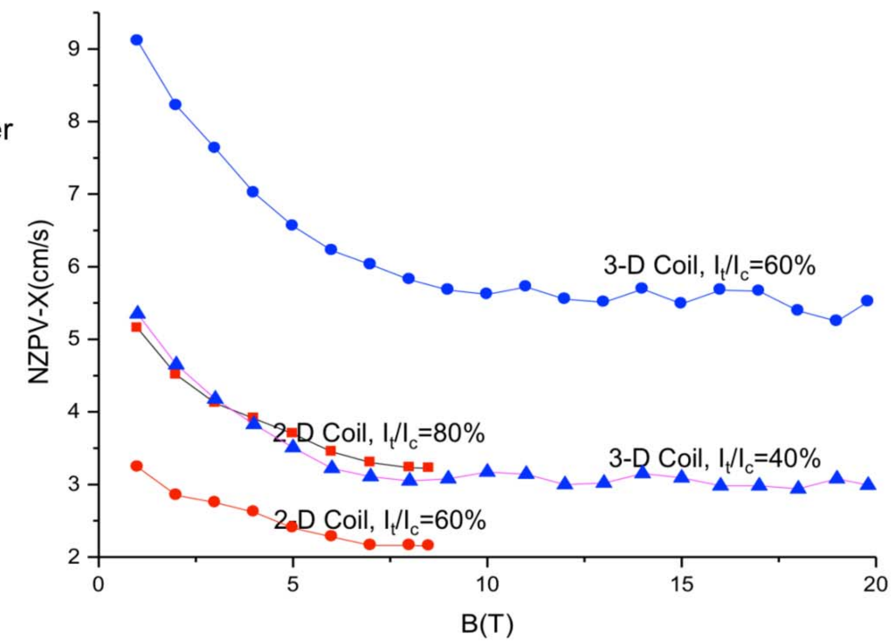




L. Ye et al., to be submitted; funded by the VHFSMC

No, it doesn't





L. Ye et al., to be submitted; funded by the VHFSMC

New approaches to address propagation

- Optical fiber based sensors to monitor (almost) everything … to improve detection
- Thermally conducting electrical insulation ... to improve propagation
  - *New paradigm: HTS magnets become even more stable AND have a very different "quench signature" that improve detection*
  - *Ultimately - can we have spherical normal zones?*

Fiber optic sensing (quench detection, ε, …)

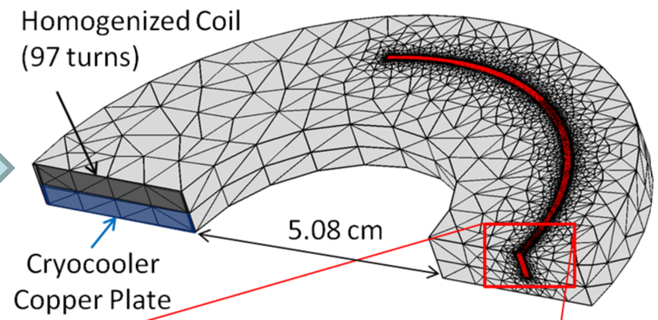
- Proof-of-concepts have succeeded for Rayleigh backscattering & fiber Bragg grating detection
- Rayleigh backscattering offers a *fully distributed* sensor w/impressive spatial resolution
- Integration into a magnet system on-going

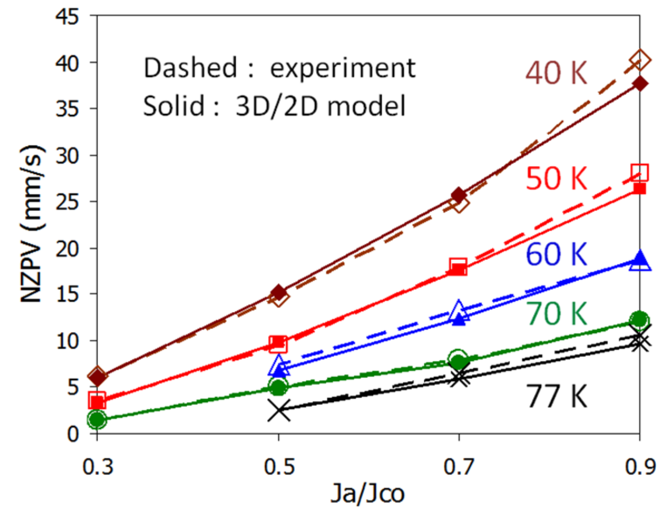
- HTS-compatible metallic and/or oxide based coatings will improve sensitivity
- *Spatial-temporal resolution trade-off must be optimized; enormous volume of data and real-time data analysis becomes limiting issue… but what does quench detection require?*

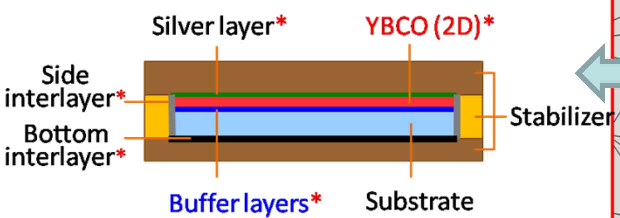
To understand resolution trade-offs for detection … use multi-scale modeling

Experimental coil

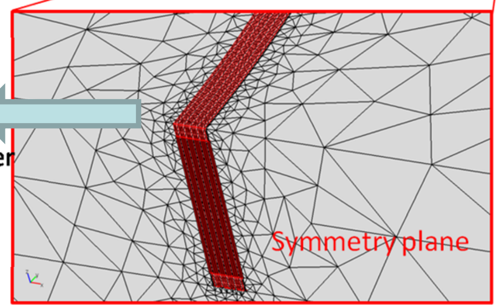
Multiscale coil model



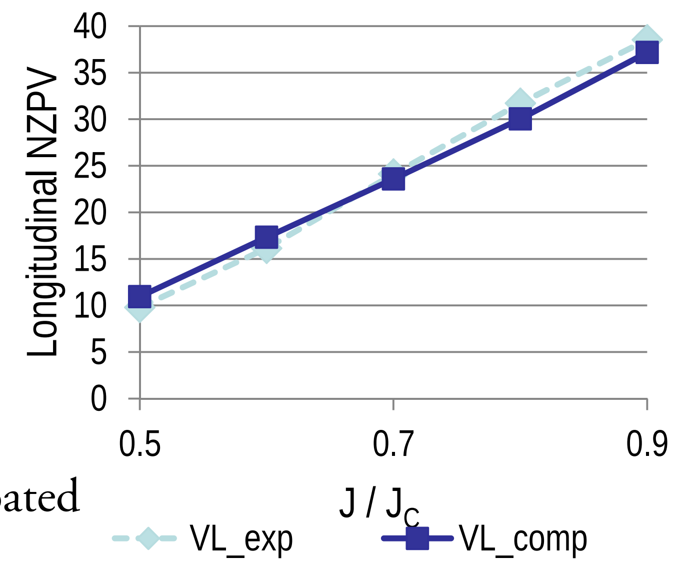




μm-scale tape model



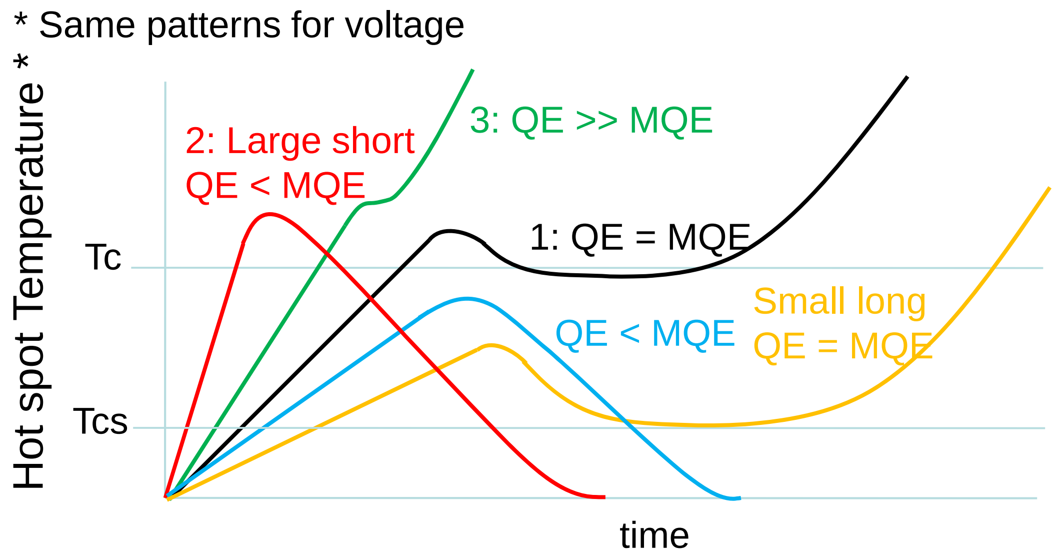
Multilayer tape model



- Accurate, hierarchically built and experimentally validated
- Multiscale– from tape-layer scale to device-scale
- μm-scale tape model includes all components of a YBCO coated conductor in real dimensions

W.K. Chan and J. Schwartz, *IEEE Transactions on Applied Superconductivity* (in press 2012)

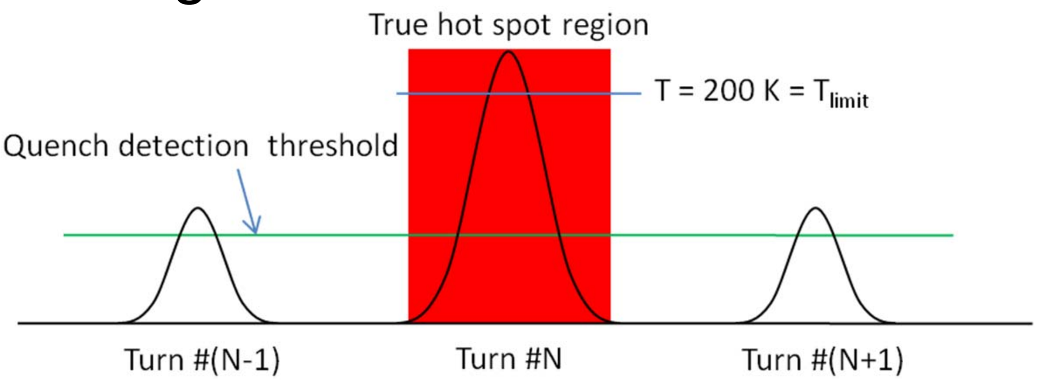
Problems in Conventional Quench Detection



Different quench patterns due to different disturbance energy

- Unpredictable heat disturbance energy (QE) dictates T(x,t) and V(x,t) quench patterns
- Common voltage/resistance-based detection schemes *trace* these quench patterns to avoid false positives
  - Rough, based on global properties detected over sparsely located taps
  - Unable to locate fault position accurately

Distributed sensing

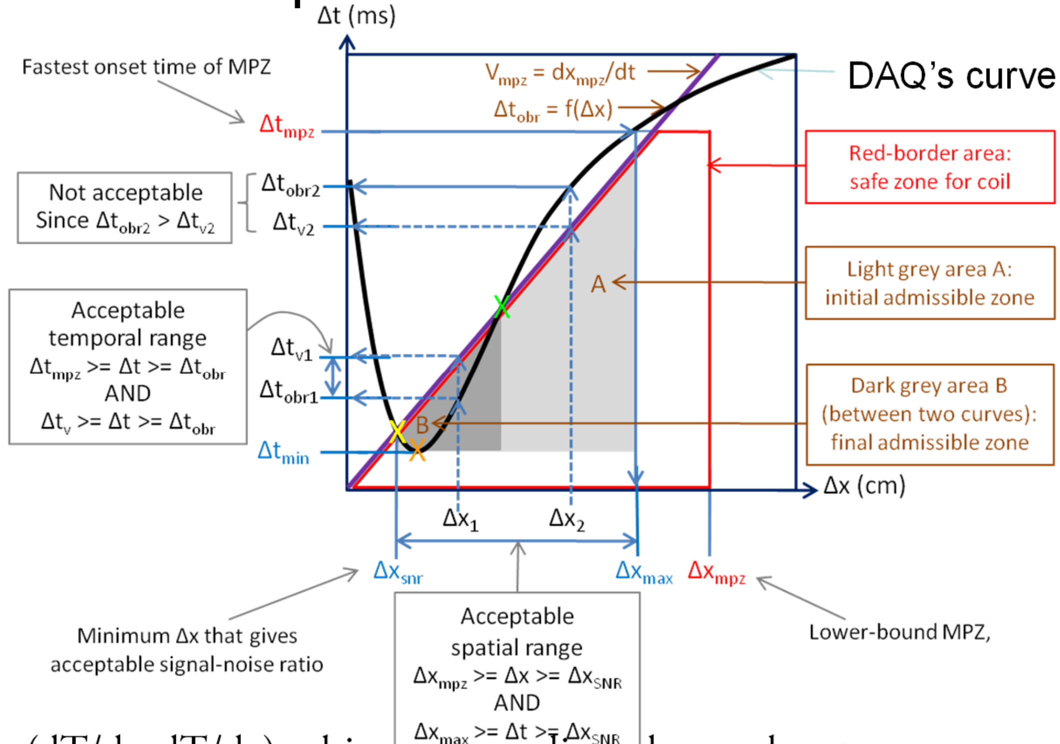


Temperature profiles on all turns are observable. True hot spot can be located.

- Rayleigh scattering based optical fiber sensing
  - Safe, immune to electromagnetic interferences – a problem in voltage-based detection.
  - Shifts in frequency spectra of input pulses translate into temperature variations.
- Continuous spatial temperature profiling over the entire length of the winding
- Complete temperature details at any location.
  - Allow simple, accurate and timely quench detection.
  - Allow fault location to be identified.
- Key to apply technology successfully:
  - Capture and process the backscattered data with sufficient spatial and temporal resolutions on fast enough data acquisition and processing (DAQ) technology.
  - Finer resolutions mean higher DAQ cost.
- Goal: First find proper DAQ technology that matches coil characteristics; then find proper spatial and temporal resolutions for efficient and safe detection.

Determining Spatial and Temporal Resolutions

Diagram used to find a proper DAQ system and the spatial & temporal resolutions



- Temperature and its gradients (dT/dt, dT/dx) subject to complicated quench patterns dictated by unknown disturbance energy.
  - No definable properties to characterize resolution requirements
  - As in voltage-based detection, need to trace dynamics of quench patterns
- Minimum Propagation Zone (MPZ) has lower/upper (for finite-length disturbance) bounds
  - Intrinsic property of a coil. Estimated via simulations.
  - Used as pivotal parameter to define the resolutions.
  - Once a normal zone >= MPZ, it never shrinks and quench is always warranted.
    - No need to trace quench pattern -> simple and fast quench detection.
- Idea: Fit DAQ technology into coil's safe zone. Capture MPZ with fine enough resolutions.

Towards a fast, reliable quench detection method

A conceptual detection algorithm based on distributed temperature sensing:

Estimate upper-bound MPZ (for finite-length heat source)
Loop
    Scan for rising T, with spatial resolution Δx and temporal resolution Δt
    If found
        Search for true hot-spot location
        If found
            Loop
                Estimate normal zone size
                If normal zone size >= MPZ + δx (δx for safe margin)
                then flag 'Quench Detected' and activate quench protection

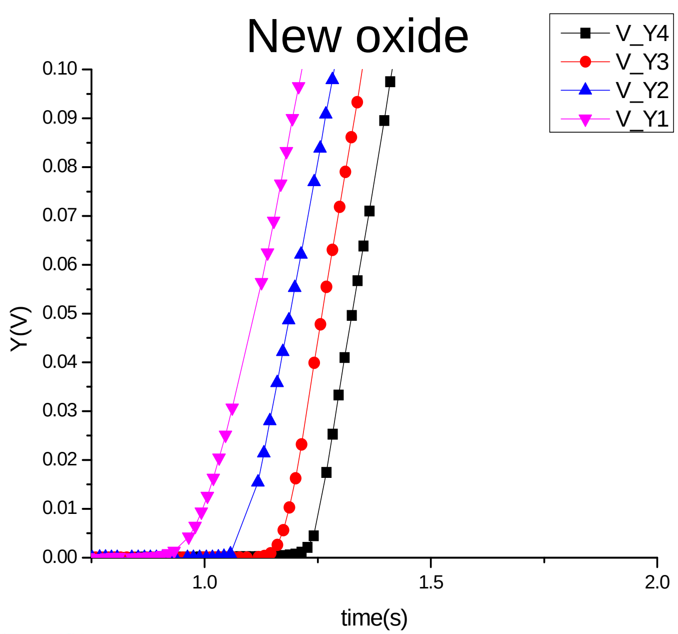
- Realized by Raleigh scattering based distributed temperature sensing
- No need to trace the quench patterns to avoid false positives

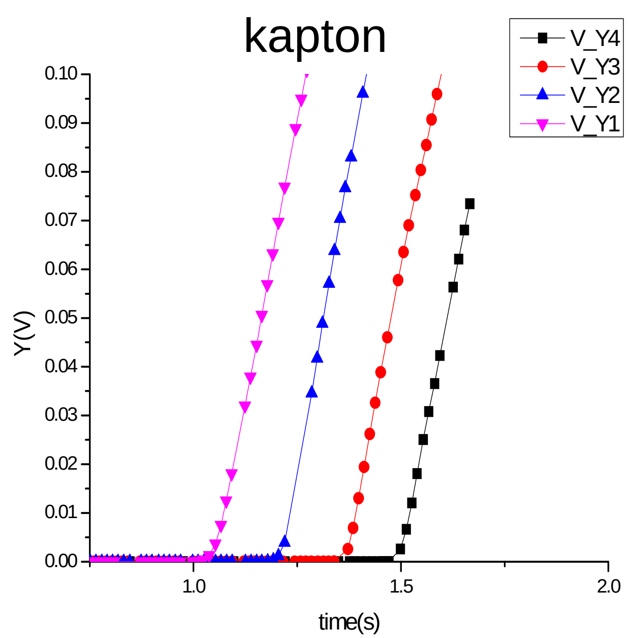
Thermally conducting electrical insulator

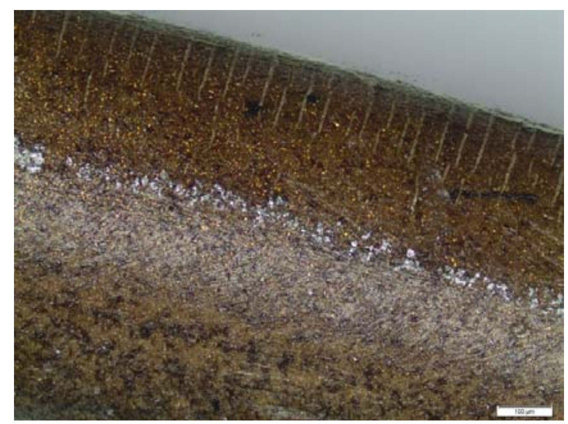
NCSU & nGimat jointly developing a thin oxide coating
see Hunt talk tomorrow for details…

- Chemically compatible with Bi2212 – I_c unchanged; leakage not catastrophic
- Improved fill factor for both Bi2212 and REBCO

275% increase in NZPV





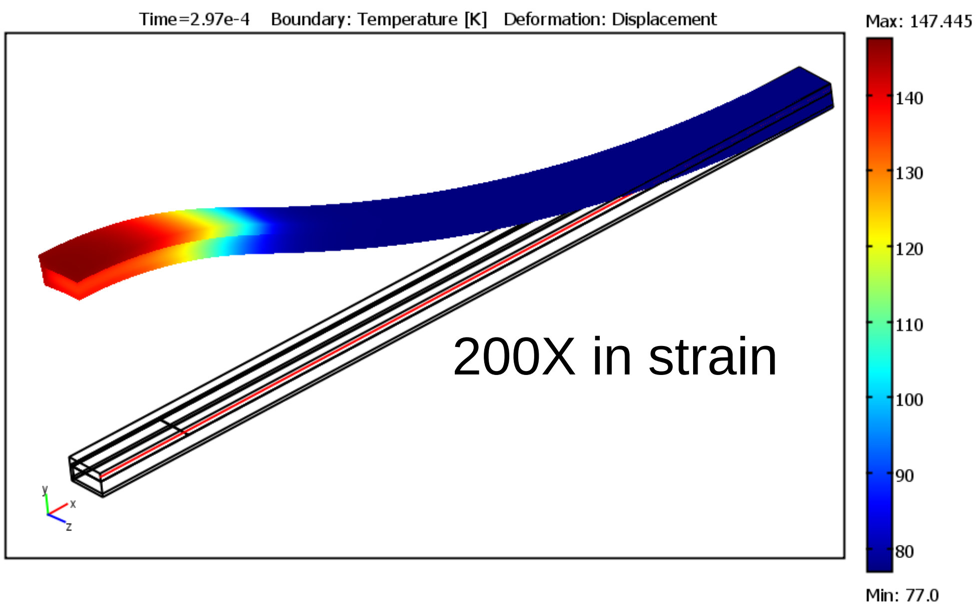


Coating on Bi2212 after heat treatment

J. Schwartz et al., to be submitted

How do HTS conductors fail (during a quench or otherwise)?

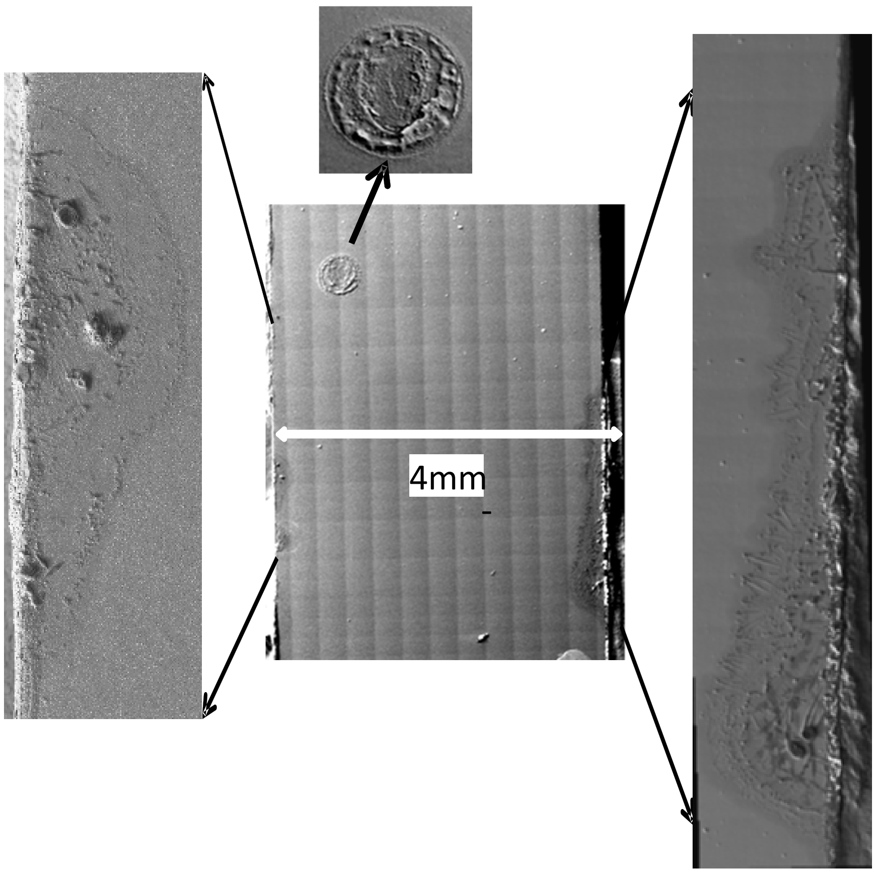
- Bi2212 failure driven by defect-dominated microstructure
  - Behavior is typical of ceramics, following Weibull statistics
- YBCO CC substrates are mechanical strong and CC is strain tolerant, but suffer from delamination
  - Delamination CAN be quench-initiated

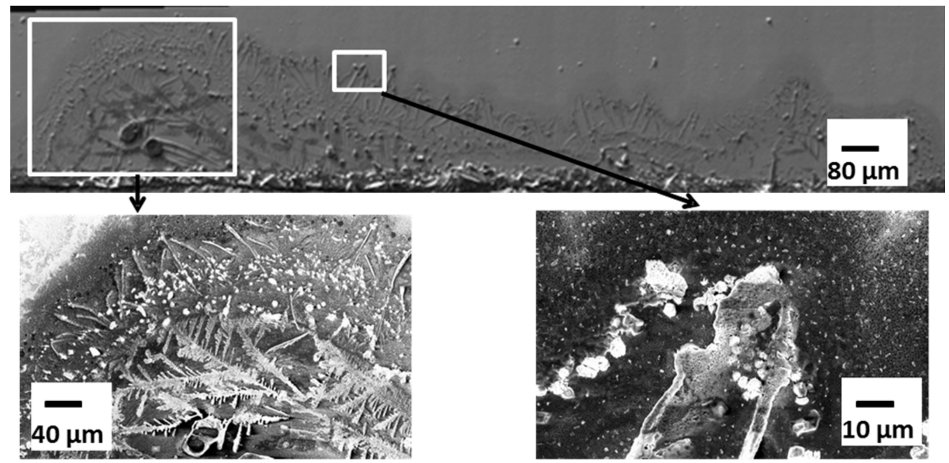


Localized strain versus temperature during a YBCO quench →Delamination risk is real

WK Chan, in progress, NCSU

Quench-related degradation… delamination and pre-existing defects

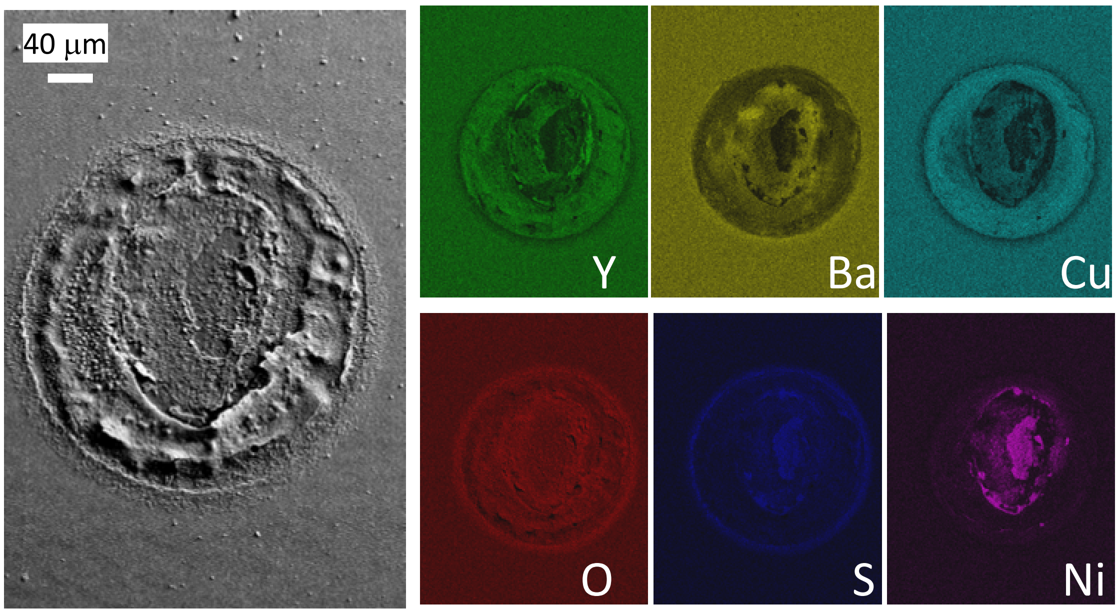


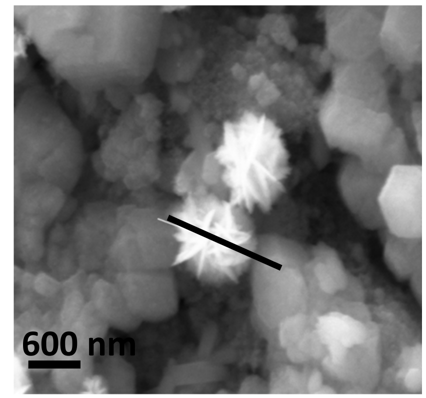


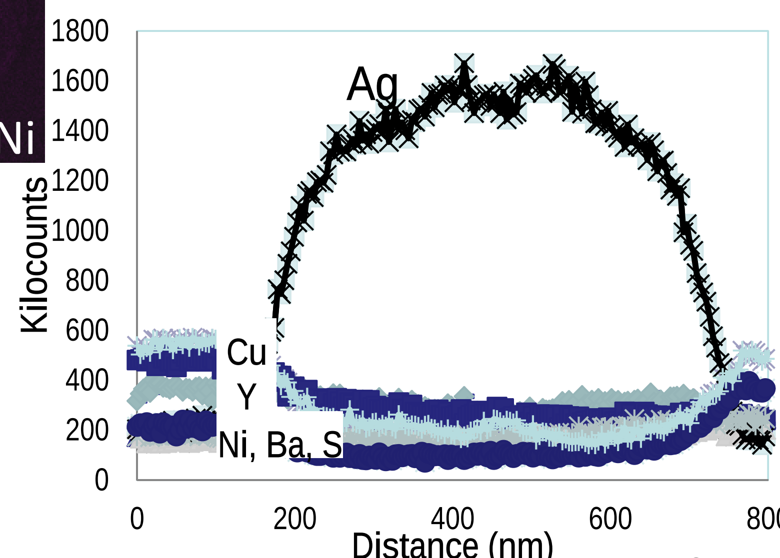
Dendritic flux penetration is evidence of Ag delamination

H. Song et al, *Acta Materialia*, submitted

Pre-existing defects → very high local temperature and degradation … due in part to high J_c in YBCO layer

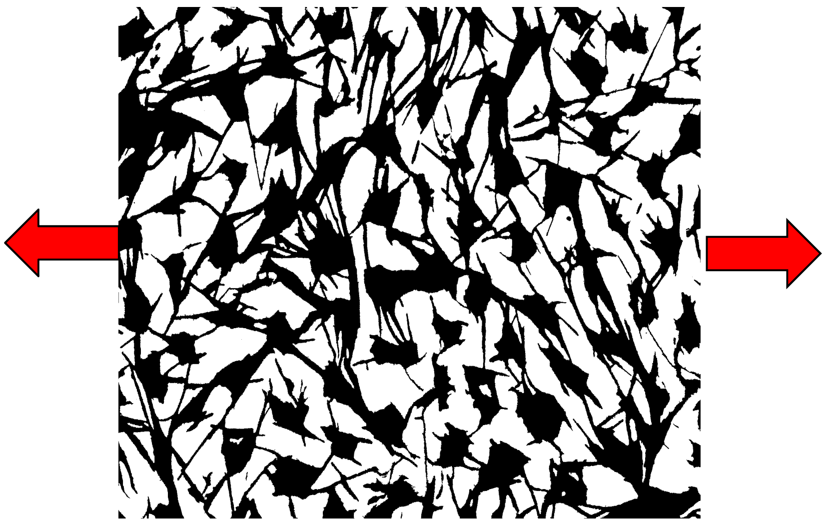


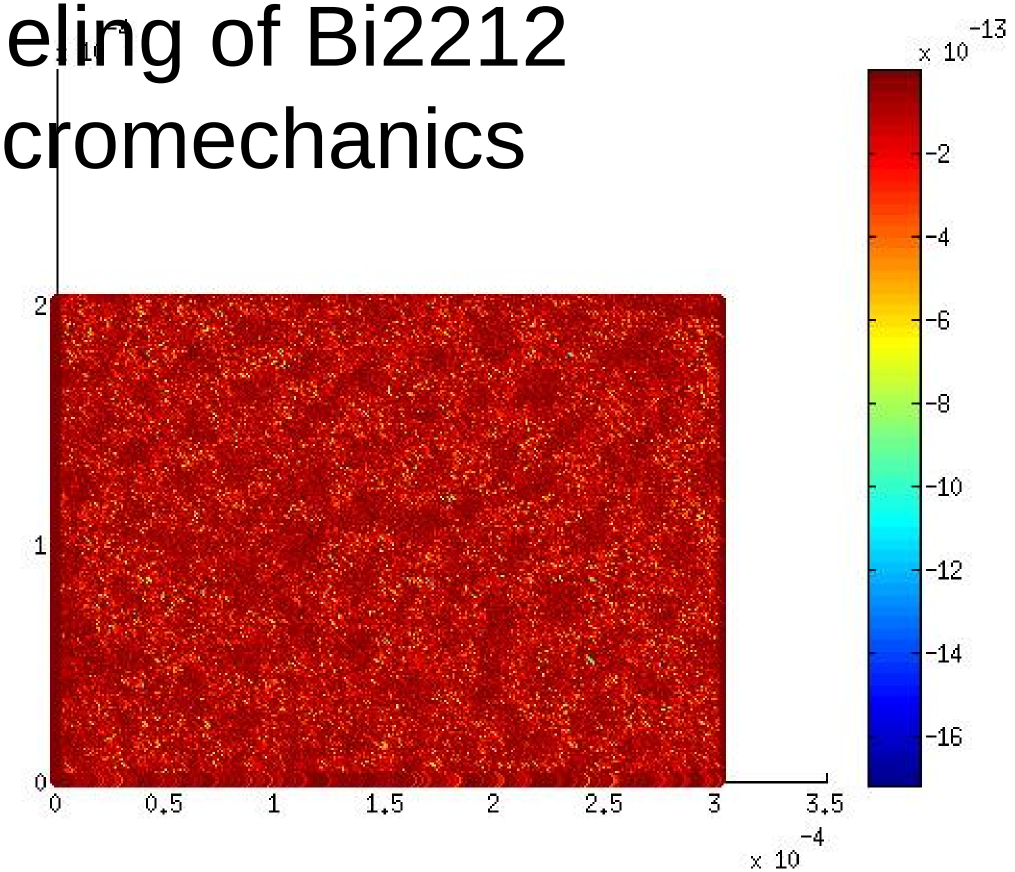




H. Song et al, *Acta Materialia*, submitted

Peridynamic modeling of Bi2212 microstructure/micromechanics





Becoming a "what-if" computational tool

"Variables" can include microstructure, AgX properties, fill factor, filament size, …

Multiscale model of YBCO quenching… affords ***"what if?" conductor engineering***

	$\Delta\alpha$ (%)	NZPV $\Delta NZPV$ (%) $\Delta NZPV/\Delta\alpha$	T_{peak} ΔT_{peak} (%) $\Delta T_{peak}/\Delta\alpha$	MQE ΔQ (%) $\Delta Q/\Delta\alpha$
Case I: increased YBCO thickness	+100%	+110.9% +1.11	+57.5% +0.58	-25% -0.25
Case II: reduced Cu thickness	-32%	+27.0% -0.84	+31.1% -0.97	-29.9% +0.93
Case III: increased Cu thickness	+35%	-17.4% -0.50	-16.1% -0.46	+44.9% +1.28
Case IV: Ni replaced Hastelloy	$+1.8\times10^{4}$% (σ) $+2.5\times10^{3}$% (κ)	-4.2% -0.00023	-13.1% -0.00071	+32.3% +0.0018
Case V: brass replaced Cu stabilizer	-90% (σ) -83.3% (κ)	+73.7% -0.82	+118.0% -1.31	-69.9% +0.78
Case VI: decreased σ_{Ag}	-99.995%	+7.5% -0.08	-7.7% +0.077	-5.4% +0.054
Case VII: increased σ_b & κ_b	10^{7}% (σ_b) 3×10^{4}% (κ_b)	+0.5% -5×10^{-8}	+0.08% $+8\times10^{-9}$	-2.1% -2.1×10^{-7}

W. K. Chan et al., *IEEE Transactions on Applied Superconductivity,* **20**(6) 2370-2380 (2010)
W. K. Chan and J. Schwartz, *IEEE Transactions on Applied Superconductivity* **21**(6) (2011)
X. Wang *et al.*, *J. Applied Physics* 2007

Conclusions

- Bi2212 has made great strides, but has significant remaining challenges .. May require significantly new approaches
- Quench protection also requires new approaches… which appear to be forthcoming
- We have a ways to go in materials and magnet engineering, and a great opportunity to blur the boundary between them via integration of computation & experimentation