NC STATE UNIVERSITY

Applied (High Temperature) Superconductivity

Academic Training
Lecture 5

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CERN/Geneva
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SCHWARTZ GROUP

Department of Materials Science and Engineering

Outline for the week of training

- Lectures 1& 2: Introduction & “Just enough” physics
  - Brief introduction … what is superconductivity and why is it useful?
  - Basic physics of superconductivity and the superconducting state
  - Applications-relevant physics of superconductivity & superconducting state
- Lecture 3: Technical superconductors
  - A brief summary of NbTi and Nb_3Sn
  - HTS conductor options: Bi2212 & YBCO
- Lecture 4: Electromechanical behavior
  - A brief summary of NbTi and Nb_3Sn
  - HTS conductor options: Bi2212 & YBCO
- **Lecture 5: Quench behavior and high field magnets**
  - What is quench protection?
  - Quench protection in HTS magnets

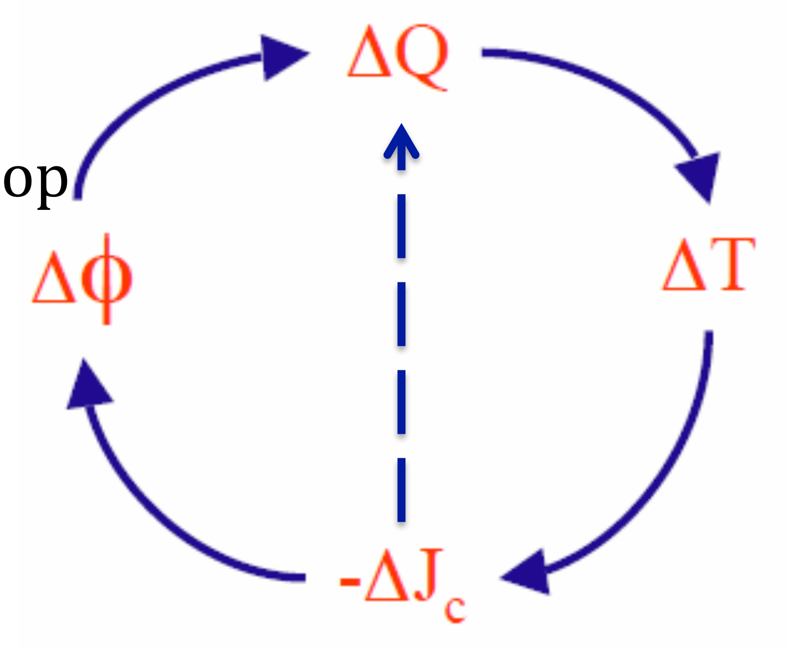
Stability and quench protection: simple definitions

Stability: A magnet is considered stable if it returns to steady-state superconducting operation after a fault condition (disturbance)

Quench: The sudden, unanticipated/unplanned transition of a magnet from superconducting to normal.

Quench protection refers to preventing a magnet from being permanently damaged from the dissipation of its own stored energy in the event of going unstable

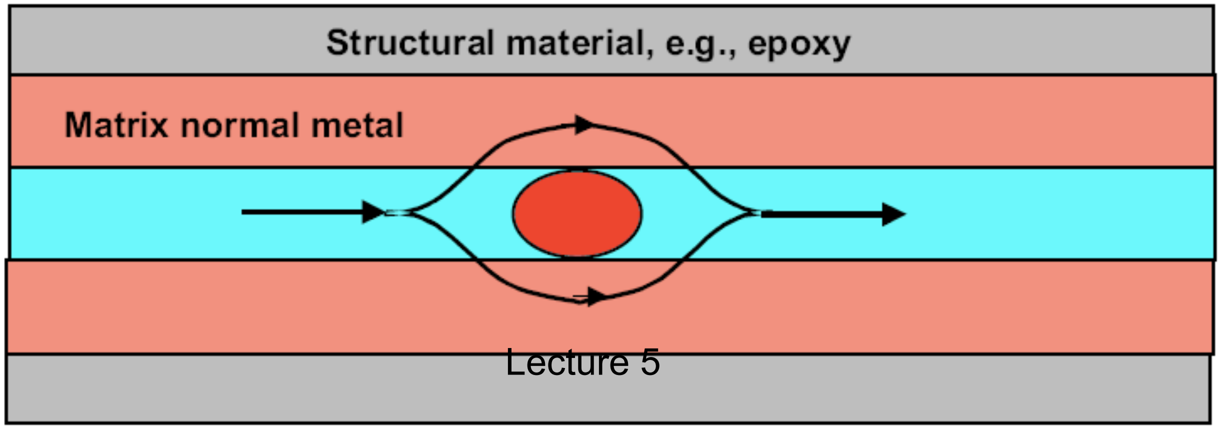
(In)stability



- An instability triggers a feedback loop
- Stability can be obtained by
  - Minimizing heat generated
  - Maximizing cooling
  - Preventing cycle altogether
- Heat (disturbance) can come from:
  - Flux jumps … high J_c is more unstable
  - Mechanical effects (e.g. conductor motion or cracking epoxy)
  - External sources (neutrons in fusion reactors, particles in HEP colliders, conduction through leads, …)
  - Resistive joints
  - AC losses, including ramping too fast or other time varying magnetic fields (MLU002)
  - …

Stabilization– doing the minimum

- Normal state resistivity of superconductors is very high
- If region of SC goes normal (locally above the "current sharing temperature, T_{cs}), shunt the current through very low resistivity "stabilizer" to reduce "feedback heat"
- ALL technical superconducting "conductors" are composites of a superconductor and a high conductivity matrix (i.e., Cu for LTS, MgB_2 and YBCO, Ag for Bi2212)
- "Stabilizer" also provides high thermal conductivity to spread the normal zone which helps for quench protection

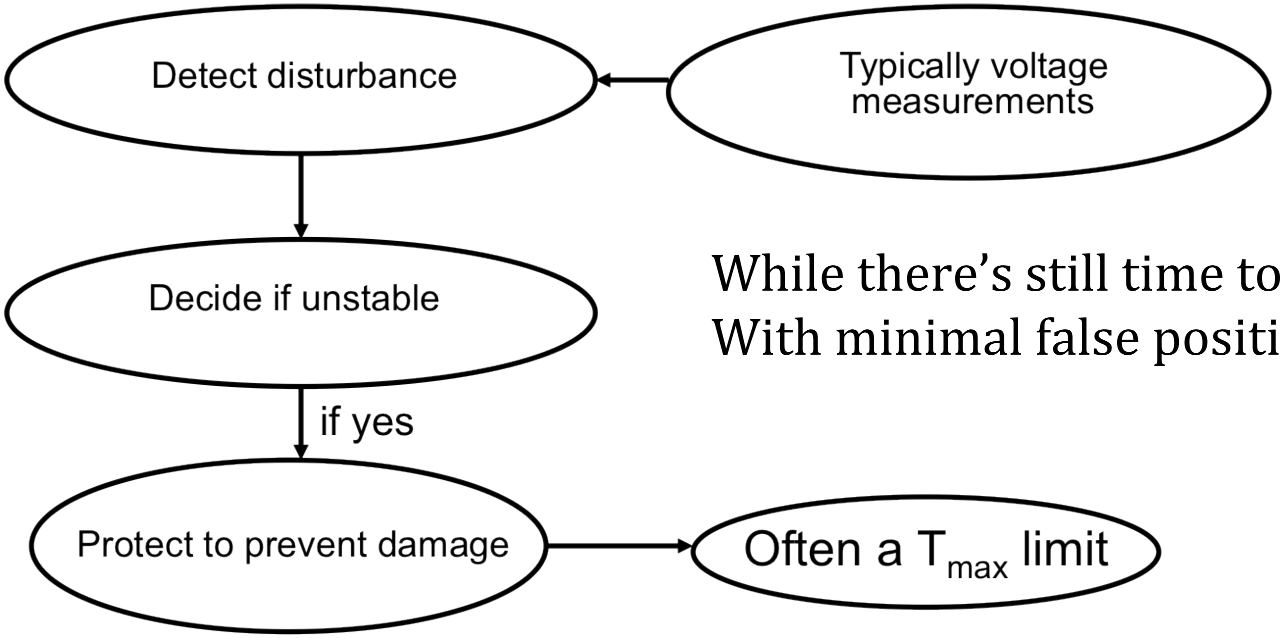


Stability versus quench protection

- Stability wants normal zone to collapse & quench protection wants normal zone to grow rapidly … sometimes conflicting demands upon the design
- Very large magnets designed to be VERY STABLE and also have quench protection systems to protect them from their own energy in the event of a quench

Quench protection – the basics

Voltage grows with time as “normal zone” propagates



Detect disturbance

Typically voltage measurements

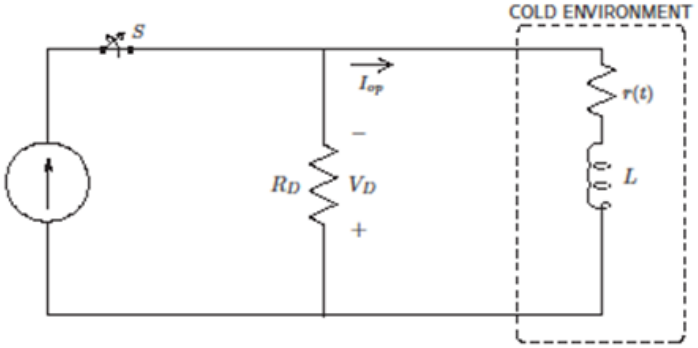
Decide if unstable

if yes

Protect to prevent damage

Often a T_{max} limit

While there’s still time to act
With minimal false positives



- Magnet absorbs energy without damage, OR
- Onset of quench is detected and energy dumped externally OR
- Magnet fails permanently

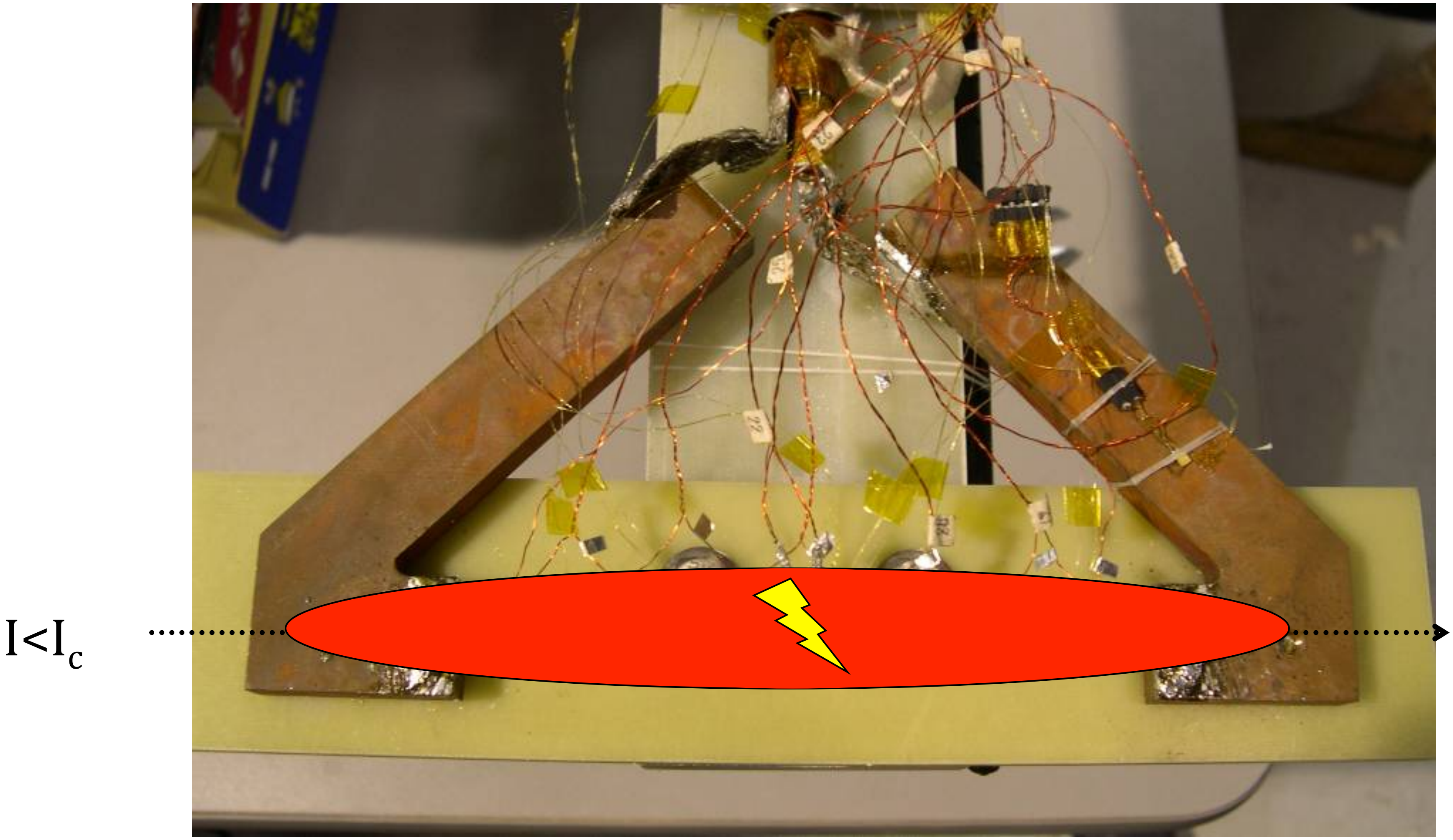
LTS v HTS quench protection

- Quench protection for LTS essentially solved
  - Magnets quench, but we know generally how to protect them
- Protection in HTS qualitatively similar to LTS
  - ❖ Most basic physics/equations/concepts unchanged

But there are key differences:

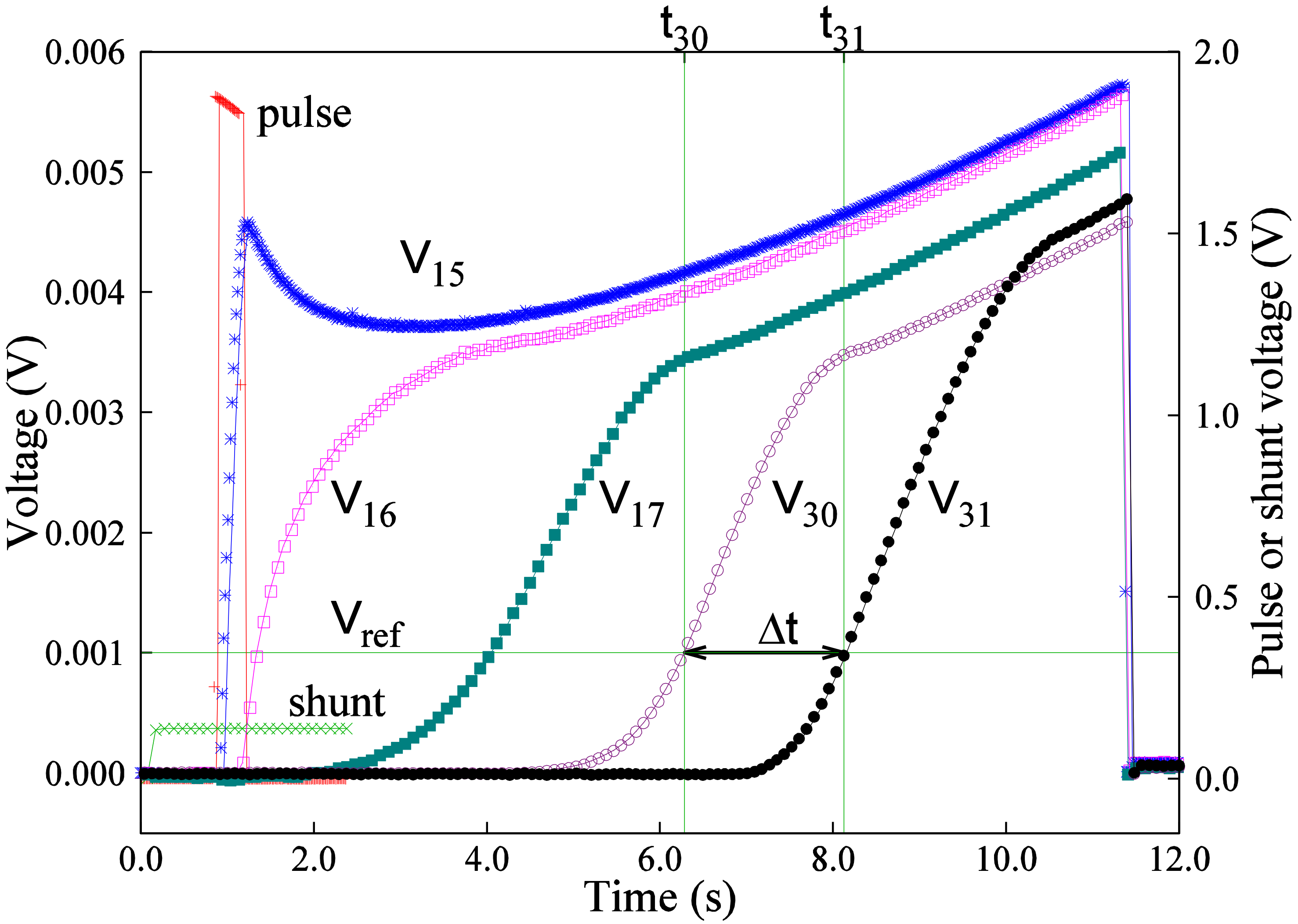
- Energy margin is large … HTS magnets are very stable
  - ❖ (Very) high heat loads may be tolerable (irradiation tolerance)
- Normal zone propagation is *very slow* … so what?
  - ❖ Voltage measurements are "length-averaged"
  - ❖ Degradation from a rising temperature is *local*
  - ❖ *So the question is whether one can detect before it's too late*

Quench studies experimental approach



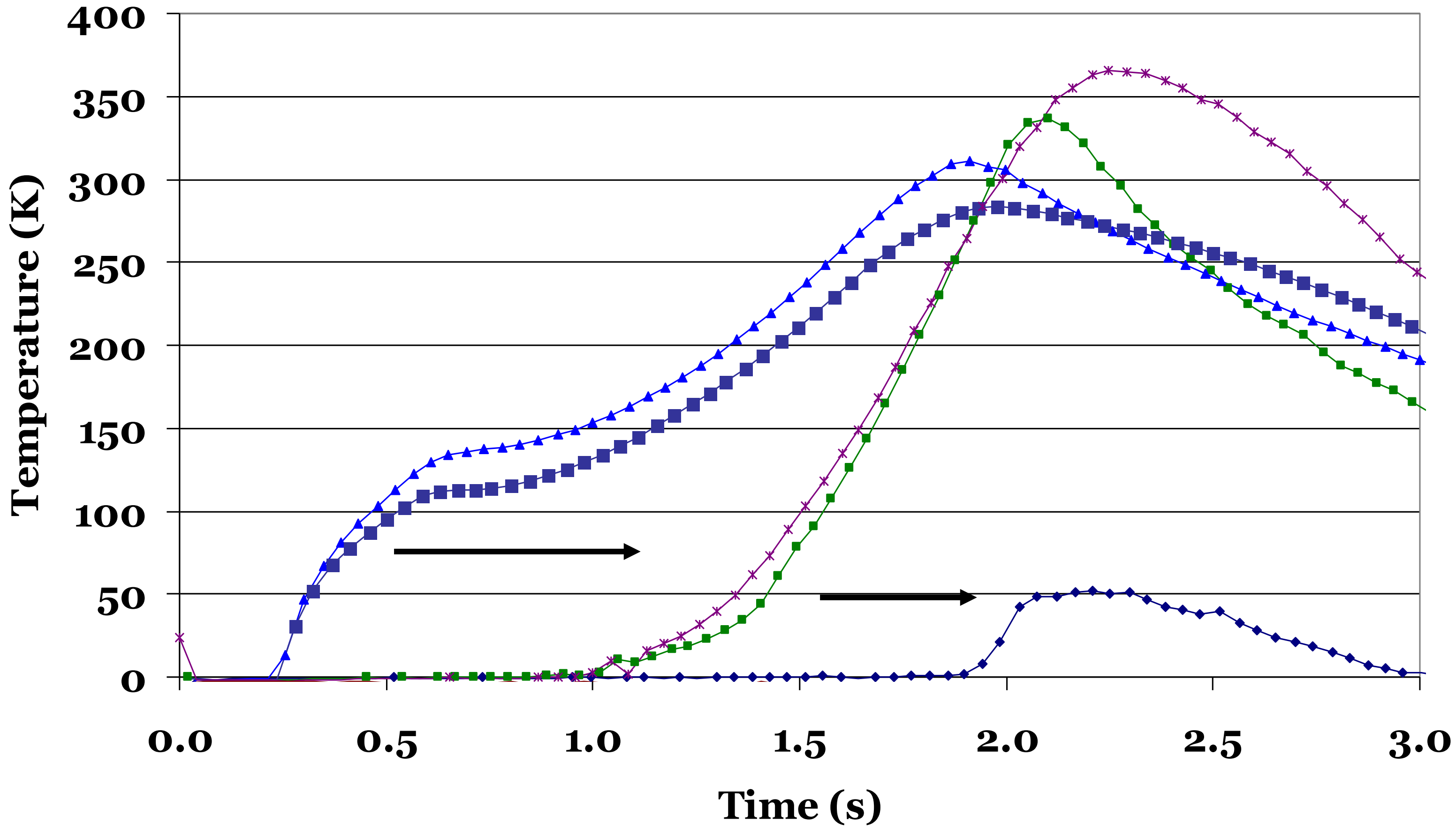
Tim Effio

Quench studies – typical data



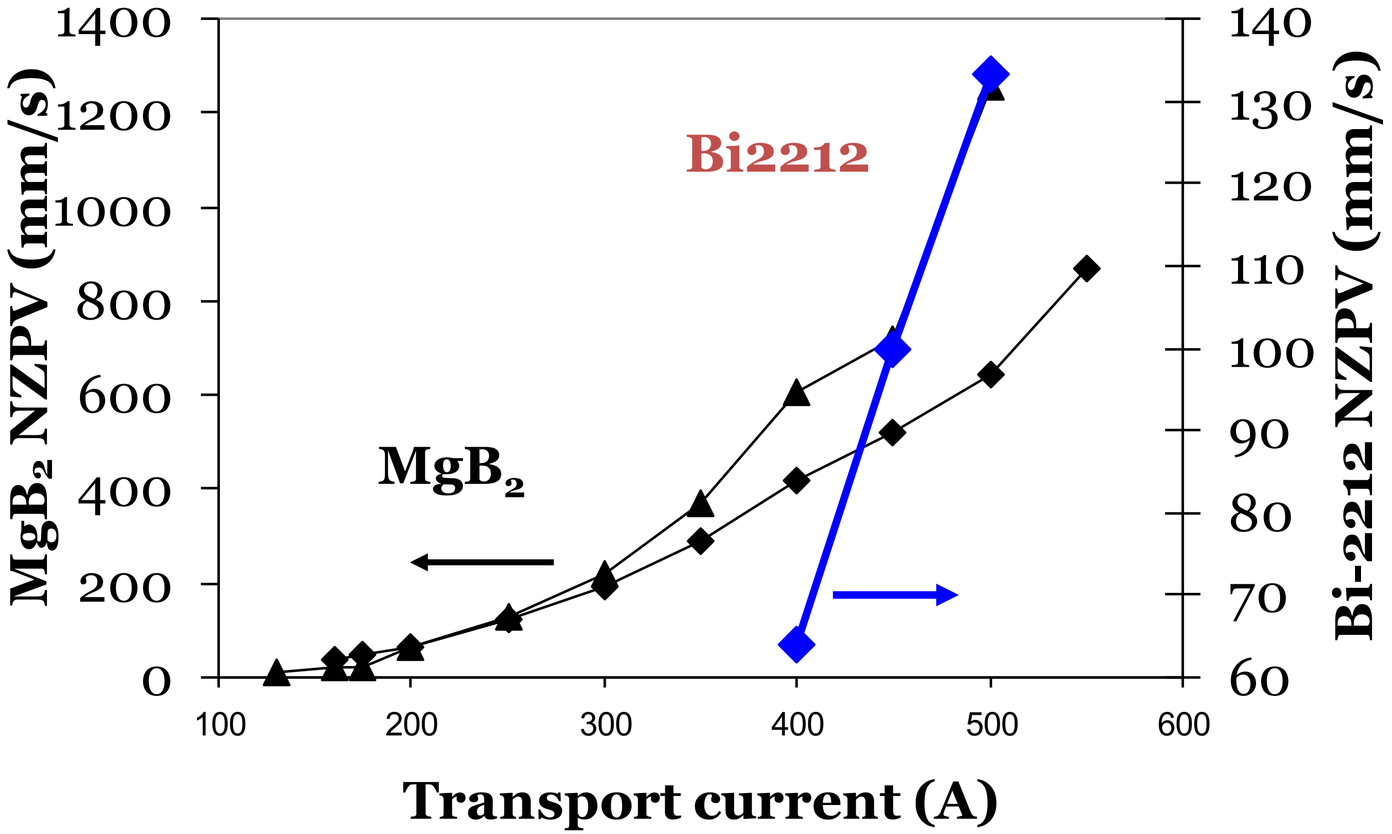
X.R. Wang, U.P. Trociewitz and J. Schwartz, *J Appl Phys* **101**(5) 053904 (2007)

Quench studies – temperature-time



X.R. Wang, U.P. Trociewitz and J. Schwartz, *J Appl Phys* **101**(5) 053904 (2007)

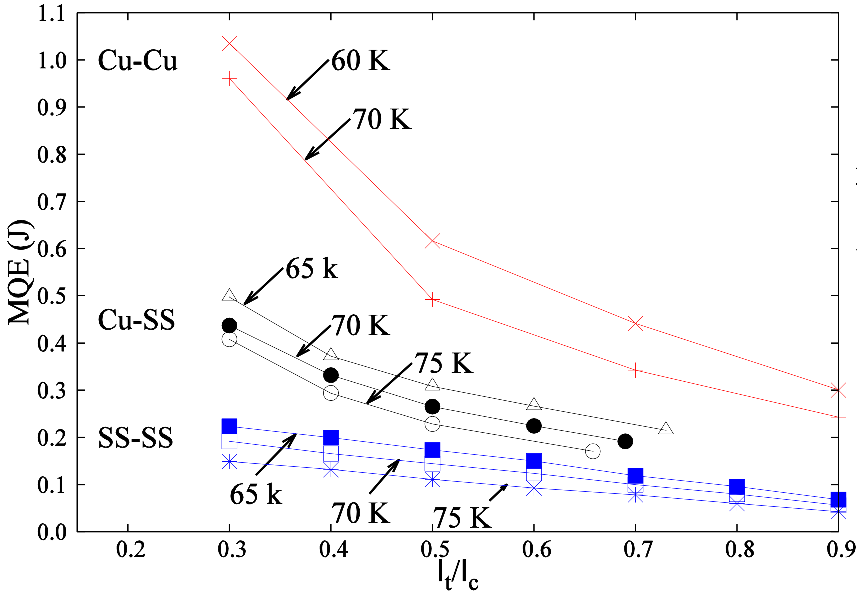
Quench results: MgB_2 & Bi2212

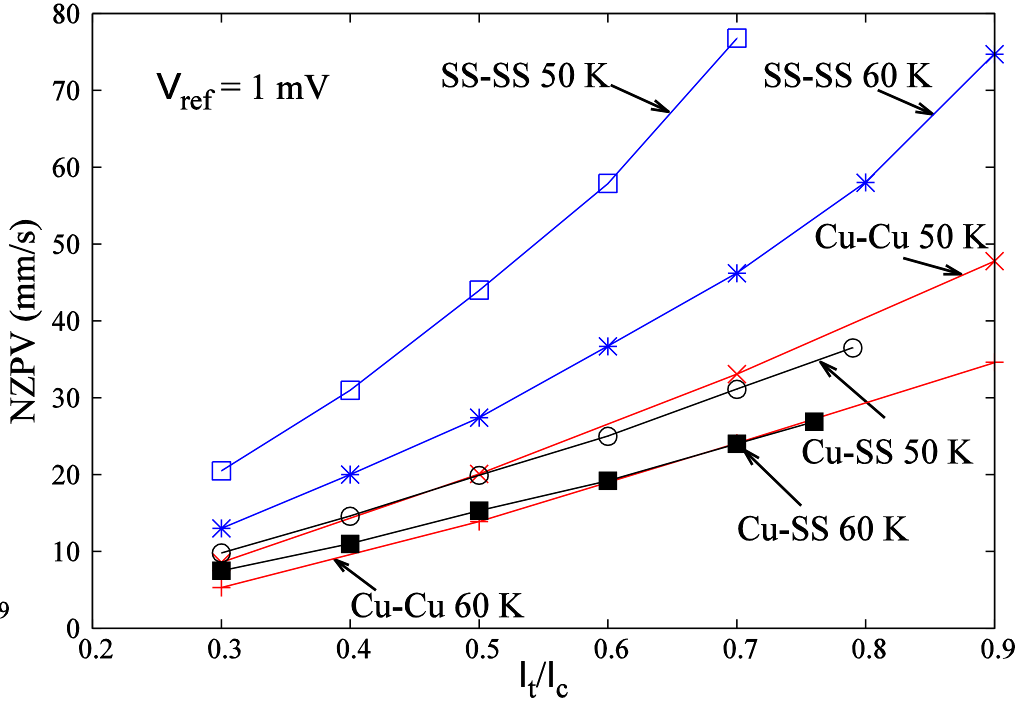


velocity ~ 100 mm/s for Bi2212, 500 mm/s for MgB_2
Nb_3Sn ~ 100-200X faster!

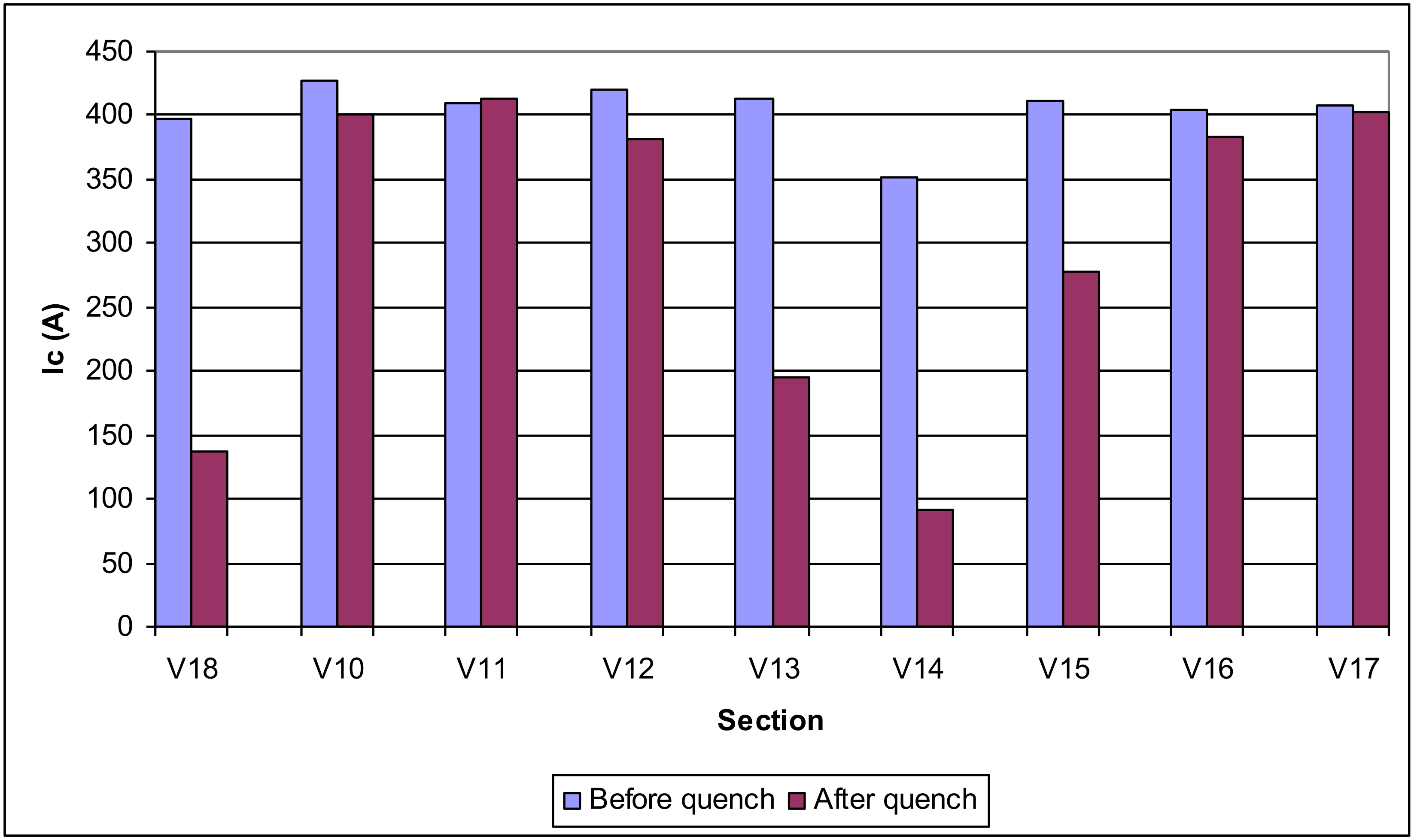
Architecture effects on YBCO (AMSC RABiTS)

- Three conductors … same underlying architecture … all laminated top & bottom
  - One Cu-Cu; One Cu-SS; One SS-SS





Quench induced degradation: Bi2212

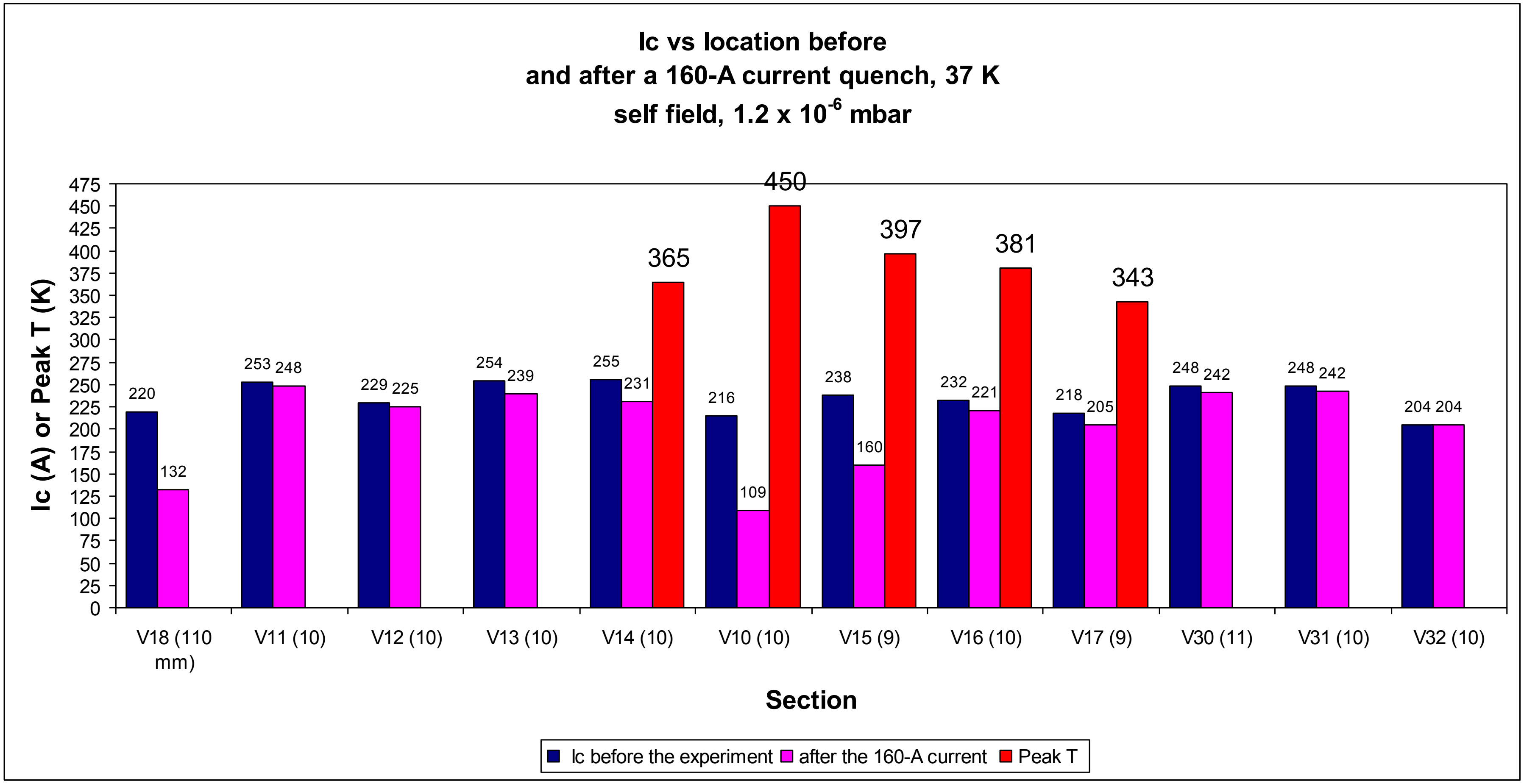


Bi2212 quench degradation

Limits to avoid conductor damage improved with wire quality

Bi2212	Tape	Round Wire
Velocity	2-3 cm/s	6-8 cm/sec
Peak T	<300 K	<330 K
dT/dt	<150 K/s	<250 K/s
dT/dx	<90 K/cm	<100 K/cm

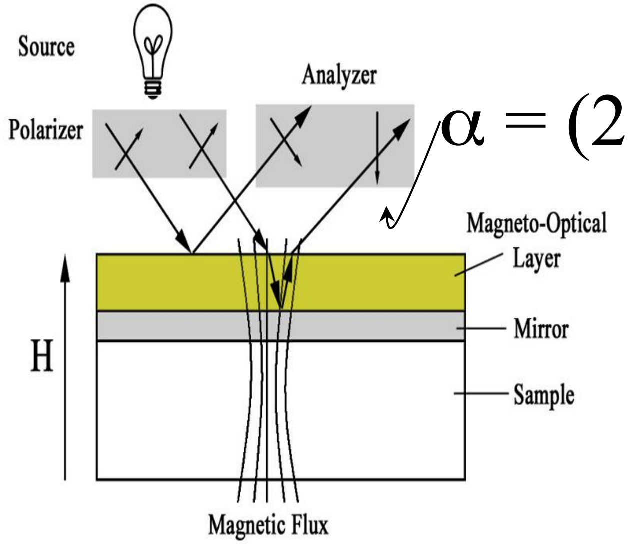
YBCO (AMSC) quench degradation



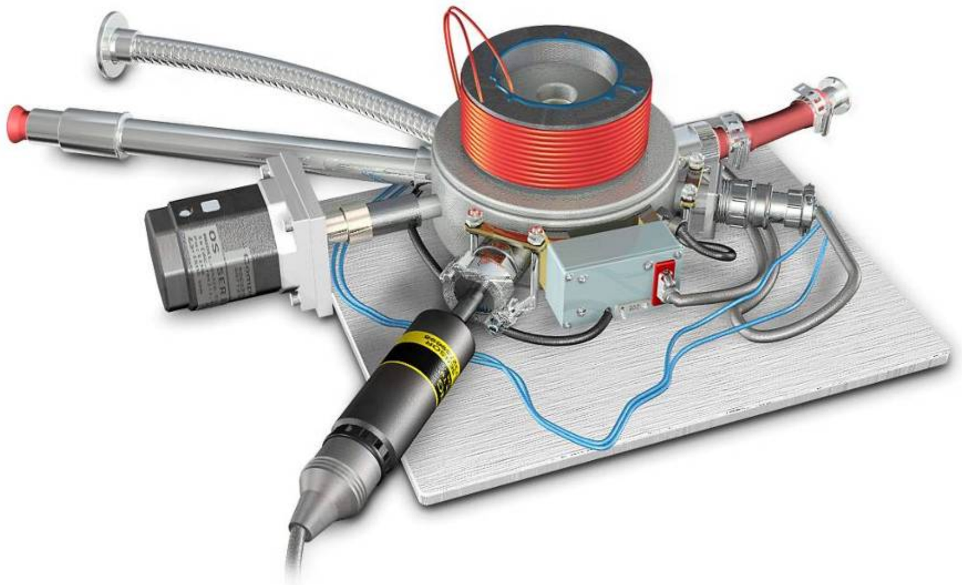
What does quenching look like?

Magneto Optical Imaging

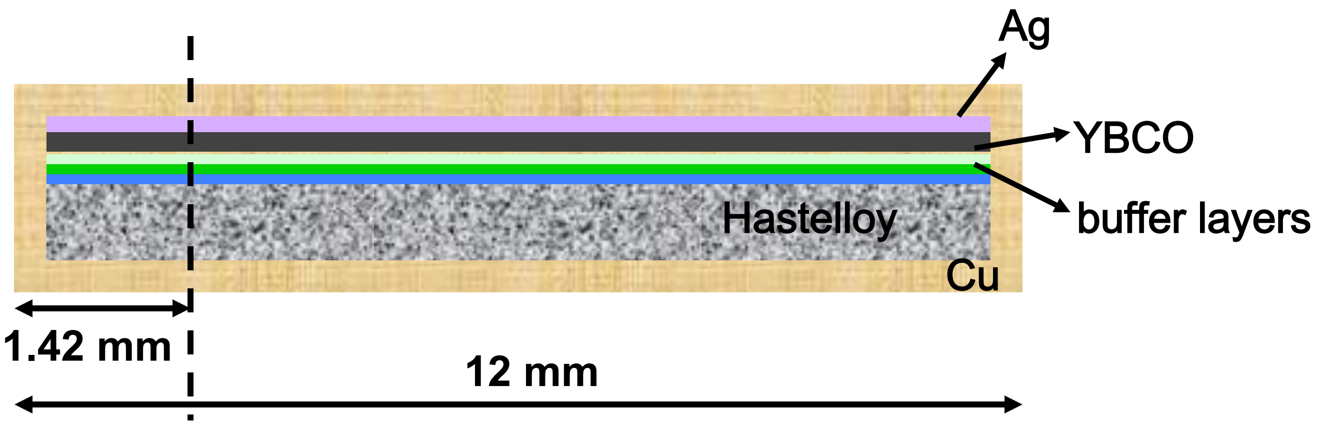
- Real-time imaging of magnetic field
- Faraday rotation through an indicator film
- Quantitatively translates magnetic field *intensity* to light *intensity*
- Directly correlate structure, defects & magnetic behavior

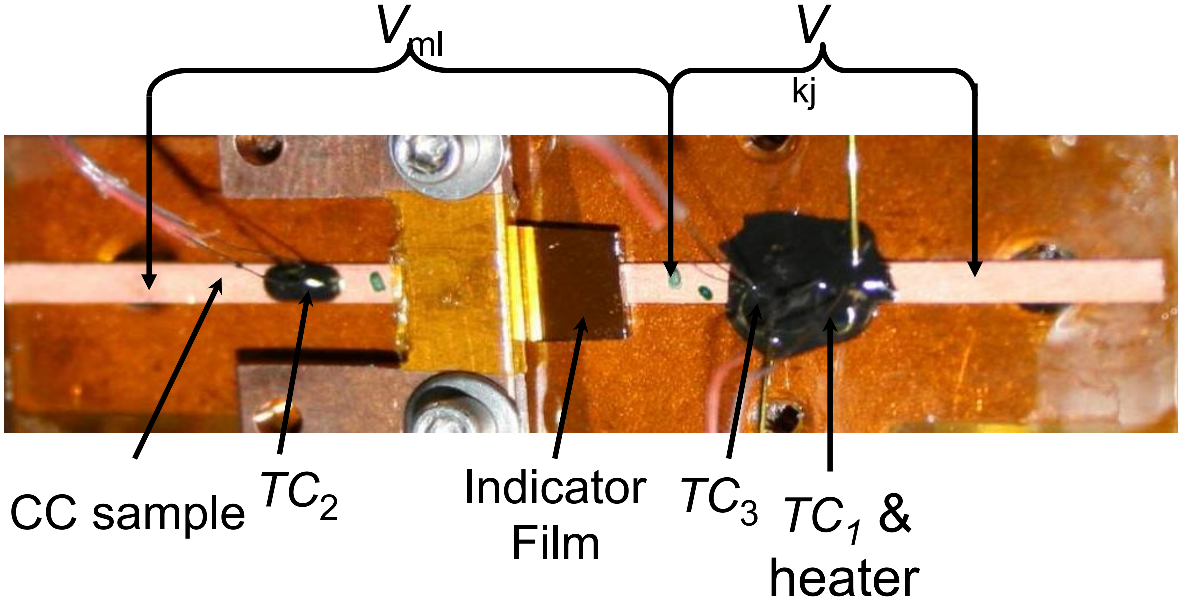


$$\alpha = (2Vd)H$$

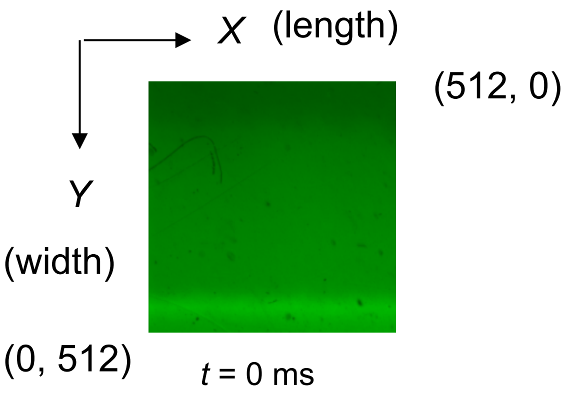


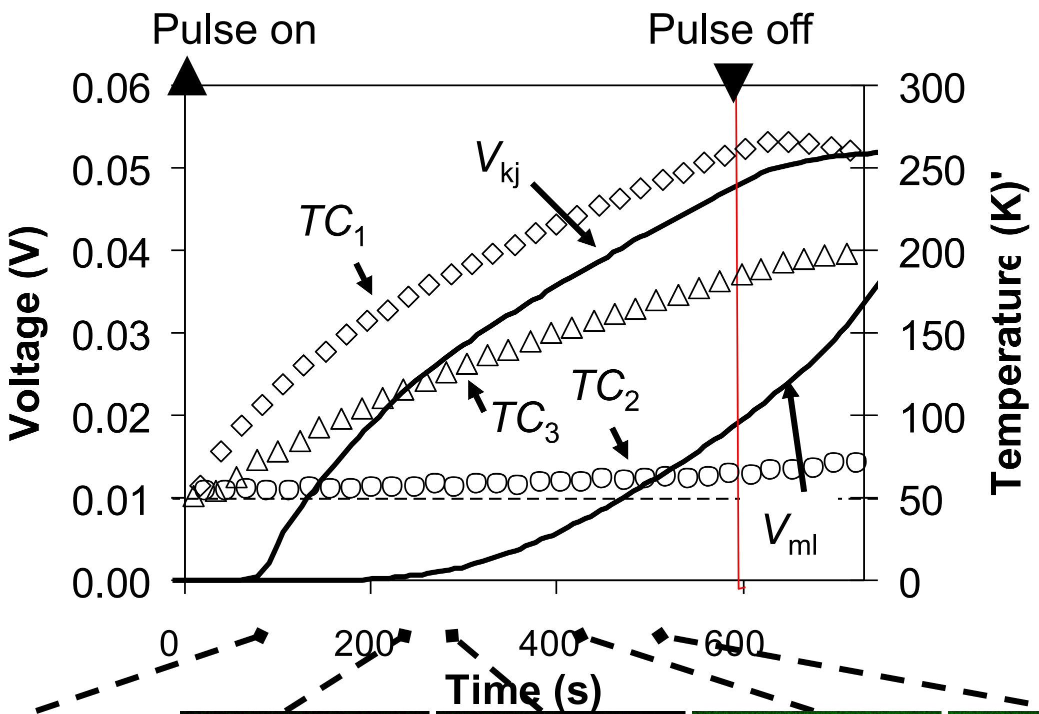
Dynamic quench imaging of YBCO w/MOI

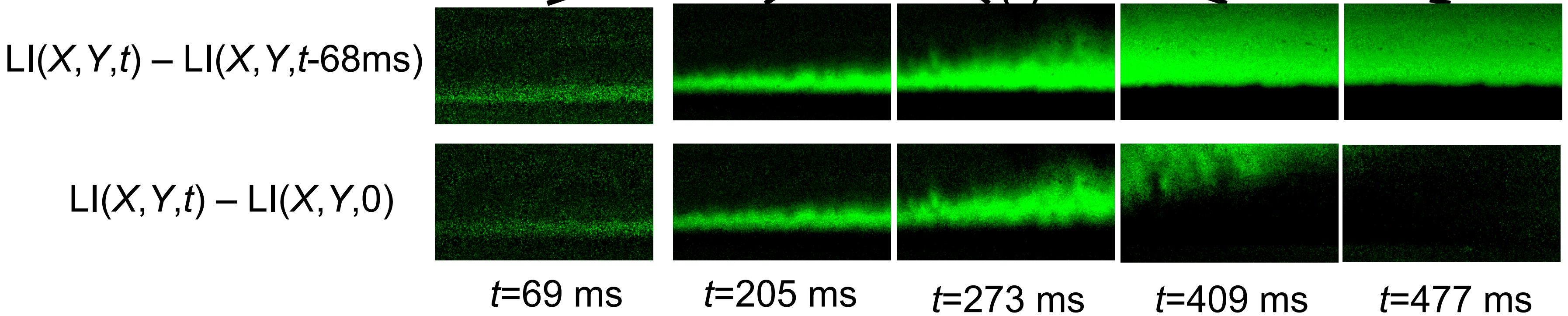




Coupled dynamic MOI & V(t), T(t) results





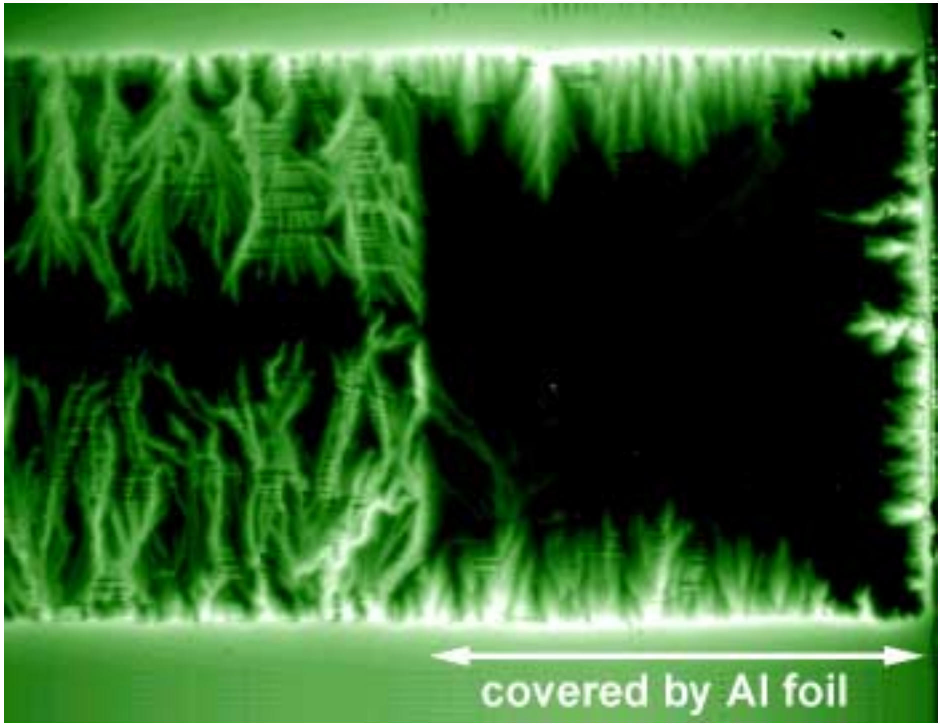


How do we evaluate degradation?

- Difficult to study YBCO layer with degradation because of uncertainty in role of etchant
- Used S-based etchant for Cu; Ag should protect YBCO layer
- Used non S-containing etchant for Ag layer
- If S on YBCO surface – Ag was delaminated during quench

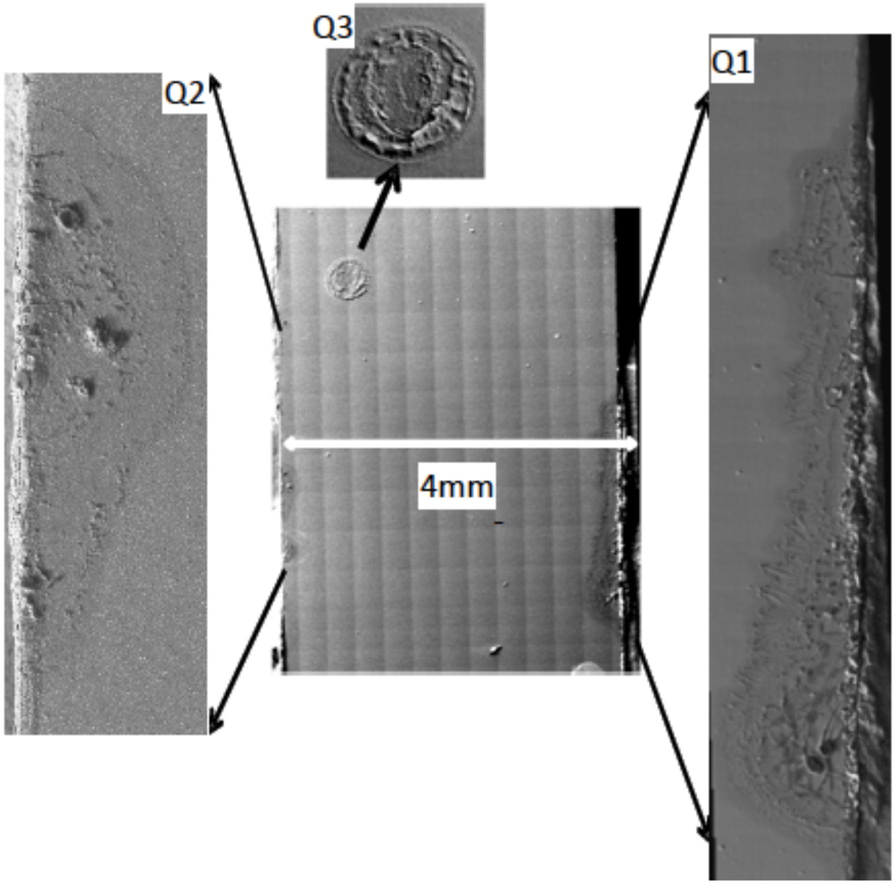
Does MOI help?

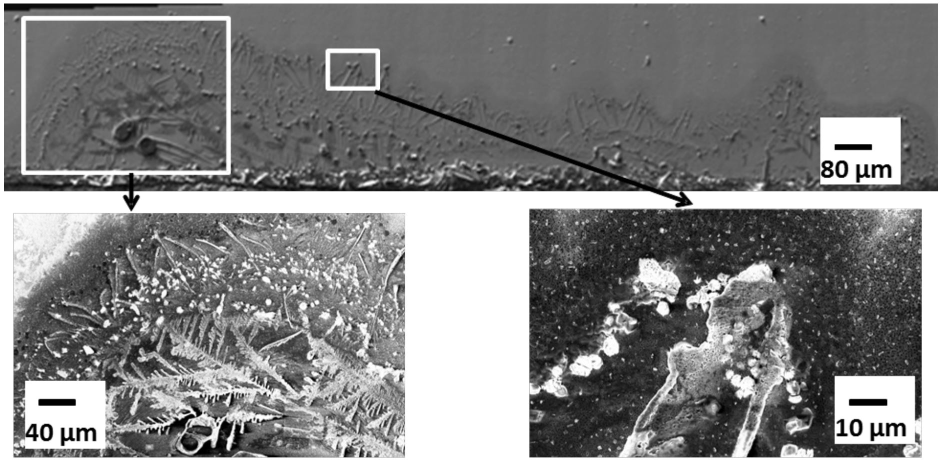
- Imaging through multiple layers may not have fine-enough resolution to interpret microstuctural damage
- Penetration Bean-like for YBCO CC
- In absence of metal, penetration is dendritic



Univ. Oslo, Norway

What does degradation look like?

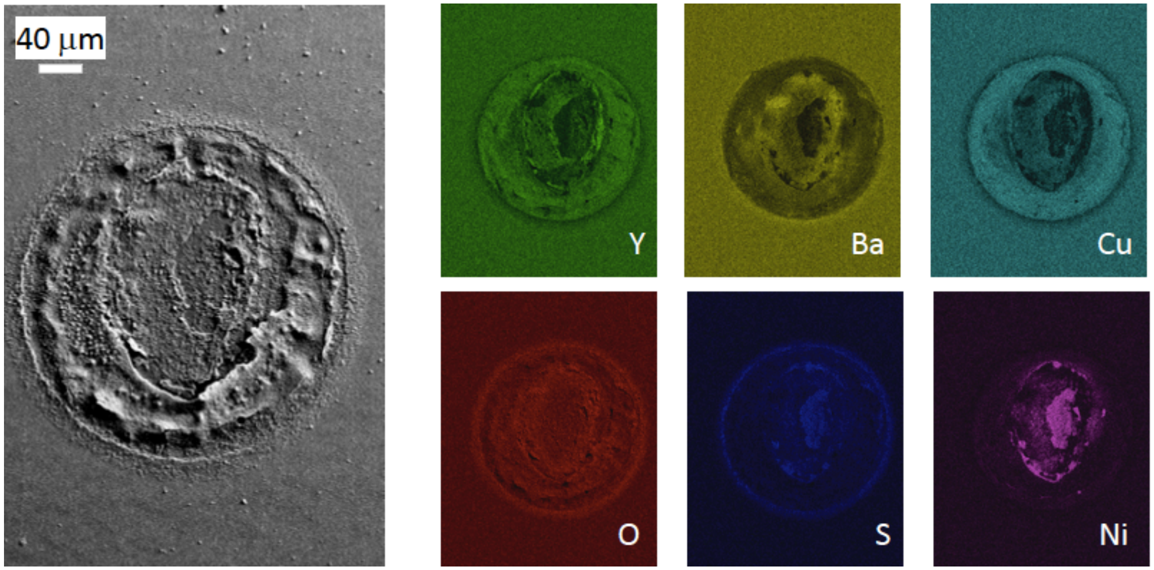


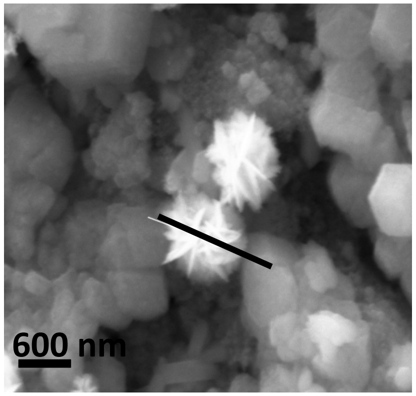


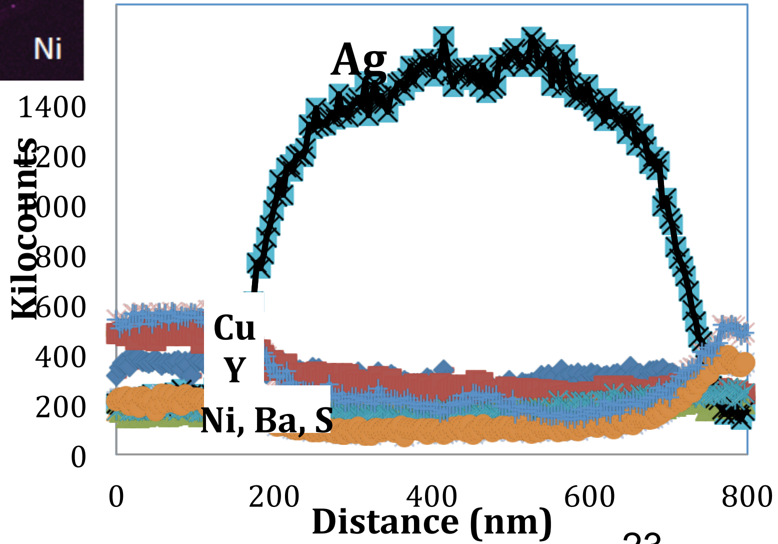
Dendritic flux penetration is evidence of Ag delamination

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



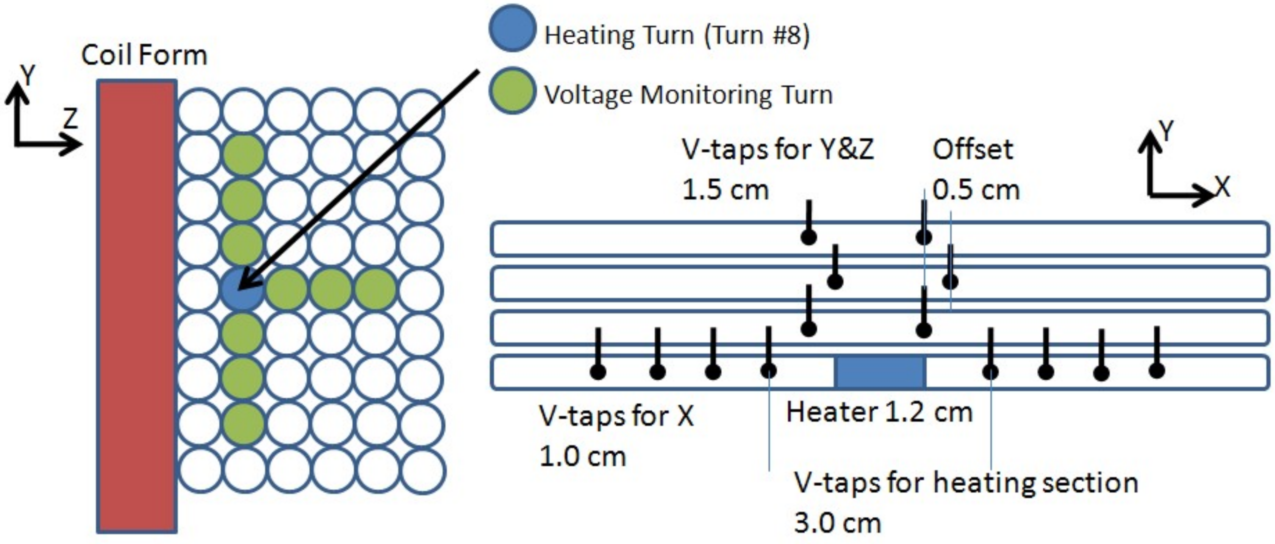


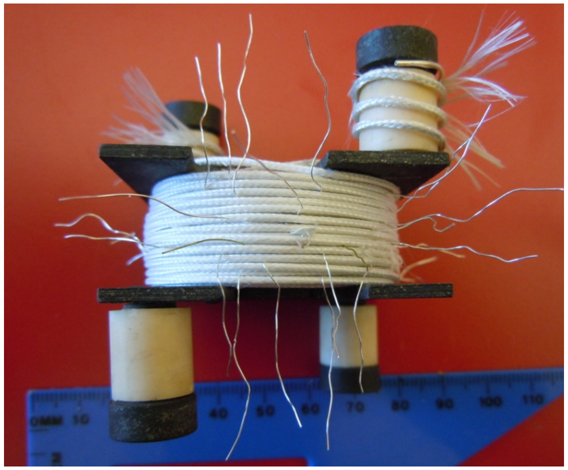


H. Song et al, *Acta Materialia*, submitted

Does high field improve propagation in Bi2212?

- High field reduces T_{cs}, so propagation should be faster

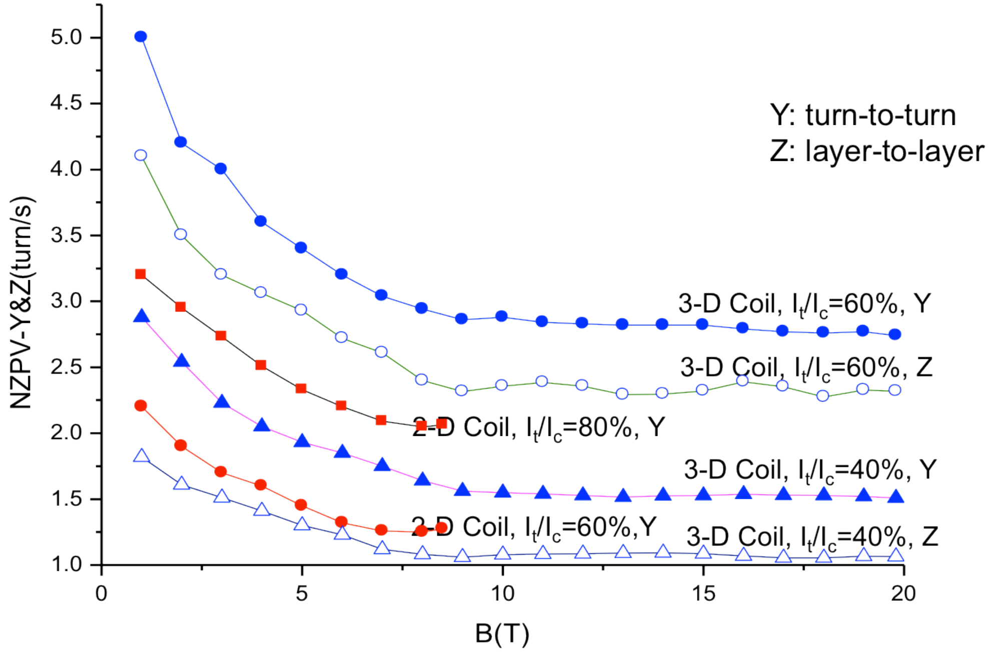


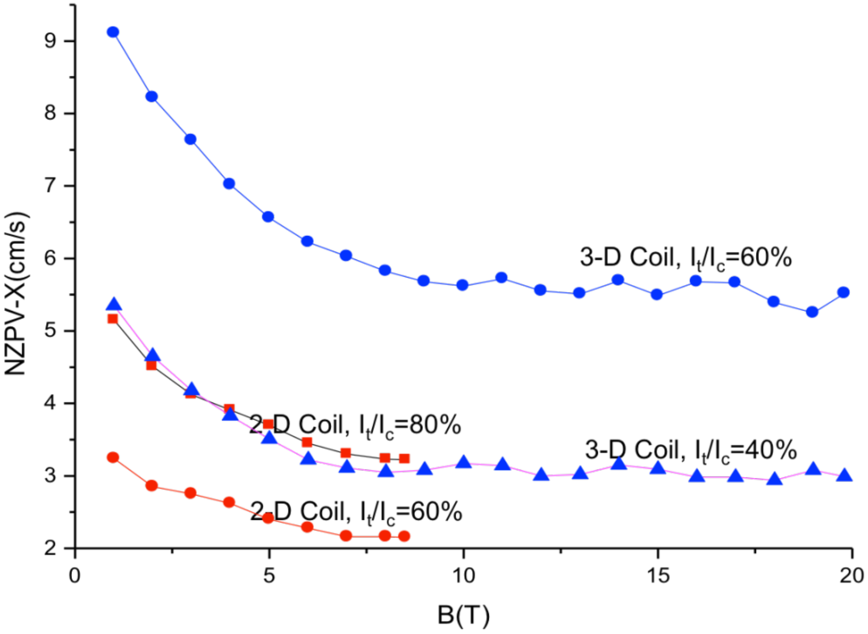


L. Ye et al., to be submitted, 2012

No, it doesn't

- Increase field reduces T_{cs} (faster propagation) but also reduces J_c (slower propagation)





L. Ye et al., to be submitted, 2012

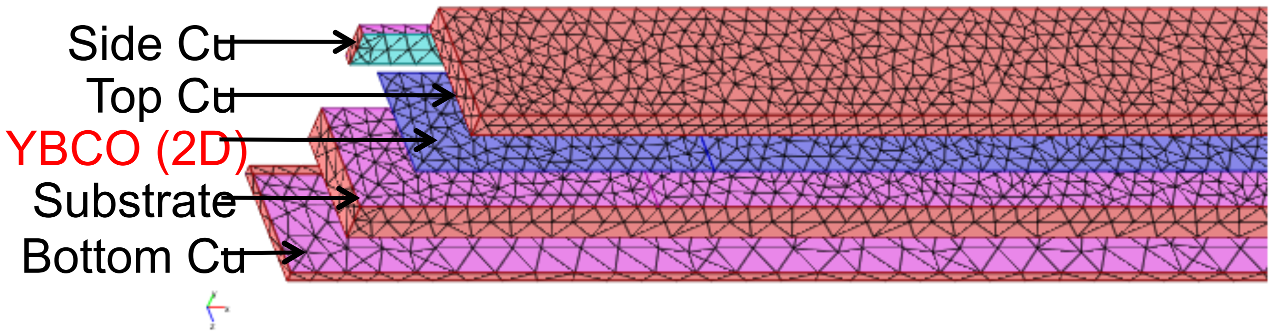
How to move forward?

- Improve detection
- Improve propagation
- Improve (understand) degradation limits

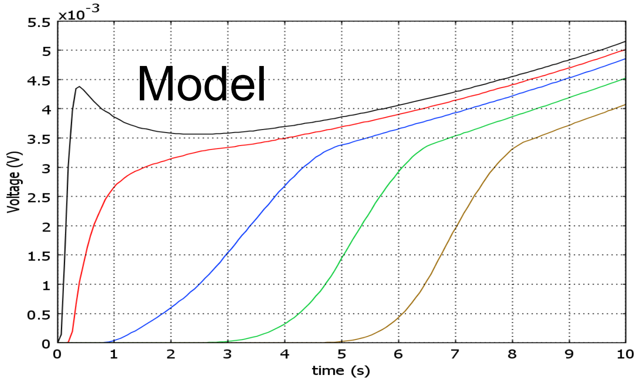
- All require a better understanding of behavior at multiple length-scales

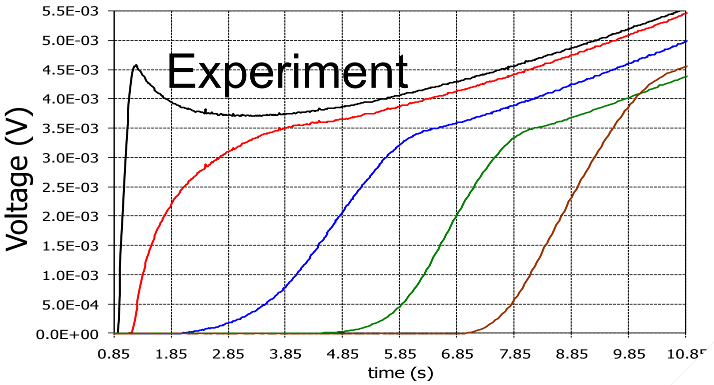
Modeling of quenching in YBCO CCs

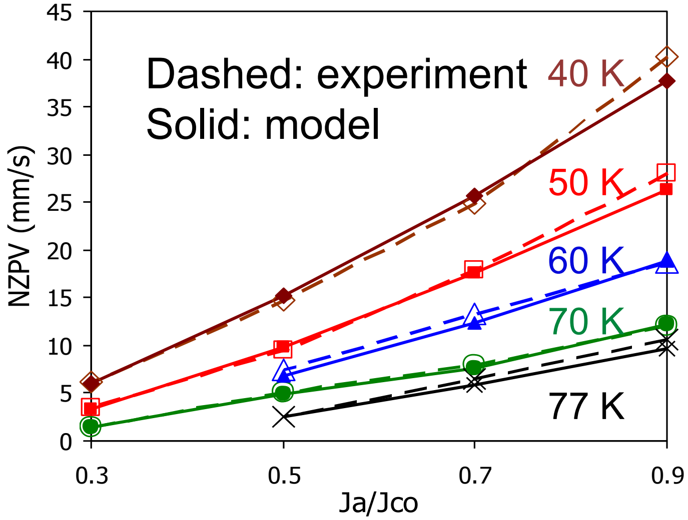
- YBCO layer has VERY high J_c encased within multiple layers of widely varying thermal, electrical and mechanical properties
- YBCO CC have multiple potential failure modes
- YBCO layer impossible to monitor experimentally real-time
- YBCO CC geometry particularly complex for modeling/simulation
- Predictive tool would be very powerful

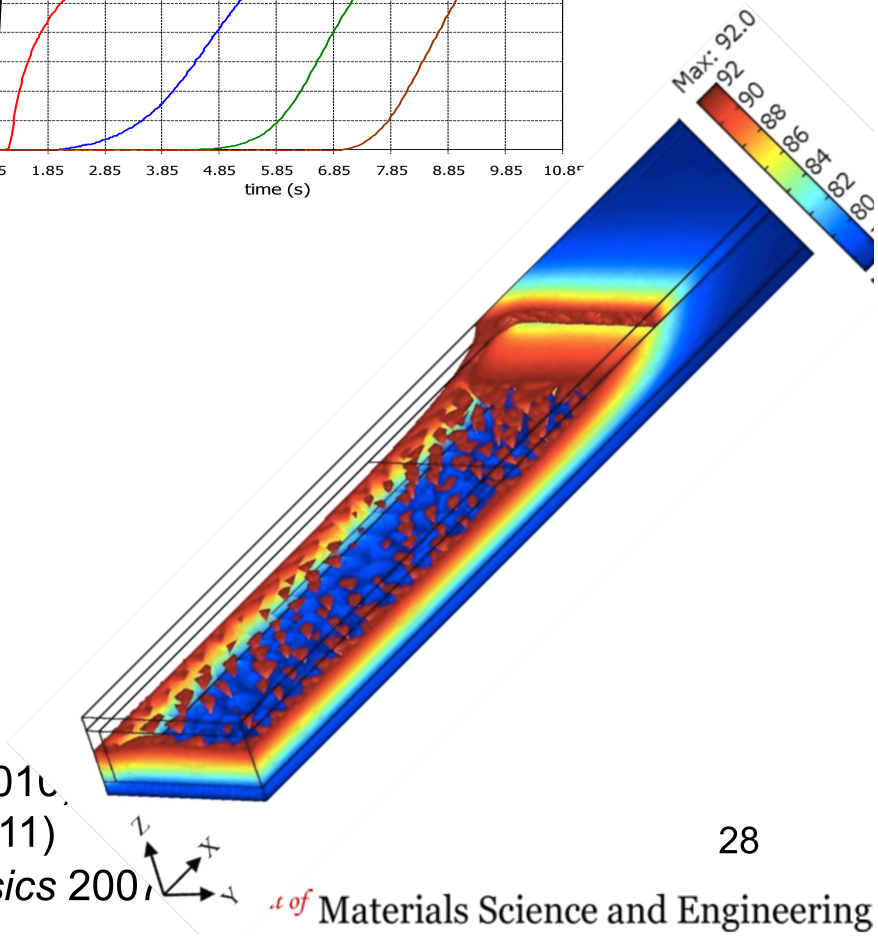


Experimentally validated 3D/2D multiscale model of YBCO quenching: conductor









W. K. Chan et al., *IEEE TASC,* **20**(6) 2370-2380 (201

W. K. Chan and J. Schwartz, *IEEE TASC* **21**(6) (2011)

X. Wang *et al.*, *J. Applied Physics* 200

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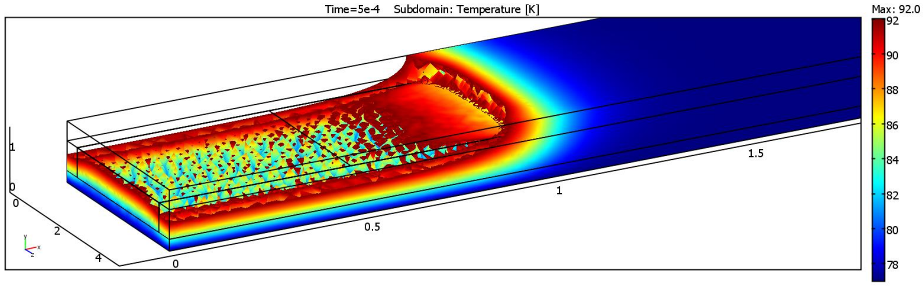
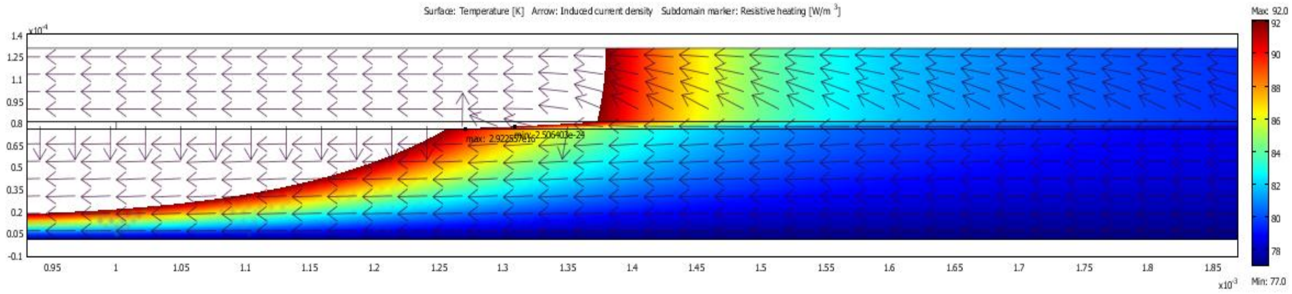
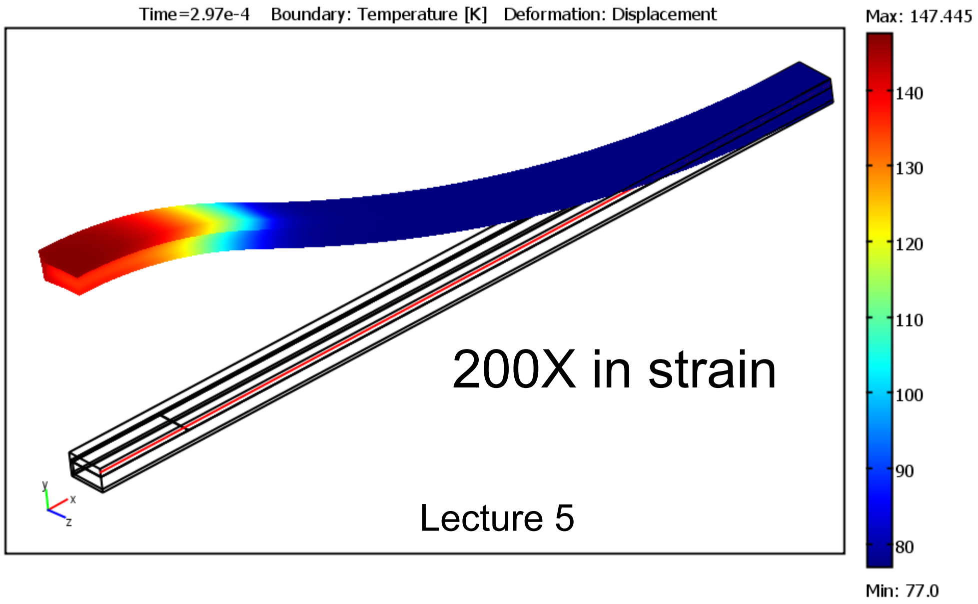
What can be learned?



- Interlayer resistances may have significant impact

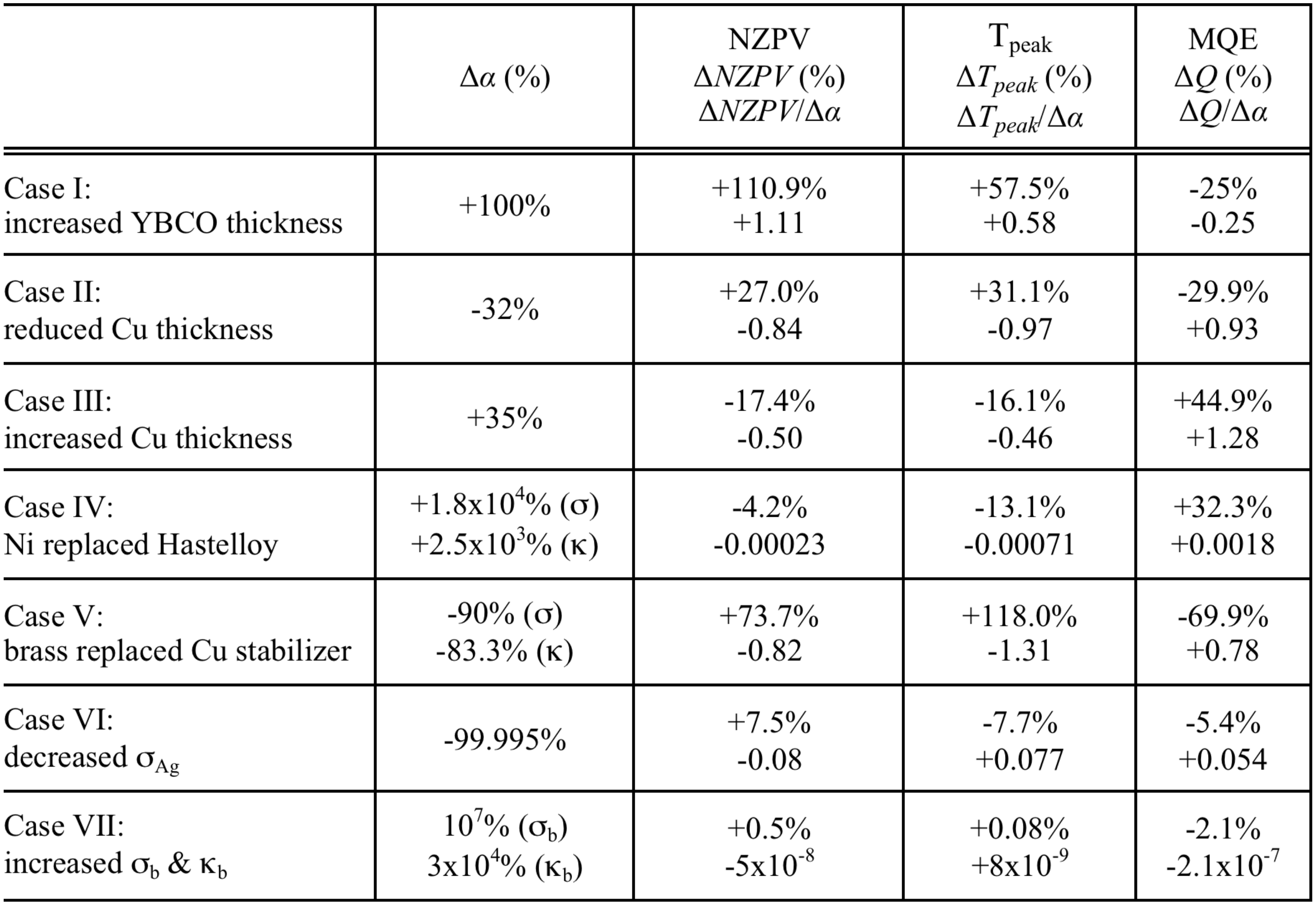


- Predicts delamination mode



200X in strain

"what if?" conductor engineering



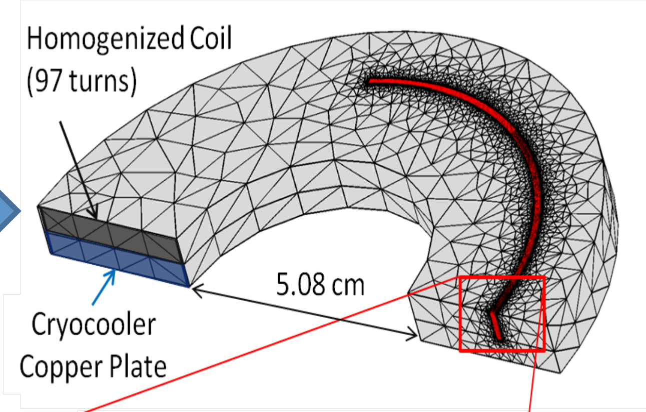
	$\Delta\alpha$ (%)	NZPV $\Delta NZPV$ (%) $\Delta NZPV/\Delta\alpha$	T_{peak} ΔT_{peak} (%) $\Delta T_{peak}/\Delta\alpha$	MQE ΔQ (%) $\Delta Q/\Delta\alpha$
Case I: increased YBCO thickness	+100%	+110.9% +1.11	+57.5% +0.58	-25% -0.25
Case II: reduced Cu thickness	-32%	+27.0% -0.84	+31.1% -0.97	-29.9% +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	$+1.8\text{x}10^4$% (σ) $+2.5\text{x}10^3$% (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) $3\text{x}10^4$% (κ_b)	+0.5% $-5\text{x}10^{-8}$	+0.08% $+8\text{x}10^{-9}$	-2.1% $-2.1\text{x}10^{-7}$

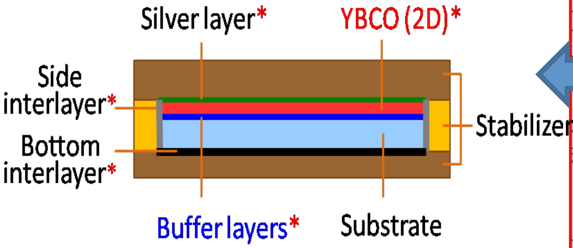
W. K. Chan and J. Schwartz, *IEEE Transactions on Applied Superconductivity* **21**(6) (2011)

Conductor model → hybrid 3D coil model

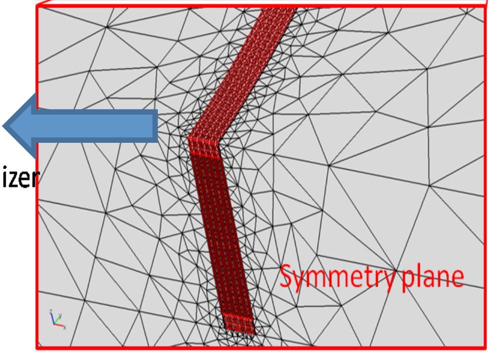
Experimental coil

Multiscale coil model

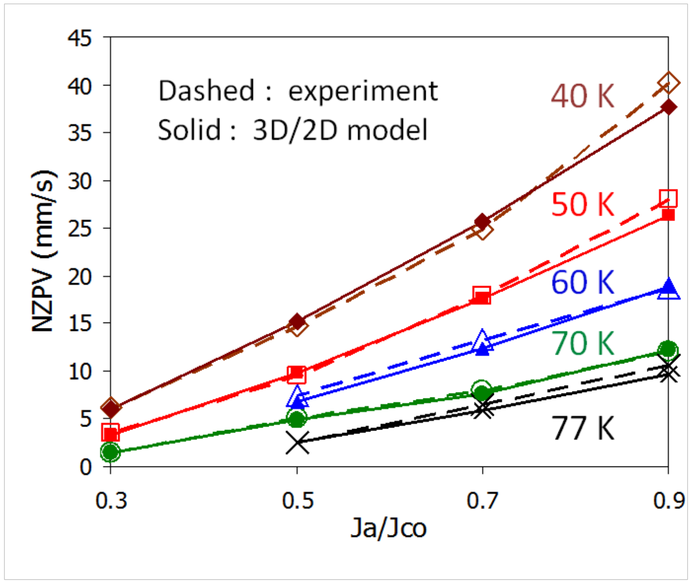


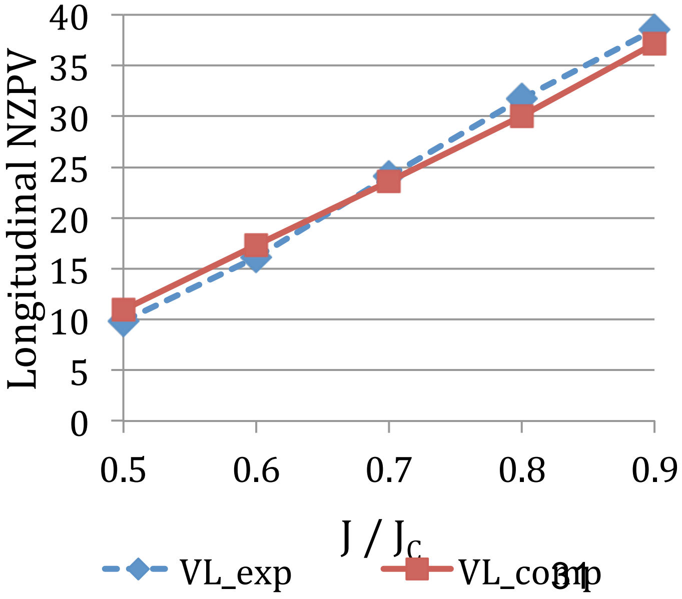


μm-scale tape model



Multilayer tape model

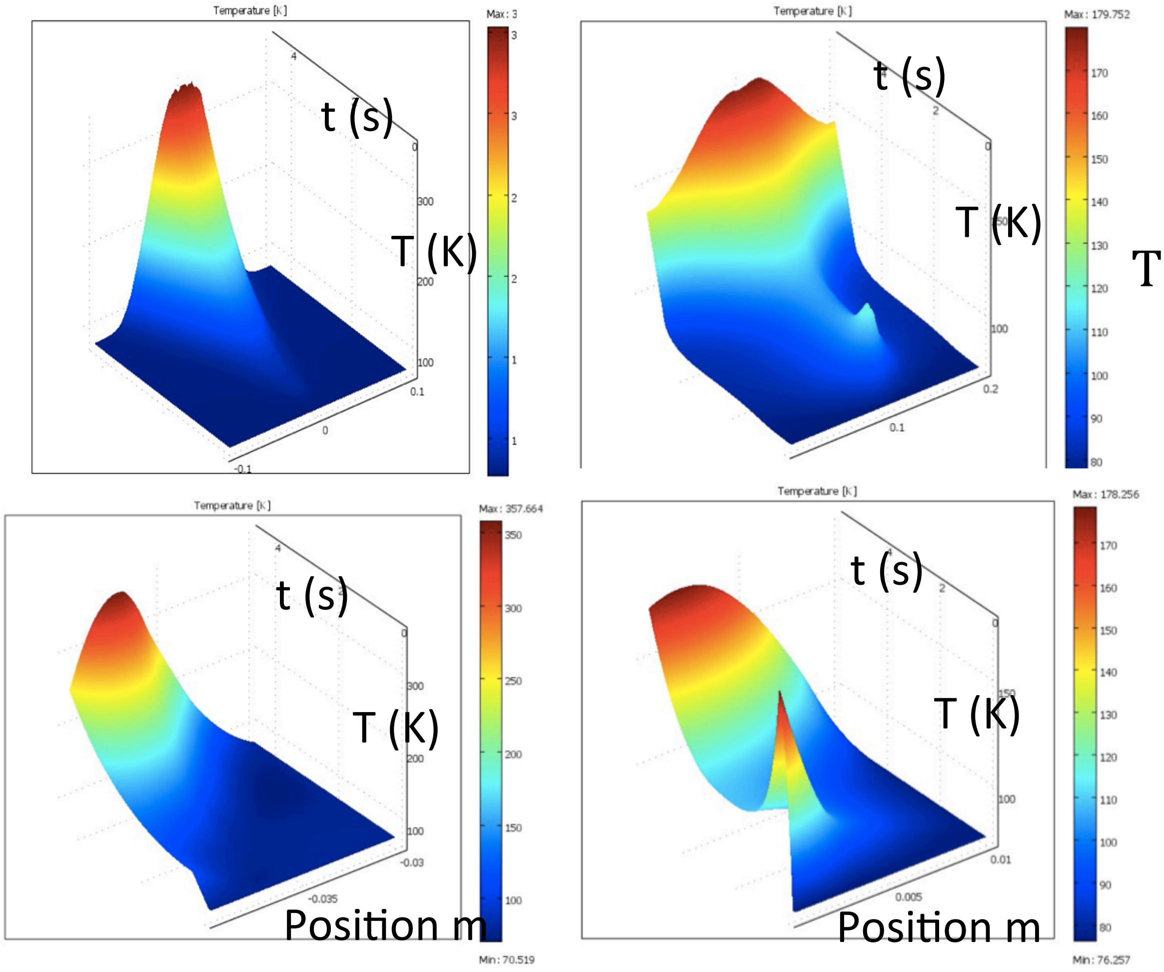




Can insulation enhance detection?

- 6X higher minimum quench energy
- Increased longitudinal & transverse propagation
- Peak temperature reduced by 2X; V across the coil increased by 2X

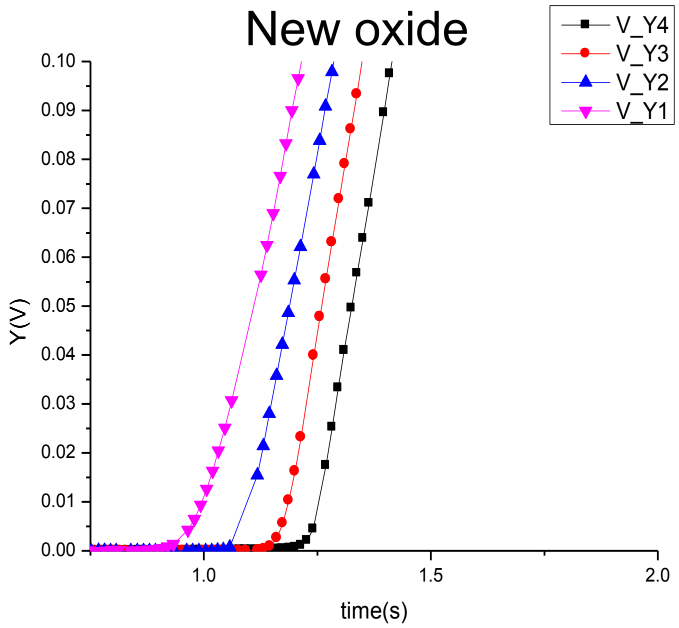
Kapton

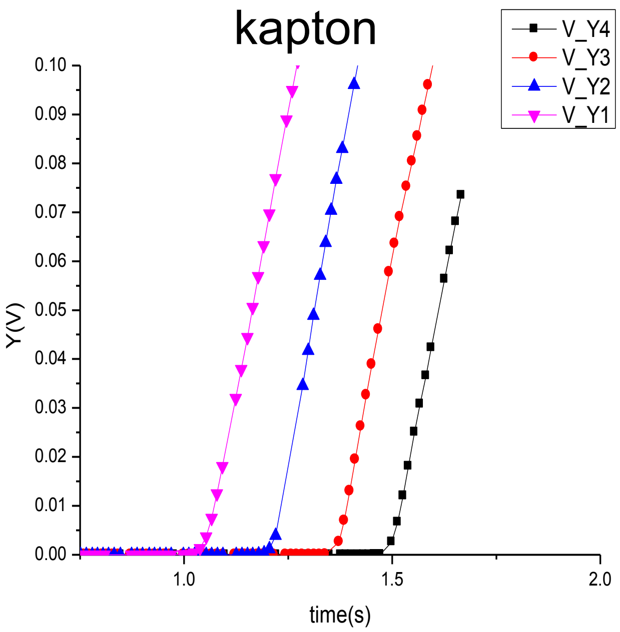


Thermally conducting electrical insulator

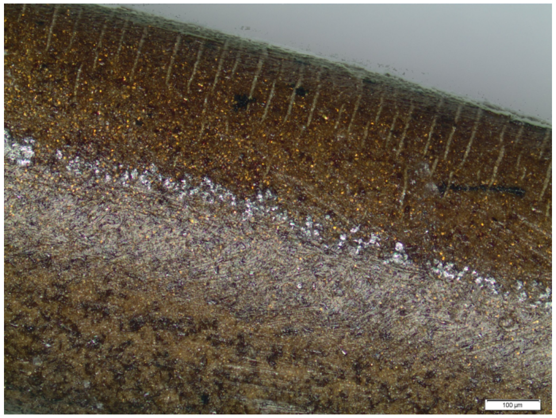
Thermally conducting electrical insulator

- Chemically compatible with Bi2212
- Improved fill factor for both Bi2212 and REBCO





275% increase in NZPV

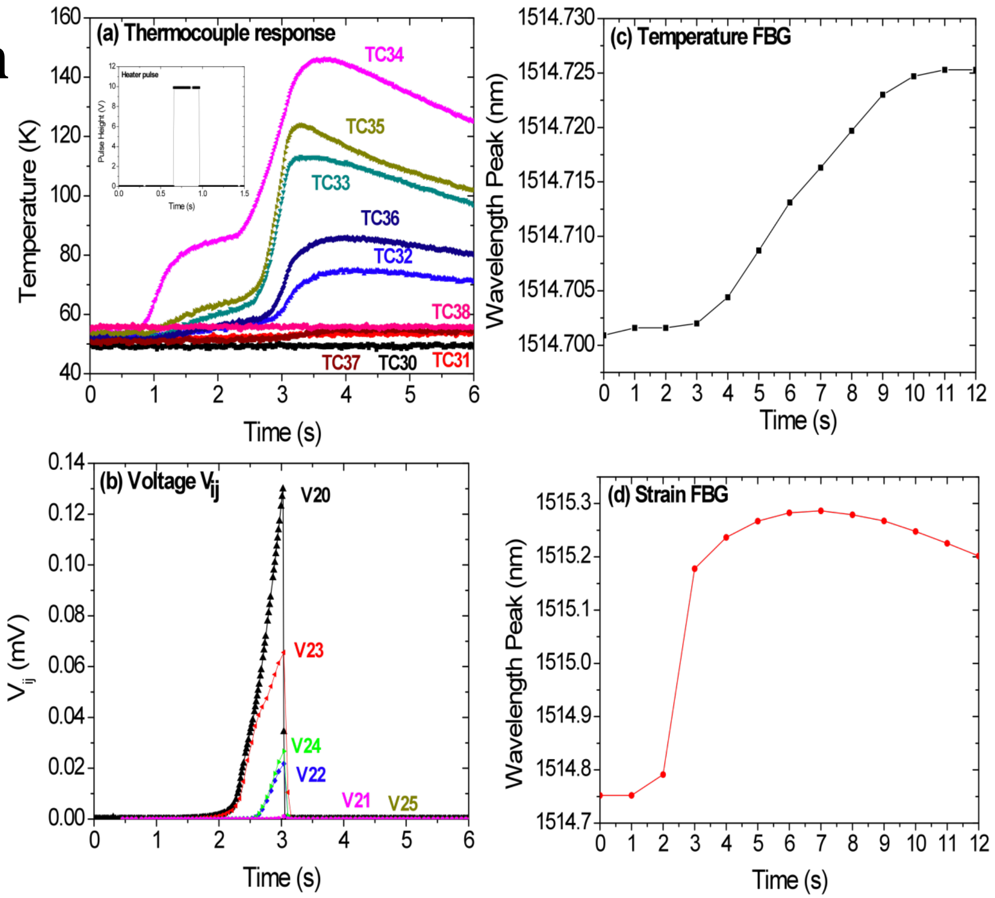


Coating on Bi2212 after heat treatment

L. Ye, X. Liu; NCSU & nGimat

Can we better detect quenches with fiber optics?

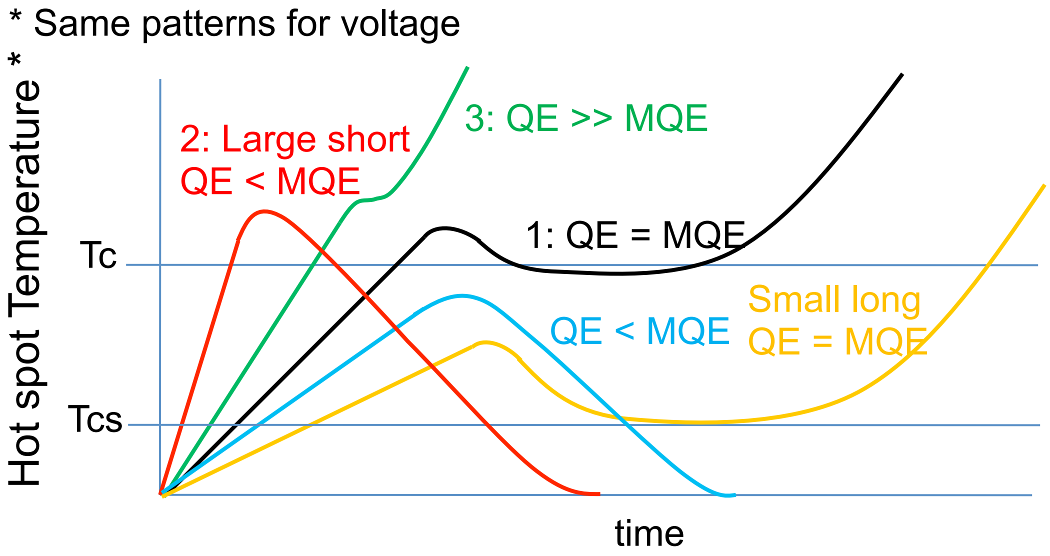
- Rayleigh backscattering and fiber Bragg gratings for quench detection
  - Rayleigh: fully distributed sensor
  - FBGs: distributed sensors with a fast sampling rate
  - Both are immune to EM noise
- Optical fibers for cryogenic environments
  - HTS compatible metallic and/or oxide based coatings for improved sensitivity
  - Integration into a magnet system



Fiber optic sensing (quench detection, ε, …)

- Proof-of-concepts have succeeded for Rayleigh backscattering & fiber Bragg grating detection
- Integration into a magnet system on-going
- Rayleigh backscattering offers a *fully distributed* sensor w/ potentially outstanding spatial resolution, but …
- Spatial-temporal resolution trade-off must be optimized; enormous volume of data and real-time data analysis becomes limiting issue… what does quench detection require?

Problems in Conventional Quench Detection

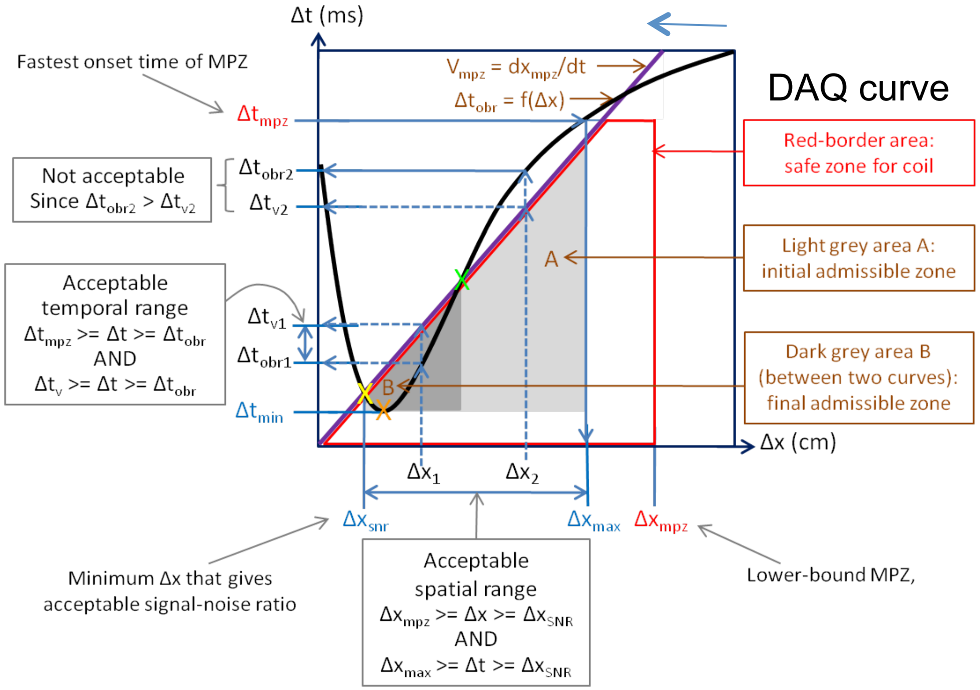


Different quench patterns due to different disturbance energy

- Unpredictable heat disturbance energy (QE) dictates T(x,t) and V(x,t) quench patterns

Determining Resolutions

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



Fastest onset time of MPZ

Not acceptable
Since $\Delta t_{obr2} > \Delta t_{v2}$

Acceptable temporal range
$\Delta t_{mpz} >= \Delta t >= \Delta t_{obr}$
AND
$\Delta t_v >= \Delta t >= \Delta t_{obr}$

Red-border area: safe zone for coil

Light grey area A: initial admissible zone

Dark grey area B (between two curves): final admissible zone

Minimum Δx that gives acceptable signal-noise ratio

Acceptable spatial range
$\Delta x_{mpz} >= \Delta x >= \Delta x_{SNR}$
AND
$\Delta x_{max} >= \Delta t >= \Delta x_{SNR}$

Lower-bound MPZ,

- Minimum Propagation Zone (MPZ) has lower/upper bounds
    - Intrinsic property of a coil. Estimated via simulations.
    - Once a normal zone = MPZ, it never shrinks
- Fit DAQ technology into coil's safe zone. Capture MPZ with fine resolution.

Quench Summary

- Quench protection is (to some extent) the last remaining uncertainty for HTS magnets
- Challenging, but solvable problems … with room for a lot of innovation and discovery

Thank you all for a very enjoyable week!