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Quench in HTS Magnets

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With contributions from the works of Wan Kan Chan, Davide Cruciani, Timothy Effio, Gene Flanagan, Andrew Hunt, Sasha Ishmael, Makita Phillips, Honghai Song, Melanie Turenne, Xiaorong Wang, Marvis White, Liyang Ye

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CERN
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Outline

- Introduction
  - Why quenching in HTS magnets is the same as LTS magnets
  - Why quenching in HTS magnets is different from LTS magnets
- A fresh look at quench protection – directions for improvements
  - More resilient conductor – buys time
  - Alternative quench detection – high resolution Rayleigh scattering optical fiber sensing
  - Conductor and magnet architecture for enhanced propagation

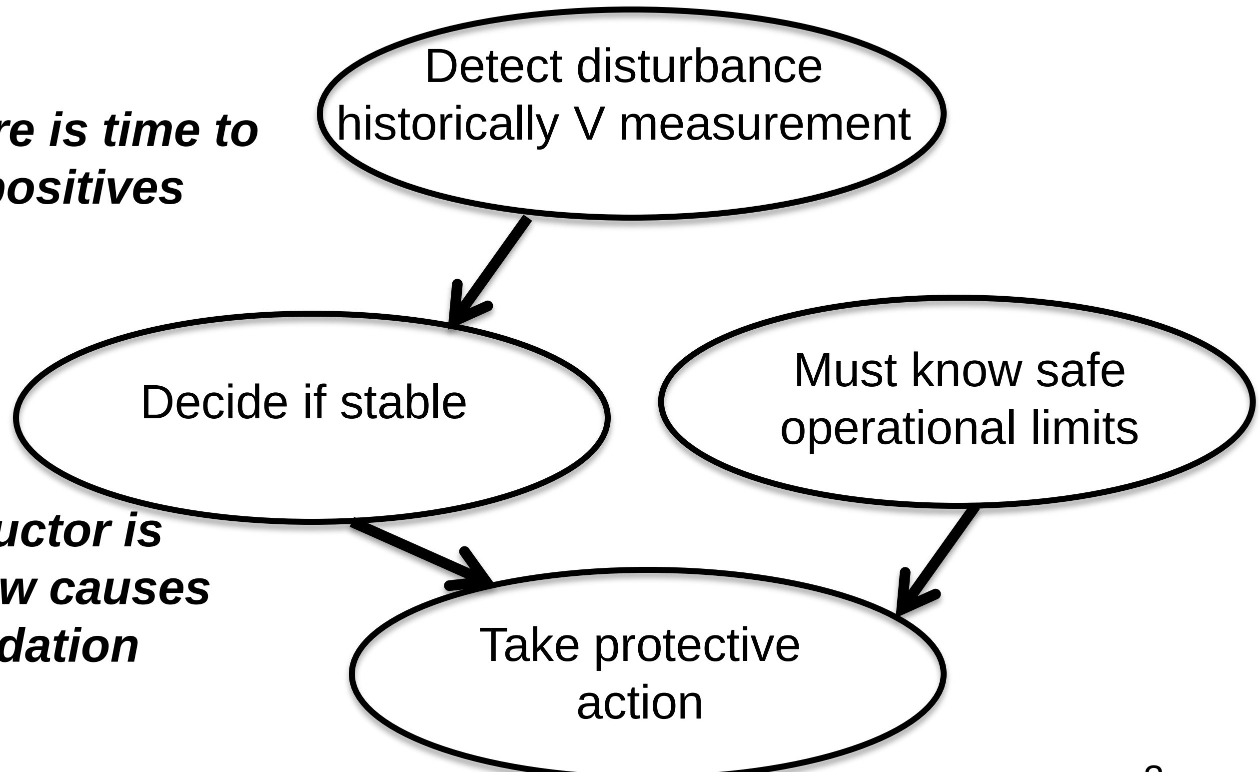
A quench is a quench is a quench …

Why quenching in HTS is the same as LTS

- Basic physics, equations and concepts are unchanged
- Primary goal: *prevent degradation without overly reducing coil J_e*

Detection, while there is time to act & without false positives

Action, before conductor is degraded; must know causes and onsets of degradation



But two quenches can be very different

How quenching in HTS differs from LTS

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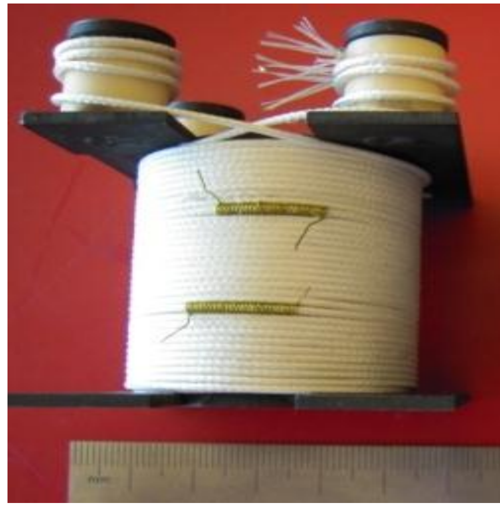
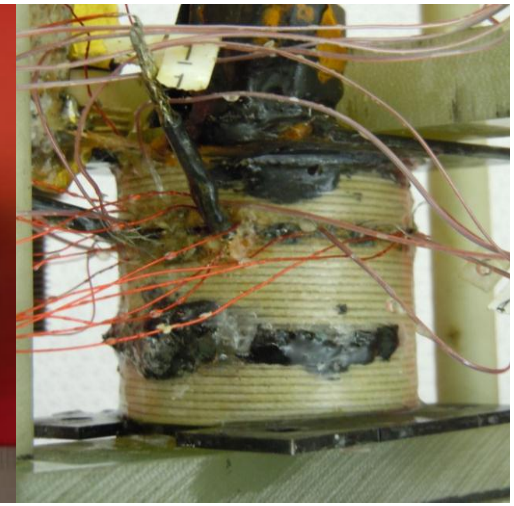
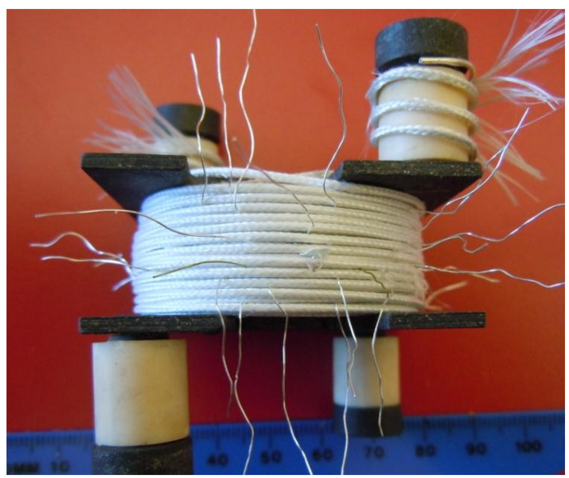
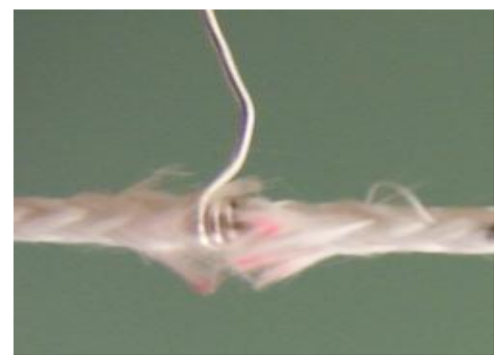
- Energy margin is much larger
  - Simulation and experiment show that quenches can be difficult to induce
  - *Is unprotected operation appropriate for some systems?*
- Normal zone propagation is slow … *very slow* … so?
  - $\mathbf{V=\int E \cdot dl}$ & the shapes of E(x) & T(x) roughly match
  - Slow propagation → same V can result from peaked or broad E(x), T(x)
  - ***So higher T_{max} and ∇T for the same voltage than LTS***
- Does high field help (since high field magnets likely to be LTS/HTS hybrids)?
  - *High field → lower T_c → lower T_{cs} → faster propagation?*
  - *High field → lower J_c → lower J → slower propagation?*
  - *Need to measure to know!*

Bi2212 coils for high field quench tests

2D propagation on cooled surface layer

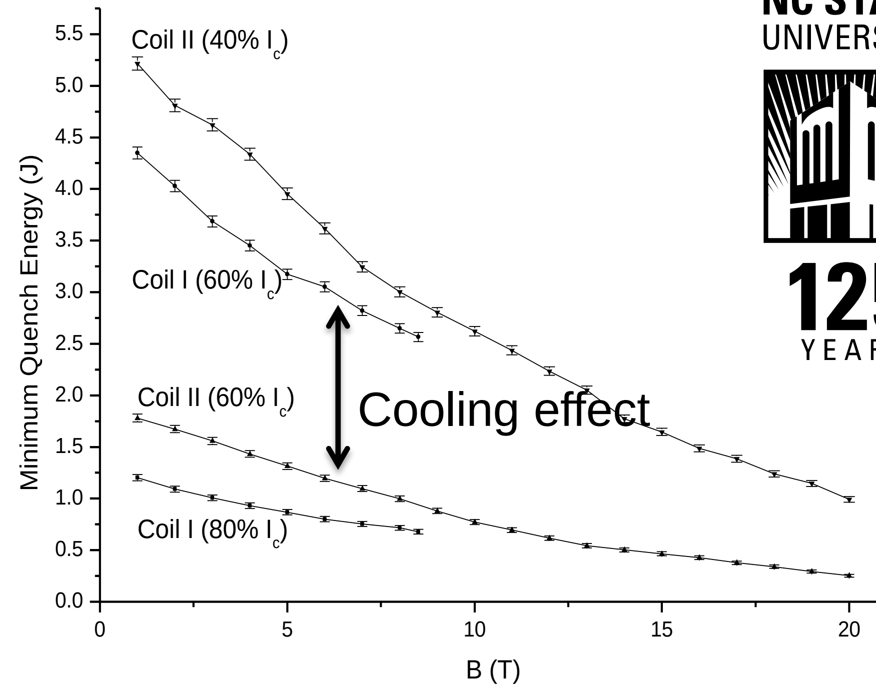



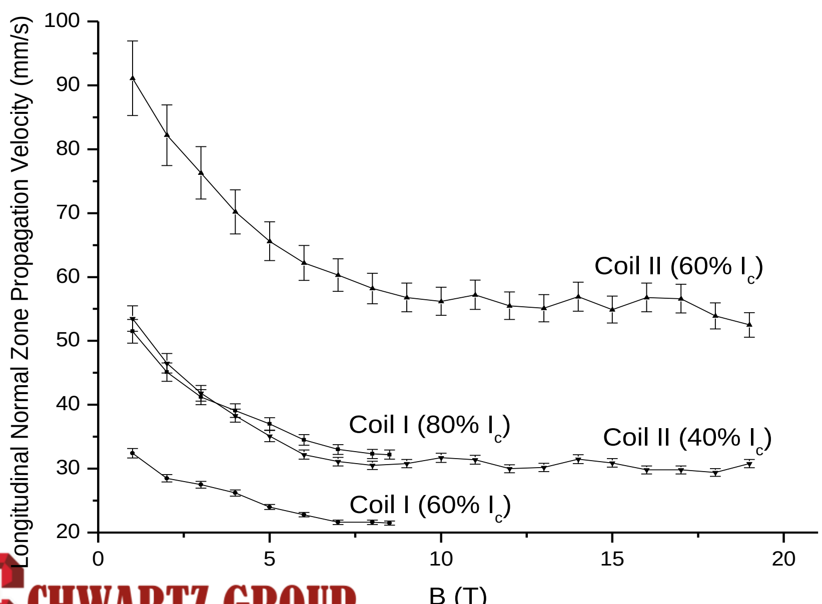
3D propagation w/embedded voltage taps

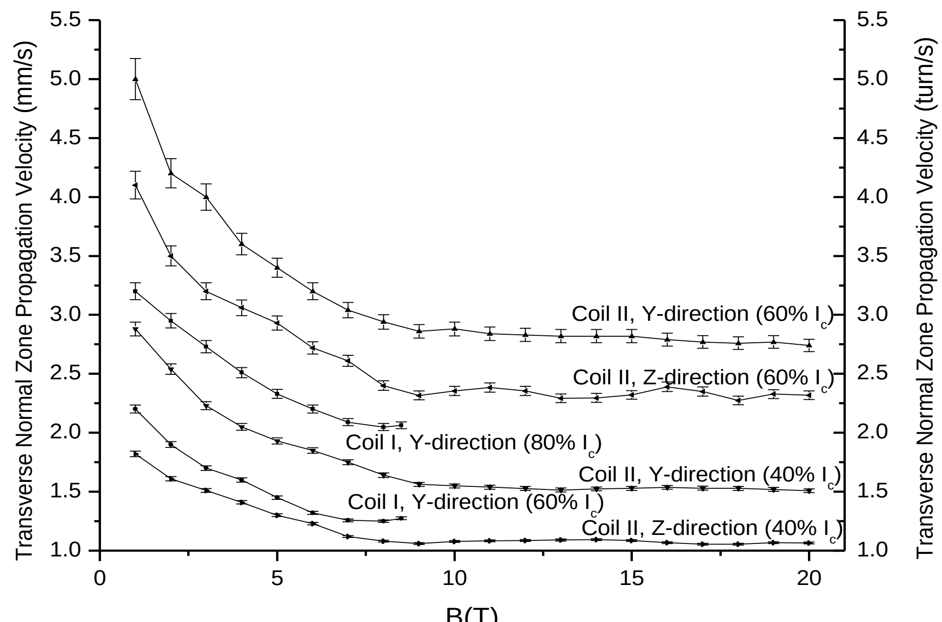



L. Ye, F. Hunte and J. Schwartz, *Superconductor Science & Technology* (submitted 2012)

Quench energy & Propagation velocities







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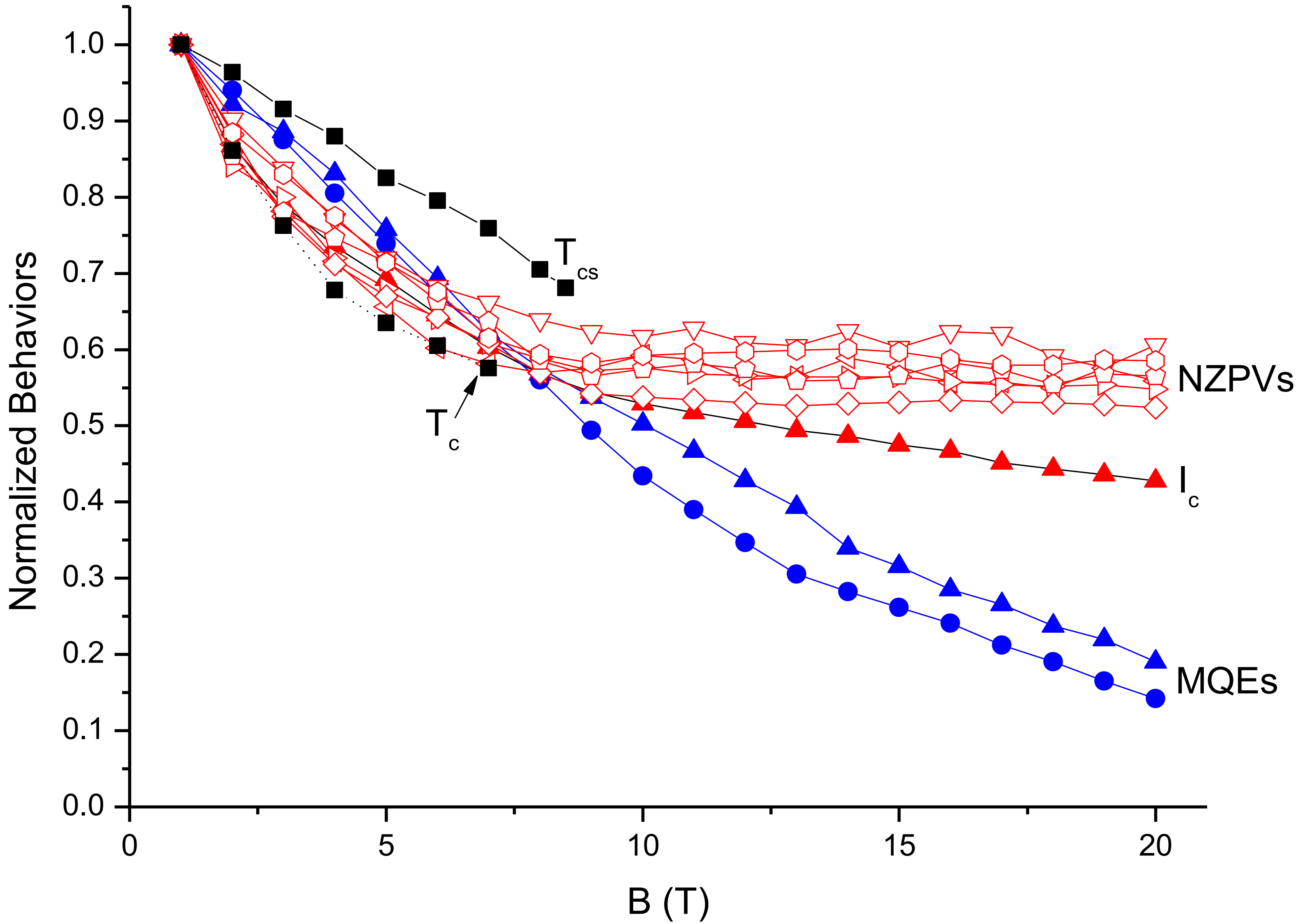
Field-dependent behaviors



What is essential?

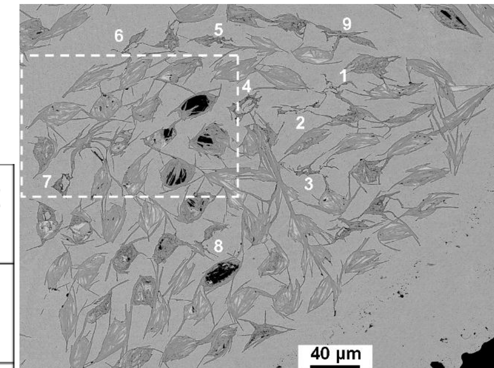
The key is to prevent degradation by limiting local temperature growth relative to the ability to detect

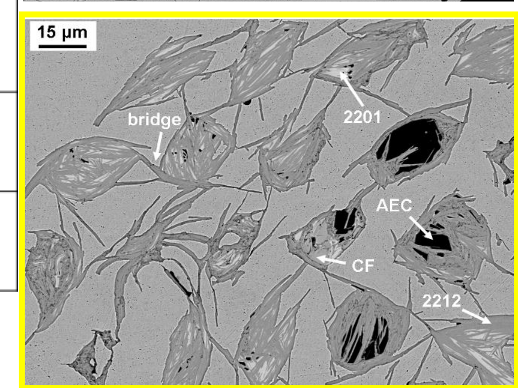
- Failure modes and safe operational limits are very different from LTS & must be understood
  - In YBCO, J_c very high & localized
  - Bi2212 wires continue to advance and evolve
- Time to take a fresh look in light of new materials & technologies

What do we know about degradation?

Understanding degradation in Bi2212

- Bi2212 round wires
  - Wire microstructure is (horrendously) defect dominated
  - Current-limiting (& current-enabling) mechanisms not fully understood
  - Failure mechanisms difficult to study at microstructural level





	J_c (A/mm^2)	I_t/I_c	Tmax (K)	Energy/time (J/s)	dT/dt|max (K/s)	dT/dx|max (K/cm)
Type I Short	2262	450A/550A =0.82	350	50 J/0.9 s	700	150
Type II Short	4420	410A/500A =0.82	200	16 J/0.6 s	600	66
Type I Coil	2056	400A/500A =0.80	358	46 J/0.9 s	802	93
Type II Coil	3183	270A/360A =0.75	167	38 J/0.9 s	258	48

- Limits may increase as microstructure improves

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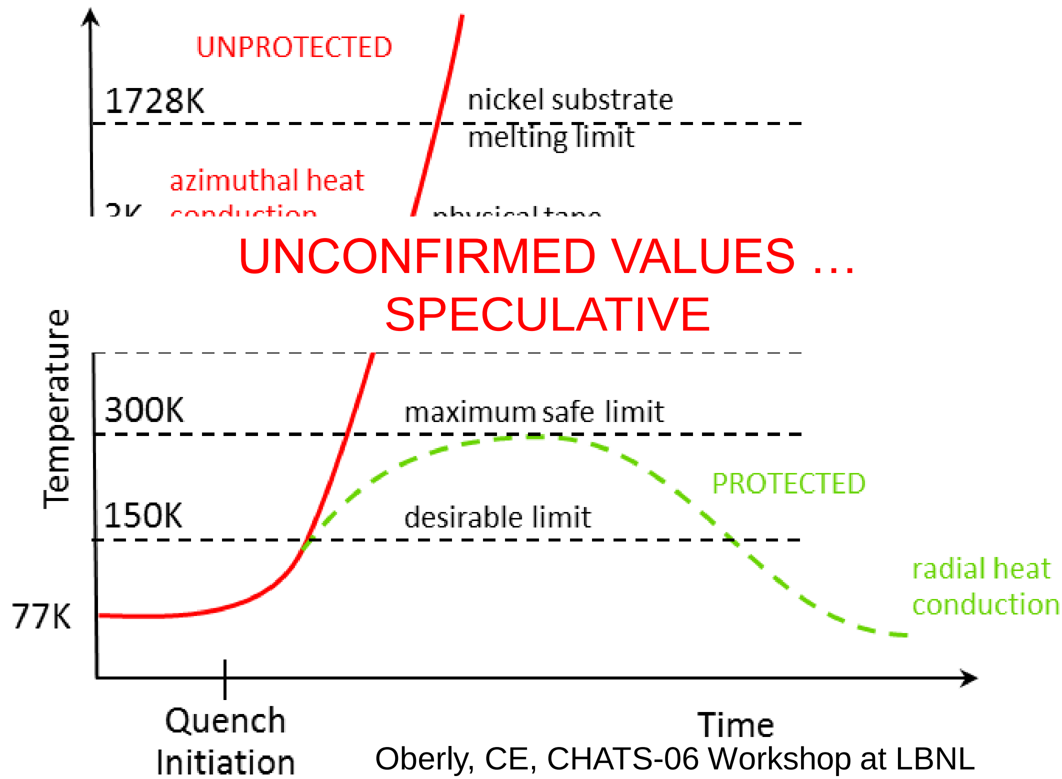
Understanding degradation in YBCO CCs

- YBCO CC substrates are mechanically strong
- Delamination is a known problem – not just a quench issue
- Defects on the edges (perhaps from slitting)
- “Drop-outs” → imply local defects/inhomogeneity
- Firm quantitative limits not known



Oberly, CE, CHATS-06 Workshop at LBNL

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YBCO degradation from quenching
- two sources identified … both defect driven

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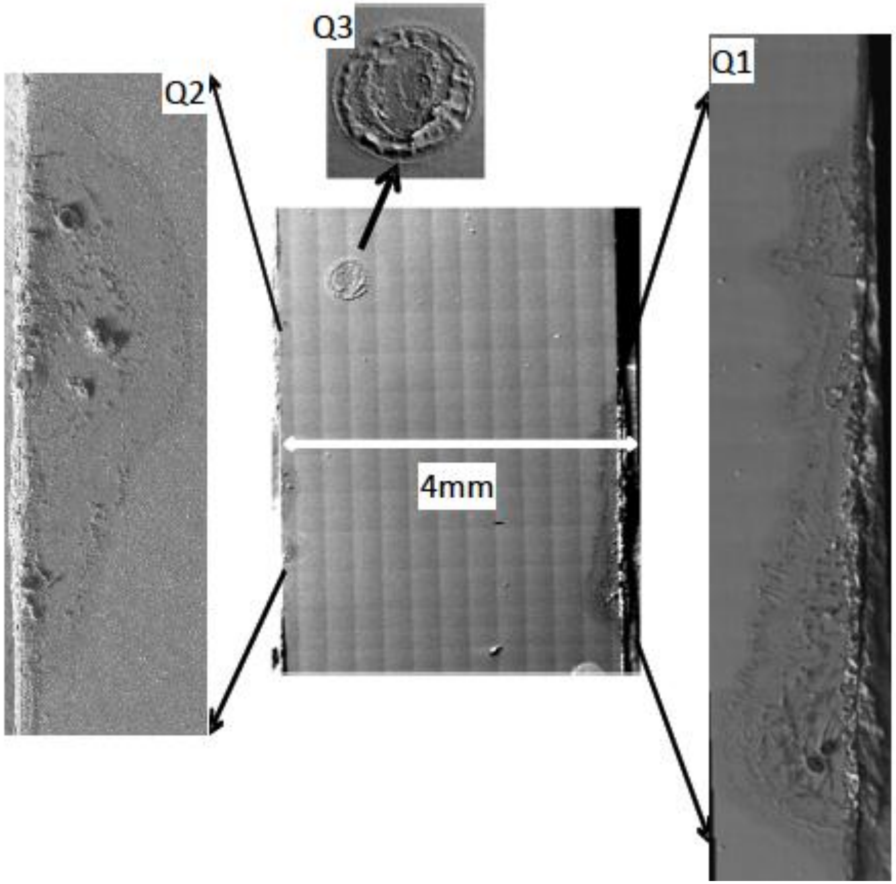
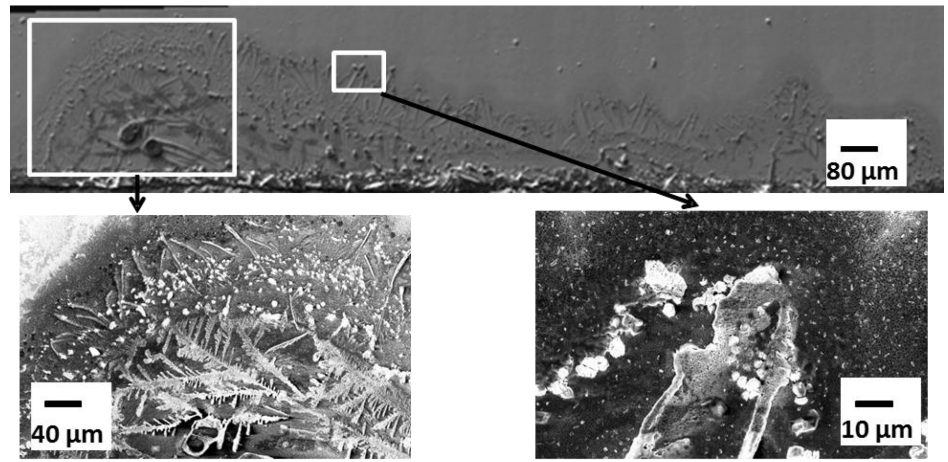


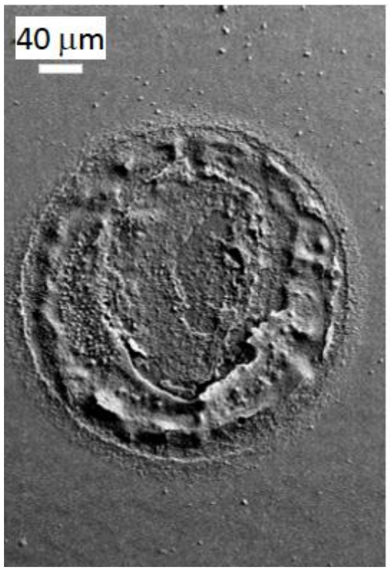
EDGE DRIVEN DEFECTS

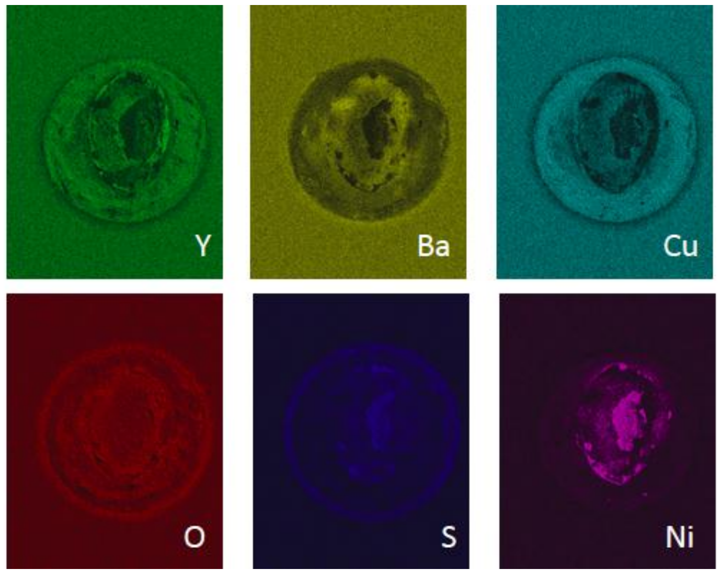


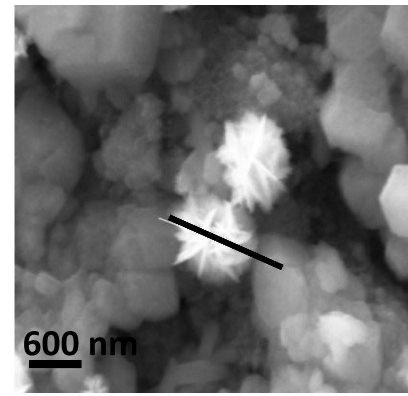
Dendritic flux penetration is evidence of Ag delamination

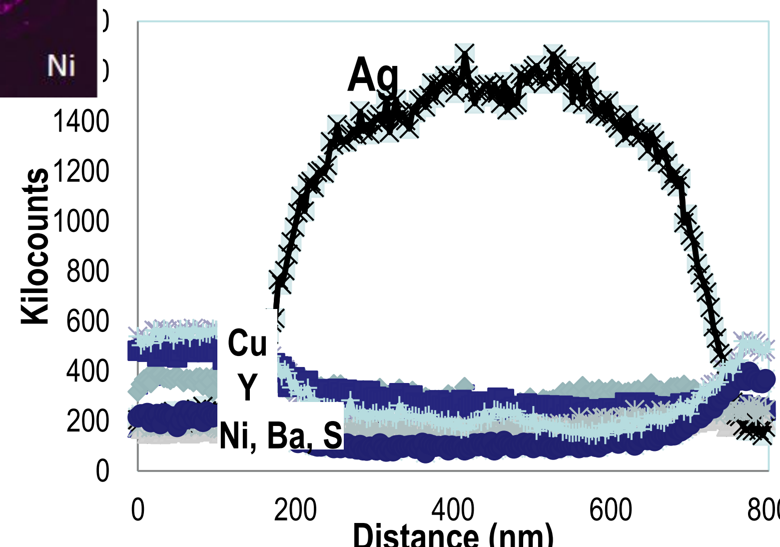
H. Song, F. Hunte, J.Schwartz, *Acta Materialia* **60**(20) 6991–7000 (2012)

Pre-existing defects → very high local T → degradation … due in part to *high* J_c in YBCO









Ag vaporized and recondensed

H. Song, F. Hunte, J.Schwartz, *Acta Materialia* **60**(20) 6991–7000 (2012)

Degradation Bottom Line

- Bi2212 and YBCO degradation is defect driven & thus limits can be increased
- Increased limits → more time to detect/protect
- Fundamental limits will exist (e.g. oxygen in YBCO)

Detection must be local and fast (enough)

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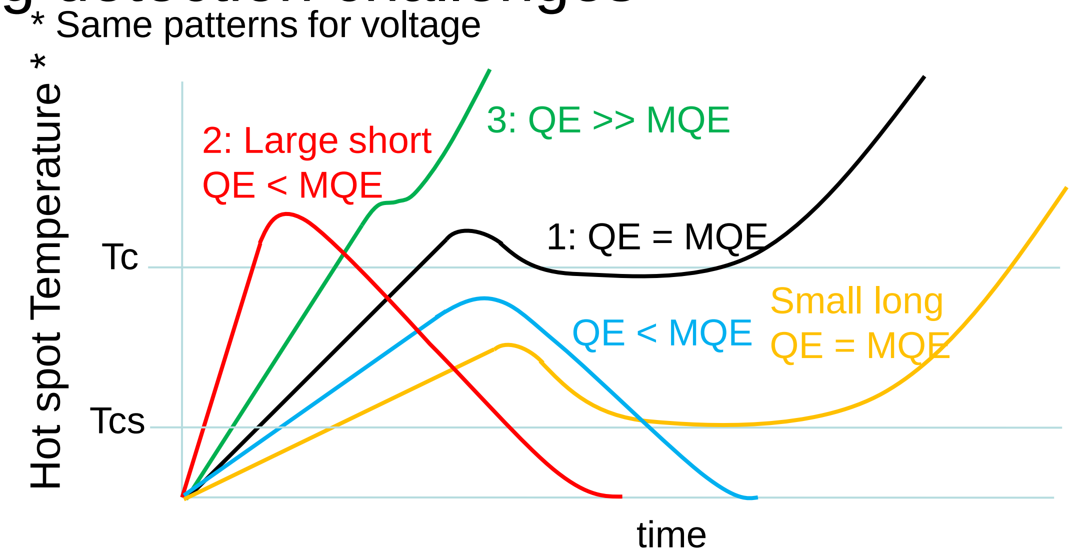
- Slow propagation → high spatial resolution
- Optical fiber sensors for detection… proof-of-concepts have succeeded
  - Fiber Bragg gratings → point measurements (albeit multiple/fiber)
  - Rayleigh scattering (naturally-occurring "continuous grating"): *fully distributed* sensor w/impressive spatial resolution … At the expense of temporal resolution
  - *Enormous volume of data & real-time analysis is a limiting issue*
- ***Where is Rayleigh scattering detection headed?***
- ***What does HTS quench detection require?***

Magnet demands

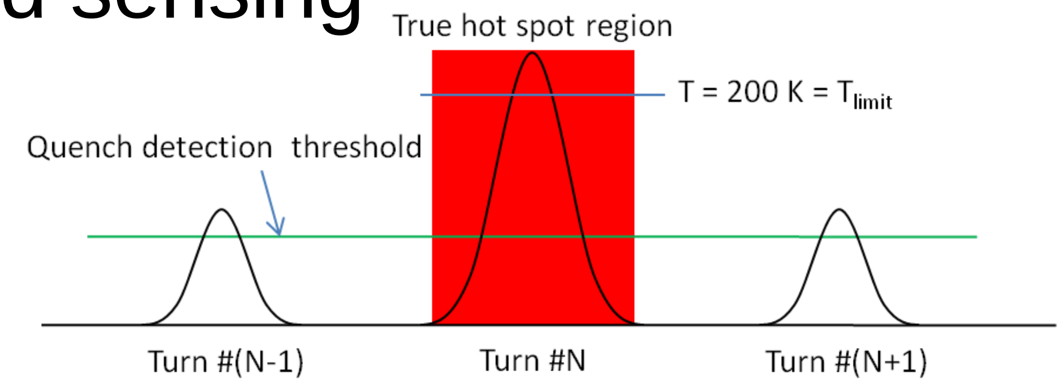
Understanding detection challenges



Different quench patterns due to different disturbance energy

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



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

- Temperature details at any location
  - Simple, accurate and timely quench detection
  - Identifies hot-spot location
- Key to apply technology successfully: capture and process the data with sufficient spatial and temporal resolutions with fast data acquisition and processing
- DAQ technology must match coil characteristics
- Modeling to find spatial and temporal resolutions for effective detection

Rayleigh Scattering Optical Fiber Quench Detection

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- Benefits
  - Fully distributed quench sensing system (100% coverage)
  - Optical interrogators have their origin in telecom fiber systems, then in structural engineering- bridges, buildings etc (timing demands not important)

- So what's taking so long to get them into magnets ?
  - Fiber response to strain/temp changes is hindered by cryogenic temperatures
    - Fiber coatings can be used to mitigate problem
  - Data processing speed – measurement scheme requires a lot of signal processing and we need unprecedented computing performance for quench protection of real magnets.
- Muons, Inc/NCSU working on this currently: High performance computing (HPC), simulation to determine requirements, validation with real coils

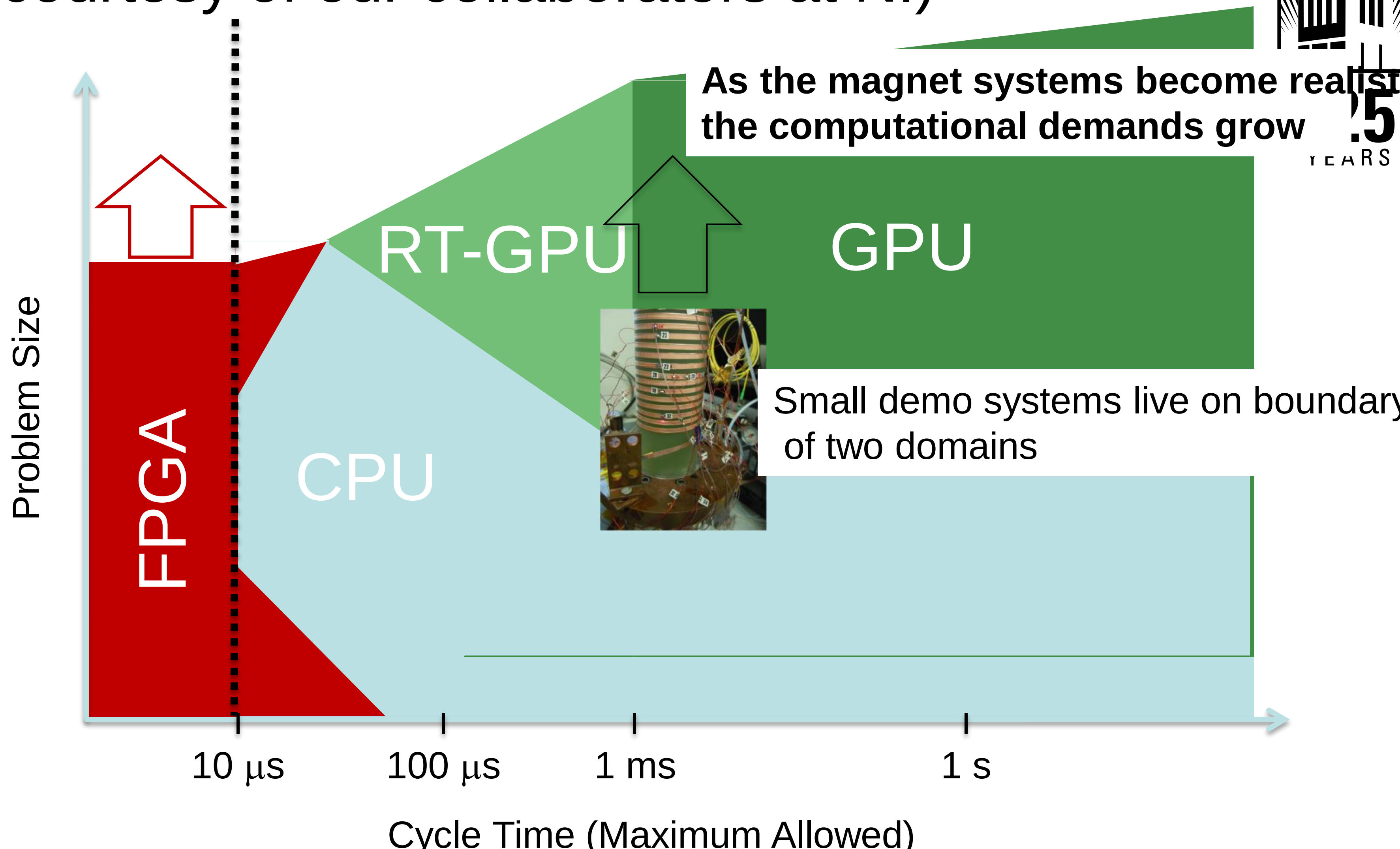
With valuable collaboration with National Instruments (Lothar Wenzel, Darren Schmidt, Qing Ruan, Christoph Wimmer)

Real-Time HPC

"Traditional HPC with a curfew."

- Processing involves live (sensor) data
- System response impacts the real-world in realistic time
- Design accounts for physical limitations
- Implementations meet/exceed exceptional time constraints – often at or below 1 ms
- Demands parallel, heterogeneous processing

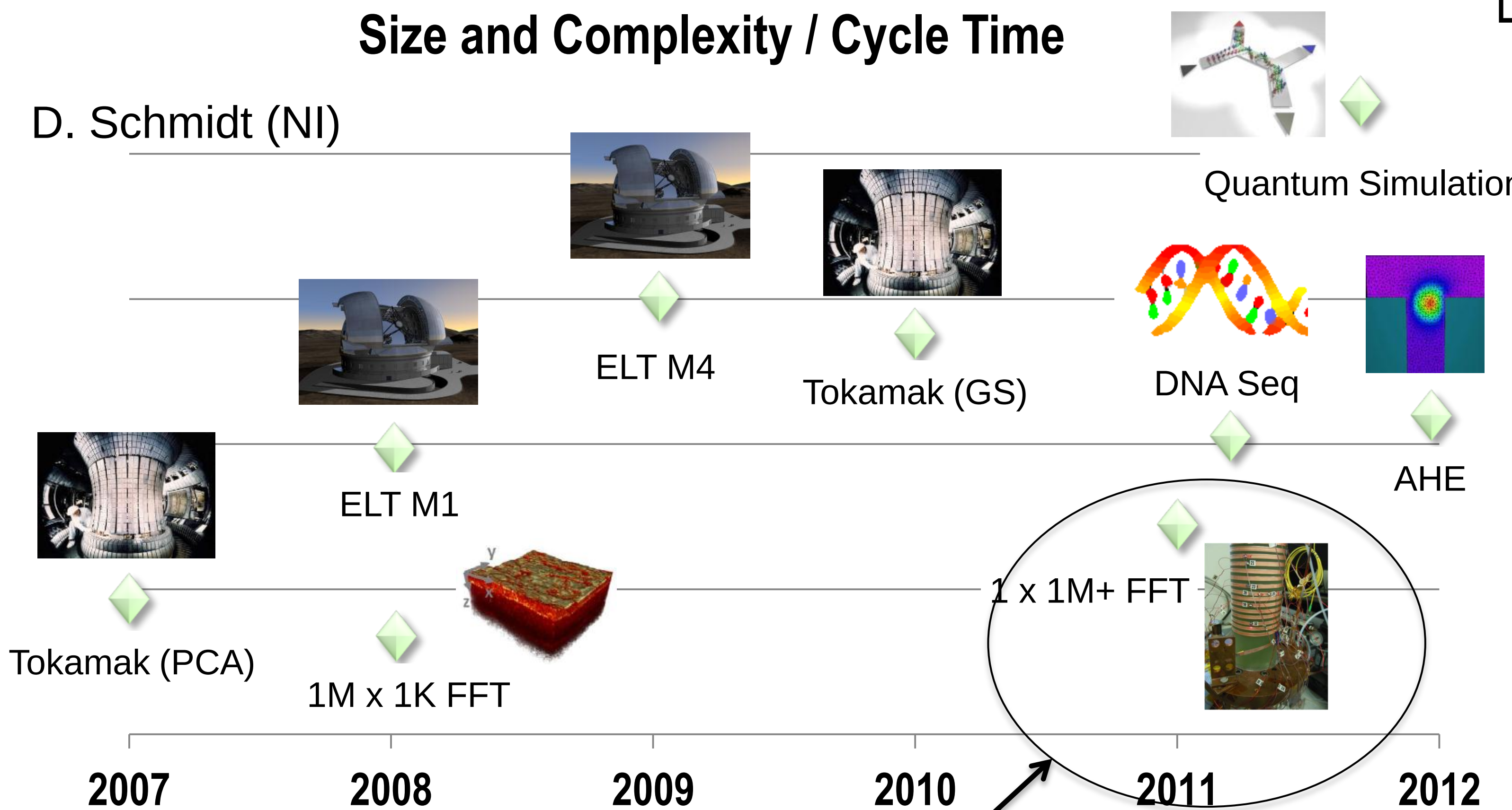
Processor Landscape for Real-time Computation (courtesy of our collaborators at NI)



As each processor target is capable of solving problems when given more time (i.e. longer cycle times), many factors come into play:

- Development difficulty: Deployment options: Power consumption / computational unit

Real-Time HPC Trend



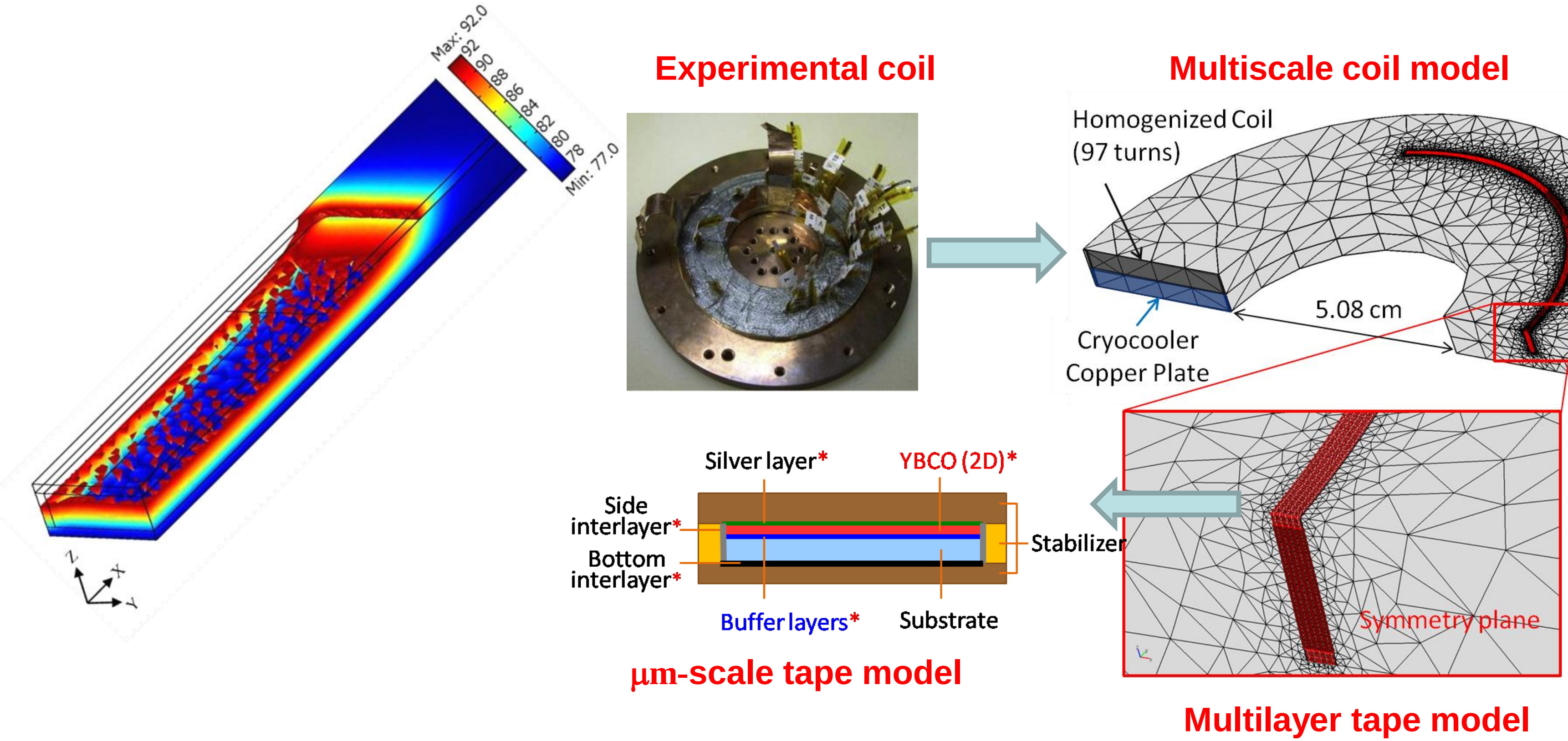
Coil instrumented with fibers. (data point reflects early benchmarking targets; reality will push us much higher on plot- note: we are already in fast company)

Currently pushing on two parallel development fronts:

- Real-time HPC development to push beyond current state of the art (scalability is always on our mind).
  - ✓ Have emulation of heterogeneous system (GPU+CPU) complete and looking at optimizations
  - ✓ Study of pure GPU implementation reasonably advanced
  - ✓ FPGA based computing study beginning
  - ✓ Scalability to real systems will most likely come from multiplexing

- Magnet/fiber integration and testing
  - ✓ Latest optical hardware is in hand and have recently finished control and integration software for fibers/voltage taps/TC etc (cold tests will begin soon)
  - ✓ Instrumented coil tests at NCSU underway with previous generation of hardware
  - ✓ Magnet modeling to quantify requirements

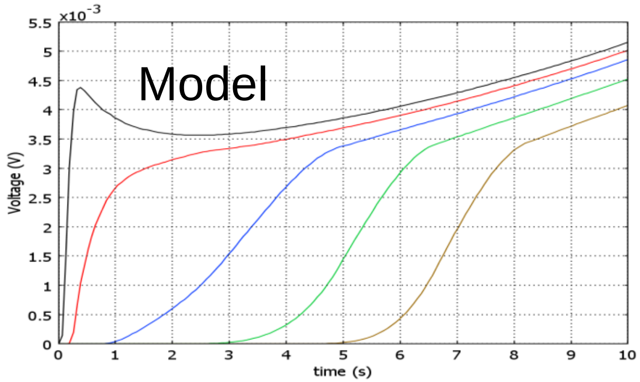
To understand detection requirements … use multi-scale modeling

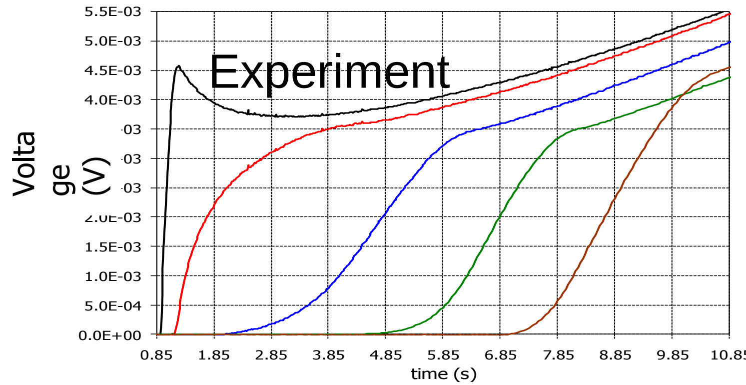


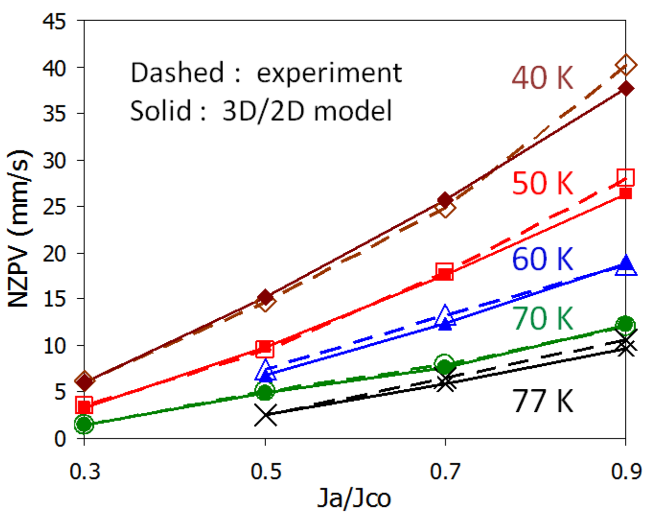
- Accurate, hierarchically built and experimentally validated
- Multiscale– from tape-layer scale to device-scale
- mm-scale tape model with all components of YBCO coated conductor in real dimensions

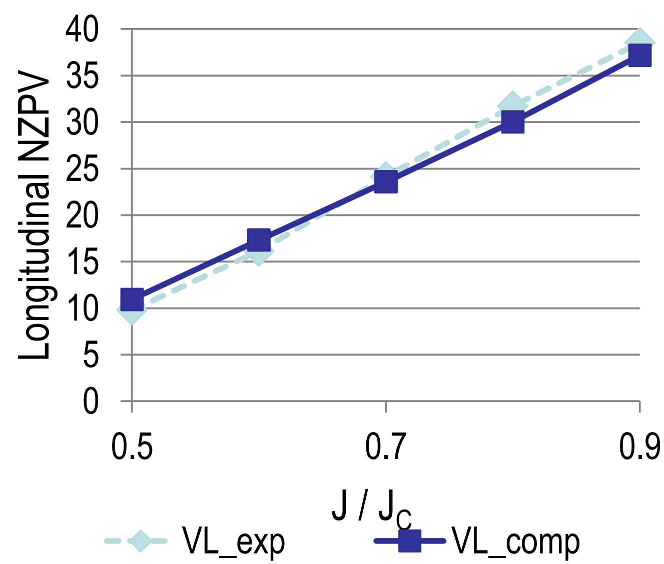
W.K. Chan and J. Schwartz, *IEEE Trans. Appl. Supercond* **22**(5) 4706010 (10pp) (2012)

Experimental validation







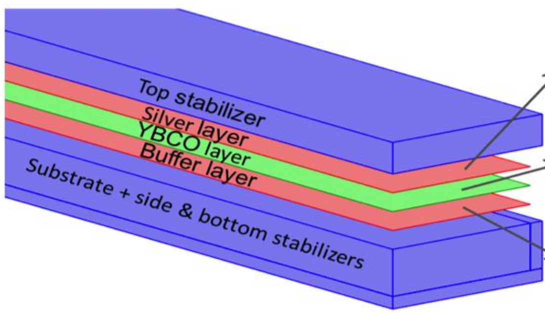


YBCO Dynamic Stress Analysis

Fabrication → Bending → Cooling → **Quench**

Static (residual) stress analyses (Fabrication, Bending, Cooling)

Dynamic stress analysis (Quench)

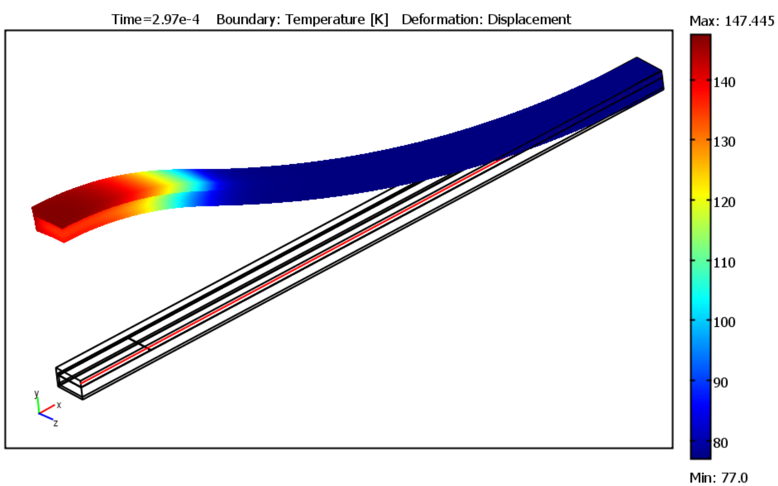


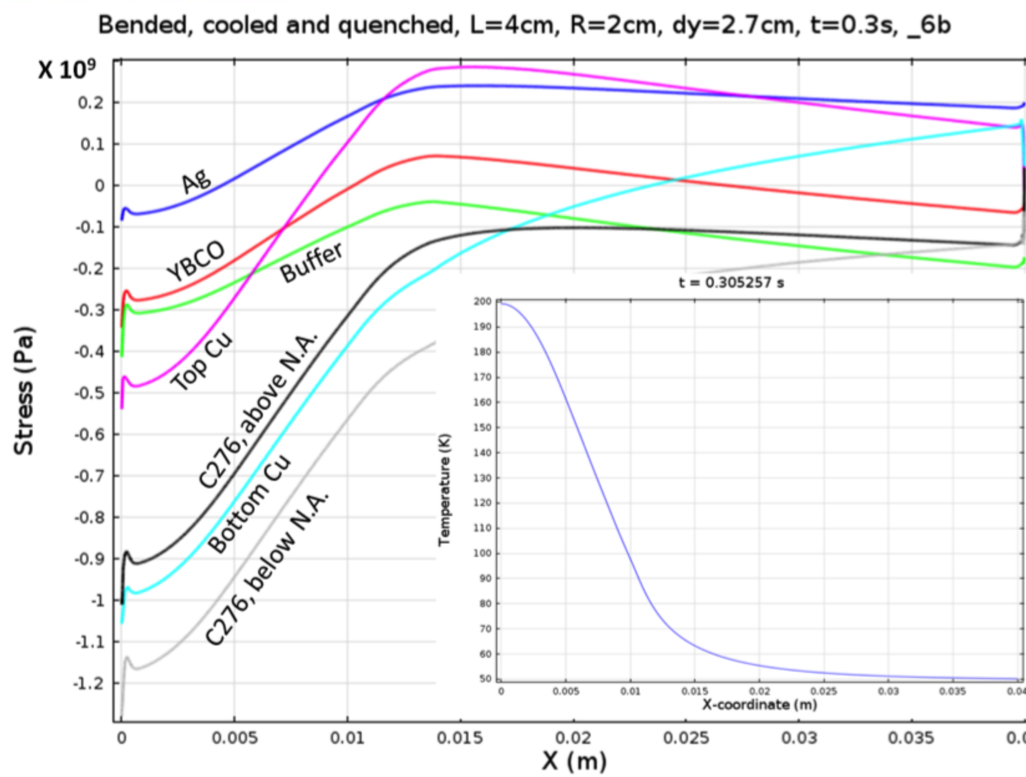
Silver ->
Heat, electric : interfacial flux + boundary heat equations
Structural mechanics : 2D shell + bond constraints

YBCO ->
Heat, electric : 2D equations + interfacial fluxes
Structural mechanics : 2D shell + bond constraints

Buffer ->
Heat, electric : interfacial flux + boundary heat equations
Structural mechanics : 2D shell + bond constraints

Compressive stress near hot-spot

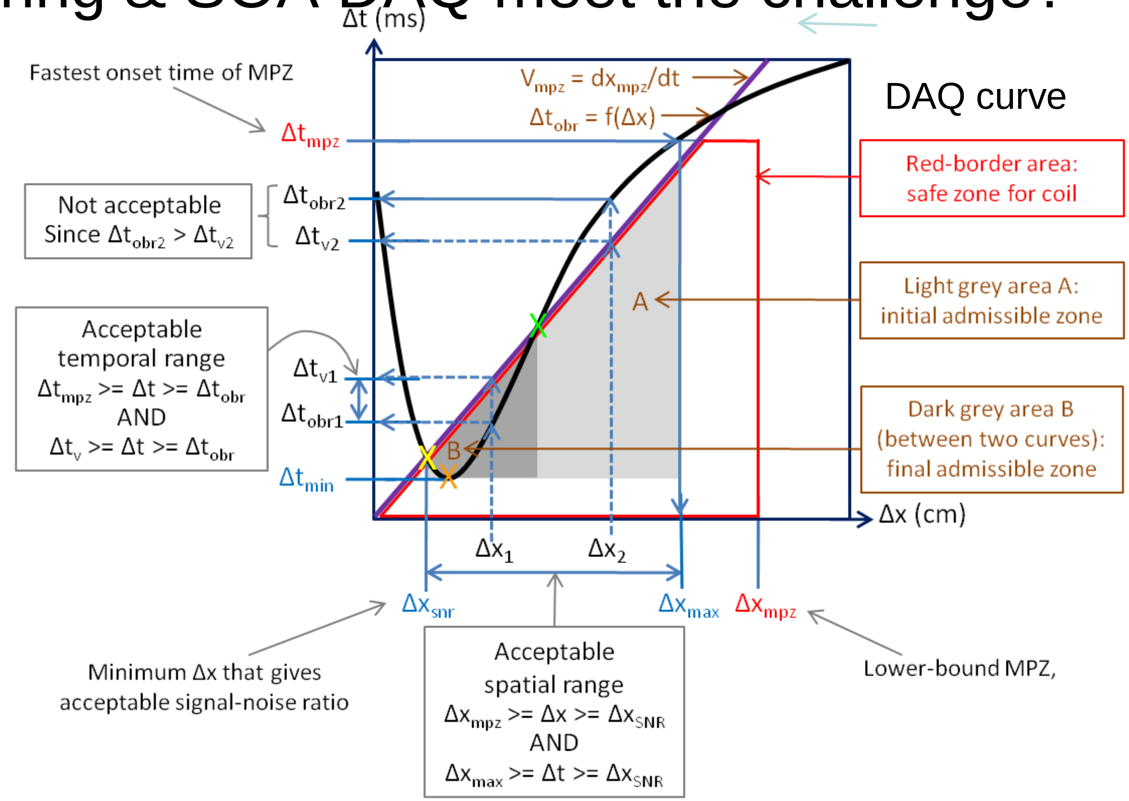




Determining Resolutions …

can Rayleigh scattering & SOA DAQ meet the challenge?

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



- 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.

Chan, Flanagan, Schwartz
Department of Materials Science and Engineering

Multiscale model of YBCO quenching… affords ***"what if?"*** ***conductor engineering to expand the admissible zone***

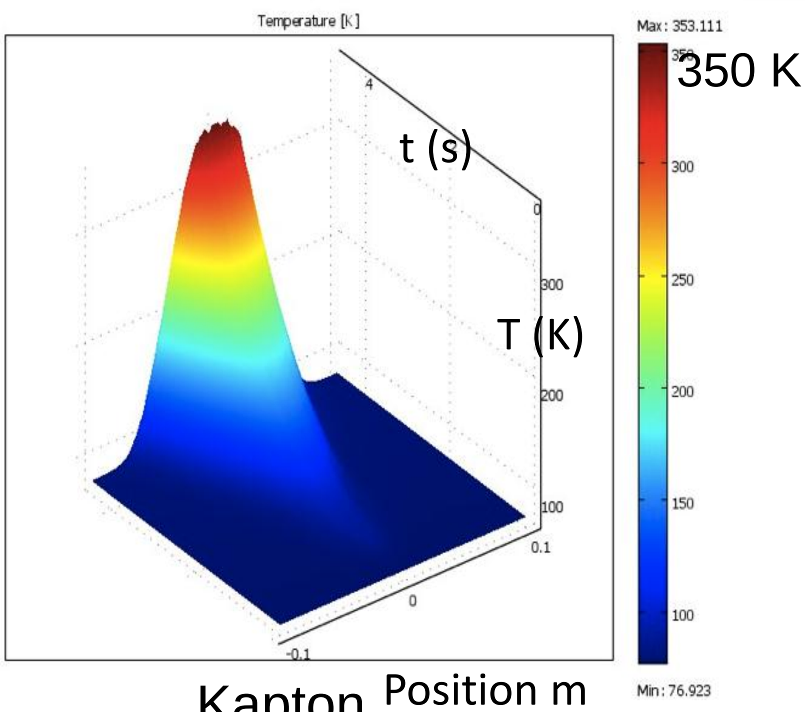
	$\Delta\alpha$ (%)	NZPV $\Delta NZPV$ (%) $\Delta NZPV/\Delta\alpha$	T_{peak} ΔT_{peak} (%) $\Delta T_{peak}/\Delta\alpha$	MQE ΔQ (%) $\Delta Q/\Delta\alpha$
→ Case I: increased YBCO thickness	+100%	+110.9% +1.11	+57.5% +0.58	-25% -0.25
Case II: reduced Cu thickness	-32%	+27.0% -0.84	+31.1% -0.97	-29.9% +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

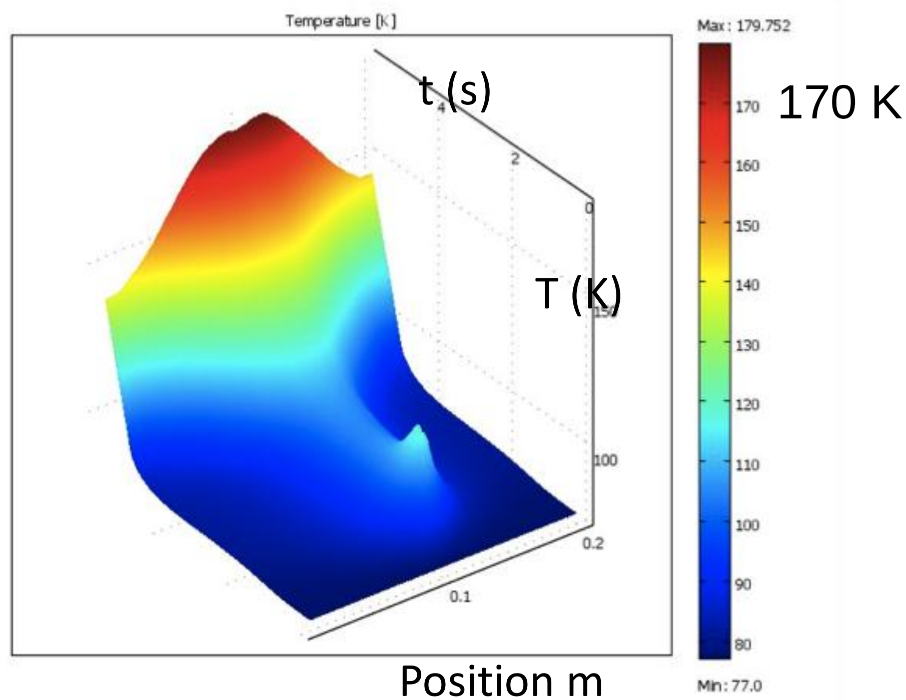
Can 3D propagation reduce dT_{max}/dt?

Thermally conducting electrical insulation enhances turn-to-turn propagation

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

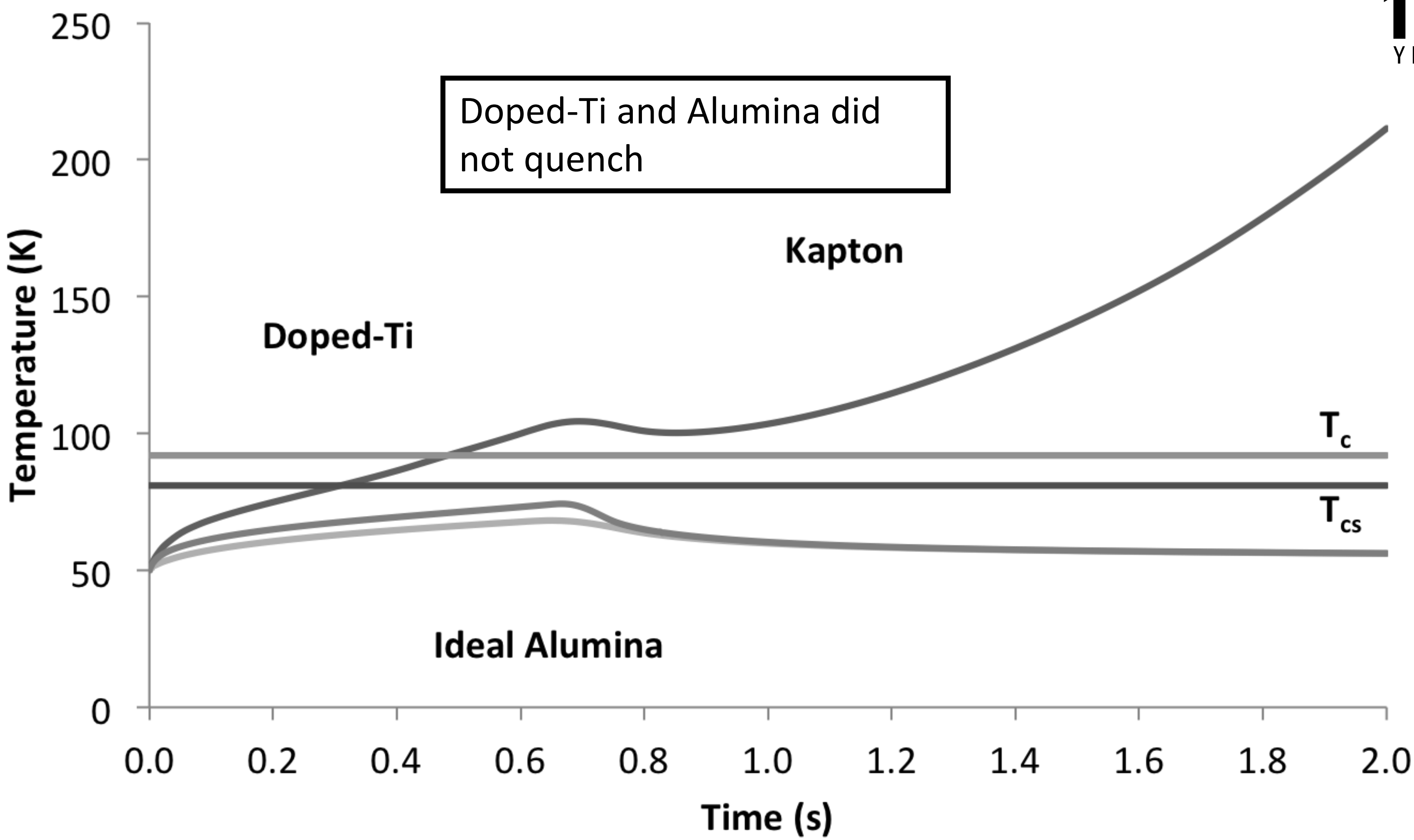


Kapton



Thermally conducting electrical insulator

Three options (20 µm thick insulation)



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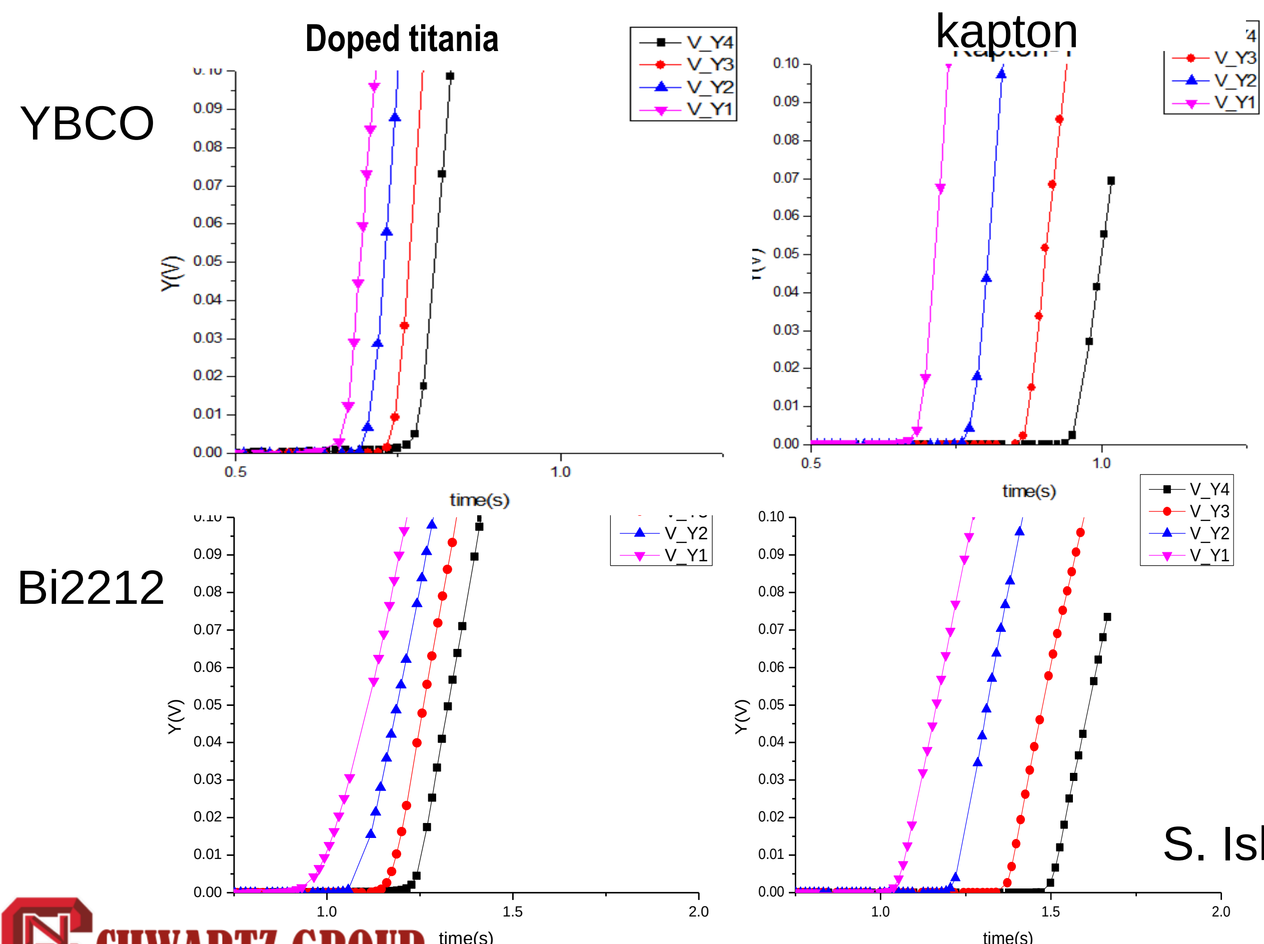
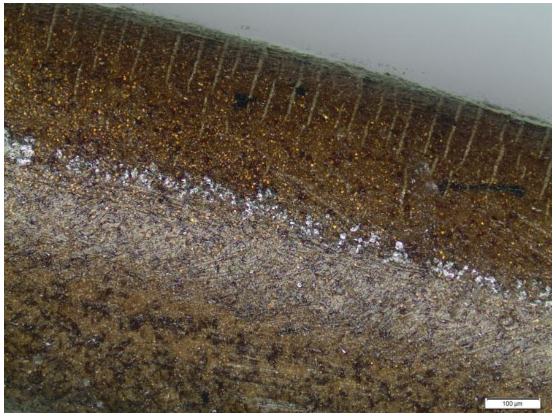
Thermally conducting electrical insulator

NCSU & nGimat jointly developing a thin oxide coating

- Chemically compatible with Bi2212 – I_c unchanged or improved
- Improved fill factor for both Bi2212 and REBCO



275% increase in NZPV



Coating on Bi2212 after heat treatment

S. Ishmael et al., submitted TASC

Summary – what knobs can we turn?

- ***Conductor quality*** – improve resilience to extend safe operating limits
- ***Detection technology***
  - Rayleigh scattering in optical fibers to replace (augment) voltage taps; needs to be coupled with improved DAQ, signal processing & interpretation
- ***Conductor architecture*** – increased stability & better quench tolerance
- ***Magnet architecture/materials*** – symmetric 3D propagation

In summary … a roadmap?