Next Generation Superconductors for Accelerator Magnets

Justin Schwartz

Florida State University
Department of Mechanical Engineering
&
National High Magnetic Field Laboratory
Applied Superconductivity Center

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The NHMFL ASC team

- David Larbalestier
- Eric Hellstrom
- Ulf Trociewitz
- Jianyi Jiang
- Abdallah Mbaruku
- Xiaotao Liu
- Xiaorong Wang
- Tengming Shen
- Honghai Song
- Quang Le
- Tim Effio
- David Myers
- Michael LoSchiavo
- Durval Rodriguez
- Fumitake Kametani

Outline

- Introduction & Goals
- The conductor candidates
- Potential of HTS & MgB_2
- Challenges of HTS & MgB_2
- Summary & Conclusions

Introduction & Goals

- Magnet technology is a primary driver for progress in accelerators
- Future accelerators are likely to rely on future superconductors
- “Pull” from accelerator community has had enormous impact on NbTi & Nb_3Sn development & commercialization
- Will accelerator community have similar impact on HTS & MgB_2 progress?
- ***More importantly, SHOULD IT?***

Future magnet technology for accelerators

- What might significant advances bring to accelerators?
  - LHC tripler → 24 T
  - Solenoid for muon collider → 40-60 T
  - “Irradiation resistant” magnets for IR → 20 K
- ***These cannot be accomplished with NbTi & Nb_3Sn … what are the options?***

Potential magnet conductors

some basics

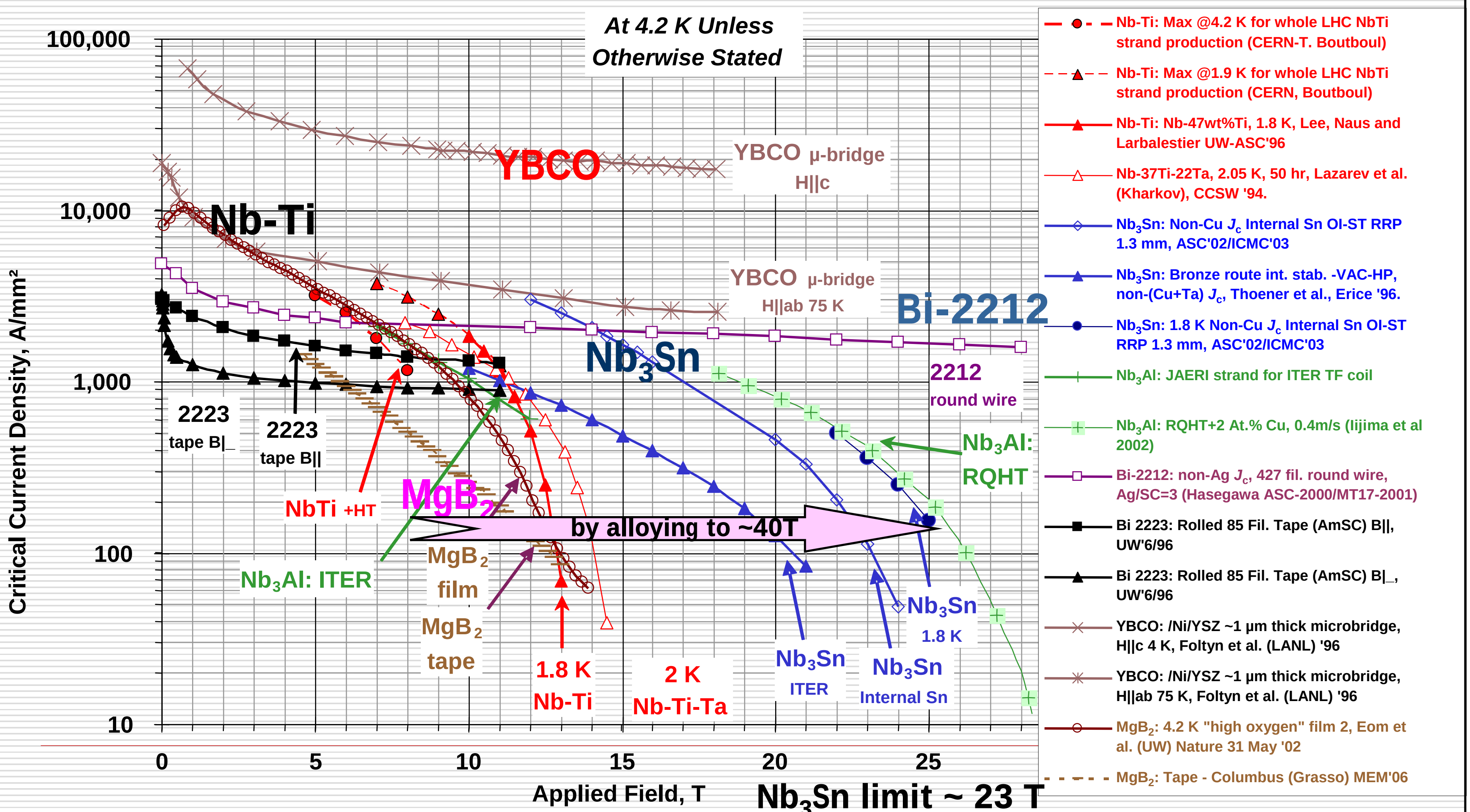
	Conductor manufacture	MF?	Shape	Isotropic	n-value	Coil manufacture	Material class
Bi2212	Powder-in-tube	Pseudo	Tape or Round	Yes or no	Low	R&W or W&R	Oxide
Bi2223	Powder-in-tube	Pseudo /yes	Tape	No	Mid	R&W	Oxide
YBCO	Deposition processing	No	Tape	No	High	R&W	Oxide
MgB_2	Powder-in-tube	Yes	Round	Yes	High	R&W or W&R	Boride

Magnet issues

- Conductor $J_c(B,T)$ & n-value
- Conductor I_c- strain and fatigue
- Conductor availability
- Packaging (insulation & reinforcement)
- Coil manufacturing: W&R v. R&W v. other
- Stability, quench detection, quench protection
- Irradiation: heat, damage, lifetime, activation
- Operating temperature
- Application specific issues (field profile, homogeneity, maintenance access, etc.)
- Reliability & impact of down time
- Cost

High field superconductors

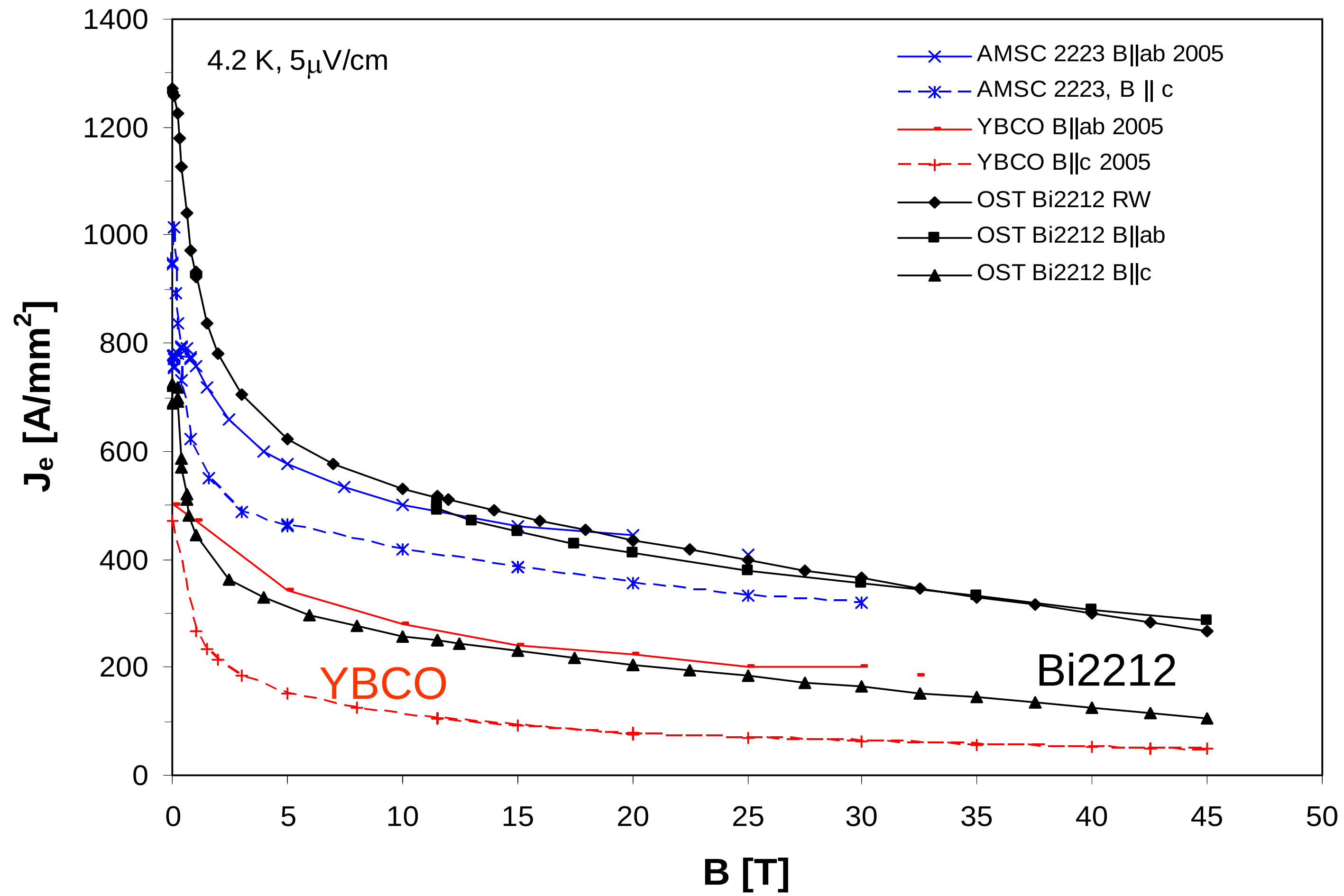
It all starts with J_c



Compilation courtesy of Peter Lee

J_e(B,4.2 K) of HTS Conductors

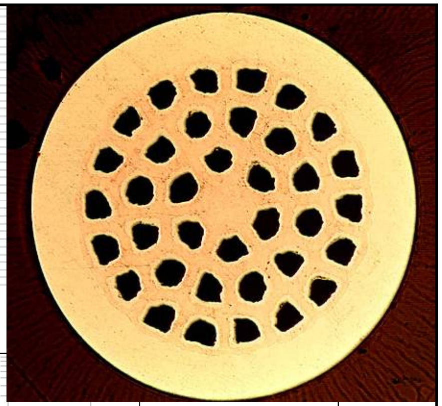
circa 2005

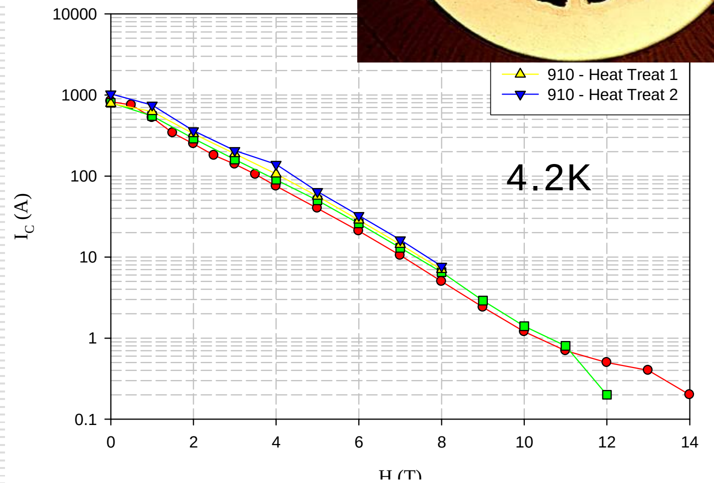


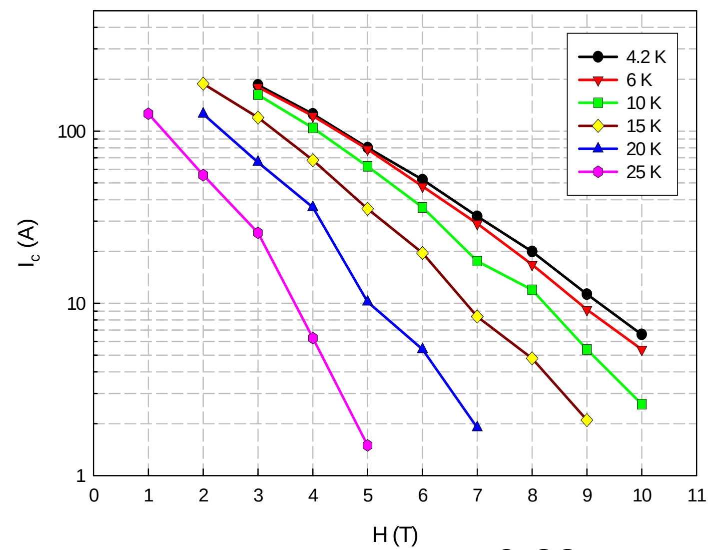
Unpublished data, Schwartz, Trociewitz, Weijers & Schneider-Muntau

Potential advantages of emerging conductors: MgB_2

- Potential for cost ~ NbTi with much higher magnetic field → primary driver
- Relatively easy transition to long lengths
- Perpendicular H_{c2} ~ 40T; paramagnetic limit > 100 T … potential for magnets above 30 T is real
- Three companies actively pursuing R&D
- ***Without elevated H_{c2}, unlikely to find niche***



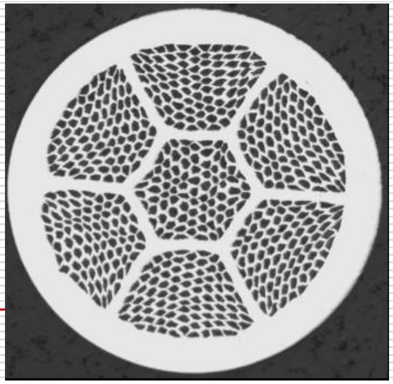




0.83 mm

Image & data courtesy of Hypertech

Potential advantages of emerging conductors: Bi2212



- High J_e at high field is driver … despite limited understanding … potential for significant further improvements!
- T_c~80 - 90 K; peak in $(J_c x B) v B$ ~ 45-50 T
- Potentially useful up to T~30 K
- Growing experience base with magnets
  - 2003- 25 T (5T + 20T); R&W tape conductor
  - 38 mm bore, 160 mm OD
  - Max stress 120 MPa, co-wound steel
  - J_w = 90 A/mm2
- Primary focus of NHMFL internal R&D program
  - Current series of small R&D test coils
  - Planned: 7 T round wire magnet operating in 18 T background
  - Springboard to 25-30 T user magnet
- ***Only round wire of HTS options***

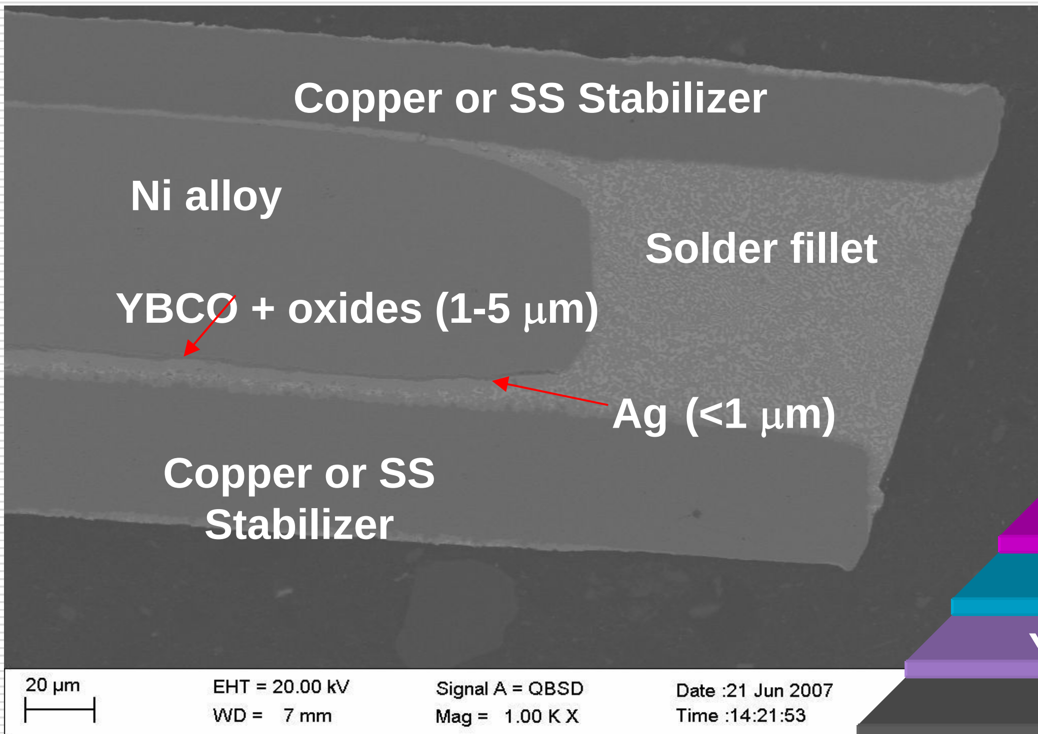
Wire image courtesy of OST

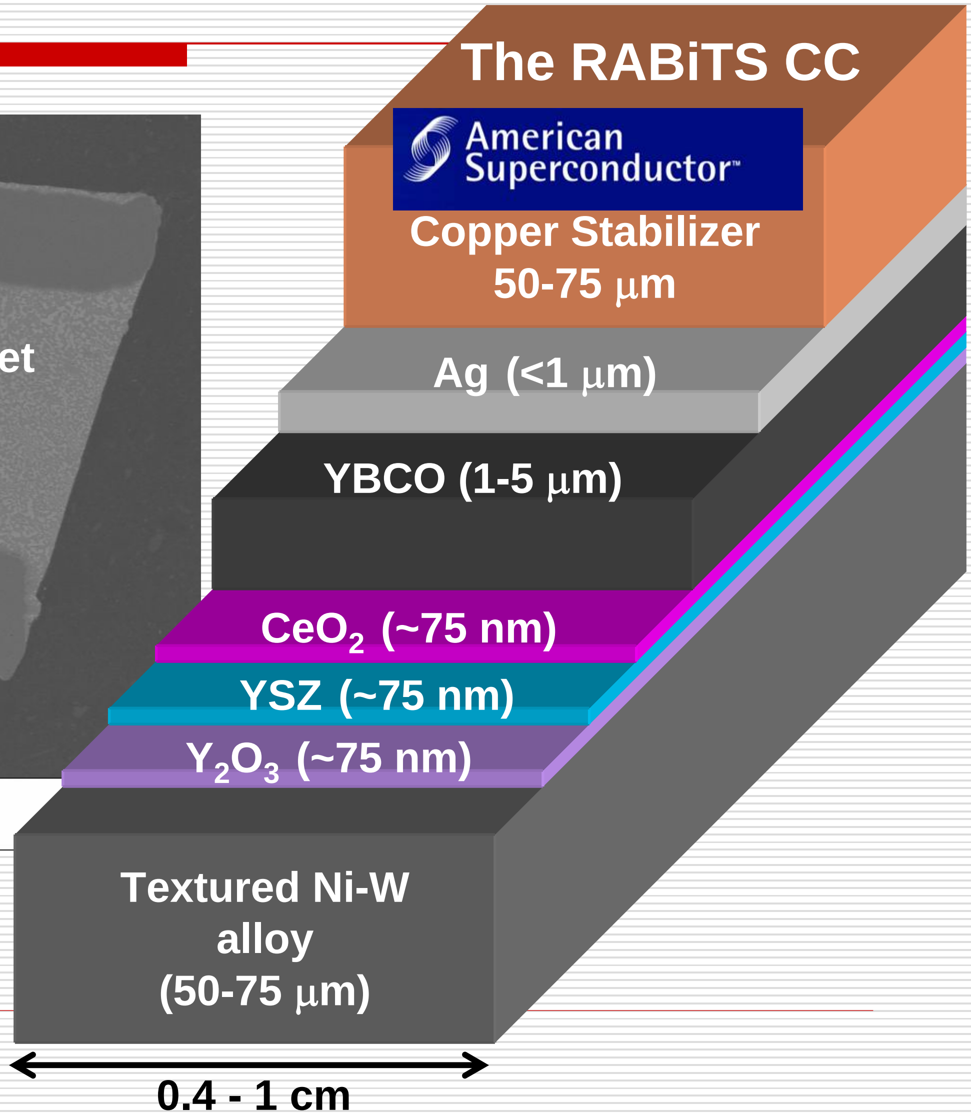
Potential advantages of emerging conductors: YBCO

- High J_c at high temperature is primary development driver for utility systems
- T_c~90 - 93 K; peak in $(J_c xB)vB$ > 45 T
- Pinning center engineering is work-in-progress
- Temperature a "design variable"
- Formed by deposition on Ni-alloy substrates
  - Much higher strength than BSCCO
  - Potentially much lower cost than BSCCO
- Present longest length ~ 200 m
- Already has ~uniform performance along length
- >300 km/yr industrial capacity expected by 12/07
- At present: demand > supply
- ***Broadest range of H-T space for magnets***

YBCO Coated Conductor

a sense of scale



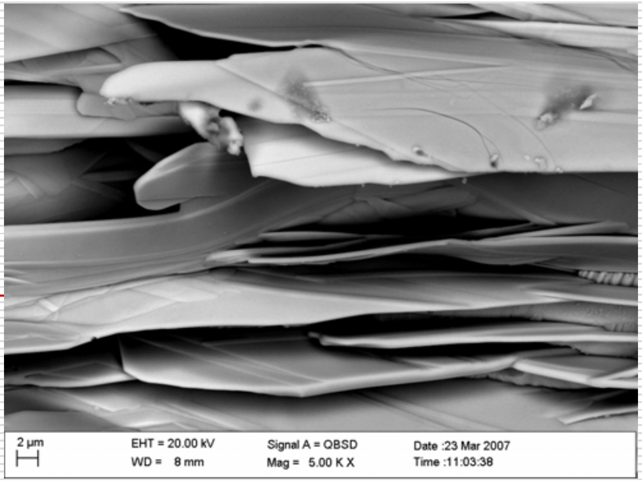


~1% fill factor!

Challenges of HTS

- Costs remain much higher than Nb_3Sn
  → HTS must become *enabling*
- Systems pull not firmly established
- Quench protection challenges
- Bi2212 & YBCO have conductor-specific challenges

Challenges of Bi2212



- Intrinsic problems
  - Cost of Ag
  - Low n-value
- Requires partial-melt heat treatment in oxygen
  - Leakage of Bi2212 liquid in W&R coils
  - Severely limits options for insulation, reinforcement, monitoring
- Strain sensitivity limits R&W coils for high field
  - R&W might be viable for low field, high T magnets
- Integrated coil manufacturing remains elusive
- Poorly understood technology -- often “mysterious” behavior
  - Why does round wire have higher J_e than either orientation of tape?
  - “Best” microstructures often have lowest J_c
  - Why do coils with more leakage often have higher I_c?
  - Where & why does current flow?
  - What really makes n-value low?
- Homogeneity (electrical & mechanical) is performance limiting (but improving)

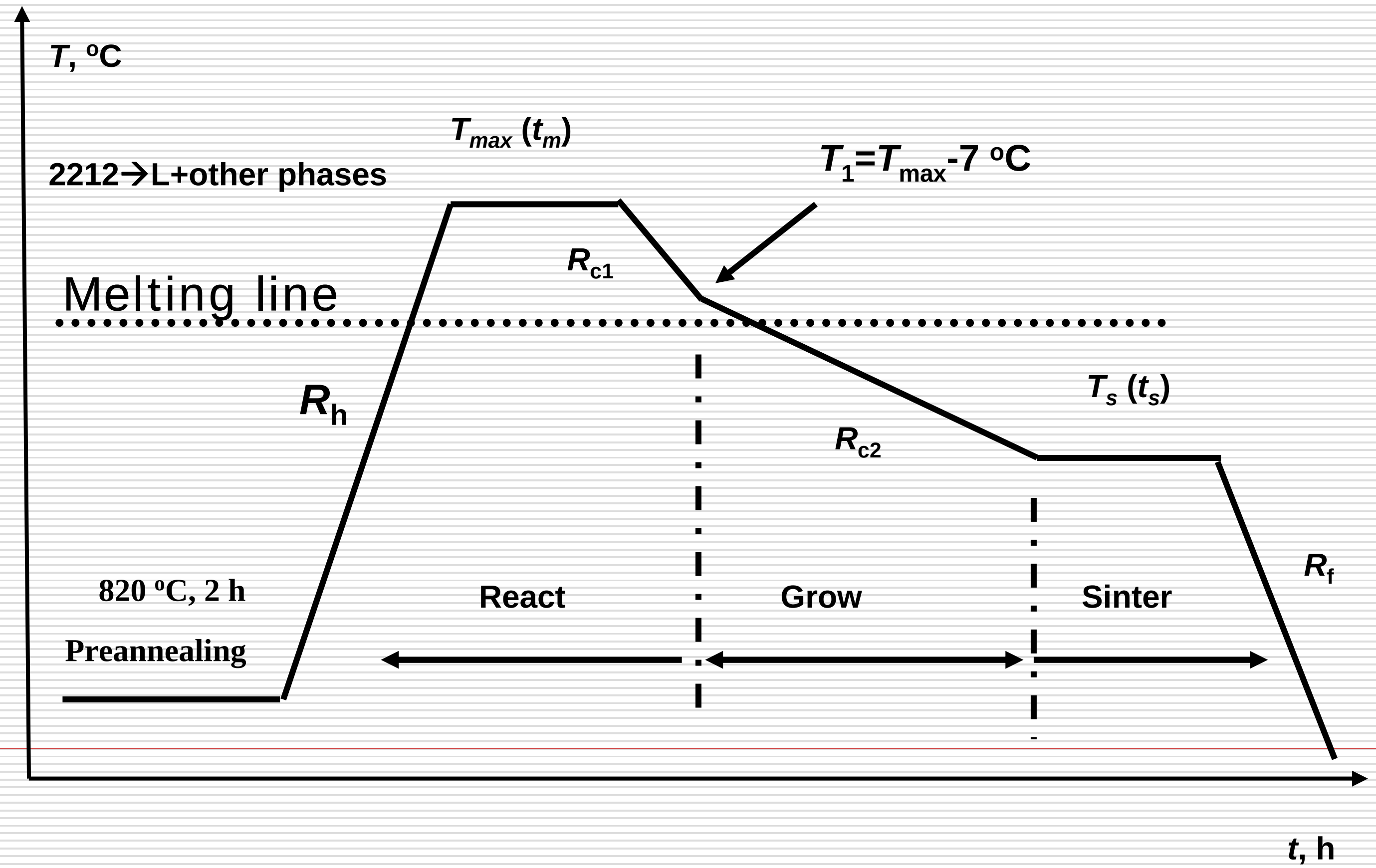
Image by Jianyi Jiang ASC-NHMFL

Challenges of YBCO CCs

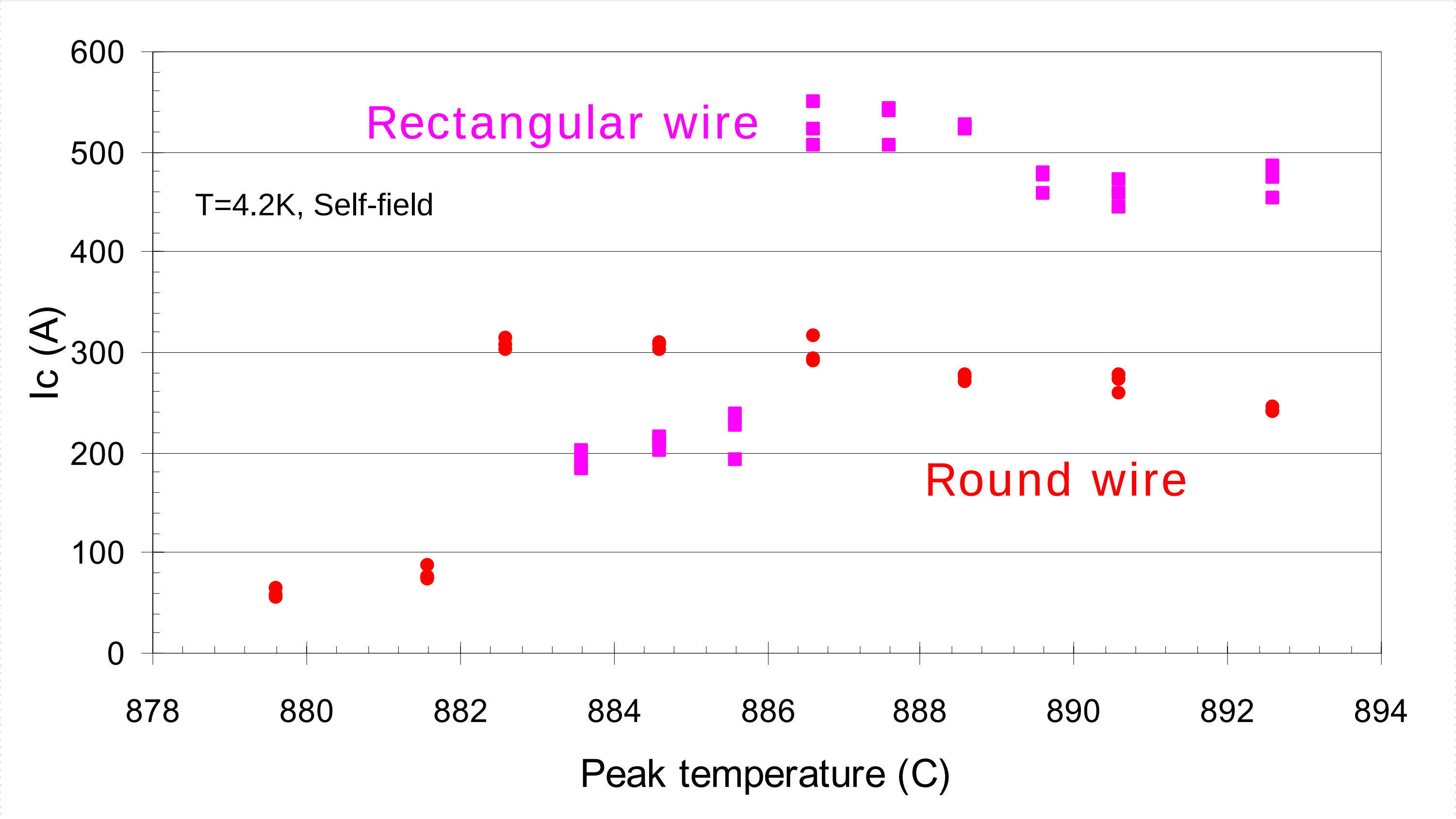
- Intrinsic problems
  - Only available as high aspect ratio tape conductors
  - Only R&W possible
  - Anisotropic electromagnetic behavior
  - Minimal flexibility in operating current
  - Complex architecture
  - Cabling challenging
  - High J_c but not high J_e
  - Turn-to-turn insulation further reduces J_e (intrinsic problem for tape relative to round wire)
- Coupled quench/strain behavior observed

Conventional Bi2212 processing

- Melt-step essential for J_c but also source of leakage in coils (but not short samples)



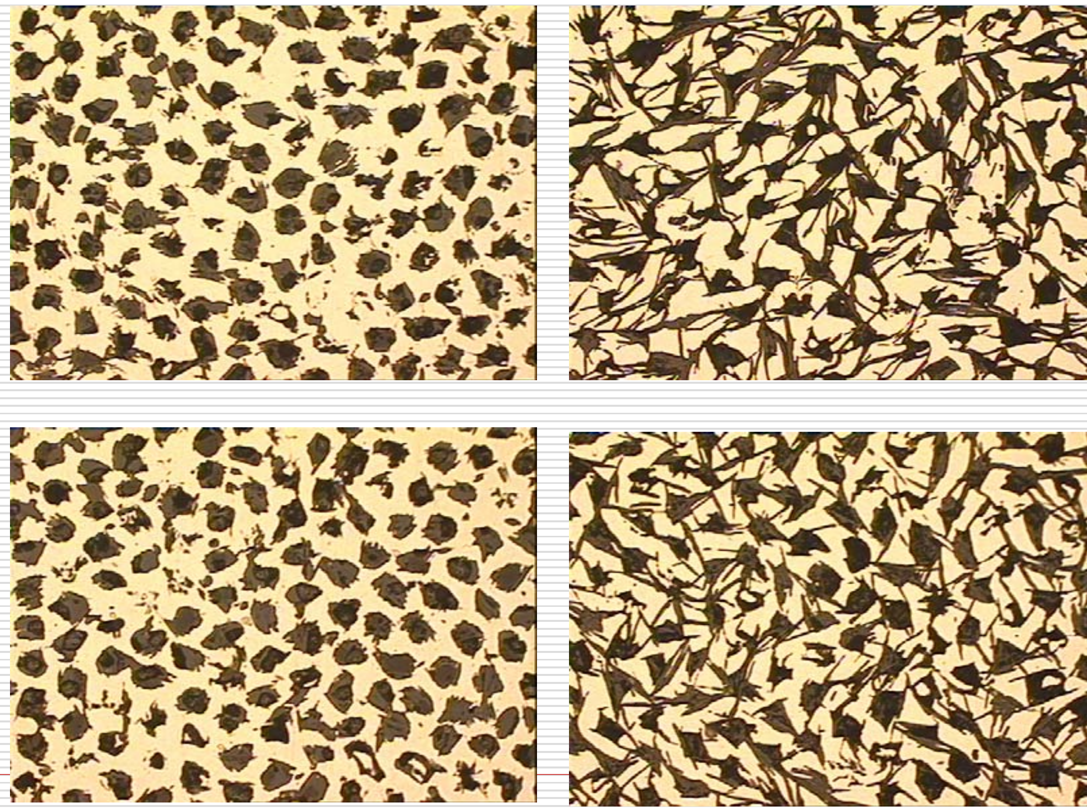
Bi2212 requires partial melting!



Xiaotao Liu (wire provided by Supercon Inc.)

Importance of melting

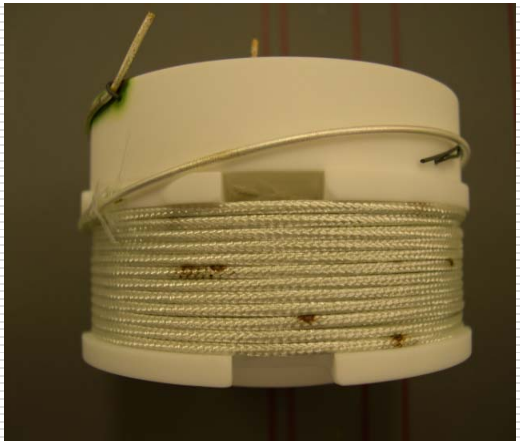
- Filaments v Current … guess which has high J_c



Bi2212 coils: leakage & performance

- Leakage is a complex issue that may be related to
  - Ag/insulation interactions
  - Ag/Bi2212 melt interactions
  - Bending (tension in Ag?)
  - Other factors
- Understanding and mitigating leakage is a primary focus of NHMFL-ASC program

TC2007-003



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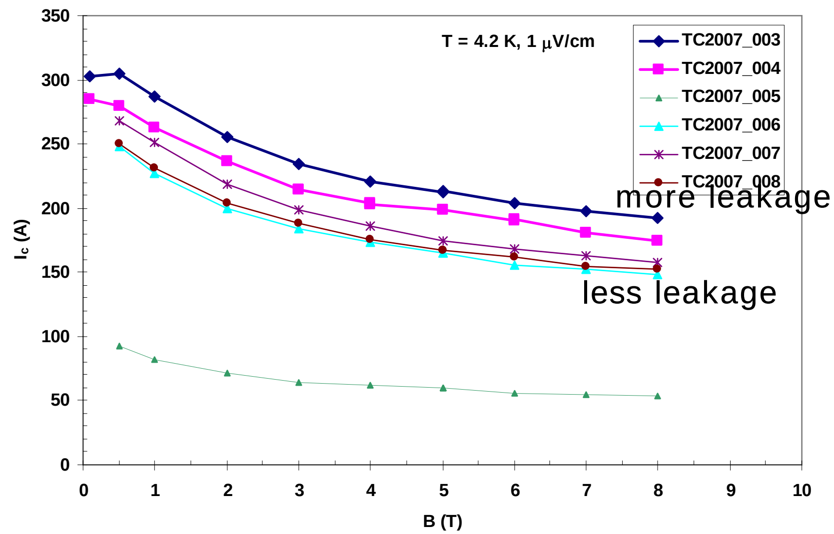
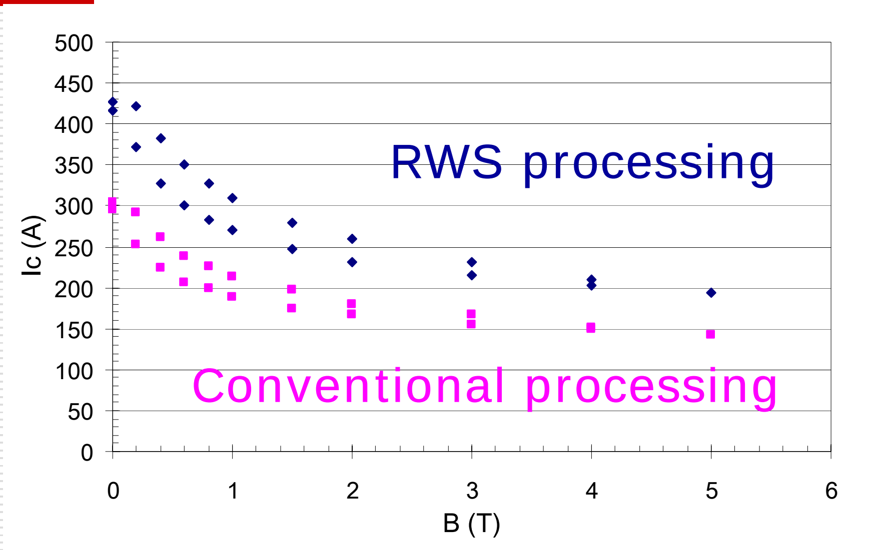
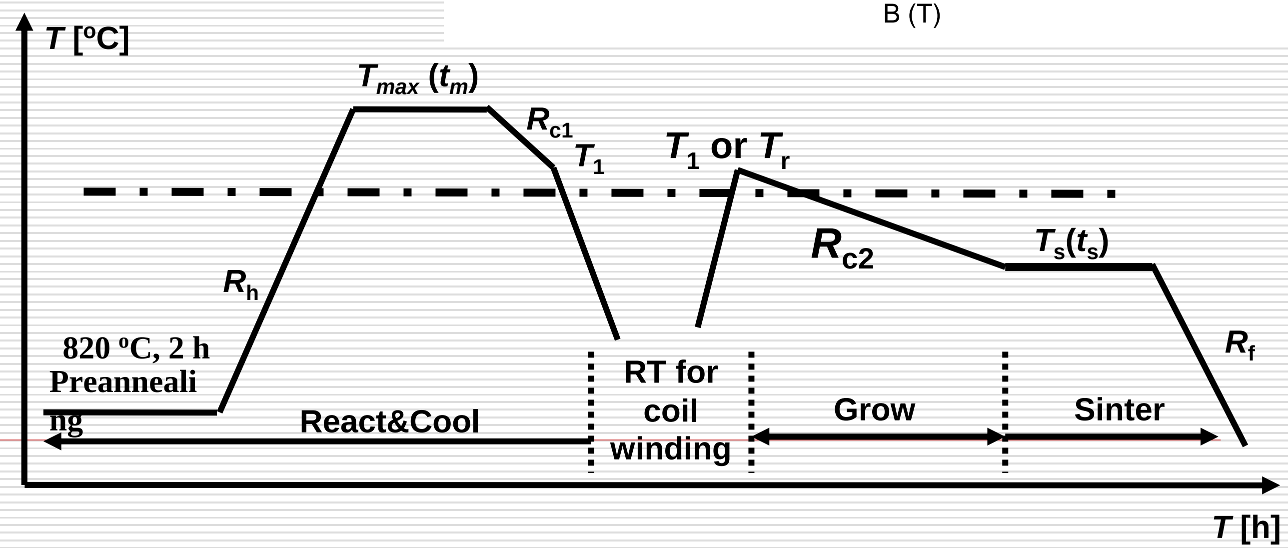


Ulf Trociewitz, NHMFL-ASC

Alternative process

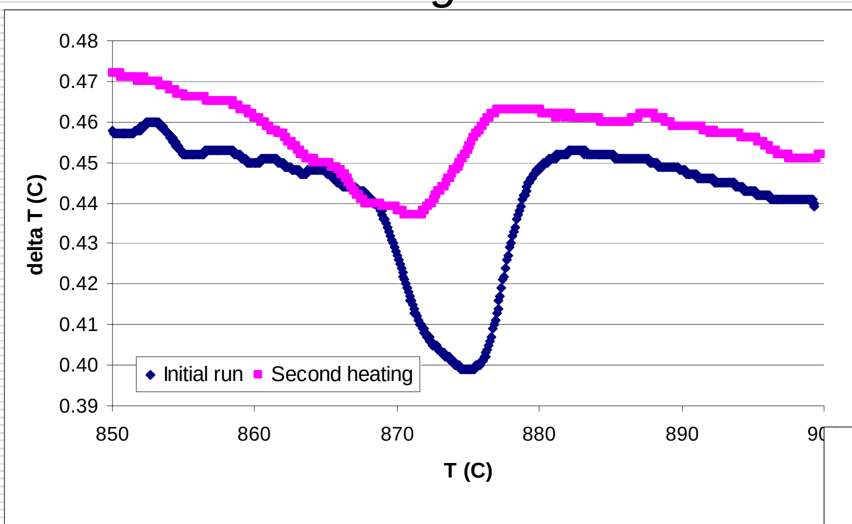
- W&R: leakage & materials compatibility problems
- R&W: mechanical problems (bending strain)
- *React-wind-sinter to avoid both?*



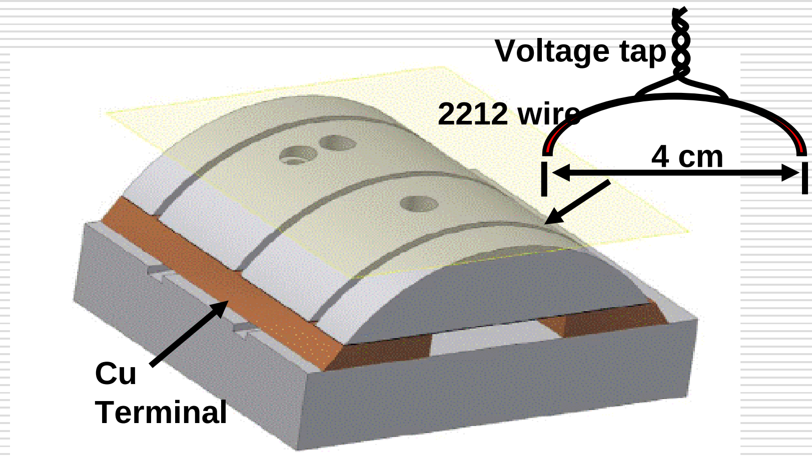


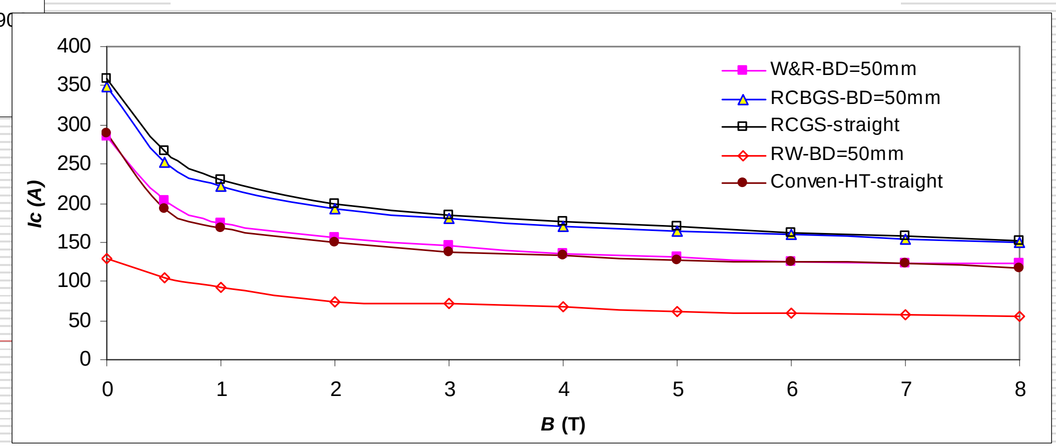
More RWS data … more questions

- Do we really reheat only within the solid state … *so will leakage be avoided?*



- Is the strain state like W&R?



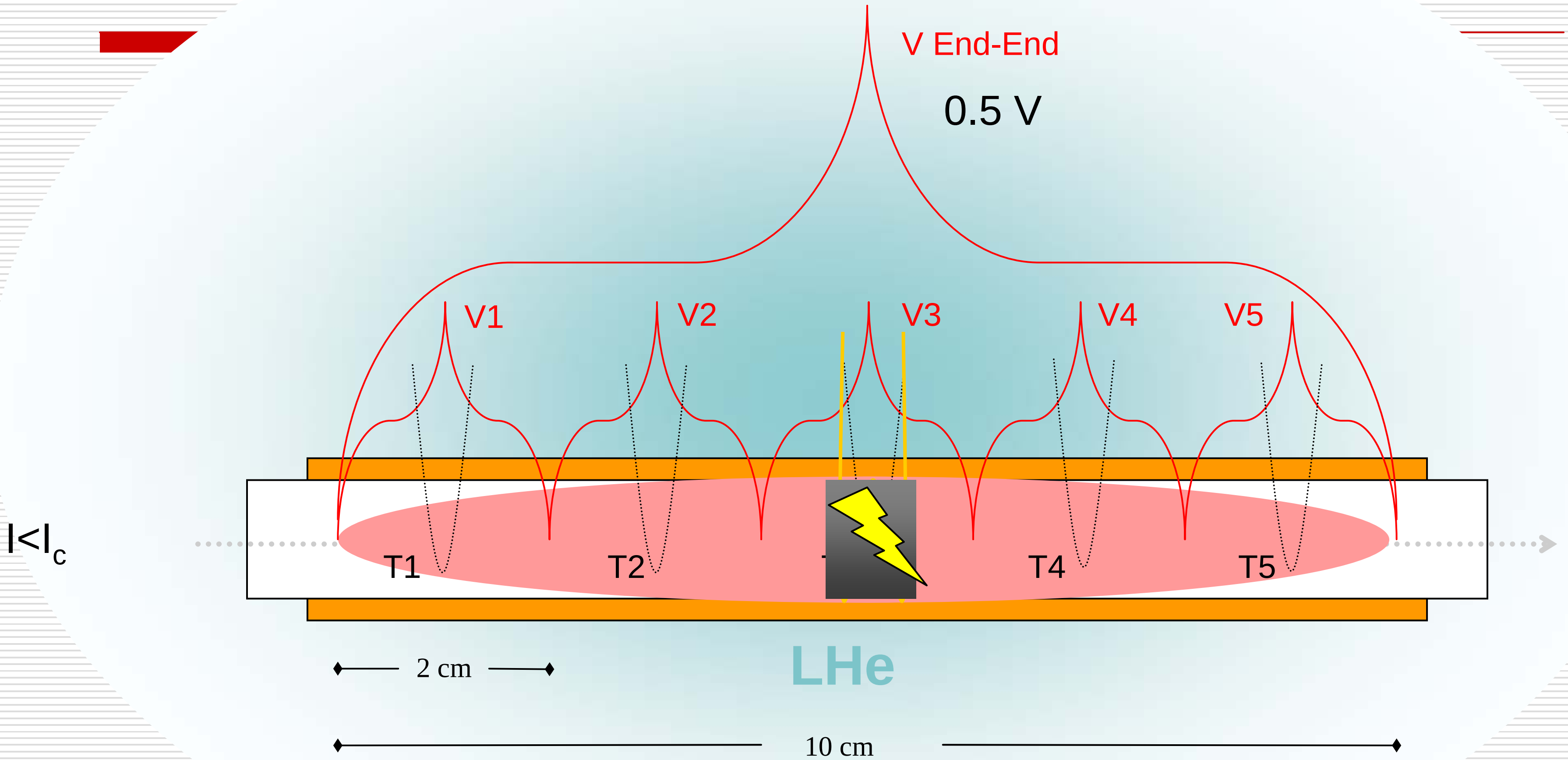


David Myers, NHMFL-ASC

Quench protection

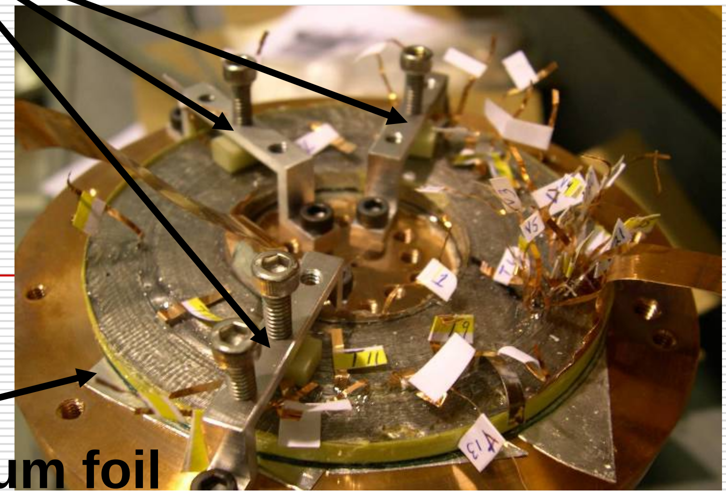
- Magnets must either be
  - Disposable & easily replaced
  - “Infinitely” stable
  - Protected
  - N.B. If YBCO does NOT require stabilizer, J_e triples
- Protection requires
  - Detection → typically depends on propagation
  - Understanding of operational limits before failure
  - Protective response
- Studies of:
  - Bi2212 & MgB_2 wires & tapes in LHe
  - Bi2212 coil
  - YBCO tapes and coils at variable temperatures w/cryocooler, variable architectures
- *We ask:*
  - *What are MQE & NZPV?*
  - *What does it take to make the conductor fail catastrophically?*
  - *Does NON-catastrophic quenching effect electromechanical behavior?*

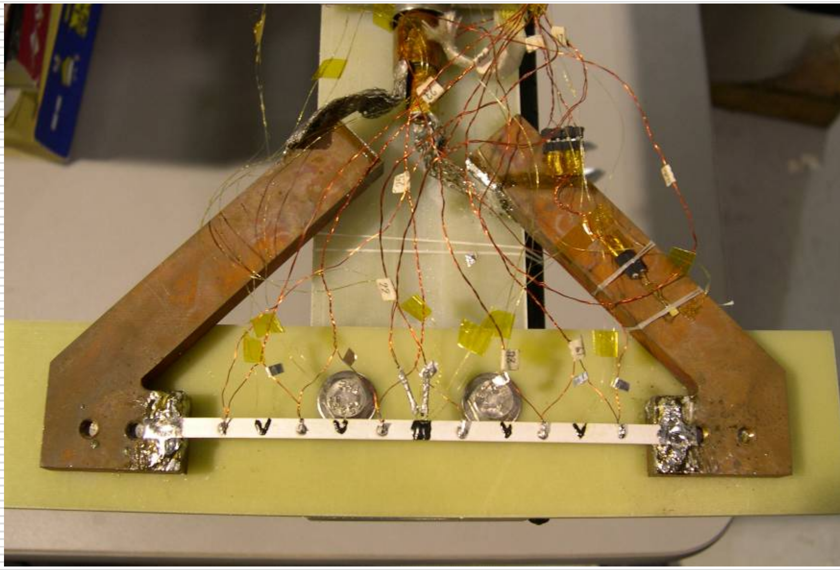
Quench studies: experimental approach



Tim Effio, NHMFL-ASC

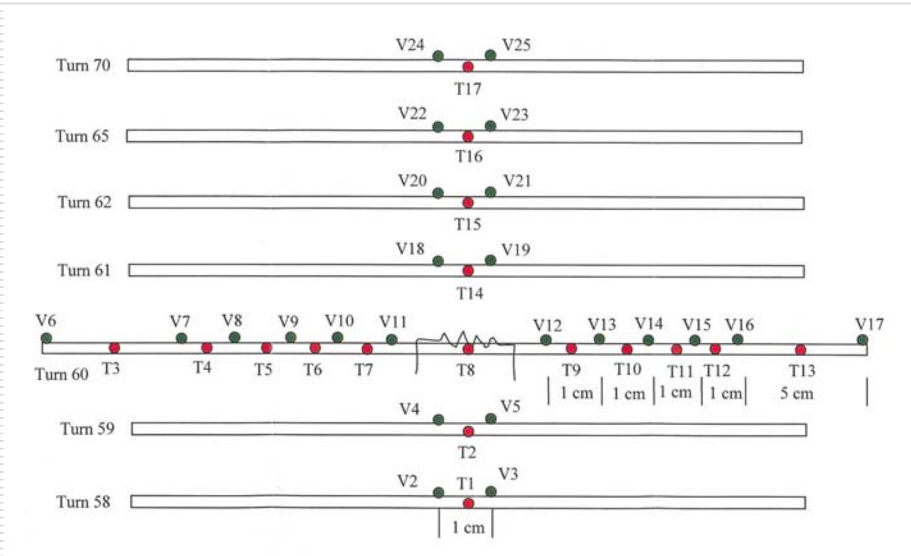
Quench studies: devices

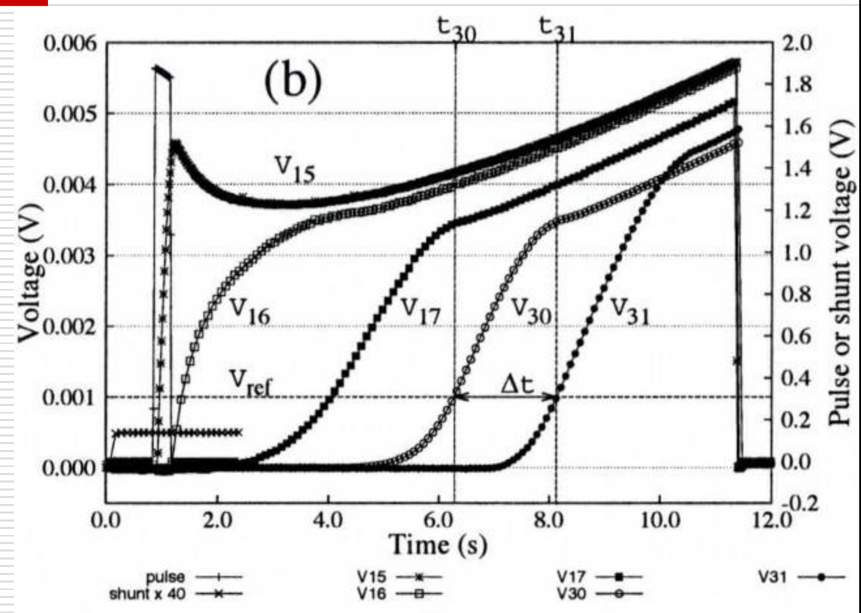


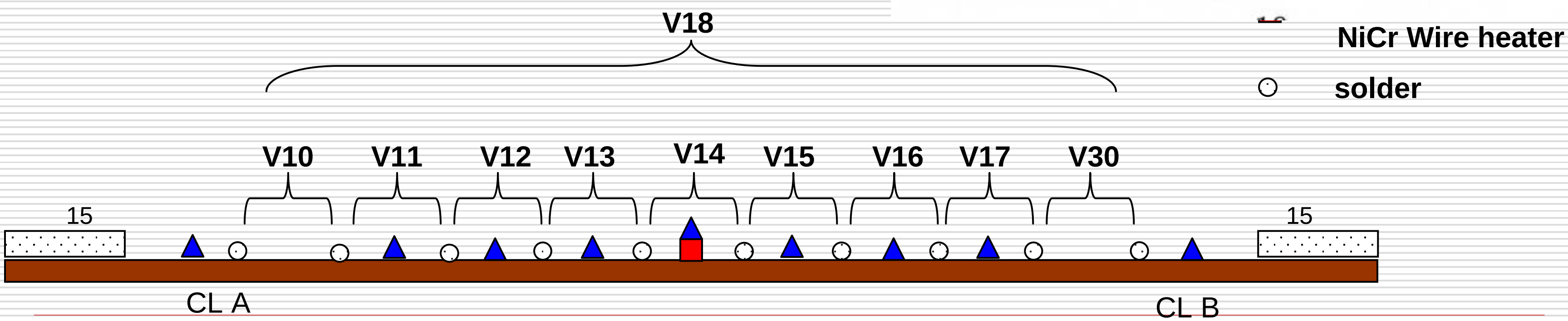


X.R. Wang, U.P. Trociewitz and J. Schwartz, *J Appl Phys* **101**(5) 053904 (2007)

Quench studies: wiring & typical data

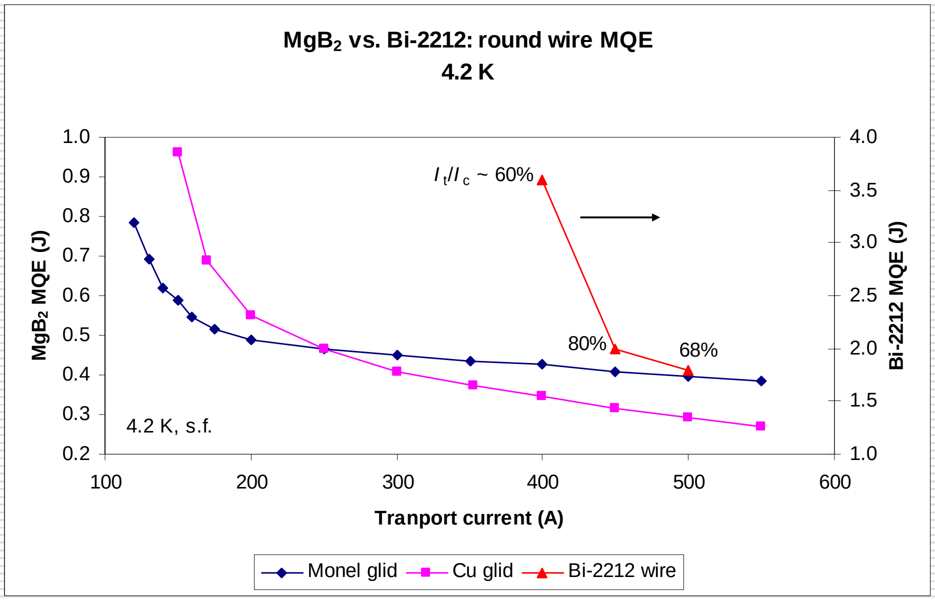


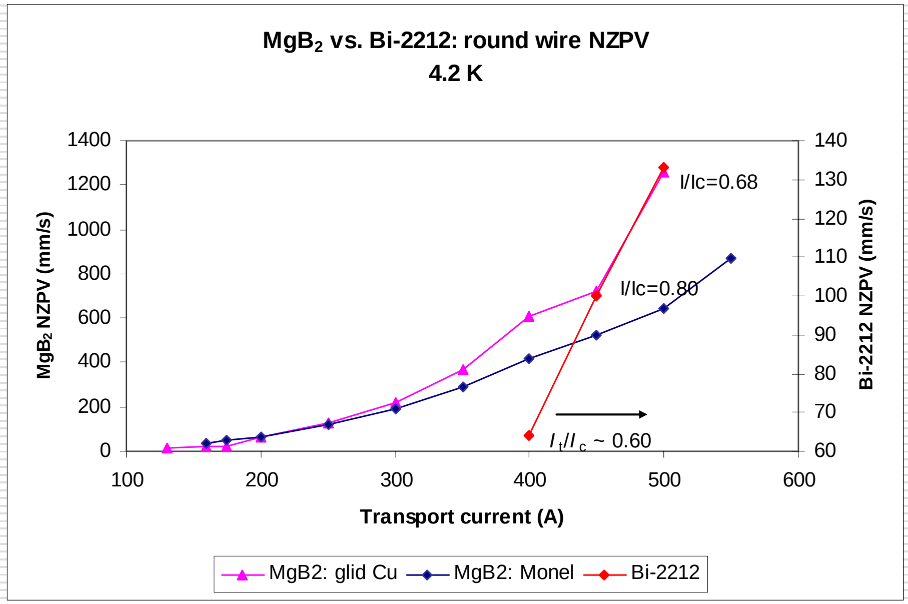




X.R. Wang, U.P. Trociewitz and J. Schwartz, *J Appl Phys* **101**(5) 053904 (2007)

Quench results: MgB_2 & Bi2212



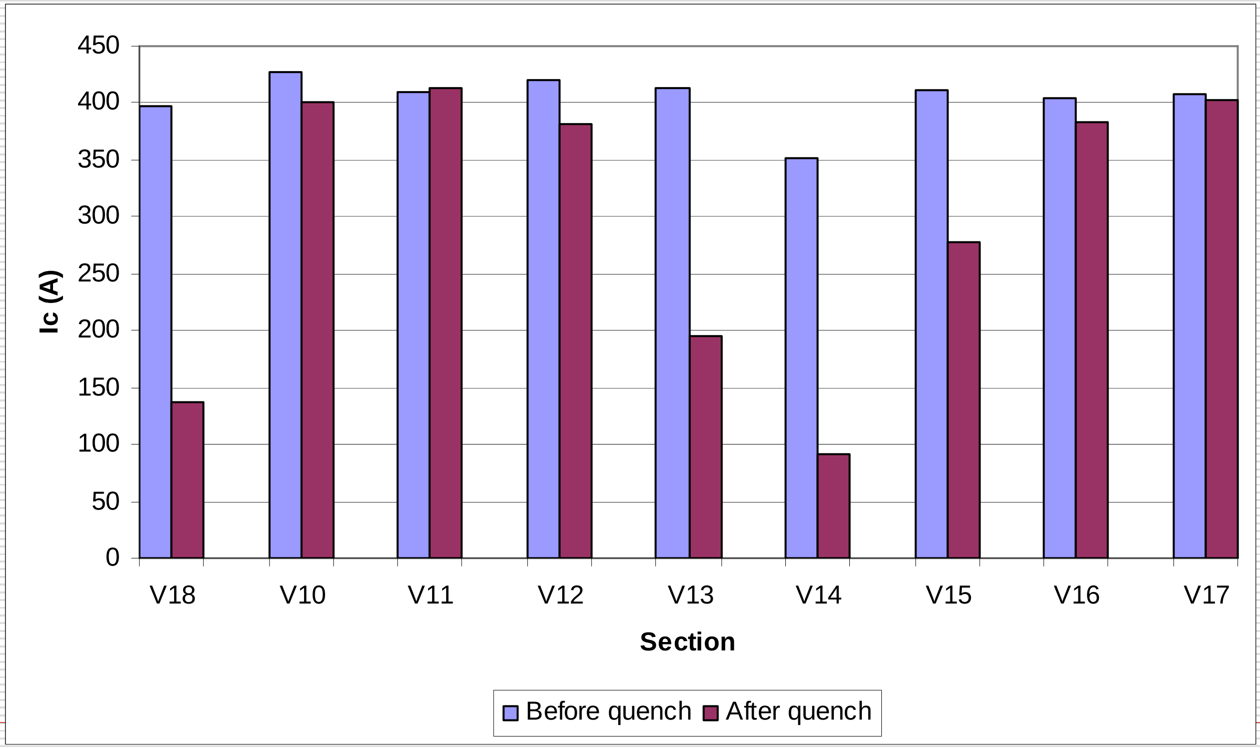


4.2 K propagation velocity ~ 10 cm/s for Bi2212, 50 cm/s for MgB_2

Tim Effio & Xiaorong Wang, NHMFL-ASC

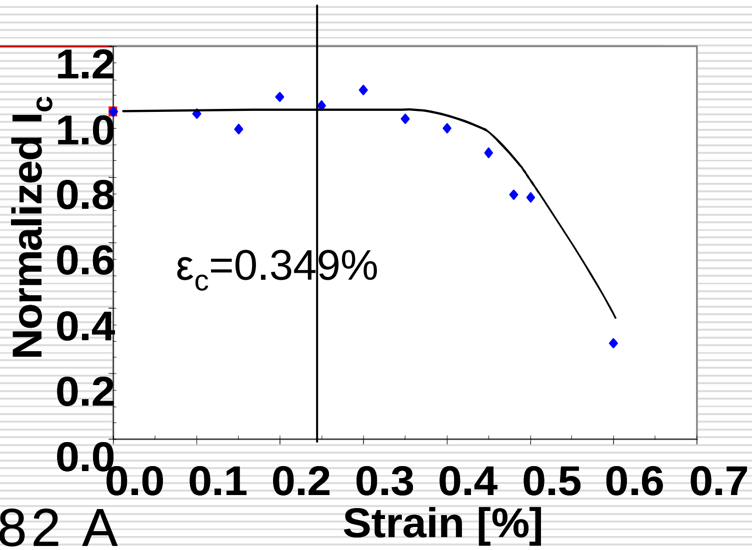
Quench induced degradation: Bi2212 tape

- In **ALL** quenches in Bi2212 tapes, I_c degraded
- Bi2212 round wires: quench not always catastrophic



Weibull study of mechanical & electrical failure

Bi2212 tape conductors circa 2003

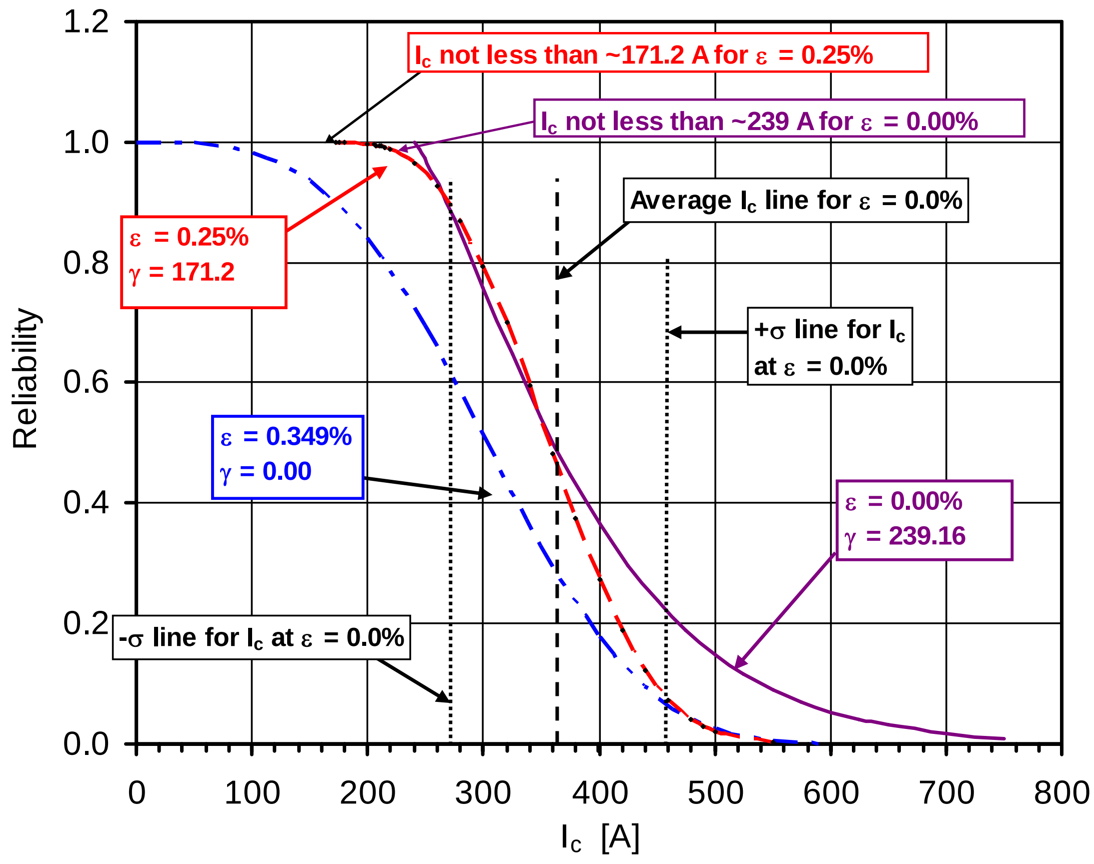


- Three parameter Weibull distributions
  - $F(x;\alpha,\beta,g)=1-e-\{(x-g)/\alpha\}\beta$
- Bi2212 tape
  - Batch avg I_c = 379.88 A, σ = 87.82 A
  - E = 70 GPa, σ_y(2% offset)= 119 MPa, σ_u = 127.5 MPa
- 24 replications samples
  - ε=0.00%, 0.25% and ε =ε_y=0.349% (72 samples total)

A. Mbaruku & J. Schwartz, J. Appl. Phys. **101**(7) 073913 2007

Weibull study results

Bi2212 tape conductors circa 2003

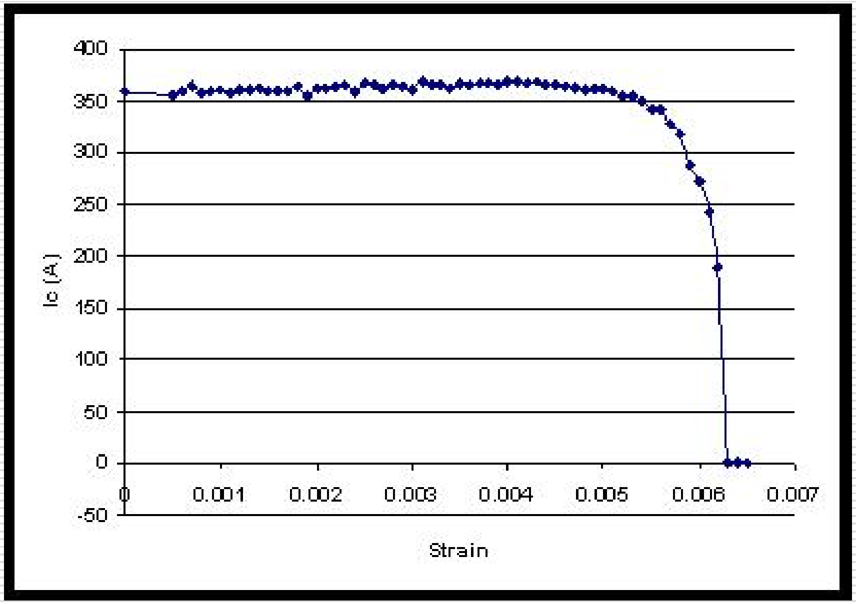


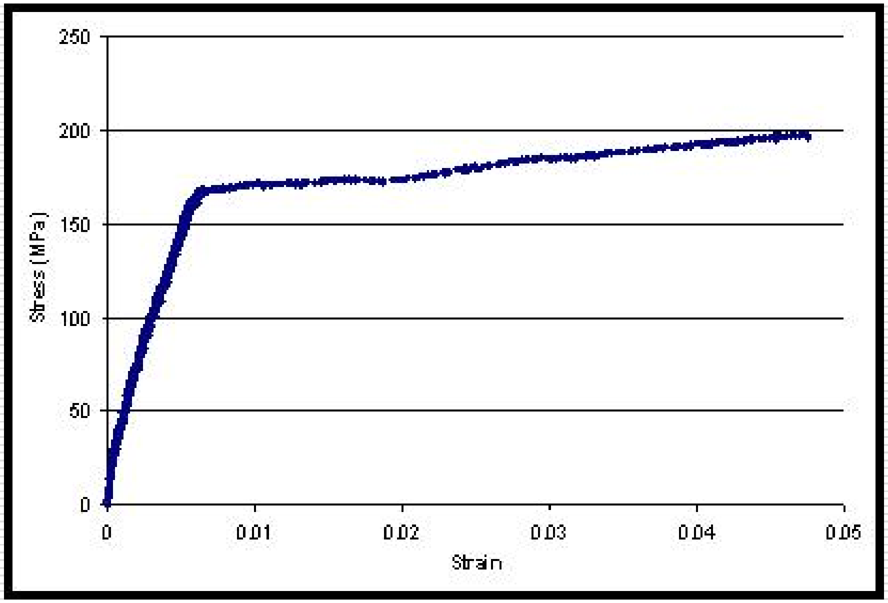
A. Mbaruku & J. Schwartz, J. Appl. Phys. **101**(7) 073913 2007

Bi2212 I_c-strain

round wire circa 2006

- Does increased critical strain also results in quench resistance & homogeneity? ... Weibull study in progress

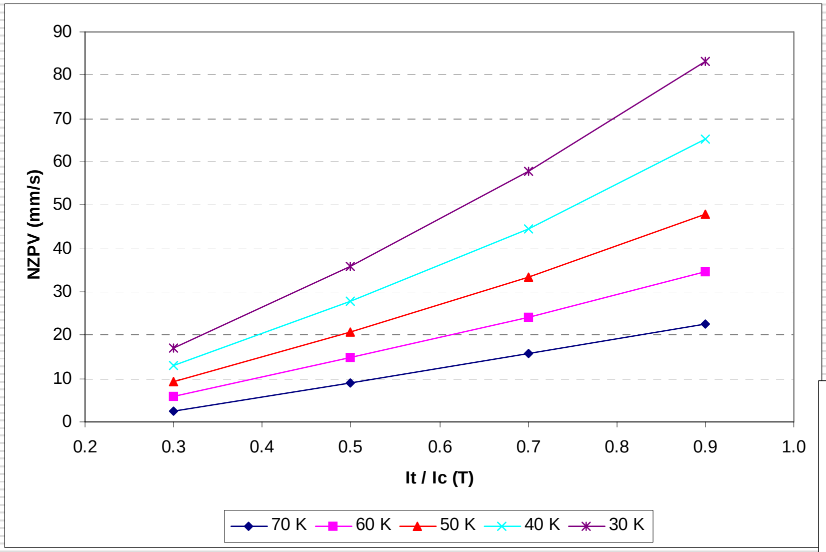


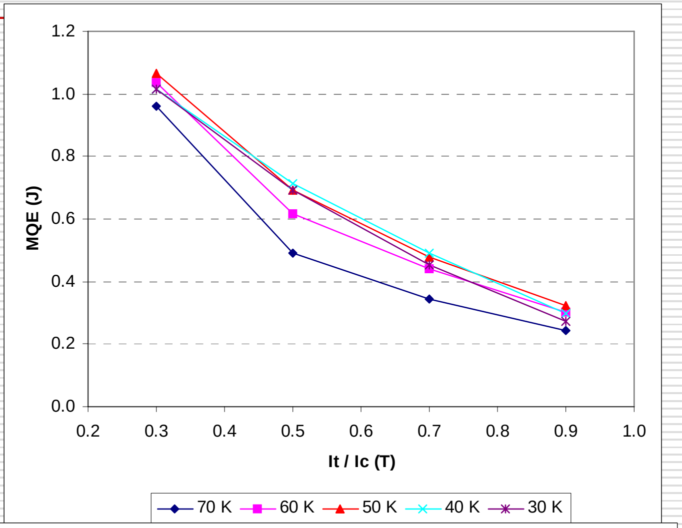


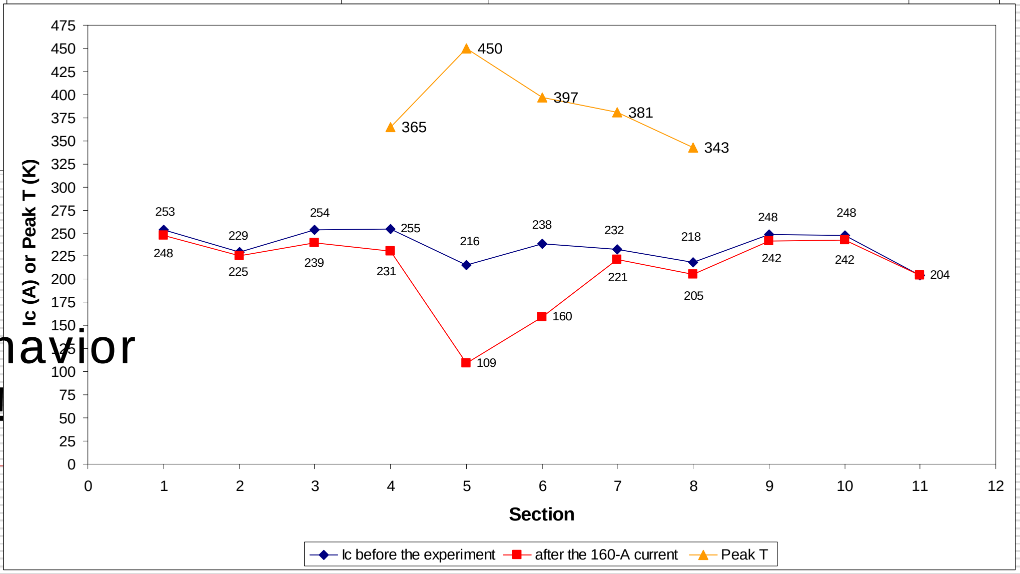
Quang Le, NHMFL-ASC

Quench behavior of YBCO CC

propagation velocities ~ 1-5 cm/s



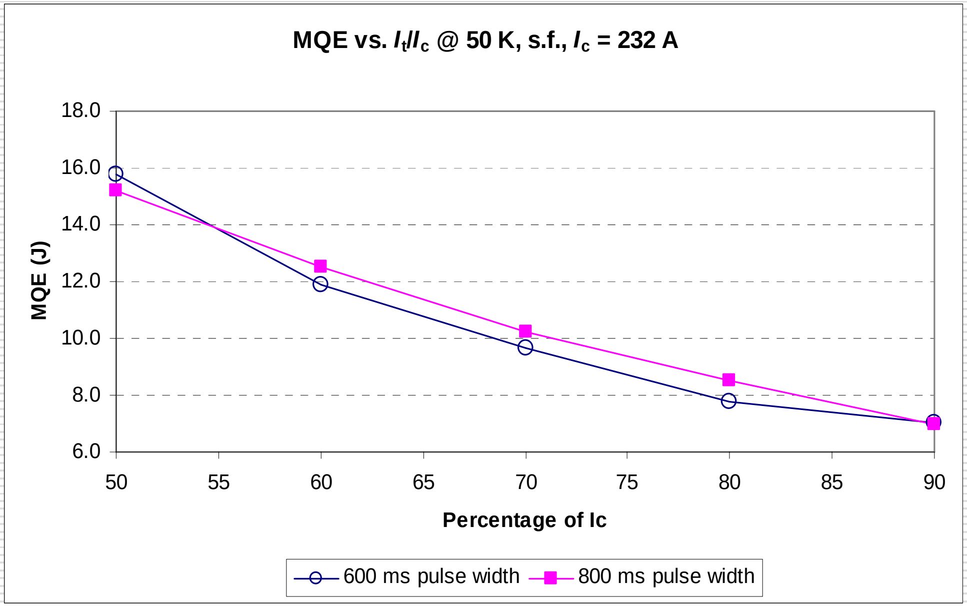


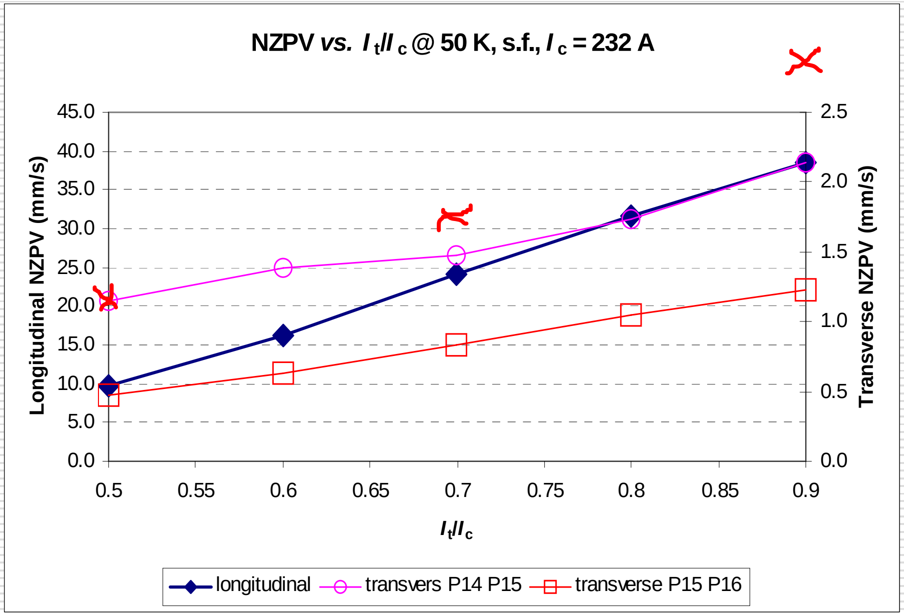


Quench also altered I_c-strain behavior – even in non-degraded regions!

Xiaorong Wang, NHMFL-ASC

YBCO CC coil quench results

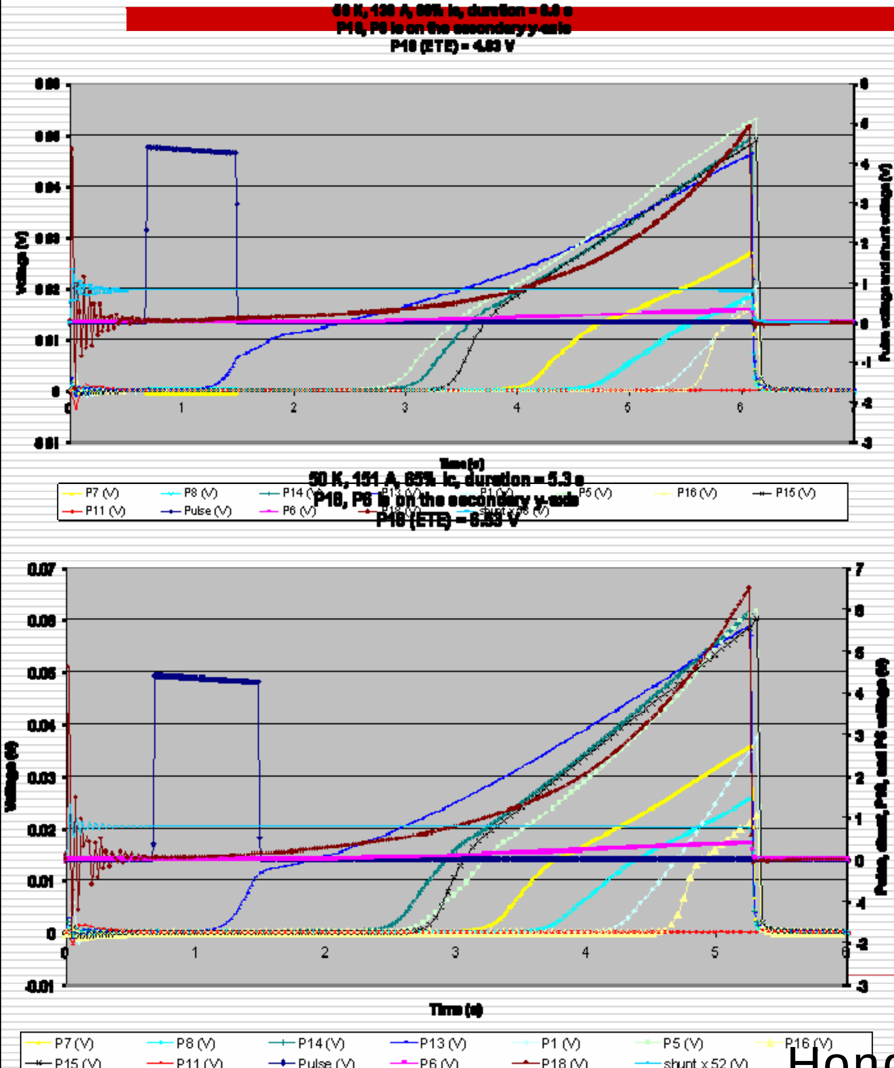


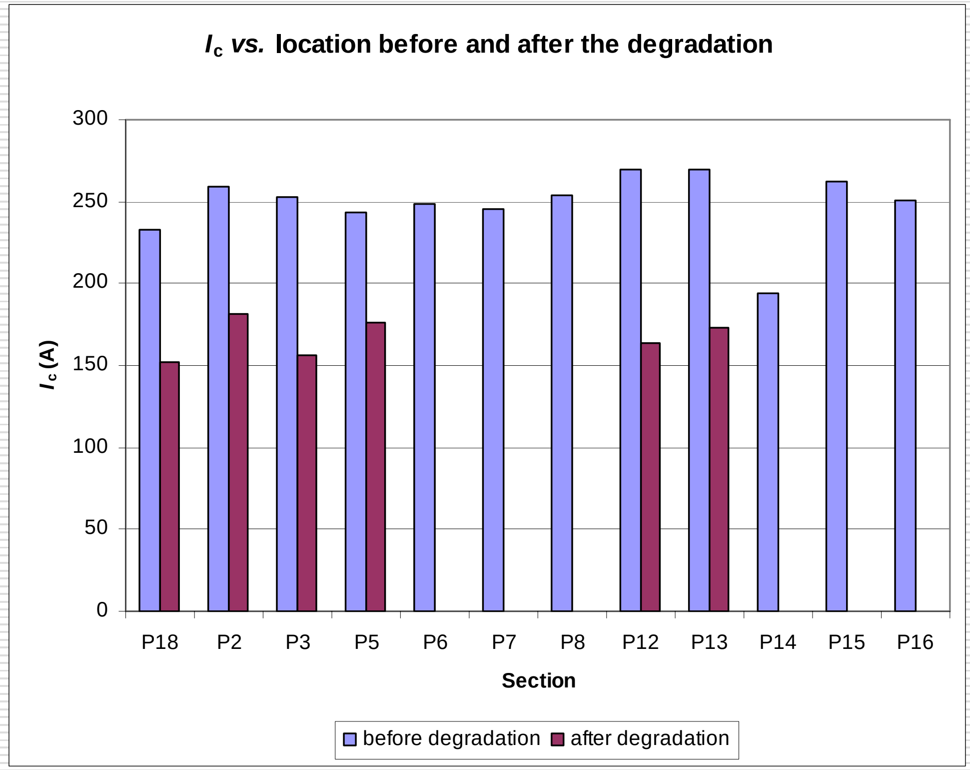


Slow longitudinal and transverse propagation observed;
Slower than straight sample
T: 60K → 95K in ~5-6 seconds

Honghai Song & Xiaorong Wang, NHMFL-ASC

YBCO CC coil quenches
No early warning signs for failure!





Honghai Song & Xiaorong Wang, NHMFL-ASC

Summary & Conclusions

- Bi2212 & YBCO are potentially enabling technology for higher fields and irradiation resistance
- Bi2212 has more significant challenges than YBCO, but is preferred for high field, low temperature magnets
- Both materials have coil packaging/manufacturing challenges that must be addressed
- Both materials have significant quench detection & protection problems
- Both materials show coupled quench-electromechanical issues
- ***Will accelerators be a driver for HTS development?***