NC STATE UNIVERSITY

Applied (High Temperature) Superconductivity

Academic Training
Lecture 4

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CERN/Geneva
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SCHWARTZ GROUP

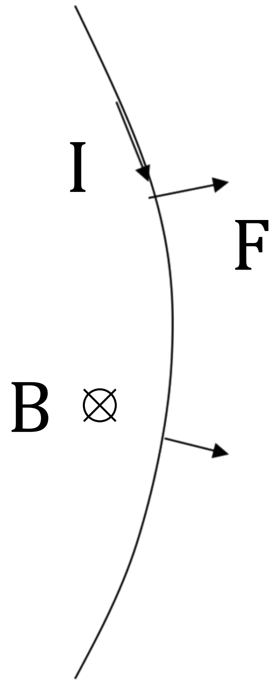
Department of Materials Science and Engineering

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
- 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

Electromechanical behavior – why care?

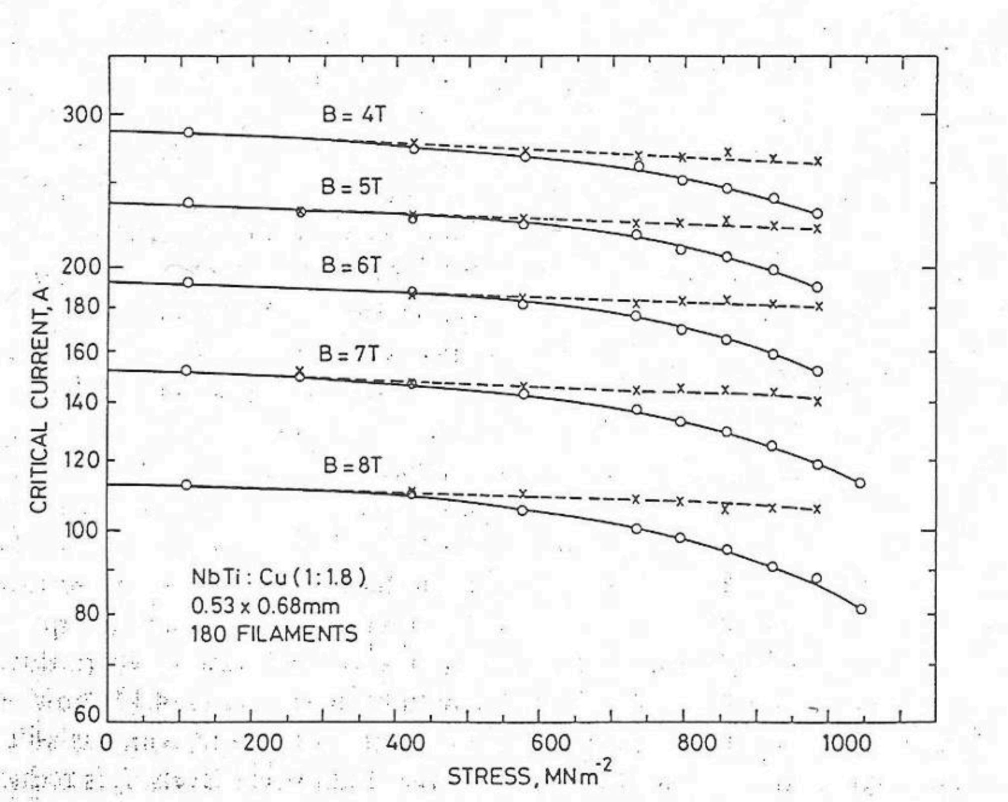
- Pressure affects H_{c2} and T_c (and thus J_c)
- Sources of strain in magnets
  - Bending and possibly torsion during magnet construction
  - Differential contraction during cool down after processing
  - Lorentz forces during operation: single cycle and fatigue
  - Thermal cycling
  - Fault conditions
  - Cables add additional complexities



- What type of materials are superconductors?
  - NbTi: ductile metal
  - Nb_3Sn: brittle intermetallic
  - Bi2212: brittle, micaceous ceramic w/ porosity & multiple secondary phases
  - YBCO → brittle but dense ceramic, deposited on high strength, ductile metal

Electromechanics of NbTi

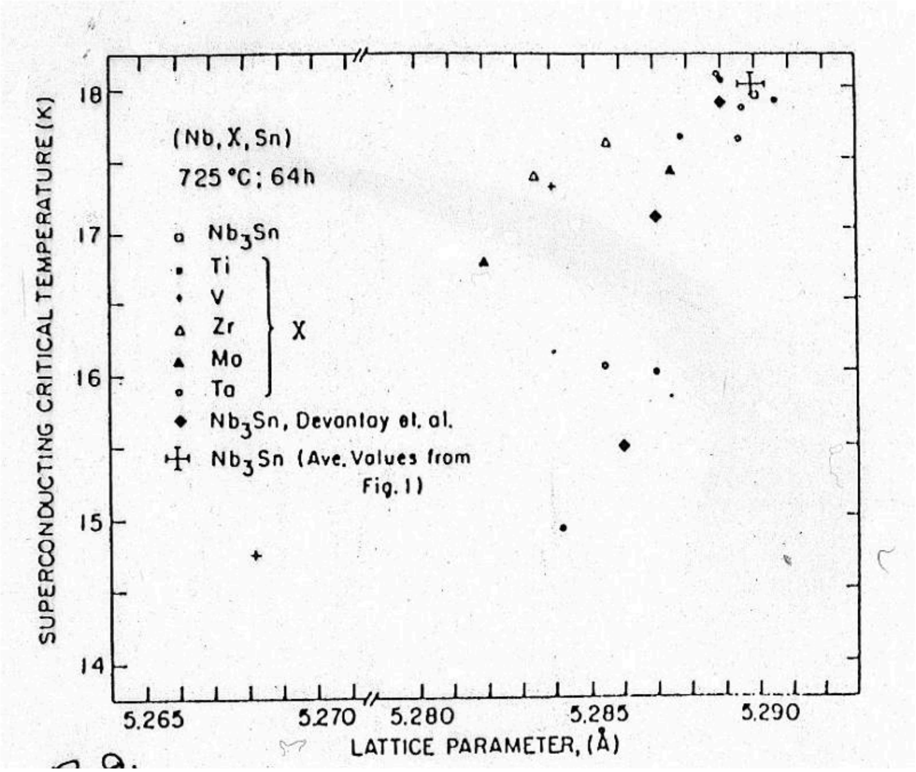
- Strain affects are largely reversible up to 2%, at which point the filaments break
- Composite behavior close to “rule of mixtures” combination of Cu and NbTi filament behaviors

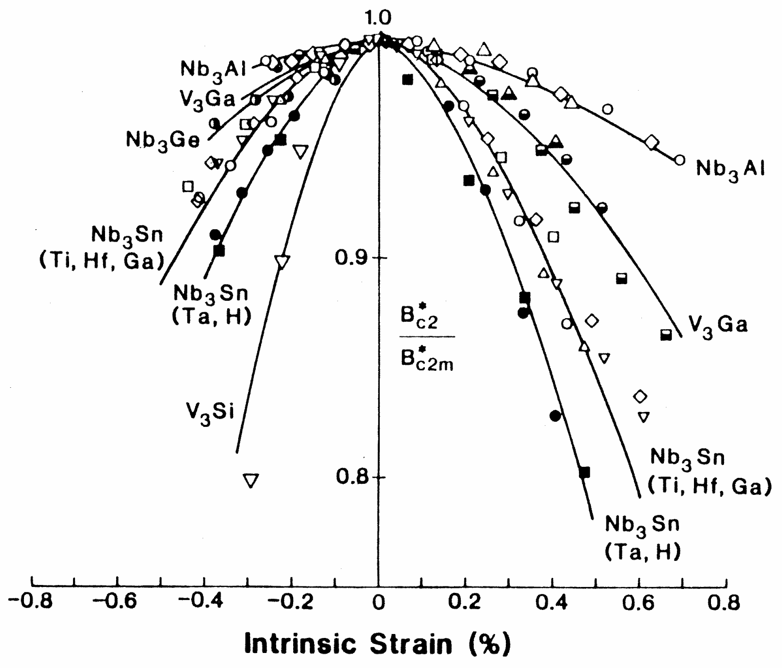


Electromechanics of Nb_3Sn

- Nb_3Sn sufficiently brittle that all magnets are “wind & react” → heat treatment is “last step”
- Lattice parameter changes (reversible) affect T_c & H_{c2}
- Microcracking & fracture (irreversible)
- Plastic deformation of matrix (Cu or bronze)

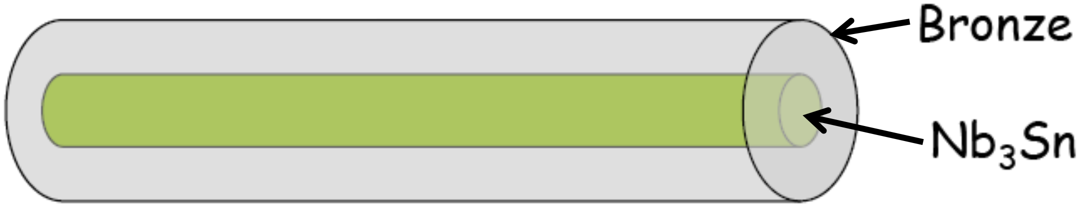
Effects on critical properties Nb_3Sn & other A15s





Pre-compression (of Nb_3Sn)

- Composite of bronze and Nb_3Sn is processed at high temperature ≈ 700 C (1000 K) then cooled to 4.2 K for operatio

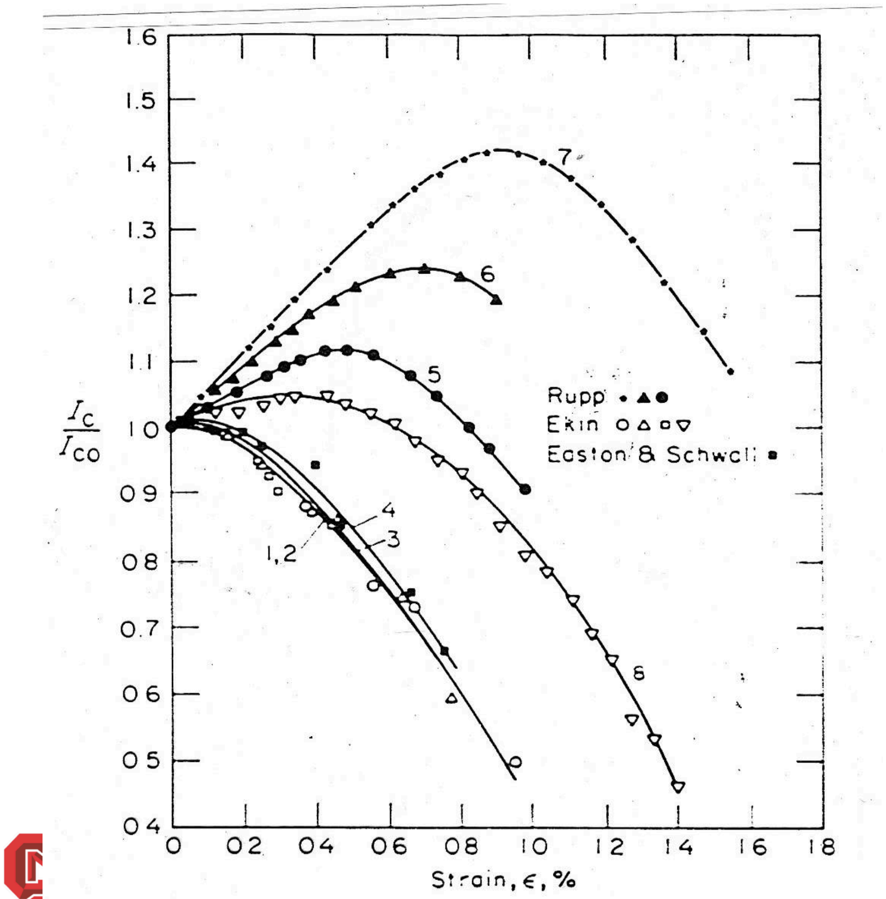


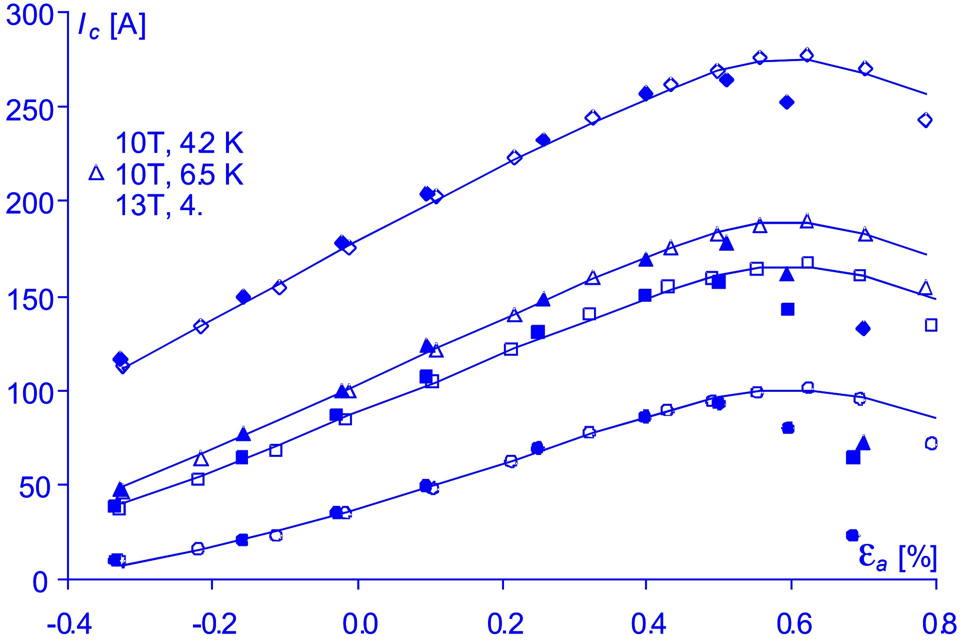
- Integrated thermal contraction:

$$\sigma_{Nb_3Sn} = \underbrace{\left(\left.\frac{\Delta L}{L}\right|_{Nb_3Sn} - \left.\frac{\Delta L}{L}\right|_{Br} \right)}_{\approx 1\%} \left(\frac{E_{Nb_3Sn} E_{Br}}{EA_{Nb_3Sn} + EA_{Br}} \right) A_{Br}$$

Effects of pre-compression

- Effect depends on Nb_3Sn:metal ration (Cu, bronze…)
- Pre-compression can be good for magnets





ITER Nb_3Sn cables

- Pre-compression varies with cable design
- Cross-over points in cables cause transverse pressure which can be problematic

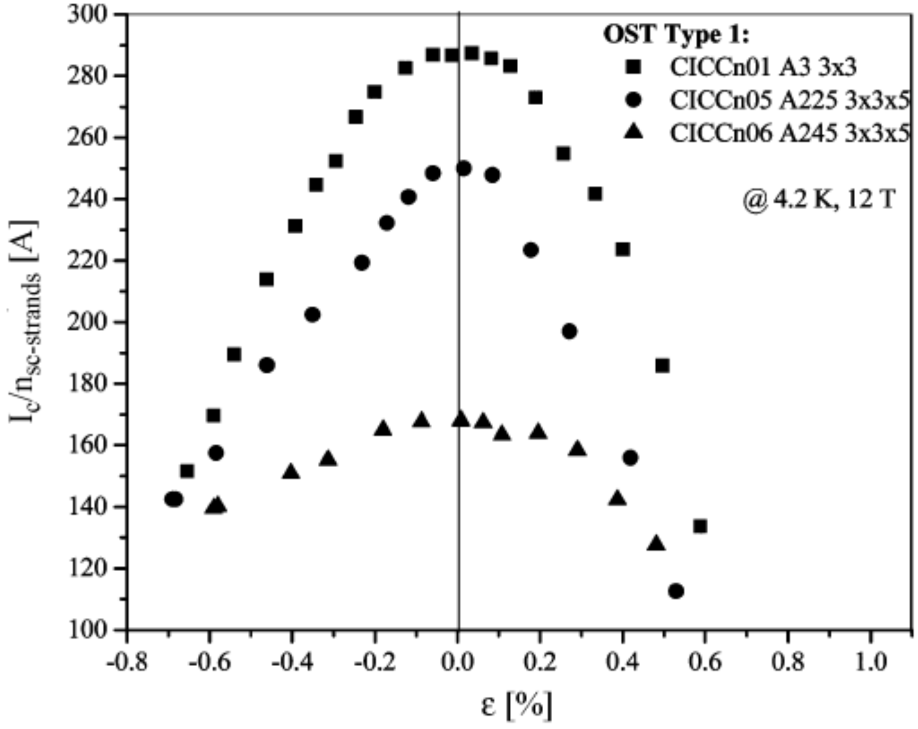


Fig. 4. $I_c(\varepsilon)$ for sub-stage CICCs manufactured from OST Type 1 strand measured at 4.2 K and 12 T.

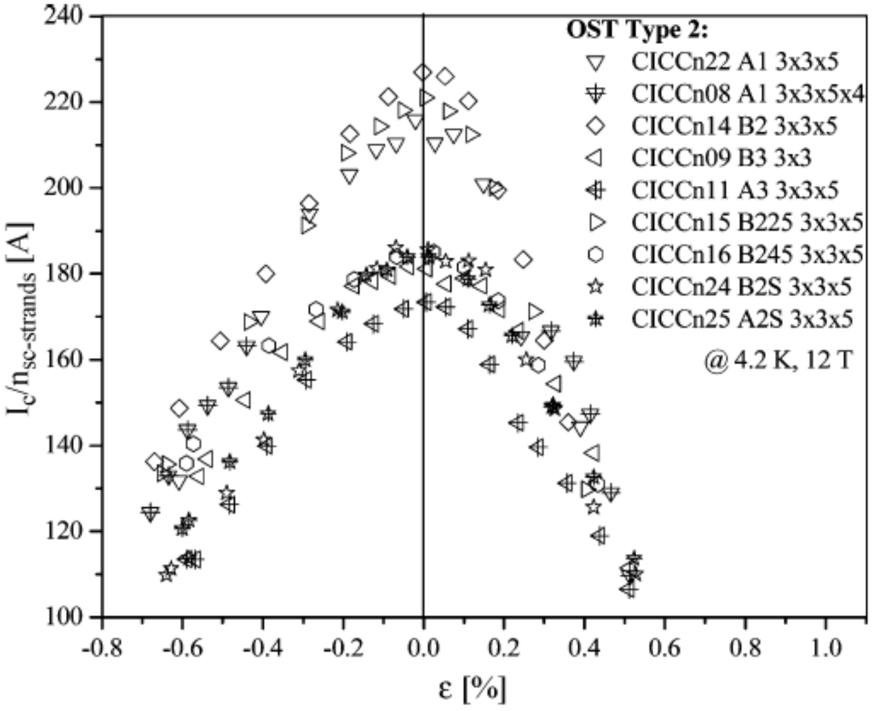


Fig. 5. $I_c(\varepsilon)$ for sub-stage CICCs manufactured from OST Type 2 strand measured at 4.2 K and 12 T.

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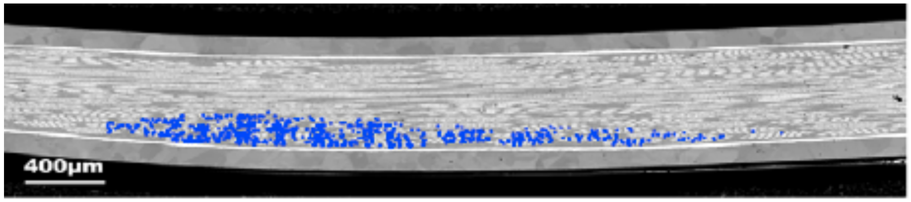
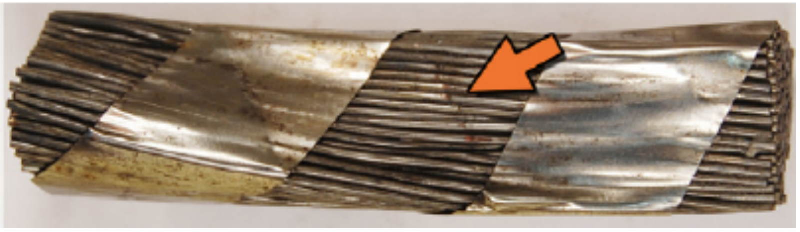
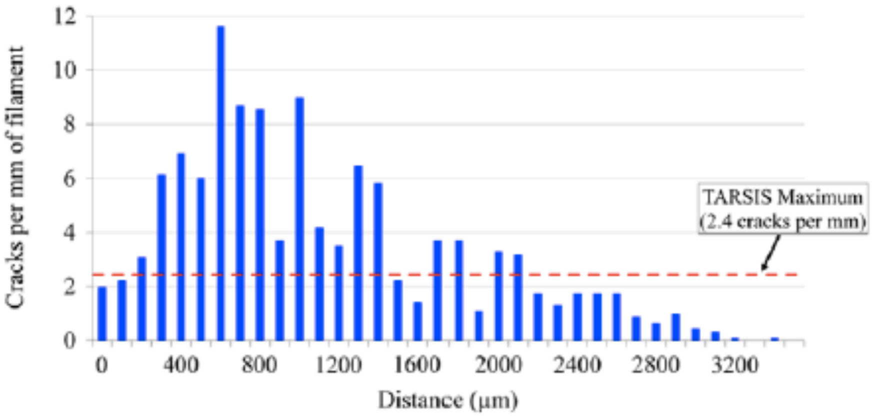
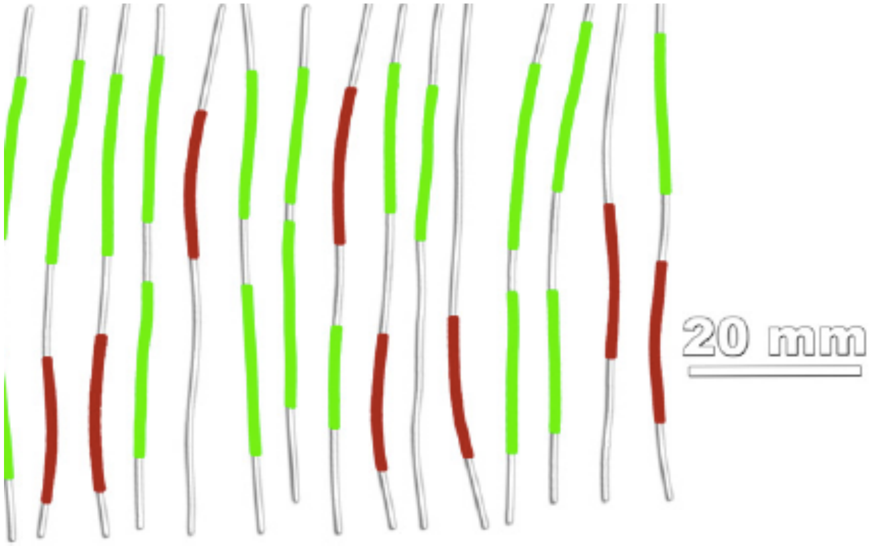
ITER cables show other problems can arise

- ITER studies have shown unanticipated results in CICC – degradation in Nb_3Sn not seen in NbTi
- Local filament fracture can be attributed to combinations of non-uniform loads leading to localized stress/strain variations









Sanabria et al SuST 25 (2012) 075007

Electromechanical behavior of HTS conductors

- One primary driver for HTS is high field, low T
  - Lorentz forces are particularly challenging
- Another driver is higher temperature, possibly low field applications for electrical/power systems
  - Will AC systems be fatigue limited?
- What do we know about YBCO & Bi2212?
  - Start with a look at statistics

Weibull statistical analysis of HTS behavior

Statistics often used to analyze brittle materials

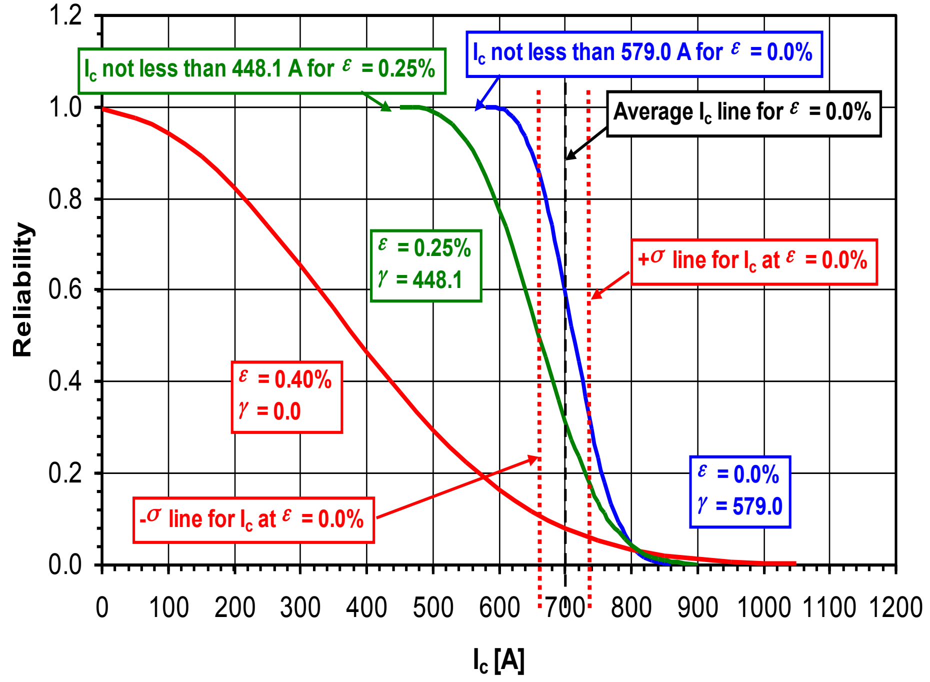
Three-parameter Weibull distribution function:

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

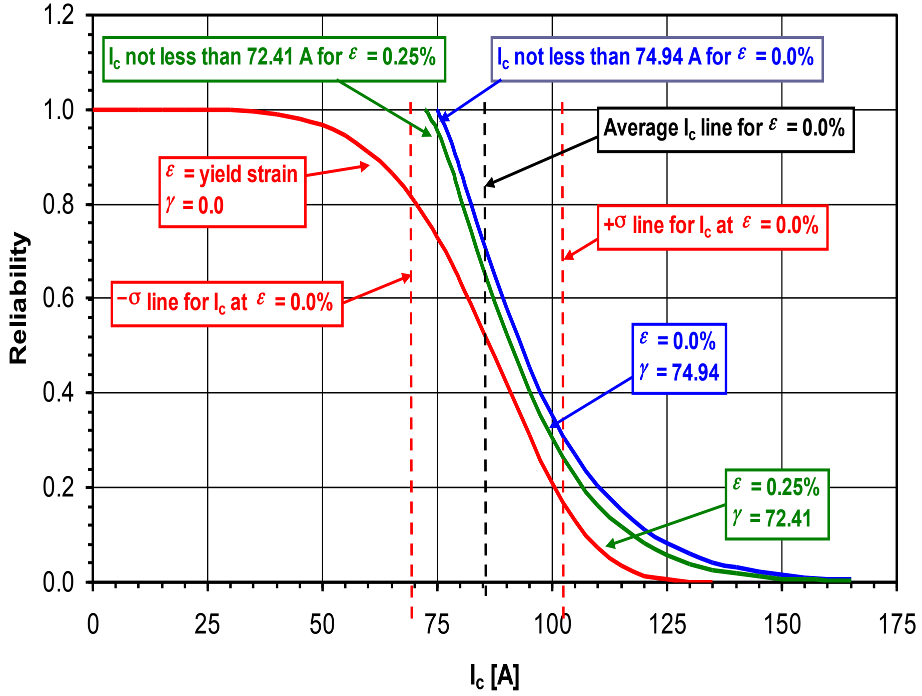
where α, β and γ are scale, shape and location parameters respectively.

- 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 wire v YBCO tapes reliability curves



Bi2212 round wires



YBCO

- $\gamma(\varepsilon)$ = zero-margin design limit
- YBCO: indicative of metallic behavior at low/intermediate strain; ceramic-like at high strain
- Bi2212: inhomogeneous, defect-dominated behavior

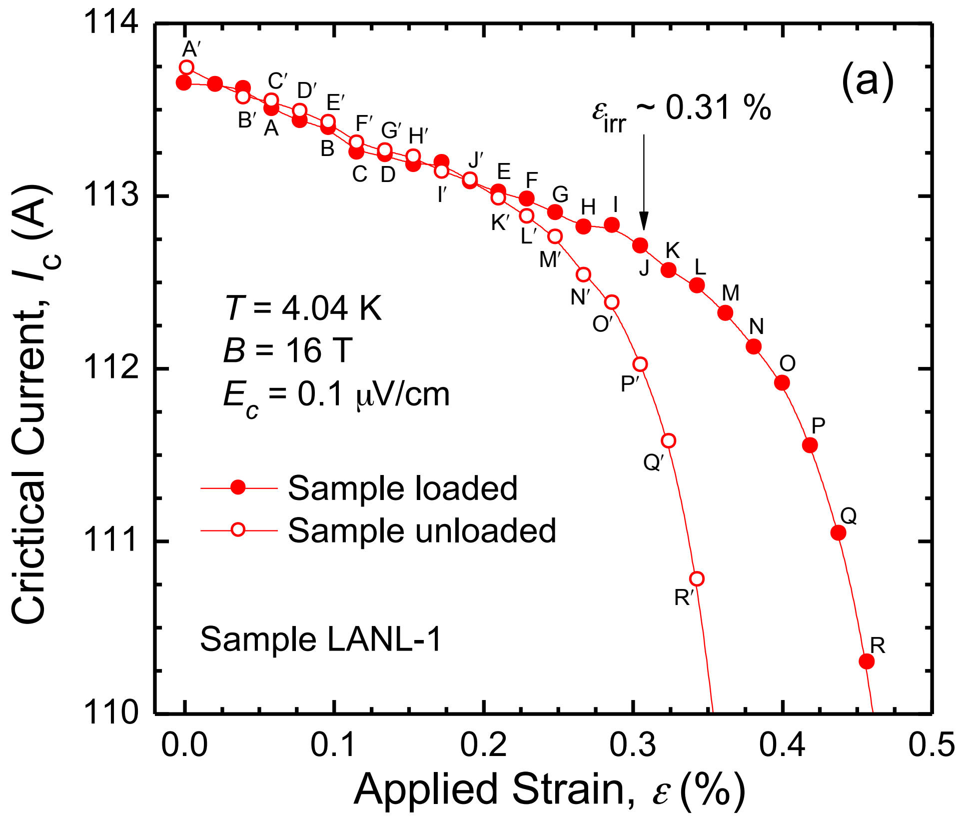
Do Weibull statistics give some general meaning?

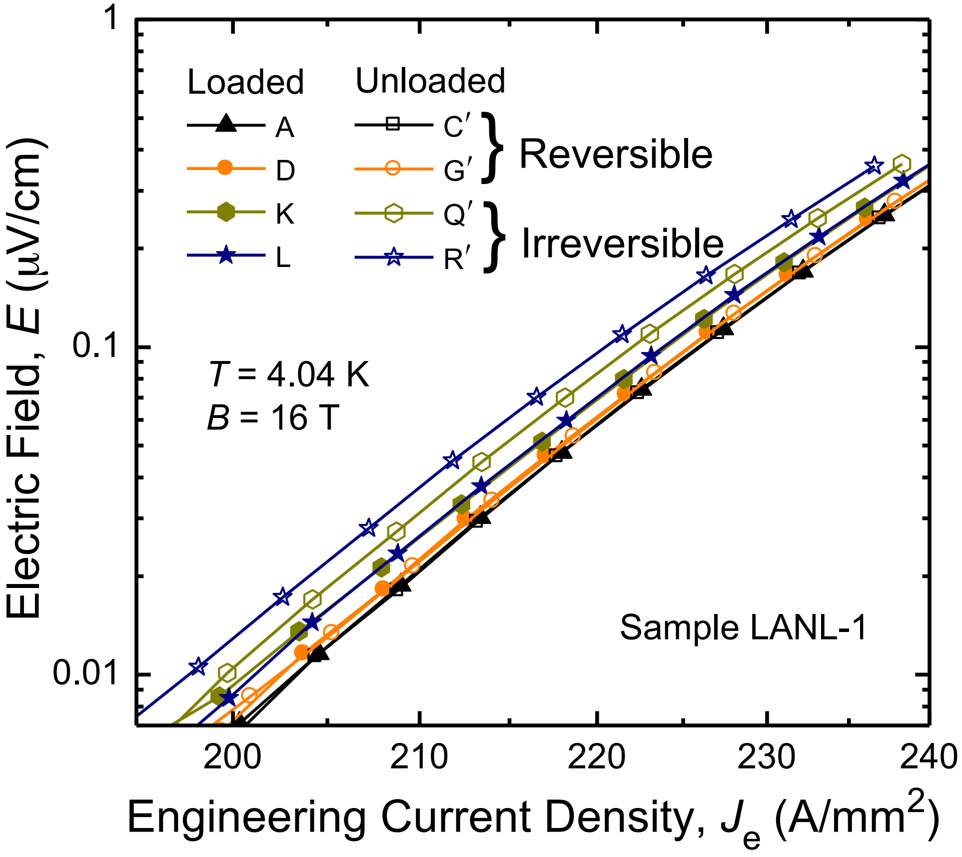
- YBCO axial tensile behavior dominated by Ni-alloy substrate and stabilizer
- Simple critical strain model does not fully capture tensile behavior for Bi2212, which acts like a ceramic
- Bi2212 has high-performing "tail" (high J_c "backbone") that indicates potential for significant improvements

Bi2212 electromechanics … so what's new?

- Bi2212 wires have progressed with J_c increasing
- Timeliness of electromechanics important as well
- Recent studies by NIST (w/FSU & LANL) and Supercon/NCSU show new insights and potential for future improvements
  - Improvements through the Bi2212 filament
  - Improvements through the sheath material
- Questions:
  - Is Bi2212 behavior reversible?
  - Can new sheaths make a difference?

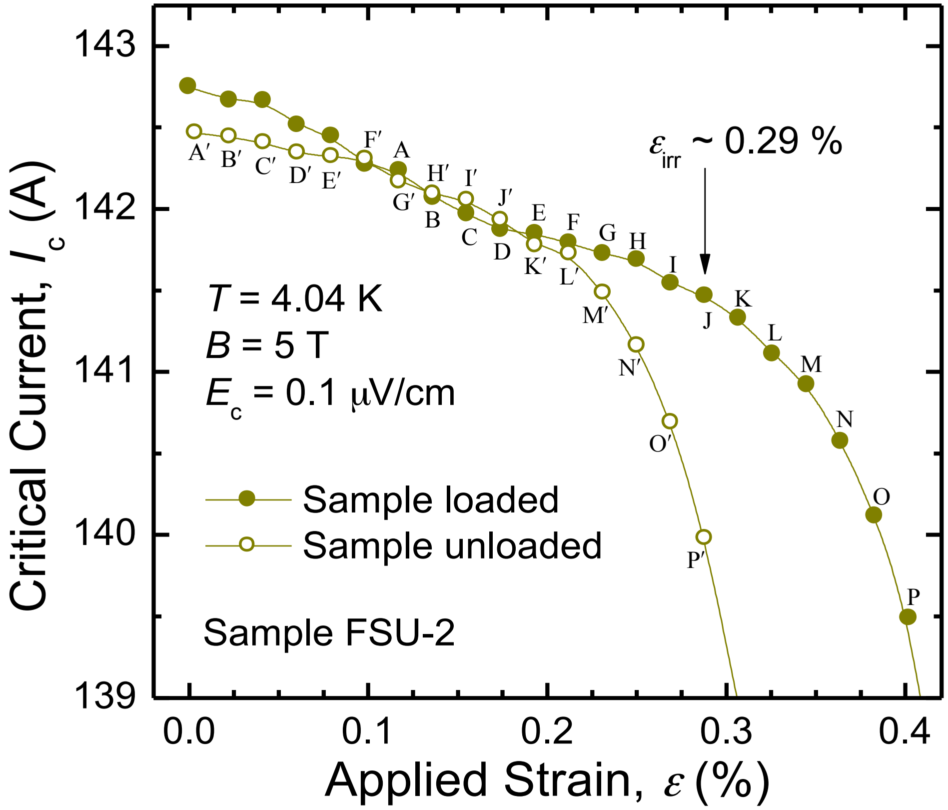
Reversible behavior in Bi2212 wires

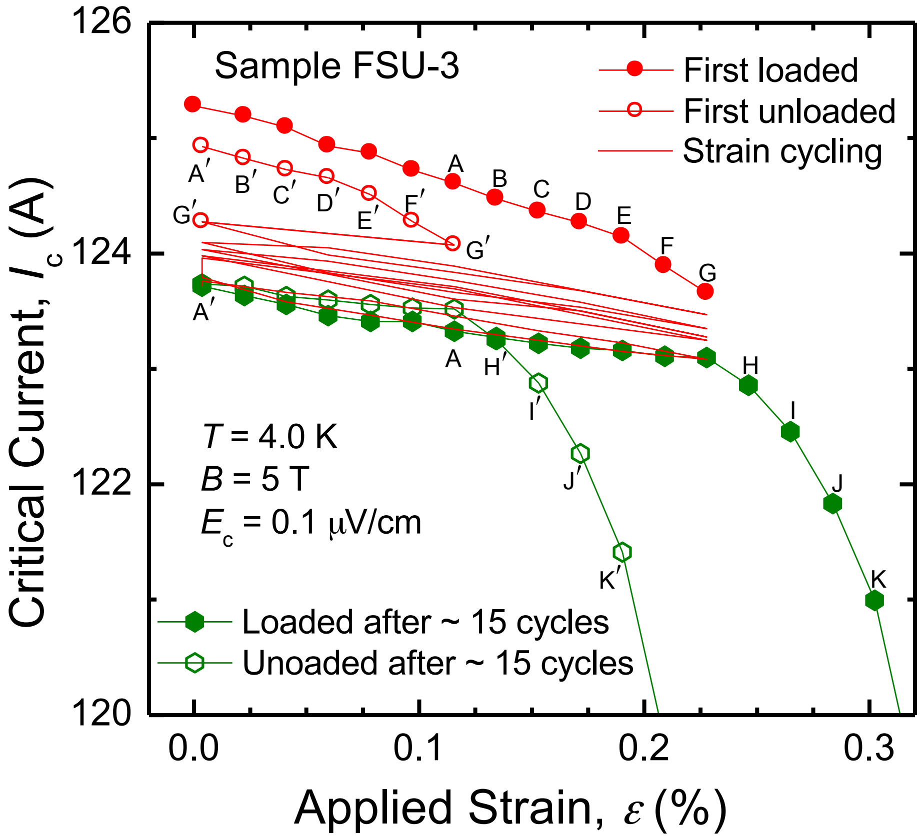




Cheggour et al, SuST 2012

But not always…





Reversibility not clear until strain is increased or cycled

Cheggour et al, SuST 2012

Two-component model proposed

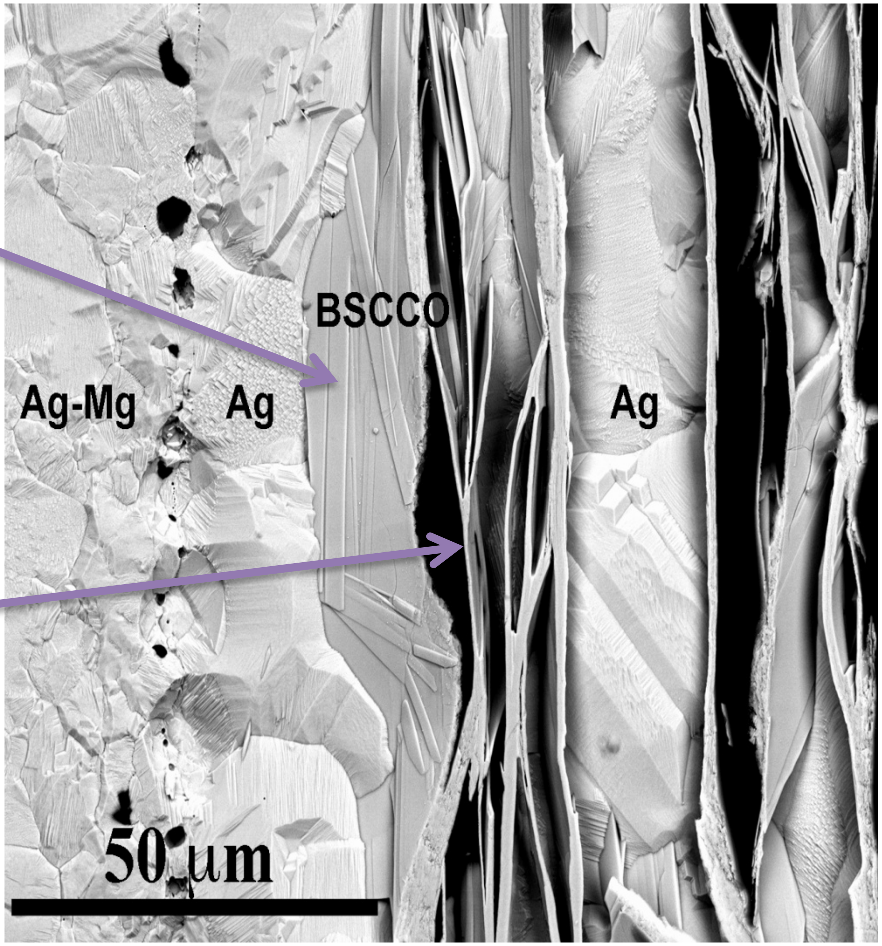
- Two “types” of Bi2212 within filaments; one mechanically weak and the other mechanically strong
- If weak component does not contribute to transport initially, then wire reversible
- If weak component contributes to transporting current initially, then irreversible behavior until this component fails mechanically due to strain or cycling
- Consistent with Weibull results as well

Cheggour et al, SuST 2012

Microstructural analysis

“*Strong*” component

“*Weak*” component



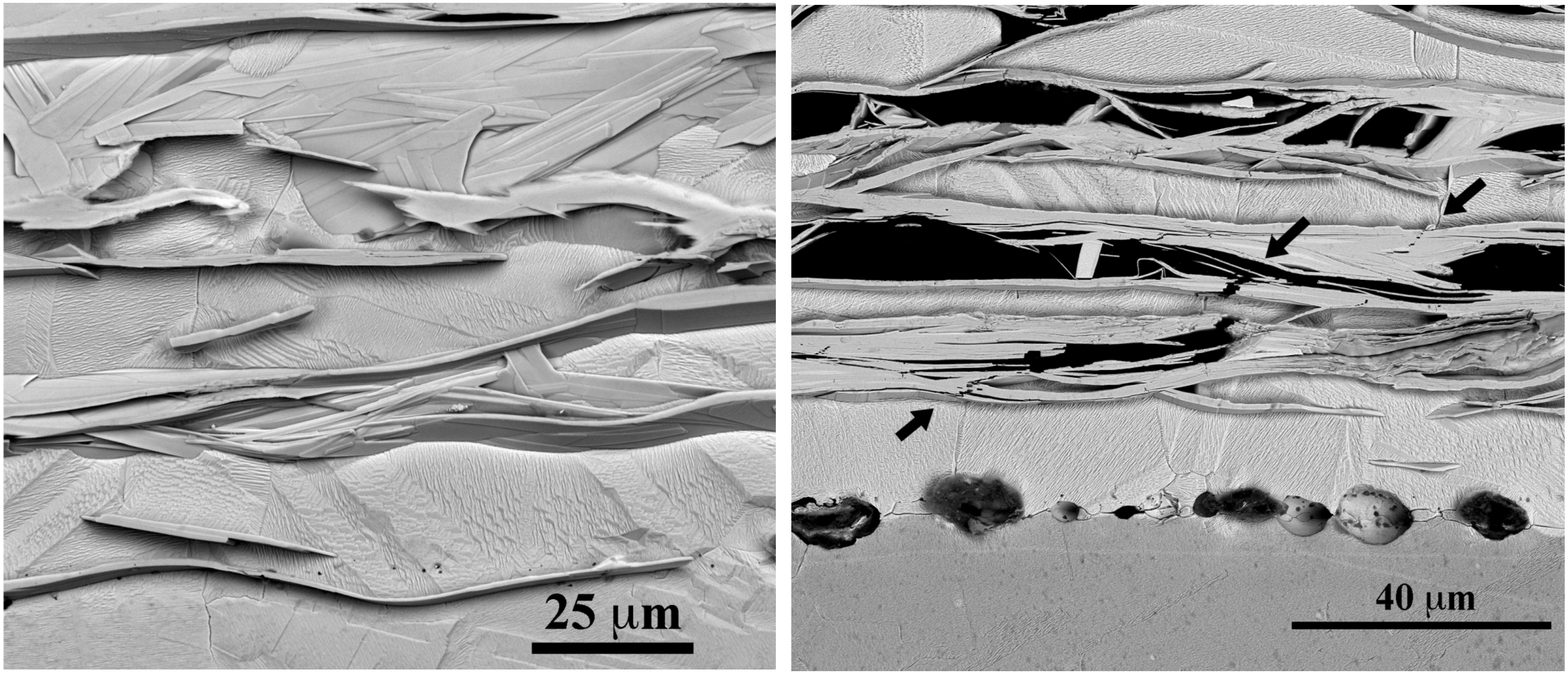
Fibrous network of Bi2212 may be the mechanically *weak* component

Cheggour et al, SuST 2012

Microstructural analysis

Los Alamos
NATIONAL LABORATORY
EST. 1943

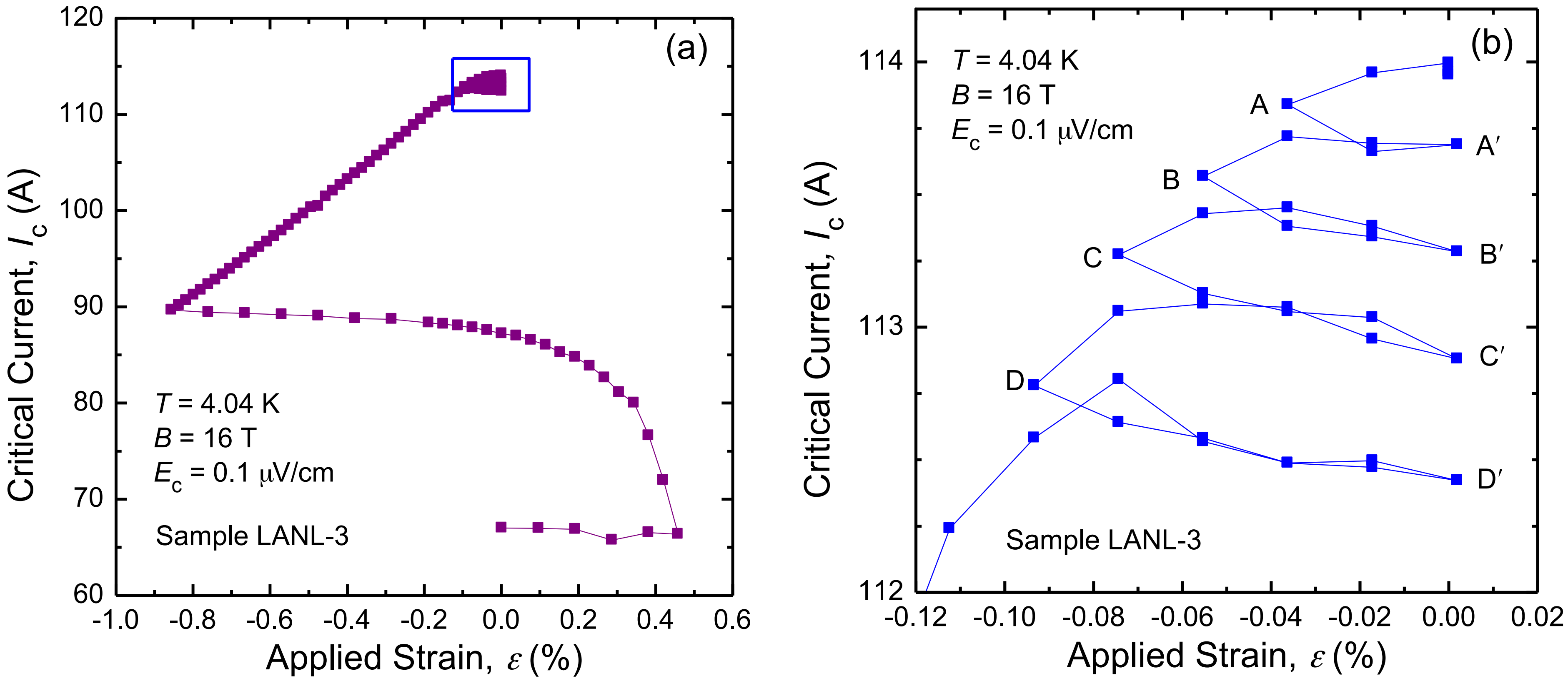
Tensile strain



Cheggour et al, SuST 2012

Porosity may serve as crack nucleation sites

What about compression?

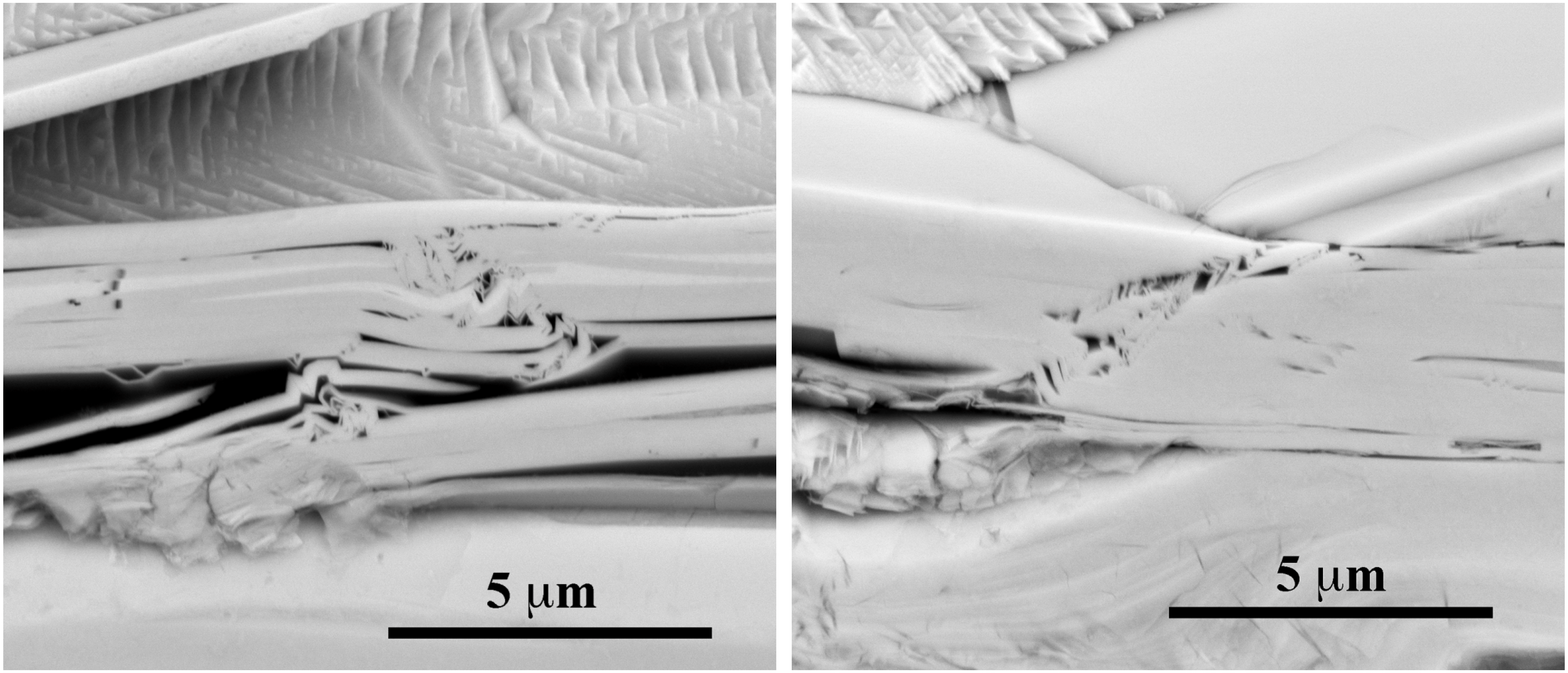


No reversibility observed under axial compressive strain

Cheggour et al, SuST 2012

Microstructural analysis

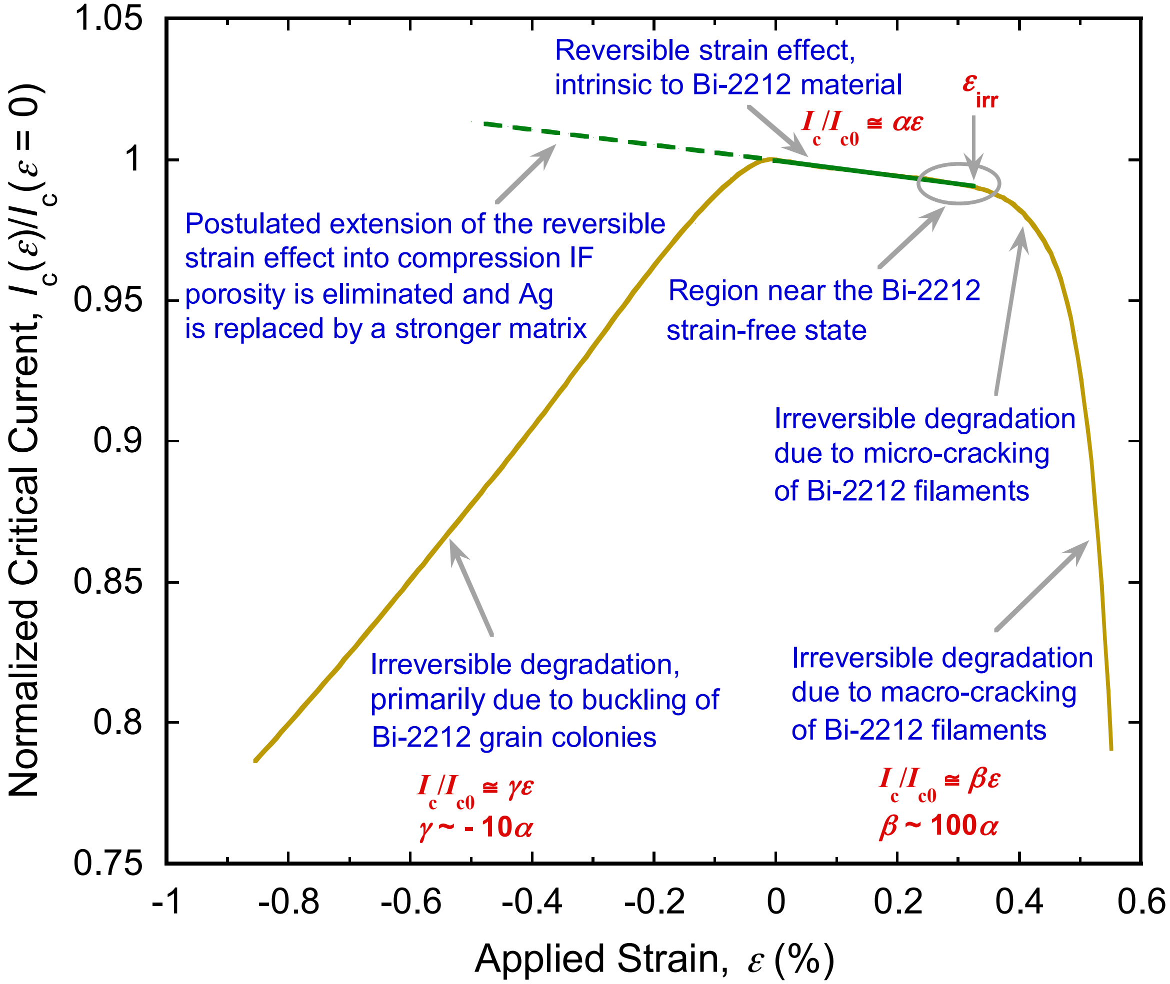
Compressive strain



Cheggour et al, SuST 2012

Buckling may be at the origin of irreversibility

Modified Descriptive Strain Model



Reversible strain effect, intrinsic to Bi-2212 material

$I_c/I_{c0} \cong \alpha\varepsilon$

Postulated extension of the reversible strain effect into compression IF porosity is eliminated and Ag is replaced by a stronger matrix

Region near the Bi-2212 strain-free state

Irreversible degradation due to micro-cracking of Bi-2212 filaments

Irreversible degradation, primarily due to buckling of Bi-2212 grain colonies

$I_c/I_{c0} \cong \gamma\varepsilon$

$\gamma \sim -10\alpha$

Irreversible degradation due to macro-cracking of Bi-2212 filaments

$I_c/I_{c0} \cong \beta\varepsilon$

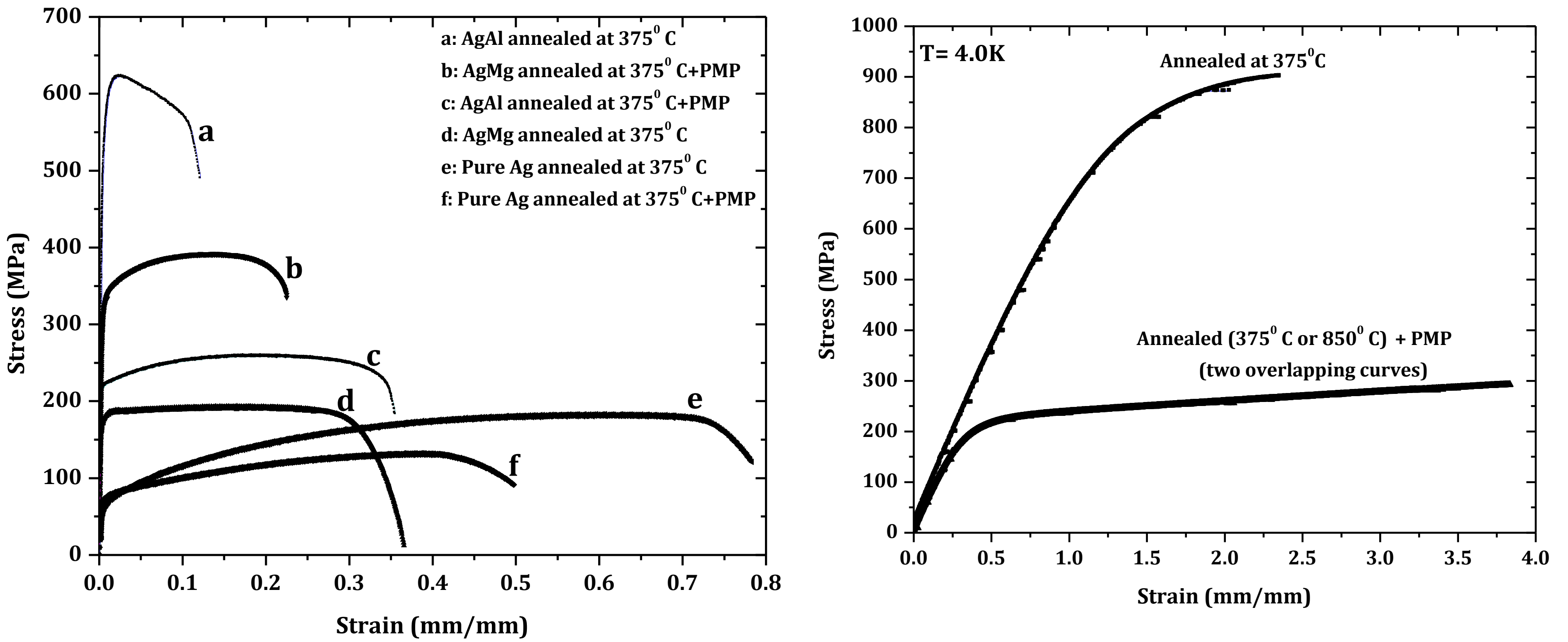
$\beta \sim 100\alpha$

Cheggour et al, SuST 2012

What about improved sheaths?

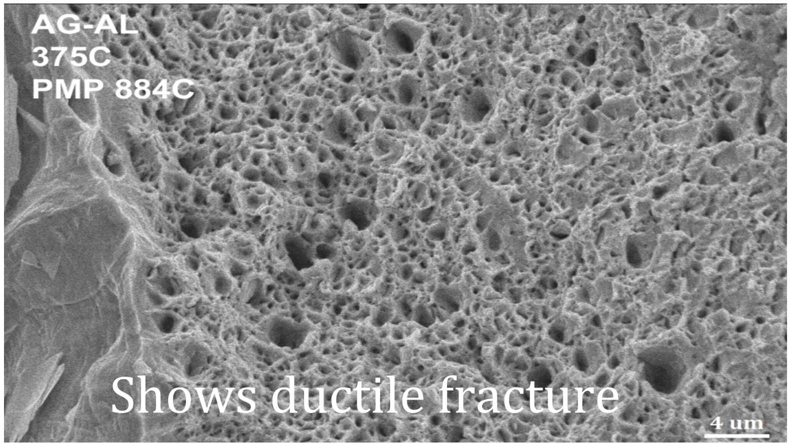
- AgMg has been used as outer sheath for over 20 years
- Cannot be adjacent to Bi2212 filament or J_c reduced
- Increased modulus and yield strength would improve Bi2212
- If compatible with filaments, then pure Ag can be eliminated
- Recent study of Ag/0.5wt%Al shows some promise

σ/ε at room temperature and 4.0 K

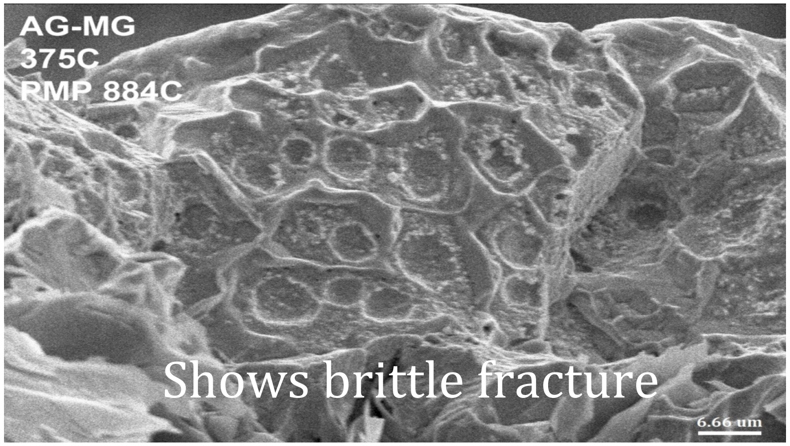


Kajbafvala et al. TASC 22 1 2012 8400210

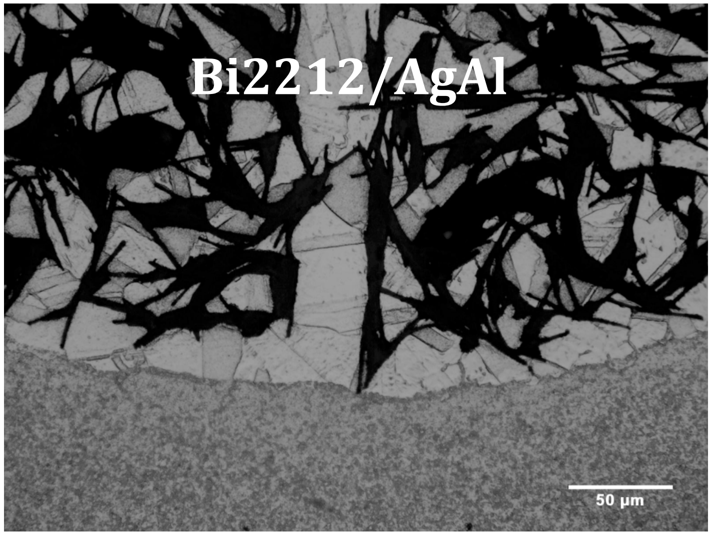
Fracture surface & grain structure comparison

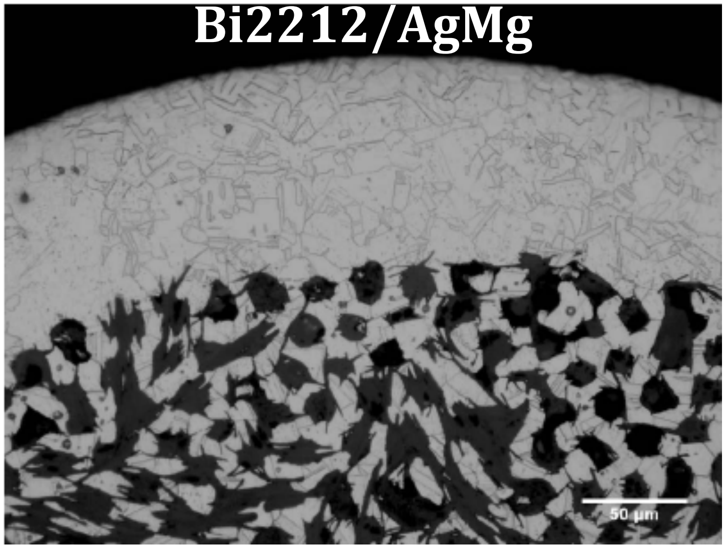


Shows ductile fracture



Shows brittle fracture


Bi2212/AgAl


Bi2212/AgMg

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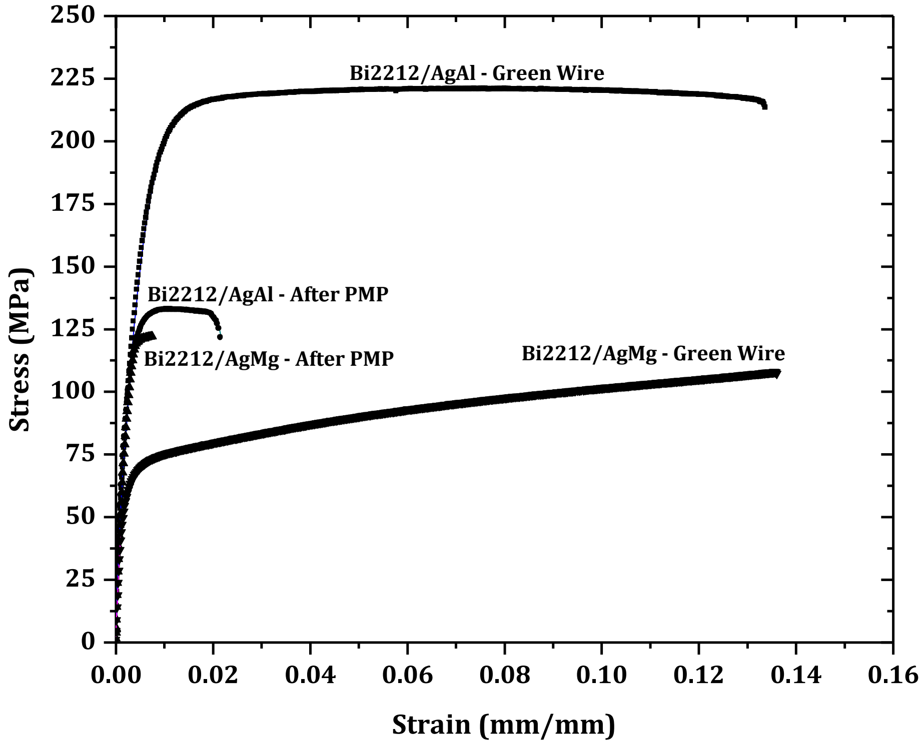
Room temperature σ/ε: Bi2212/AgMg and Bi2212/AgAl wire

Mechanical Parameters	Bi2212/ AgAl				Bi2212/AgMg			
	E(GPa)	YS (MPa)	UTS (MPa)	El%	E(GPa)	YS (MPa)	UTS (MPa)	El%
Green Wire	48	130	220	13.38	42	62.5	107	-
PMP Heat Treated	56	125	135	2.17	56	65	122	0.8



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I_c measurements

- I_c in AgAl wire higher than AgMg
- Chemical compatibility or effects of sheath mechanical properties? … unknown … but increased strength and I_c is a good start

Conductor	**Short samples**	**I_c (A)**	**n - value**
Bi2212/AgAl – HT1 (PMP)	**w/out insulation**	**328**	**20.4**
	with insulation	**283**	**19.8**
Bi2212/AgMg wire	**w/out insulation**	**269**	**18.6**

Kajbafvala et al. TASC 22 1 2012 8400210

Electromechanics of (RE)BCO conductors

- Past 5 years has seen significant growth in studies of YBCO electromechanics (albeit mostly in LN_2)
- Relatively low defect density in superconducting layer & high strength metallic sheath → sharp contrast to Bi2212
- YBCO layer is highly aligned and highly engineered … so electromechanical studies are interesting for technology and science
- Ni-alloys give (RE)BCO intrinsic functional advantage

Factors to consider that influence YBCO behavior

- Type of CC (grain orientation, morphology & size, …)
- Direction of load relative to crystallographic axes
- Direction of applied magnetic field
- Degree of bi-axial texture & existing misalignment
- Effects of pressure on T_c & H_{c2} (and of T_c and H_{c2} on J_c)
- Pinning center types/geometry and relationship to magnetic field orientation
- Temperature-dependence of pinning center effectiveness
- Role of defects and imperfections
- Role of grain boundaries

Gets complex very quickly, and difficult to generalize details from one conductor to another

Self-field I_c-strain in YBCO CC (SuperPower IBAD)

$$I_c(\varepsilon)/I_c(\varepsilon_m) = 1\text{-}a\,|\,\varepsilon - \varepsilon_m\,|^{2.2}$$

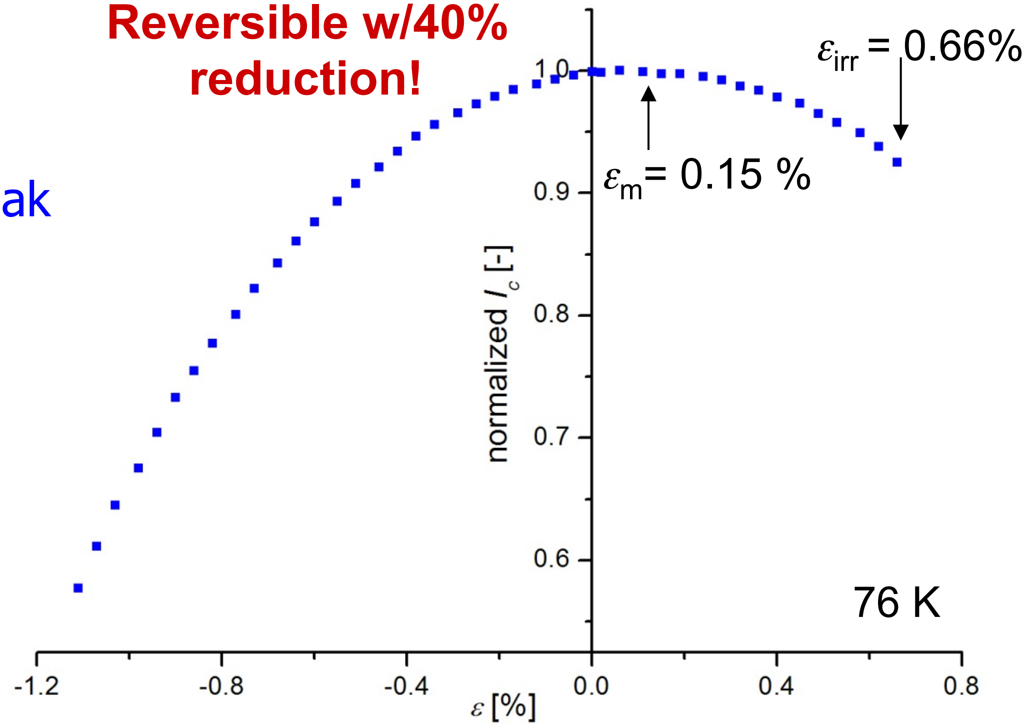
strain sensitivity

strain at peak

ε_m is related to the initial strain state of the YBCO:

- thermal contraction
- lattice mismatch YBCO/buffer
- strain due to YBCO defects

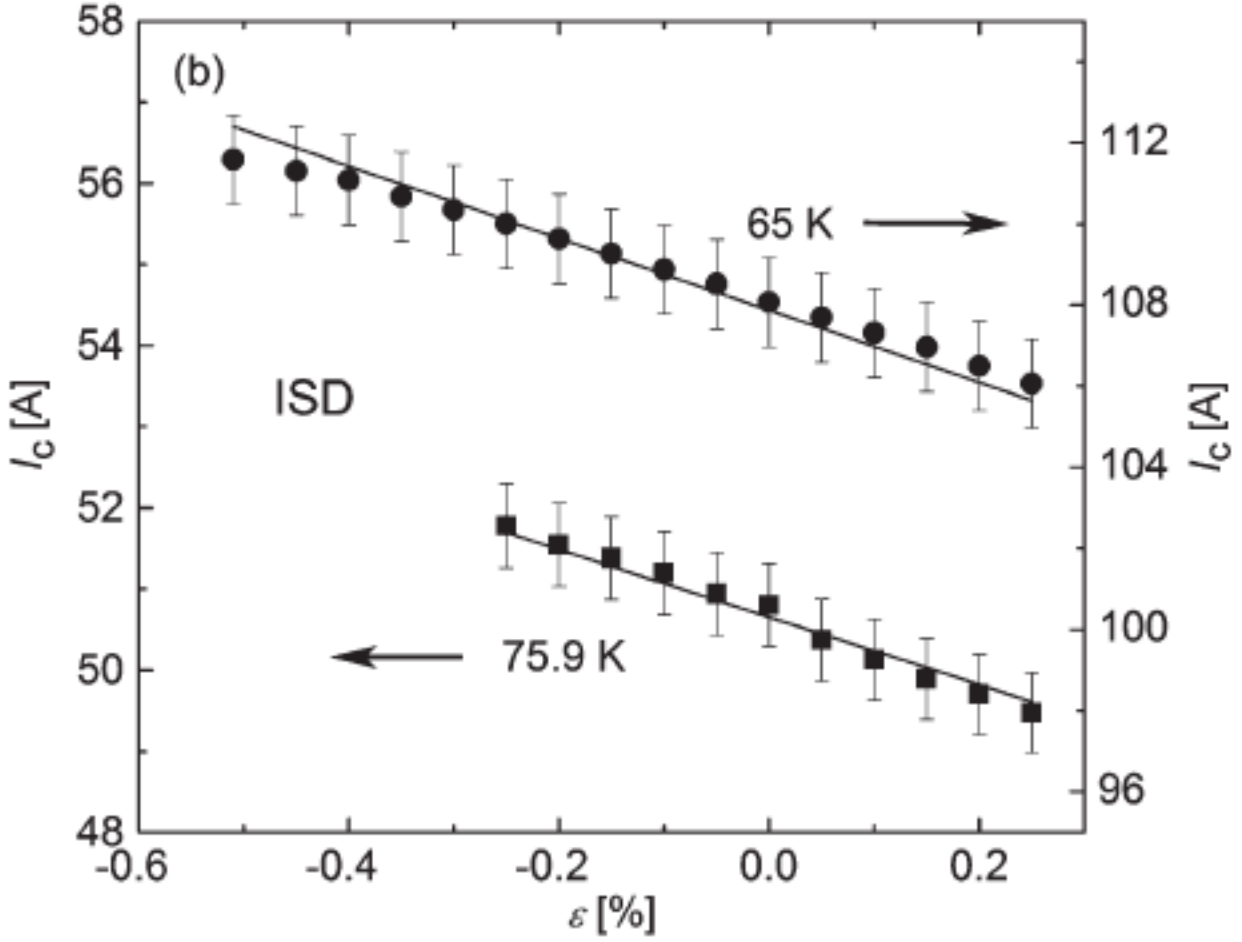
Reversible w/40% reduction!



D.C. van der Laan, *et al., Appl. Phys. Lett.* **90**, 052506, 2007

Same test – different conductor (ISD $DyBa_2Cu_3O_{7-\delta}$)

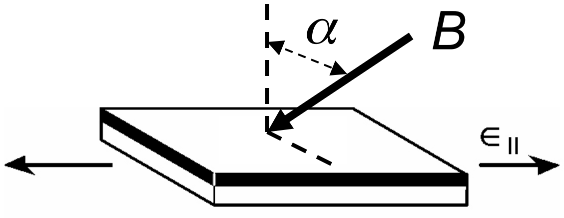
- Very different behavior



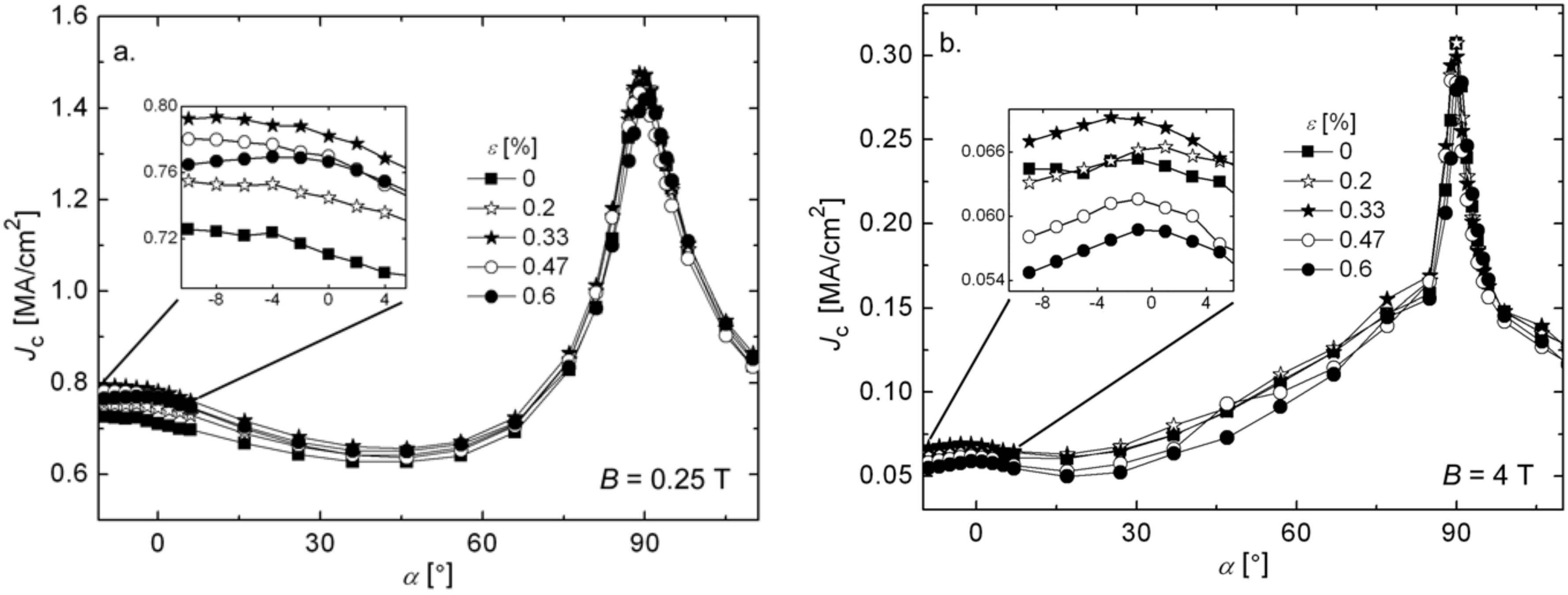
What about in-field effects?

$I_c(B,T,\varepsilon,\alpha)$

- strain ε
- magnetic field B
- field angle α
- temperature T

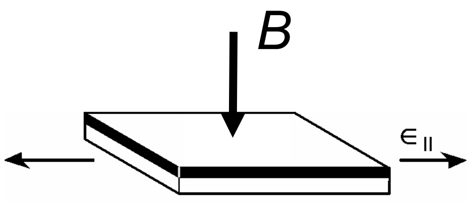


SuperPower IBAD: clearly a magnetic field dependence!

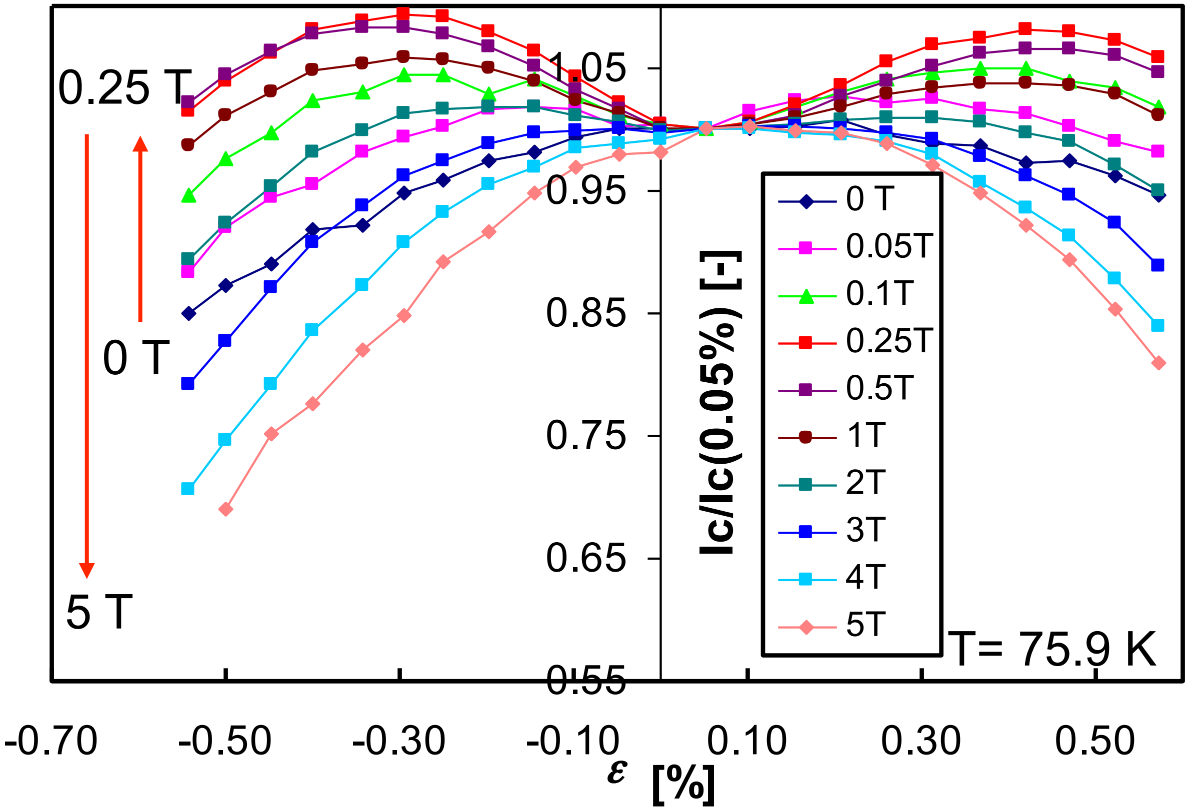


D. van der Laan et al., SuST 23 (2010) 072001

$I_c(\varepsilon,B)$ for B||c (SuperPower IBAD)



$I_c(\varepsilon)$ normalized to its peak at ε_m= 0.05%



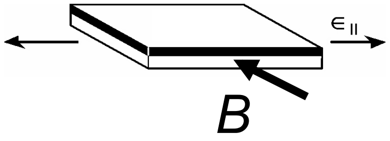
$I_c(\varepsilon)$ with double maximum at low field.

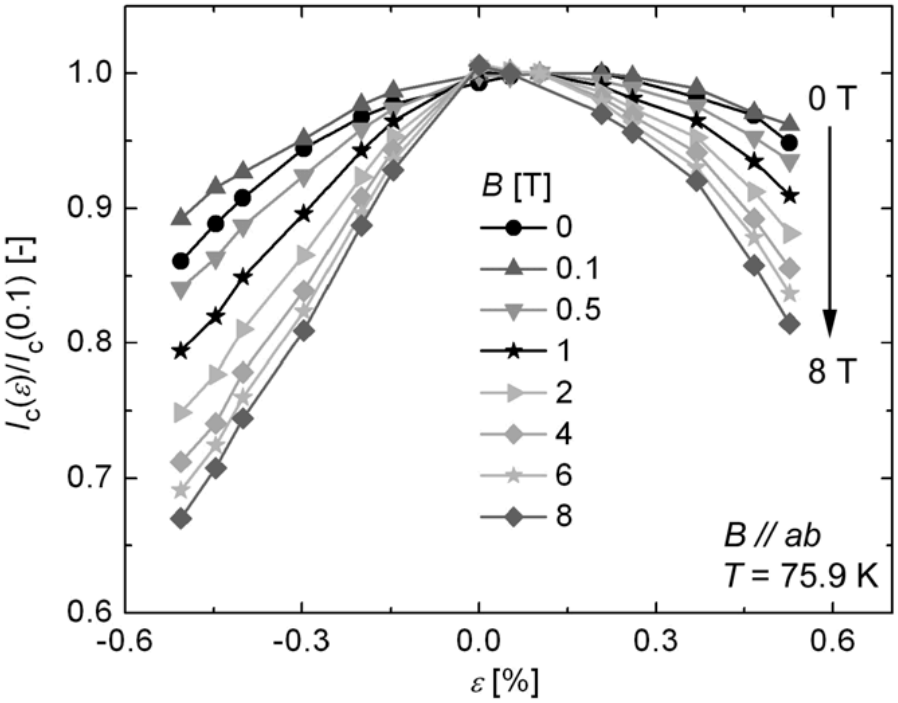
Different behavior between low- and high B: grain boundary role?

Strain sensitivity of I_c increases at high field.

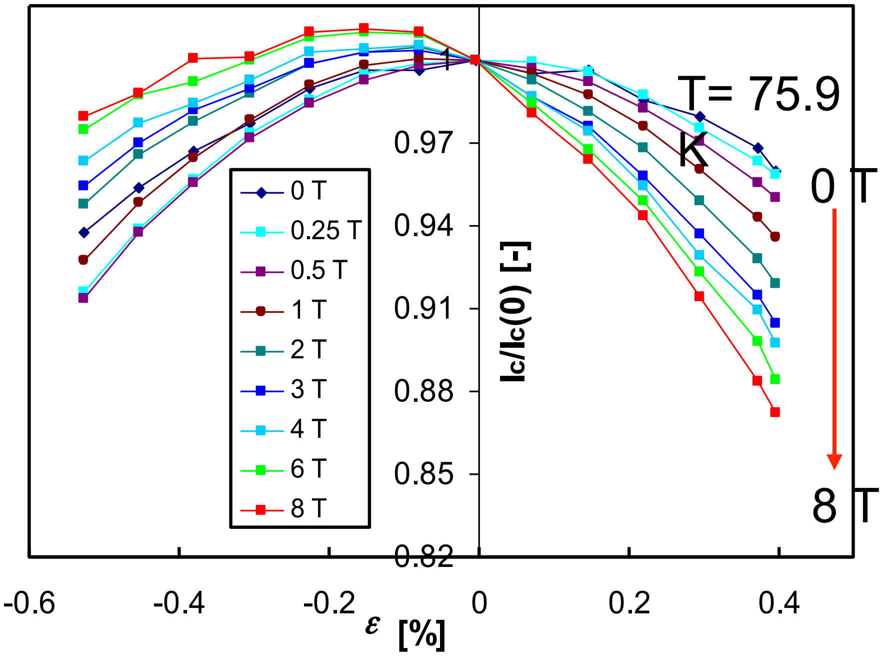
D. van der Laan et al., SuST 23 (2010) 072001

$I_c(\varepsilon,B)$ for B|| c (SuperPower IBAD & AMSC RABiTs)





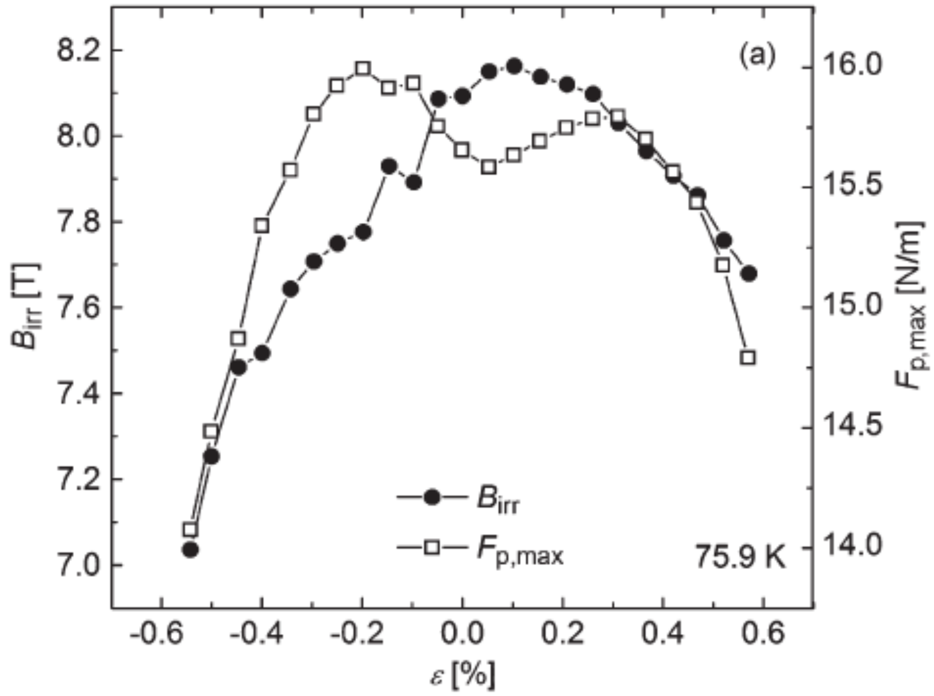
SuperPower IBAD



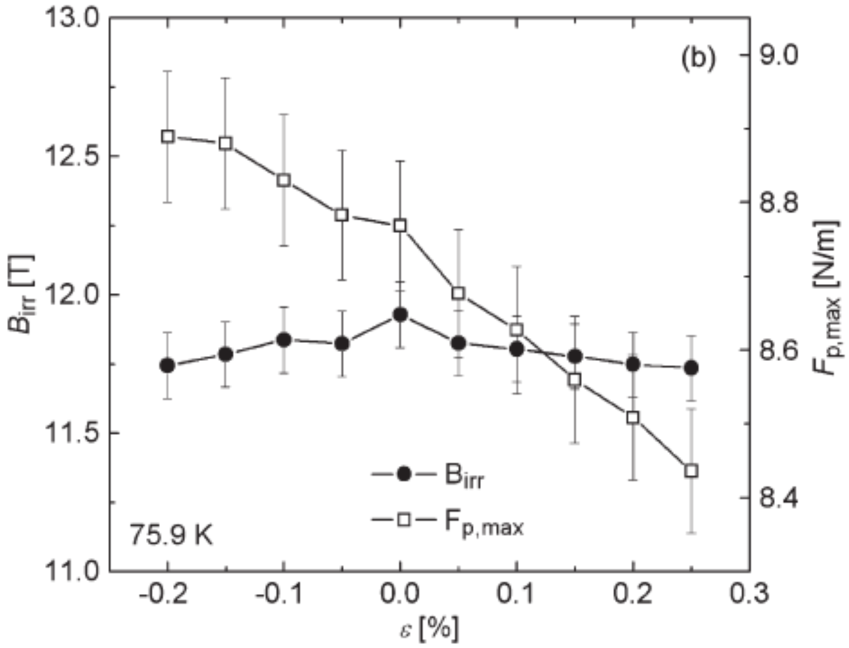
AMSC RABiTs

D. van der Laan et al., SuST 23 (2010) 072001

Pinning force density and H_{irr}(IBAD & ISD)



IBAD



ISD

D. van der Laan et al., TASC 22 (2012) 8400707

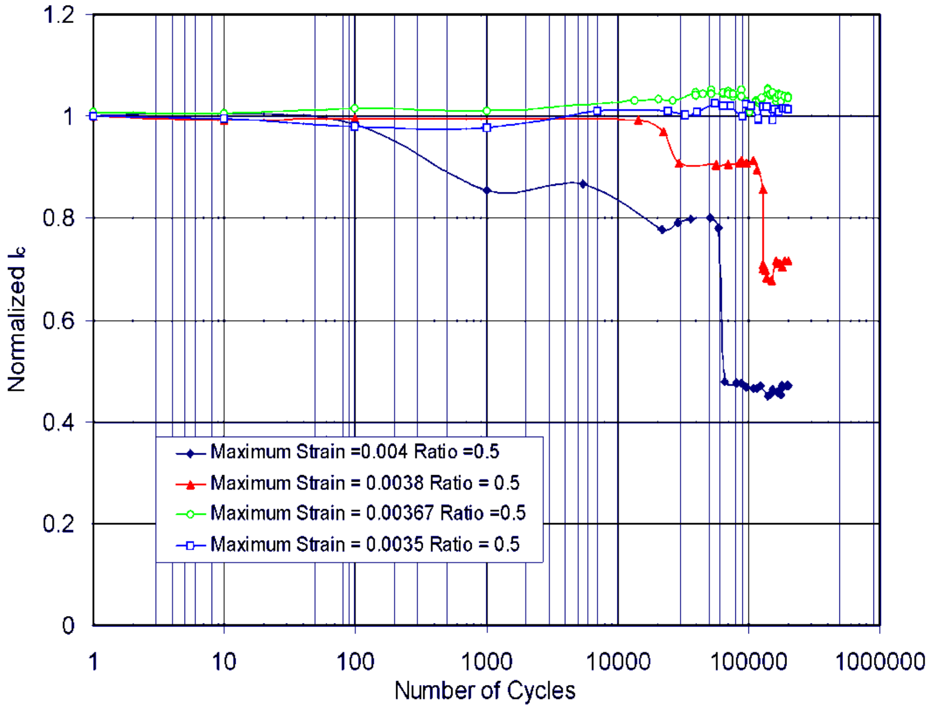
Immediate lessons learned

- General conclusion is that there are no general conclusions
- Behaviors between different conductor types varies greatly
- Different behavior for B||ab and B||c → field orientation matters
- Strain dependence depends on |B|
- Location (ε_m) of the peak in $I_c(\varepsilon)$ depends on magnetic field → ***NOT*** simply prestrain!

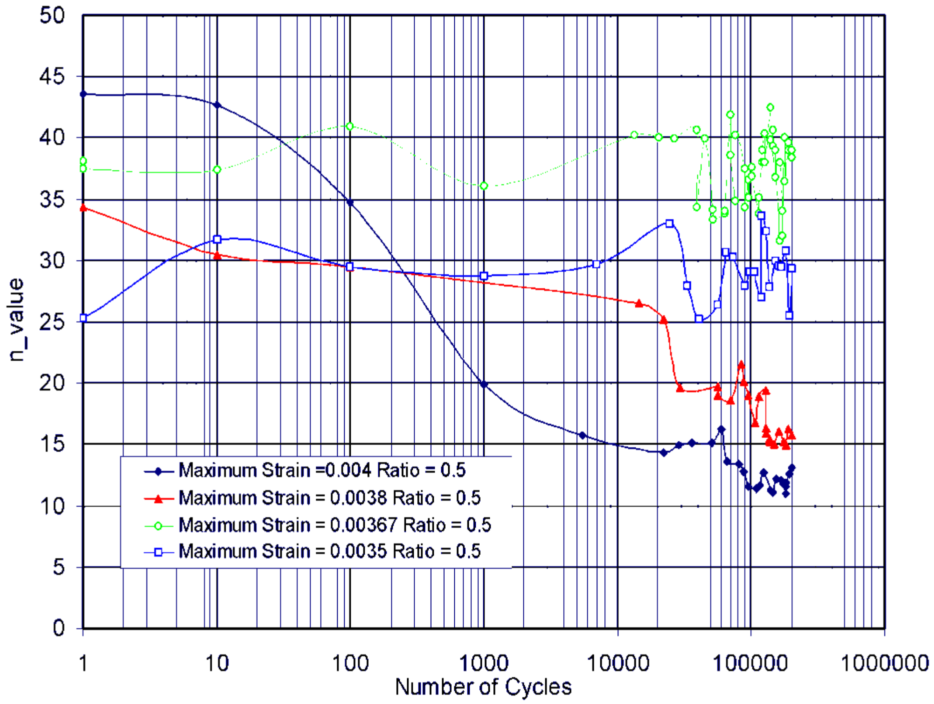
What about fatigue?

- Overall – very little fatigue behavior has been measured for any HTS conductor
- One study looked at SuperPower tape
  - Strain controlled fatigue I_c tests
  - Strain ratios 0.5 and 0.2 at different ε_{max}
- 2004-06; conductor availability limited at that time & not of same quality as today
- Fatigue testing is time and conductor intensive

Strain-controlled fatigue R=0.5 @ 0.4 Hz



Normalized I_c versus N (log scale)



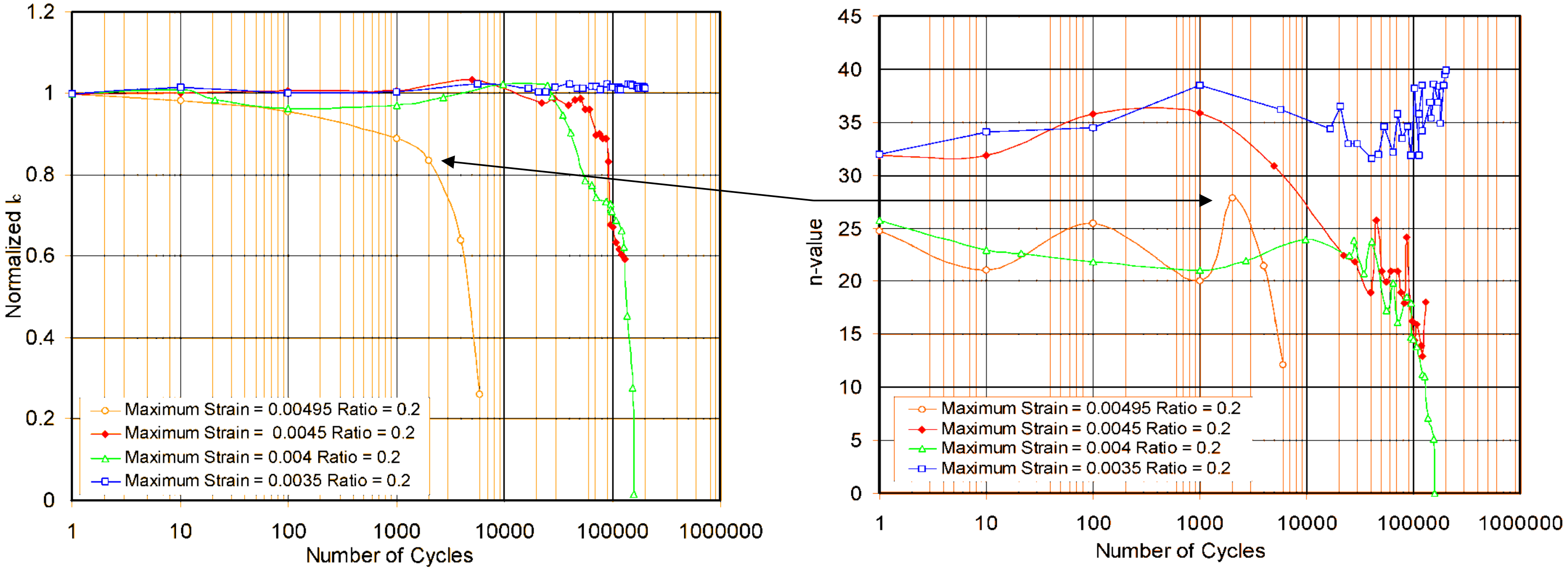
n-value versus N (log scale)

- No I_c or n-value degradation for ε_{max} = 0.35% and 0.367%
- I_c & n-value degradation for ε_{max} = 0.38% and 0.40%
- I_c degradation step-like

A.L. Mbaruku, U.P. Trociewitz and J. Schwartz, *IEEE Trans. Appl. Supercond.* **15** (2005) & A.L. Mbaruku, Ph.D. dissertation, FSU 2006

A. Mbaruku & J. Schwartz (in prep)

Strain-controlled fatigue R=0.2 @ 0.4 Hz



Normalized I_c versus N (log scale)

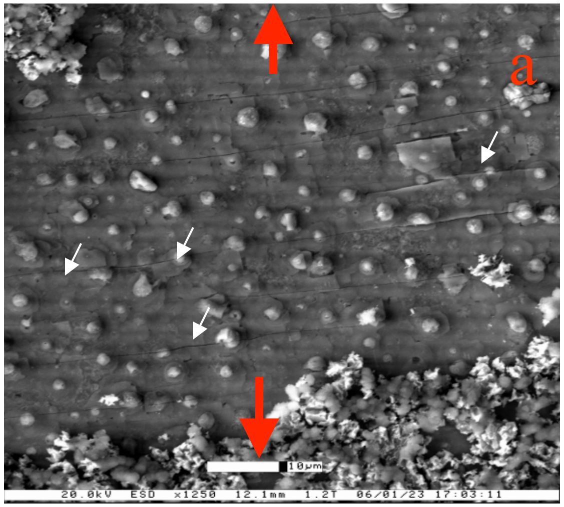
n-value versus N (log scale)

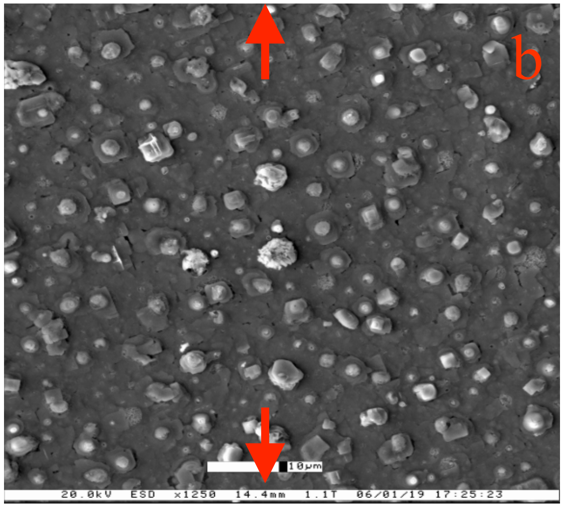
- No I_c or n-value degradation for $\varepsilon_{max} = 0.35\%$
- I_c & n-value degradation for $\varepsilon_{max} = 0.40\%$ and above
- R-dependence significant
  - Degradation not step-like
- High N: n-value increases precede I_c decreases
  - Strain-field induced pinning

A.L. Mbaruku, U.P. Trociewitz and J. Schwartz, *IEEE Trans. Appl. Supercond.* **15** (2005) & A.L. Mbaruku Ph.D. dissertation, FSU 2006

SEM of fatigued samples

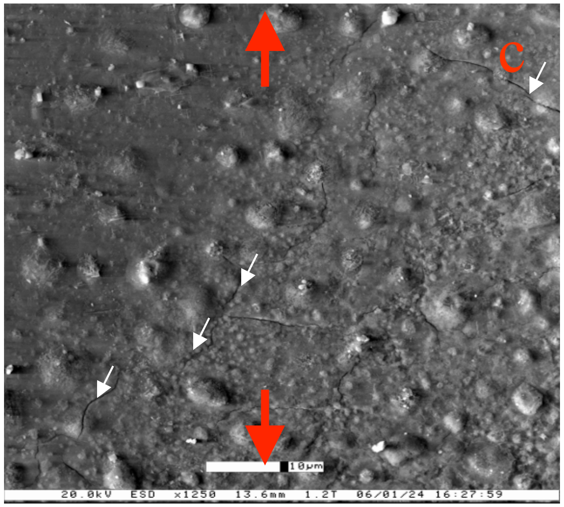
single cycle σ-ε to failure (3.1%); very fine cracks

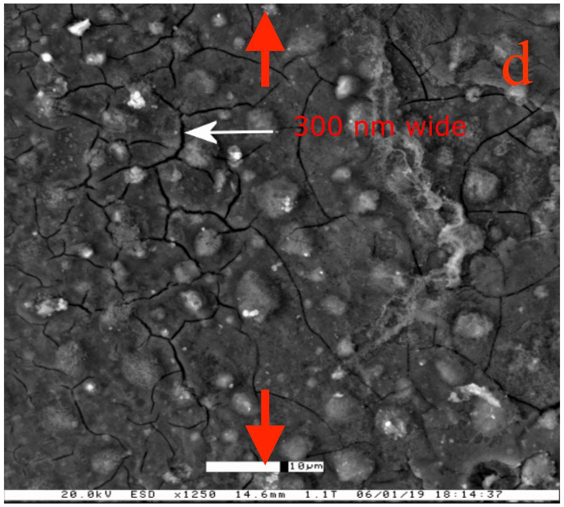




typical non-cracked area from samples ***with and w/ out I_c degradation*** 0.45%,R=0.2

fatigue cracks on partially failed sample 0.38%, R=0.5





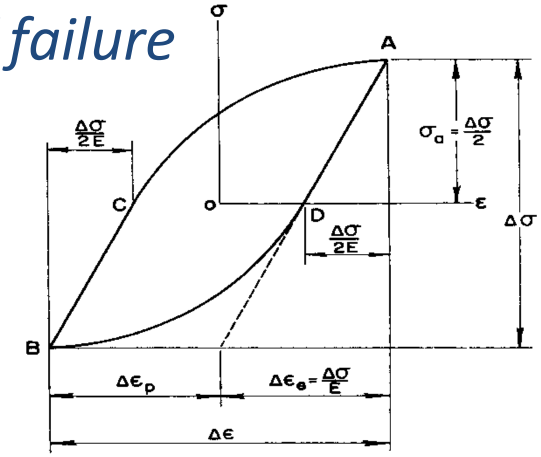
fatigue cracks on completely failed sample; 0.45%,R=0.5

intergranular/ grain boundary or crack bridging?

Cracks initiate @ edge and propagate inward:
Stress concentration factor or defect driven?

Fatigue loading effects results

Classical analysis with electrical definition of failure



Basquin equation $\sigma_a = \frac{\Delta\sigma}{2} = \sigma'_f(2N_f)^b$

Coffin-Manson equation $\frac{\Delta\varepsilon_p}{2} = \varepsilon'_f(2N_f)^c$

$2N_f$ = # of reversals to failure where $\boldsymbol{I_c(N_f)=0.95I_c(N=0)}$

σ'_f = fatigue strength coefficient = true monotonic fracture stress

→ indicative of HCF; *b* = (-0.04 to -0.15 for metals)

→ here, *b* = -0.0855 is obtained → metallic behavior

→ **HCF controlled by Hastelloy behavior**

ε'_f = fatigue ductility coefficient = true monotonic fracture strain

→ indicative of LCF; *c* = (-0.3 to -1.0 for metals)

→ here, *c* = -0.1103 is obtained → non-metallic behavior

→ **LCF controlled by YBCO, BL and/or interfacial behavior**

Delamination due to transverse loads

- REBCO CC is strong axially where Ni-alloy dominates
- Transverse strength is low → delamination at
  - Buffer layer/Ni-alloy interface
  - REBCO/buffer layer interface
  - REBCO/Ag interface
- Important for epoxy impregnation and for magnets with complex mechanical loads
- Important for quench protection, our final topic!

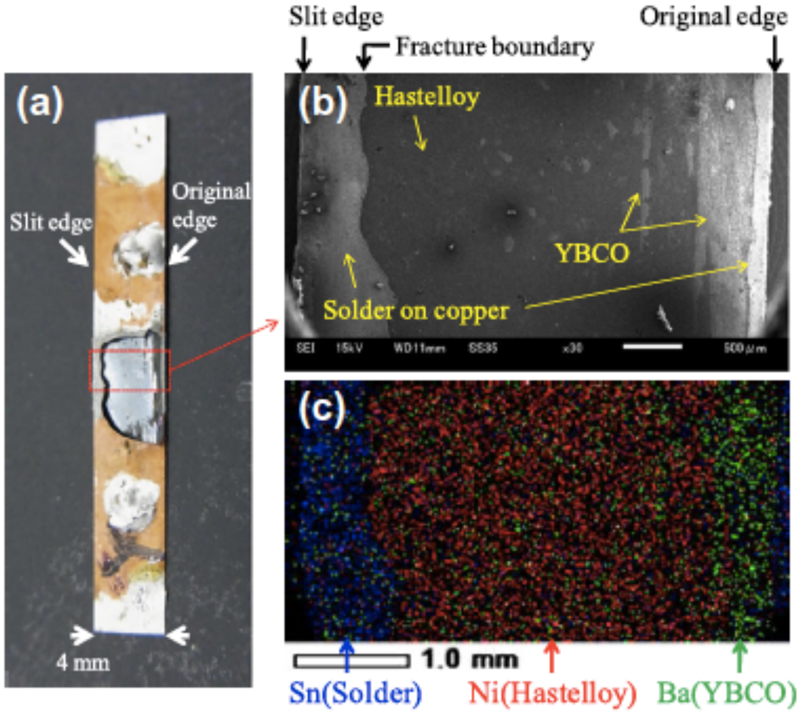


Image from Yanagisawa et al., Physica C 471 (2011) 480–485