Fracture in ITER and HEP Nb_3Sn strands under bending at 77 K

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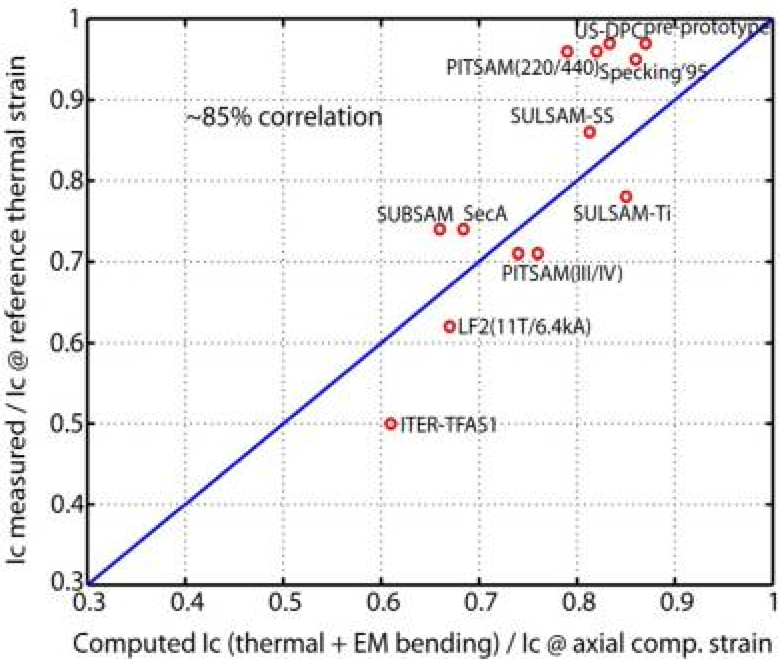
Motivation

CICC performance history



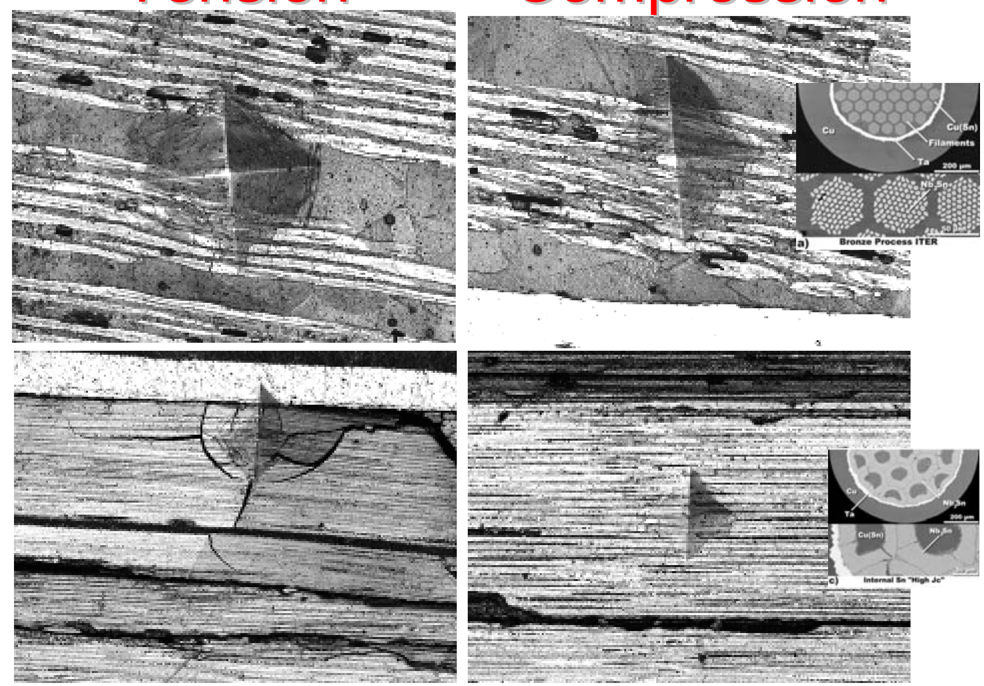
Y. Zhai and M.D. Bird, *IEEE Trans. Appl. Supercond.*, 18, 1127 (2008)

Nb_3Sn filament susceptibility to fracture

Tension Compression

Bronze

Internal Sn



Vickers indenter; P = 300 g

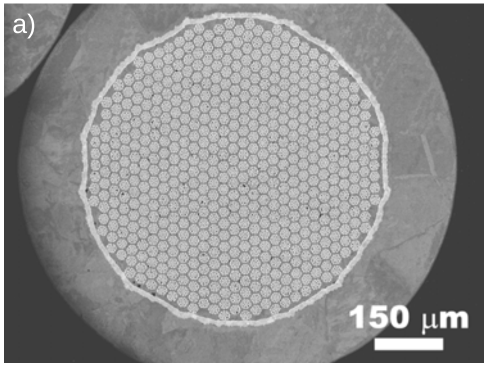
- **Motivating question: how does the size and arrangement of the filament pack affect fracture?**
- **Technique: Bend testing at 77 K**

Sample set

HEP strands

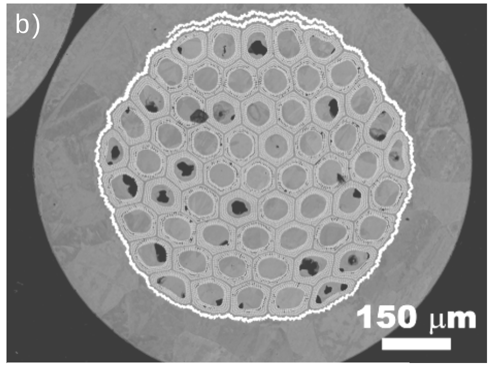
ITER strands

Hitachi



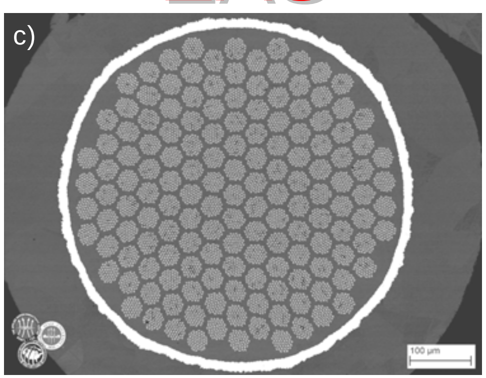
bronze

Mitsubishi



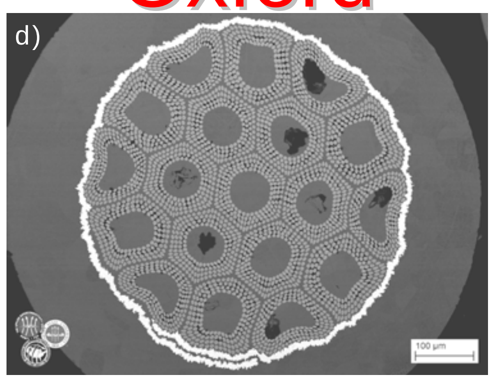
Internal tin

EAS



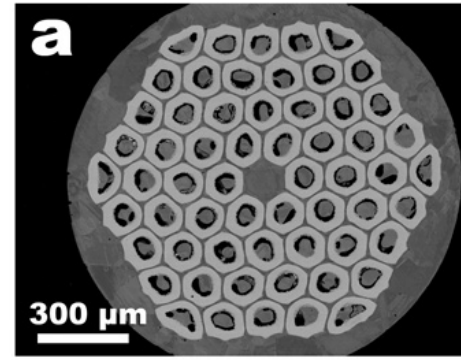
bronze

Oxford

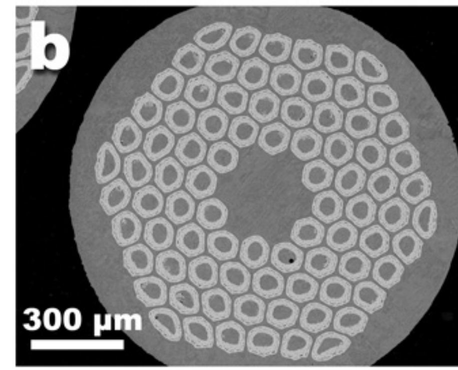


Internal tin

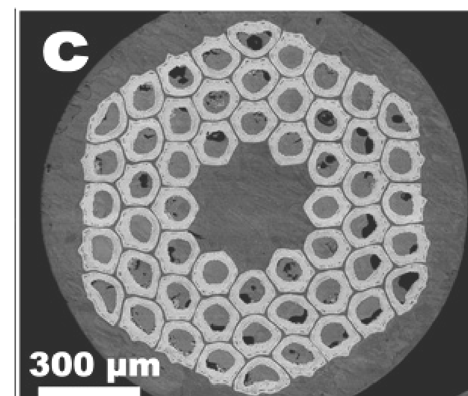
OST-3000



OST-2400



OST-1700



Internal tin

Bend testing

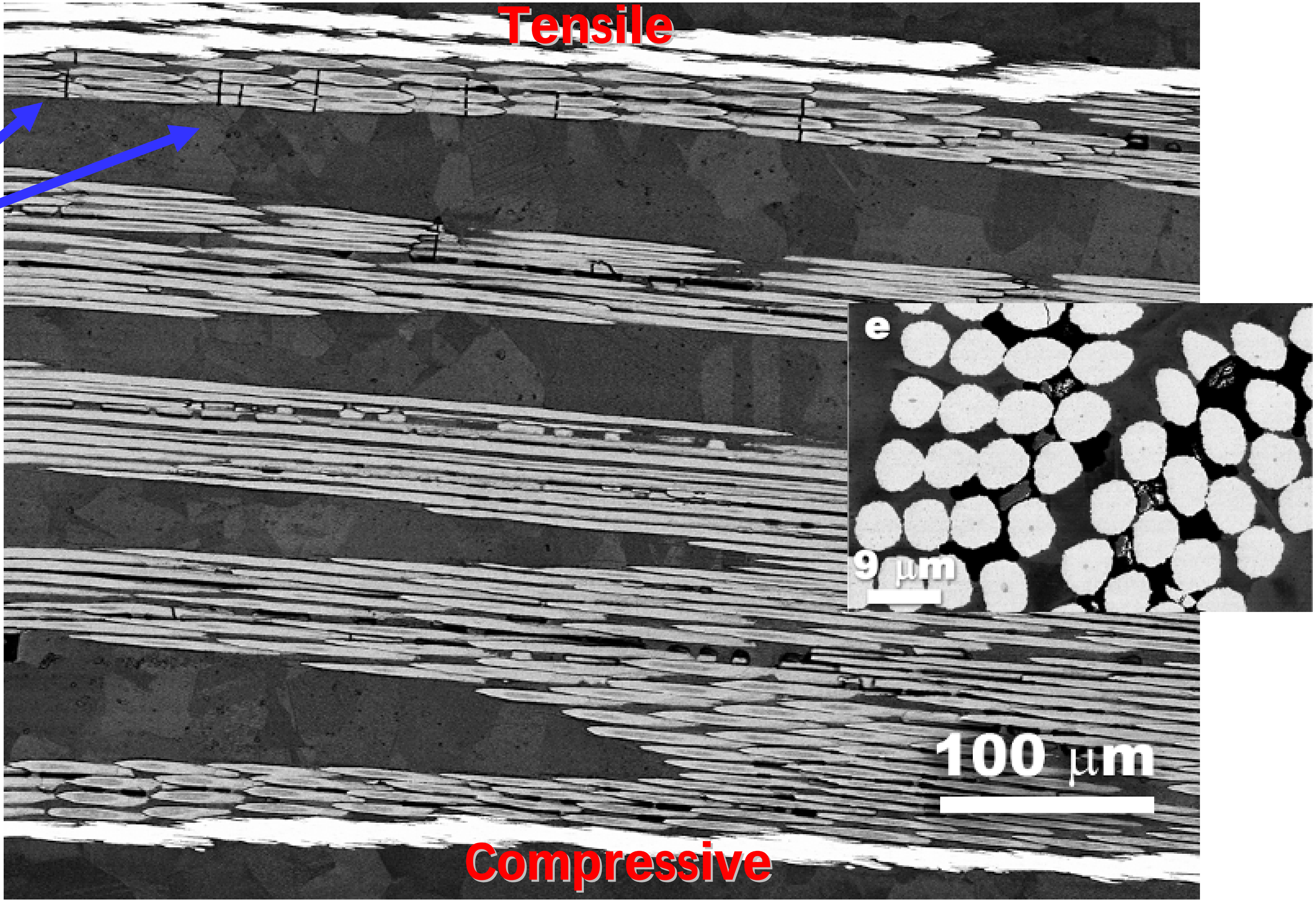
- 1 cm-long samples were mounted in Al clamps with a variety of radii and bent at 77K to 0.5%, 1.0%, 1.5%
- Samples removed from clamp after warming and longitudinal face hot-mounted, ground, and polished to 0.05 μm
- Samples etched in 37% HNO_3, 13% HF for ~5 sec. to reveal crack location – but not enough to create false voids.
- Images acquired over > 1 cm length on field-emission scanning electron microscope and/or scanning laser confocal microscope

	Cu			Nb		
Temp (K)	E [GPa]	σ_y [MPa]	ΔL /L (%)	E [GPa]	σ_y [MPa]	ΔL /L (%)
293	128	48.5	0	105	50.5	0
77	136	75.4	-0.285	108	96	-0.127
4.2	137	86.2	-0.334	110	194	-0.148
Deviation from 4.2K value at 77K	1%	13%	15%	2%	51%	14%

	Ta			Nb_3Sn		
Temp (K)	E [GPa]	σ_y [MPa]	ΔL /L (%)	E [GPa]	σ_y [MPa]	ΔL /L (%)
293	180	265.9	0	135	---	0
77	186	457	-0.123	123	---	-0.143
4.2	188	874.3	-0.152	100	---	-0.185
Deviation from 4.2K value at 77K	1%	48%	19%	23%	---	23%

Bend testing – OST @ 1.5%

Correlated fracture events



Bend testing at 1.5% – comparison

- Direct comparison of relative fracture propensity
- Fracture is more collective in the internal Sn strands
- Filament fracture density is highest in the Oxford strand

% filaments cracked	
EAS	1.8%
MIT	3.4%
HIT	4.6%
OST	12.1%

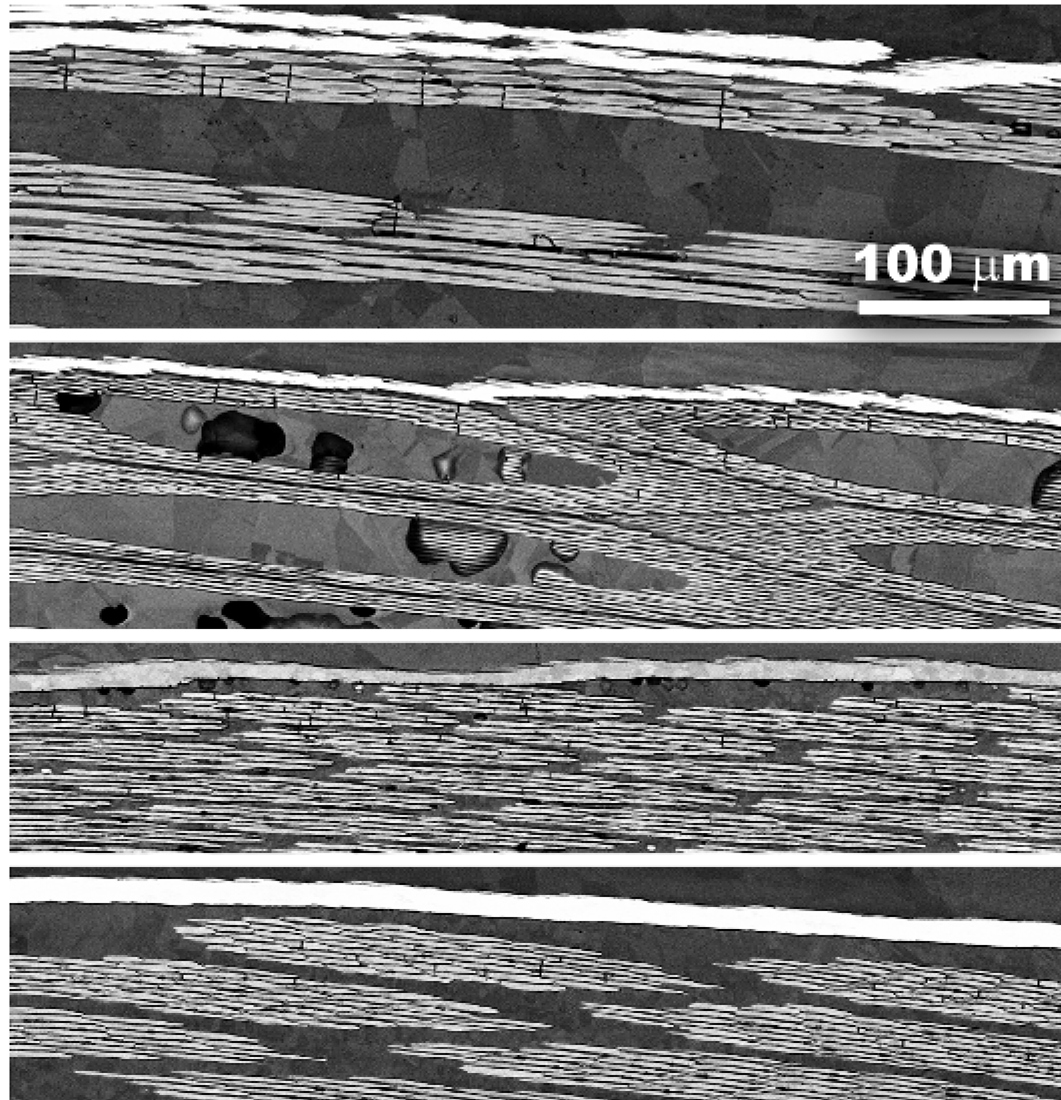
Theses values scale with the localization of fracture in the TARSIS test

OST

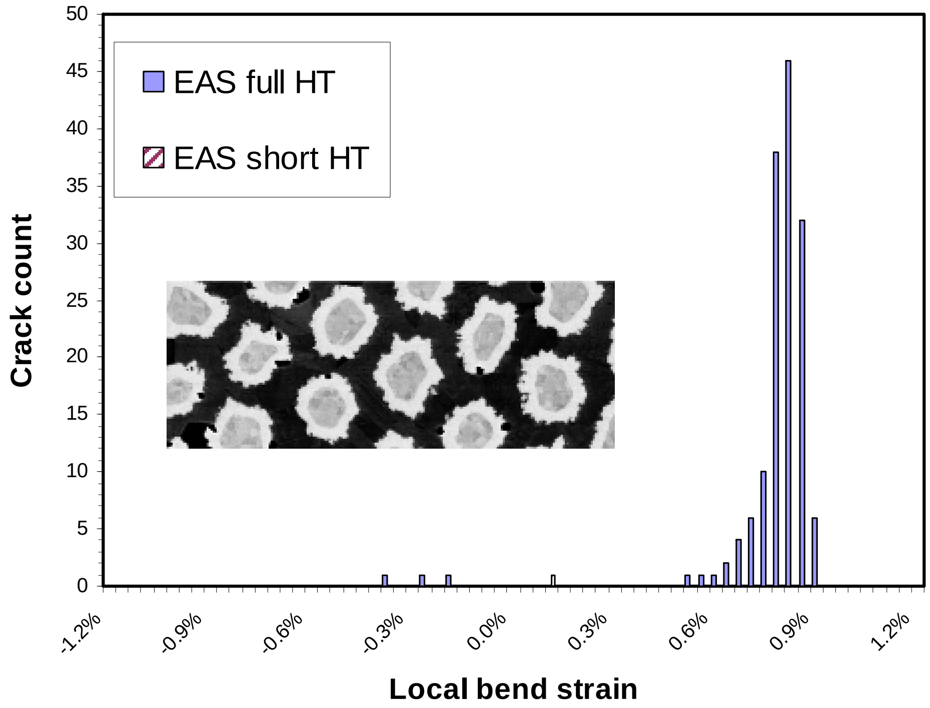
MIT

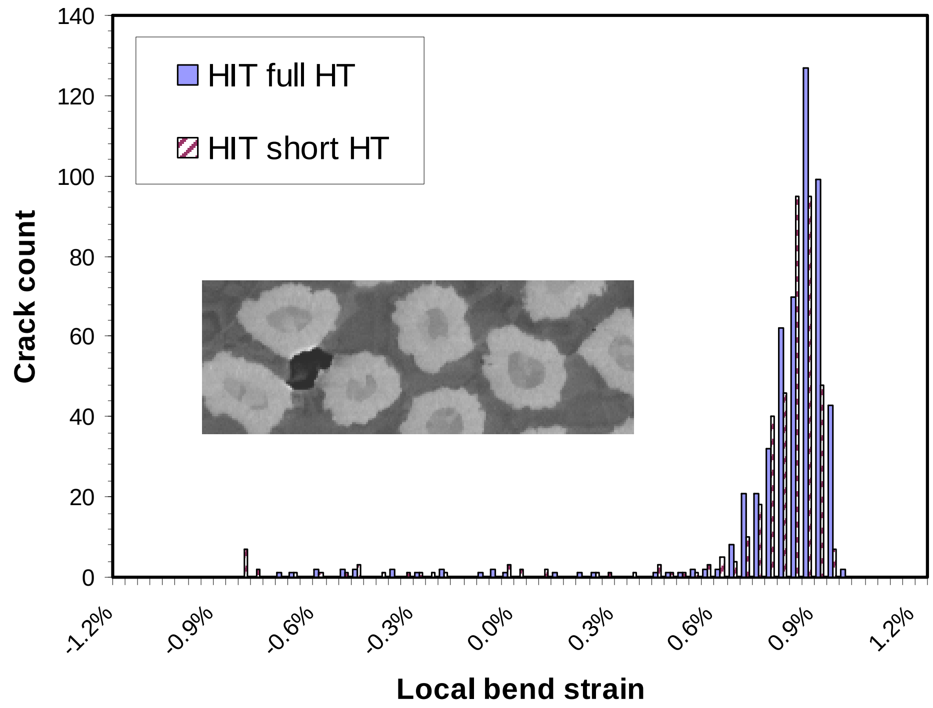
HIT

EAS



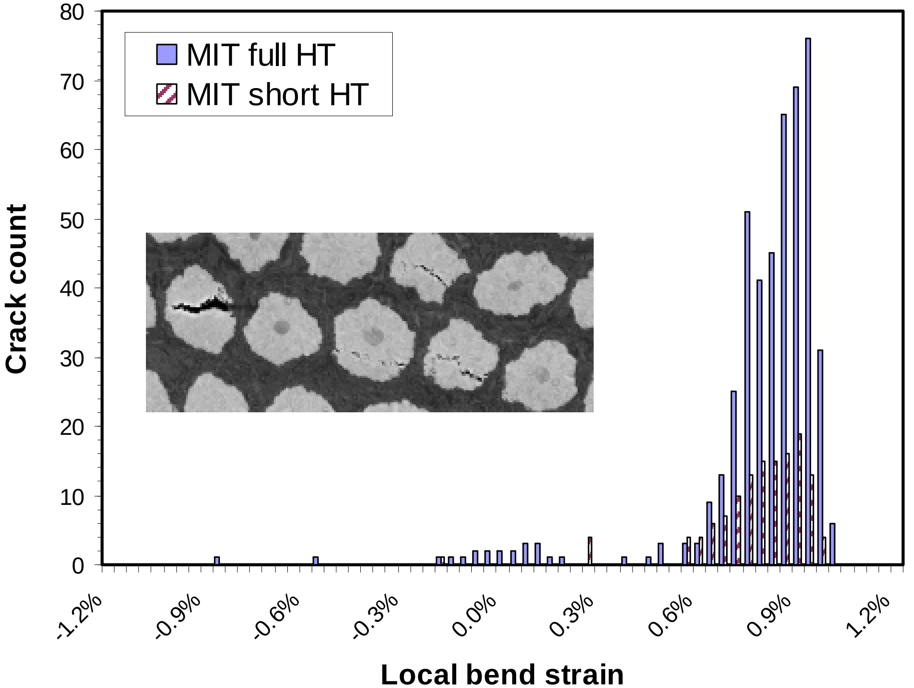
Bronze bend test fracture distributions

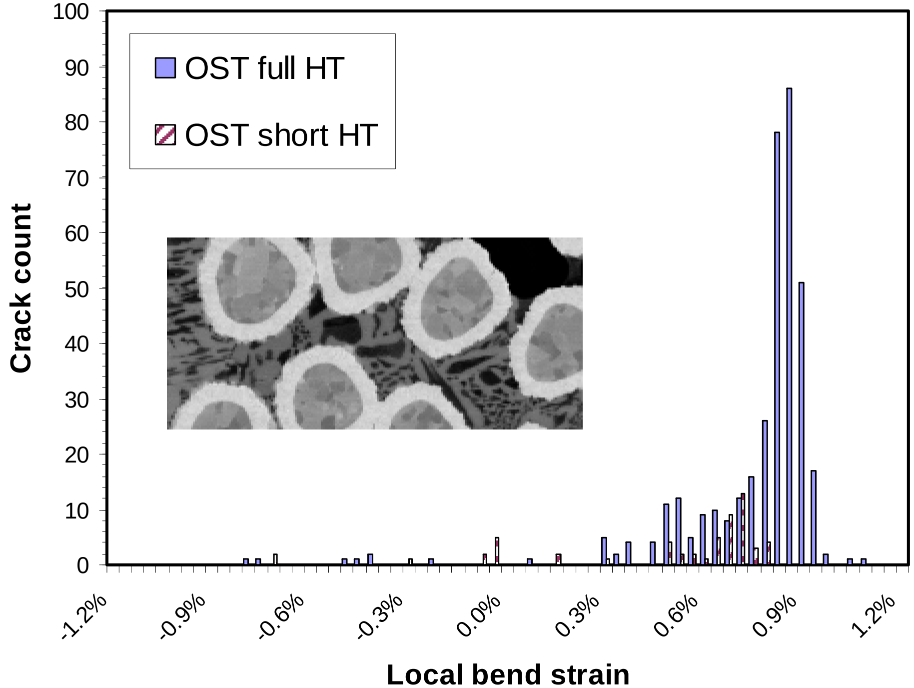




- Both strands have very similar onset of irreversible damage – around 0.7% bend strain, relative to the geometric wire center.
- The distribution shape is very similar for both strands
- EAS shows almost no cracking in under-reacted sample; HT shows significant cracking, but same shape to distribution

Internal tin bend test fracture distributions





- MIT has a bronze-like distribution of fracture events, with an onset near 0.7%.
- The MIT distribution is "flatter", presumably due to the collective cracking observed.
- OST has an earlier fracture onset – around 0.5% bend strain. This is consistent with a Griffith fracture criterion view of the system.

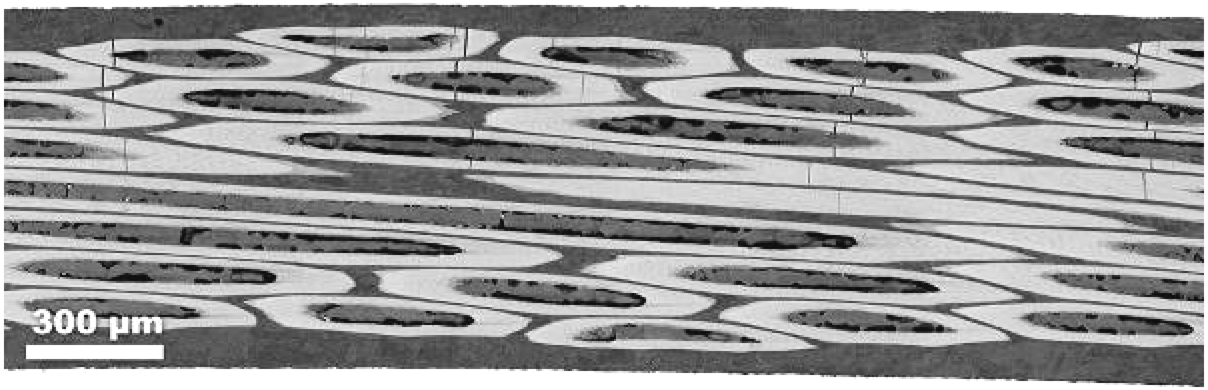
All bend test fracture data

Complete fracture results for 1.0% and 1.5% bend strain							
Bend radius (%)	Strand	HT	Crack count	Sampled area (mm^2) inside diffusion barrier	Fraction of Nb_3Sn inside Diffusion barrier	Cracks/mm^2 of Nb_3Sn	Cracks/filament
1.0	**EAS**	**Full**	**4**	**8.36**	**0.319**	**1.5**	**0.0%**
1.0	**Hitachi**	**Full**	**28**	**8.16**	**0.369**	**9.3**	**0.3%**
1.0	**Mitsubishi**	**Full**	**7**	**7.48**	**0.325**	**2.9**	**0.1%**
1.0	**Oxford**	**Full**	**10**	**7.96**	**0.401**	**3.1**	**0.3%**
1.5	**EAS**	**Short**	**1**	**5.31**	**0.198**	**0.9**	**0.0%**
1.5	**EAS**	**Full**	**150**	**6.83**	**0.319**	**68.9**	**1.8%**
1.5	**Hitachi**	**Short**	**410**	**5.39**	**0.309**	**246.0**	**3.7%**
1.5	**Hitachi**	**Full**	**514**	**6.85**	**0.369**	**203.3**	**4.6%**
1.5	**Mitsubishi**	**Short**	**131**	**7.62**	**0.307**	**56.0**	**1.0%**
1.5	**Mitsubishi**	**Full**	**463**	**7.24**	**0.325**	**196.8**	**3.4%**
1.5	**Oxford**	**Short**	**56**	**4.70**	**0.201**	**59.4**	**1.8%**
1.5	**Oxford**	**Full**	**374**	**6.14**	**0.401**	**151.8**	**12.1%**

- **No significant cracking at 1.0% or 0.5% bend strain.**
- **Clear trend of less cracking with less HT (even when normalized to A15 area) in EAS, MIT, OST.**
- **Hitachi is the interpretive challenge –cracks the most (on a normalized basis) in bend testing. Normalized crack density actually increases with reduced HT.**
  - **Not so much of an outlier on a cracks/filament basis**
  - **Remember that cracks are well-distributed, which is key to minimizing I_c degradation**

Bend testing @ 1.5% – HEP strands

OST-3000

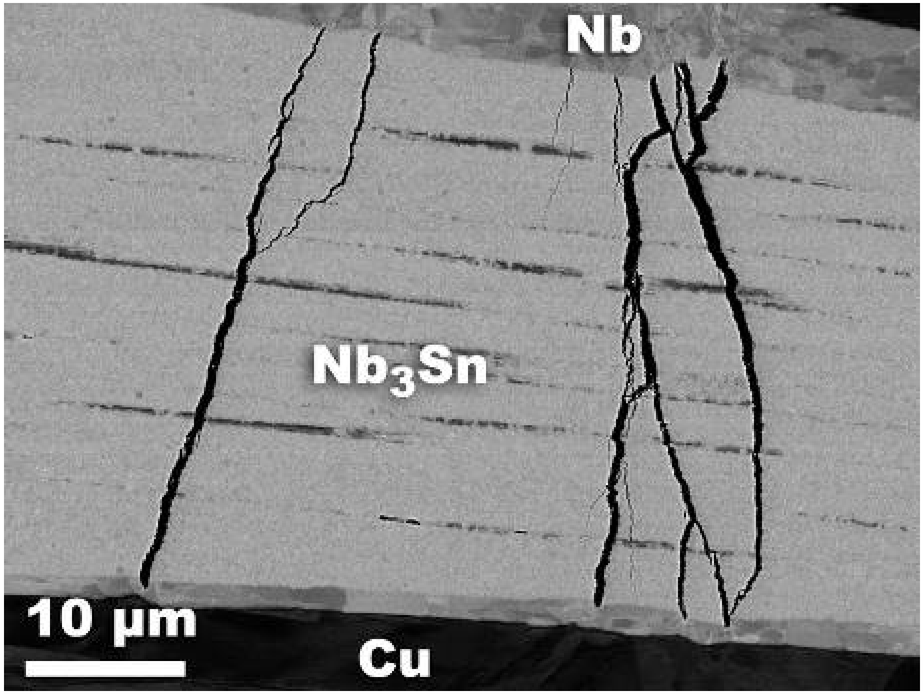


OST-2400

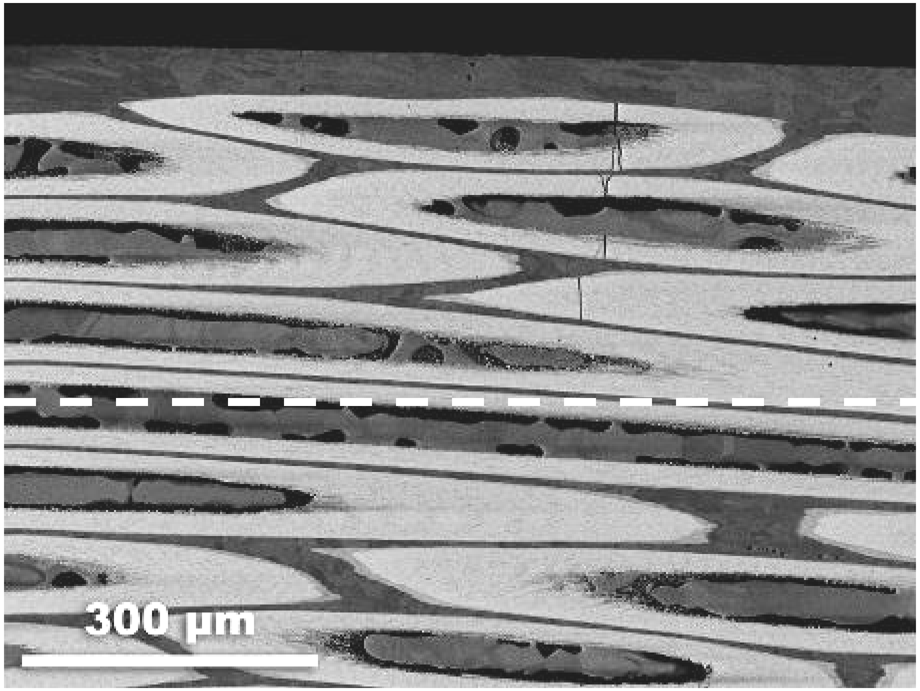
OST-1700

Bend testing – HEP strands

OST-3000 @1.5% bend strain

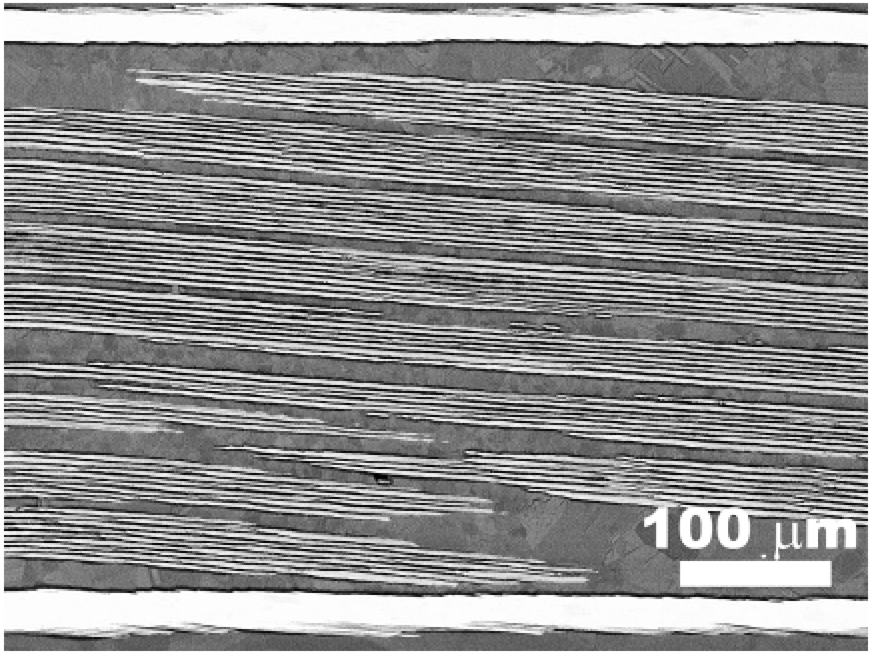


OST-3000 @ 1.0% bend strain

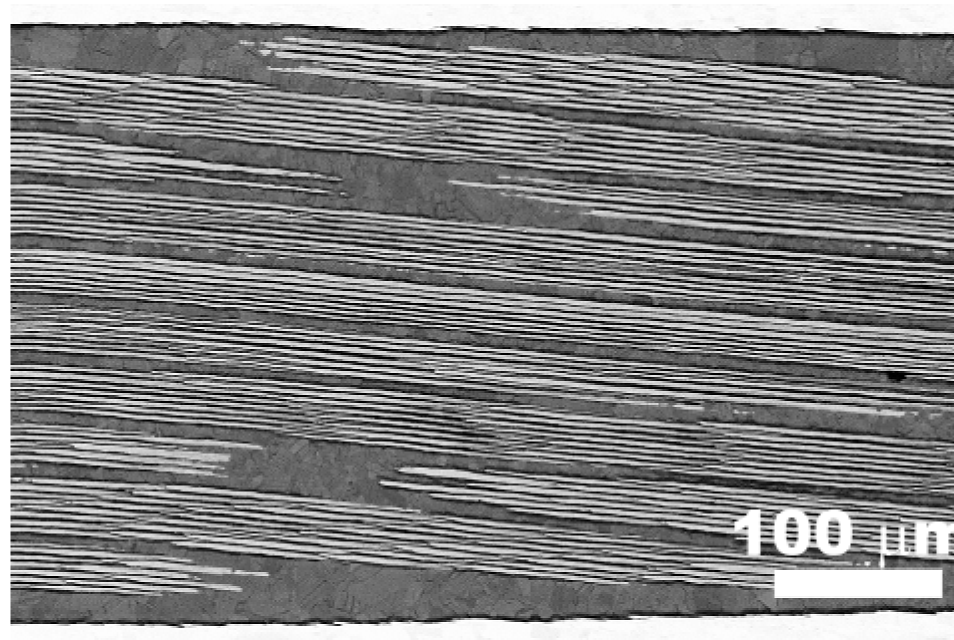


- Closer look reveals multiple correlated fracture events
- Cracks from both directions
- 1.0% still shown fracture to near the neutral axis (dashed line) – clear “threshold” behavior

Comparison to uniaxial tension – EAS ITER strand



0.0% strain

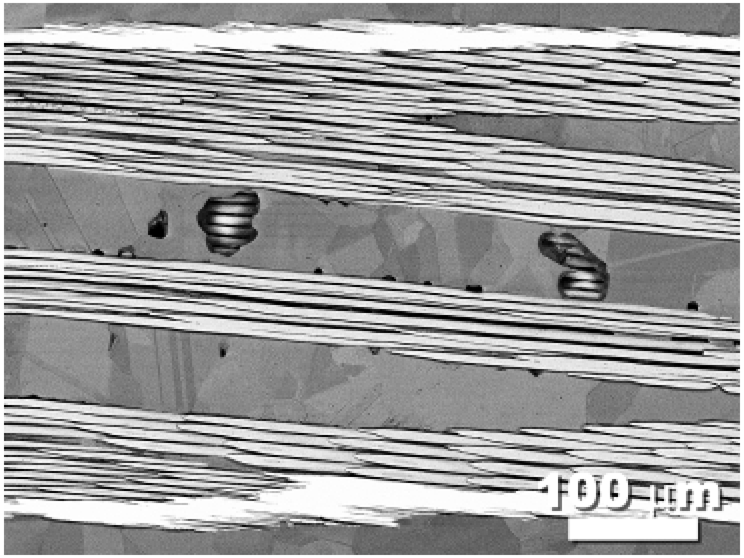


0.7% strain

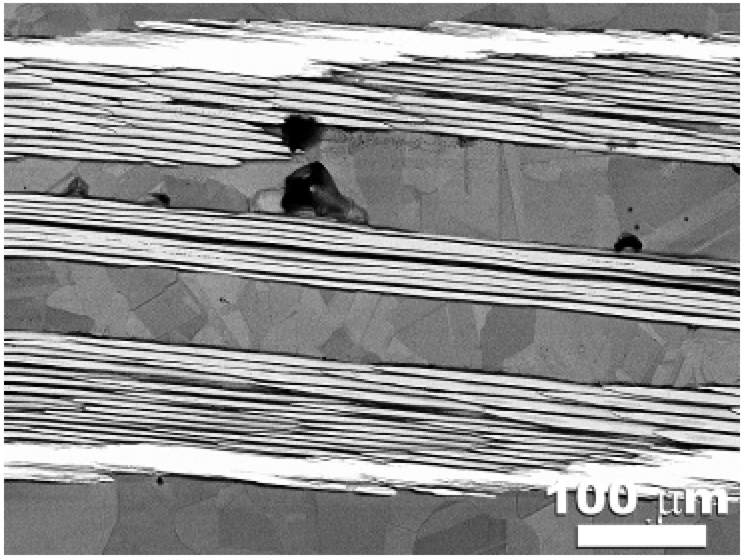
- 4 K uniaxial tension test (H = 0; I = 0) in 0.1% strain increments
- Essentially no fracture events in the strand from 0.0% - 0.7%!
- This is the kind of "toughness" we would like to build into every strand

Uniaxial tension – Oxford ITER strand

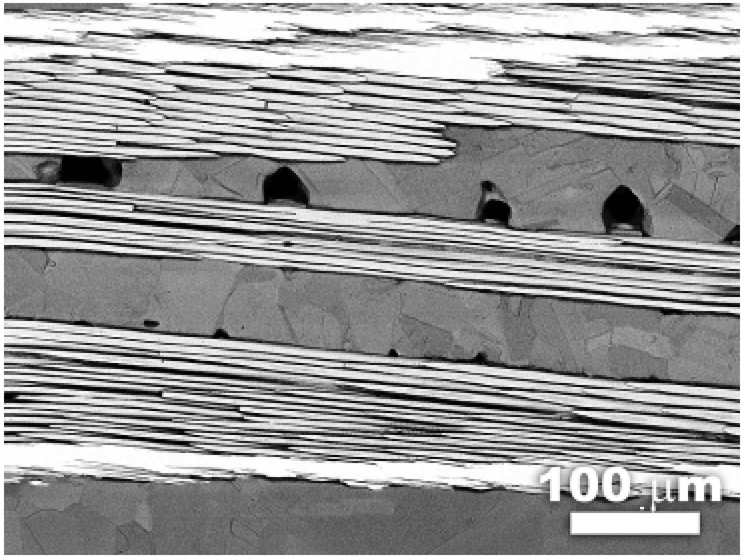
0.0% strain



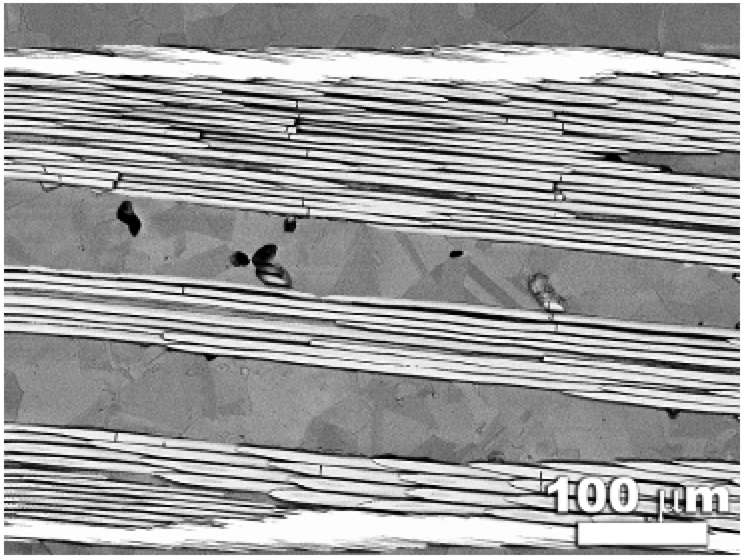
0.3% strain



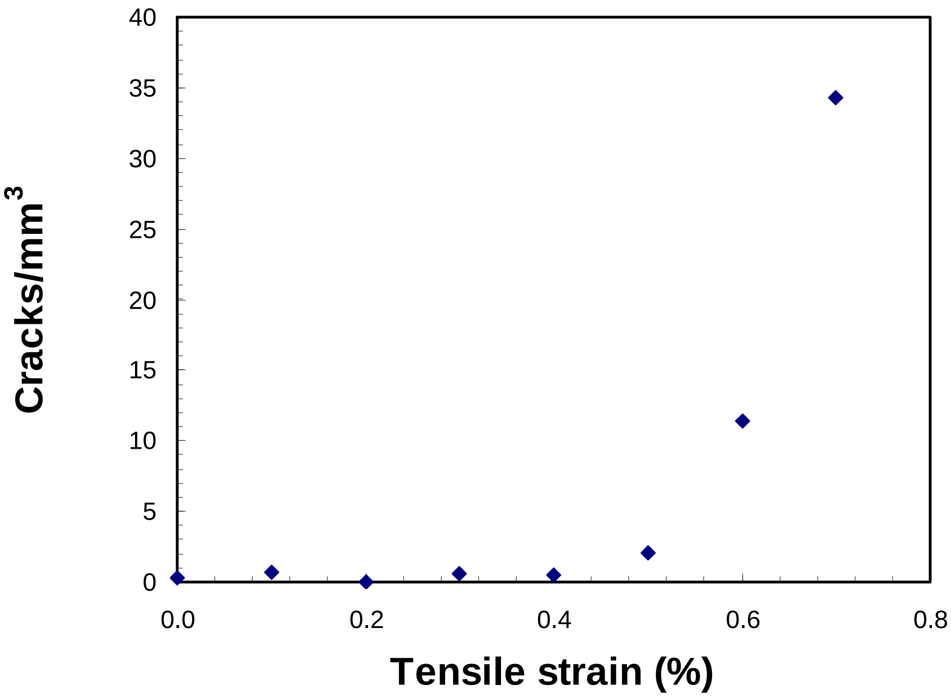
0.5% strain

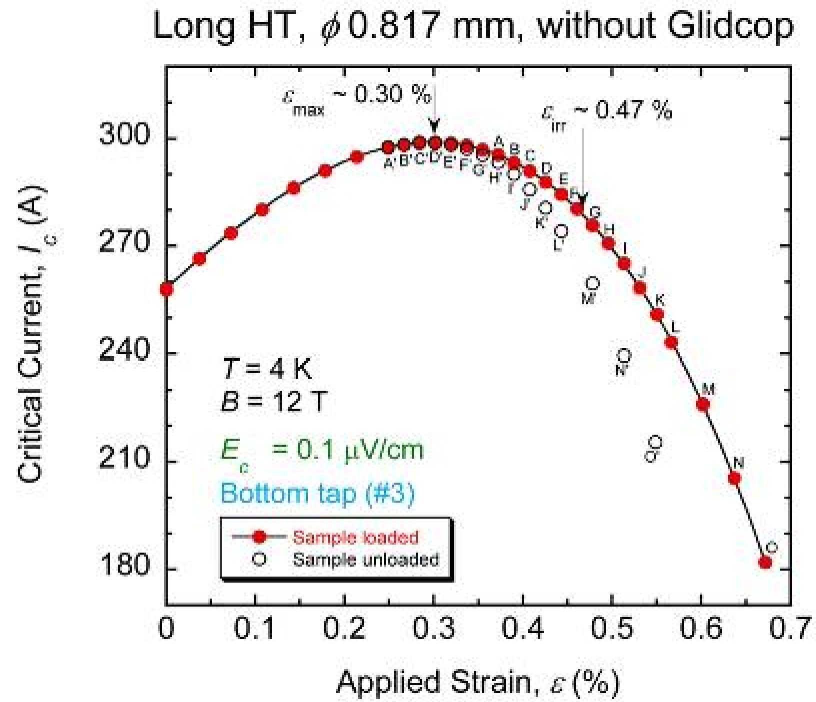


0.7% strain



OST longitudinal cracking summary





Data courtesy N. Cheggour, NIST

- Crack density scales exponentially with tensile strain – we can estimate the true 3-d density of cracks
- Onset agrees (to within 0.1% or so) of onset from NIST Walters spring data
- The fracture onset and trend is consistent with the bend test data

Implications for strand design

- Fracture is a tensile strain phenomenon: so stay in compression!
  - Cable design
  - Strand strengthening
  - More strand pre-compression
- Filament size matters…if they are small already:
  - For ITER strands, filament size is small enough that further size reductions are likely to be beneficial
  - For HEP strands, filament size is not likely to reduce crack initiation, but could reduce stress concentrations
- Filament agglomeration is important: so separate the filaments/sub-bundles
  - ITER IT strands could eliminate agglomeration with some additional design work
  - HEP strands could have larger spacing between sub-bundles

$$F(V) = 1 - EXP\left(\frac{-V}{V_0}\right)$$