Irreversible strain in Nb_3Sn conductors

M.C. Jewell, P.J. Lee, D.C. Larbalestier
Applied Superconductivity Center
National High Magnetic Field Laboratory

A. Nijhuis
University of Twente

CARE-HHH-AMT WAMSDO 2008
May 20, 2008

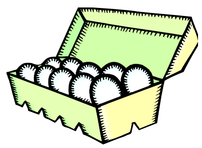
Acknowledgements

- Funding
  - DOE-HEP
    - DE-FG02-07ER41451 (Florida State University)
    - DE-FG02-91ER40643 (University of Wisconsin)
  - DOE-Fusion
    - DE-FG02-06ER54881 (Florida State University)
  - ITER IO
    - ITER-CT-07-012 (Florida State University)
- Samples
  - Alex Vostner, F4E
  - Kiyoshi Okuno, JAEA

Motivation (1)

- Driving force: Degradation concerns in Nb_3Sn CICC design magnets
- Our approach: Understand how strand architecture affects filament fracture propensity

- The "egg crate" approach



  - Improve the packaging (the cable design)
  - Variables include void fraction, twist pitch, twist geometry, jacket material, etc.

- The "egg shell" approach

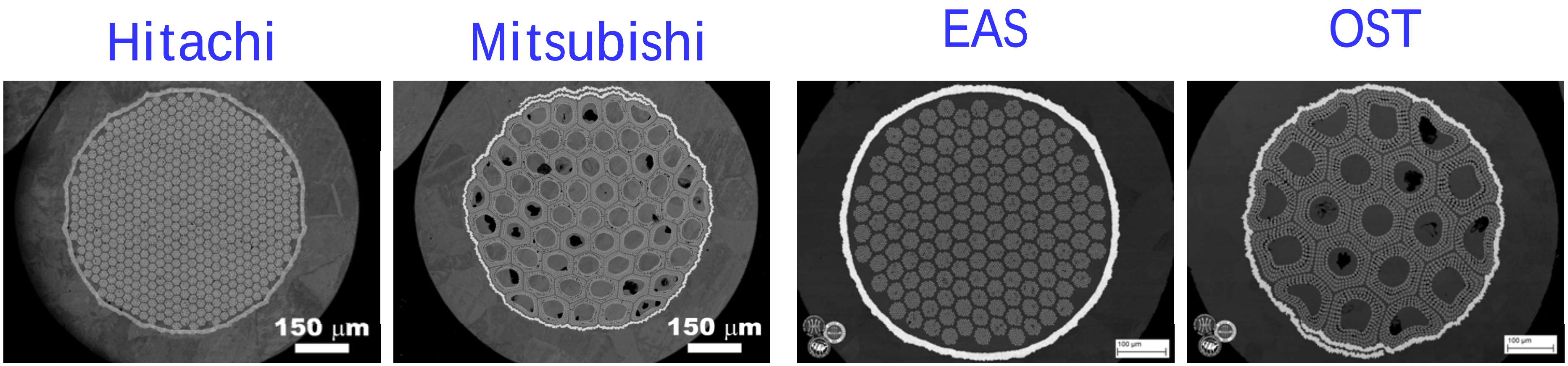
  - Make the strand fundamentally tougher
  - Variables include filament size, spacing, shape, location; microstructural features like voids

Motivation (2)

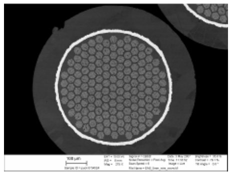
We are concerned with two issues:

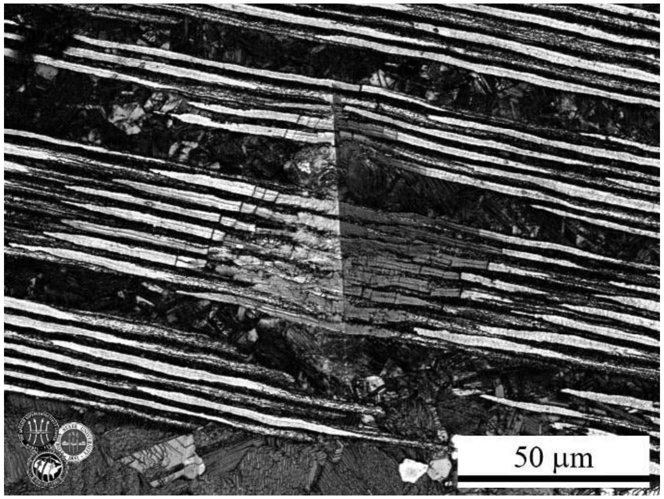
- Under what conditions does a filament crack?
- Under what conditions does that crack propagate to adjacent filaments?

Strand design	HIT	MIT	EAS	OST
Type	bronze	IT	bronze	IT
Fil/bundle	19	224	55	163
Bundles/strand	583	61	151	19
Total filaments	11077	13664	8305	3097
Total fil. X-section (μm^2)	103151	84085	78283	95039
% breakage				
One filament	0.009%	0.007%	0.012%	0.032%
One bundle	0.2%	1.6%	0.7%	5.3%

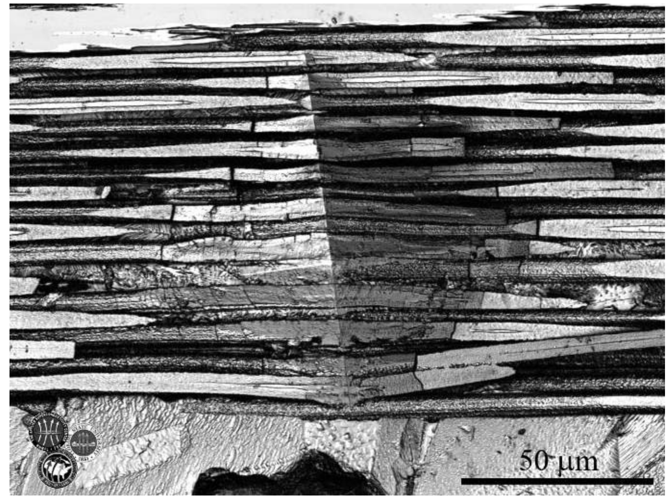


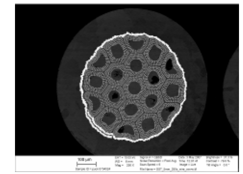
Indentation of various unstrained conductors



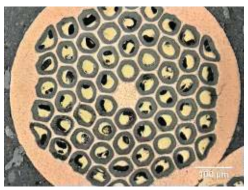


EAS bronze: each filament cracks; the cracks are relatively narrow; the cracks are stacked 2-3 deep near the edge of the indent. **J_c = 780 A/mm²**





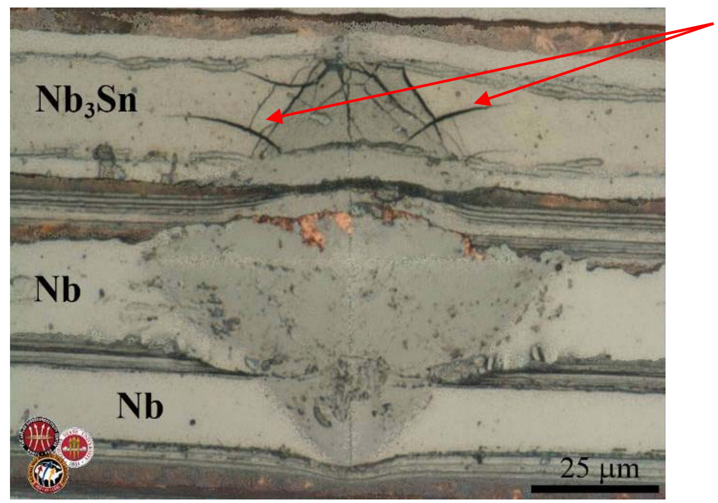
OST ITER-style: each filament cracks; the cracks are wider than EAS and in general just one large crack near the edge of indent. **J_c = 1100 A/mm²**

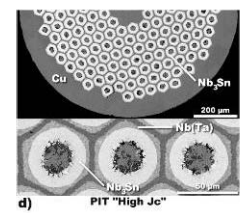


Edge-normal cracks

OST RRP: cracking is highly collective but still localized. Some cracks perpendicular to indent edge (see arrows) . **J_c = 2400 A/mm²**

Edge-normal cracks

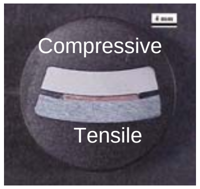




SMI PIT: Difficult to image multiple "filaments". Clear 45° cracks that extend further than other strand types. **J_c ~ 2000 A/mm²**

In a nominally strain-free condition, cracking from indentation is localized - not extensive like in tensile-side indents of previous slide. However, each conductor (with its unique strand design) displays a different crack morphology.

Indentation changes dramatically in tensile strain state



Some crack propagation

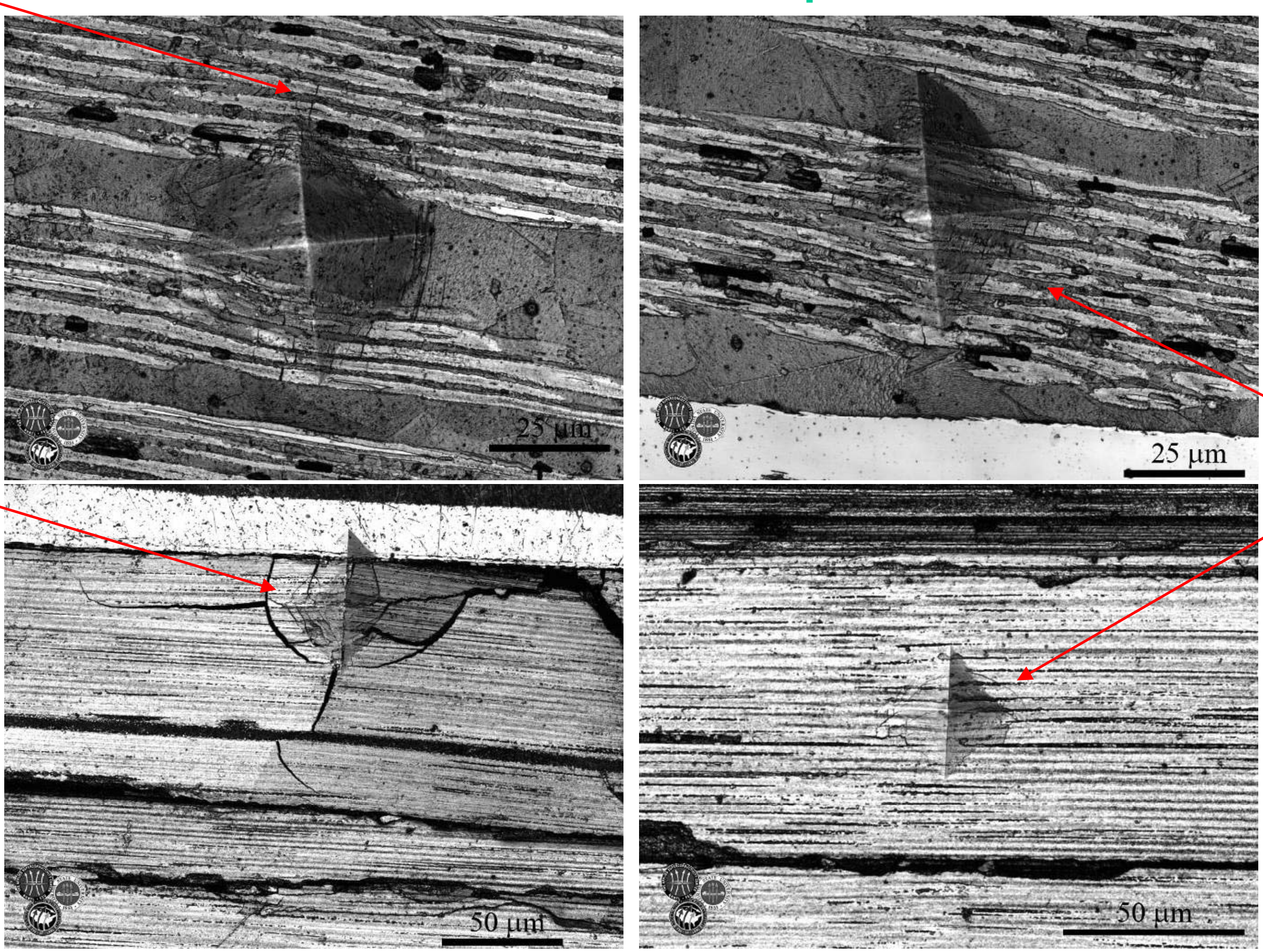
Tensile side indent

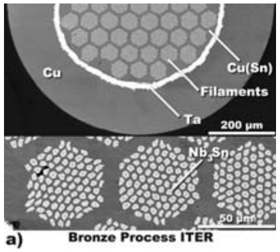
Compressive side indent

VAC bronze – well separated filaments

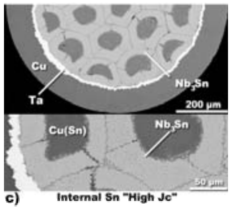
IGC high-J_c prototype – highly agglomerated filaments

Massive crack propagation





Cracking decidedly localized



- **In a highly agglomerated filament pack, the tensile strain field causes catastrophic propagation of cracks.**
- **In a well-distributed filament pack, the interfilamentary Cu can greatly blunts crack propagation on the tensile side.**
- **Fracture mechanics accepts that cracks cannot be forbidden - propagation is inhibited by remaining under compression and enhancing K_{Ic} - by separating filaments.**

Some initial observations

- Nb_3Sn behaves as a *classic* brittle material
- The effect of tensile strain on crack propagation is dramatically demonstrated.
  - Design compression into the conductor under all cable loading conditions
- The cable design plays a critical role in preventing fracture, because it determines the global and local strain state
- Initiation vs. propagation
  - Preventing crack initiation is a tricky business, because, for brittle materials, there exists a statistically determined distribution of critical stress values
  - Our indentation results clearly show the effect of both cable design and strand design in minimizing crack propagation

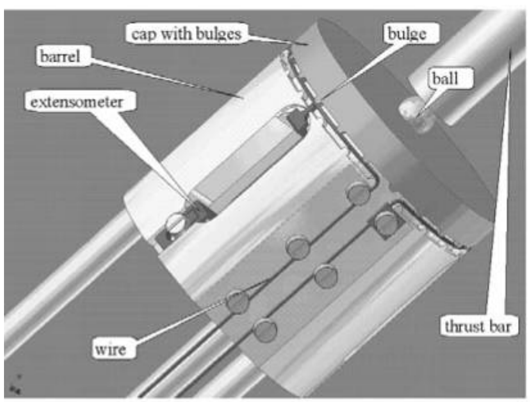
Our experimental approach

- How do we evaluate the effect of strand architecture on fracture?
- We have a simple, two step approach

1. Deform various strands is a controlled, repeatable manner
   - Indentation
   - Pure bending
   - TARSIS
2. Image the fracture distribution
   - Traditional metallography
   - Deep etching
   - -Magneto-optical imaging (not shown today)

TARSIS strand evaluation

- Strand damage shows up in I-V curve by degraded J_c and n-value. N-value is more sensitive.
- Studied both EAS and OST-II using the 5mm bend rig and crossing strands (x-strands) rig
- We receive extracted, post-testing strand and examine damage metallography
- The samples have been severely deformed – $J_c \sim 0.1 J_{c,max}$
- Control sample ensures no damage from polishing procedure



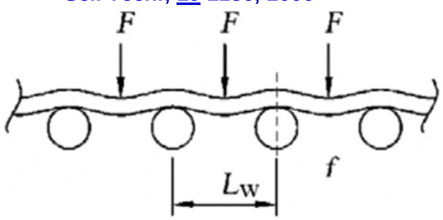
A. Nijhuis *et al.*, *Supercond. Sci. Tech.*, 19 1136, 2006

A. Nijhuis *et al.*, *Supercond. Sci. Tech.*, 19 1089, 2006

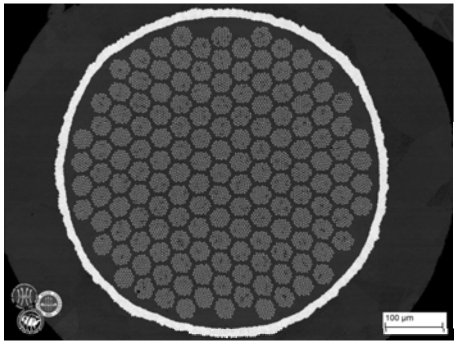
Collaboration with Arend Nijhuis at U. Twente

Strand architecture results

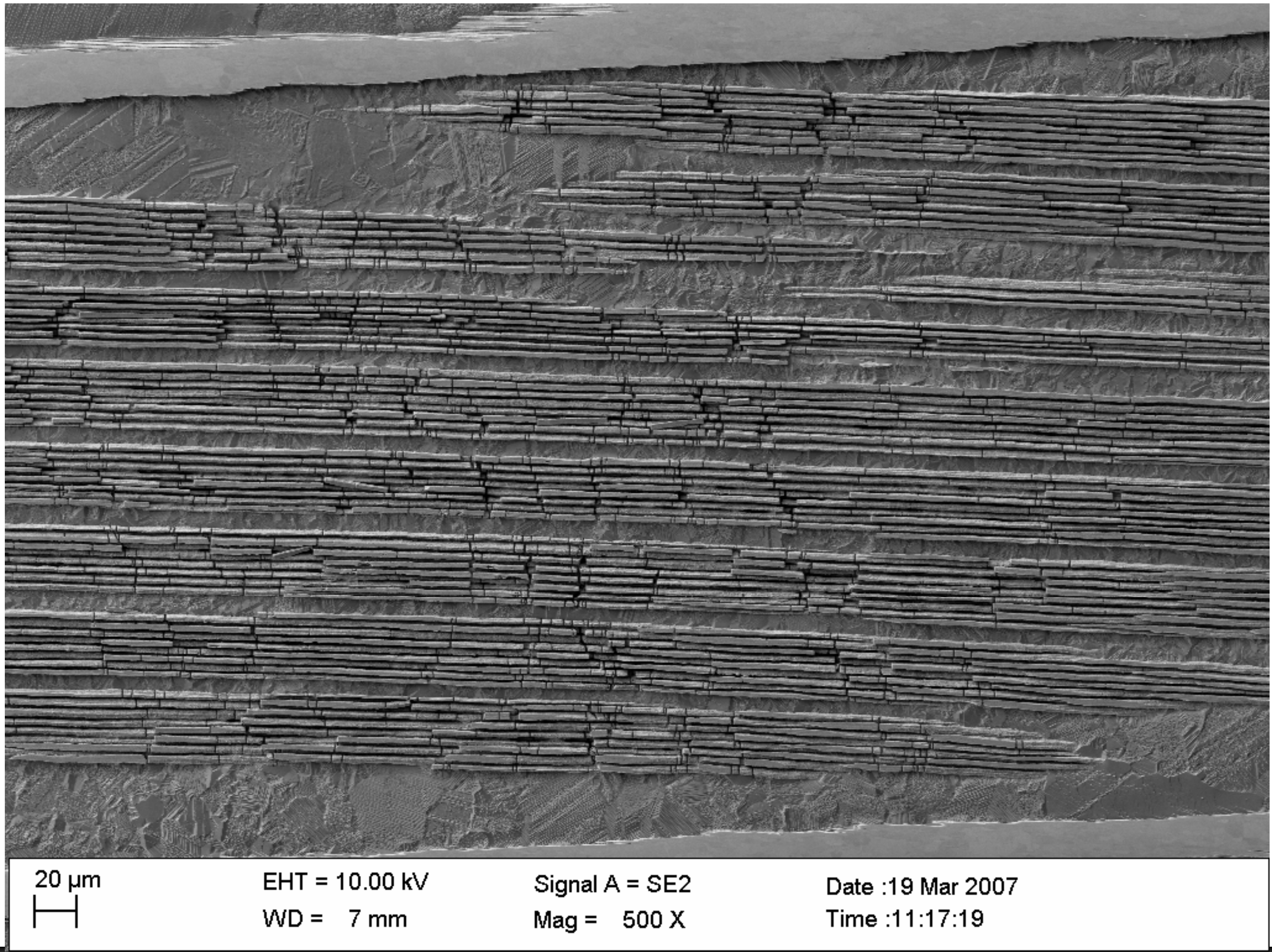
A. Nijhuis *et al.*, *Supercond. Sci. Tech.*, 19 1136, 2006



- 5mm wavelength samples:
  - Highly distributed fracture morphology

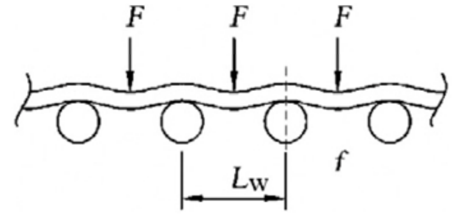


EAS



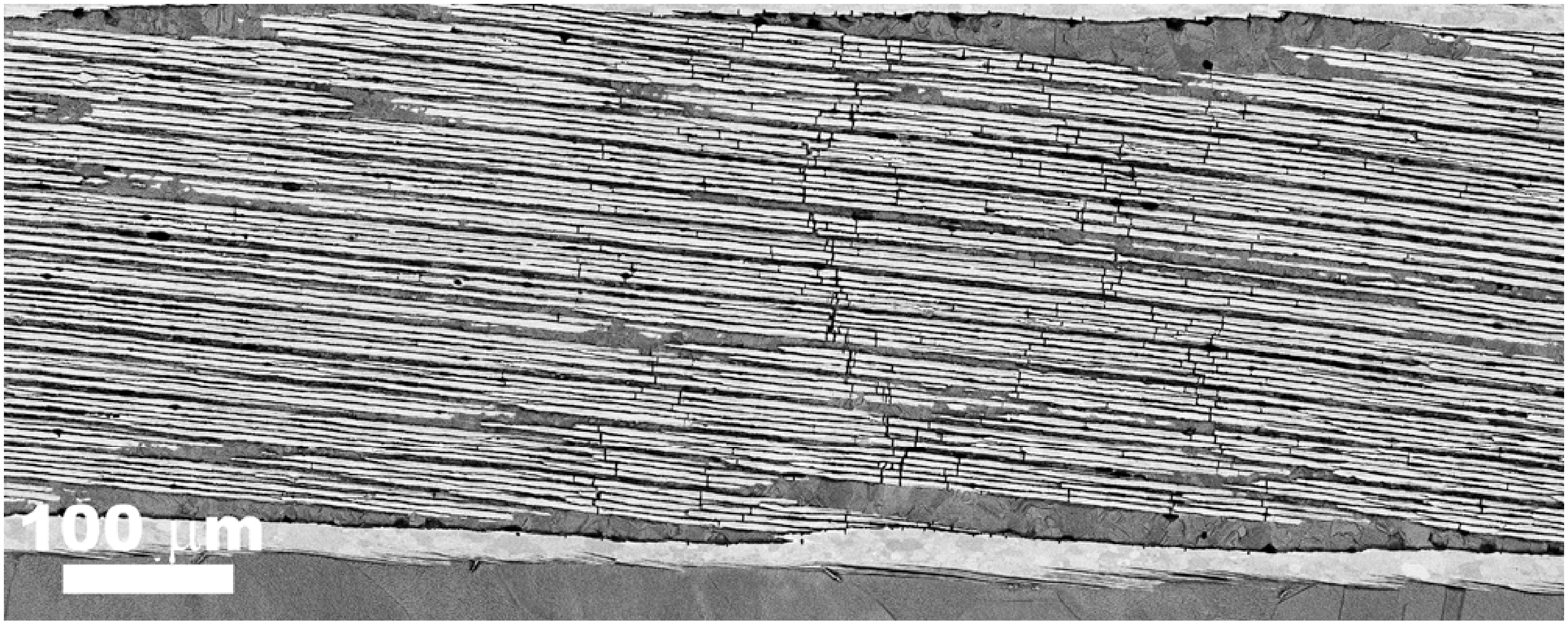
Strand architecture results

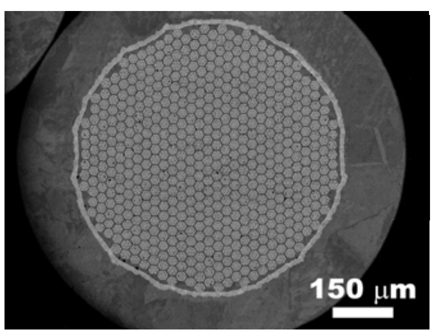
A. Nijhuis *et al.*, *Supercond. Sci. Tech.*, 19 1136, 2006



- 5mm wavelength samples:
  - Fracture somewhat more localized than EAS, despite seeing higher peak bending strain!

Hitachi

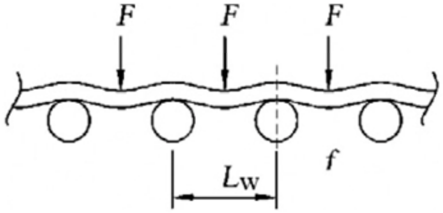




Transverse view

Strand architecture results

A. Nijhuis *et al.*, *Supercond. Sci. Tech.*, 19 1136, 2006



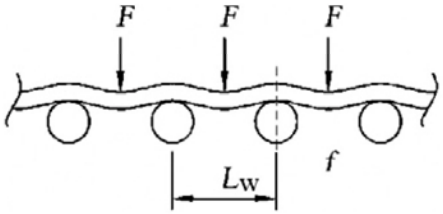
- 5mm wavelength samples:
  - Switch to internal Sn increases collective nature of fracture.

Korean

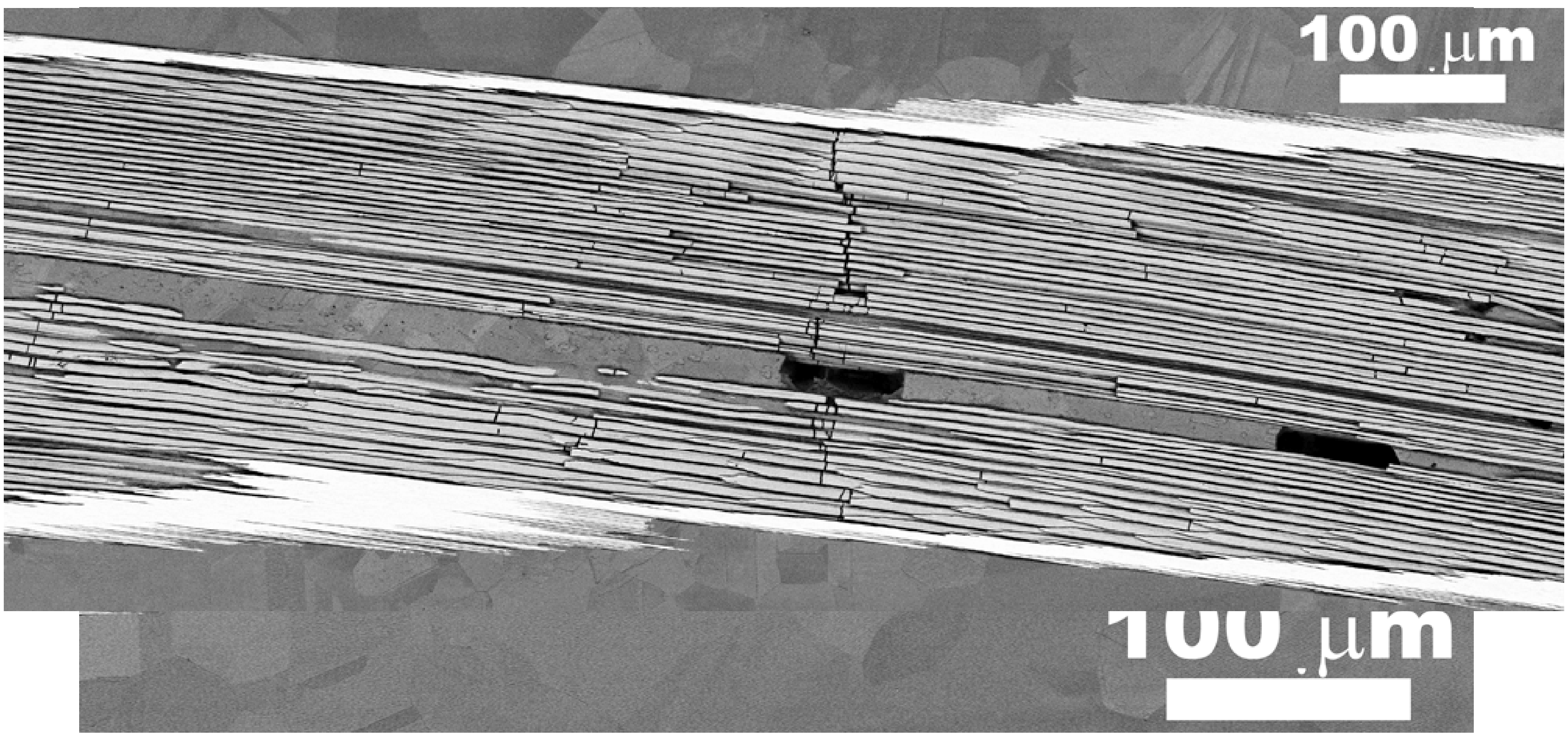
Strand architecture results

- 5mm wavelength samples:
  - Further collective cracking…
  - Very clean at compressive edge

A. Nijhuis *et al.*, *Supercond. Sci. Tech.*, 19 1136, 2006

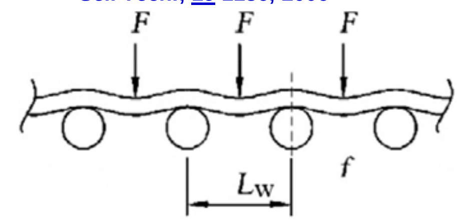


NiN & WST

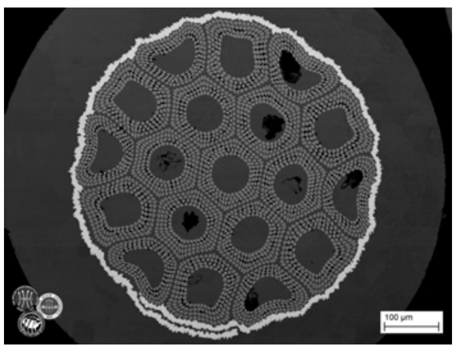


Strand architecture results

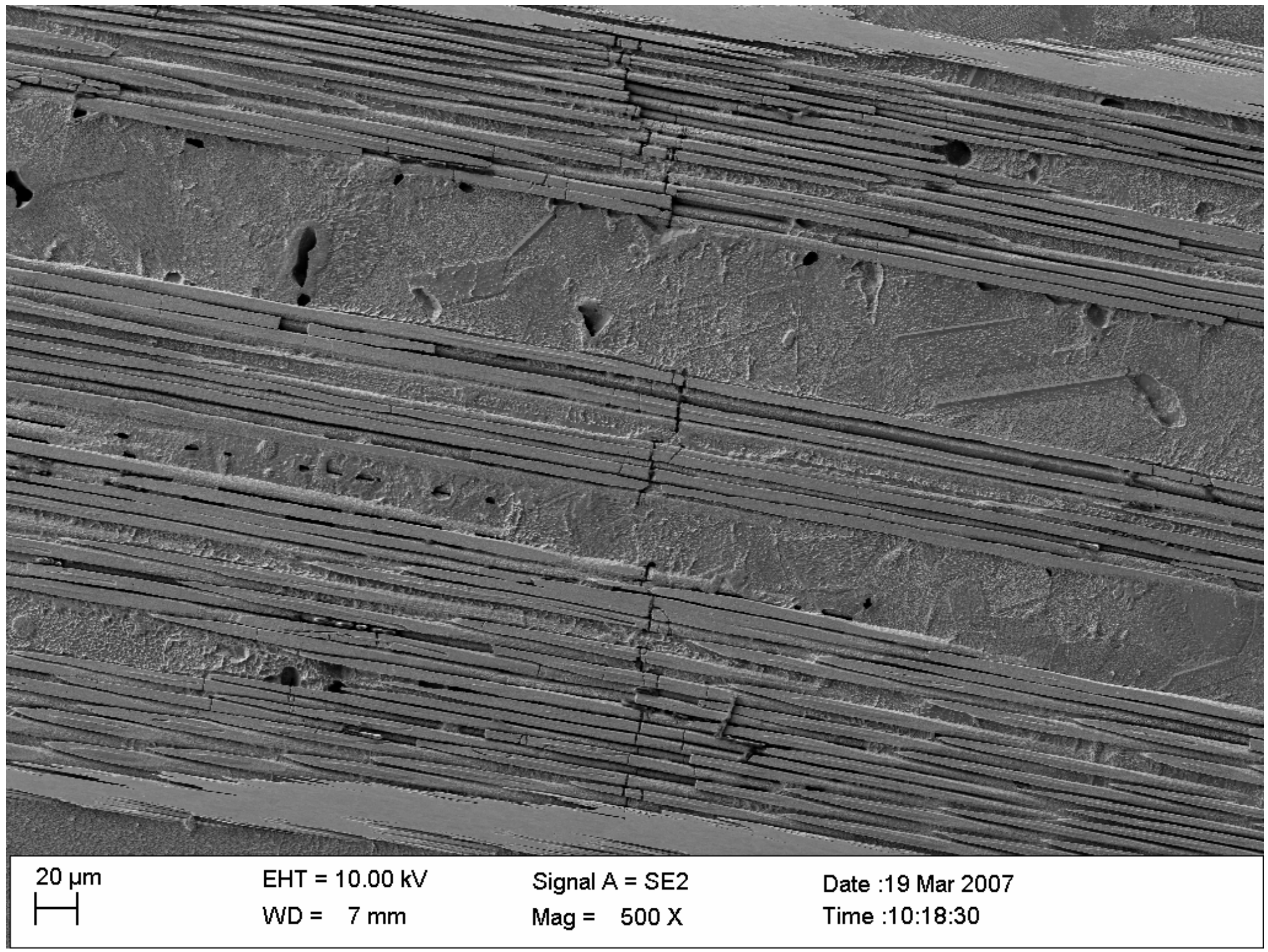
A. Nijhuis *et al.*, *Supercond. Sci. Tech.*, 19 1136, 2006



- 5mm wavelength samples:
  - Almost a single crack – extremely collective
  - Cracking elsewhere is sparse – but some damage at 2.5mm in OST strand

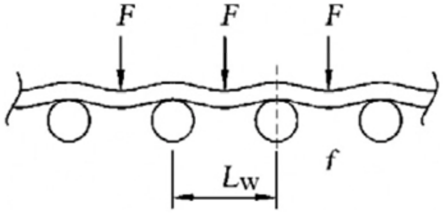


OST

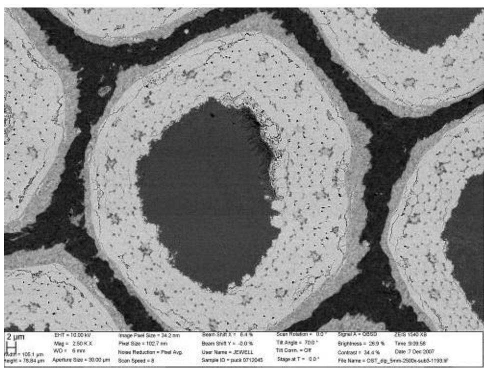


Strand architecture results

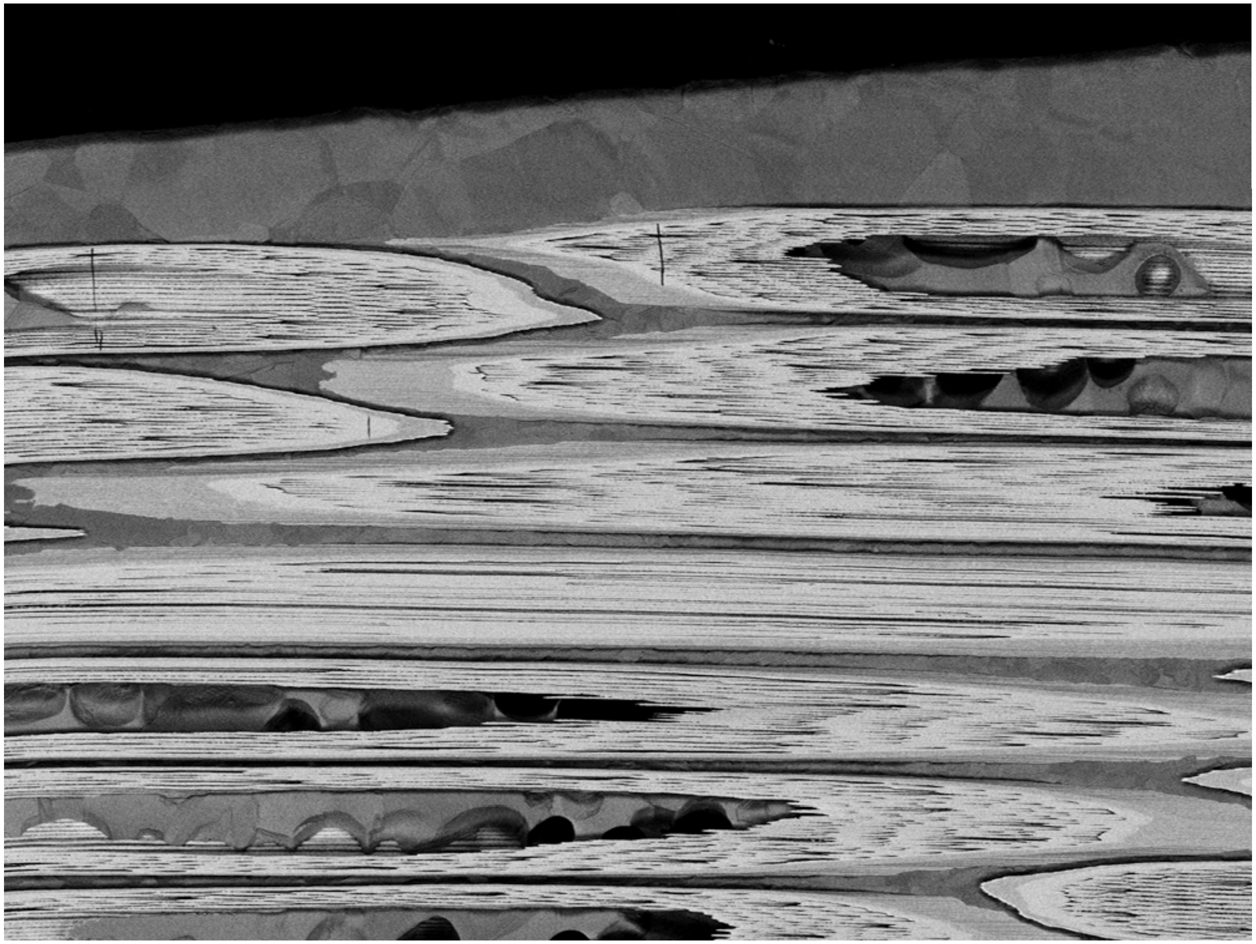
A. Nijhuis *et al.*, *Supercond. Sci. Tech.*, 19 1136, 2006



- 5mm wavelength samples:
  - Completely collective cracking in OST-dipole
  - But distributed barrier does help!

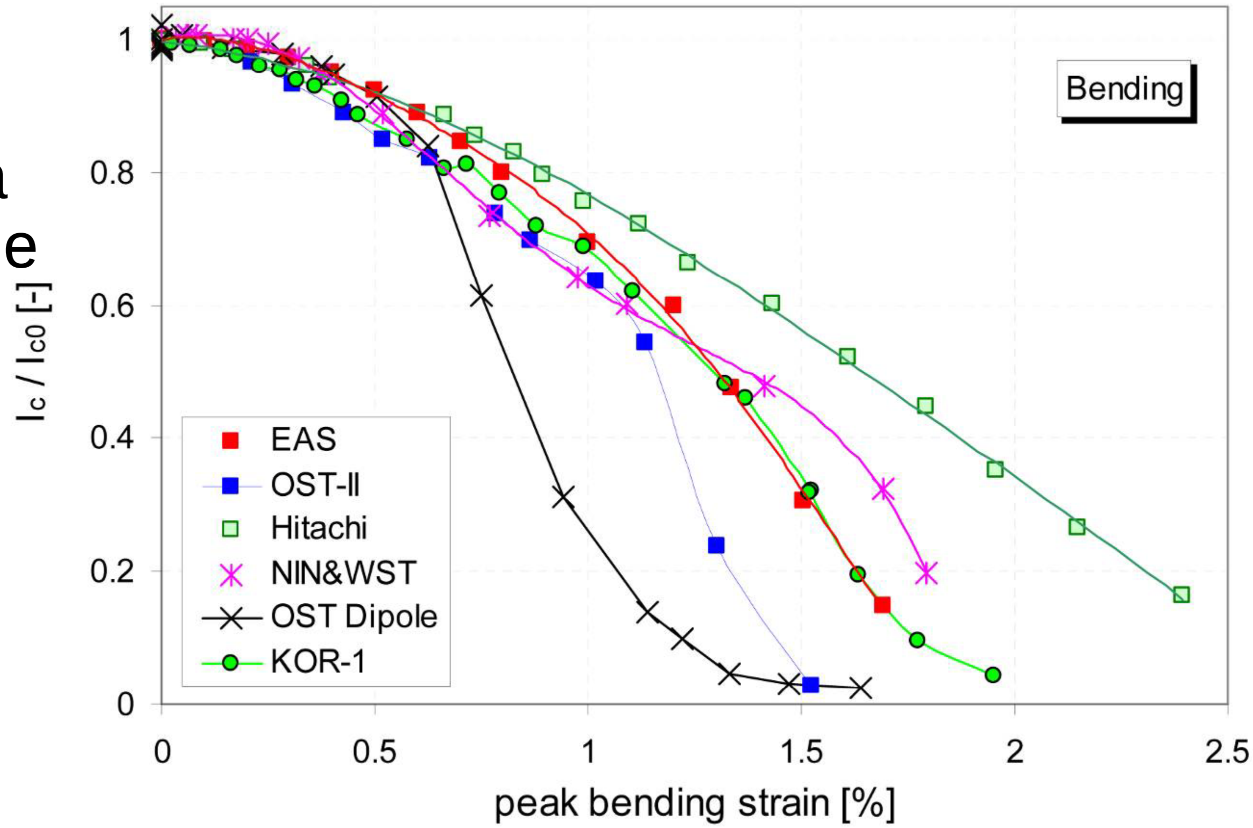


OST-dipole



TARSIS strand I_c comparison

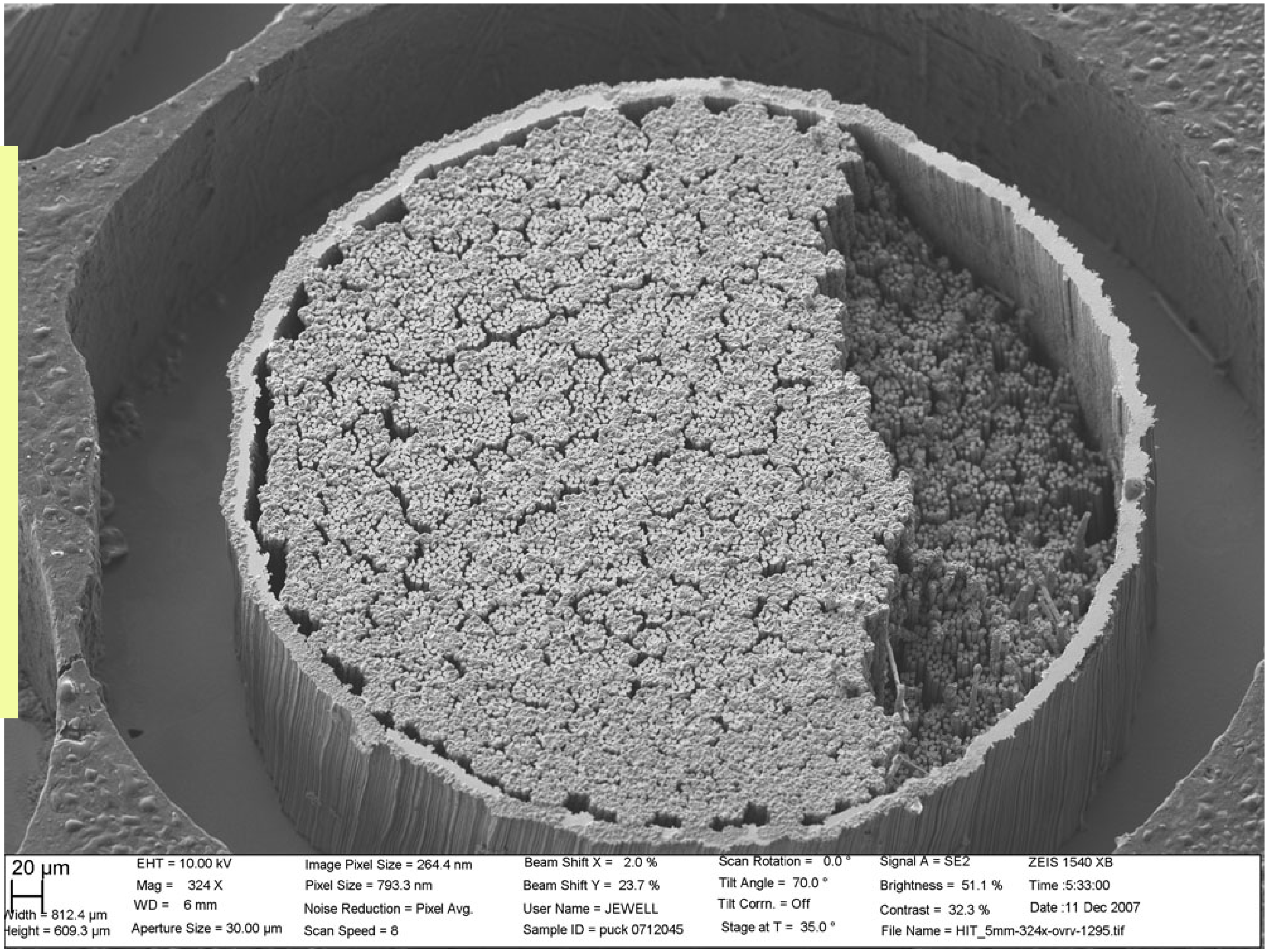
- Clearly, agglomerated structures have a higher irreversible strain sensitivity than well-separated structures
- Not as simple as bronze vs. IT, though!



Data compiled by A. Nijhuis, U. Twente

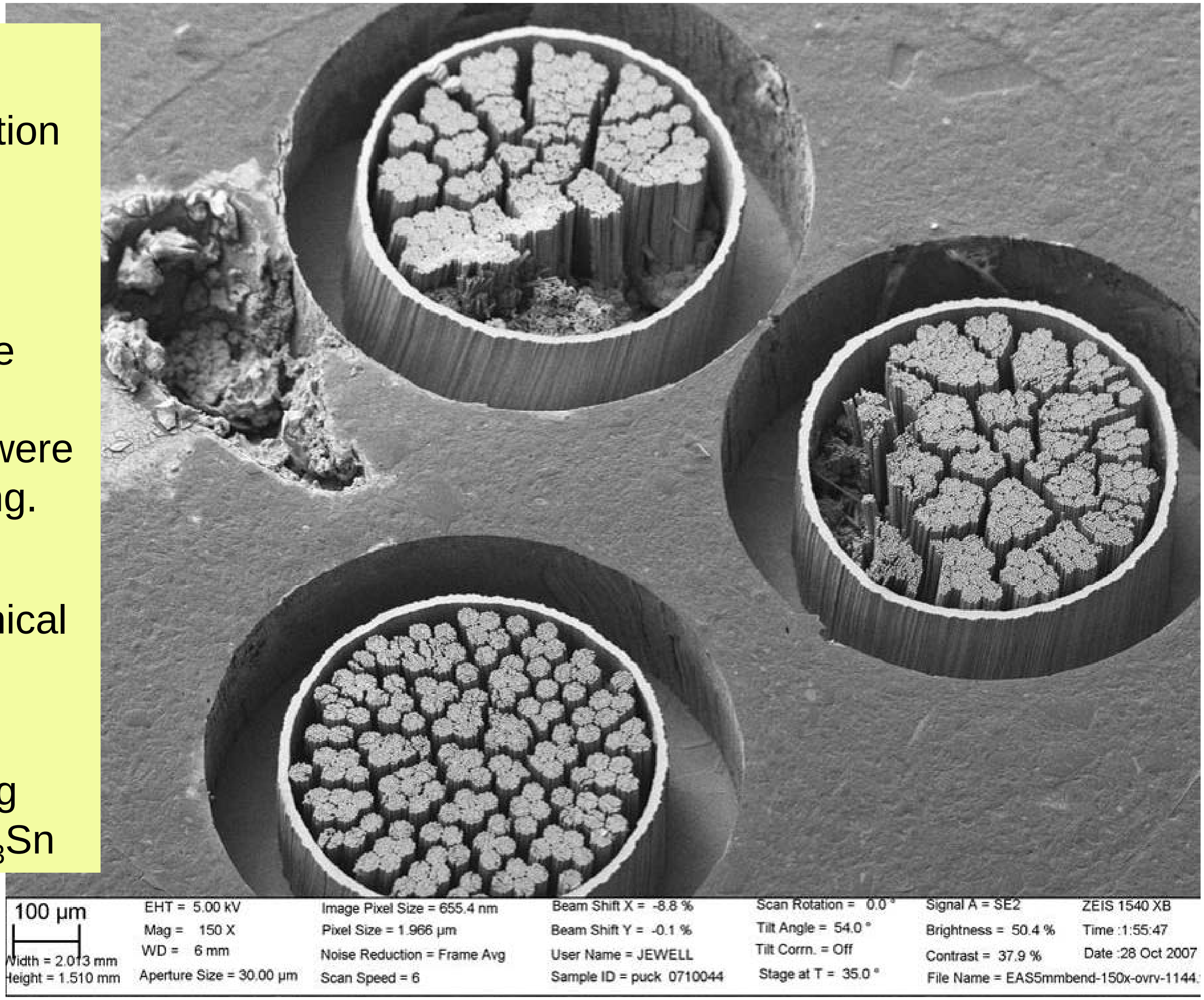
Hitachi 5 mm bend sample

- Notice the fracture damage is directly opposite the indentation mark
- Filament fracture very complete/destructive here, since this sample saw over 2% peak bending strain in the TARSIS rig



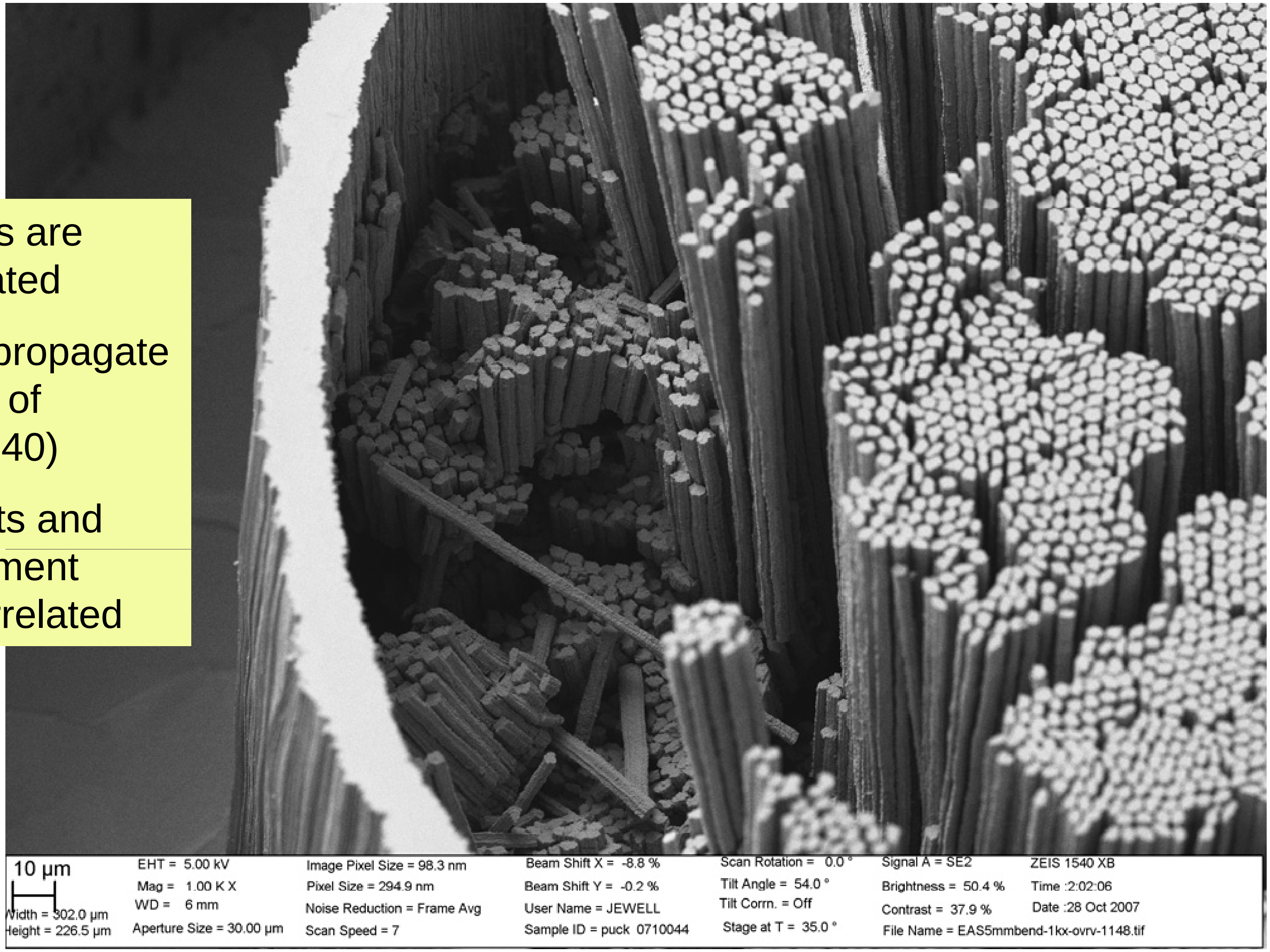
TARSIS EAS 5 mm bend

- The plot thickens…
- Sub-bundle segregation is accompanied by a pocket of destroyed filaments!
- These filaments were likely near the peak bending strain, and were cracked during testing.
- The removal of Cu destroys the mechanical support
- Potentially powerful method for identifying crack damage in Nb_3Sn



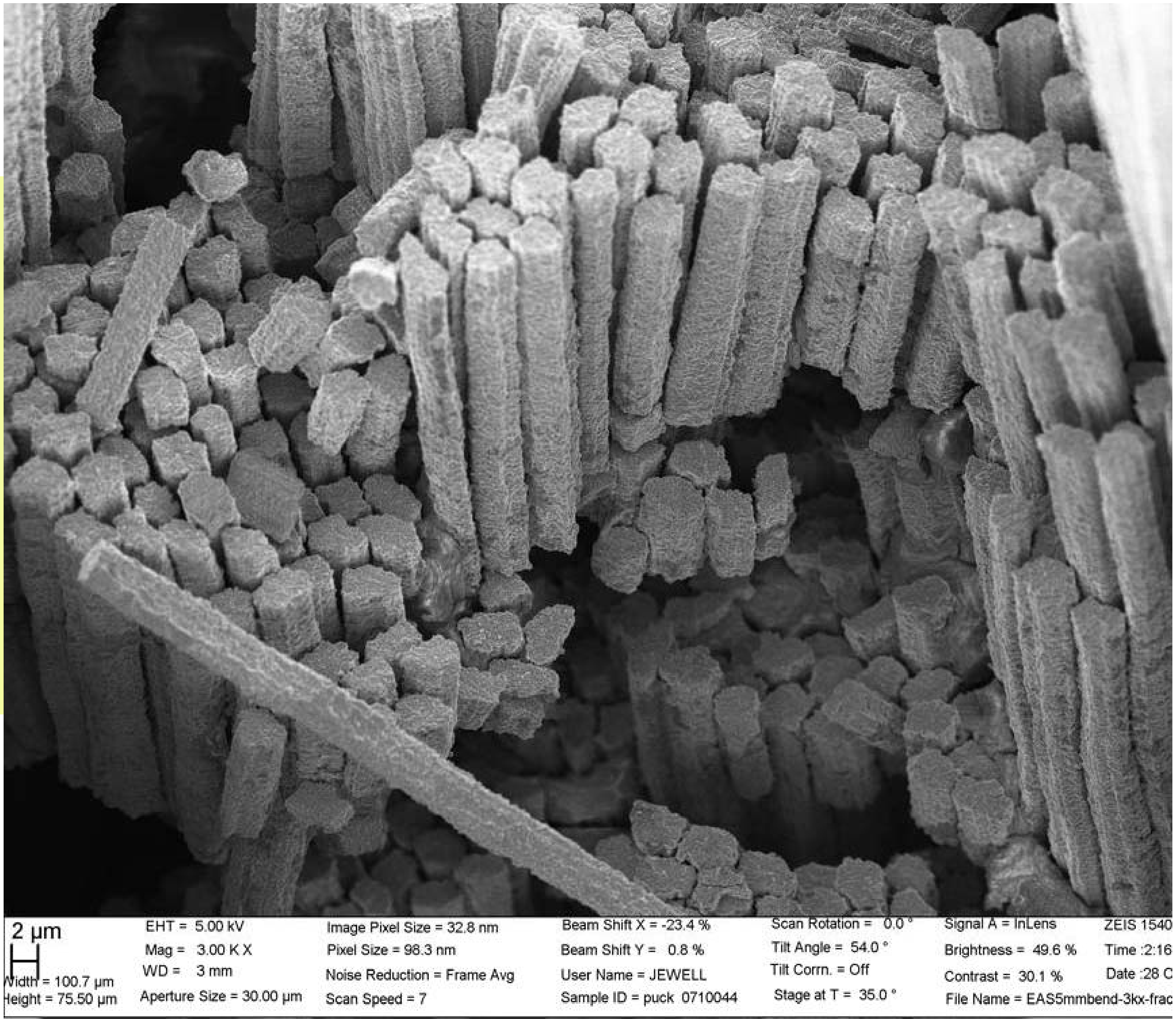
TARSIS EAS 5 mm bend

- Cracking events are spatially correlated
- Clearly cracks propagate across bundles of filaments (20 – 40)
- Broken filaments and segregated filament bundles not correlated



TARSIS EAS 5 mm bend

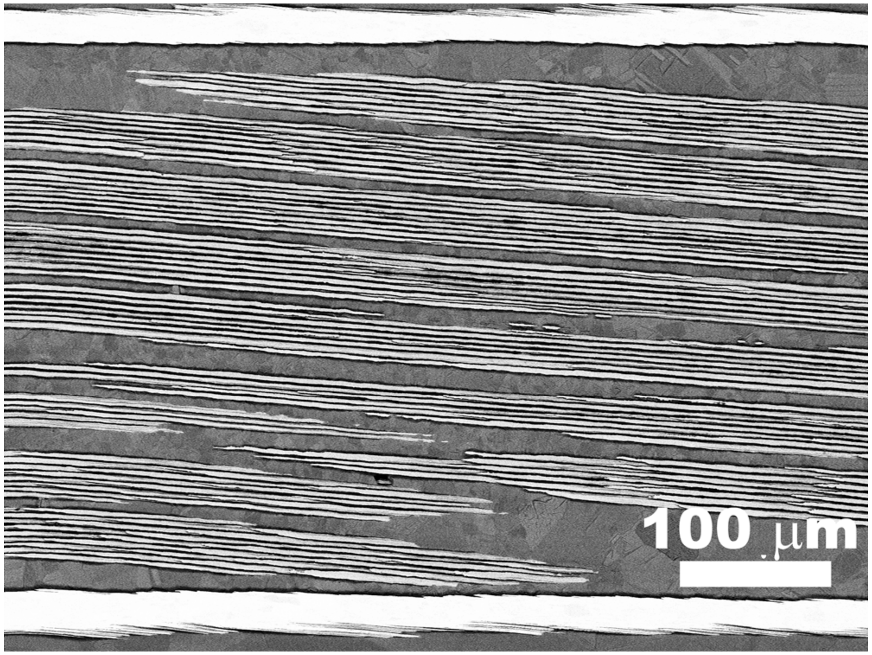
- More evidence of group cracking
- Notice the fracture surfaces are quite clean
- On some filaments we can see the break at both ends, giving us part of the fracture density distribution

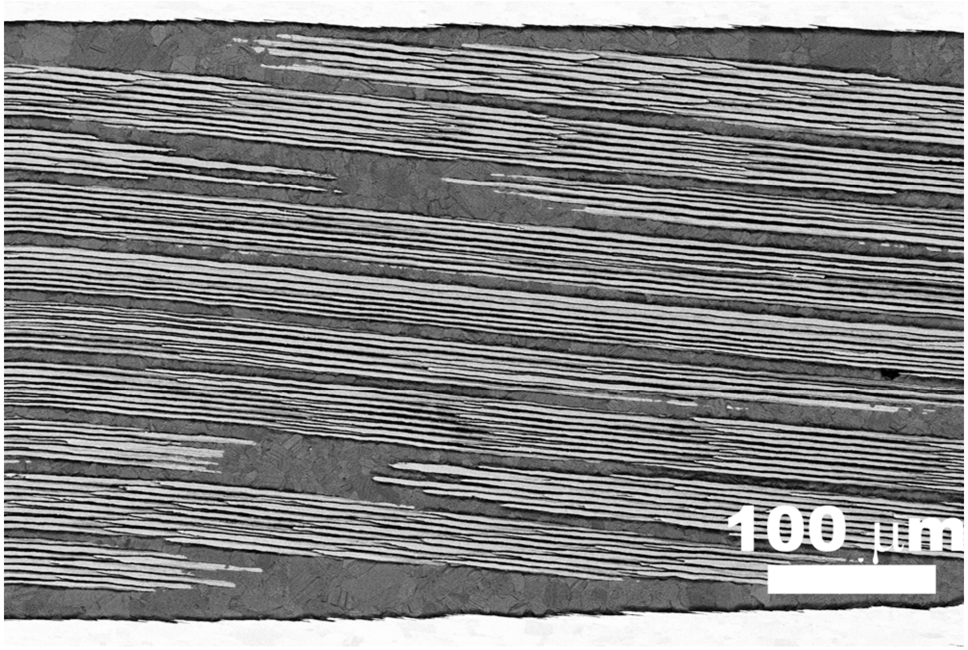


Uniaxial strain testing

- Testing performed at U. Twente
  - EAS and OST ITER strands
  - Each strained in 0.1% increments from 0.0% to 0.7% uniaxial strain
  - T = 4K; H = 0; I = 0
- Metallography performed at Florida State
  - Longitudinal cross-sections of each sample
  - Analysis of crack density, distribution, etc.

Longitudinal imaging - EAS





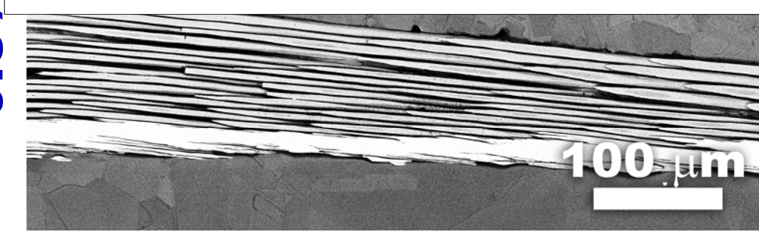
0.0% strain **0.7% strain**

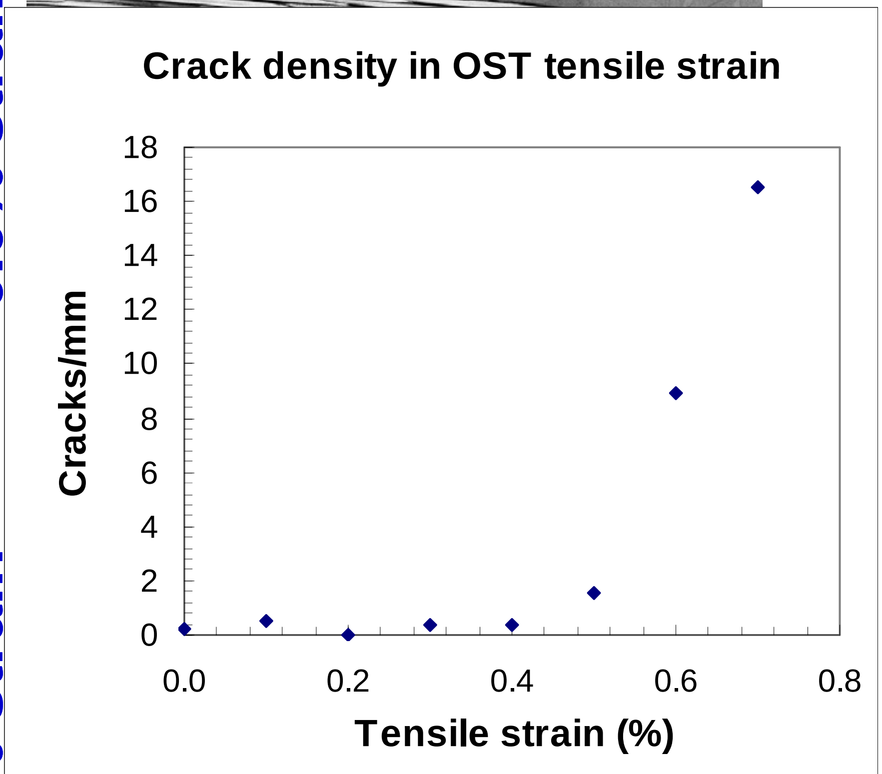
- **Essentially no fracture events in the strand from 0.0% - 0.7%!**
- **This is the kind of "toughness" we would like to build into every strand**

Longitudinal imaging - OST

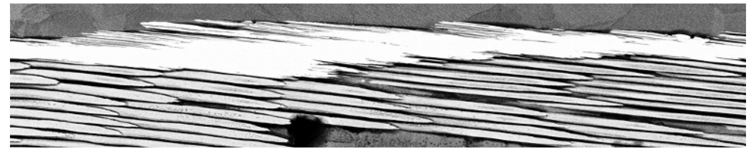
0.0% strain

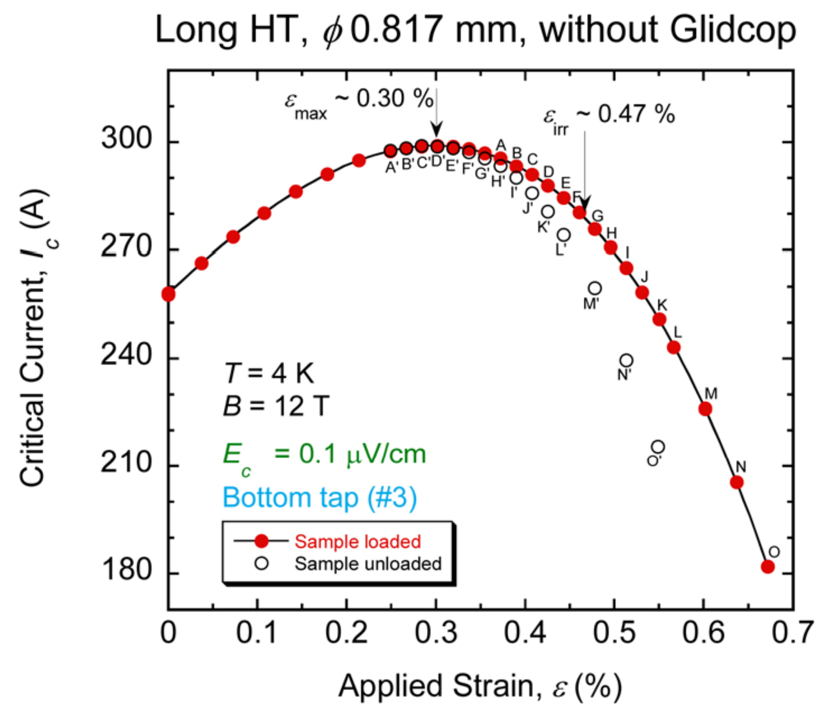
0.5% strain



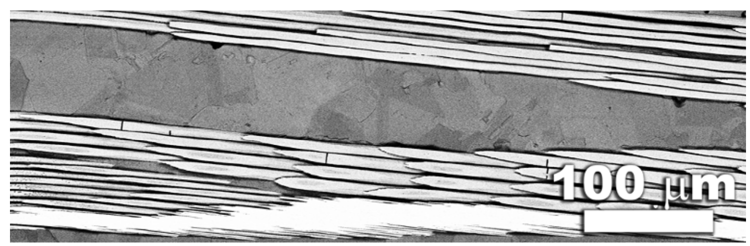


0.3% strain



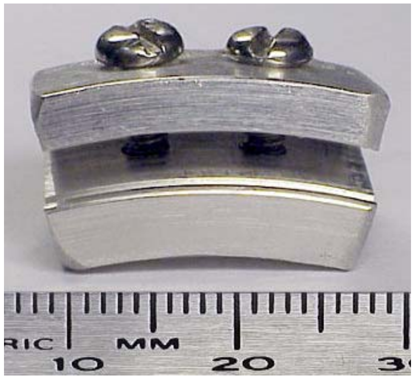


0.7% strain



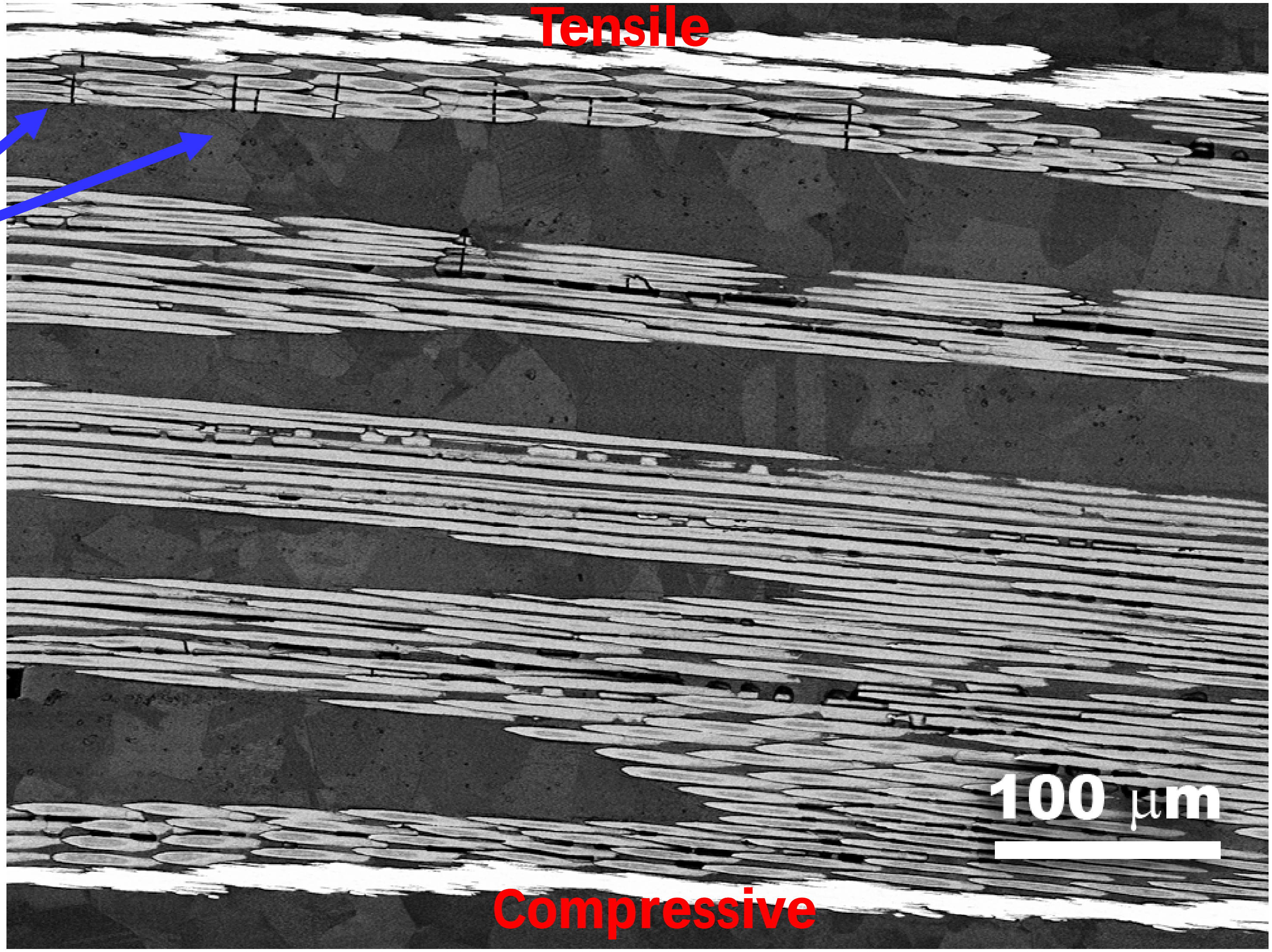
Bend testing

- 1 cm-long samples were mounted in Al clamps with a variety of radii and bent at 77K
- 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 on field-emission scanning electron microscope and light microscope
- All wires received manufacturer recommended heat treatment
- Today I will show results from 1.5% bend strain



Bend testing - OST

Correlated fracture events

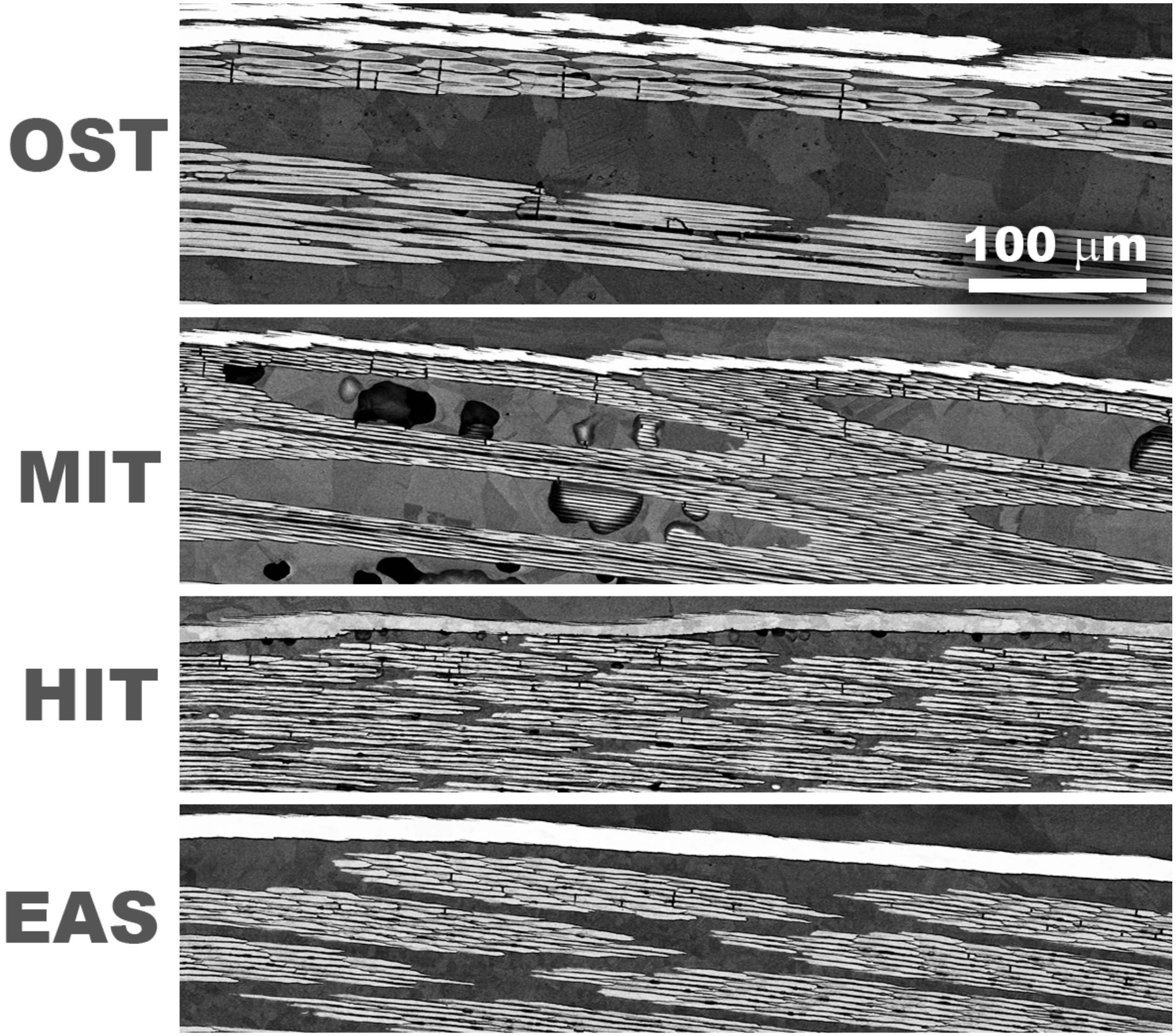


Bend testing – comparison

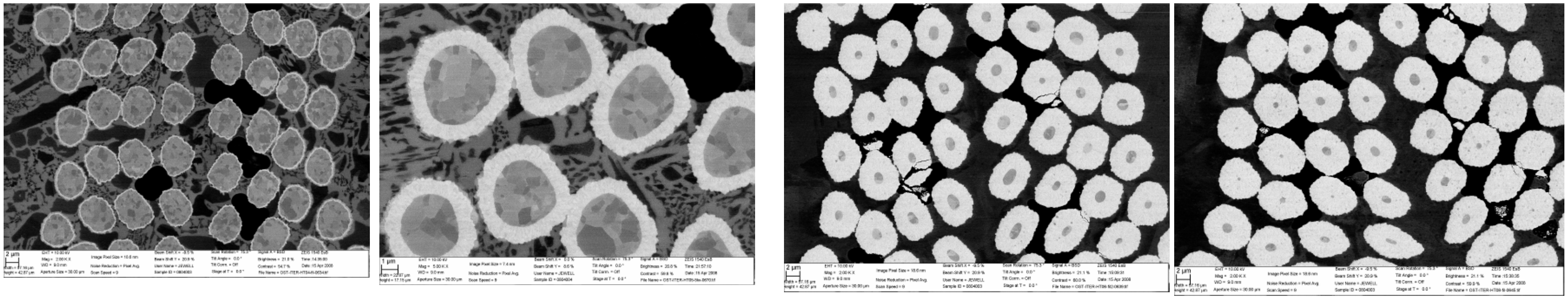
- Direct comparison of relative fracture propensity
- Fracture is more collective in the internal Sn strands
- Filament fracture density is highest in the Oxford strand

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

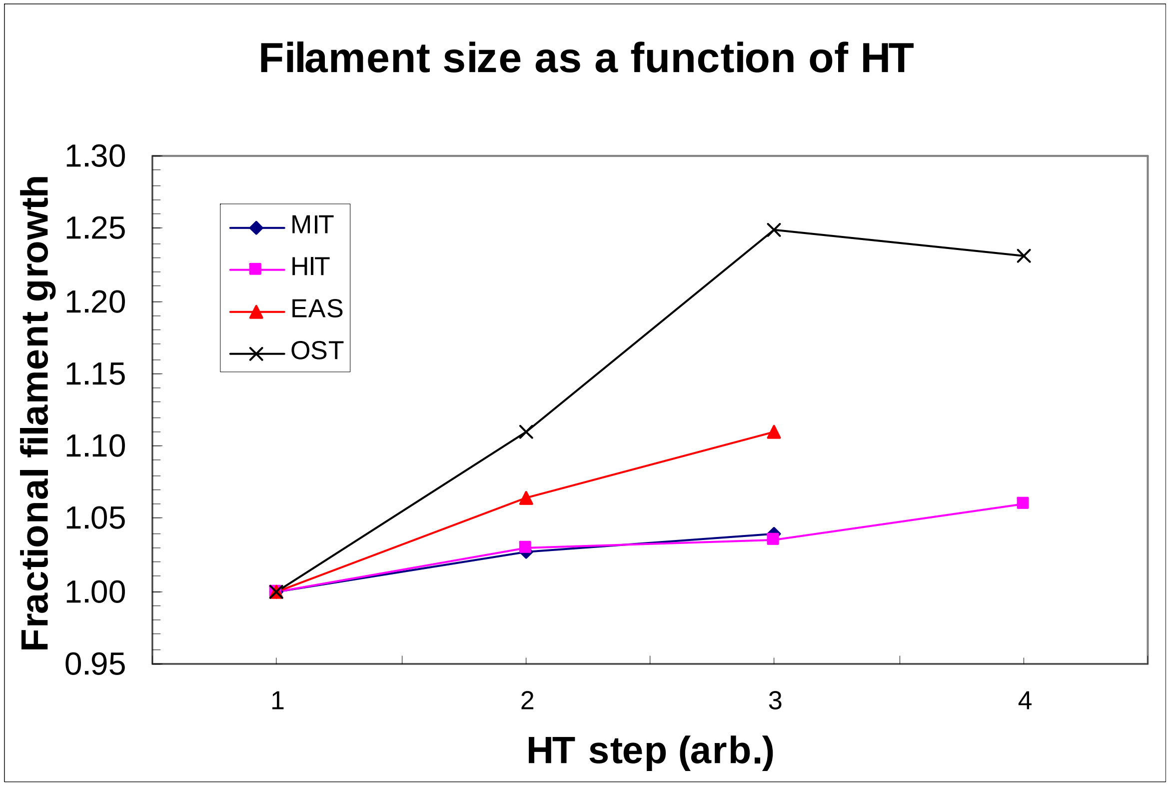
Theses values scale with the localization of fracture in the TARSIS test



Effect of HT on geometry



- OST has the steepest growth curve
- The fact that there is not a bimodal IT/bronze distribution highlights the importance of Sn content and phase thermodynamics
- With the exception of OST, there is not much room for "tuning" the filament spacing – only a few percent.
- This growth suggests the presence of a tensile hoop stress on each filament



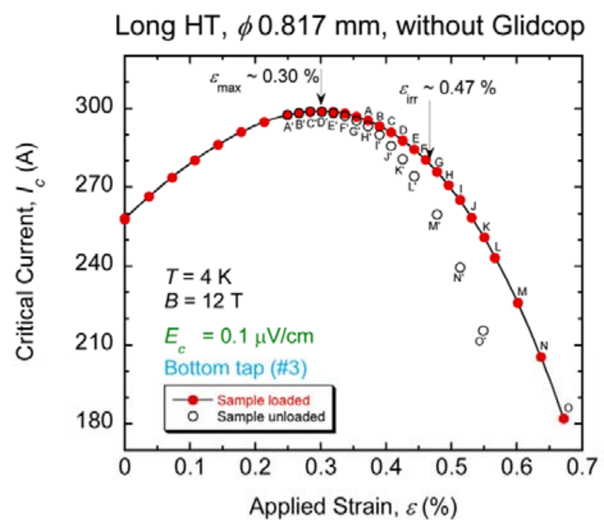
Key results

- Indentation:
  - The stress state governs the fracture morphology
  - When tensile strains are inevitable, geometry can mitigate the damage
- TARSIS
  - There is a clear progression towards collective cracking as filament agglomeration occurs
- Uniaxial strain:
  - Not all strands are created equal
  - These results should allow us to extract a strength distribution (e.g. Weibull) to inform modeling efforts
- Bend strain:
  - Direct, "fair" comparison of fracture in dissimilar strands
  - Trend of collective cracking confirmed
- HT growth:
  - With the exception of OST, the strands studied did not grow more than 10% after the "candy coating" stage
  - The stress distribution in the filament is complex, as the brittle shell is forced to continue expanding outwards.

Summary thoughts

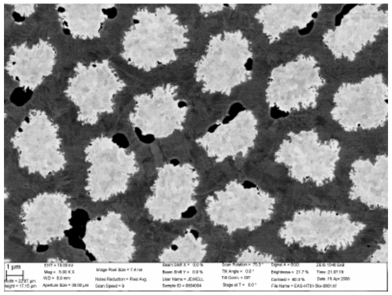
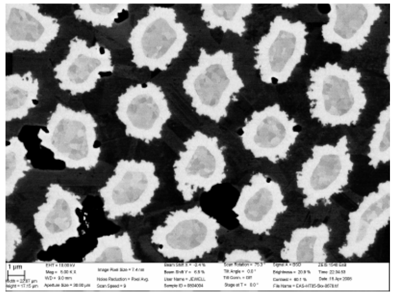
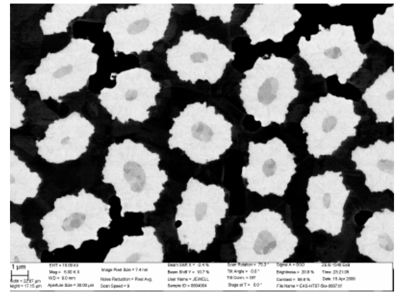
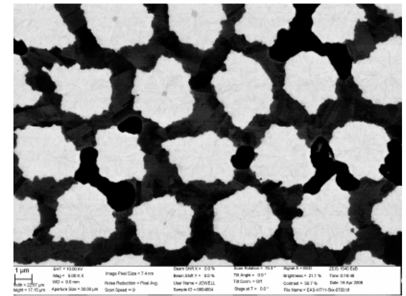
- Implications for fusion magnets:
  - Tool to judge strand variability in procurement
  - Tool to sort vendors best to worst, which is helpful if you have some procurement flexibility
  - Inform modeling efforts – peak local strain is key

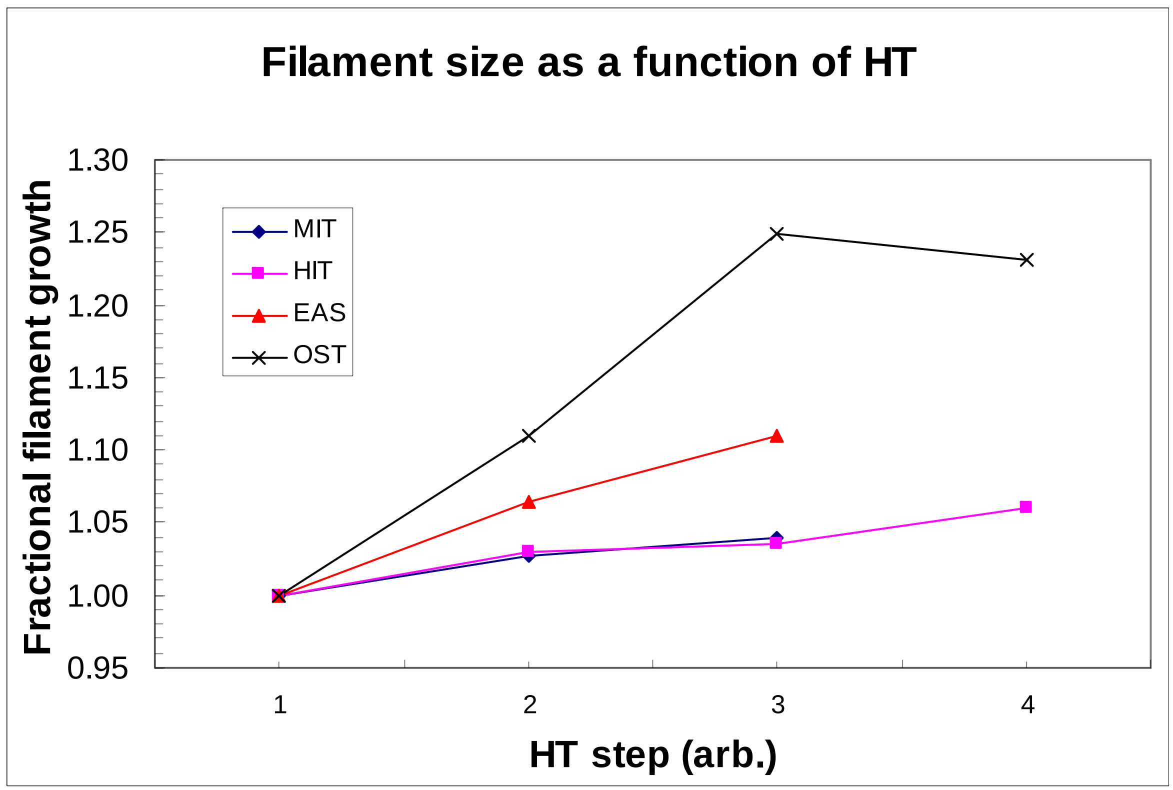
- Implications for HEP magnets:
  - The strands are well-behaved in the compressive zone…but surely there is a limit. What is it?
  - Strain scaling has become significantly more sophisticated in the last 10 years – but if fracture is ignored then the tensile curve is still empirical



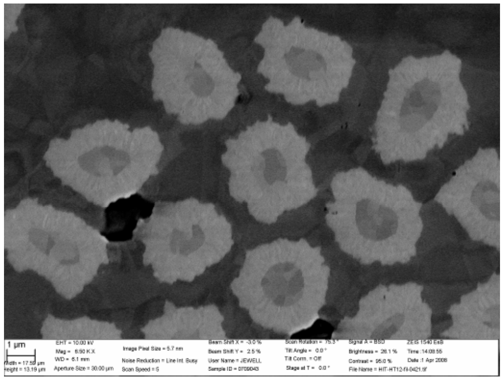
The End

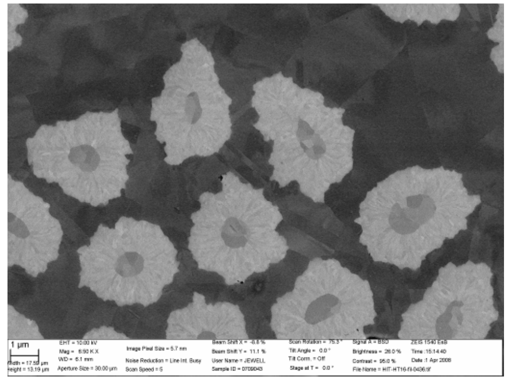
Quantitative info. - EAS

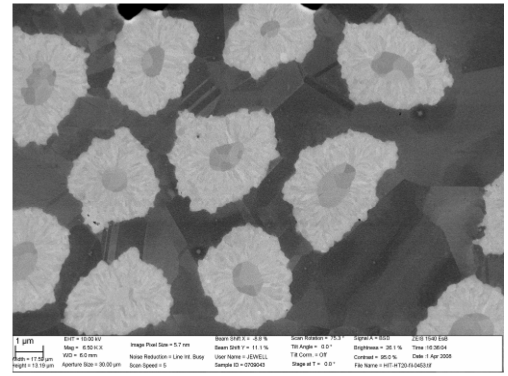





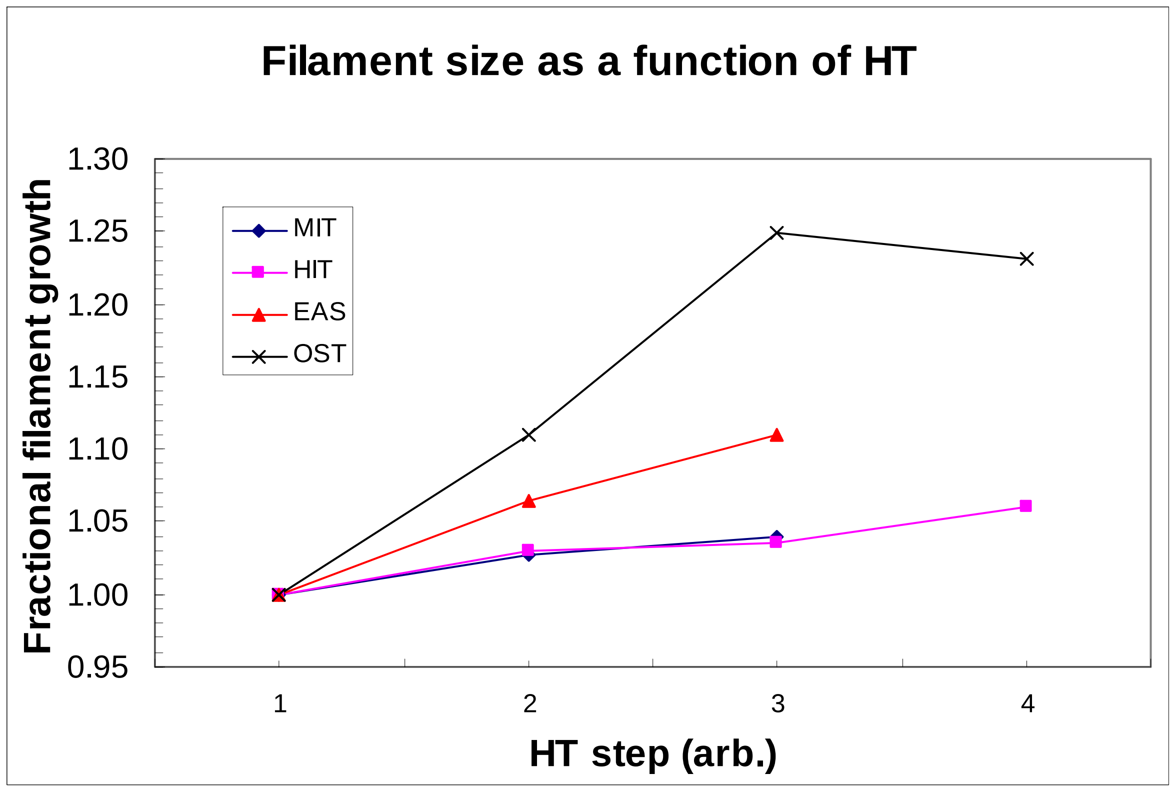


Quantitative info. - Hitachi









Quantitative info. - Mitsubishi