Modes of Strand Damage Observed by Magneto-Optical Imaging and Metallography

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Motivation

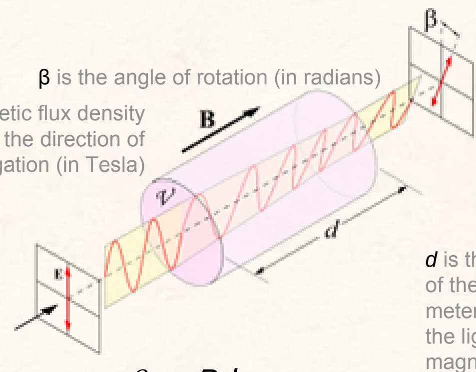
- Many factors degrade the performance of Nb_3Sn strands:
  - Plastic deformation during cabling
  - Lorentz force during operation at high field
  - Precompression during magnet fabrication
- In this study, the impact of cabling deformation on Nb_3Sn strand microstructure and properties under controlled conditions has been simulated using rolling (performed at Fermilab).

Summary of Microstructural and Property Measurements Reported Here

- Microstructure
  - Scanning Laser Confocal Microscopy (SLCM)
  - Field emission SEM
- Spatially Resolved Superconducting Properties
  - Magneto-Optical Imaging (MOI)
- Electromagnetic measurements:
  - I_c, T_c and magnetization measurements

Principle Of Magneto-optical Imaging

Faraday Effect: The rotation of the plane of polarization is proportional to the intensity of the component of the magnetic field in the direction of the beam of light.



β is the angle of rotation (in radians)

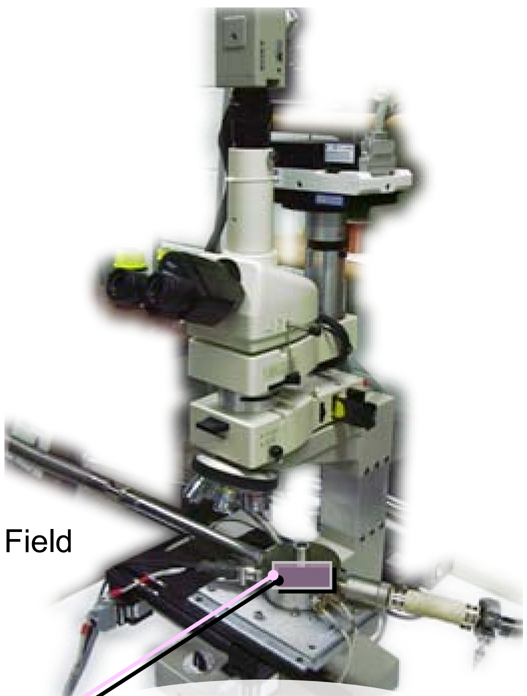
B is the magnetic flux density in the direction of propagation (in Tesla)

ν is the Verdet constant for the material (but varies with wavelength and temperature). Units of radians per Tesla per meter.

d is the length of the path (in meters) where the light and magnetic field interact

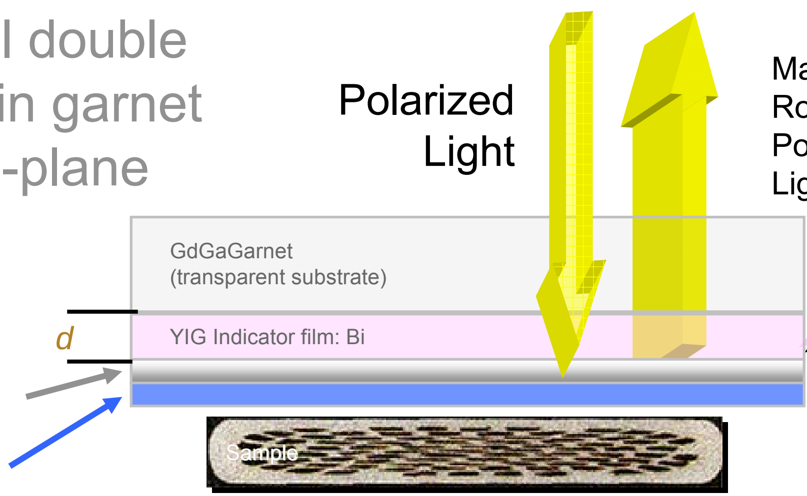
$$\beta = \nu B d$$

Polarized light microscope

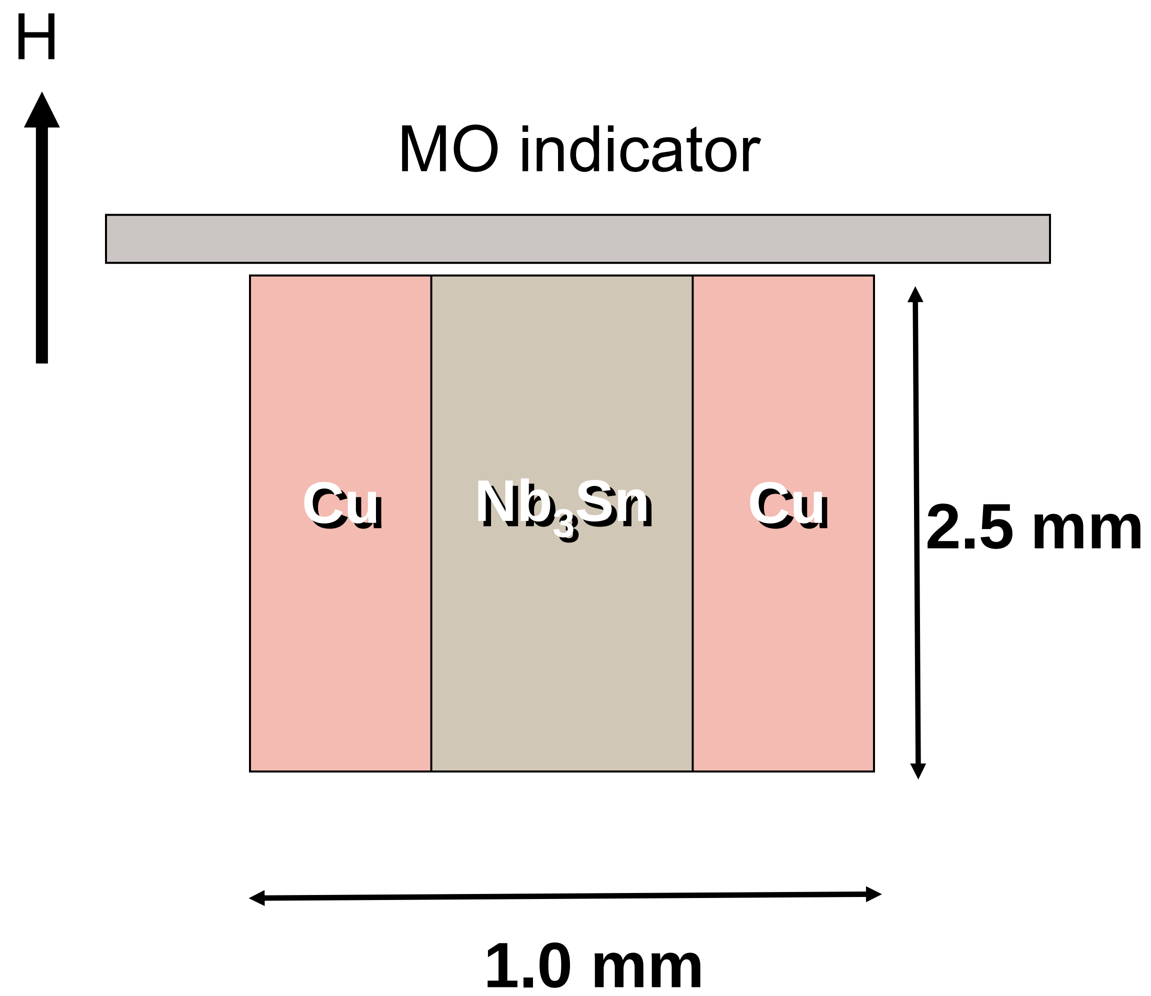


Continuous flow cryostat with solenoids to generate magnetic fields

Magneto-optical double Faraday Effect in garnet indicator with in-plane magnetization



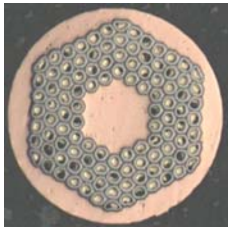
Magneto-Optical Experiment on Nb_3Sn Strand



SAMPLES

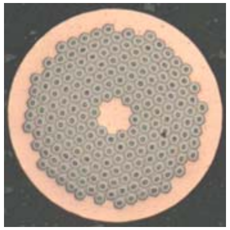
- Strands manufactured by:
  - Oxford Superconducting Technology (OST)
  - IT- Internal Tin strands

    RRP - Restack Rod Process,



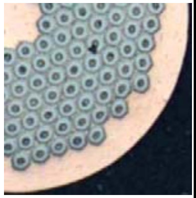
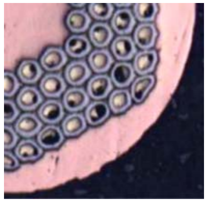
  - ShapeMetal Innovation (SMI),

    PIT - Powder-In-Tube



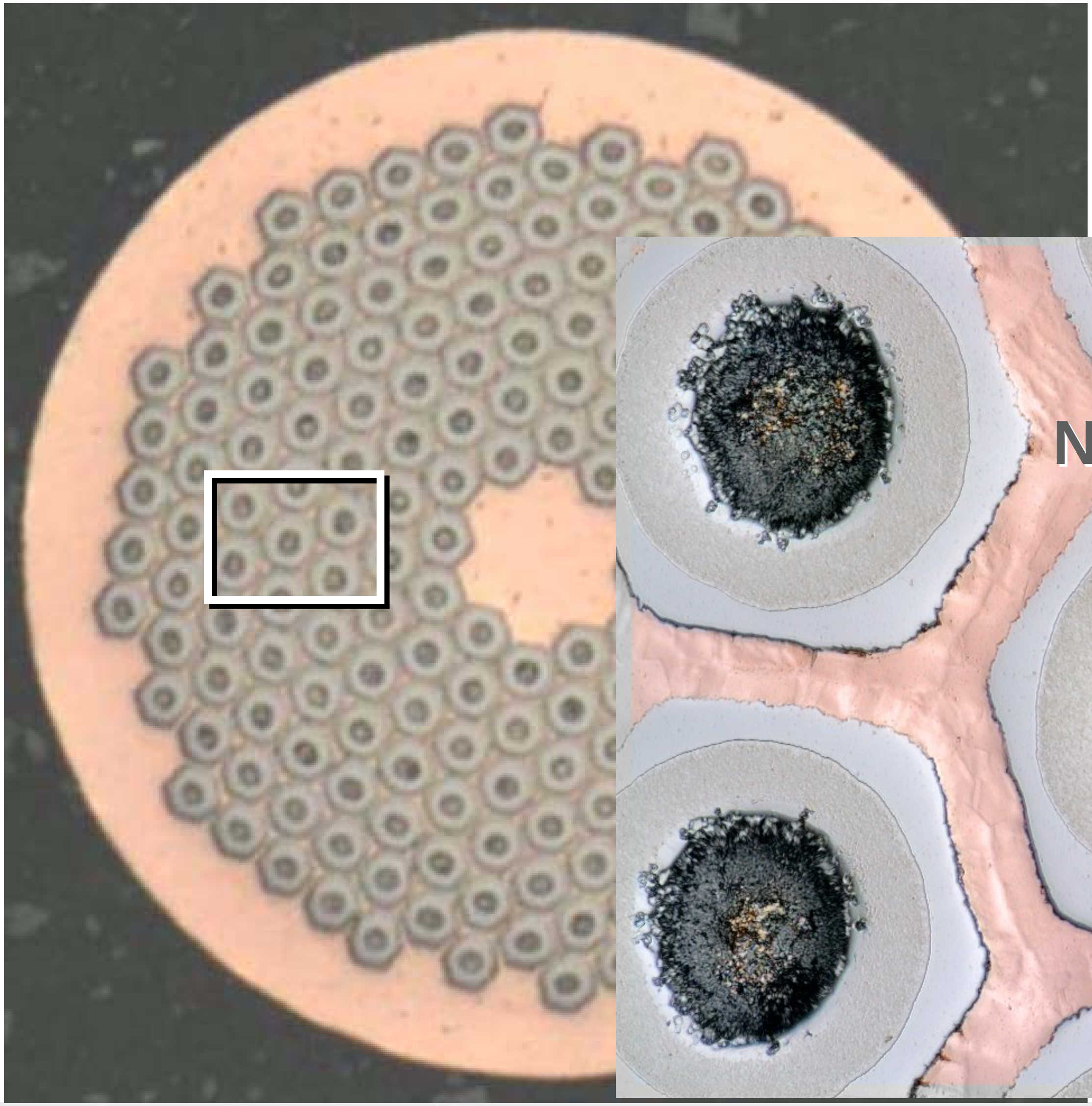
- Sample Conditions Examined
  - Virgin (round 1 mm) strands
  - Strands Flat-Rolled down a maximum reduction of 50% strand thickness.

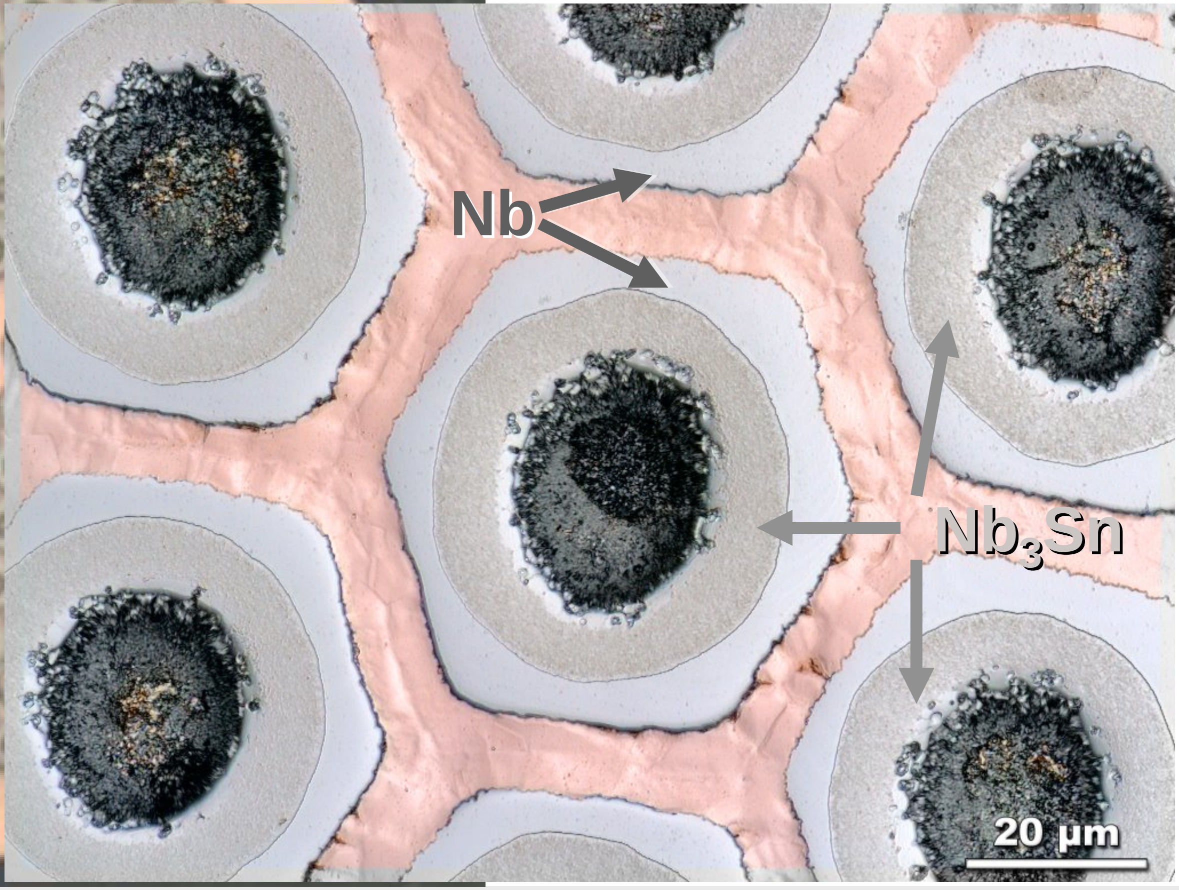
SAMPLE DESCRIPTION

Strand ID	PIT 	RRP 
Billet ID	187	8195-97
No. of filaments	192	108/127
Strand diameter, mm	1.0	1.0
Alloying Element	Ta	Ti (Nb-47Ti rods)
Ic(12T, A)	~700	~900
Deff, μm	45	84
Geometric filament size, μm	50-57	64-75
RRR	250	300
Twist pitch, mm	20	12
Cu fr., %	52	49

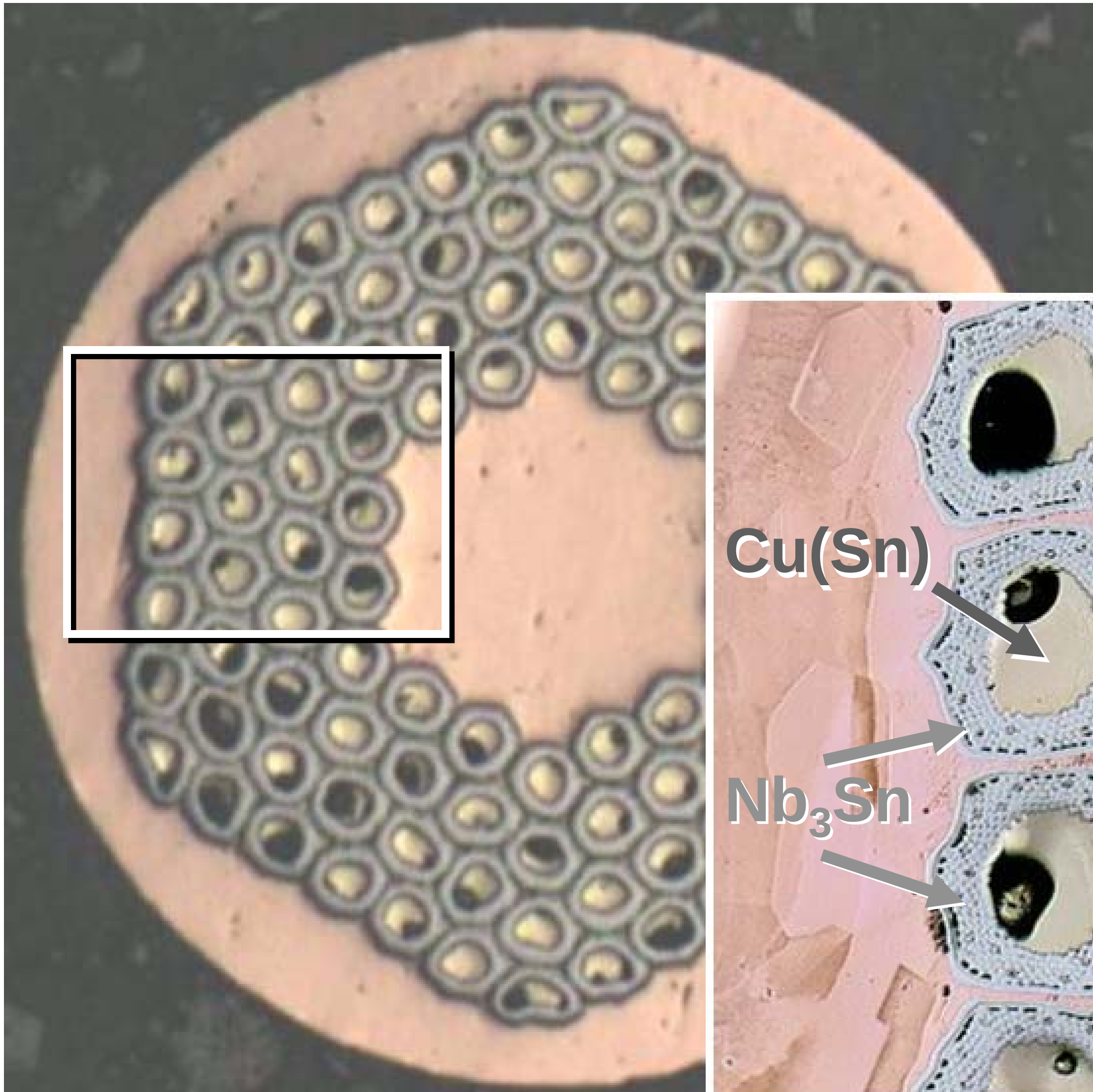
Cross-section of Virgin 1 mm Diam. PIT

After chemical etching

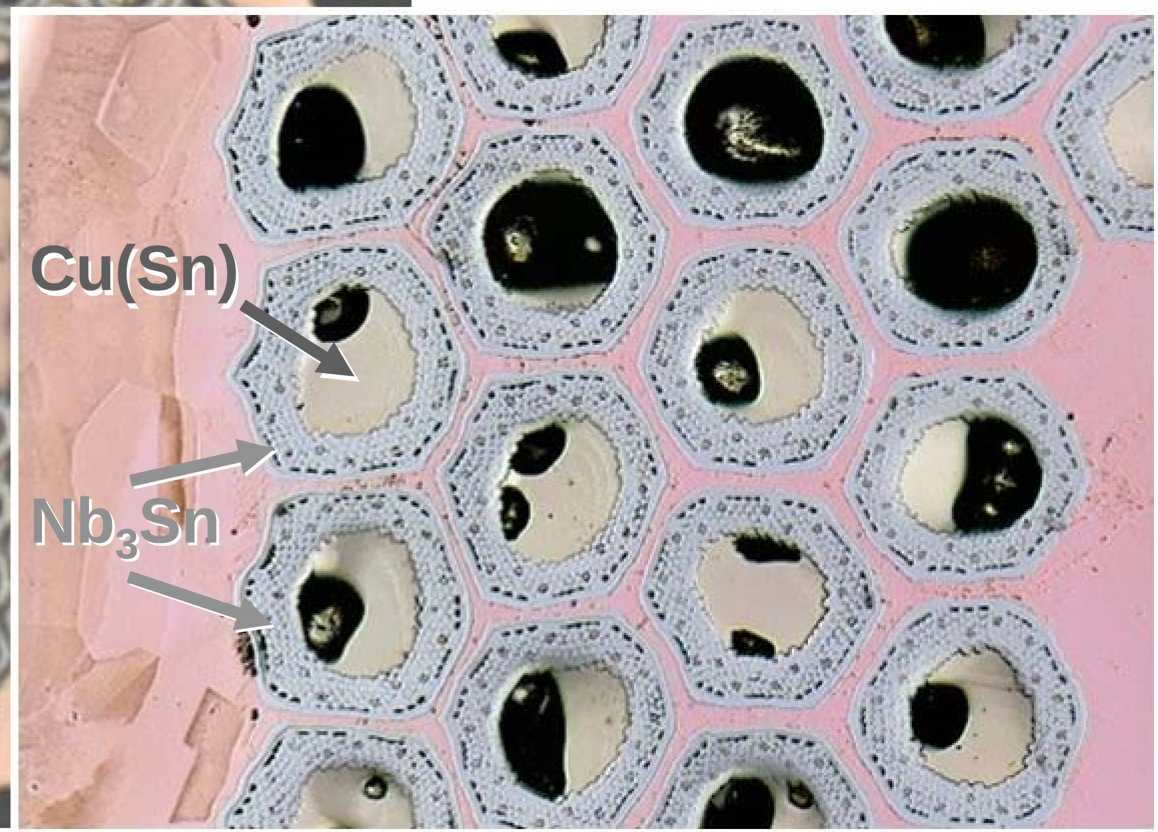




Cross-section of Virgin 1 mm Diam. IT (RRP)

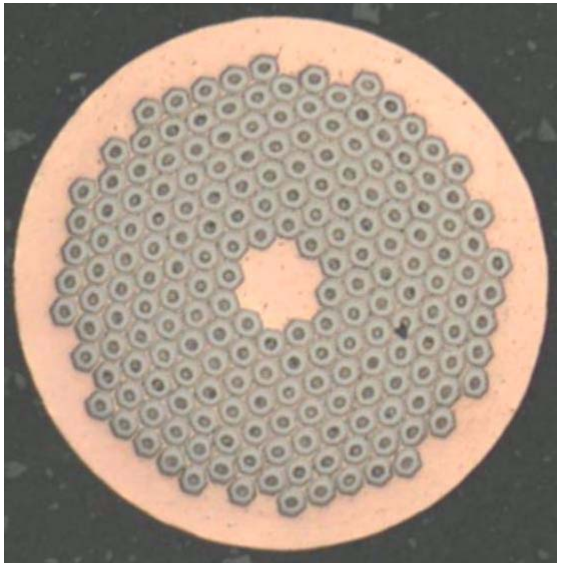


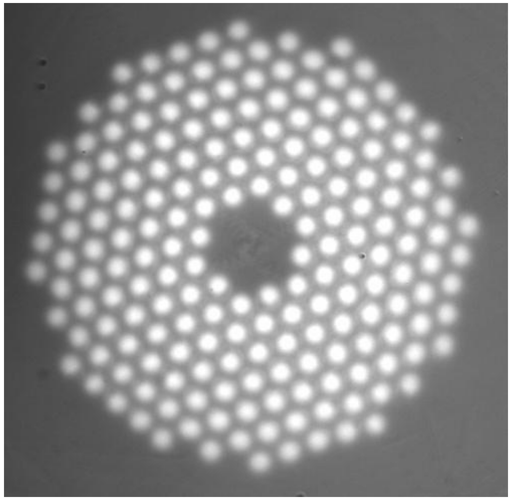
After chemical etching



MOI at T=12 K and H=0 (after FC in H=120 mT)

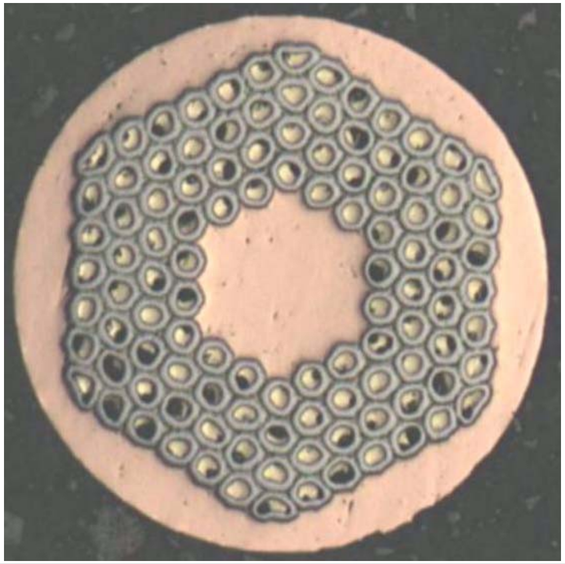
PIT

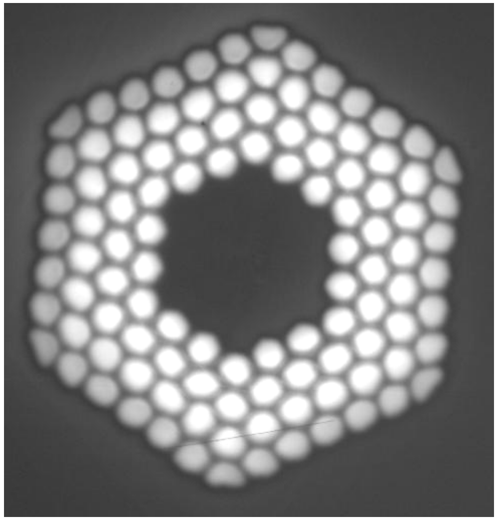




MO images of trapped flux

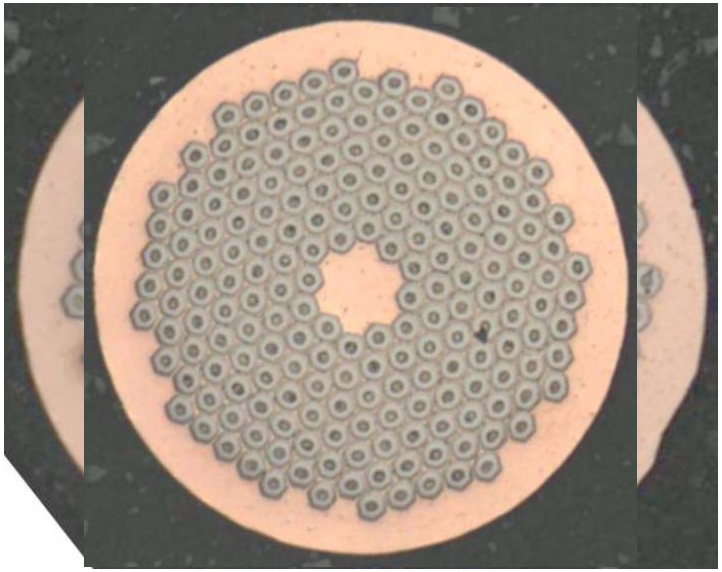
RRP

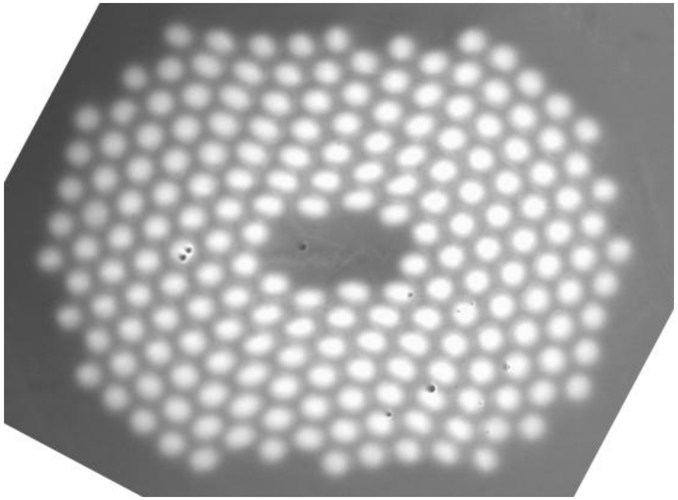




PIT ROLLED TO 0.8 mm : OPTICAL AND MO IMAGES at T=12K, H=0

H=0, FC in H=120 mT

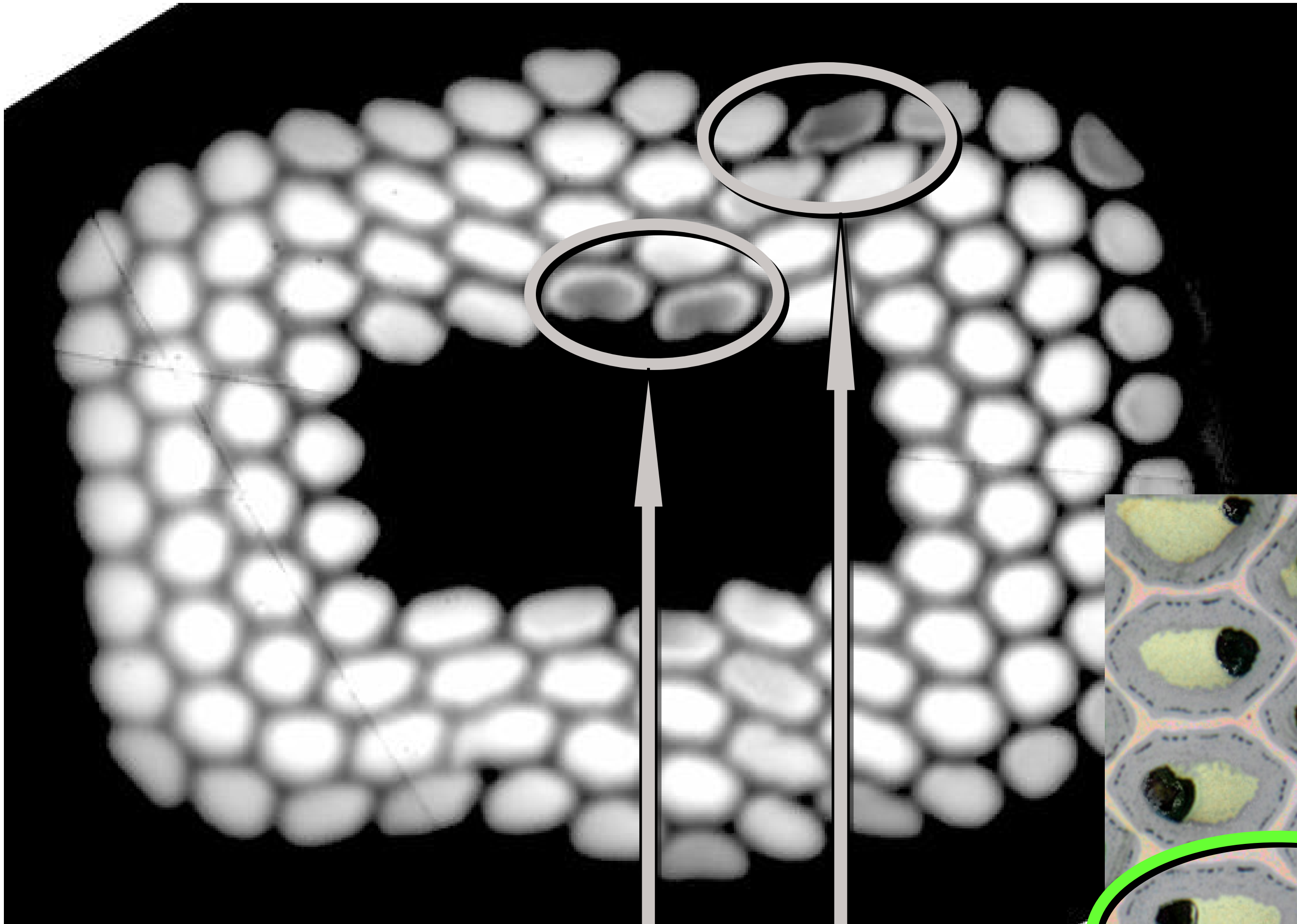




No damage to filament integrity observed by microscopy filament

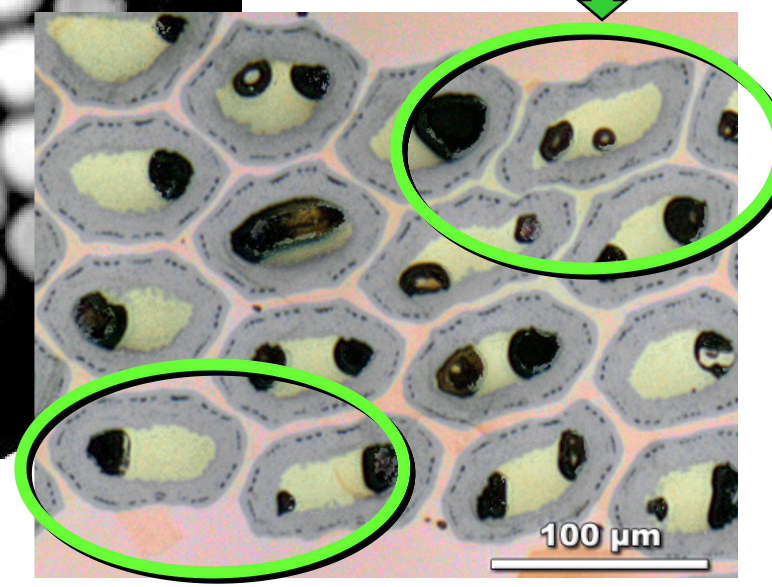
MO shows no significant variation in properties from filament to filament

IT RRP Rolled to 0.8 mm: MO T=12 K, H=0

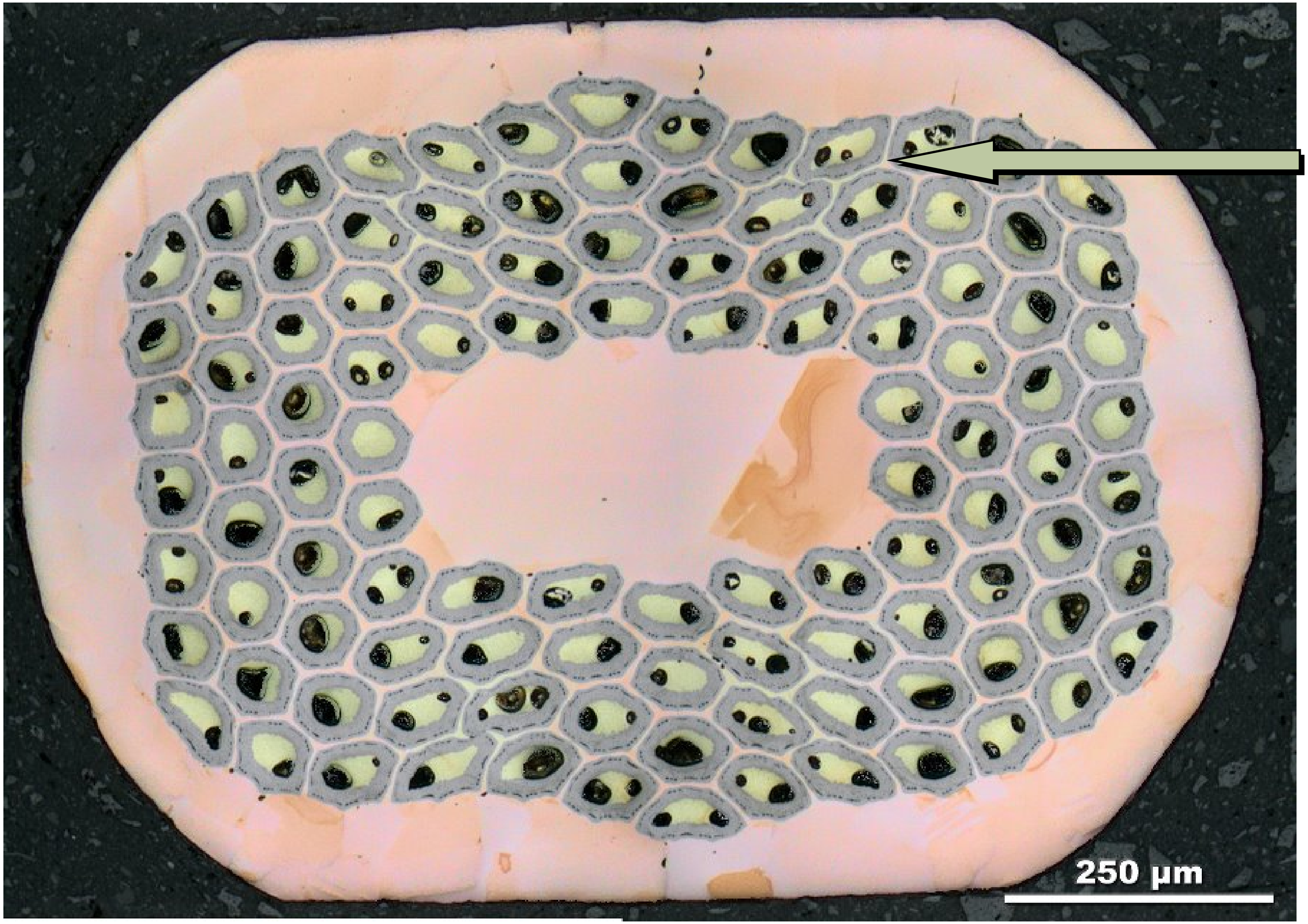


MO shows damage to both outer and inner sub-elements

LSCM+color image shows Sn leakage between outer sub-elements only



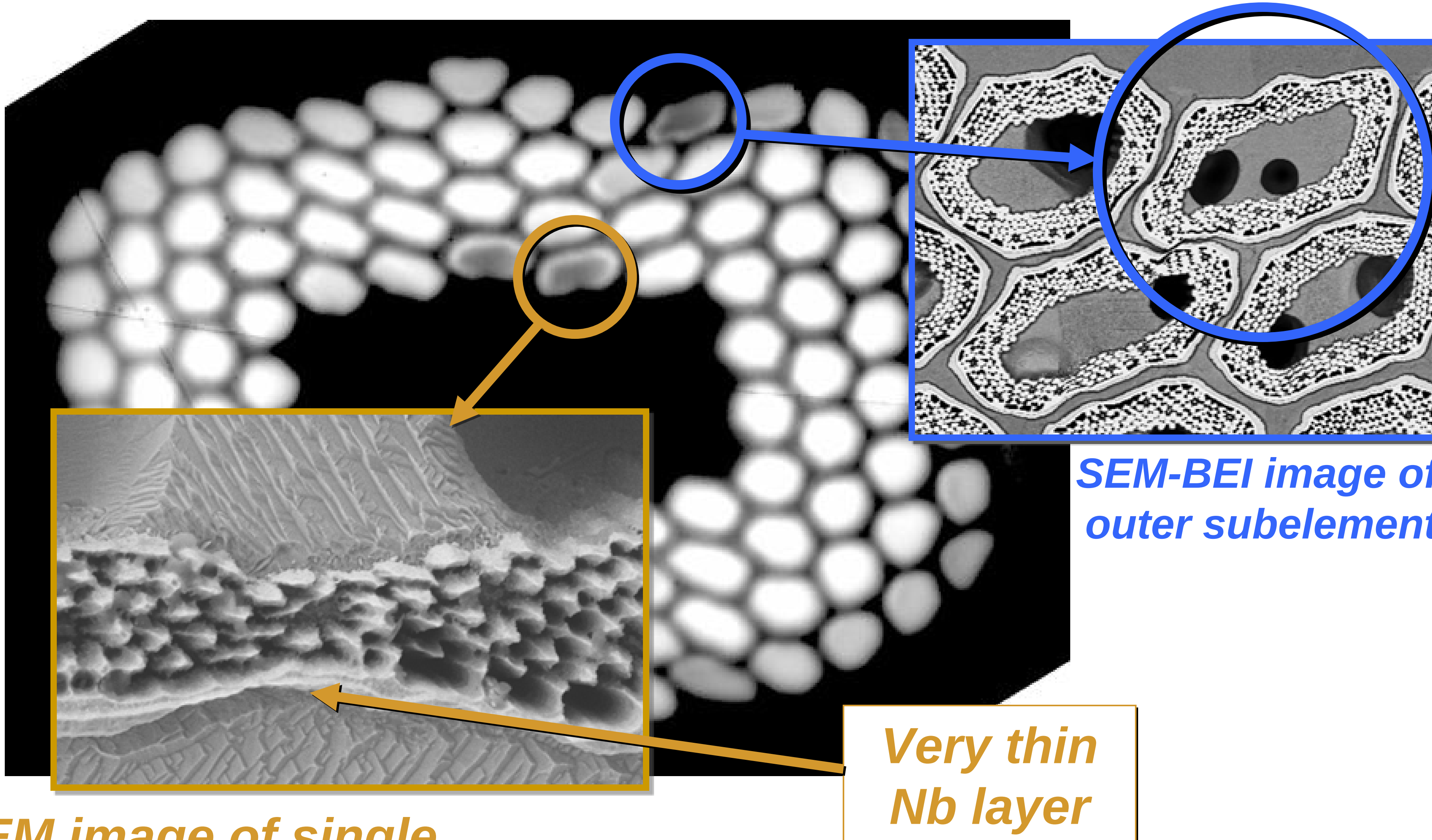
IT RRP Rolled to 0.8 mm : Cross-Section



Sub-elements not broken but some Sn leakage observed by color contrast

LSCM/LED-confocal image with Sn-rich Cu enhanced with green tint

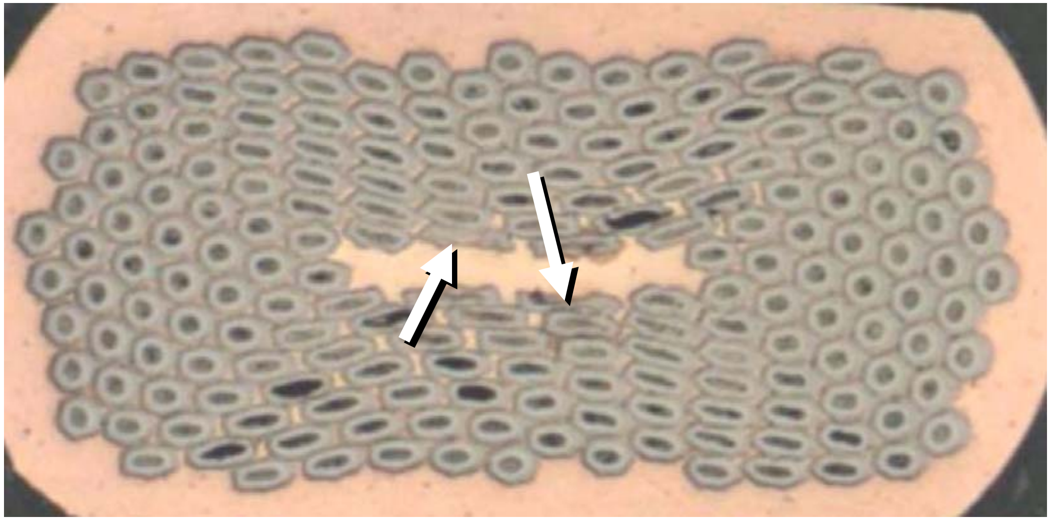
IT RRP Rolled to 0.8 mm: SEM of Sub-Element

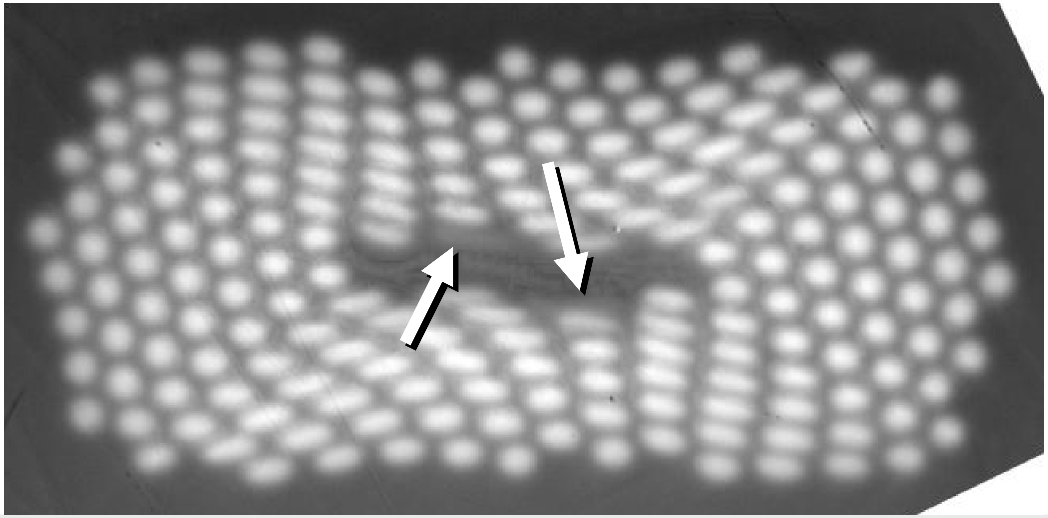


SEM-BEI image of outer subelement

SEM image of single subelement, after deep etching

PIT Rolled to 0.6 mm: Color & MO: T=12 K, H=0



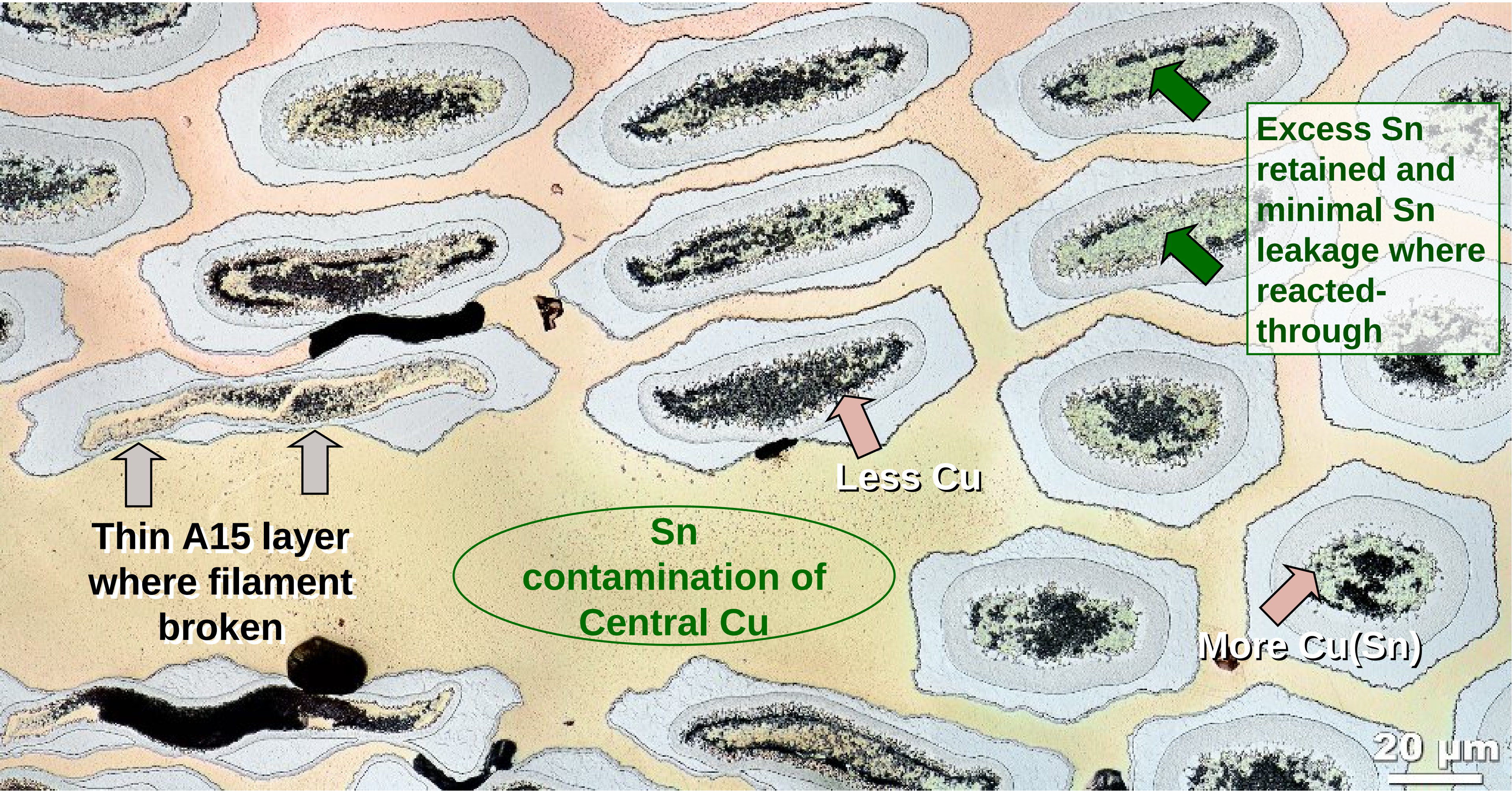


- Only a few central filaments have been broken by the rolling.
- *But* all the superconductivity in those filaments is lost at 12 K

When PIT filaments break . . .

PIT Rolled to 0.6 mm

LSCM+color enhanced to shows Sn leakage



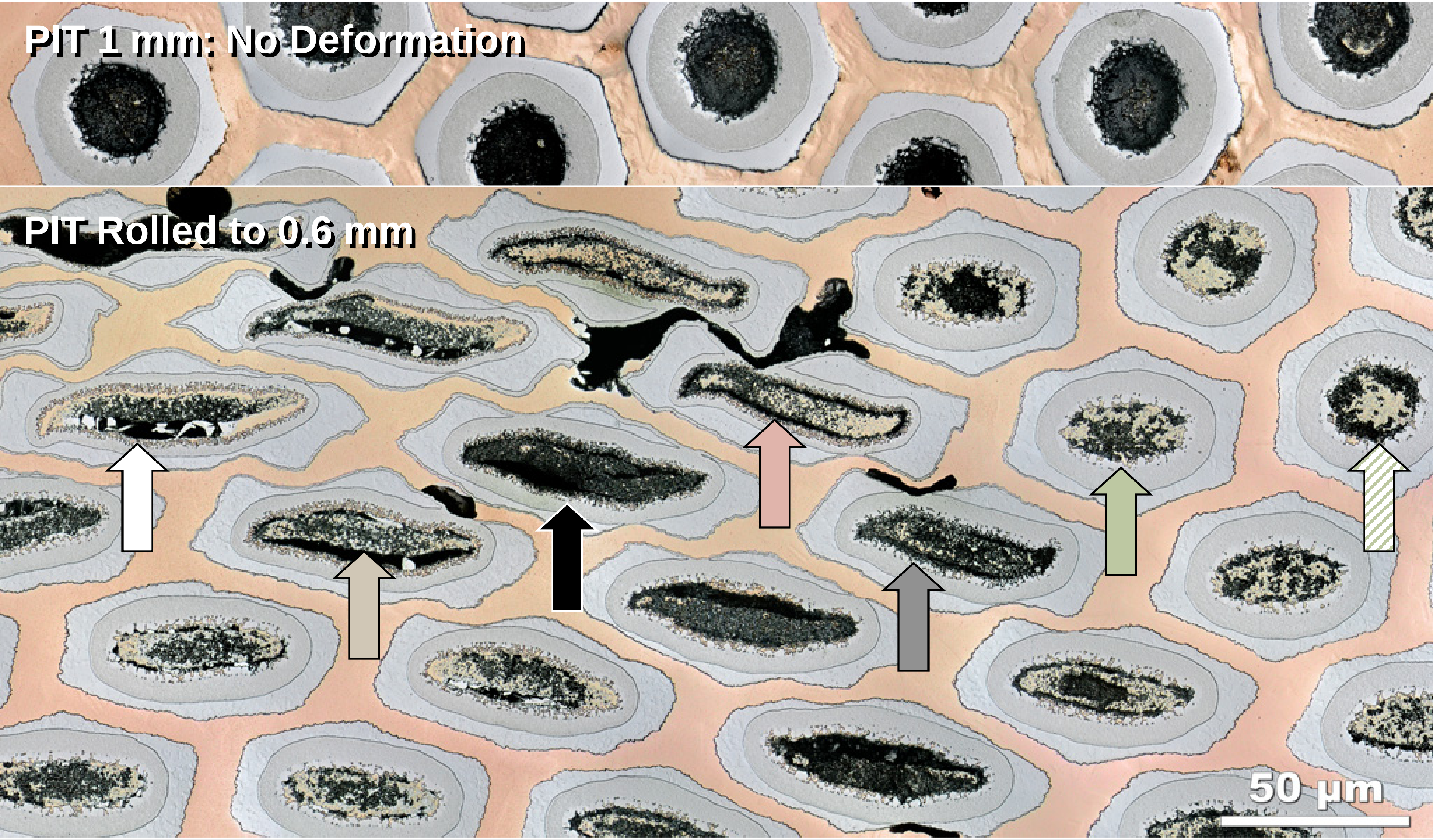
Detail from PIT Rolled to 0.6 mm

No large interior A15 grains.

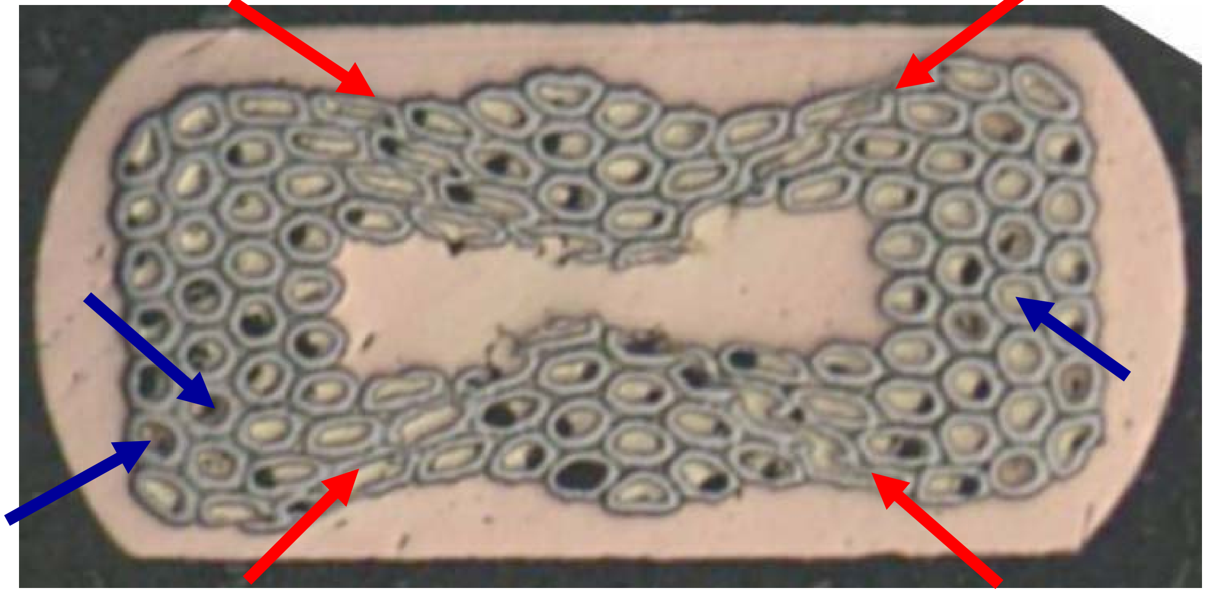
Mostly Cu left in core.

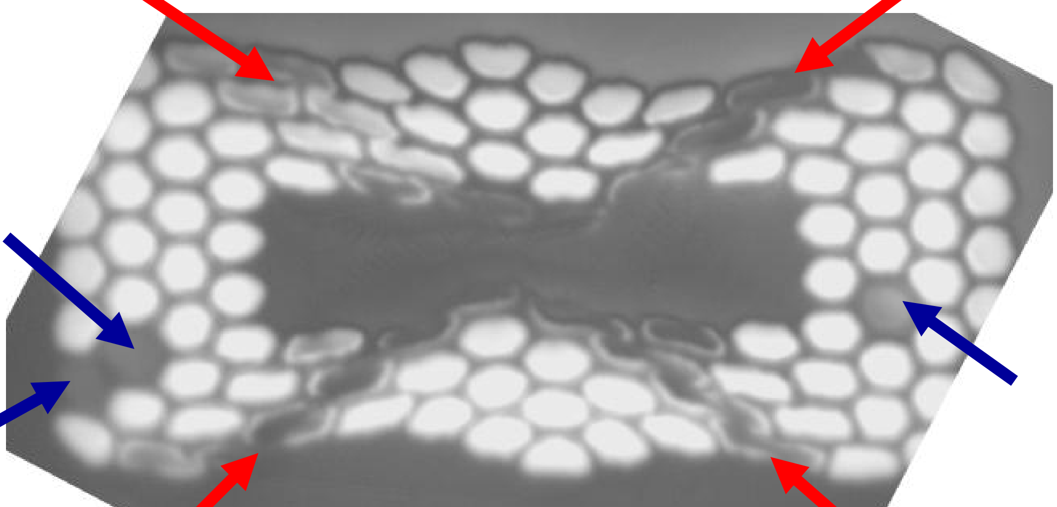
External reaction layer still thin – *short PIT reaction time*

PIT Core Components Change After Rolling



RRP Rolled to 0.6 mm: Color & MO: T=12 K, H=0



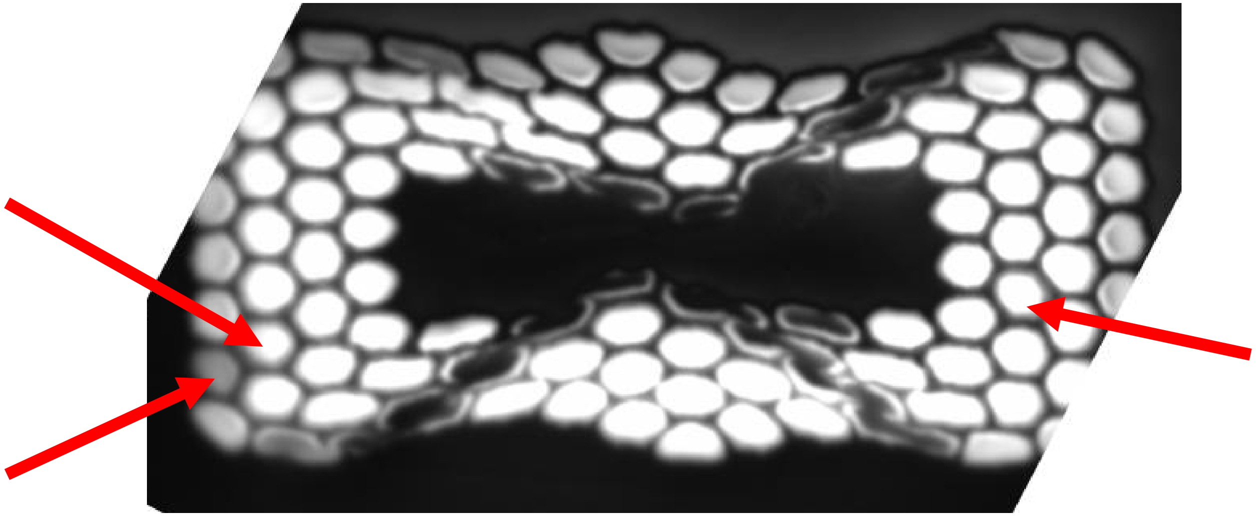


Broken subelements along shear planes

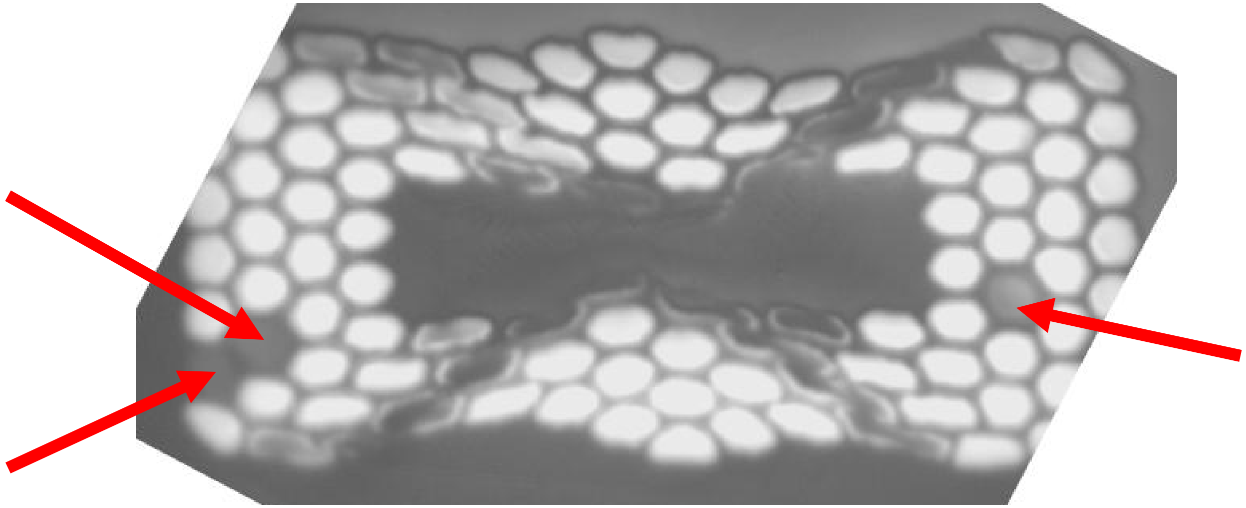
Low T_c subelements with partially reacted Nb (Sn loss from sub-elements)

MO shows two types of defects in RRP1

MO Shows T_c Reduction in Sub-Elements that are *Not* Damaged in this Cross-Section

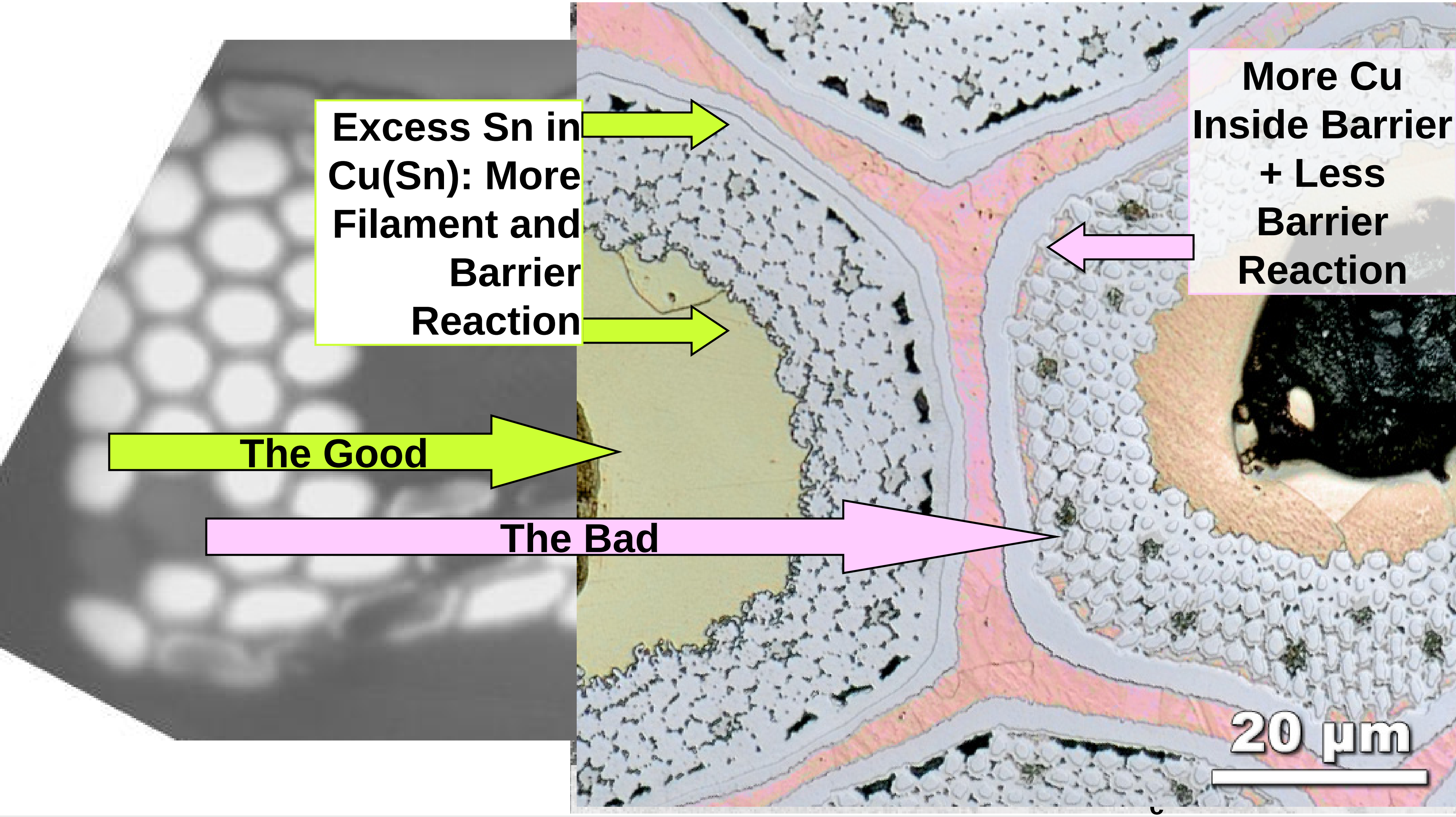


T=6 K

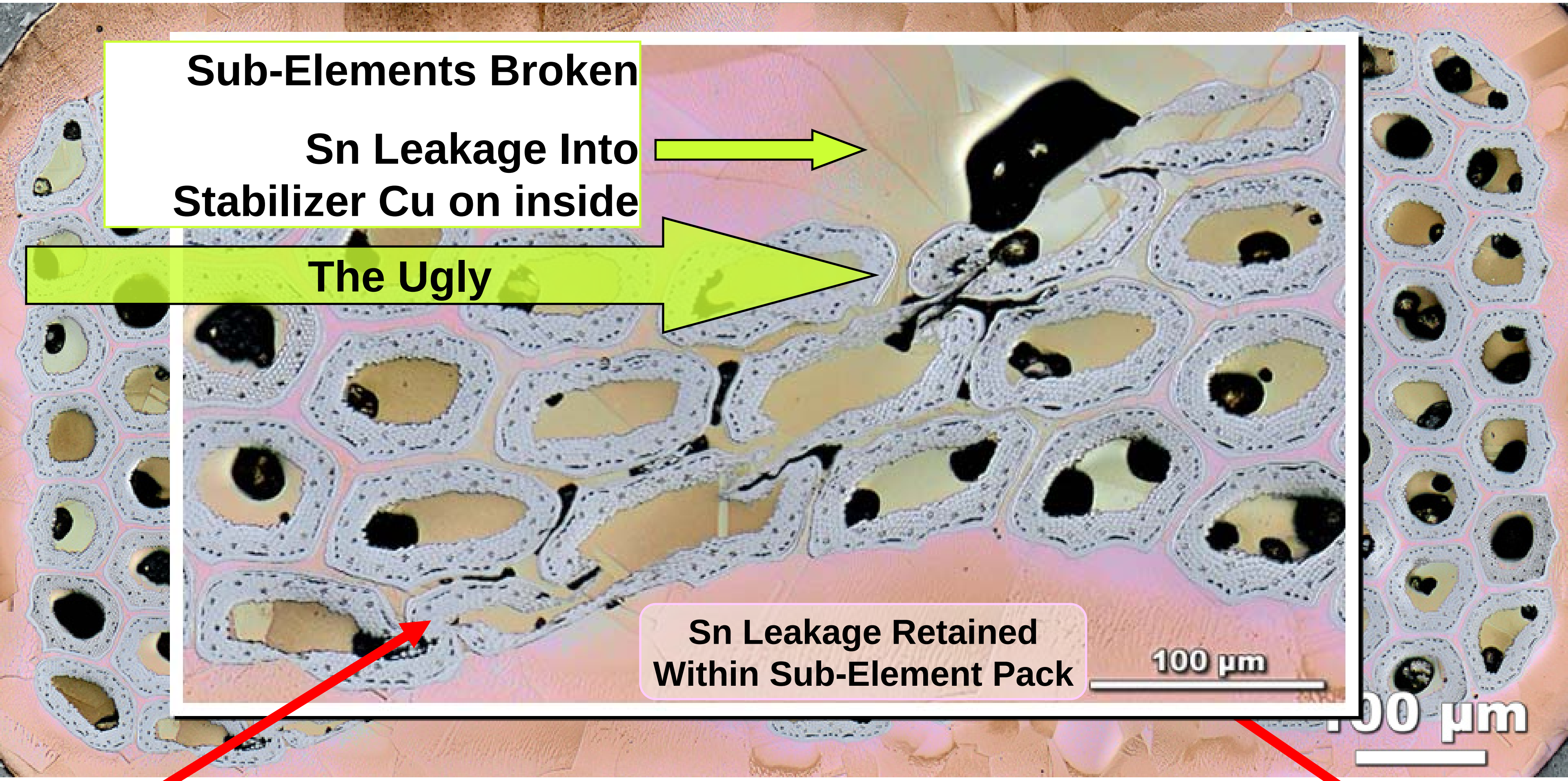


T=12 K

Unreacted Nb Filament Cores In Low T_c Sub-Elements



Broken Sub-Elements In Shear Planes

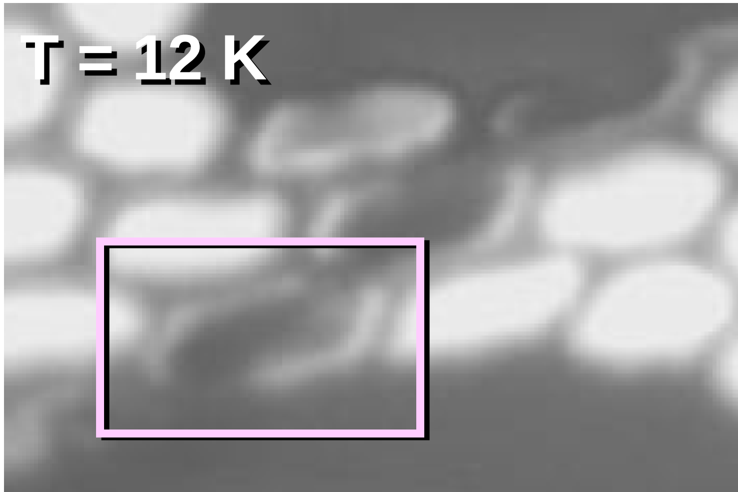


Shear Plane

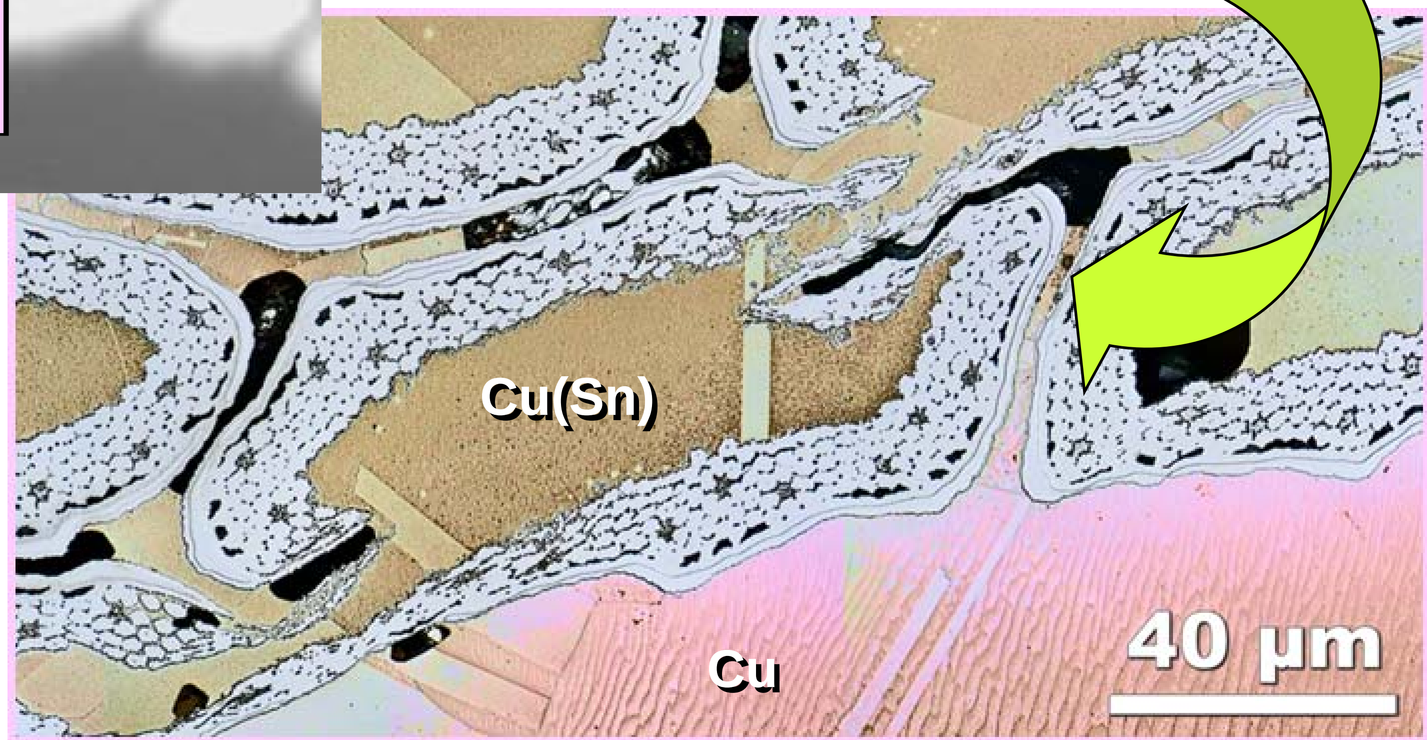
Rolling Causes Greatest Damage Along Shear Planes

Shear Plane

Sn Retained In Sub-Element Pack

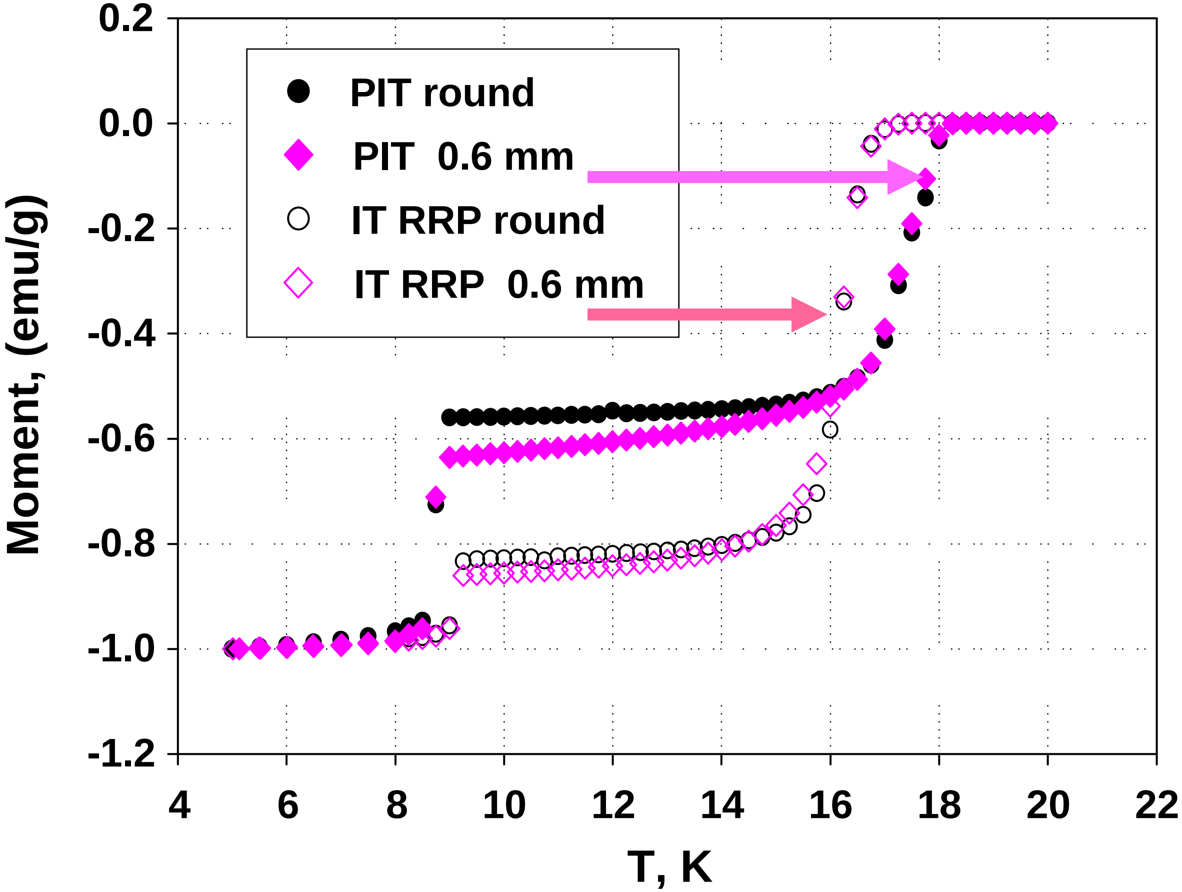


- Restriction in Cu between sub-elements reduces Sn loss into outer Cu



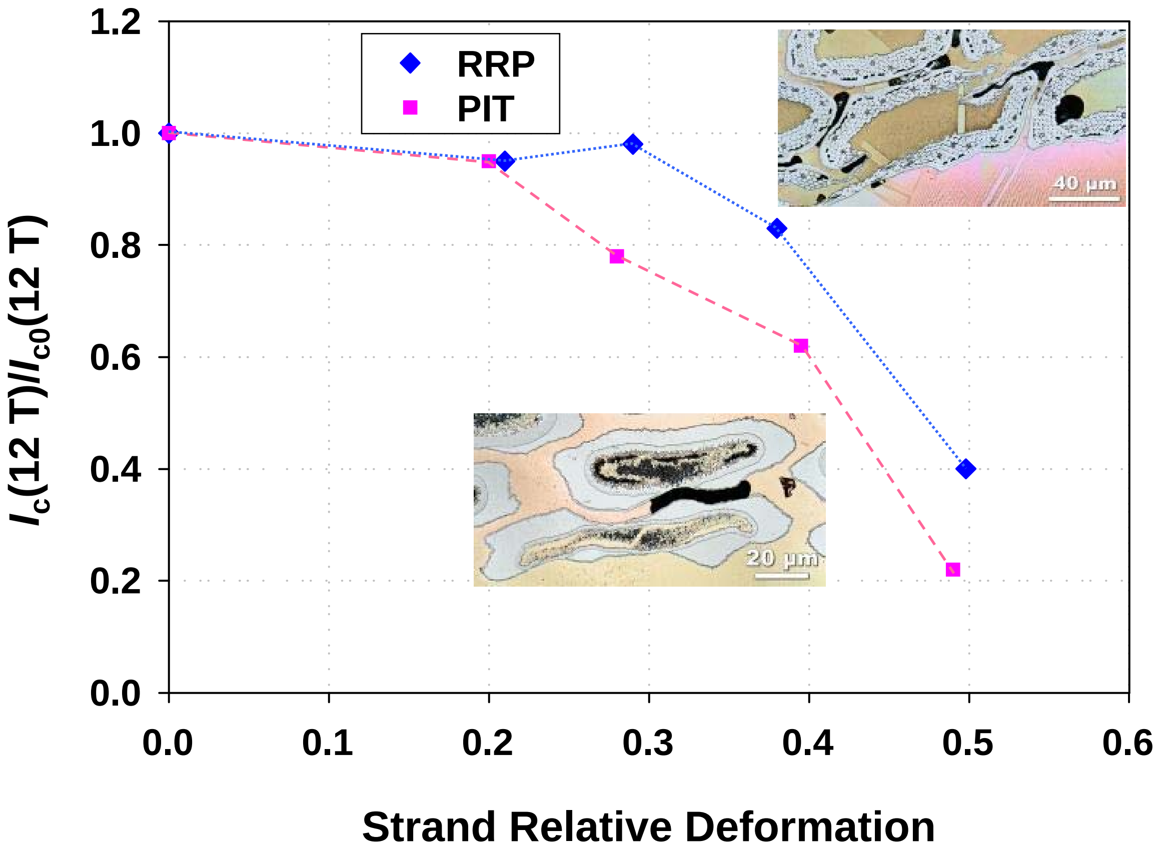
Sufficient excess Sn retained to maintain superconduct-ivity at 12 K

T_c Dependence vs. Rolling Deformation



- The IT RRP strand uses Ti doping (from Nb-Ti rods) to enhance high field J_c and consequently has a lower T_c than the $Nb(Ta)_3Sn$ of the PIT strand.
- Deformation of the strands produces some broadening at the low end of the A15 transition due to lower-Sn A15 being formed.

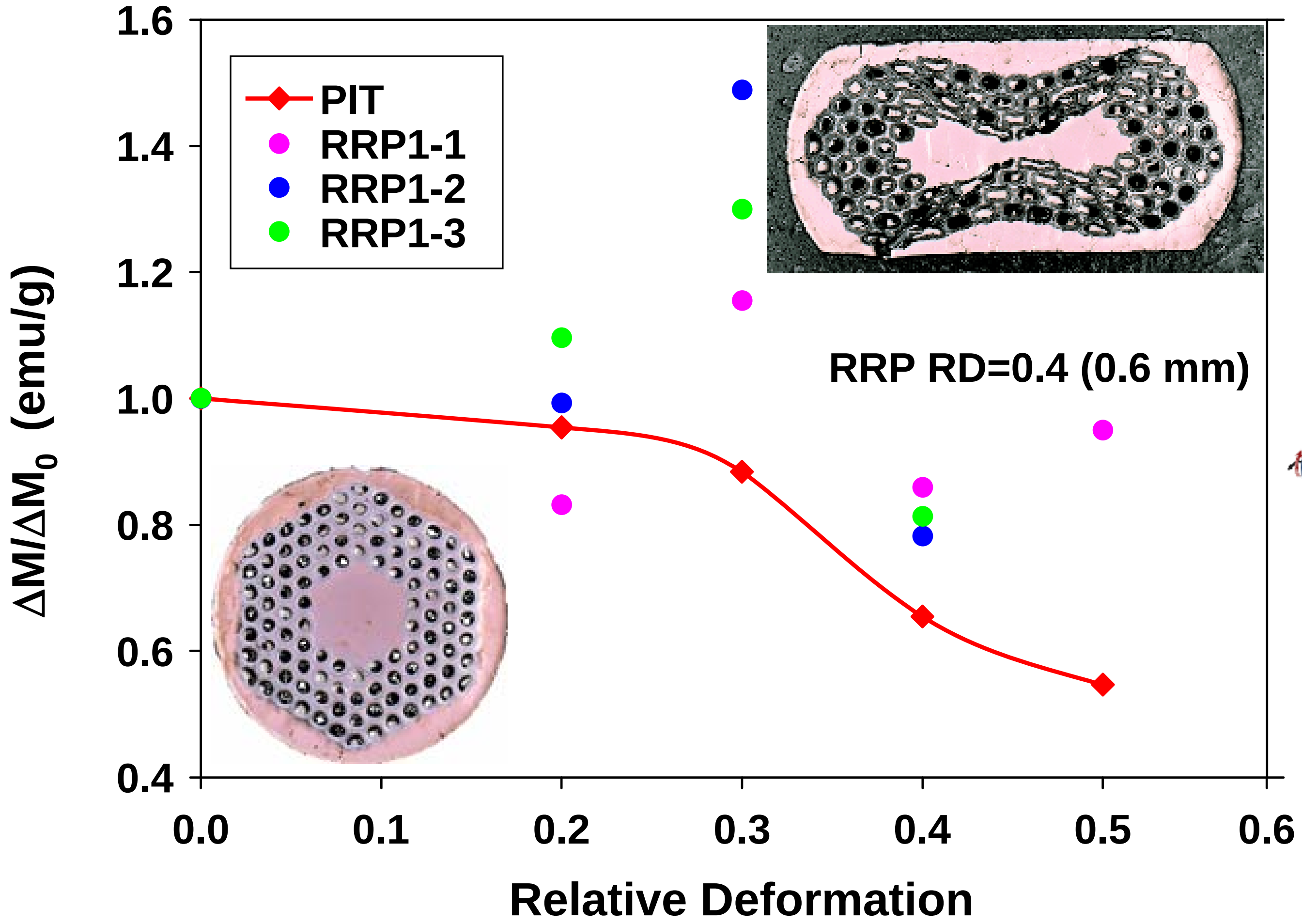
Transport I_c Dependence at 12 T (4.2 K)



Measurement at FNAL

- Both Strand Designs maintain J_c out to 80% of original diameter.
- PIT I_c drops faster after that perhaps because the short HT used for PIT strands (47-64 hr) means that loss of the high Sn is more catastrophic to A15 volume.

Magnetic Moment at T=12 K and H=2 T



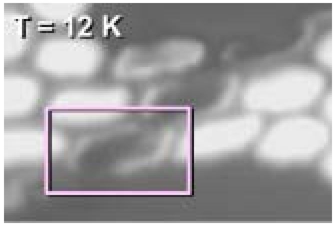
- Three different 5 mm RRP strand sets measured.
  - 12 mm twist pitch applies different geometric distortions
- Magnetization measurements show considerable scatter in measurements for the deformed RRP strands

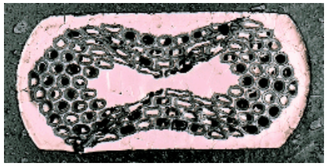
Conclusions

RRP and PIT behave differently under rolling deformation used to simulate cabling damage.

RRP:

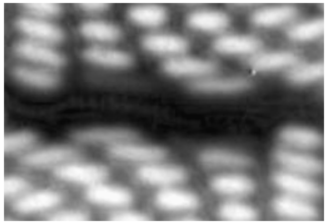
- In high-Sn RRP, Sn leaked from broken sub-elements but trapped in the sub-element pack can still be used locally to produce current carrying Nb_3Sn (indicated by MO).
- Deformation inhomogeneous along length because of twisting.





PIT:

1. Sn lost from filament breakage in PIT strands results in critical loss of A15 layer.



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