Chris Segal,

Chiara Tarantini, Peter J. Lee, David C. Larbalestier

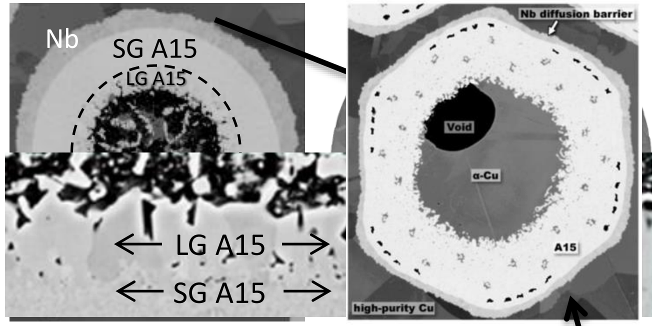
Applied Superconductivity Center, National High Magnetic Field Lab, FSU

How Nb(Ta) tube leakage induced by inhomogeneous deformation robs a huge potential from Nb_3Sn PIT conductors

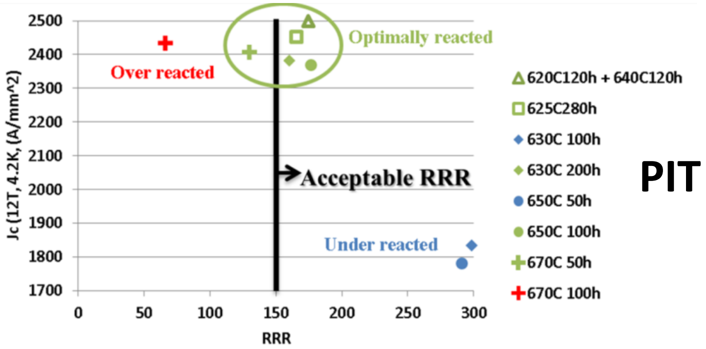
Many thanks to Bernd Sailer[1], Manfred Thoener[1], Klaus Schlenga[1] (Bruker[1]) and Bernardo Bordini[2] and Amalia Ballarino[2] (CERN[2]) for discussions

Introduction

Limitations in state of the art Nb_3Sn[1,2]



	PIT [1]	RRP[2]
J_c (12T, 4.2K)(A/mm^2)	2500	~2900
RRR	175	>150
Total A15 area fraction	58%	~60%
SG/LG ratio	2.9	--

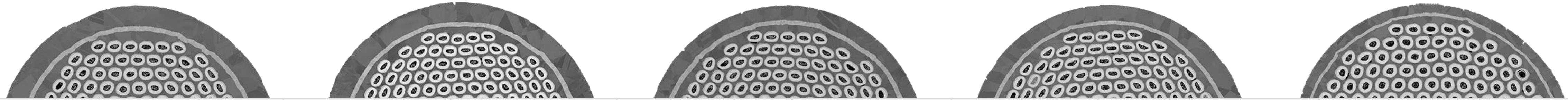


PIT

[1] C. Tarantini *et al.*, "Composition and connectivity variability of the A15 phase in PIT Nb3Sn wires," *SUST* 2015.
[2] Sanabria PhD Thesis 2017 ASC-NHMFL-FSU

A large variety of architectures and properties

Medium Sn			High Sn	Very High Sn
Luca	Bernardo	Bernardo 2	Lucio	Bernd

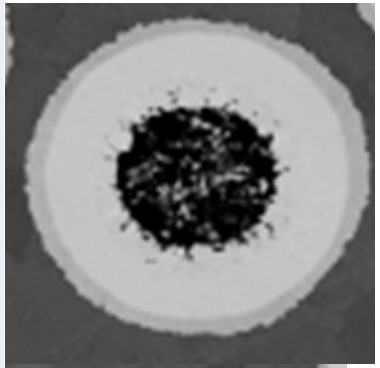


Sample name	Sample ID	Sn	filaments	Jc(12T) A/mm2	Jc (15T) A/mm2	SG layer Jc (12T)	RRR	wire d (mm)	fil d (um)	Cu:non-Cu	bundle DB	Total A15	SG/LG A15	% SG A15	% LG A15	% Core A15	%Nb	% Cu	% Void	K-void
0.7 mm																				
Luca	P2693	med	156	2658	1508	6515	190	0.71	36.0	1.2	5.6%	59.2%	2.55	40.8%	16.0%	2.4%	21.0%	5.1%	14.7%	0.03%
Bernardo	P2658	med	192	2561	1462	6308	132	0.71	33.3	1.1	5.4%	58.6%	2.59	40.6%	15.7%	2.3%	21.7%	5.3%	14.4%	0.13%
Bernardo II	P2743	med	192	2455	1389	5859	141	0.72	34.7	0.97	6.0%	60.5%	2.64	41.9%	15.9%	2.7%	21.5%	4.6%	13.5%	0.27%
Lucio	P2689	high	192	2434	1363	6257	168	0.72	35.0	0.99	5.0%	58.1%	2.30	38.9%	16.9%	2.3%	20.9%	6.4%	14.6%	0.36%
Bernd	P2499	very high	192	2310	1315	5474	61	0.71	36.3	0.87	3.6%	59.0%	2.78	42.2%	15.2%	1.6%	19.9%	6.9%	14.2%	0.34%
0.85mm																				
Luca	P2686	med	156	2640	1488	7021	112	0.86	44.0	1.19	5.6%	56.4%	2.28	37.6%	16.5%	2.3%	22.6%	7.0%	14.1%	0.04%
Bernardo**	P2656	med	192	2599	1481	6370	127	0.87	40.5	1.12	5.4%	59.3%	2.63	40.8%	15.5%	3.0%	21.9%	5.4%	13.4%	0.10%
Bernardo II	*P2736/P2774	med	192	2473	1400	6136	131	0.87	42.1	0.98	5.9%	58.8%	2.53	40.3%	15.9%	2.6%	23.0%	4.9%	13.3%	0.09%
Lucio	P2683	high	192	2458	1390	6145	109	0.87	42.2	0.99	5.0%	59.6%	2.37	40.0%	16.9%	2.7%	20.9%	5.3%	14.3%	0.21%
std (no bundle barrier)	B31284	low	192	2237	1259	5564	--	0.78	39.0	1.2	0.0%	56.0%	3.02	40.2%	13.3%	2.5%	23.4%			0.00%

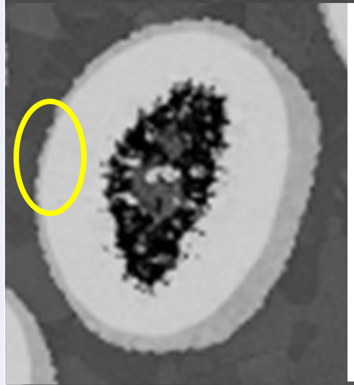
All higher J_c! BUT, why doesn't J_c increase with Sn content? We suspect Sn leaks

Leaked filaments lose Sn and SG A15 volume suffers

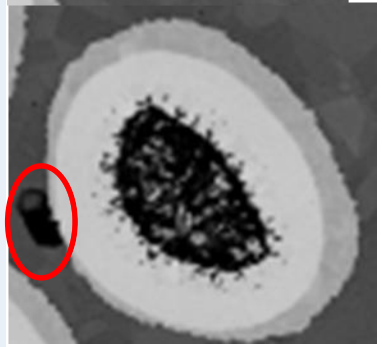
3 types of filaments



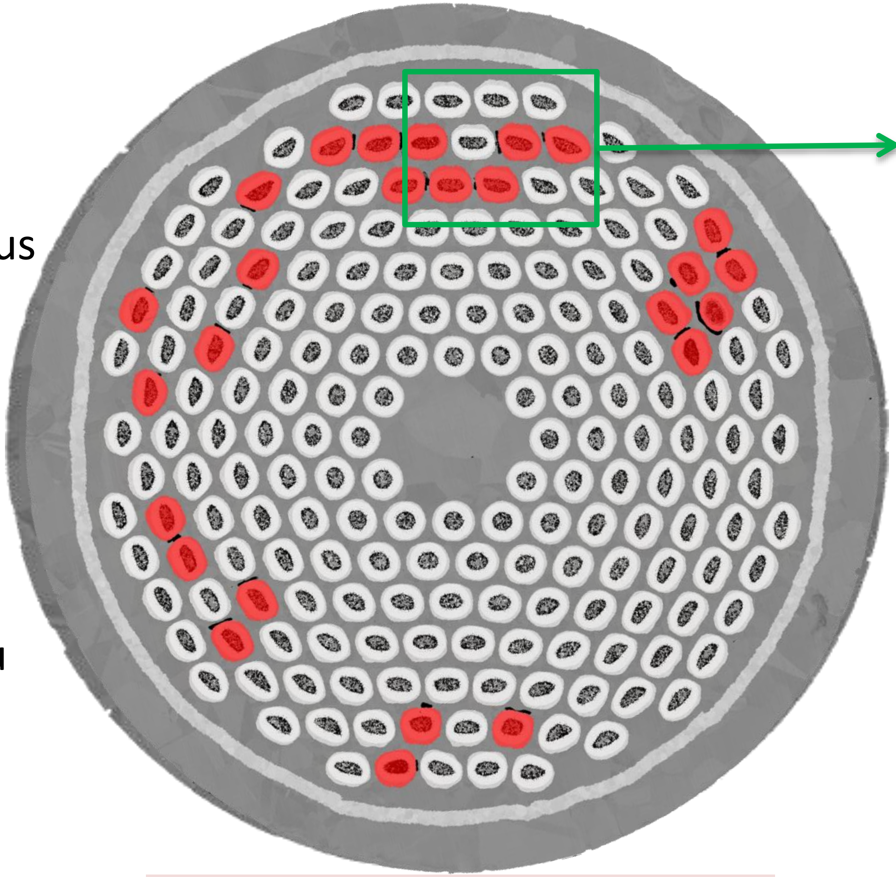
Unbreached: fully continuous barrier



Breached: A15 contacts Cu

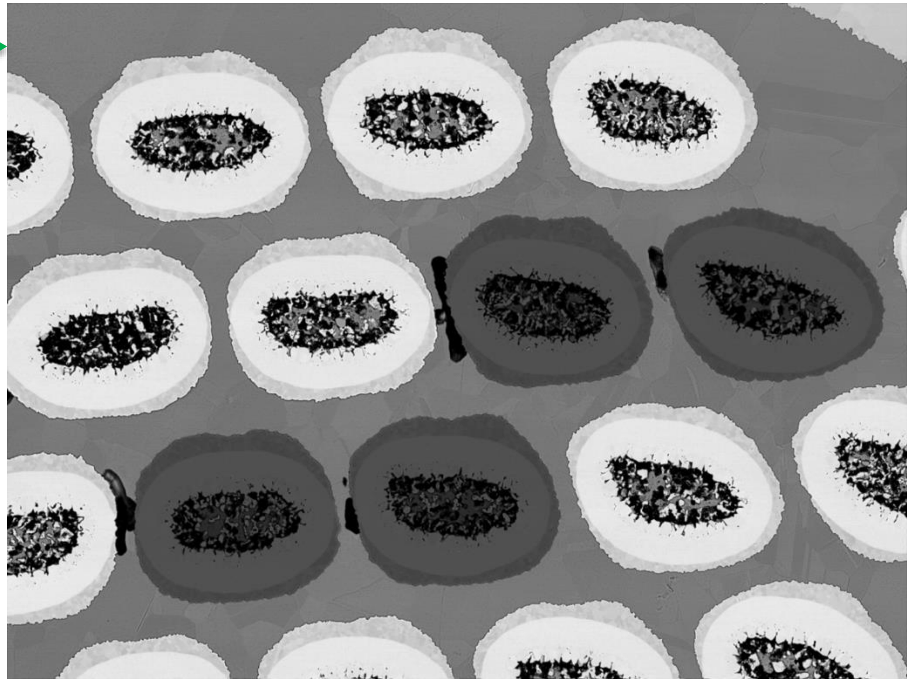


Breached: Kirkendall void -severe Sn leak



Bernardo 2, 0.7 mm, 27 leaks

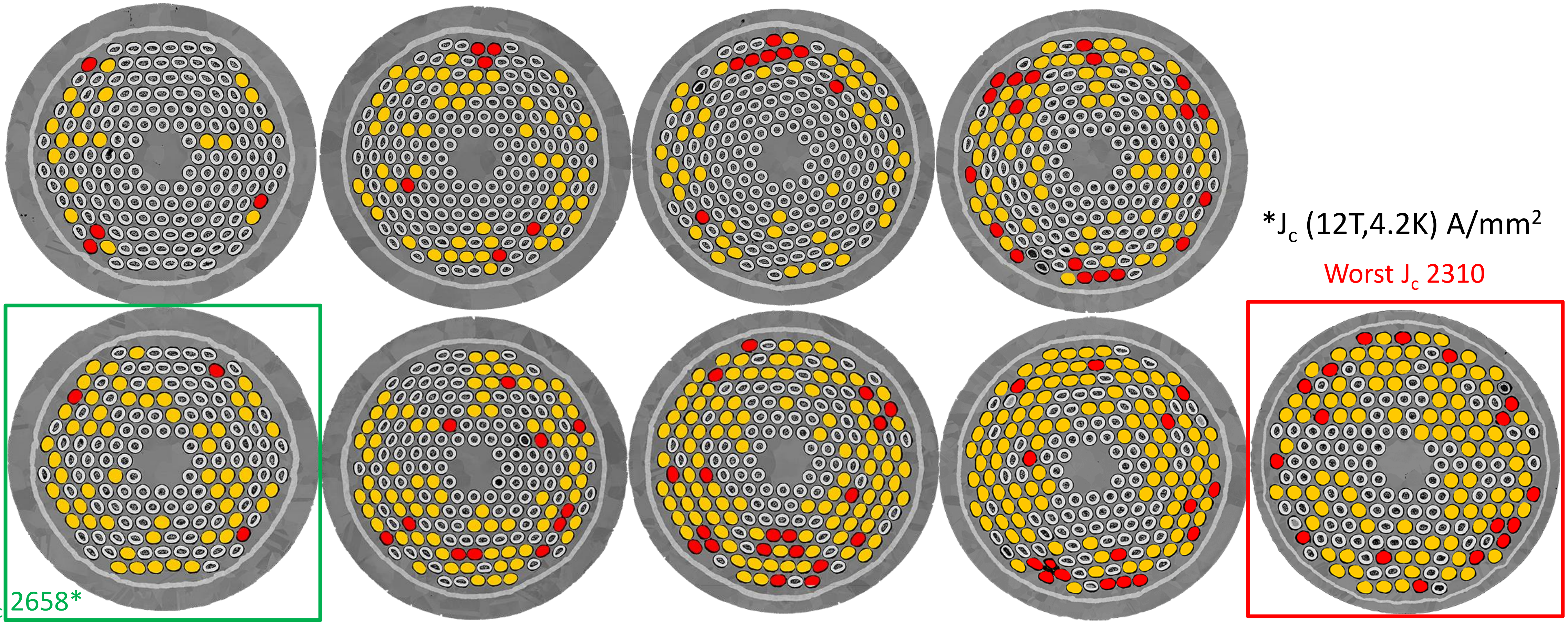
- 10% of filaments have SG A15 area reduced by ~5% in a single cross section



	normal area	leaky area	Change	Weighted filaments
Nb	21.5%	23.9%	2.4%	21.7
SG A15	41.9%	36.8%	-5.1%	41.4
LG A15	15.9%	15.9%	0.0%	15.9
Core A15	2.7%	2.2%	-0.5%	
Core Cu	4.6%	8.4%	3.8%	
Core void	13.5%	12.8%	-0.7%	

Wire architecture strongly effects filament integrity

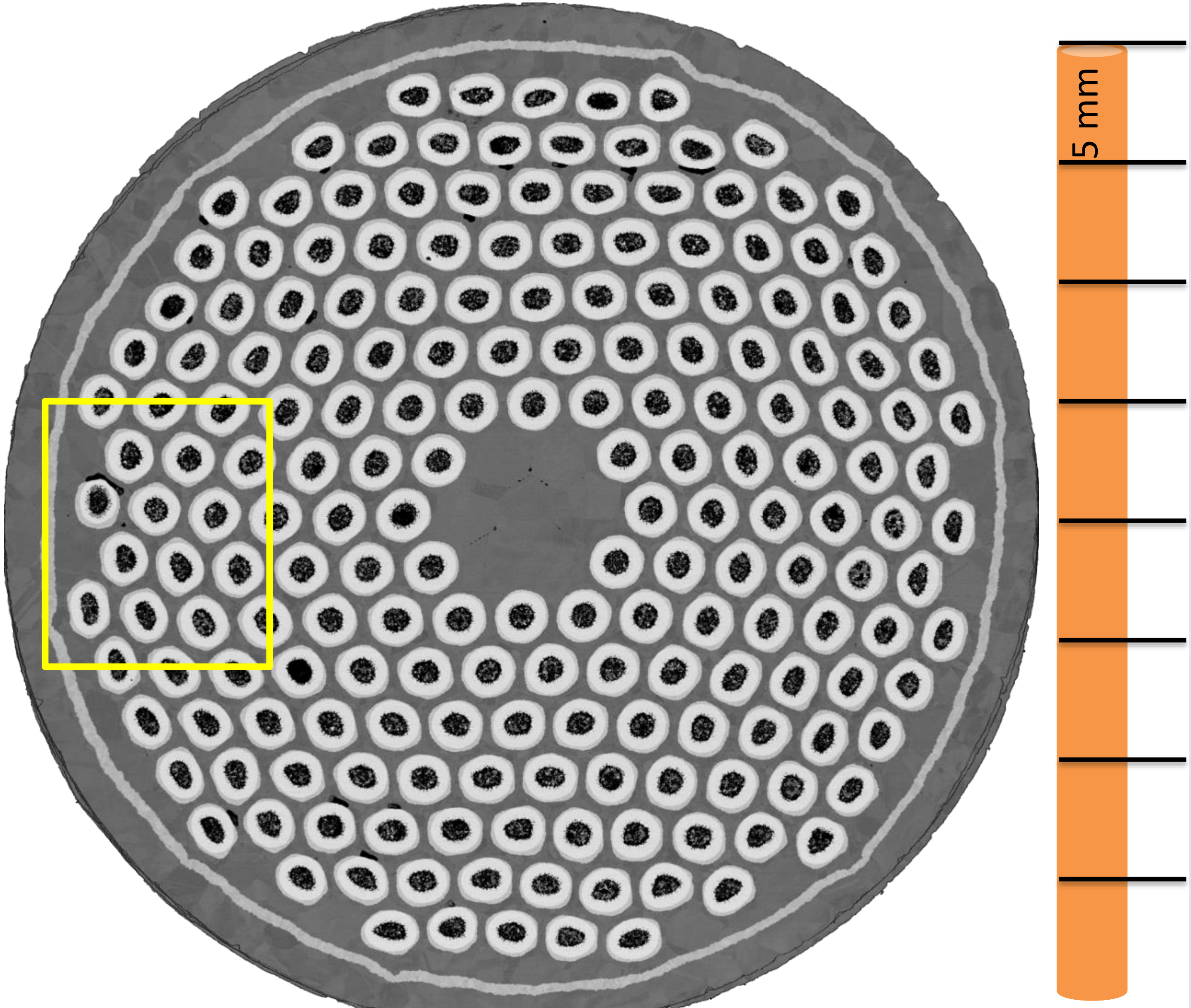
- A15 in contact with Cu
- Kirkendall void, indicating a major Sn leak to the Cu, also appears



Driving questions of the bundle barrier design

- Are leaky filaments compromised for long lengths?
- Do all leaky filaments show a Kirkendall void somewhere along the length of the leak?
  - If so, too many filaments are compromised
    - 4 cm long sample cut into 8 pieces
    - Polished and imaged in SEM
- What are the driving factors causing breached filaments?
- Do inner filaments have higher I_c than outer filaments due to their less frequent barrier breaks?
  - I_c etch experiment

Breached filaments can be seen over many centimeters

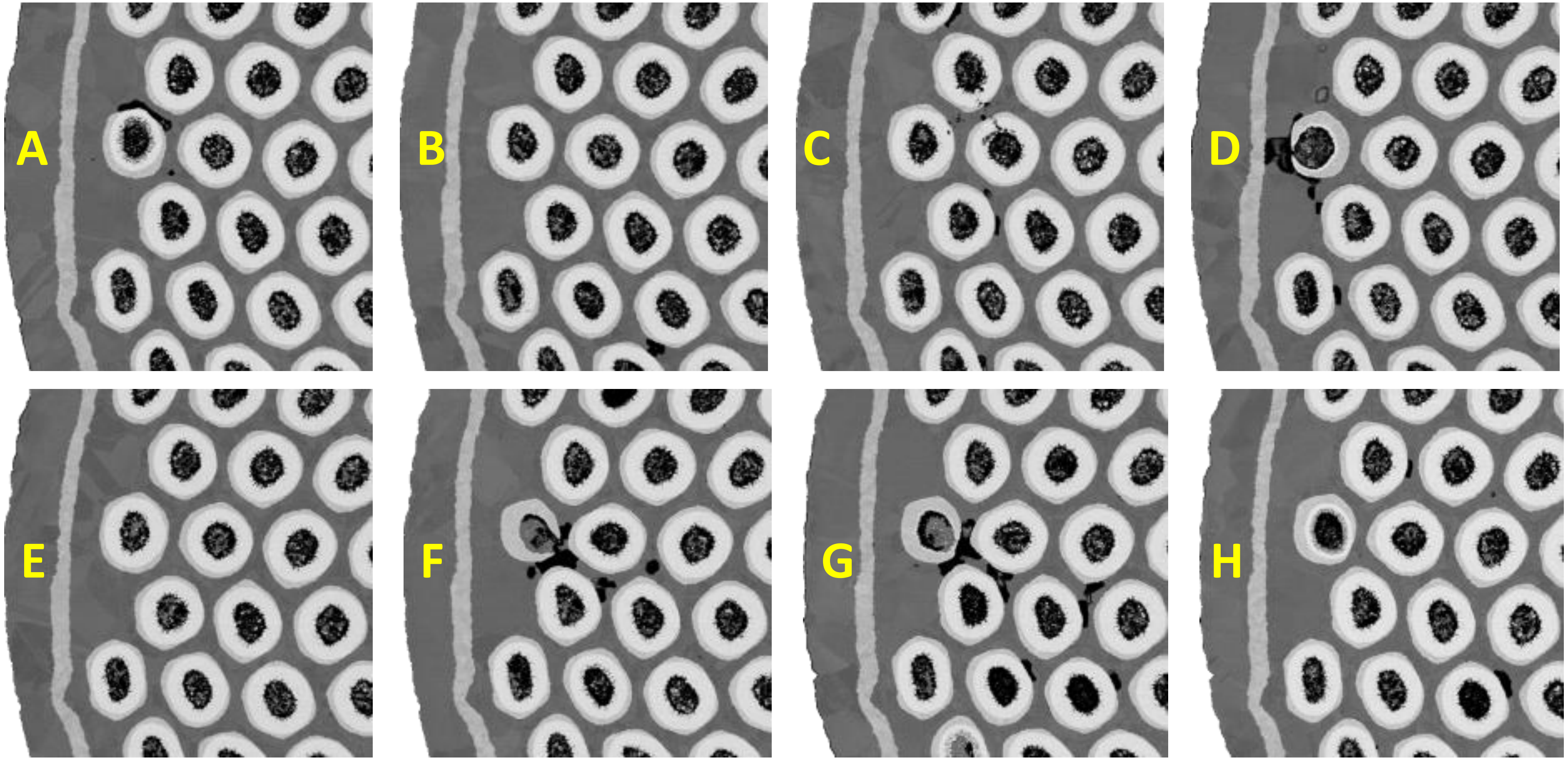


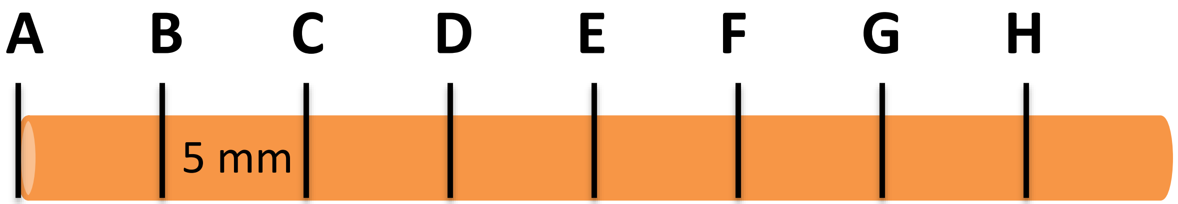
The effect of a breached filament can be much larger than suggested by a single cross-section

Bernd 0.7 mm very high Sn

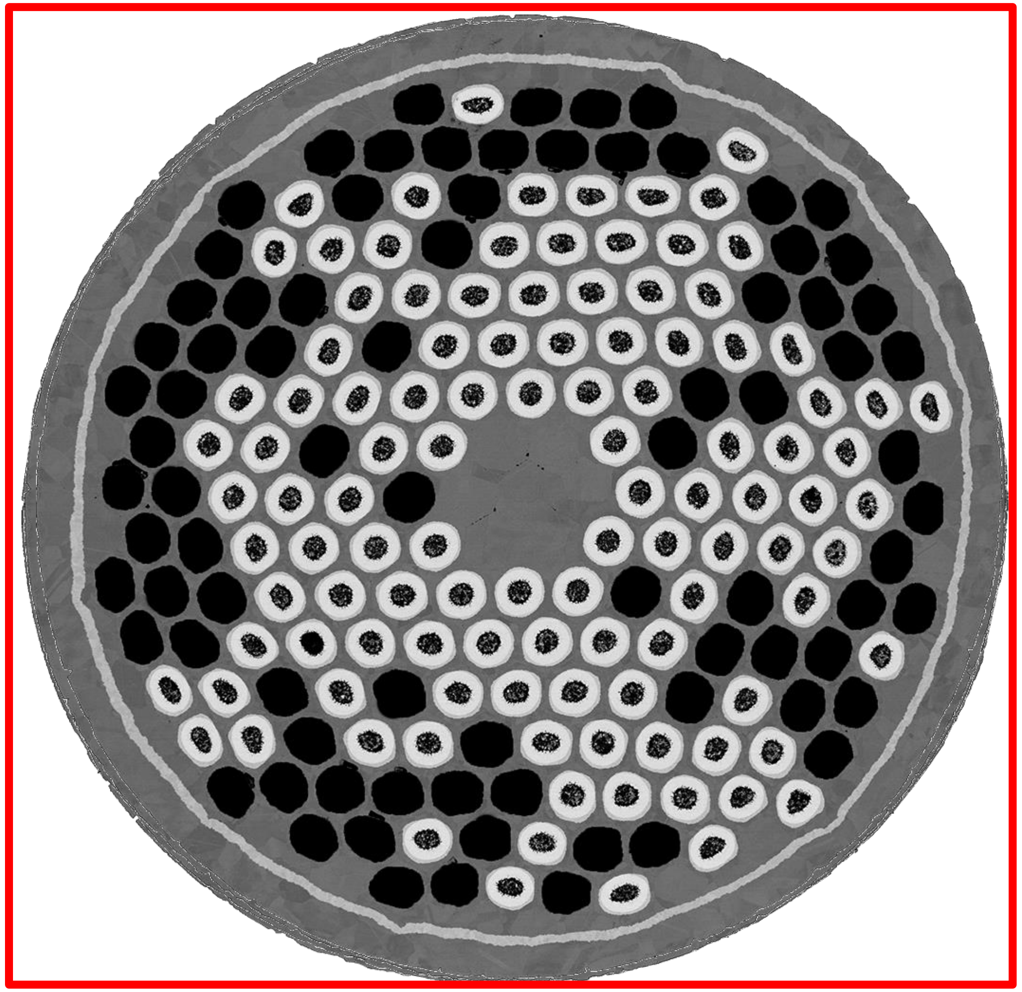
4 cm – 8 cross sections

One filament is severely breached in 4/8 cross sections





Leaks are plentiful along the entire 4 cm of wire



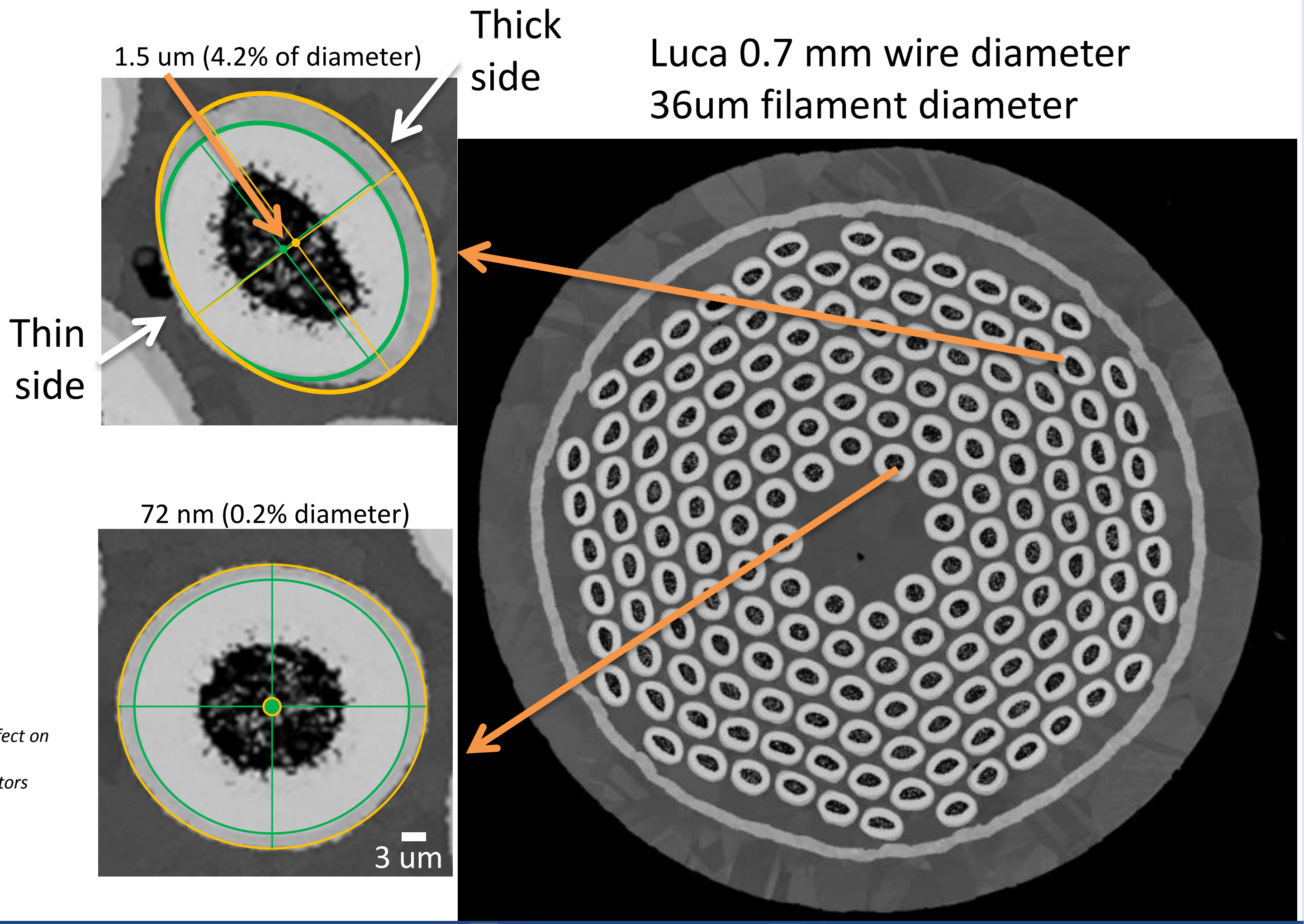
- Bernd 0.7 mm wire, very high Sn
- 15-20 K-void leaks in any given cross-section
- 81 leaked filaments with K-voids over 4 cm, 8 cross sections

- 171/192 breached filaments with A15 in contact with Cu
- Shading corresponds to how many cross-sections show a breach: black = all 8 cross-sections

The leading cause of barrier breach appears to be non-uniform deformation during wire fabrication

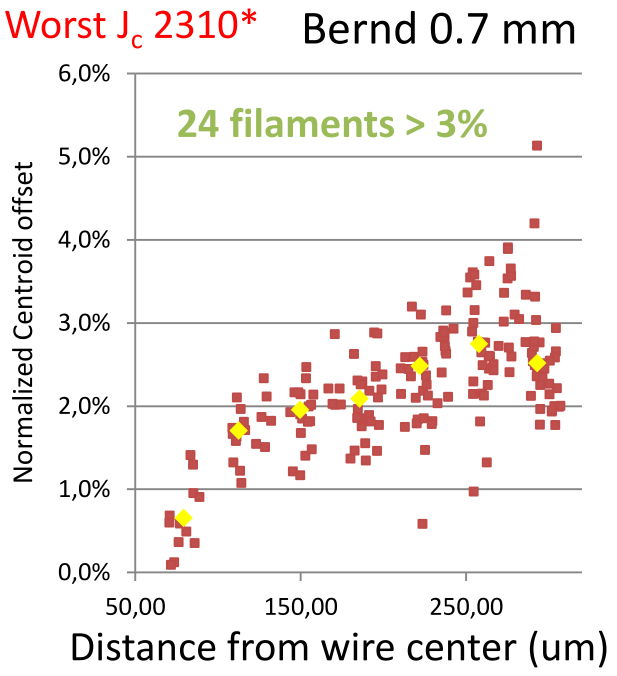
- The centroid offset is the distance between the centroid of the entire filament (orange) and the centroid of the A15 layer (green)

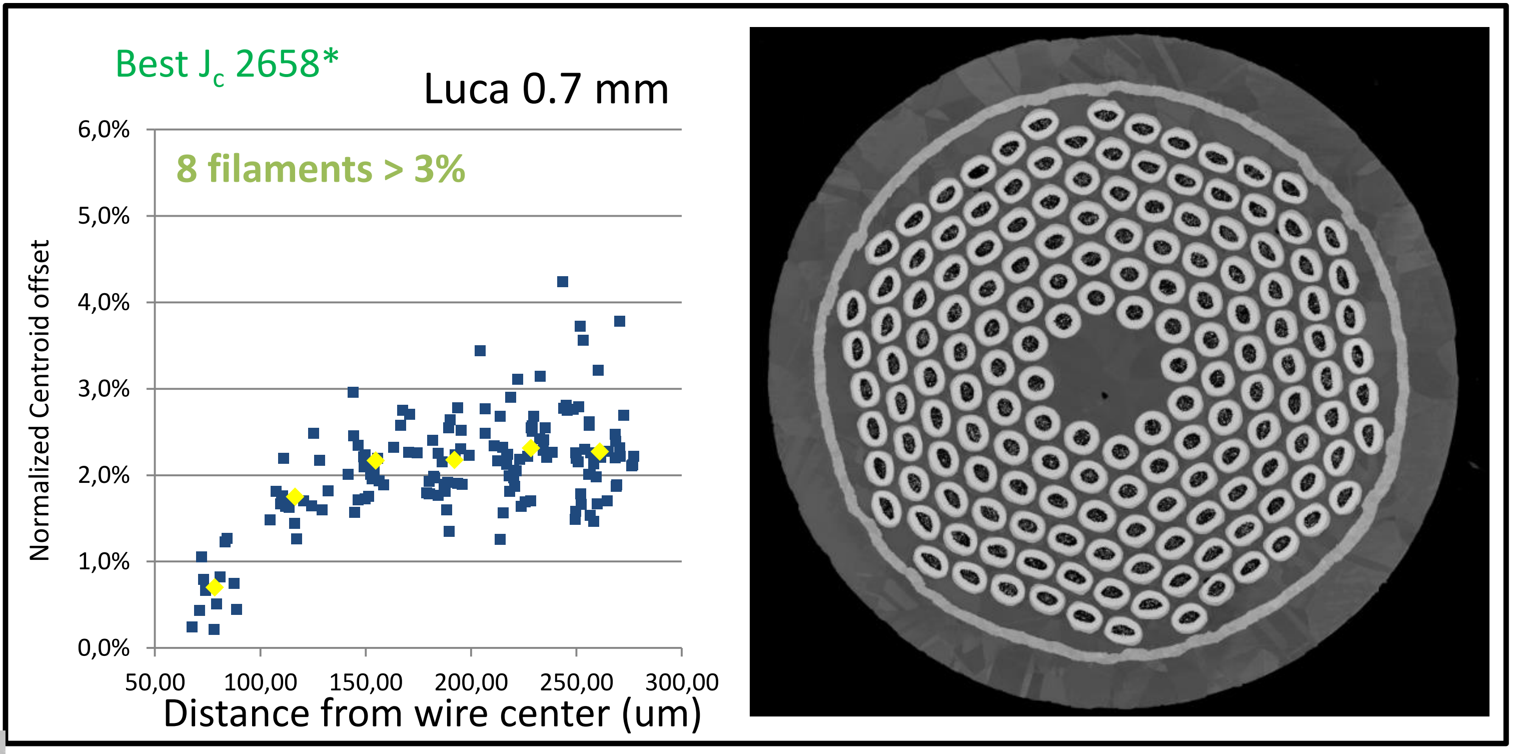
- To most accurately compare between filaments and wires, we normalize each filament's core offset to its own effective diameter, derived from its area.

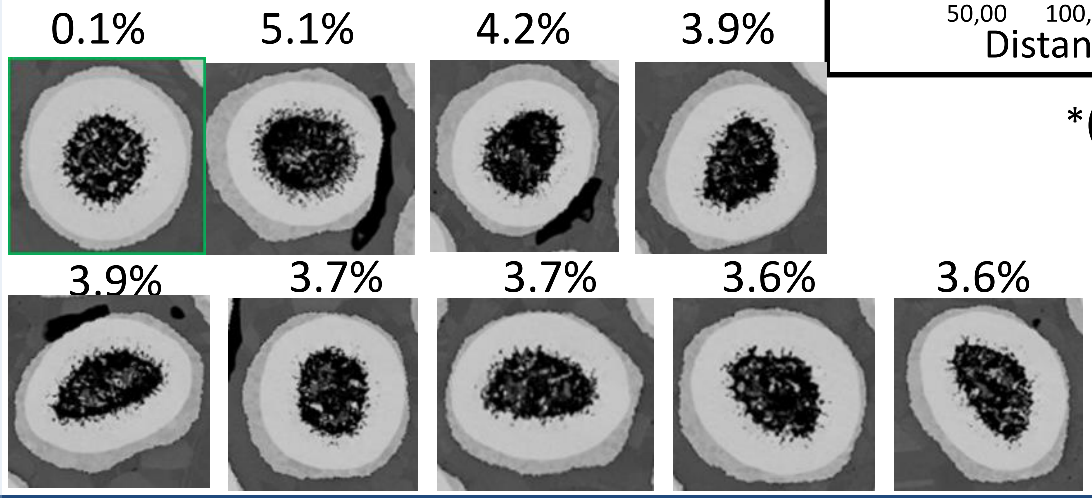


[1] Segal, C.; Tarantini, C.; Lee, P. and Larbalestier, D., *Observations of Local Barrier Breakdown in PIT Wires and its Effect on RRR*, Low Temperature Superconductivity Workshop (LTSW), St. Petersburg, FL, November 4-6 (2013)
[2] Segal, C.; Tarantini, C.; Lee, P.J. and Larbalestier, D.C., *Novel Methods for Improving Nb_3Sn Powder in Tube Conductors for the FCC and Beyond*, Cryogenic Engineering Conference and International Cryogenic Materials Conference, (CEC-ICMC), Madison, WI July 9-12 (2017)
[3] C. Segal *et al.*, "Evaluation of critical current density and residual resistance ratio limits in powder in tube Nb 3 Sn conductors," *Supercond. Sci. Technol.*, vol. 29, no. 8, p. 85003, 2016.

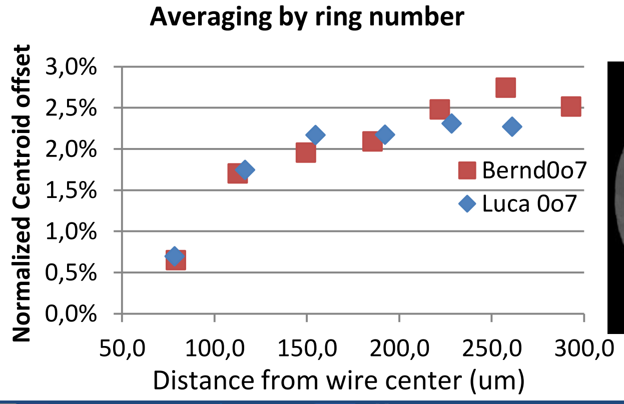
Filaments with large centroid drift are much more likely to leak Sn

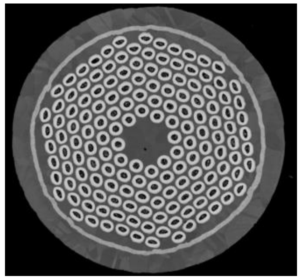






*(12T, 4.2K)A/mm^2

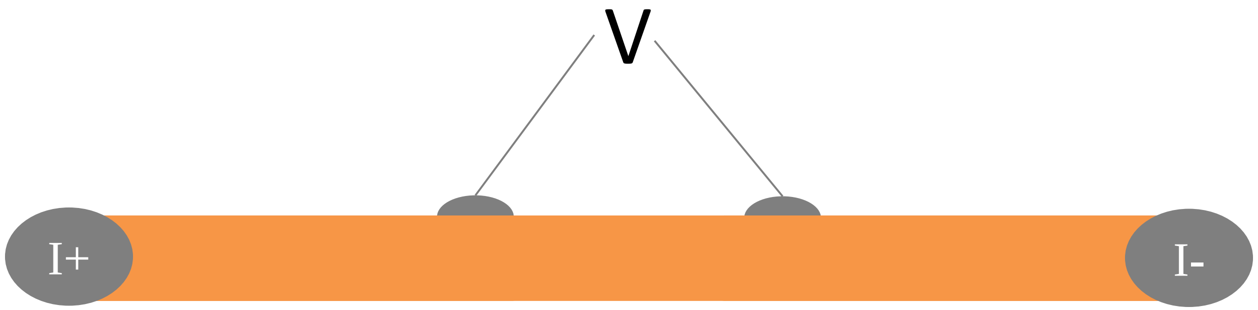




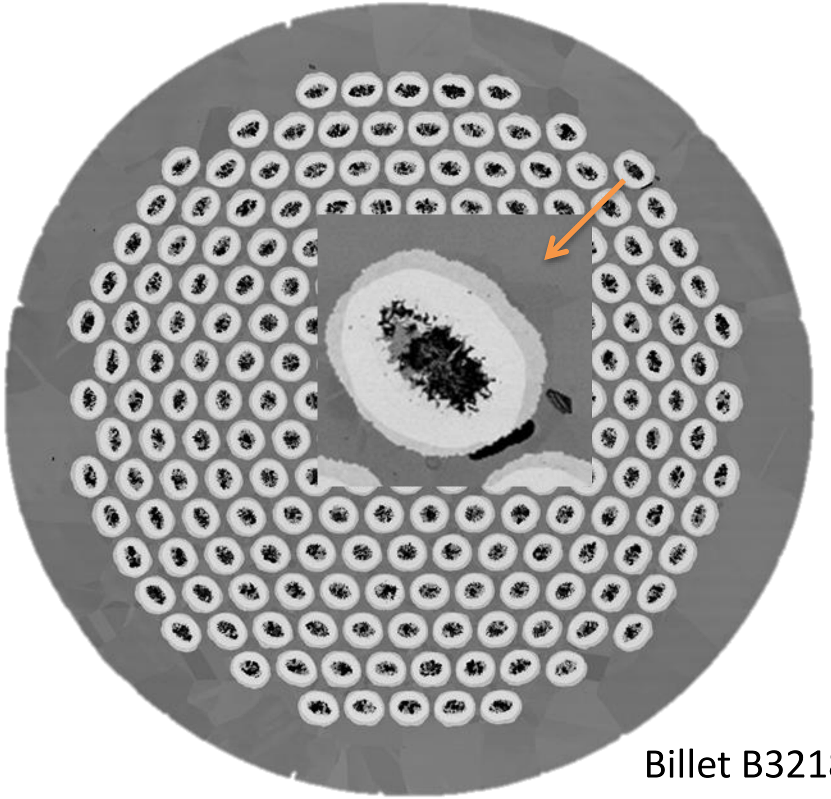
Do inner filaments with less likelihood of leaks have higher J_c than outer filaments?

<u>Procedure and proof of concept</u>

- Measure I_c of wire (1 uV/cm criterion)
- Etch Cu away, break away filaments (<40 um diameter)
  - Measure I_c of remaining inner filaments
- Mount sample in puck for serial imaging
  - Determine which filaments were fully intact for transport measurements

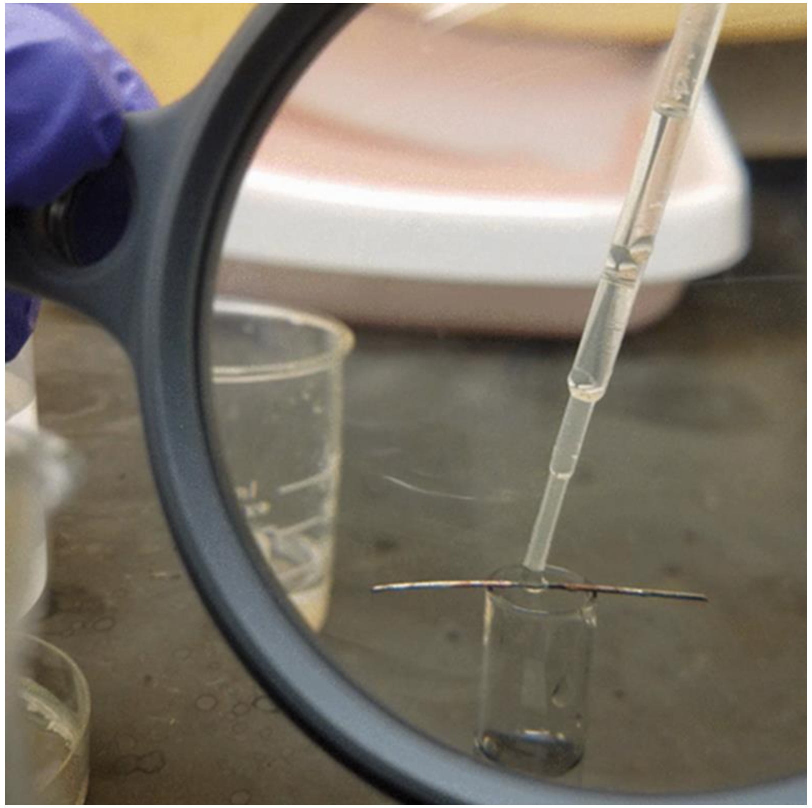


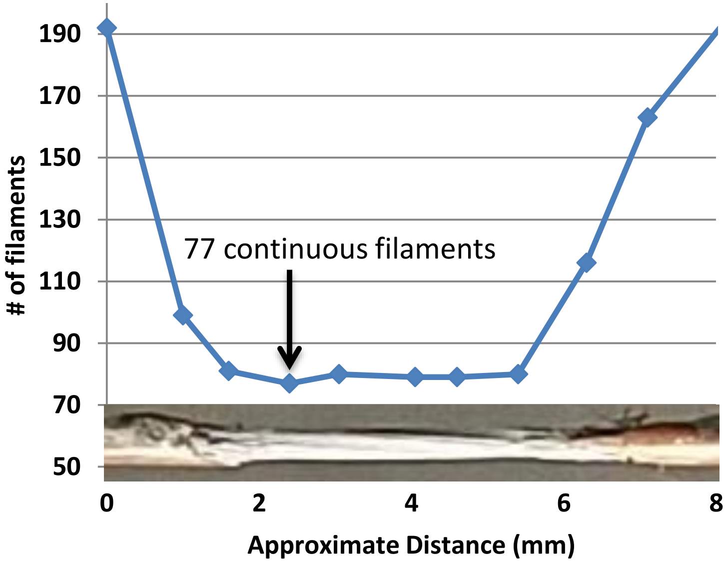
0.78mm wire after full reaction
-no bundle barrier, low Sn, only 1 severe leak with Kirkendall void

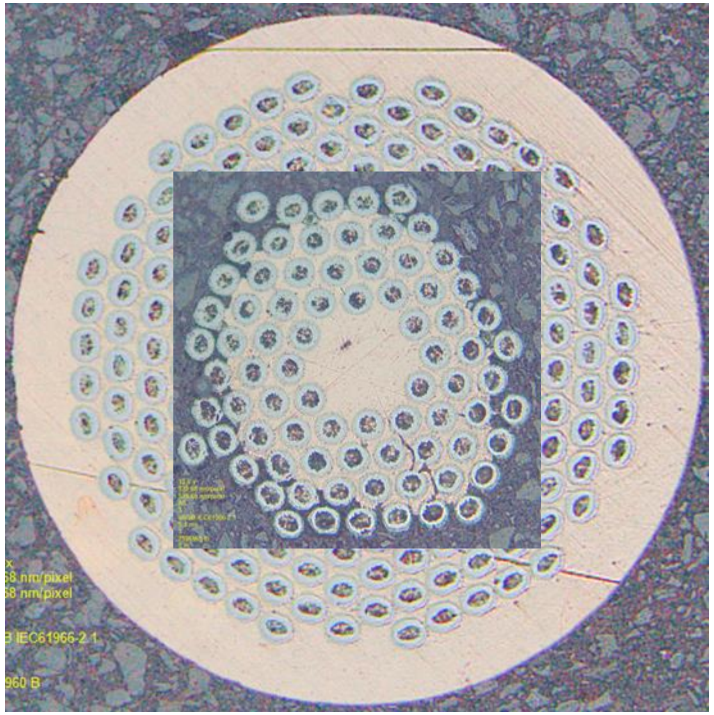


Billet B32184

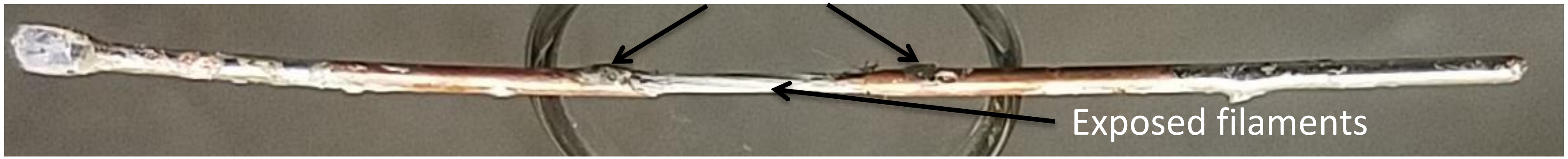
Etching the wire







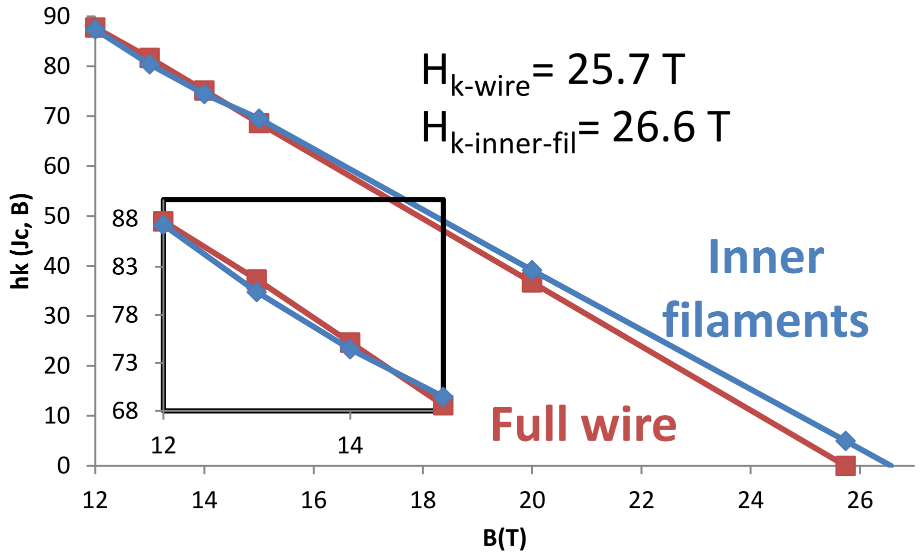
Voltage Taps

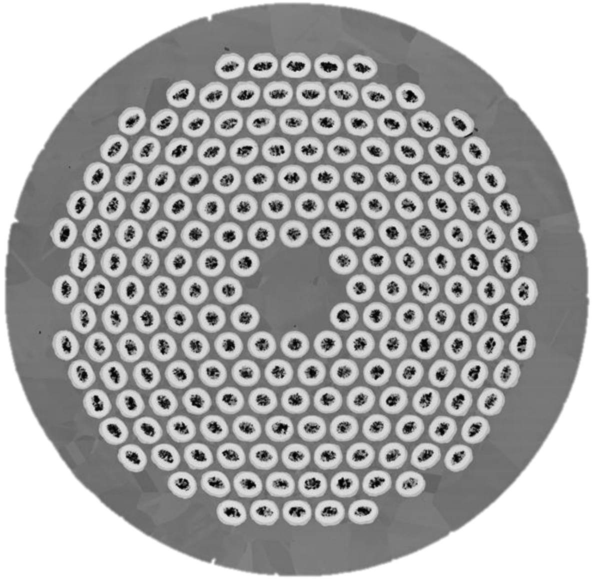


Exposed filaments

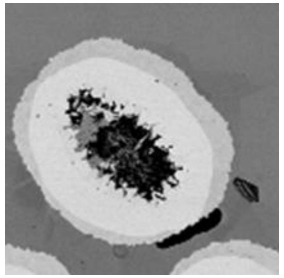
Acid was carefully applied to the area between the voltage contacts

Inner filaments have slightly higher H_k than entire wire

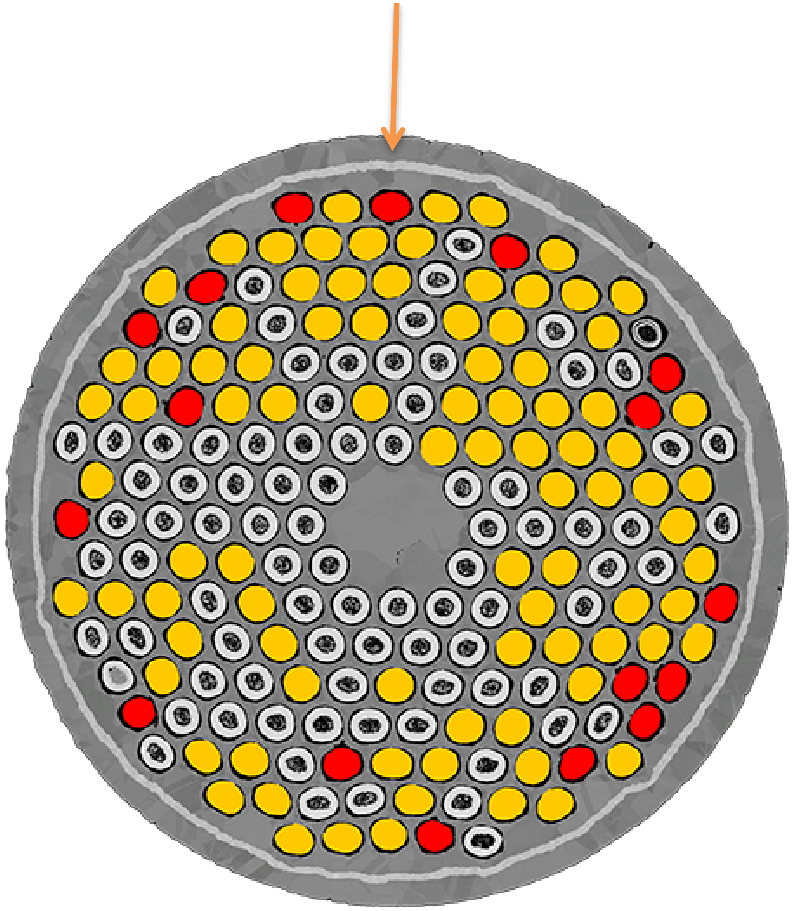




Only a single leak in this cross section.

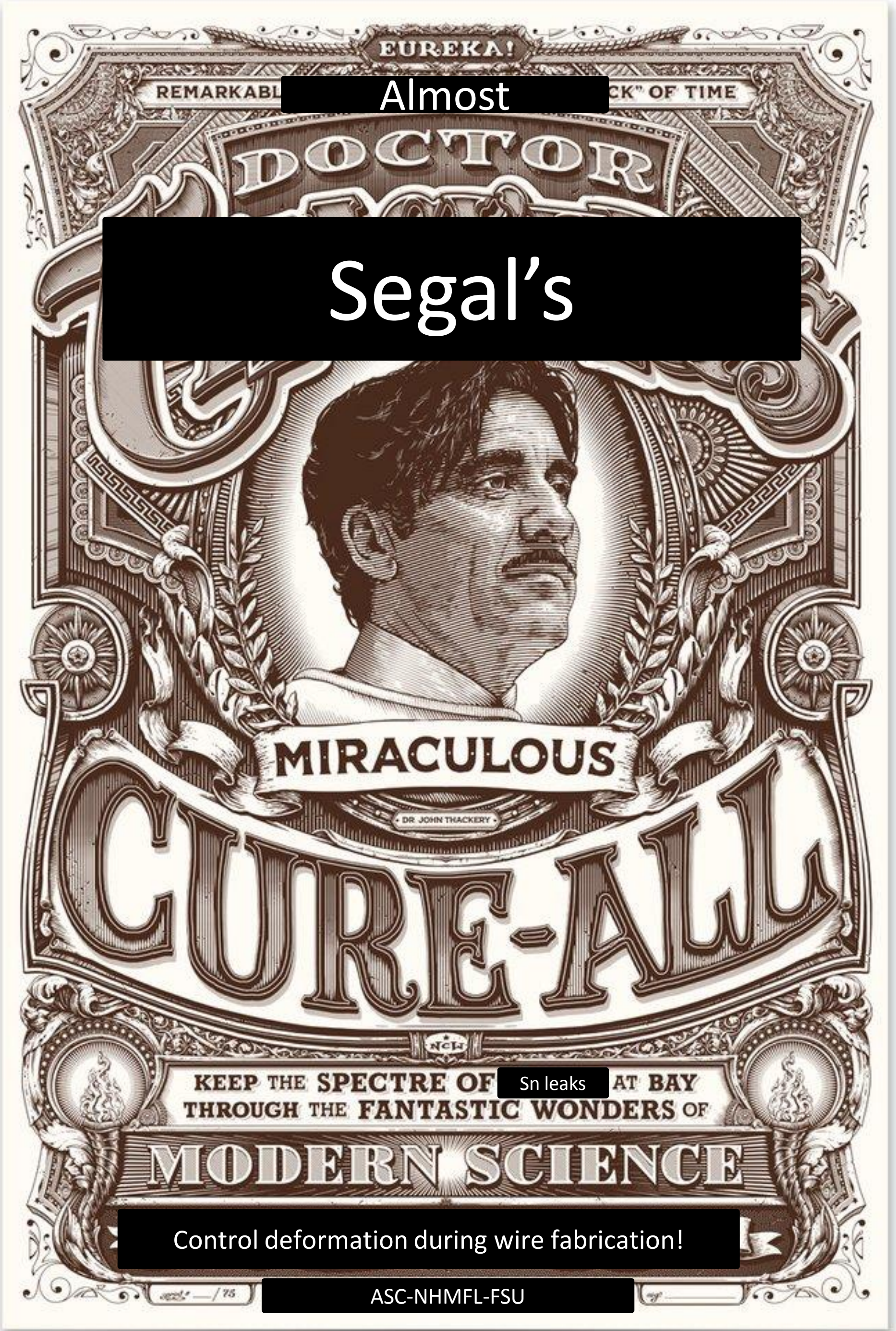


Nb bundle barrier requires HF acid for removal



Concl … work

- Non-uniform deformation during … ays
  - J_c: the full A15 volume canno…
  - RRR: Sn leaks out poisons the…
  - H_k: Outer filaments have less … r filaments at higher fields needed for FCC
- The biggest contributor to Sn leaki… e center of its Nb(ta) tube
- A reduction of the non uniform de… eturns since it appears to impact all electrical properties
- My simple suggestion: Use the ver… architecture (Luca) to retain as much Sn as possible.
  - This means: more reaction to… e in the wire, and push H_k higher
- Repeat etching experiment to mea… Sn leak effects on H_k



Funding : This work was supported by CERN under grant… f High Energy Physics under award DE-SC0012083, by CERN, and by the National High Magnetic Field Laborato… -1157490), and the State of Florida. Experiments on 0.78 mm wires were carried out on Bille… rogram (LARP), which is a BNL, FNAL, LBNL, and SLAC collaboration with CERN for the High Luminosity LHC pro… on.