Development of Nb_3Sn (and Bi-2212) strands in preparation for the FCC

J.A. Parrell, M.B. Field, H. Miao, A. Wu, K. Damborsky, Y. Huang

Oxford Superconducting Technology, Carteret, NJ 07008 USA

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Outline

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- Nb_3Sn FCC conductor: a significant challenge!
  - Incremental improvement opportunities if D_{eff} ~60 µm
  - Renewed need for more fundamental Nb_3Sn R&D
- Properties of present Nb_3Sn accelerator strand
- Bi-2212 development progress
- Nb_3Sn is not Nb-Ti: Review of conductor cost drivers
- Bridging technical and industrial gaps until the FCC

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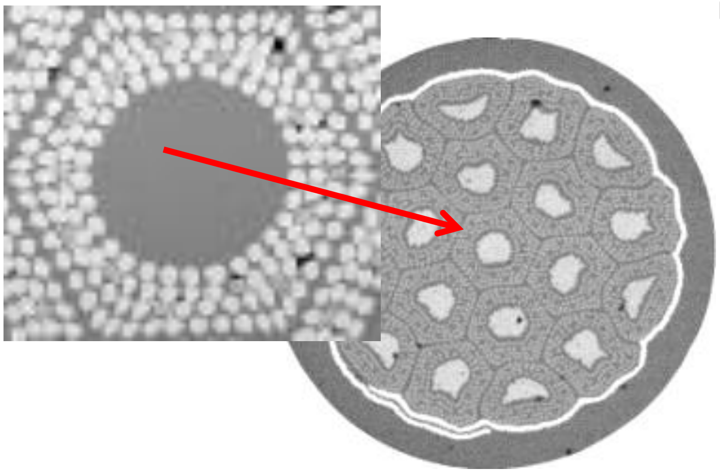
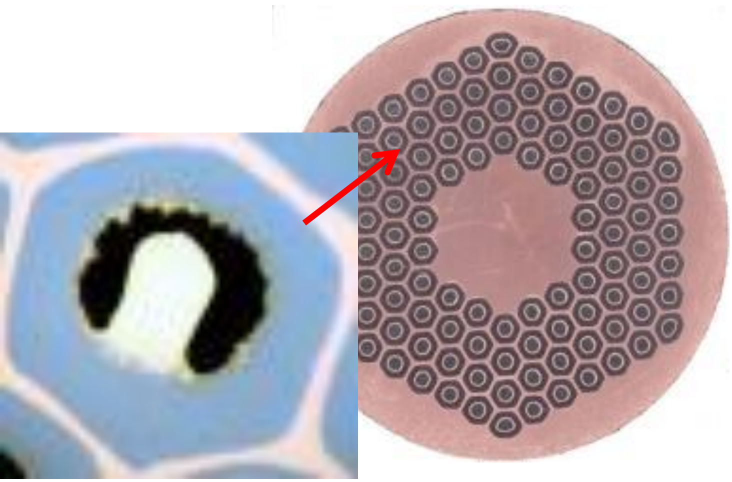
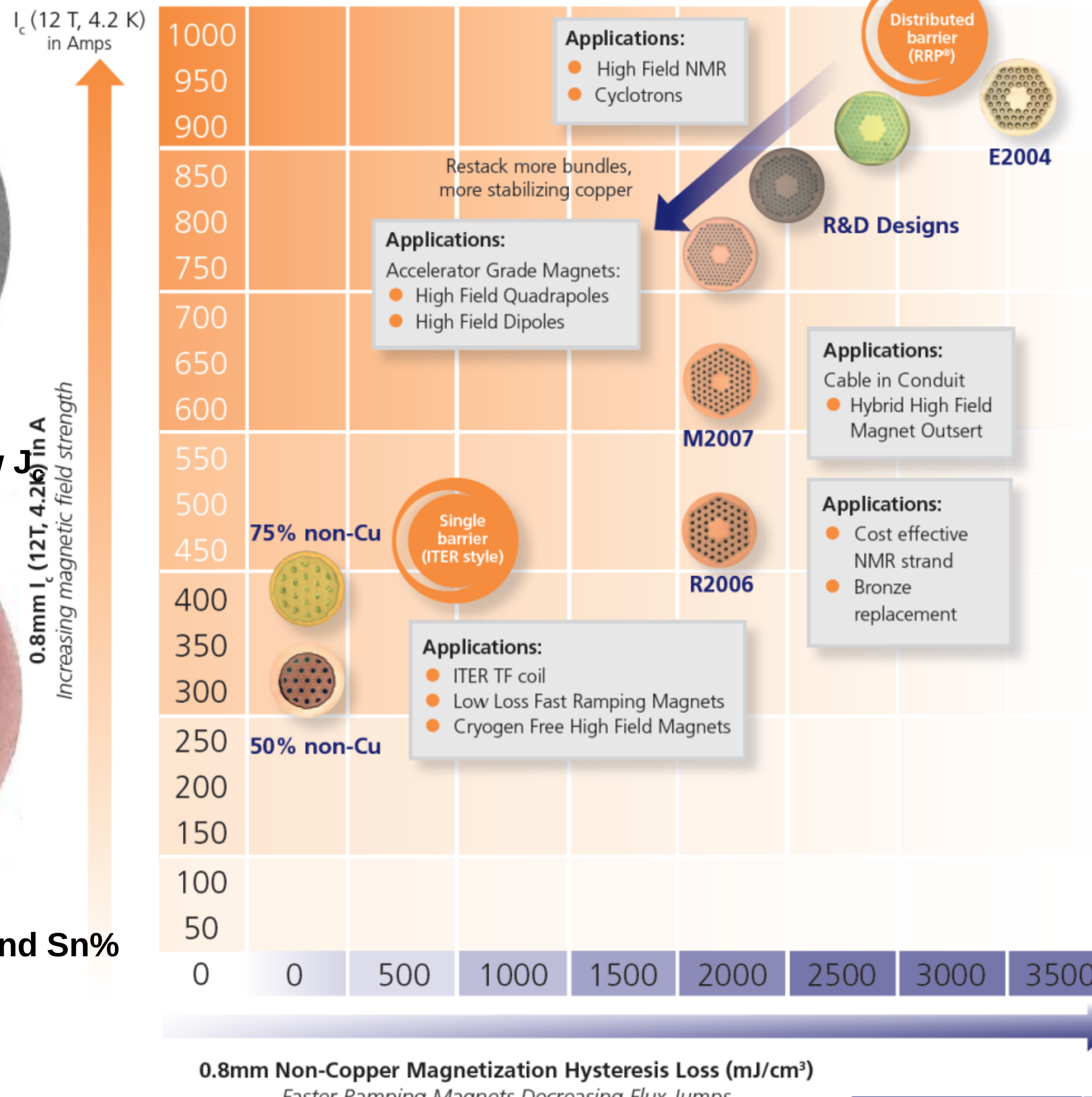
Nb_3Sn is an engineering material



Single Barrier – Discrete filaments, low J$_c$



Distributed Barrier RRP® – high Nb% and Sn%



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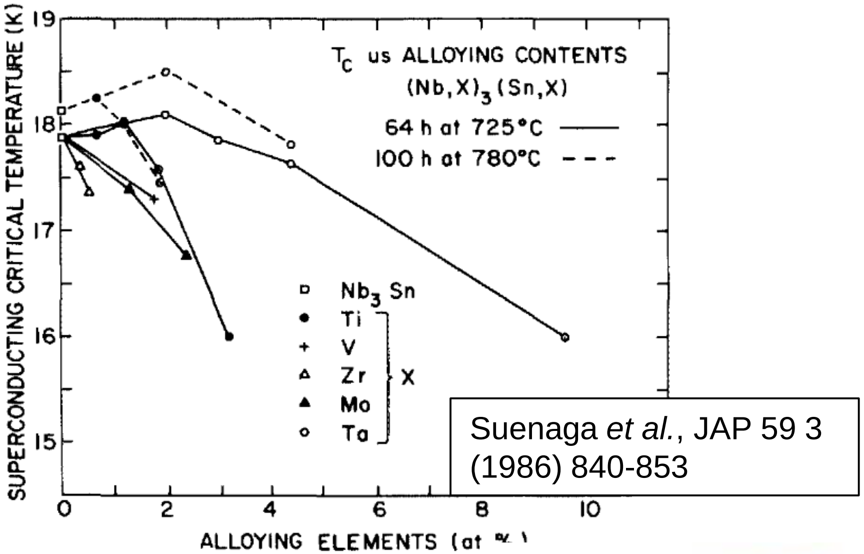
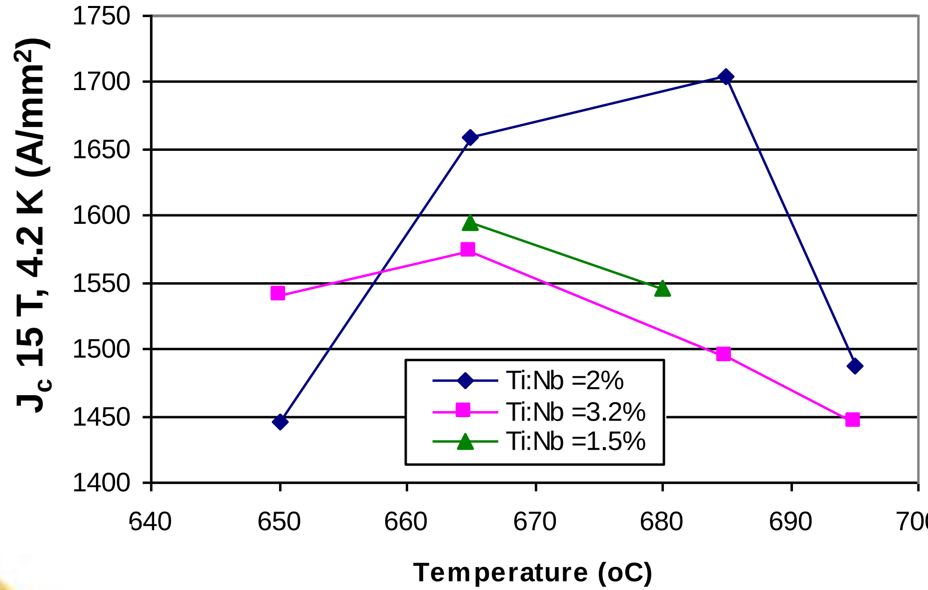
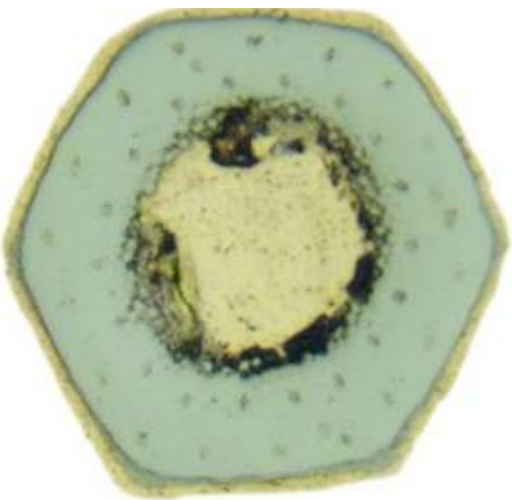
From materials science to actual strands

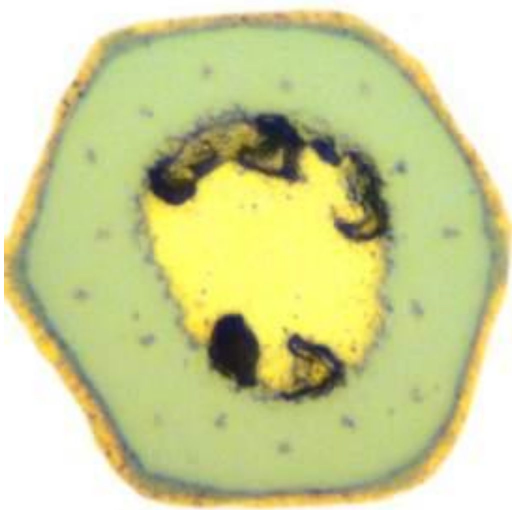


Suenaga *et al.*, JAP 59 3 (1986) 840-853

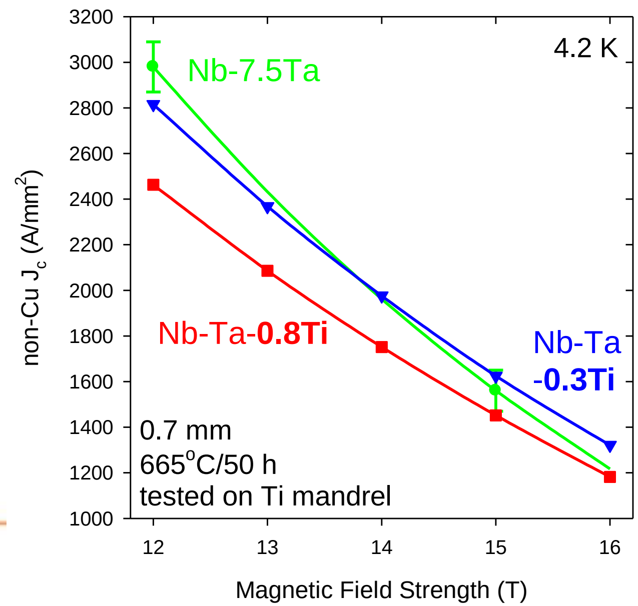




Nb-7.5 Ta-0.8 Ti



Nb-7.5 Ta-0.3 Ti



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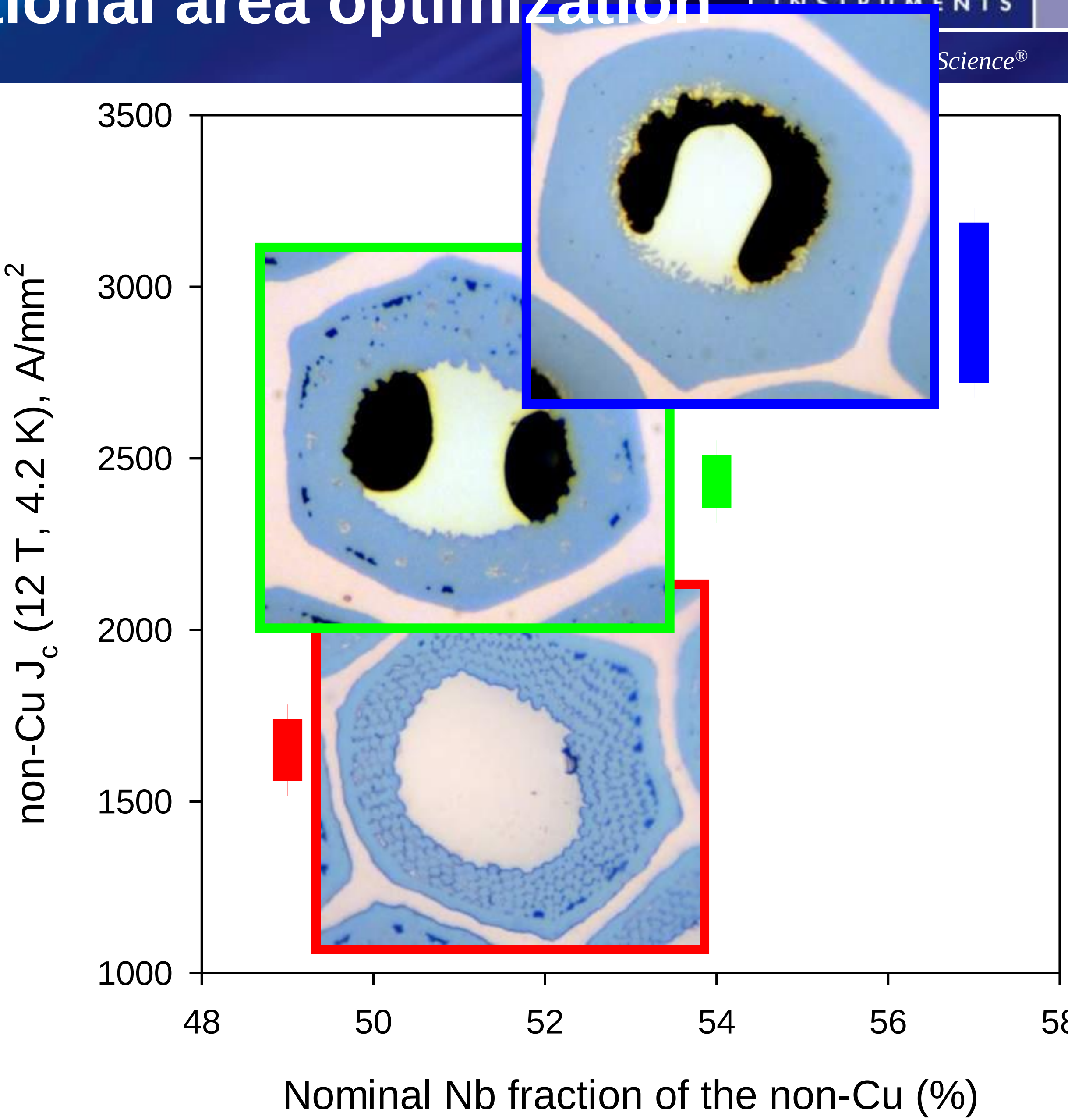
Strand cross sectional area optimization

More Nb =
Less Cu

More Nb
(+Sn) =
More Nb_3Sn

Less Cu +
More Sn =
Better Nb_3Sn



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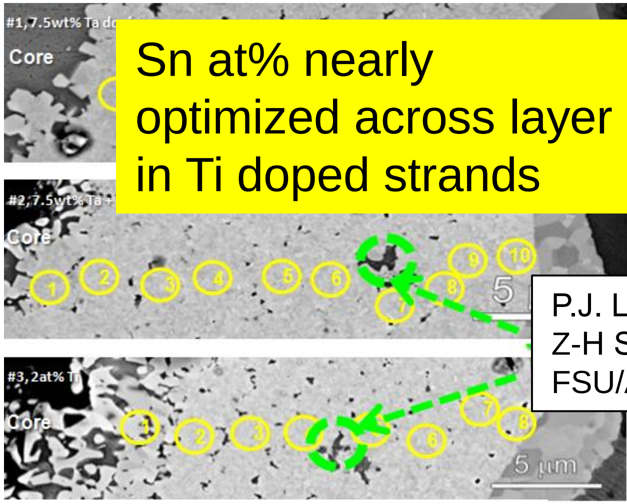
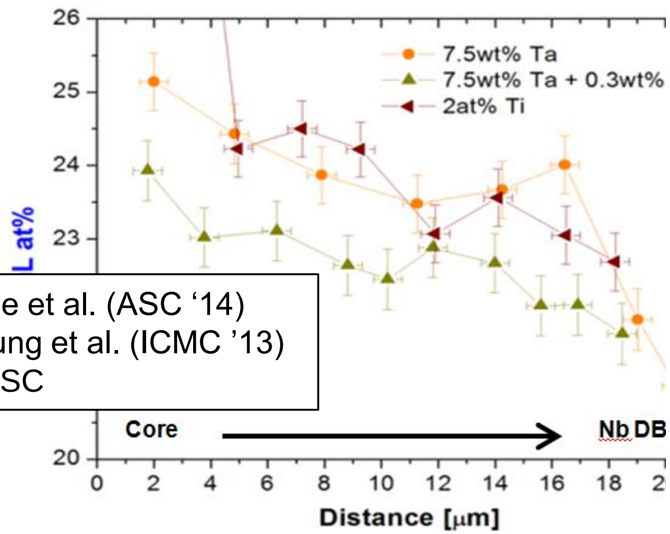
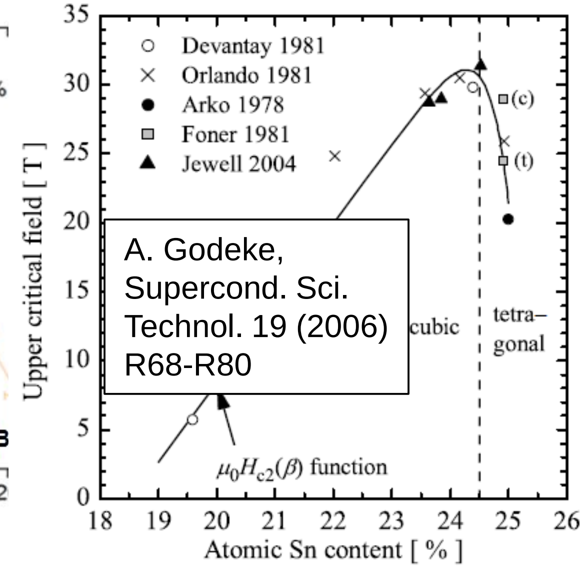
Present strands: J_c already nearly optimized(?)



Sn at% nearly optimized across layer in Ti doped strands



P.J. Lee et al. (ASC '14)
Z-H Sung et al. (ICMC '13)
FSU/ASC

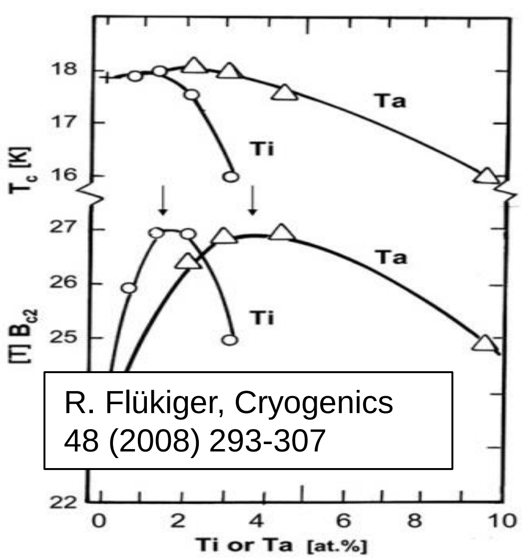


A. Godeke, Supercond. Sci. Technol. 19 (2006) R68-R80

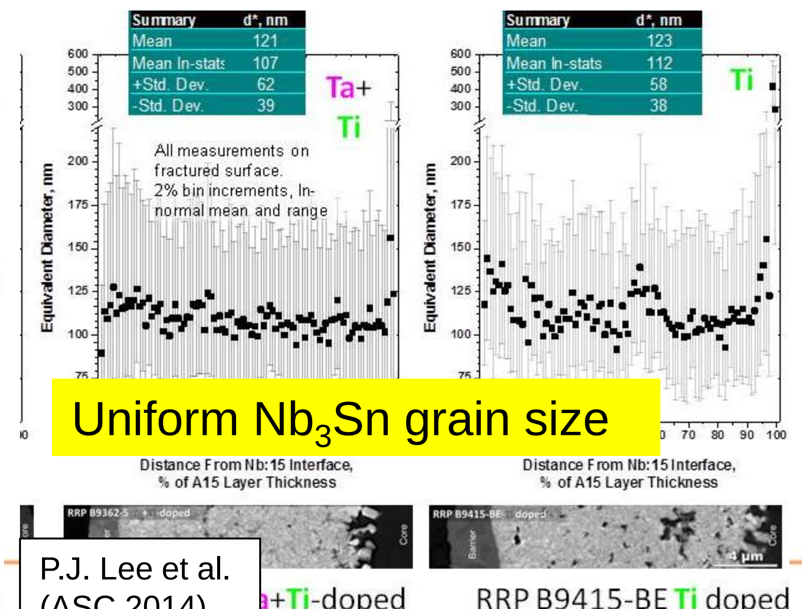
Heat treatment		$T_{c,onset}$	$T_{c,mid}$
Temp (°C)	Time (h)	(K)	(K)
620	192	18.10	16.83
650	96	18.09	17.06
665	50	18.31	17.14
680	48	18.40	17.24
695	48	18.36	17.51
750	96	18.34	17.57

C.Tarantini et al., SuST 27 (2014) 065013

Ti doping close to optimal



R. Flükiger, Cryogenics 48 (2008) 293-307



Uniform Nb_3Sn grain size

P.J. Lee et al. (ASC 2014)

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Target FCC Nb_3Sn strand performance

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Ballarino and Bottura, *IEEE Trans Appl. Supercond.* **25,** (2015).

Property	Units	Target	RRP®	Single barrier
Strand diameter	(mm)	0.5 - 1.0 mm	✓	✓
J_c (4.2 K, 16 T)	(A/mm^2)	≥ 1500	? Need ↑ 25%	✗
Filament size (D_{eff})	(μm)	≤ 20	? Need ↓ 50%	✓
RRR		≥ 150	✓	✓
Unit Length	(km)	≥ 5 km	? 1 billet = 9 km @ 0.85 mm	
Cost (@ 12 T, 4.2 K)	€/kA·m	1/3 of today's costs of approximately €10/kA·m		

- Only distributed barrier strands come close to target J_c
- Internal tin billets are not extruded → limited billet mass, maximum length

Focus on distributed barrier, RRP® strand

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Reducing the effective filament diameter seems to be the largest challenge

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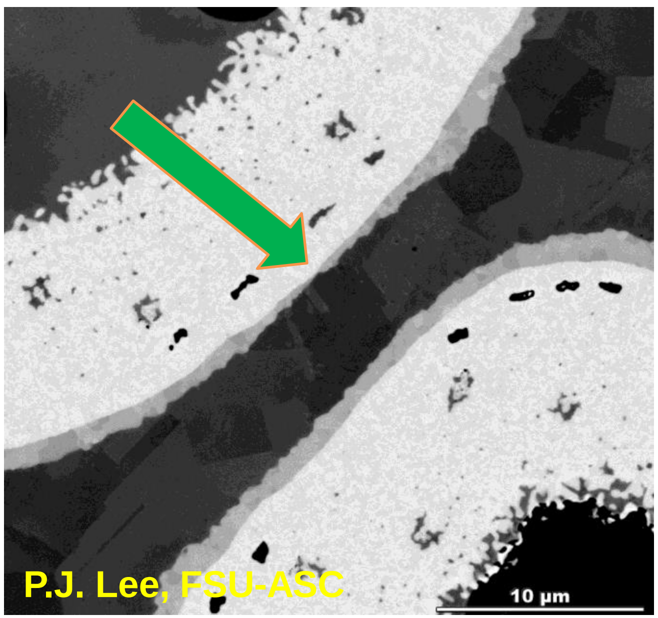
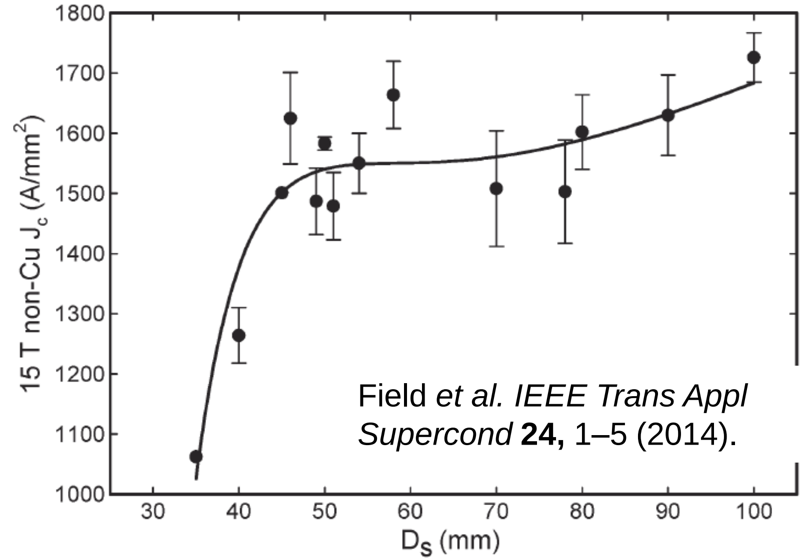
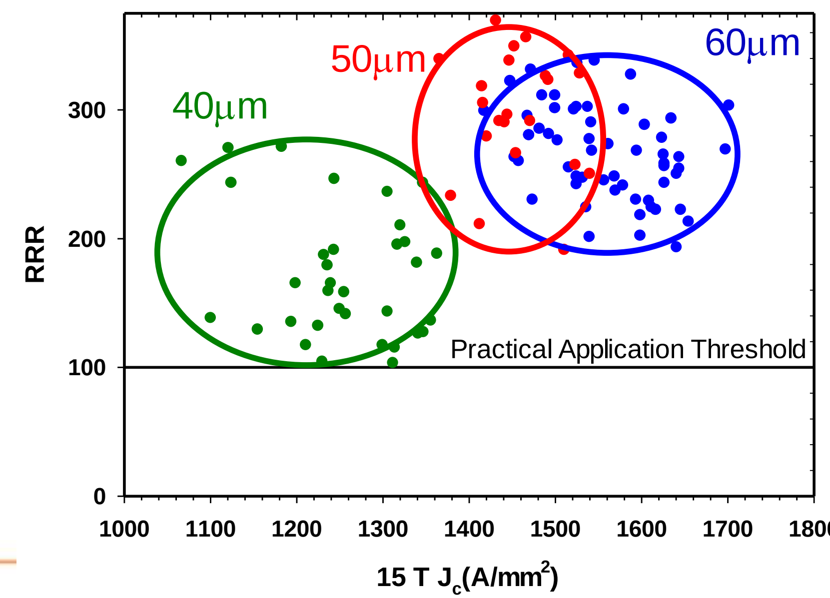
- Means to keep RRR high:
  - Use less Sn
  - Use lower HT temperatures

→ Both result in lower J_c



High J_c, RRR when D_{eff} ~50-60 µm





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Reducing manufacturing variation might get us *close* to the target J_c performance

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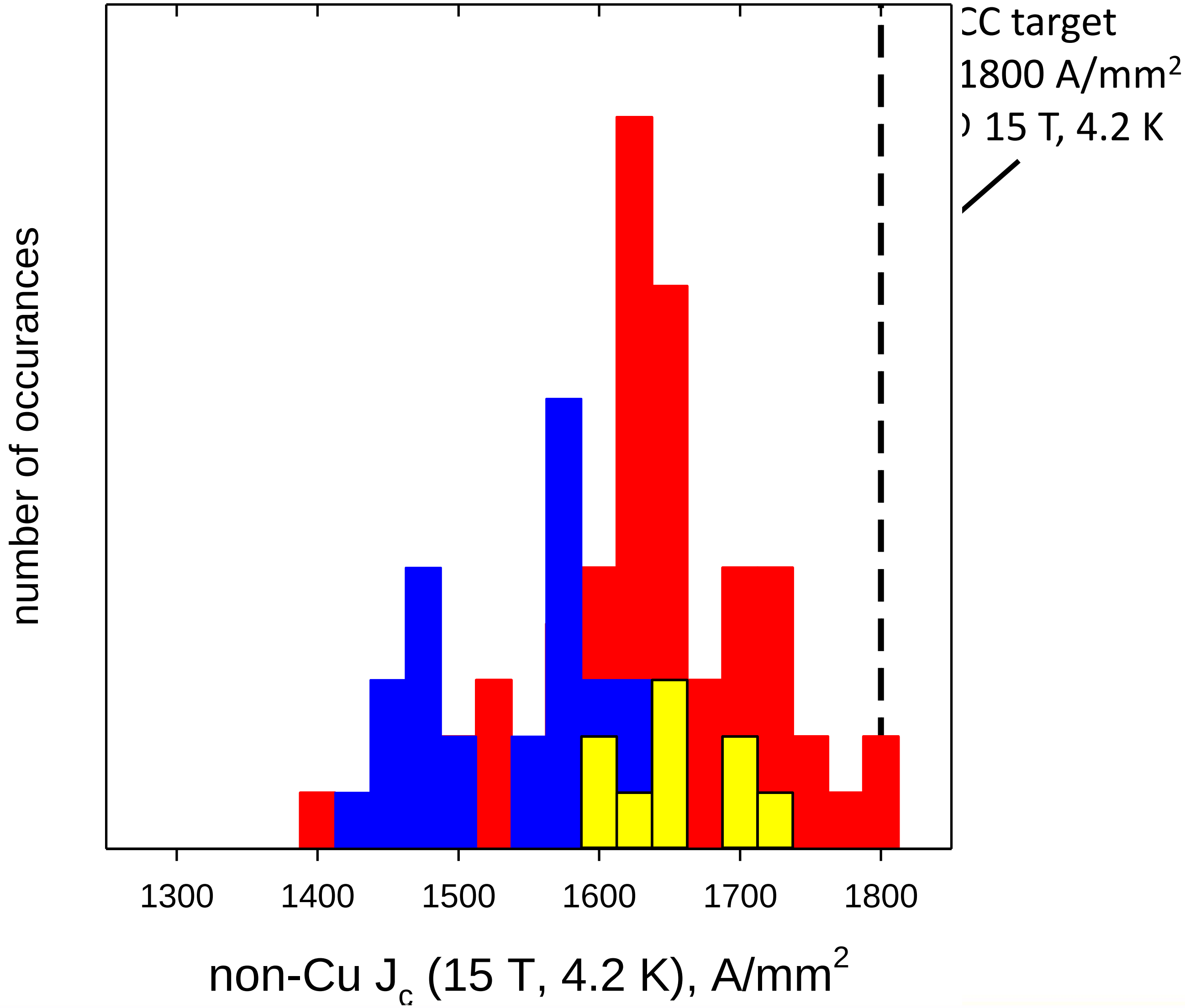
Needed J_c improvement may be modest when:

60 µm D_{eff}

RRR > 100

- Near term R&D work will focus on maximizing J_c when D_{eff} ~60 µm

- Step change may need to come from e.g. artificial pinning centers



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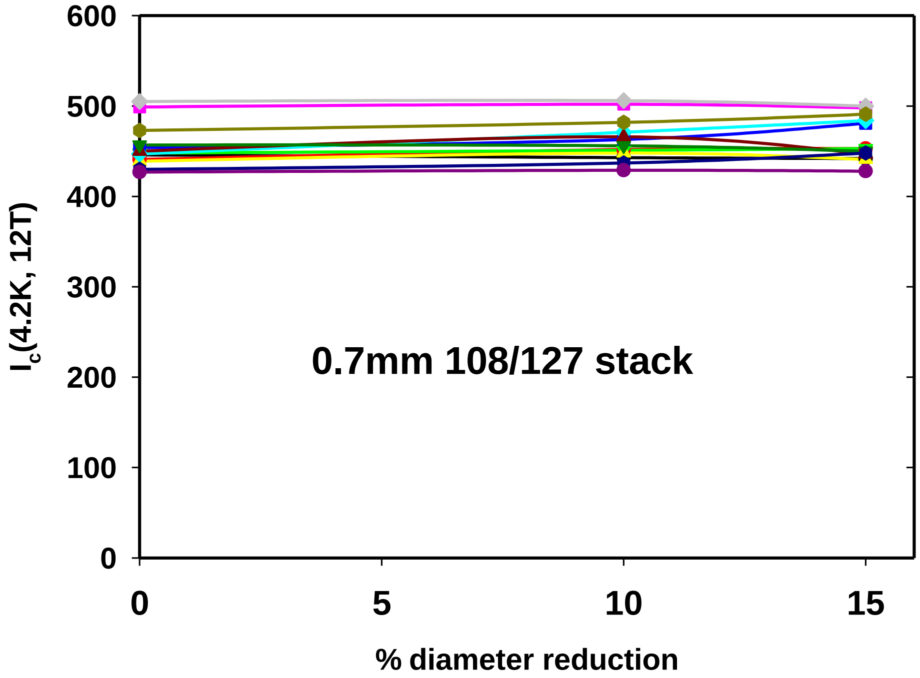
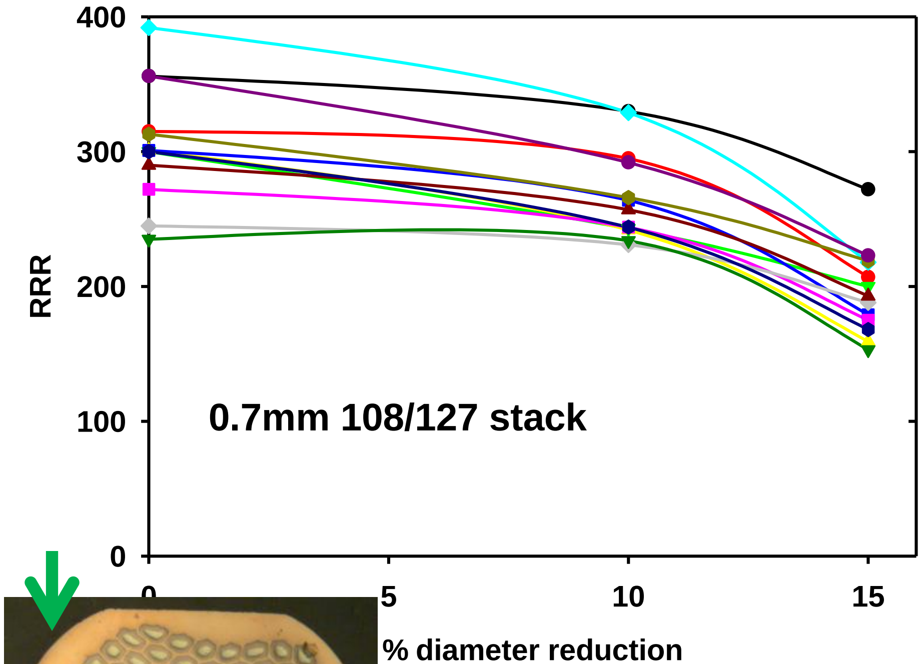
High RRR, J_c maintained after cabling

- I_c values are maintained through >15% rolling

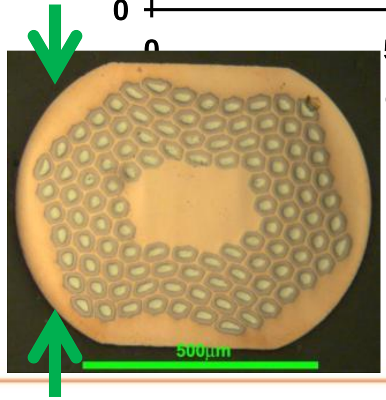


- RRR decreases >10% rolling, but remains >150



RRP® is compatible with Rutherford cabling

15% rolled



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Comparison of Nb-Ti and Nb_3Sn production scale and cost drivers

Parameter	Nb-Ti	Nb_3Sn	Cost challenge
Nb content	18 wt%	26 wt%	Nb is most expensive raw material (Cu:SC 1.3 assumed)
Strand billet size	400 kg	40 kg	Limited Nb_3Sn piece lengths
Billet stacking steps	2	3	↑ Labor and time costs, also yield loss at each step
Ongoing demand (infra-structure)	1000's tons per year	10's tons per year	• LHC was a fraction of annual Nb-Ti market • FCC (6000 tons/5 yrs) would be >50x base Nb_3Sn market

Nb_3Sn market is different from Nb-Ti; FCC demand would dominate

Projecting future costs Nb_3Sn strand

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- Potential cost reduction contributions:
  - + Raw materials: ? Market driven
  - + Incremental Conductor Improvement: ~10% J_c gain
  - + Efficiency gains from scale up of billet sizes
  - + Continued incremental piece length gains

Together these may reduce $/kA-m cost by ~ ⅓

To cut the $/kA-m by ⅔ requires a more significant J_c gain

- Layer J_c increase could yield largest cost benefit- provided conductor fabrication cost is not increased cost elsewhere

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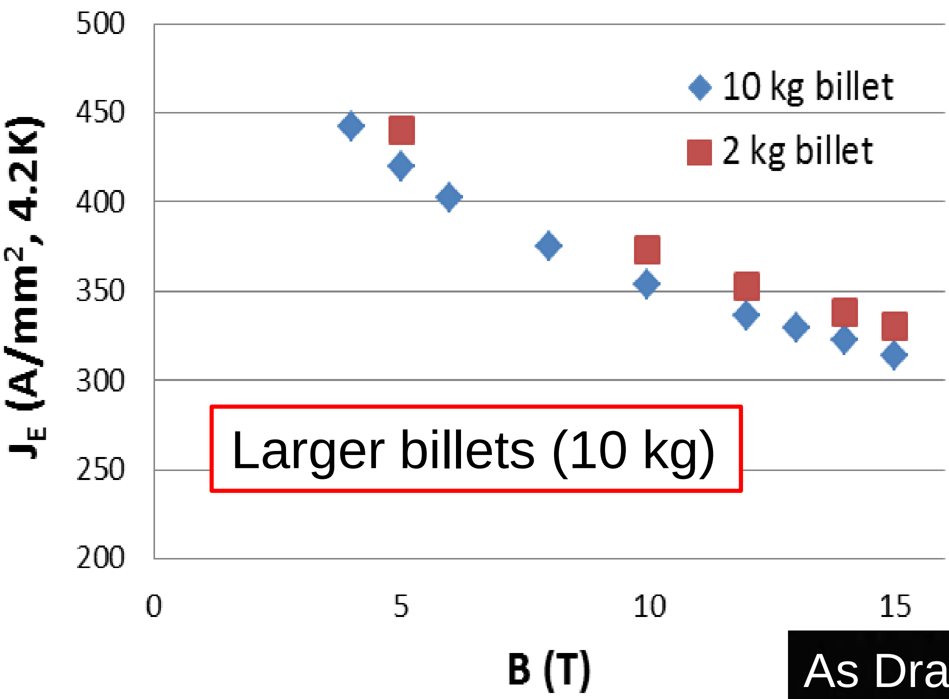
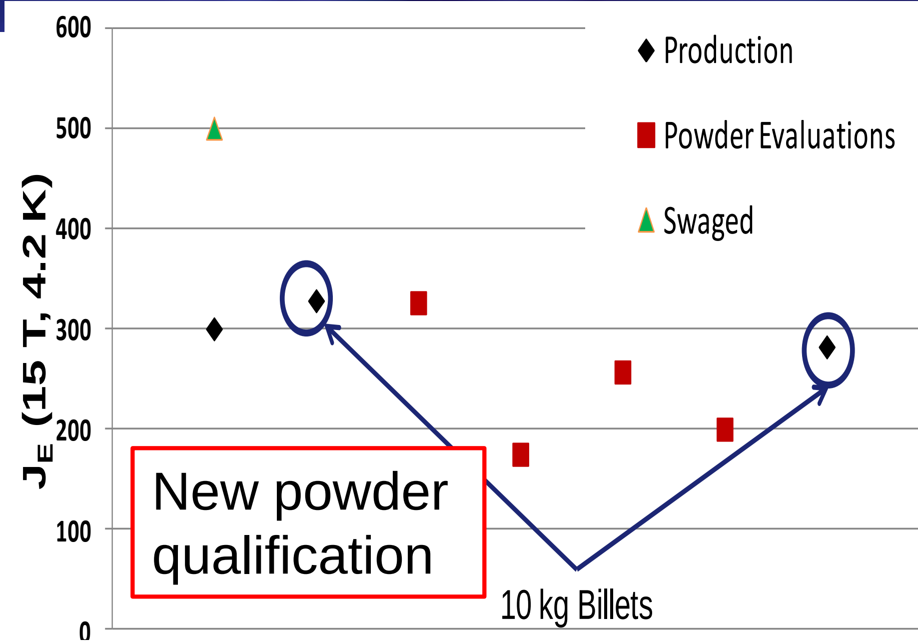
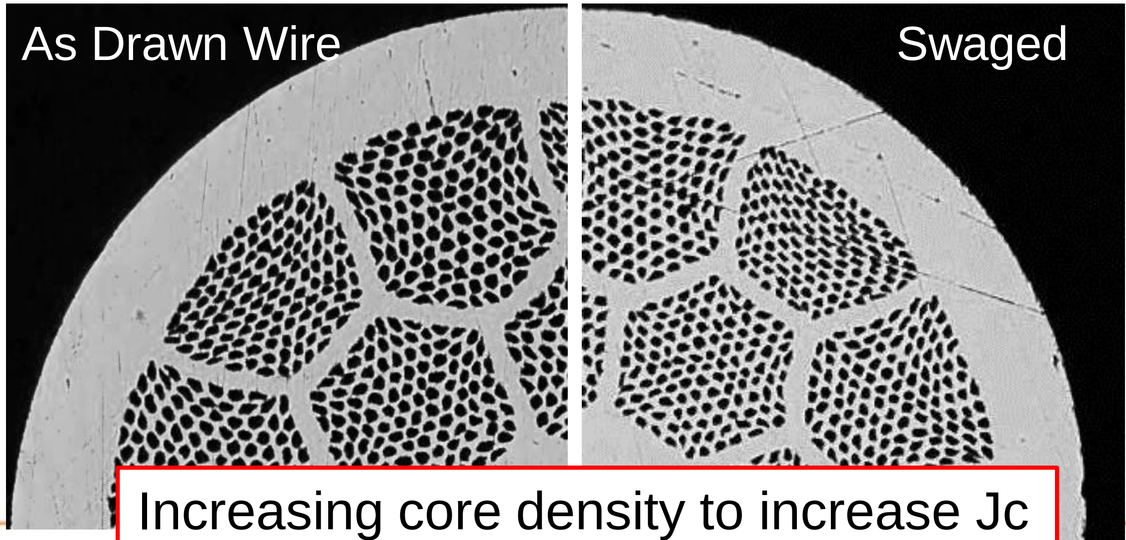
Progress with Bi-2212





- Increasingly consistent properties billet to billet
- J_E (16 T) now about ⅔ that of Nb_3Sn strands



Increasing core density to increase Jc

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Cost: Opportunity in $/kA-m, Not Materials

- Silver
  - No known alternatives, metals market dictates price
  - 2212 fill factor limited to ~30% (already achieved)
- Powders
  - Significant overhead costs dominate today
  - Modest annual volumes do not drive cost reductions
- Production Scale Comparisons:

	Bi-2212	Internal Tin (w/o ITER)	Internal Tin (For ITER)	Nb-Ti (MRI)
Approximate Billet Mass (kg)	10	30	60	400
Approximate Annual Market (tons)	0.01	10's	100's	1000's

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Summary

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- (J_c– RRR –D_{eff}) of today's Nb_3Sn is well optimized
- FCC requirements stretch beyond the state of the art
  - Target J_c & RRR are "close" for D_{eff} ~60 µm
  - Basic R&D again required for Nb_3Sn layer J_c breakthrough
  - HEP-specific development requires sustained HEP "pull"
- And then, there's cost…
  - Scale up can help reduce cost, *if demand is consistent*
  - Nb_3Sn is not Nb-Ti; FCC would <u>be</u> the market
- Opportunities
  - R&D today supports conductor in production 2025-2030
  - Layer J_c breakthrough (for free!) may solve cost challenge

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