Essential Features of LARP Strands and Prospects for Still Better High-Field Superconductors

Lance Cooley

Condensed Matter Physics and Materials Science Department

BROOKHAVEN NATIONAL LABORATORY

Outline

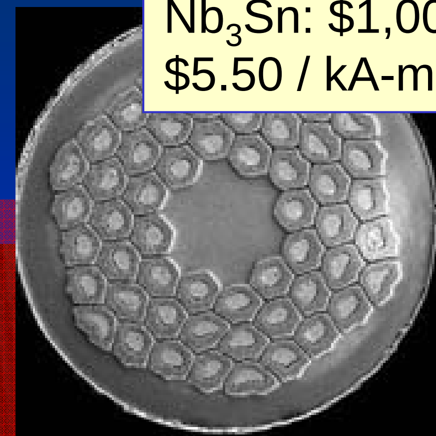
- Factors that limit performance of superconductors
- Nb_3Sn: Why has RRP* emerged over bronze-route, MJR†, and PIT‡ as the LARP strand process?
  - – Maximizing current density
  - – Overcoming limitations imposed by gradients of the tin content
  - – Managing stability
- Is further improvement of Nb_3Sn possible?
- If not, what's next? Clues from emerging areas in superconducting materials for HEP

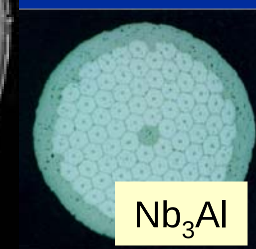
* Restacked Rod Process™ † Modified jelly-roll process
‡ Powder-in-tube process

Our portfolio of long-length superconductors

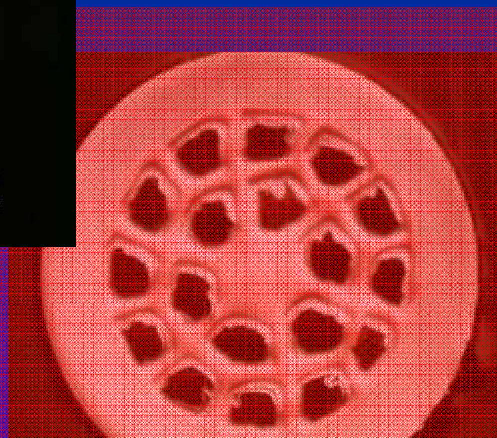
Nb-Ti: $150/kg, 60¢/m,
$1.50/kA-m @8T,2K

Nb_3Sn: $1,000/kg, $4/m
$5.50 / kA-m @ 12T, 4K

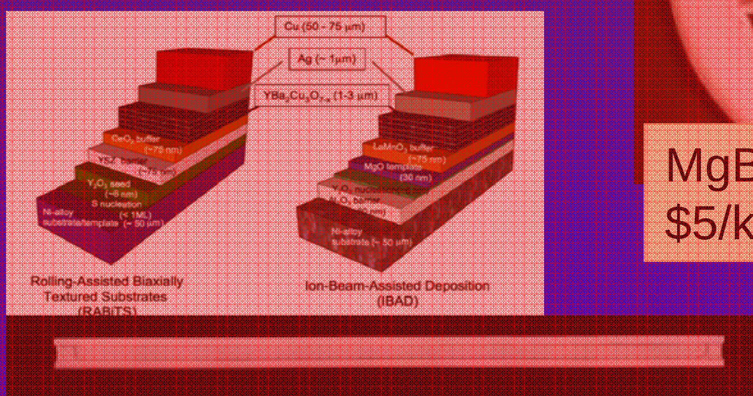




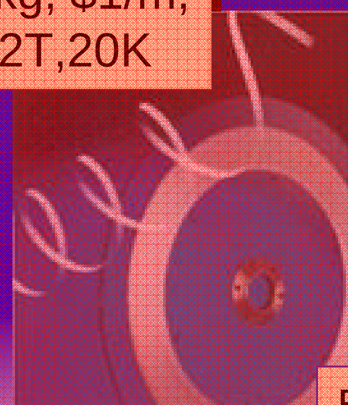
Nb_3Al



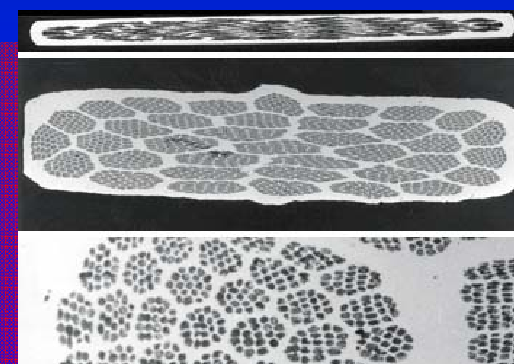
MgB_2: $50/kg, $1/m,
$5/kA-m @2T,20K



YBCO ("2G"): >$100/m,
>$400/kA-m @ 20T, 4K



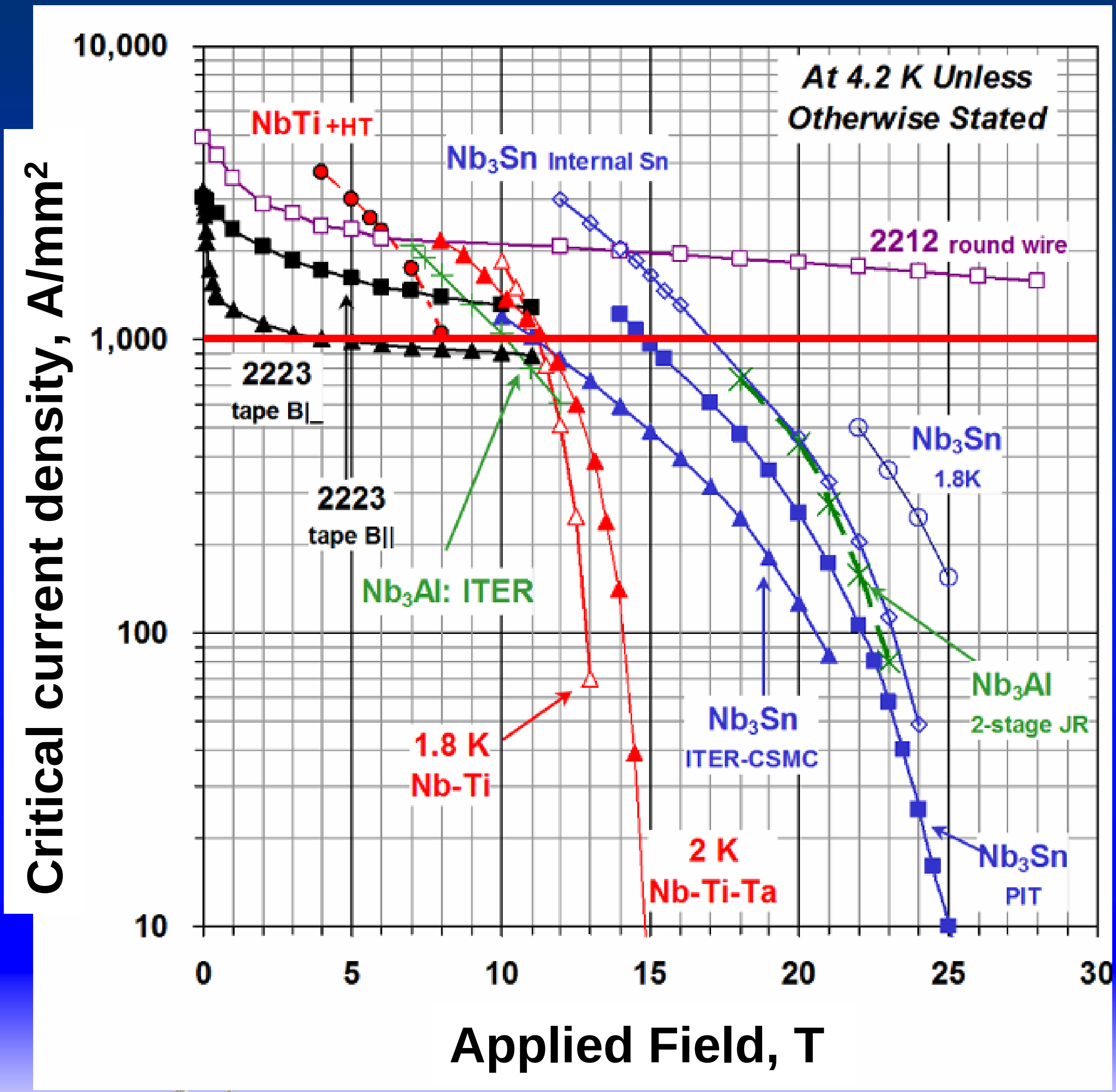
Bi-2223 ("1G")



Bi-2212: $3,000/kg,
>$10/m, >$50/kA-m
@20T, 4K

BROOKHAVEN NATIONAL LABORATORY

Long-length Superconductor Performance



- J_c, J_c, J_c …
- Plot shows J_c over wire area that is not stabilizer or support
- Highest non-copper area fractions:
  - Nb-Ti ~65%
  - Nb_3Sn ~55%*
  - Bi-2212 ~35%
  - Bi-2223 ~35%
  - MgB_2 ~35%
  - YBCO ~1%
  - * Includes Sn and Cu used to convert Nb to Nb_3Sn. Nb_3Sn itself is ~35% of wire area

Plot by Peter Lee http://magnet.fsu.edu/~lee/

BROOKHAVEN NATIONAL LABORATORY

Performance has limits at multiple levels

- >100,000 A/mm^2 : Depairing current limit (T_c and λ_L)

Cumulative losses that limit current density in practical forms

- Material & physics factors
  - Flux pinning at high fields: 90 to >99% lost
  - Material anisotropy: large losses in ⊥ applied fields and at high T
- Factors related to forming the superconductor
  - Diffusion barriers: 2 to 10%
  - Materials needed to form the superconducting phase: 0 to >90%
  - Obstacles and grain connections: 0 to >90%
- Engineering factors
  - Strain, mechanical degradation: 0 to 20% lost
  - Stabilization, mechanical support: 30 to 60% lost

Example: Effects of cumulative limitations on LHC magnet strands

Nb-Ti LHC strand

- $J_D \approx$ 150,000 A/mm^2
- Flux pinning: 97% lost @ 8T, 2K
- Diffusion barrier: 4% lost
- Copper: 50% lost
- Manufacturing: 25% lost
- Total current density in strand: 150,000 x 0.03 x 0.96 x 0.5 x 0.75 $\approx$ 1,600 A/mm^2

Nb_3Sn LARP strand

- $J_D \approx$ 400,000 A/mm^2
- Flux pinning: 98% lost 12T, 4.2K
- Nb-Sn reaction: 30% lost
- Diffusion barrier: 10%
- Bronze (or copper + tin) & manufacturing: 40%
- Copper: 50%
- Total current density in strand: 400,000 x 0.02 x 0.7 x 0.9 x 0.6 x 0.5 $\approx$ 1,500 A/mm^2

Lessons from these analyses

1. The superconductor area must be maximized.
   - The superconductor often is formed during a later reaction.

2. Manufacturing losses should be minimized.
   - Must make long continuous pieces.
   - Must also control shape distortions and other geometric factors.
   - Pure metals have the most ductility!
   - Except for Nb-Ti, high-field superconductors are brittle.

3. All processing must serve the optimization of flux pinning.
   a. The superconducting properties must be as good as possible.
   b. The defect nanostructure must be preserved.

   Note: (a) and (b) often produce conflicting processing requirements!

Outline

- Factors that limit performance of superconductors
- Nb_3Sn: Why has RRP* has emerged over bronze-route, MJR†, and PIT‡ as the LARP strand process?
  - Maximizing current density
  - Overcoming limitations imposed by gradients of the tin content
  - Managing stability
- Is further improvement of Nb_3Sn possible?
- If not, what's next? Clues from emerging areas in superconducting materials for HEP

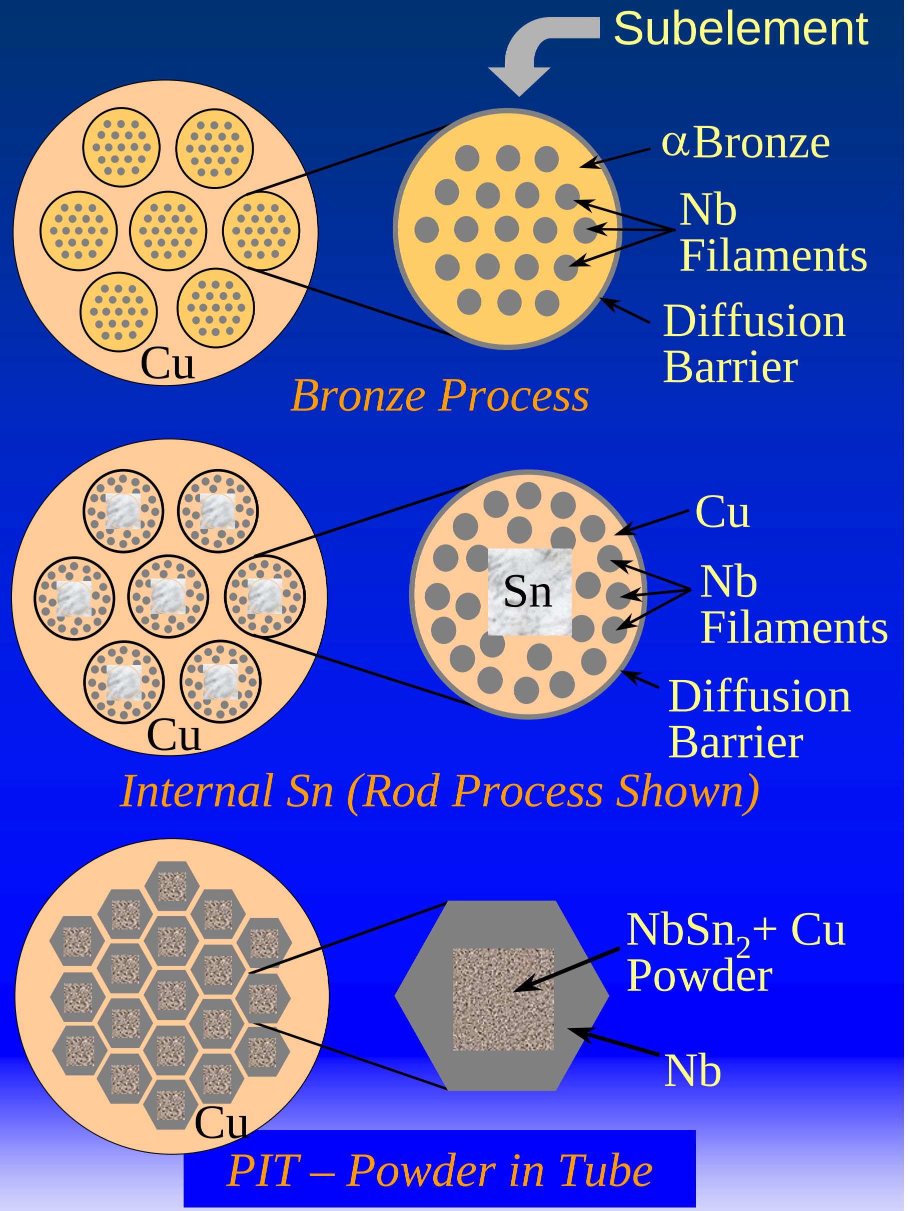
* Restacked Rod Process™ † Modified jelly-roll process
‡ Powder-in-tube process

BROOKHAVEN NATIONAL LABORATORY

Solid State Routes to Nb-Sn Wires

Schematic by Mike Naus

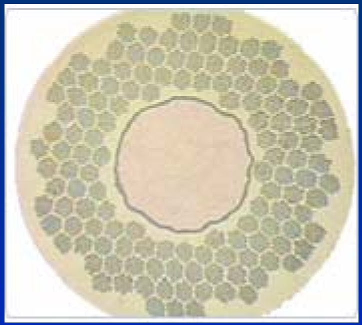
- Bronze route
  - Alpha bronze is ductile, but must be annealed often
  - 1-10 µm Nb filaments possible
- Internal Sn conductors
  - Start from Cu, Sn, Nb alloy
  - Components are more ductile than bronze, but pure Sn limits processing temperature
- Powder in Tube (PIT)
  - $NbSn_2$ inside Nb tubes

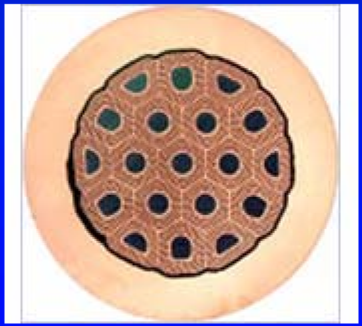


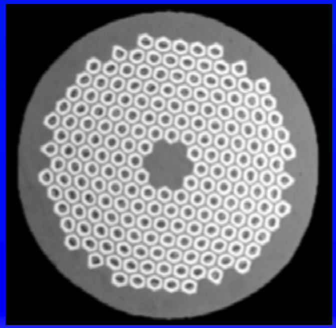
BROOKHAVEN NATIONAL LABORATORY

Nb_3Sn state of the art, c.1998 VLHC workshop

- Bronze-route: ~1,000 A/mm^2 available in long length at >$15 per kA-m
- Modified Jelly-Roll (MJR) internal-tin composite: >1,500 A/mm^2 available in long length at ~$10 / kA-m
- ITER-style internal tin composite modified for >1,500 A/mm^2
- New player: Powder-in-tube







Photos courtesy of Jeff Parrell and Chad Fischer

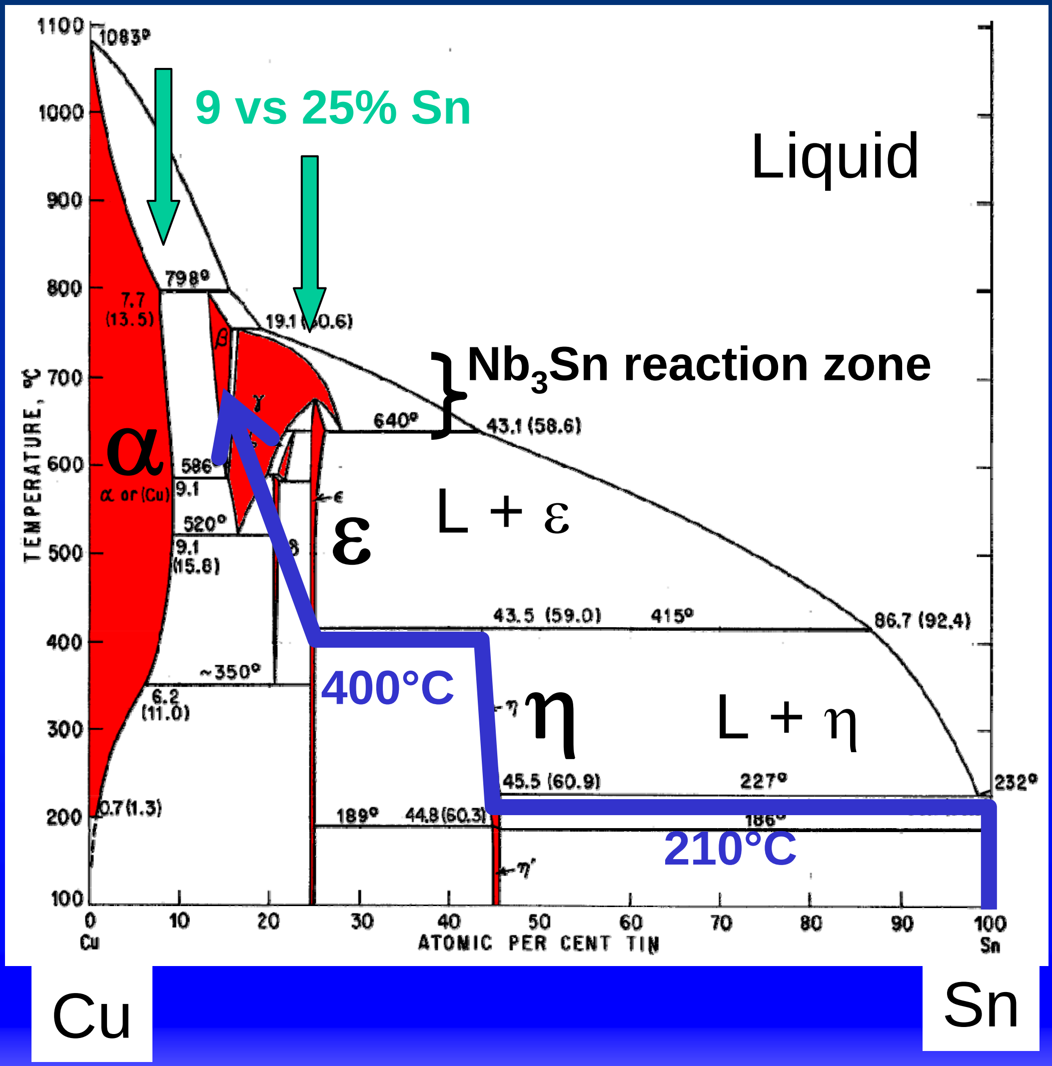
BROOKHAVEN NATIONAL LABORATORY

HEP specifications for VLHC (and LARP) strand

- Nb_3Sn
- J_c = 3,000 A/mm^2 (non-Cu) @ 12 T, 4.2 K
- Total HT time < 200 hrs
- Effective filament diameter (d_{eff}) < 40 µm
- Average piece length > 10 km at 0.3 to 1.0 mm diameter
- Cost less than $1.50 / kA-m @ 12 T, 4.2 K

Consequences of Cu-Sn Phase Diagram

- Internal tin routes provide more tin than bronze route
  - Improved tin activity
  - Faster reactions
  - Less wire area required to supply tin atoms
- Reaction strategy avoids melting

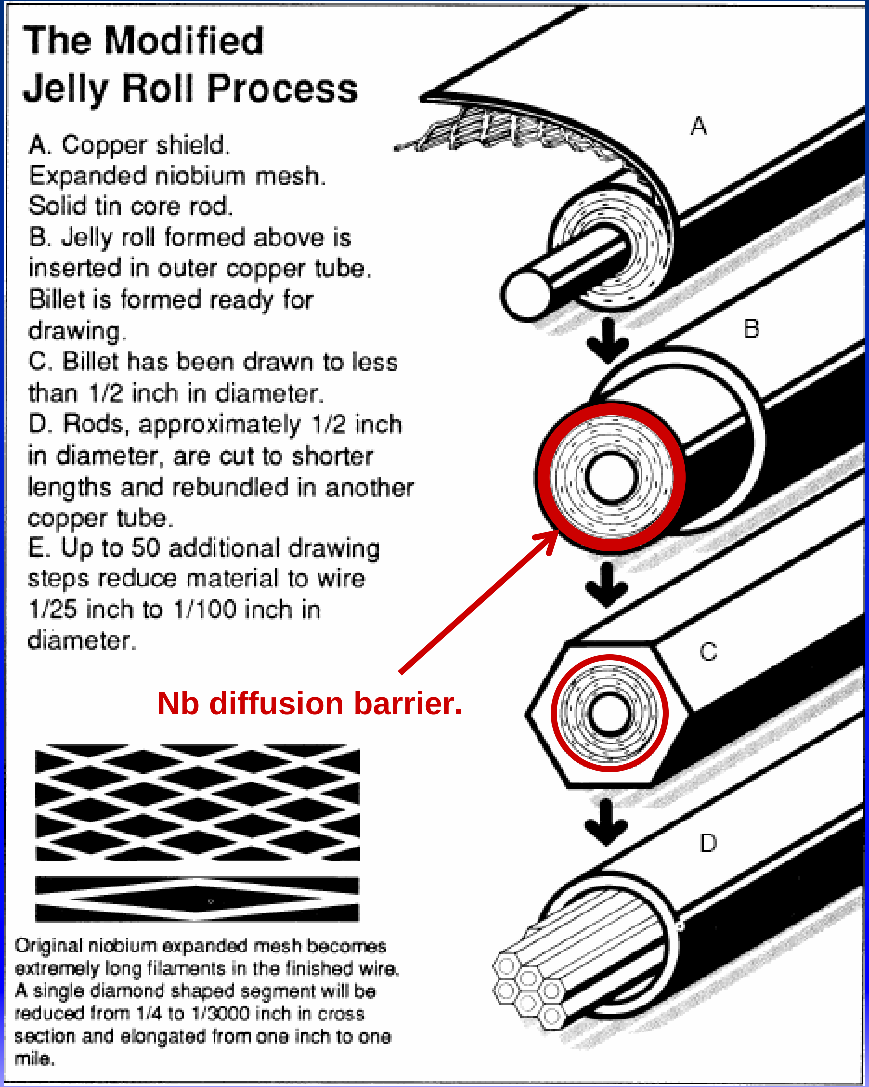


From Hansen “Phase diagrams of binary alloys”

Initial response fell short …

- Subelement redesigned: less Cu, more Nb
- More tin added
- Filaments allowed to merge (so $d_{eff} = d_{sub}$)
- Diffusion barrier reacted about halfway through

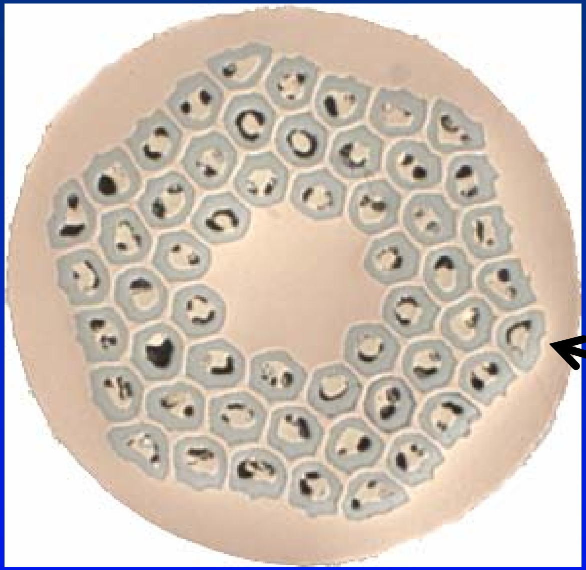
- Result: 2,000 to 2,200 A/mm^2, slightly higher cost (but same \$/kA-m)
- Redesign needed ⇒ RRP



BROOKHAVEN NATIONAL LABORATORY

The LARP strand: Re-stacked Rod Process RRP™

Subelement combines materials with like surfaces (Cu), results in good bonding and long piece length



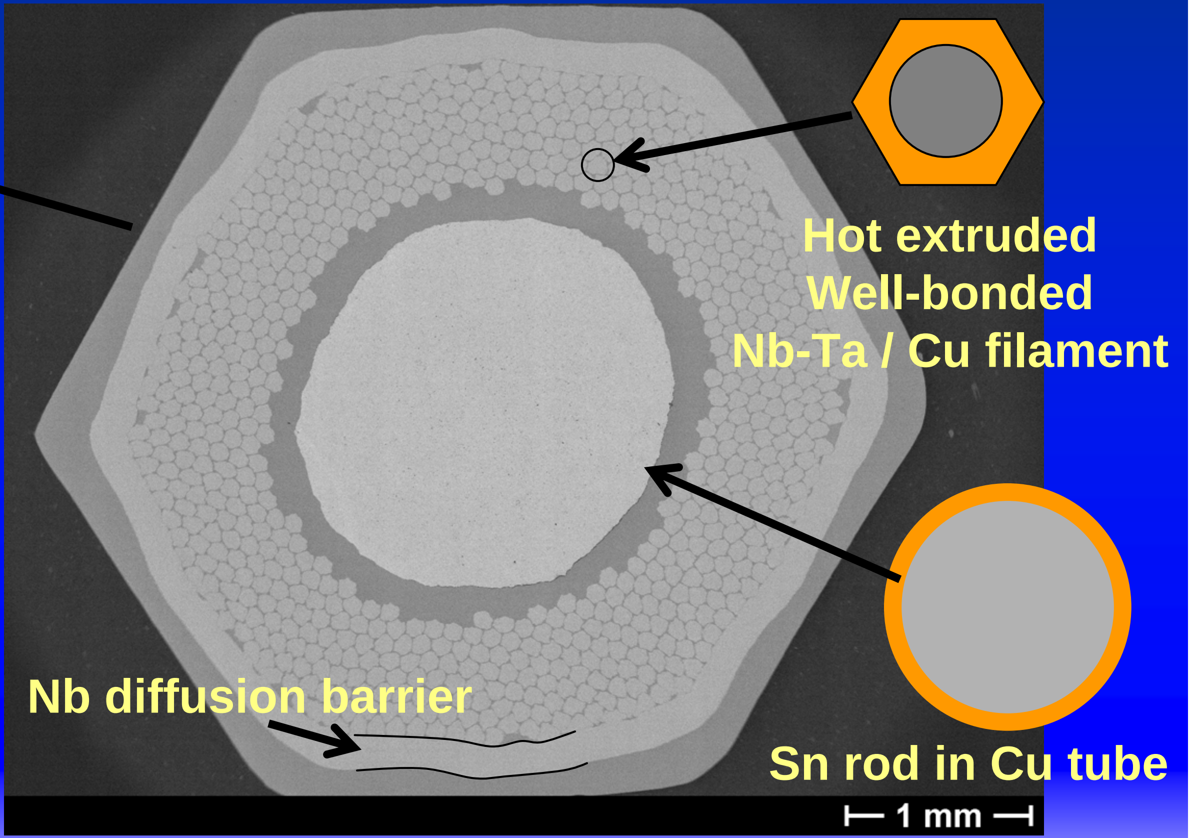
$Nb_{0.73}Ta_{0.02}Sn_{0.25}$

RRP 8220

54 subelements of 61

Cu ~ 48%

d_s ~ 69 μm @ 0.7 mm Ø

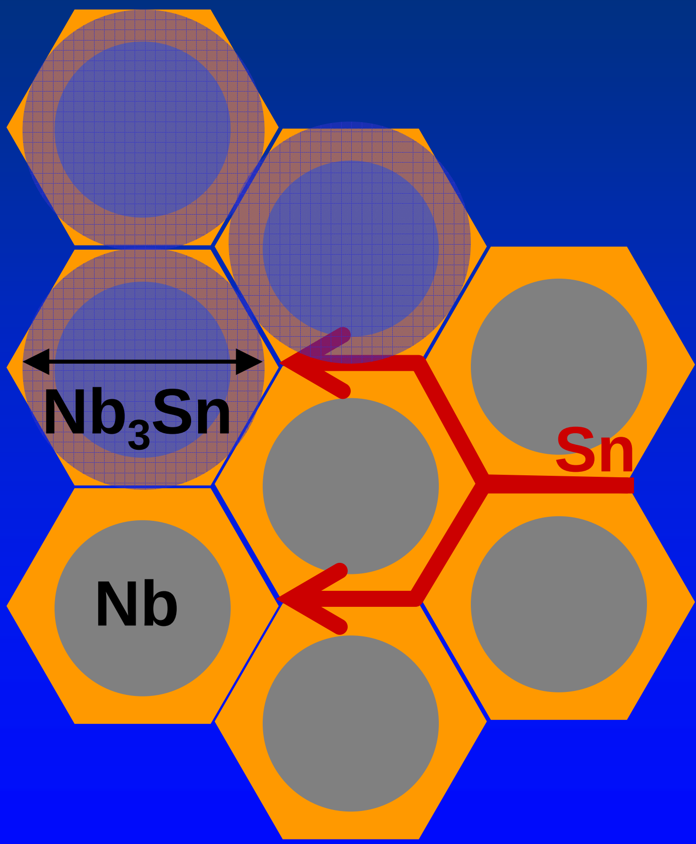


RRP strand gets closer to HEP goals

- Max J_c ~ 3100 A/mm^2 at 12 T, 4.2 K
- Piece lengths are many kilometers
- Cost $5.50 / kA-m at 12 T, 4.2 K
- Total reaction time typically 160 hrs
  - 48 h @210°C + 48 h @400°C + 48 h @665°C, with ramp @50°C/h
- Effective filament diameter d_{eff} ~ 70 µm for 54/61 stack
  - Further progress discussed shortly

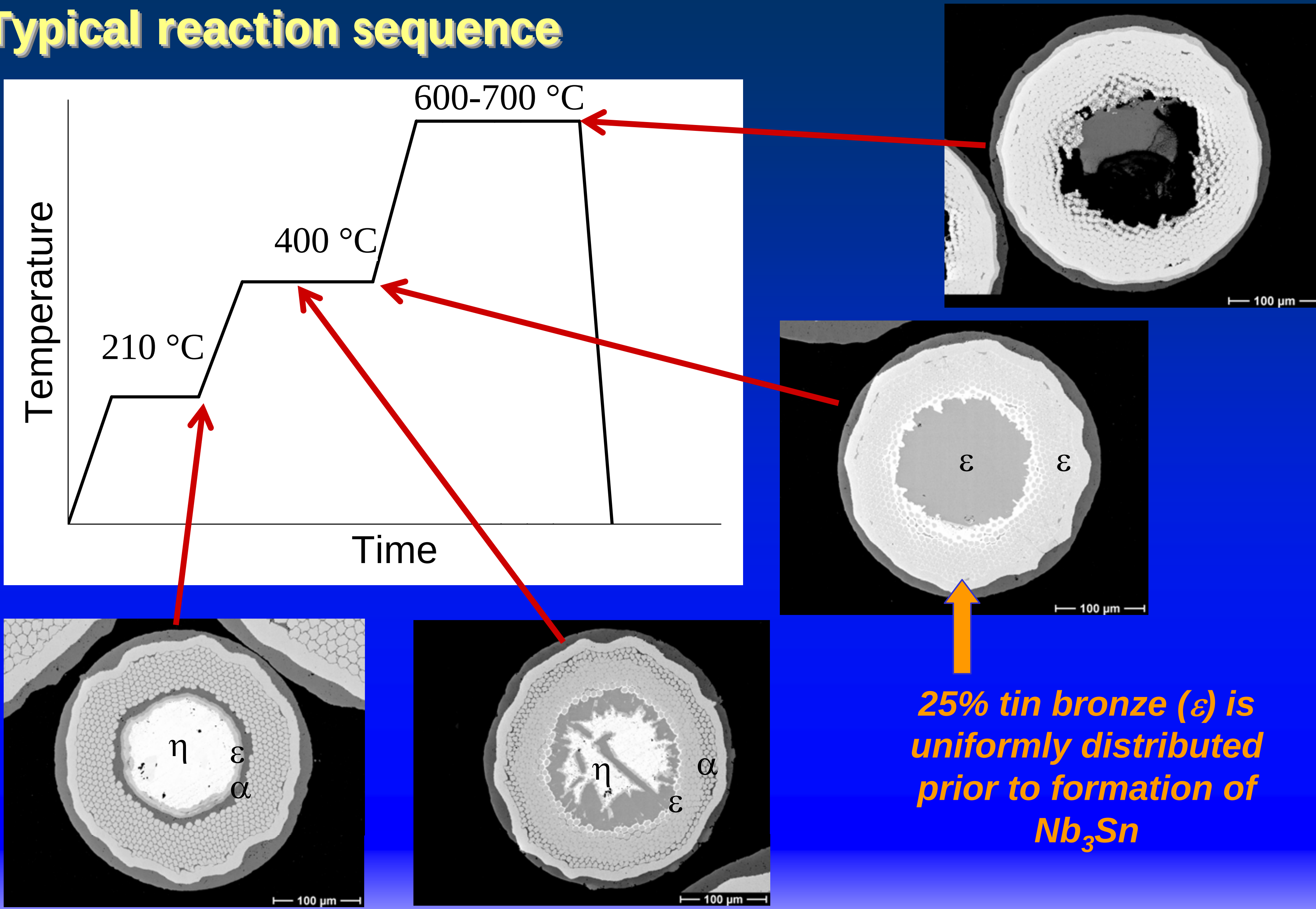
RRP is the engineering strand we need for LARP R&D!!

RRP provides optimum control over Cu:Nb Local Area Ratio (LAR)



- Lower LAR: more Nb_3Sn is possible if tin can get to Nb
- Higher LAR: wider diffusion pathways for tin
- Shape control reduces pinch-off as filaments grow and gives better balance of opposed trends above
  - Nb increases area by 37% upon conversion to Nb_3Sn

Typical reaction sequence



25% tin bronze (ε) is uniformly distributed prior to formation of Nb_3Sn

Microscopy by Seth Hynes, M.S. 2003 Wisconsin

RRP addressed critical current lessons

1. The superconductor area must be maximized.
   - The superconductor often is formed during a later reaction.

✓

2. Manufacturing losses should be minimized.
   - Must make long continuous pieces.
   - Must also control shape distortions and other geometric factors.
   - Pure metals have the most ductility!
   - Except for Nb-Ti, high-field superconductors are brittle.

✓

3. All processing must serve the optimization of flux pinning.
   - erconducting properties must be as good as possible.
   - ct nanostructure must be preserved.

   Note: (a) and (b) often produce conflicting processing requirements!

Next…

BROOKHAVEN NATIONAL LABORATORY

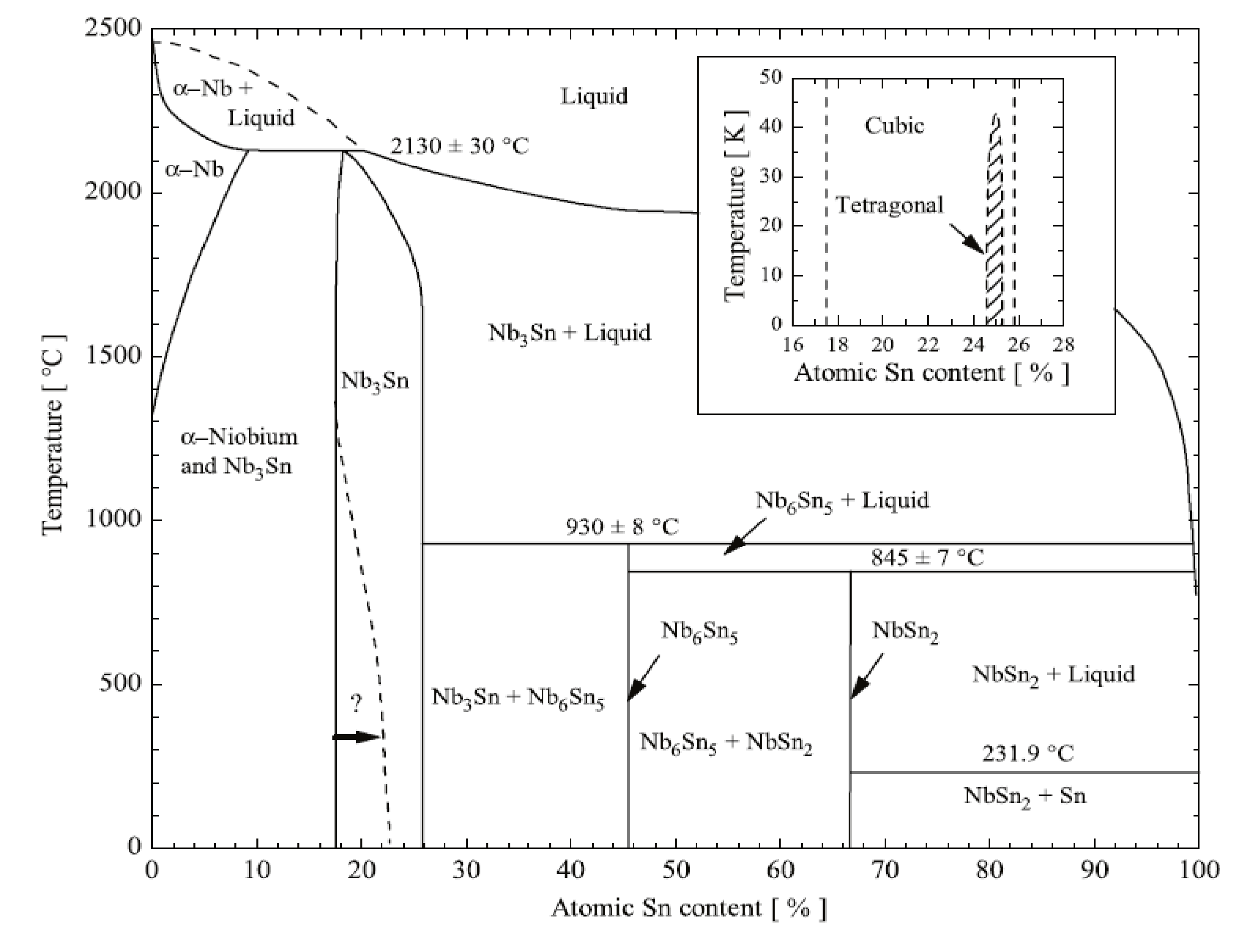
Outline

- Factors that limit performance of superconductors
- Nb_3Sn: Why has RRP* has emerged over bronze-route, MJR†, and PIT‡ as the LARP strand process?
  - Maximizing current density
  - Overcoming limitations imposed by gradients of the tin content
  - Managing stability
- Is further improvement of Nb_3Sn possible?
- If not, what's next? Clues from emerging areas in superconducting materials for HEP

* Restacked Rod Process™ † Modified jelly-roll process
‡ Powder-in-tube process

Consequences of Nb-Sn phase diagram

- The desired Nb_3Sn phase exists from 18 to 25.5% Sn
- Thermo: Any solid-state reaction MUST produce a variation of %Sn across the SC layer
- Must have high kinetics: Variations in %Sn then occur steeply across small regions

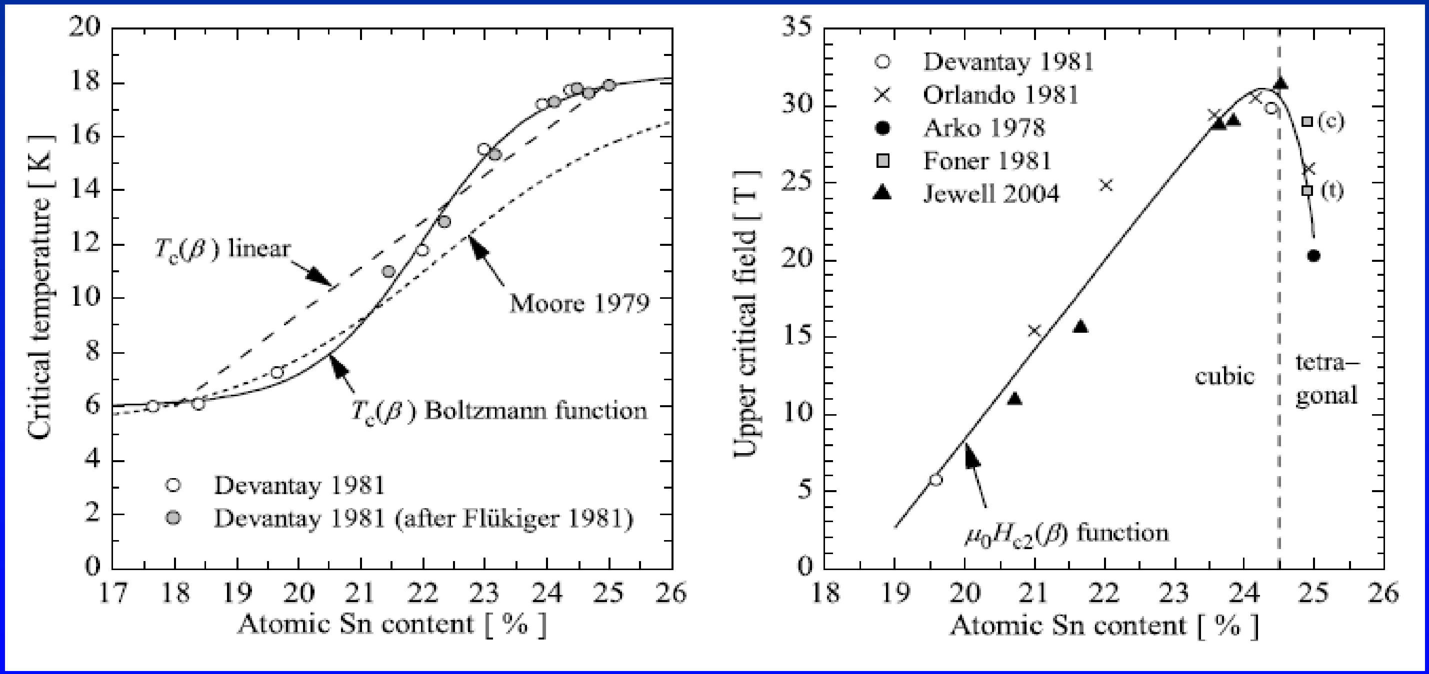


A. Godeke, Supercond. Sci. Technol. 19 (2006) R68–R80

BROOKHAVEN NATIONAL LABORATORY

Composition variation leads to property variation

- More tin = better superconductor
- What are the consequences for strands?



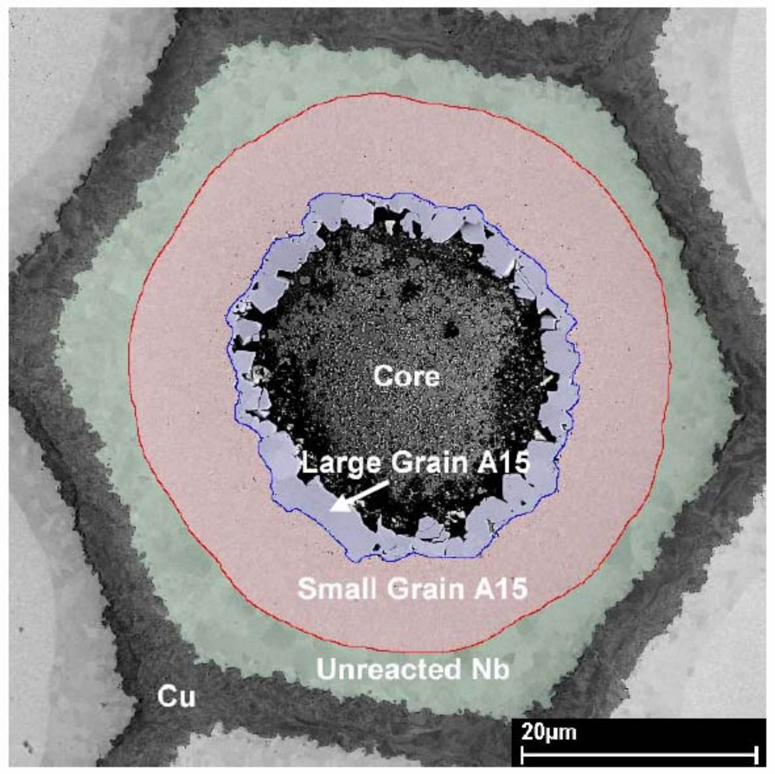
Critical Temperature

Upper Critical Field
(unalloyed)

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

BROOKHAVEN NATIONAL LABORATORY

PIT Nb_3Sn wires are a model system to study Sn gradients

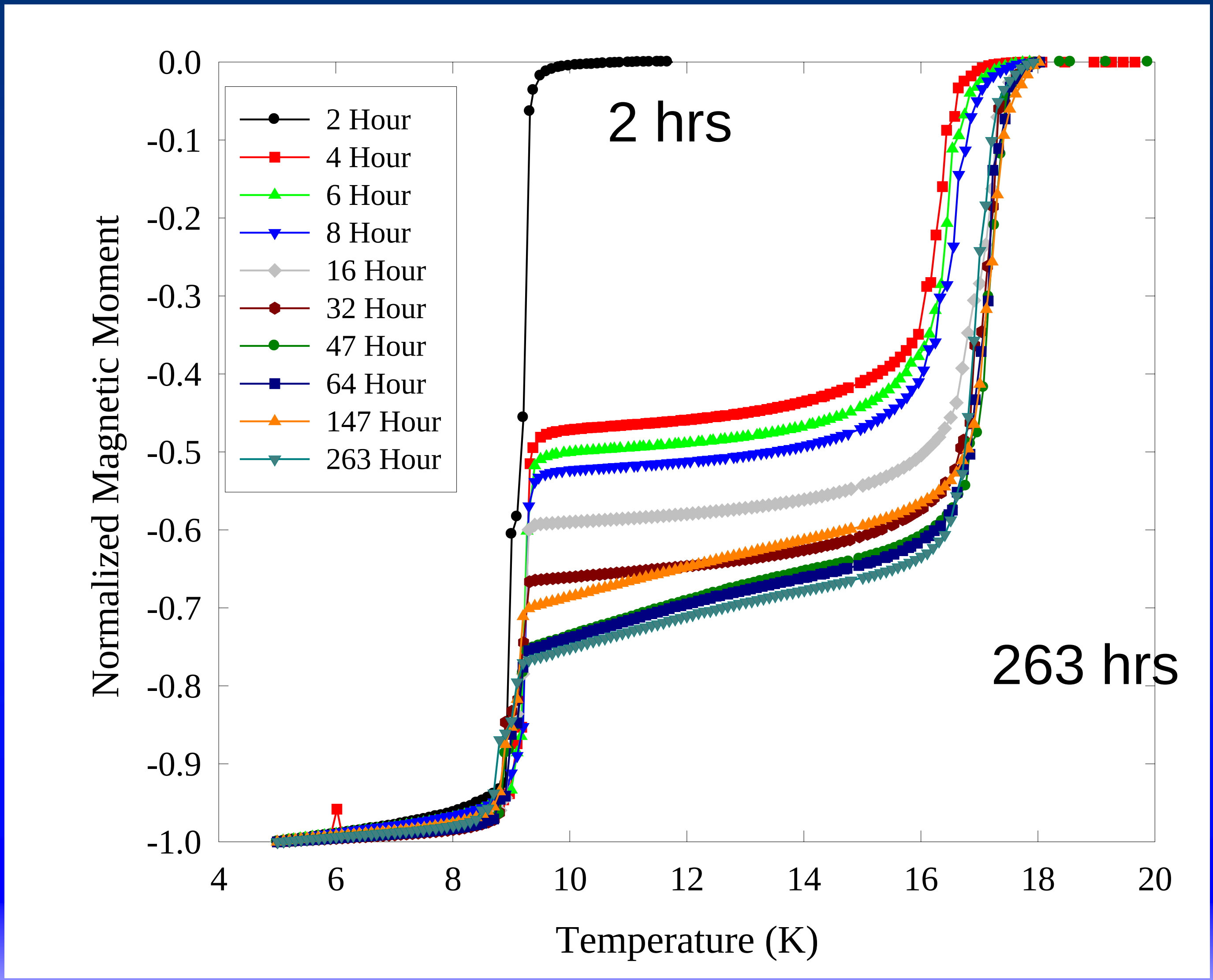


Lowest %Sn is on outside
$\Rightarrow$ transparent to magnetic probes!

- PIT is RRP in the limit of no copper (LAR = 0)
- Tin diffuses radially outward
- A new morphology forms: large grains near core
  - Large grains have poor flux pinning and do not contribute to current-carrying area

Strands courtesy Jan Lindenhoevius, SMI
Photos courtesy Chad Fischer (M.S. Thesis, Wisconsin 2002) and Peter Lee (see magnet.fsu.edu/~lee)

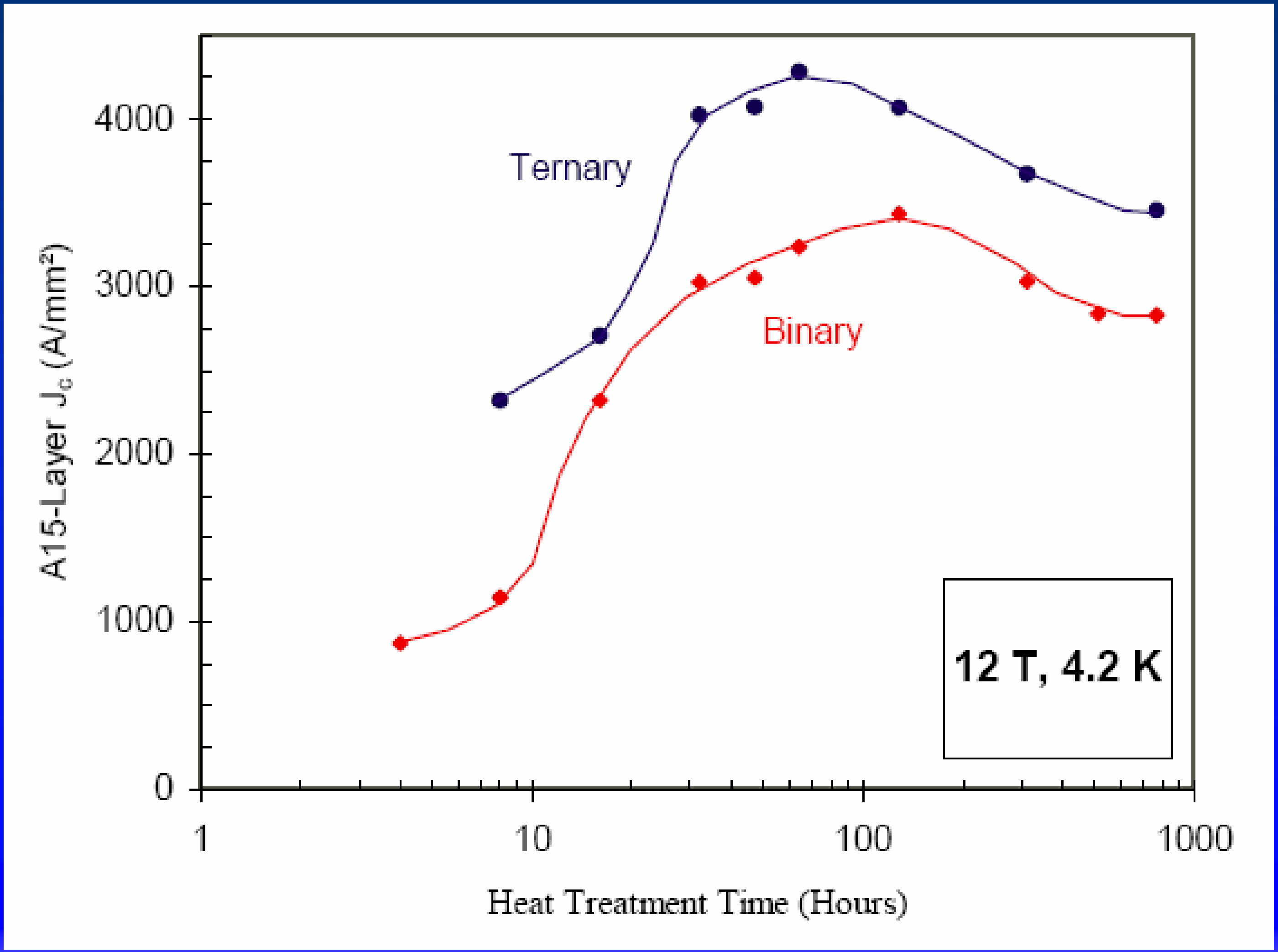
Longer time @ 675°C: more Nb_3Sn, higher Tc



Chris Hawes et al, SuST (EUCAS invited) 2006

BROOKHAVEN NATIONAL LABORATORY

Longer time @ 675°C: flux pinning peaks, drops



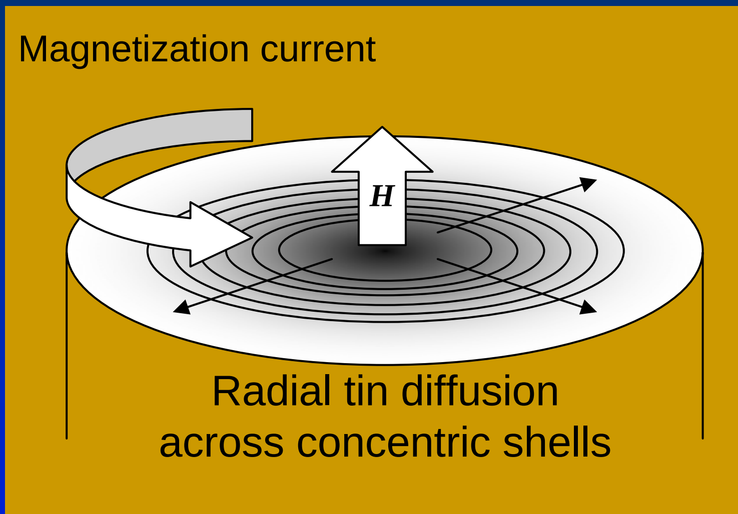
Chad Fischer M.S. 2002 Wisconsin

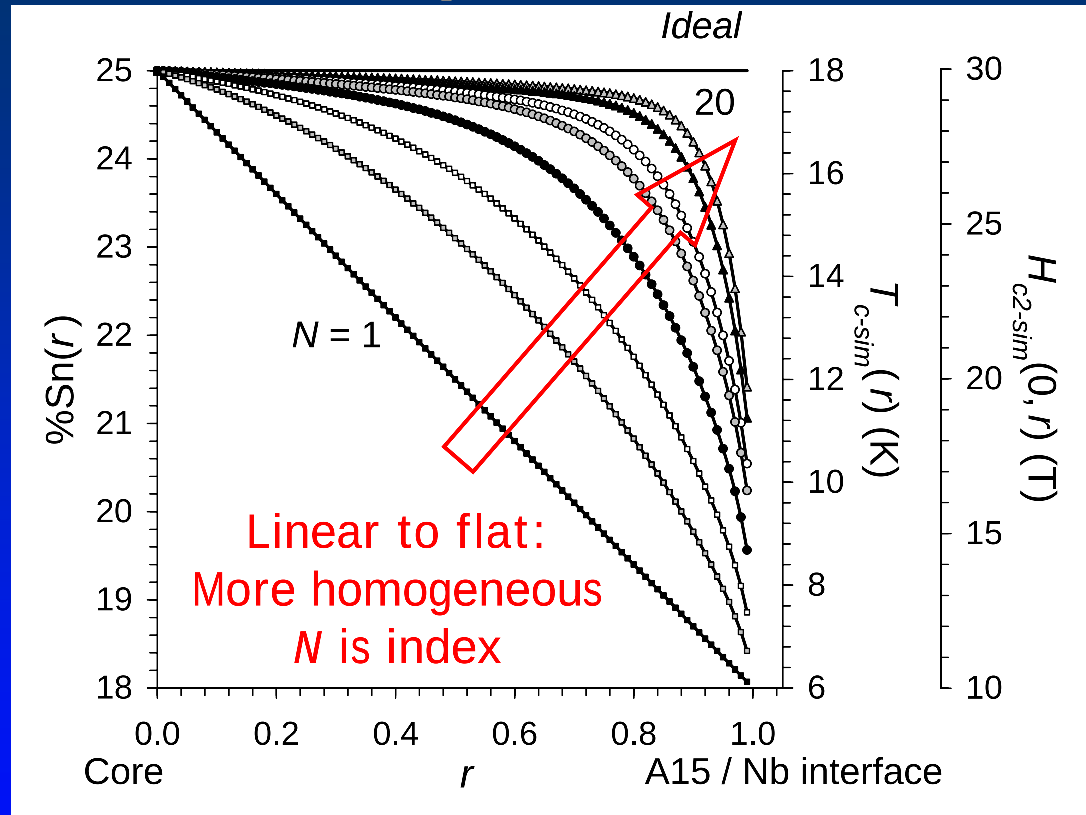
PIT Lesson 1: Optimization of performance is complex!

- Longer time @ temperature, or higher temperature at fixed time...
  - ... Produces more superconductor
  - ... Produces higher T_c and B_{c2}, which increase flux pinning
  - ... Eventually produces larger grains, which reduces flux pinning and the J_c of the Nb_3Sn layer
- Overall $J_c(T,H) = J_c$ layer × amount of Nb_3Sn
- Mapping of optimum time / temperature matrix can be different for each wire
  - Tight geometry control is needed for reproducible HT recipe

BROOKHAVEN NATIONAL LABORATORY

Simulated tin gradients in PIT Nb_3Sn wires





- Divide %Sn(r) profile into 100 points
  - *Concentric shells of magnetization current*
- From %Sn(r) get $T_c(r)$, $H_{c2}(0,r)$

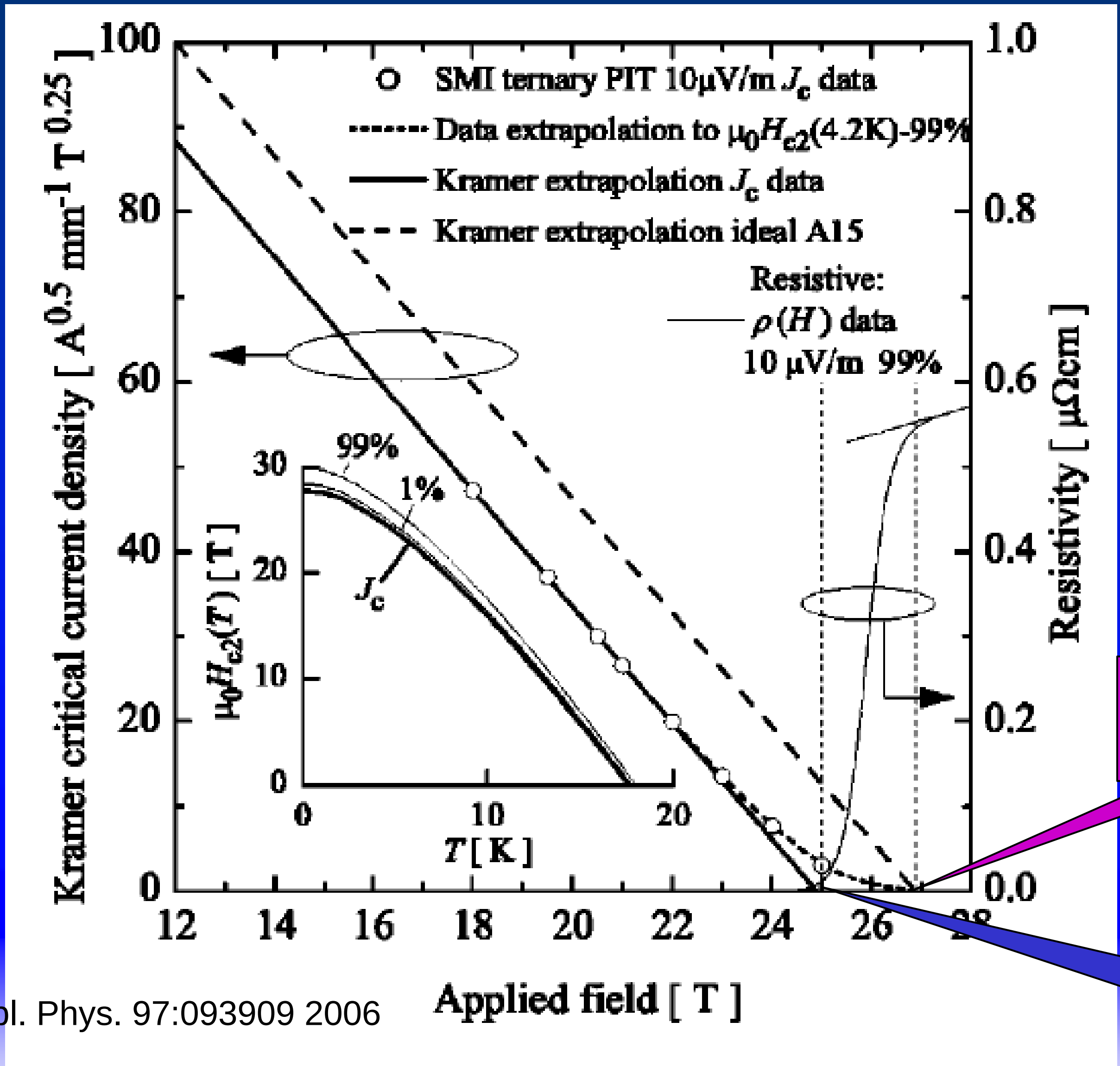
$$\%Sn(r) = 18 + 3.5\,[1 - r^N + (1 - r)^N]$$

$$T_{c\text{-}sim}(r) = 6 + 12\,[(\%Sn(r) - 18) / 7]\ \text{Kelvin}$$

$$\mu_0 H_{c2\text{-}sim}(0,r) = 0.69 \cdot 2.4 \cdot T_{c\text{-}sim}(r)\ \text{Tesla}$$

L. D. Cooley, C. M. Fischer, P. J. Lee, and D. C. Larbalestier, J. Appl. Phys. 2004.

Kramer plot extrapolation field $\mu_0 H_K$



$\mu_0 H_{c2}$

$\mu_0 H_K$

Godeke et al., J Appl. Phys. 97:093909 2006

BROOKHAVEN NATIONAL LABORATORY

Kramer extrapolation represents average of H_{c2}(%Sn)

Flatter profiles ↓

Gradient index N	Weighted mean of $H_{c2\text{-}sim}(r)$ at 4.2 K (T)	H_K at 4.2 K (T)	Weighted mean of $H_{c2\text{-}sim}(r)$ at 12 K (T)	H_K at 12 K (T)
1	15.7	19.1	7.1	9.6
5	23.0	23.3	10.5	11.4
10	24.6	24.6	11.7	12.1
Ideal	26.5	26.4	13.6	13.6

This is the average H_{c2}(%Sn), which is always less than the ideal value (H_{c2} @ 25% Sn).

This is the Kramer plot extrapolation that fixes Jc(H)

L. D. Cooley, C. M. Fischer, P. J. Lee, and D. C. Larbalestier, J. Appl. Phys. 2004.

PIT Lesson 2: %Sn profile is averaged by critical current

- To improve performance at high fields, it is absolutely necessary to minimize the number of tin-poor regions
- $J_c(H)$ scales with H_K = average $H_{c2}(\%Sn)$

- RRP advantage over PIT: Cu provides rapid pathways for radial diffusion of Sn, eliminating radial Sn gradients
  - Because Cu in RRP diffuses toward the tin core, practically no tin-poor Nb_3Sn area results. Thus, RRP produces better Nb_3Sn AND does it more efficiently.
  - By contrast, the large-grain region wastes ~20% of the Nb_3Sn layer in PIT, even though it is rich in Sn.

BROOKHAVEN NATIONAL LABORATORY

Summary of RRP advantages

- Well bonded materials give long pieces
- Control and flexibility of LAR permits systematic adjustment of tin diffusion
- High tin activity produces rapid reactions and minimizes extent of tin-poor regions
- Radial dispersion of tin prior to formation of Nb_3Sn reduces gradients

BROOKHAVEN NATIONAL LABORATORY

Outline

- Factors that limit performance of superconductors
- Nb_3Sn: Why has RRP* emerged over bronze-route, MJR†, and PIT‡ as the LARP strand process?
  - Maximizing current density
  - Overcoming limitations imposed by gradients of the tin content
  - Managing stability
- Is further improvement of Nb_3Sn possible?
- If not, what's next? Clues from emerging areas in superconducting materials for HEP

* Restacked Rod Process™
† Modified jelly-roll process
‡ Powder-in-tube process

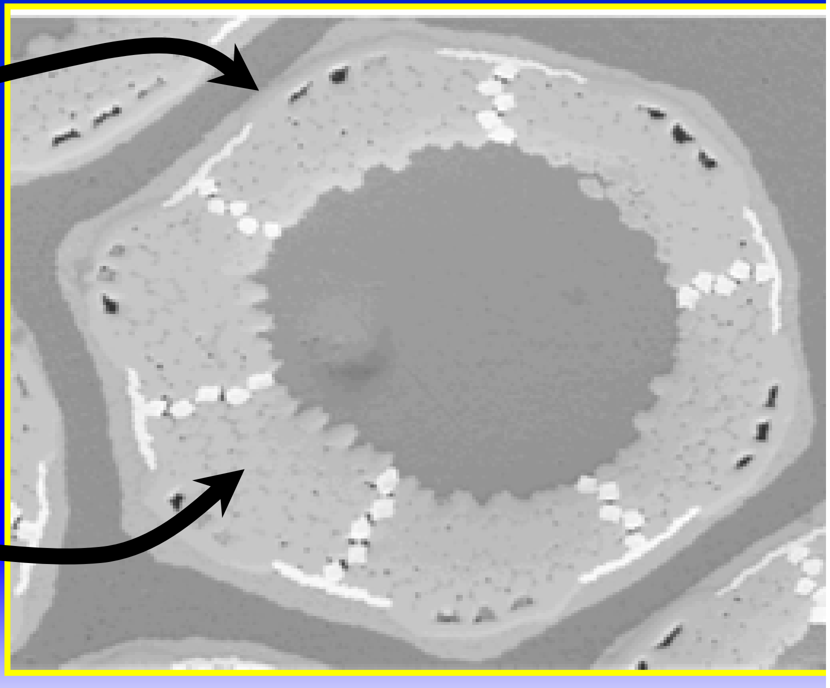
BROOKHAVEN NATIONAL LABORATORY

Origins of strand instability

- Large d_{eff} makes wires prone to flux jumps
- If heat released by flux jump cannot escape to helium in time (e.g. due to dirty copper), strand will quench
- Many magnets can operate with unstable strands!

Tin may breach the barrier and contaminate copper

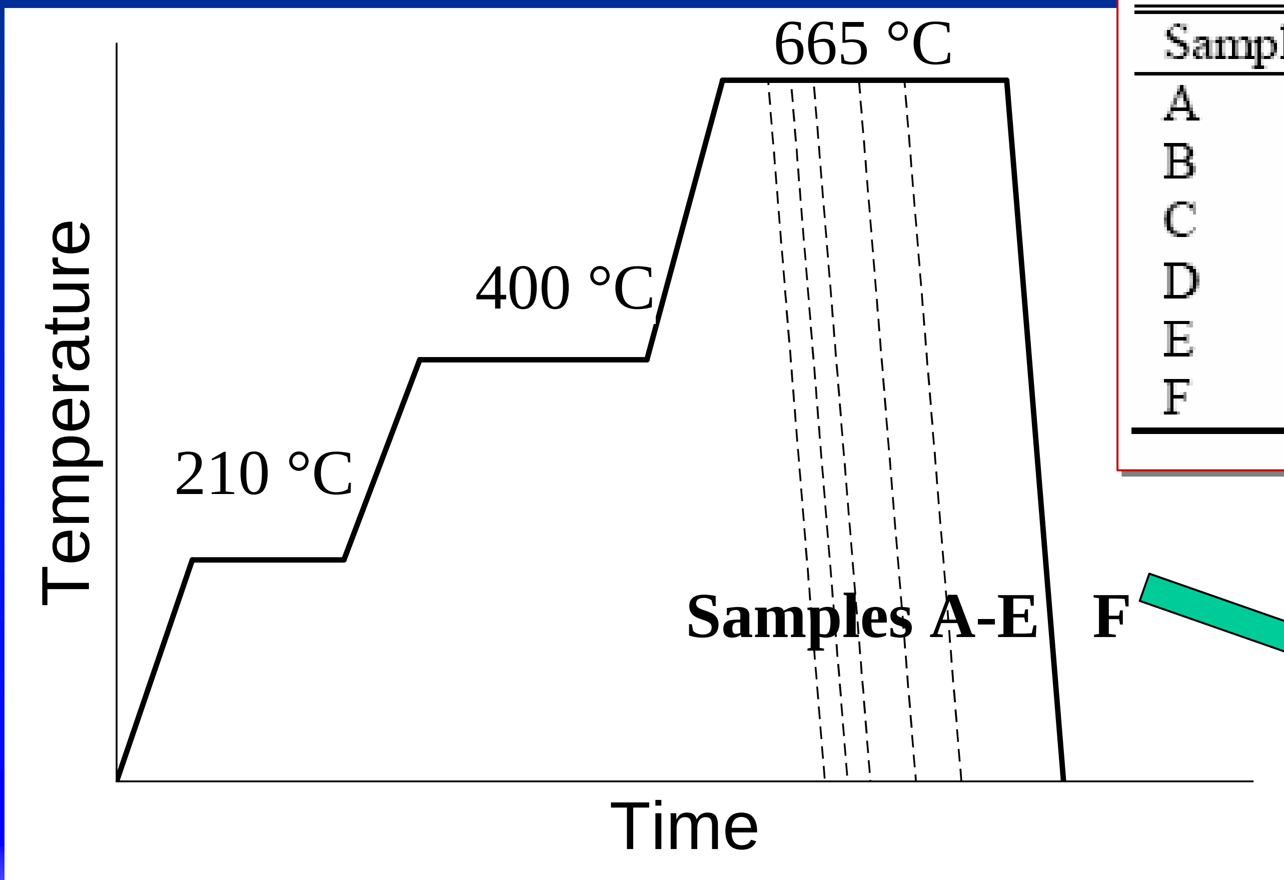
Filaments merge into a solid superconducting mass after reaction
(Sometimes separators are incorporated to break up the filament ring, as shown here)



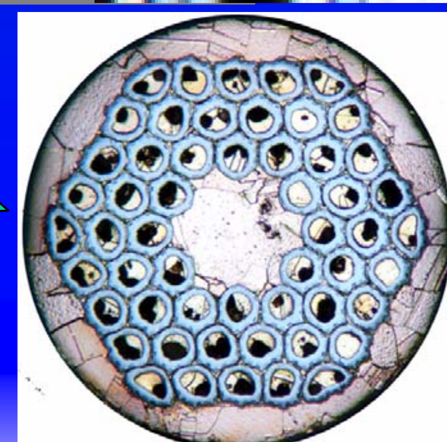
BROOKHAVEN NATIONAL LABORATORY

Experiment - RRP 7054 (LARP predecessor)

Limit reaction to keep tin from leaking through Nb barrier



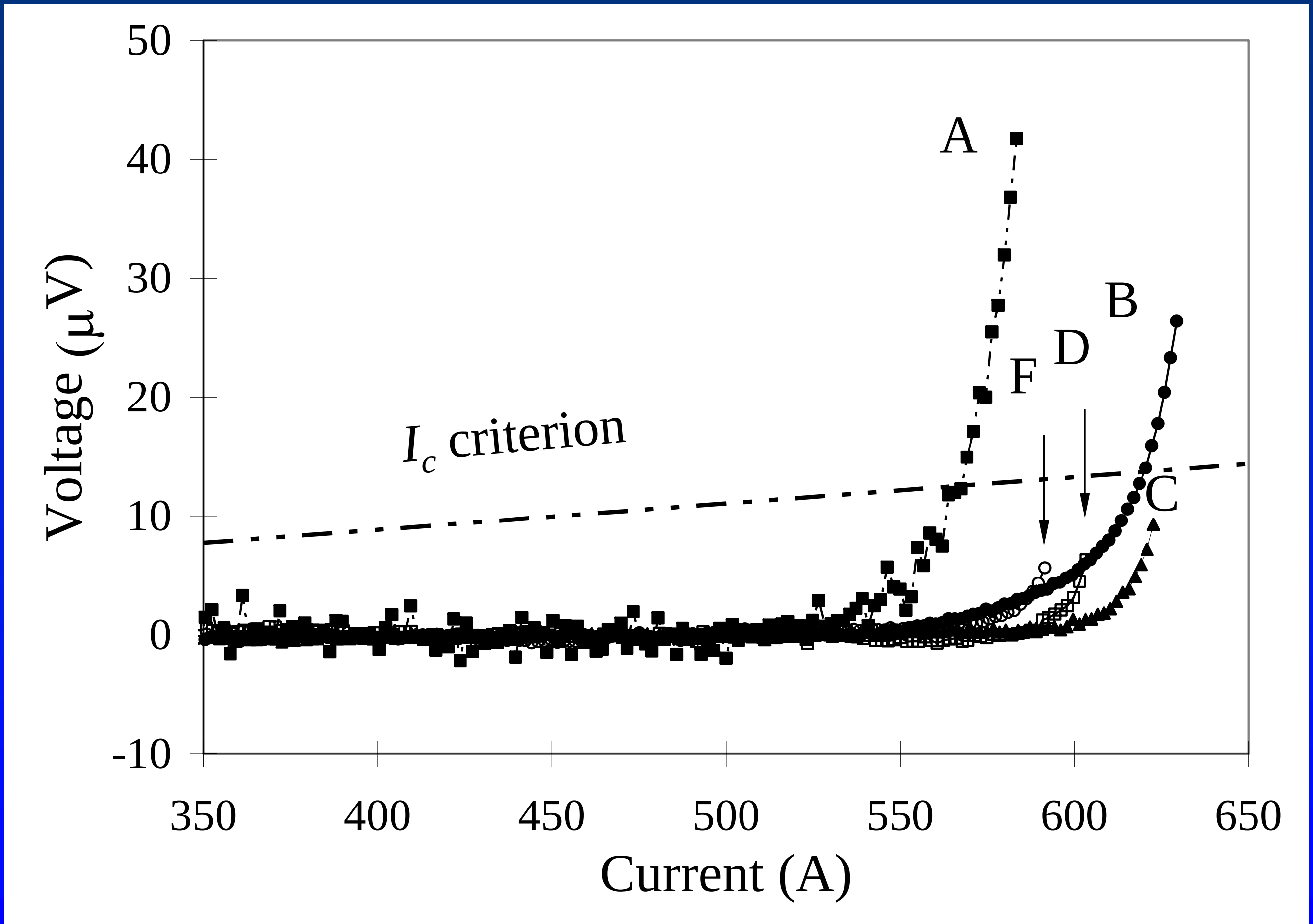
Sample	HT time (h)
A	24
B	36
C	48
D	72
E	96
F	150



A. Ghosh et al., Supercond. Sci. Technol. **18**, L5 (2005)

Courtesy Jeff Parrell

High tin activity helps J_c reach 90% of the maximum J_c for a reaction of only 24 hours

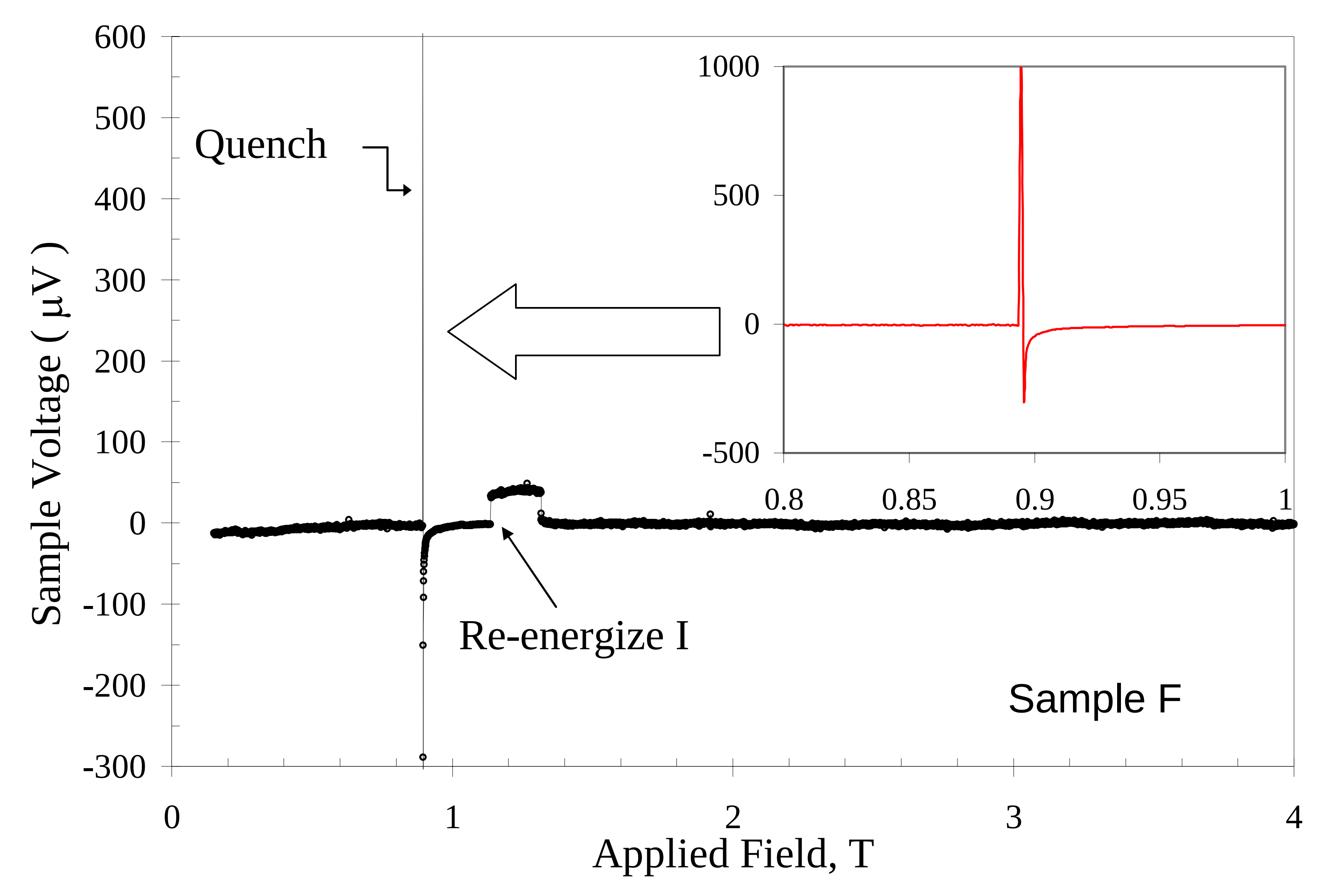


Voltage-current transitions acquired at 11.5 T for samples A-F. The resistivity criterion used to determine I_c is also shown.

BROOKHAVEN NATIONAL LABORATORY

Non-Traditional V-H plot

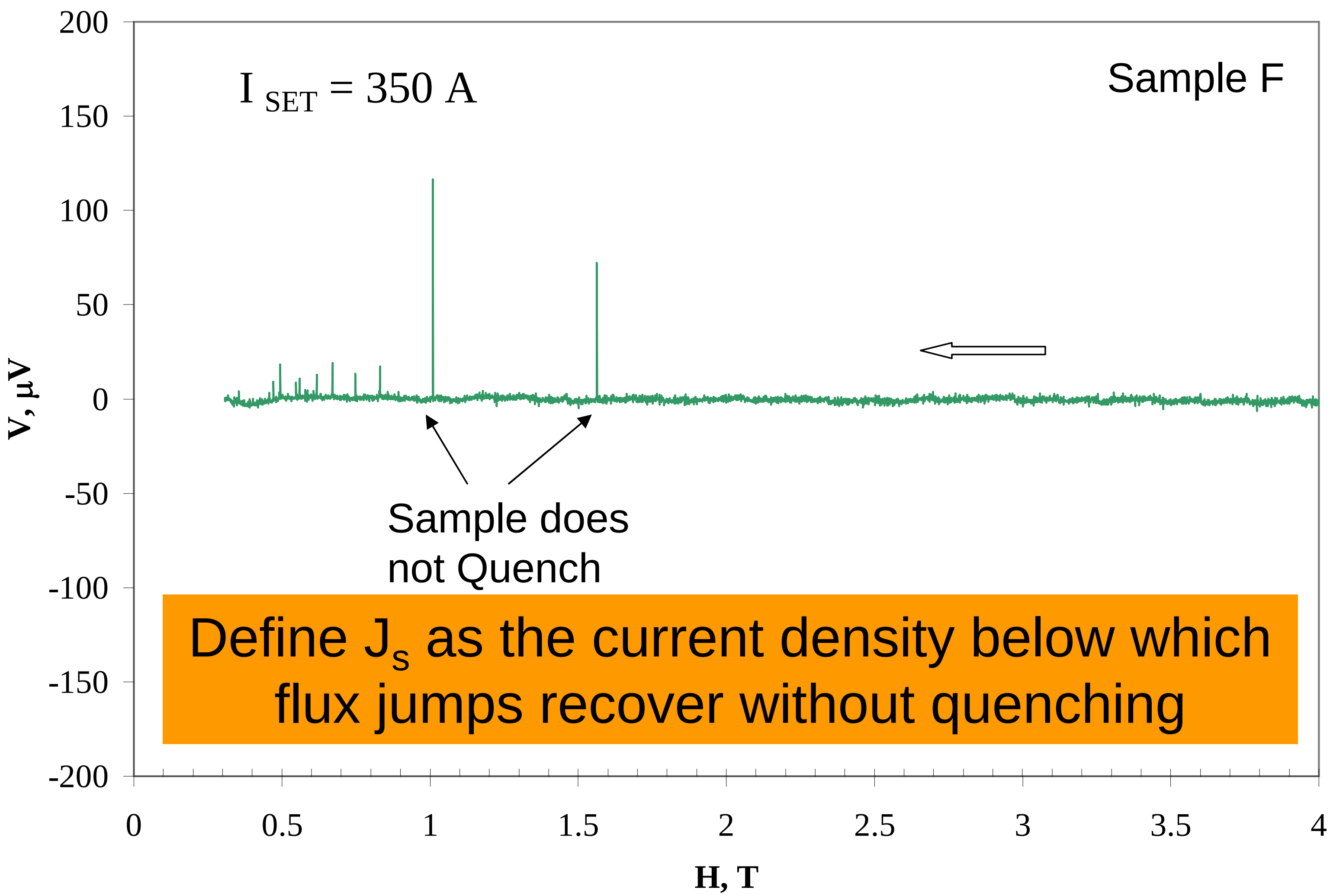
I_{SET}=400 A   d*B*/d*t* = 5 mT/s



Arup Ghosh, ASC 2004

BROOKHAVEN NATIONAL LABORATORY

Dynamic stability threshold

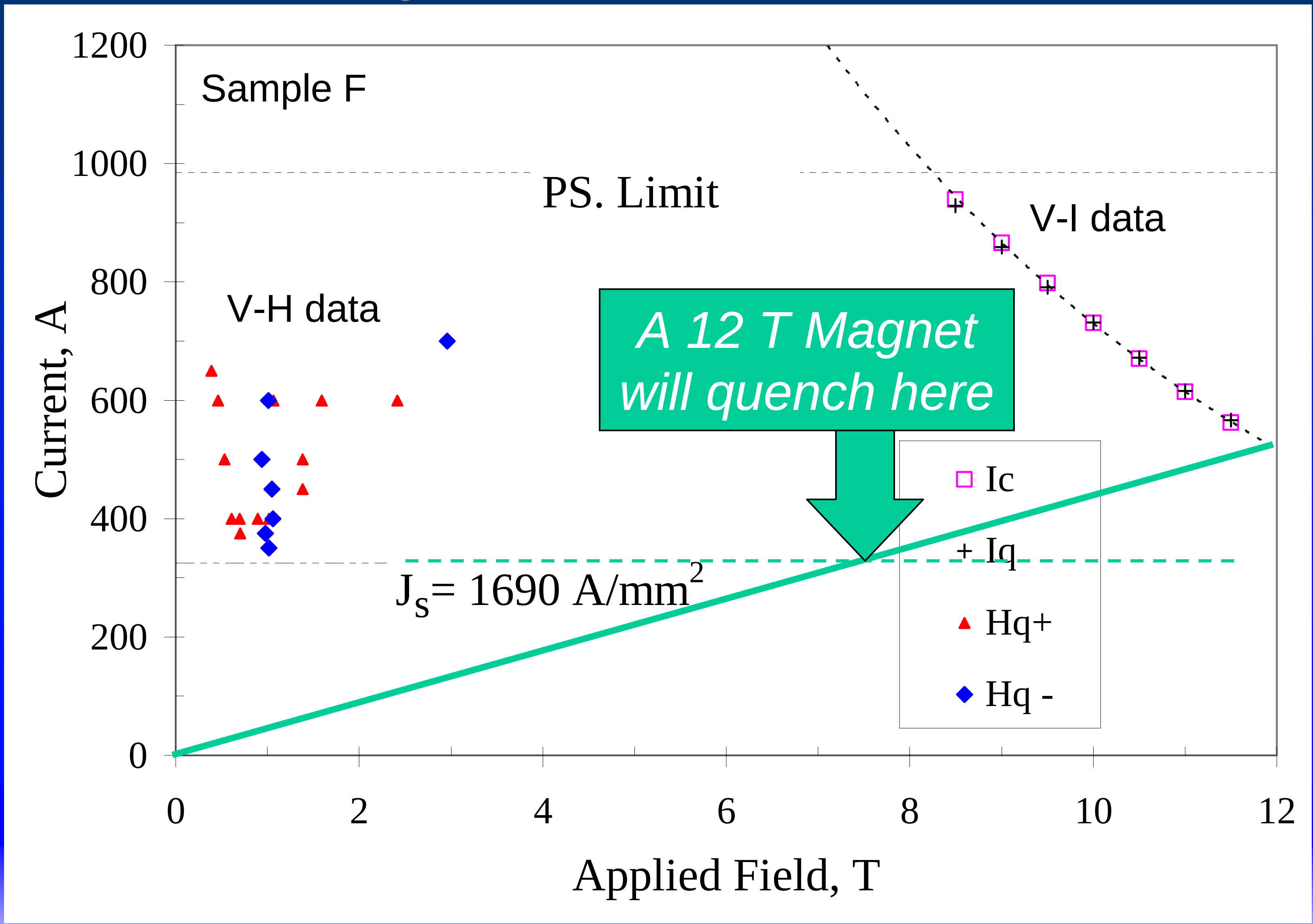


Define J_s as the current density below which flux jumps recover without quenching

Arup Ghosh, ASC 2004

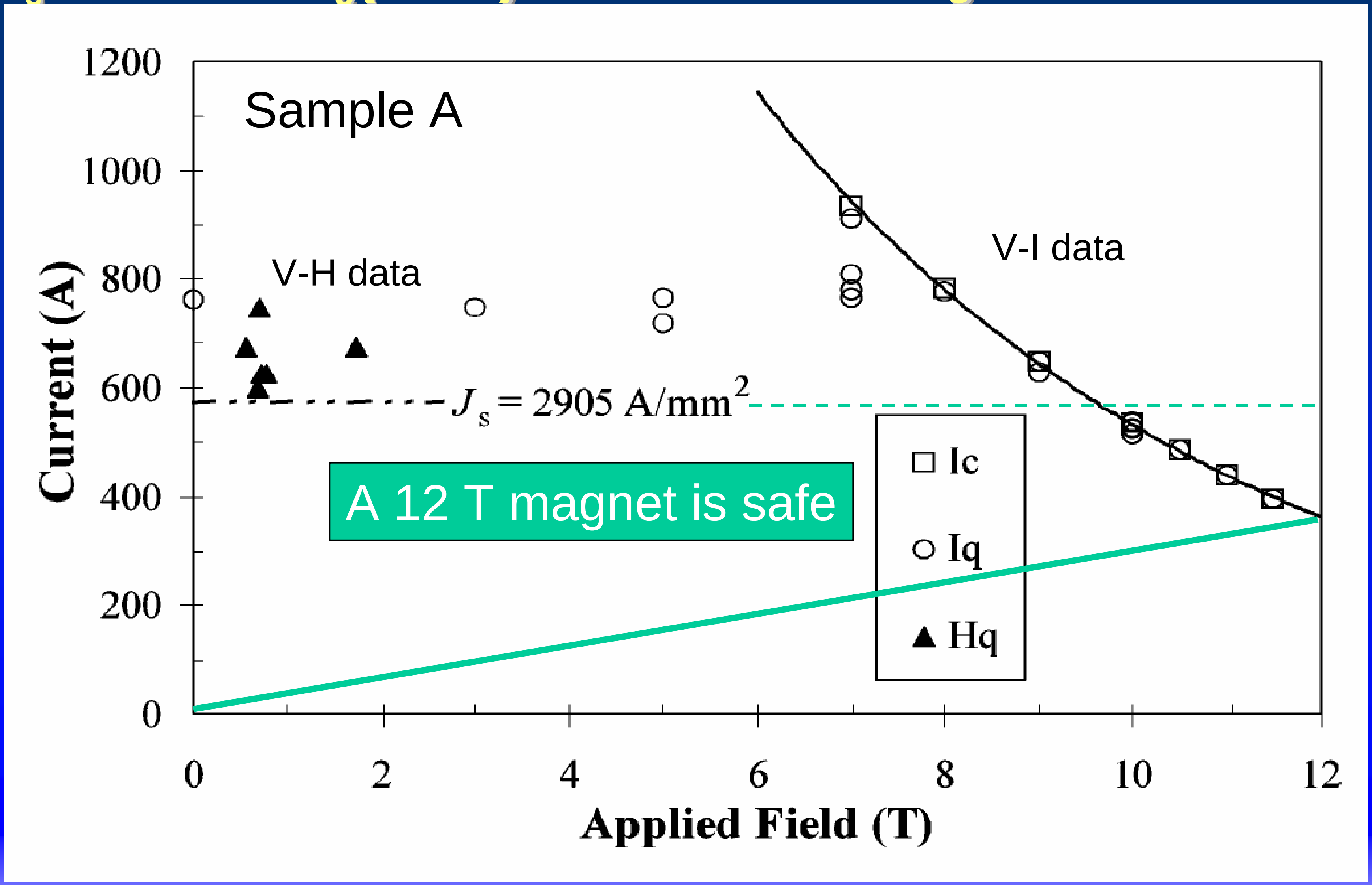
BROOKHAVEN NATIONAL LABORATORY

J_s is far below J_c(12 T) when RRR is low



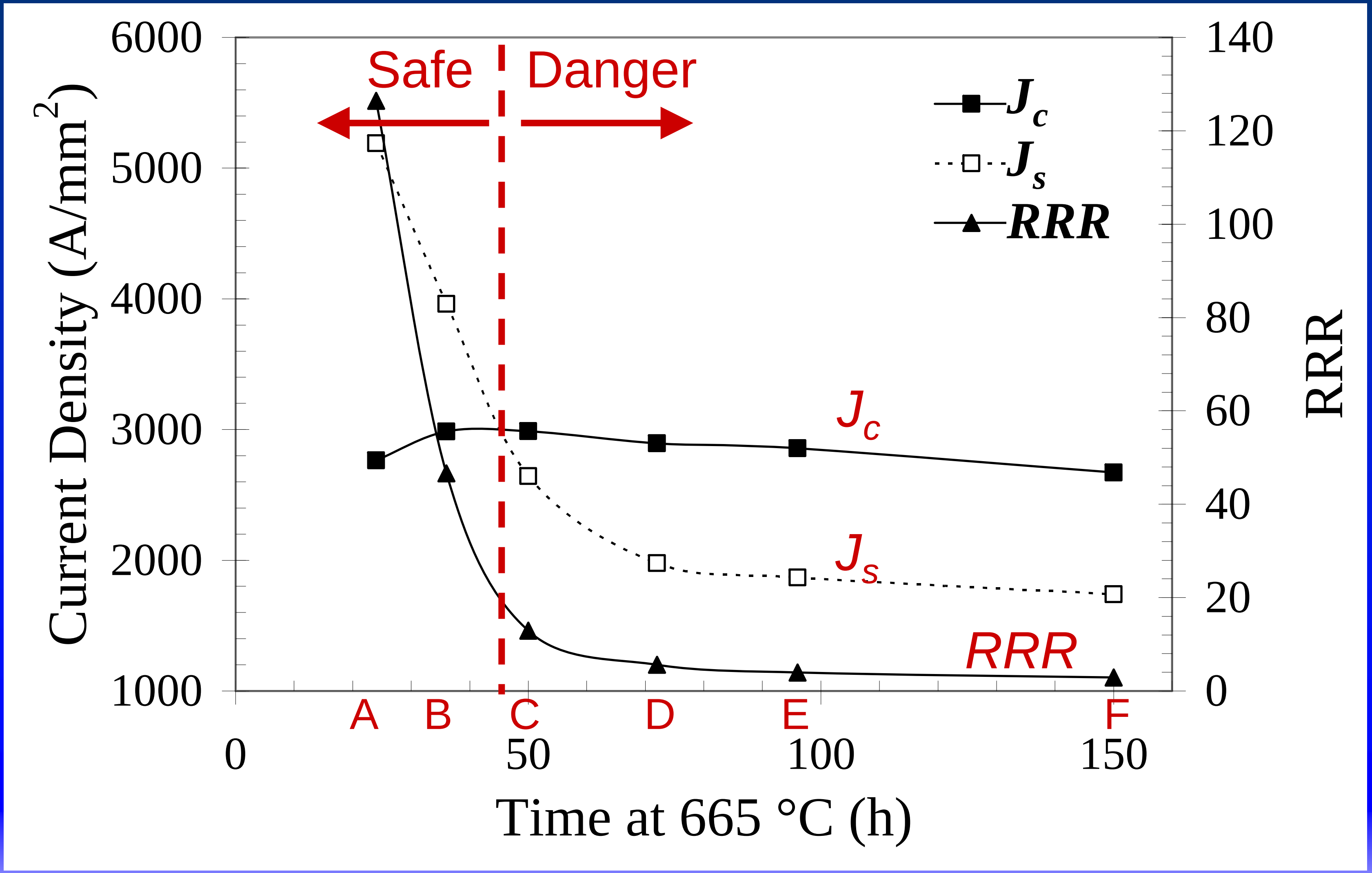
BROOKHAVEN NATIONAL LABORATORY

J_s is above J_c(12 T) when RRR is high



BROOKHAVEN NATIONAL LABORATORY

Experiment Summary: Keep $J_s > J_c$

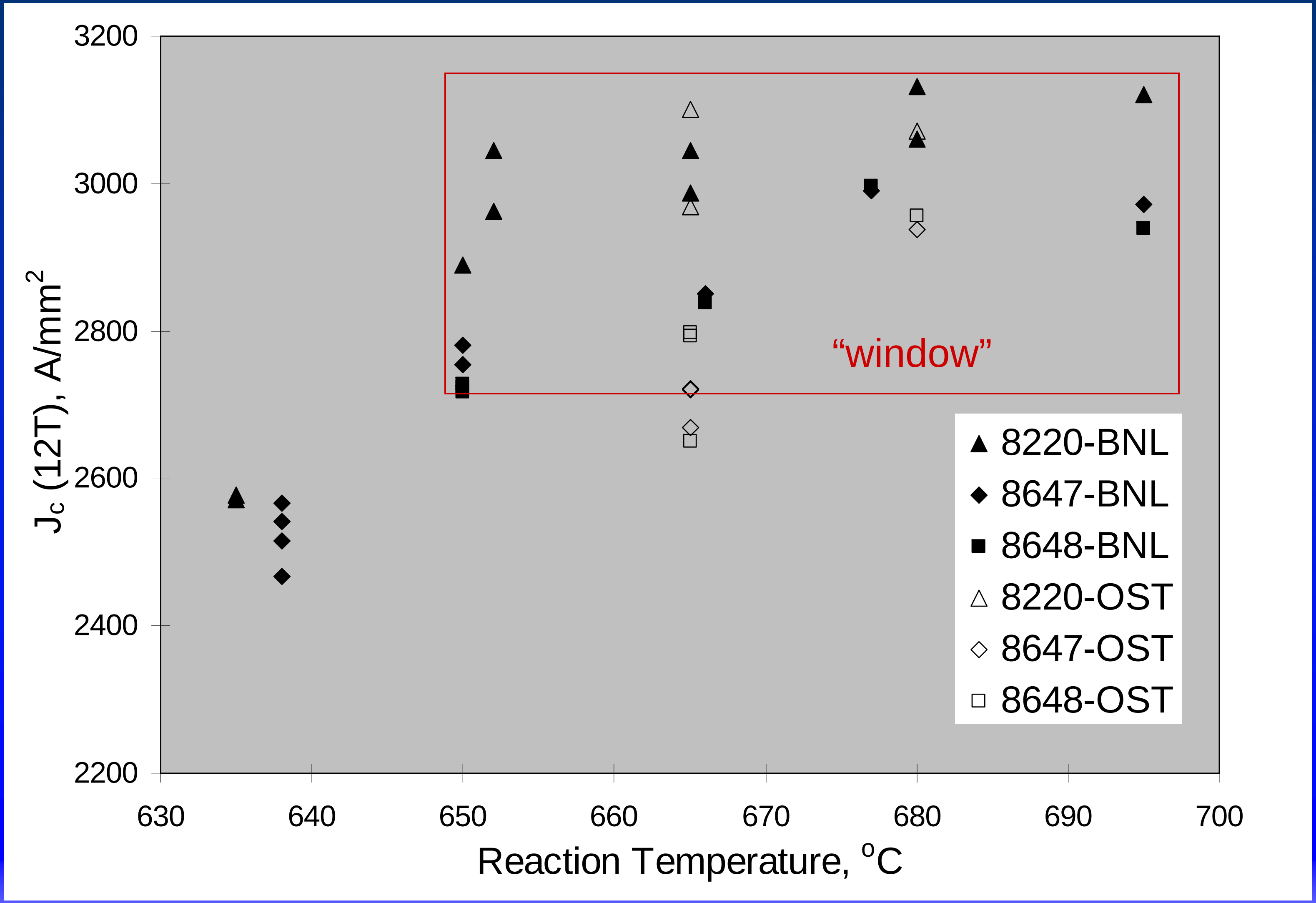


BROOKHAVEN NATIONAL LABORATORY

Lessons from stability work

- Two parameters (RRR and J_c) must be optimized.
- Fortunately, RRP provides so much tin activity that J_c optimizes rapidly, opening a fairly wide window to tune RRR

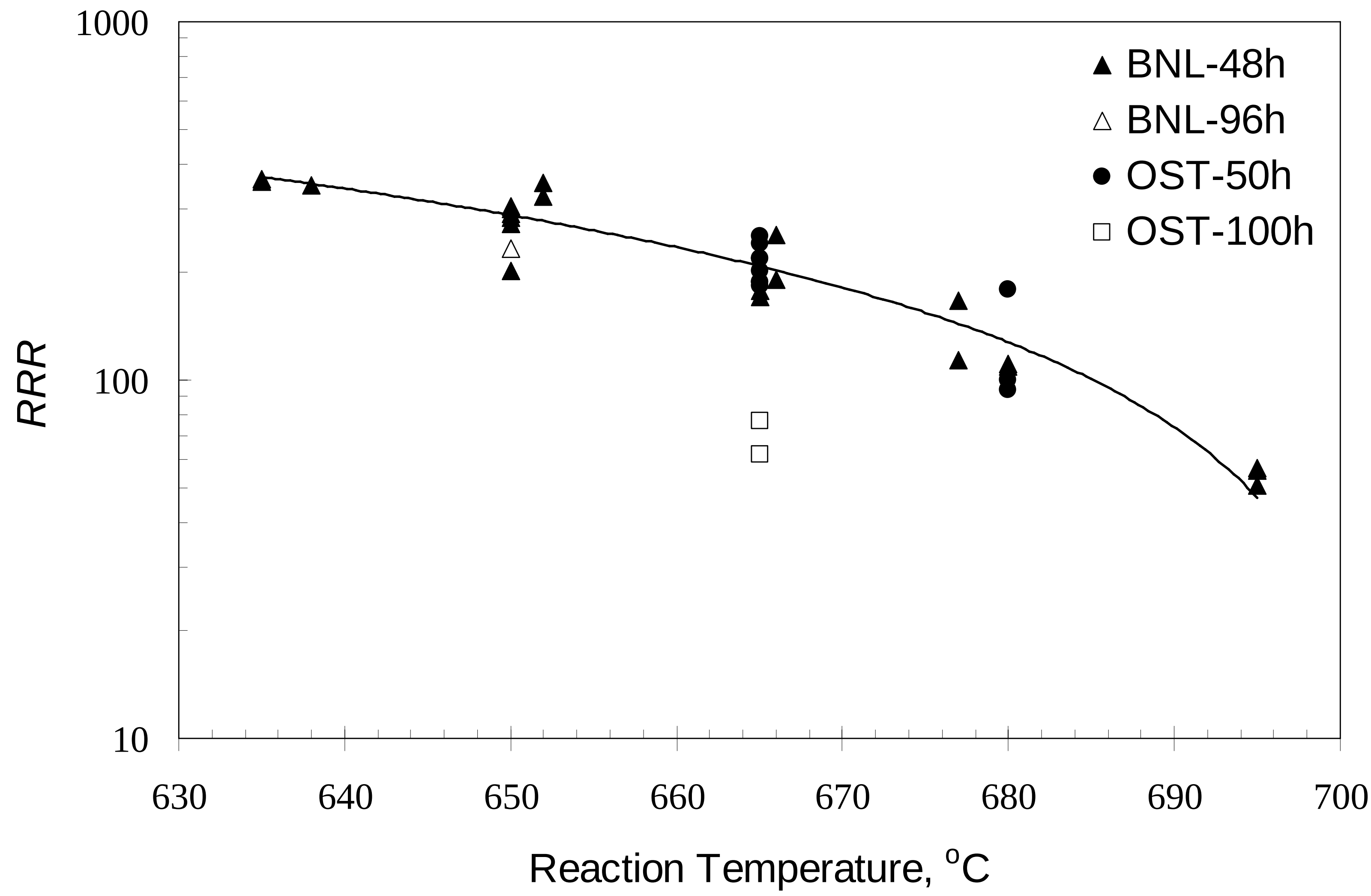
Jc (12T) BNL and OST 48-50h data



A Ghosh et al, ASC2006

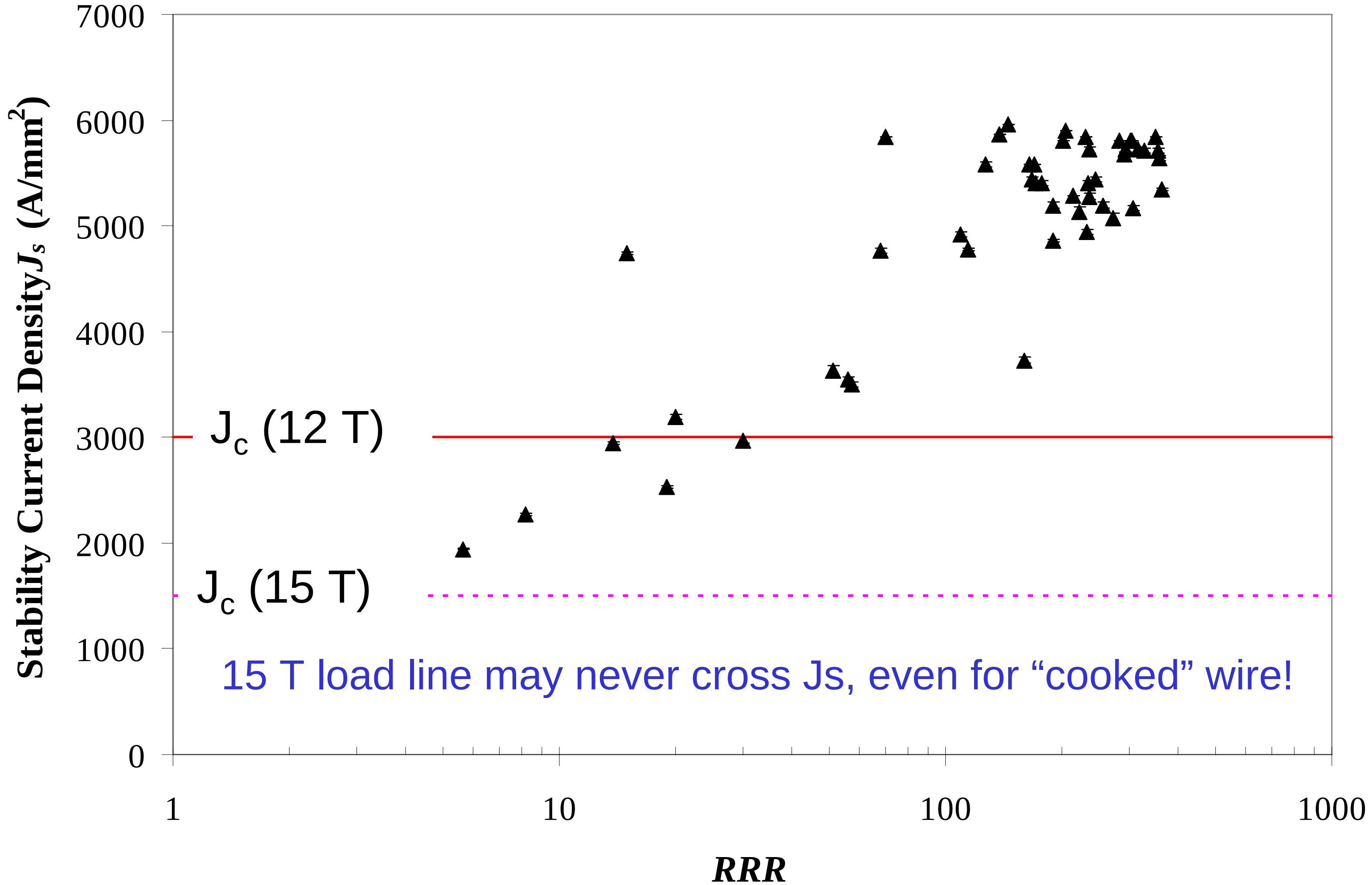
BROOKHAVEN NATIONAL LABORATORY

RRR as a function of reaction time and temperature



BROOKHAVEN NATIONAL LABORATORY

Stability current density of RRP 54/61 wire



BROOKHAVEN NATIONAL LABORATORY

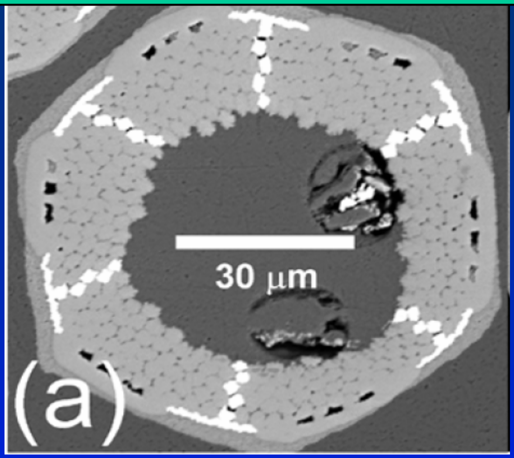
Outline

- Factors that limit performance of superconductors
- Nb_3Sn: Why has RRP* has emerged over bronze-route, MJR†, and PIT‡ as the LARP strand process?
  - Maximizing current density
  - Overcoming limitations imposed by gradients of the tin content
  - Managing stability
- Is further improvement of Nb_3Sn possible?
- If not, what's next? Clues from emerging areas in superconducting materials for HEP

* Restacked Rod Process™ † Modified jelly-roll process
‡ Powder-in-tube process

Toward smaller d_{eff}

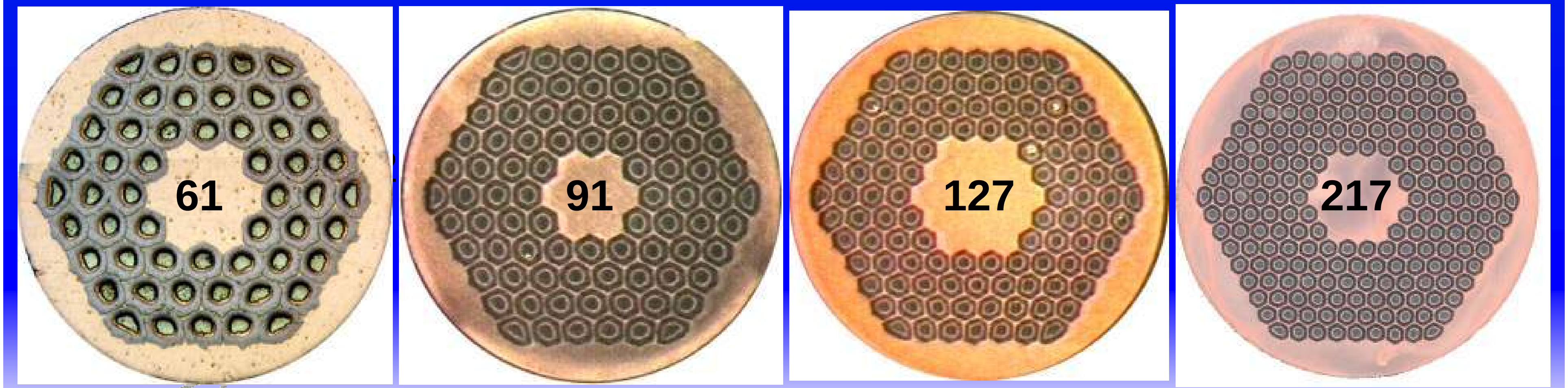
Also one composite with a divided subelement

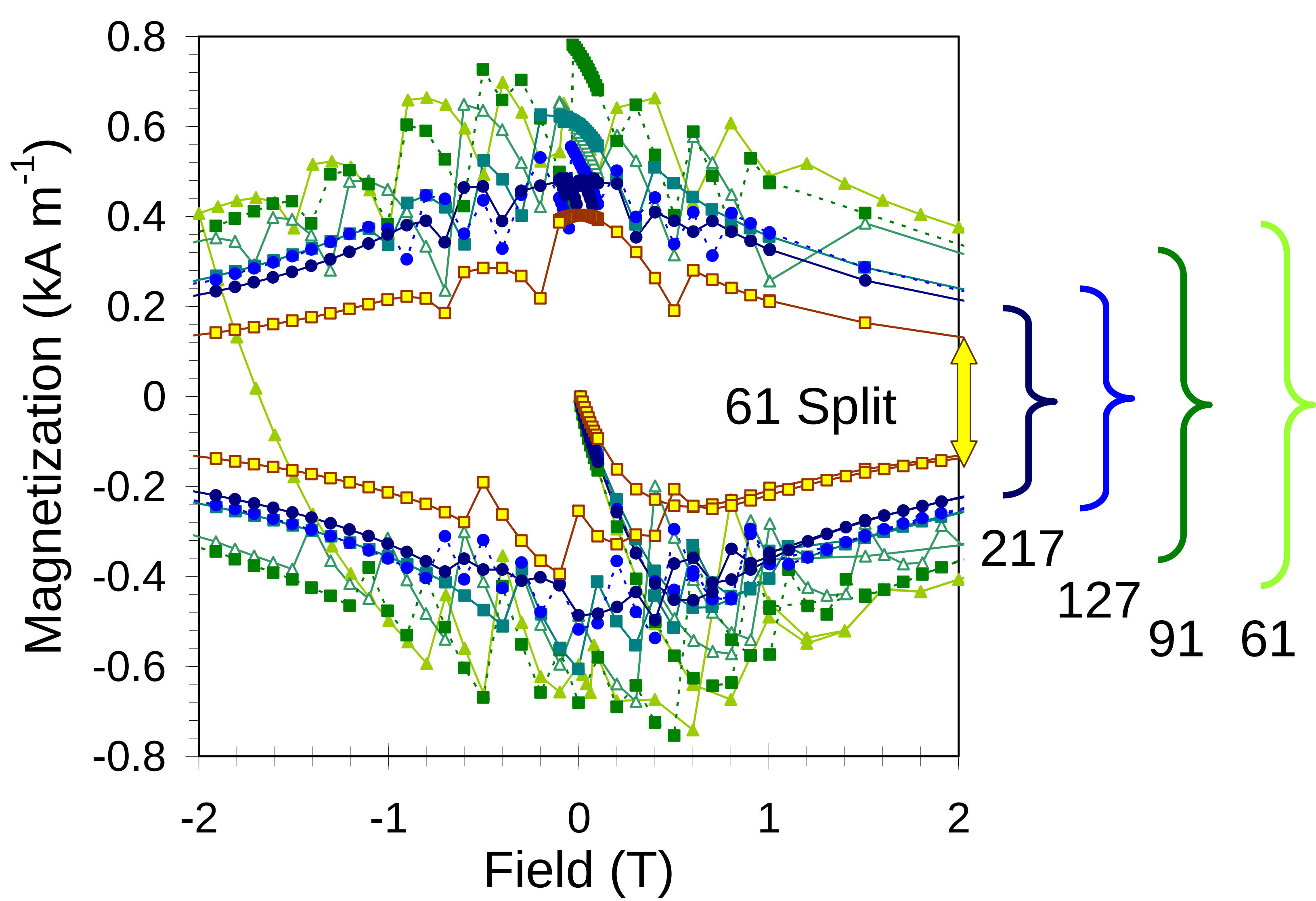


Restacked Rod Process (RRP)
Subelements are not divided,
just smaller in diameter

0.7 mm dia.

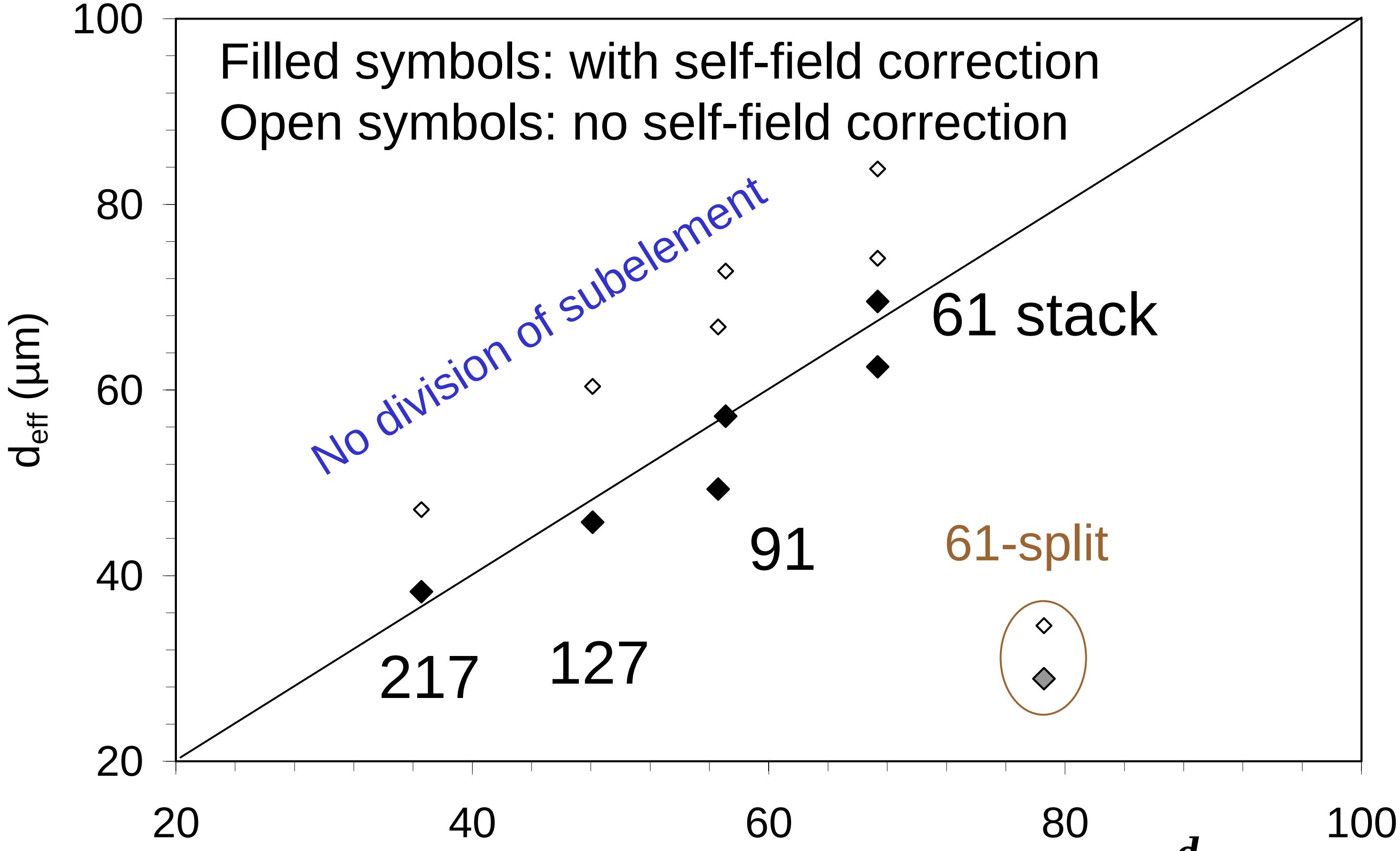
Courtesy Jeff Parrell ASC 2006





Magnetization (kA m^{-1})
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-2
-1
0
1
2
Field (T)
61 Split
217
127
91
61

Effective filament diameter and subelement diameter are equal; 40 μm has been achieved!



$$d_s = \frac{d_w}{\sqrt{N(1+R)}}$$

Smaller d_{eff} comes with performance sacrifice

N	d_S µm	HT type	HT	$J_c(12)$ A mm^{-2}	RRR
54 (61)	68	A	72h@675°C	2900	6
		B	36@660	2985	47
		C	24@650	2760	127
84 (91)	57	B	48@650	3050	165
90 (91)	57	A	48@695	2680	20
		C	36@635	2330	344
108 (127)	49	B	48@665	2830	127
126 (127)	48	A	72@665	2260	4
		B	72@635	2040	9
		C	36@635	1910	114
198 (217)	37	B	48@650	2460	12
54 split	79	A	100@665	2290	6
		B	50@665	2120	96

Where to look for more layer Jc

- Grain size as small as 30 to 50 nm have been achieved (proof of principle)
- 50% gain in pinning might be realized by reducing grain size to ~80 nm
  - ~150 nm obtained for 650 to 665 °C right now
- IN PROGRESS: LARP 54/61
  - 2 x HT 96 h @ 620 °C
  - HT 150 h @ 605 °C

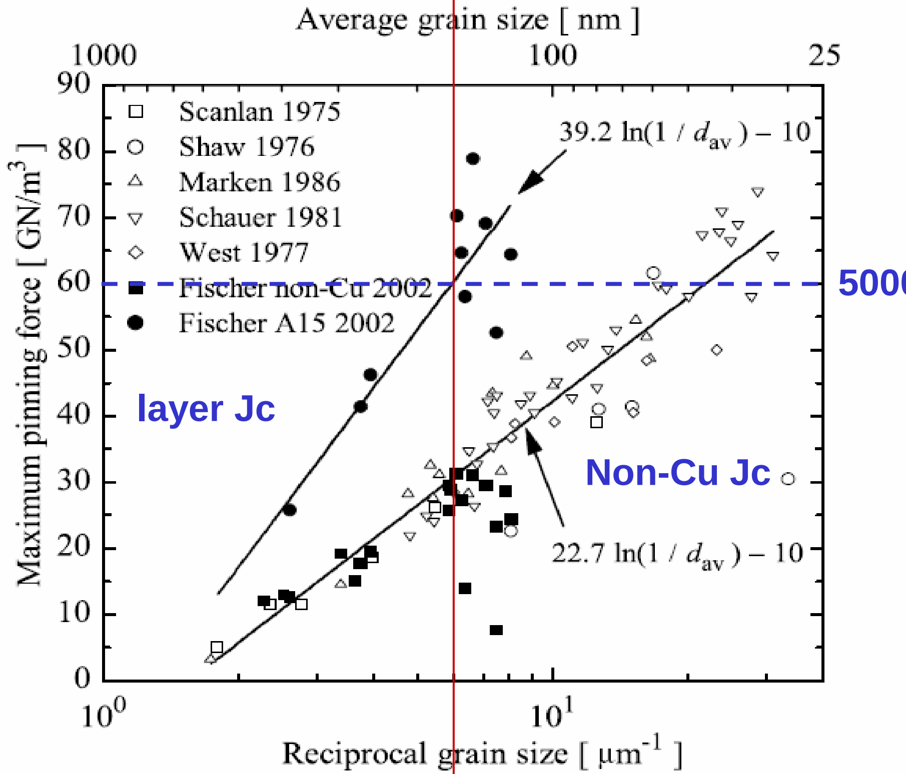


Figure 10. Maximum pinning force as function of reciprocal grain size, after Fischer [89]. (*Adapted with kind permission of C M Fischer*).

Can this line be moved to the right, e.g. by a long reaction at 550 to 600 °C?

Godeke SuST review 2006

Can a wire design yield still higher Nb_3Sn %?

- Ultimate limit: 2 volume units Nb fully react with 1 unit Sn to provide 2.67 units Nb3Sn
  - i.e., not more than 89% of non-copper area can be converted to Nb_3Sn when starting from elements
  - (2:1 volume = 3:1 mol Nb:Sn)
- Must let tin escape from core, else large grains form
  - PIT, RIT cannot therefore achieve the ultimate limit above!
- Lower LAR: increases Nb content, but pinches off tin diffusion
- Smaller Nb filaments at same LAR provides more access for Sn, but sacrifice shape control
- Better roundness of Nb and smaller Nb grain size will improve geometry stability, but this requires changes in Nb supply
- ACTIVITIES IN PROGRESS UNDER CONDUCTOR DEVELOPMENT GROUP (OI-ST)

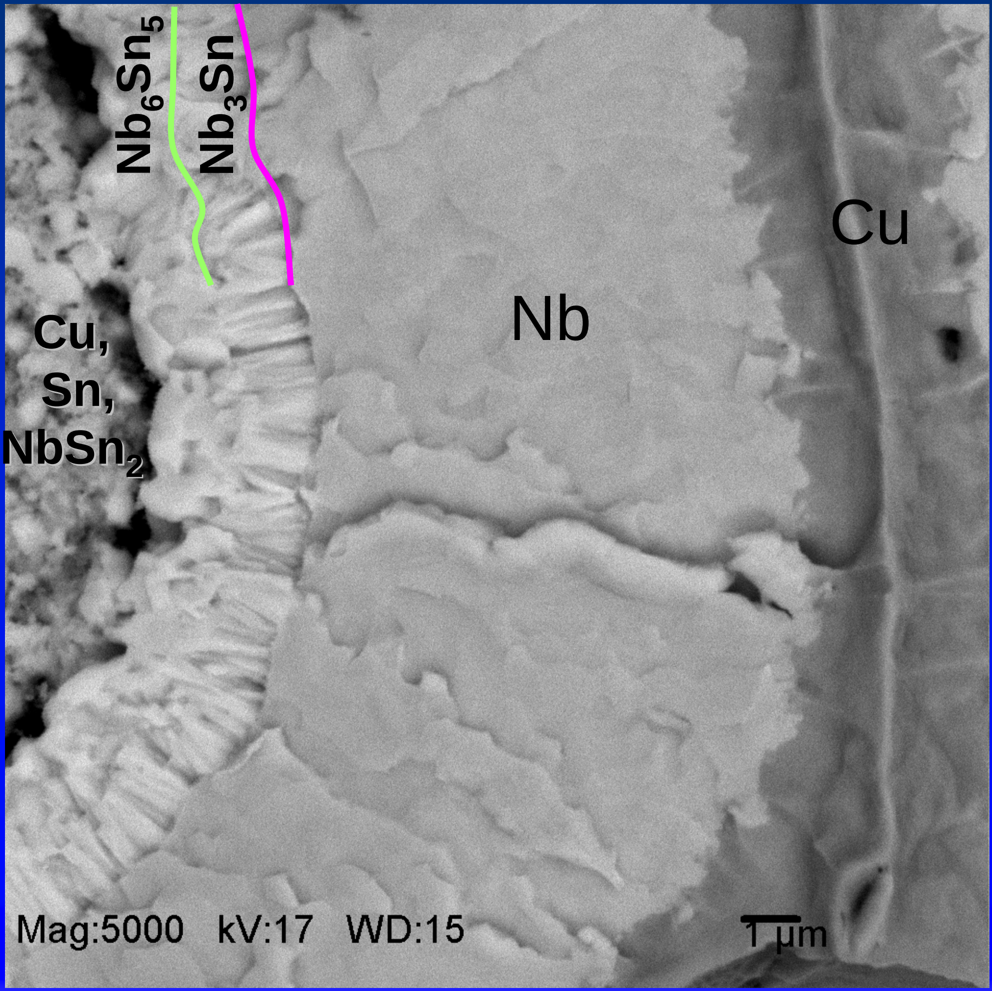
BROOKHAVEN NATIONAL LABORATORY

Regarding trapped tin in PIT…

SMI billet 34
24 h @ 575°C

Lesson: It was not possible to form Nb_3Sn without first forming Nb_6Sn_5, no matter how low the reaction temp.

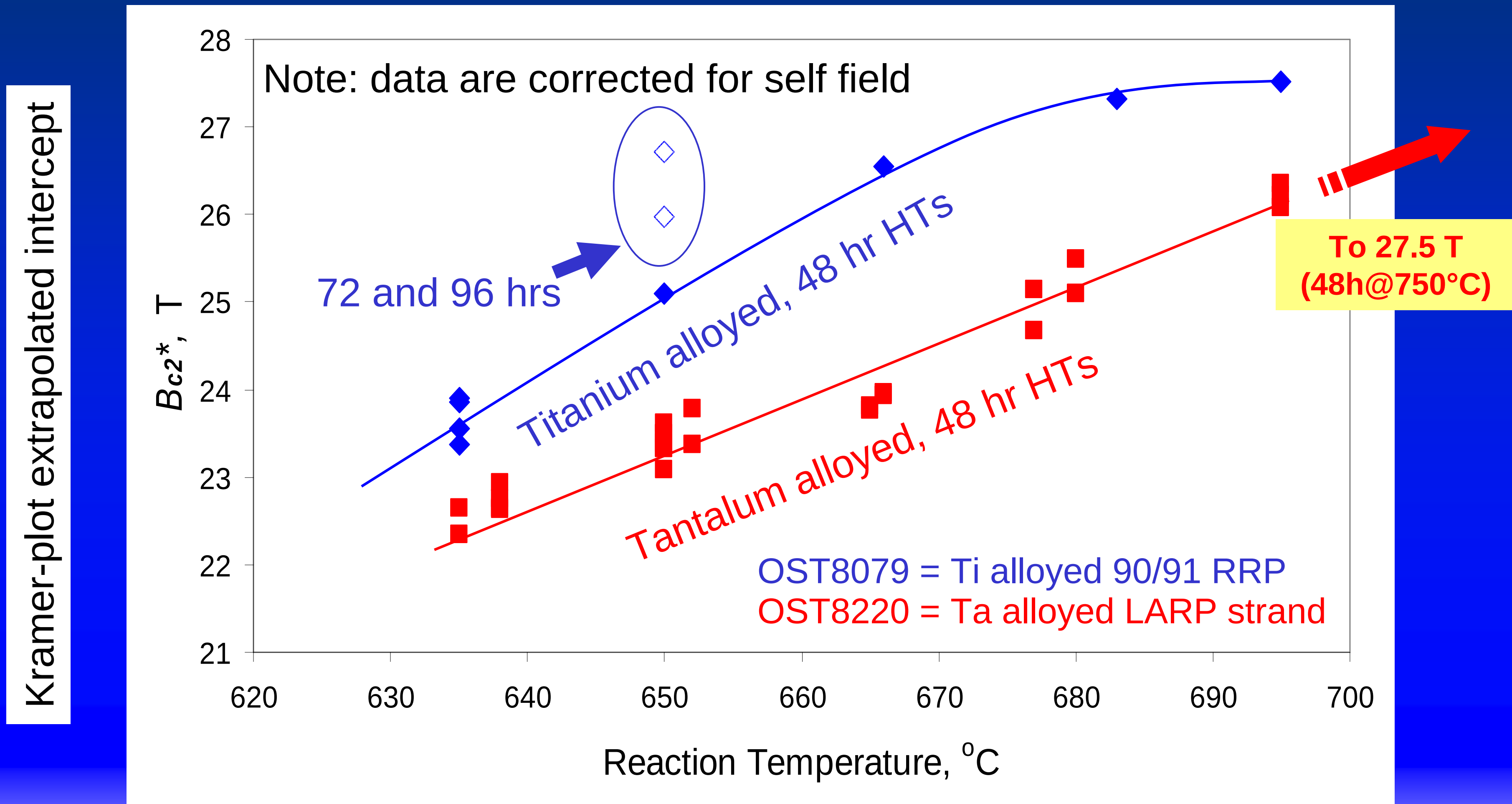
Can a thick layer of fine-grained Nb_6Sn_5 be formed first, and then converted to Nb_3Sn without coarsening?
(We were not successful)



SEM and prep by Jesse Wright & Bob Sabatini
Wire samples from FNAL

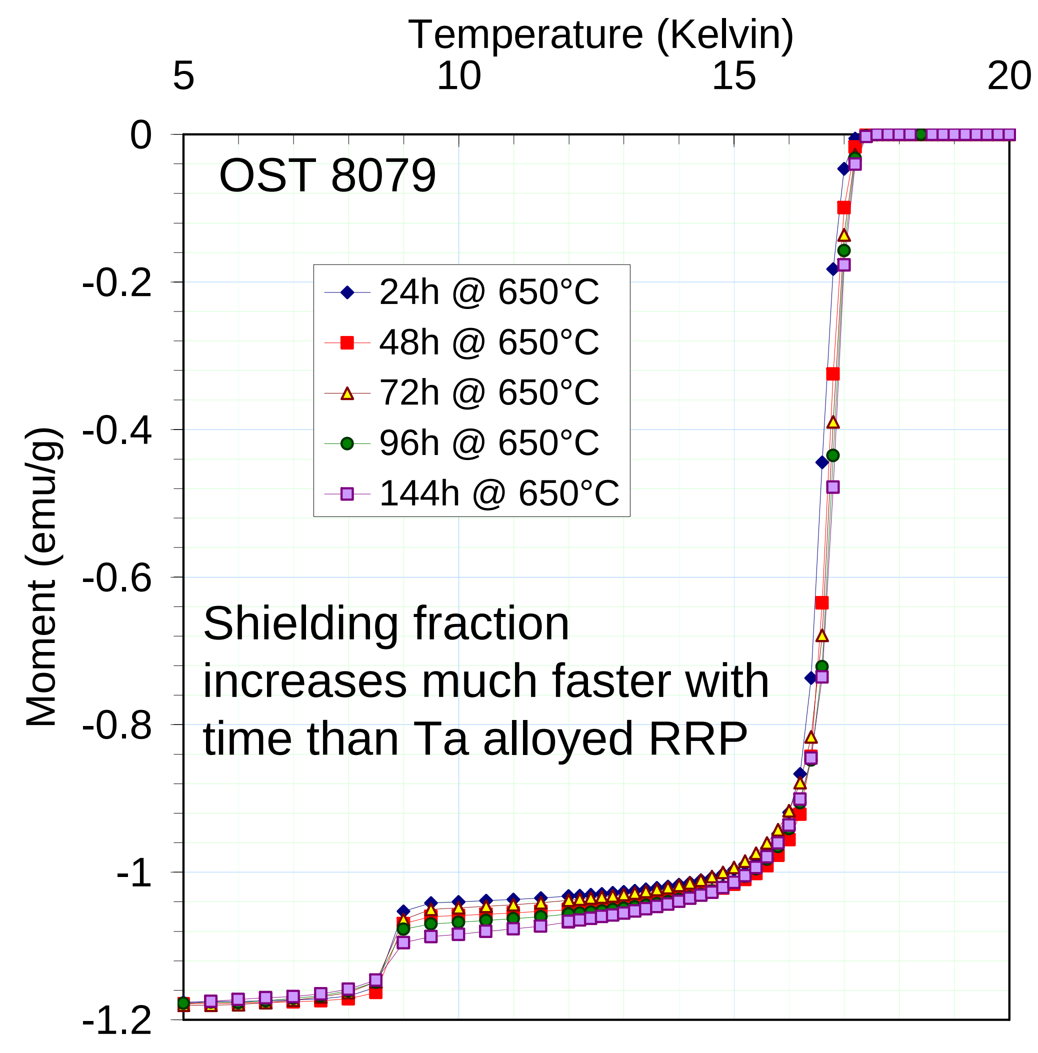
BROOKHAVEN NATIONAL LABORATORY

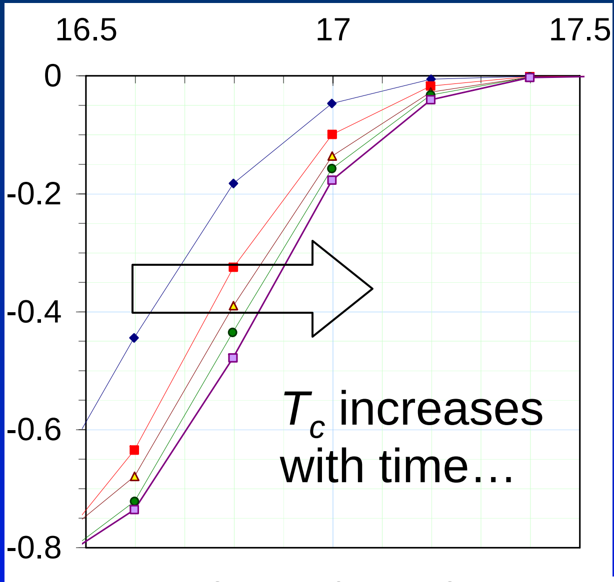
Ti alloying –
Faster way to get high-field performance?

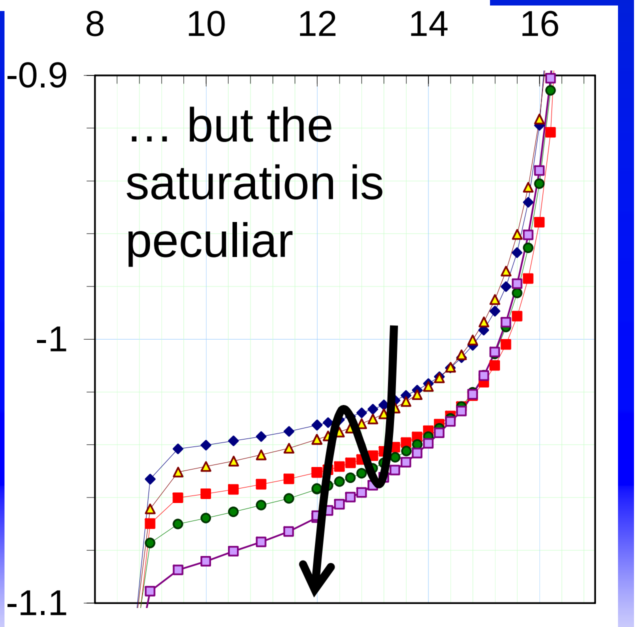


Ghosh, Cooley, OST collaborators ASC2006

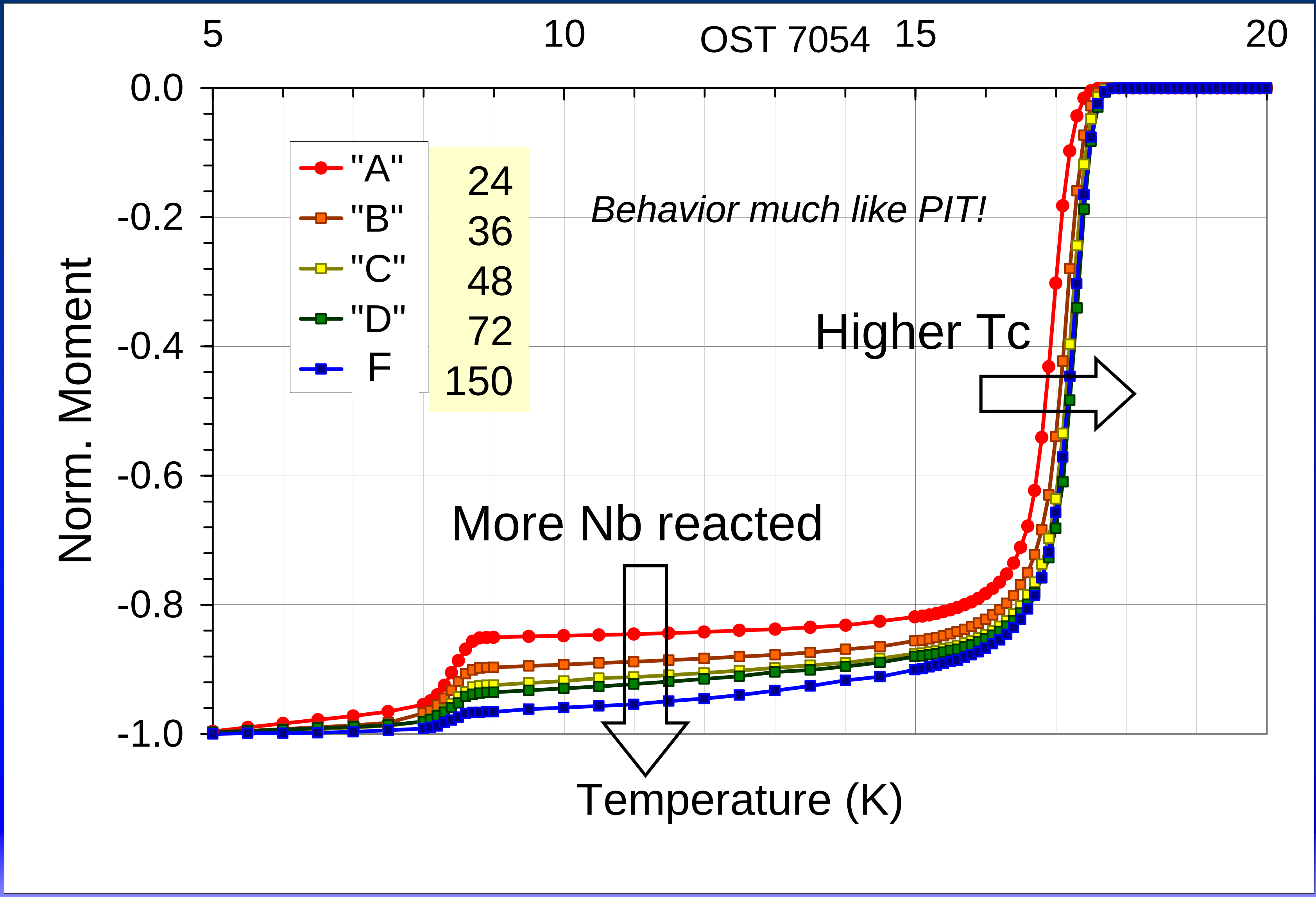
Ti gradients as well as Sn gradients?







(Ta alloyed RRP for comparison)



What's going on with Ti?

- Possibility 1: Ti is a more effective alloying agent than Ta (contrary to past results...).
- Must adjust LAR to accommodate Ti diffusion
- IN PROGRESS: RRP 8079 given intermediate 575°C step to diffuse Ti uniformly prior to Nb_3Sn reaction
- Possibility 2: Better Ti results are an ARTIFACT of faster tin diffusion
  - It is known that Ti penetrates quickly along grain boundaries, which would widen the "pipes" through which tin flows.
- If so, then does Ti really alloy?
  - Past work: 2% Ti at GBs, 1.3% in Nb_3Sn region

Billet	Design %Ti	LAR	Max B_{c2}^*	Comment
RRP-8079	2.4	0.26	27.5	
HER-7981	2.5	0.28	26.5	Tin starved?
RRP-8720	2.0	0.20	25.8	B_{c2}^* decreases with HT time

BROOKHAVEN NATIONAL LABORATORY

Outline

- Factors that limit performance of superconductors
- Nb_3Sn: Why has RRP* has emerged over bronze-route, MJR†, and PIT‡ as the LARP strand process?
  - Maximizing current density
  - Overcoming limitations imposed by gradients of the tin content
  - Managing stability
- Is further improvement of Nb_3Sn possible?
- If not, what's next? Clues from emerging areas in superconducting materials for HEP

* Restacked Rod Process™ † Modified jelly-roll process
‡ Powder-in-tube process

BROOKHAVEN NATIONAL LABORATORY

SRF flux entry barrier: Breaking the Nb monopoly

- A Gurevich: a thin layer of a high-field superconductor over Nb will keep out fluxons and their normal electrons
- $H_S \sim (\lambda_L / d)\, H_S^{bulk}$
- Several materials challenges!

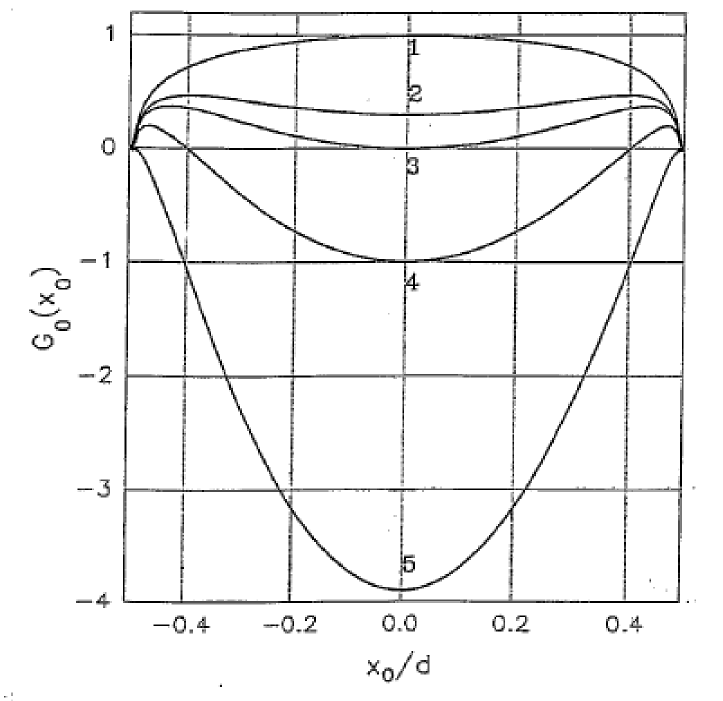
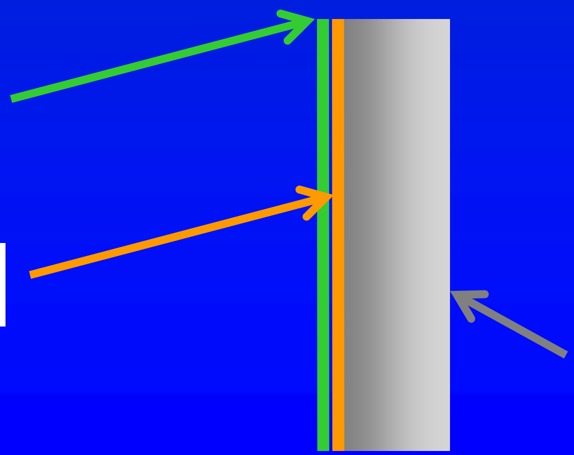


FIG. 7. Single-vortex thermodynamic potential (15) for different H at $J=0$: $H<H_m$ (1), $H_m<H<H_{c1}$ (2), $H=H_{c1}$ (3), $H_{c1}<H<H_s$ (4), and $H>H_s$ (5).



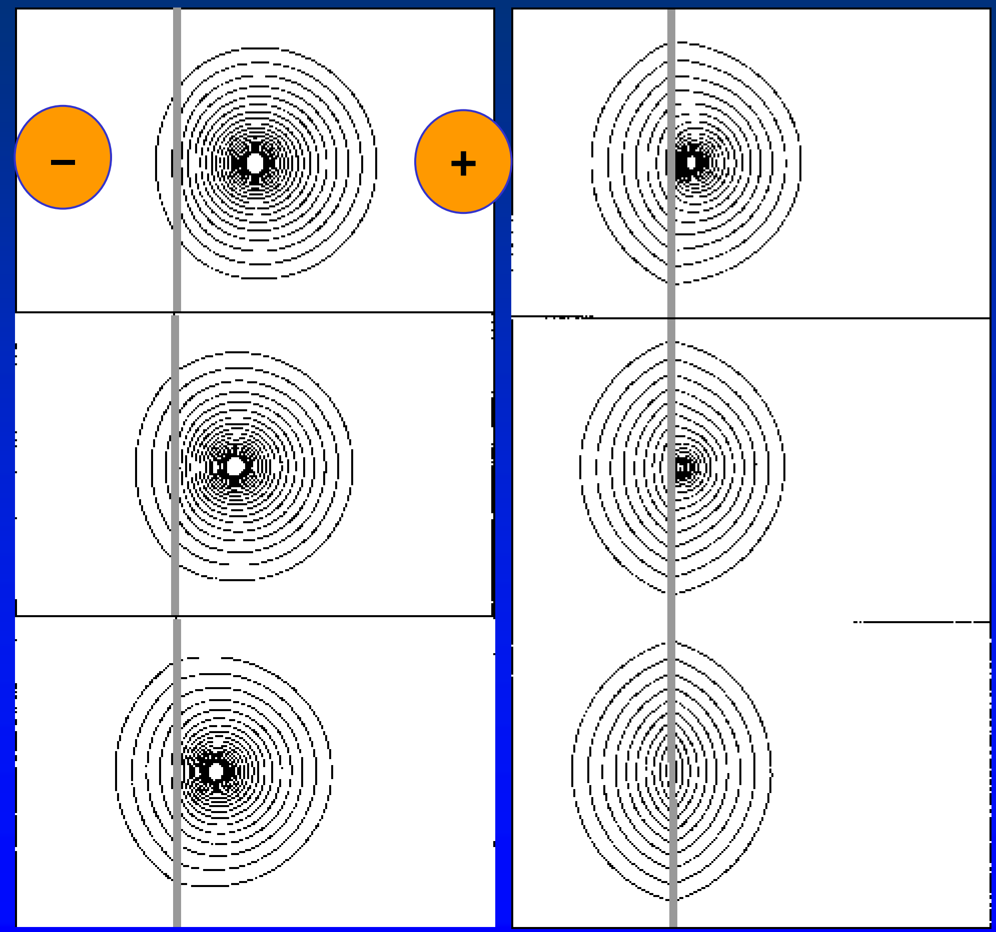
$$H_s = \phi_0 / 2\pi d \xi \, .$$

Gurevich APL88-012511; Stejic et al PRB 49:1274 (1994)

BROOKHAVEN NATIONAL LABORATORY

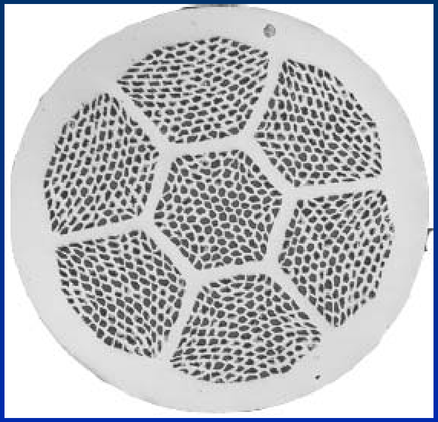
AJ vortices at Nb grain boundaries?

- "Hybrid" Abrikosov-Josephson vortices will penetrate boundaries even though the boundaries themselves do not obstruct current



A Gurevich PRB 2003-2005

50 T solenoid for muon cooling

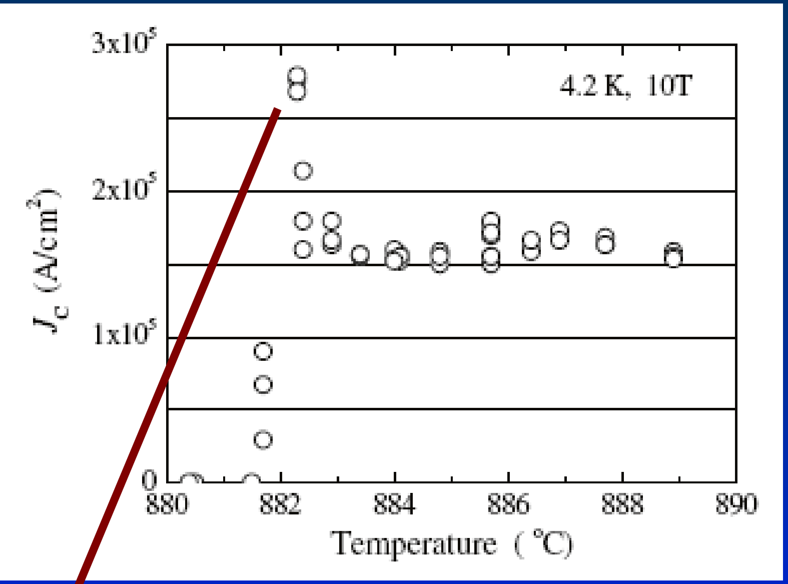


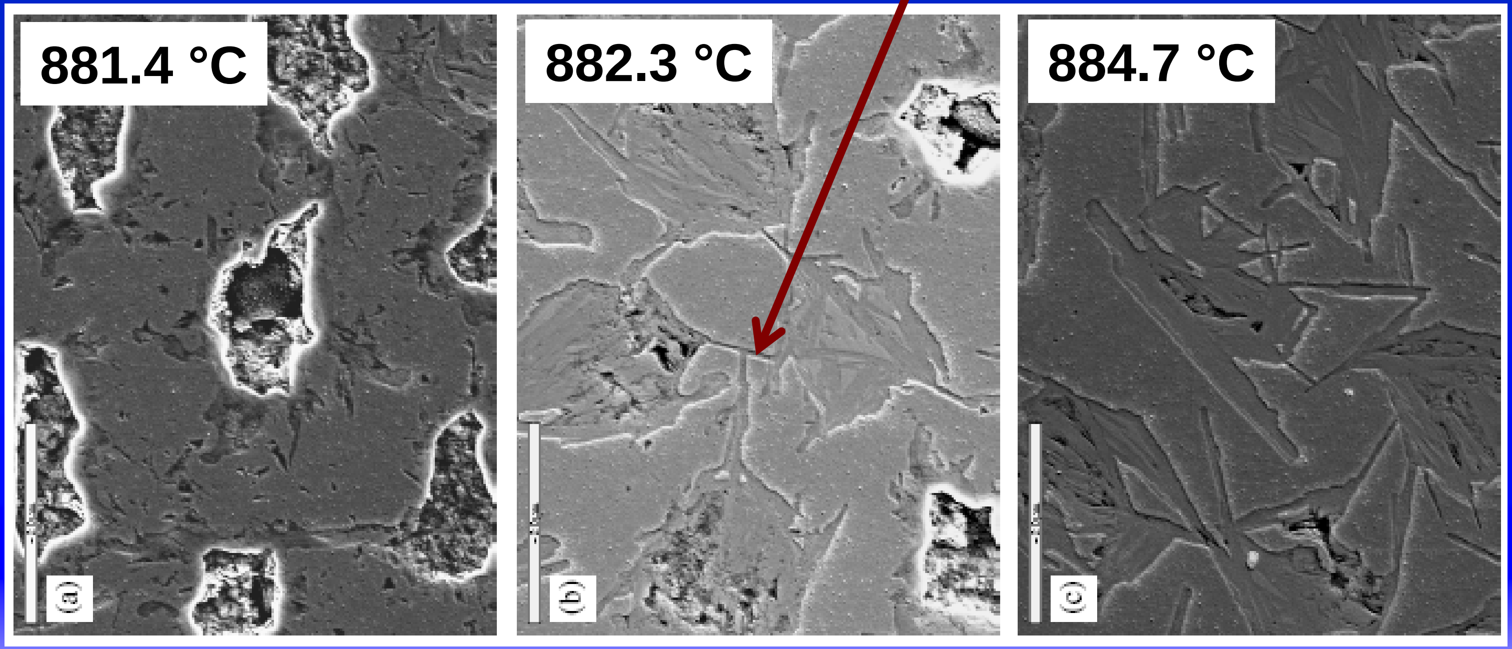
- A Bi-2212 + stainless steel monster?

Challenges

- Open the reaction window to enable wind and react
  - Reaction temperature depends on melting point of $Bi_{2+x}Sr_{2+y}CaCu_2O_8$ ceramic, which is sensitive to Bi:Sr ratio and must be controlled to ±2°C at > 880°C
  - ±15 °C possible but at expense of homogeneity and therefore current density (i.e. highest current density for smallest window)
  - How to heat a coil so uniformly?
- Explore react and wind
- Increase the current density and fill factor

Thin needles carry most of the current!





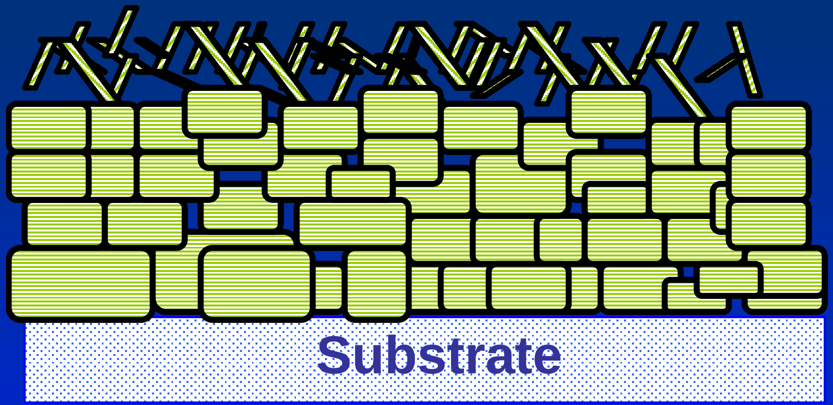
A Matsumoto et al., Supercond.Sci. Technol. 17:989 (2004)

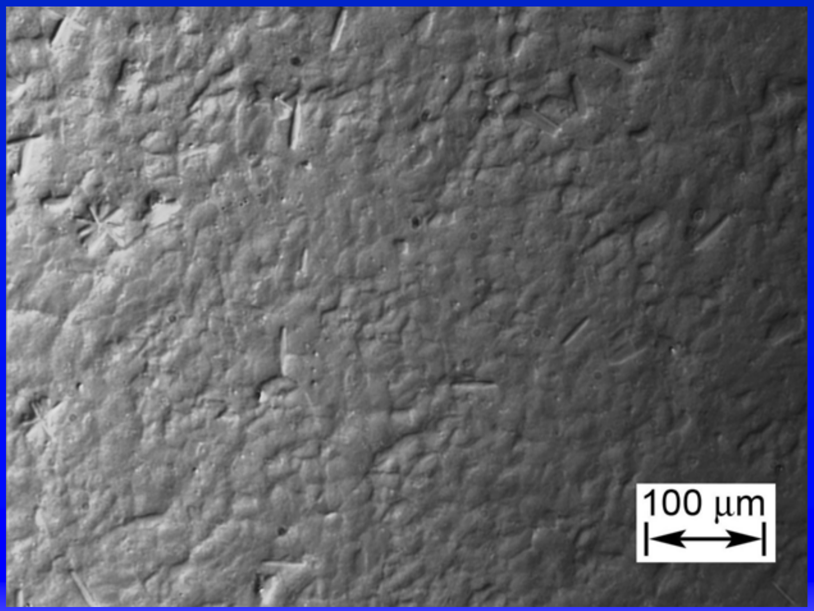
BROOKHAVEN NATIONAL LABORATORY

Can magnet designers use tapes?

Horizon: thick YBCO in long length
- 1000 A/cm tape @ 77K, 0.1T
- (= 2,500 A/cm @ >20T, 4.2K)

- Right now, basic research is making 100% gains in improving flux pinning
- Growth mechanisms are also better understood – new pathways toward thicker YBCO layers
  - Rapid nucleation provides grain-boundary-like pinning for the first time!





V. Solovyov et al, BNL

Summary

- RRP strand is the engineering material that will allow LARP magnet construction!

- Lesson: Vertical nature of discussions within DOE-AARP greatly accelerated development to suit needs of LARP.
  - HEP Low Temperature Superconductor Workshop: End users, industry, and materials scientists together in one room for 2.5 days on an annual basis!
  - Efforts continue under Conductor Development Program

- Can we do better to facilitate R&D?
  - Example: DOE / NSF Center of Excellence

BROOKHAVEN NATIONAL LABORATORY

Summary, cont.

- LARP strand has room for further improvement. Incremental advances are likely given present effort.
  - Must sustain for long term
  - Must allow curiosity to produce breakthroughs
- Changing specs often has repercussions!
  - Example: Nb grain size affects roundness and shape stability, which affect efficiency of tin diffusion and thereby J_c
- New materials offer new opportunities and present new challenges. We need to attack the scientific and technological questions with the same coherent vertical effort.

BROOKHAVEN NATIONAL LABORATORY

Acknowledgments

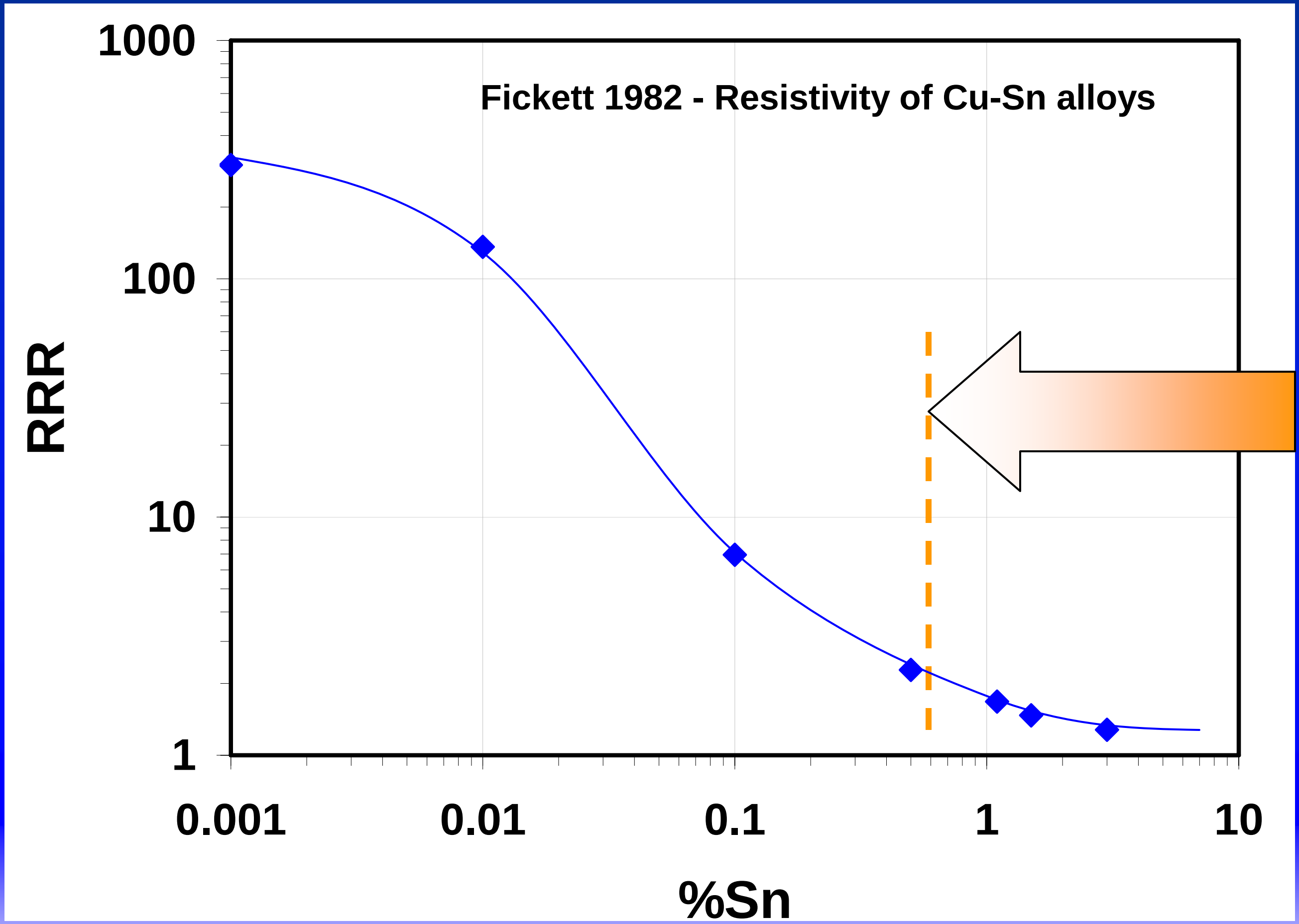
- BNL Superconducting Magnet Division: Arup Ghosh (co-PI), Ed Sperry, Joe D'Ambra
- BNL CMPMSD: Mas Suenaga, Arnold Moodenbaugh, Bob Sabatini, Jesse Wright (student), Paul Chang (student)
- Wisconsin / NHMFL: David Larbalestier, Peter Lee, Arno Godeke (now LBNL), Matt Jewell, Seth Hynes, Chad Fischer (now Intel), Chris Hawes (now Micron Semiconductor)
- Oxford Instruments-Superconducting Technology: Jeff Parrell, Mike Field, Seung Hong, Ken Marken (now LANL)

... And many pleasant discussions with the AARP community!

Reserve slides

Tin destroys thermal conductivity of copper

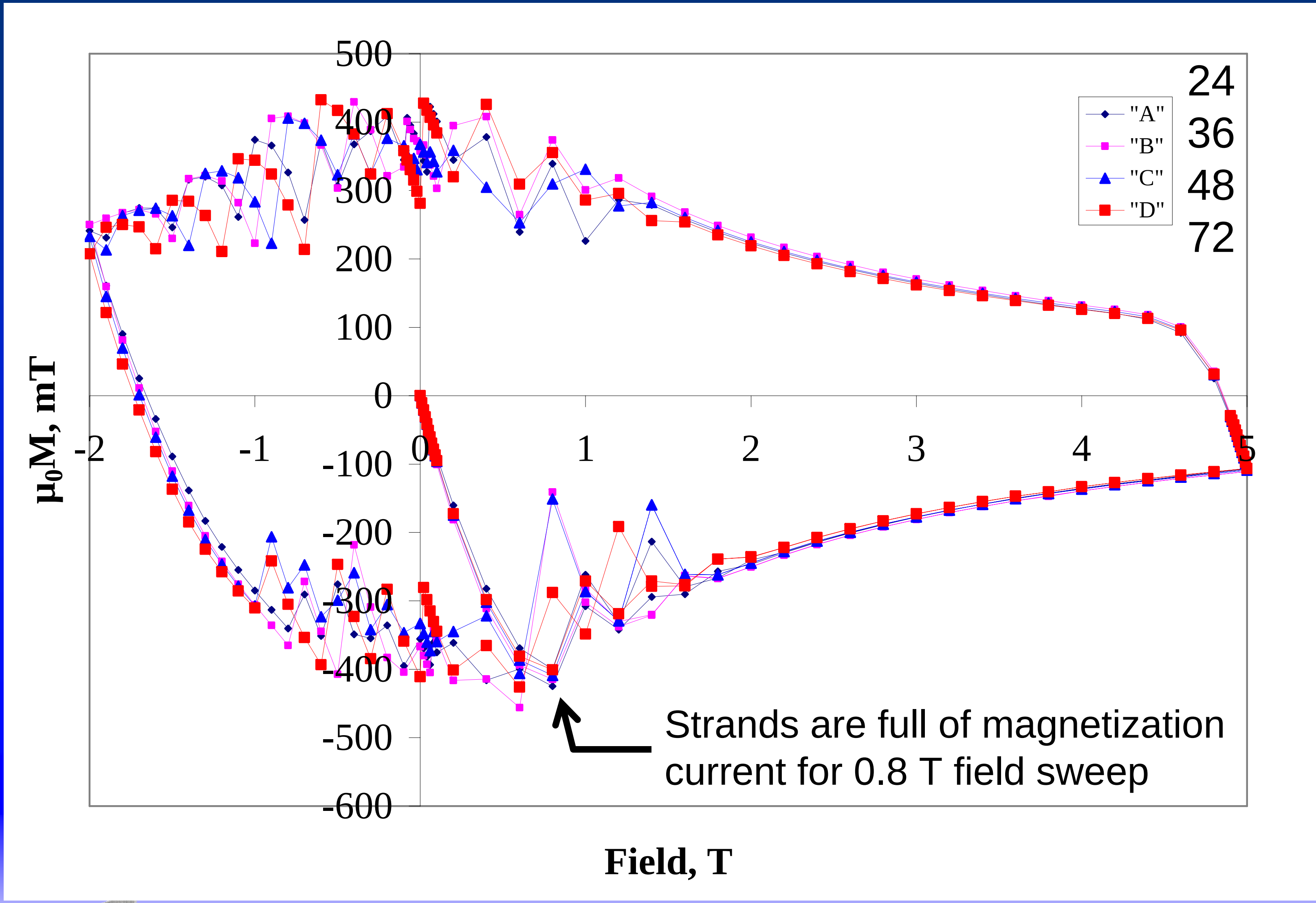
- Tin is a potent electron scatterer: 0.1% Sn will reduce RRR from 300 to 7 —Fickett, Cryogenics vol. 22, p. 135 (1982)



Resolution limit of Scanning Electron Microscopy with Energy-Dispersive X-Ray Spectroscopy (SEM-EDX)

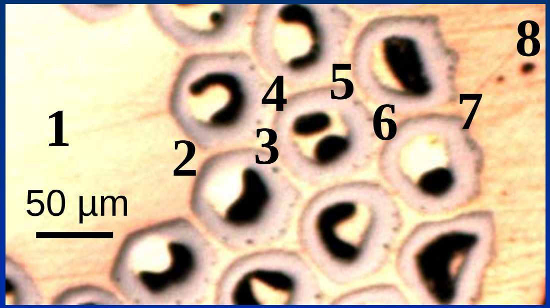
BROOKHAVEN NATIONAL LABORATORY

All reactions produce unstable strands because barrier reacts to form ring of Nb_3Sn around subelement



BROOKHAVEN NATIONAL LABORATORY

How contaminated is the copper?



SEM-EDX microanalyses:

- 120-300 sec., 17 kV
- 2,500-10,000 counts
- no Nb detected

Table II. Atomic fraction of tin (%) determined by EDX as a function of location in Fig. 1 for various samples.

Location	Samples				
	A	C	D	E	F
1	<0.5	<0.5	<0.5	<0.5	0.66
2	<0.5	2.67	1.61	1.32	1.62
3	<0.5	4.26	2.69	3.02	1.72
4	<0.5	2.82	1.95	2.44	2.07
5	<0.5	2.41	[illegible]	[illegible]	1.88
6	<0.5	1.73	1.68	1.67	1.61
7	<0.5	0.60	0.59	0.51	0.64
8	<0.5	<0.5	<0.5	<0.5	<0.5

THERMAL PATHWAY IS DEAD

Traditional V-I curve