Performance Boundaries in Nb_3Sn Superconductors

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May 1, 2006

Acknowledgments

University of Twente

The Applied Superconductivity Center

The University of Wisconsin Madison

Bennie ten Haken

Herman ten Kate

Sasha Golubov

…

David Larbalestier

Peter Lee

Alex Gurevich

Matt Jewell

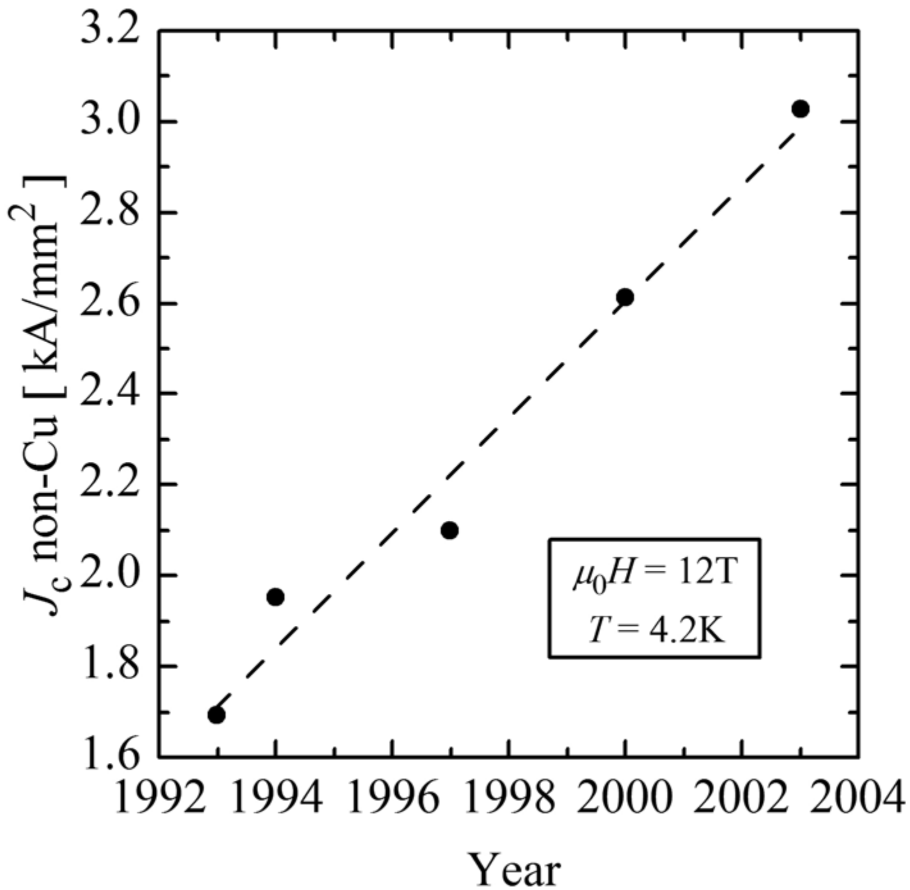
Chad Fischer

…

Outline

- Critical current density and critical current
- Composition variation in Nb_3Sn wires
- Composition and $H_{c2}(T)$
- Pinning capacity, grain boundary pinning, grain size
- Composition and J_c
- Strain dependence (*time allowing*)
- Present status and future prospects

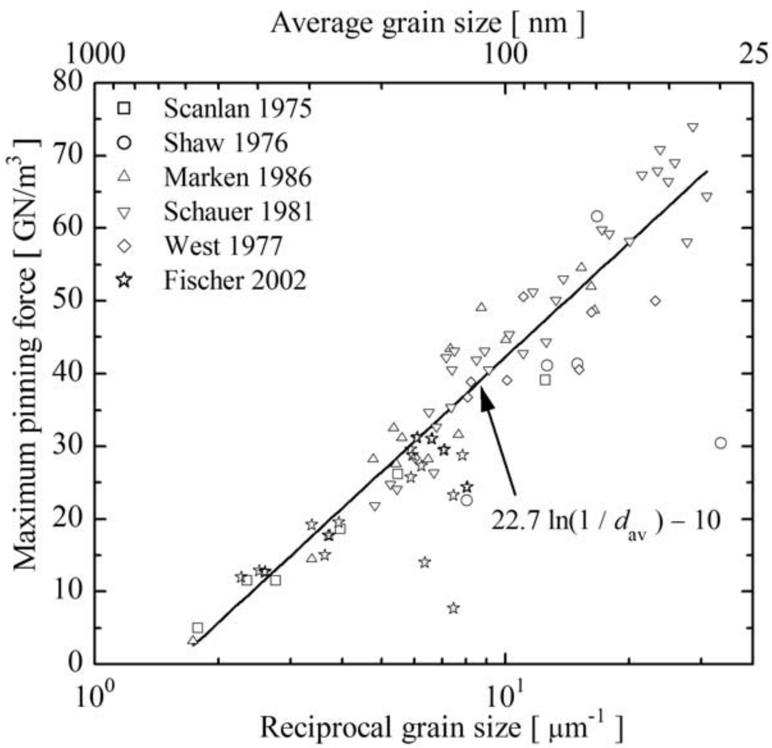
Wire J_c progress versus time



- Parrell, ACE 2004

What determines J_c?

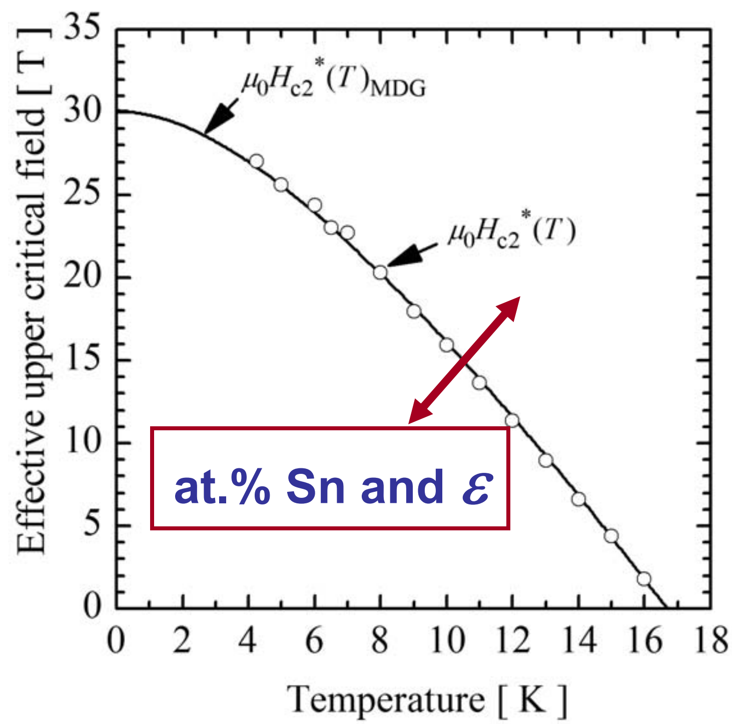
Pinning capacity



- Average grain size

+

Effective $H - T$ phase boundary



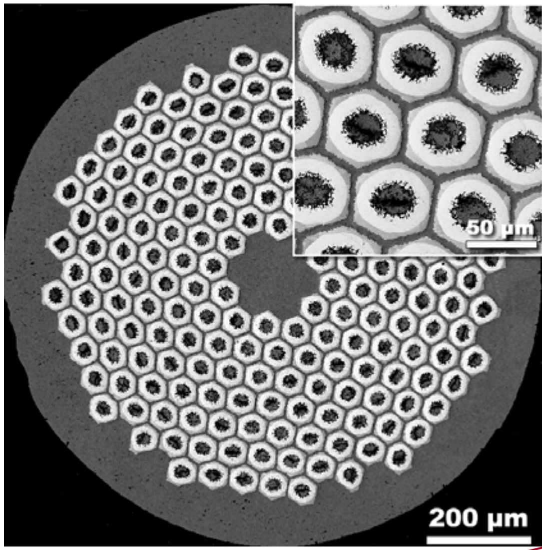
- Composition
- Strain state

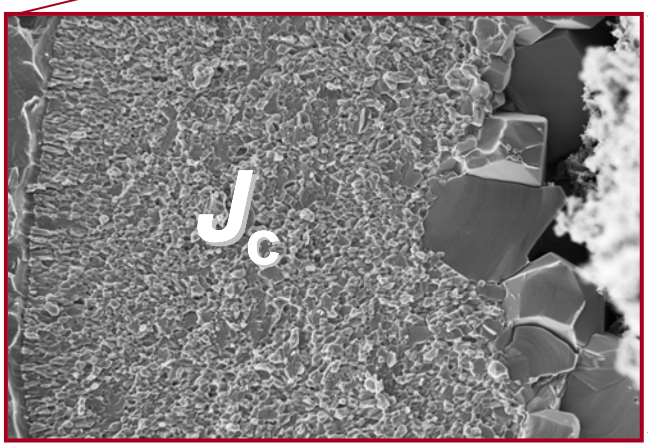
= J_c

$J_c \rightarrow I_c$?

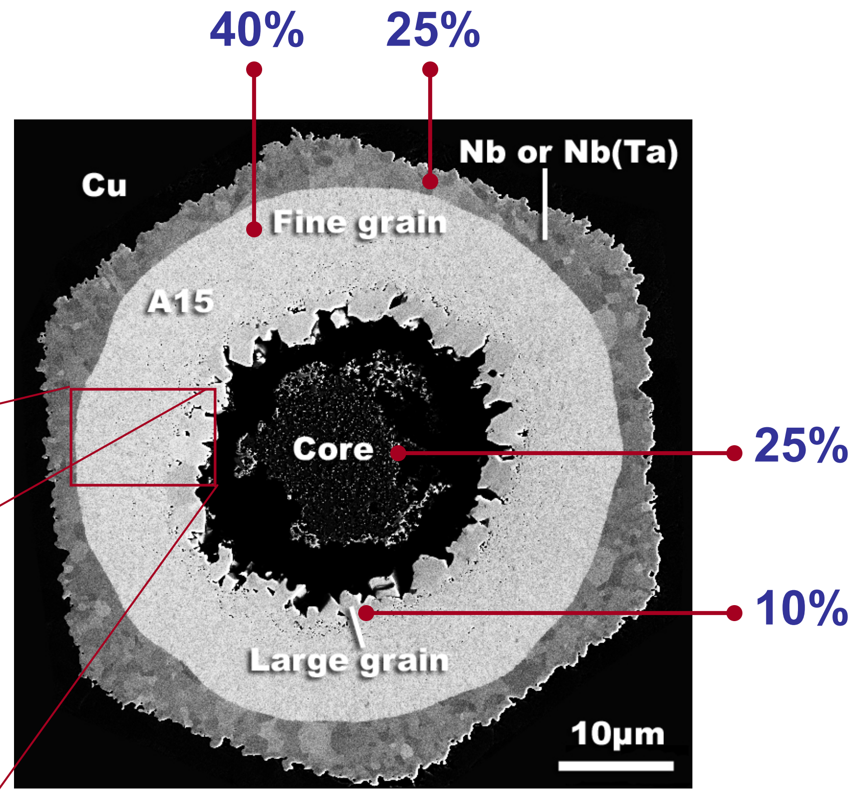
What determines I_c?

- Powder-in-tube wire (SMI)





- 50% Non – Cu fraction



- Only 20% of the wire carries J_c

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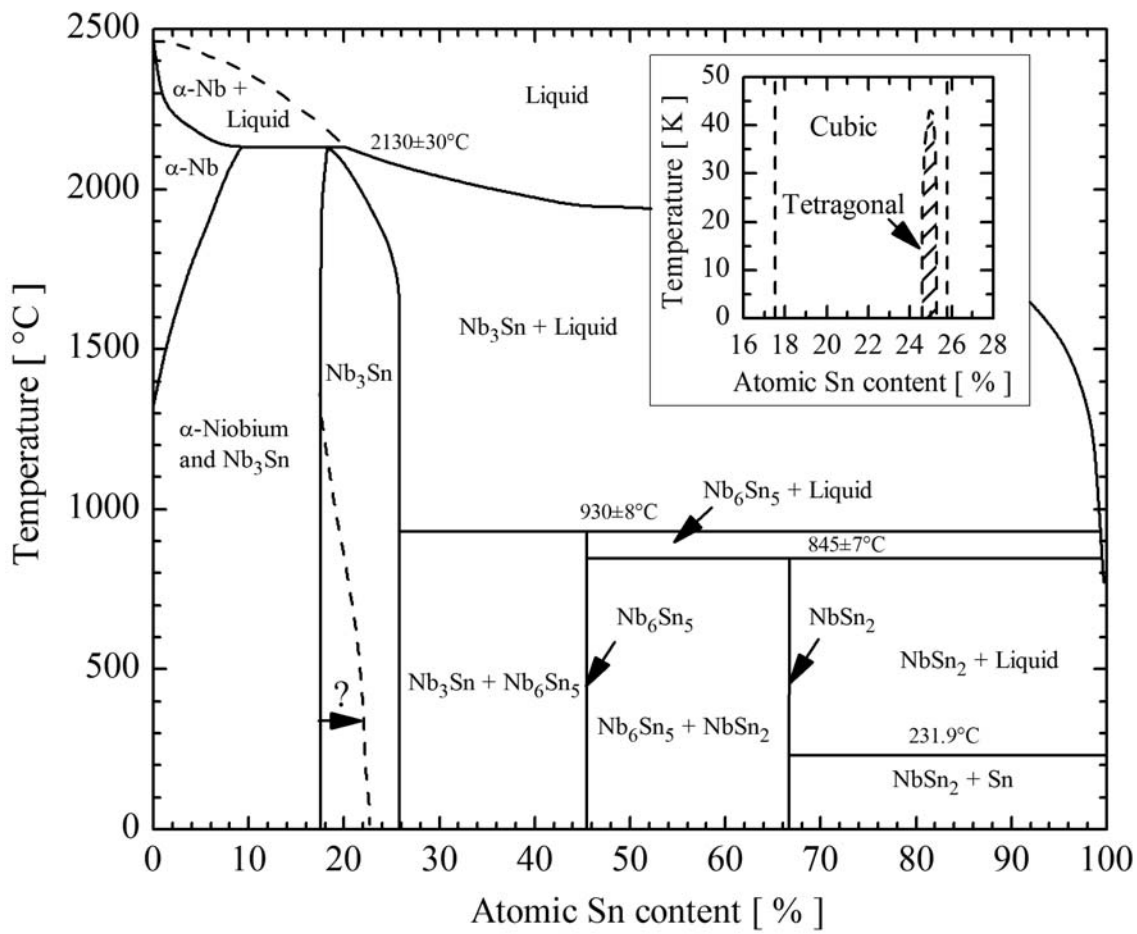
Composition: $Nb_3Sn \rightarrow Nb_{1-\beta}Sn_{\beta}$

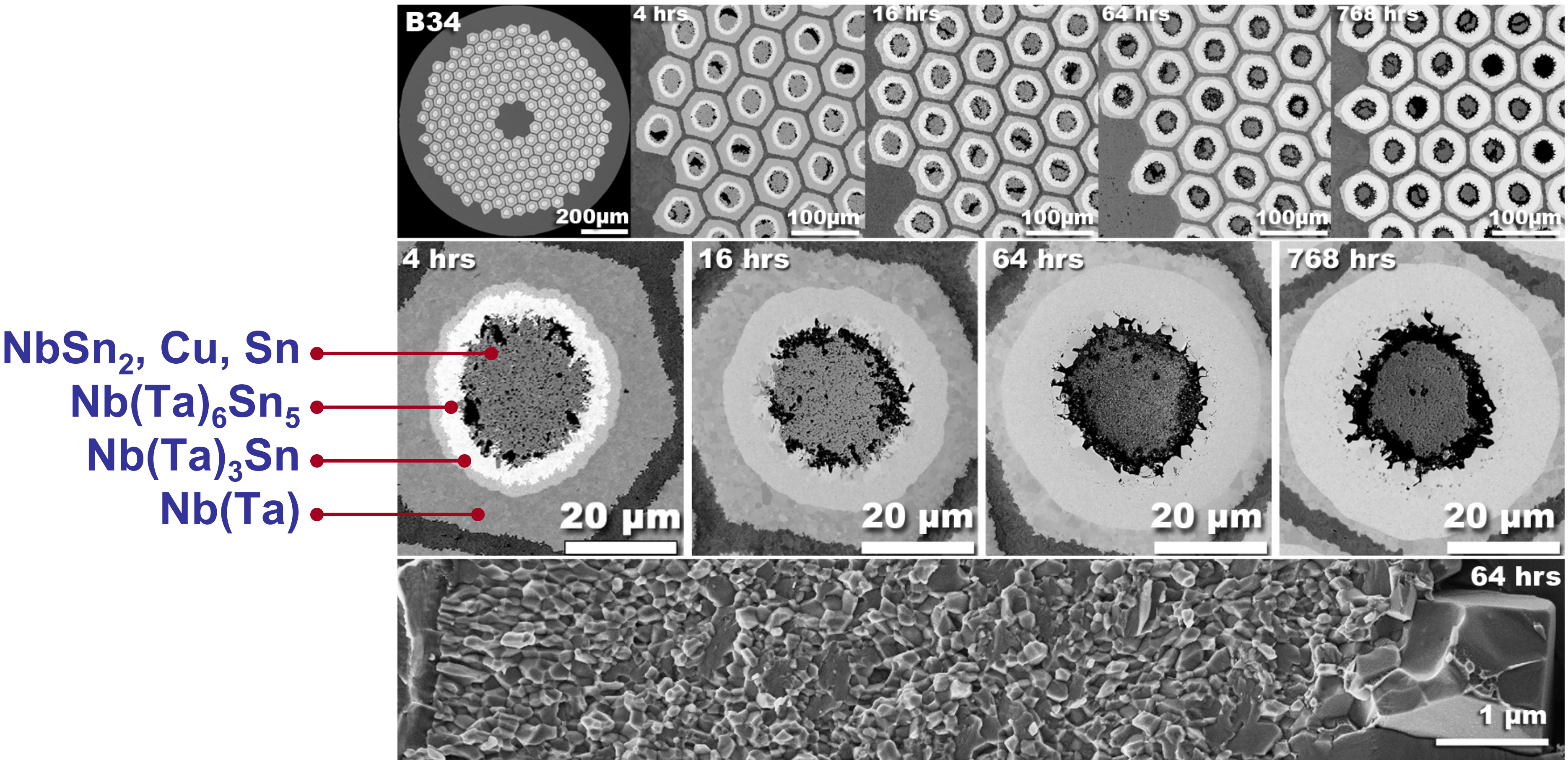
- **Binary phase diagram → 18 to 25 at.% Sn → 'A15'**



- **Charlesworth, JMS 1970, Flükiger, ACE 1982**

Nb_3Sn diffusion reaction in wires

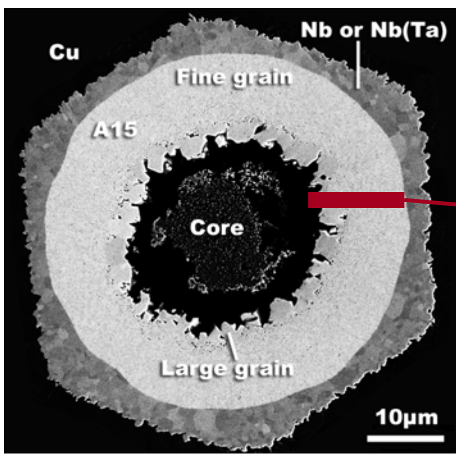
- **Reaction at 675°C vs time in Powder-in-Tube wire (SMI)**

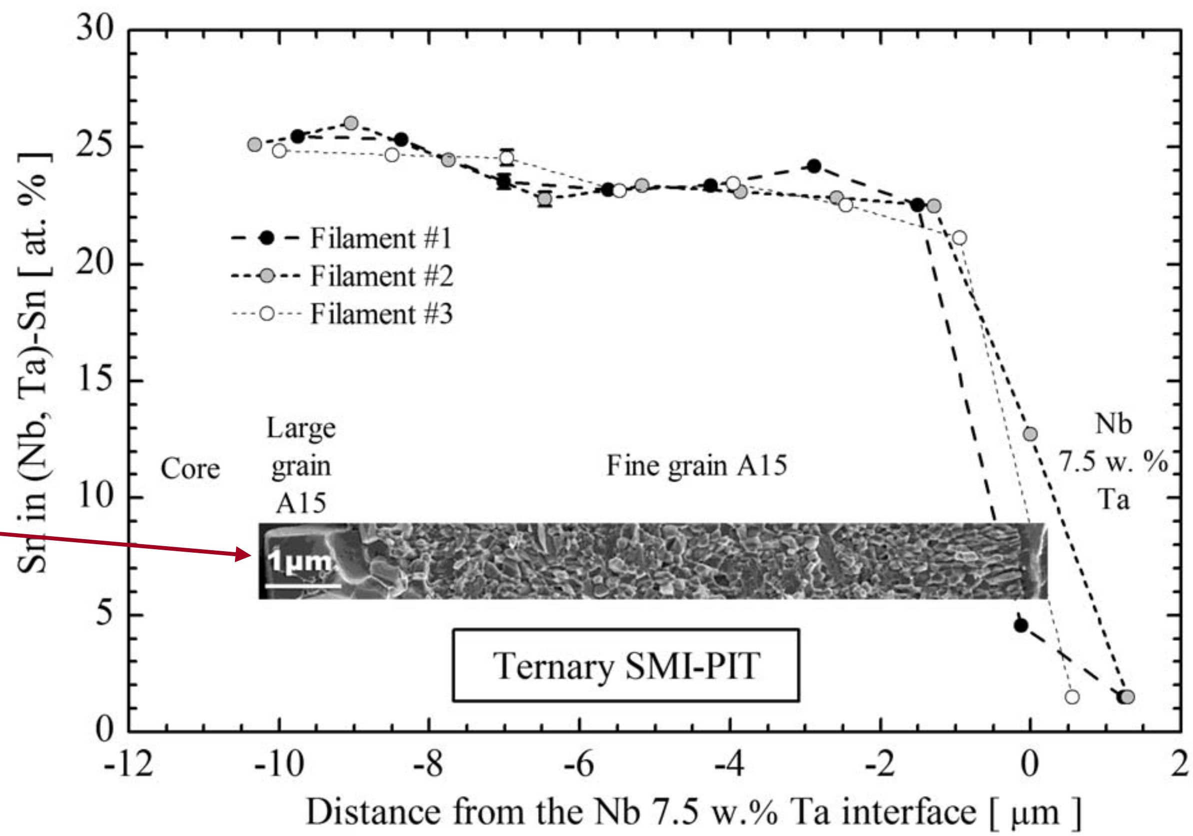


Composition variation in wires

- Composition analysis on SMI Powder-in-Tube wire

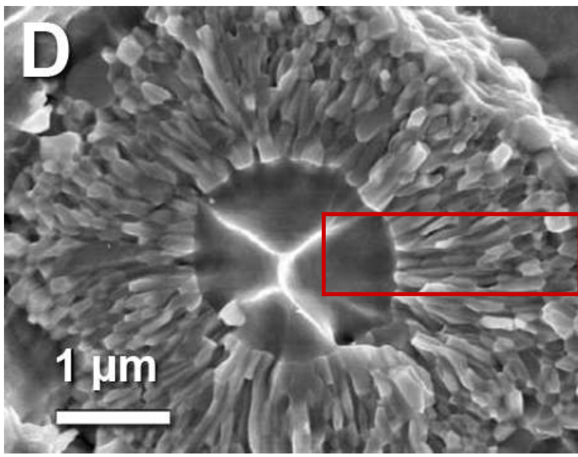
- 0.3 at.% Sn/μm
- J_c(12T,4.2) = 2250 A/mm^2

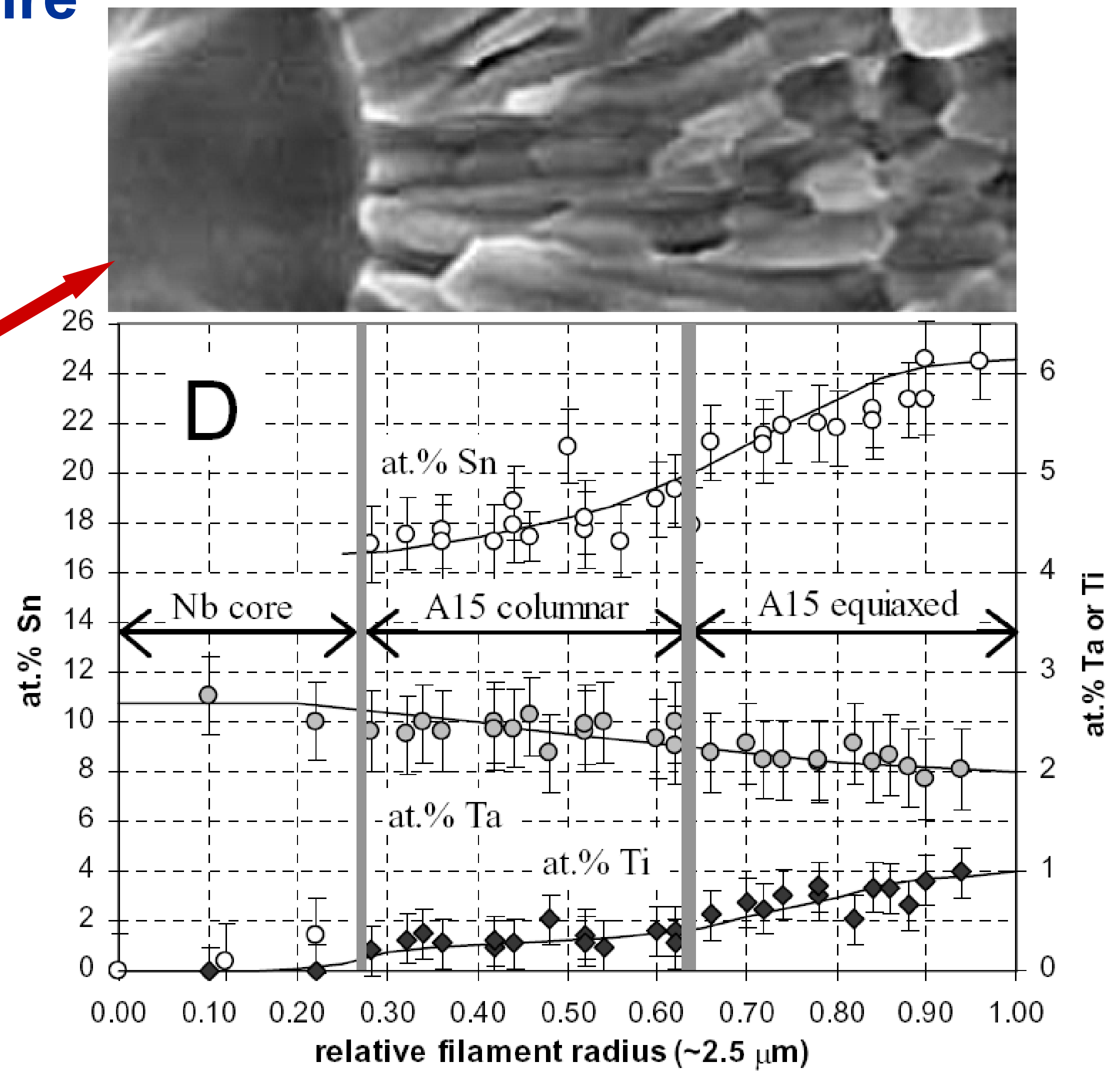




Composition variation in wires

- **Bronze process wire Univ. of Geneva**



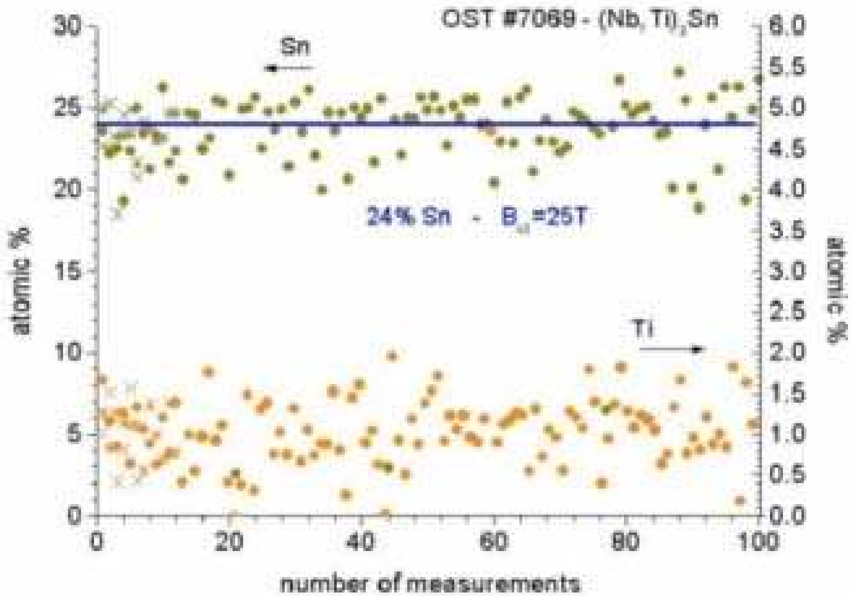


- **4 at.% Sn/µm**
- **J_c(12T,4.2) = 720 A/mm^2**

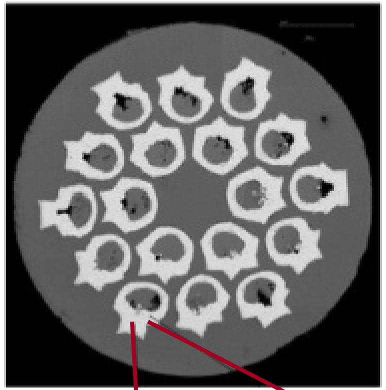
  - **Abächerli, TAS 2005**

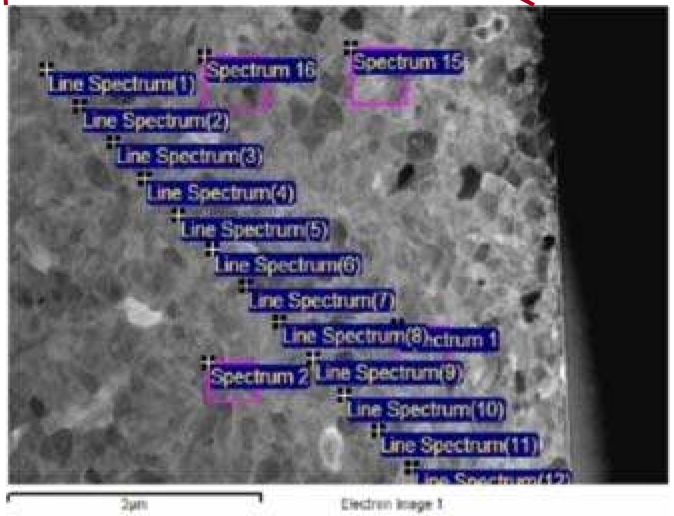
Composition variation in wires

- OST Internal-Tin wire
- Flat Sn content at 24 at.%
- J_c(12T,4.2) = 3000 A/mm^2



- Uglietti, MT19 2005





Increasing J_c with increasing Sn

Geneva Bronze Process	25 at.% Sn @ source 4 at.% Sn/µm gradient	J_c(12T,4.2) = 720 A/mm^2
SMI Powder-In-Tube	25 at.% Sn @ source 0.3 at.% Sn/µm gradient	J_c(12T,4.2) = 2250 A/mm^2
OST Internal Tin	24 at.% Sn no gradient	J_c(12T,4.2) = 3000 A/mm^2

Sn richer
Higher J_c
Why?

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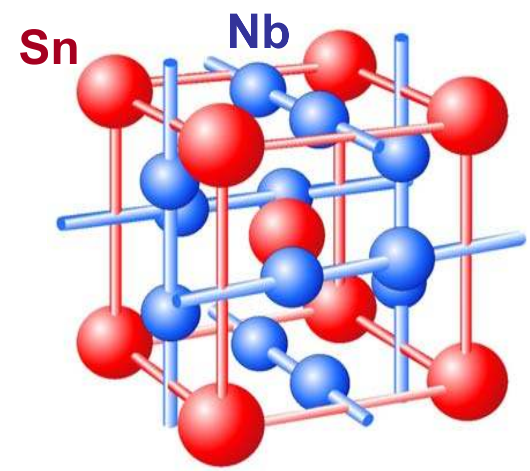
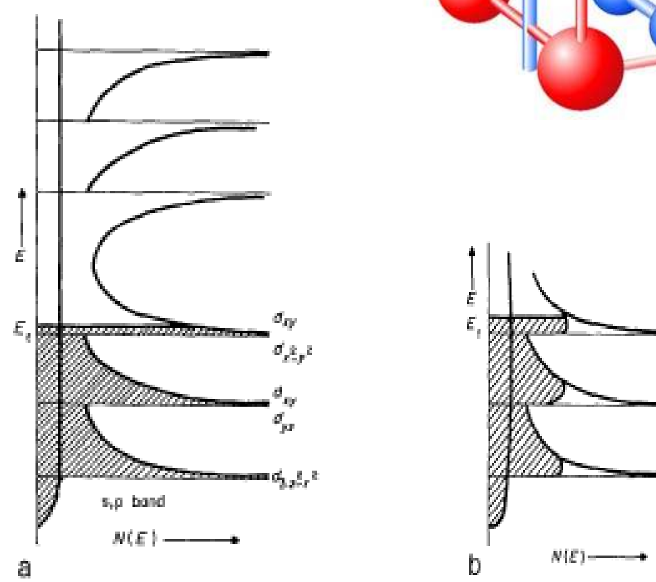
What happens with changing Sn content?

- Pure Nb
  - *bcc* Nb spacing 0.286 nm
  - T_c = 9.2 K
- Nb_3Sn → A15 unit cell
  - *bcc* Sn, orthogonal Nb chains
  - Nb spacing 0.265 nm
  - High peaks in d-band DOS
  - Increased T_c = 18 K
- Off-stoichiometry
  - Sn vacancies unstable
  - Excess Nb on Sn sites
    - Additional d-band
    - Less electrons for chains
    - Rounded off DOS peaks
    - Reduced T_c

A15 lattice and DOS





- Dew-Hughes, Cryogenics 1975

Nb chain continuity, $N(E_F)$, λ_{ep}, T_c, H_{c2}

In general

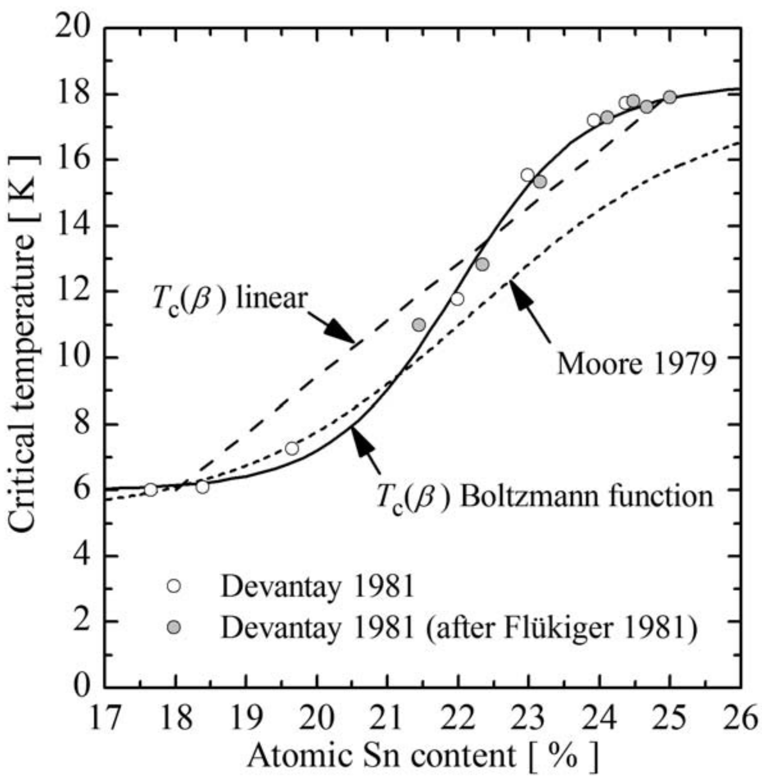
- Sn deficiency
- Tetragonal distortion
  - 24.5 – 25 at.% Sn
- Strain
- Alloying (Ti, Ta, …)
- Dislocations
- Anti-site disorder

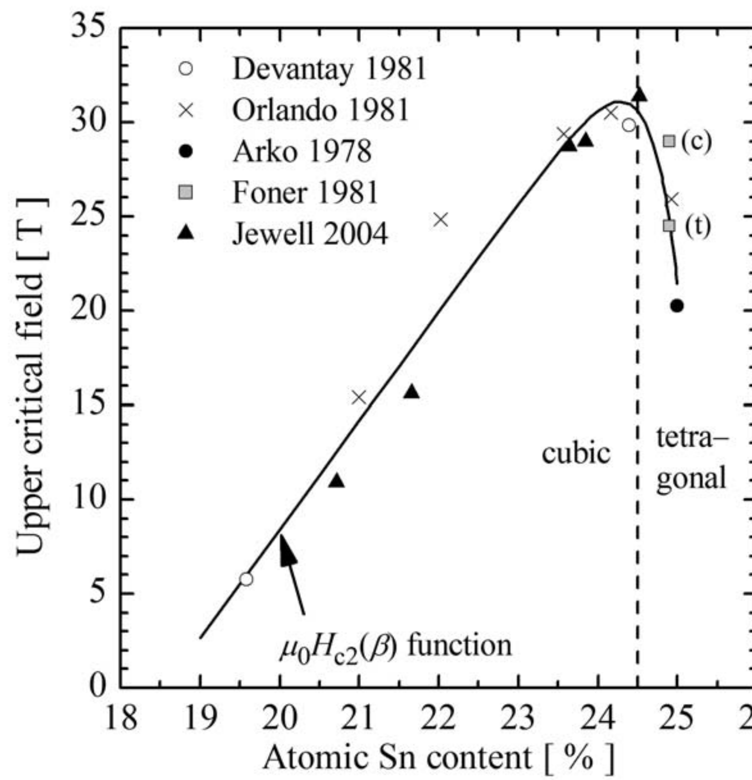
All affect Nb chain integrity ('Long Range Order')

- And thus $N(E_F)$ and λ_{ep}
- And thus T_c and H_{c2}

T_c and H_{c2} versus Sn content

Single crystal, bulk and thin film samples



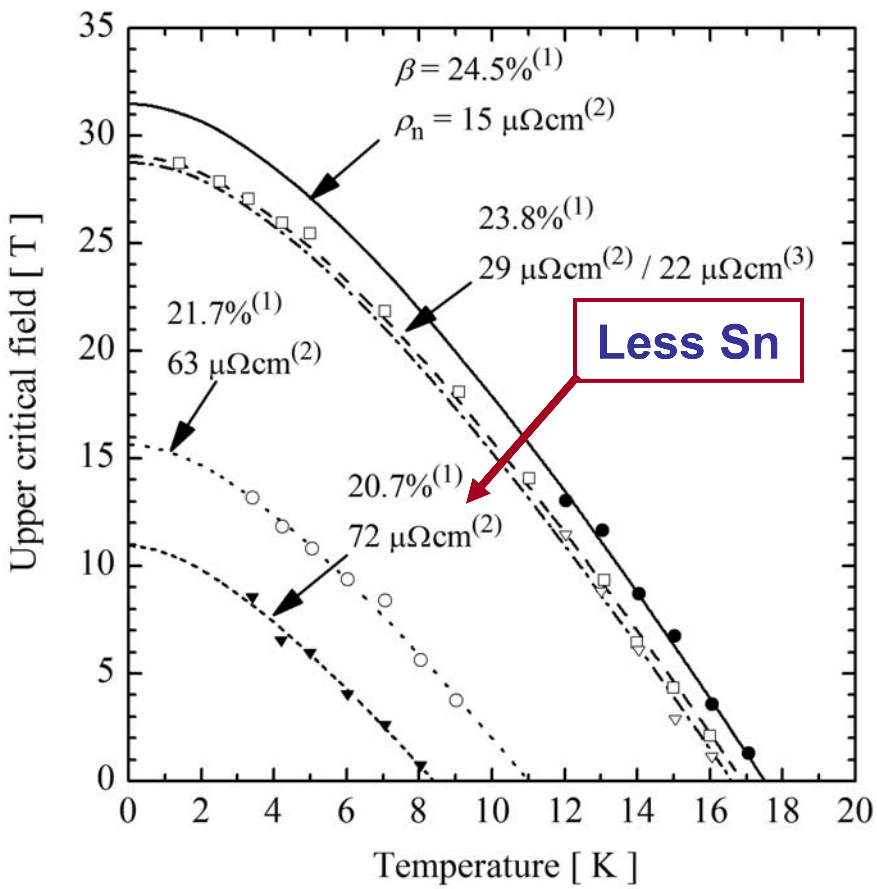


$$T_c(\beta) = \frac{-12.3}{1+\exp\left(\frac{\beta-0.22}{0.009}\right)} + 18.3$$

$$\mu_0 H_{c2}(\beta) = -10^{-30}\exp\left(\frac{\beta}{0.00348}\right) + 577\beta - 107$$

$H_{c2}(T)$ versus Sn content

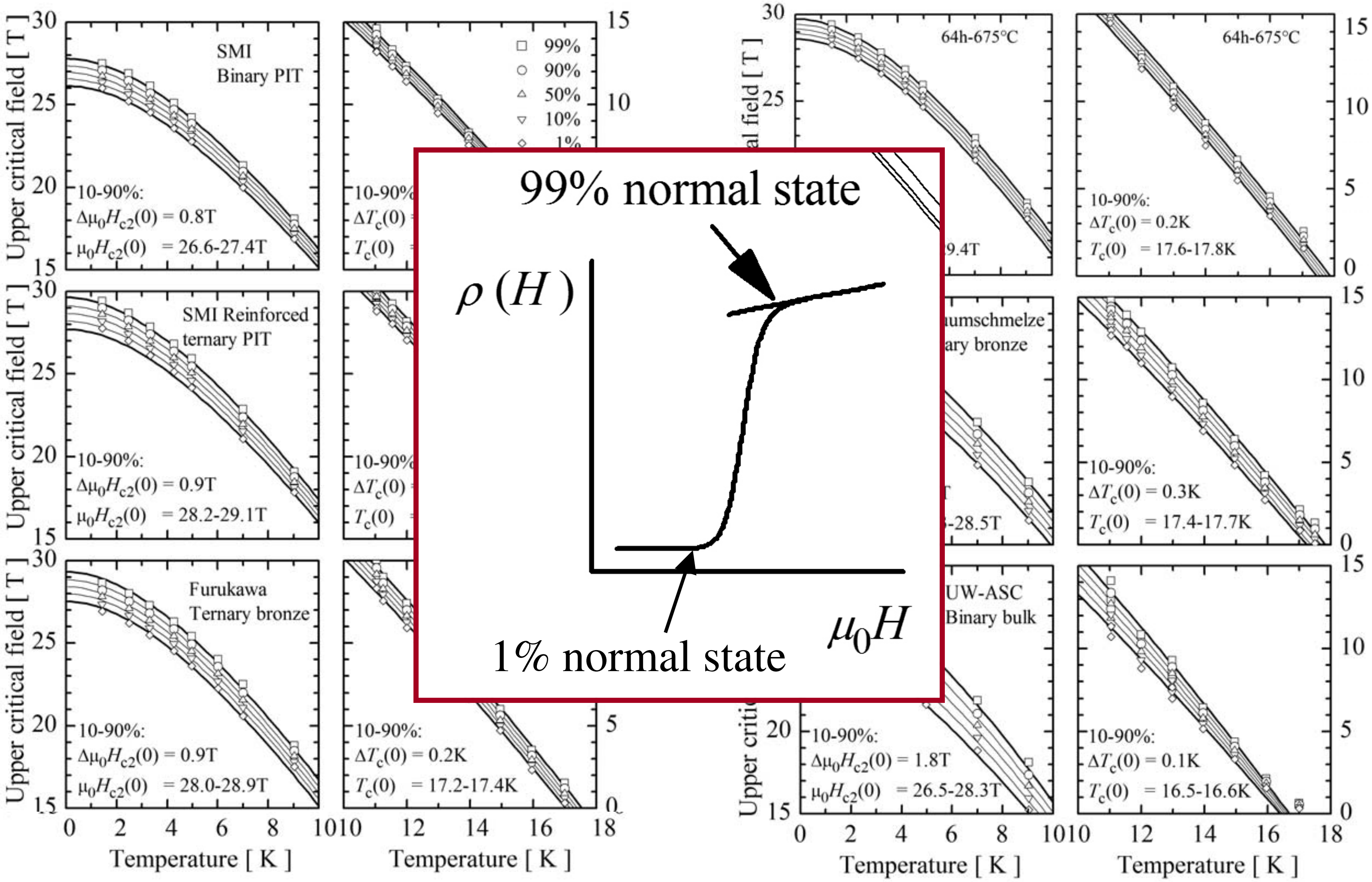
- **Jewell, ACE 2004, bulk samples**



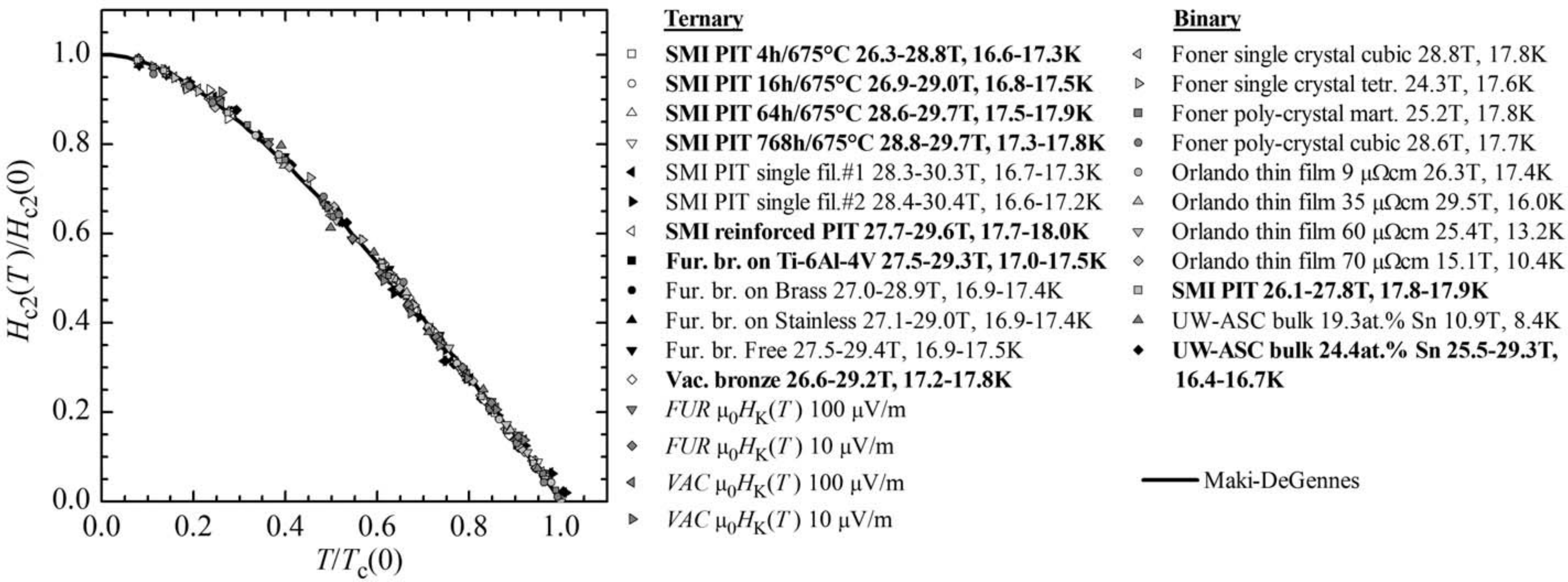
- **Sn richer A15 has higher $H_{c2}(T)$ (until ~ 24.5 at.% Sn)**

$H_{c2}(T)$ in wires

- $H_{c2}(T)$ from small current, resistive transitions



Normalized $H_{c2}(T)$ all available results



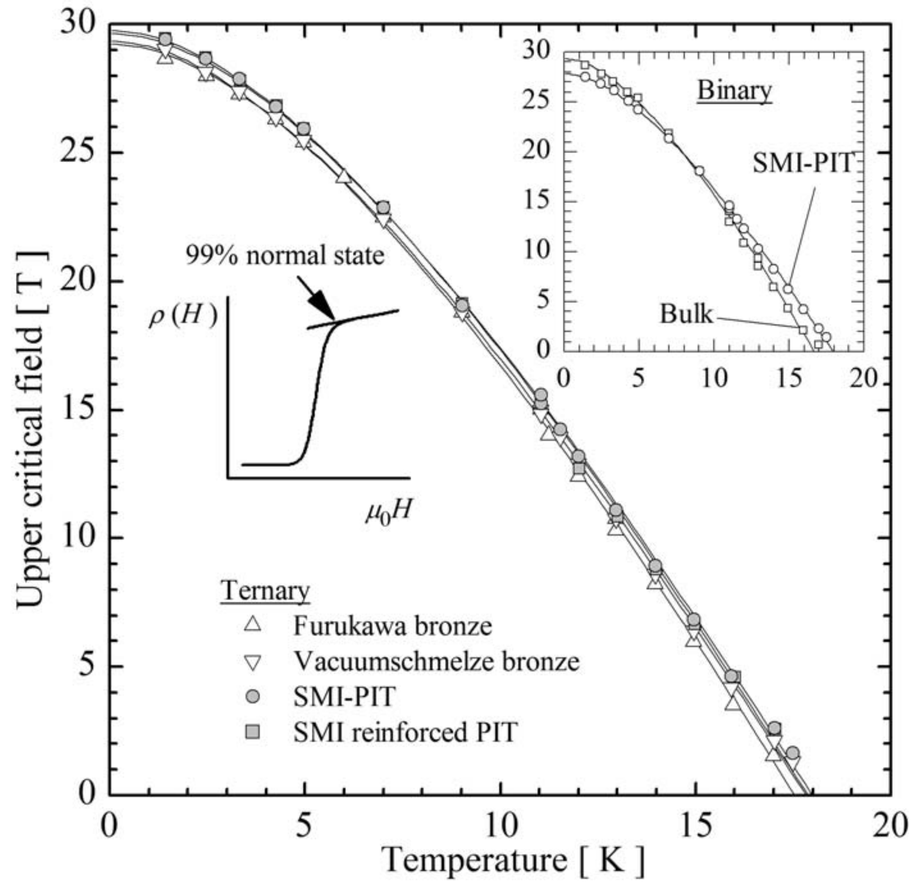
- Shape $H_{c2}(T)$ independent of
  - Composition
  - Morphology
  - Strain state
  - Applied critical state criterion

$$\ln\left(\frac{T}{T_c(0)}\right)=\psi\left(\frac{1}{2}\right)-\psi\left(\frac{1}{2}+\frac{\hbar D\mu_0 H_{c2}(T)}{2\phi_0 k_B T}\right)$$

Approximation:

$$\frac{H_{c2}(t)}{H_{c2}(0)}\cong 1-t^{1.52},\quad t=\frac{T}{T_c(0)}$$

Highest $H_{c2}(T)$ in wires



$\mu_0 H_{c2}(0)$ = 30 T, $T_c(0)$ = 18 K is upper limit

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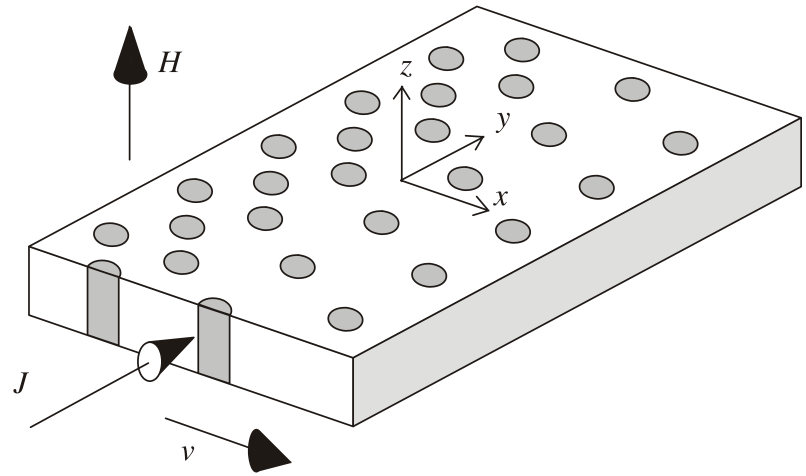
Pinning: Why does Nb_3Sn need it?

- Nb_3Sn slab in $H_{c1} < H < H_{c2}$
- Field quanta $\phi_0 = h / 2e$ (flux-lines) penetrate slab

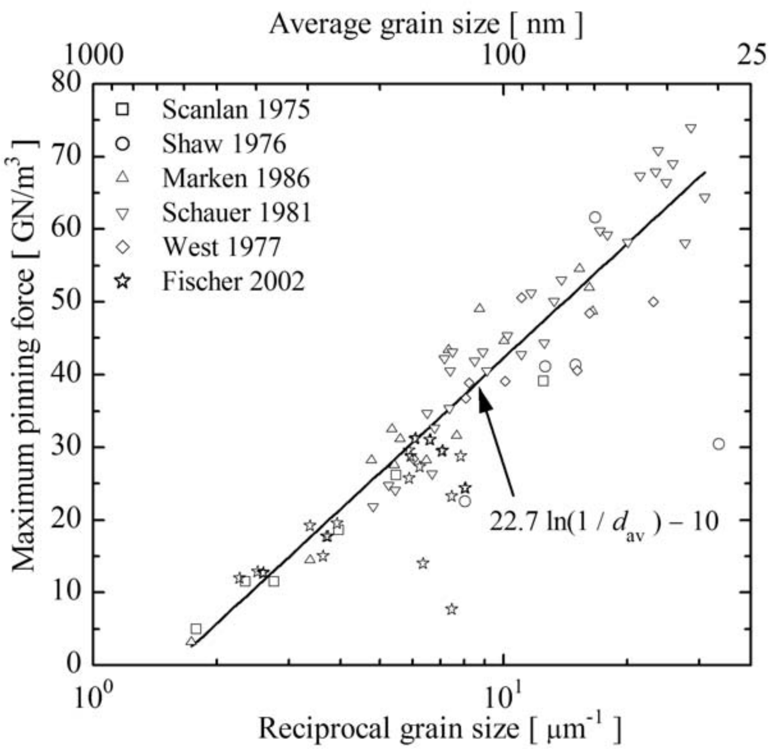


- Transport current ($\nabla\times B = \mu_0 J$) causes gradient B_x
- Flux-lines repel → move ($\nabla\times E = -dB/dt$) → E_y → Loss
  - Need to be 'pinned' at 'pinning centers' by 'pinning force' F_P
- Optimal pinning at 1 pinning center / flux-line

What determines pinning capacity?

Pinning centers

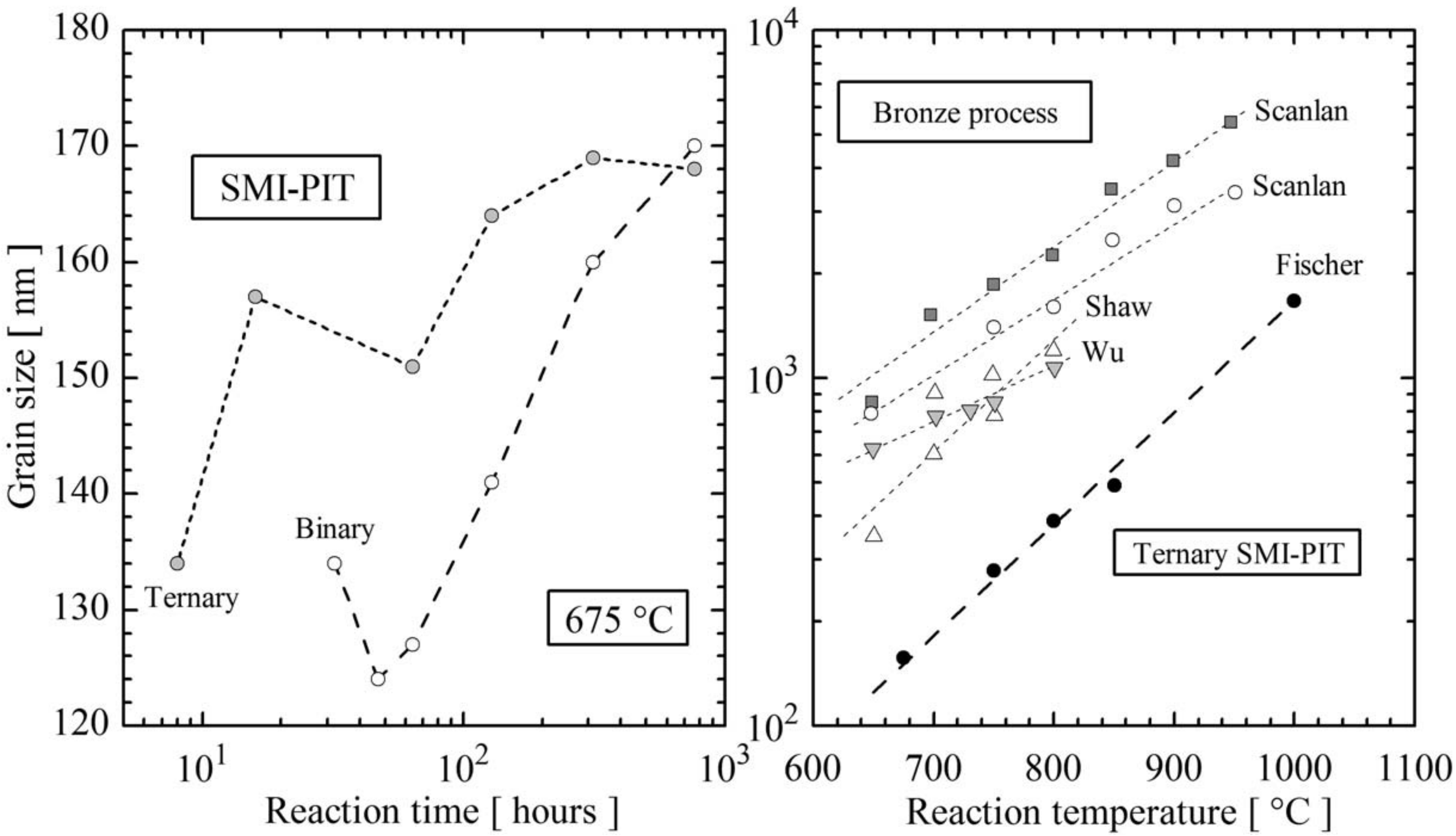
- Positions with minima in SC wave function
  - Normal regions
  - Grain boundaries
  - Lattice imperfections
  - …



- Nb_3Sn
  - Grain boundaries
    → Main pinning centers
  - Grain size determines F_{Pmax}

What determines grain size?

- Presence of grain nucleation points
- Reaction time and temperature



What is an optimal grain size?

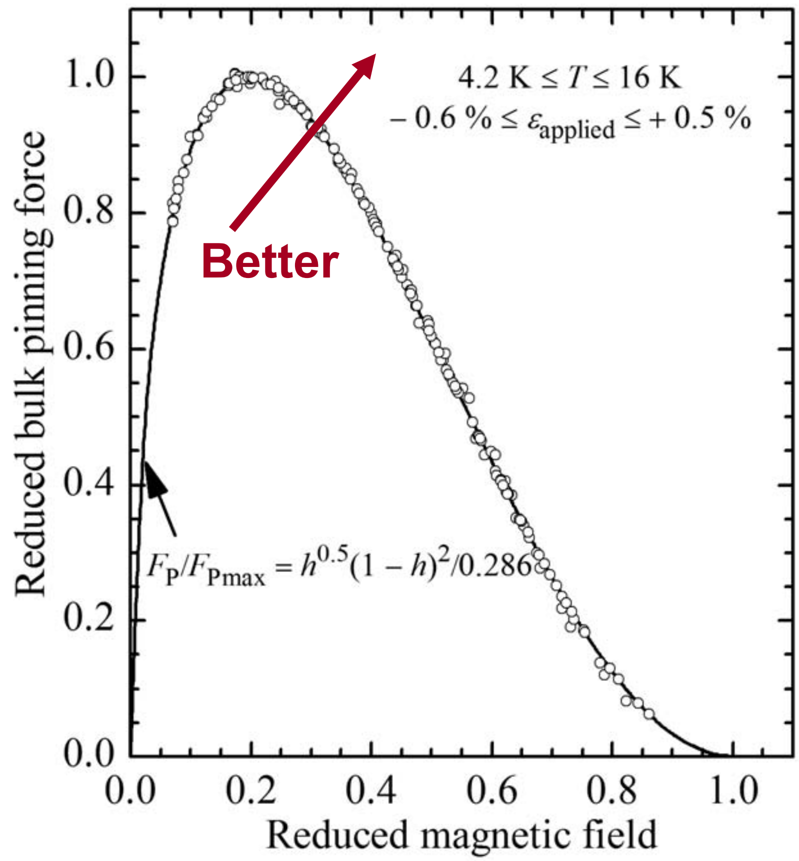
Ideal: One pinning center per flux-line → $a_\Delta \approx d_{av}$

- Flux-line spacing → field dependent
  - E.g. at 12 T $a_\Delta = (4/3)^{1/4}(\phi_0/\mu_0 H)^{1/2} = 14$ nm
  - Grain size in Nb_3Sn wires → 100 – 200 nm
  - Order of magnitude from optimal
- For any practical field $a_\Delta << d_{av}$
  - Collective pinning ('shearing' of FLL)
  - $a_\Delta \rightarrow d_{av}$ only for $\mu_0 H << 1$ T
- NbTi in contrast
  - Nano-scale distribution of α-Ti precipitates
  - $a_\Delta \approx \alpha$-Ti distribution for application fields
  - NbTi is fully optimized

What does a_Δ << d_{av} mean in practice?

- De-pinning → Synchronous shearing of FLL
- F_{Pmax} at H/H_{c2} = 0.2
  - About 6 T for Nb_3Sn
  - Far below application fields
- Grain refinement / APC
  - F_{Pmax} to higher field
  - F_{Pmax} → H/H_{c2} > 0.4 shown by Cooley, ACE 2002
  - Higher fields accessible with Nb_3Sn
- Much room for improvement!

- Example: Bronze processed ITER wire (Furukawa)



Alternative presentation $a_\Delta << d_{av}$

- **Flux shear model**
  - **Kramer JAP 1973**

$$F_P(H) = 12.8 \frac{(\mu_0 H_{c2})^{2.5}}{\kappa_1^2} \frac{h^{0.5}(1-h)^2}{\left(1-a_\Delta(H)/d_{av}\right)^2}, \quad h = \frac{H}{H_{c2}} \quad [\mathrm{GN/m^3}]$$

$$\therefore \quad J_c^{0.5}(\mu_0 H)^{0.25} = \frac{1.1\times10^5}{\kappa_1} \frac{\mu_0(H_{c2}-H)}{\left(1-a_\Delta(H)/d_{av}\right)}$$

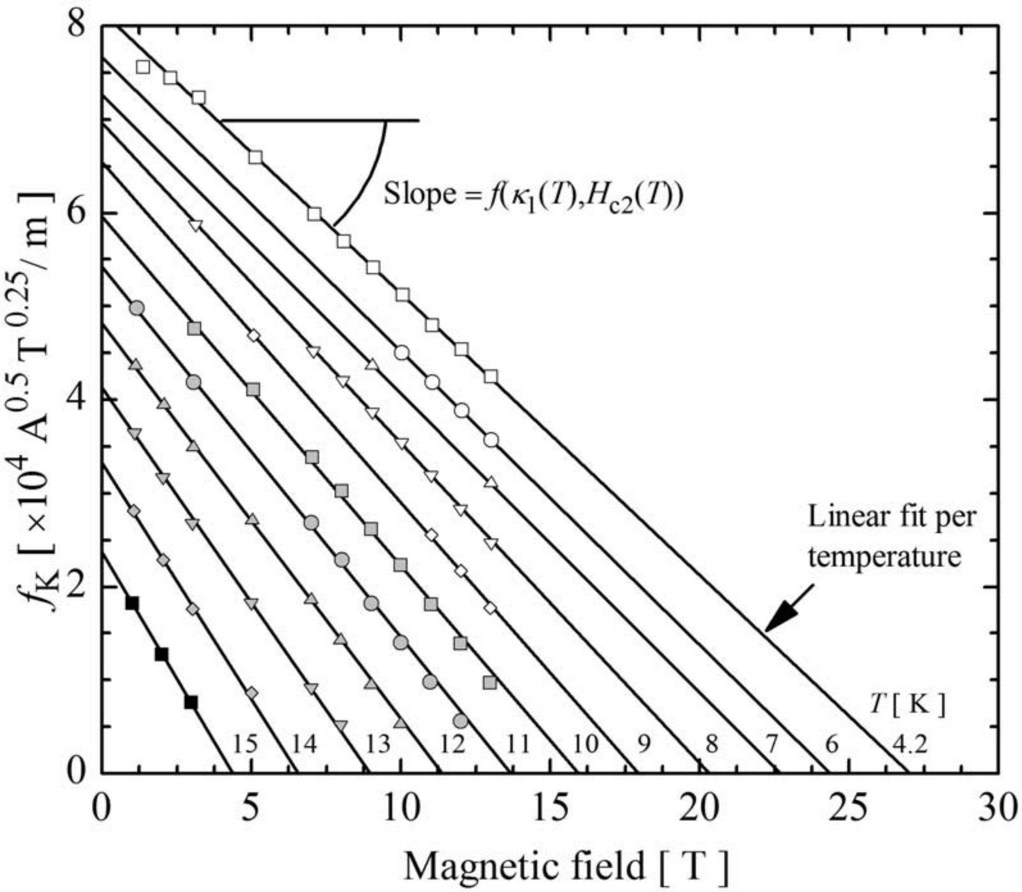
- **$a_\Delta << d_{av}$: Kramer plot**

$$f_K(H) \equiv J_c^{0.5}(\mu_0 H)^{0.25} \cong \frac{1.1\times10^5}{\kappa_1}\mu_0(H_{c2}-H) \quad \therefore \boxed{f_K(H) \propto H}$$

- **Linear in H**

‘Kramer’ plot

- **Plot of $f_K(H)$ at various temperatures**



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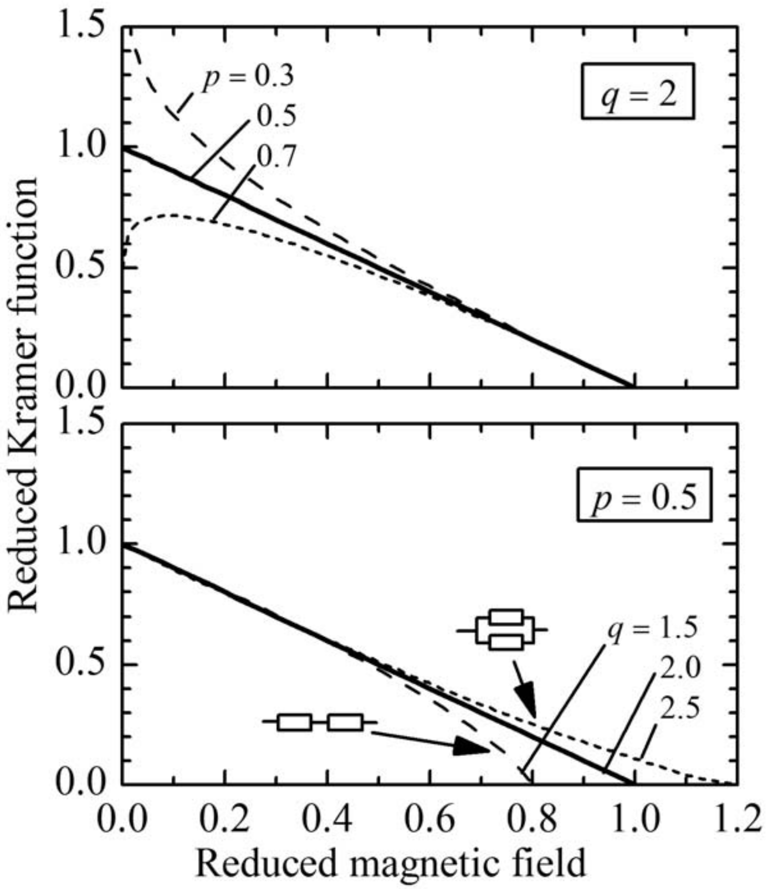
Are Kramer plots linear?

$$F_P(h) = 12.8\frac{(\mu_0 H_{c2})^{2.5}}{\kappa_1^2} h^{0.5}(1-h)^2 \quad a_\Delta \ll d_{av}$$

$$\triangleq \quad F_P(h) = F_{P\max} h^p (1-h)^q \quad p = 0.5, \quad q = 2$$

- **Linearity from $h \cong 0.03$ to 0.8**
  - **Confirmed by measurements**
- **$a_\Delta \cong d_{av}$ only below $h \cong 0.03$**
- **Different pinning mechanism?**
  - **only below $h \cong 0.03$**

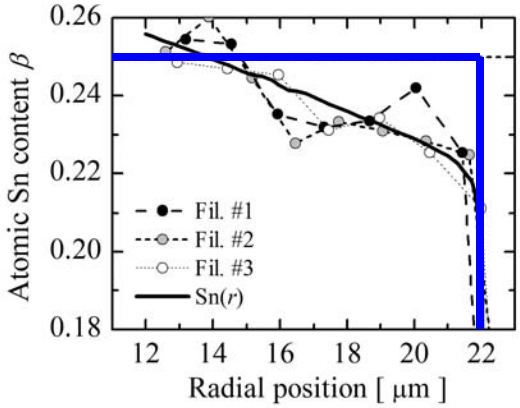
- **Non-linearity below $h \cong 0.03$**
  - **Different pinning mechanism**
- **Non-linearity above $h \cong 0.8$**
  - **Inhomogeneity artifacts**
    - **Averaging over H_{c2} distribution**

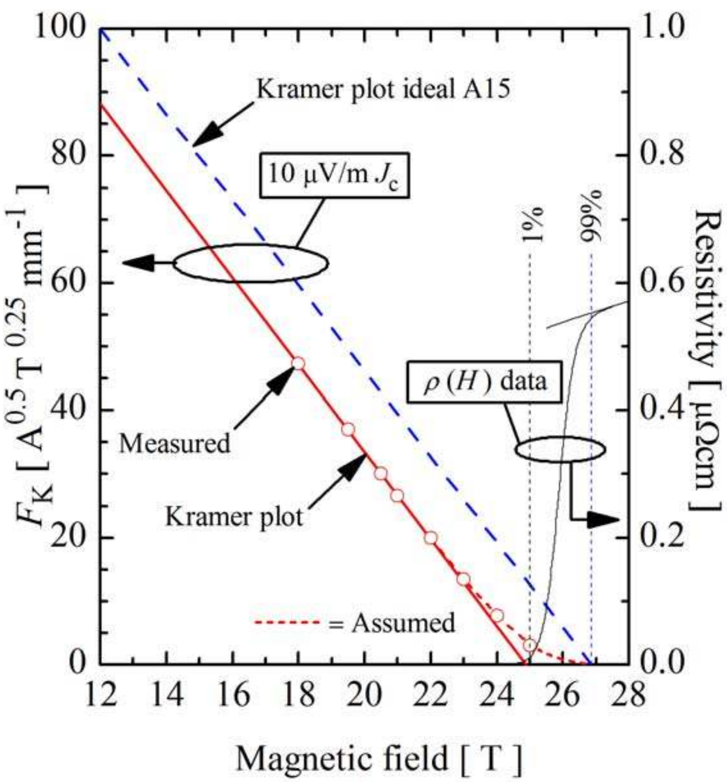


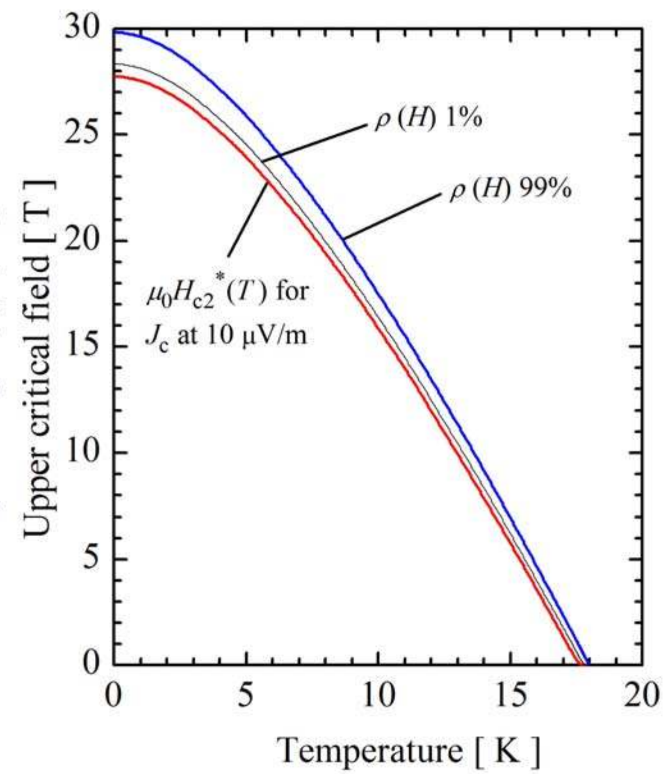
Effective $H_{c2}(T)^*$ for J_c

J_c scales with 'some' average $H_{c2}(T)^*$

- J_c gain if all A15 is stoichiometric?







J_c(12T,4.2K)

- From 2250 A/mm² to 2900 A/mm²

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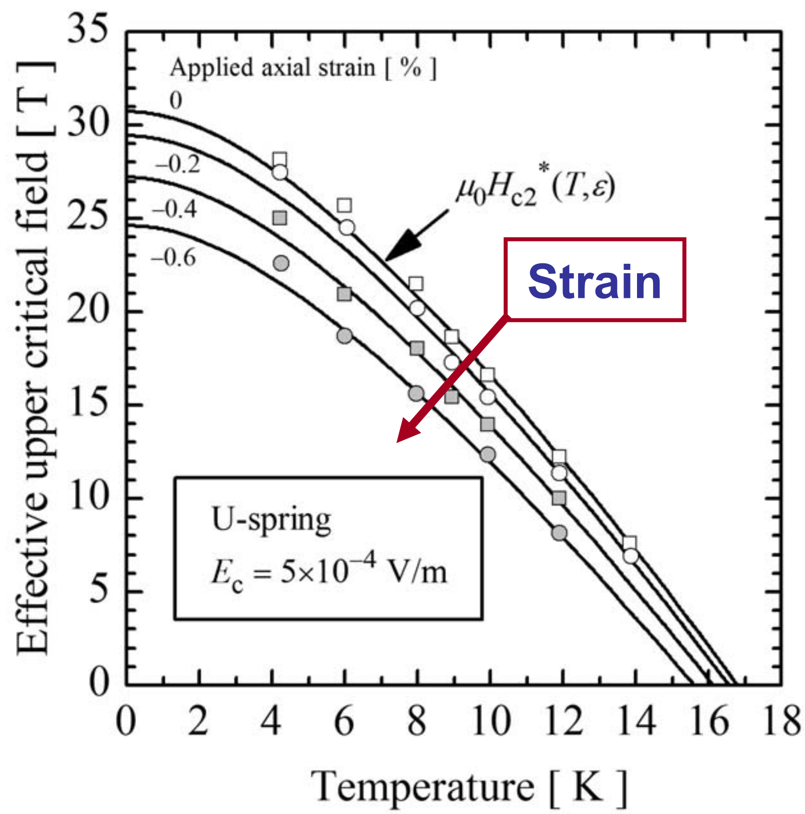
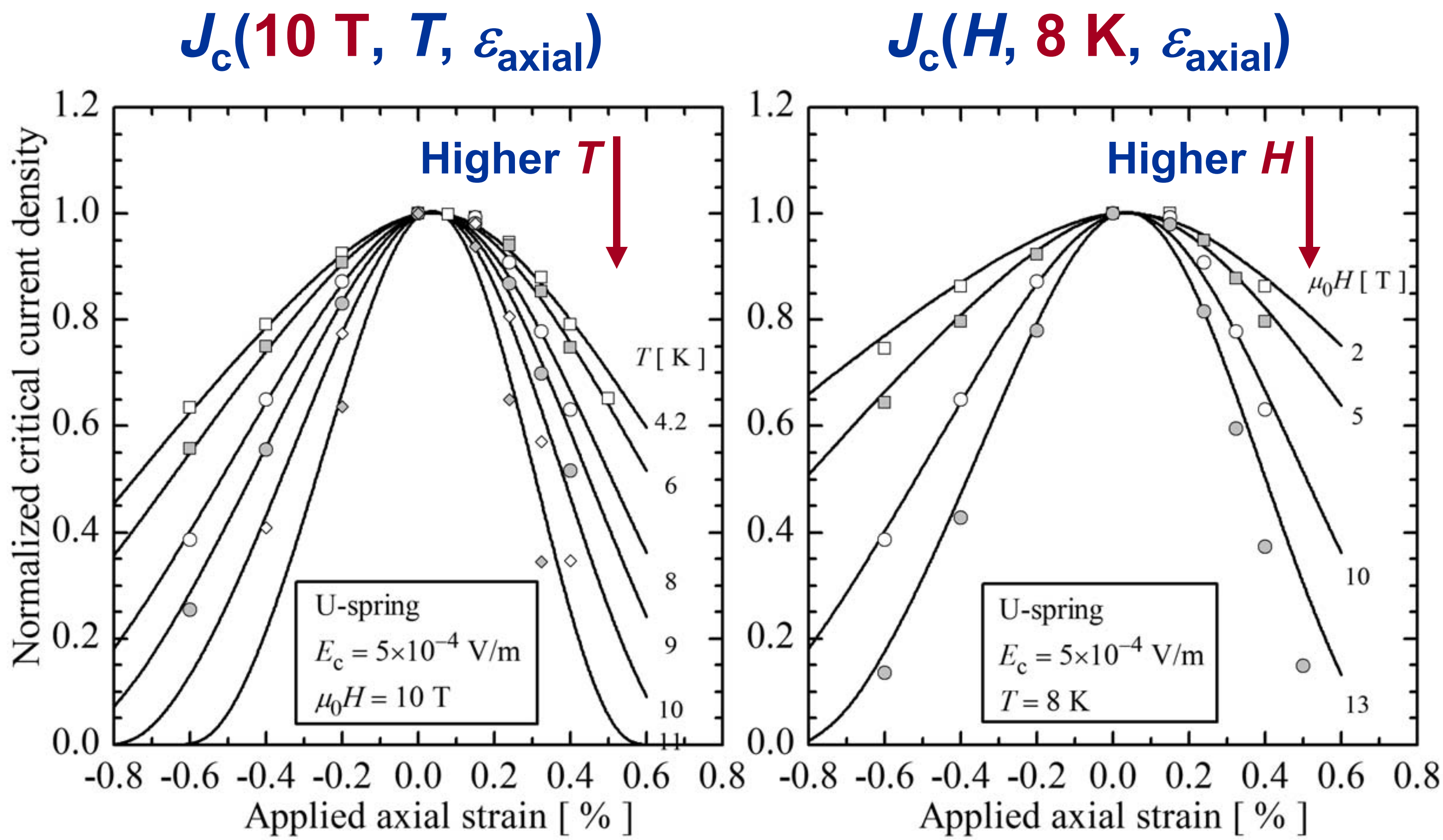
Strain sensitivity of $H_{c2}(T)$

- Longitudinal strain effects on ***effective*** $H_{c2}(T)$*



- Strain and composition have similar effects
  - Need for a separation of parameters

Strain sensitivity of $J_c(H,T)$

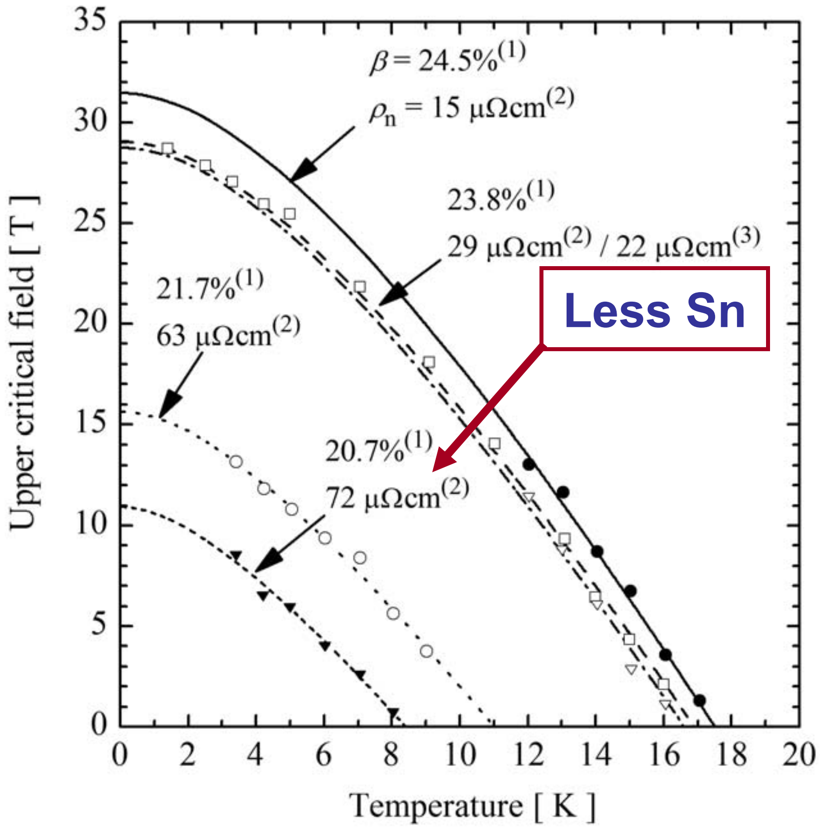


- **Why is strain sensitivity increased at higher H and T?**

Strain sensitivity versus composition

At higher *H* and *T*

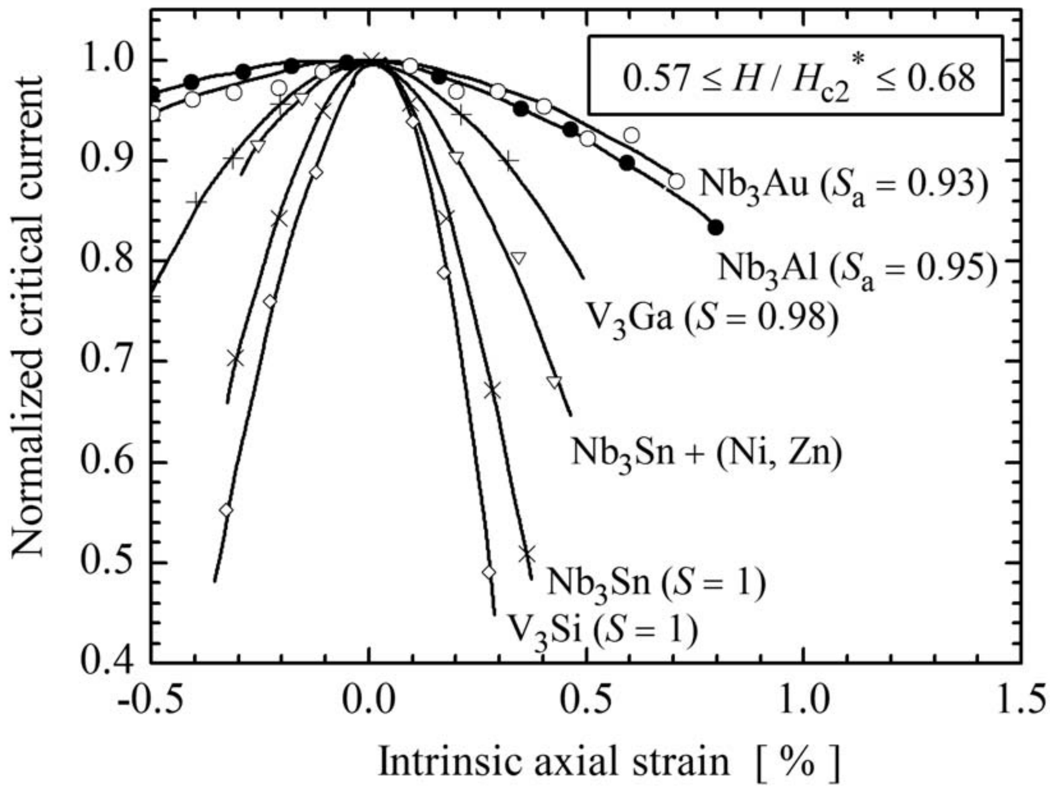
- Low Sn A15 sections "die out"
  - Benefit PIT and IT vs Bronze:
    - Larger volume fraction high Sn
  - High Sn sections determine SC properties
- Increased strain sensitivity
  - Is Sn rich A15 more strain sensitive than Sn poor A15 ?



- Does wire optimization through Sn enrichment cause higher strain sensitivity?

Strain sensitivity versus LRO

- *S* → Bragg-Williams order parameter

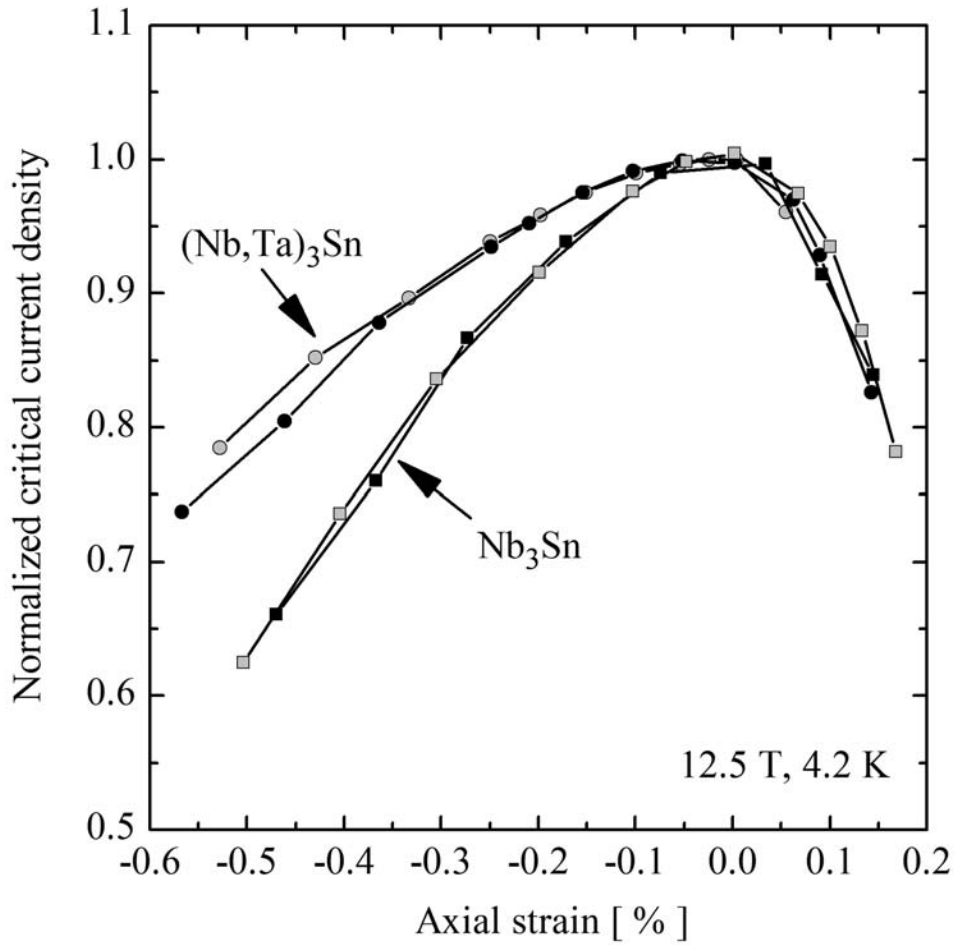


- Flükiger, ACE 1984

- Higher LRO (≙ more Sn) → larger strain sensitivity

Strain in ternary and binary wires

- Alloyed → more disorder → reduced strain sensitivity?



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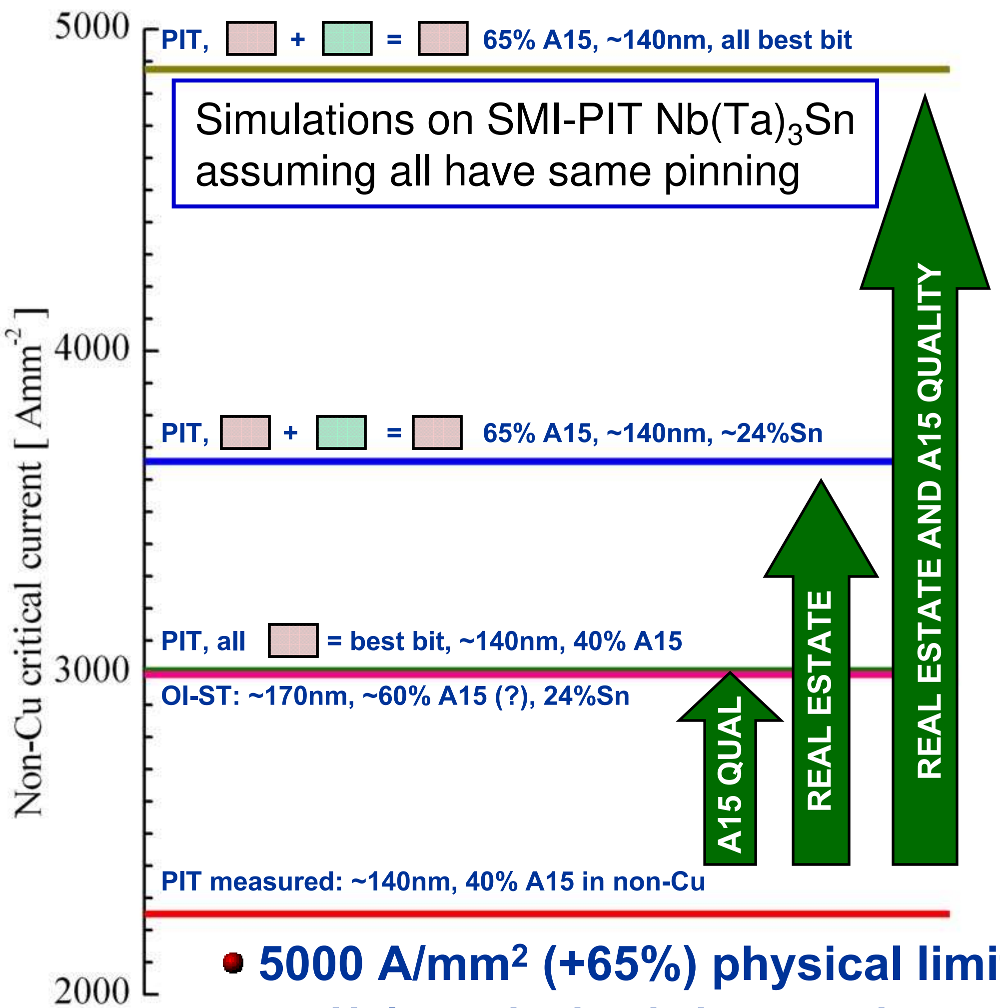
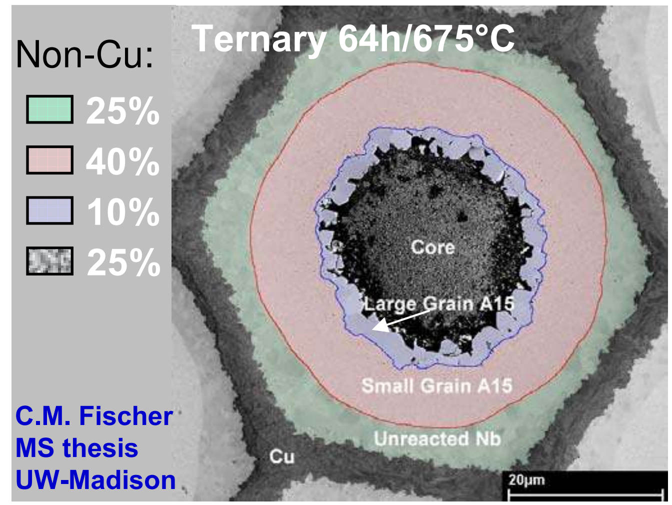
Prospects for critical current density





- Pinning?
  - SMI-PIT grains ~ 140 nm
  - OST-IT grains ~ 170 nm
  - 12 T → a_Δ = 14 nm
- Large gains possible

- 5000 A/mm² (+65%) physical limit with present wire designs?
  - Unless pinning is improved
- 4000 A/mm² realistic optimization goal?

Summary

Wire optimizations past decade

- Sn enrichment
- A15 fraction in non-Cu optimization
- Physical limit 5 kA/mm^2, realistic limit 4 kA/mm^2

Grain refinement / APC

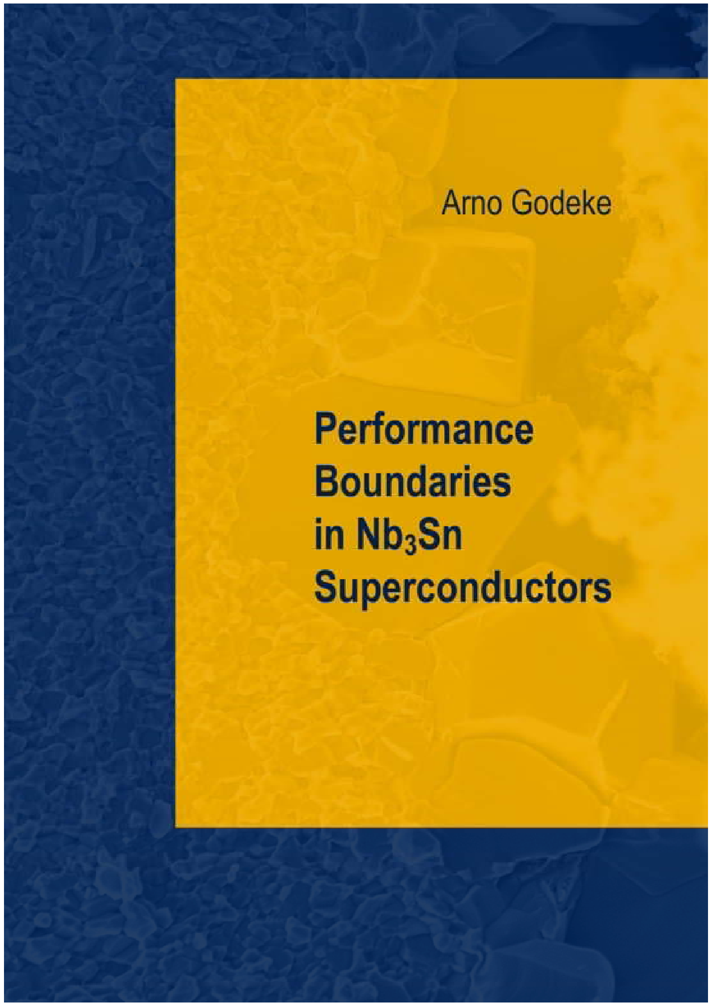
- The next big step?
- Grain size one order above optimal
- Grain 10 – 20 nm desired → nano technology

Strain

- Strain and composition parameter separation needed
- Sn enrichment = more strain sensitivity?
- Much work to be done (3D, theory, bulk, film,…)

More information

- Available on request → agodeke@lbl.gov



Optional theory section

$N(E_F)$ and $\lambda_{ep} \rightarrow T_c$ and H_{c2}

- **Weak coupling (BCS based)**

$$T_c(0) \cong \frac{2e^{\gamma_E}}{\pi k_B}\hbar\omega_c \exp\left[-\frac{1}{V_0 N(E_F)}\right] \quad \therefore \quad T_c(0) \cong 1.134\Theta_D \exp\left[-\frac{1}{\lambda_{ep}}\right]$$

$$\mu_0 H_{c2}(0) \cong k_B e N(E_F)\rho_n T_c(0) = \frac{3e}{\pi^2 k_B}\gamma\rho_n T_c(0)$$

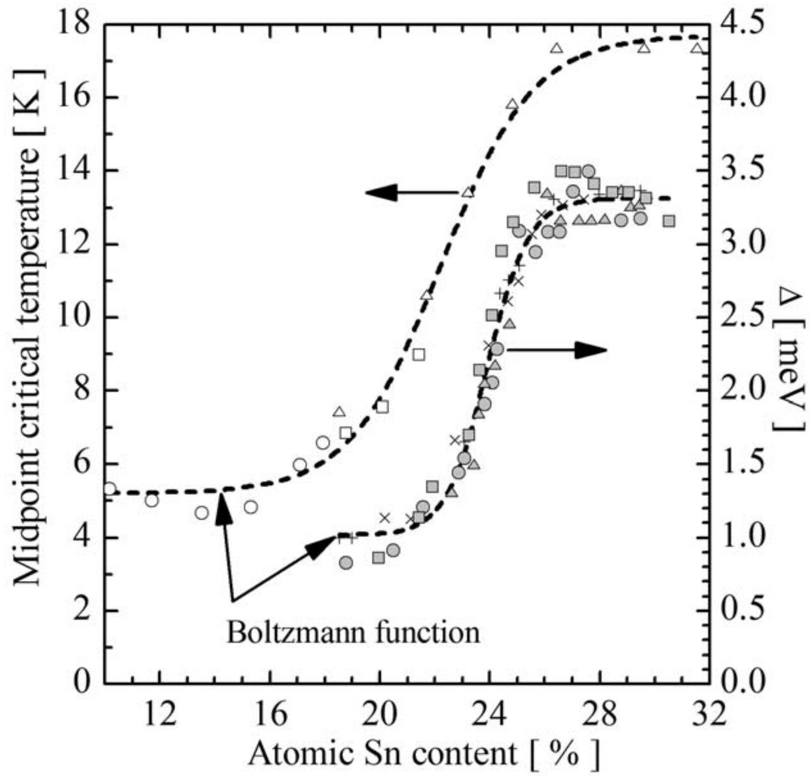
- **Interaction strength independent (Eliashberg based)**

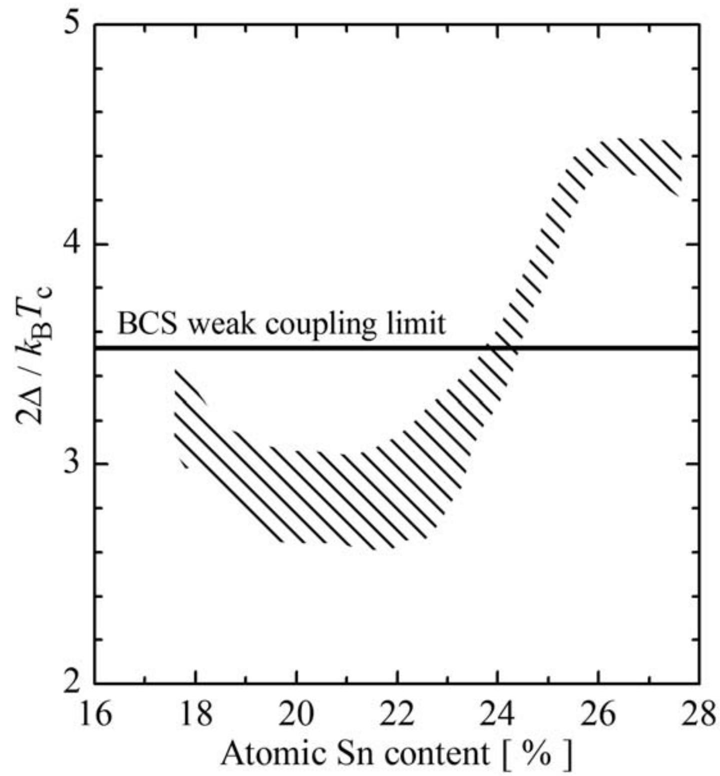
$$\lambda_{ep} = 2\int \frac{\alpha^2(\omega)F(\omega)}{\omega}d\omega \qquad \lambda_{eff} = \frac{(\lambda_{ep} - \mu^*)}{\left(1 + 2\mu^* + 1.5\lambda_{ep}\mu^* e^{-0.28\lambda_{ep}}\right)}$$

$$T_c = \frac{0.25\langle\omega^2\rangle^{\frac{1}{2}}}{\left(\mathrm{e}^{2/\lambda_{eff}} - 1\right)^{\frac{1}{2}}} \qquad \mu_0 H_{c2} = \ldots$$

Is Nb_3Sn weak or strong coupling?

- Moore, PRB 1979, thin film samples





- Weak coupling below 23 – 24 at.% Sn
- Strong coupling approaching stoichiometry

Applicable theory

$N(E_F)$ and $\lambda_{ep} \rightarrow T_c$ and H_{c2}

- Wires → 18 – 25 at.% Sn, polycrystalline
- Interaction strength independent theory
- Not done for entire composition range
- $N(E_F)$ and $\lambda_{ep} \rightarrow T_c$ and H_{c2} remains empirical

Promising recent work

- Eliashberg-based description of $T_c(\varepsilon)$ and $H_{c2}(\varepsilon)$
  - Markiewicz, Cryogenics 2004
  - Oh, JAP 2006