Lawrence Berkeley National Laboratory

Title
Performance Boundaries in Nb3Sn Superconductors

Author
Godeke, Arno

Publication Date
2006-05-01

Performance Boundaries in Nb_3Sn Superconductors

Arno Godeke

Berkeley, CA

May 1, 2006

Acknowledgments

BERKELEY LAB

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

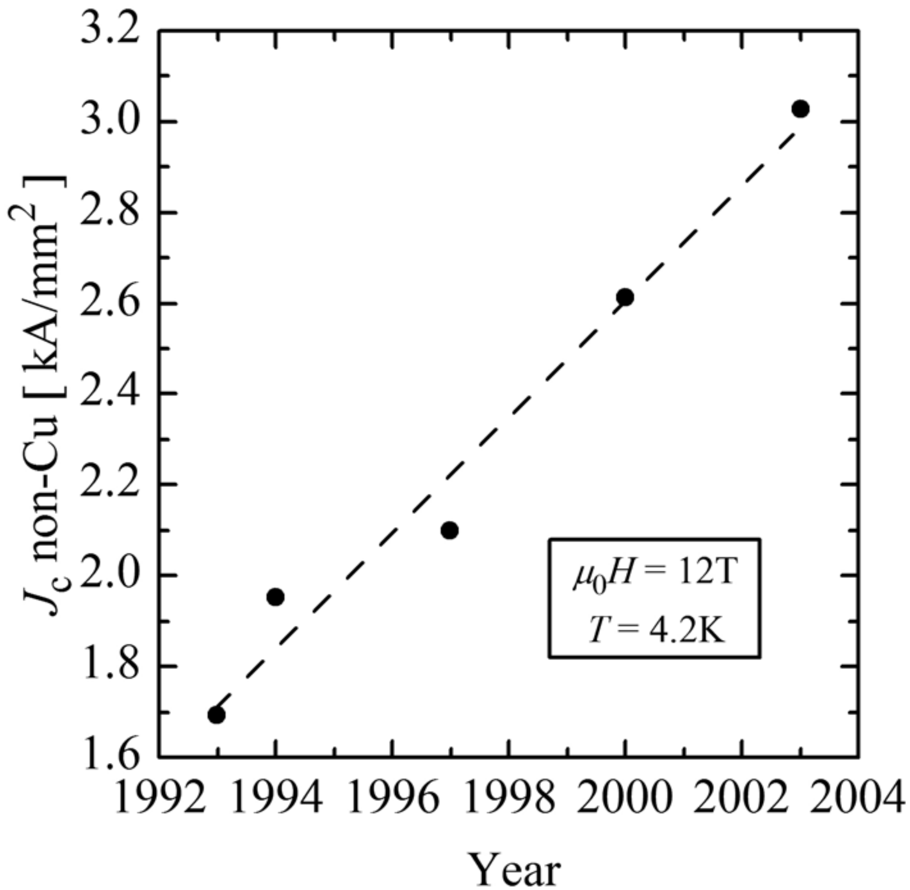
Chad Fischer

…

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

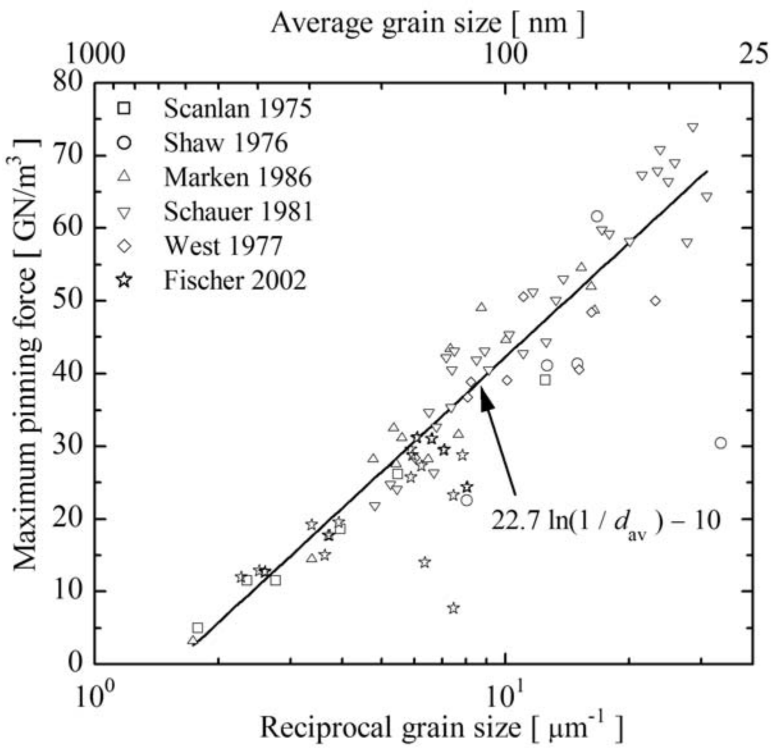
Wire J_c progress versus time



- **Parrell, ACE 2004**

What determines J_c?

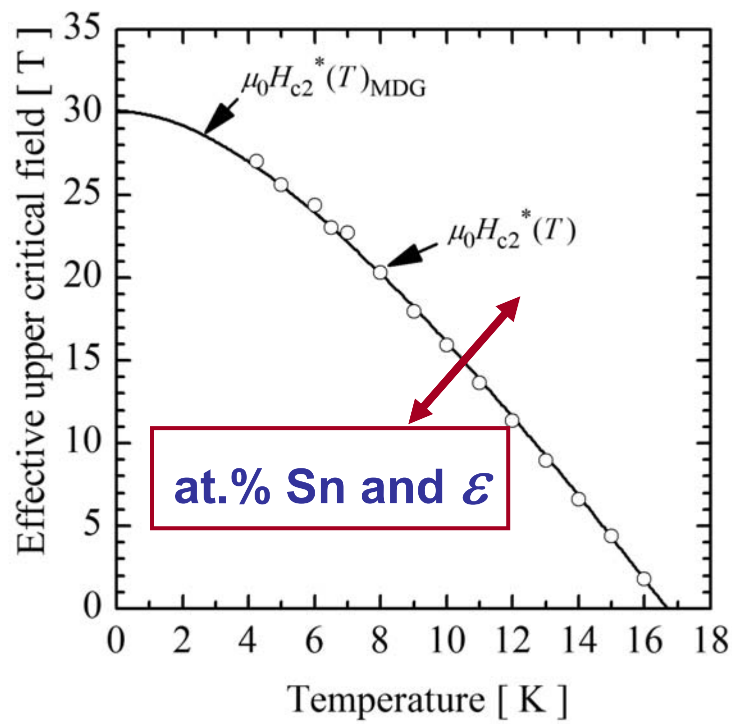
Pinning capacity



- Average grain size

+

Effective H – T phase boundary



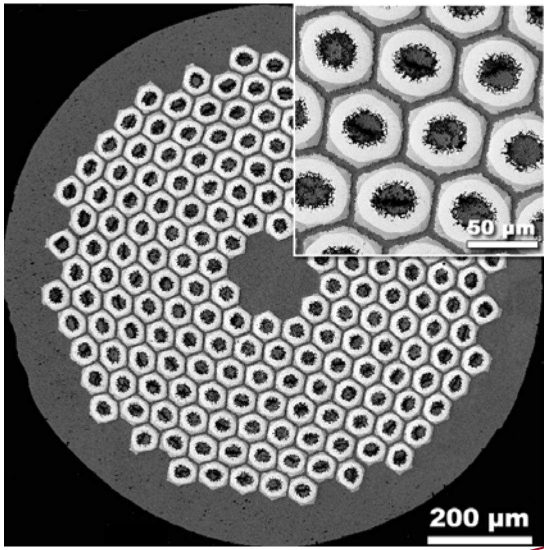
- Composition
- Strain state

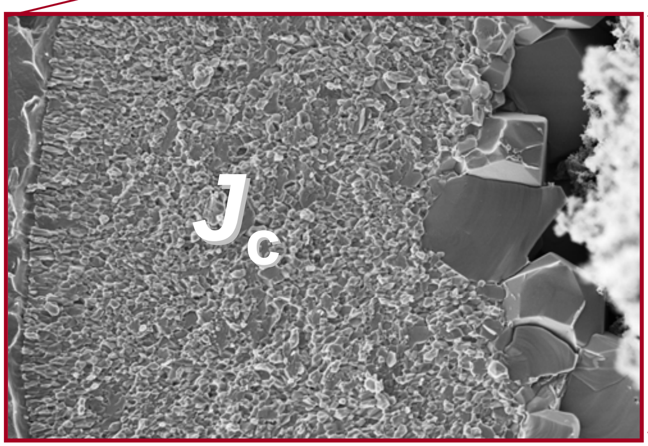
= J_c

$J_c \rightarrow I_c$?

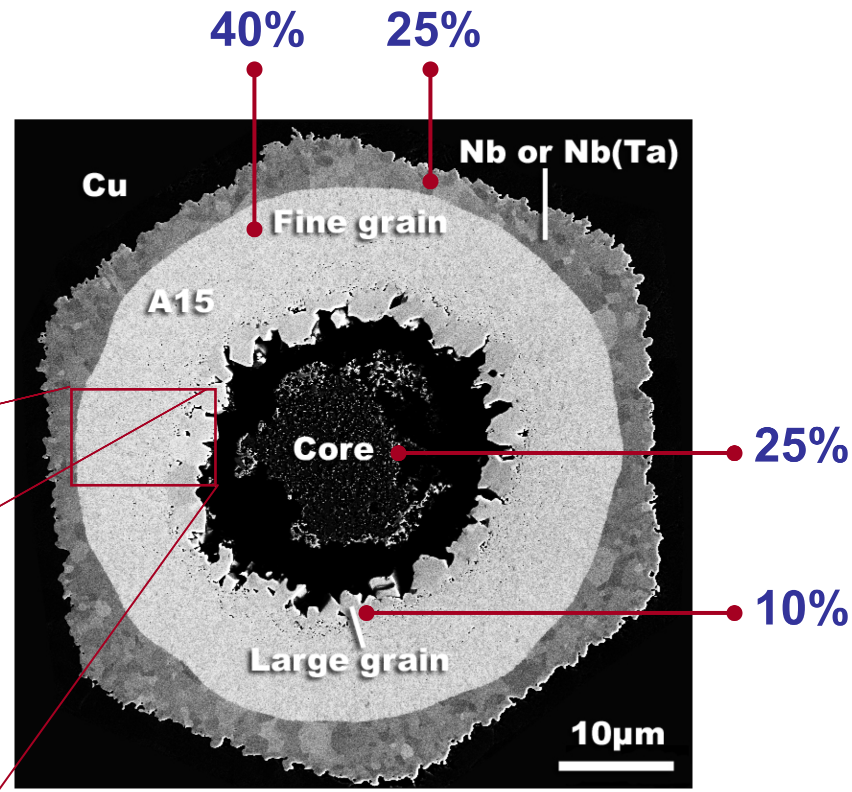
What determines I_c?

- Powder-in-tube wire (SMI)





- 50% Non – Cu fraction



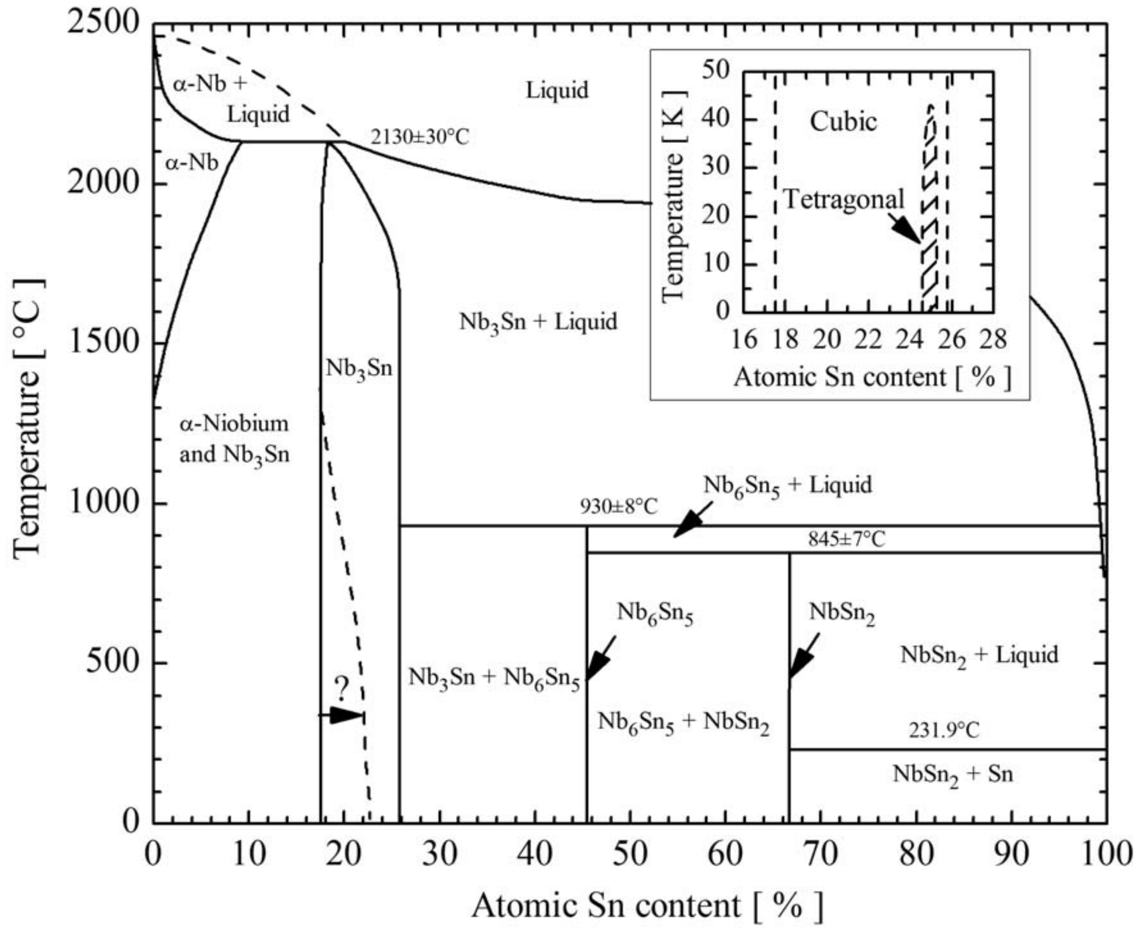
- Only 20% of the wire carries J_c

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
- Present status and future prospects

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

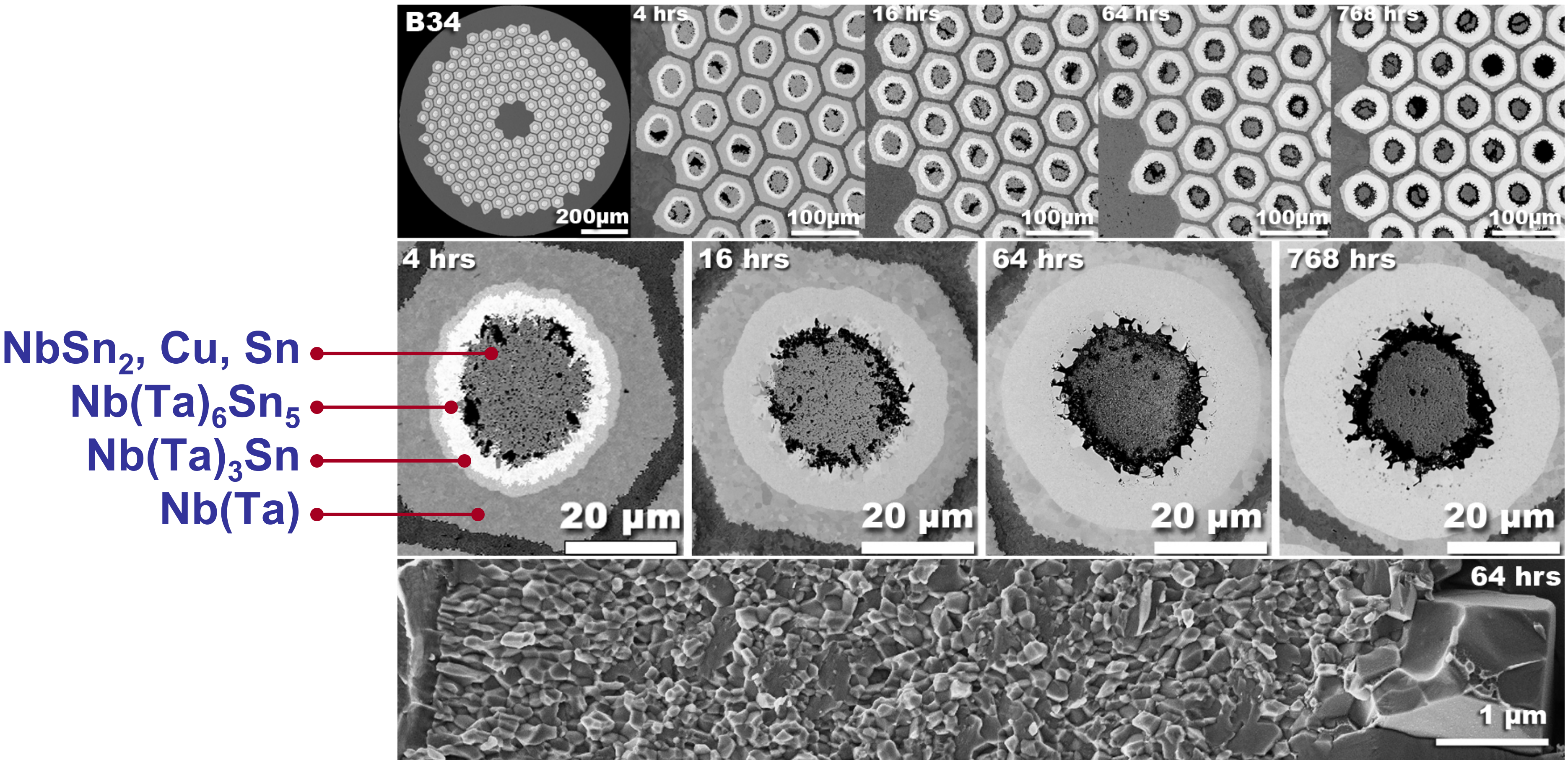
- Binary phase diagram → 18 to 25 at.% Sn → 'A15'



➡ Charlesworth, JMS 1970, Flükiger, ACE 1982

Nb_3Sn diffusion reaction in wires

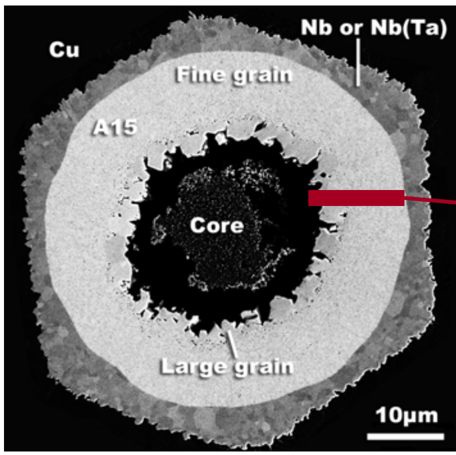
- Reaction at 675°C vs time in Powder-in-Tube wire (SMI)

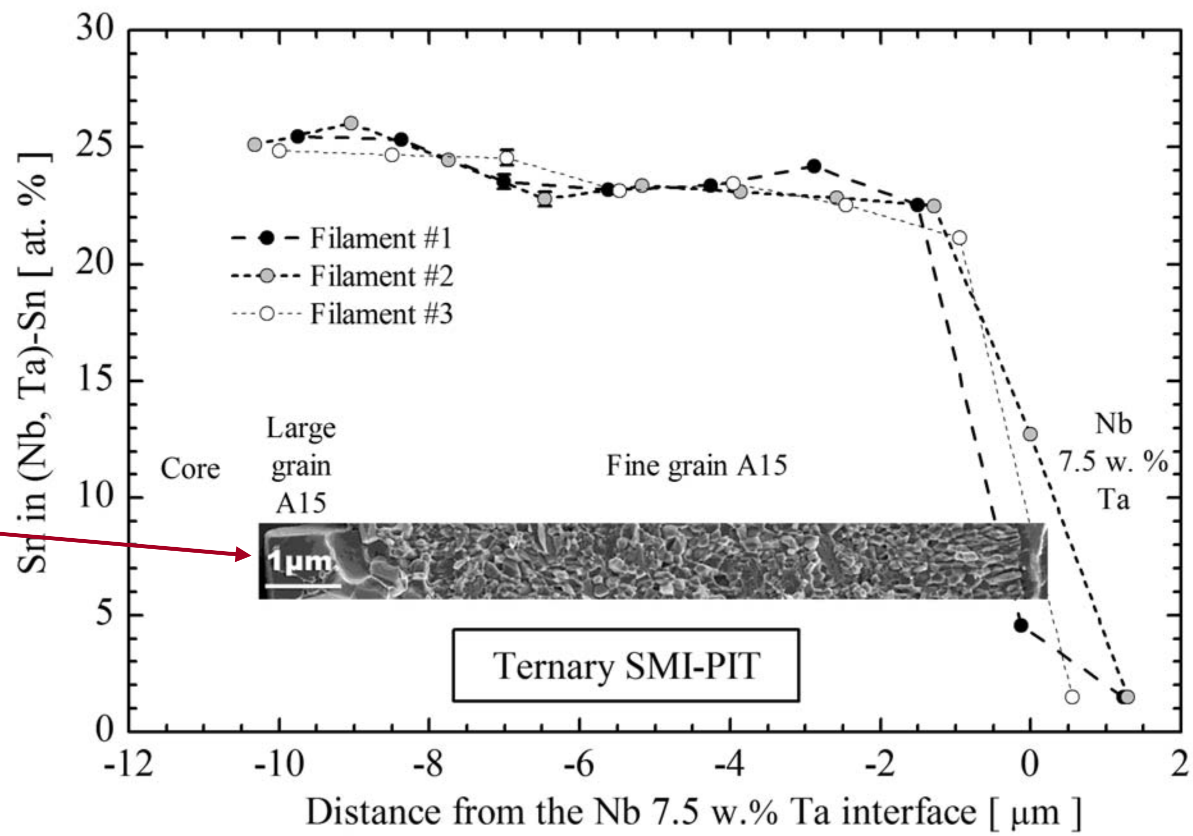


Composition variation in wires

- Composition analysis on SMI Powder-in-Tube wire

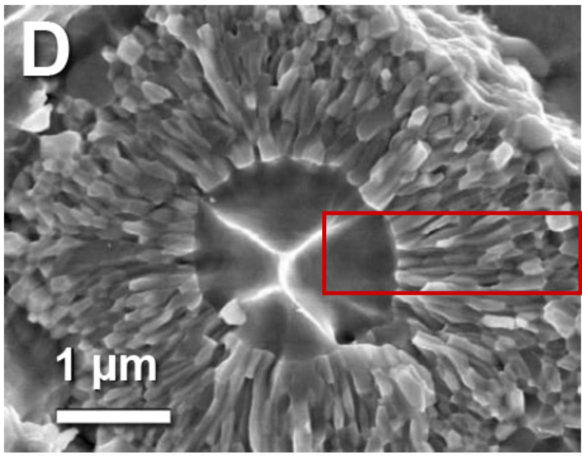
- 0.3 at.% Sn/μm
- J_c(12T,4.2) = 2250 A/mm²

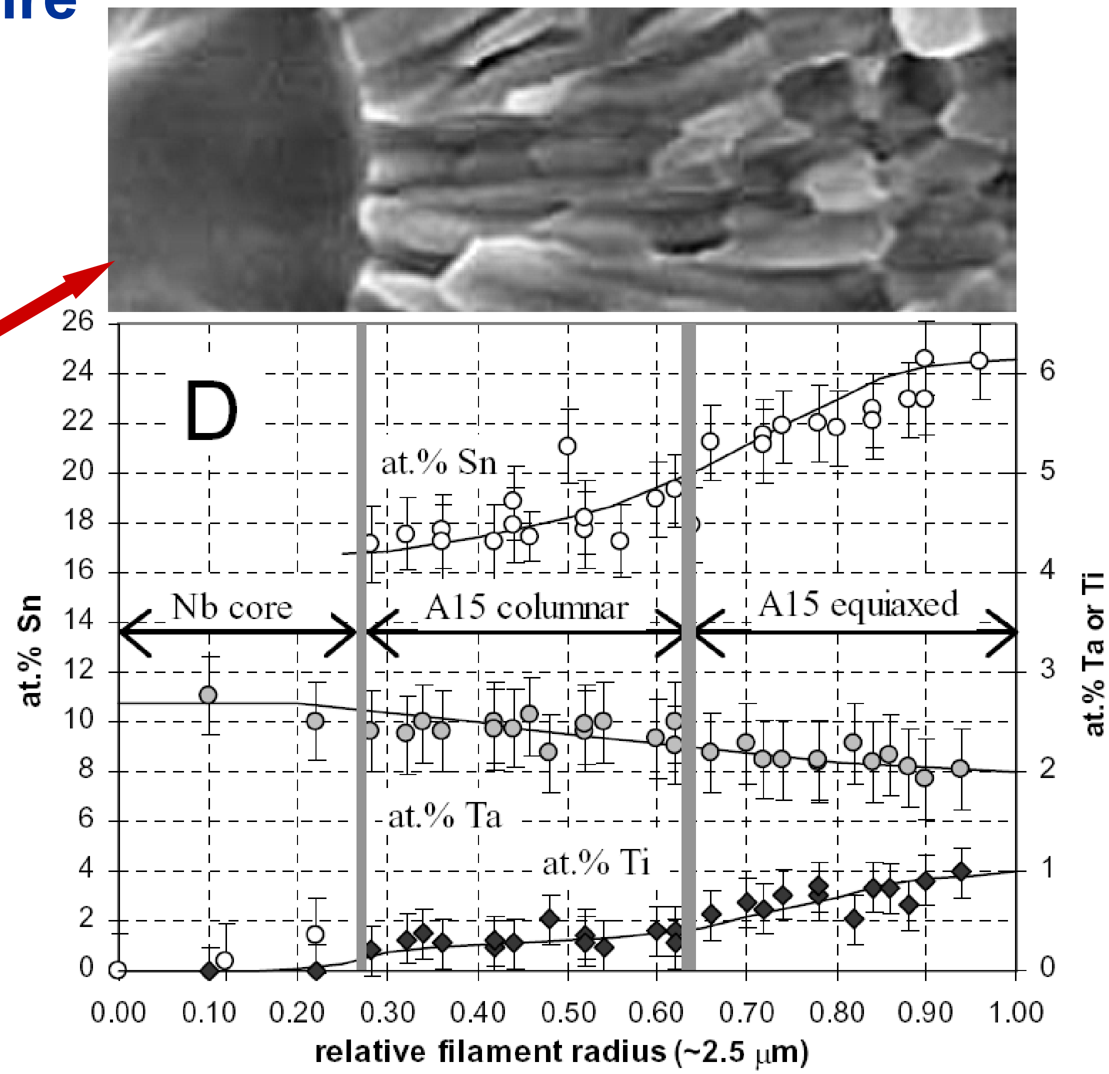




Composition variation in wires

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



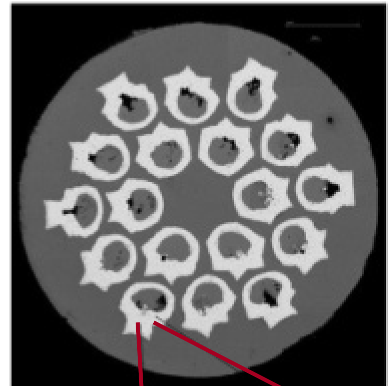


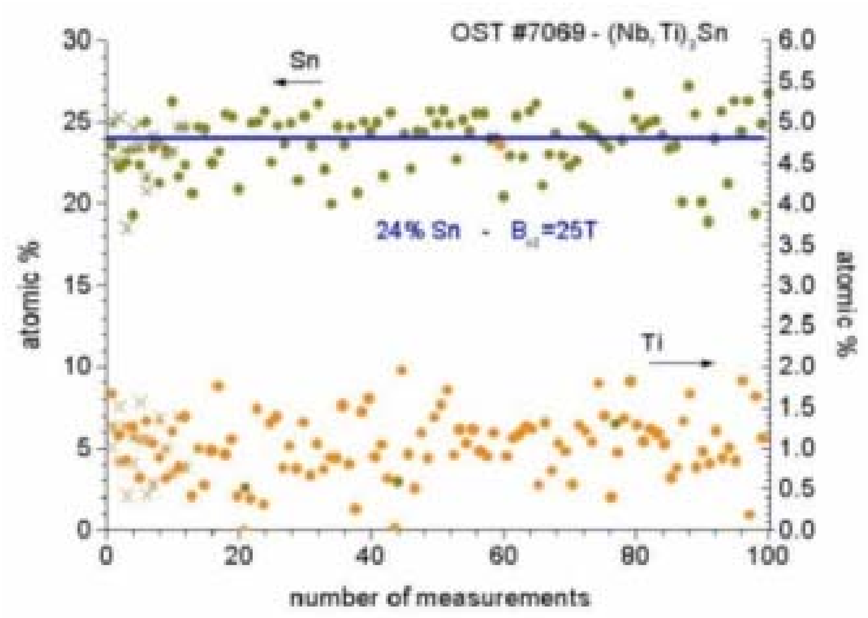
- **4 at.% Sn/µm**
- **J_c(12T,4.2) = 720 A/mm^2**

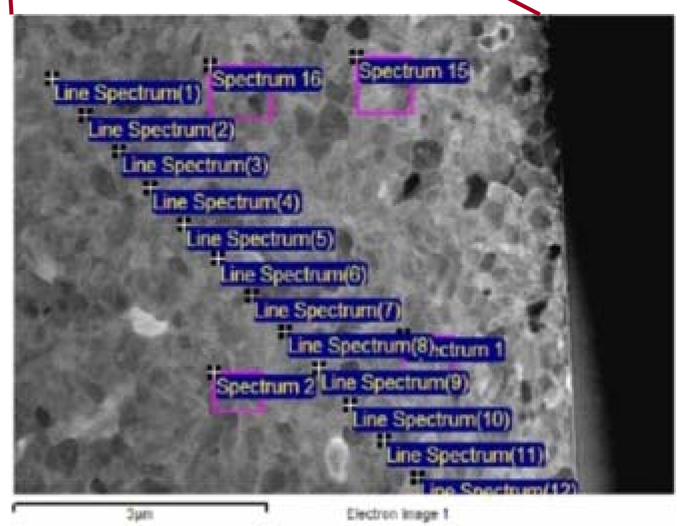
  - **Abächerli, TAS 2005**

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?

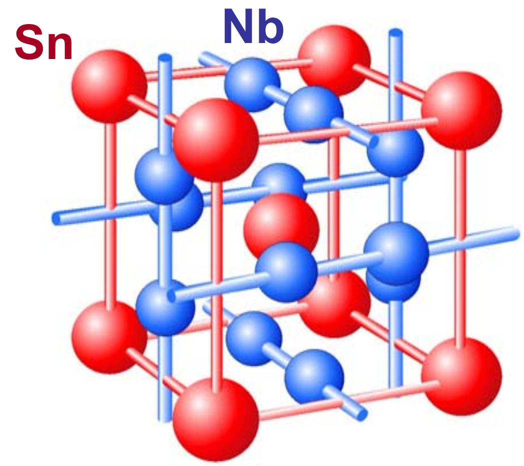
Outline

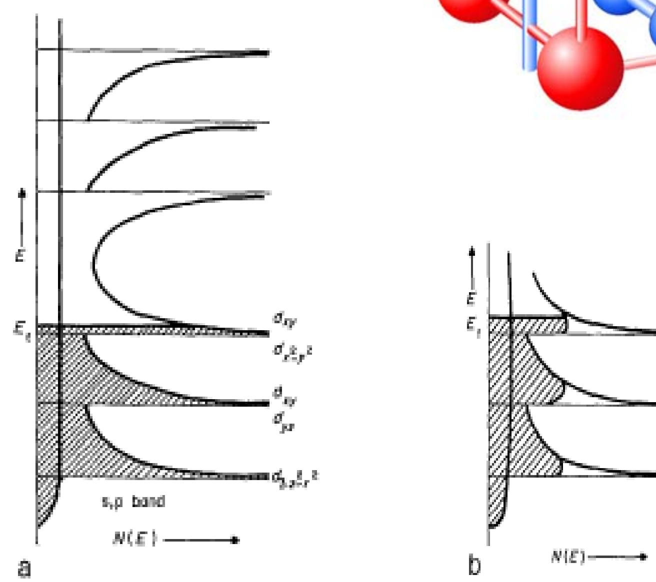
- Critical current density and critical current
- Composition variation in Nb_3Sn wires
- Composition and $H_{c2}(T)$
- Pinning capacity, grain boundary pinning, grain size
- Composition and J_c
- Strain dependence
- Present status and future prospects

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

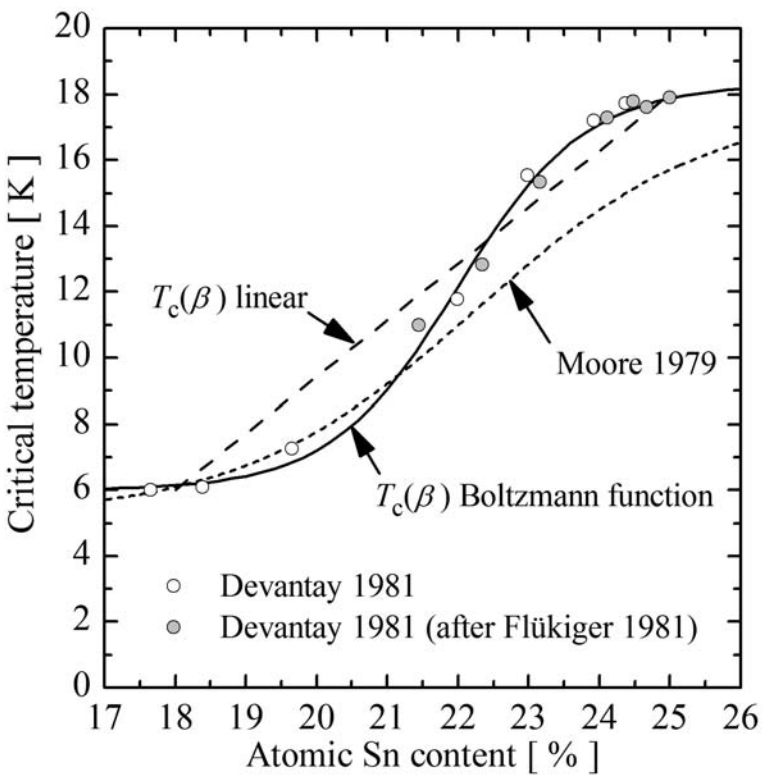
- Sn deficiency
- Tetragonal distortion
  - 24.5 – 25 at.% Sn
- Strain
- Alloying (Ti, Ta, …)
- Dislocations
- Anti-site disorder

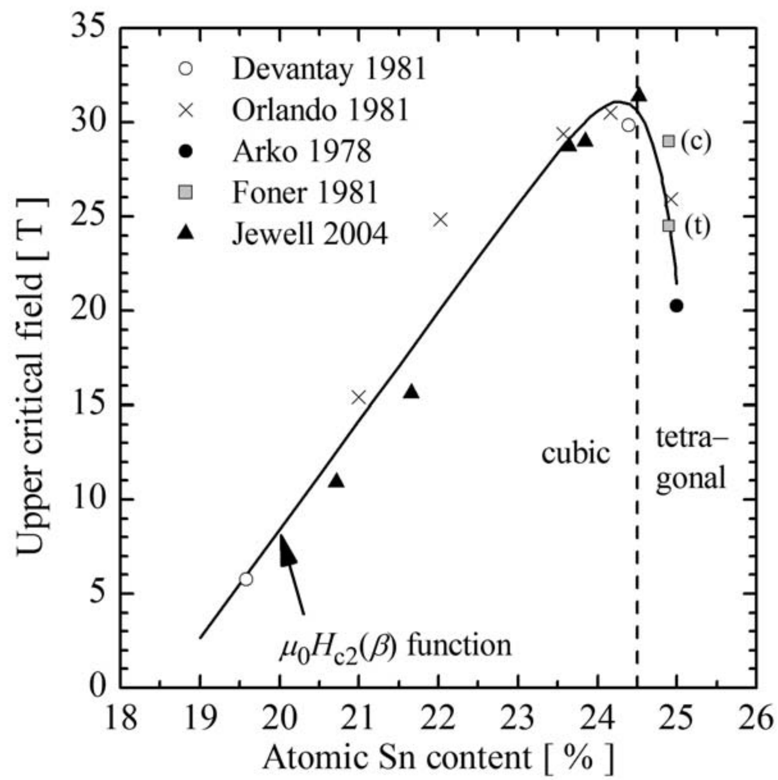
All affect Nb chain integrity ('Long Range Order')

- 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



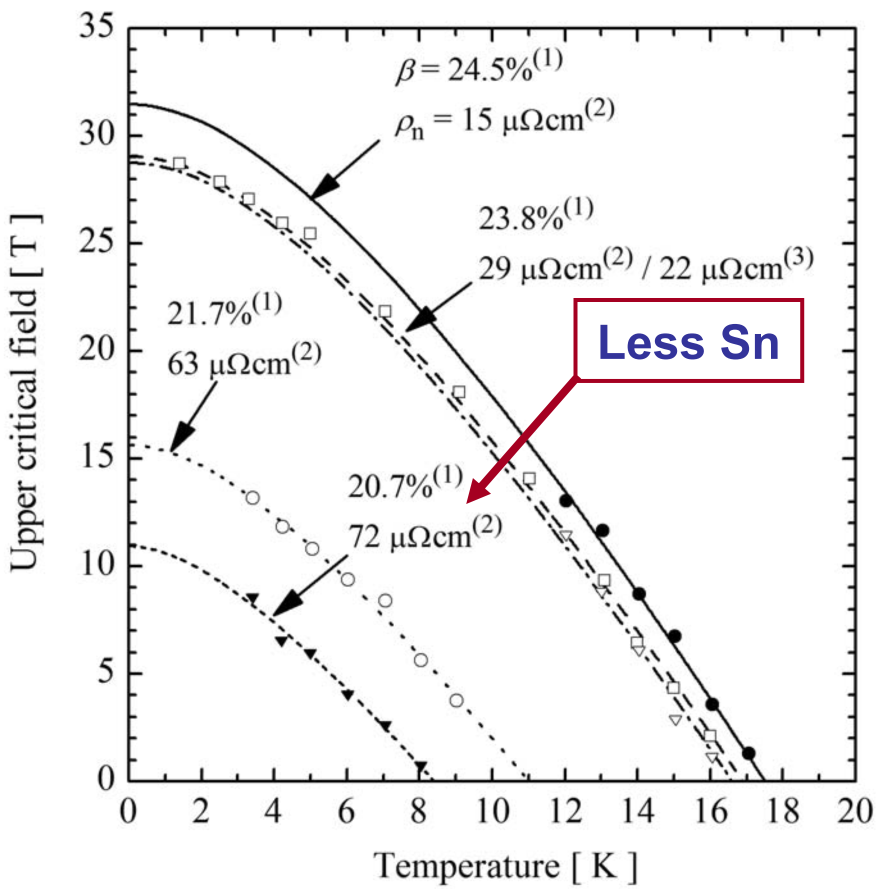


$$T_c(\beta) = \frac{-12.3}{1+\exp\left(\frac{\beta-0.22}{0.009}\right)} + 18.3$$

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

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

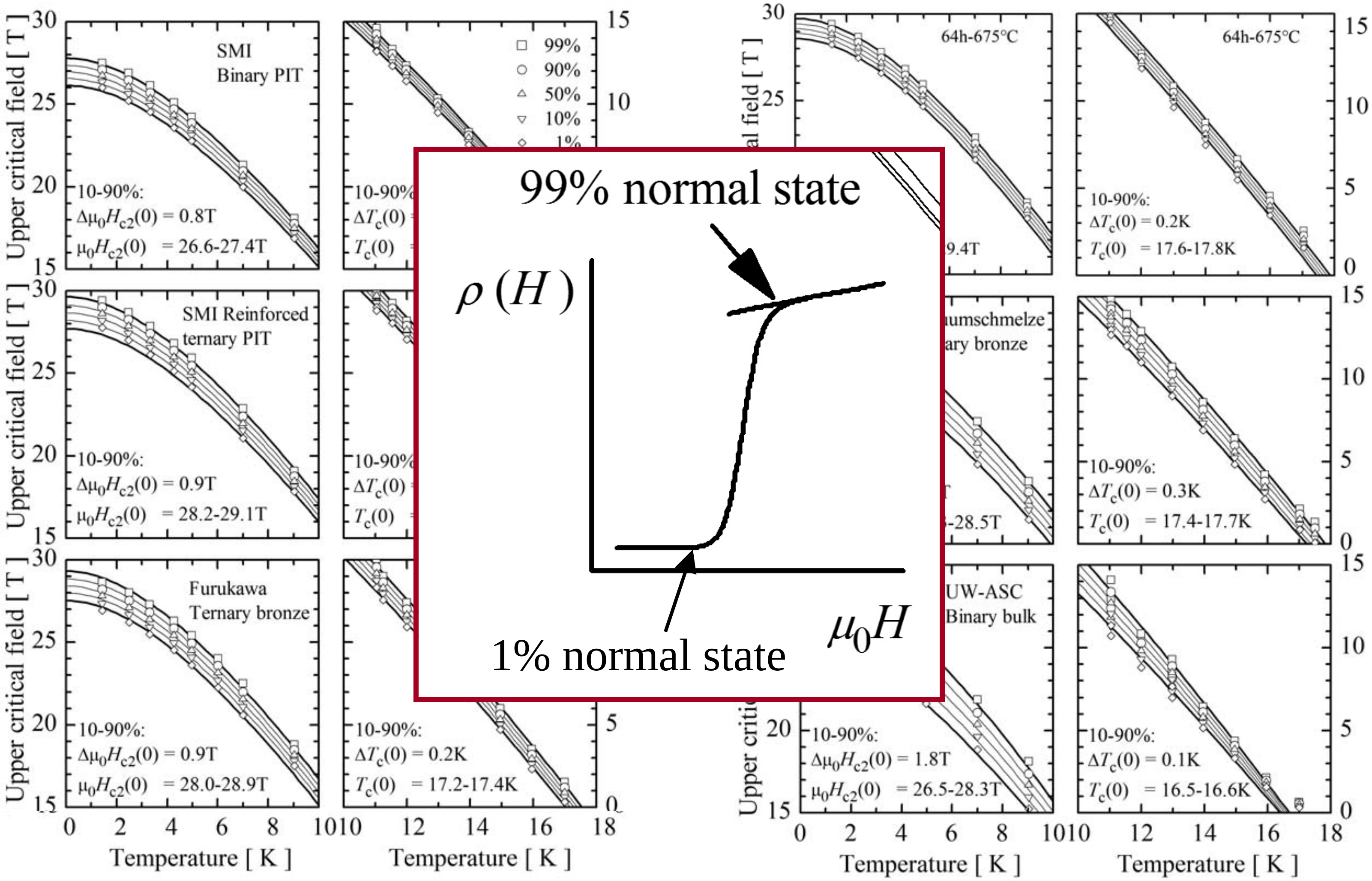
- Jewell, ACE 2004, bulk samples



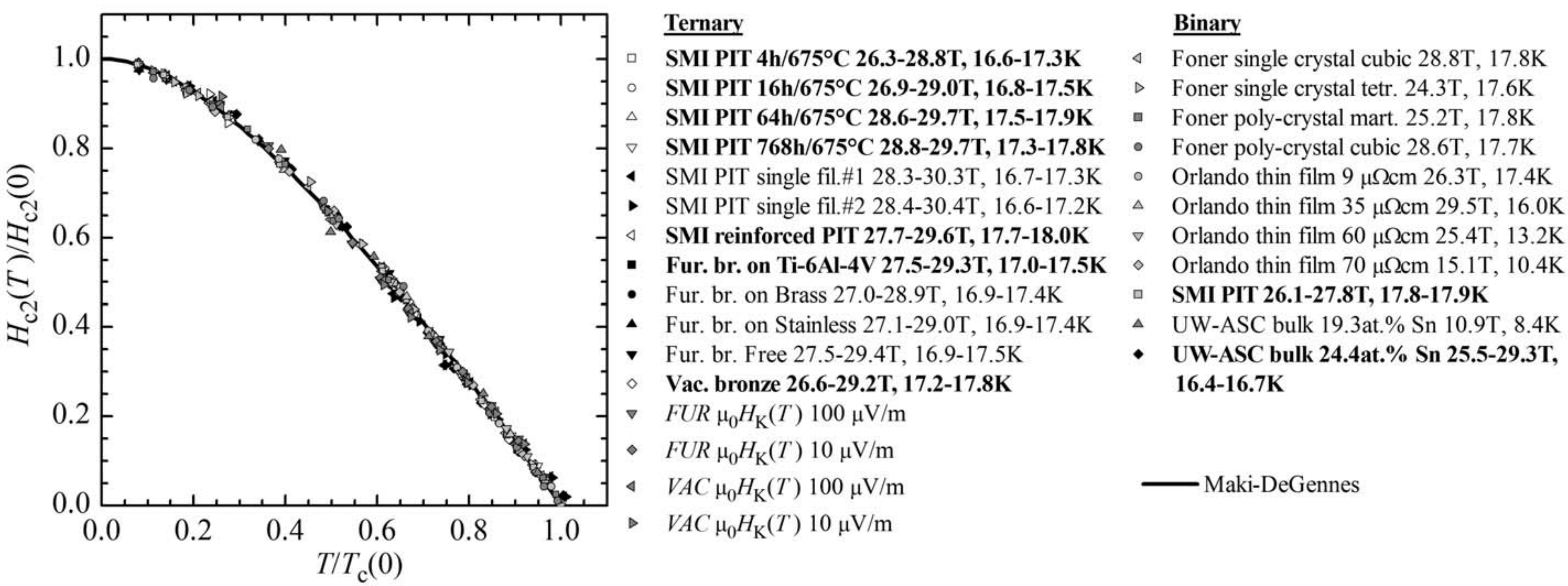
- Sn richer A15 has higher $H_{c2}(T)$ (until ~ 24.5 at.% Sn)

$H_{c2}(T)$ in wires

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



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



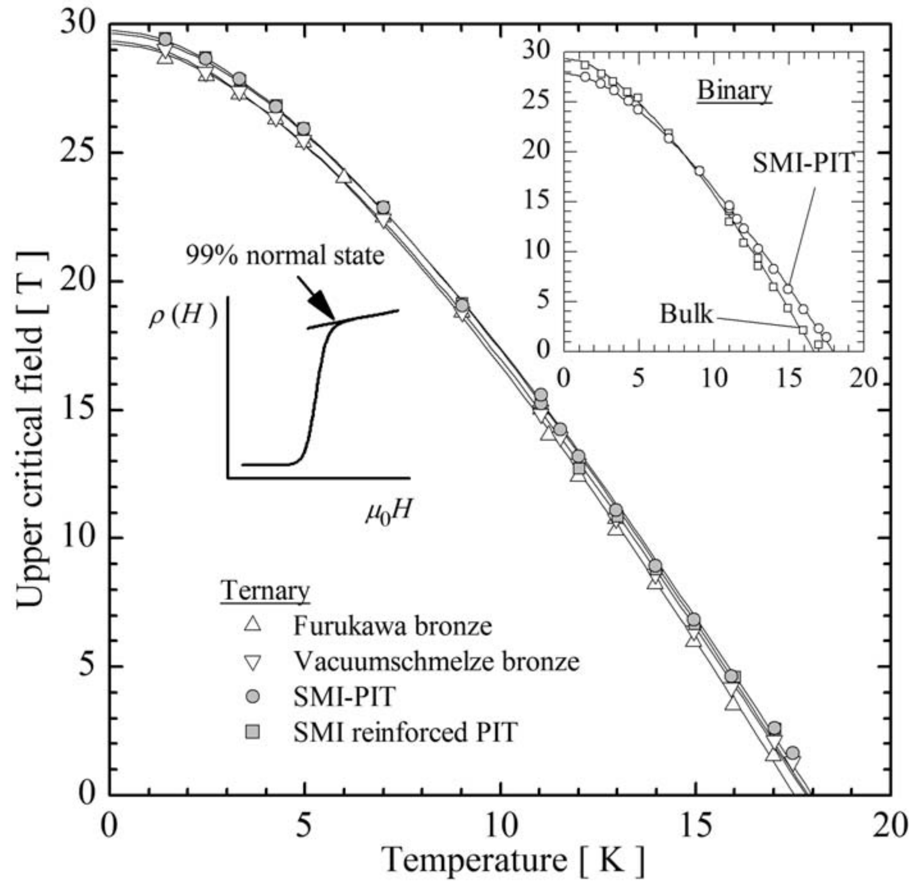
- Shape $H_{c2}(T)$ independent of
  - Composition
  - Morphology
  - Strain state
  - Applied critical state criterion

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

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



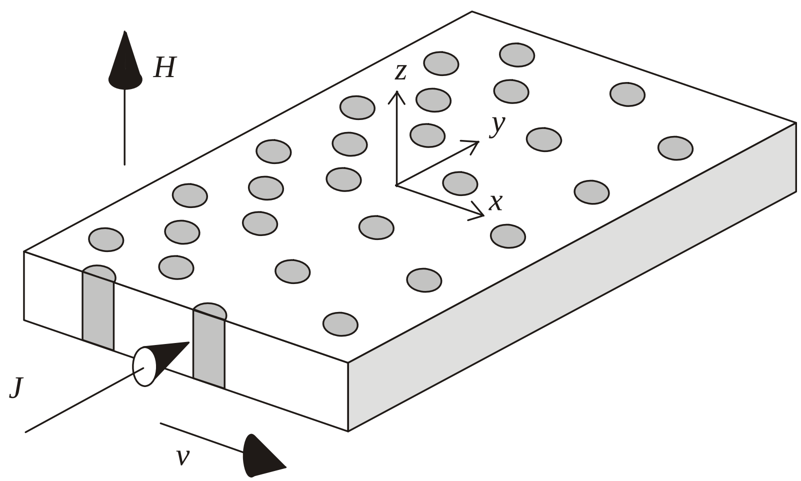
$\mu_0 H_{c2}(0)$ = 30 T, $T_c(0)$ = 18 K is upper limit

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
- Present status and future prospects

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

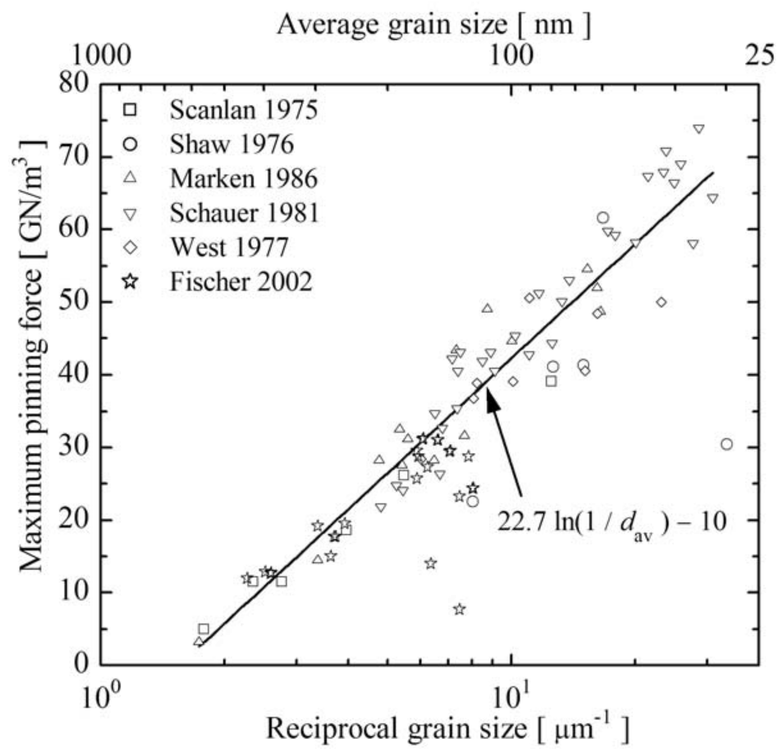


- Transport current ($\nabla \times B = \mu_0 J$) causes gradient B_x
- Flux-lines repel → move ($\nabla \times E = - dB/dt$) → E_y → Loss
  - Need to be 'pinned' at 'pinning centers' by 'pinning force' F_P
- Optimal pinning at 1 pinning center / flux-line

What determines pinning capacity?

Pinning centers

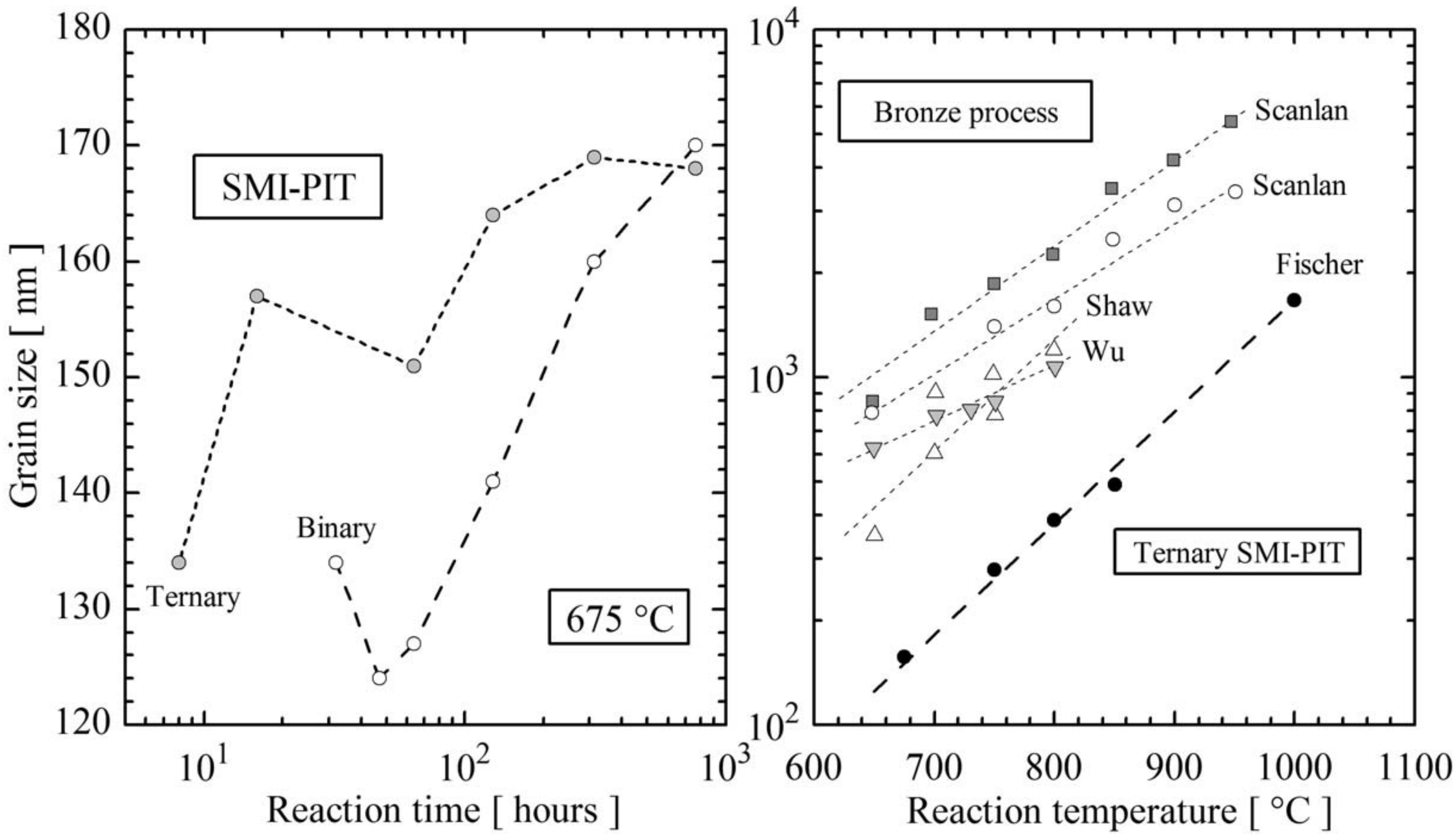
- Positions with minima in SC wave function
  - Normal regions
  - Grain boundaries
  - Lattice imperfections
  - …



- 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?

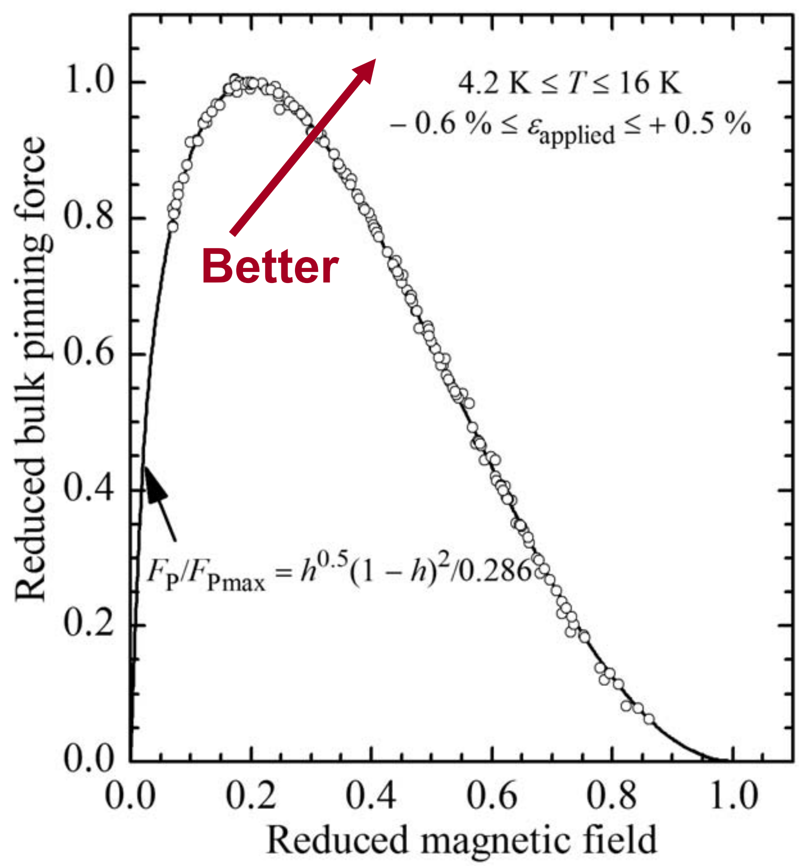
Ideal: One pinning center per flux-line → $a_\Delta \approx d_{av}$

- 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 $a_\Delta \ll d_{av}$
  - Collective pinning ('shearing' of FLL)
  - $a_\Delta \rightarrow d_{av}$ only for $\mu_0 H \ll 1$ 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 $a_\Delta << d_{av}$ 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
  - $F_{Pmax} \rightarrow H/H_{c2} > 0.4$ shown by Cooley, ACE 2002
  - Higher fields accessible with Nb_3Sn
- Much room for improvement!

- Example: Bronze processed ITER wire (Furukawa)



Alternative presentation a_Δ << d_{av}

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

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

$$\therefore \quad J_c^{0.5}(\mu_0 H)^{0.25} = \frac{1.1\times 10^5}{\kappa_1}\frac{\mu_0(H_{c2}-H)}{\left(1-a_\Delta(H)/d_{av}\right)}$$

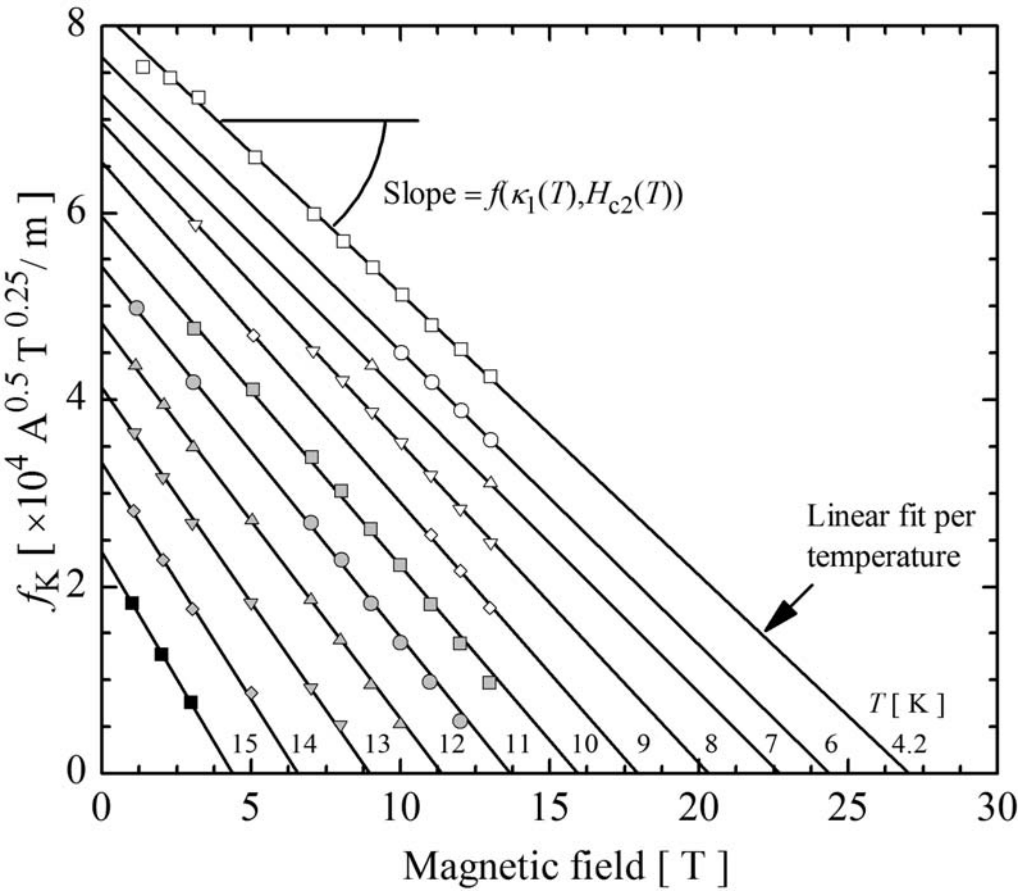
- **a_Δ << d_{av}: Kramer plot**

$$f_K(H) \equiv J_c^{0.5}(\mu_0 H)^{0.25} \cong \frac{1.1\times 10^5}{\kappa_1}\mu_0(H_{c2}-H) \quad \therefore \boxed{f_K(H) \propto H}$$

- **Linear in *H***

'Kramer' plot

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



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
- Present status and future prospects

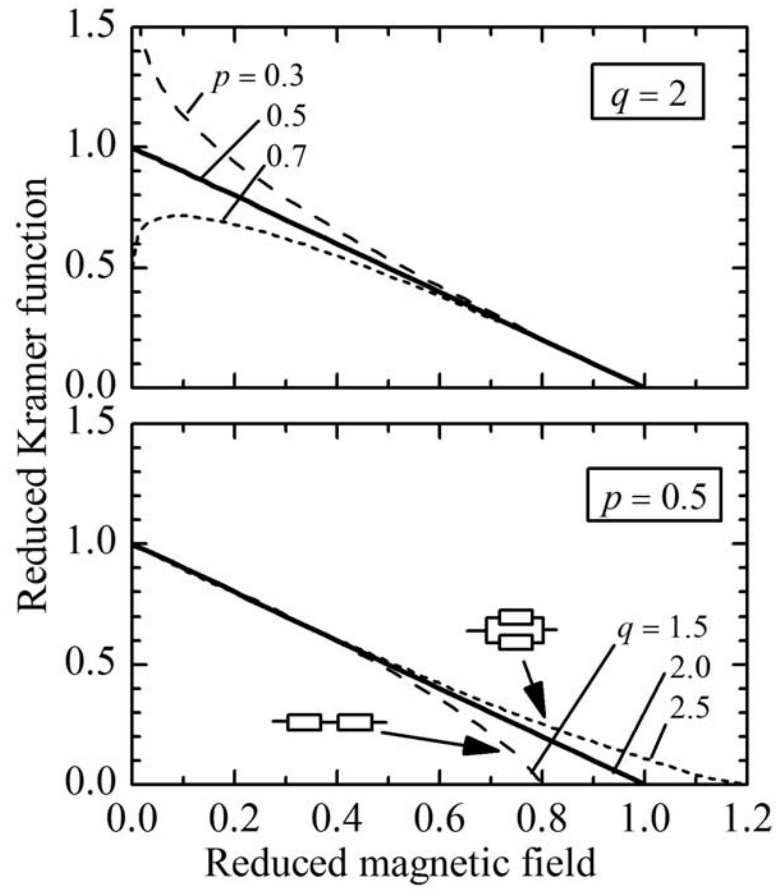
Are Kramer plots linear?

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

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

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

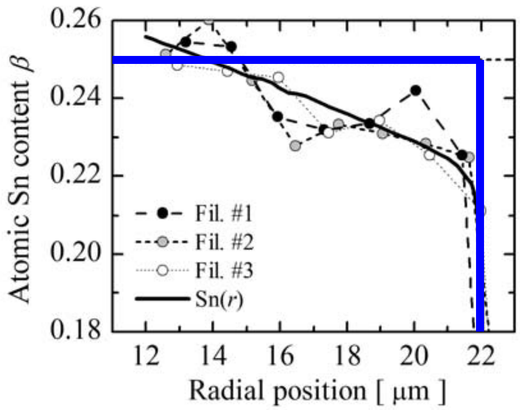
- **Non-linearity below $h \cong 0.03$**
  - **Different pinning mechanism**
- **Non-linearity above $h \cong 0.8$**
  - **Inhomogeneity artifacts**
    - **Averaging over H_{c2} distribution**

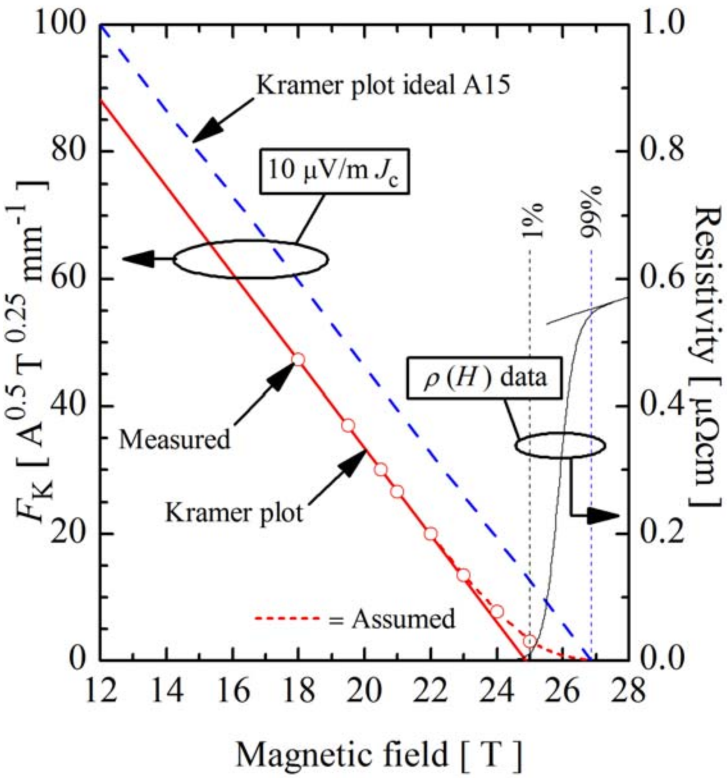


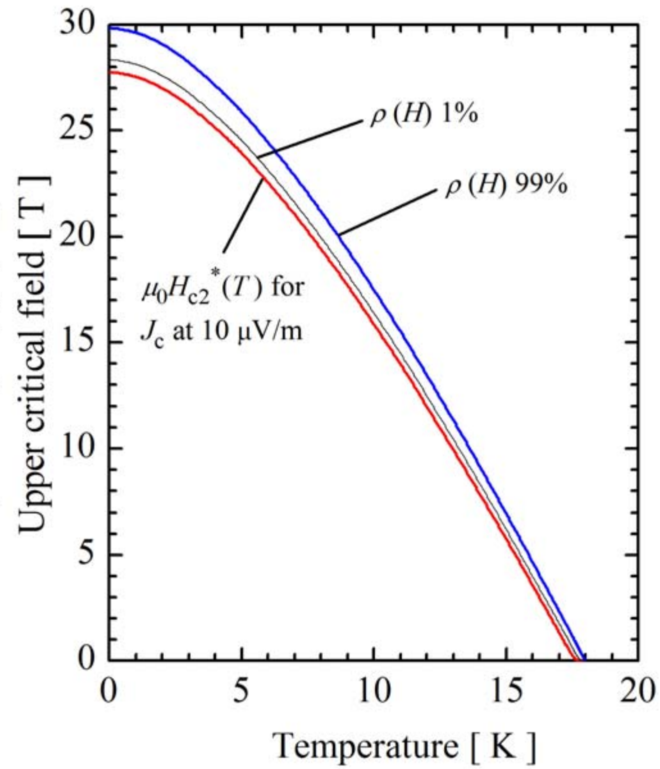
Effective $H_{c2}(T)^*$ for J_c

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

- J_c gain if all A15 is stoichiometric?







J_c(12T,4.2K)

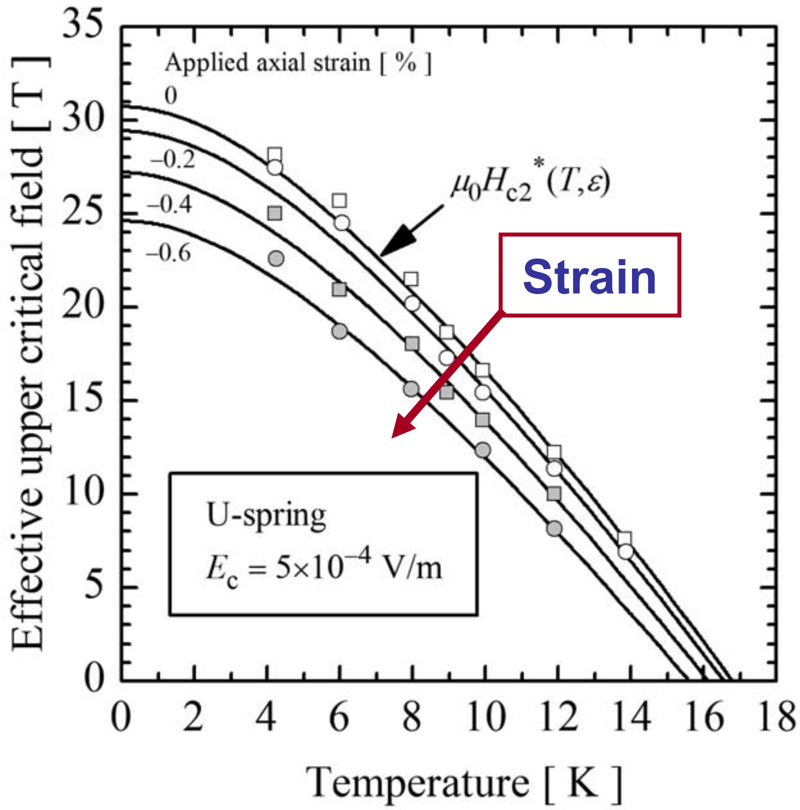
- From 2250 A/mm² to 2900 A/mm²

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
- Present status and future prospects

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

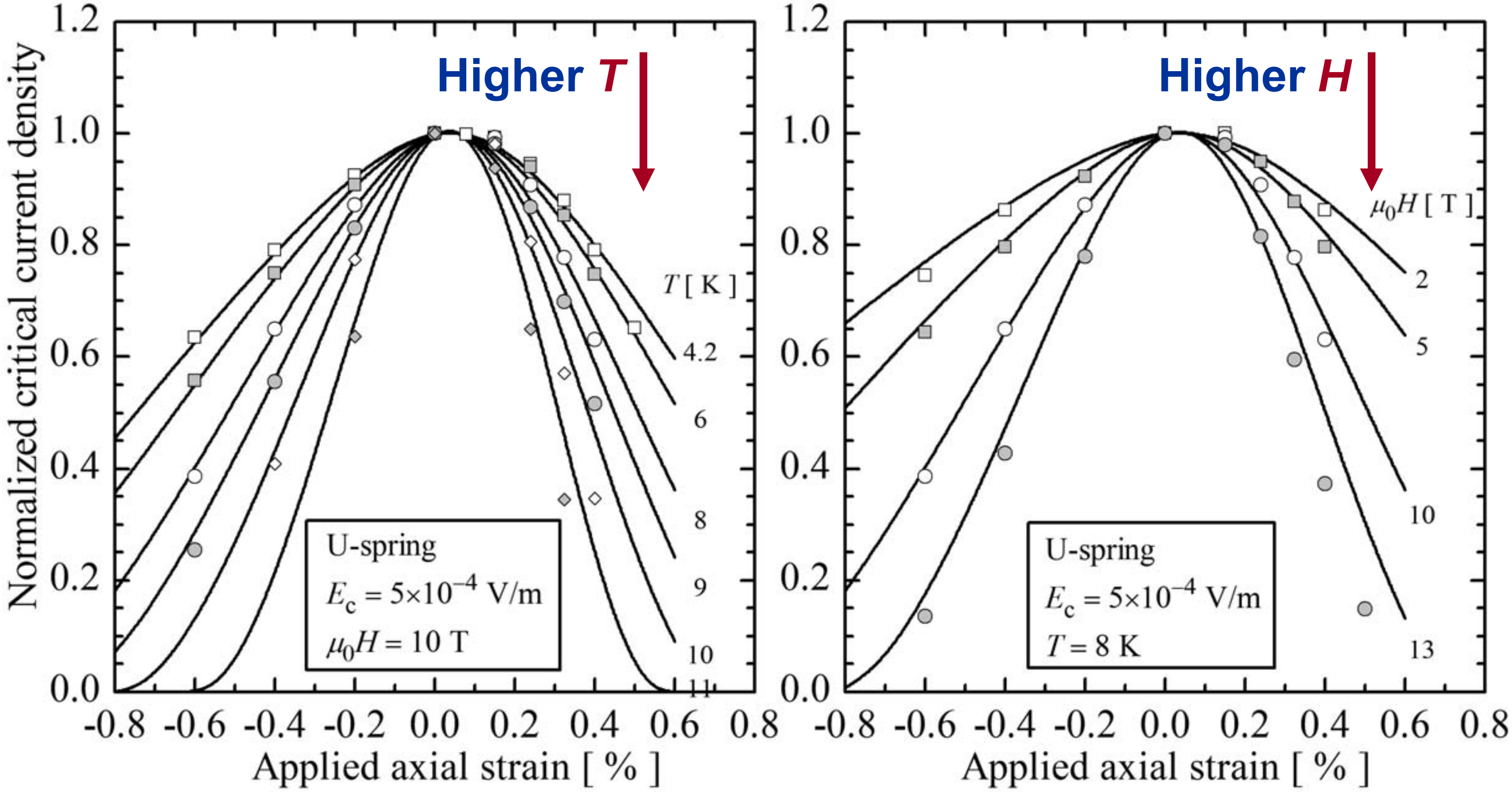
- Longitudinal strain effects on ***effective*** $H_{c2}(T)$*



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

Strain sensitivity of $J_c(H,T)$

J_c(10 T, T, ε_{axial}) J_c(H, 8 K, ε_{axial})

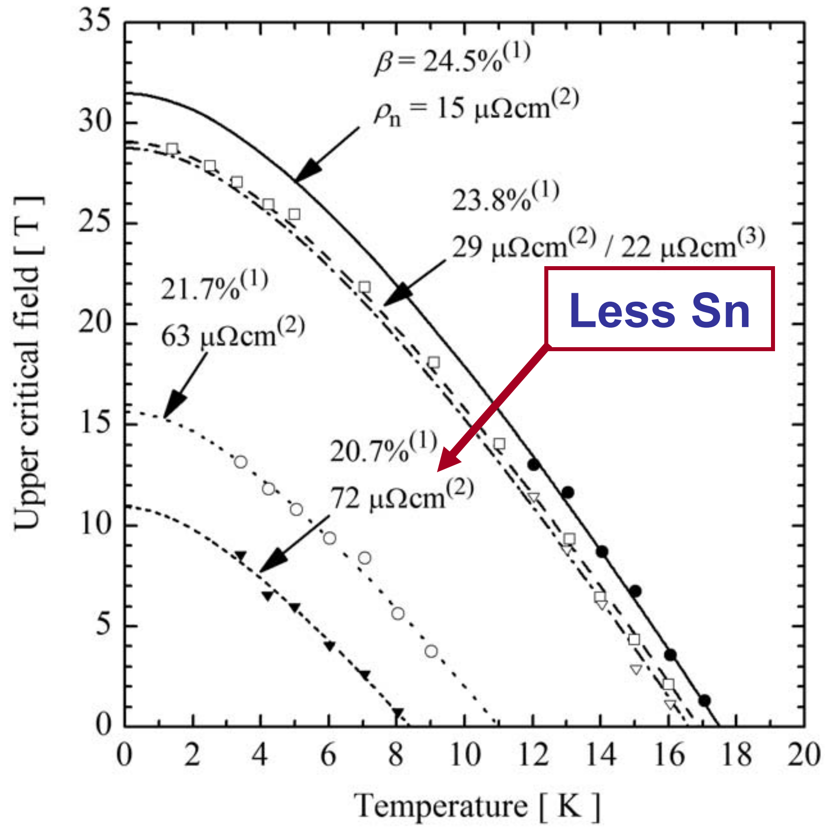


- **Why is strain sensitivity increased at higher *H* and *T* ?**

Strain sensitivity versus composition

At higher *H* and *T*

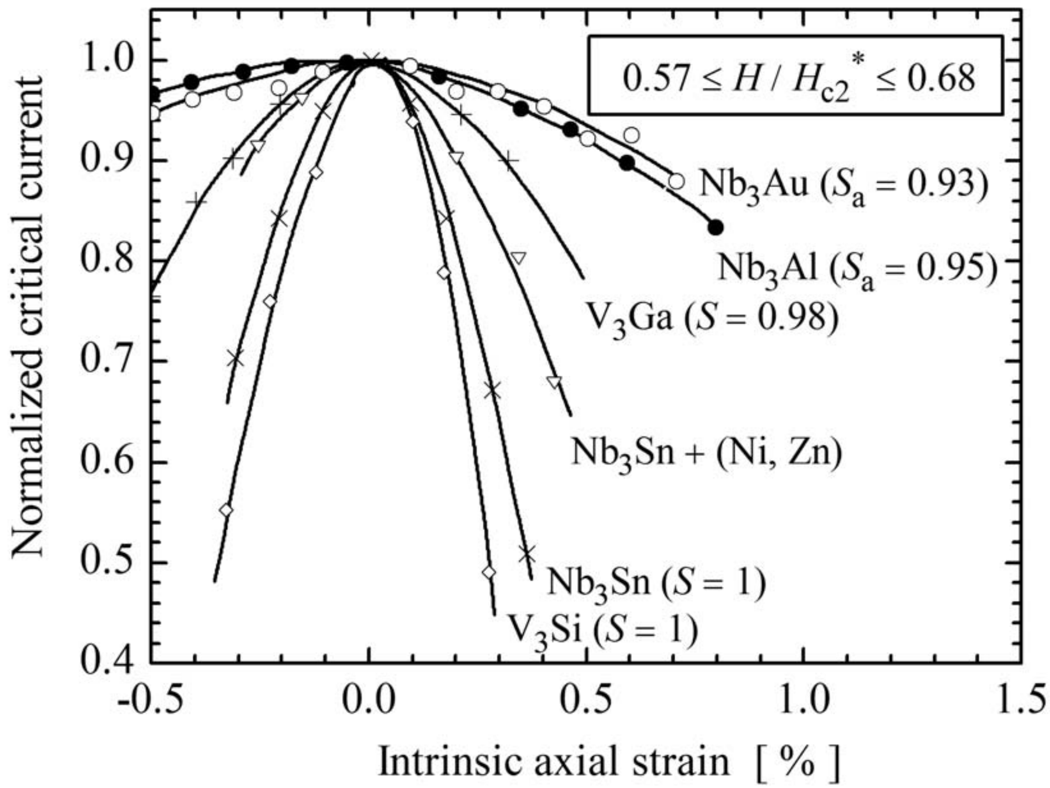
- Low Sn A15 sections "die out"
  - Benefit PIT and IT vs Bronze:
    - Larger volume fraction high Sn
  - High Sn sections determine SC properties
- Increased strain sensitivity
  - Is Sn rich A15 more strain sensitive than Sn poor A15 ?



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

Strain sensitivity versus LRO

- *S* → Bragg-Williams order parameter

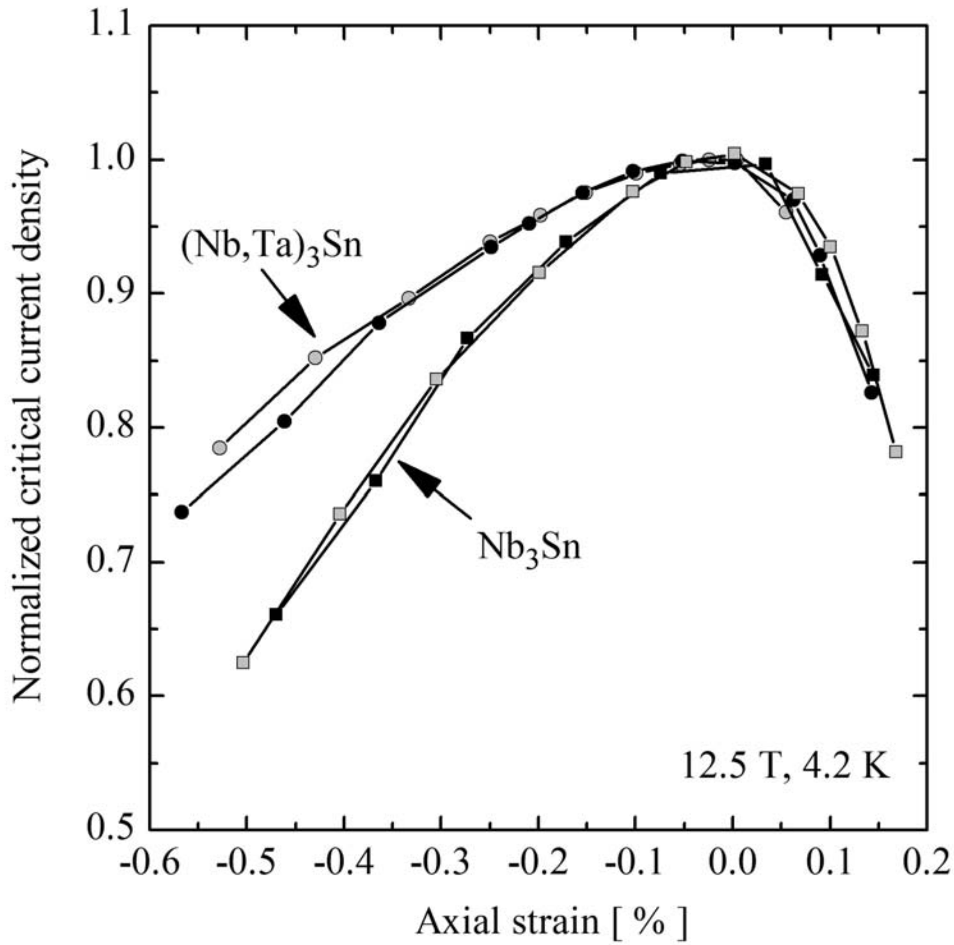


- **Flükiger, ACE 1984**

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

Strain in ternary and binary wires

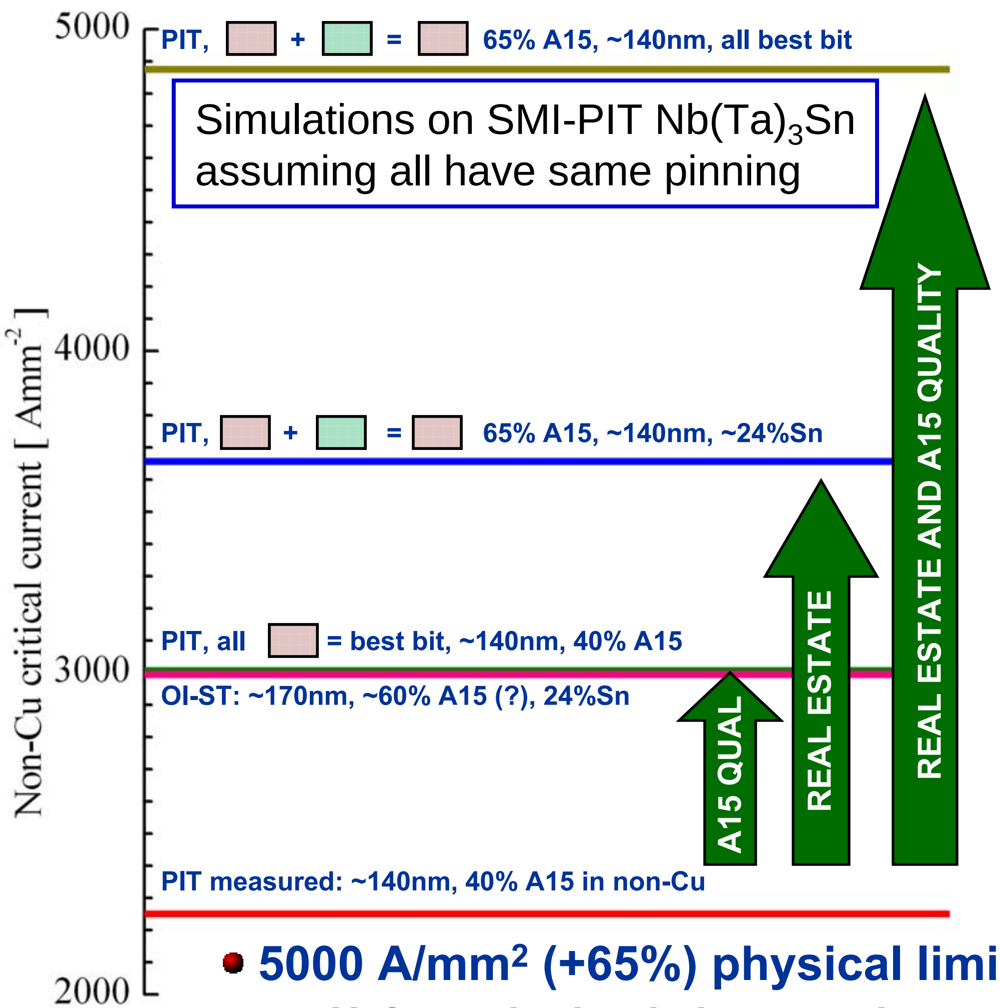
- Alloyed → more disorder → reduced strain sensitivity?

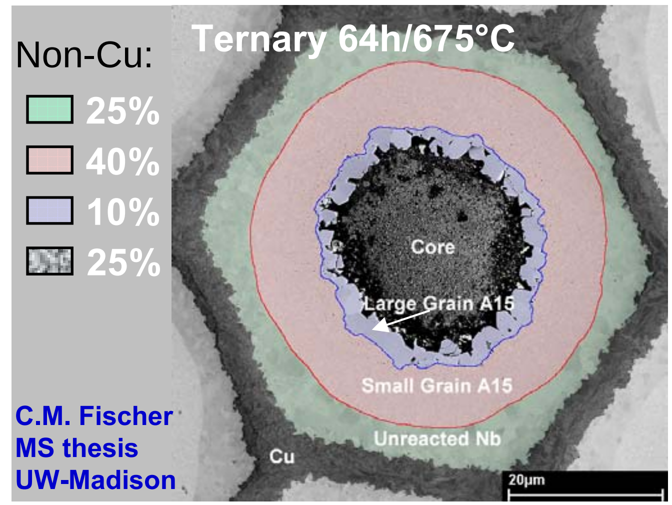


Outline

- 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
- Present status and future prospects

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

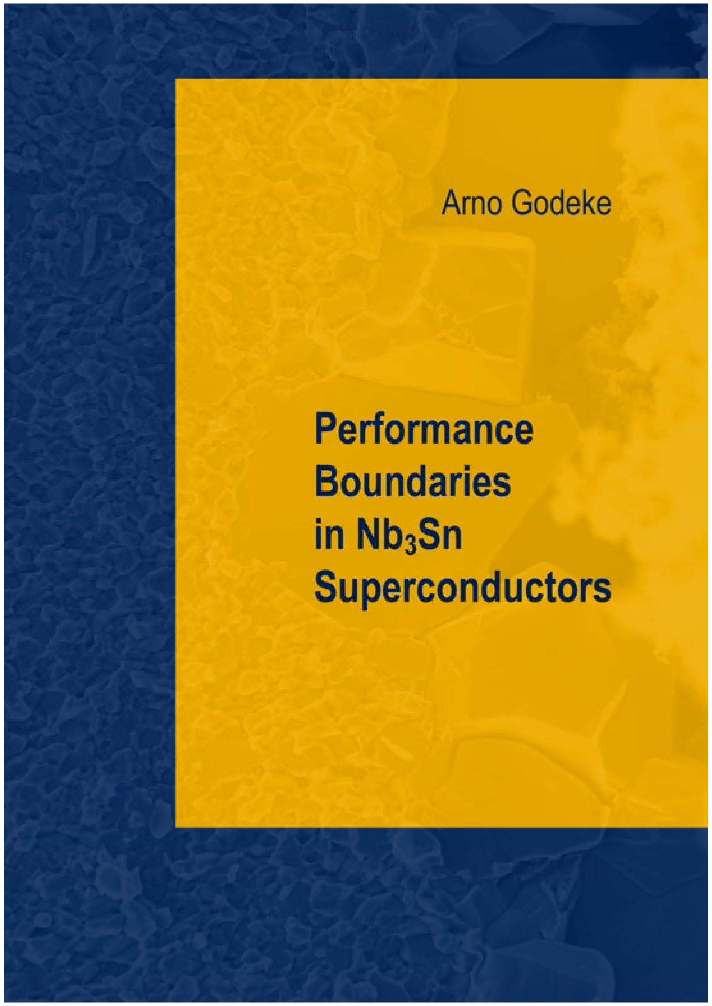
- The next big step?
- Grain size one order above optimal
- Grain 10 – 20 nm desired → nano technology

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)**

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

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

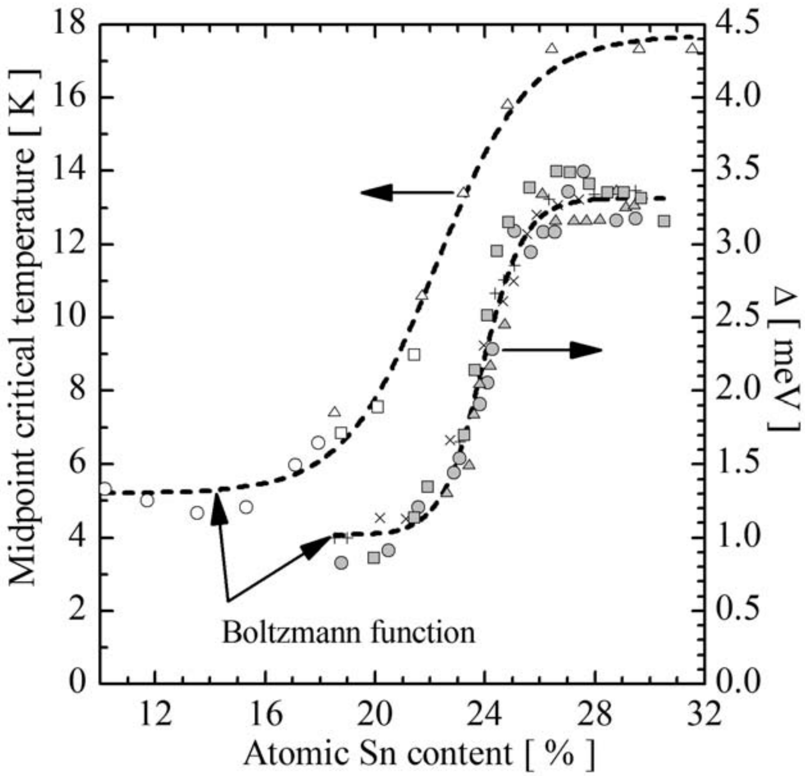
- **Interaction strength independent (Eliashberg based)**

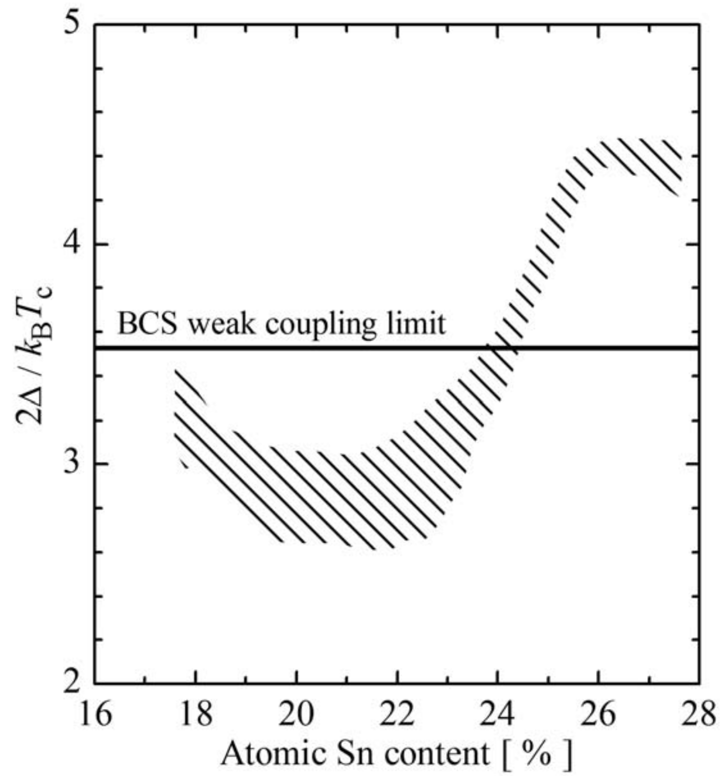
$$\lambda_{ep} = 2\int \frac{\alpha^2(\omega) F(\omega)}{\omega} d\omega \qquad \lambda_{eff} = \frac{\left(\lambda_{ep} - \mu^*\right)}{\left(1 + 2\mu^* + 1.5\lambda_{ep}\mu^* e^{-0.28\lambda_{ep}}\right)}$$

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

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