Advances in Nb_3Sn Performance

Medium magnetic fields, very high current densities

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OXFORD INSTRUMENTS

SMI SHAPEMETAL INNOVATION B.V.

EAS

SupraMagnetics

SUPERCON INC.

Supergenics I LLC

- **OST:** Hong, Parrell
  SMI Lindenhovius

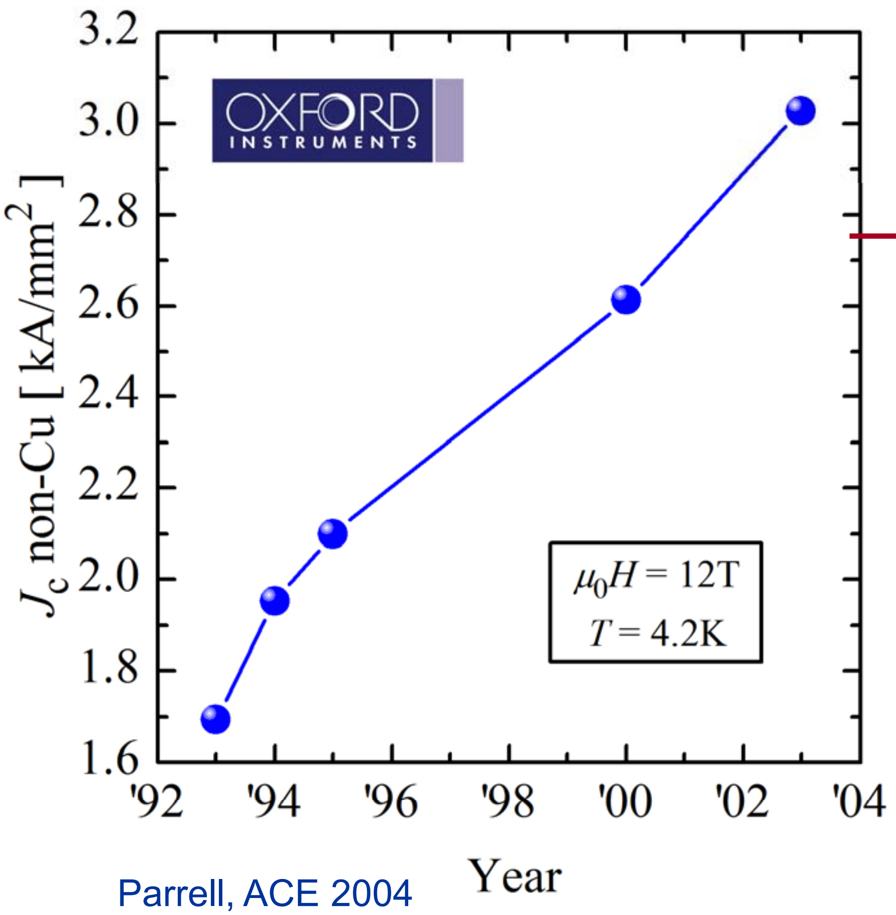
SupraMagnetics: Motowidlo
EAS: Schlenga, Thoener

Supergenics: Gregory
Supercon: Wong, Renaud

U.S. DEPARTMENT OF ENERGY

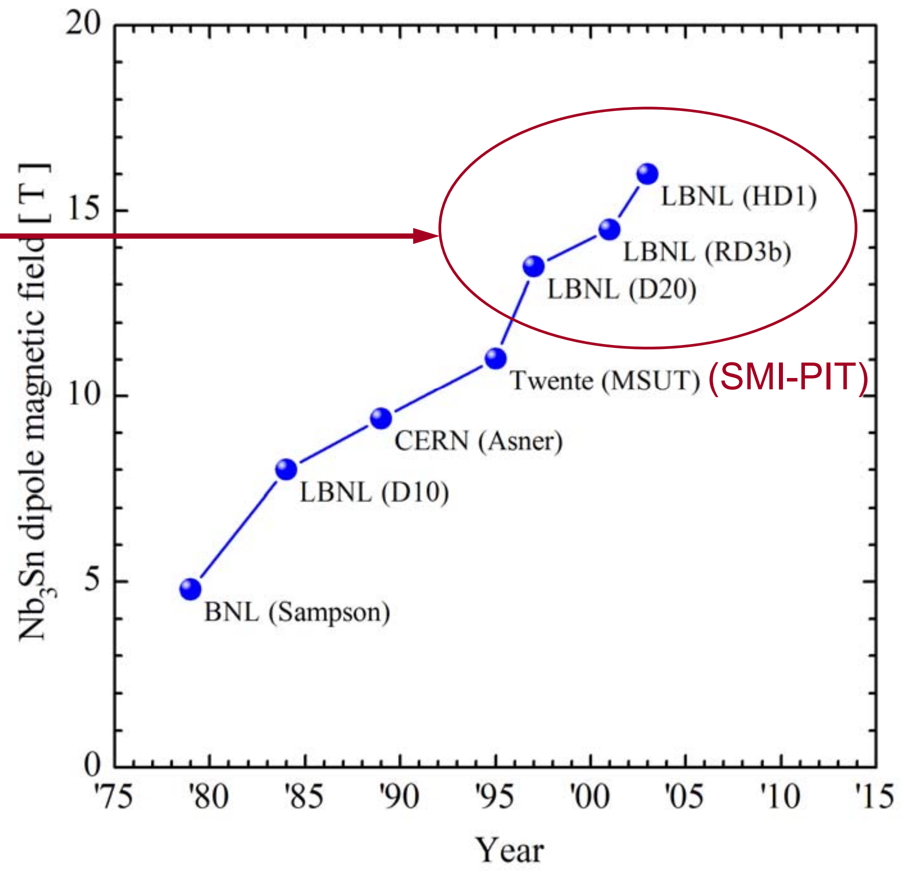
Increasing non-Cu J_c pays off

Progress in Nb_3Sn wire J_c…



Parrell, ACE 2004

…and in Nb_3Sn dipole magnetic fields



Dietderich, Cryogenics 2008

But where does J_c come from…

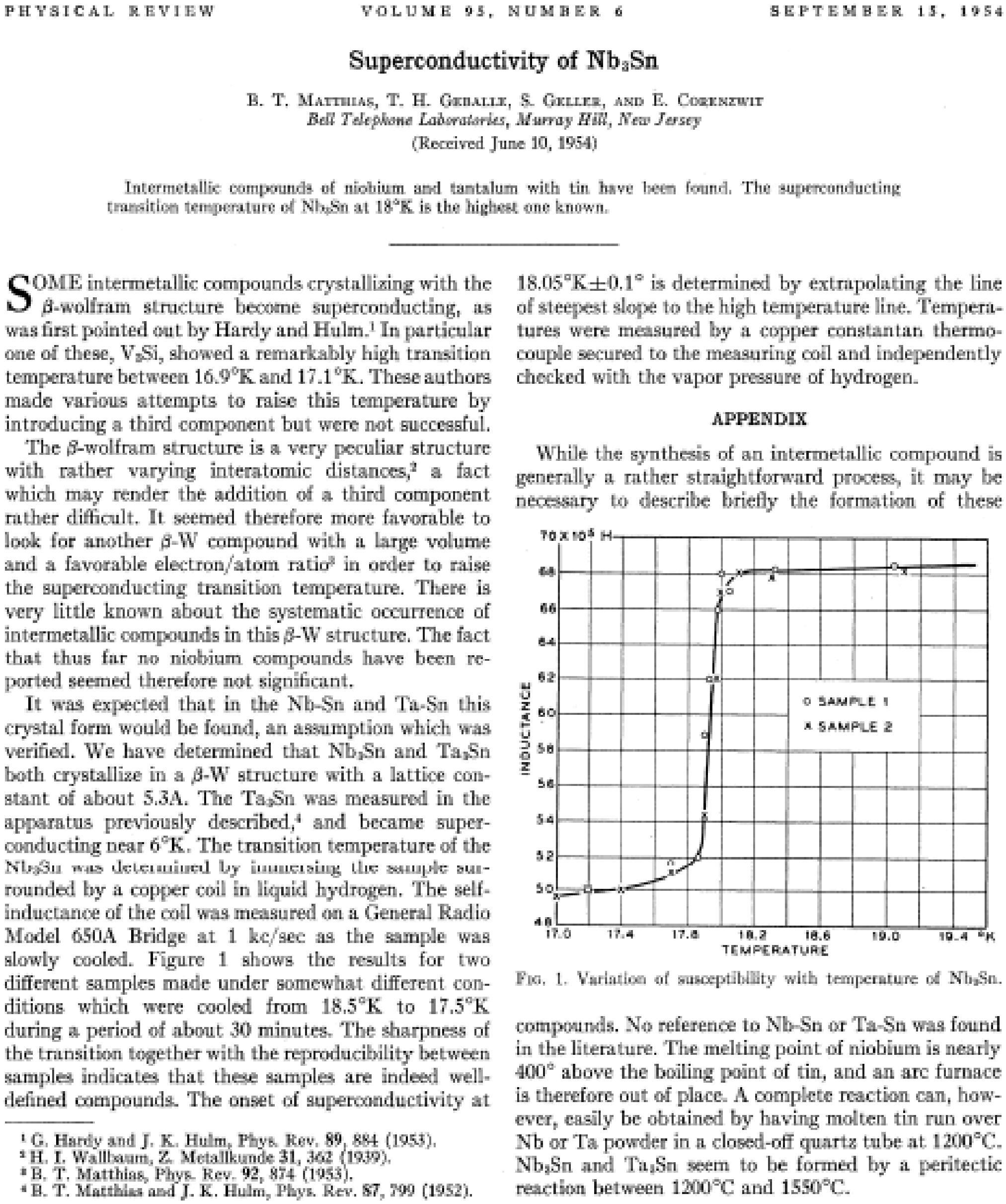
Outline

- Main properties of Nb_3Sn
    - Composition
    - Pinning
    - Strain
- Critical current density and critical current
    - What determines these?
- Modern high J_c Nb_3Sn wires
    - Overview of (some) manufacturers
- Prospects for future improvements
    - Possible ways to increase J_c
- Scaling of the critical current density

Superconductivity in Nb_3Sn

Matthias, PRB 95 (1954)

- Molten Sn over Nb powder in a quartz tube at 1200 C
- T_c onset at 18.05 ± 0.1 K



PHYSICAL REVIEW VOLUME 95, NUMBER 6 SEPTEMBER 15, 1954

Superconductivity of Nb_3Sn

B. T. Matthias, T. H. Geballe, S. Geller, and E. Corenzwit
Bell Telephone Laboratories, Murray Hill, New Jersey

(Received June 10, 1954)

Intermetallic compounds of niobium and tantalum with tin have been found. The superconducting transition temperature of Nb_3Sn at 18°K is the highest one known.

SOME intermetallic compounds crystallizing with the β-wolfram structure become superconducting, as was first pointed out by Hardy and Hulm.[1] In particular one of these, V_3Si, showed a remarkably high transition temperature between 16.9°K and 17.1°K. These authors made various attempts to raise this temperature by introducing a third component but were not successful.

The β-wolfram structure is a very peculiar structure with rather varying interatomic distances,[2] a fact which may render the addition of a third component rather difficult. It seemed therefore more favorable to look for another β-W compound with a large volume and a favorable electron/atom ratio[3] in order to raise the superconducting transition temperature. There is very little known about the systematic occurrence of intermetallic compounds in this β-W structure. The fact that thus far no niobium compounds have been reported seemed therefore not significant.

It was expected that in the Nb-Sn and Ta-Sn this crystal form would be found, an assumption which was verified. We have determined that Nb_3Sn and Ta_3Sn both crystallize in a β-W structure with a lattice constant of about 5.3A. The Ta_3Sn was measured in the apparatus previously described,[4] and became superconducting near 6°K. The transition temperature of the Nb_3Sn was determined by immersing the sample surrounded by a copper coil in liquid hydrogen. The self-inductance of the coil was measured on a General Radio Model 650A Bridge at 1 kc/sec as the sample was slowly cooled. Figure 1 shows the results for two different samples made under somewhat different conditions which were cooled from 18.5°K to 17.5°K during a period of about 30 minutes. The sharpness of the transition together with the reproducibility between samples indicates that these samples are indeed well-defined compounds. The onset of superconductivity at 18.05°K±0.1° is determined by extrapolating the line of steepest slope to the high temperature line. Temperatures were measured by a copper constantan thermocouple secured to the measuring coil and independently checked with the vapor pressure of hydrogen.

APPENDIX

While the synthesis of an intermetallic compound is generally a rather straightforward process, it may be necessary to describe briefly the formation of these compounds. No reference to Nb-Sn or Ta-Sn was found in the literature. The melting point of niobium is nearly 400° above the boiling point of tin, and an arc furnace is therefore out of place. A complete reaction can, however, easily be obtained by having molten tin run over Nb or Ta powder in a closed-off quartz tube at 1200°C. Nb_3Sn and Ta_3Sn seem to be formed by a peritectic reaction between 1200°C and 1550°C.

Fig. 1. Variation of susceptibility with temperature of Nb_3Sn.

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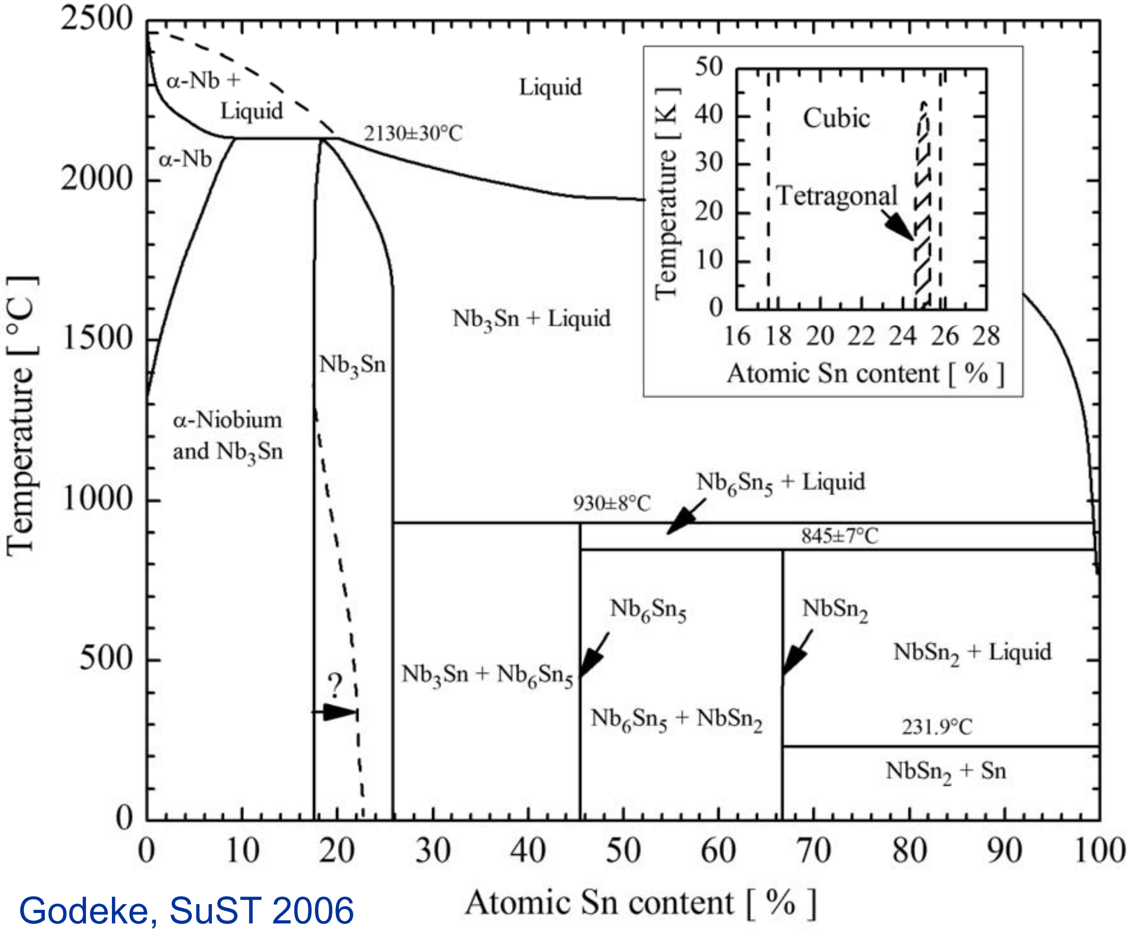
[1] G. Hardy and J. K. Hulm, Phys. Rev. 89, 884 (1953).
[2] H. I. Wallbaum, Z. Metallkunde 31, 362 (1939).
[3] B. T. Matthias, Phys. Rev. 92, 874 (1953).
[4] B. T. Matthias and J. K. Hulm, Phys. Rev. 87, 799 (1952).

Nb_3Sn is not a line compound: $Nb_{1-\beta}Sn_\beta$

Binary phase diagram

- Charlesworth, JMS 1970; Flükiger, ACE 1982

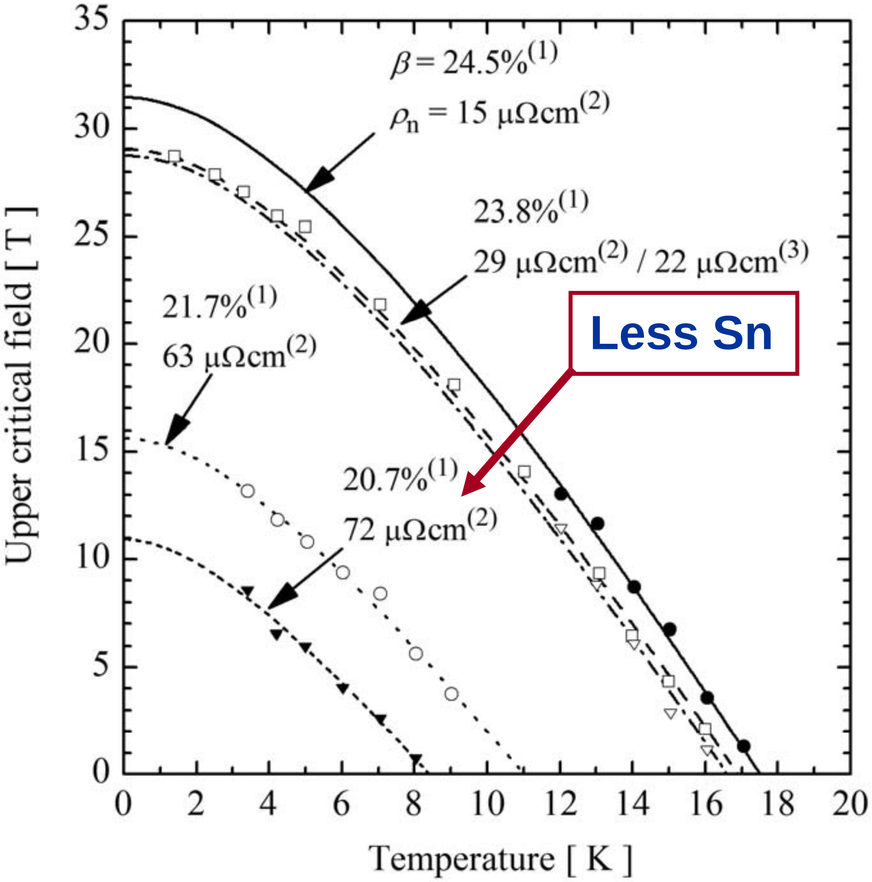


Godeke, SuST 2006

Nb-Sn stable from 18 to 25 at.% Sn → 'A15'

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

Jewell, ACE 2004, bulk samples



Less Sn

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

Alloying of Nb-Sn

Suenaga, JAP 1986

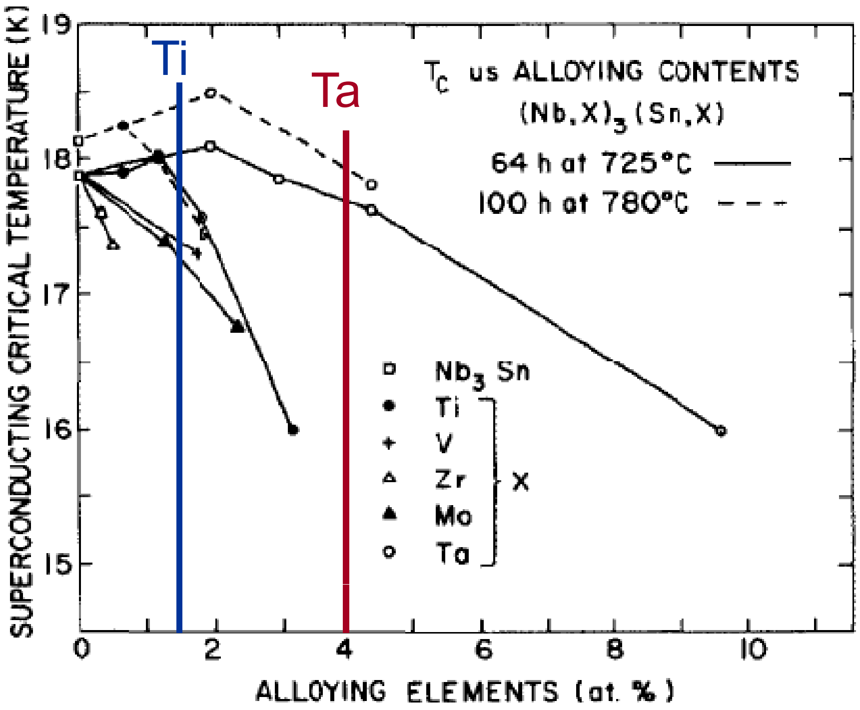
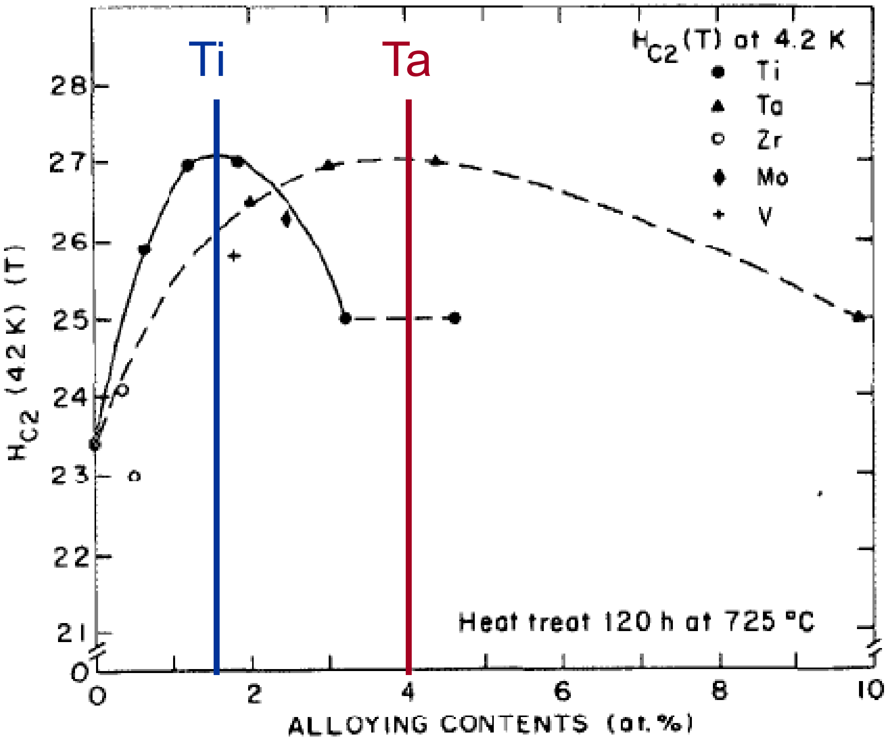


FIG. 7. Effect on the critical temperature T_c of alloying Nb_3Sn with several



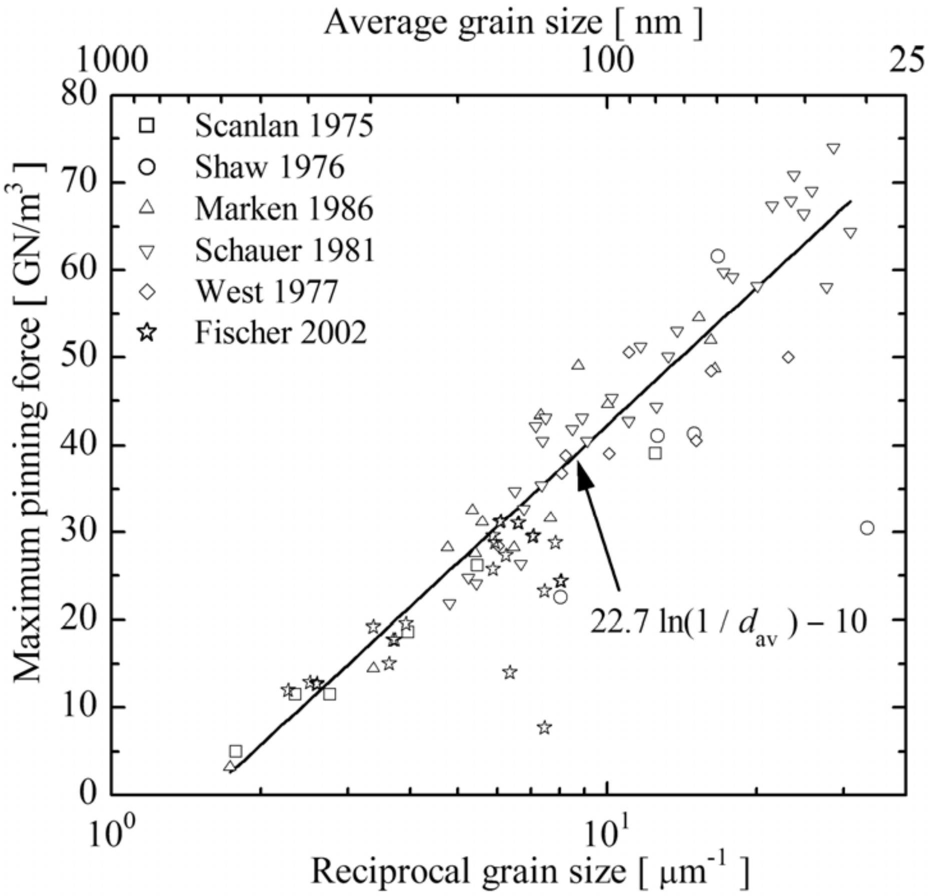
- Ti: Optimal H_{c2} at 1.5 at.%, Ta: Optimal H_{c2} at 4 at.%, Both: slight variation T_c
- Flükiger, SuST 2008: Different optima: $(Nb_{1-x}Ta_x)_3Sn$ and $Nb_3(Sn_{1-x}Ti_x)$

Alloying increases H_{c2}

What determines pinning capacity?

Pinning centers

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



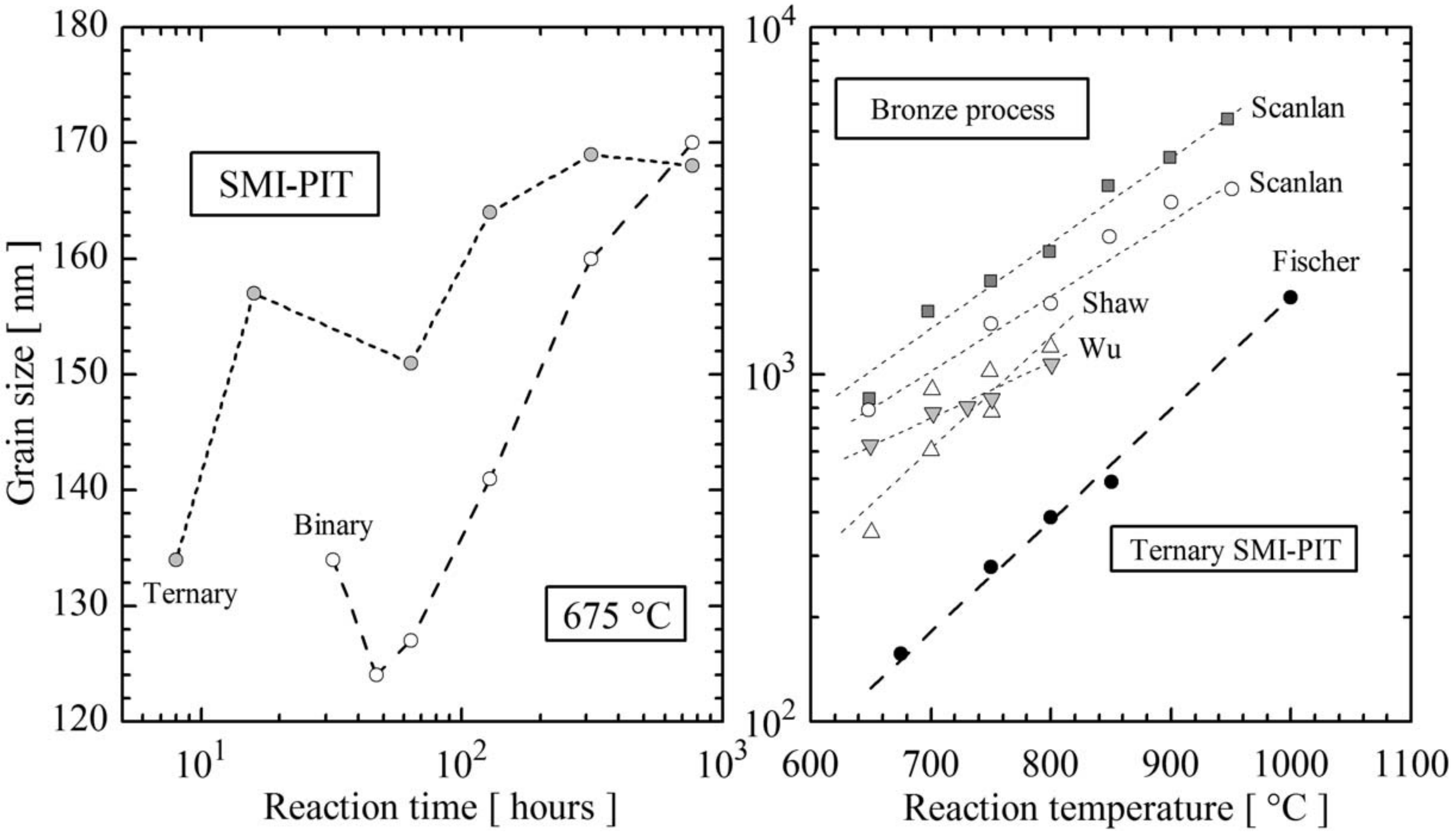
Godeke, SuST 2006

Nb_3Sn

- Grain boundaries
  - Main pinning centers

Grain size determines F_{Pmax}

What determines grain size?



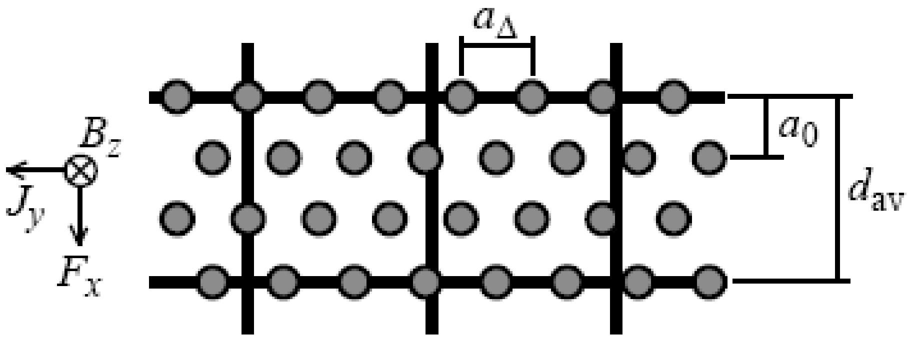
Godeke, Cryogenics 2008

Reaction time (somewhat) and temperature (a lot)

What is an optimal grain size?

Ideal: One pinning center per flux-line

- Flux-line spacing $a_0 \approx$ average grain size d_{av}



Schematic: Cubic grains and flux-line lattice
Godeke, to be published 2008

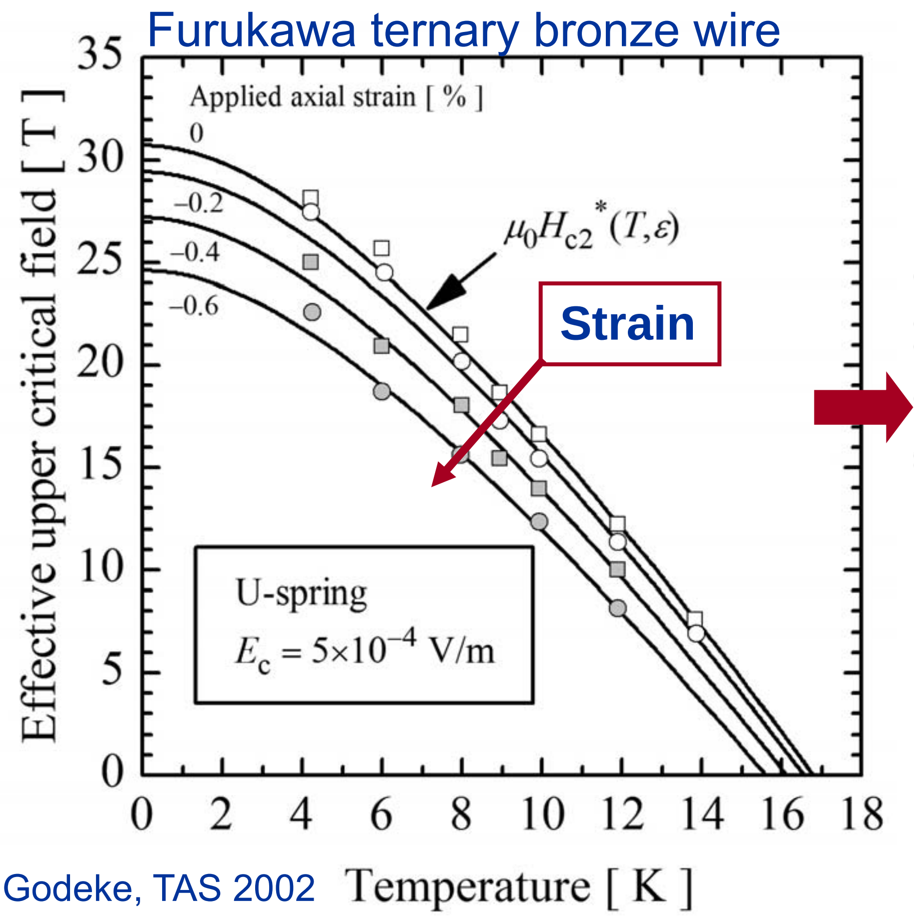
- Flux-line spacing → field dependent
  - E.g. at 12 T $a_0 = (3/4)^{1/4}(\phi_0/\mu_0 H)^{1/2} = 12$ nm
  - Grain size in Nb_3Sn wires → 100 – 200 nm

Grain sizes in wires are one order of magnitude from optimal

Strain sensitivity

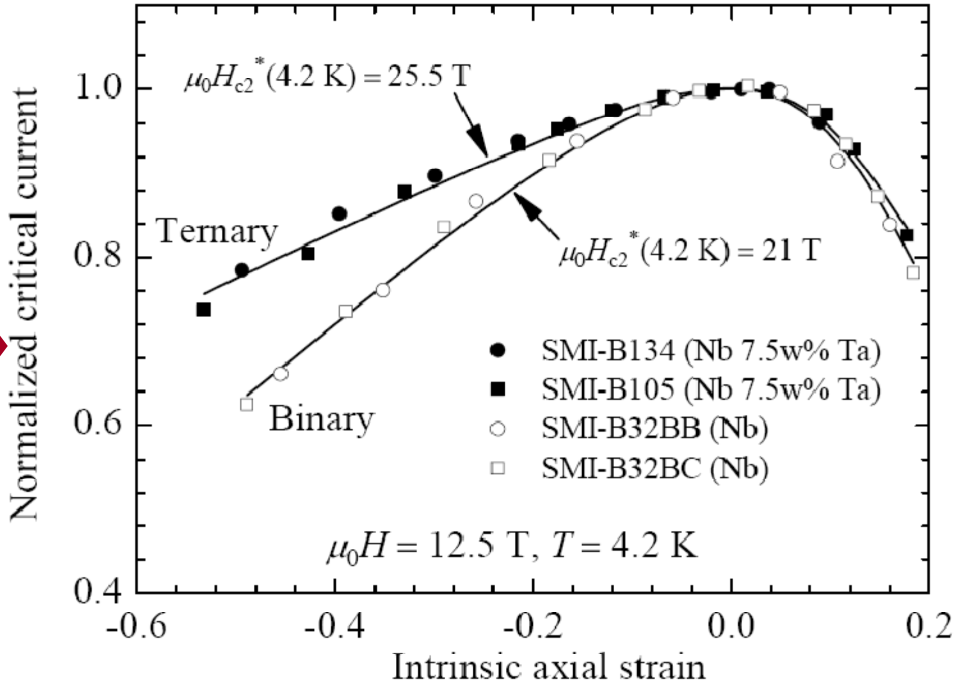
Longitudinal strain effects on ***effective*** $H_{c2}(T)$*

Furukawa ternary bronze wire



Godeke, TAS 2002

SMI-PIT: Ternary and binary wires



Godeke, Cryogenics 2008

Note: Increased H_{c2}* can provide lower strain dependence at medium fields

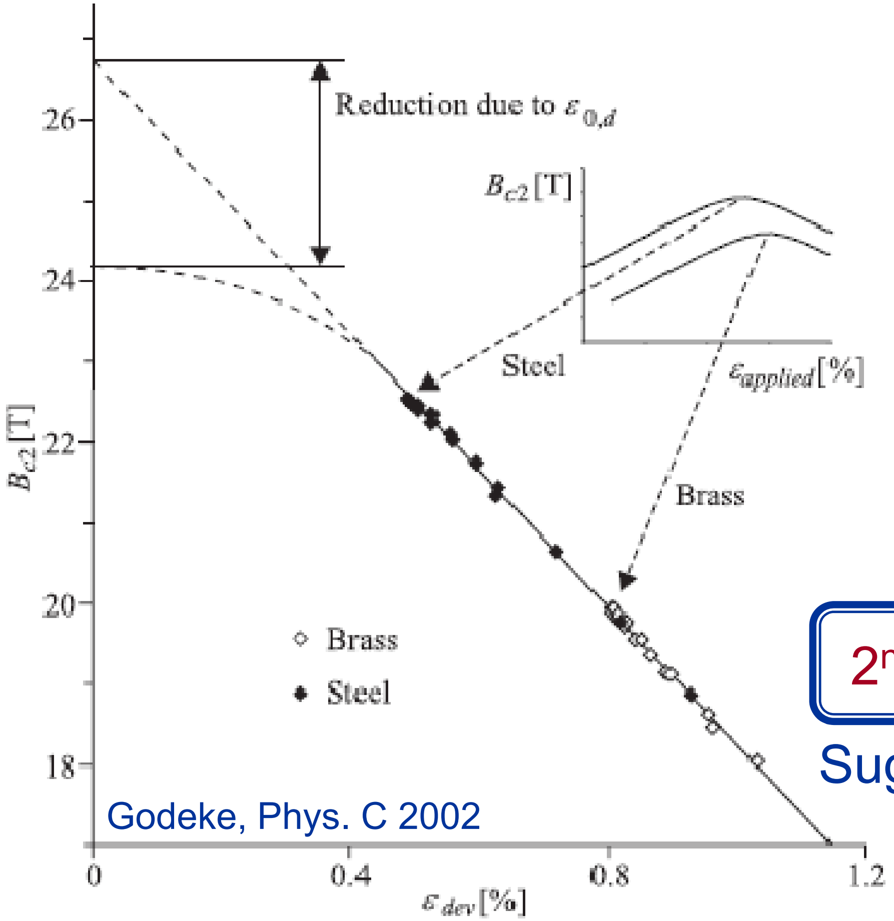
Strain and Sn content have similar effects

Strain models existing

- 1D empirical (Ekin, Cryogenics 1980, Taylor, SuST 2005):

$$s(\varepsilon)=1-a\left|\varepsilon_{\mathrm{axial}}\right|^{u} \qquad s(\varepsilon)=1+c_2\varepsilon^2+c_3\varepsilon^3+c_4\varepsilon^4$$

- 3D empirical (Ten Haken, Thesis 1994): Data from quasi 2D tapes



Godeke, Phys. C 2002

$$s(\varepsilon_{\mathrm{dev}})\cong 1-C_{\mathrm{d}}\sqrt{\left(\varepsilon_{\mathrm{dev}}\right)^2+\left(\varepsilon_{0,\mathrm{d}}\right)^2}$$

$$H_{\mathrm{c2}}^{*}(\varepsilon)\equiv H_{\mathrm{c2m}}^{*}\,s(\varepsilon)$$

$$T_{\mathrm{c}}^{*}(\varepsilon)\equiv T_{\mathrm{cm}}^{*}\,s(\varepsilon)^{\frac{1}{\varpi}}$$

2nd invariant (deviatoric strain) dominates

Suggested originally by Welch and Testardi

Strain models progress (I)

More fundamental approach (Markiewicz, Cryogenics 2004)

- Strain modifies
  - Lattice vibration modes (phonons)
  - Electron-phonon interaction spectrum

$$\lambda_{\mathrm{ep}} = 2\int \frac{\alpha^2(\omega)F(\omega)}{\omega}\,d\omega$$

$$\downarrow$$

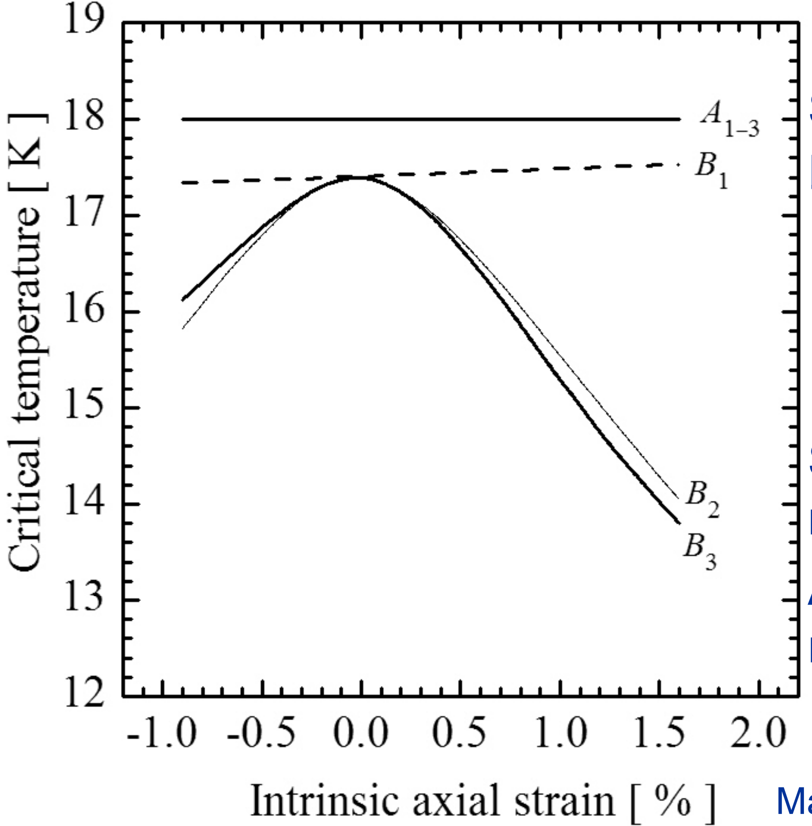
$$\lambda_{\mathrm{eff}} = \frac{\left(\lambda_{\mathrm{ep}} - \mu^*\right)}{\left(1 + 2\mu^* + 1.5\lambda_{\mathrm{ep}}\mu^* e^{-0.28\lambda_{\mathrm{ep}}}\right)}$$

$$\swarrow \qquad \searrow$$

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

$$\downarrow$$

$$s(\varepsilon) = \frac{1}{1 + c_2\varepsilon^2 + c_3\varepsilon^3 + c_4\varepsilon^4}$$



Strain free value

Hydrostatic (1st inv)

Symmetric (2nd inv) non-hydrostatic

Asymmetric (3rd inv) non-hydrostatic

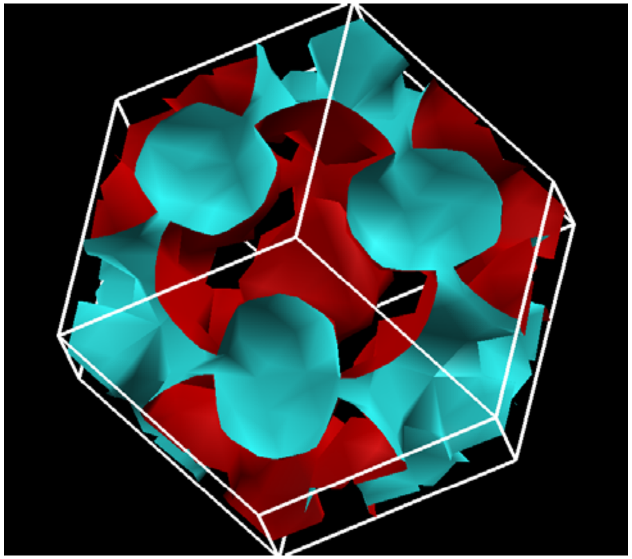
Markiewicz, TAS 2005

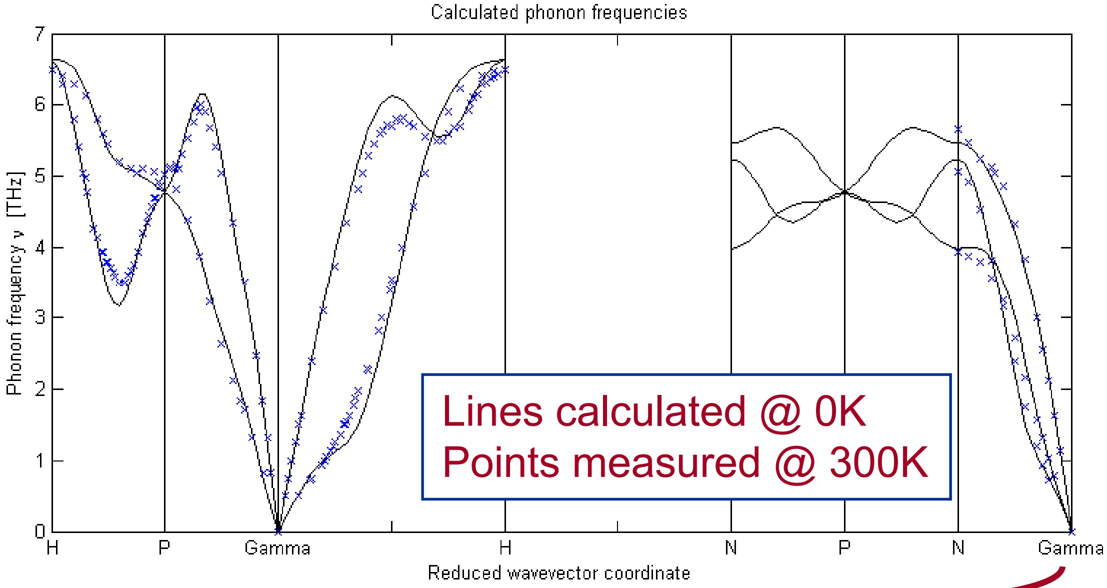
2nd invariant dominates, $H_{c2}(\varepsilon)$ missing

Strain models progress (II)

Truly fundamental approach (Salvetti, in progress):

- Goal: Ab-initio calculation of critical properties Nb, Nb_3Sn and Nb_3Al
  - Only external input is lattice deformation (strain)
- Density Functional Theory ➔ Phonon dispersion curves and e-p interactions
- Example: Calculated Fermi surface and phonon dispersion curves Nb



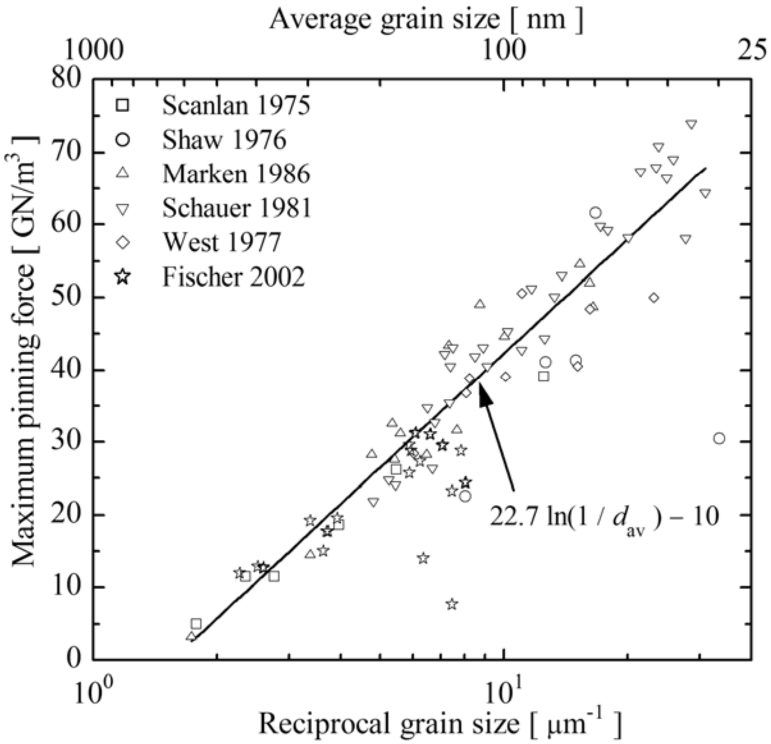


$$+\varepsilon \text{ and } \lambda_{\mathrm{ep}} = 2\int \frac{\alpha^2(\omega)F(\omega)}{\omega}\,d\omega \rightarrow T_{\mathrm{c}}(\varepsilon)$$

- Principally also allows calculation of Sn deficiency

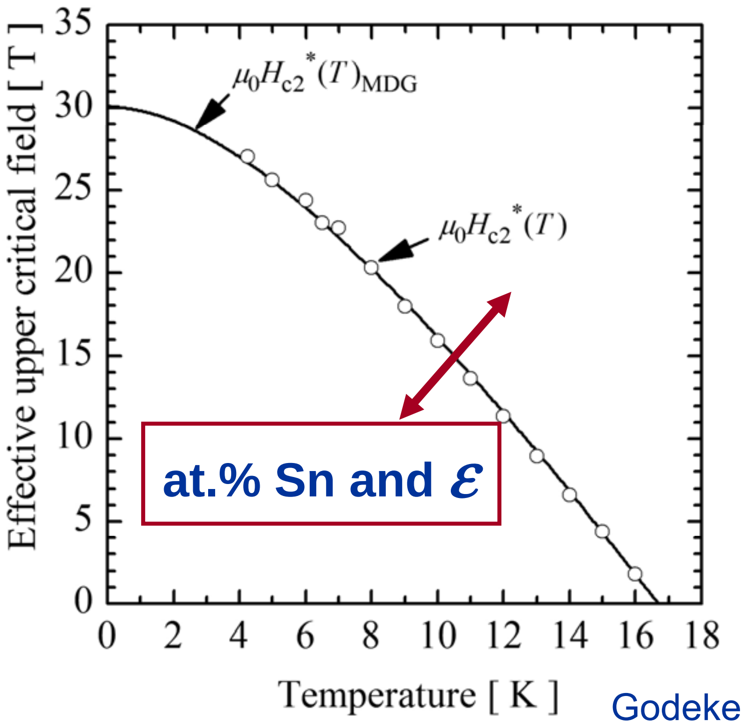
In summary: What determines J_c?

Pinning capacity



+

Effective *H* – *T* phase boundary



at.% Sn and ε

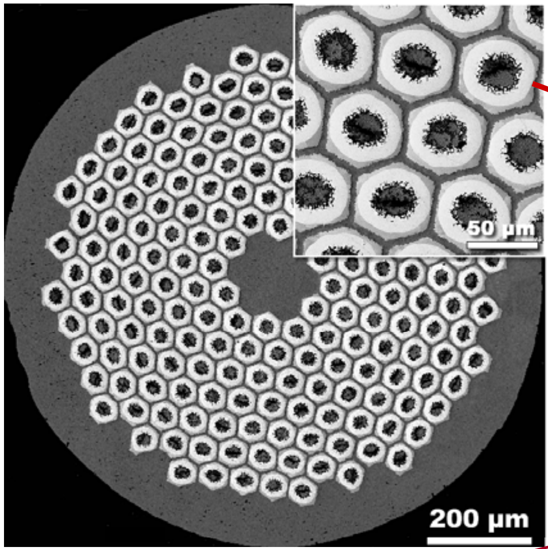
= J_c

Godeke, SuST 2006

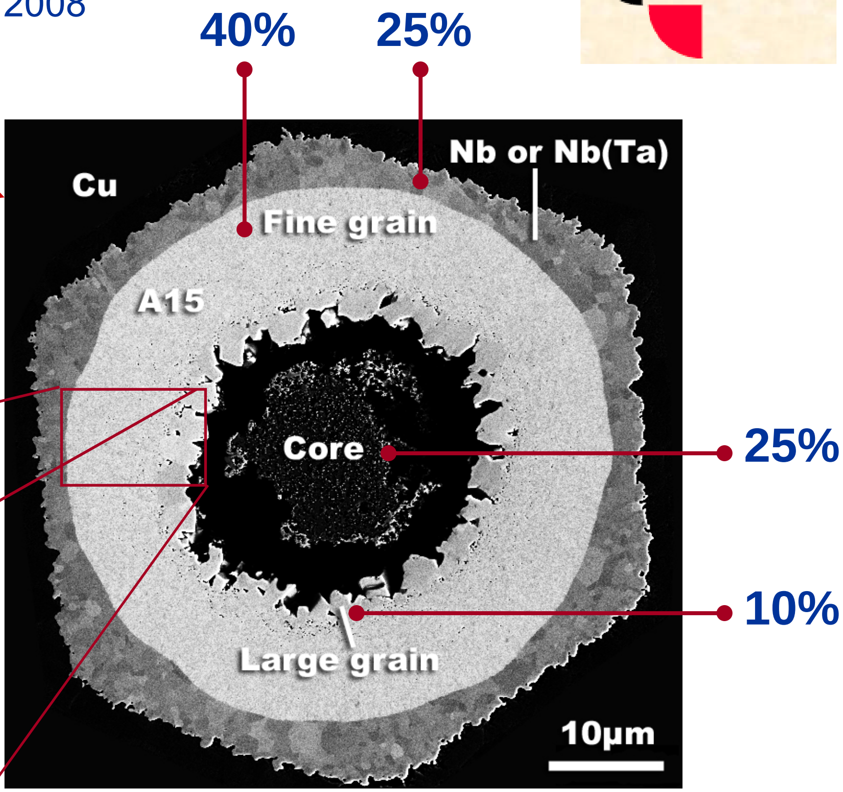
- Average grain size
- Composition
- Strain state

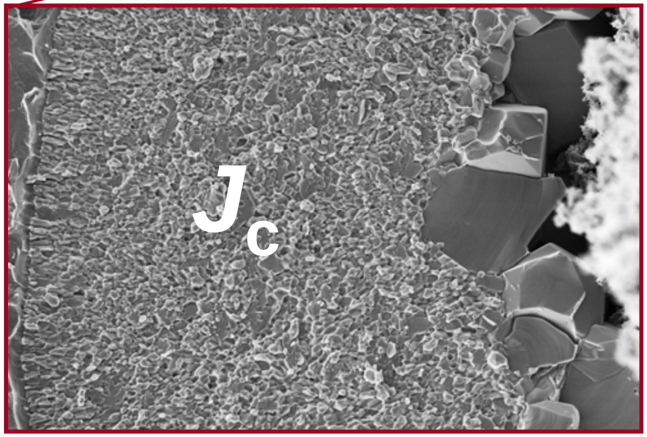
What determines I_c?

- Powder-in-tube wire (SMI)
- 50% Non – Cu fraction



Courtesy, Lee and Fisher 2005
Godeke, Cryogenics 2008





Only ~20% of a wire carries J_c

Recipe for a very high current wire

Filaments / sub-elements below ~50 micrometer

Real estate

- As much A15 in the non-Cu cross-section as possible
  - Much (typically ~ 25%) is still lost as Sn source

Sn content

- Optimal around 24.5 at.% Sn
- Abundant Sn supply

Short diffusion distances

- Long diffusion distances inevitably result in Sn gradients

Alloying: 1.5 at.% Ti and 4 at.% Ta additions

- Commercial alloys: Nb 47 wt.% Ti and Nb 7.5 wt.% Ta

Grain sizes around 10 – 15 nm for optimal pinning in 10 – 15 T regime

- Requires short, low temperature reactions (which result in Sn deficiency)
- Wire grain sizes typically 100 – 200 nm

Strain dependence

- Engineer applications around it
- Present status of knowledge does not suggest tweaks (much to be done here!)

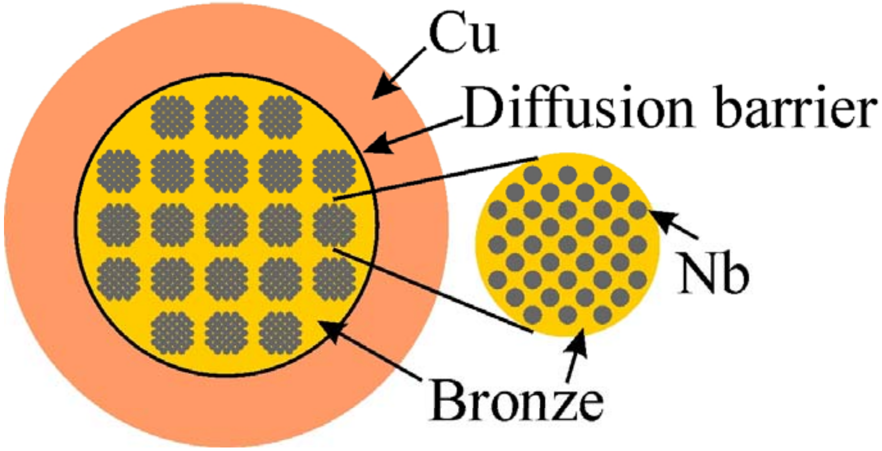
Wires

What is being made using the aforementioned knowledge?

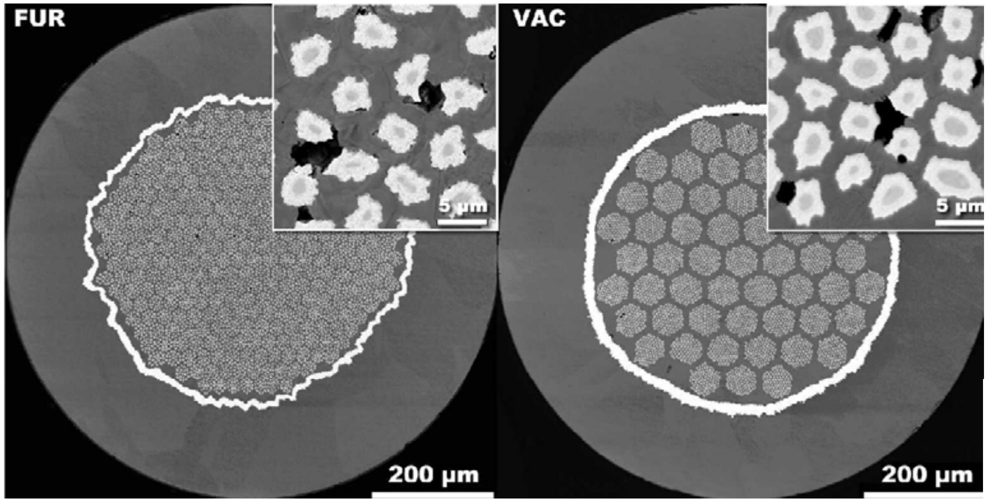
A very **incomplete** list!

Apologies to those not included

The ‘classic’ Bronze process



Godeke, JAP 2005 (Courtesy, Lee 2005)



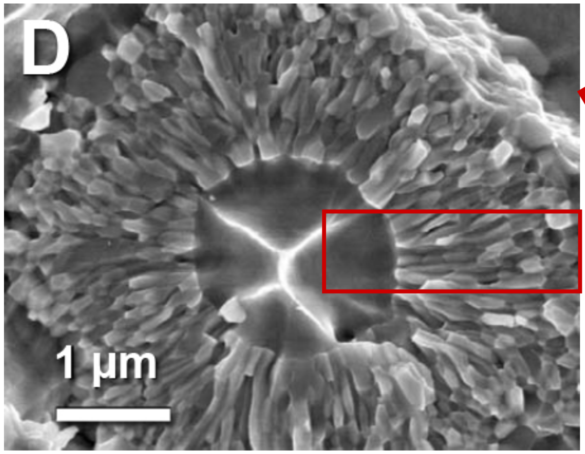
Made by many manufacturers

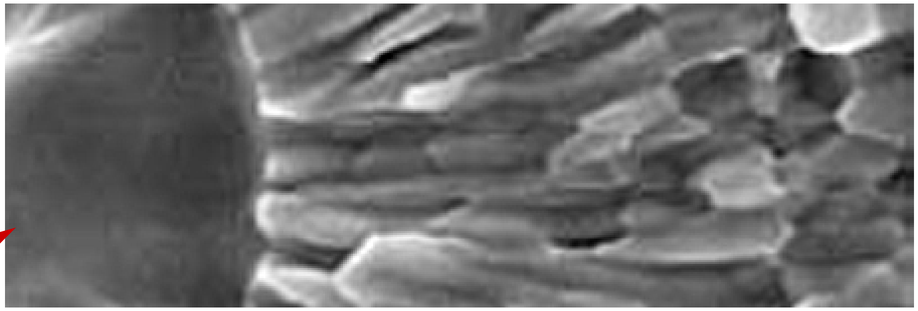
- Proven technology, large billets, very fine filaments, low loss, but…

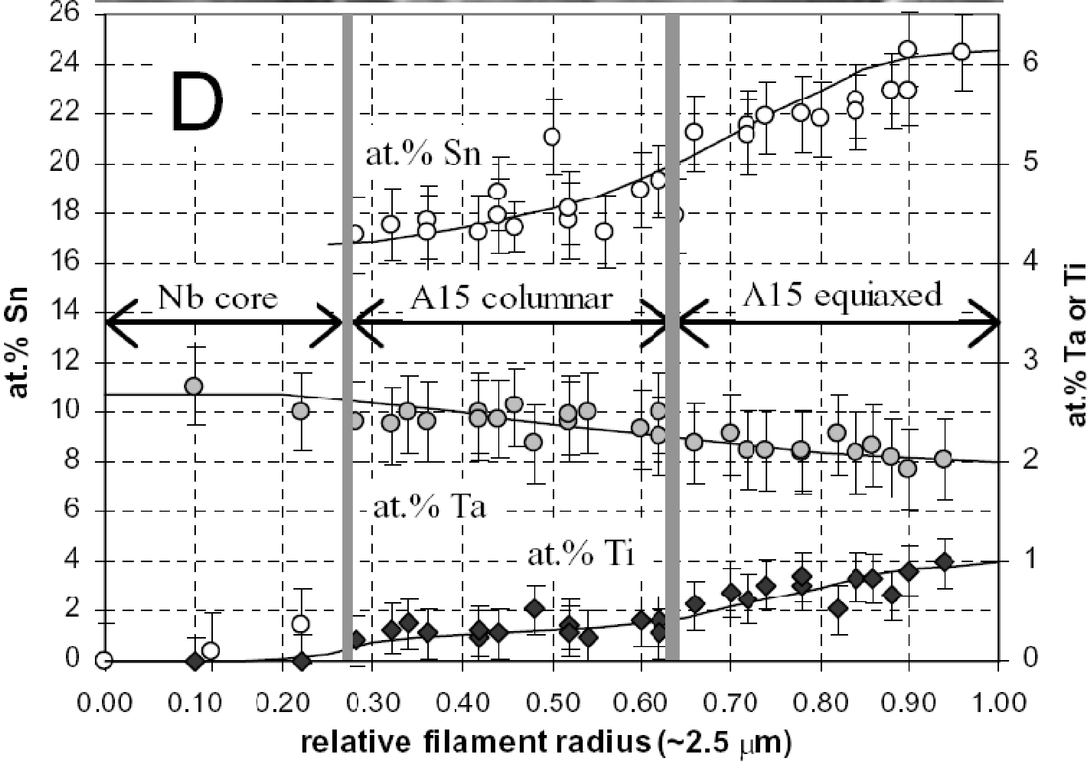
- Limited J_c due to limited Sn source
  - Solubility of Sn in Cu < 16%
  - Sn depletion of source gives Sn gradients

Composition variation in Bronze wires

Bronze process wire







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

Small A15 fraction is high Sn

Abächerli, TAS 2005

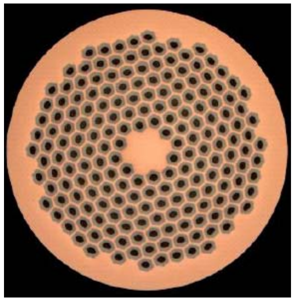
Powder-in-Tube wires from SMI-EAS

Process

- Powder: $NbSn_2$ plus Cu
- Tubes: pure Nb or Nb-7.5Ta
- Production unit ~45 kg net

Maximum performance

- Non-Cu J_c(12T, 4.2K) 2582 A/mm^2
- 192 filaments, 1 mm
- 52% Cu



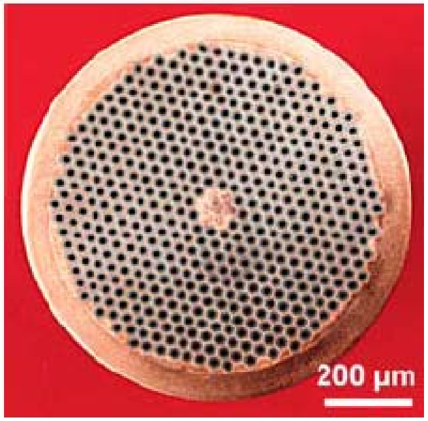
M. Thoener: Wednesday 15.45

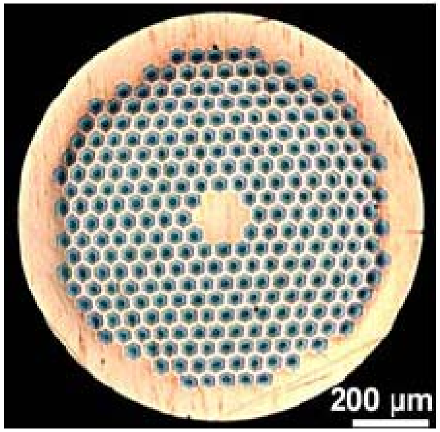
Low loss (ITER) version

- 504 filaments @ 25 micrometer
- 0.81 mm
- 50% Cu
- 1350 A/mm^2 (Binary)
- 1950 A/mm^2 (Ternary)

High current (NED) version

- 288 filaments @ 35 micrometer
- 1.25 mm
- 55% Cu
- 2500 A/mm^2 (Ternary)

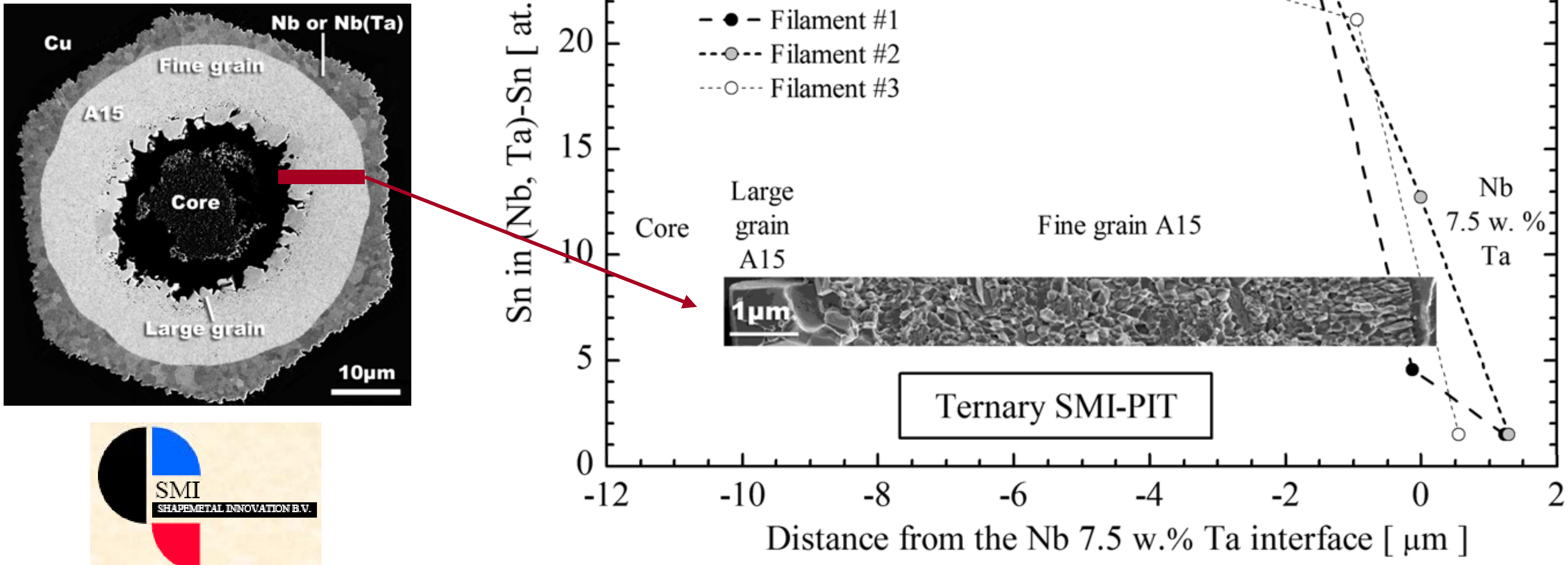




Composition variation in PIT wires

Composition analysis on SMI Powder-in-Tube wire (from ~2001)

- 0.3 at.% Sn/µm, J_c(12T,4.2) = 2250 A/mm^2 (Now ~2600)



Godeke, Cryogenics 2008

Large A15 fraction is high Sn

High current wires from Supercon

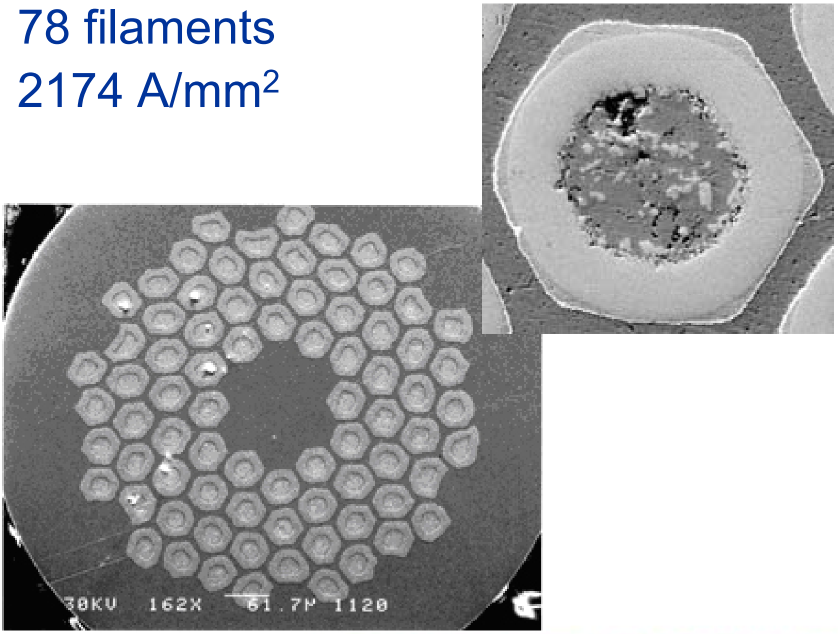
PIT with novel modifications

- Cost effective $NbSn_2$ powder
- Custom Nb-Ti and Nb-Ta alloy tubes
    - From fine grain Nb, Nb-7.5Ta and Nb-47Ti sheets
- Thin Ta barrier around each filament

SUPERCON INC.

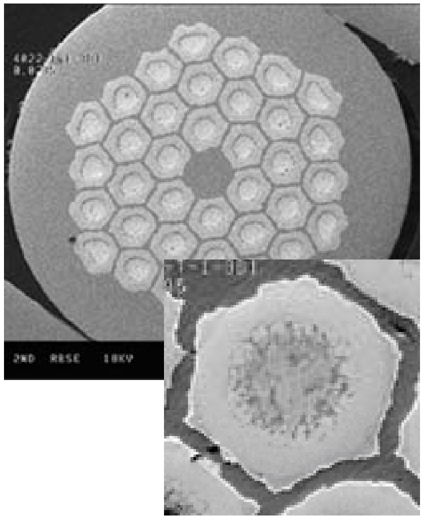
Best results

- Nb7.5wt.%Ta ternary
- 78 filaments
- 2174 A/mm^2

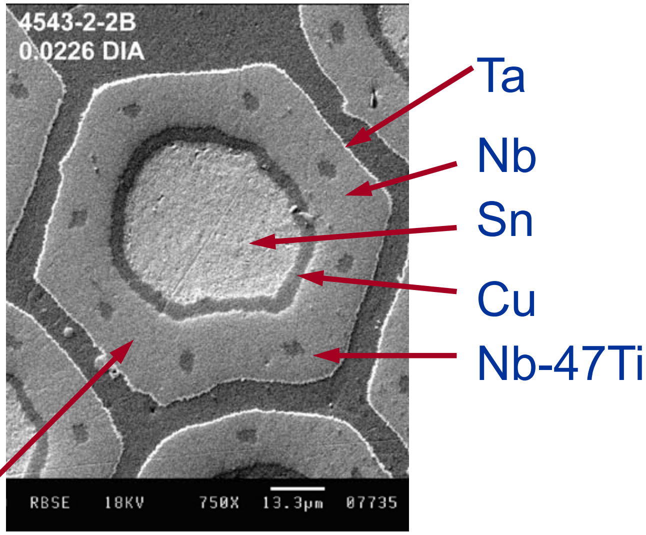


Internal-Tin-Tube process

- Nb-7.5Ta Tubes
- Sn-3Cu powder
- 36 filaments
- 1371 A/mm^2



- Present work:

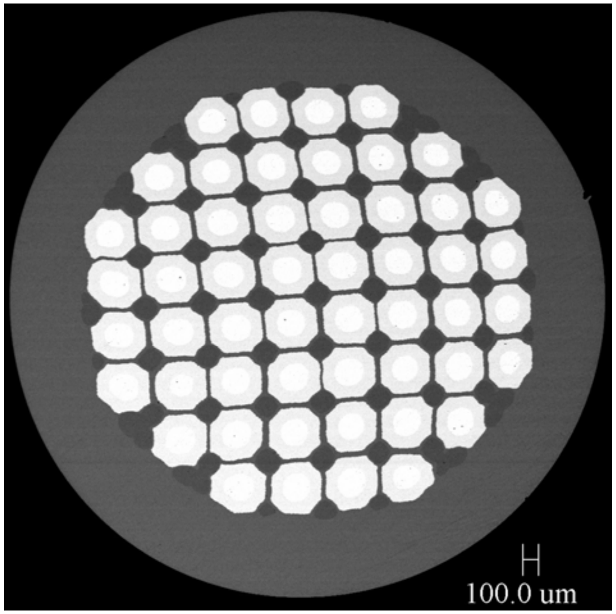


- Becomes Nb 1.5 at.%Ti, 1800 A/mm^2

Powder-in-Tube wires at SupraMagnetics

PIT with novel modifications

- Jet milled Cu_5Sn_4 powder
  - Cost effective, more Sn available
- Octagonal filament design allows for internal strengthening

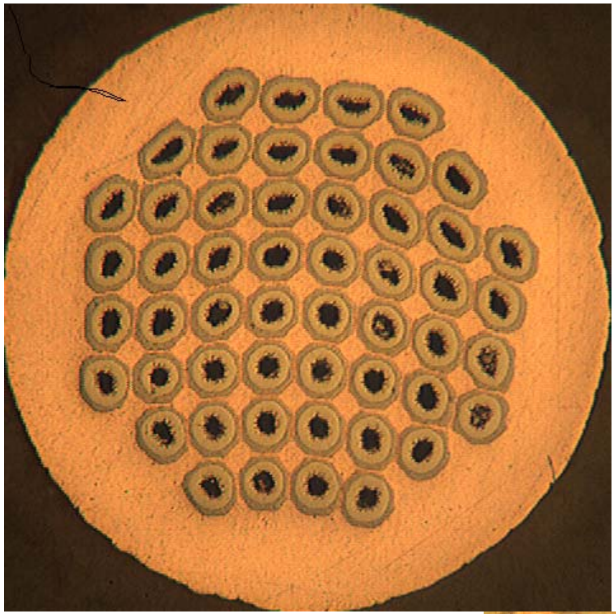


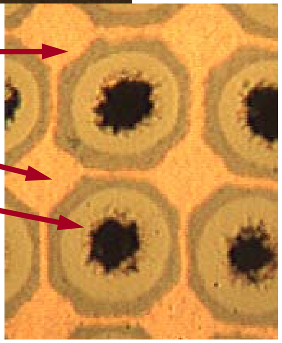
- 52 filaments
- Drawn down to 0.25 mm (20 μm fil.)
- 17.2% Monel between filaments

SupraMagnetics

New high strength conductor

- 52 filaments at 0.5 mm OD





- Octagonal filaments
- Glid Cop Al-15
- A15 layer 675Cx96h

- J_c ~2000 A/mm^2
  - In earlier hexagonal Cu_5Sn_4 wires

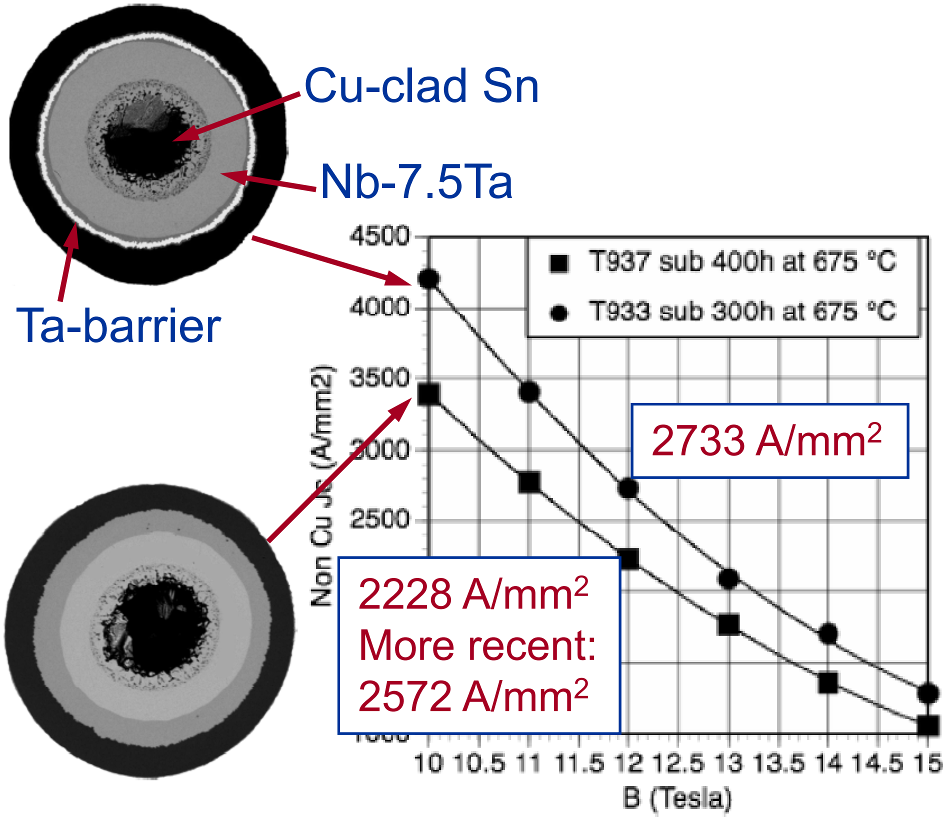
Tubular process at Supergenics I LLC

Process:

- Cu-clad Sn in Nb-7.5Ta tube
  - Sn can be pure or alloyed

Pure Cu-clad Sn

- Sub-elements at 0.25 mm

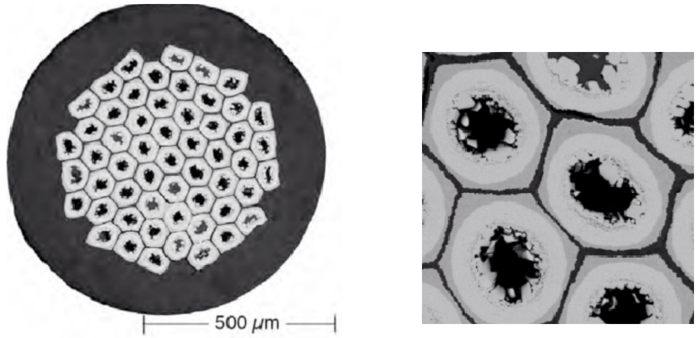


2733 A/mm²

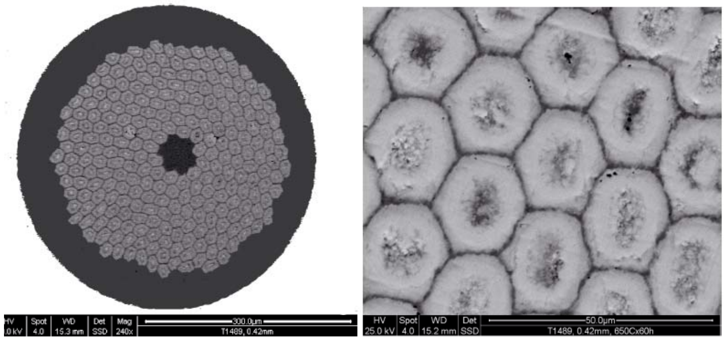
2228 A/mm²
More recent:
2572 A/mm²

Wires

- ~0.8 mm, filaments 70 μm, 55+6



- 0.42 mm, filaments 18 μm, 246+25



Performance

- 2050 A/mm² at 18 μm, 2250 @ 35 μm
- Billet 37mm x 1m: 2km @ 0.7mm done
- Now: 37mm x 5m billet

Internal-Tin wires at OST

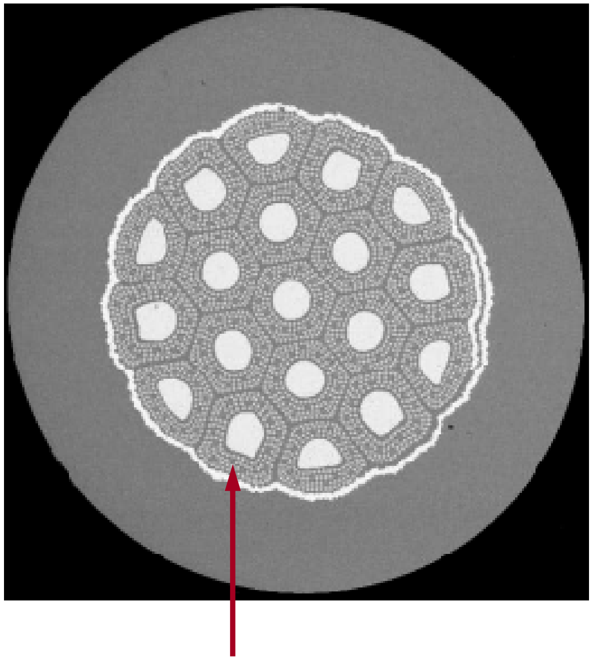
Modified Jelly Roll, Hot Extruded Rod ➔ Rod Restack Process (RRP®) wires

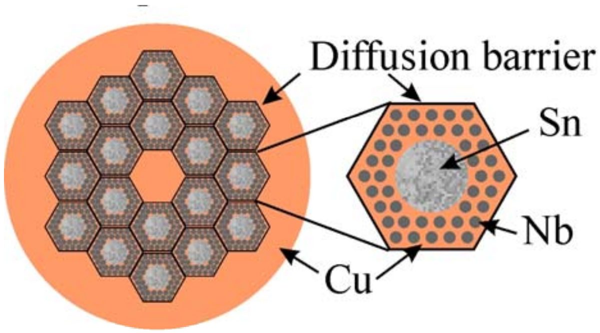
Low loss, medium current

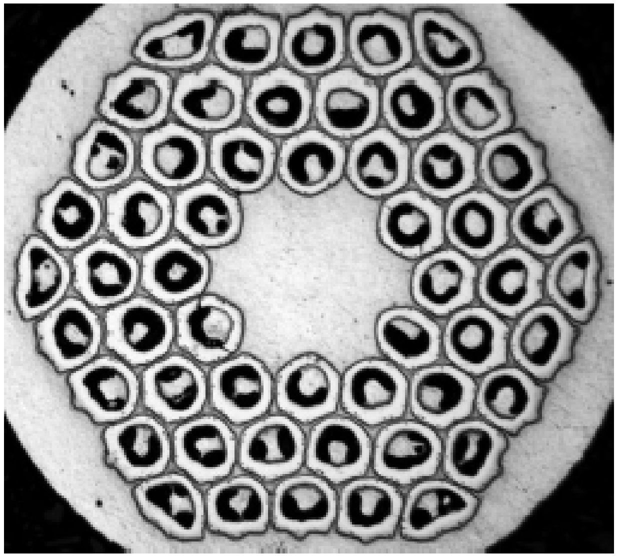
- Sub-element contains separate filaments after reaction
- J_c(12T,4.2K) 800 – 1200 A/mm^2
- Single Ta diffusion barrier

High current 54/61

- Filaments in sub-elements grow together during reaction
- Record J_c(12T,4.2K) > 3 kA/mm^2
- Each sub-element has its own Nb-Ta diffusion barrier (partially reacts)


Nb-47w.%Ti rods



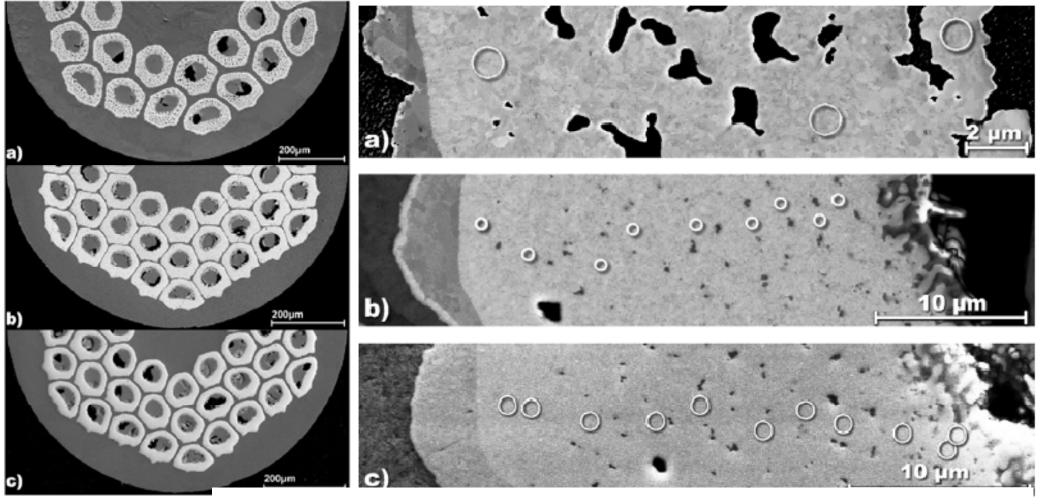


Composition variation in IT wires

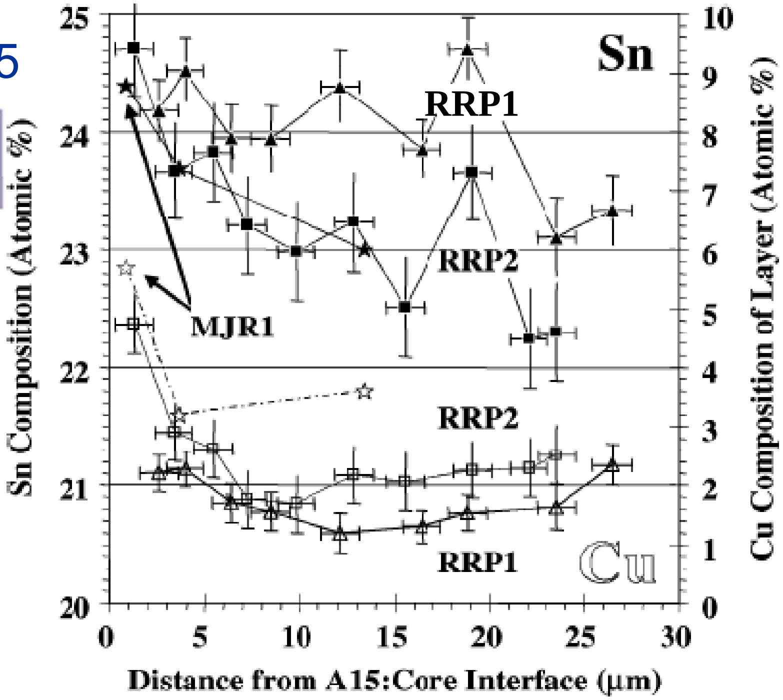
- MJR1 J_c(12T,4.2) = 2200 A/mm^2

- RRP1 J_c(12T,4.2) = 2900 A/mm^2

- RRP2 J_c(12T,4.2) = 3000 A/mm^2



Lee, TAS 2005



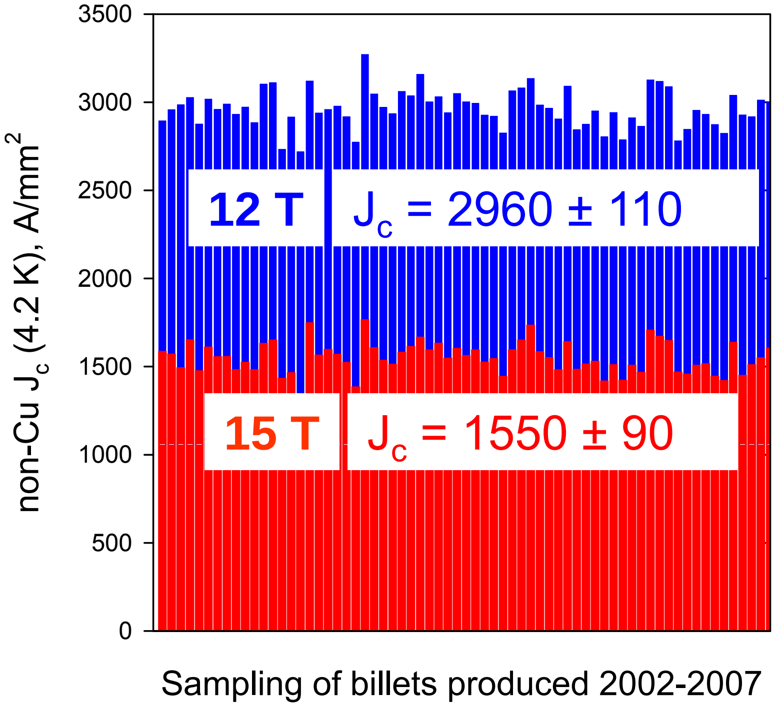
- OST Internal-Tin
  - Inter-filament Cu
  - Relatively flat Sn gradient
  - Optimized A15 fraction in non-Cu

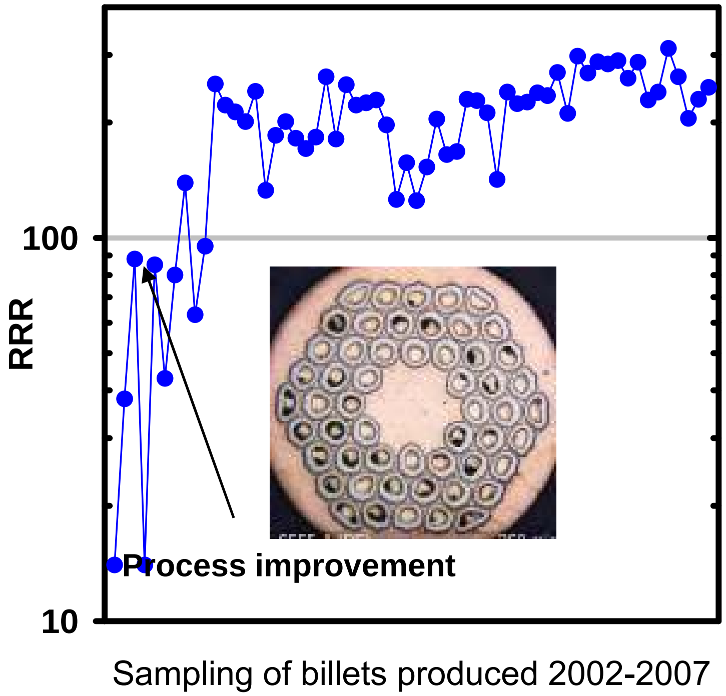
Large A15 fraction is close to optimal Sn

3 kA/mm^2 RRP® commercial production

- Production measured in tons per year
- Consistent J_c and RRR
- Unit lengths >10 km

0.7mm and 0.8 mm strands ~80µm d_{eff}





But…Large d_{eff}, *very* high J_c, cabling distorting barriers (RRR loss):
Low and medium field instabilities (Sumption and Bordini, this workshop)

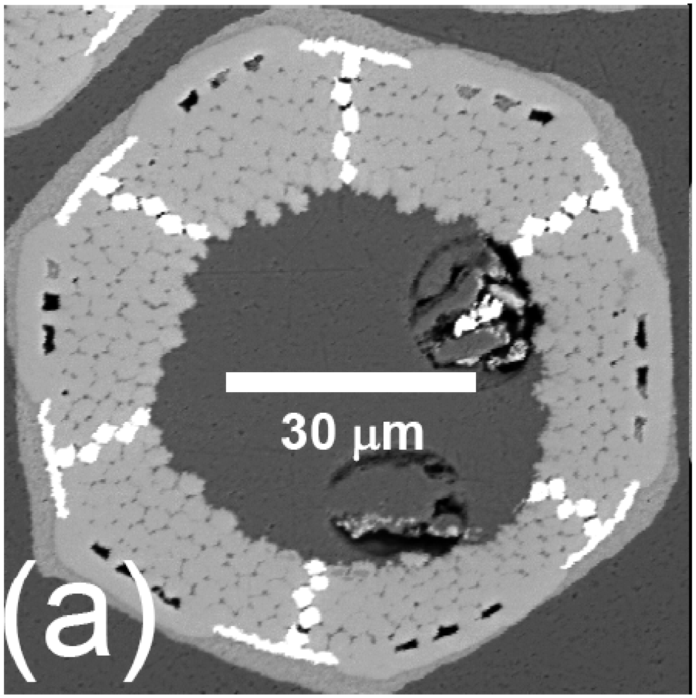
Attempts at OST to reduce d_{eff}

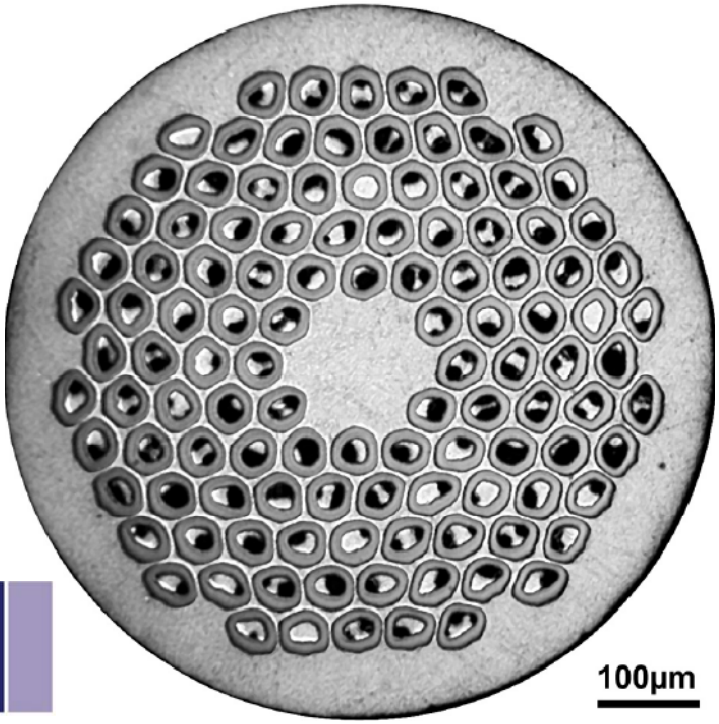
Sub-divided sub-elements

- Using Ta rods
- Now abandoned

Restacking

- 114 – 127 version (~40 μm)
- Further restacks under development





Restacking appears route towards smaller d_{eff}

An outlook to the future

(An academic exercise on performance potential)

General trend: 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 (2600 A/mm^2)
OST Internal Tin	24 ± 1 (or more?) at.% Sn Virtually no gradient	J_c(12T,4.2) = 3000 A/mm^2

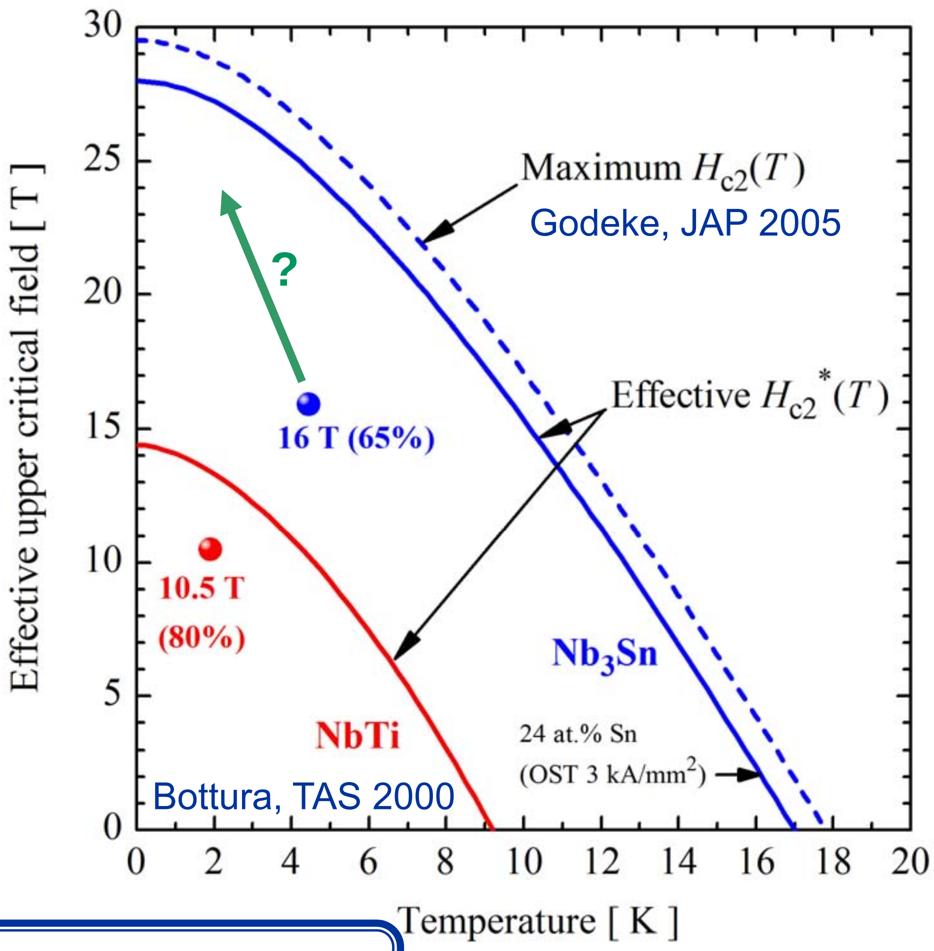
Sn richer
Higher J_c

Homogenization potential exhausted?

Nb_3Sn wire performance in dipole magnets

Field – temperature limitations and achieved dipole fields

- NbTi
  - 10.5 T (Leroy, Proc. MT15 1998)
  - 80% of H_{c2}*(1.8 K)
- Nb_3Sn
  - 16 T (LBNL HD1, 2004)
  - 65% of H_{c2}*(4.5 K)
  - 80% of H_{c2}*(4.2 K)?
    - 20 T
  - 80% of H_{c2}*(1.8 K)?
    - 22 T



What limits Nb_3Sn to 65% of H_{c2}*?

What limits high field performance of Nb_3Sn?

NbTi

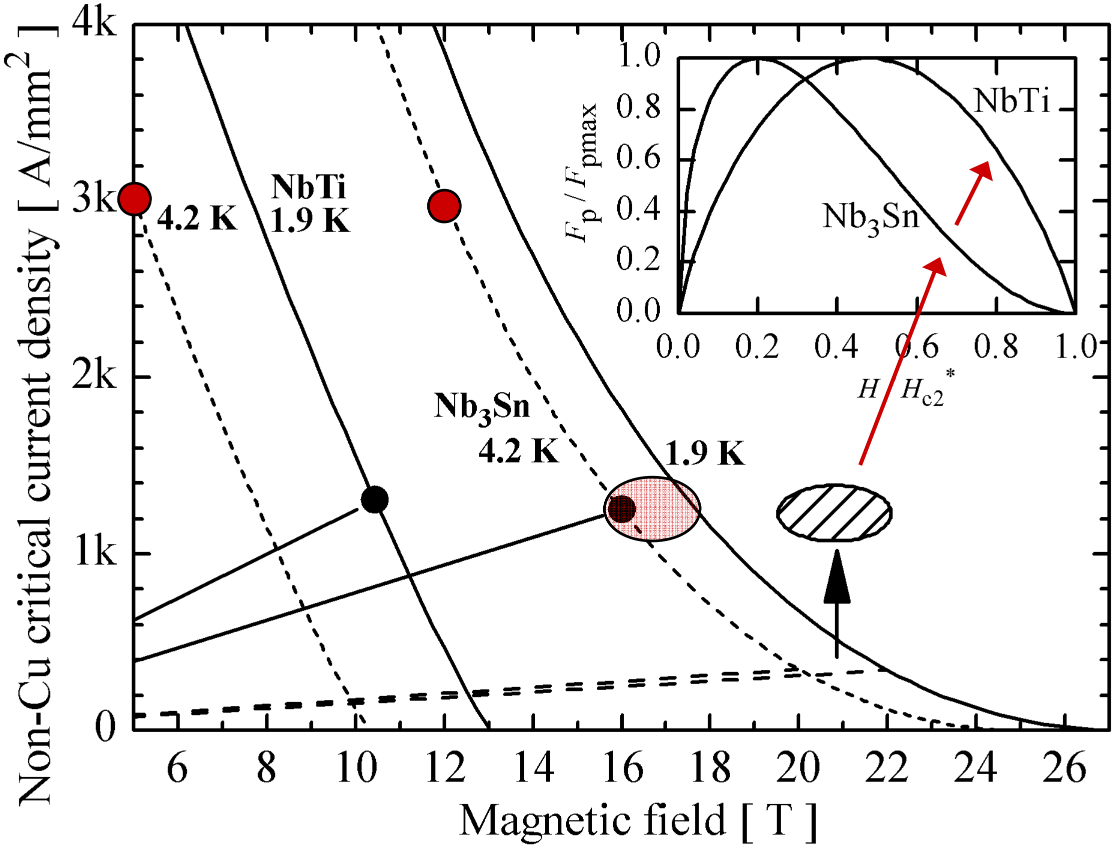
- Pinning optimized
  - ~1 pinning cite/vortex
  - $F_p \propto h(1 - h)$

Nb_3Sn

- Insufficient pinning centers
  - Collective pinning
  - $F_p \propto h^{0.5}(1 - h)^2$
  - Reduced high field efficiency

- Practical dipole limitation 17 – 18 T

NbTi: *Bottura, TAS 2000*
Nb_3Sn: *Godeke, SuST 2006*

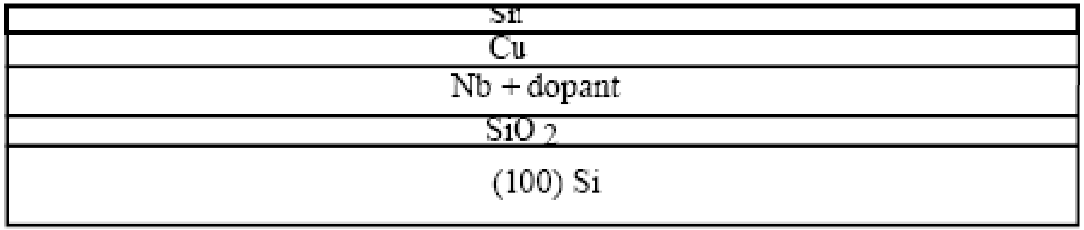


Pinning inefficiency at higher fields limits performance

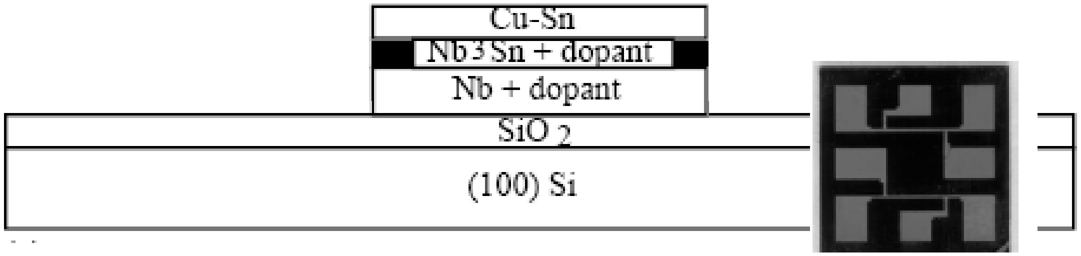
Can high field pinning be improved?

Doping in thin films (Dietderich, ACE 1998)

- As deposited

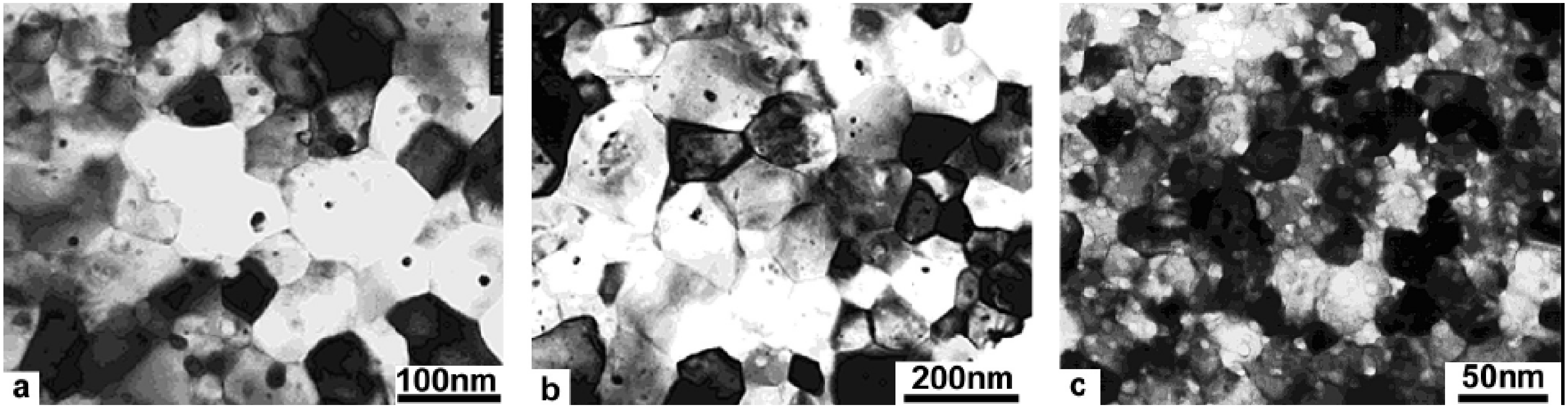


- After HT and etch



Average grain sizes:

Undoped: 75 nm Ti-doped: 130 nm Sc+Al2O3 doped: 25 & 7 nm

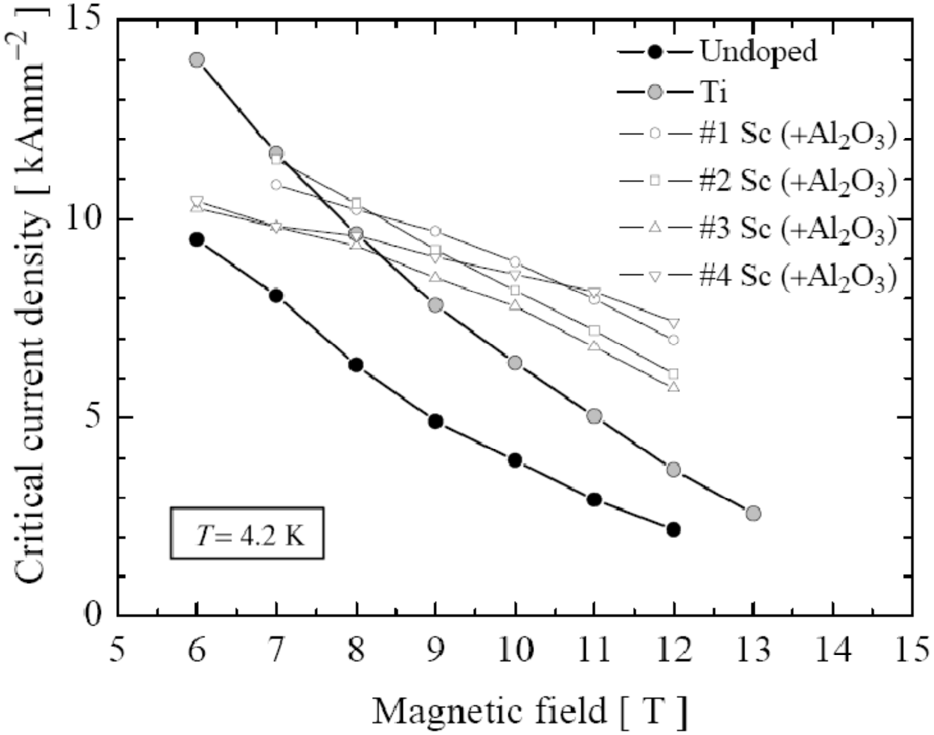


Improved high field pinning

Field dependence of J_c

- J_c(12T, 4.2K):
  - Undoped 2200 A/mm^2
  - Ti-doped 3700 A/mm^2
  - Sc+Al2O3 doped 7400 A/mm^2

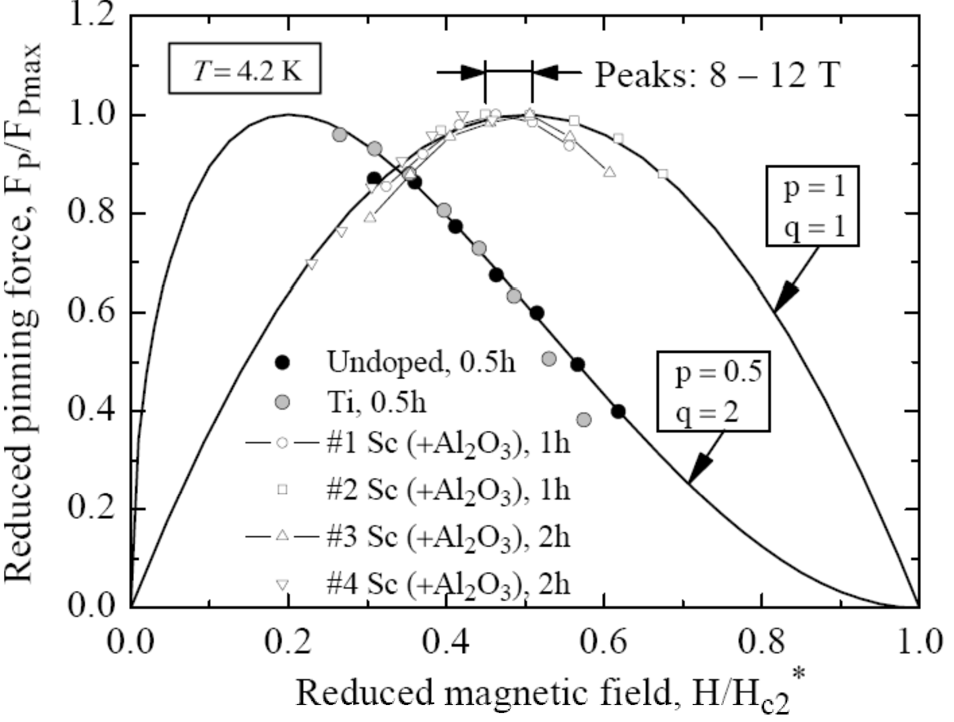
x3.4 (!)



Normalized pinning curves

- Peaks at 50% of H_{c2}^*

Dietderich, Cryogenics 2008
Godeke, to be published 2008



Grain refinement could be the next big step (but how to do this in wires…?)

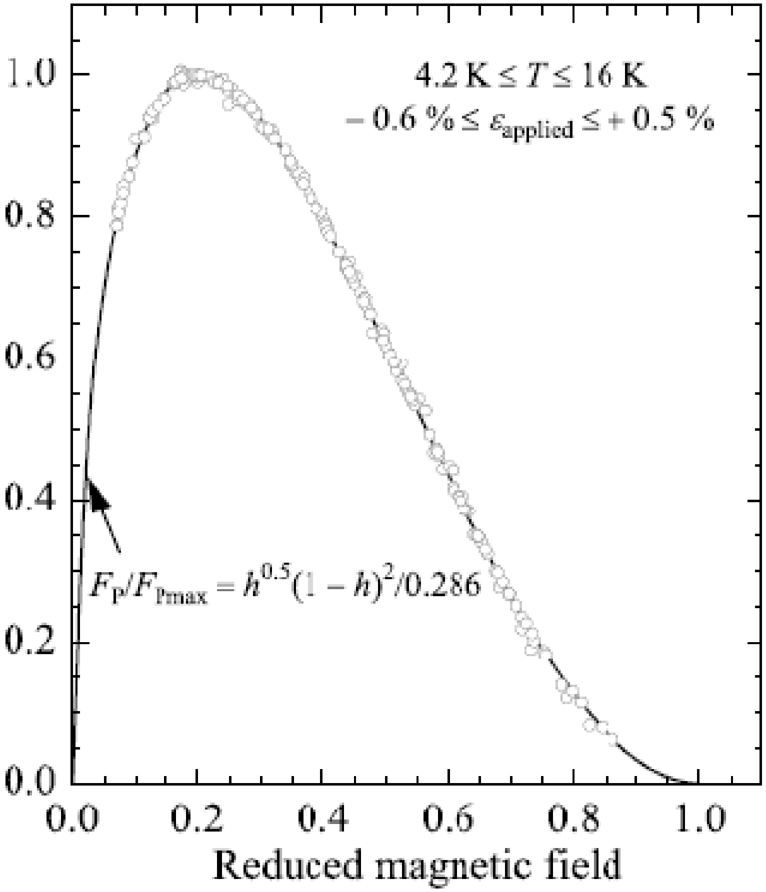
Some words on scaling…

A tool to describe the critical surface

$J_c = F_P(H) + H_{c2}^*(T)$

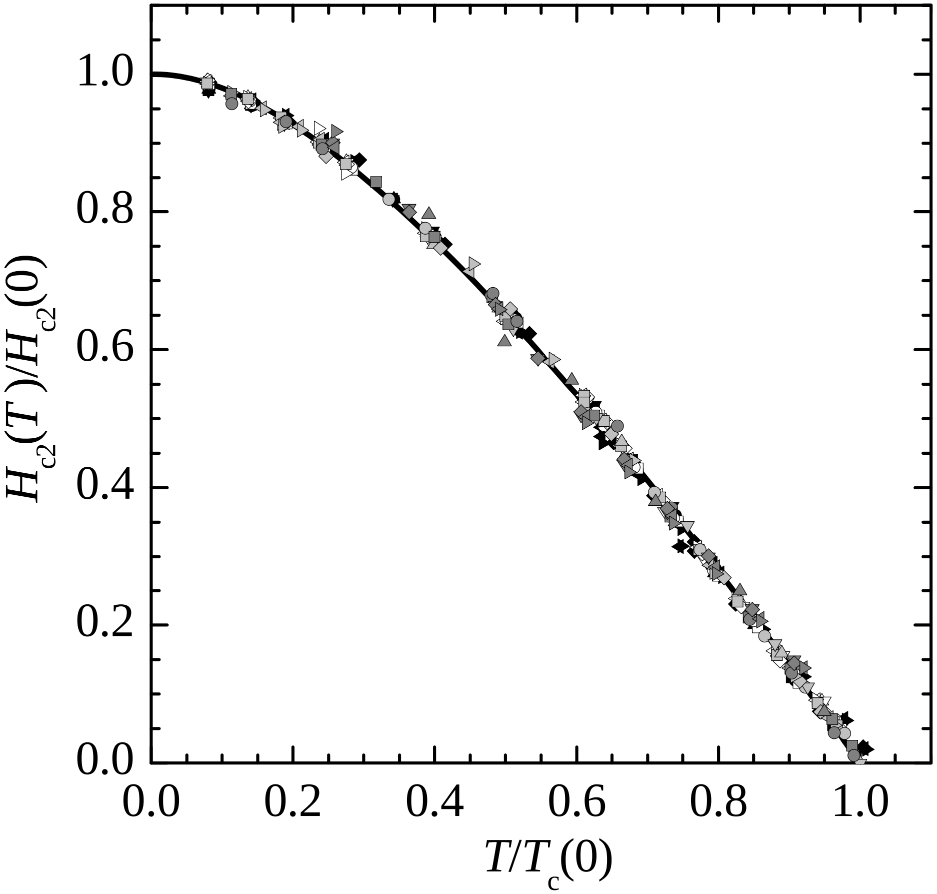
Pinning force as a function of field

- Example: Furukawa bronze wire
- All temperatures and strain states



Field-temperature phase boundary

- All literature results (27 samples)
- Thin film, bulk, single X-tals, wires



Scaling of J_c can be done accurately

Twente scaling relation for $J_c(H,T,\varepsilon)$

University of Twente

- $J_c(H,T,\varepsilon)$ data & general form

Applied Superconductivity Center

- Materials basis

$$J_c\left(H,T,\epsilon\right) \cong \frac{C_1}{\mu_0 H} s\left(\epsilon\right) \underbrace{\left(1-t^{1.52}\right)} \left(1-t^2\right) \overset{(p)}{h^{0.5}} \overset{(q)}{\left(1-h\right)^2},$$

Godeke, SuST 2006

with

$$C_1 = C\left[\mu_0 H^*_{\mathrm{c2m}}\left(0\right)\right]^2 / \kappa_{1\mathrm{m}}\left(0\right),$$

$$t \equiv T/T^*_{\mathrm{c}}\left(\epsilon\right), \qquad h \equiv H/H^*_{\mathrm{c2}}\left(T,\epsilon\right),$$

$$H^*_{\mathrm{c2}}\left(T,\epsilon\right) \cong H^*_{\mathrm{c2m}}\left(0\right) s\left(\epsilon\right)\left(1-t^{1.52}\right),$$

$$T^*_{\mathrm{c}}\left(\epsilon\right) = T^*_{\mathrm{cm}} s\left(\epsilon\right)^{\frac{1}{3}},$$

More accurately:

$$MDG\left(t\right) \cong \left(1-t^{1.52}\right)$$

6 fit parameters:

Deformation			Superconducting		
C_{a1}	C_{a2}	$\epsilon_{0,\mathrm{a}}$	$\mu_0 H^*_{\mathrm{c2m}}(0)$	$T^*_{\mathrm{cm}}(0)$	C_1
47.6	6.4	0.273	30.7	16.8	46.3

Accepted by ITER in 2008 with *p* and *q* variable

Longitudinal strain description:

$$\begin{aligned} s\left(\epsilon_{\mathrm{a}}\right) &= \frac{1}{1-C_{\mathrm{a1}}\epsilon_{0,\mathrm{a}}}\left(C_{\mathrm{a1}}\left[\sqrt{\left(\epsilon_{\mathrm{sh}}\right)^2+\left(\epsilon_{0,\mathrm{a}}\right)^2}\right.\right. \\ &\quad \left.\left. -\sqrt{\left(\epsilon_{\mathrm{a}}-\epsilon_{\mathrm{sh}}\right)^2+\left(\epsilon_{0,\mathrm{a}}\right)^2}\right]-C_{\mathrm{a2}}\epsilon_{\mathrm{a}}\right)+1, \\ \epsilon_{\mathrm{sh}} &= \frac{C_{\mathrm{a2}}\epsilon_{0,\mathrm{a}}}{\sqrt{\left(C_{\mathrm{a1}}\right)^2-\left(C_{\mathrm{a2}}\right)^2}}, \\ \epsilon_{\mathrm{a}} &= \epsilon_{\mathrm{applied}}+\epsilon_{\mathrm{m}}. \end{aligned}$$

Mathematical simplification

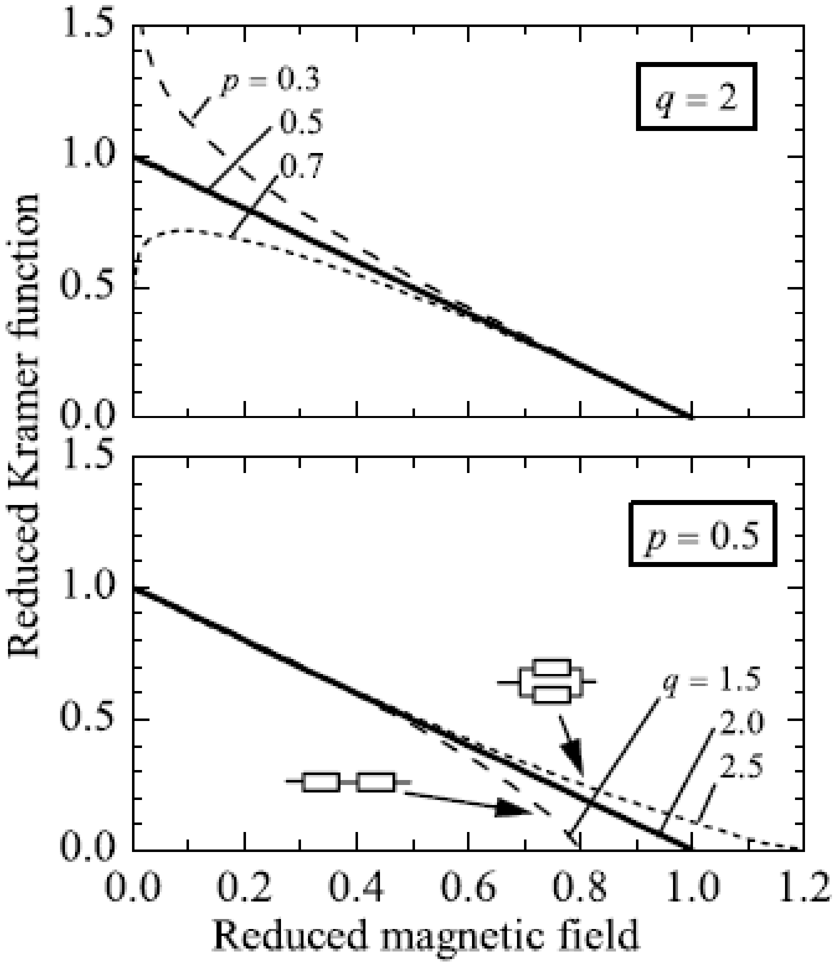
Matthijs Mentink (Univ. of Twente) @ LBNL, 2008:

$$J_c\left(H,T,\varepsilon\right)=\sqrt{2}C\mu_0H_c\left(t\right)h^{p-1}\left(1-h\right)^q$$

Relevant:

- *p* and *q*
  - I.e.: Linearity of Kramer plots
  - $F_K=J_c^{0.5}B^{0.25}$ vs *B*
    - *linear if p=0.5, q=2*
- Thermodynamic critical field

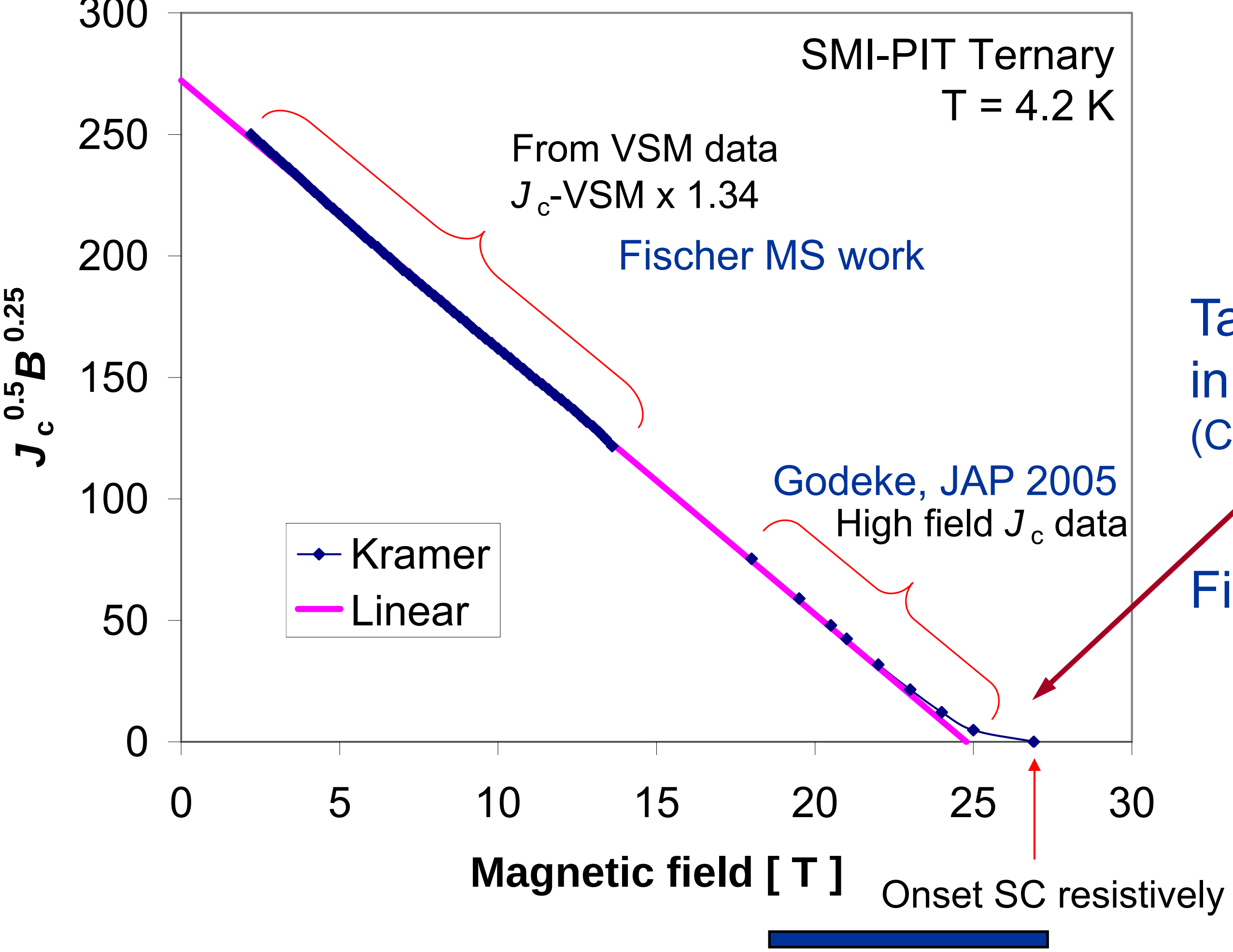
$$H_c\left(t\right)\cong H_c\left(0\right)\left(1-t^2\right)$$



Godeke, Thesis 2005

How linear are Kramer plots? (I)

SMI-PIT data (~2003)



22 – 25 at.% Sn

Tail due to compositional inhomogeneity

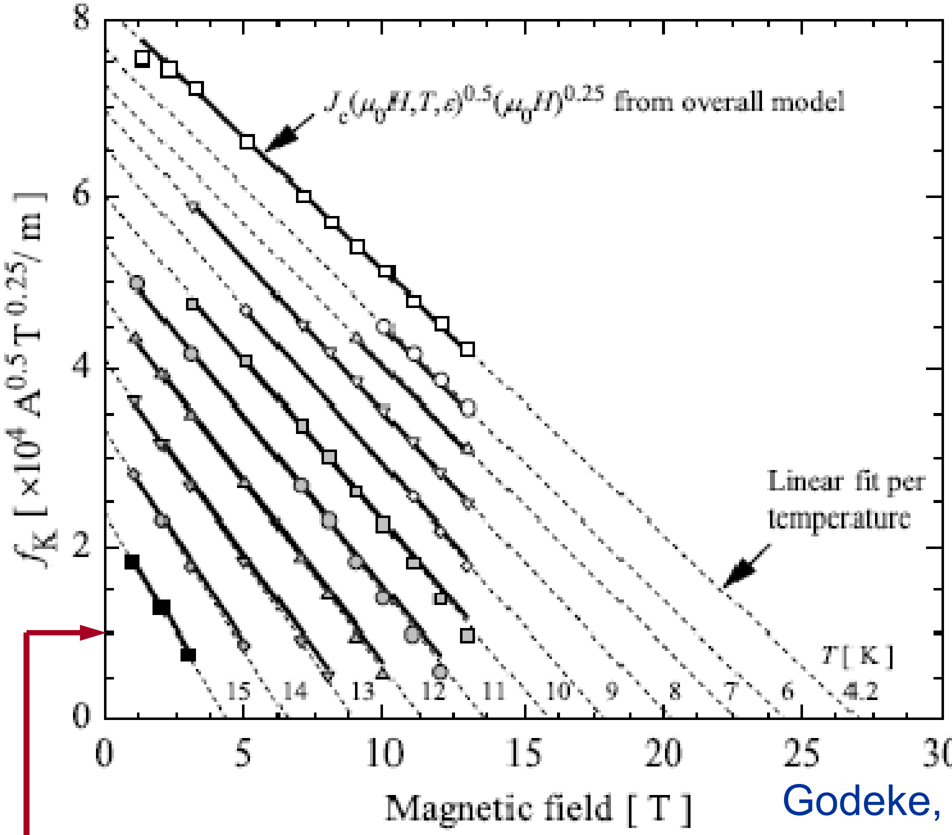
(Cooley, JAP 2004)

Fit: q larger than 2

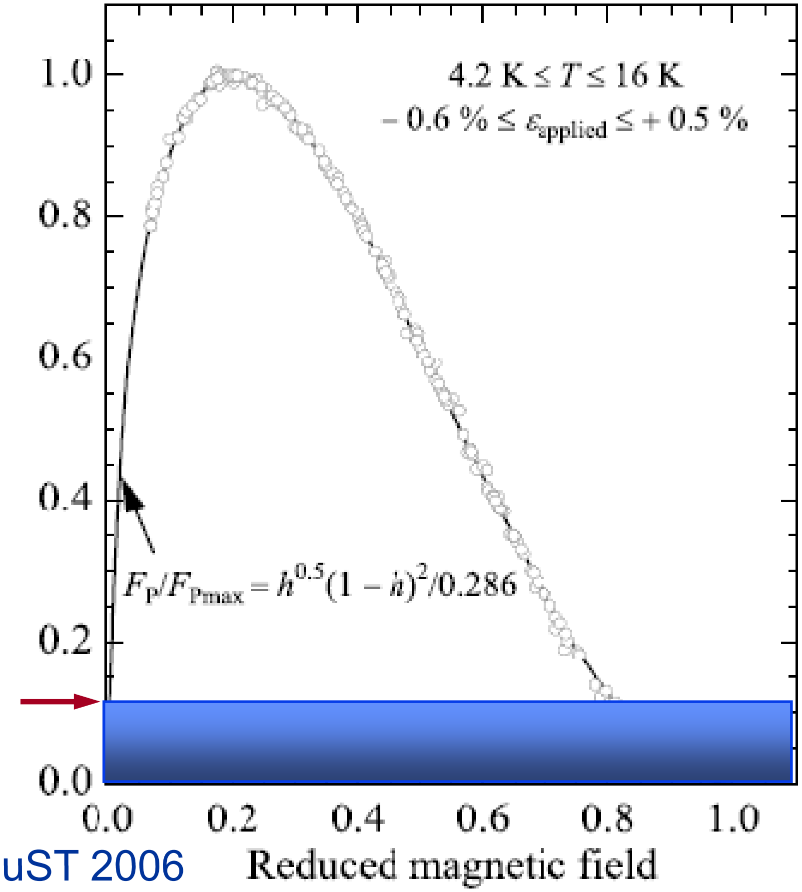
Kramer plots can be very linear

How linear are Kramer plots? (II)

Furukawa ternary bronze (~1998)



Godeke, SuST 2006



Below this less relevant for applications ➔ *q* = 2 to remain generic?

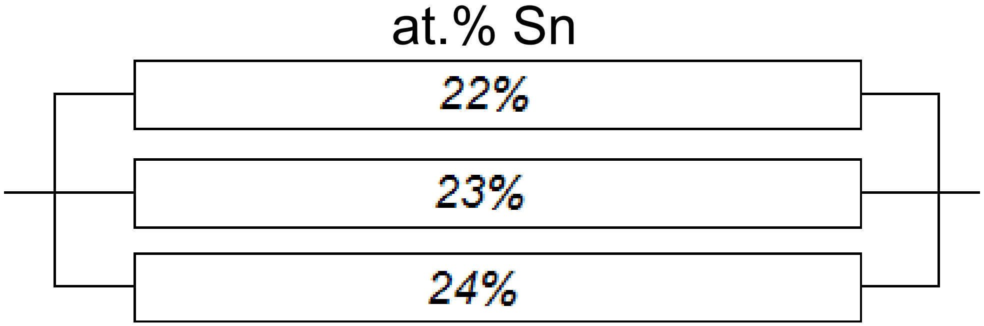
Generality *apparently* retainable by keeping *q* = 2, **BUT**…

Simulation of three homogeneous conductors

Mentink, 2008

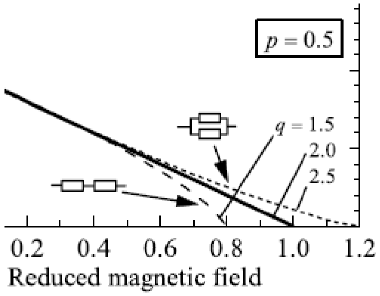
- 3 homogeneous conductors in parallel

$$H_c(t) \cong H_c(0)\left(1-t^u\right)$$



T_c*	H_{c2}*	*p*	*q*	*u*
12	20	0.5	2	2
15	25	0.5	2	2
17	30	0.5	2	2

$$J_c(H,T,\varepsilon) = \sqrt{2}C\mu_0 H_c(t)\,h^{p-1}(1-h)^q$$



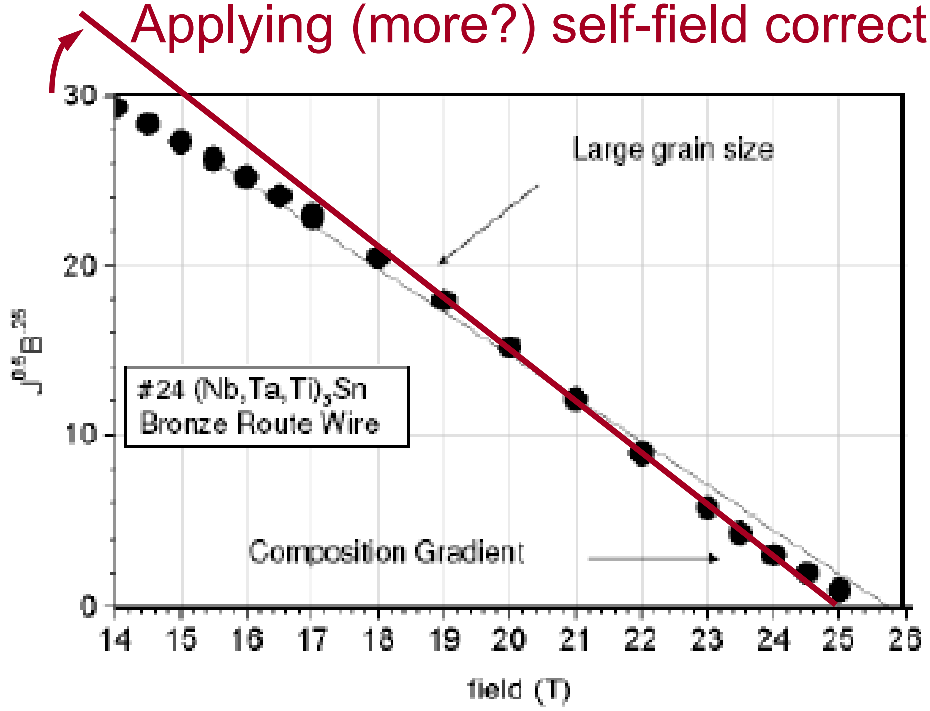
- Overall fit with *p* = 0.5 and *q* = 2 enforced yields *u* = 1.6
  - An *apparent* different temperature dependence of H_c occurs
    - But we defined *u* = 2 for each independent conductor!
  - *u* = 2 can be retained if *q* is larger than 2 (which it should)

Inhomogeneities have to be accounted for by allowing *q* variable

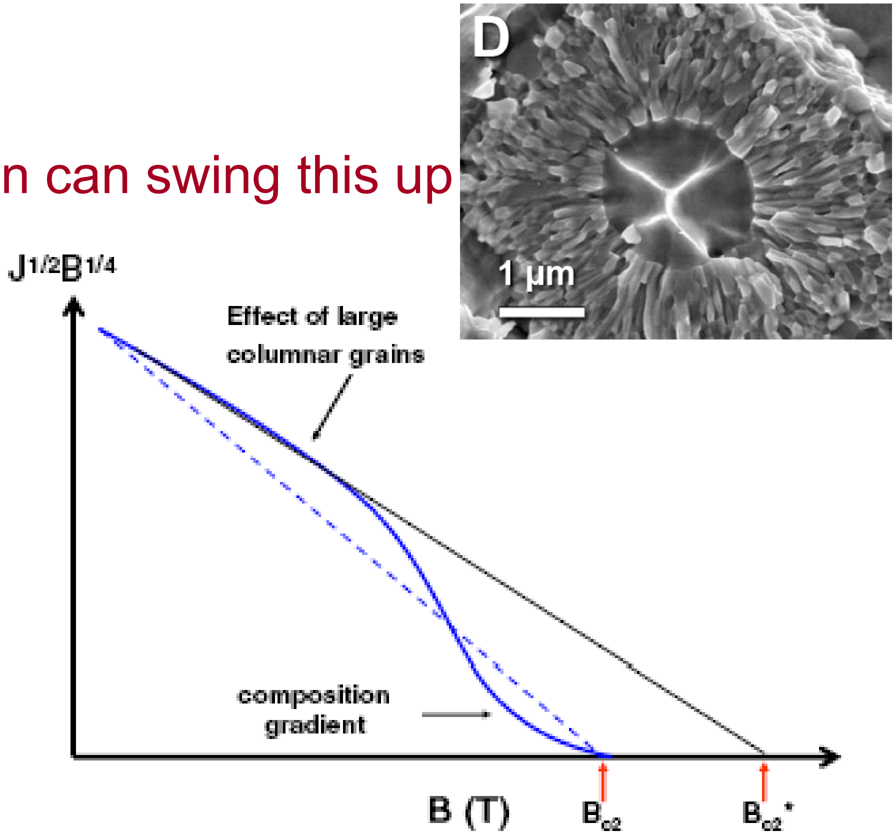
What about *p*?

Flükiger, SuST 2008

- Kramer plots bronze wires
  - Applying (more?) self-field correction can swing this up



a



b

- Low field behavior: large, columnar, Sn poor grains + fine, Sn rich grains
- High field behavior: fine, equiaxed, Sn rich grains + compo. averaging

Having *q* (and *p*) variable does not seem such a bad choice

Summary

Optimizations of…

- Sn content
- homogeneity
- A15 fraction

…led to commercially available > 3000 A/mm^2 and very high field magnets

- Combining high J_c with smaller filaments is present development

Future optimizations could include

  - Grain refinement/APC ➔ Very large potential (x2 – x3)
  - Further optimization of A15 fraction in non-Cu (retain Sn source for A15)

Scaling relations

- Have become accurate and refined (but appear a never ending story…)
- …but fundamental understanding of strain dependence is sorely lacking
  - This needs to be known for multi-billion \$ applications
  - Fundamental knowledge might provide ways to 'tweak' strain dependence
  - How much would it really cost to properly tackle this?