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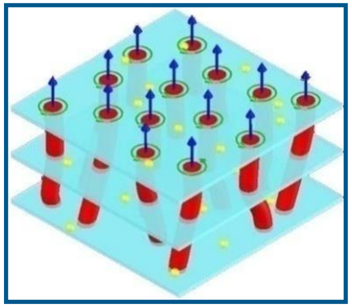
Superconductivity and its applications

Lecture 6



Carmine SENATORE

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Department of Quantum Matter Physics
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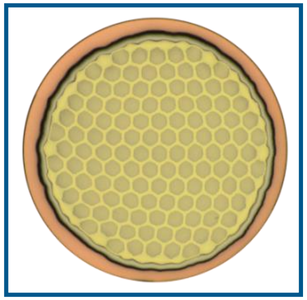
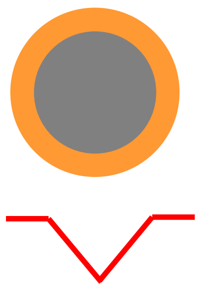
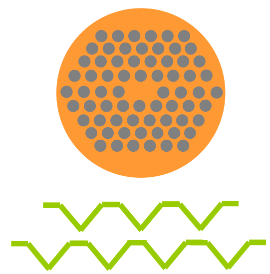


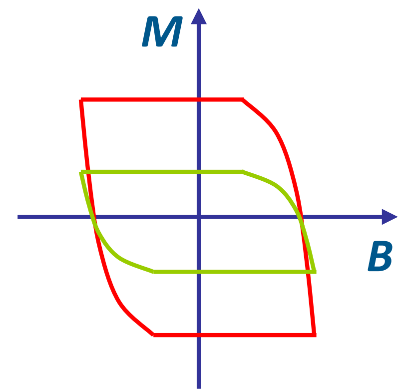
Previously, in lecture 5

1) *In a wire the subdivision of the superconductor in fine filaments is required*

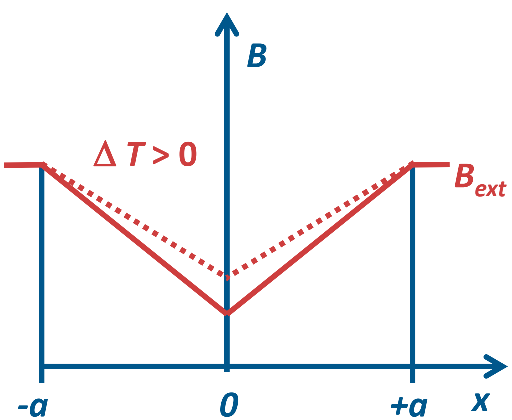
- *to reduce hysteretic losses*



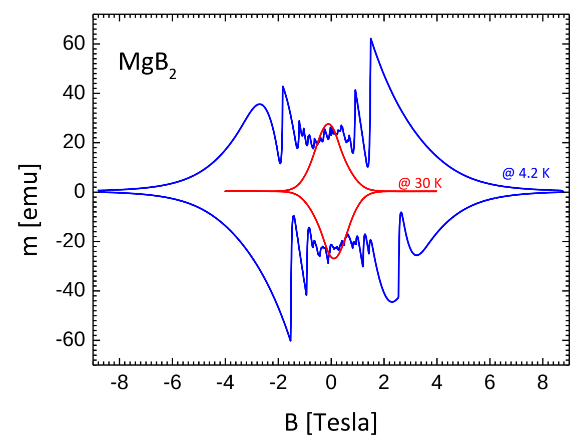




- *to reduce thermal instabilities*

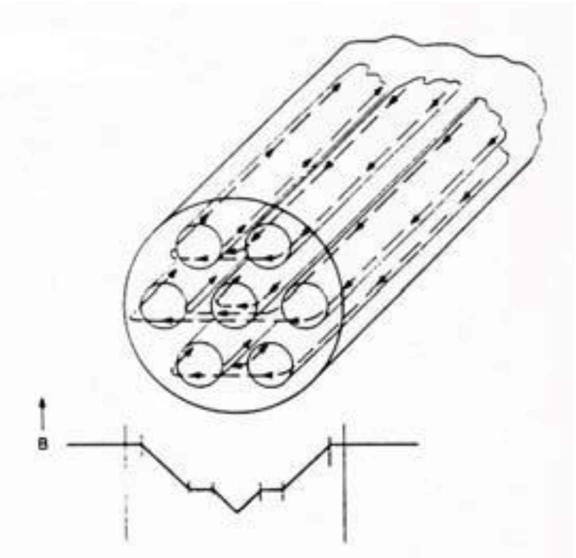


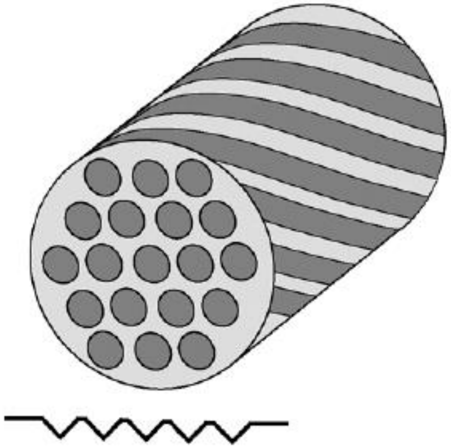
$$c_{eff} = \frac{\Delta Q_{ext}}{\Delta T} = c - \frac{\mu_0 J_c^2 a^2}{3\left(T_c - T_{op}\right)}$$



Previously, in lecture 5

2) When the matrix resistivity is too low, wires have to be twisted to avoid inductive coupling among the filaments (and thus losses)

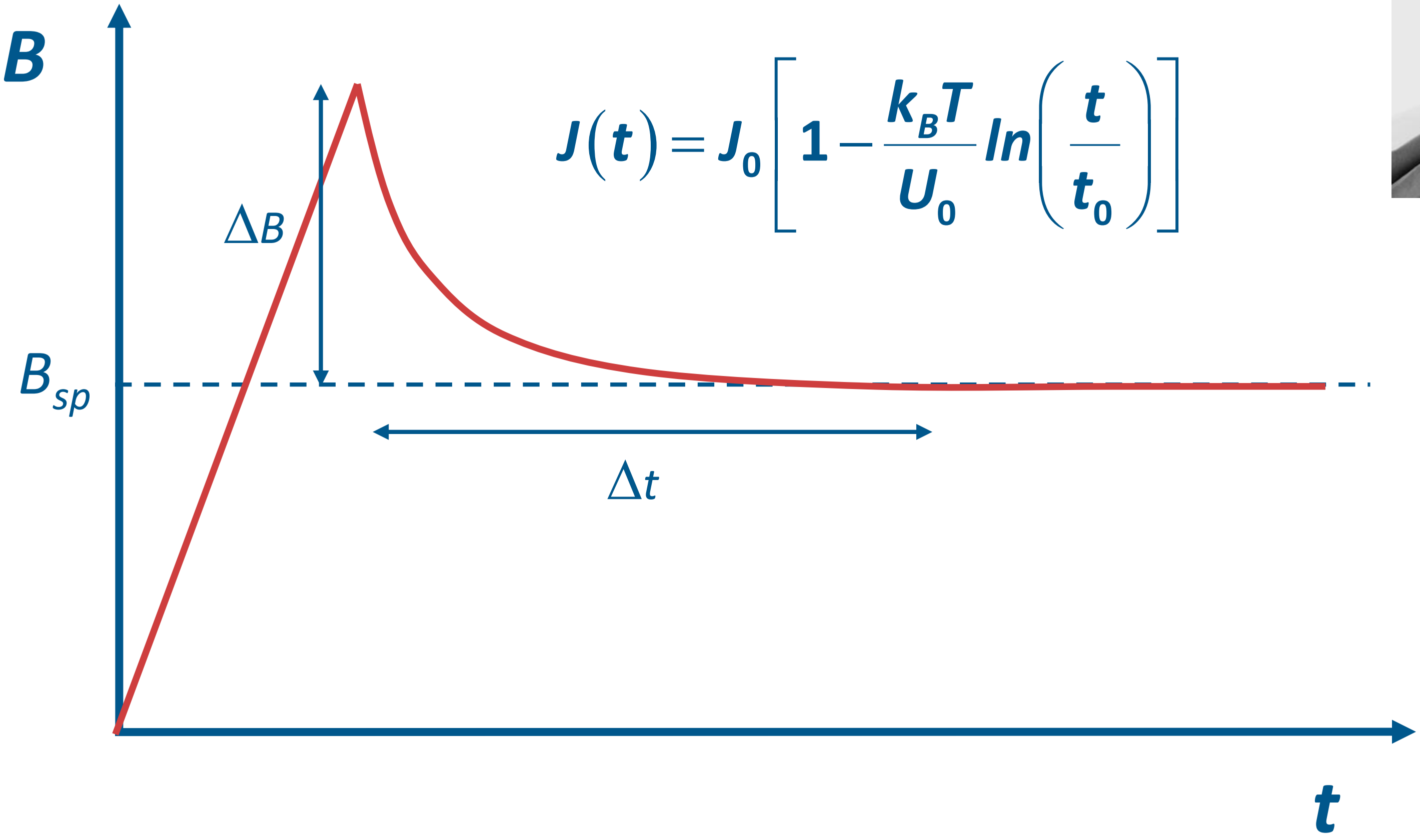




$$\ell_c = \sqrt{\frac{2\rho_n J_c d_f}{\mu_0 \dot{B}}}$$

Previously, in lecture 5
Flux creep and Persistent mode operation in a magnet

$$J(t) = J_0\left[1 - \frac{k_B T}{U_0} ln\left(\frac{t}{t_0}\right)\right]$$

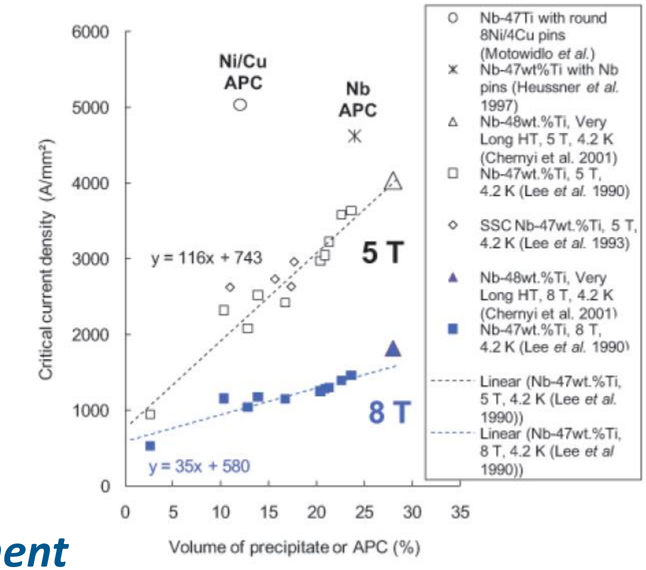


At the operation, the drift of the field is 10 ppb/hour

The field is reduced by half in ~6’000 years !!

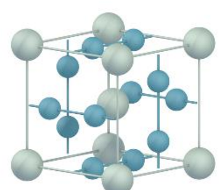
Previously, in lecture 5

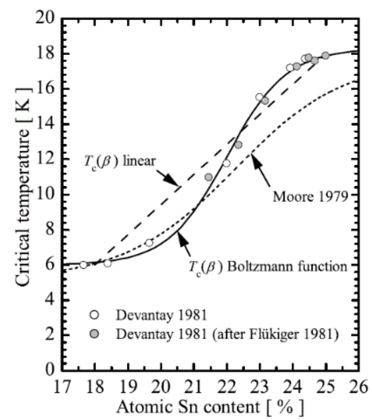
	T_c [K]	B_{c2} [T]
Nb-Ti	9.8	10.5

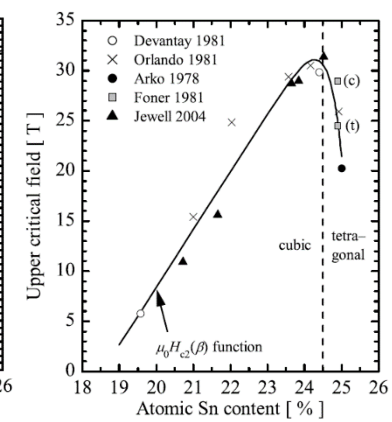


- *Alloy*
- *Easy to produce in multifilamentary wires*
- *Wires does not need reaction heat treatment*
- *Key parameter for J_c optimization* → *α-Ti precipitates acts as pinning centers*

	T_c [K]	B_{c2} [T]
Nb_3Sn	18.0	30+



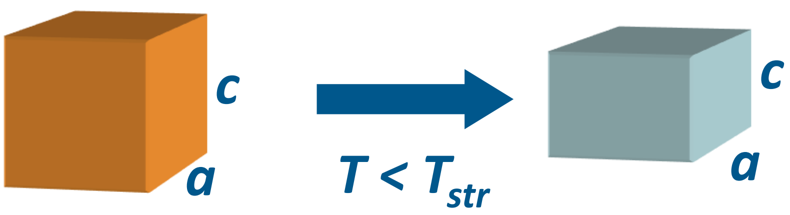




- *Intermetallic A15 compound*
- *The critical parameters depend on the Sn composition*

Martensitic transformation

Structural phase transformation from cubic to tetragonal at low temperatures



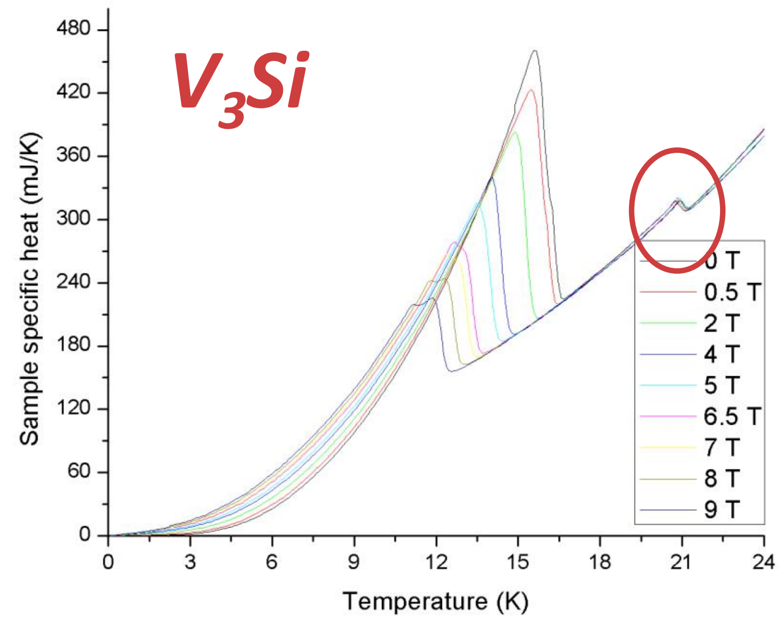


Table 3.7 Structural Transformation Temperature T_{str} and Anisotr
Low-Temperature Tetragonal Phase of Several *A*15 type Supercon

Compound	T_{str} (K)	T_c (K)	Anisotropy $(c-a)/a$	Reference
V_3Si	21	17	0.0024	Batterman and Barrett (1964)
Nb_3Sn	43	18	−0.0061	Mailfert *et al.* (1967)
V_3Ga	> 50	14.5	—	Nembach *et al.* (1970)
Nb_3Al	80	17.9	—	Kodess (1973, 1982)
$Nb_3(Al_{0.75}Ge_{0.25})$	105	18.5	−0.003	Kodess (1973, 1982)
$Nb_{3.1}(Al_{0.7}Ge_{0.3})$	130	17.4	—	Kodess (1973, 1982)

How to rise H_{c2} – Let's play it dirty

For a clean, ordered superconductor

$$H_{c2} = \frac{\Phi_0}{2\pi\xi^2}$$

Disorder reduces the electron mean free path ℓ, which in turn leads to decrease of ξ

$$\frac{1}{\xi(\ell)} = \frac{1}{\xi(\infty)} + \frac{1}{\ell}$$

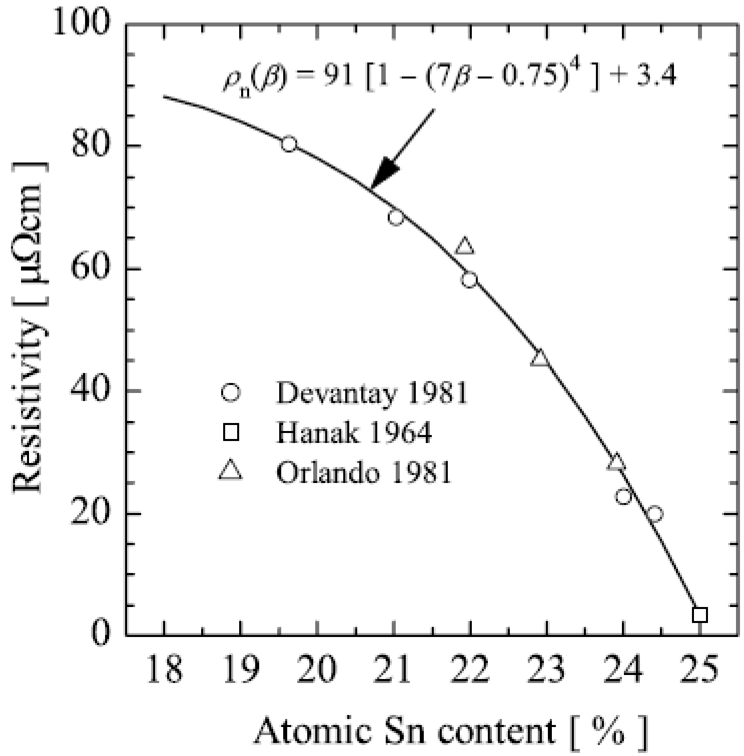
An useful expression of H_{c2} in the dirty limit

$$H_{c2}(T=0) \cong \frac{k_B e}{\mu_0} N(E_F)\rho_n T_c \propto \gamma\rho_n T_c$$

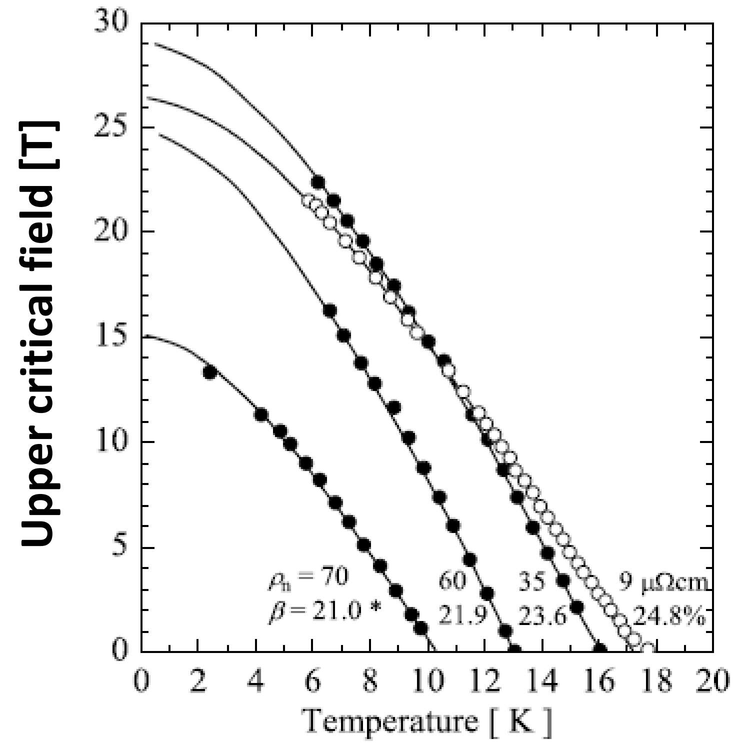
How to rise H_{c2} in Nb_3Sn

$$H_{c2} \propto \gamma \rho_n T_c$$

Resistivity vs. Sn at.%



H_{c2} vs. T at various Sn at.%



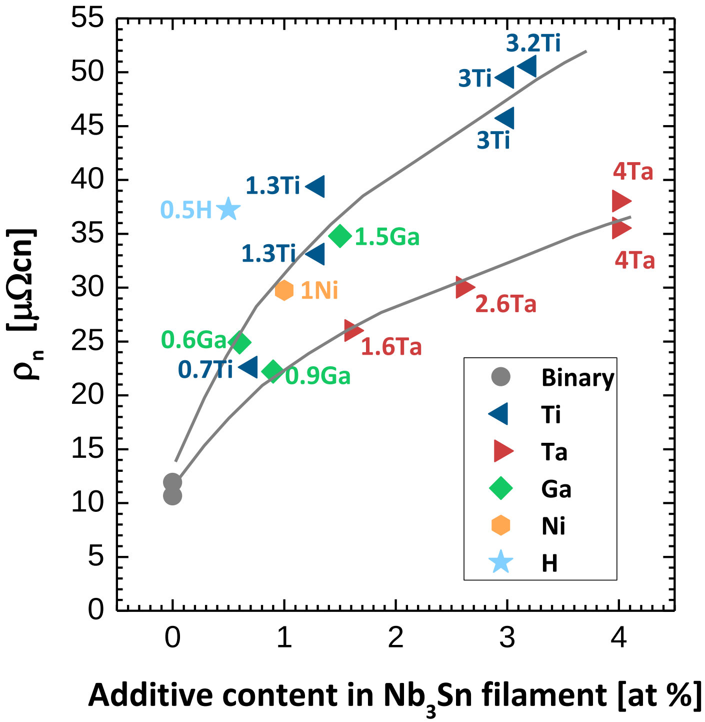
Reducing Sn content rises ρ_n, but reduces T_c. Other ideas ?

Graphs from A. Godeke, PhD Thesis, UTwente

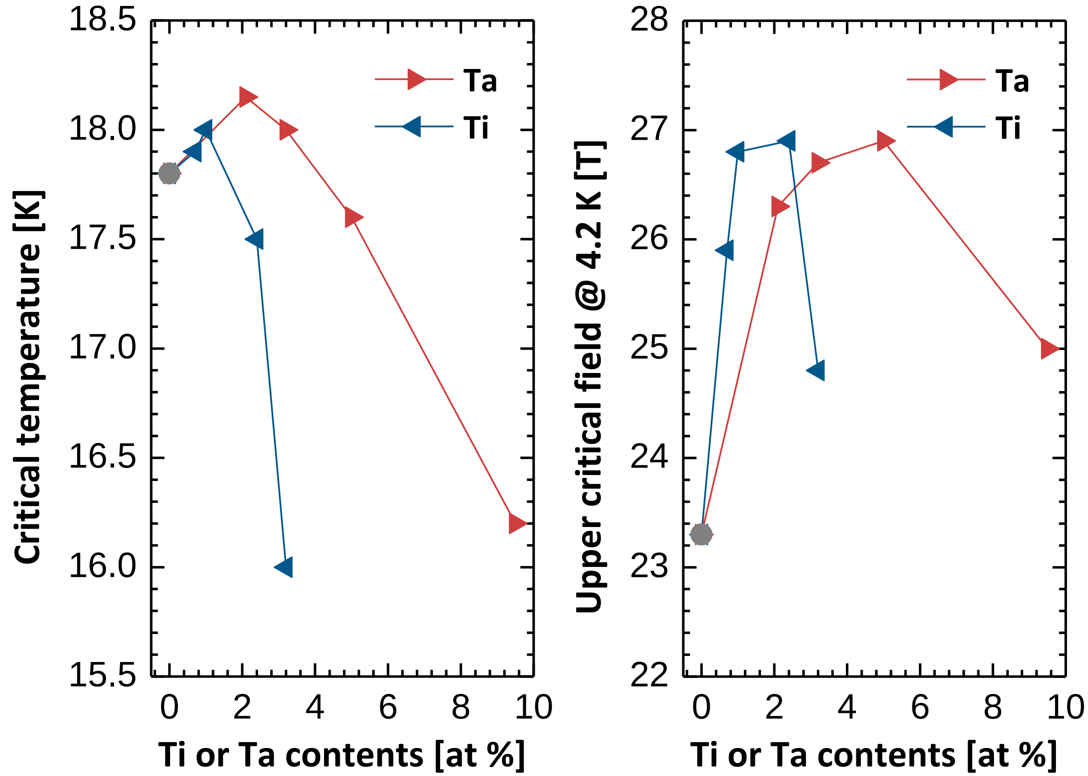
Alloying (doping) Nb_3Sn to rise H_{c2}

$$H_{c2} \propto \gamma \rho_n T_c$$

The additions of Ta and Ti are particularly beneficial



R. Flükiger et al., Cryogenics 48 (2008) 293



Ti substitutes Nb

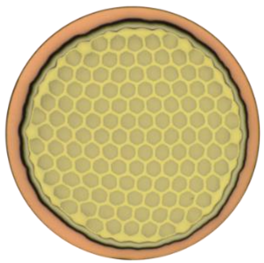
Ta substitutes both Nb and Sn

$$\frac{H_{c2}(4.2\ K)}{H_{c2}(0\ K)} = 0.89$$

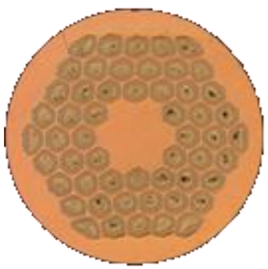
M. Suenaga et al., JAP 59 (1986) 840
S.M. Heald et al., Sci. Rep. 8 (2018) 4798

Industrial fabrication of Nb_3Sn wires

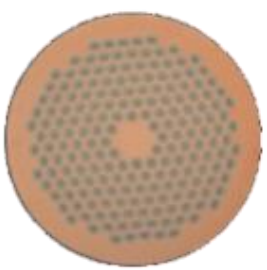
Three technologies have been developed at industrial scale



- Bronze route



- Internal Sn diffusion

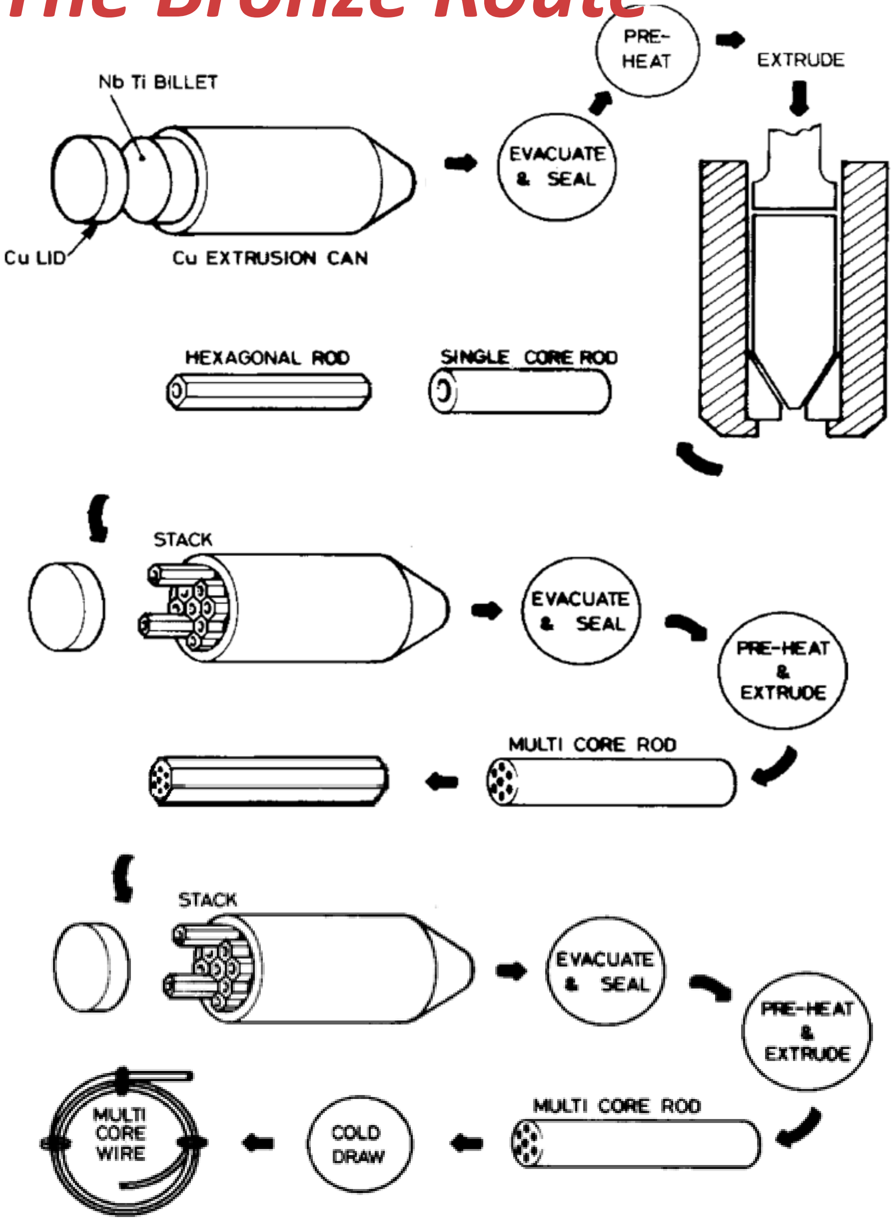


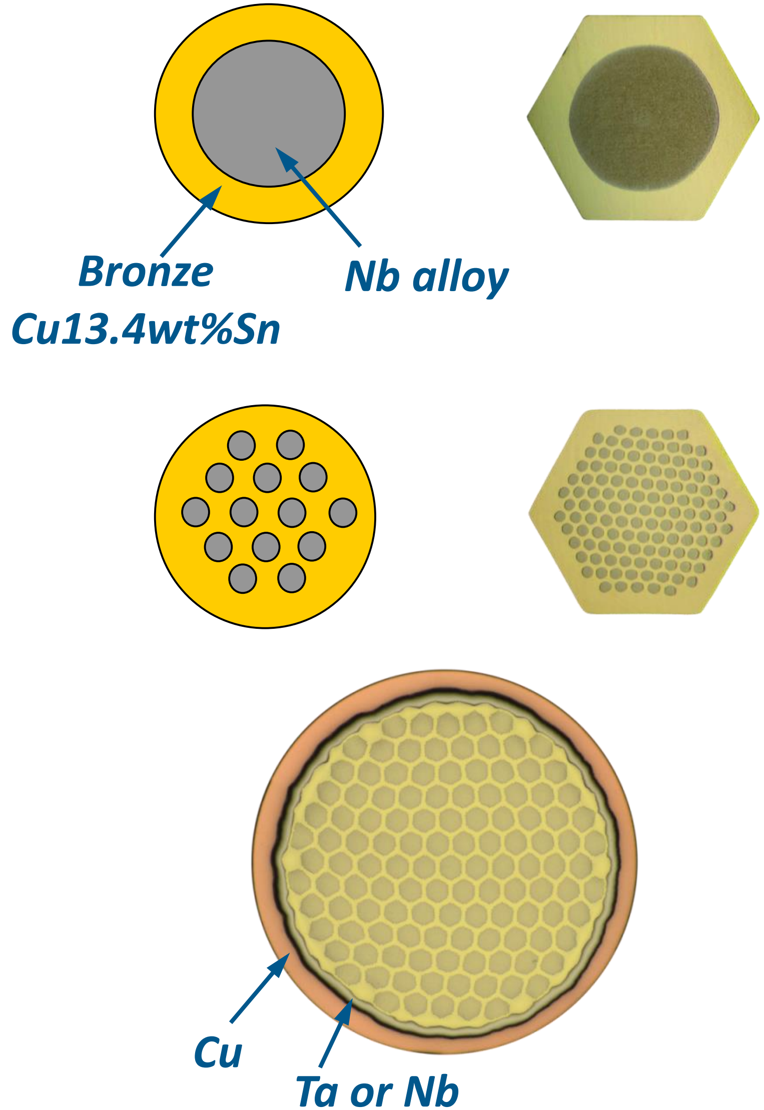
- Powder in tube

The Sn source is the main difference

Presently produced by BRUKER, LUVATA, Western Superconducting Technologies Co.,Ltd., Bochvar Institute of Inorganic Materials JSC VNIINM, Kiswire, KOBELCO Kobe Steel, Ltd., JASTEC Superconductor

The Bronze Route



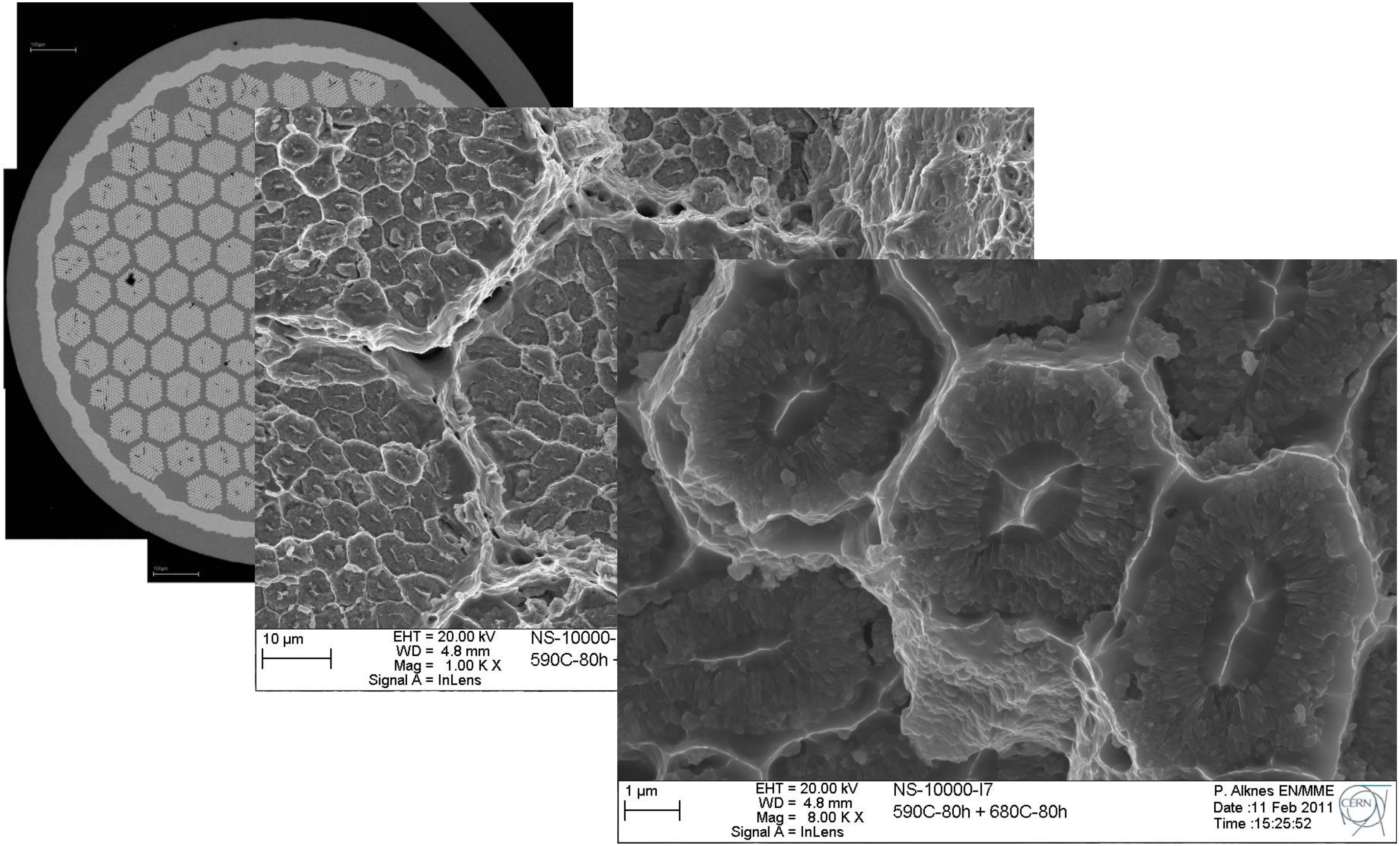


Cu-Sn bronze is used as Sn source

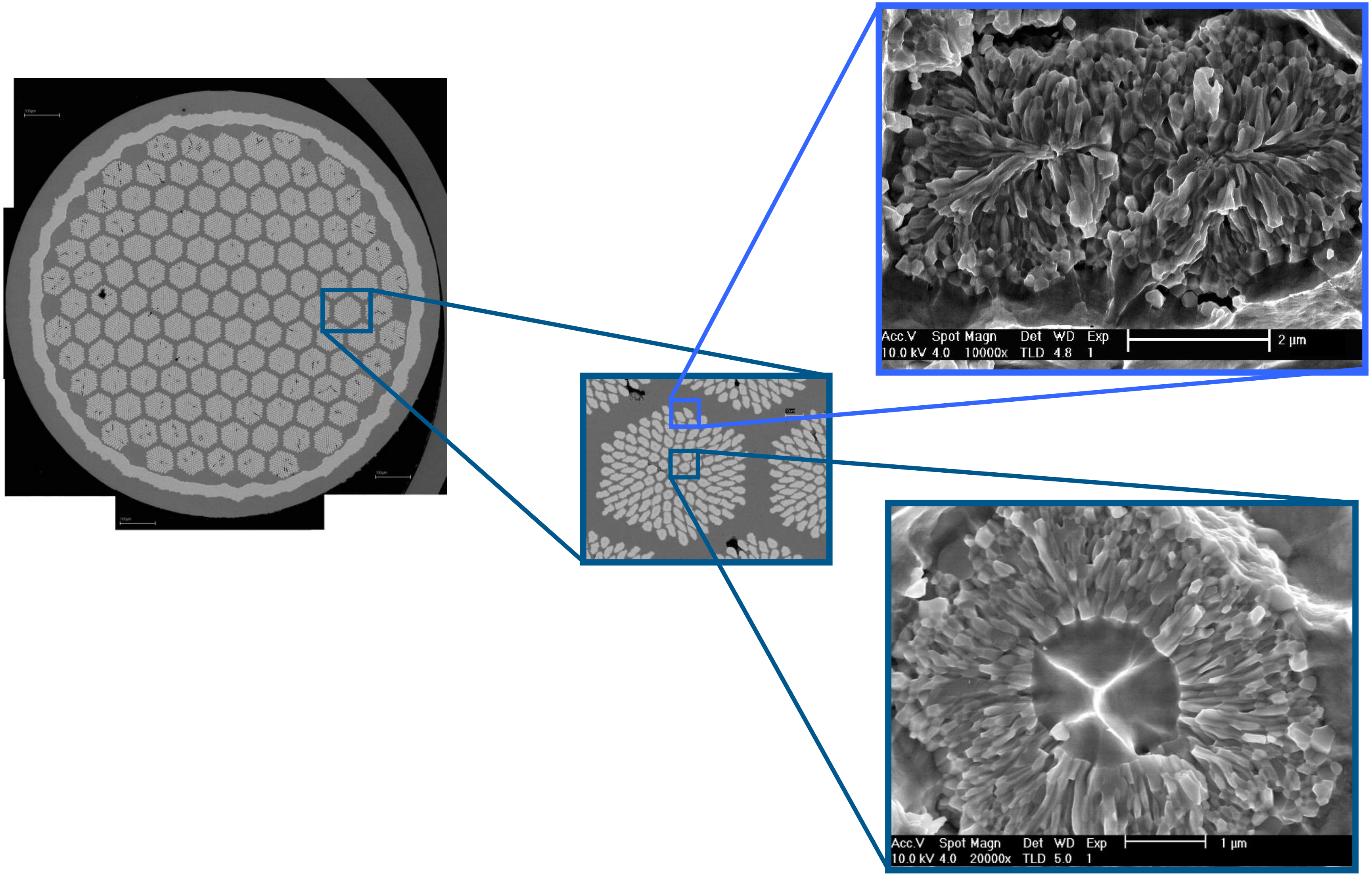
The final filament size is ~5 µm

Wires are then reacted at ~650°C for >100 hours to form Nb_3Sn

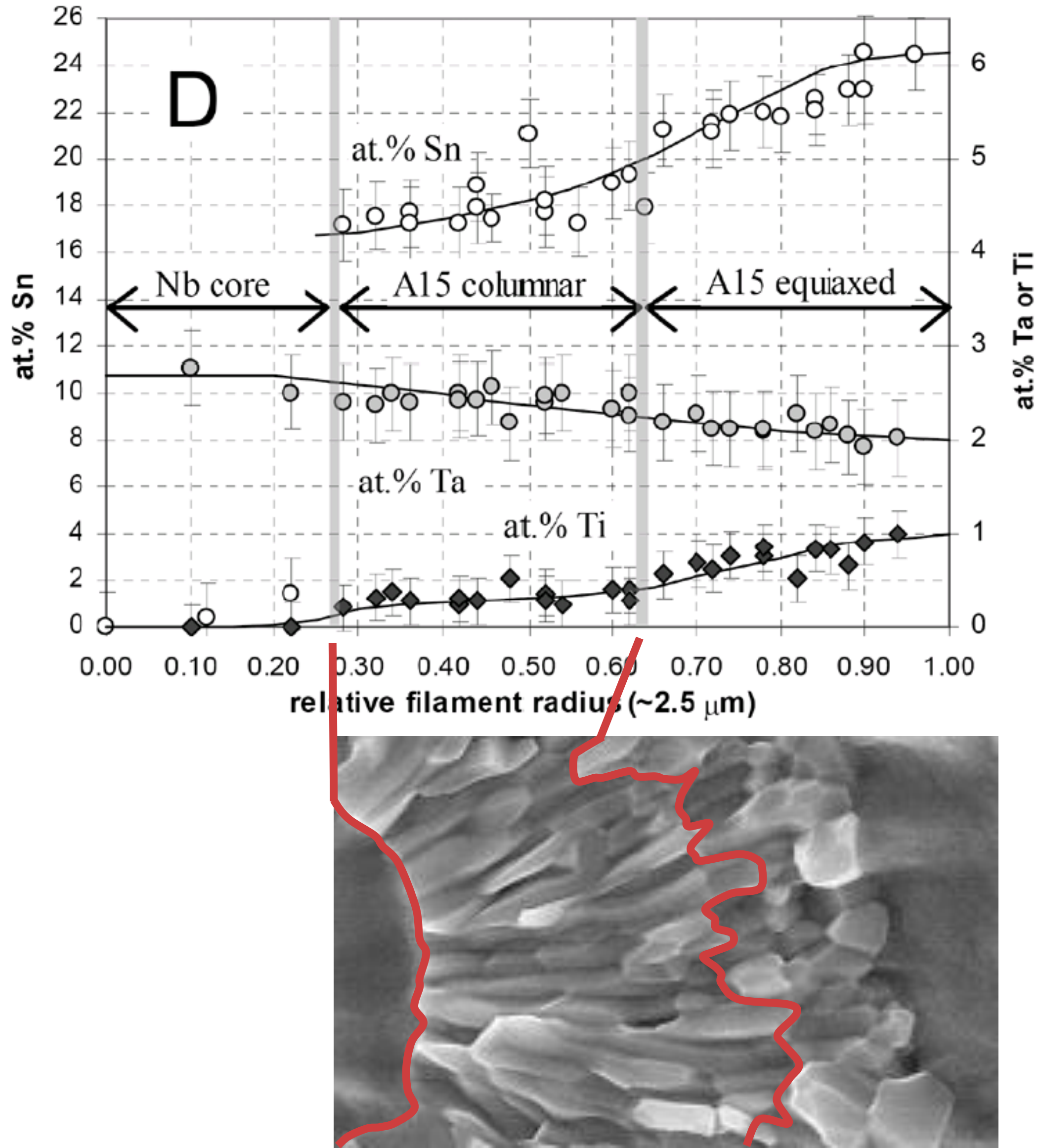
Bronze Route Nb_3Sn wires, after reaction



Bronze Route Nb_3Sn wires, after reaction



Sn gradient over the filament radius: Bronze Route



Correlation between Sn content and grain morphology

Equiaxed grains: 21-25 at.% Sn

Columnar grains: 18-21 at.%

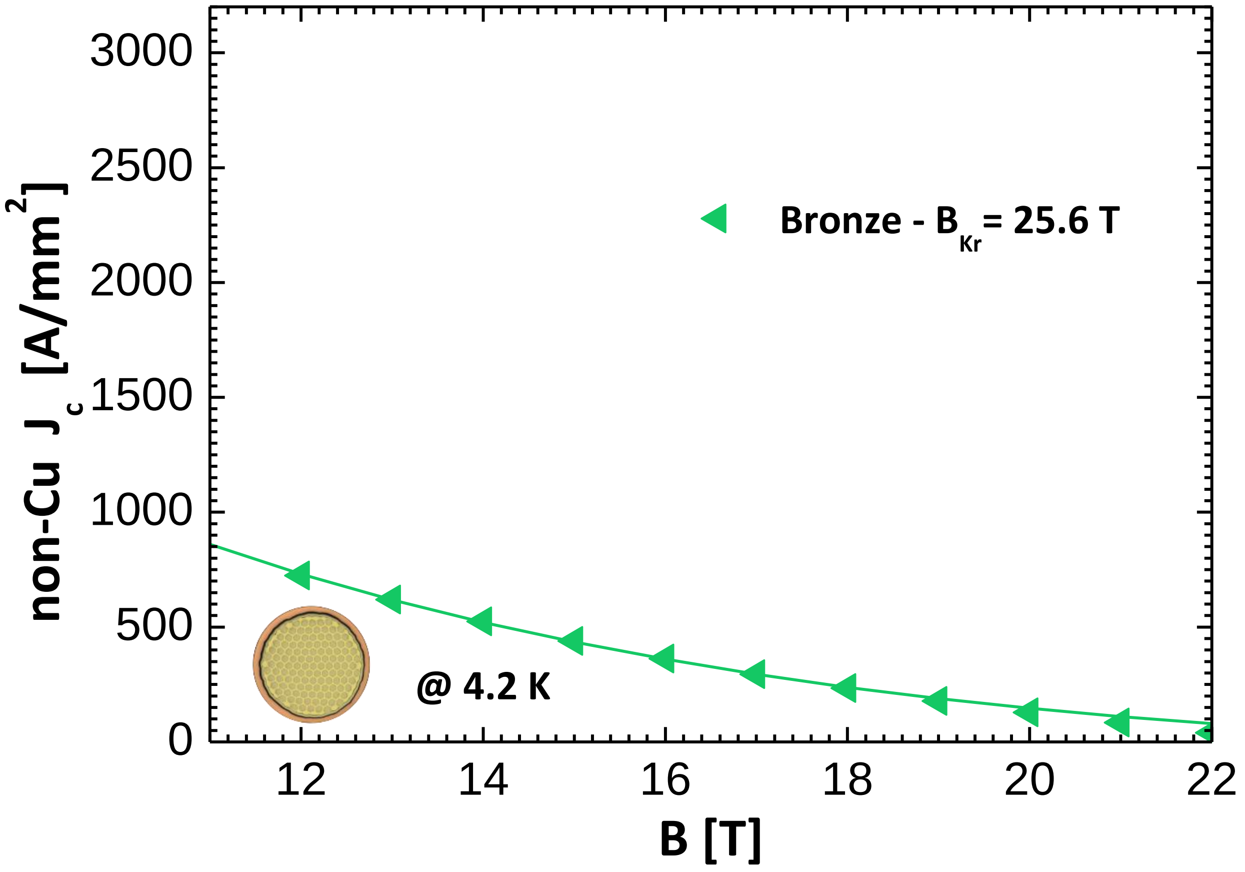
Equiaxed grain size ~150 nm

Columnar grain size up to 400 nm

V. Abächerli et al., IEEE TASC 15 (2005) 3482

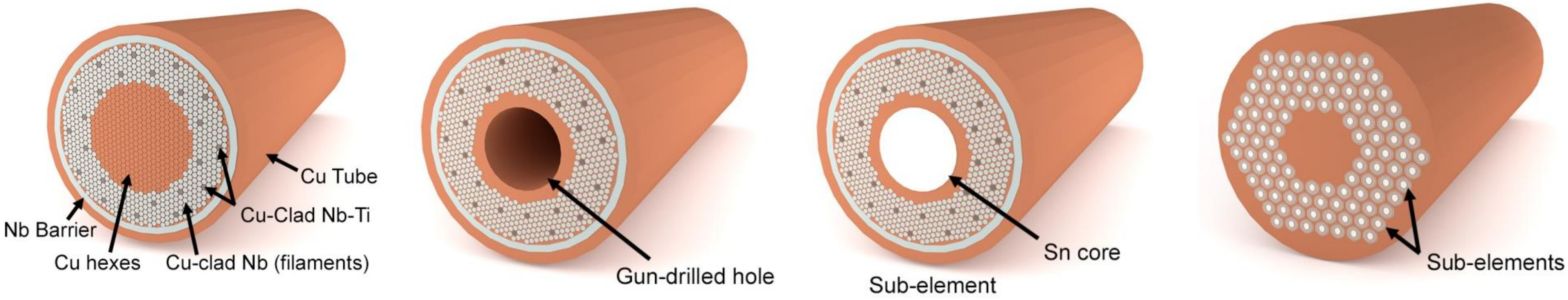
Critical current density vs. magnetic field

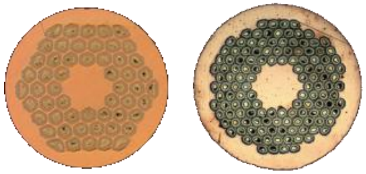
Best performance achieved so far in industrial wires



V. Abächerli et al., IEEE TASC 17 (2007) 2564

The Internal Sn diffusion process

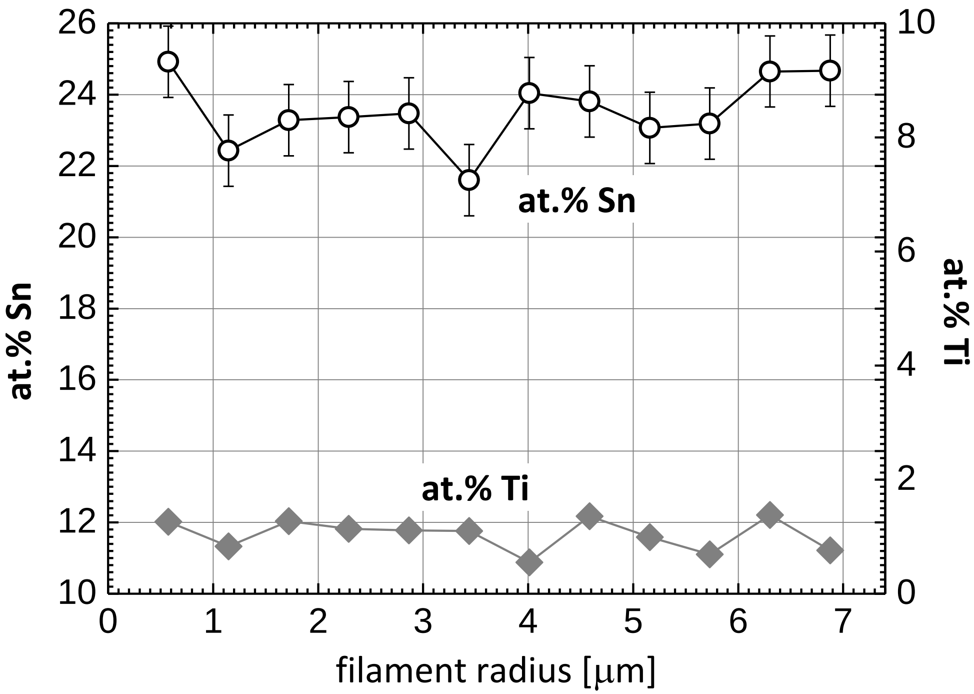




- *A Sn rod is inserted in the subelement core*
- *After the insertion of Sn, only cold deformations are possible*
- *Subelement size ranges between 20 and 100 µm*
- *A long-duration multistep reaction schedule is required to form Nb_3Sn*

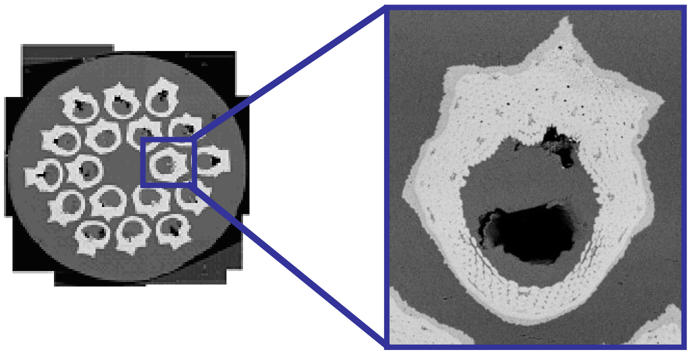
Pictures from C. Sanabria, PhD Thesis, FSU

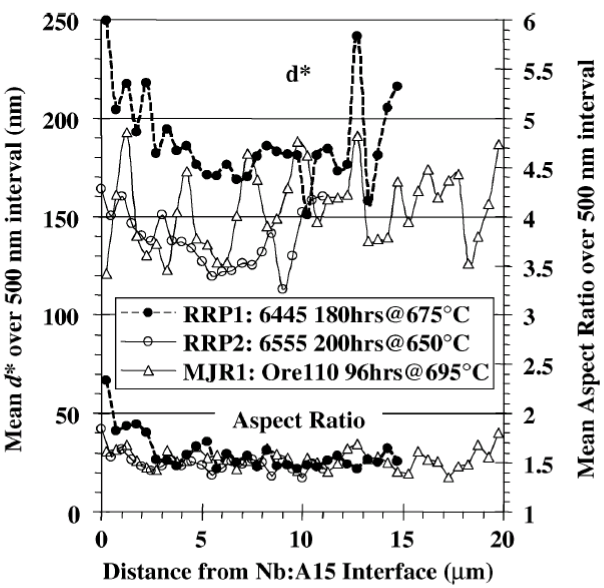
Sn gradient over the filament radius: Internal Sn



D. Uglietti, PhD Thesis (2006)

All the grains are equiaxed and almost stoichiometric !!

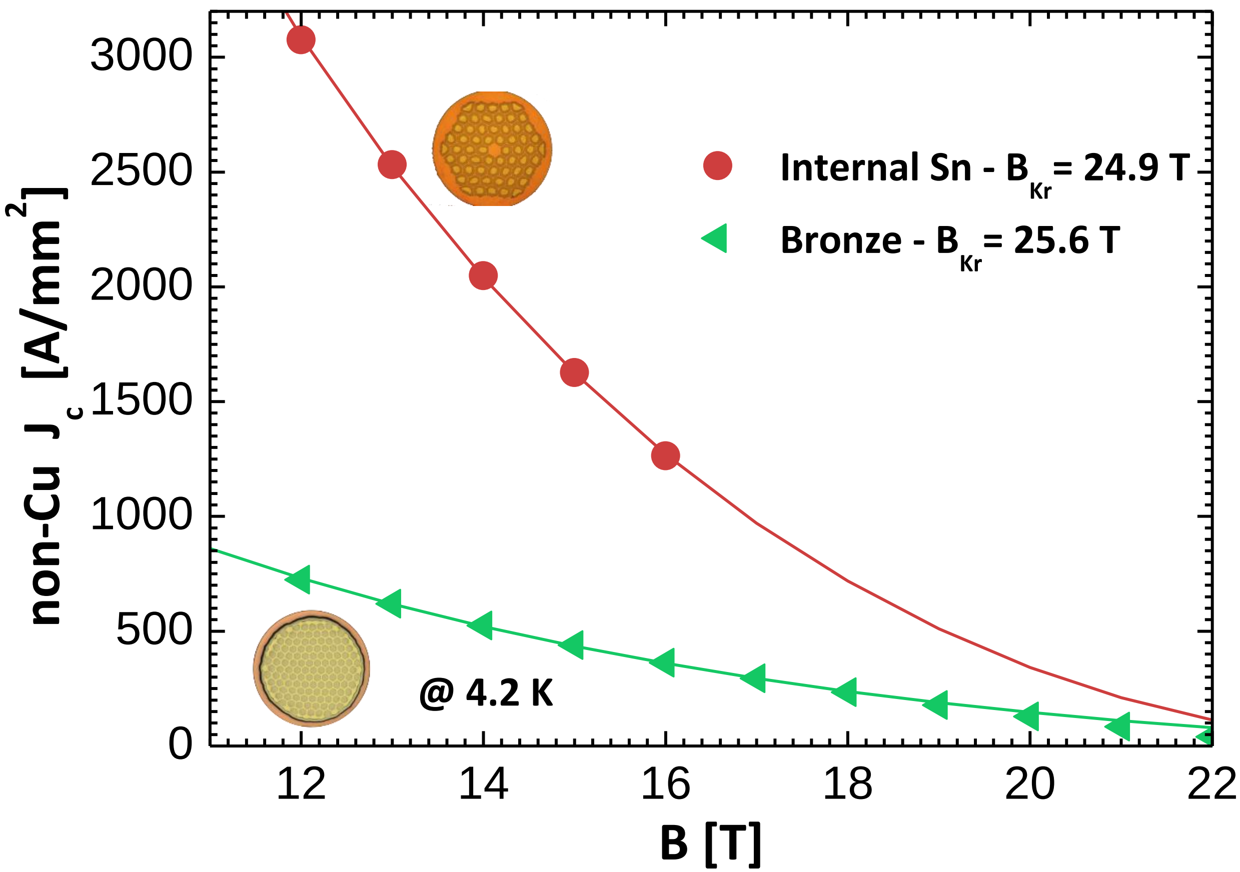




P. J. Lee and D. Larbalestier, IEEE Trans. Appl. Supercond. 15 (2005) 3474

Critical current density vs. magnetic field

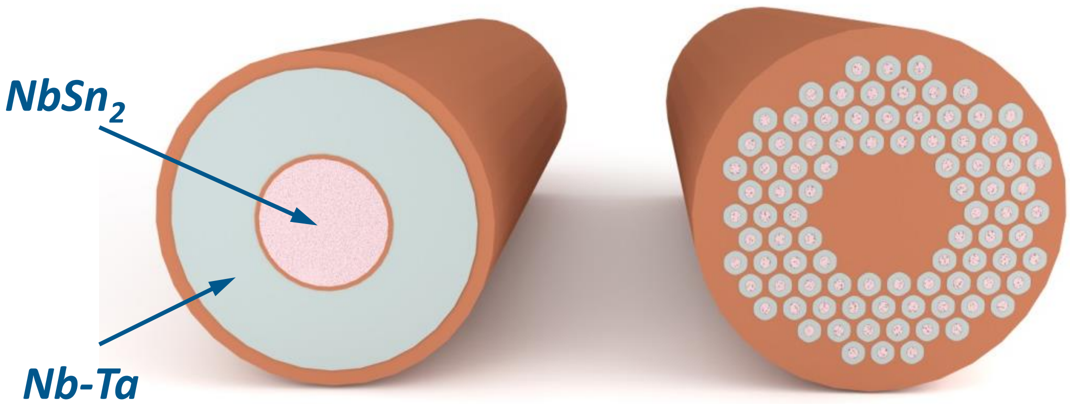
Best performance achieved so far in industrial wires



J. Parrell et al., AIP Conf. Proc. 711 (2004) 369

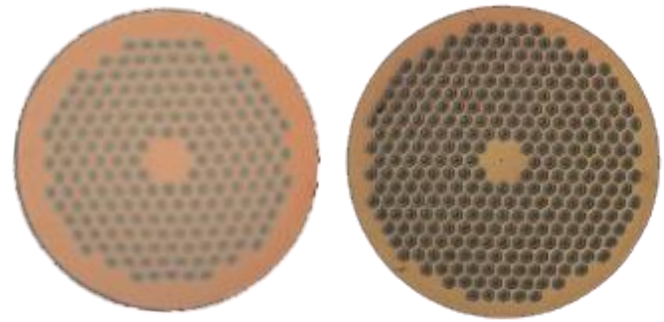
V. Abächerli et al., IEEE TASC 17 (2007) 2564

The Powder-In-Tube method



Powder-in-Tube filament

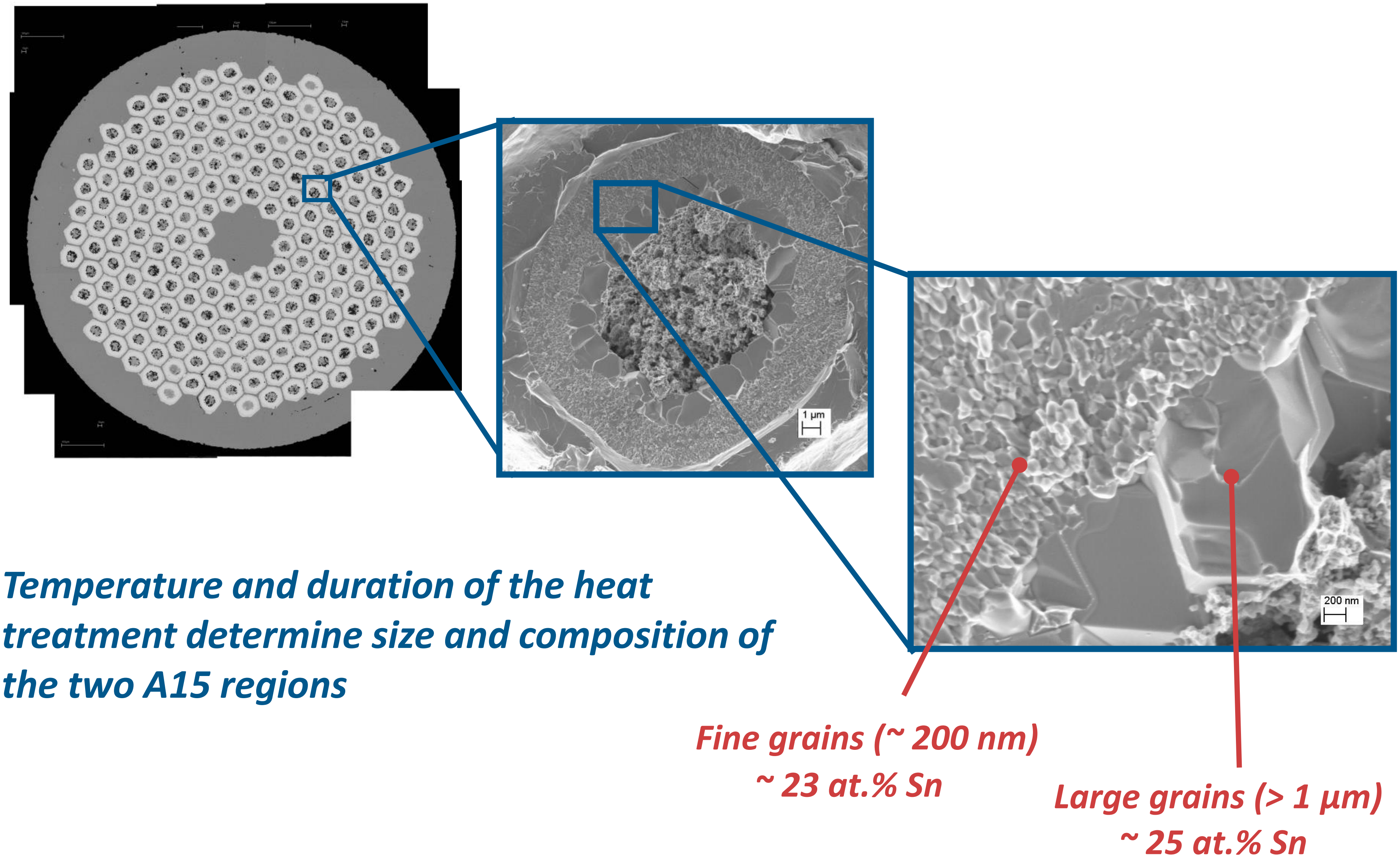
Powder-in-Tube stack



- $NbSn_2$ and Sn powders are used as Sn source
- Subelement size ranges between 20 and 100 µm
- A long-duration multistep reaction schedule is required to form Nb_3Sn

Pictures from C. Sanabria, PhD Thesis, FSU

Formation and Microstructure of the A15 phases (1)



Temperature and duration of the heat treatment determine size and composition of the two A15 regions

Formation and Microstructure of the A15 phases (2)

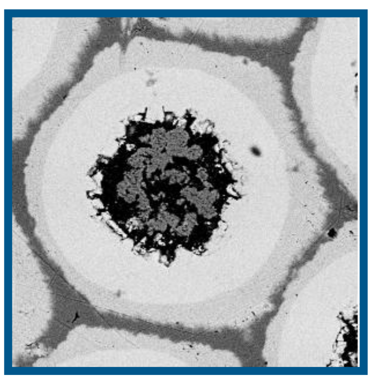
IOP Publishing — Superconductor Science and Technology
Supercond. Sci. Technol. **20** (2007) L55–L58 — doi:10.1088/0953-2048/20/10/L01

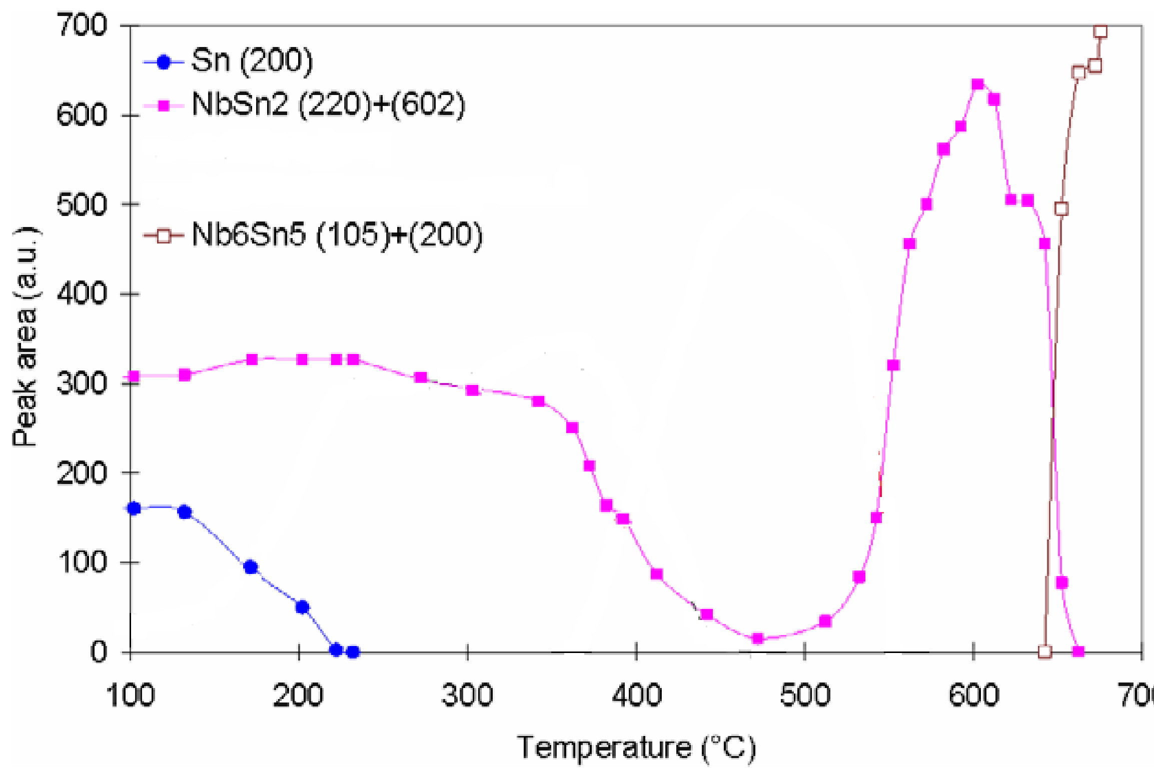
RAPID COMMUNICATION

Phase transformations during the reaction heat treatment of powder-in-tube Nb_3Sn superconductors

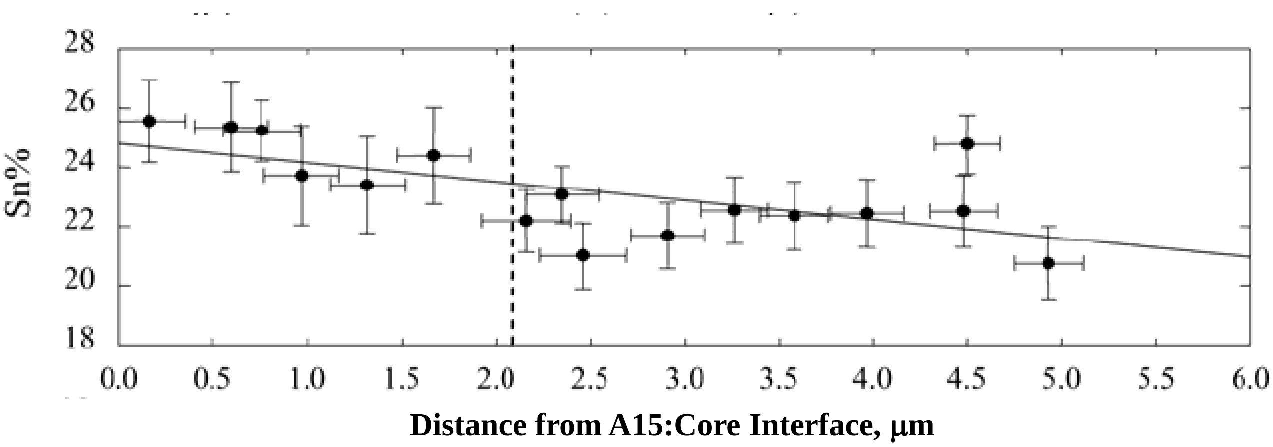
M Di Michiel[1] and C Scheuerlein[2]

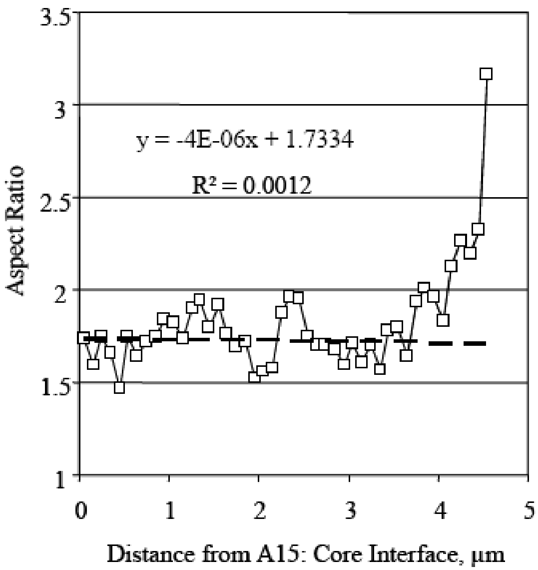
[1] European Synchrotron Radiation Facility (ESRF), 6 rue Jules Horowitz, F-38043 Grenoble, France
[2] European Organization for Nuclear Research (CERN), CH-1211 Geneva 23, Switzerland



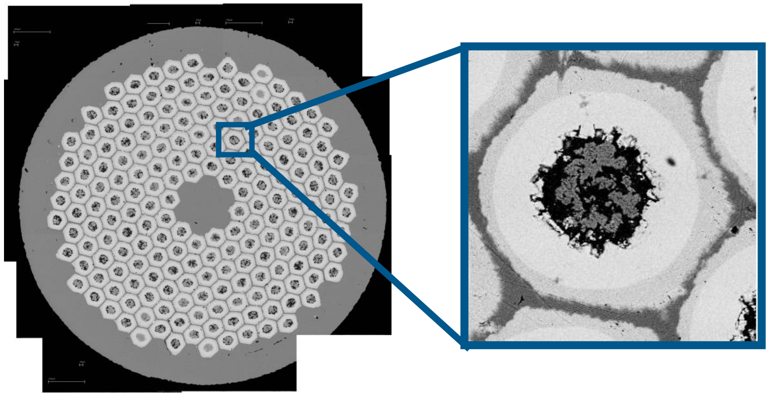


Sn gradient over the filament radius: PIT





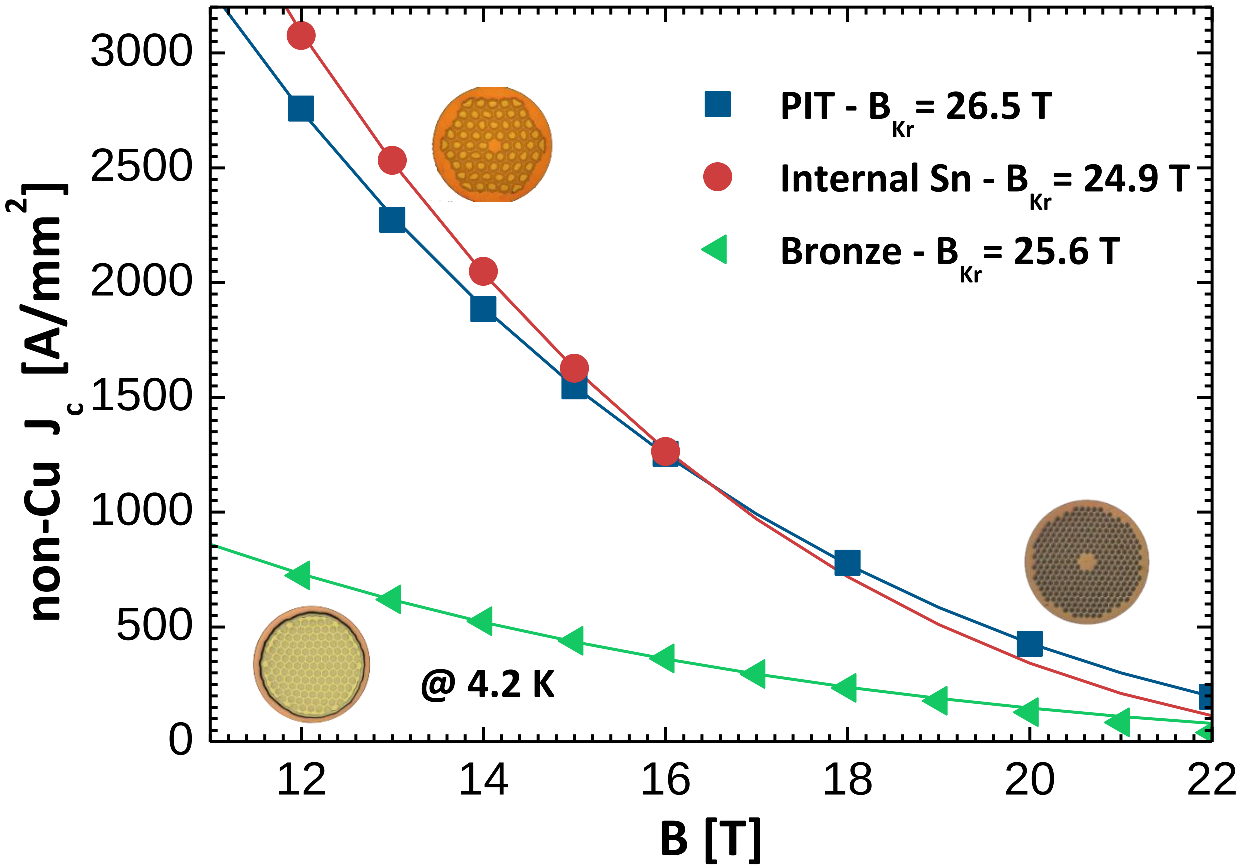
- ***Sn content decreases linearly along the filament radius***
- ***Both fine and large grains are (almost) equiaxed***



C.D. Hawes et al., Supercond. Sci. Technol. 19 (2006) 27

Critical current density vs. magnetic field

Best performance achieved so far in industrial wires



T. Boutboul et al., IEEE TASC 19 (2009) 2564

J. Parrell et al., AIP Conf. Proc. 711 (2004) 369

V. Abächerli et al., IEEE TASC 17 (2007) 2564

Bronze Route vs. Internal Sn vs. PIT

Technology	Filament size	non-Cu J_c(12T,4.2K)	
Bronze Route	1-5 µm	750 A/mm²	Fine filaments ⇒ low hysteretic losses Bronze matrix ⇒ high mechanical strength Low Sn content ⇒ columnar grains, low J_c
Internal Sn	20-100 µm	3'200 A/mm²	High Sn content + Fine grains ⇒ very high J_c Large filaments ⇒ high hysteretic losses
Powder-In-Tube	20-100 µm	2'700 A/mm²	Fine grain region ⇒ high J_c Large grain region ⇒ very low J_c Large filaments ⇒ high hysteretic losses

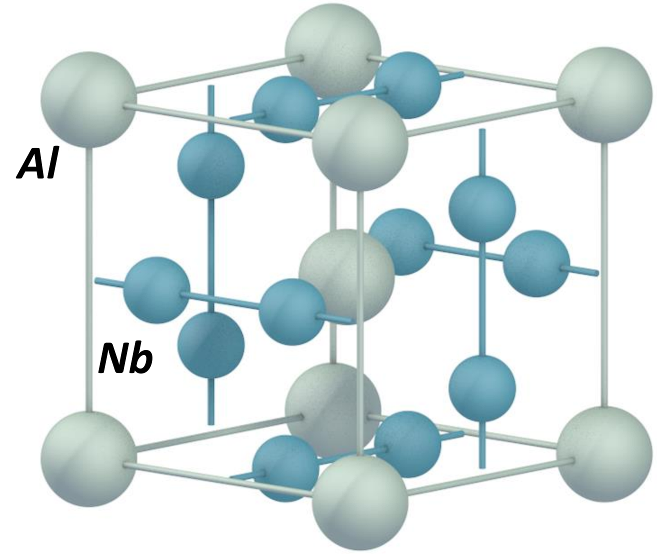
What we need:

Small grain size & high grain boundary density to get high pinning and thus high J_c

High Sn content & appropriate Ta/Ti doping to get high B_{c2} and thus high in-field J_c

Another (almost) industrial A15 conductor: Nb_3Al

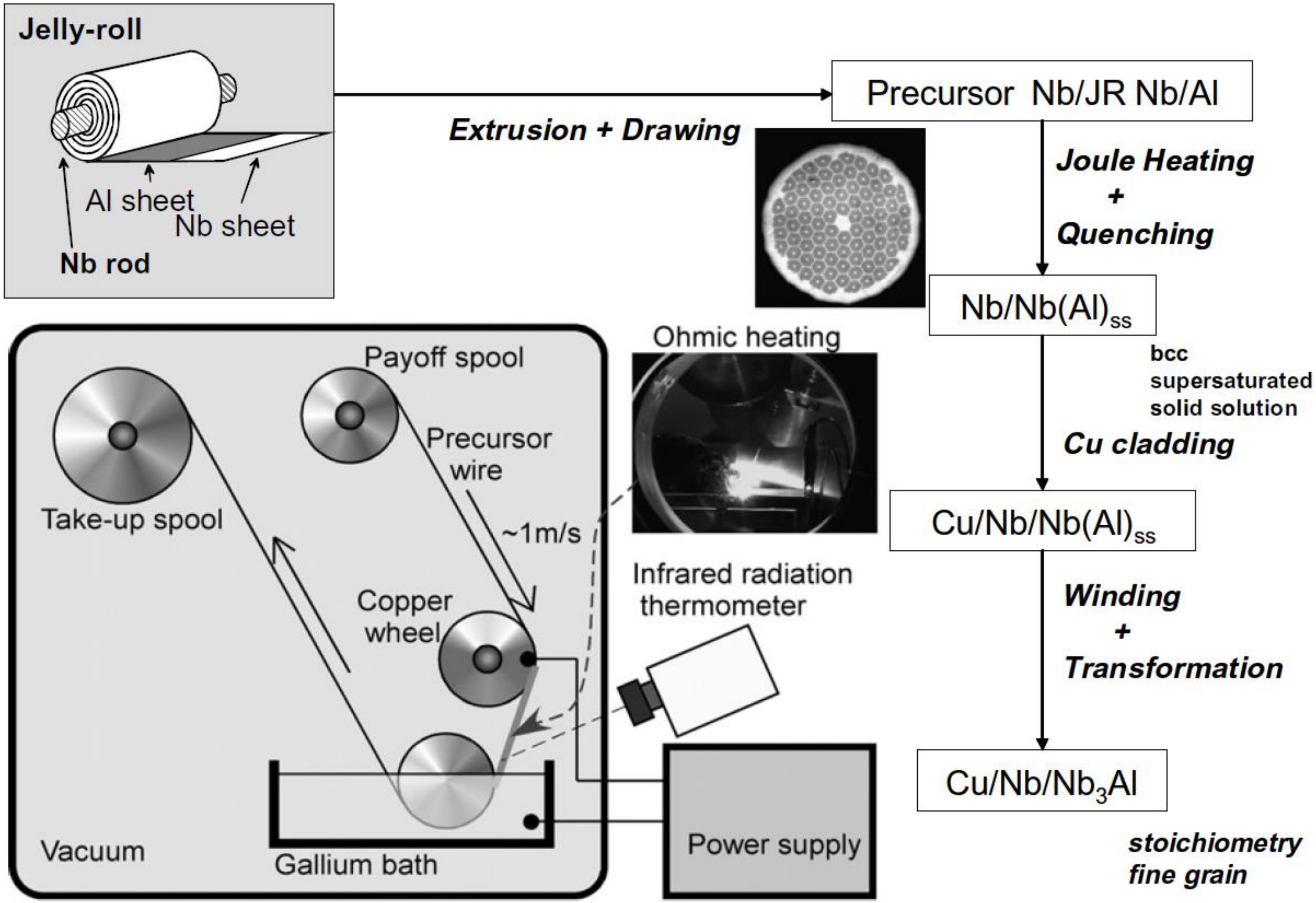
	T_c [K]	B_{c2} [T]
Nb_3Al	18.8	33



- Higher B_{c2} compared to Nb_3Sn
- Stoichiometric Nb_3Al cannot be formed by Al diffusion in Nb, with reaction @ 700°C
- Wire are fabricated by rapid-heating, quenching and transformation annealing (RHQT)
- The RHQT process enables the formation of stoichiometric Nb_3Al via a metastable bcc supersaturated-solid-solution of Nb and Al

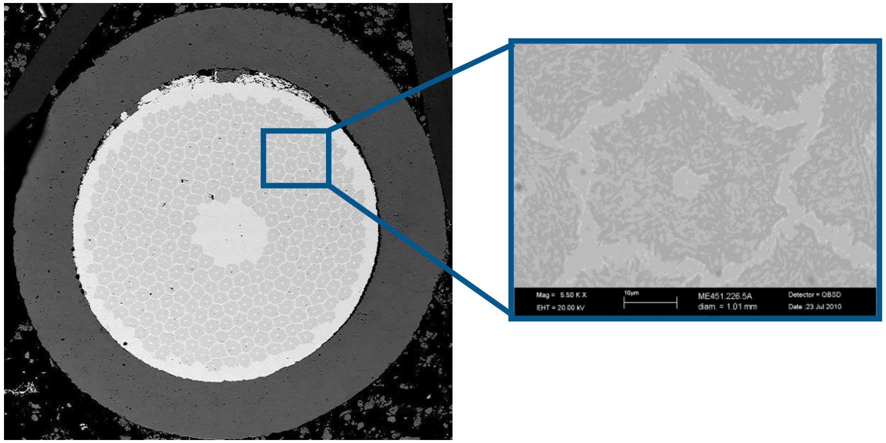
T. Takeuchi et al., Cryogenics 48 (2008) 371

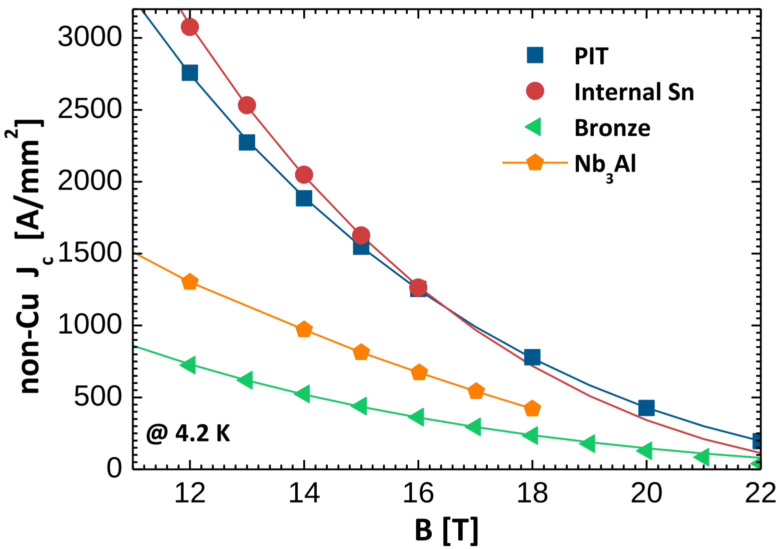
Nb_3Al wires: the RHQT process

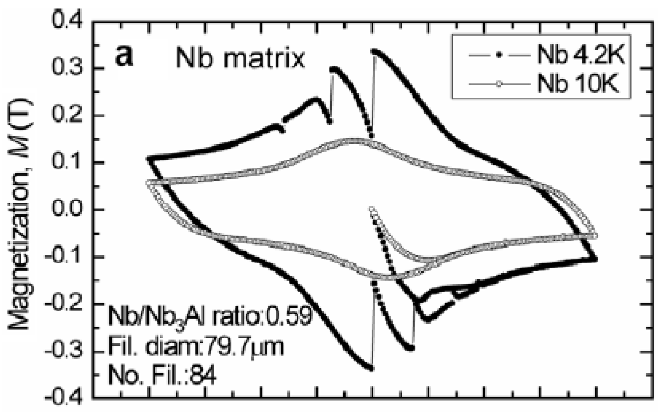


T. Takeuchi et al., Cryogenics 48 (2008) 371

Nb_3Al wires: cross section, filament layout & J_c







Coupling among filaments due to the Nb matrix

- *J_c is lower compared to PIT and Internal Sn Nb_3Sn wires*
- *The advantage of Nb_3Al is the low sensitivity to applied strain*

Bibliography

Rogalla & Kes
100 Years of Superconductivity
Chapter 3 Section 7
Chapter 11 Section 2 (NbTi)
Section 3 (Nb_3Sn)

Poole, Farach, Creswick, Prozorov
Superconductivity
Chapter 3

Papers cited in the slides