# LTS Conductors

**Michael Eisterer**
Atominstitut, TU Wien, Vienna, Austria

Acknowledgement:

**Carmine Sentatore**
University of Geneva, Switzerland

**CAS, St. Pölten, November 21st 2023**

# Copyright statement and speaker’s release for video publishing

The author consents to the photographic, audio and video recording of this lecture at the CERN Accelerator School. The term “lecture” includes any material incorporated therein including but not limited to text, images and references.

The author hereby grants CERN a royalty-free license to use his image and name as well as the recordings mentioned above, in order to post them on the CAS website.

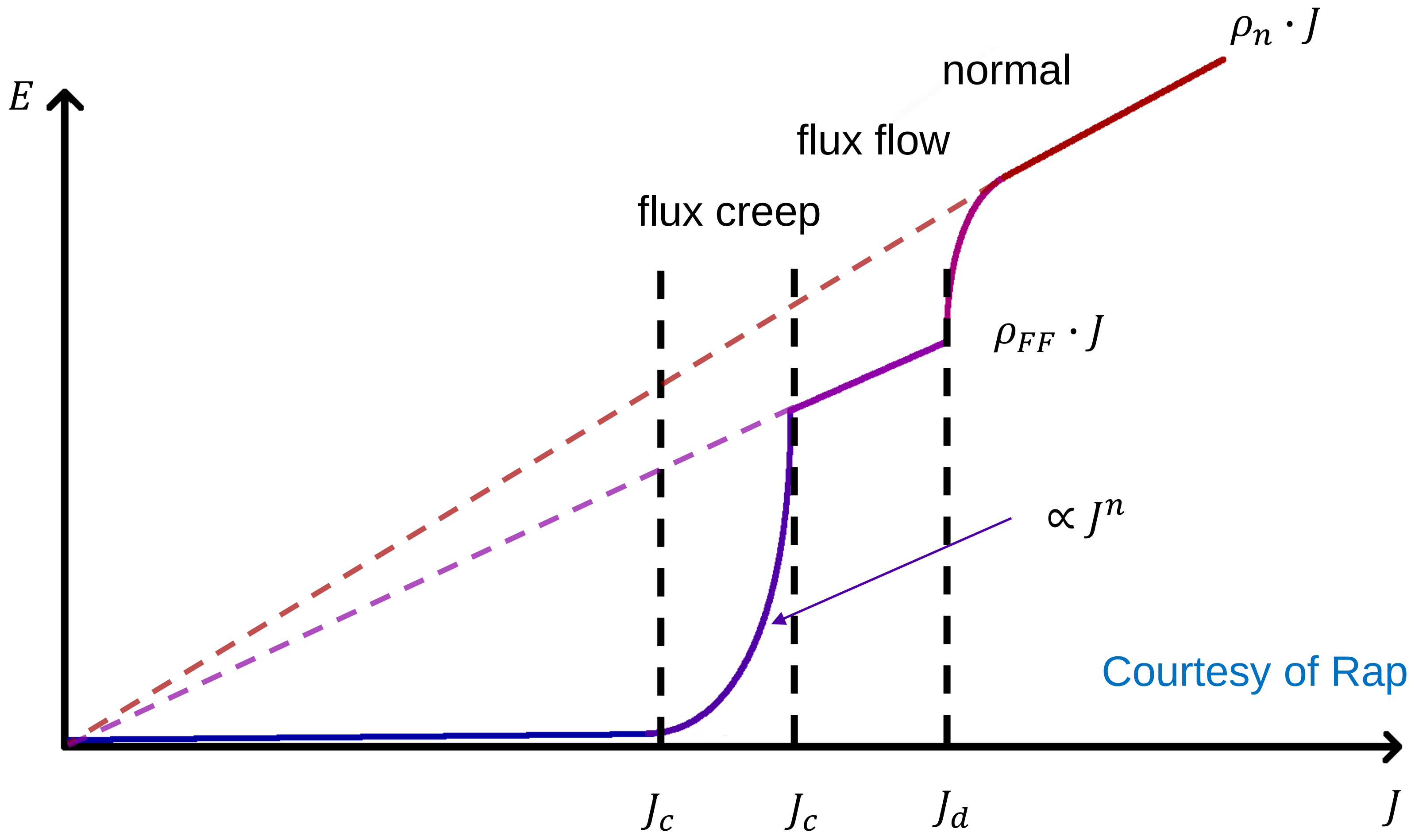
The material is used for the sole purpose of illustration for teaching or scientific research. The author hereby confirms that to his best knowledge the content of the lecture does not infringe the copyright, intellectual property or privacy rights of any third party. The author has cited and credited any third-party contribution in accordance with applicable professional standards and legislation in matters of attribution.

# Outline

- Technical $I_c$
- Stabilization
  - Multifilamentary wires
- Superconducting materials used for conductors
  - NbTi
  - $Nb_3Sn$
  - ($MgB_2$)
- Effect of forces on superconductors

# Technical $I_c$

- Dissipation in superconductors

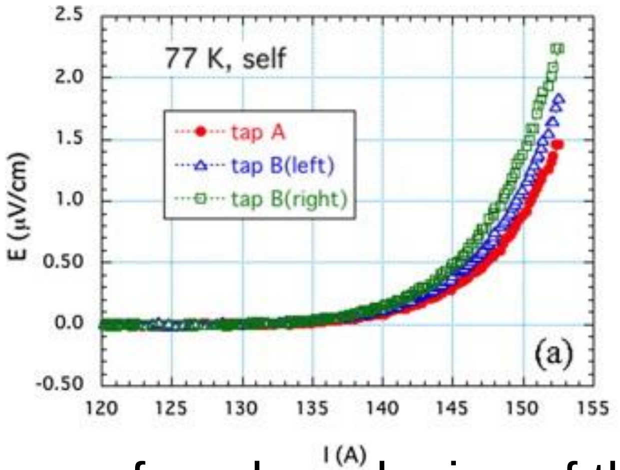


Courtesy of Raphael Unterrainer

$J_c \neq J_c$? Technical $J_c$ defined by arbitrary electric field criterion, e.g. 0.1 µV/cm

# Resistive transition

- Transition can be often approximated by $E = E_c\left(\frac{J}{J_c}\right)^n$ or $I \propto E_c\left(\frac{I}{I_c}\right)^n$
  - Linear on a double logarithmic scale



Tsuchiya et al., *Cryogenics* **85** (2017) 1

- Two main reasons for a broadening of the transition
  - Intrinsic: thermal activation of vortices out of the pinning potential $U$

$$n = \frac{U}{k_B T}$$

  - Material inhomogeneities $n = ?$
- “Well-behaved” superconductors: $n \gtrsim 30$
- Important for applications: predictable (extremely) low loss behavior.

# Requirements on a superconducting wire

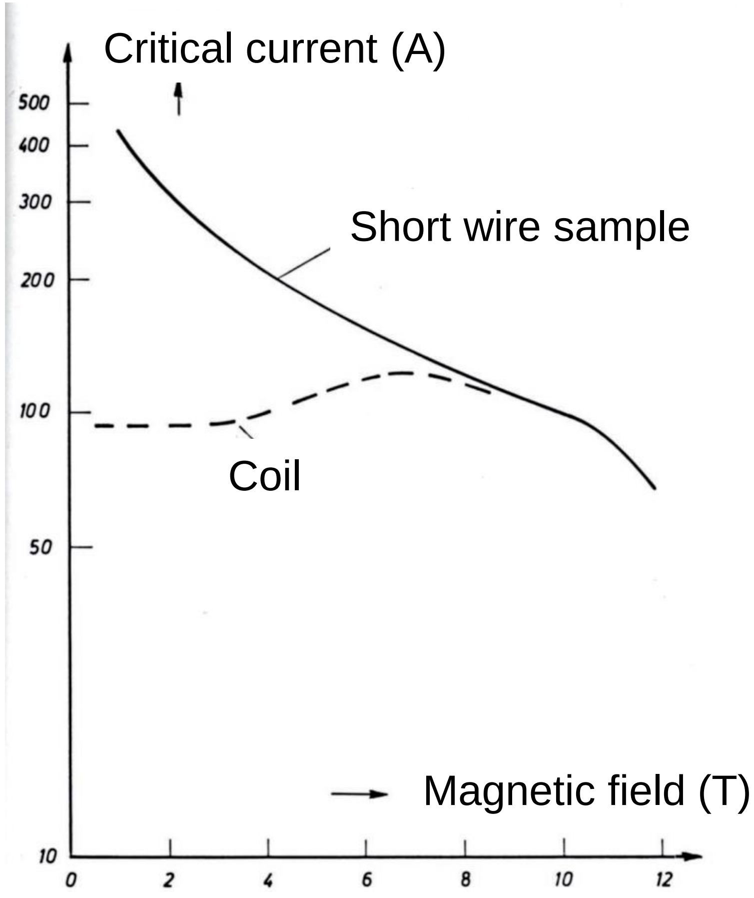
***A high current density is a necessary condition for applications, but it is not sufficient.***

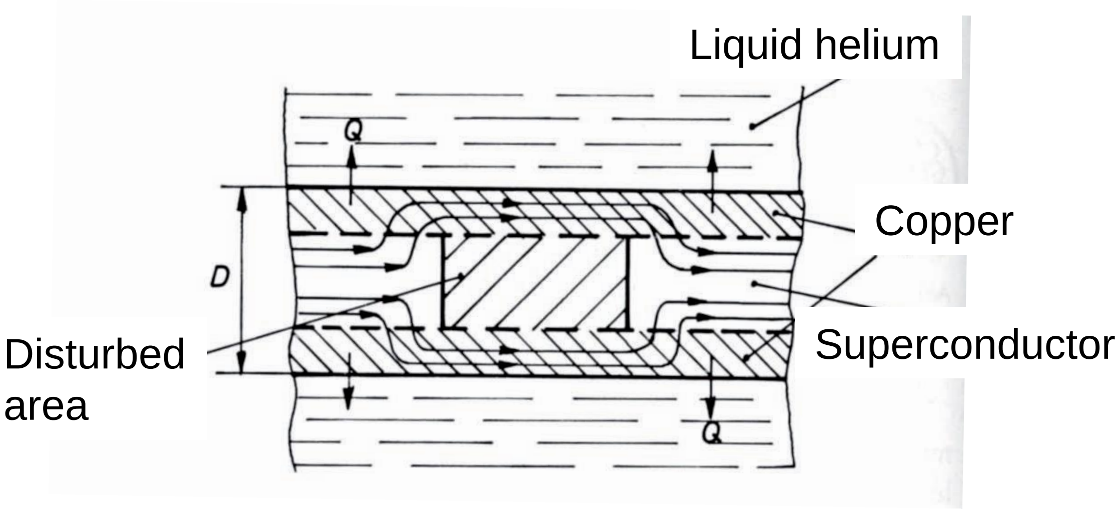
***Other crucial requirements:***

- ***Have high tolerance to stress*** *Magnetic forces*
- ***Be safe in case of magnet quench*** *Quench detection, NZPV*
- ***Have low magnetization*** *Applications to NMR, MRI, HEP magnets*
- ***Have a persistent joint technology*** *Applications to NMR, MRI*
- ***Stability against small thermal perturbances***

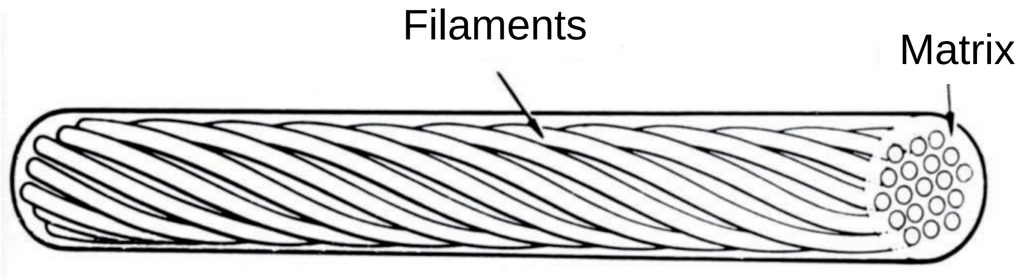
# Stabilization

- A technical conductor needs stabilization otherwise:
  - A small disturbance leads to dissipation
  - The superconductor heats up
  - Dissipation increases
  - Quench
- Idea: Current can bypass the disturbed area
  - Allows the superconductor to recover





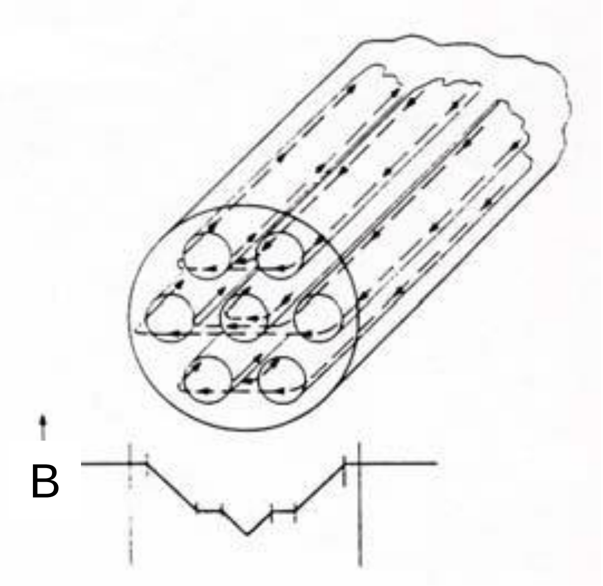
# Multifilamentary wires

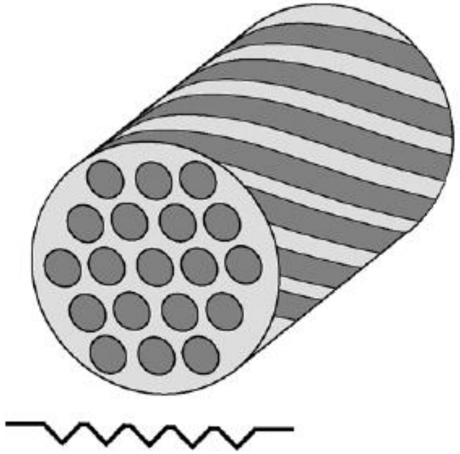


- Thin filaments: Large surface to volume fraction
  - Efficient heat and current transfer
- Matrix
  - Low resistivity
  - Compatible properties
- Twisted filaments
  - Avoid inductions loops

# Multifilamentary wires

- Induction loops
  - store energy that may trigger an instability
  - distort the field quality
- Self screening of filaments cannot be avoided
  - Transport current only flows in a small part of the filament when ramping a magnet at low fields
  - Remaining part shields any field changes
- Current loops can close over the low ohmic matrix driven by the induction voltage (or over bridges)
- Twisting reduces inductive filament coupling efficiently
  - Current loops become smaller (longitudinally and transversal)
  - A local disturbance releases less energy





# LTS materials (typical values)

| | $T_c$(K) | $B_{c2}$(T)[1] | $J_d$(MA/cm$^2$)[1] | Advantages | Disadvantages |
|---|---|---|---|---|---|
| NbTi | 9.5 | 11 | 40 | • easy to handle<br>• optimized<br>• cheap | • low $T_c$<br>• small $B_{c2}$ |
| $Nb_3Sn$ | 18 | 27 | 200 | • higher $T_c$<br>• high $B_{c2}$ | • brittle<br>• in-situ process<br>• wind and react<br>• expensive<br>• under optimization |
| $MgB_2$ | 39 | 10 | 130 | • “High“ $T_c$<br>• cheap? | • small $B_{c2}$<br>• wind and react?<br>• expensive<br>• not optimized |

[1] at 4.2 K

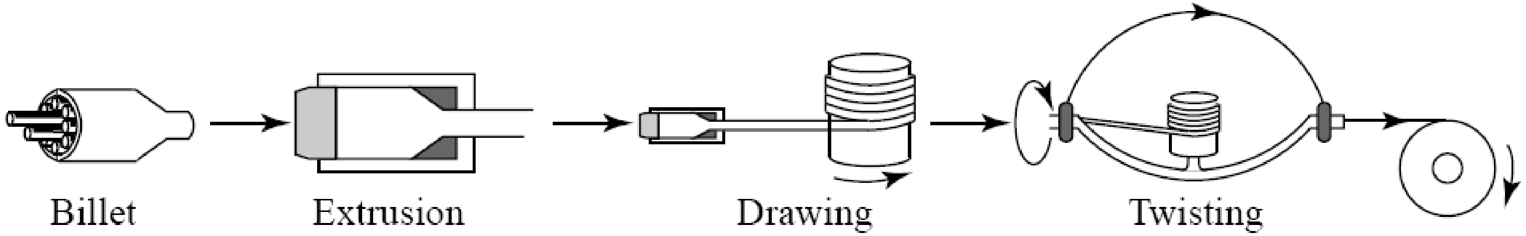
# NbTi

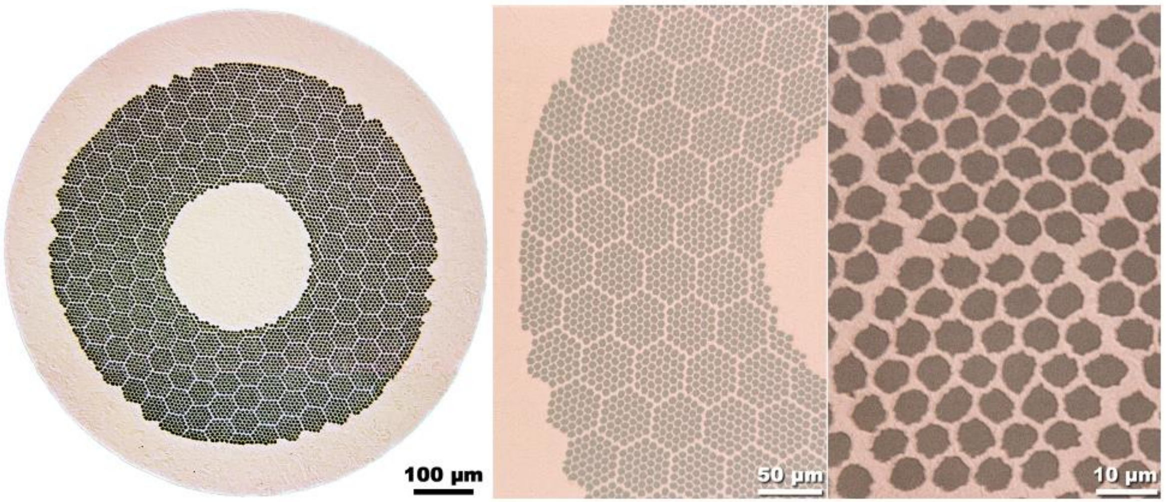
## Life is easy

# Nb-Ti : the King of the Hill

| *Type II* | $T_c$ [K] | $\mu_\circ H_{c_2}{}^*$ [T] |
|---|---|---|
| Nb (metals) | 9.5 | 0.2* |
| NbTi (alloys) | 9.8 | 10.5† |

- **Enabling technology for the large diffusion of MRI (a 4’000 M€ market!)**
- **1200+ tonnes of Nb-Ti in LHC**





# Nb-47wt%Ti : How to get high $J_c$

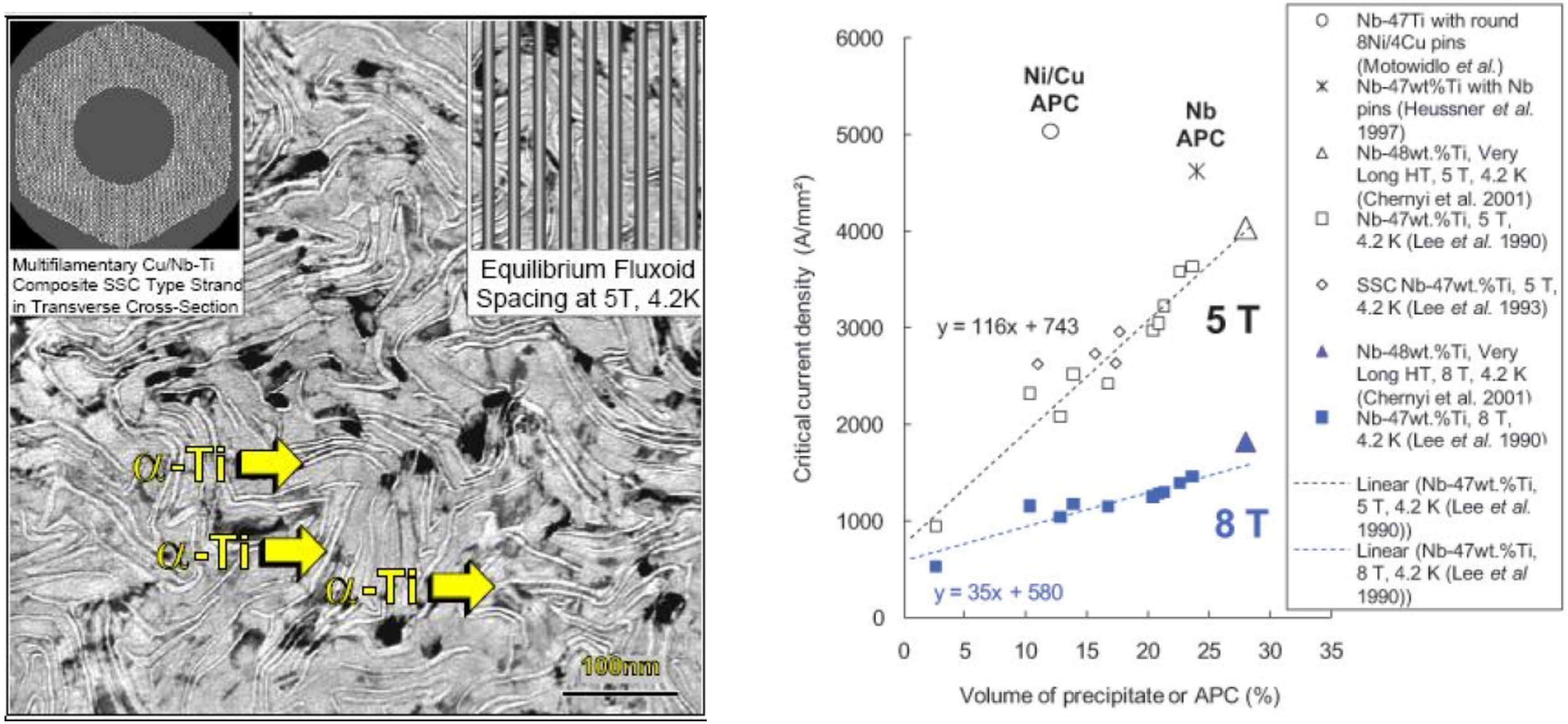


**FIGURE 11.15:** TEM image of the microstructure (transverse cross-section) of the first 3700 A/mm$^2$ (5 T, 4.2 K) multifilamentary strand from a US manufacturer (OST). This previously unpublished image taken on September 5th 1986, shows the dense array of folded $\alpha$-Ti ribbons (lighter contrast) that create the strong vortex pinning.

$\alpha$-Ti → hcp

$\beta$-Ti → bcc

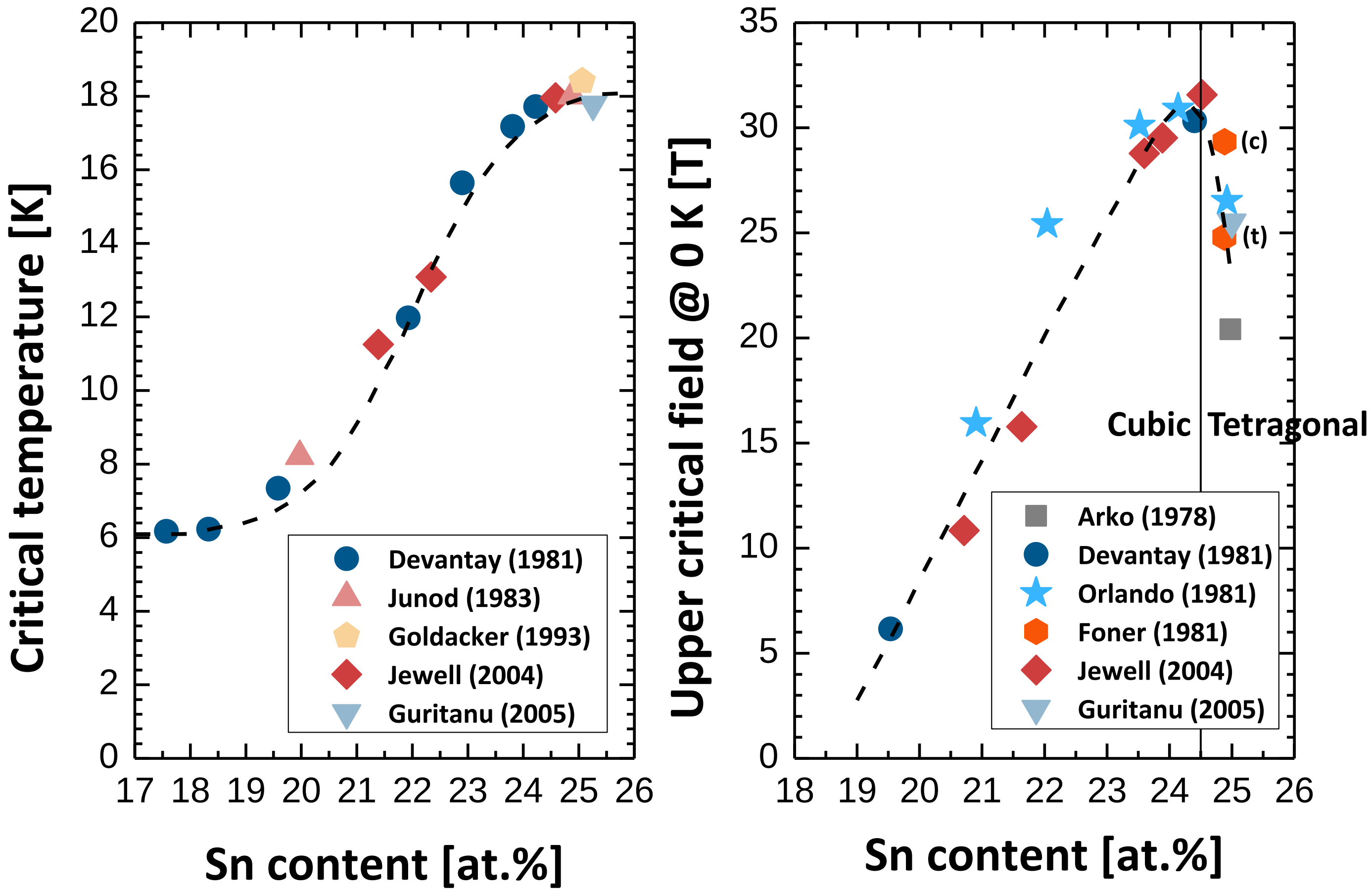
$\alpha$-Ti precipitates are adjusted to the proper dimensions in order to pin vortices

# Nb$_3$Sn

## It’s a hard life

# $Nb_3Sn$ : the LTS conductor for high fields

## Influence of the Sn content on $T_c$ and $B_{c2}$



**$Nb_{3+x}Sn_{1-x}$ remains superconducting when it deviates from stoichiometry**

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

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

**Upper critical field of a superconductor**

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

**Disorder reduces the electron mean free path $\ell$, which in turn leads to decrease of $\xi$**

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

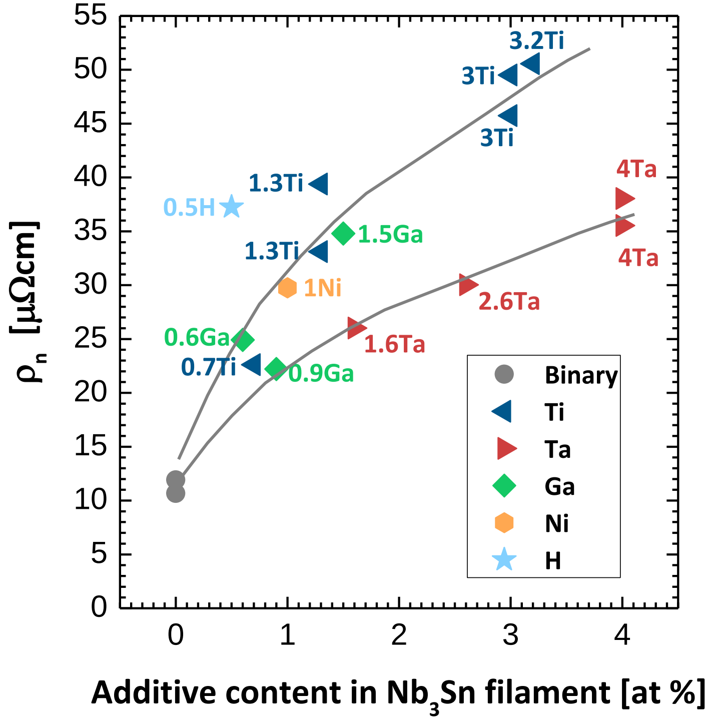
**An useful expression of $H_{c2}$ in the dirty limit**

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

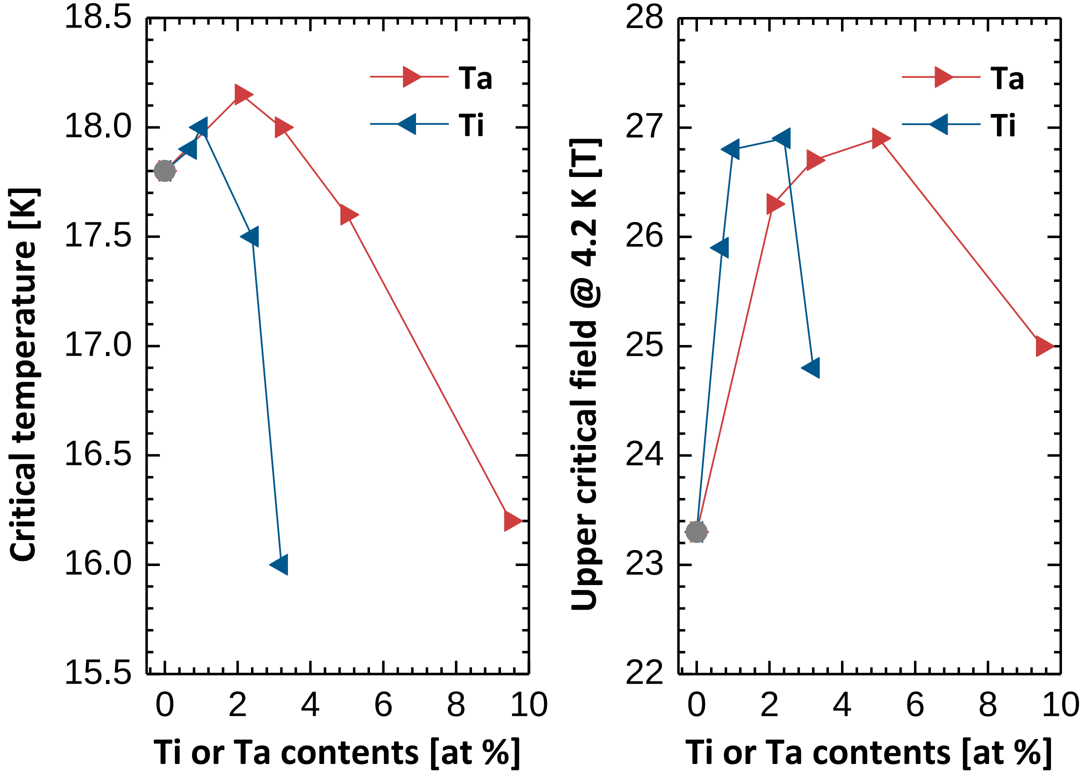
# Alloying (doping) $Nb_3Sn$ to rise $H_{c2}$

## The additions of Ta and Ti are particularly beneficial

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



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



**Ti substitutes Nb**

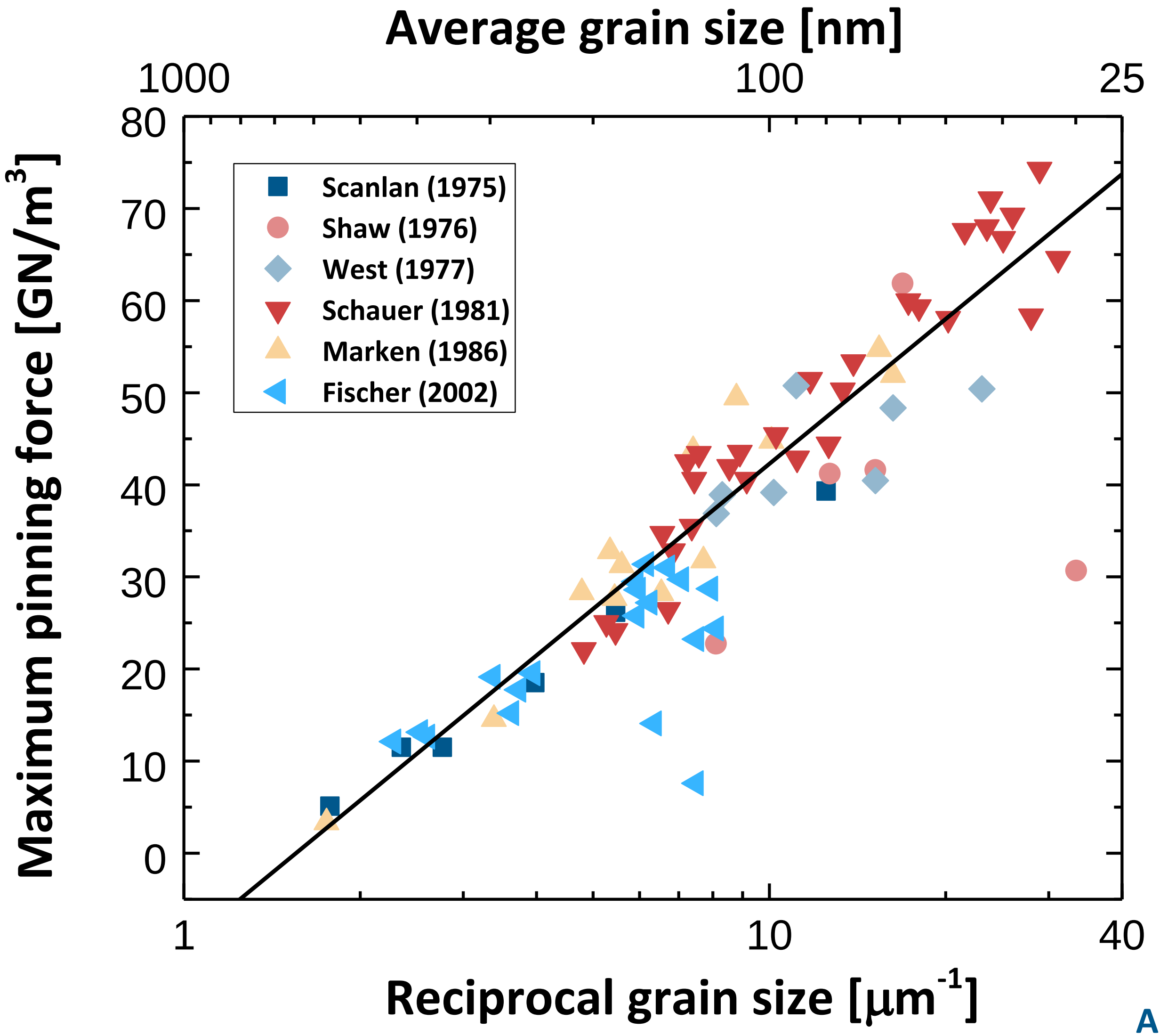
**Ta substitutes both Nb and Sn**

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

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

# Vortex pinning at the grain boundaries in $Nb_3Sn$

## Grain boundaries impede vortex motion to increase $J_c$

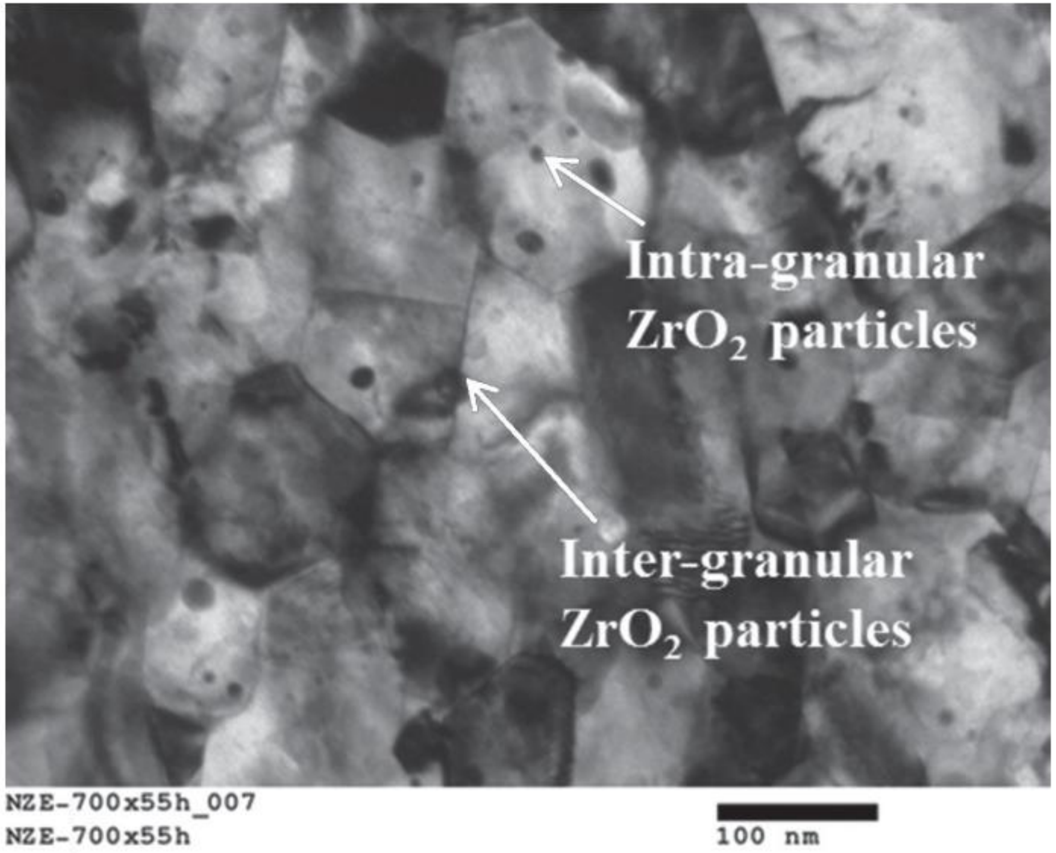


Adapted from A. Godeke, SUST 19 (2006) R68

# Artificial pinning in $Nb_3Sn$

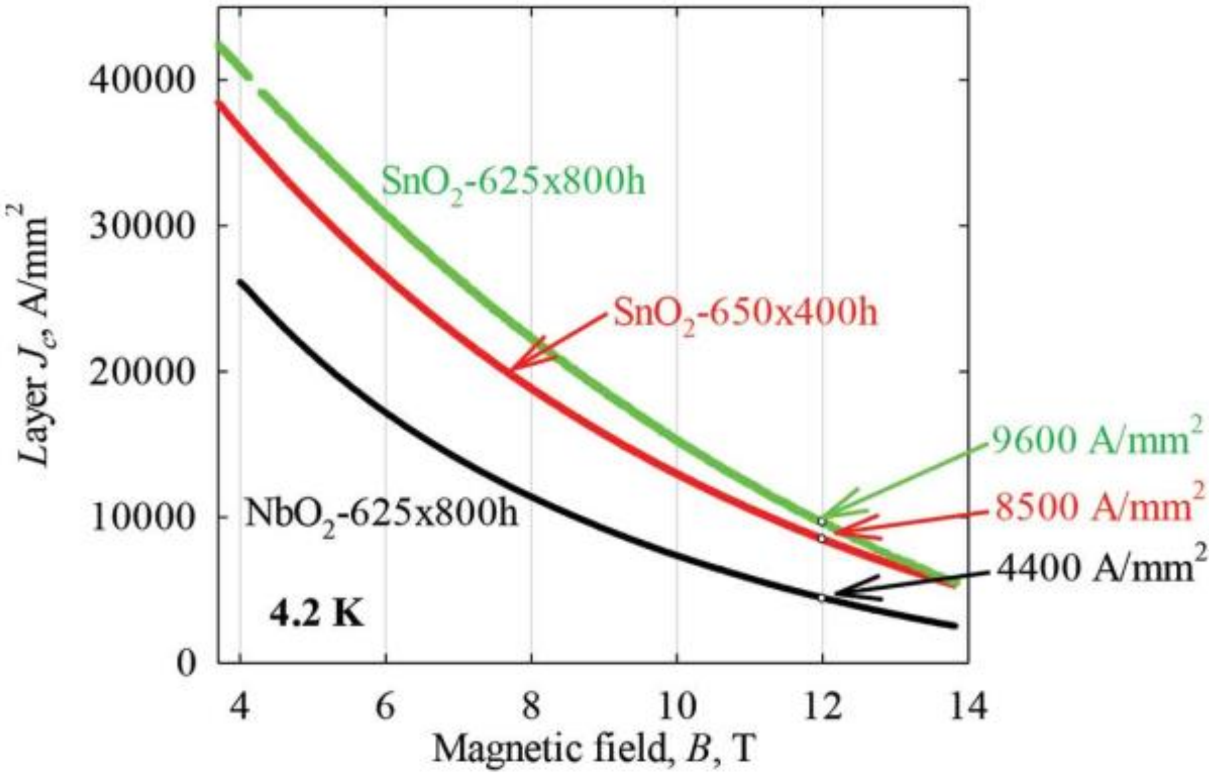
Introduction of $ZrO_2$ nanoparticles

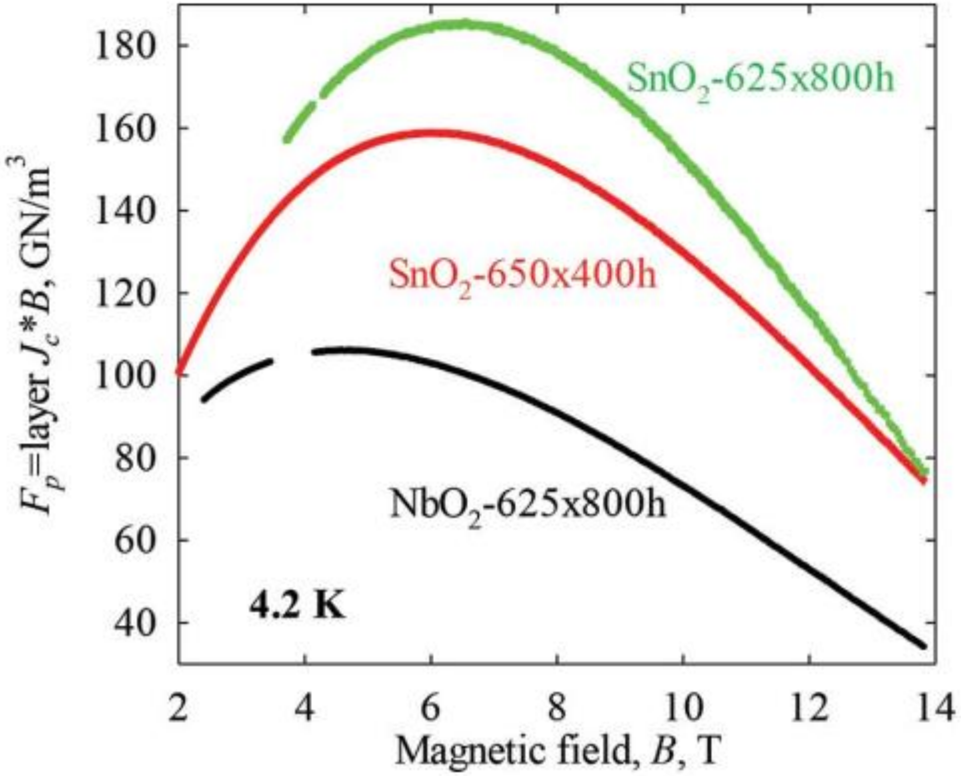
- Alloy Zr to Nb
- Add an oxygen source (e.g. $NbO_2$ or $SnO_2$)
- $ZrO_2$ forms during heat treatment („internal oxidation“)



Xu et al, *Adv. Mat*. **27** (2015) 1346

# Artificial pinning in $Nb_3Sn$





$J_c$ increases due to both a grain refinement and pinning on nanoparticles.

Not commercially available yet.

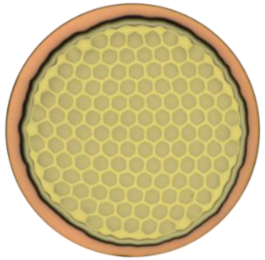
Xu et al, *Adv. Mat*. **27** (2015) 1346

# $Nb_3Sn$

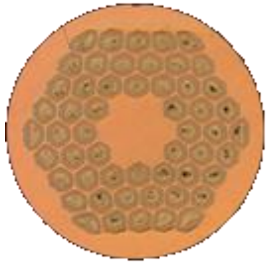
## Production routes

# *Industrial fabrication of $Nb_3Sn$ wires*

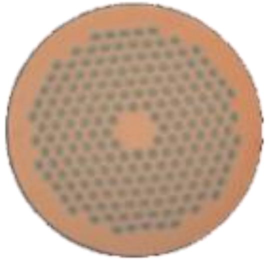
## *Three technologies have been developed at industrial scale*



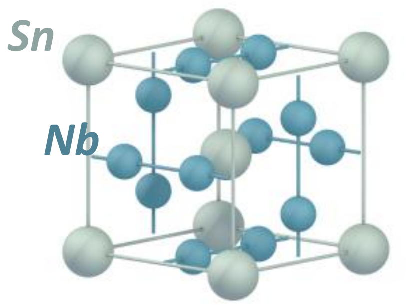
- ***Bronze route***



- ***Internal Sn diffusion***



- ***Powder-In-Tube (PIT)***

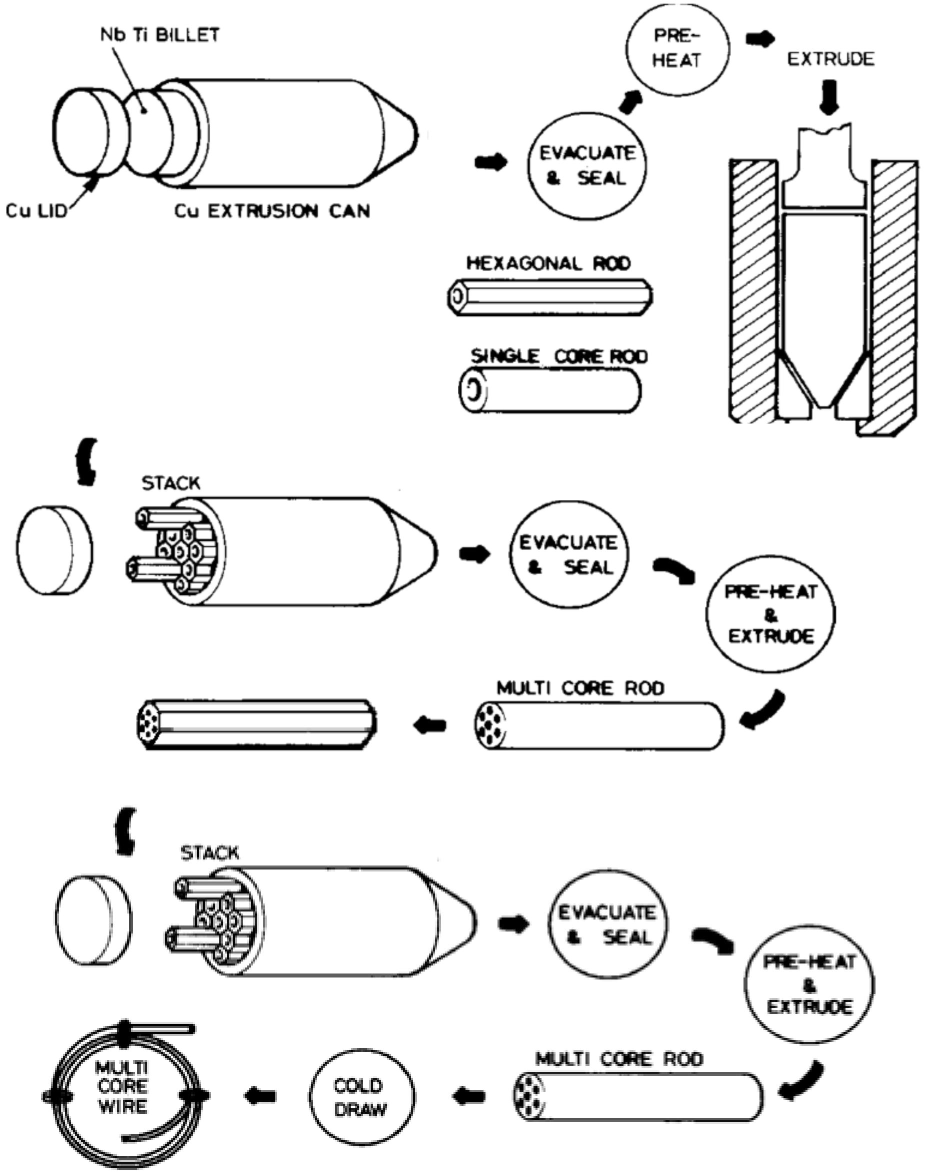


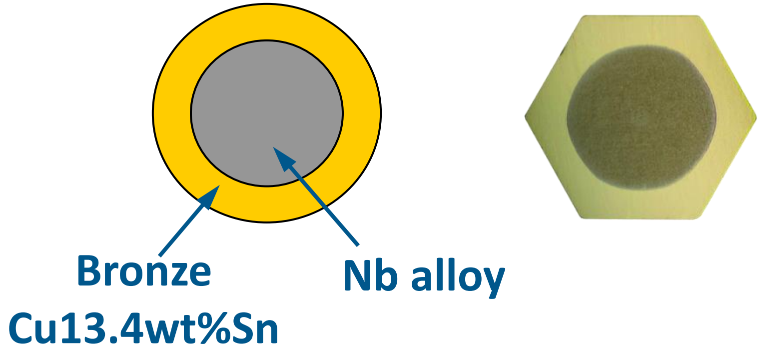
***The Sn source is the main difference***

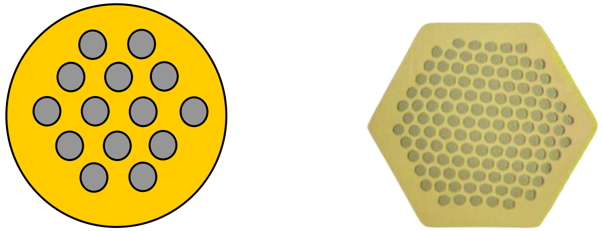
*Presently produced by* BRUKER LUVATA Western Superconducting Technologies Co.,Ltd.

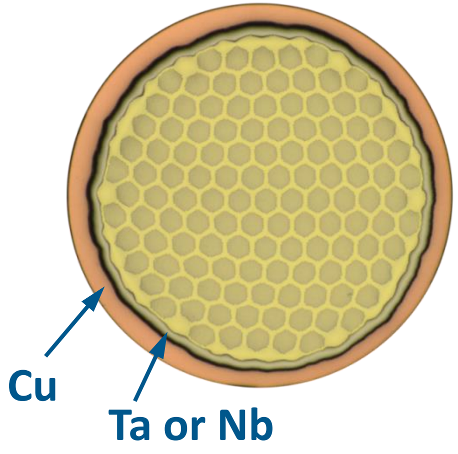
BOCHVAR INSTITUTE OF INORGANIC MATERIALS JSC VNIINM Kiswire KOBELCO KOBE STEEL, LTD. JASTEC SUPERCONDUCTOR

# The Bronze Process for multifilamentary $Nb_3Sn$ wires







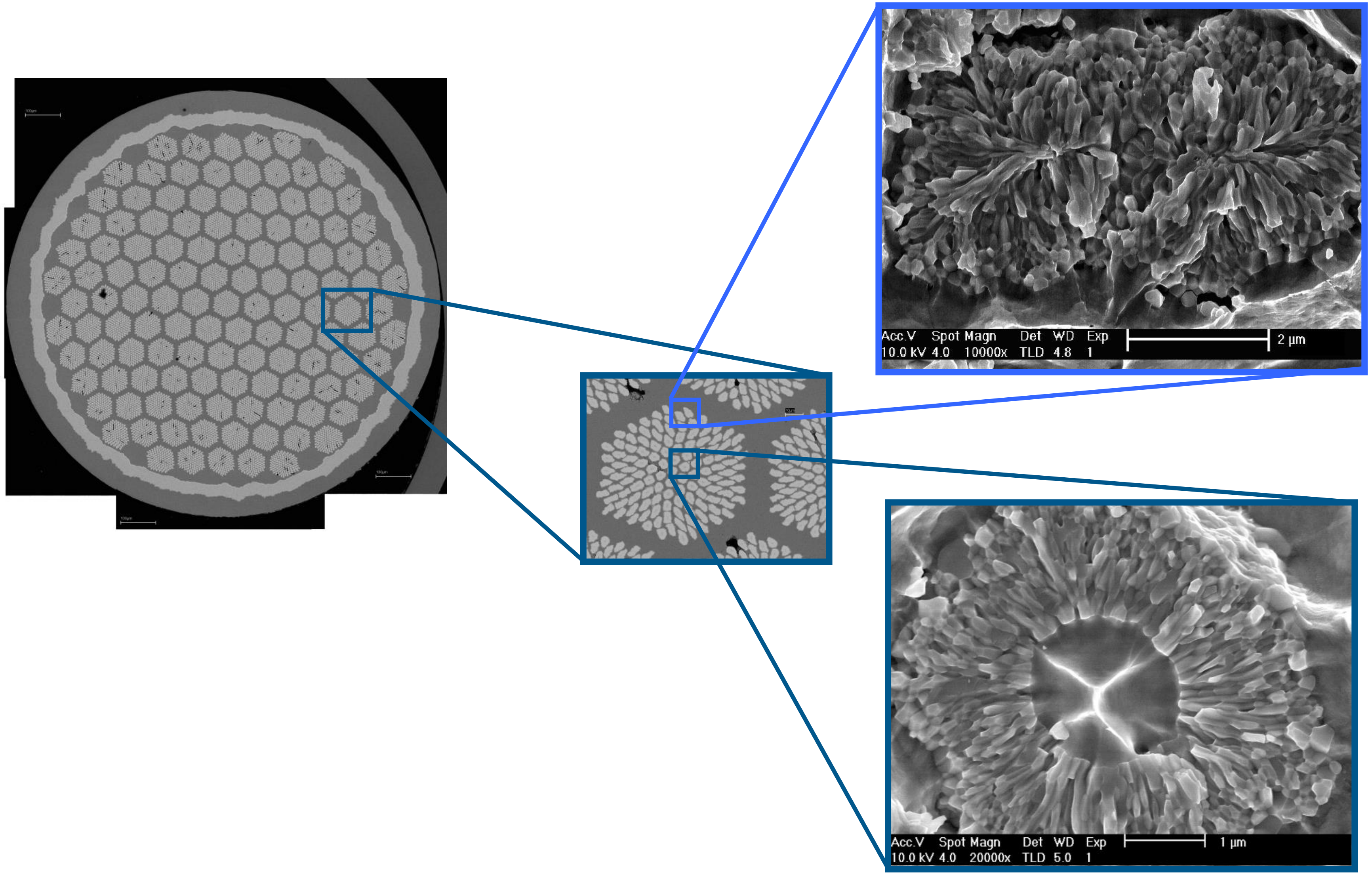


Cu-Sn bronze is used as Sn source

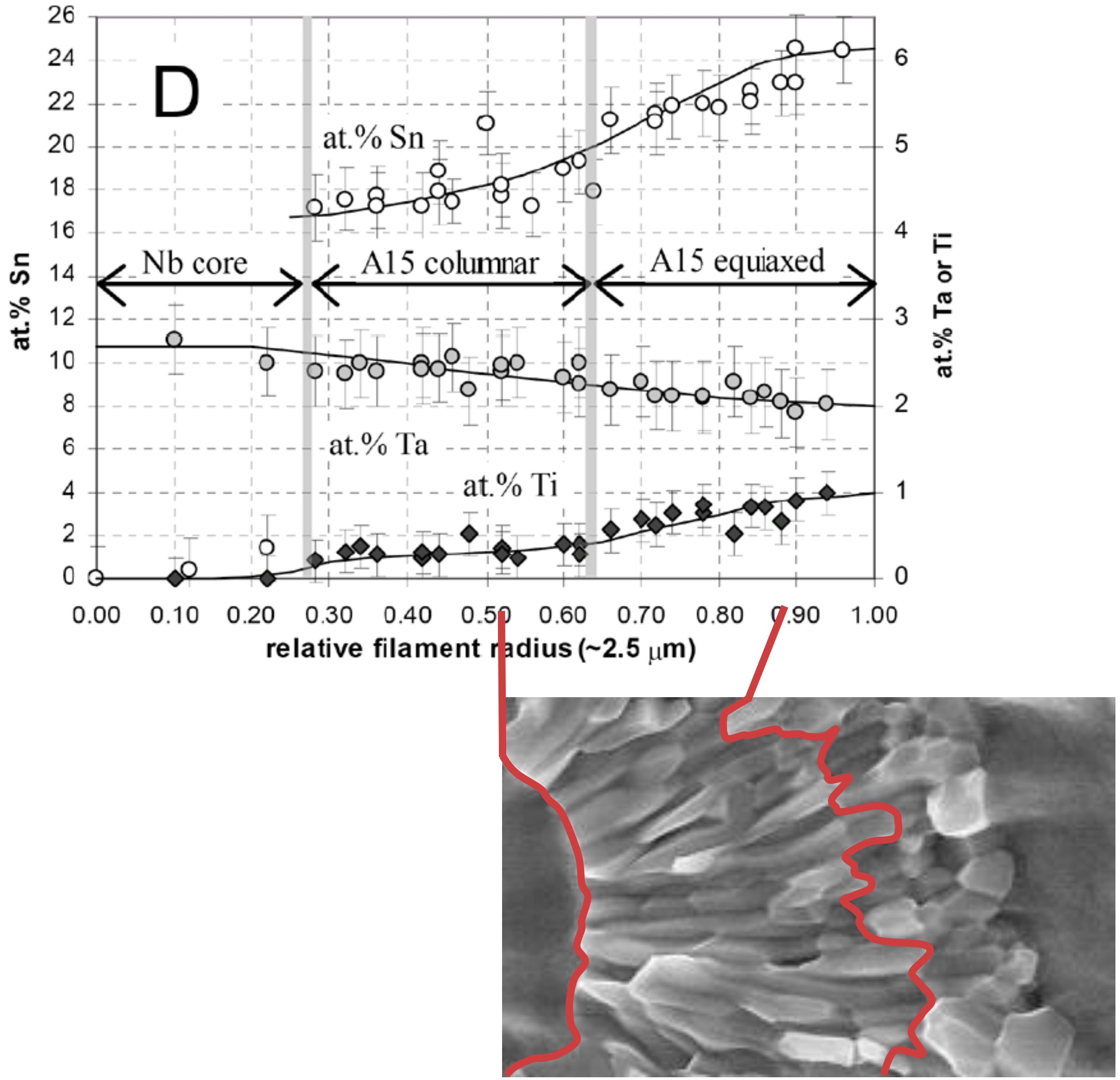
The final filament size is ~5 µm

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

# Bronze Route $Nb_3Sn$ wires, after reaction



# Sn gradient over the filament radius: Bronze Route



Correlation between Sn content and grain morphology

Equiaxed grains: 21-25 at.% Sn

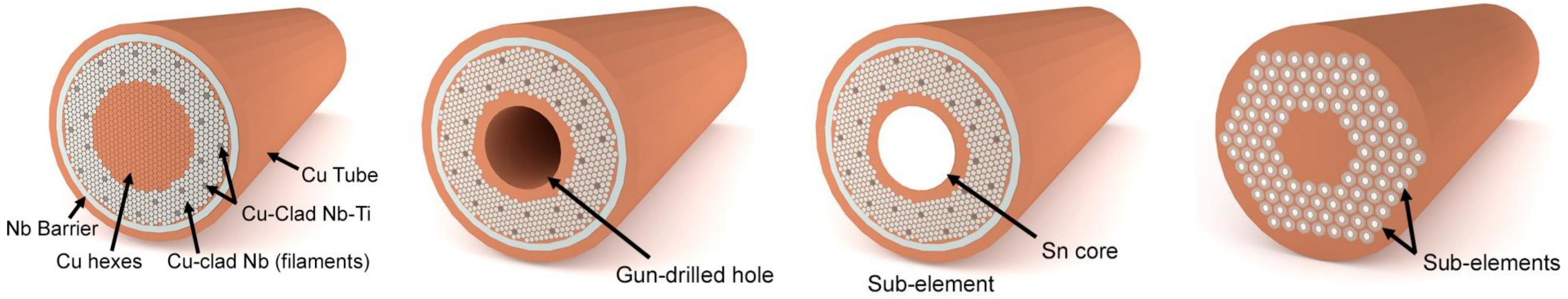
Columnar grains: 18-21 at.%

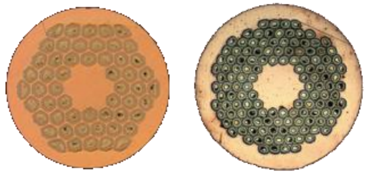
Equiaxed grain size ~150 nm

Columnar grain size up to 400 nm

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

# The Internal Sn diffusion process

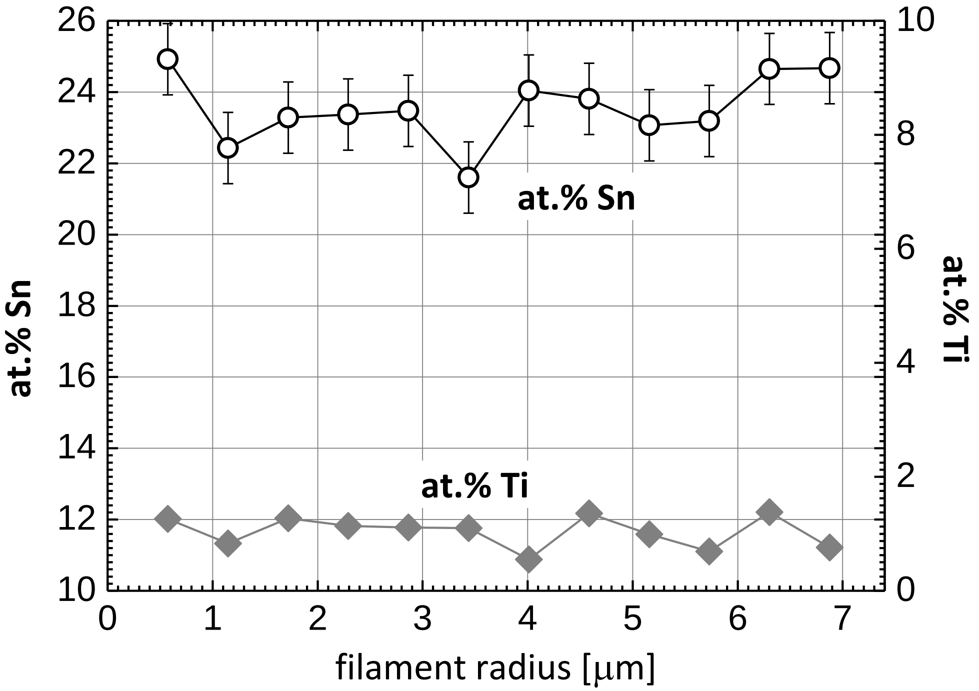




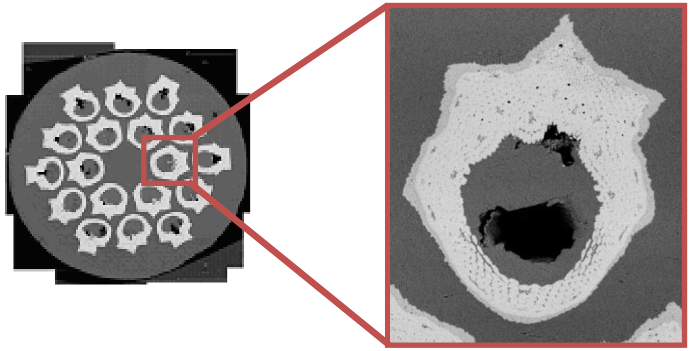
- A Sn rod is inserted in the subelement core
- After the insertion of Sn, only cold deformations are possible
- Subelement size ranges between 20 and 100 µm
- A long-duration multistep reaction schedule is required to form $Nb_3Sn$

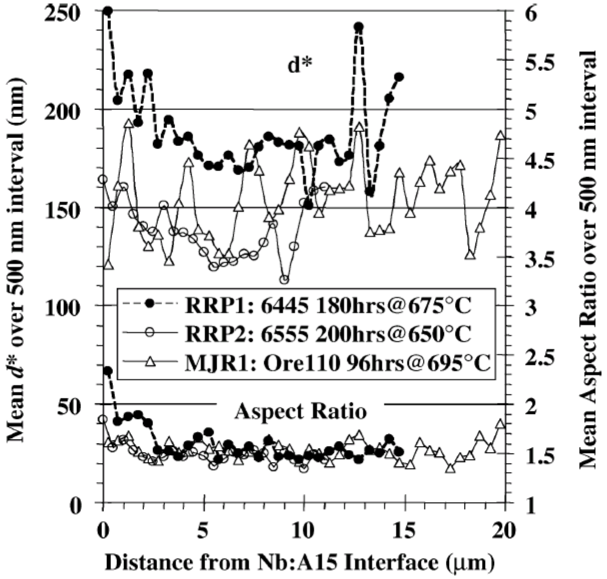
Pictures from [C. Sanabria, PhD Thesis (2017), FSU]

# Sn gradient across the filament radius: Internal Sn



D. Uglietti, PhD Thesis (2006), UNIGE

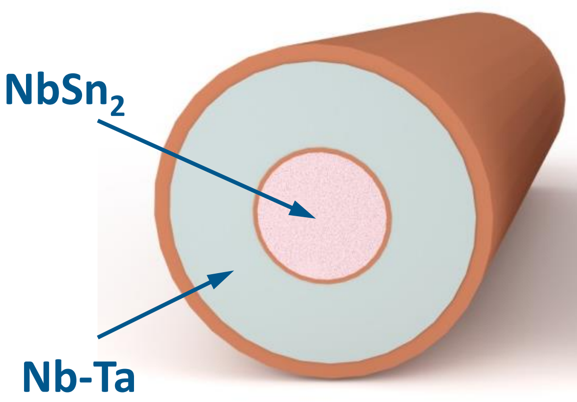




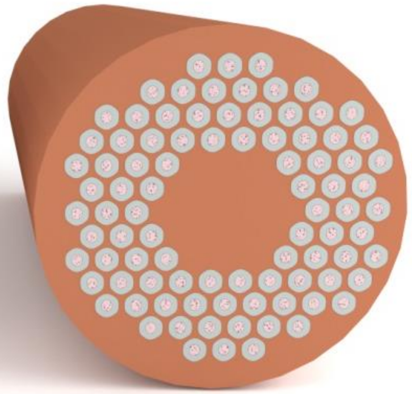
**All the grains are equiaxed and almost stoichiometric !!**

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

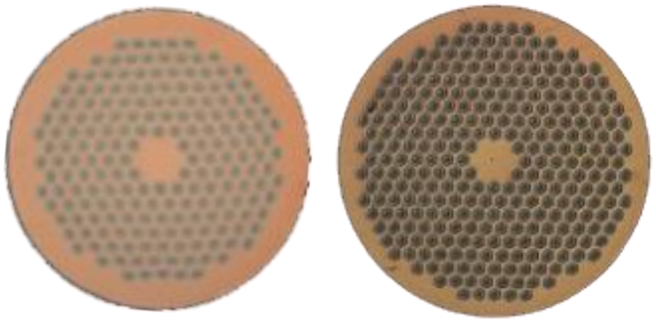
# The Powder-In-Tube method



Powder-in-Tube filament



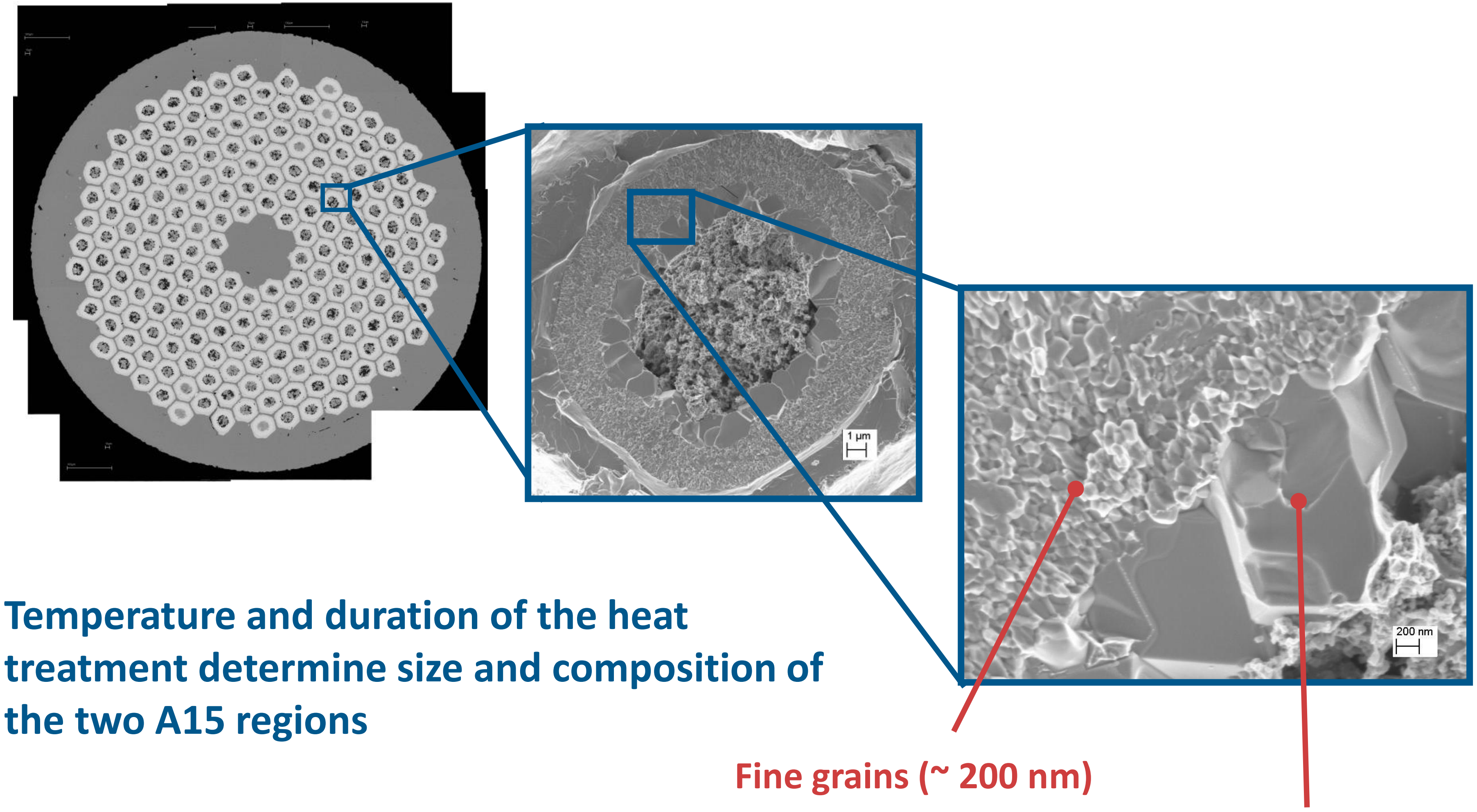
Powder-in-Tube stack



- $NbSn_2$ 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 (2017), FSU

# Formation and Microstructure of the A15 phases

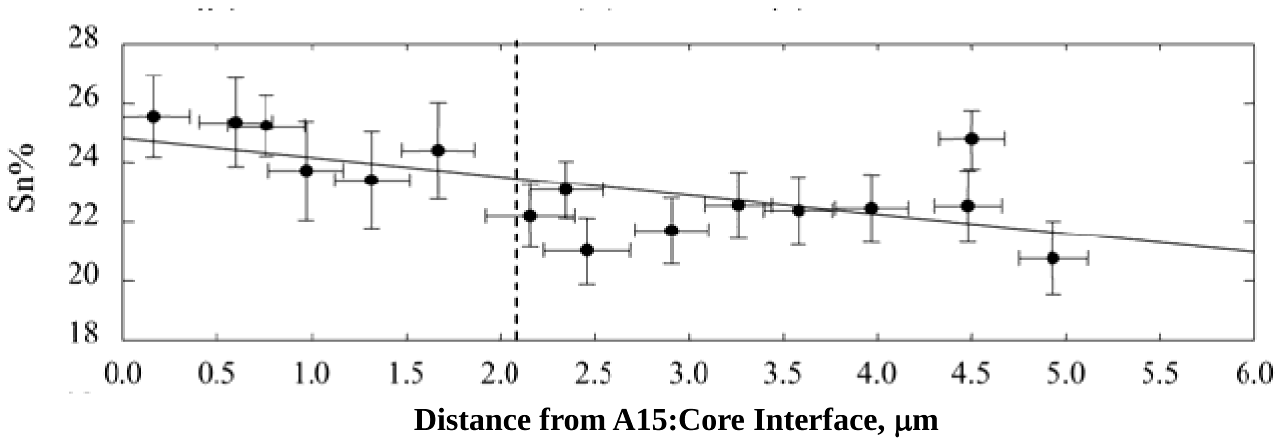


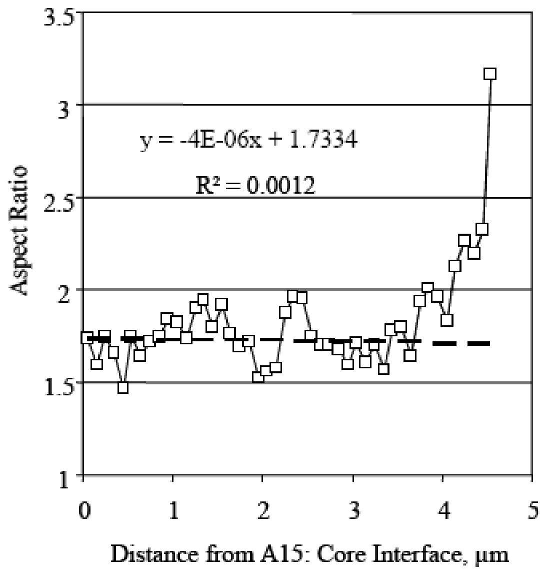
**Temperature and duration of the heat treatment determine size and composition of the two A15 regions**

Fine grains (~ 200 nm)
~ 23 at.% Sn

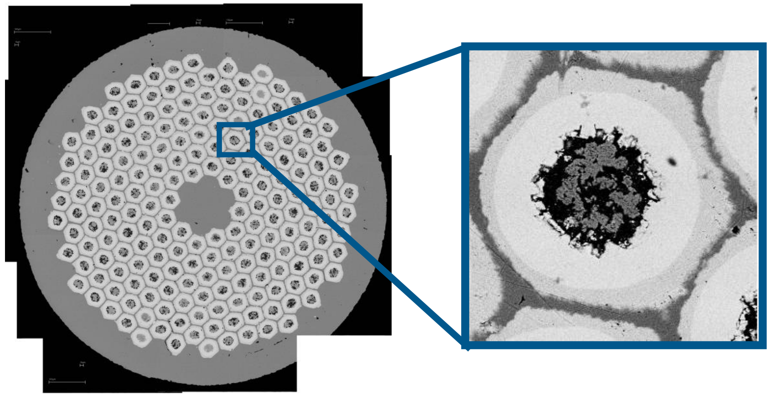
Large grains (> 1 µm)
~ 25 at.% Sn

# Sn gradient over the filament radius: PIT





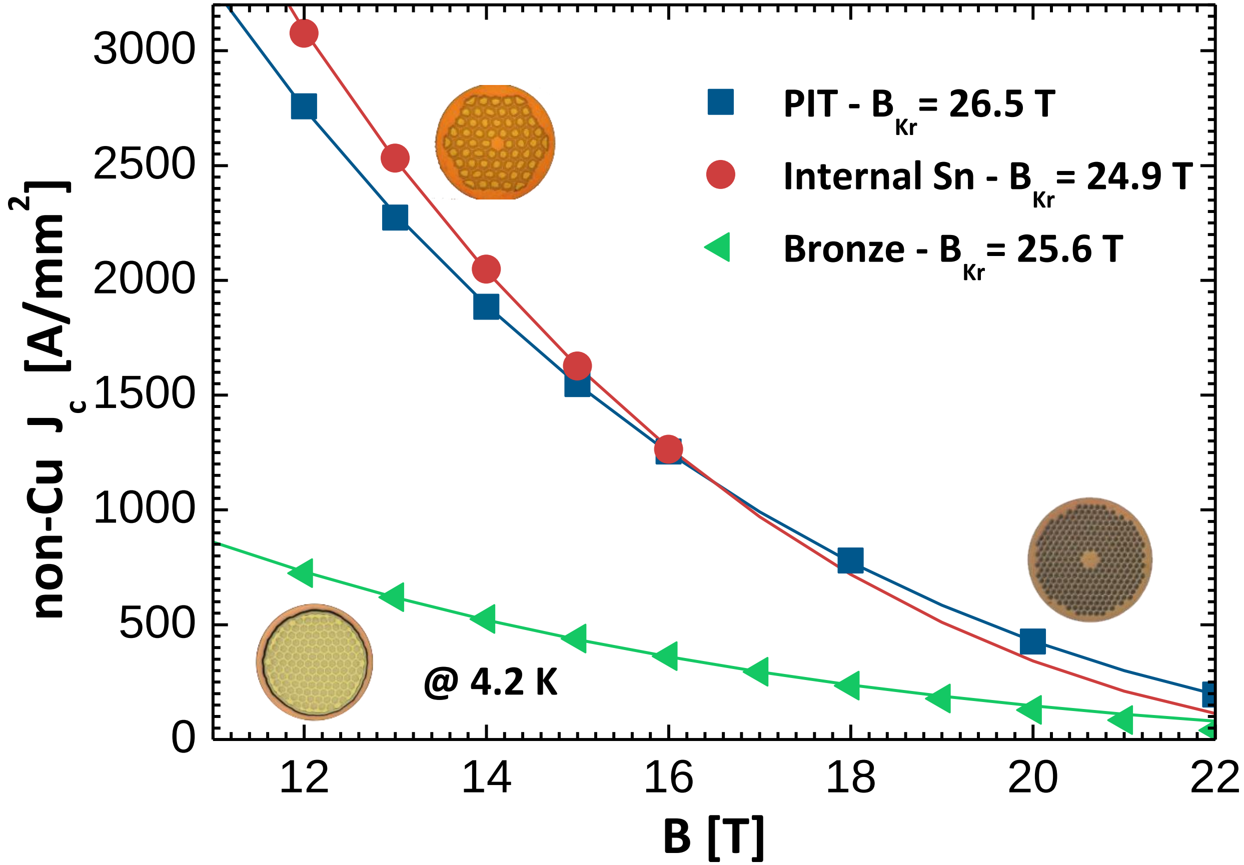
- Sn content decreases linearly along the filament radius
- Both fine and large grains are (almost) equiaxed



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]

# Nb3Sn

## It’s a hard life (stress and strain)

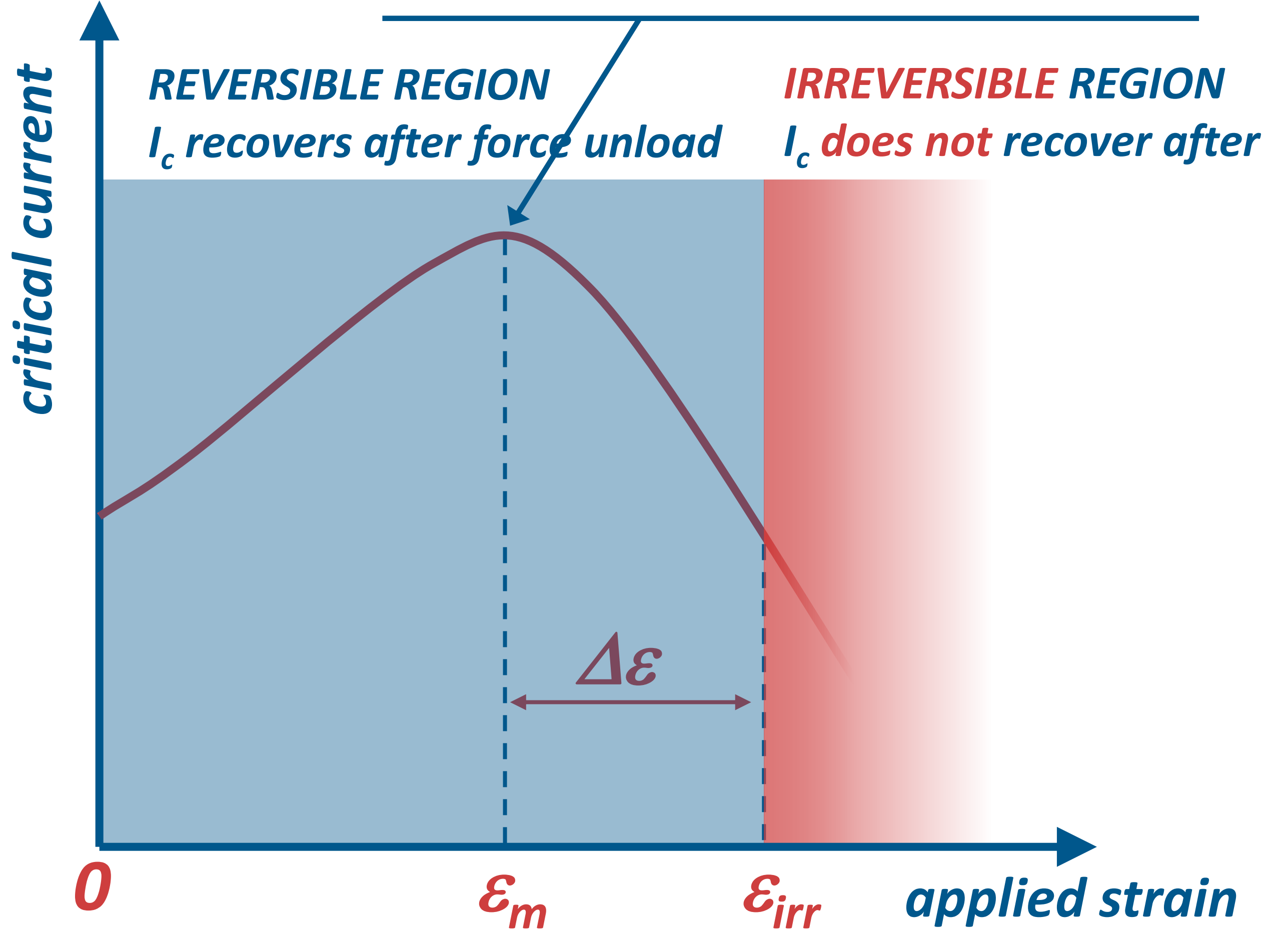
# Strain-induced changes in the critical current

## *Effects of the longitudinal strain*

*The applied force reduces the effects of the thermal precompression and the critical current increases up to a maximum*

**REVERSIBLE REGION**
*$I_c$ recovers after force unload*

**IRREVERSIBLE REGION**
*$I_c$ does not recover after force unload*

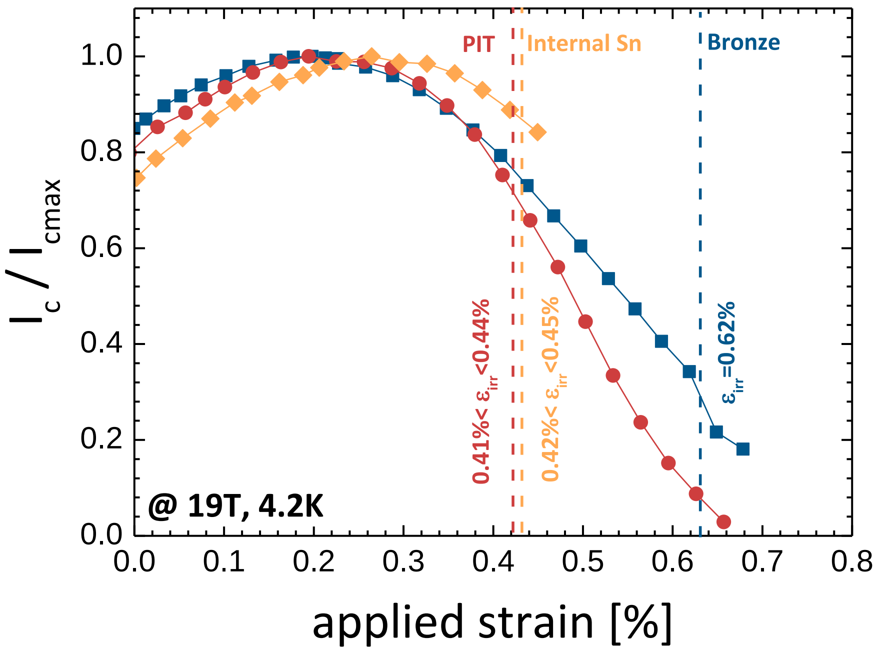


| Technology | $\Delta\varepsilon = \varepsilon_m - \varepsilon_{irr}$ [%] |
|---|---|
| *Bronze Route* | 0.4 – 0.6 |
| *Internal Sn* | 0.05 – 0.2 |
| *Powder-In-Tube* | 0.15 – 0.3 |

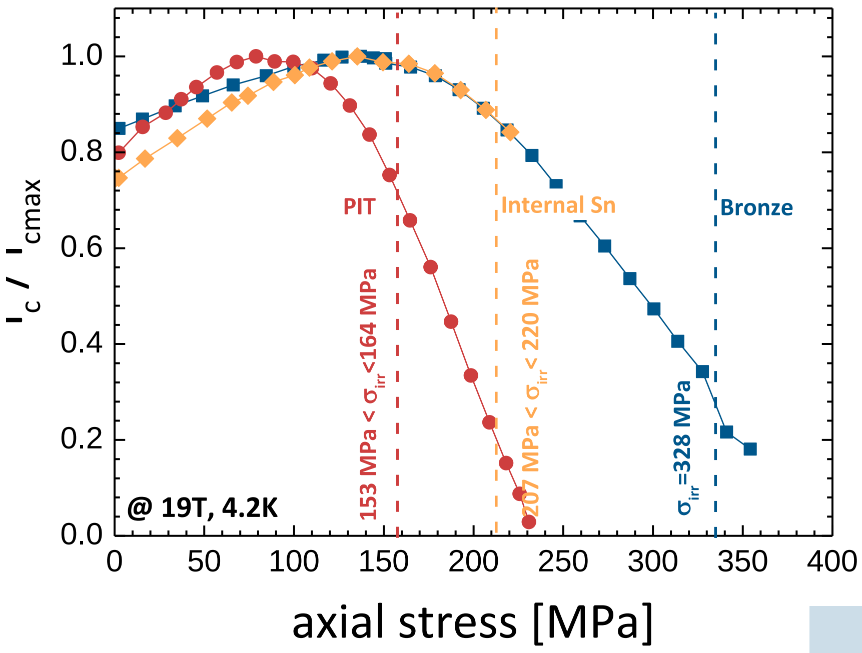
# Bronze Route, Internal Sn and PIT

## Reversible behaviour and irreversible limit

### $I_c$ vs. axial strain

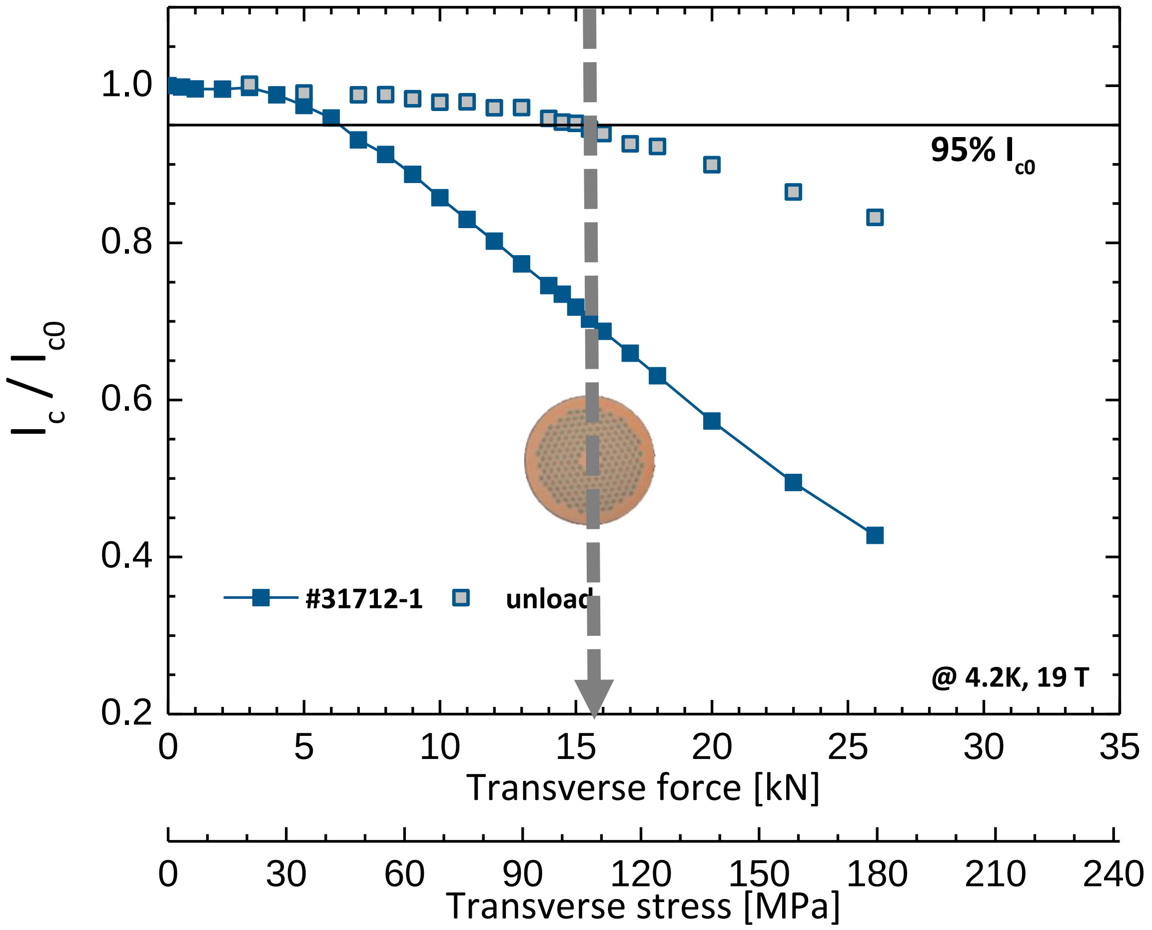


### $I_c$ vs. axial stress



| *Technology* | $\sigma_{irr}$ |
|---|---|
| *Bronze Route* | 330 MPa |
| *Internal Sn* | 210 MPa |
| *Powder-In-Tube* | 150 MPa |

# $I_c$ vs. transverse stress



***The irreversible limit is defined at the force level leading to a 95% recovery of the initial $I_c$ after unload***

***Here***

$$F_{irr} = 16\ \mathrm{kN}$$

***The corresponding irreversible stress limit is***

$$\sigma_{irr} = 110\ \mathrm{MPa}$$

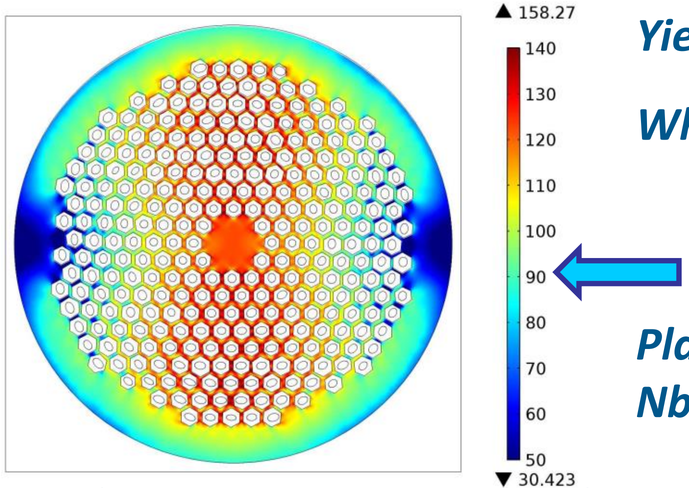
***where***

$$\mathit{Stress} = \frac{\mathit{Force}}{\mathit{groove\ length} \times \mathit{groove\ width}}$$

# *Irreversible degradation phenomena*

## *Two irreversible phenomena play together*

- ***Plastic deformation of the Cu matrix***



*PIT $Nb_3Sn$ wire under transverse load*
*Stress map of the Cu matrix*

***Yield strength of Cu $\sigma_y$~ 90 MPa***

***What is the residual stress on Cu after unload ?***

$$\sigma_{res}^{Cu} = \max(\sigma_{Mises}^{Cu} - \sigma_y , 0 )$$

***Plastically deformed Cu imposes a stress on $Nb_3Sn$ after force unload (= lattice deformation)***

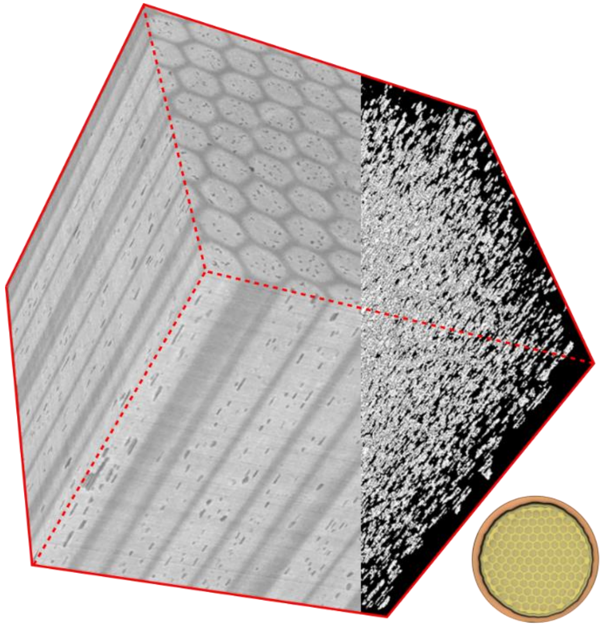
- ***Crack formation in $Nb_3Sn$***

***$Nb_3Sn$ is a brittle material and is characterized by a strong propensity to fracture***

***Voids formed during the reaction cause localized stress concentrations where cracks nucleate***

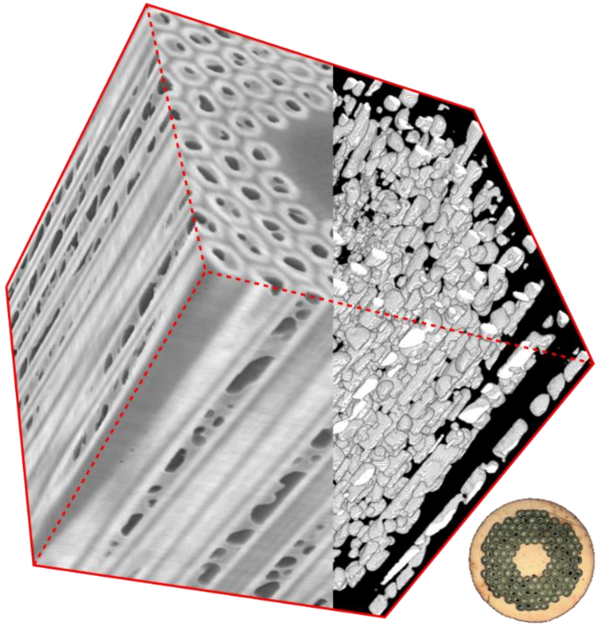
# *Voids in $Nb_3Sn$ wires*

*XRD microtomography reconstruction*



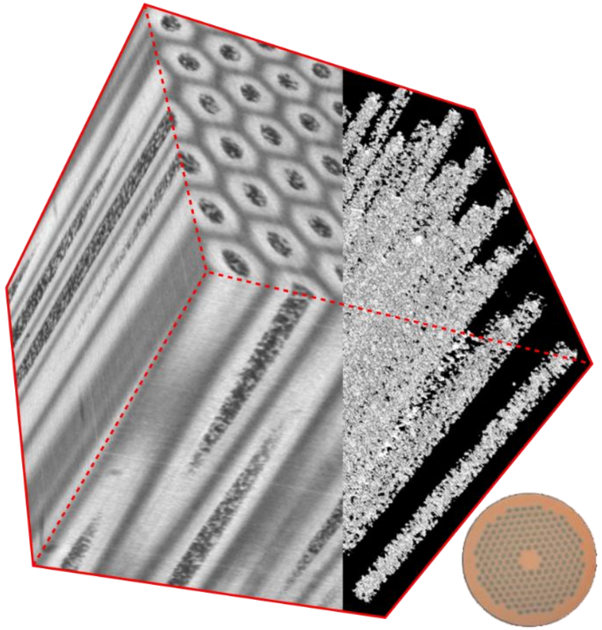
**Bronze Route**

*121 x 121 filaments*



**Internal Sn**

*132/169 subelements*

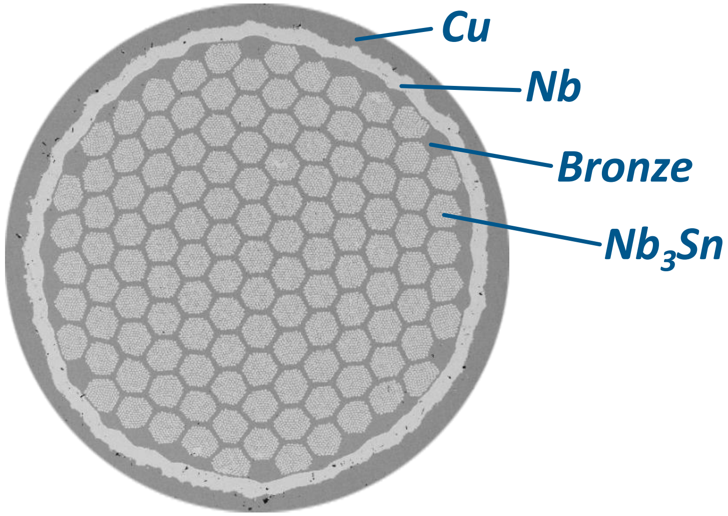


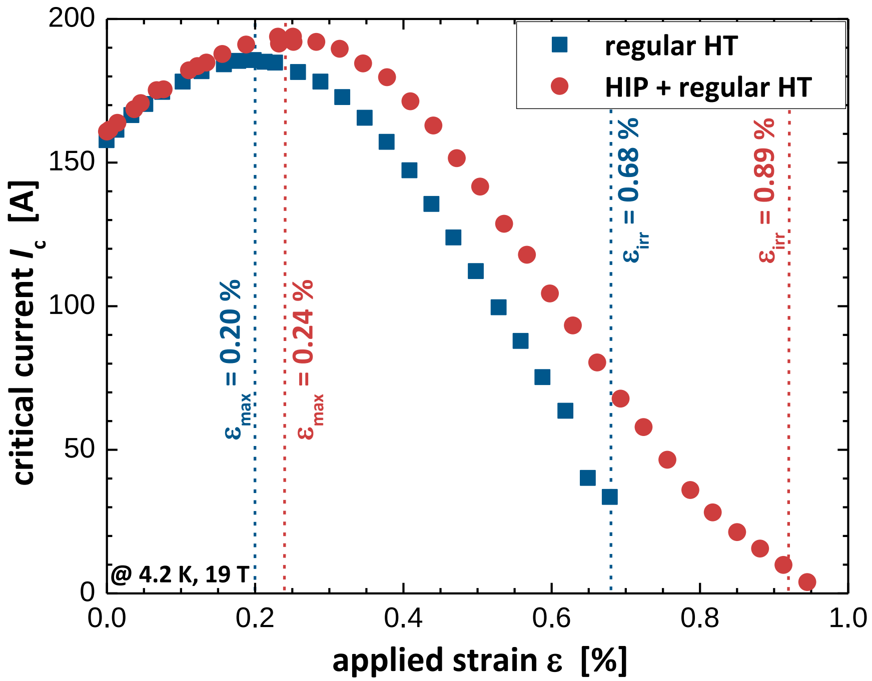
**PIT**

*192 filaments*

*Can we quantify the impact of voids on the electromechanical limits?*

# *A case study on Bronze Route $Nb_3Sn$ wires*





| | |
|---|---|
| *manufacturer* | UNIVERSITÉ DE GENÈVE<br>FACULTÉ DES SCIENCES |
| *wire diameter* | *1.25 mm* |
| *# of filaments* | *121 x 121* |
| *filament size* | *4.5 μm* |

***Regular HT: 600°C/100h + 670°/150h***

$\varepsilon_c = \varepsilon_{irr} - \varepsilon_{max} = 0.48\ \%$

***HIP 550°C/1h/200MPa + Regular HT***

$\varepsilon_c = \varepsilon_{irr} - \varepsilon_{max} = 0.65\ \%$

***With HIP treatment $\varepsilon_c$ increases by +0.17 %***

# Summary

- A superconducting wire for magnet application should consist of tiny twisted filaments in a highly conductive matrix.
- NbTi is close to an ideal superconductor if cooling is not an issue and the magnetic field remains below about 8 T
- $Nb_3Sn$ is the actual LTS high field conductor
  - It is brittle (wind and react)
  - It has to be produced in-situ
    - Imperfect, inhomogeneous microstructure
    - Stoichiometry issues
    - Voids increase the strain sensitivity
  - Strain is a crucial parameter for the design of superconducting magnets

# Bibliography

Rogalla & Kes
100 Years of Superconductivity
Chapter 3 Section 7
Chapter 11 Section 2 (Nb-Ti)
Section 3 ($Nb_3Sn$)

Poole, Farach, Creswick, Prozorov
Superconductivity (2nd edition)
Chapter 3

Papers cited in the slides