UNIVERSITÉ DE GENÈVE
FACULTÉ DES SCIENCES

CERN

ESRF The European Synchrotron

LNCMI

PSI

Swiss National Science Foundation

Nb_3Sn advanced pinning technology for FCC-hh and other high field projects

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HFM High Field Magnets

CHART Swiss Accelerator Research and Technology

Outline

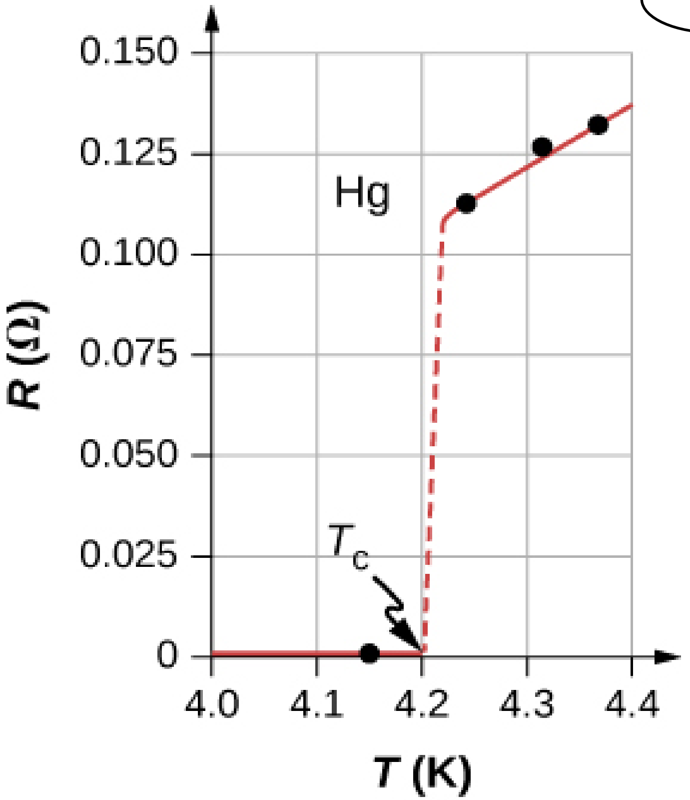
- *A brief history of Nb_3Sn*
- *From bronze to internal Sn wires: the multifilamentary wires age*
- *J_c and B_{c2} are essential, yet not sufficient for applications*
- *FCC-hh and the new challenges for Nb_3Sn*

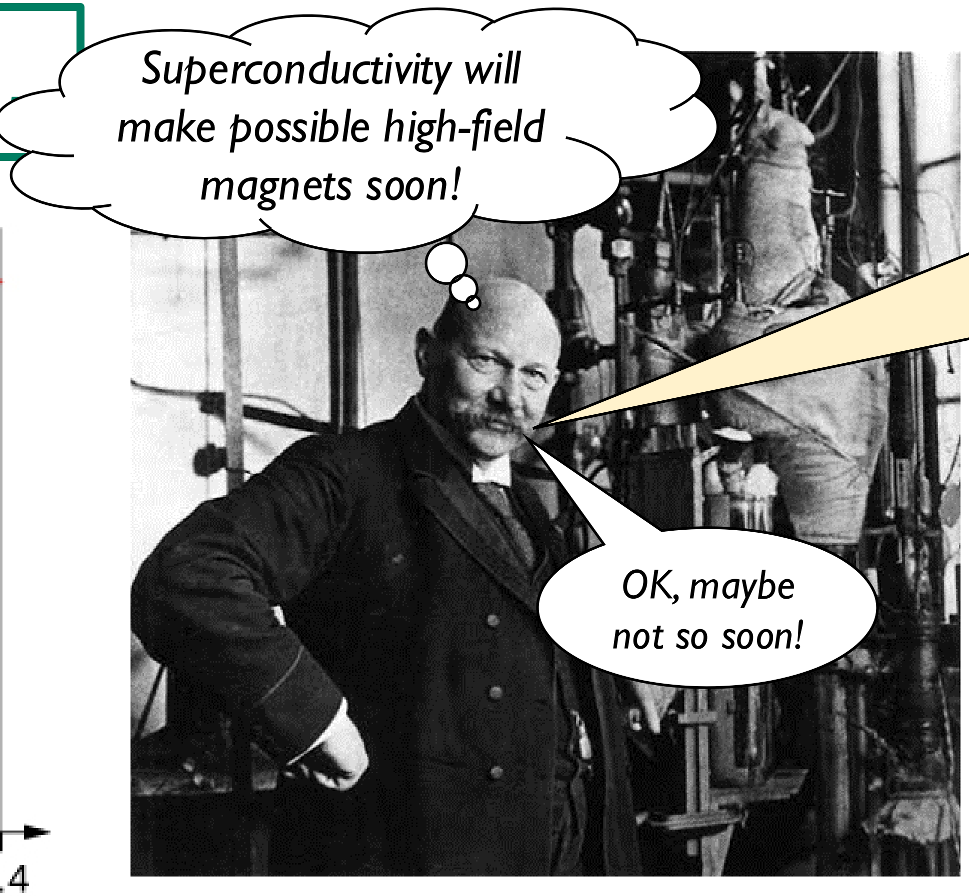
Outline

- *A brief history of Nb_3Sn*
- *From bronze to internal Sn wires: the multifilamentary wires age*
- *J_c and B_{c2} are essential, yet not sufficient for applications*
- *FCC-hh and the new challenges for Nb_3Sn*

Discovery of superconductivity

Discovery of superconductivity in 19





Heike Kamerlingh Onnes

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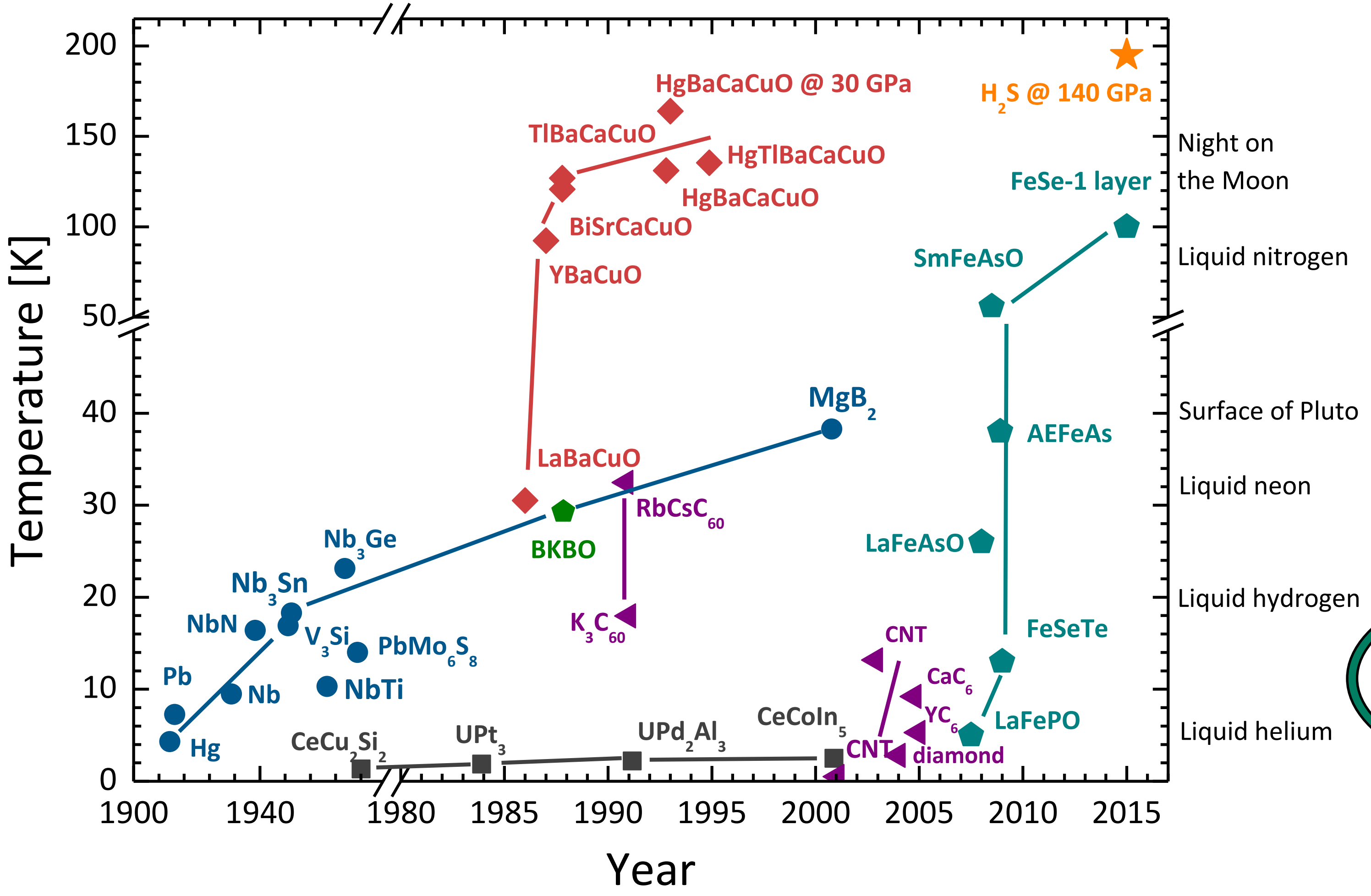
TABLE I. Critical constants for superconducting mercury.

Sample	T_c (°K)	H_0 (gauss)	γ millijoules/mole°K²
Hg-1	4.1535±0.000	415.4+0.5, −1.5	.103+0.01, −0.04
Hg-3	4.153 ±0.001	415.1±0.5	.088±0.01
Hg-4	4.1531±0.000	414.9+0.5, −1.5	.108+0.01, −0.04
Hg-5	4.1532±0.0005	414.4±0.4	2.079±0.01

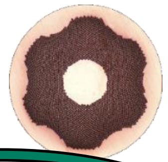
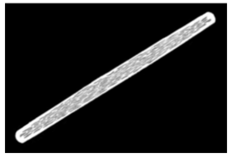
M. Wilson *IEEE TAS* (2012) 22 3800212
D. K. Finnemore *et al. Physical Review* (1960) 1181

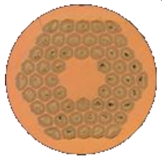
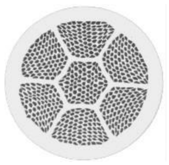
Superconductors are not created equal



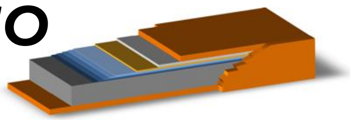
❑ *Have a T_c?*	***>10000***
❑ *T_c > 4.2 K, B_{c2} > 10 T?*	***100***
❑ *High J_c?*	***10***

LTS ***HTS***

NbTi

Bi2223


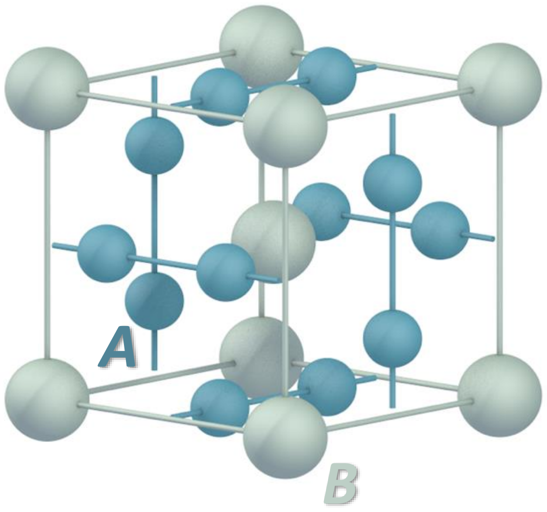
Nb_3Sn

Bi2212


MgB_2

YBCO


A15 compounds

Nb_3Ge held the record for the highest T_c (23.2 K) until 1986

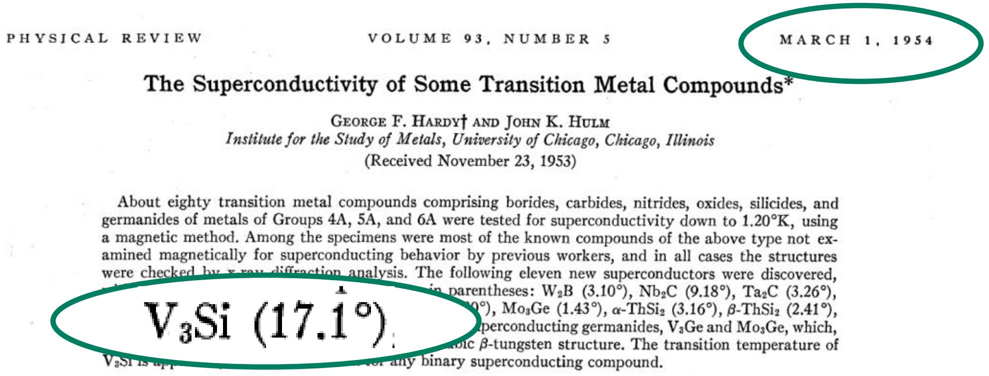


The name originates from Strukturbericht notation with chemical formula A_3B

More than 50 superconductors, 10 of them with $T_c \geq 15$ K

V_3Ga, Nb_3Sn and Nb_3Al can be produced as practical conductors

V_3Si is the earliest example, T_c = 17.1 K (Hardy, 1954)



PHYSICAL REVIEW VOLUME 93, NUMBER 5 MARCH 1, 1954

The Superconductivity of Some Transition Metal Compounds*

GEORGE F. HARDY† AND JOHN K. HULM
Institute for the Study of Metals, University of Chicago, Chicago, Illinois
(Received November 23, 1953)

About eighty transition metal compounds comprising borides, carbides, nitrides, oxides, silicides, and germanides of metals of Groups 4A, 5A, and 6A were tested for superconductivity down to 1.20°K, using a magnetic method. Among the specimens were most of the known compounds of the above type not examined magnetically for superconducting behavior by previous workers, and in all cases the structures were checked by x-ray diffraction analysis. The following eleven new superconductors were discovered, ... in parentheses: W_2B (3.10°), Nb_2C (9.18°), Ta_2C (3.26°), ...°), Mo_3Ge (1.43°), α-$ThSi_2$ (3.16°), β-$ThSi_2$ (2.41°), ... superconducting germanides, V_3Ge and Mo_3Ge, which, ... cubic β-tungsten structure. The transition temperature of V_3Si is ... for any binary superconducting compound.

V_3Si (17.1°)

	Ti	Zr	V	Nb	Ta	Cr	Mo
Al			11.8 K	18.8 K			0.6 K
Ga			16.8 K	20.3 K			0.8 K
In			13.9 K	9.2 K			
Tl				9.0 K			
Si			17.1 K	19.0 K			1.7 K
Ge			11.2 K	23.2 K	8.0 K	1.2 K	1.8 K
Sn	5.8 K	0.9 K	7.0 K	18.0 K	8.4 K		
Pb		0.8 K		8.0 K	17.0 K		
As			0.2 K				
Sb	5.8 K		0.8 K	2.2 K			
Bi		3.4 K		4.5 K			
Tc							15.0 K
Re							15.0 K
Ru						3.4 K	10.6 K
Os			5.7 K	1.1 K		4.7 K	12.7 K
Rh			1.0 K	2.6 K	10.0 K	0.3 K	
Ir	5.4 K		1.7 K	3.2 K	6.6 K	0.8 K	9.6 K
Pd			0.08 K				
Pt	0.5 K		3.7 K	10.9 K	0.4 K		8.8 K
Au		0.9 K	3.2 K	11.5 K	16.0 K		

Nb_3Sn: an old material still to be unraveled

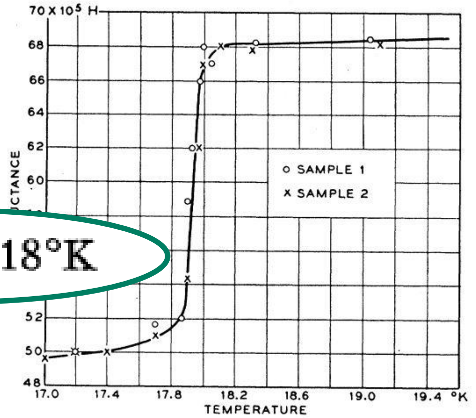
Nb_3Sn came 6 month after V_3Si, T_c = 18 K (Matthias, 1954)

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.



Nb_3Sn at 18°K

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

VOLUME 6, NUMBER 3 PHYSICAL REVIEW LETTERS FEBRUARY 1, 1961

SUPERCONDUCTIVITY IN Nb_3Sn AT HIGH CURRENT DENSITY IN A MAGNETIC FIELD OF 88 kgauss

J. E. Kunzler, E. Buehler, F. S. L. Hsu, and J. H. Wernick
Bell Telephone Laboratories, Murray Hill, New Jersey
(Received January 9, 1961)

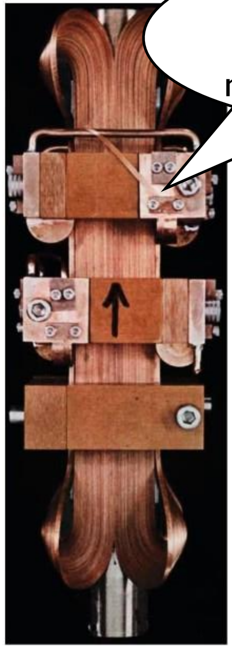
… and Nb_3Sn exhibited very high in-field J_c (Kunzler, 1961)

exceeding 100 000 amperes/cm² in magnetic fields as large as 88 kgauss.

B.T. Matthias *et al. Physical Review* (1954) 95.6 1435
J. E. Kunzel *et al. Physical Review Letters* (1961) 6.3

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

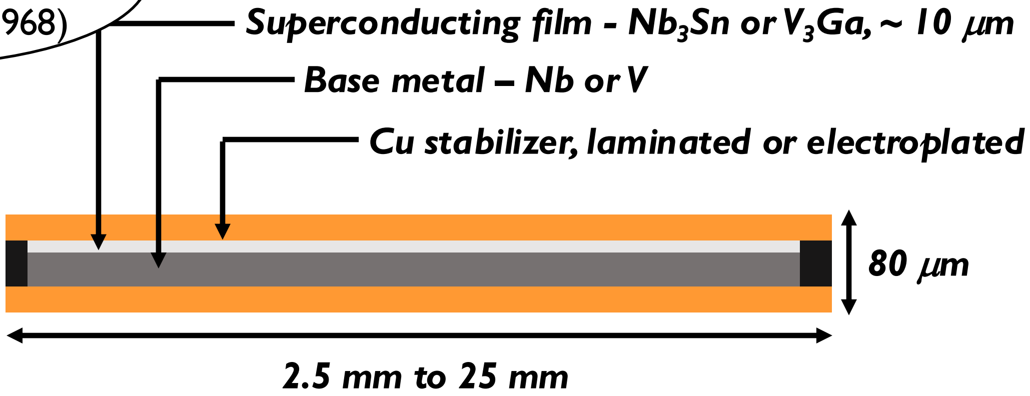
Nb_3Sn: the first high field Nb_3Sn magnet

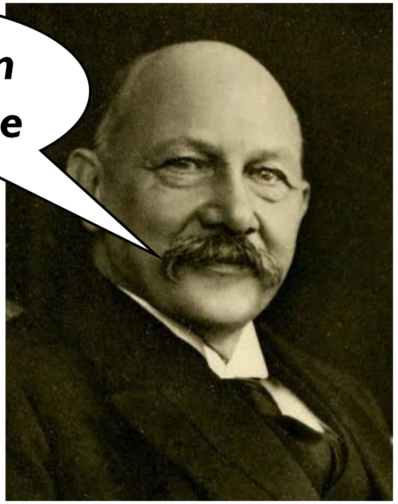


Magnet, fabricated and tested by: L. Martin, C. Bruch, M. Benz and C. Rosner (left to right)

Worked only ONCE!

Nb_3Sn coated conductors (!!)





Liquid Diffusion Process:

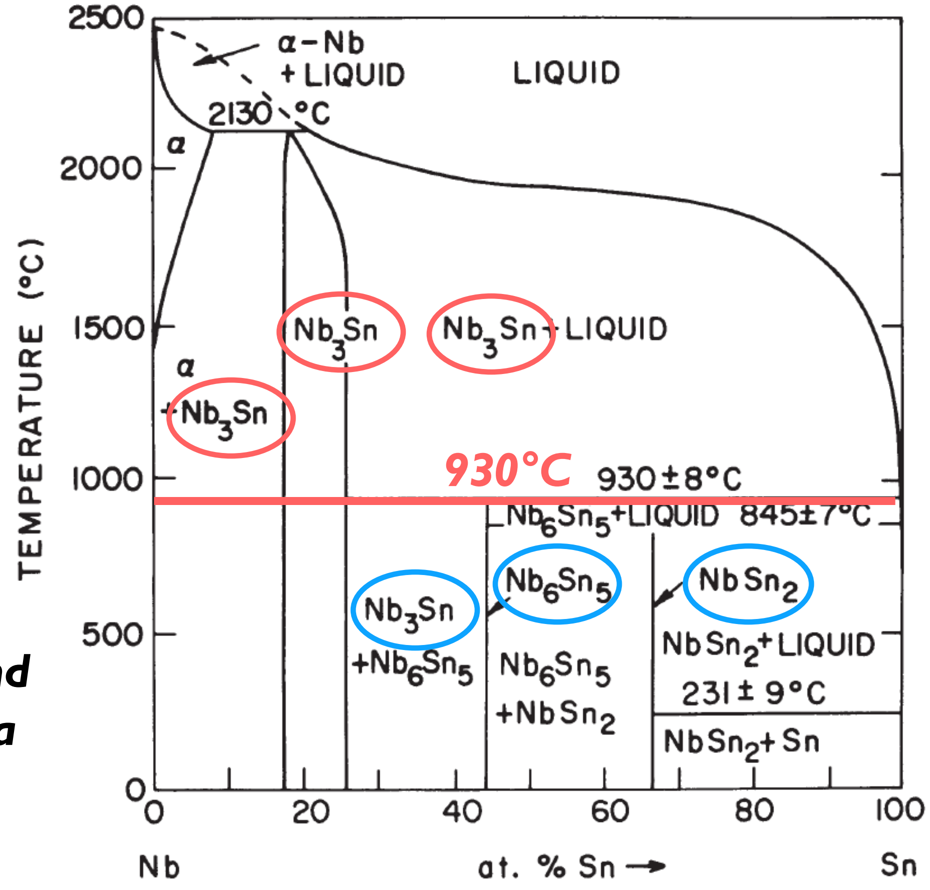
***Nb ribbon* coated with *Sn* and heat treated at 900-1200°C for several hours**

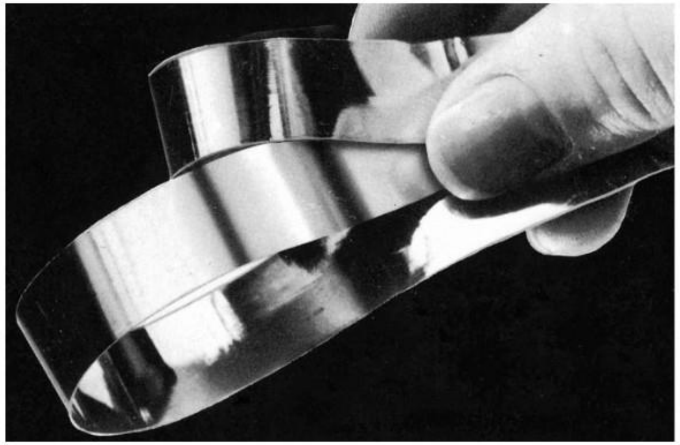
Developed at General Electric and used in 15 T-class R&W magnets

B.T. Matthias *et al. Physical Review* (1954) 95.6 1435
L. Rossi and A.V. Zlobin *Nb_3Sn Accelerator Magnets* (2019): 53
M. G. Benz *IEEE Trans. Mag*. (1966) 2 760
H. Rosner et al. *IEEE-CSC ESAS Eur. Supercond. News Forum*. No. 9. (2012)
E. Barzi and A.V. Zlobin *Nb_3Sn Wires and Cables for High-Field Accelerator Magnets* (2019)

Nb_3Sn: a complicated family

Nb_3Sn is the only stable compound above 930 °C



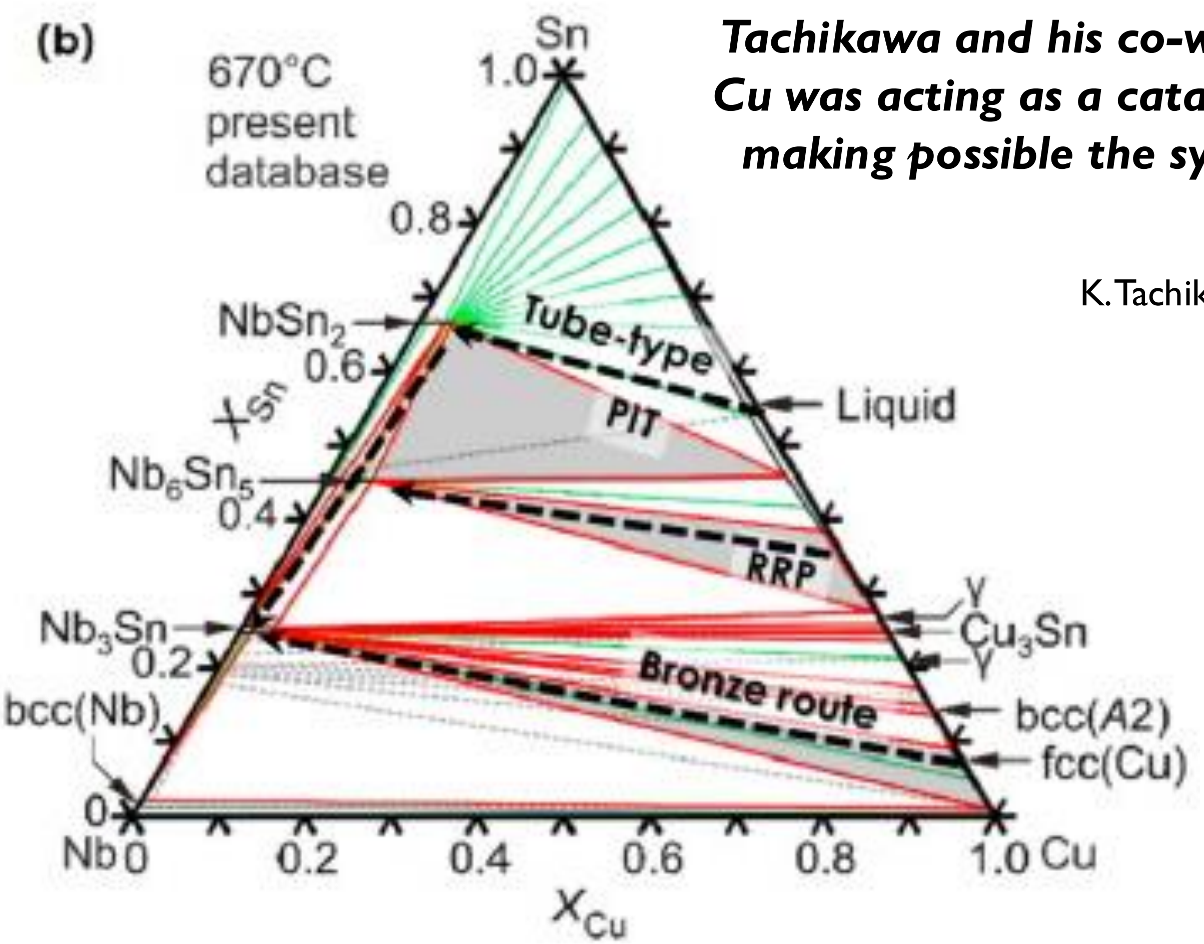


Below 930 °C also Nb_6Sn_5 and $NbSn_2$ are stable, and have a better kinetics of formation

The reaction of Nb and Sn to form Nb_3Sn needs to be performed at T > 930°C

D. P. Charlesworth et al., J. of Mat. Sci. (1970) 5 580

Not only Nb and Sn



Tachikawa and his co-workers at NRIM, Tokyo, discov
Cu was acting as a catalyst for the formation of the A15 phase,
making possible the synthesis of V_3Ga at lower temperatures

If it works for V_3Ga, why not trying in Nb_3Sn?

Prof. Kyoji TACHIKAWA

K. Tachikawa, Y. Tanaka and S. Fukuda, Japan Pat. 0670619 (Filed June 25, 1966)

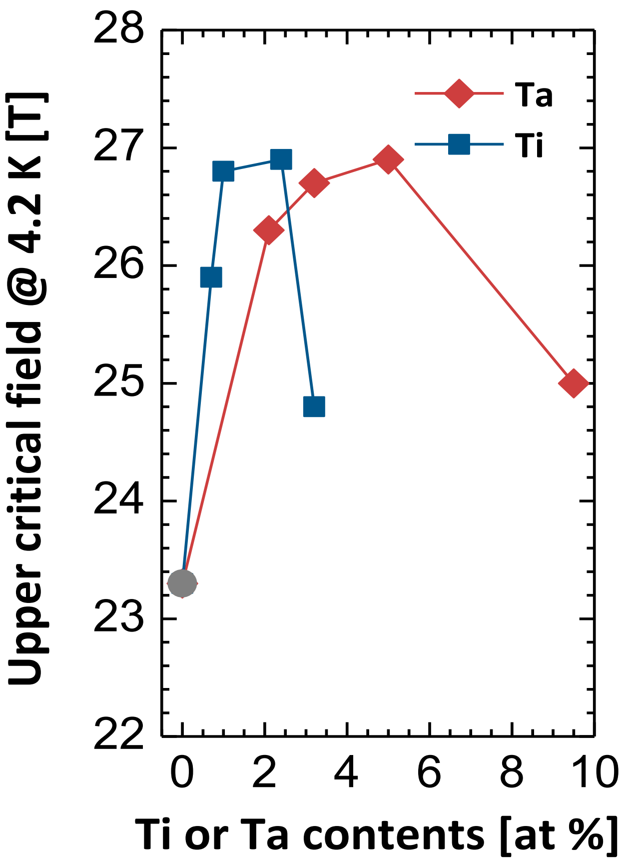
K. Tachikawa and Y. Tanaka, Jap. J. Applied Physics <u>6</u> (1967) 782

Researcher in UK and US came at the same conclusion almost at the same time

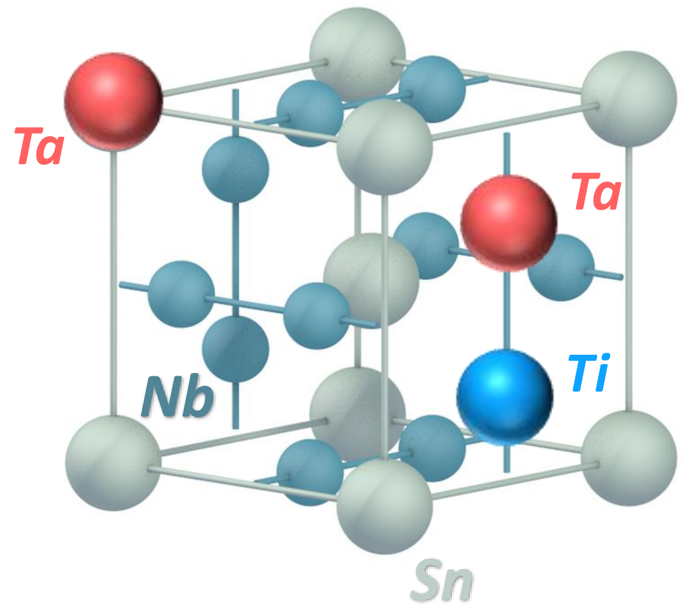
The addition of Cu lowers the formation temperature of Nb_3Sn down to ~650°C

Not only Nb and Sn

Ta and Ti enhance B_{c2} and now are used in all industrial wires



Adapted from M. Suenaga et al., JAP 59 (1986) 840



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

B_{c2} is proportional to defects

From EXAFS investigations

- **Ta substitutes both Nb and Sn**
- **Ti substitutes Nb**

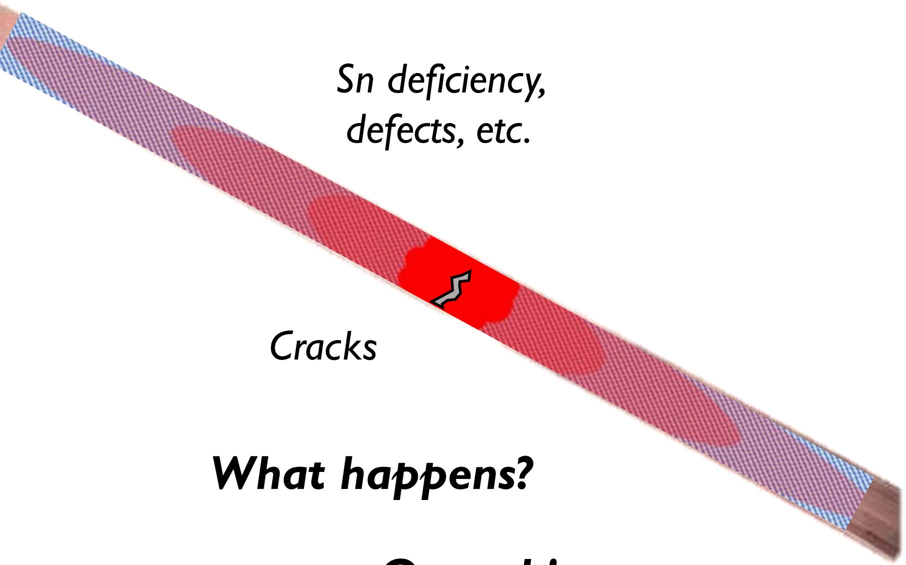
S. M. Heald *et al.* Sci. Rep. (2018) 8 4798

Outline

- *A brief history of Nb_3Sn*
- ***From bronze to internal Sn wires: the multifilamentary wires age***
- *J_c and B_{c2} are essential, yet not sufficient for applications*
- *FCC-hh and the new challenges for Nb_3Sn*

Why multifilamentary wires are important

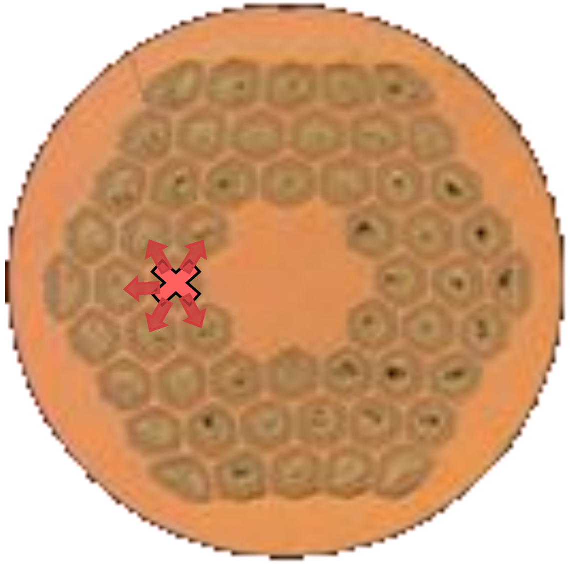
Nb_3Sn tape, Cu plated



What happens?

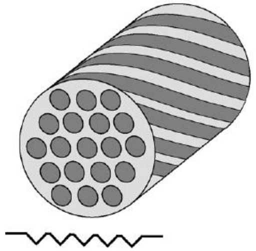
Quench!

The sudden and undesirable transition from a superconducting state to a normal state. When a quench occurs, the stored energy in the superconductor is rapidly converted into heat



In a multifilamentary wire, in case of cracks or defects, J_c can be shared by adjacent filaments!

Filaments can be twisted to avoid current coupling in case the matrix resistivity is low

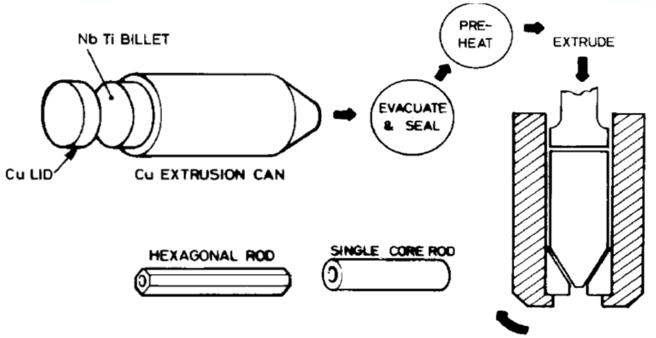


- *Minimize AC losses*
- *Reduce coil magnetisation*
- *Improve electromechanical stability*

Multifilamentary wire are more "stable"!

The bronze route and multifilamentary wires

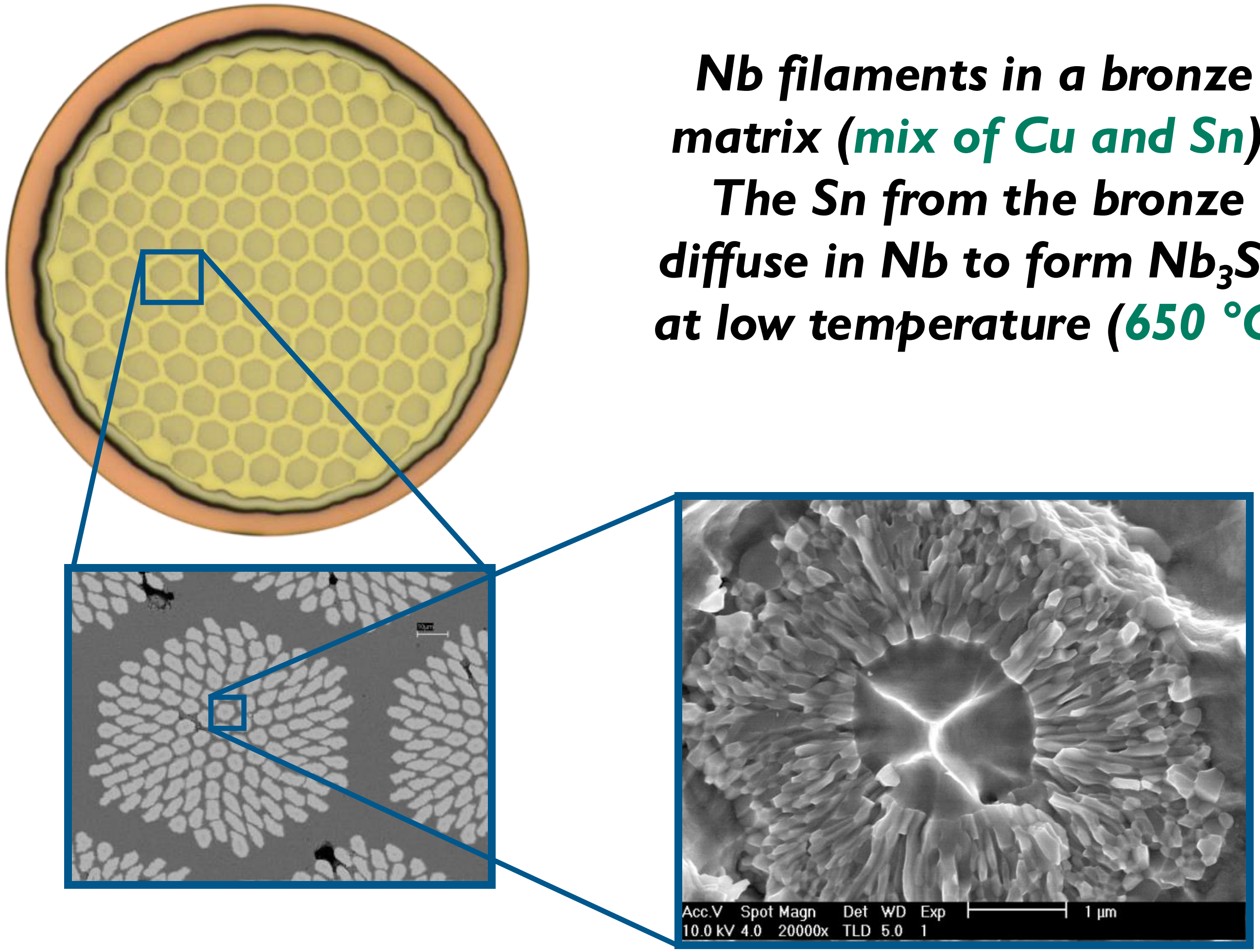
Bronze ingots for Nb_3Sn wires
(Courtesy of Osaka Alloying Works Co)



K. Tachikawa and P. Lee, Nb_3Sn and related A15s, Chapter 11

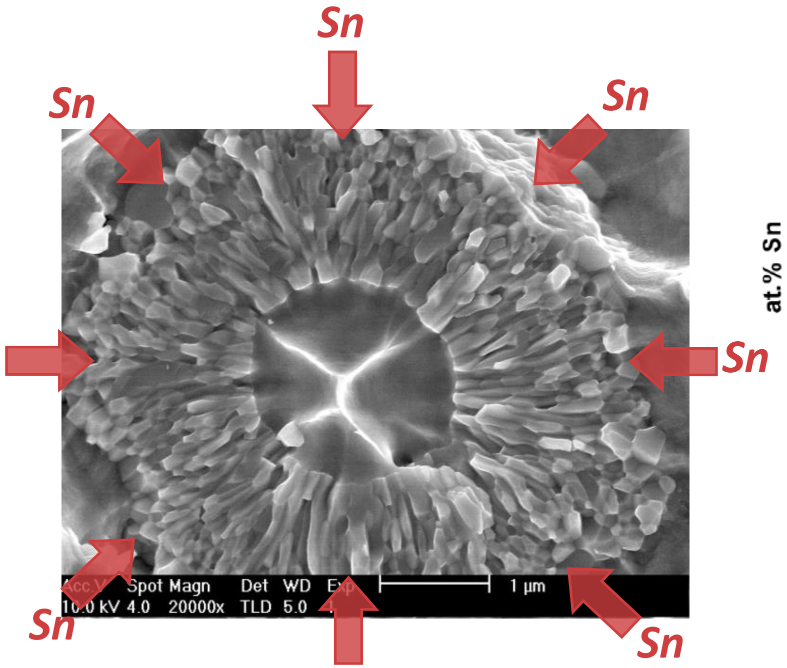
E.W. Howlett, Great Britain Pat. 52, 623/69 (Filed Oct. 27, 1969)

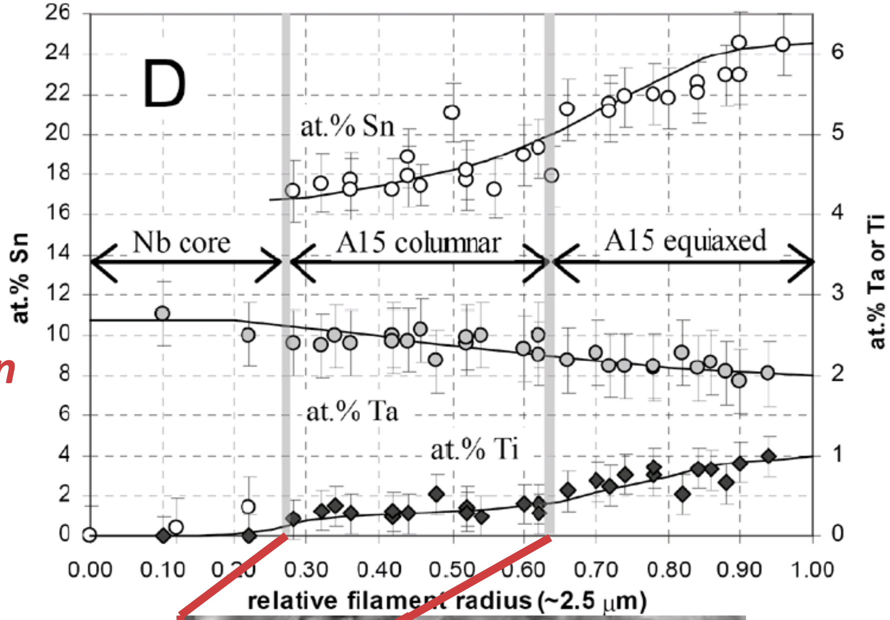
A. R. Kaufman and J. J. Pickett, Bull. Am. Phys. Soc. (1970) 15 833

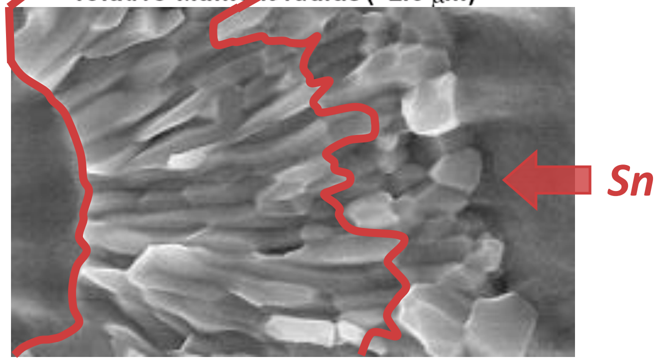


Nb filaments in a bronze matrix (mix of Cu and Sn). The Sn from the bronze diffuse in Nb to form Nb_3Sn at low temperature (650 °C)

Different grains, different properties







Sn content changes drastically along the Nb_3Sn layer

Equiaxed grains: 21-25 at.% Sn

Columnar grains: 18-21 at.%

Also grain size is different

Equiaxed grain size ~150 nm

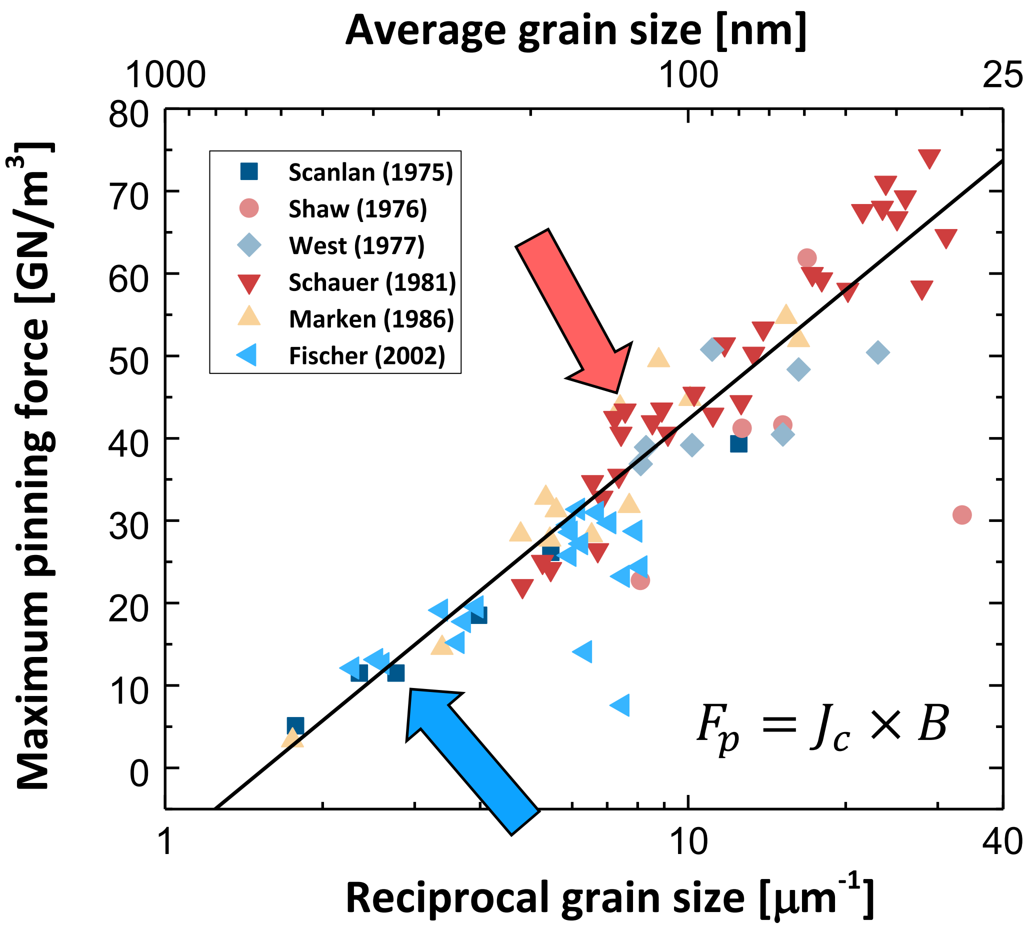
Columnar grain size up to 400 nm

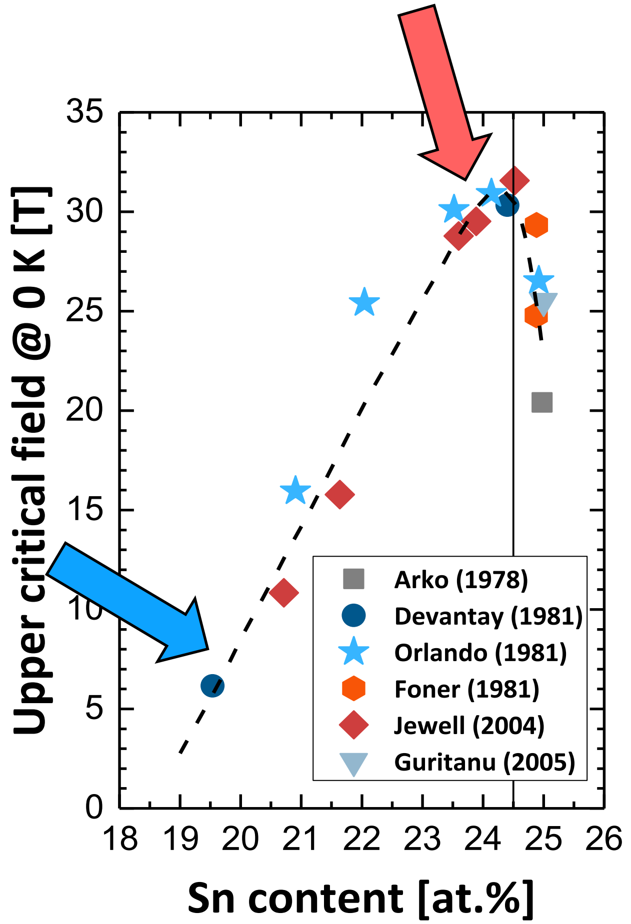
Effect due to low Sn content in bronze

Does these differences affect superconducting properties?

V. Abächerli *et al.* *IEEE TAS* (2005) 15 3482

Different grains, different properties



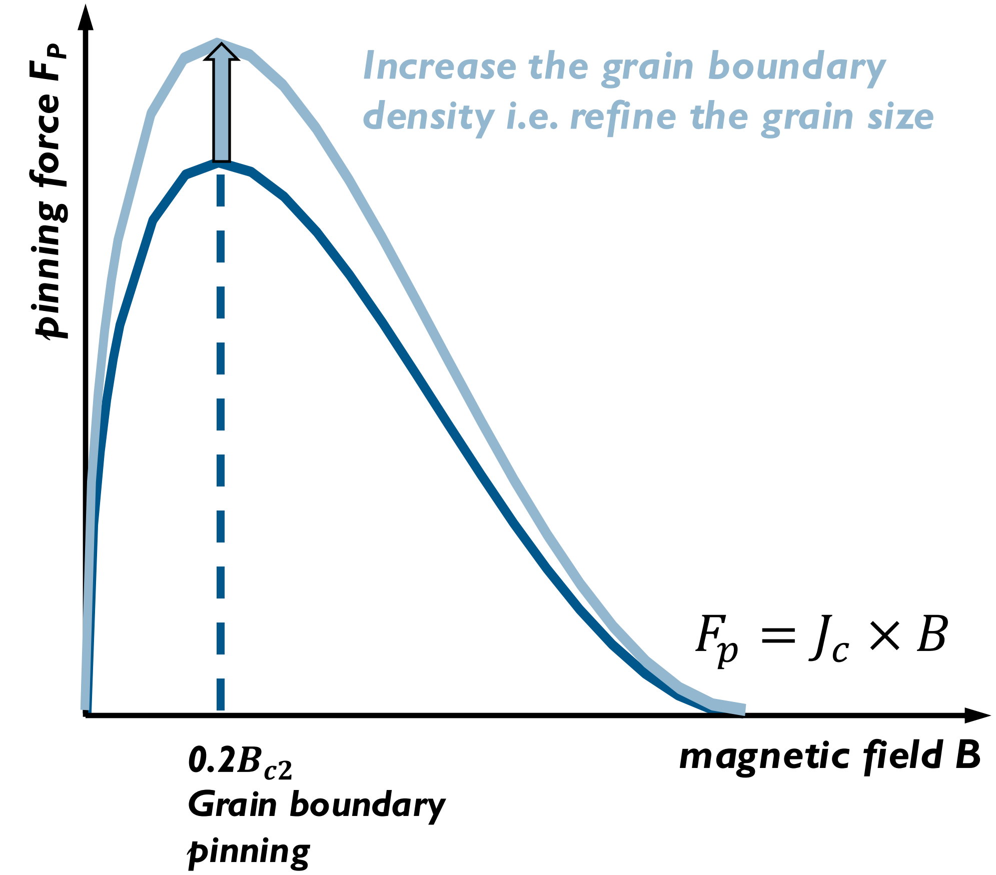


Columnar grains (18-21 at.% Sn, 400 nm) have lower B_{c2} and contribute less to J_c then equiaxed grains (21-25 at.% Sn, 150 nm)

Why J_c increase at finer grain size?

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

Different grains, different properties



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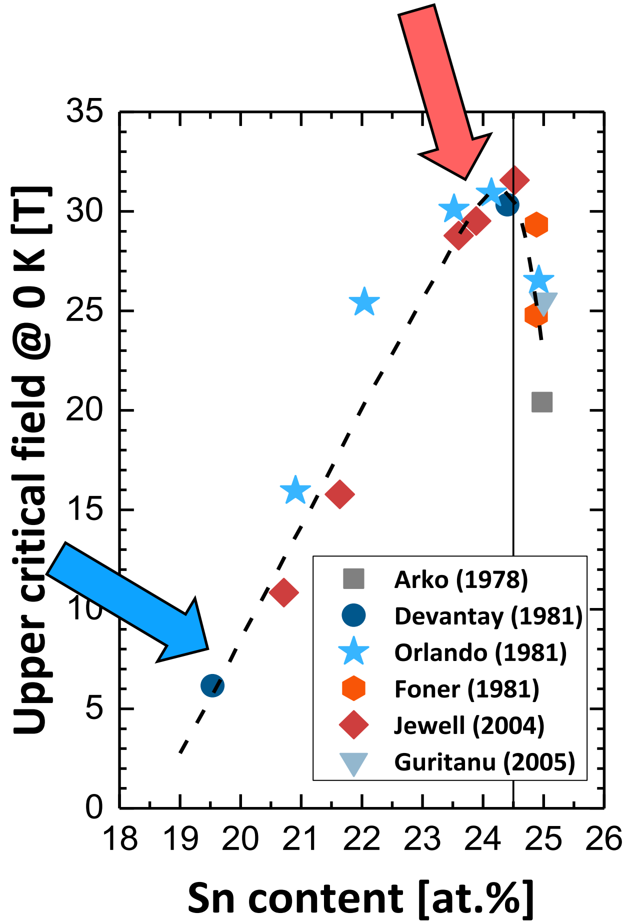


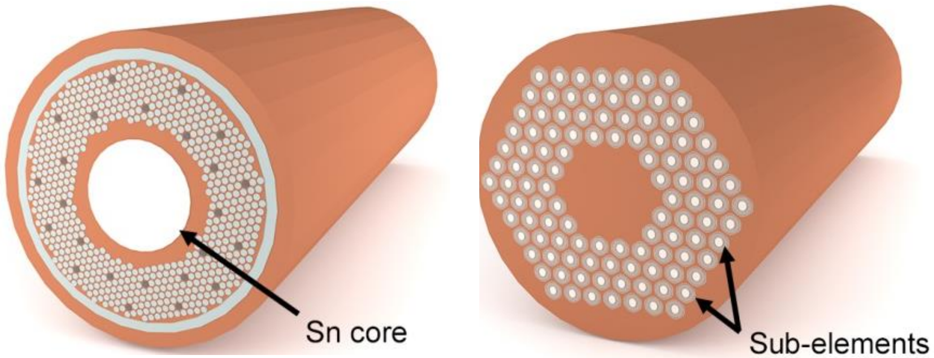
Columnar grains (18-21 at.% Sn, 400 nm) have lower B_{c2} and contribute less to J_c then equiaxed grains (21-25 at.% Sn, 150 nm)

Why J_c increase at finer grain size?

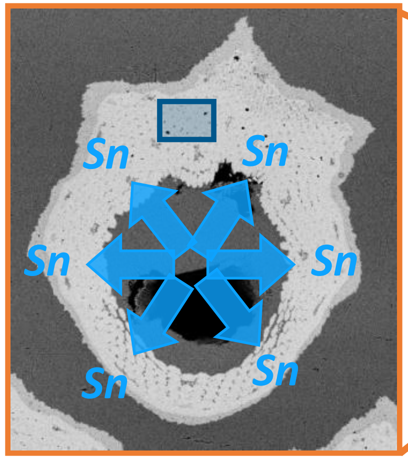
The flux line lattice is pinned by pinning centers (e.g., grain boundaries). The more grain boundaries, the higher the F_p

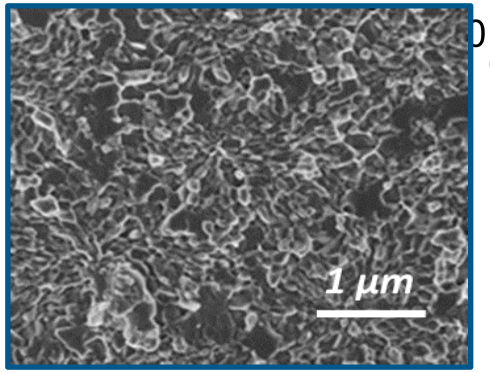
How to have more Sn and good deformability?

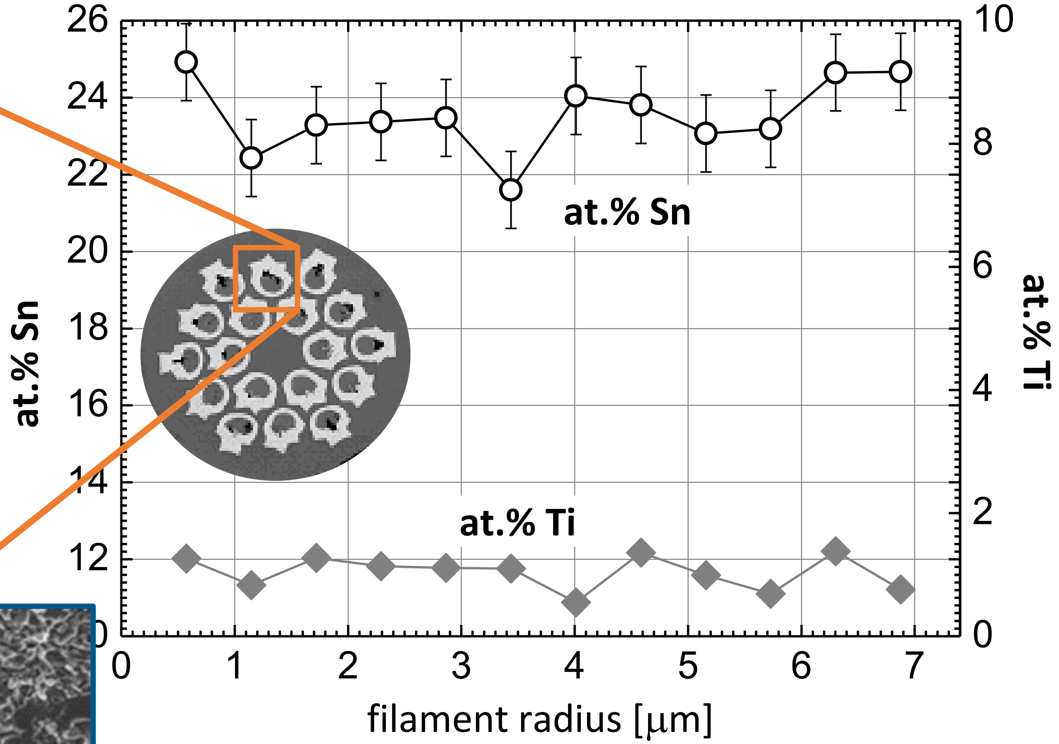
More Sn for the internal Sn



RRP subelement







Bronze is substituted by a Sn rod in a Cu matrix

Sn and Cu are deformed easily Sn content can be maximized

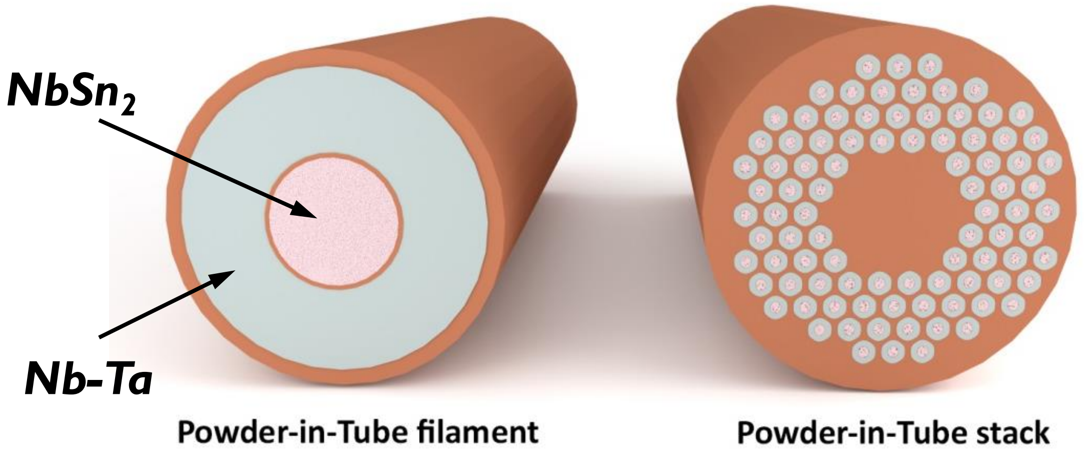
Internal Sn includes different type of wires. The most notable are the Rod Restack Process (RRP) wires

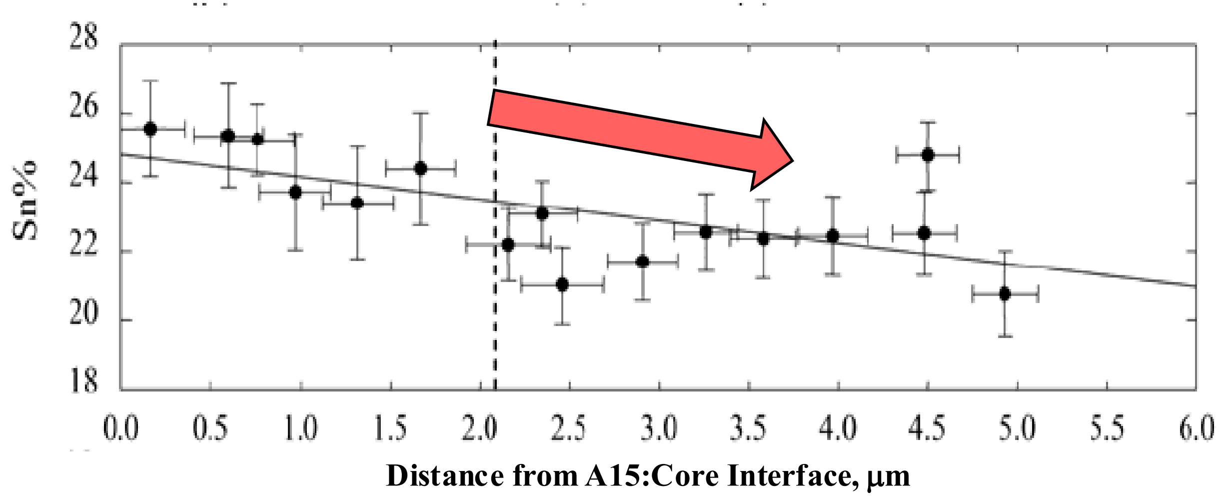
Higher Sn content makes all the grains equiaxed and stoichiometric!

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

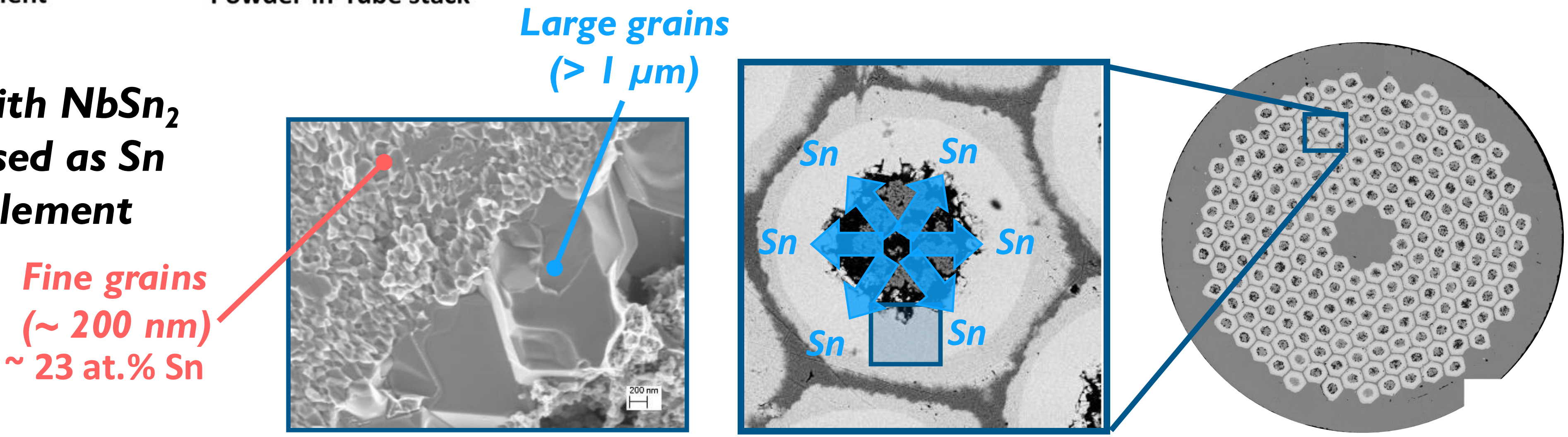
Another wire fabrication method: Powder In Tube (PIT)

Sn content decreases linearly along the filament radius



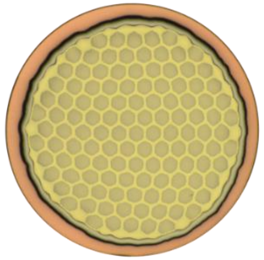


A Nb tube is filled with $NbSn_2$ powders, which is used as Sn source in the subelement



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

Performances in industrial wires



Bronze Process

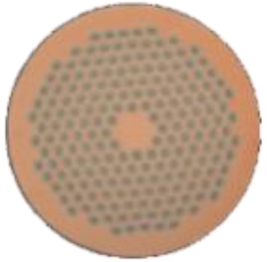
Bronze is the Sn source, limited by the solubility of Sn in Cu

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

Internal Sn / RRP

A metallic Sn rod is inserted in the subelement core

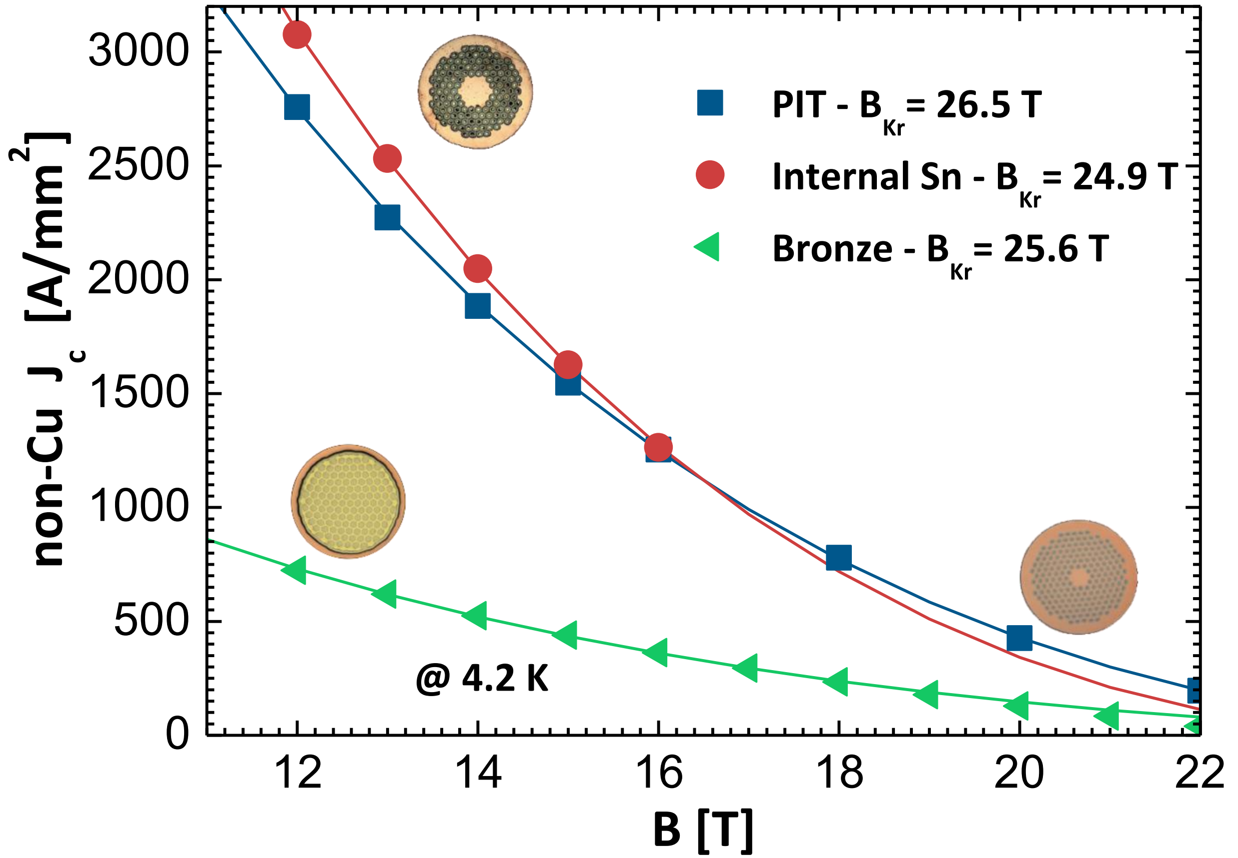
J. Parrell *et al.* *AIP Conf. Proc.* (2004) 711 369



Powder-In-Tube (PIT) method

Each subelement is a Nb-alloy tube filled with $NbSn_2$ and Sn powders

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



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

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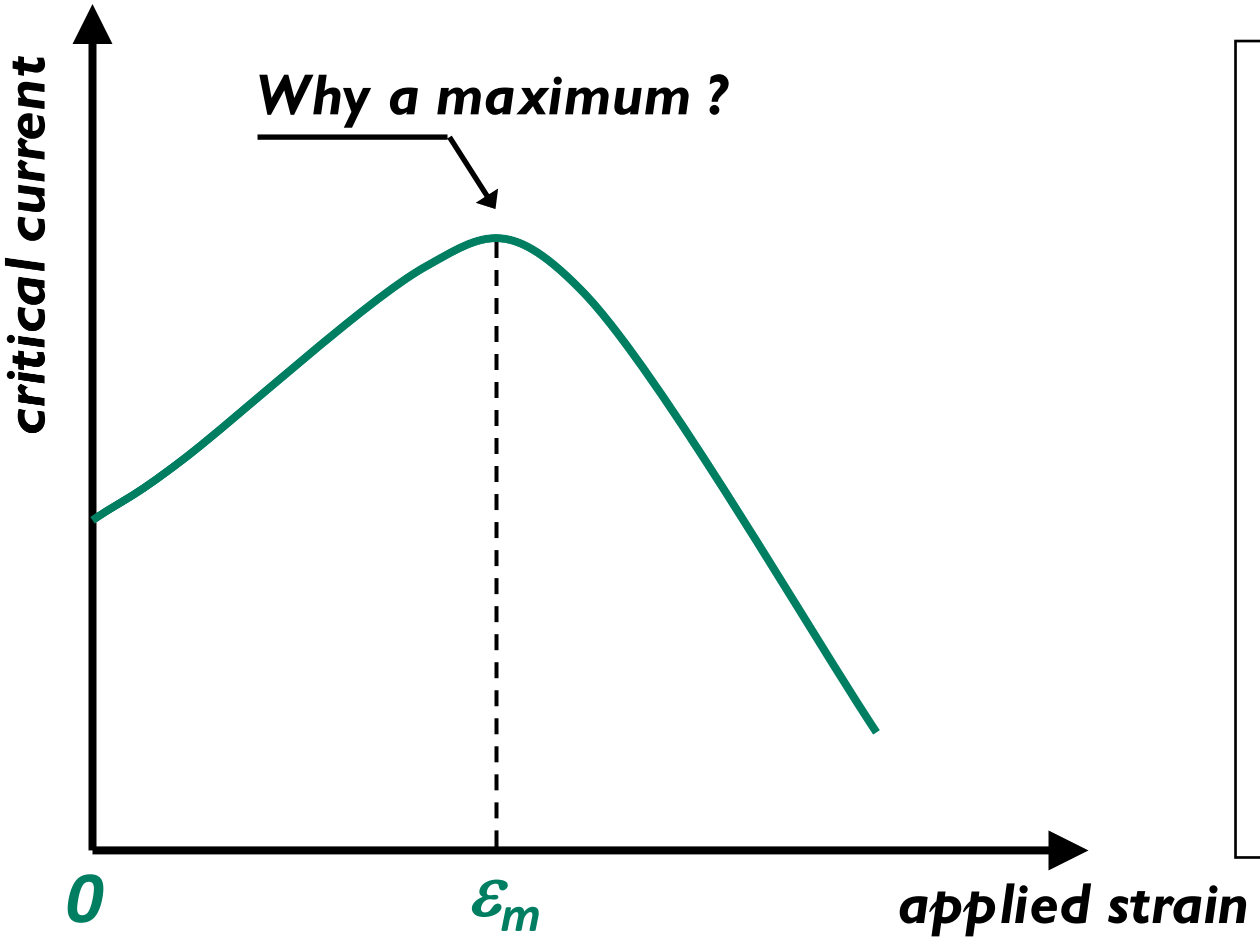
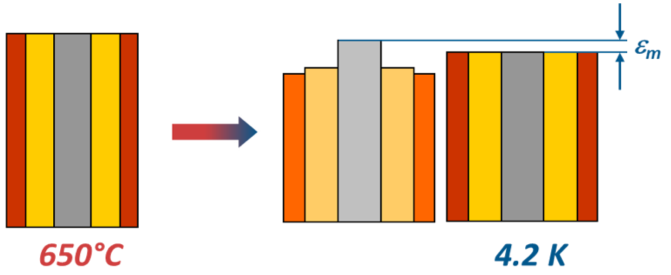
- FCC-hh and the new challenges for Nb_3Sn

How axial strain modify Nb_3Sn wires J_c

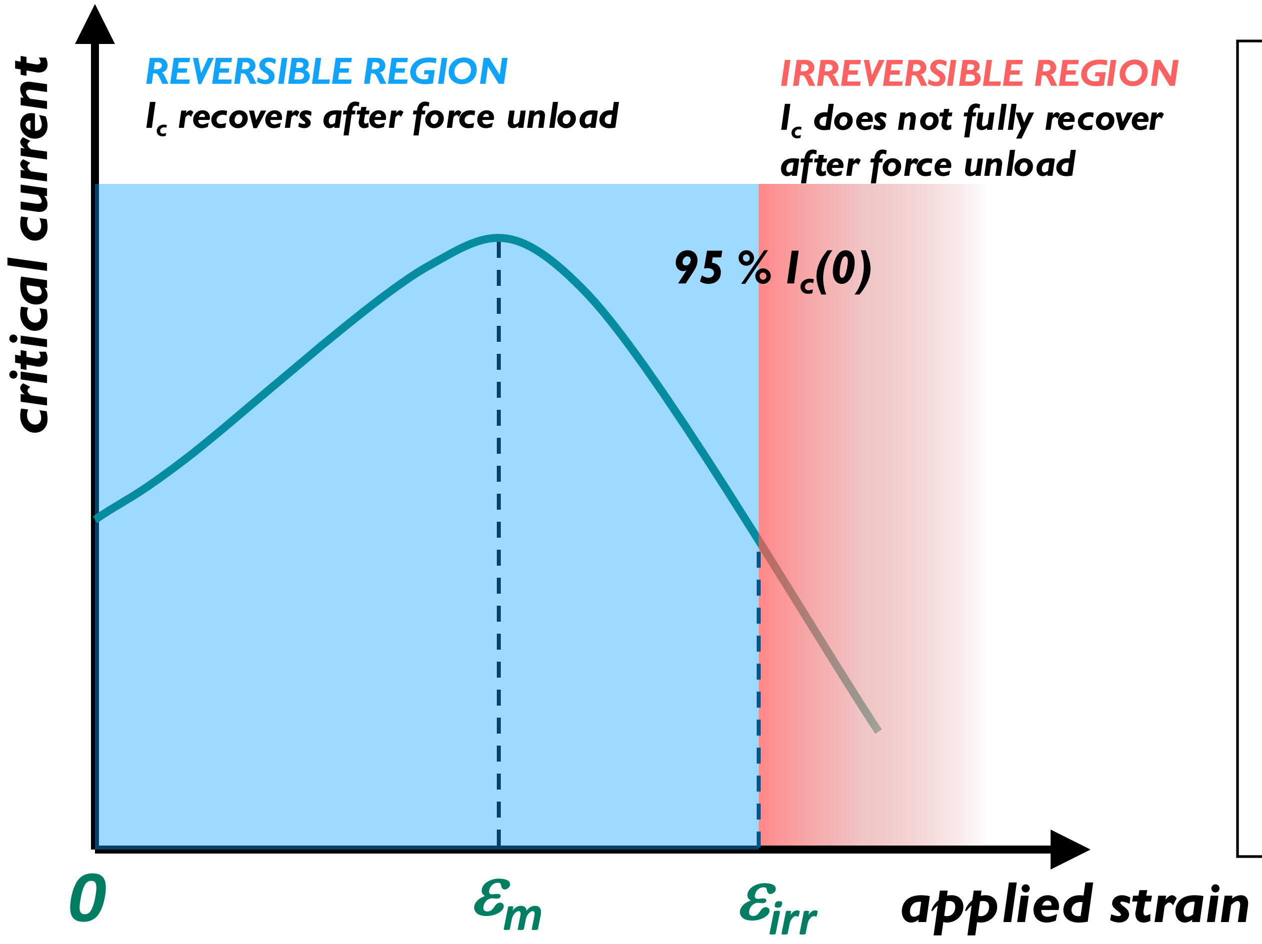


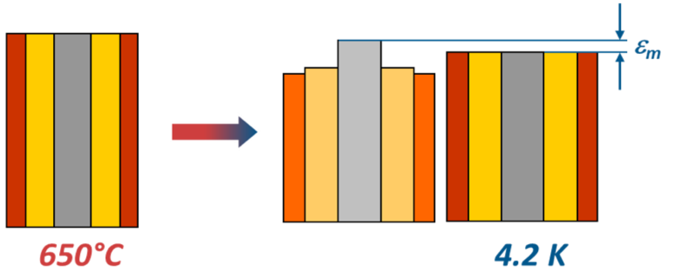


Mismatch in thermal contraction within the composite induces a precompression in Nb_3Sn

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

How axial strain modify Nb_3Sn wires J_c



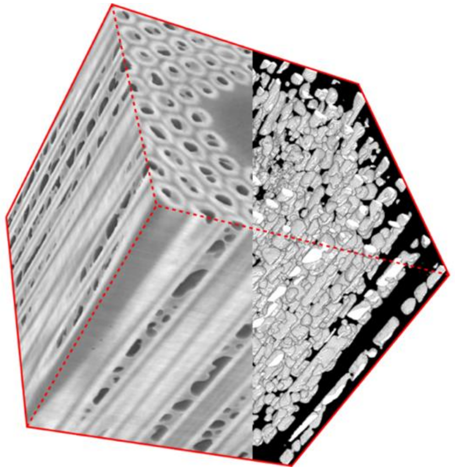


Mismatch in thermal contraction within the composite induces a precompression in Nb_3Sn

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

Irreversible degradation phenomena

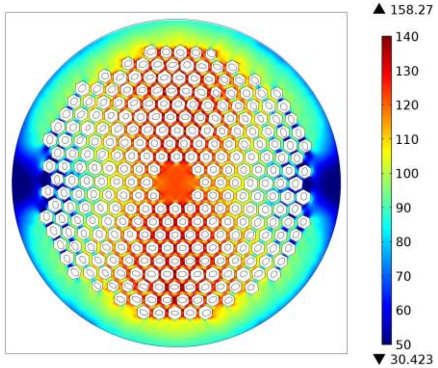
Two mechanisms govern the irreversible degradation of the critical current



Analysis of the phenomenon in two load geometries

1 - Formation of cracks in the Nb_3Sn filaments due to the stress concentration

1 – Axial tension and the role of cracks at the voids

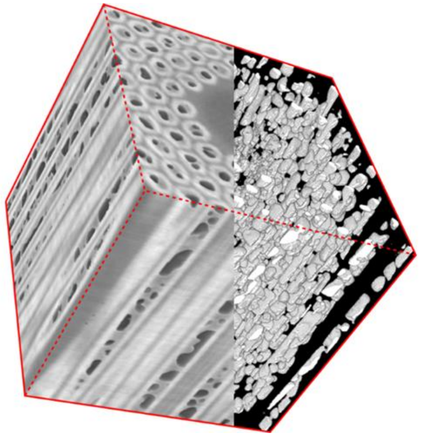


2 - Plastic deformation of the matrix and residual stress on the Nb_3Sn filaments.

2 – Transverse compression, plastic deformation of the matrix and residual stress on Nb_3Sn

Analysis of the phenomenon in two load geometries

1 – Axial tension and the role of cracks at the voids



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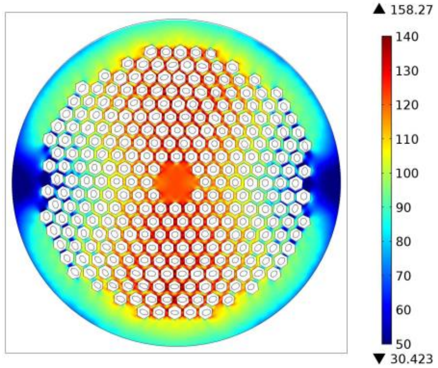
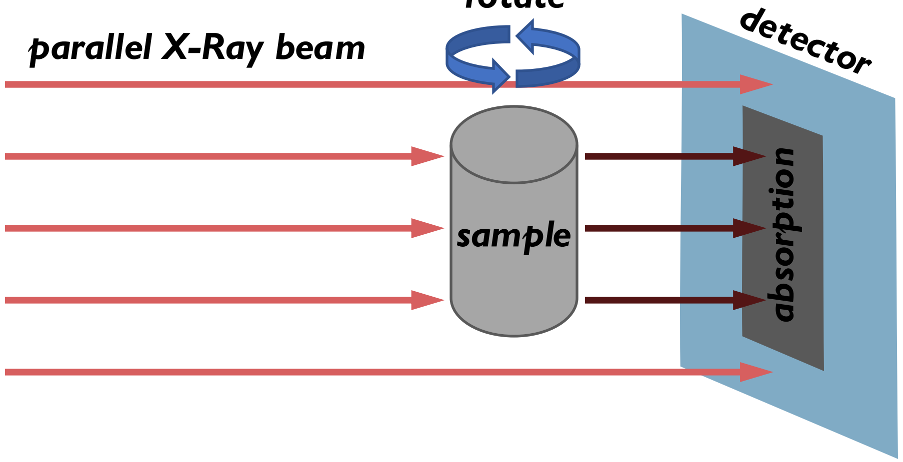
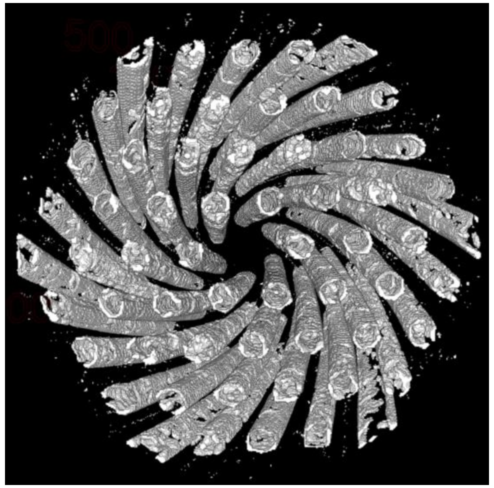


Voids detection in Nb_3Sn wires

X-ray microtomography reconstruction @ ESRF Grenoble

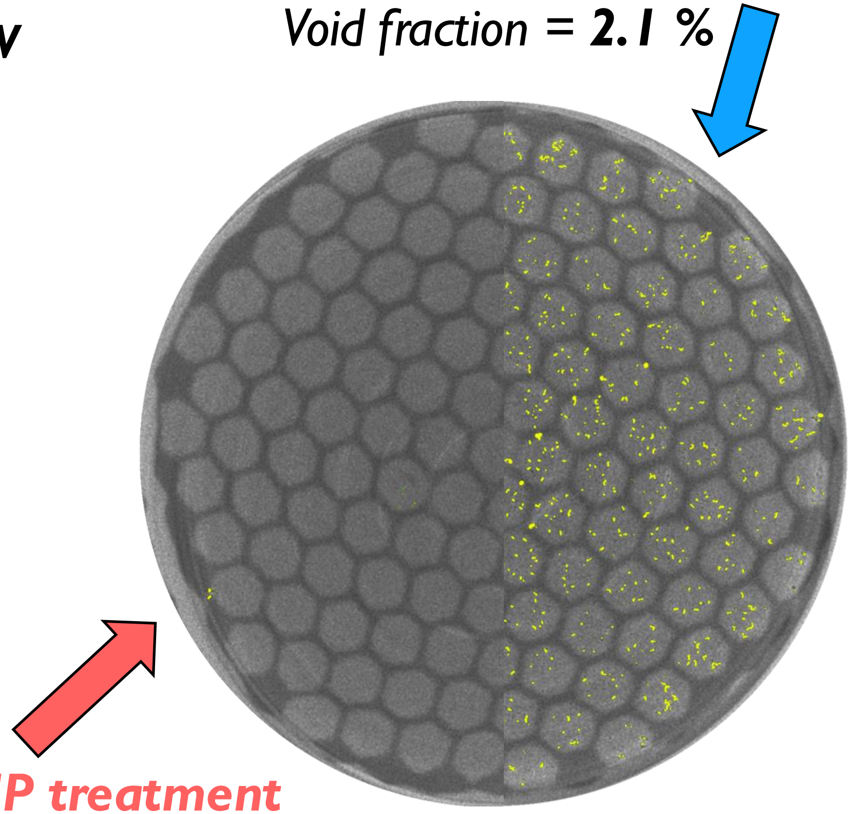


- X-ray photon energy = 89 keV
- 360° rotation of the sample
- 30'000 projections
- 2560 x 2160 pixels
- 0.57 μm/pixel resolution



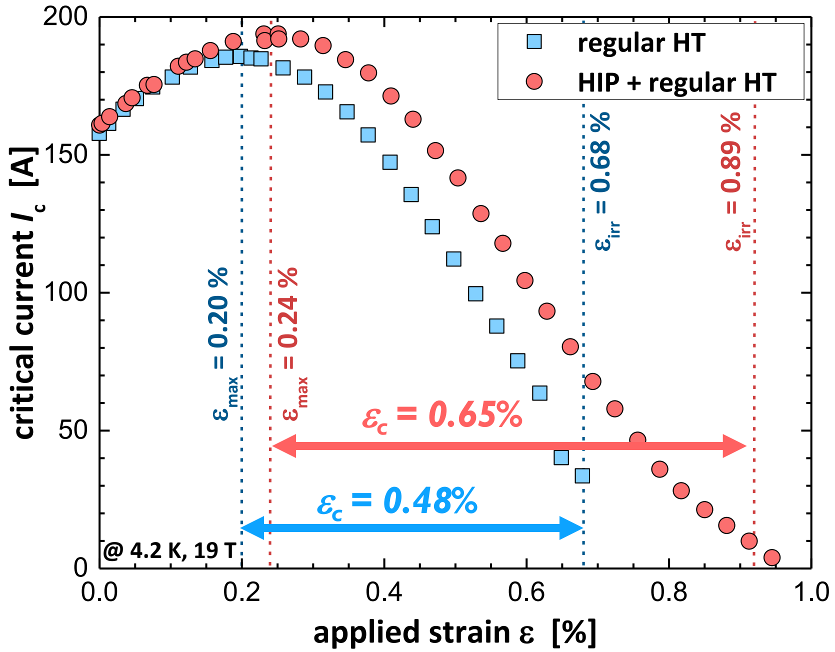
Non-destructive 3D volume reconstruction with separation of internal features to study voids distribution

Regular HT treatment
Void fraction = **2.1 %**



With HIP treatment
Void fraction = **0.05 %**

Irreversible limit measurement



Regular HT: 600°C/100h + 670°/150h

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

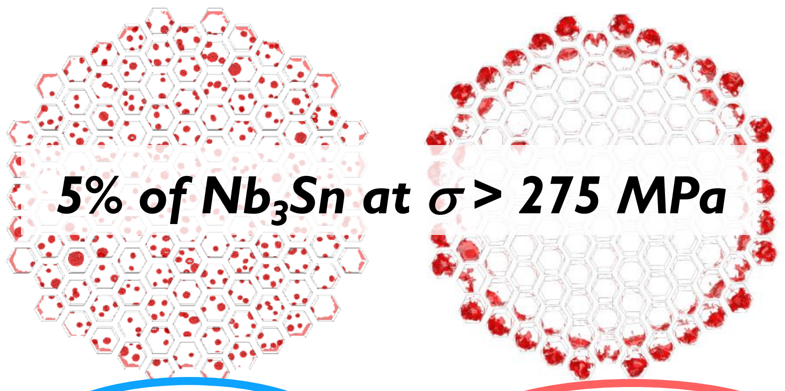
HIP 550°C/1h/200MPa + Regular HT

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

With HIP treatment ε_c increases by +0.17 %

FEM simulations

with voids ***without voids***



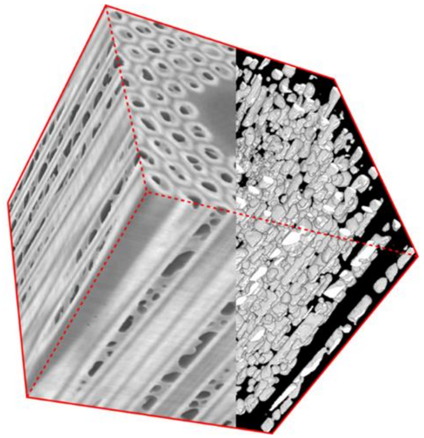
ε_c = 0.50% ε_c = 0.65%

C. Barth *et al. Sci. Rep.* (2018) 8 6589

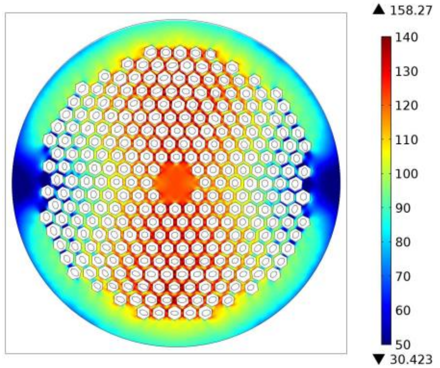
Changes in the voids correlate quantitatively with the changes in the electromechanical limits

Analysis of the phenomenon in two load geometries

1 – Axial tension and the role of cracks at the voids

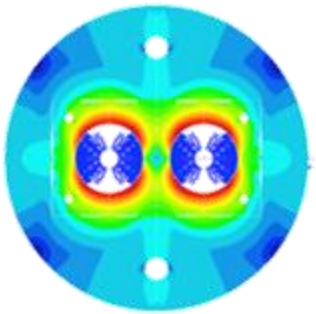


2 – Transverse compression, plastic deformation of the matrix and residual stress on Nb_3Sn

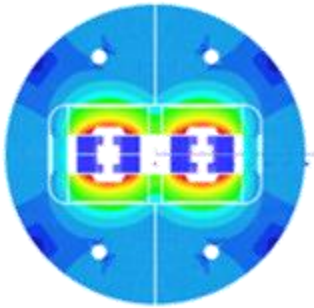


Design options for the FCC-hh dipoles

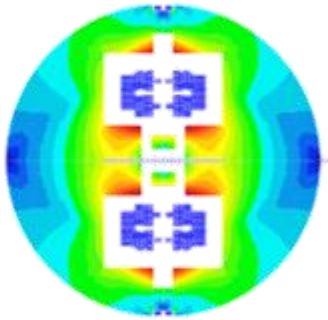
h2020 EuroCirCol WP5, started in 2015



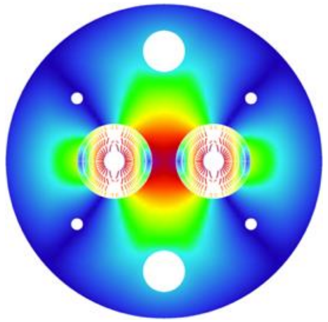
Cosine Theta Coil



Block Coil



Common Coil



Canted Cosine Theta (CCT)

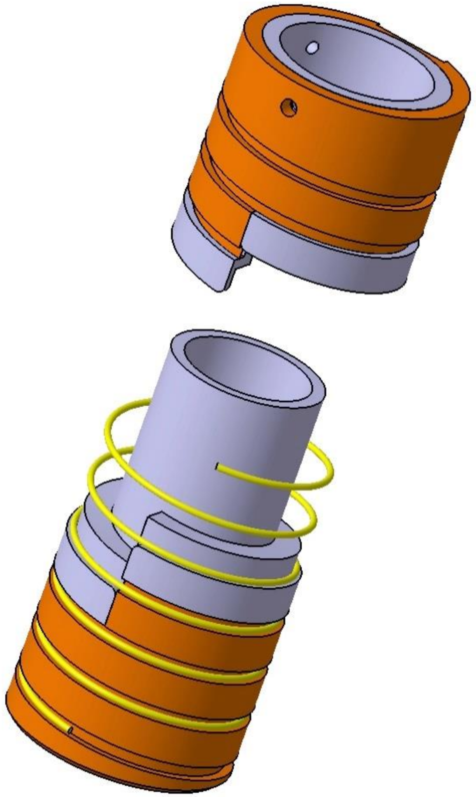
All designs for the 16 T dipoles share a peak in transverse stress at operation of 150-200 MPa

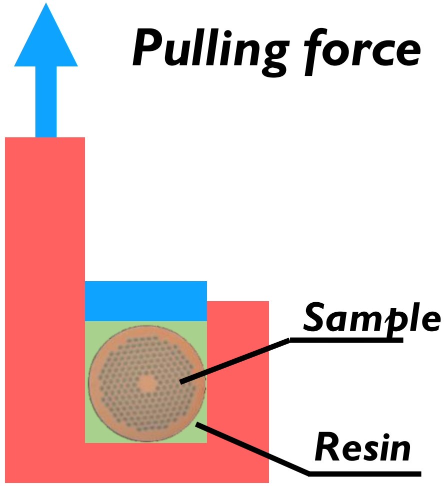
Nb_3Sn Rutherford cable for HL-LHC, 40 strands

Are the Nb_3Sn wires in the Rutherford cables able to withstand such a high stress level? Which degradation is tolerable?

I_c vs. transverse stress on a single wire

The WASP concept



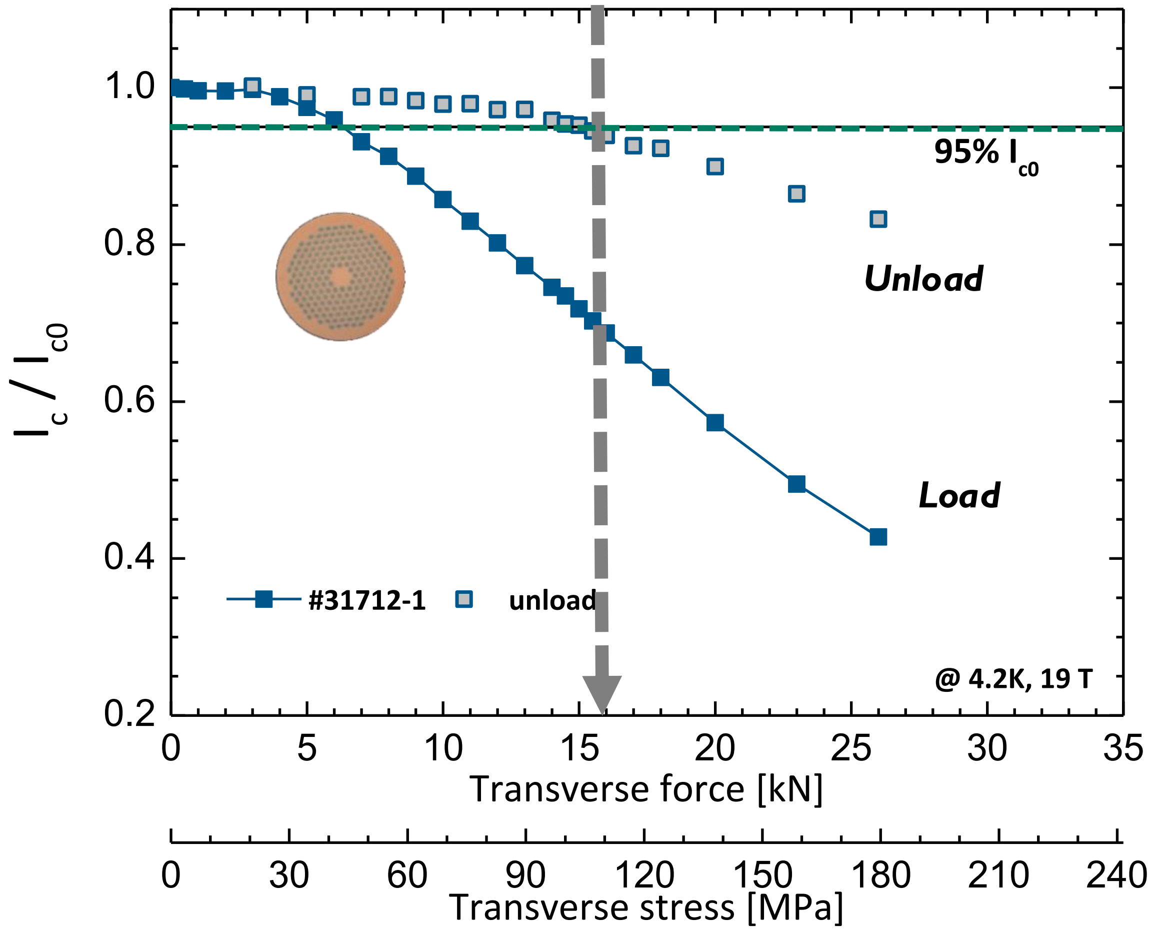


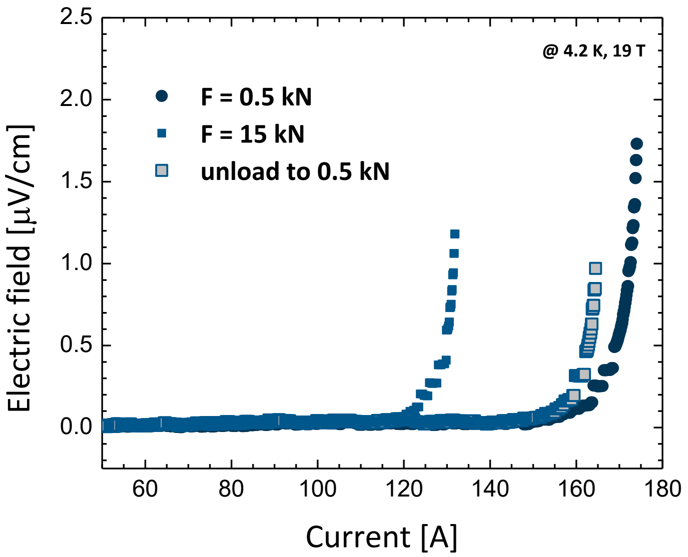
B. Seeber *et al.* *IEEE TASC* (2007)17 2643

G. Mondonico *et al.* *SuST* (2012) 25 115002

UNIVERSITÉ DE GENÈVE FACULTÉ DES SCIENCES CERN ***collaboration agreement K1629/TE (2009-2012)***

I_c vs. transverse stress on a single wire





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

Here

$F_{irr}(B=19T) = 16$ kN

The corresponding irreversible stress limit is

$\sigma_{irr}(B=19T) = 110$ MPa

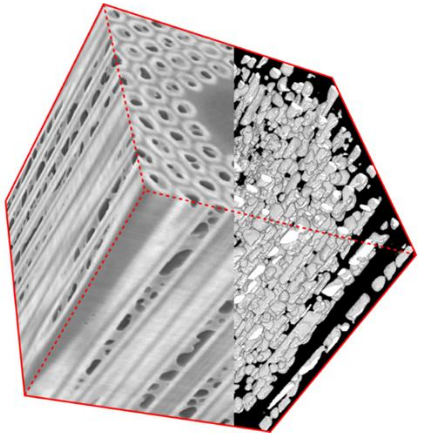
where

$$Stress = \frac{Force}{Groove\ length \times width}$$

I_c vs. transverse stress on a single wire

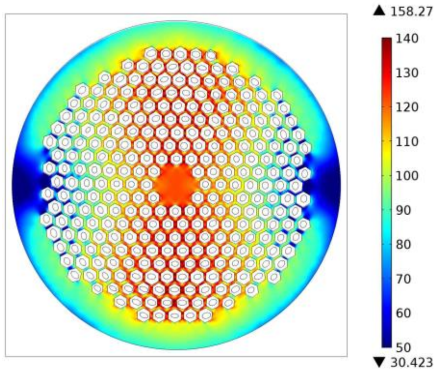
Two mechanisms govern the irreversible degradation of the critical current

- ❑ *Formation of cracks in the Nb_3Sn filaments due, for instance, to the stress concentration at the voids formed during the reaction heat treatment*



Cracks generate a reduction of the current carrying cross section ⇒ I_c^{unload}/I_{c0} is independent of the magnetic field

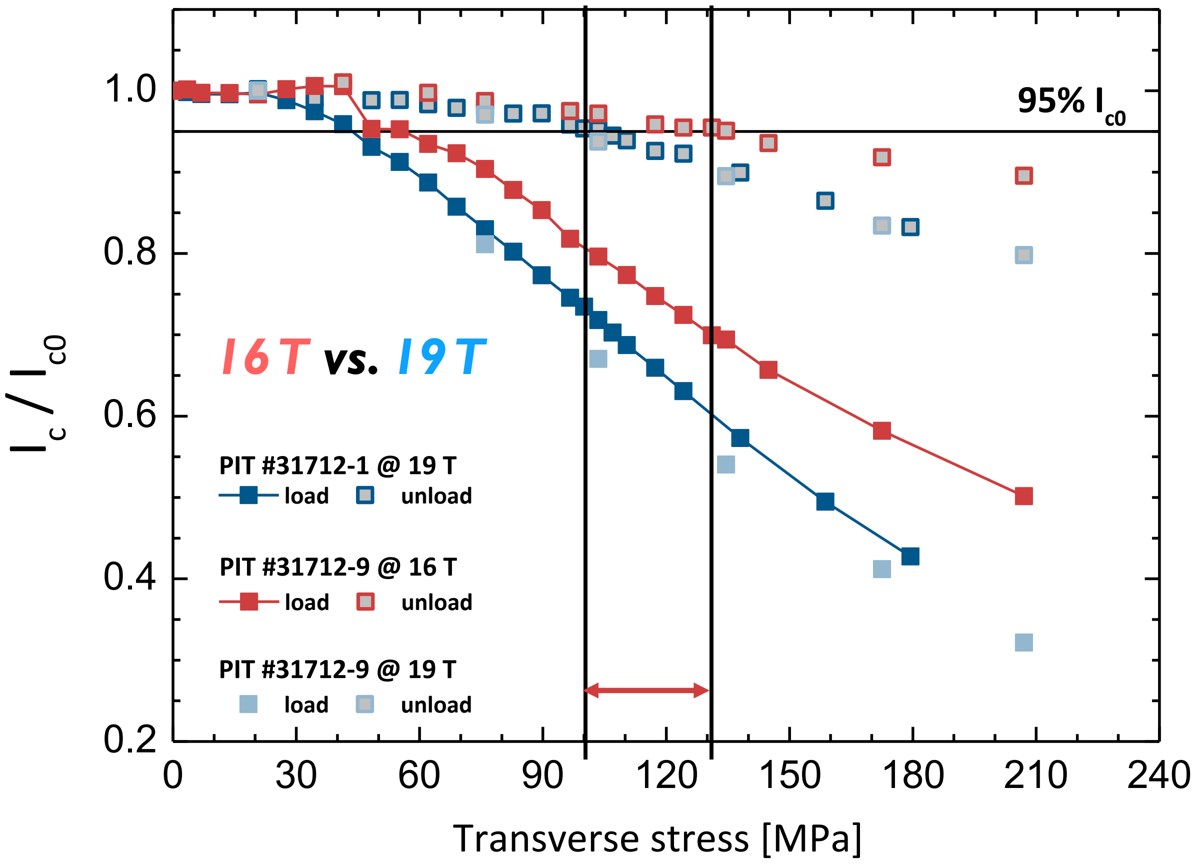
- ❑ *Plastic deformation of the matrix and residual stress on the Nb_3Sn filaments.*



Residual stress induces a permanent reduction of B_{c2} after unload ⇒ I_c^{unload}/I_{c0} depends on of the magnetic field

I_c vs. transverse stress on a single wire

Field dependence of the irreversible stress limit

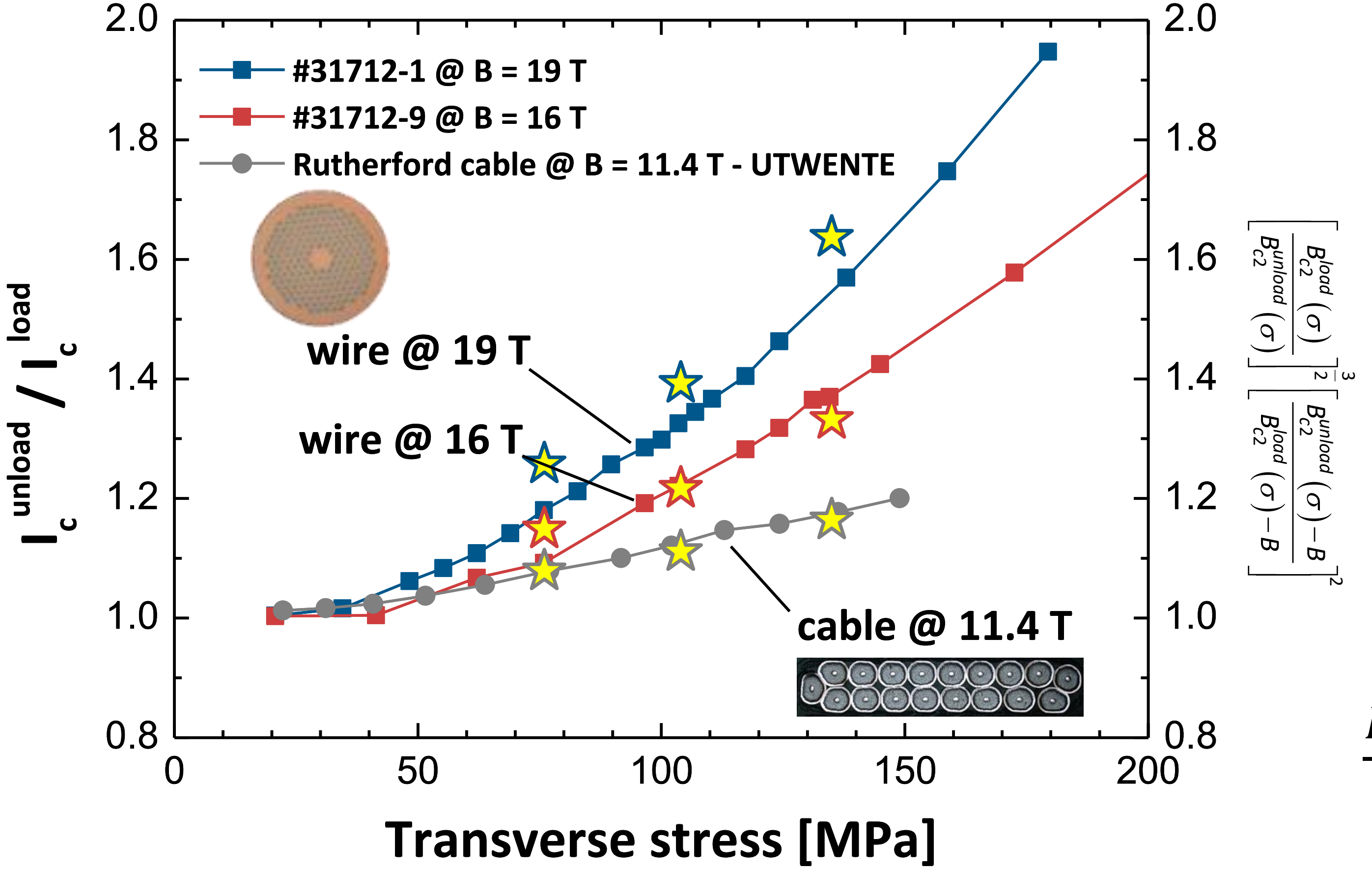


Clear field dependence!

L. Gamperle *et al. Physical Review Research* (2020) 2.1 013211.

I_c vs. transverse stress on a single wire

Field dependence of the irreversible stress limit



Clear field dependence!

A simple model, based only on the effects of residual stress, reproduces the experimental dependences on field and stress

It proves also that the experiments performed on the single wire are consistent with those on cables

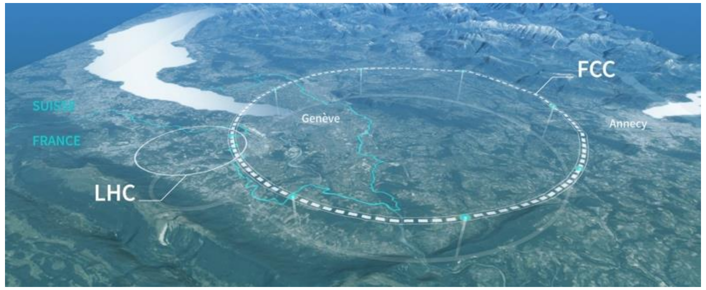
$$\frac{I_c^{unload}}{I_c^{load}}(B,\sigma) = \left[\frac{B_{c2}^{load}(\sigma)}{B_{c2}^{unload}(\sigma)}\right]^{\frac{3}{2}} \left[\frac{B_{c2}^{unload}(\sigma) - B}{B_{c2}^{load}(\sigma) - B}\right]^2$$

L. Gamperle *et al. Physical Review Research* (2020) 2.1 013211.

Outline

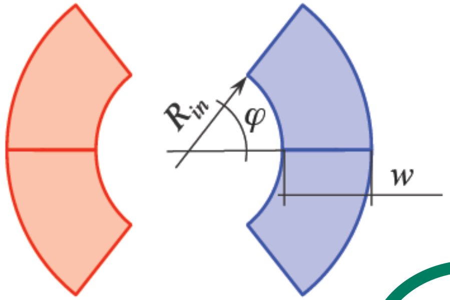
- *A brief history of Nb_3Sn*
- *From bronze to internal Sn wires: the multifilamentary wires age*
- *J_c and B_{c2} are essential, yet not sufficient for applications*
- ***FCC-hh and the new challenges for Nb_3Sn***

The Future Circular Collider

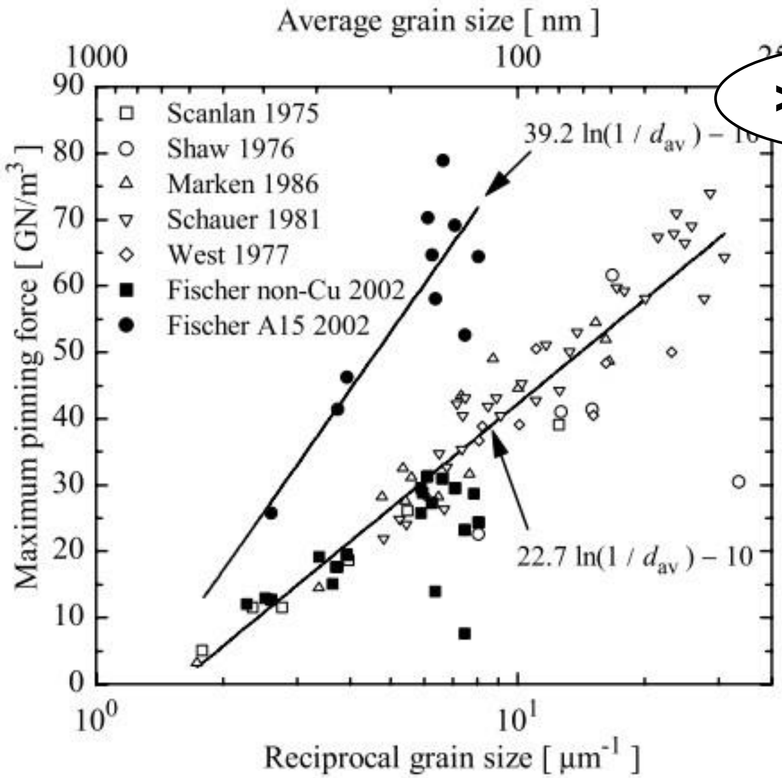


LHC	*FCC-hh*
27 km, 8.33 T	***91 km, 14 T***
14 TeV (c.o.m.)	***~ 85 TeV (c.o.m.)***
1'300 tons NbTi	***~10'000 tons Nb_3Sn***

A huge amount of Nb_3Sn!!

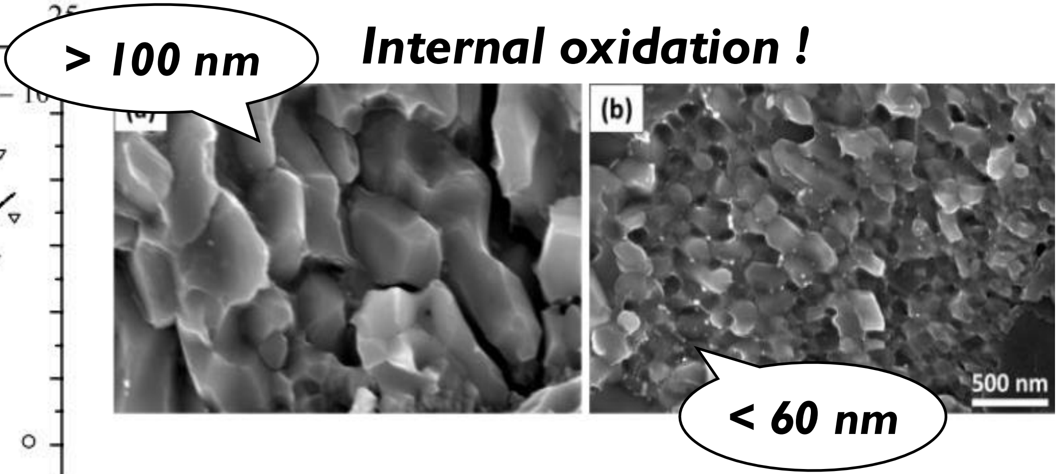


$$A_{coil} = 2\varphi(w + 2R_{int}w) \propto \frac{1}{J}$$



How can we reduce effectively grain size?

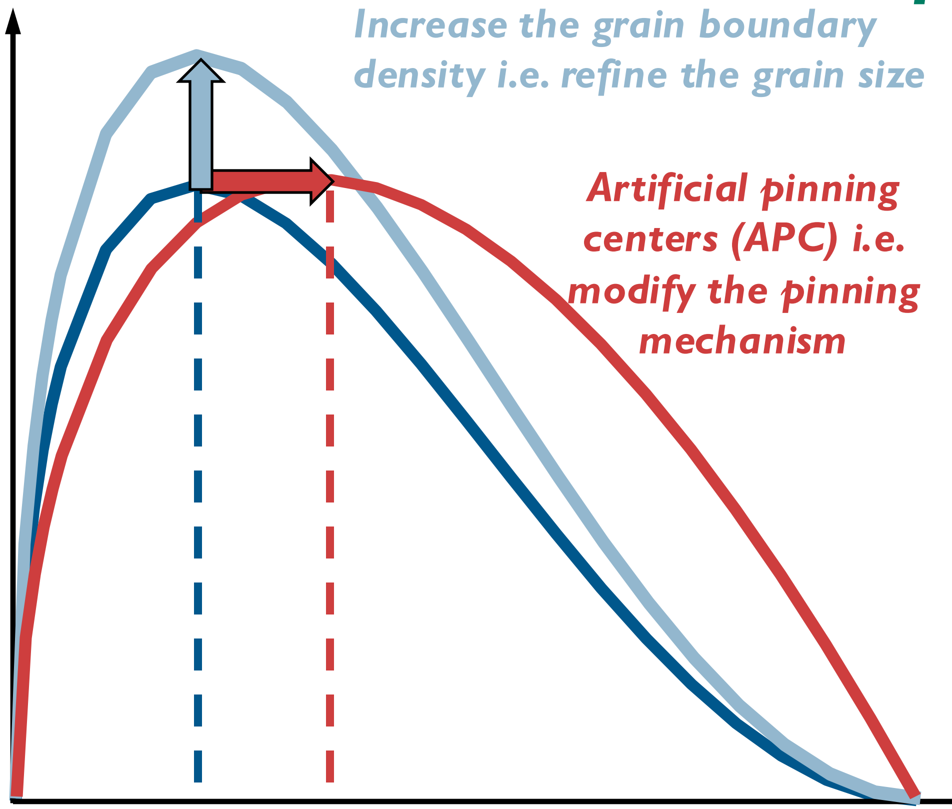
Internal oxidation !



Grain refinement induced by precipitation of oxides nanoparticles

X. Xu *et al.* Appl. Phys. Lett. (2014) 104, 082602
DOI:10.1063/1.4866865.
M. G. Benz, Trans. Met. Soc. AIME, (1968) 242: 1067-70.
L. E. Rumaner *et al.* Metall Mater Trans A (1994) 25, 213–219
DOI: 10.1007/BF02646689.
A. Godeke, Supercond. Sci. Technol (2006)19 R68
DOI: 10.1088/0953-2048/19/8/R02
E. Todesco, IEEE Transactions on Applied Superconductivity (2025) **DOI:**10.1109/TASC.2025.3558196

More then just a F_p increase



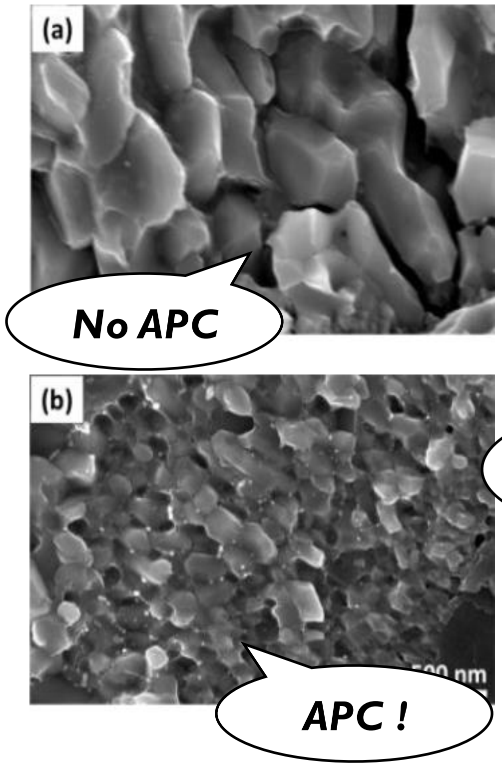
Increase the grain boundary density i.e. refine the grain size

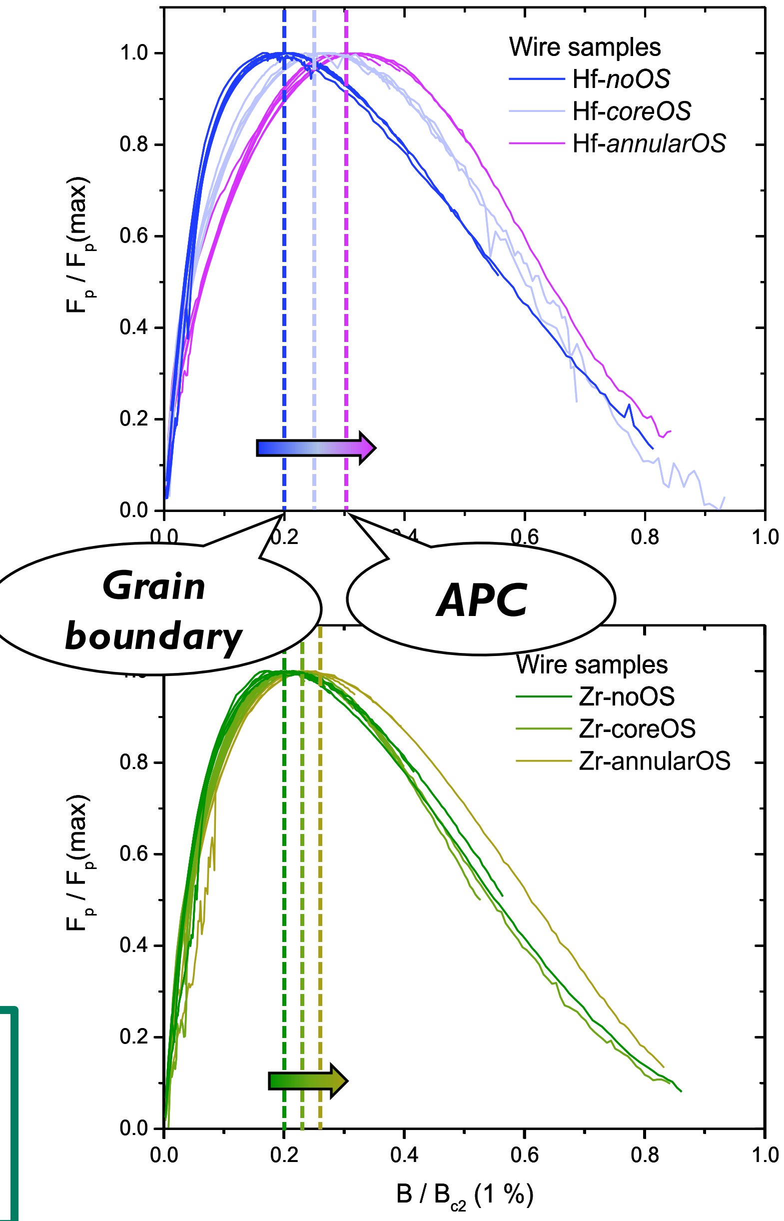
Artificial pinning centers (APC) i.e. modify the pinning mechanism

$0.2B_{c2}$
Grain boundary pinning

$0.33B_{c2}$
APC pinning

$$F_p = J_c \times B$$

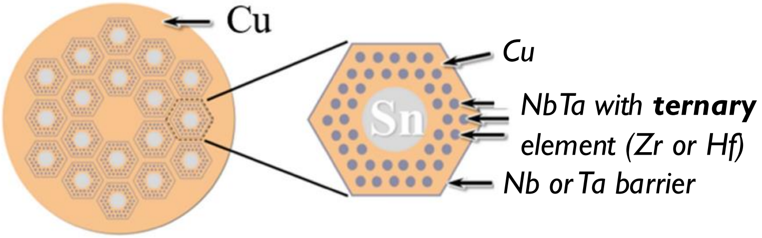


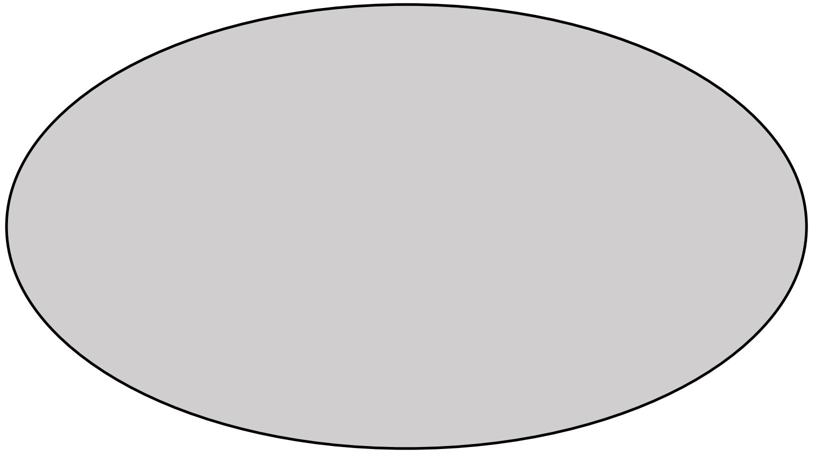


Internal Oxidation leads to grain refinement AND produces Artificial Pinning Centers (APCs)

Internal oxidation process

What happens during heat treatment

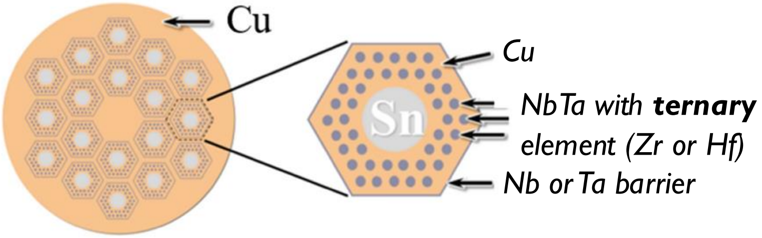


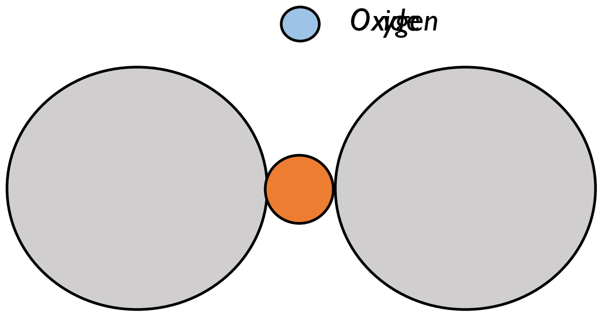


During heat treatment, grains grows and join together when their boundaries touches

Internal oxidation process

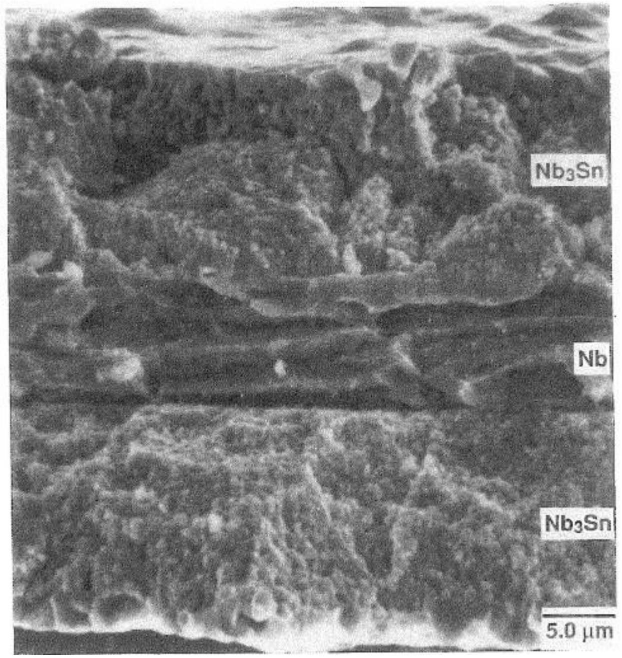
What happens during heat treatment





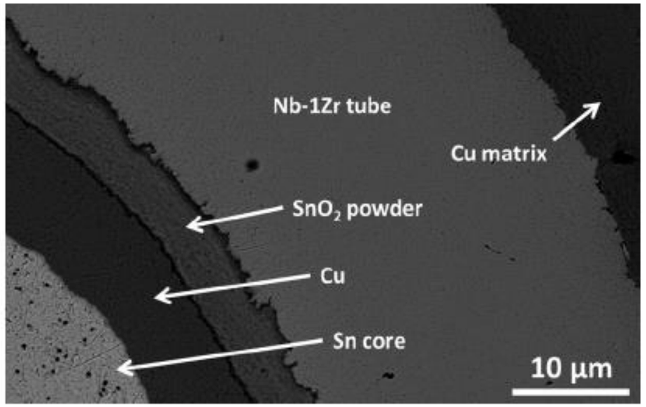
Oxygen reacts with Hf or Zr (higher oxygen affinity)

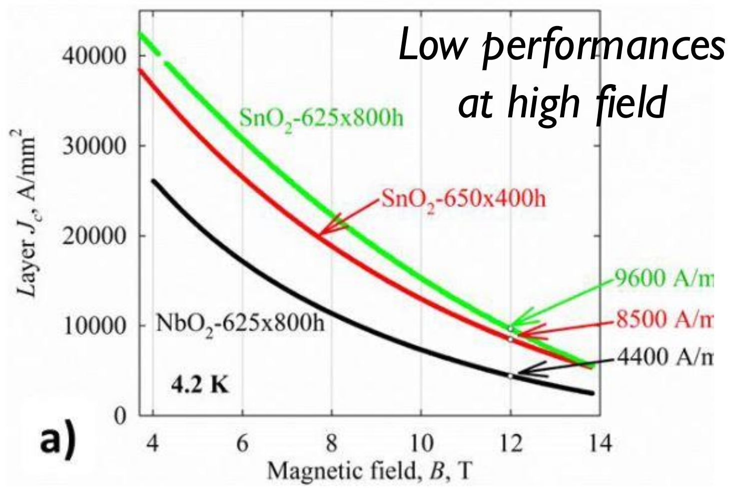
ZrO_2 (or HfO_2) nanoparticles inhibits grain boundaries movement



Proposed in 1968 on tape samples, the year before bronze route was developed. Forgotten for a long time as considered impossible to be implemented in wires

The first wire was fabricated in 2014, using a separate oxygen source to allow wire deformation



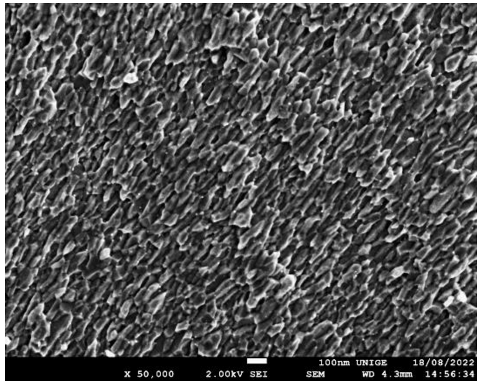


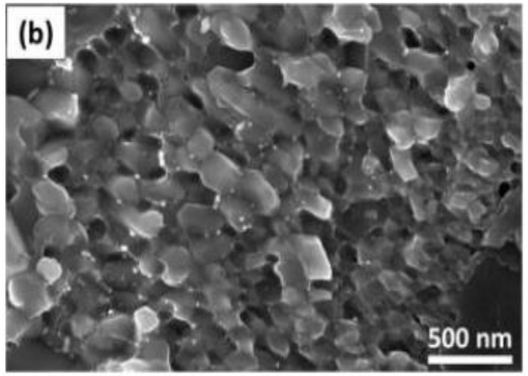
M. G. Benz *Transaction of the Metal. Soc. of AIME* (1968) 242
X. Xu et al. *Applied Physics Letters* (2014) 104.8 082602)

G. Bovone et al. Supercond. Sci. Technol. (2023) 36 095018
DOI: [10.1088/1361-6668/aced25](https://doi.org/10.1088/1361-6668/aced25)

The benefits of internal oxidation

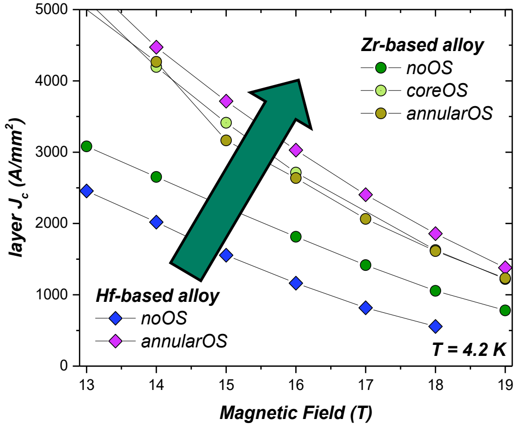
Grain refinement induced by precipitation of oxides nanoparticles

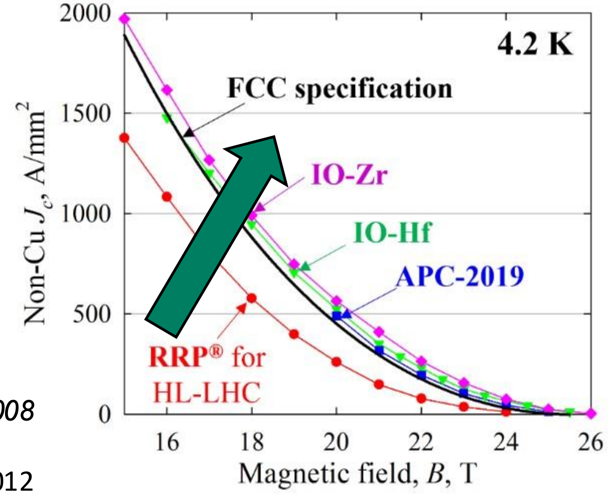




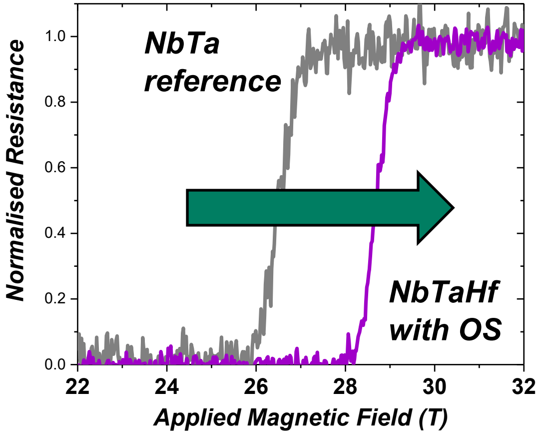
X. Xu et al. Supercond. Sci. Technol. (2023) 36 085008
DOI: [10.1088/1361-6668/acdf8c](https://doi.org/10.1088/1361-6668/acdf8c).
X. Xu et al. Supercond. Sci. Technol. (2023) 36 035012
DOI: [10.1088/1361-6668/acb17a](https://doi.org/10.1088/1361-6668/acb17a)

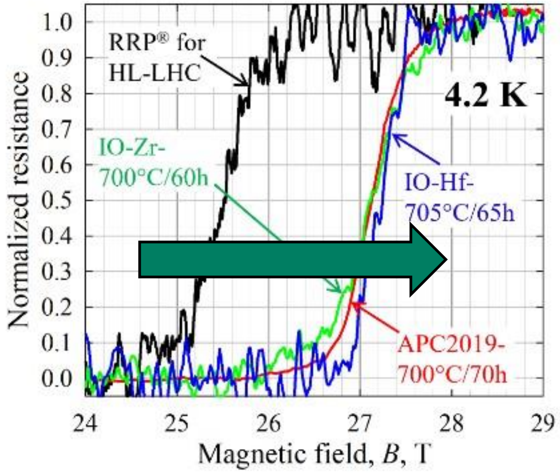
Higher J_c induced by finer Nb_3Sn grains



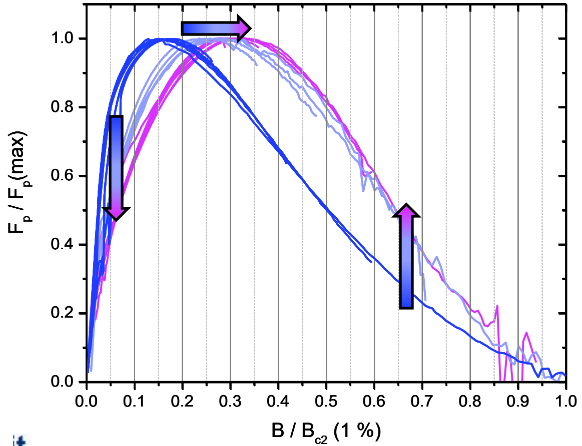


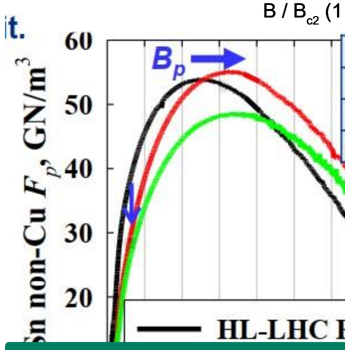
Higher B_{c2} that contribute to enhance J_c





Modification of pinning mechanism

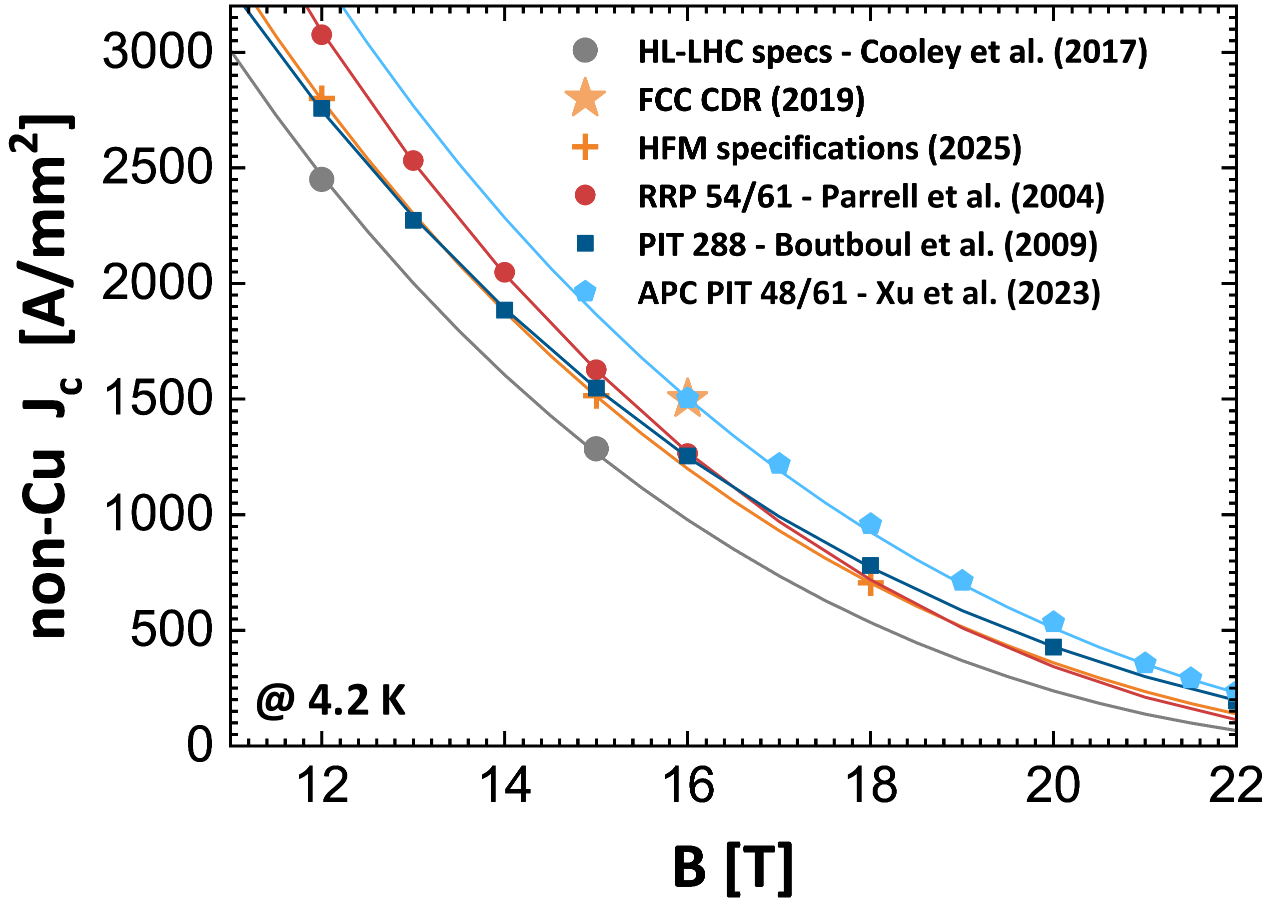




	B_p, T	B_p/B_{irr}
RRP	4.9	0.21
APC-Zr	6.7	0.29
APC-Hf	7	0.31

Results confirmed by different groups in multiple studies

Specifications for FCC-hh



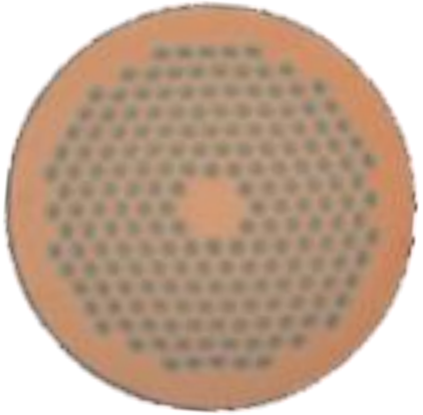
The best non-Cu J_c values for RRP and PIT wires meet the HFM specifications

Prototype PIT wires with internal oxidation (APC) exhibit even higher non-Cu J_c

Improved conductor performance could either reduce the coil size at a given field or enable higher fields

Cooley et al., IEEE TASC 27 (2017) 6000505
Abada et al., Eur. Phys. J. Special Topics 228 (2019) 755–1107
Todesco, HFM Forum (2025), URL: indico.cern.ch/event/1501797/
Parrell et al., AIP Conf. Proc. 711 (2004) 369
Boutboul et al., IEEE TASC 19 (2009) 2564
Xu et al., Supercond. Sci. Tech. 36 (2023) 035012

Manufacturing process: RRP vs PIT

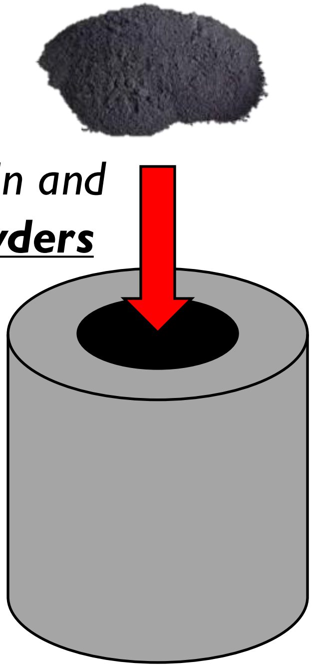


Nb_3Sn multifilamentary wire are not created equal!

The nature of the wire sub-unit (Subelement) matters!

Remember, internal oxidation requires the addition of oxide powders!

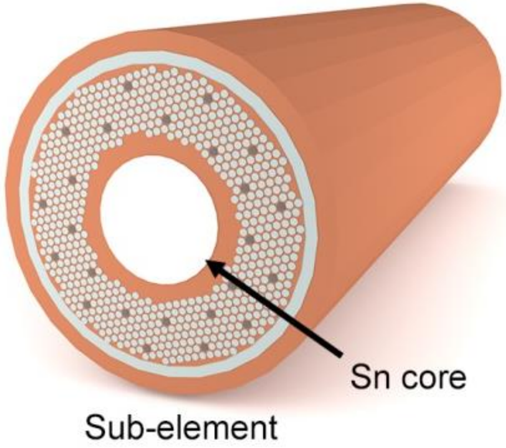
PIT wires



Mix of Cu, Sn and ***SnO_2 powders***

Easier route to introduce powders

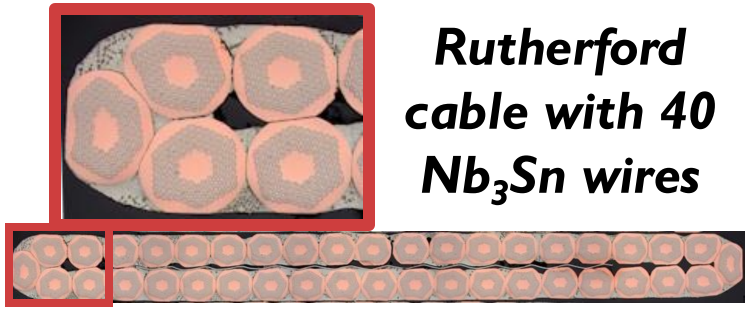
RRP wires



Powders not present in wire layout

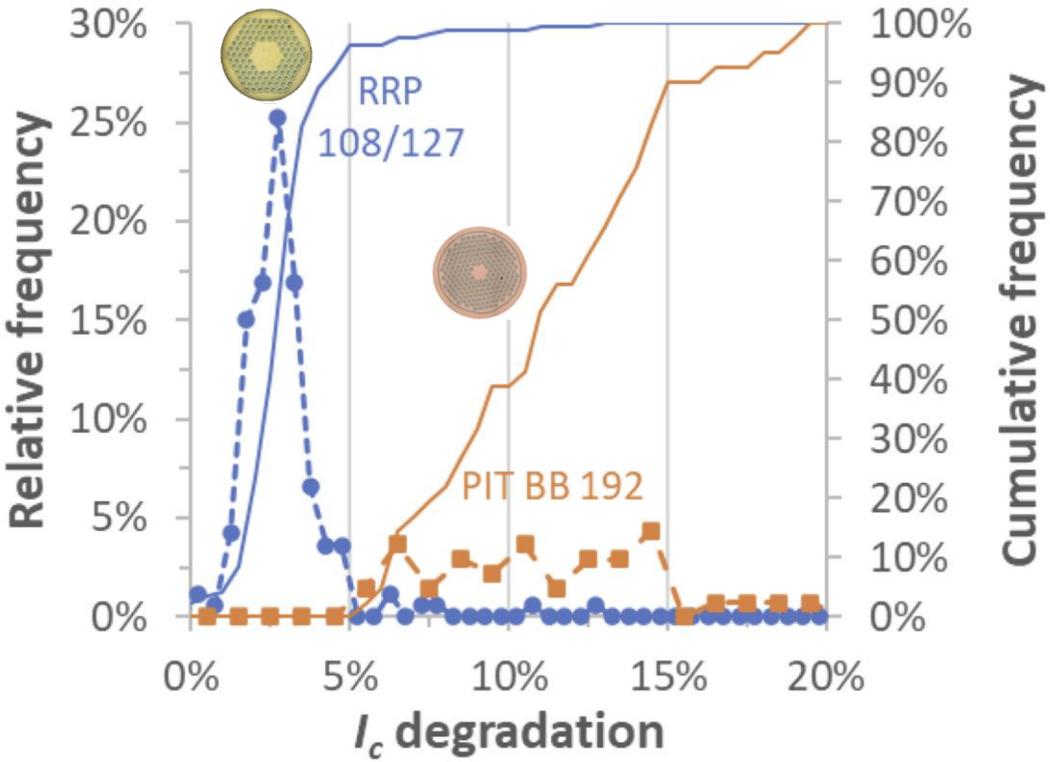
Pictures from C. Sanabria, PhD Thesis (2017), FSU

Manufacturing process: RRP vs PIT

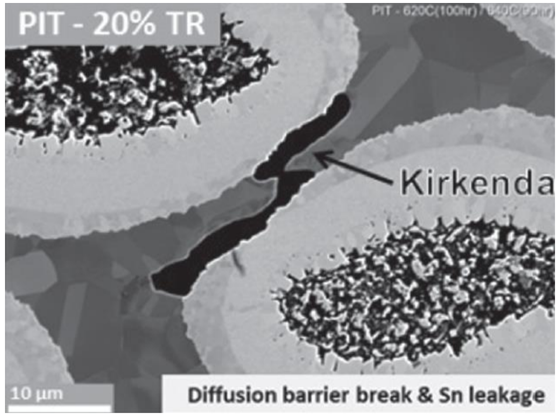


Rutherford cable with 40 Nb_3Sn wires

Section of a Nb_3Sn dipole magnet



Lower cabling degradation in Internal Sn RRP wires compared to PIT wires



Distorted filaments produce Sn leak. Reaction is not complete, leading to the lower I_c and Cu contamination

S. Hopkins *et al. IEEE Trans. Appl. Supercond.* 34 (2024) 6001308 **DOI:** 10.1109/TASC.2024.3375274

M. Brown *et al. Supercond. Sci. Technol.* 29 (2016) 084008 **DOI:** 10.1088/0953-2048/29/8/084008

C. Segal *et al. Supercond. Sci. Technol.* 29 (2016) 085003 **DOI:** 10.1088/0953-2048/29/8/085003

How it’s made: high-J_c RRP Nb_3Sn wire

1. Filament processing

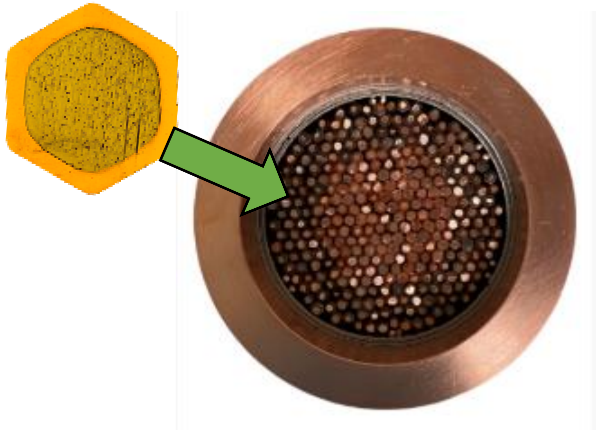
Critical Point!

Hot Extrusion

Cold Deformation

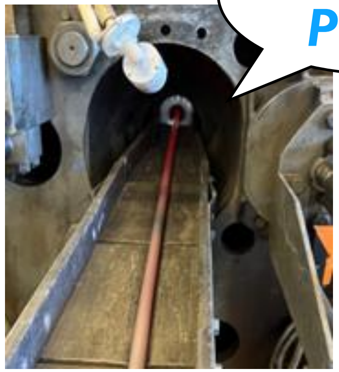
RRP wire production involves hot extrusion, hot isostatic pressing and cold deformation

2. Subelement processing



HIP

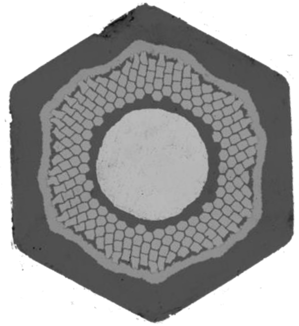
Critical Point!



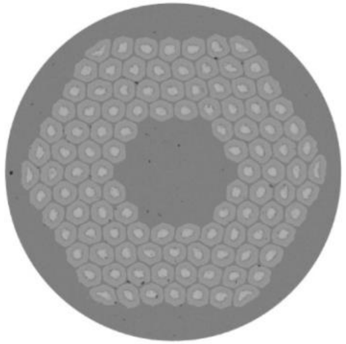
Critical Point!

Hot Extrusion

3. Wire processing



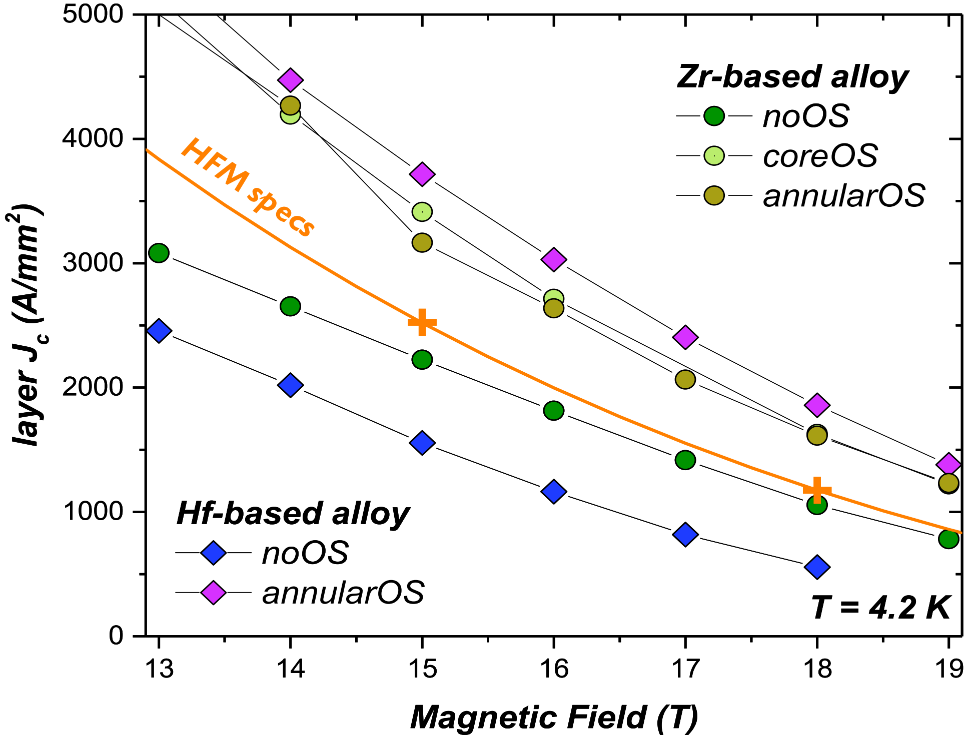
Sn rod insertion and cold deformation



Subelement restack and cold deformation to final diameter

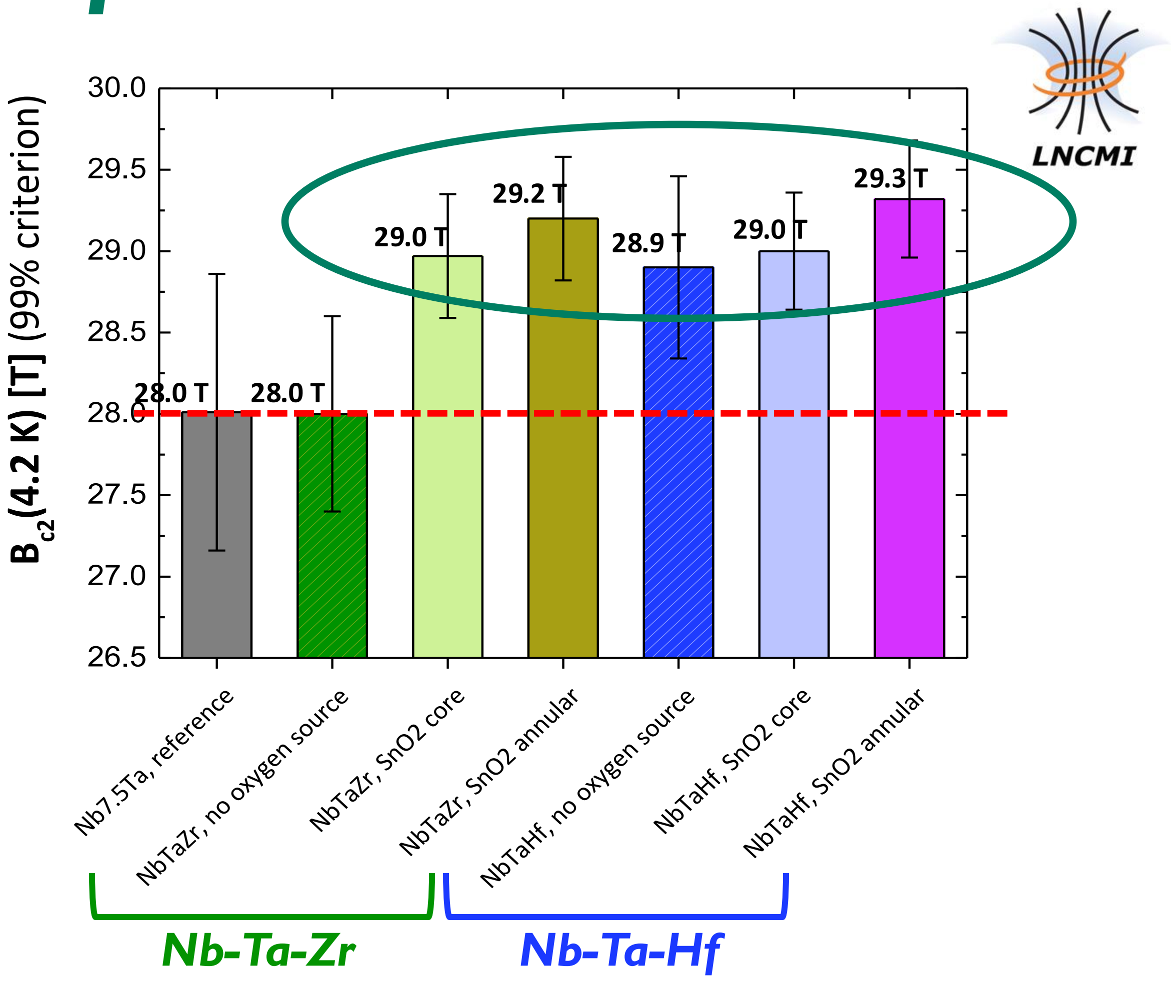
Internal oxidation in simplified RRP wires

Transport I_c and B_{c2} measurements



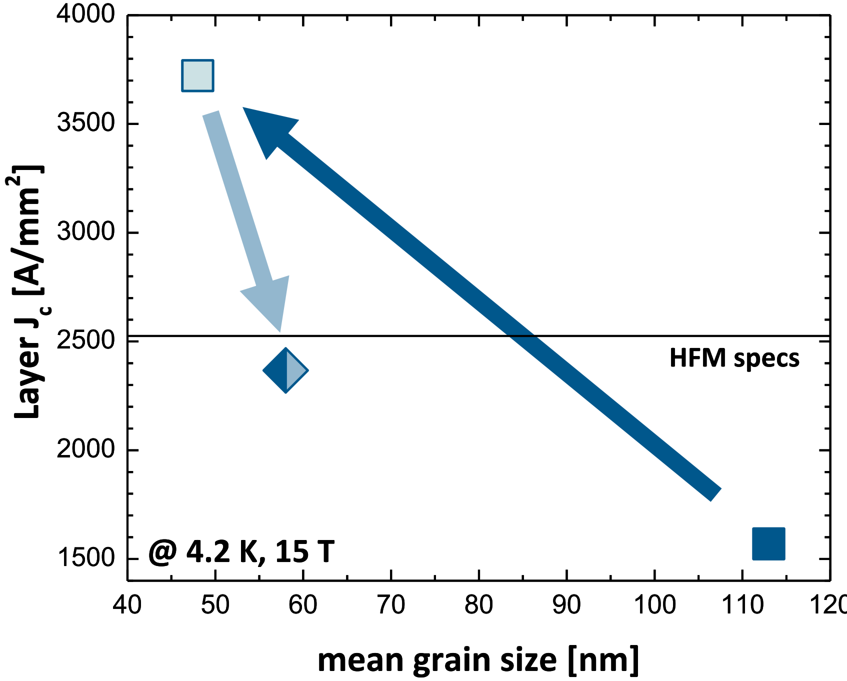
Layer J_c determined from transport measurements

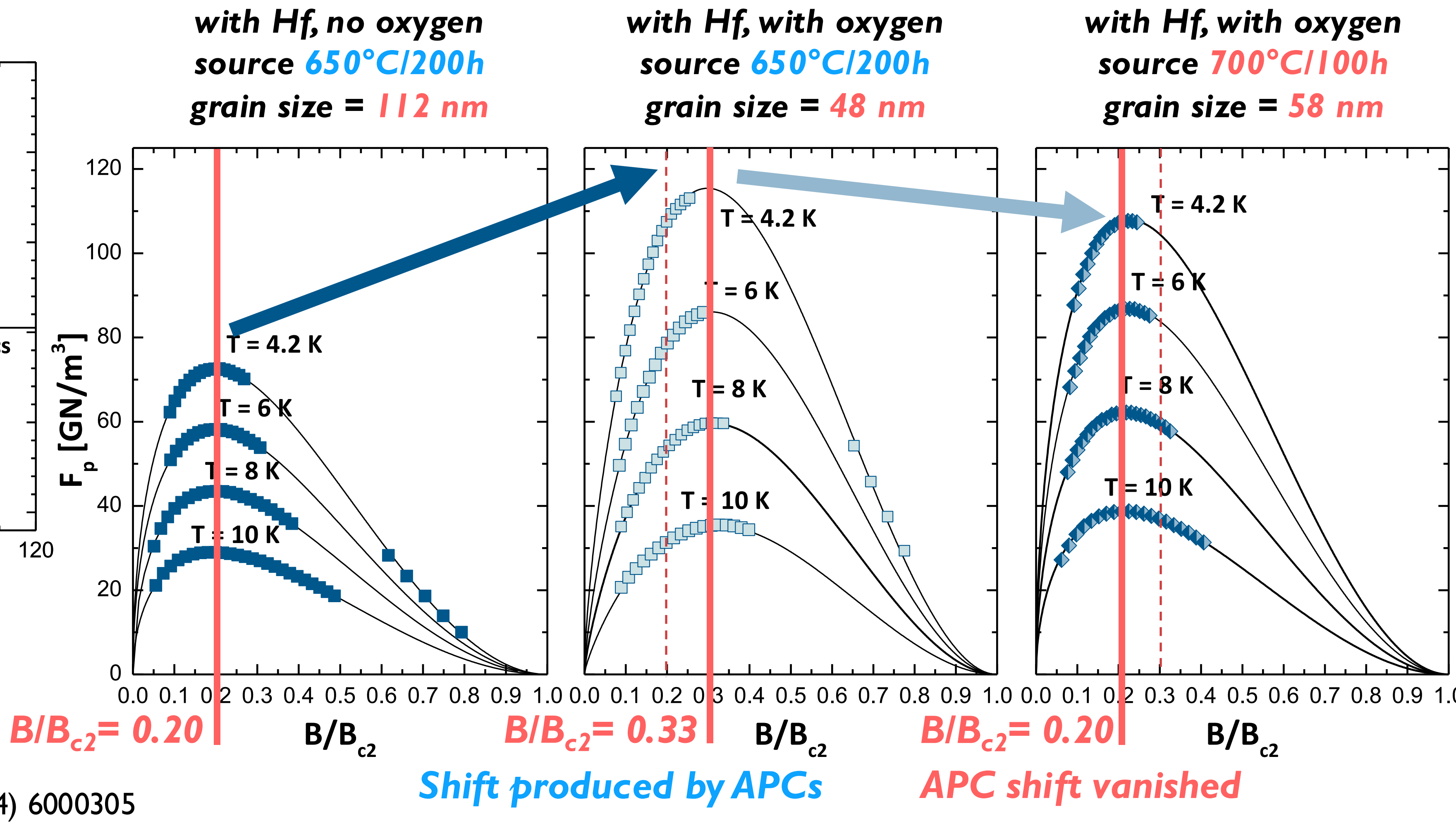
G. Bovone *et al. Supercond. Sci. Tech.* 36 (2023) 095018
DOI: 10.1088/1361-6668/aced25



R(B) tests performed up to 33 T at LNCMI-Grenoble show record high B_{c2} values achieved both with Hf and Zr

The size of APC nanoparticles matters

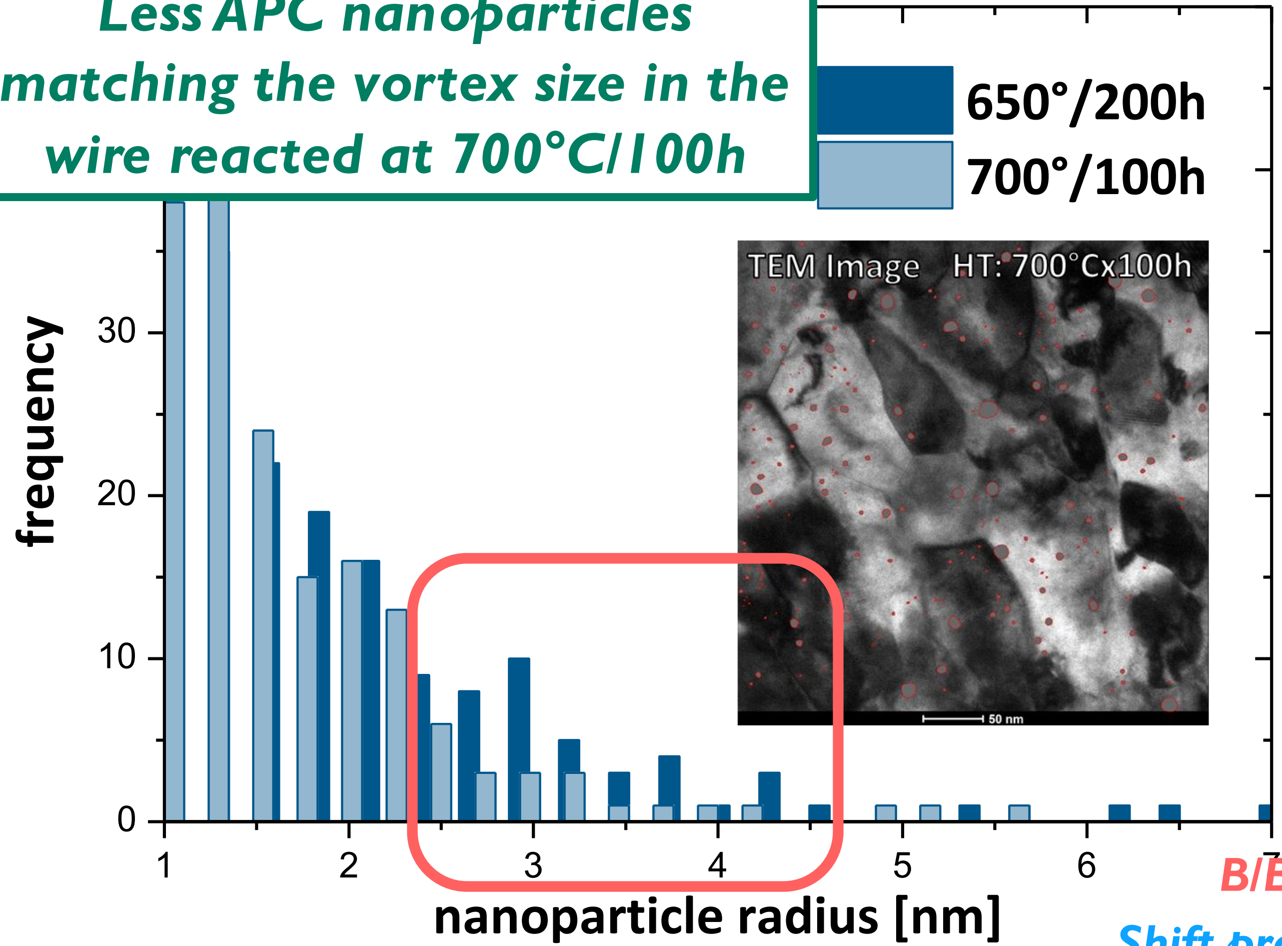




F. Lonardo *et al. IEEE Trans. Appl. Supercond.* 34 (2024) 6000305
DOI: 10.1109/TASC.2024.3355353

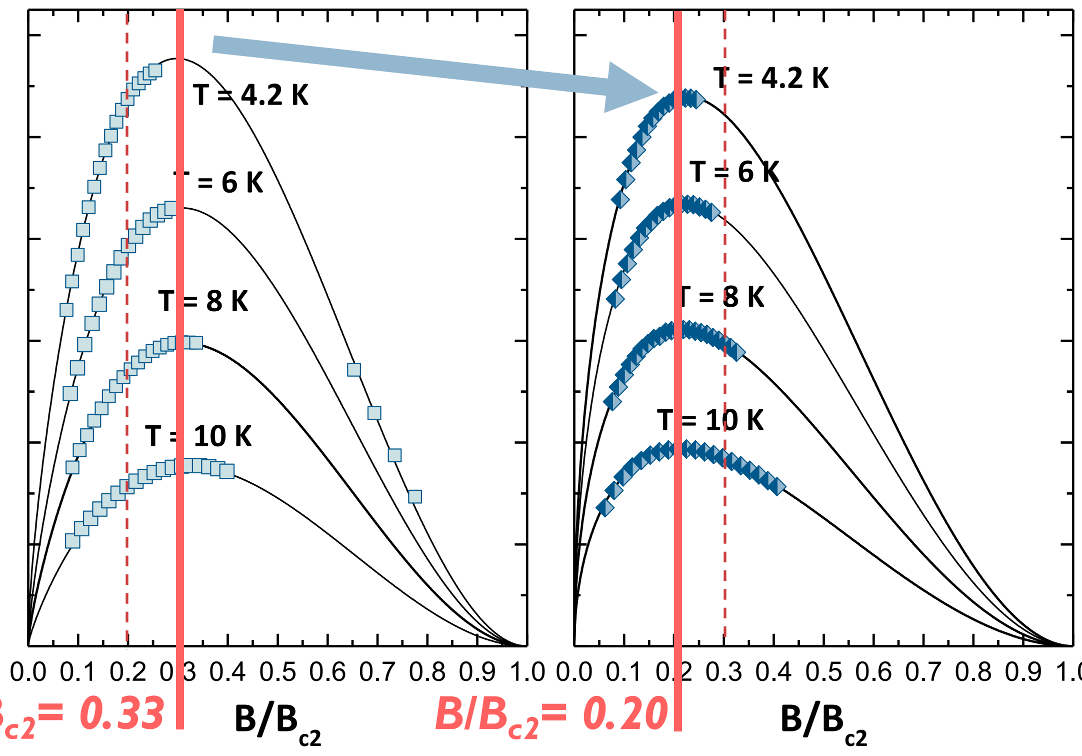
The size of APC nanoparticles matters

Less APC nanoparticles matching the vortex size in the wire reacted at 700°C/100h



with Hf, with oxygen source 650°C/200h grain size = 48 nm

with Hf, with oxygen source 700°C/100h grain size = 58 nm



B/B_{c2}= 0.33 *B/B_{c2}= 0.20*

Shift produced by APCs *APC shift vanished*

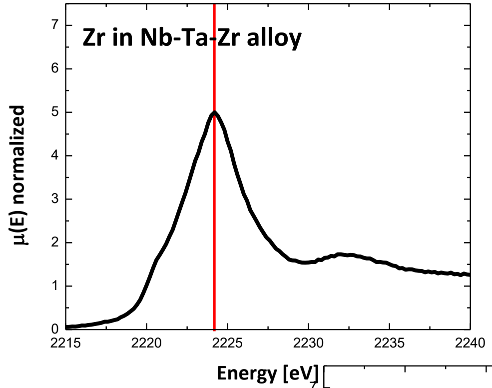
F. Lonardo *et al. IEEE Trans. Appl. Supercond.* 34 (2024) 6000305
DOI: 10.1109/TASC.2024.3355353

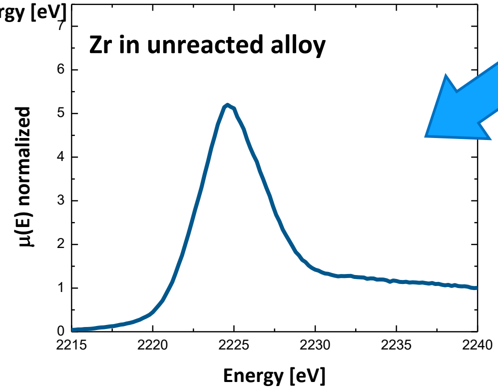
APC nanoparticles forms along with Nb_3Sn

Spatial distribution of the nanoparticles by X-ray Absorption Spectroscopy

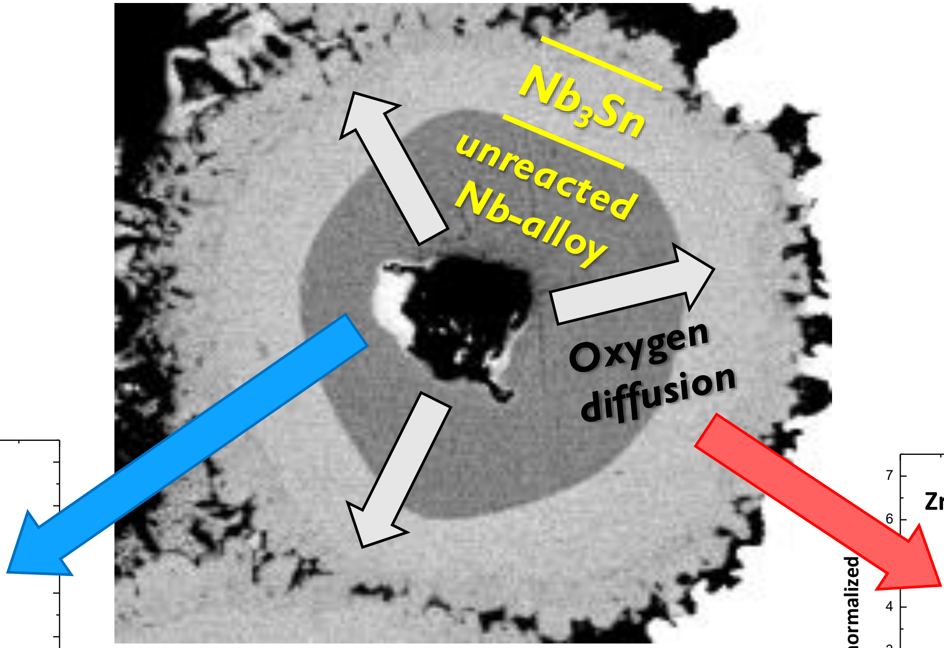
REFERENCE #1

XAS spectrum of Zr in Nb-Ta-Zr alloy





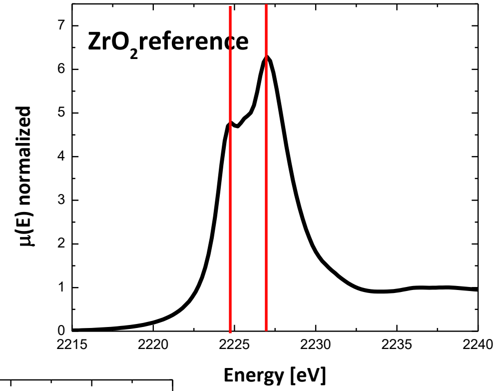
Reacted Monofilamentary Wire

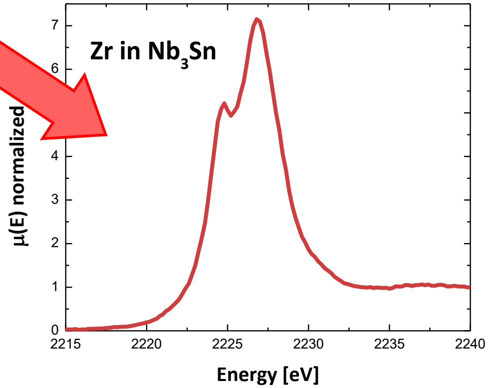


Zr spectrum in unreacted alloy very similar to reference #1 despite the oxygen diffusion during the heat treatment

REFERENCE #2

XAS spectrum of Zr in ZrO_2



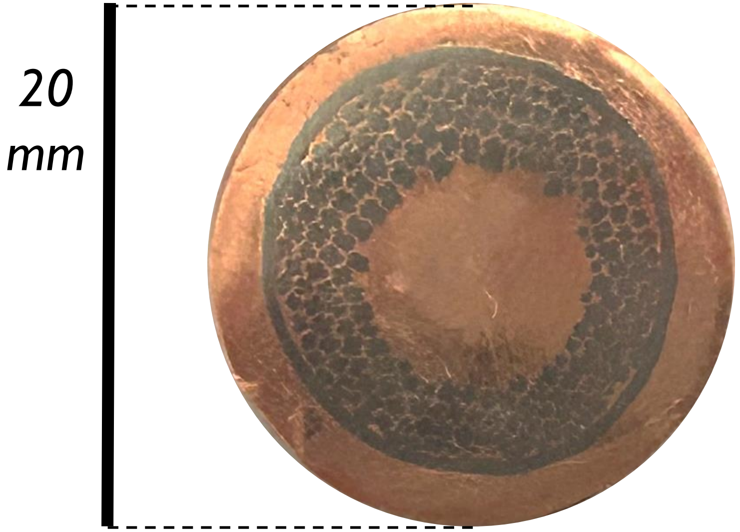


ZrO_2–like spectrum found only in Nb_3Sn!

PSI

G. Bovone *et al. IEEE Trans. Appl. Supercond.* 34 (2024) 6000205
DOI: 10.1109/TASC.2024.3354232

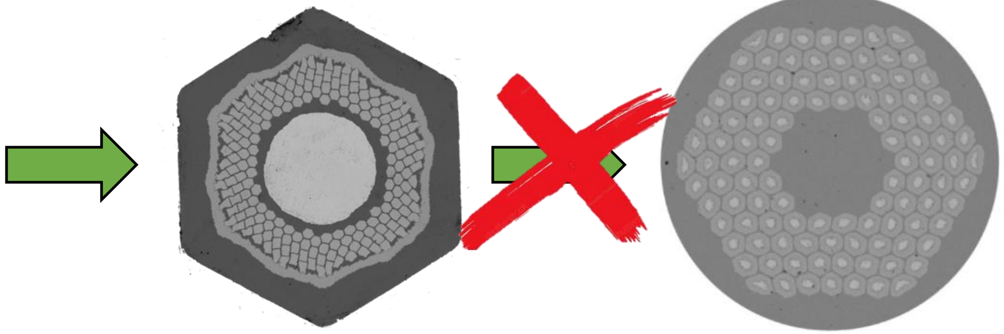
Internal oxidation in extruded subelement

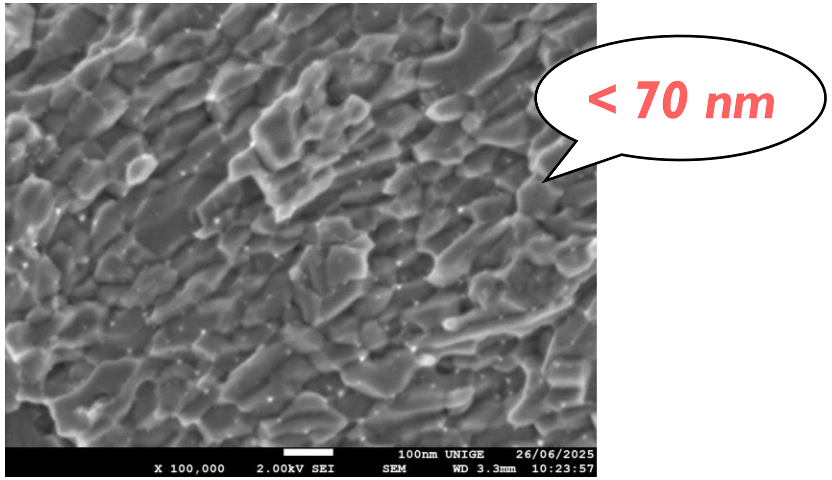


Subelement extruded at 600 °C. Each filament contains OS at the periphery of Nb

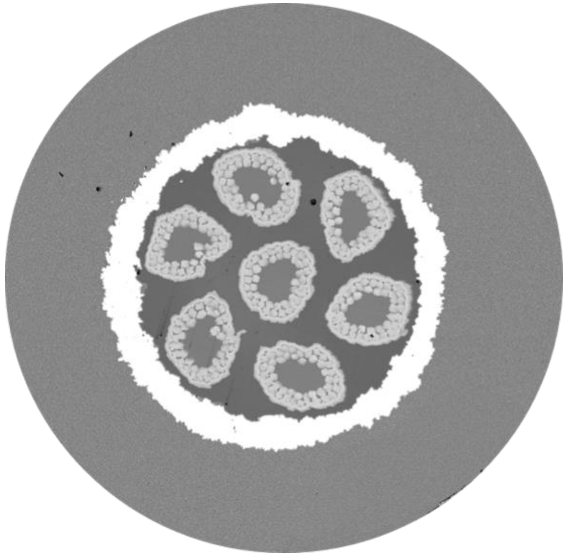
The oxygen source promoted grain refinement of Nb_3Sn

3. Wire processing





Internal oxidation in a simplified RRP

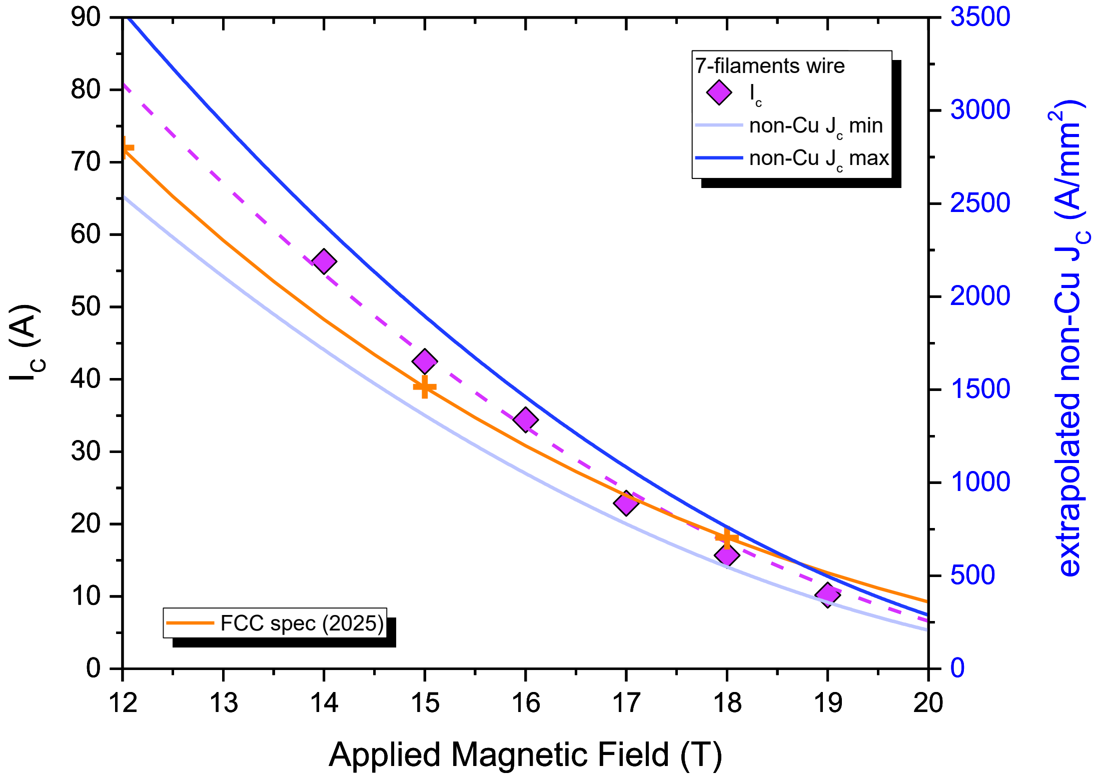


Simplified RRP wire (7/7) made from cold deformed subelements ***(filaments and subelements are cold deformed)***

Wire Properties	*Value*	*Ideal*
Reaction %	*53.8 %*	*100 %*
Nb/non Cu Area %	*50.0 %*	*50 – 60 %*
Nb/Sn at	*3.1*	*3.1 – 3.6*
Sn/Sn+Cu wt %	*45.1 %*	*50 – 60 %*

Excess of Cu and low Sn content causes the thin reaction layer.

Wide spread results on J_c due to very variable cross-section, low reaction layer and broken subelements



Internal oxidation successfully implemented in a (simplified) Nb_3Sn RRP multifilamentary wire

To conclude

- *Despite its "age"* ***Nb_3Sn is still an important material***
- ***FCC-hh*** *reignite the* ***fundamental research on Nb_3Sn***
- *The* ***internal oxidation*** *is the best way to meet* ***FCC-hh specification*** *for the wire*
- ***Internal oxidation*** *promote* ***J_c enhancement*** *due to* ***grain refinement, enhancement of B_{c2}*** *and* ***modified pinning mechanism (APC pinning)***
- *For applications,* ***J_c is not all,*** *as the wire need to be "****robust****"*

Thank you for your attention