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Swiss National
Science Foundation

Challenges and Approaches for Introducing Internal Oxidation in Rod-in-Tube Nb_3Sn wires

Gianmarco BOVONE, Francesco LONARDO, Florin BUTA,

and Carmine SENATORE

Department of Quantum Matter Physics, University of Geneva, Switzerland
Department of Nuclear and Particle Physics, University of Geneva, Switzerland

Simon C. HOPKINS and Thierry BOUTBOUL

CERN, Switzerland

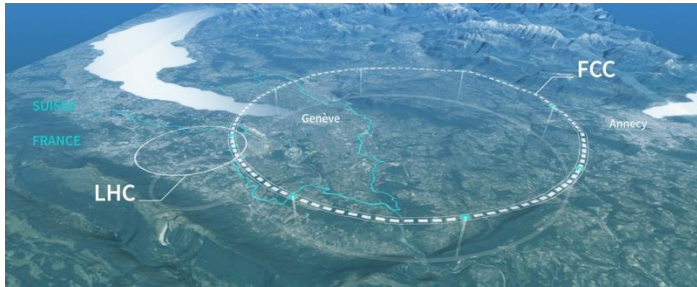


Swiss Accelerator
Research and
Technology

Outline of the presentation

- **The importance of internal oxidation**
 - *Role of APCs in superconducting and microstructural properties*
- **Nb_3Sn wires are not created equal**
 - *Differences between PIT and RRP wires*
 - *Is there a better wire technology for accelerator magnets?*
- **How to implement APCs in RRP wires**
 - *Where should we add the OS?*
 - *How to make the OS resist to high temperature?*
- **Wires from extruded billets with internal oxidation**

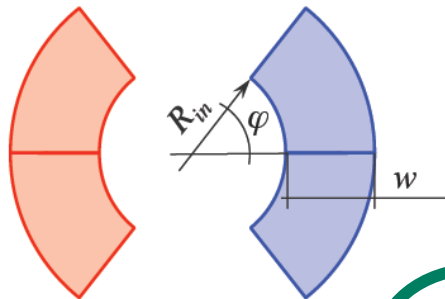
The importance of oxidation for Nb₃Sn



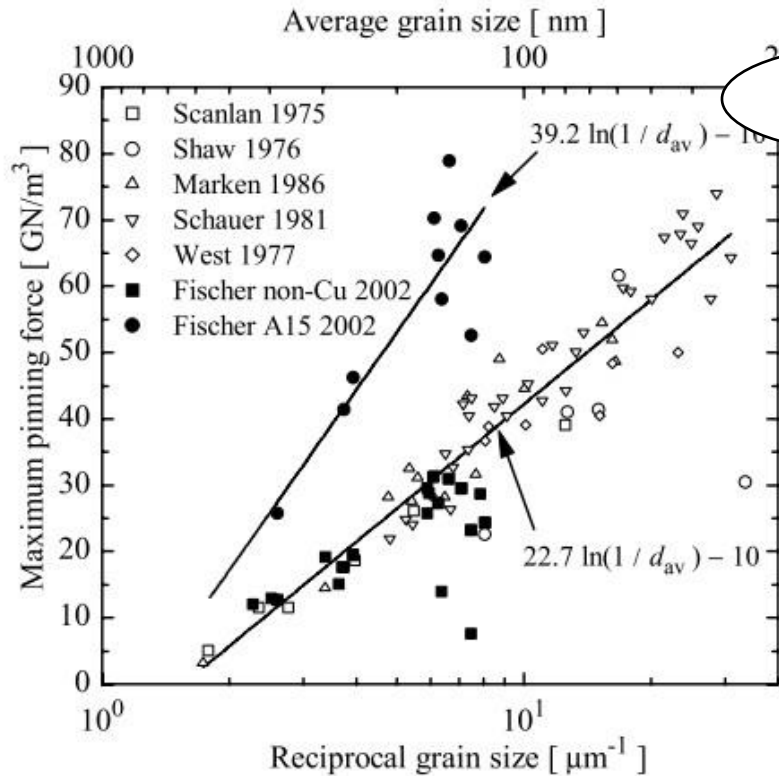
LHC
27 km, 8.33 T
14 TeV (c.o.m.)
1'300 tons NbTi

FCC-hh
91 km, 14 T
~ 85 TeV (c.o.m.)
~10'000 tons Nb₃Sn

A huge amount of Nb₃Sn!!

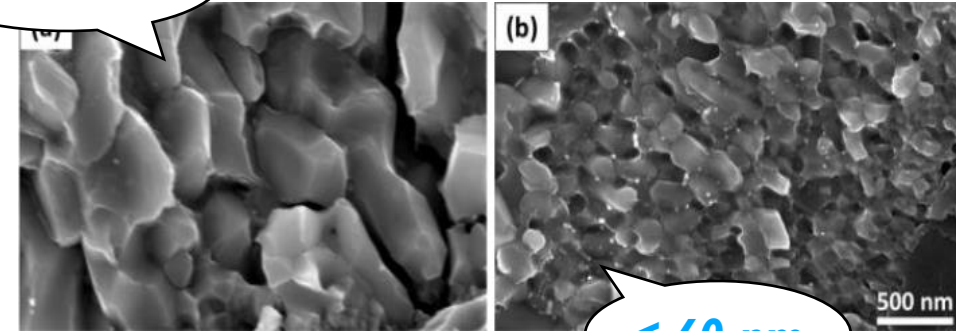


$$A_{coil} = 2\phi(w + 2R_{int}V) \propto \frac{1}{J}$$



How can we reduce effectively grain size?

> 100 nm



Internal oxidation !

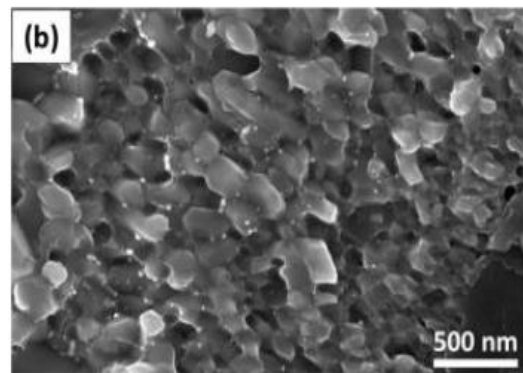
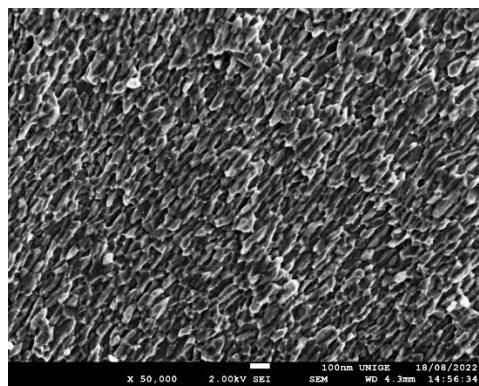
< 60 nm

Grain refinement induced by precipitation of oxides nanoparticles

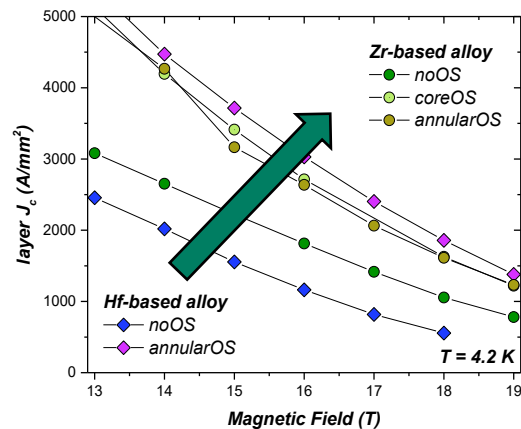
- Xu X et al. *Appl. Phys. Lett.* 104, 082602 (2014)
DOI: [10.1063/1.4866865](https://doi.org/10.1063/1.4866865).
- Benz M G, *Trans. Met. Soc. AIME*, 242: 1067-70 (1968).
- Rumaner L E et al. *Metall Mater Trans A*. 25, 213-219 (1994)
DOI: [10.1007/BF02646689](https://doi.org/10.1007/BF02646689).
-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

The benefits of internal oxidation

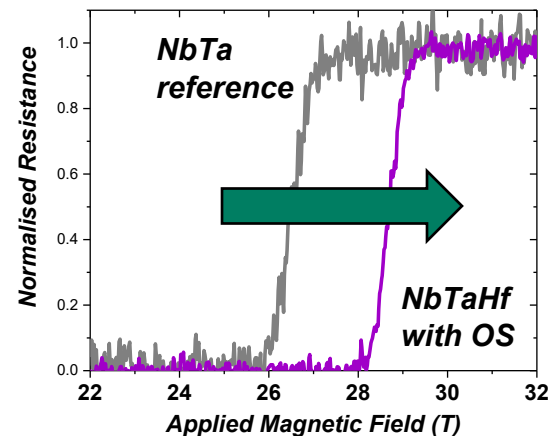
Grain refinement induced by precipitation of oxides nanoparticles



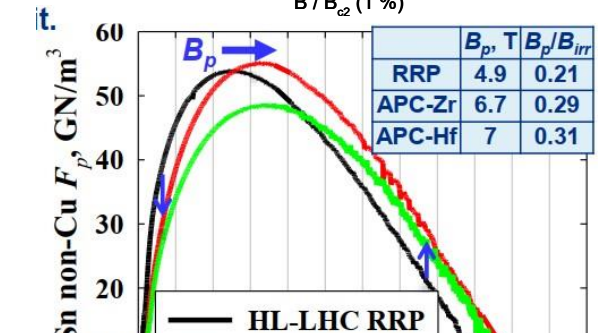
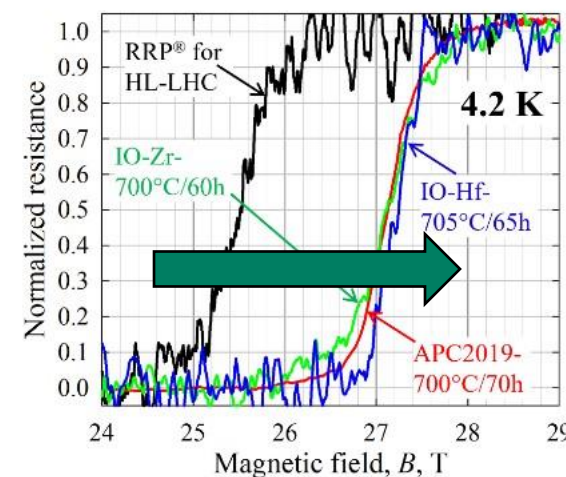
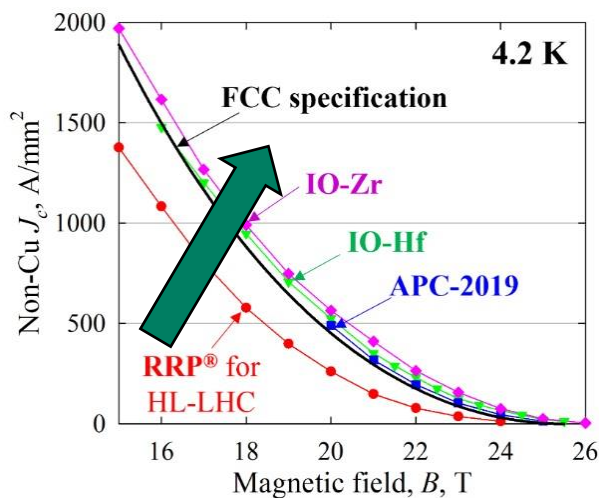
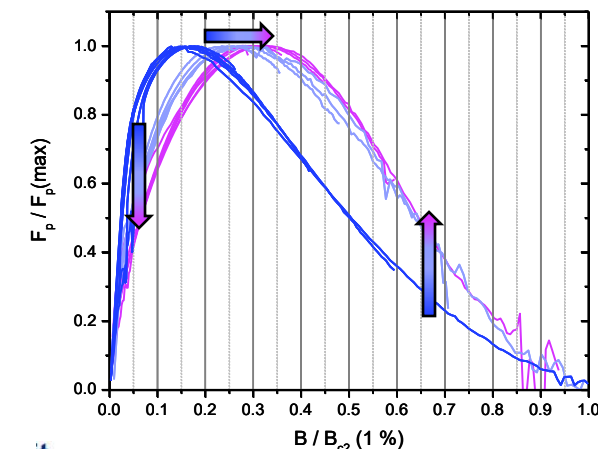
Higher J_c induced by finer Nb_3Sn grains



Higher B_{c2} that contribute to enhance J_c



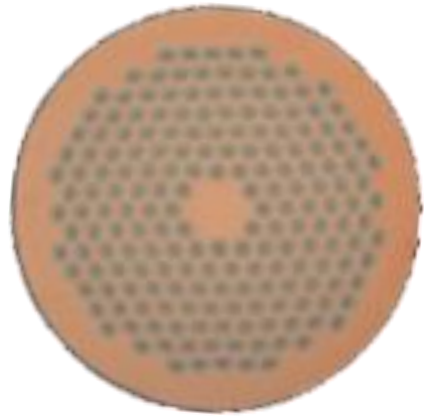
Modification of pinning mechanism



Results confirmed by different groups in multiple studies

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

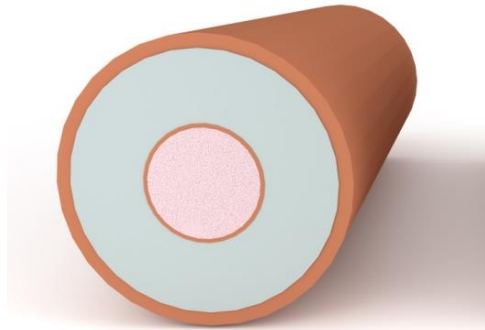
Manufacturing process



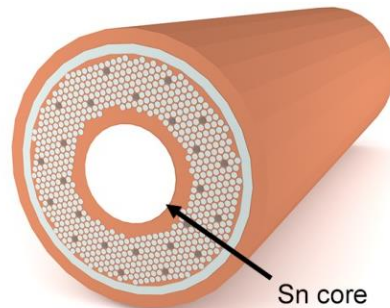
Nb_3Sn multifilamentary wire are not created equal!

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

Remember, internal oxidation requires the addition of oxide powders!



Powder-in-Tube filament

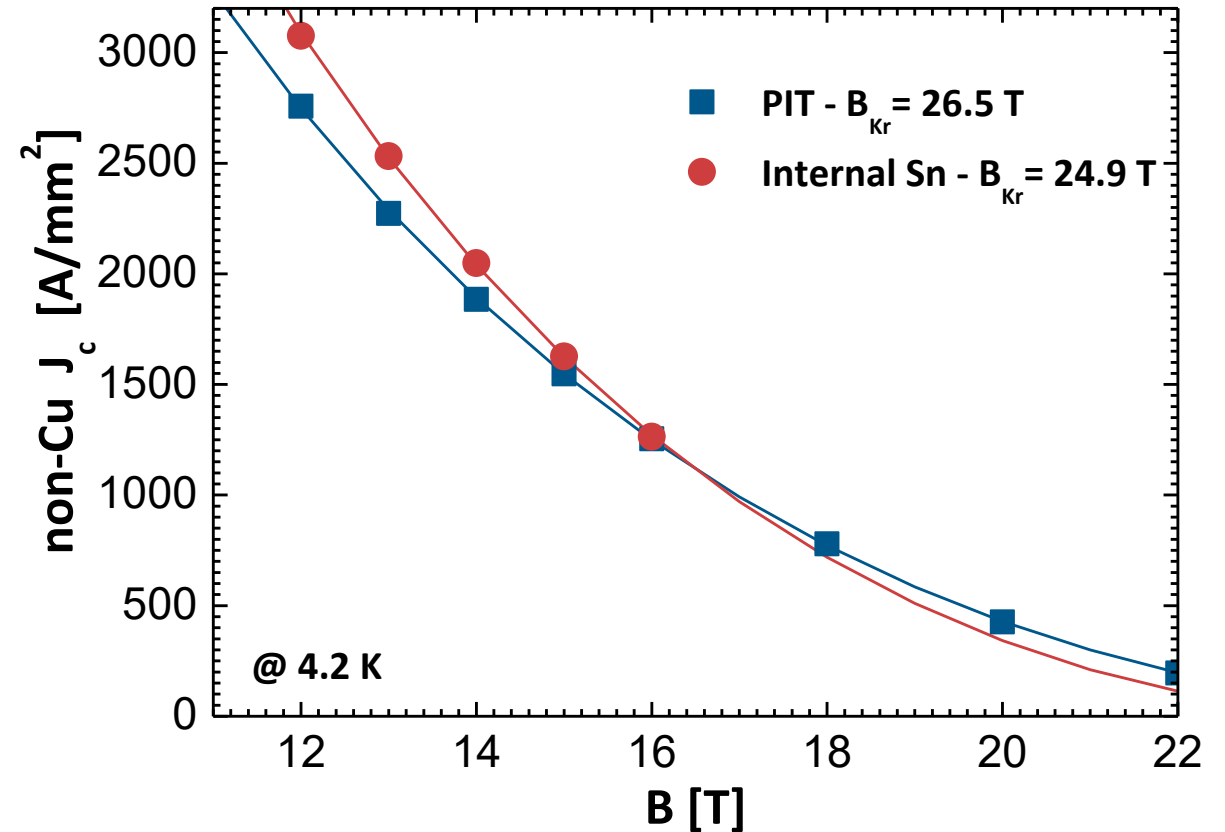


Sub-element

Sn core

PIT wires:

- Higher J_c at high field
- Easier route to introduce powders

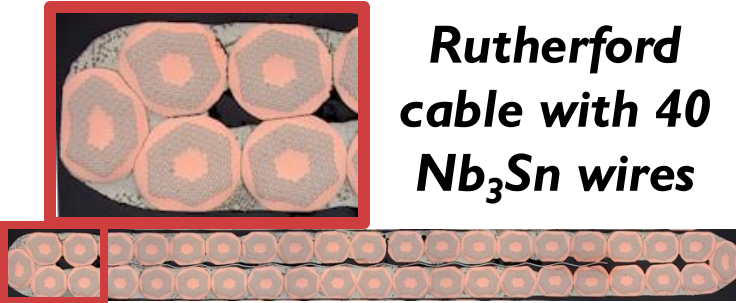


RRP wires:

- Higher J_c in the field regime of FCC
- Powders not present in wire layout

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

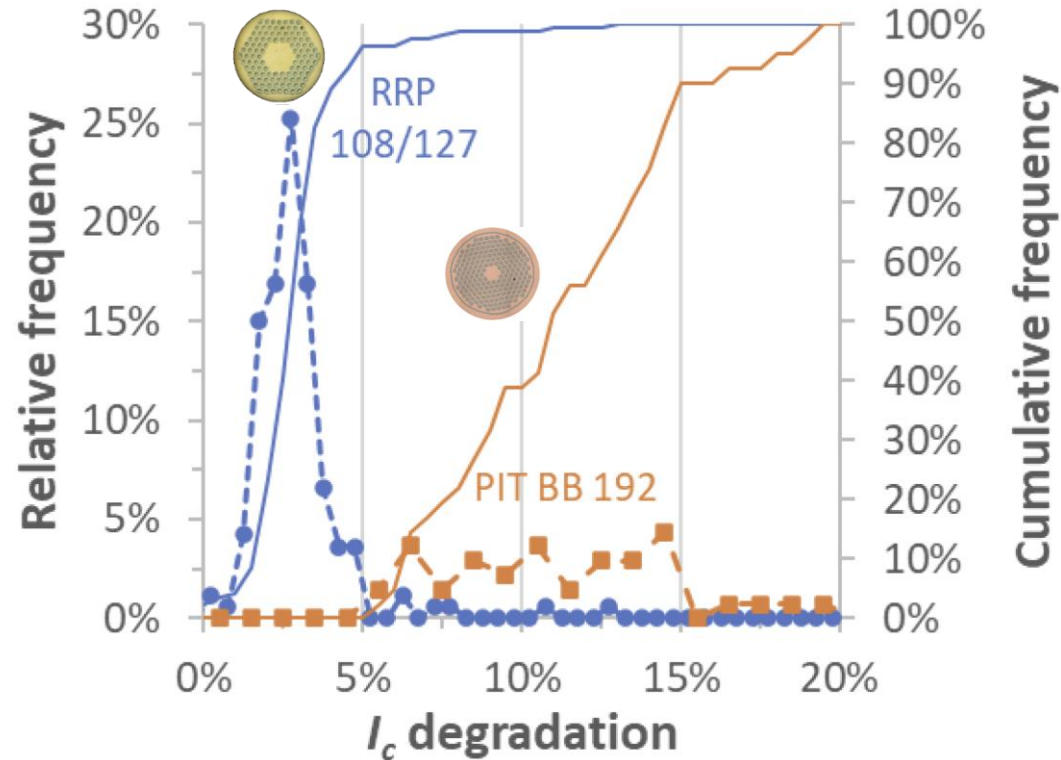
Manufacturing process: RRP vs PIT



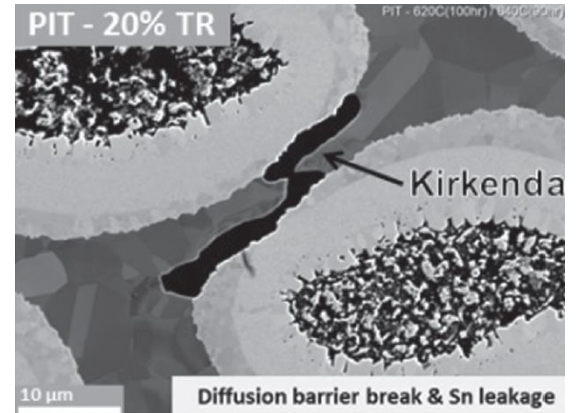
Rutherford cable with 40 Nb_3Sn wires



Section of a Nb_3Sn dipole magnet



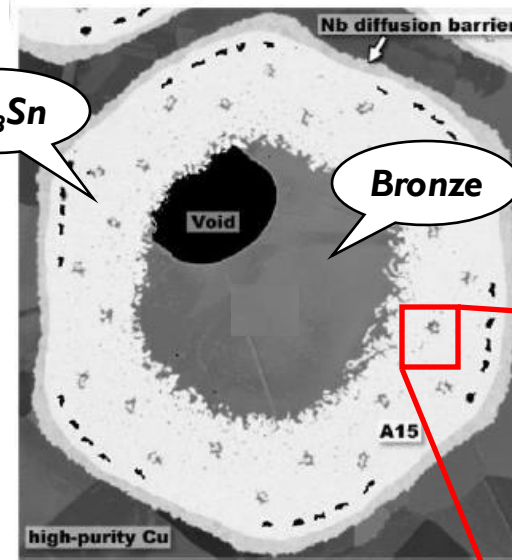
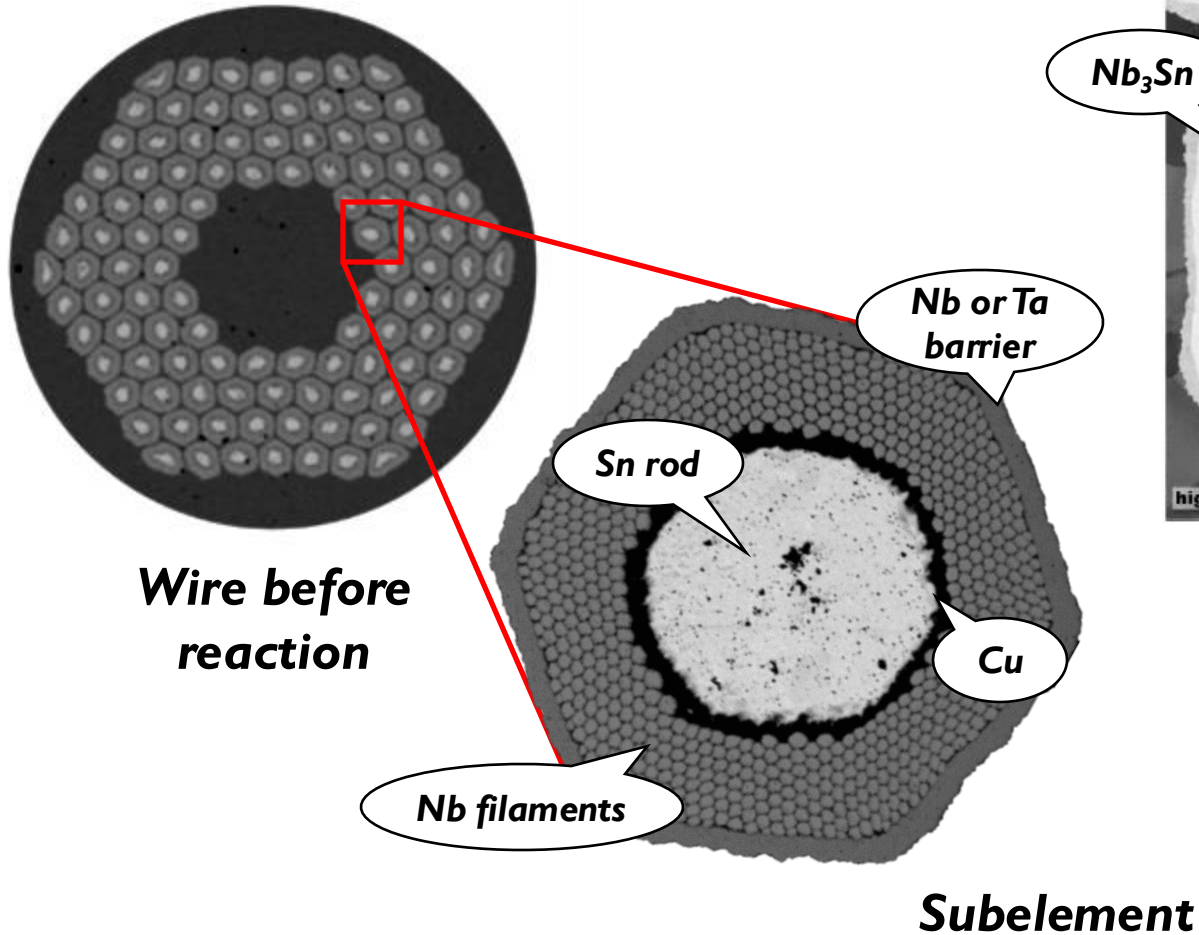
Lower cabling degradation in RRP wires compared to PIT wires



Distorted filaments produce Sn leak and thus are only partly reacted, leading to the lower I_c

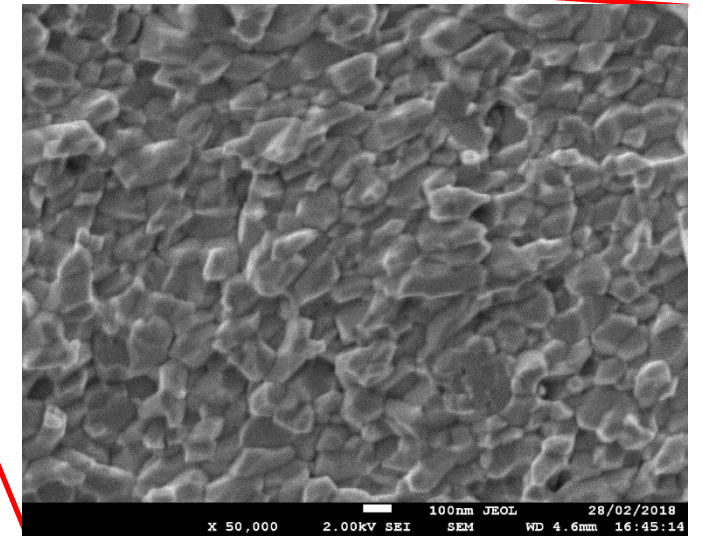
- M. Brown et al. *Supercond. Sci. Technol.* 29 084008 (2016) DOI: [10.1088/0953-2048/29/8/084008](https://doi.org/10.1088/0953-2048/29/8/084008)
- C. Segal et al., *Supercond. Sci. Technol.* 29 (2016) 085003 DOI: [10.1088/0953-2048/29/8/085003](https://doi.org/10.1088/0953-2048/29/8/085003)
- S. Hopkins et al. *IEEE Trans. Appl. Supercond.* 34 6001308 (2024) DOI: [10.1109/TASC.2024.3375274](https://doi.org/10.1109/TASC.2024.3375274)

How it's made: Nb_3Sn RRP wire



Subelement after reaction

No powder in the wire layout! Where should we add the OS?

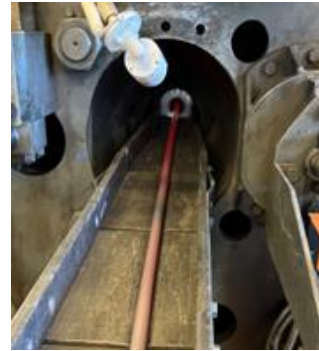
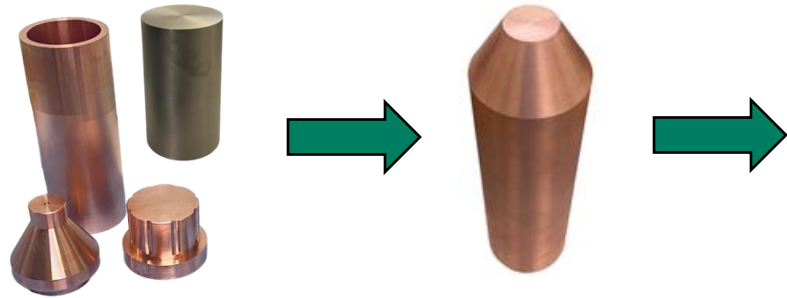


Nb_3Sn microstructure

Critical current density $\propto 1/(\text{grain size})$

How it's made: Nb_3Sn RRP wire

1. Filament processing



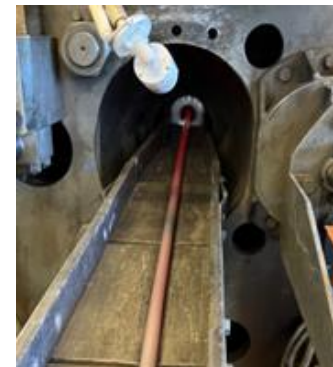
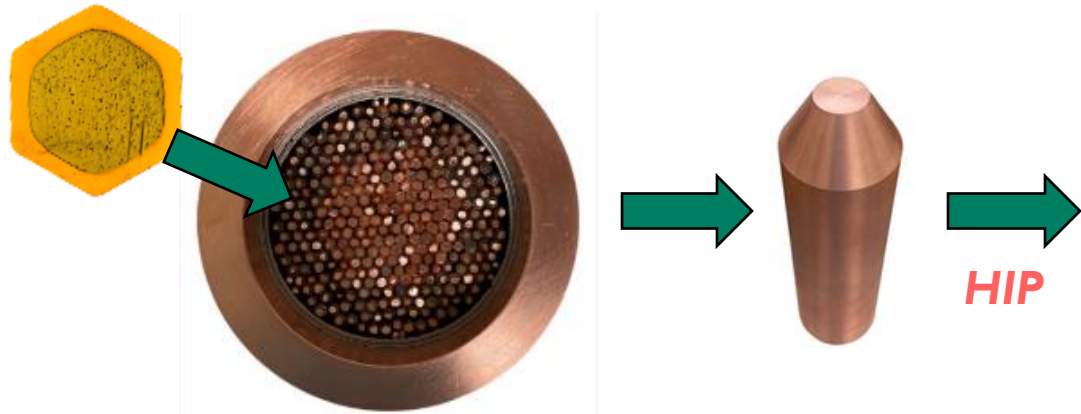
Hot Extrusion

Cold
Deformation



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

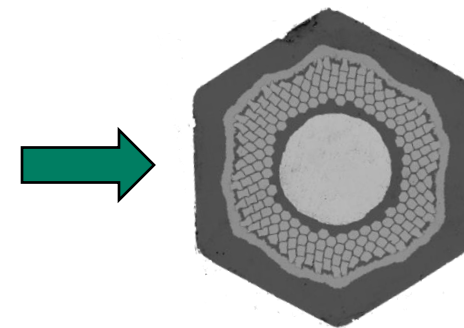
2. Subelement processing



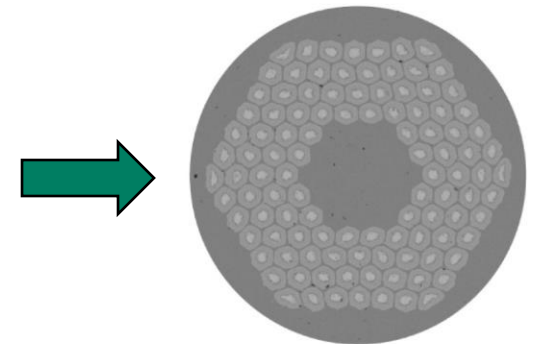
Hot Extrusion

HIP

3. Wire processing



**Sn rod insertion
and cold deformation**



**Subelement restack
and cold deformation
to final diameter**

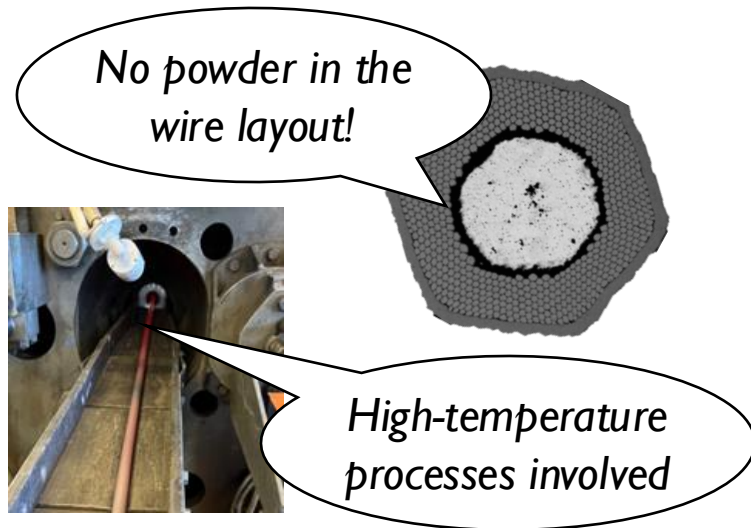
The challenges we are facing at



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Challenges for internal oxidation in RRP wires



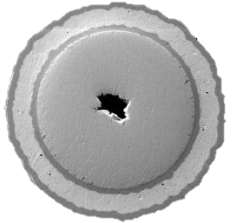
The challenges for RRP

- Where should we add the OS?
- How to make the OS resist to high temperature?

The three steps to solve them

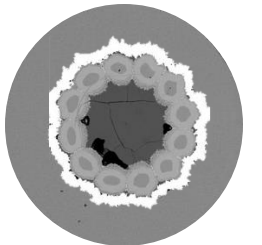
1. Material study

Test of various alloys and oxides (and their combinations) on monofilament



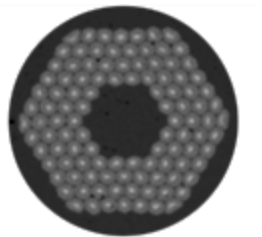
2. Determination of OS efficiency

Study of oxygen source configurations to optimize superconducting properties (I_c , B_{c2} , pinning) on simplified subelement



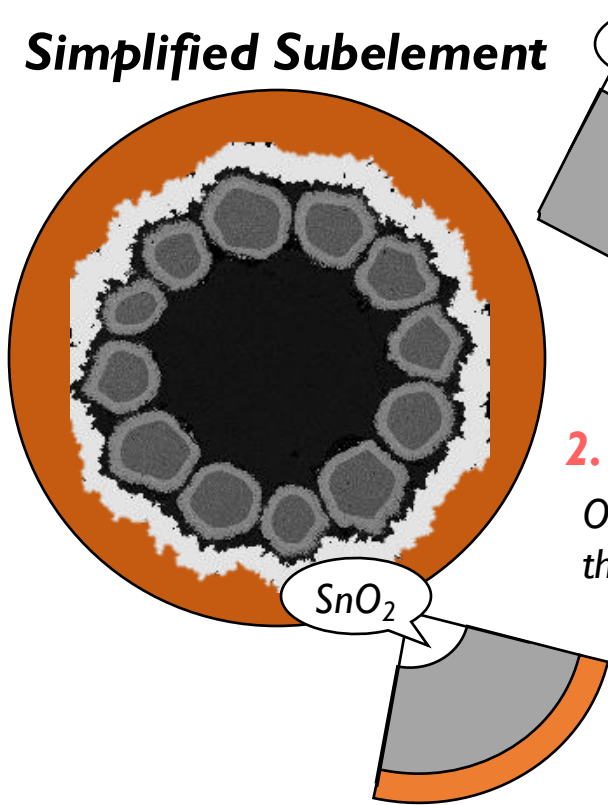
3. OS stability during wire manufacture

Verify OS stability along high temperature treatment along the preparation of a multifilamentary wire



Where should we add the OS?

Simplified Subelement



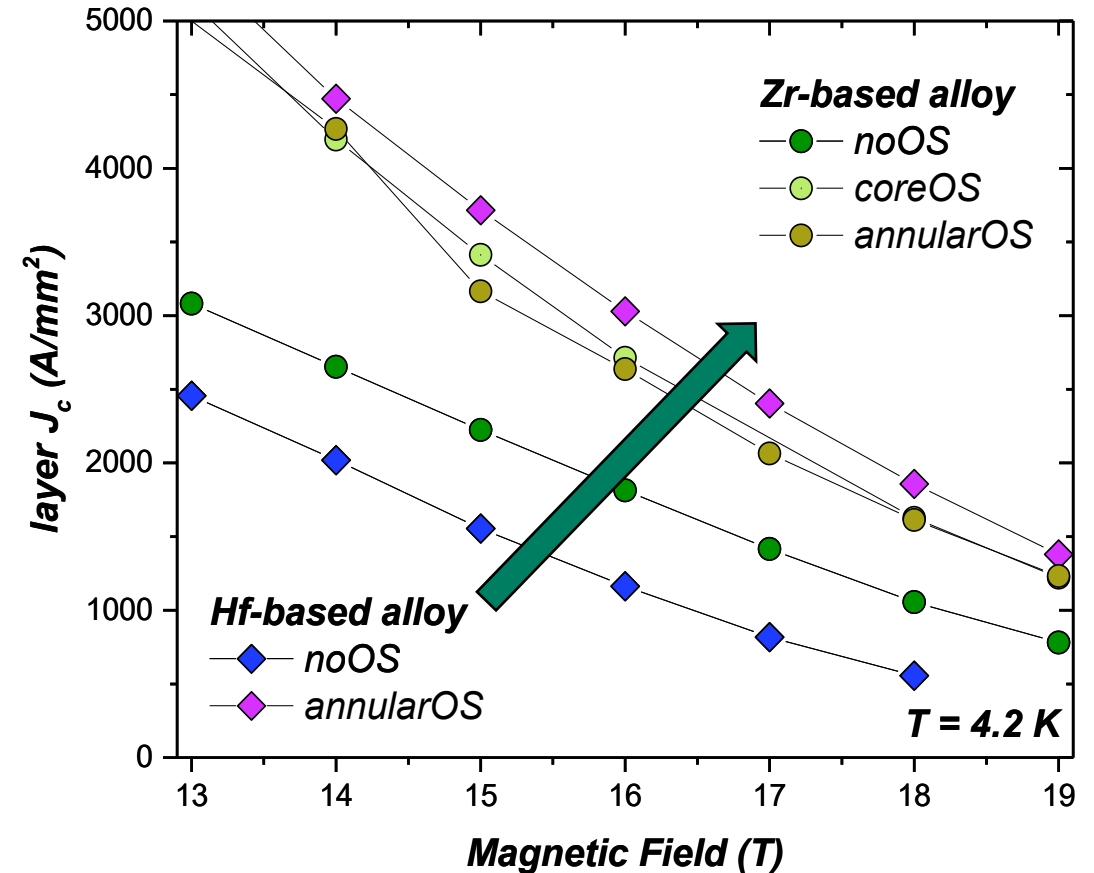
Two OS configurations

1. AnnularOS

Oxide powder between the Nb-alloy filament and the copper jacket

2. CoreOS

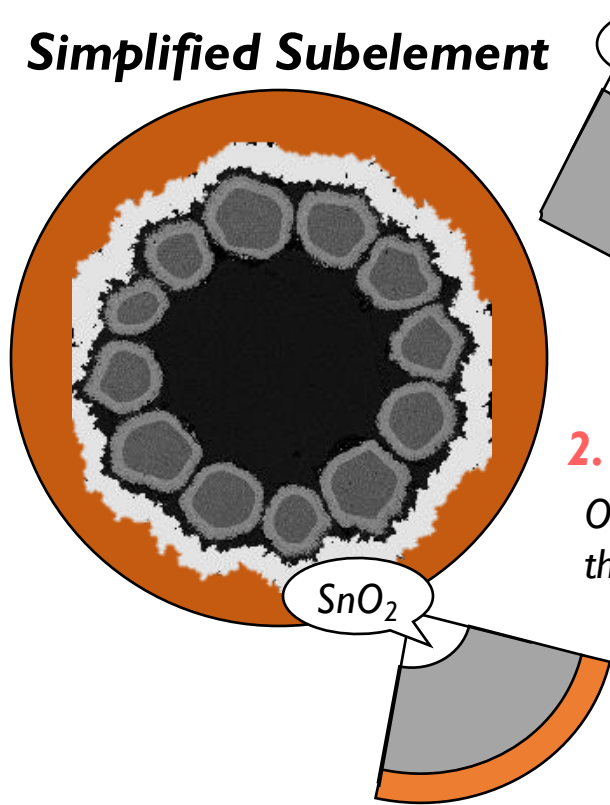
Oxide powder inside the Nb-alloy filaments



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

Where should we add the OS?

Simplified Subelement



Two OS configurations

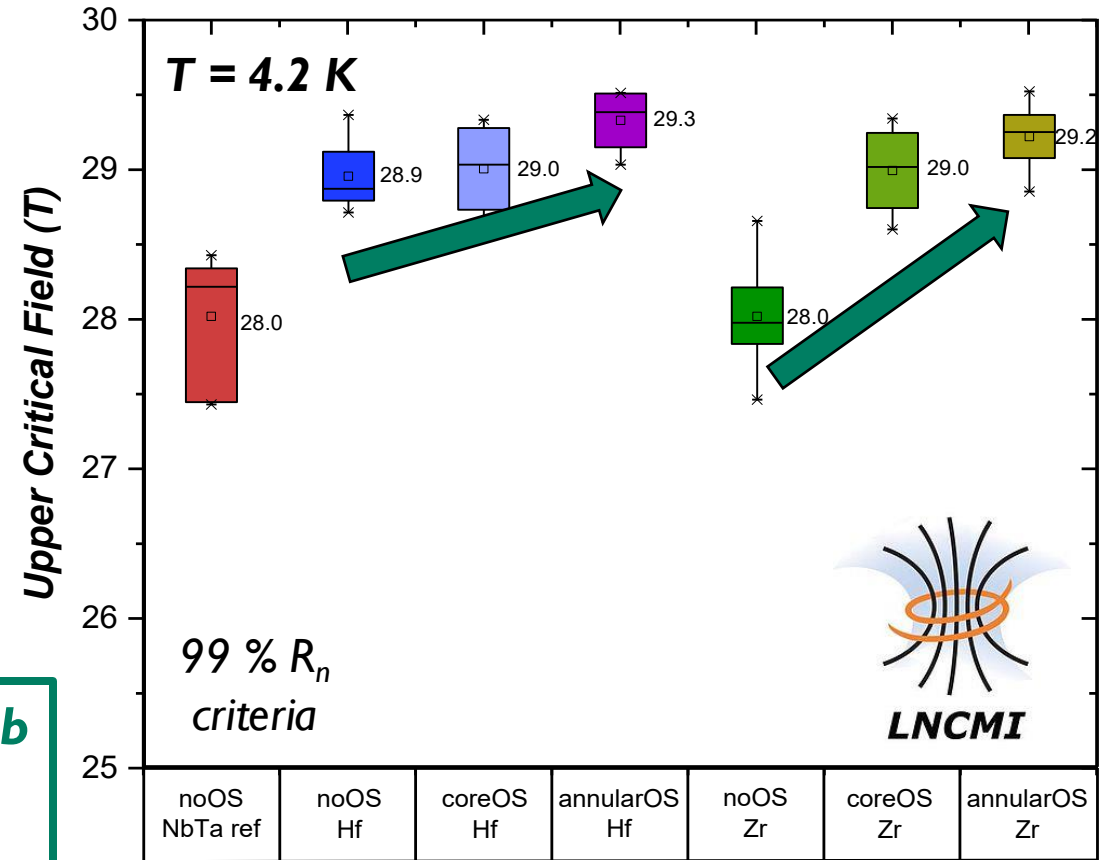
1. Annular OS

Oxide powder between the Nb-alloy filament and the copper jacket

2. Core OS

Oxide powder inside the Nb-alloy filaments

OS at the periphery of Nb (annular OS) is more effective to enhance B_{c2}

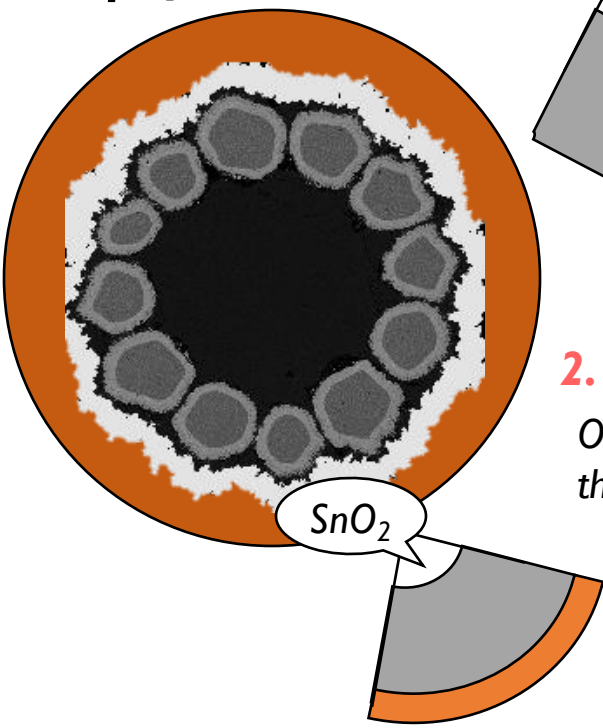


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Where should we add the OS?

- The challenges for RRP**
- Where should we add the OS?
 - How to make the OS resist to high temperature?

Simplified Subelement



Two OS configurations

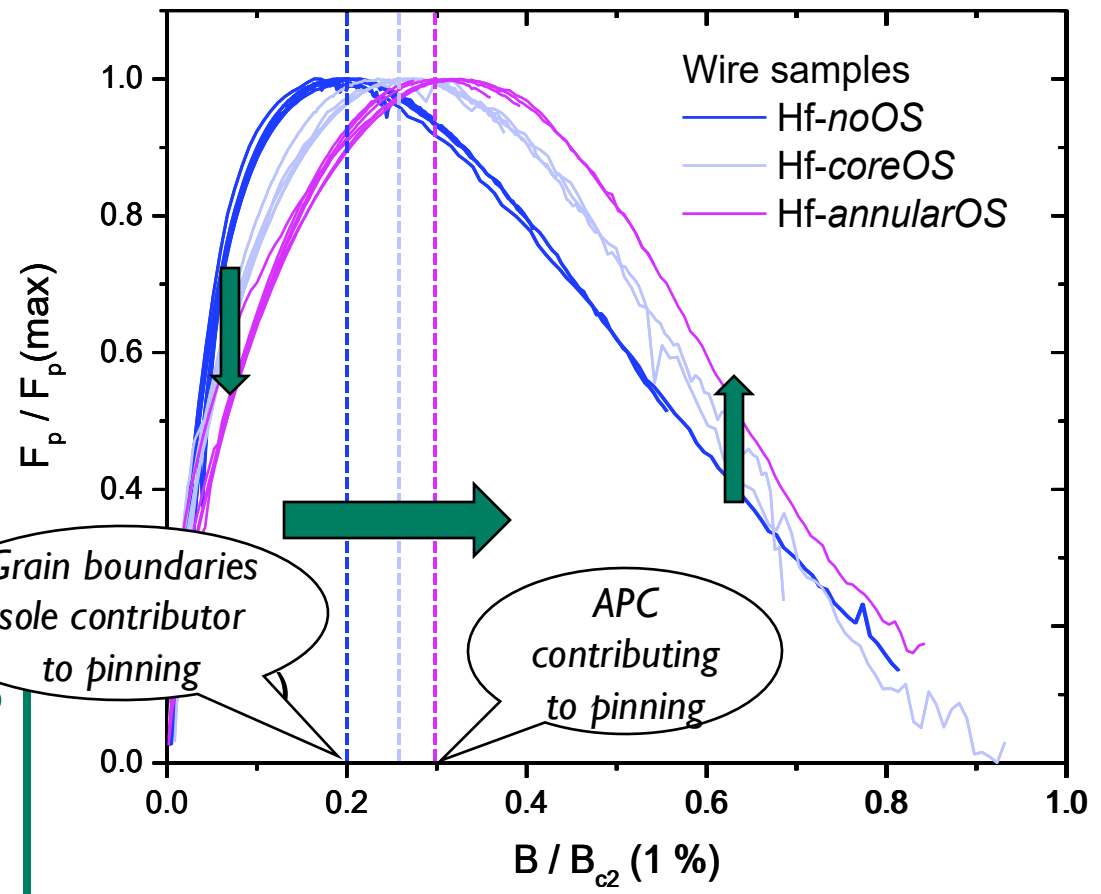
1. Annular OS

Oxide powder between the Nb-alloy filament and the copper jacket

2. Core OS

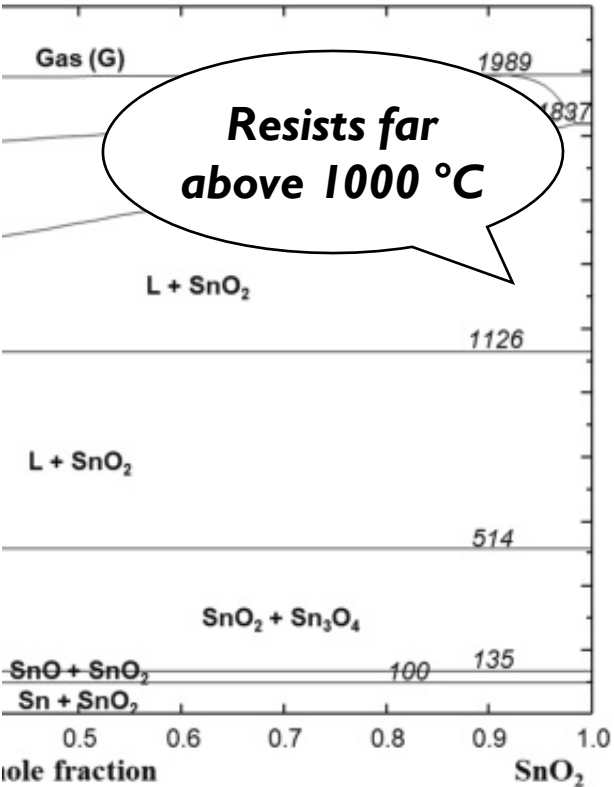
Oxide powder inside the Nb-alloy filaments

OS at the periphery of Nb (annular OS) is more effective to enhance B_{c2} and promote APC pinning

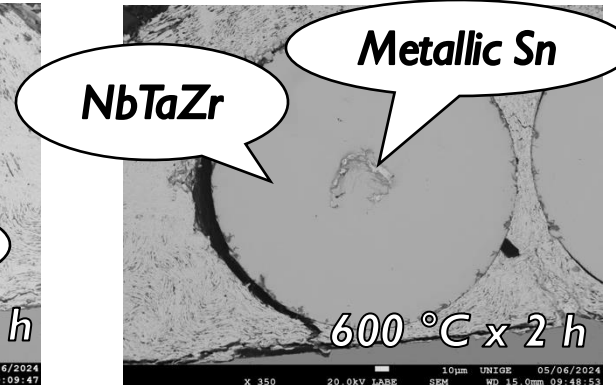
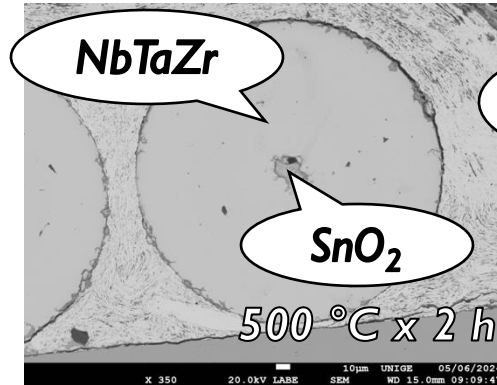


- Bovone G et al. Supercond. Sci. Technol. 36 095018 (2023)
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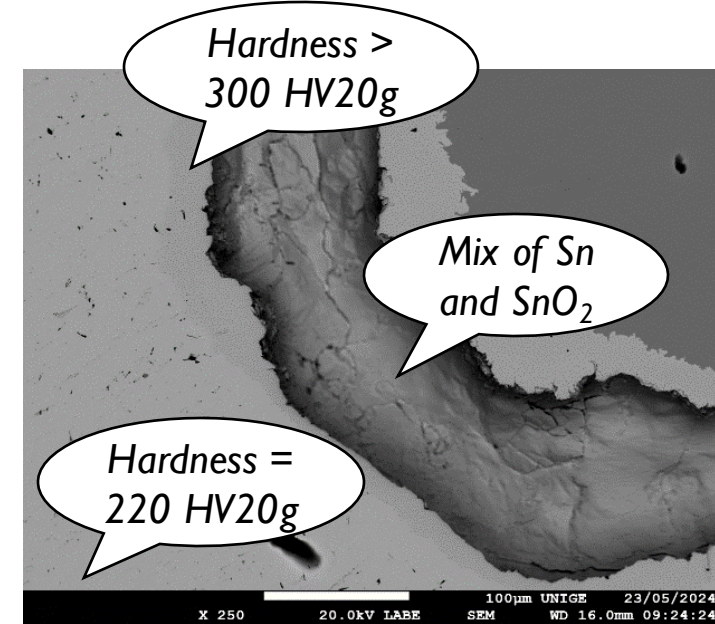
SnO₂ resistance to high temperature



Extrusion to produce the subelement is performed around **600 °C**

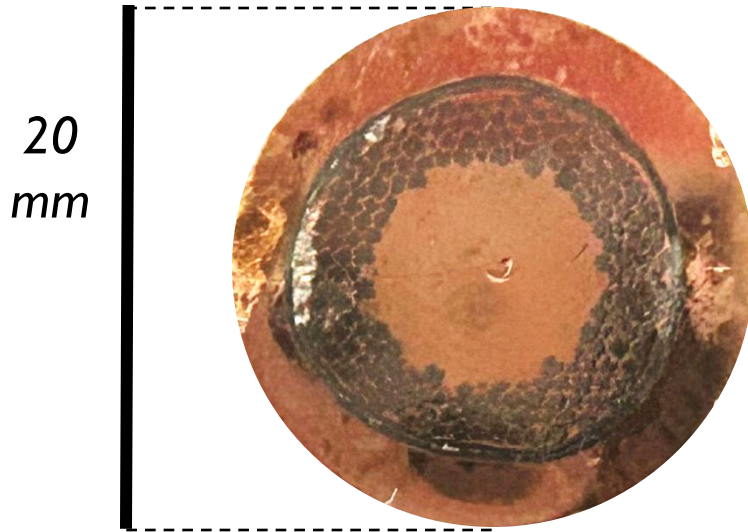


Within Nb, **decomposition** takes place between **500 and 600 °C**. Oxygen diffuses in the Nb and compromises its deformability



- The challenges for RRP**
- ✓ Where should we add the OS?
 - ✗ How to make the OS resist to high temperature?

Internal oxidation in extruded subelement

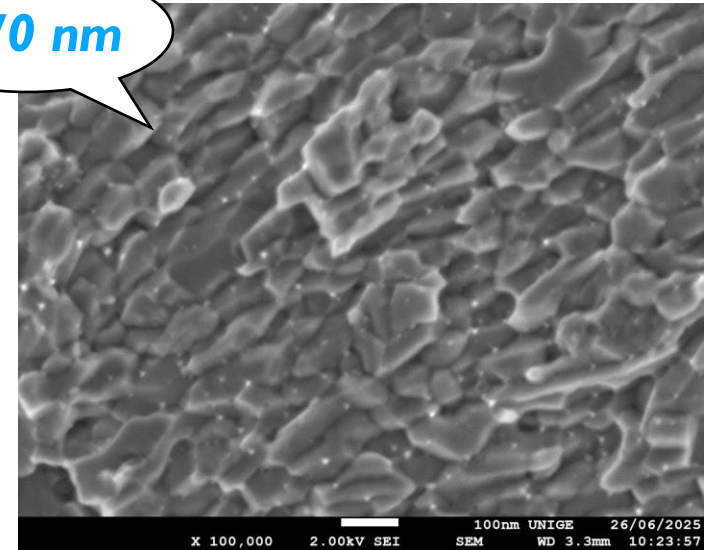


Subelement extruded at 600 °C.
Each filament contains OS at the periphery of Nb

Properties	Before extrusion	After extrusion	NOTE
Hardness, inner Nb filaments	169	188	200 g, 10 s
Hardness, Nb next to OS	164	185	200 g, 10 s
O/Sn ratio	2.05	2.07	EDS

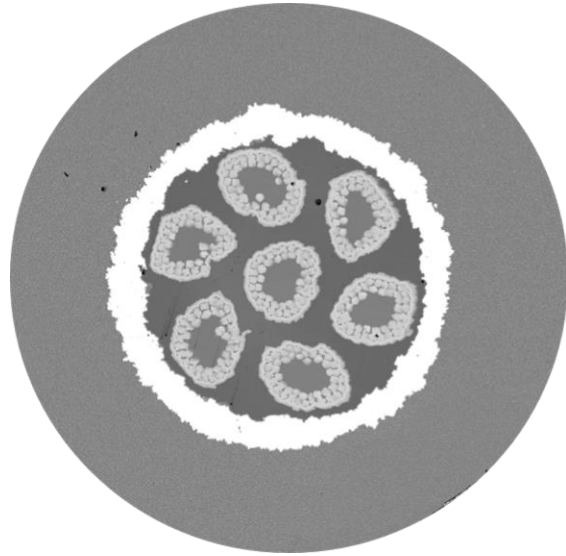
Insertion of Sn in a 50 mm long segment, deformed **down to 2.0 mm**. Observed **grain refinement** down to **70 nm!**
Currently deforming the long rod!

< 70 nm



- The challenges for RRP**
- ✓ Where should we add the OS?
 - ✓ How to make the OS resist to high temperature?

Characterization on simplified sample



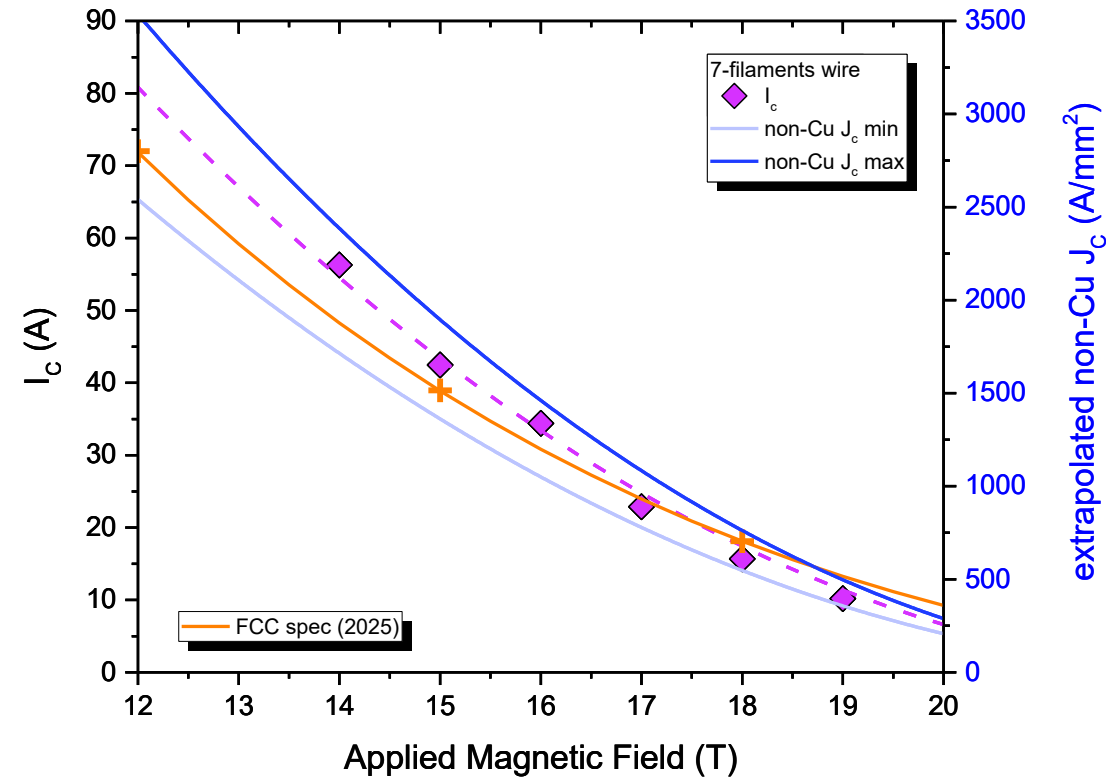
Wire Properties	Value	Ideal
Reaction %	53.8 %	100 %
Nb/non Cu Area %	50.0 %	50 – 60 %
Nb/Sn at	3.1	3.1 – 3.6
Sn/Sn+Cu wt %	45.1 %	50 – 60 %

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

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

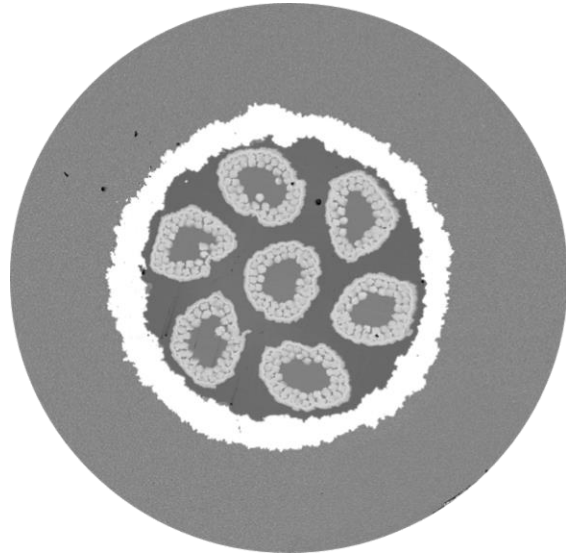
Large error on the determination of J_c due to thin and inhomogenous reaction layer.

HT schedule to be optimized!



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

Characterization on simplified sample

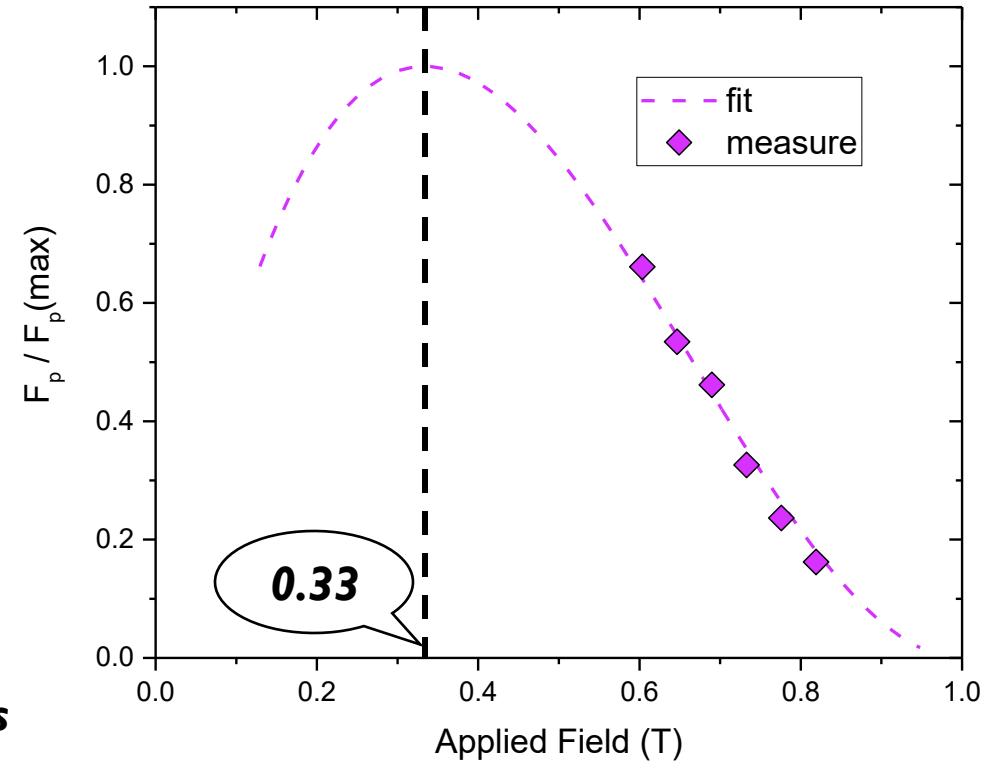


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Simplified RRP wire (7/7) made from cold deformed subelements (filaments and subelements are cold deformed)

Peak at 0.33 indicates APCs are contributing to the pinning force. More data (B_{c2} at high field and low field I_c) to confirm



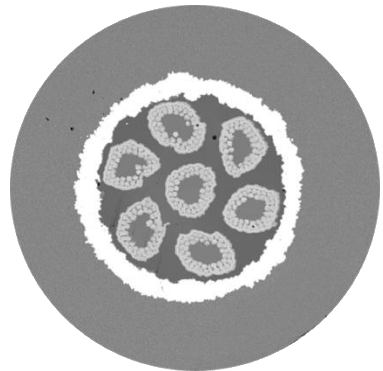
Internal oxidation successfully implemented in a (simplified) Nb_3Sn RRP multifilamentary wire

Internal oxidation in Nb_3Sn RRP wire

1. Done

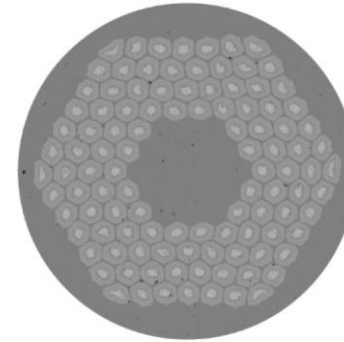


Subelement with OS extruded without premature degradation of oxides. Filaments were produced by cold deformation



Fabrication of a simplified RRP wire (7 subelements) with internal oxidation. Subelement was cold deformed and made from cold deformed filaments

2. To Do



Multifilamentary RRP wire with OS made from extruded subelement



Extrusion of filaments with OS, to assemble a subelement for the production of multifilamentary RRP wires

Summary and future work

- ✓ Successful implementation of **internal oxidation** and **APCs** in a **simplified RRP wire (7 subelements, cold deformed)**. Properties to be verified with additional **high-magnetic field analysis**
- ✓ **Extrusion of a subelement for RRP without decomposition of SnO_2**
 - The extruded subelement is being deformed to **assemble a multifilamentary wire**
 - A **Nb filament with OS** is ready to be **extruded** to follow the entire **RRP fabrication process**
 - **Optimization of elemental ratio** in future subelements

*Thank you for
your attention*

