

UNIGE Progress on LTS Conductors = Nb₃Sn wires

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Simon HOPKINS, Thierry BOUTBOUL

Outline

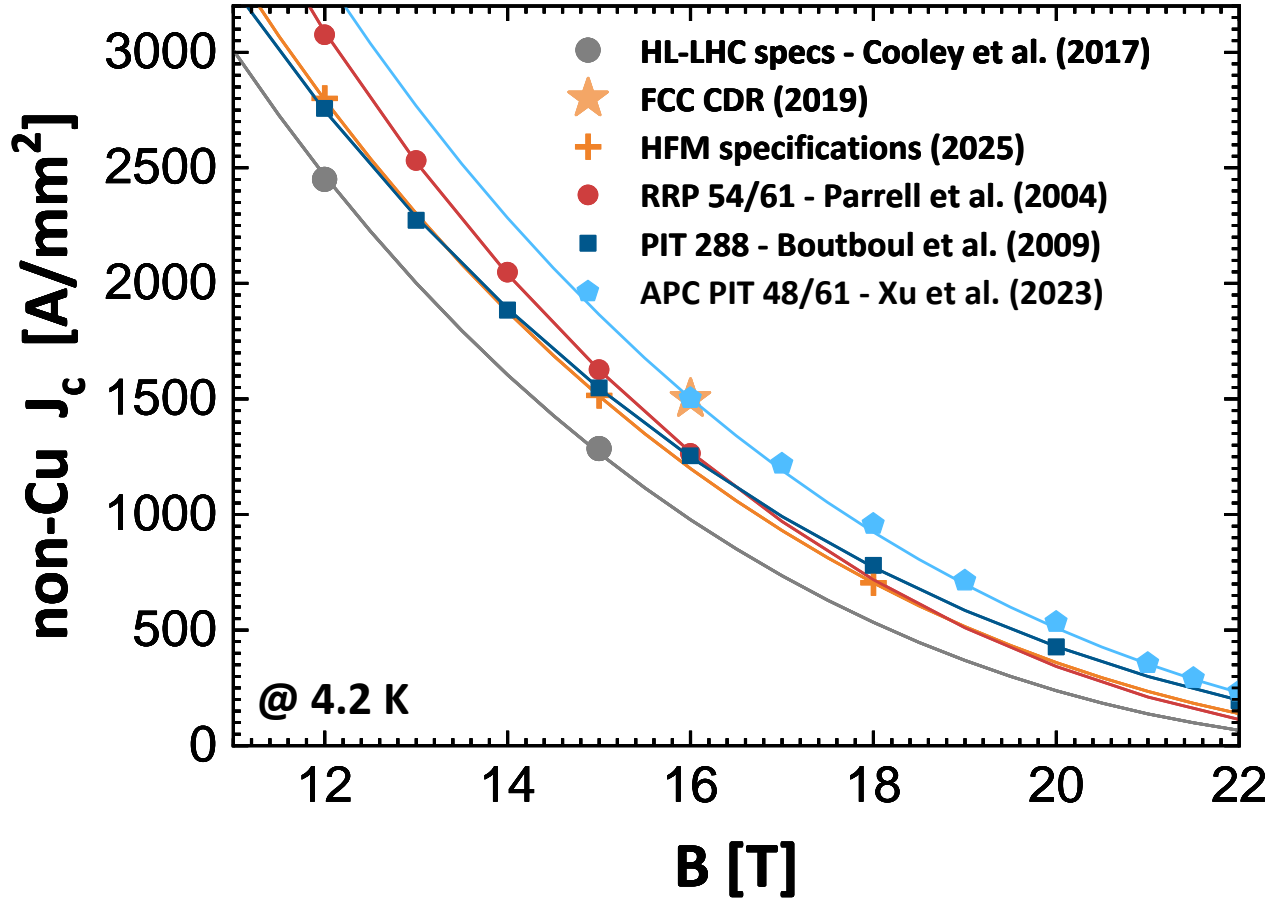
- **Nb₃Sn commercial wires: present performance and targets**
 - from the FCC CDR target to the HFM specifications
 - The HL-LHC experience with RRP and PIT wires
 - High-J_c RRP wires: wire layout and processing
- **Towards the ultimate performance of Nb₃Sn**
 - The Internal Oxidation Process
- **Wire R&D at UNIGE: Internal Sn Rod-Type wires with Internal Oxidation**
 - Materials Science ≅ RRP wires ≅ APC
 - Wire Technology
- **Summary and conclusions**

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Wire performance targets for a future proton-proton collider

HL-LHC specs, FCC CDR target and HFM specs



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/

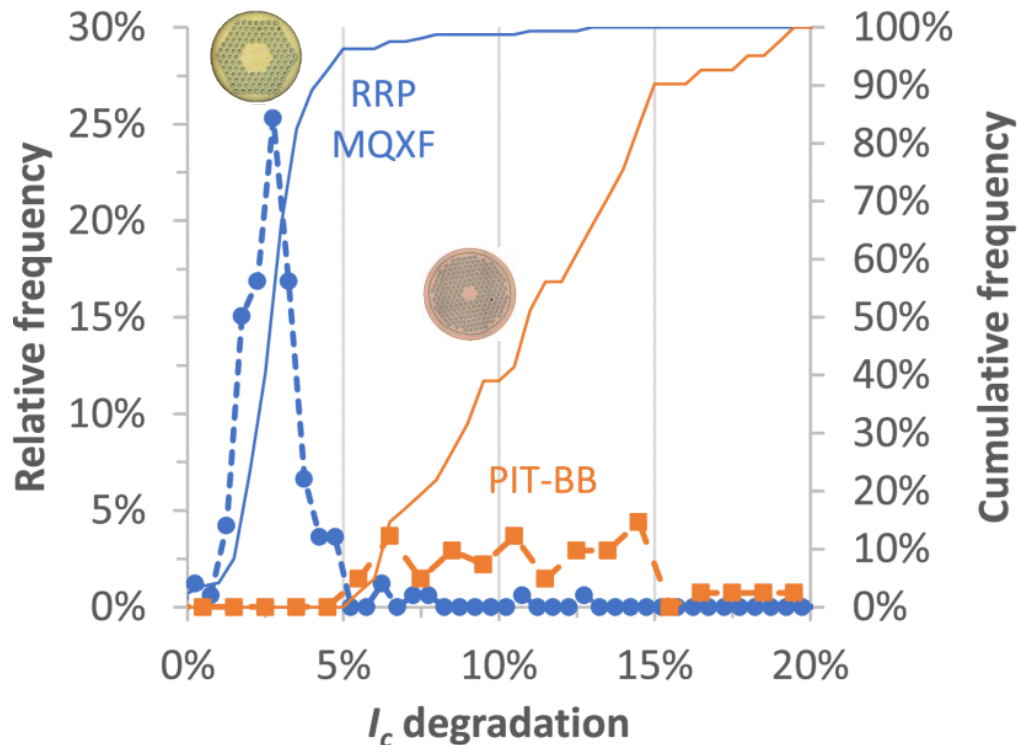
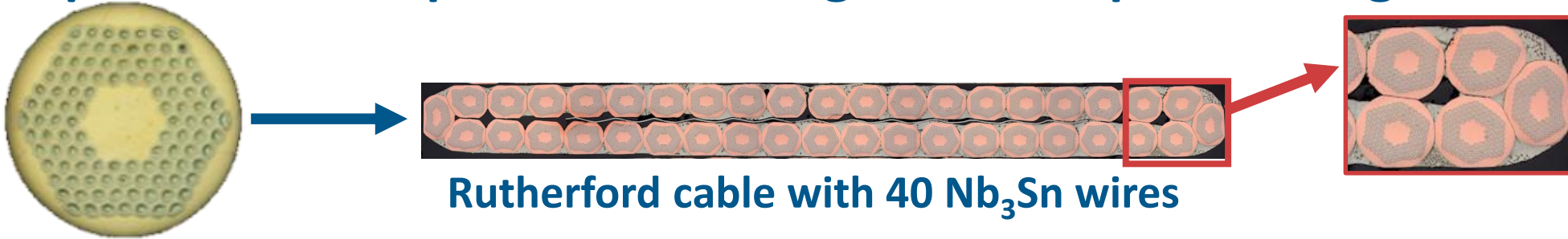
Parrell *et al.*, AIP Conf. Proc. 711 (2004) 369

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

Xu *et al.*, Supercond. Sci. Tech. 36 (2023) 035012

Rutherford cables for HL-LHC: RRP vs PIT

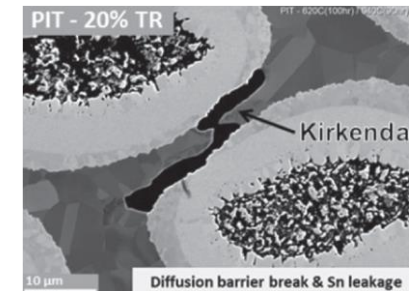
Comparison of the performance degradation upon cabling



- Cabling of **PIT wires** induces filament distortion
- Distorted filaments produce Sn leak and thus are only partly reacted
- This leads to the lower I_c

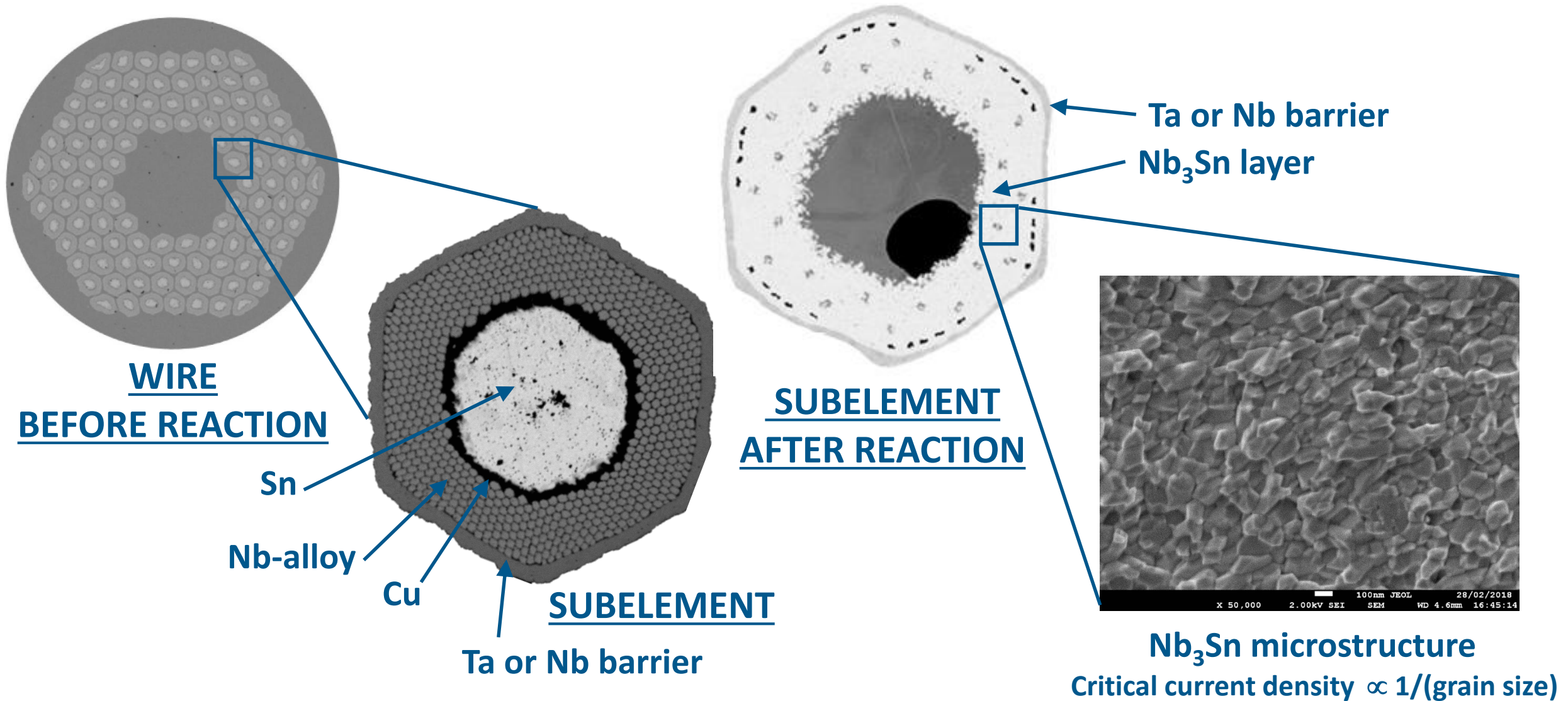
Segal *et al.*, *Supercond. Sci. Technol.*, **29** (2016) 085003
DOI: [10.1088/0953-2048/29/8/085003](https://doi.org/10.1088/0953-2048/29/8/085003)

Brown *et al.*, *Supercond. Sci. Technol.*, **29** (2016) 084008
DOI: [10.1088/0953-2048/29/8/084008](https://doi.org/10.1088/0953-2048/29/8/084008)



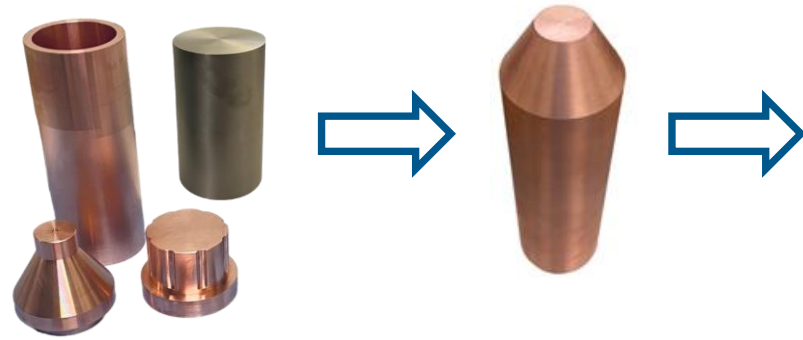
Cabling degradation is much less pronounced in Internal Sn RRP wires compared to PIT wires

How it's made: Internal Sn RRP Nb₃Sn wire



How it's made: Internal Sn RRP Nb₃Sn wire

1. Filament processing



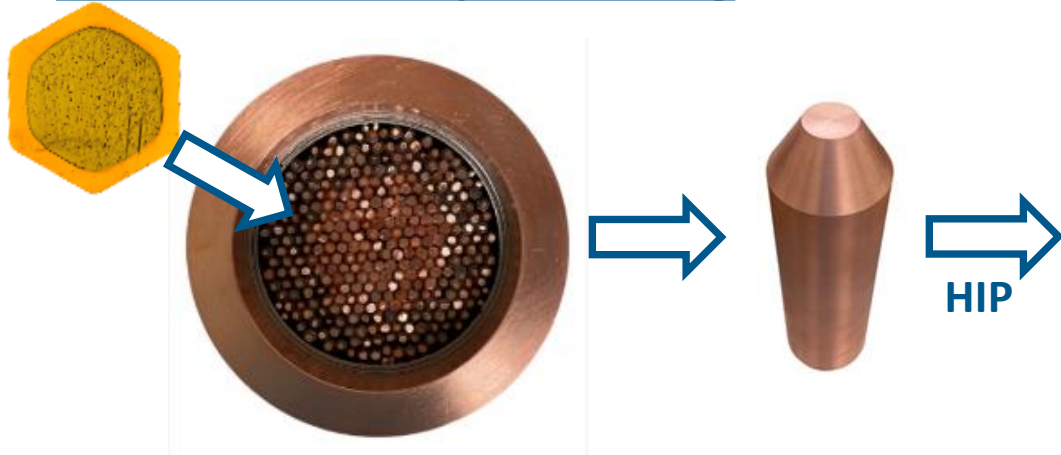
Hot Extrusion

Cold Deformation

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

A yellow hexagonal cross-section of a filament is shown above a blue-bordered text box. The text box contains the text: "RRP wire production involves hot extrusion, hot isostatic pressing and cold deformation". An arrow labeled "Cold Deformation" points from the text box to the hexagonal cross-section.

2. Subelement processing

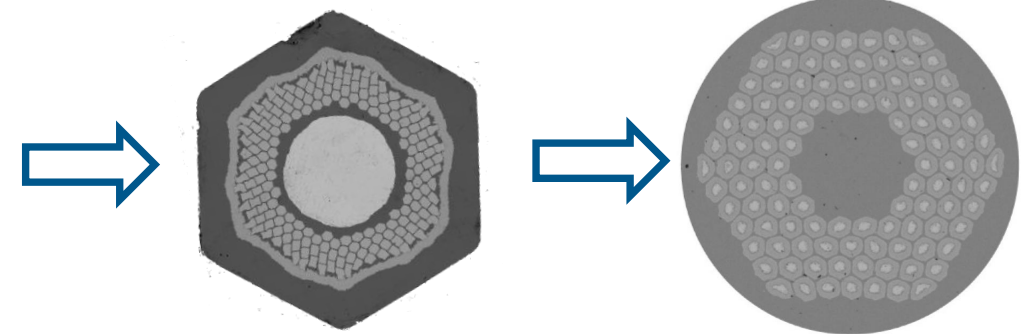


HIP



Hot Extrusion

3. Wire processing



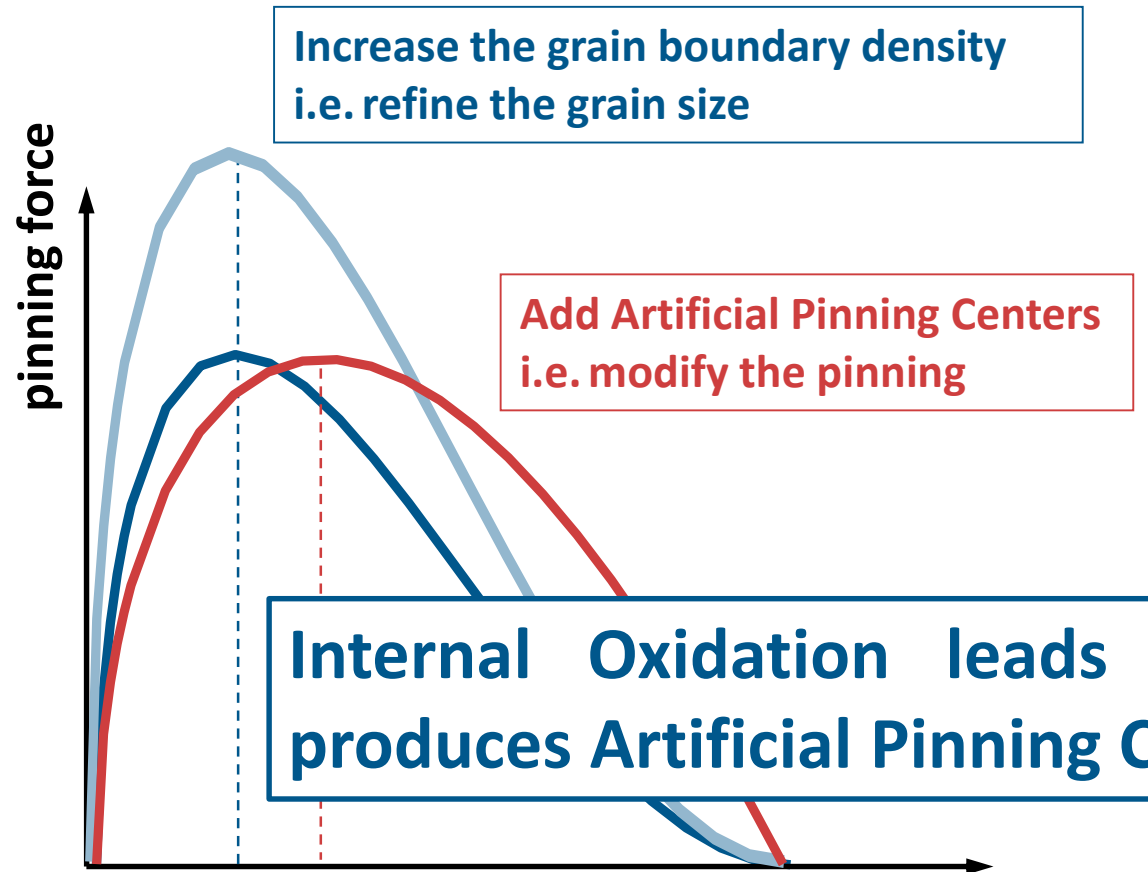
Drilling,
Sn rod insertion
and cold deformation

Subelement restack
and cold deformation
to final diameter

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Internal Oxidation to increase the in-field critical current density = to enhance vortex pinning at high field



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

Add Artificial Pinning Centers
i.e. modify the pinning

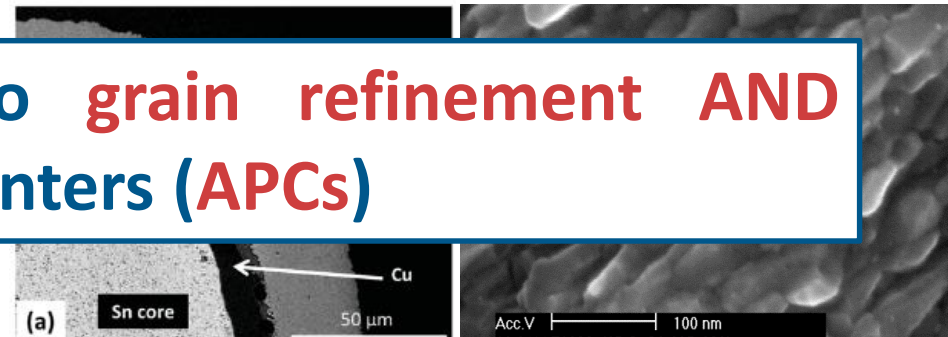
Internal Oxidation leads to grain refinement AND produces Artificial Pinning Centers (APCs)

max at $B = 0.2 B_{c2}$ max at $B = 0.33 B_{c2}$
Grain boundary pinning Point-like pinning

Idea from Benz (1968) of an **internal oxidation** to form fine precipitates in Nb to impede the Nb_3Sn grain growth Benz, Trans. Metall. Soc. AIME, 242 (1968) 1067-1070

Use of a Nb-alloy containing Zr or Hf: Zr and Hf have stronger affinity to oxygen than Nb

Oxygen supply added to the composite: oxidation of Zr (Hf) and formation of nano- ZrO_2 (HfO_2)



The first evidence of average grain size reduced down to **~ 50 nm** (vs **~ 100 nm** in regular wires)

Xu et al., APL 104 (2014) 082602
Xu et al., Adv. Mat. 27 (2015) 1346



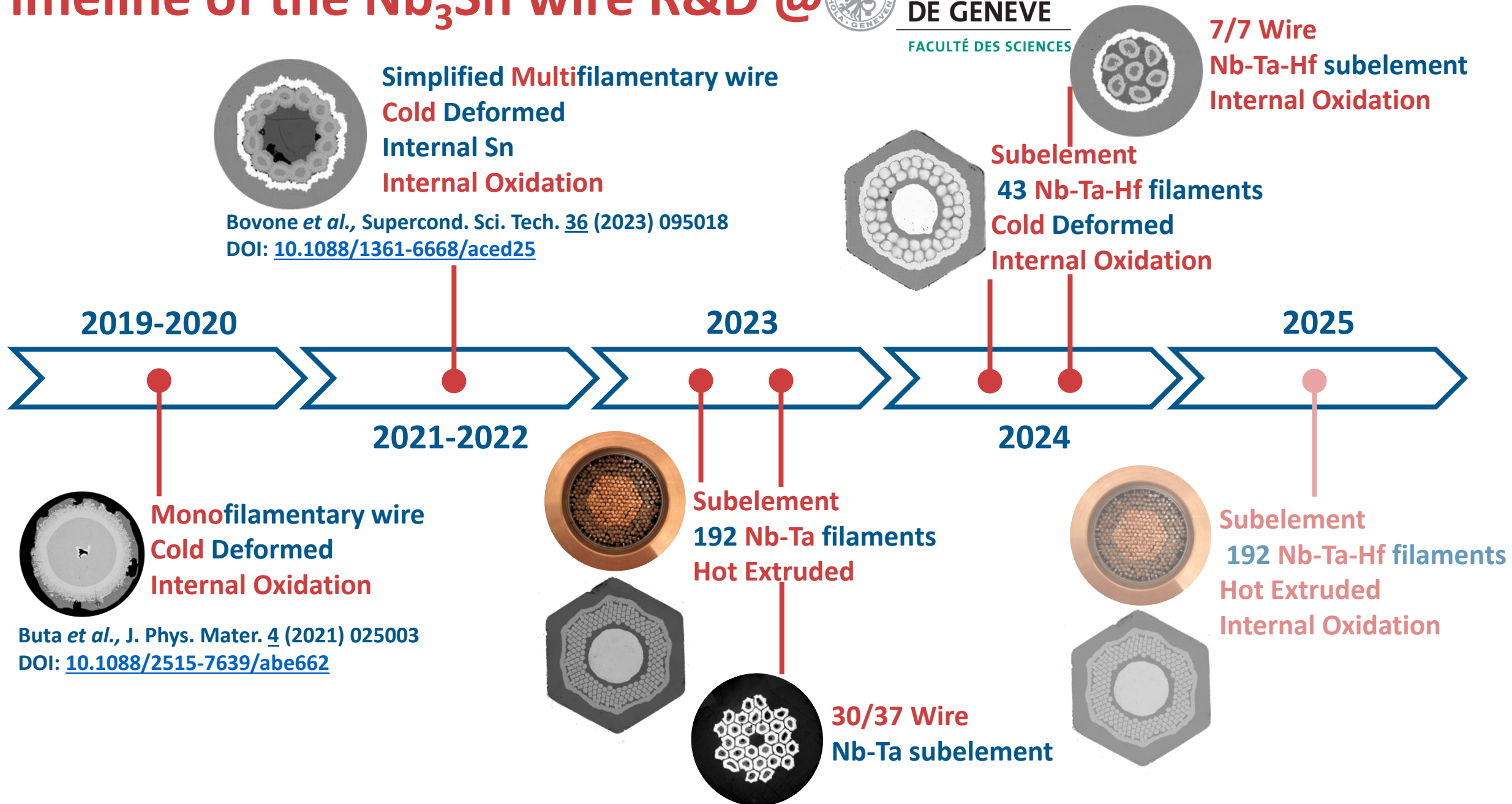
THE OHIO STATE UNIVERSITY

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Timeline of the Nb₃Sn wire R&D @ UNIVERSITÉ DE GENÈVE

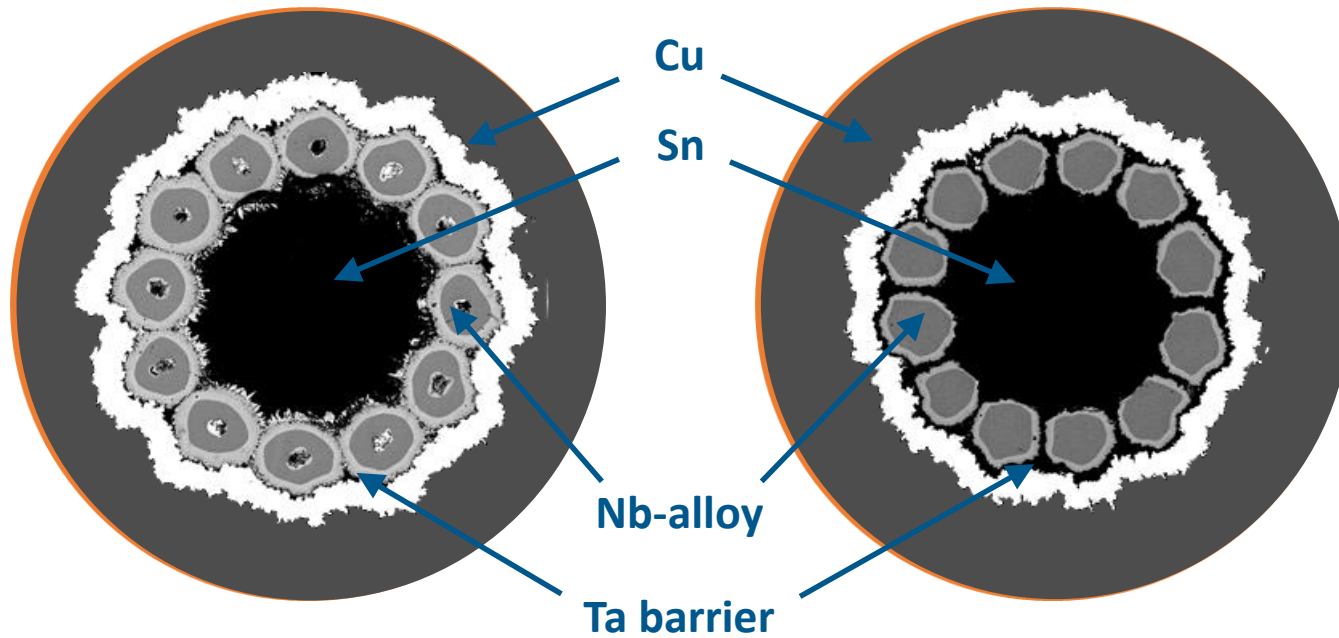
FACULTÉ DES SCIENCES



Internal Oxidation of simplified multifilamentary wires

A platform to test Internal Oxidation in an Internal Sn wire

Two possible configurations for the oxygen source



SnO₂ Core

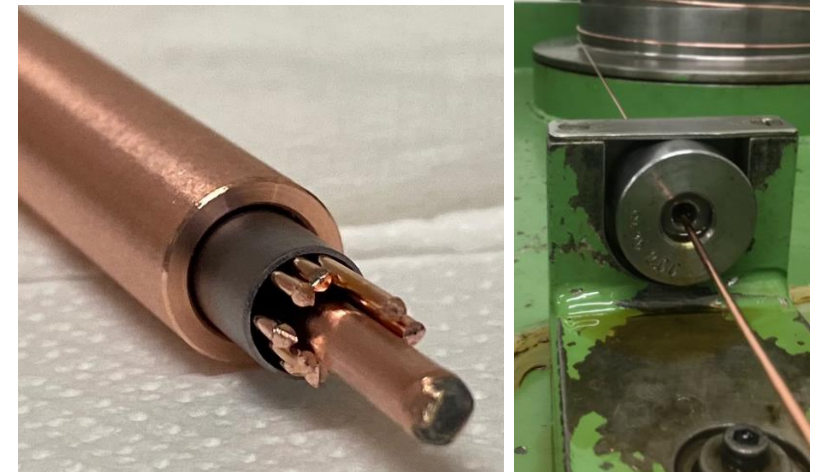
SnO₂ powder inside the Nb-alloy filaments

SnO₂ Annular

SnO₂ powder between the Nb-alloy filaments and the Cu tube

Nb-alloy	Oxide configuration
Nb-7.5wt%Ta-1wt%Zr	None
	SnO ₂ Core
	SnO ₂ Annular
Nb-7.5wt%Ta-2wt%Hf	None
	SnO ₂ Core
	SnO ₂ Annular

Two commercial ternary alloy were tested with 1wt%Zr and 2wt%Hf



Internal Oxidation of simplified multifilamentary wires

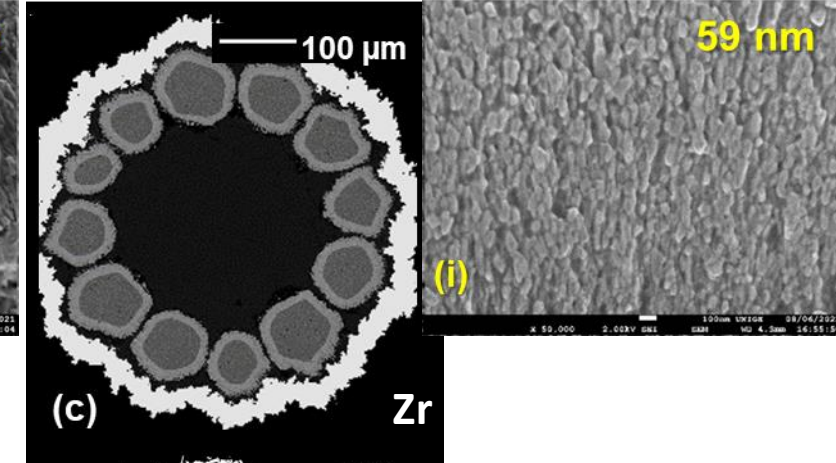
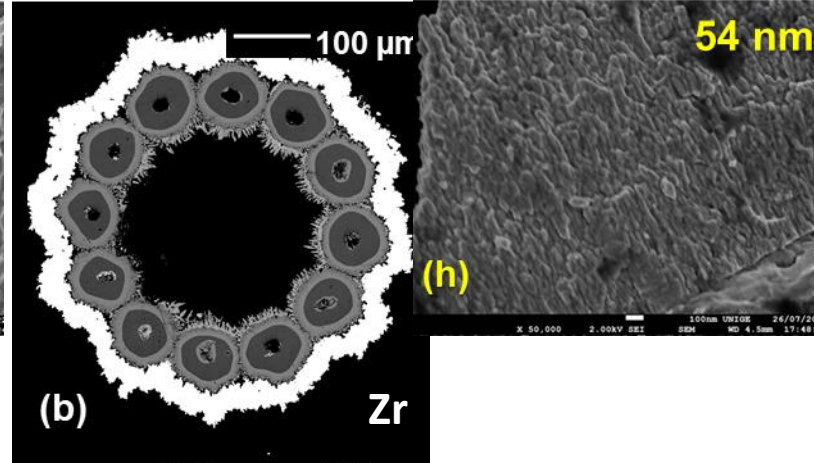
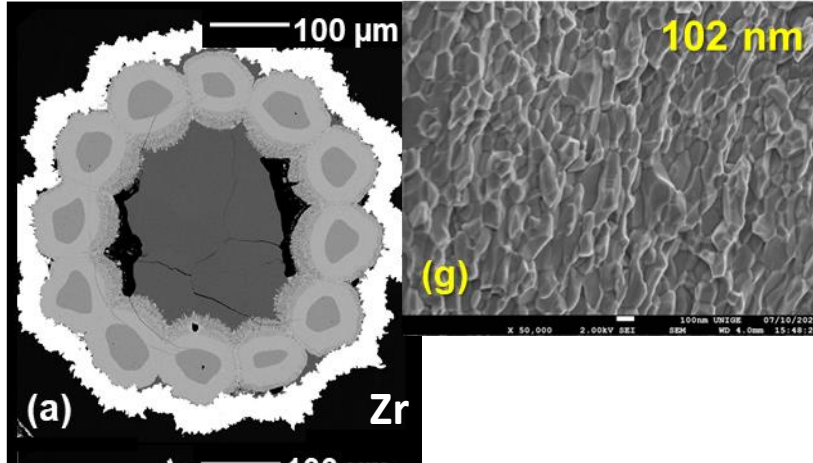
12-filament wires with an Internal Sn source

w/o oxygen source

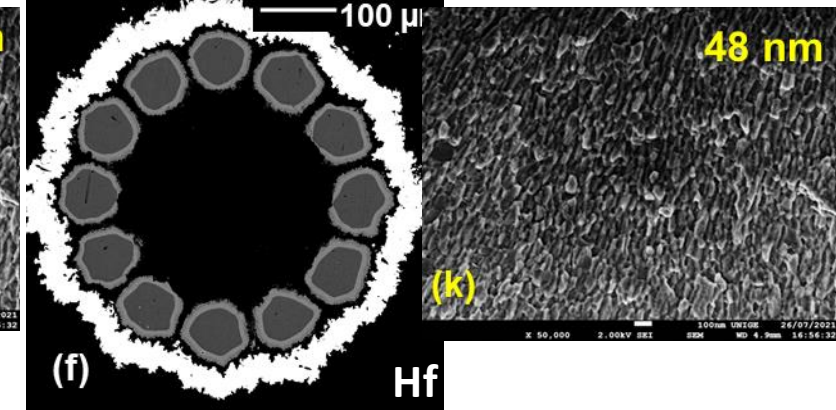
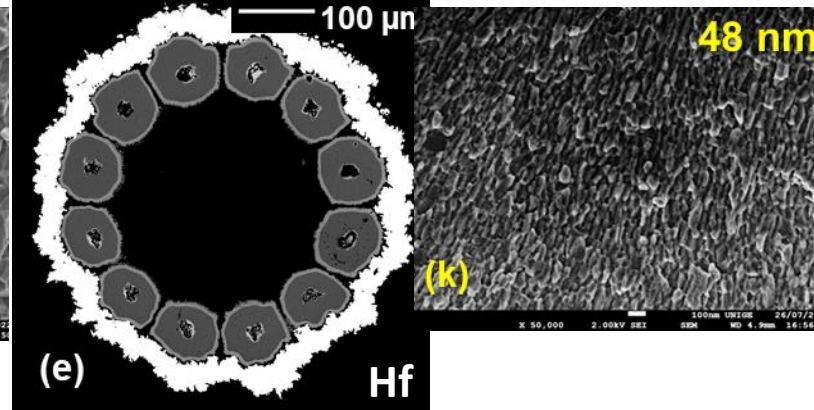
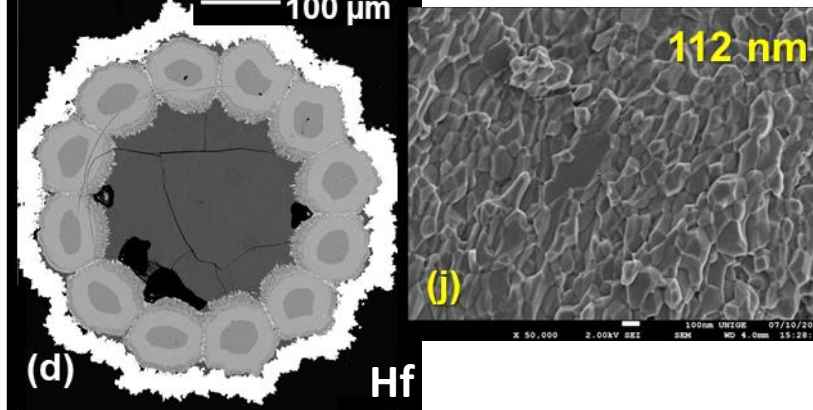
SnO₂ Core

SnO₂ Annular

Nb-7.5wt%Ta-1wt%Zr



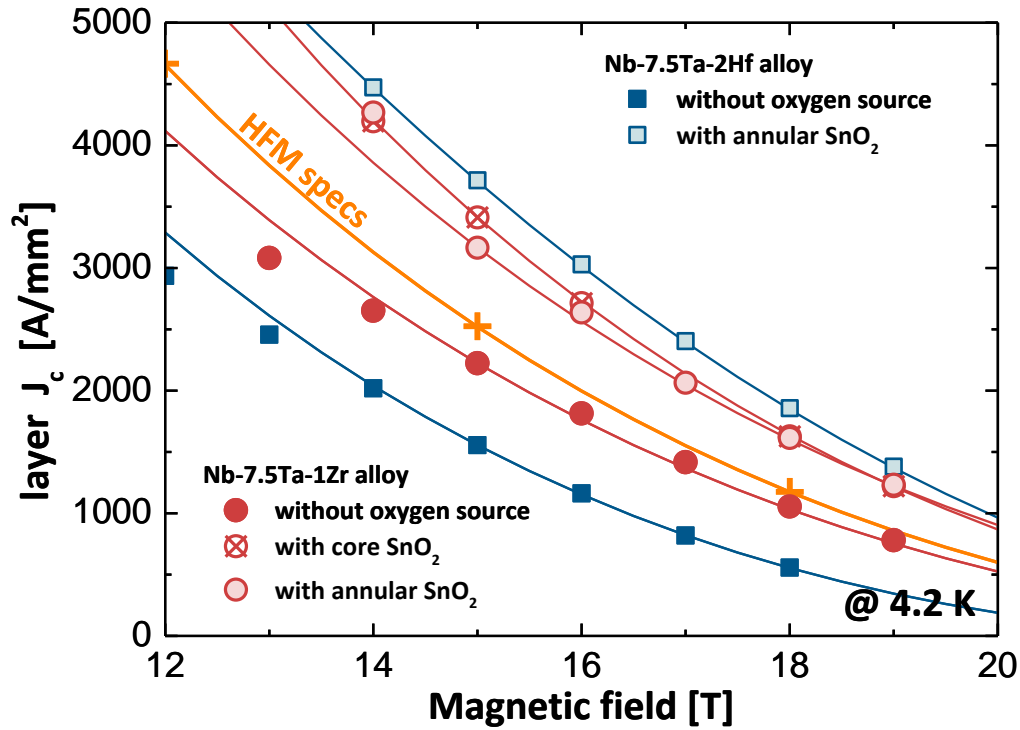
Nb-7.5wt%Ta-2wt%Hf



Internal oxidation leads to a refinement of the grain size from ~100 nm to ~50 nm regardless of the oxygen source configuration

Internal Oxidation of simplified multifilamentary wires

Transport J_c and B_{c2} measurements

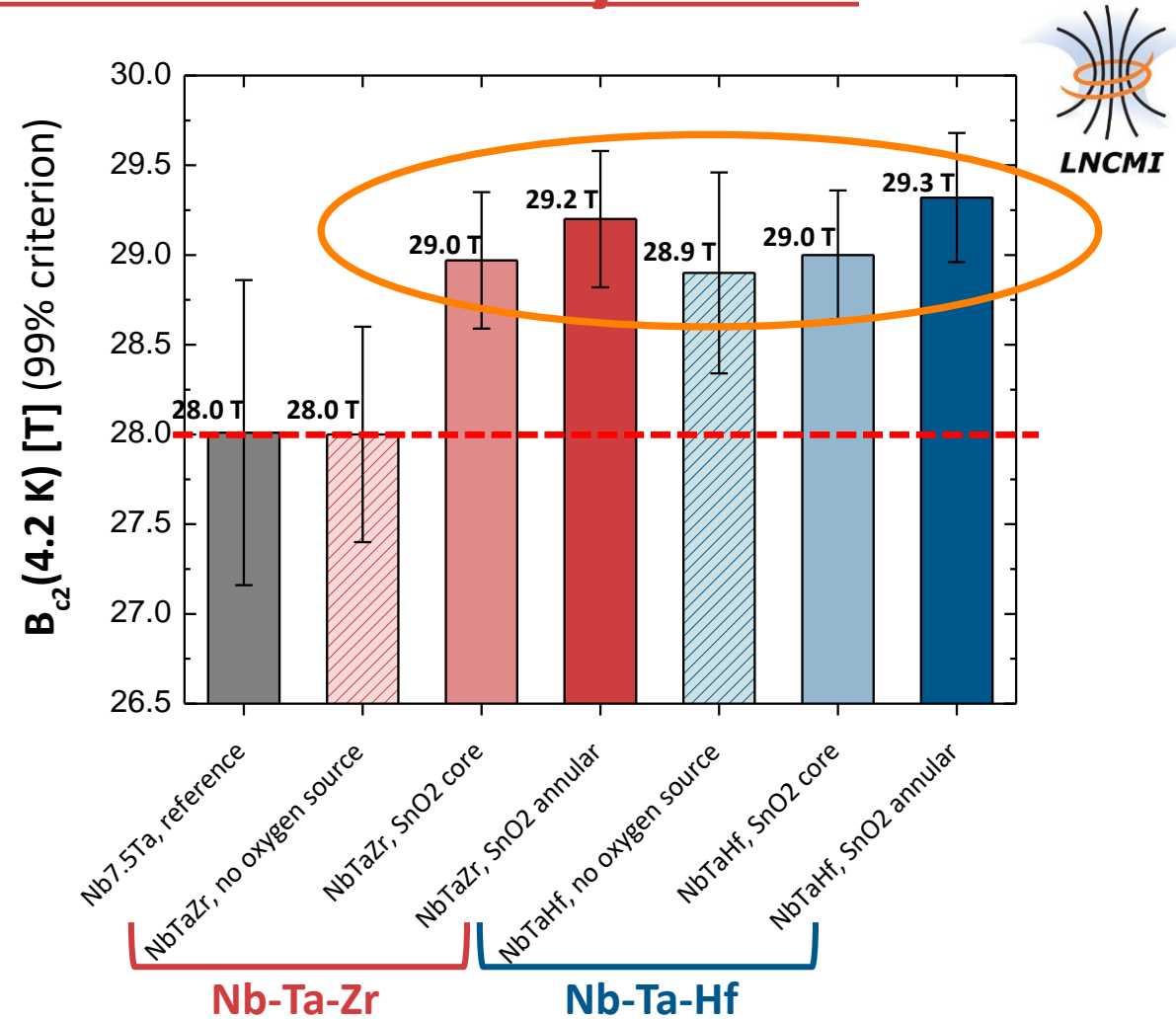


Layer J_c determined from transport measurements

non-Cu $J_c = 0.6 * \text{layer } J_c$ in HL-LHC wires
 considering 60% of Nb₃Sn in the non-Cu area

Bovone *et al.*, Supercond. Sci. Tech. **36** (2023) 095018

DOI: [10.1088/1361-6668/aced25](https://doi.org/10.1088/1361-6668/aced25)



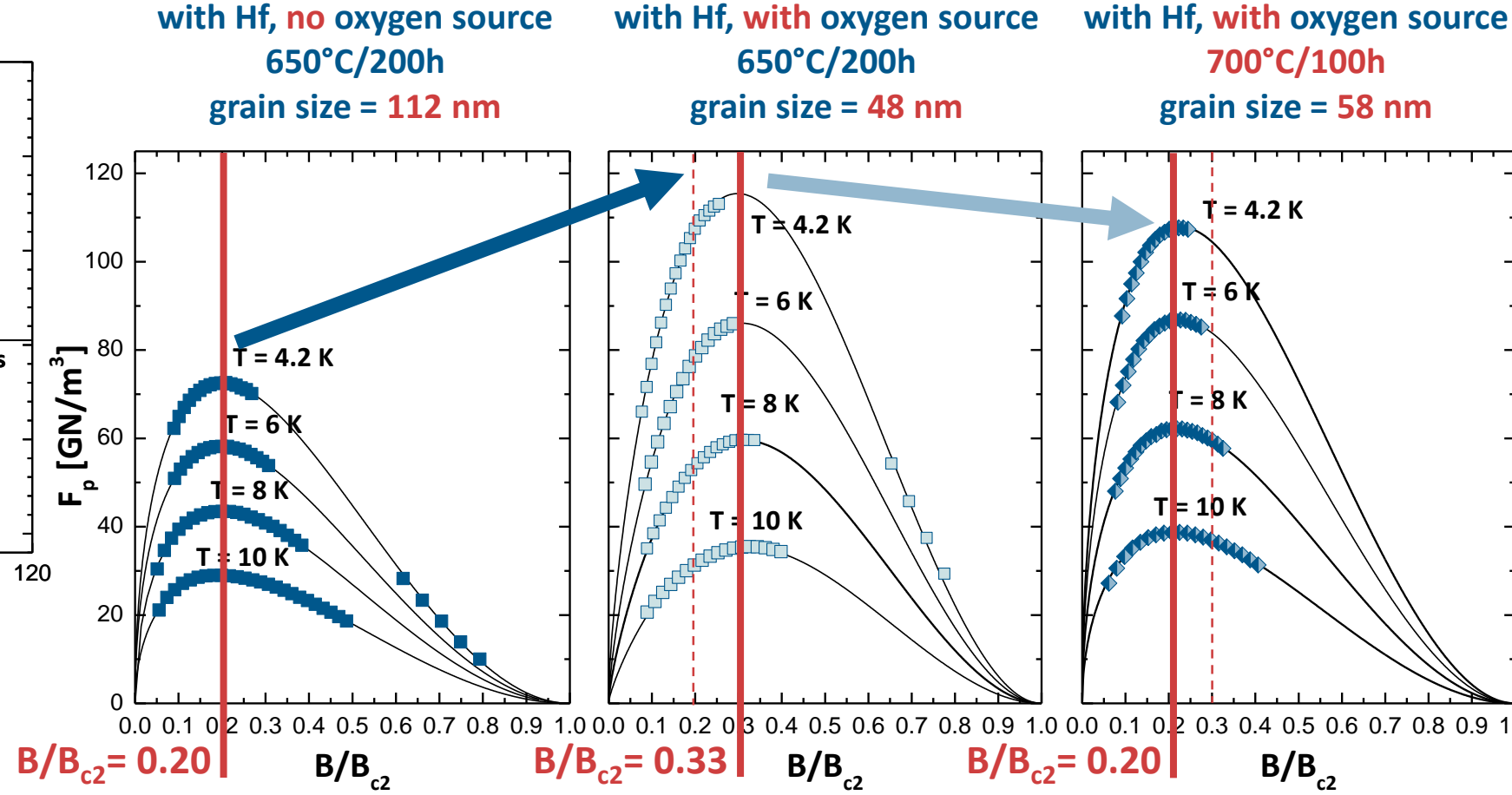
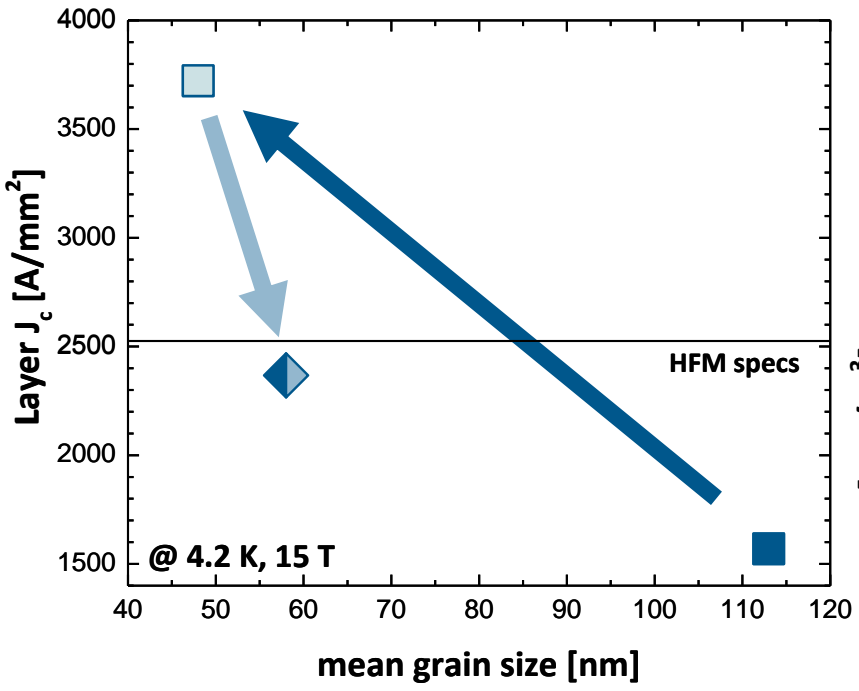
R(B) tests performed up to 33 T at LNCMI-Grenoble show record high B_{c2} values achieved both with Hf and Zr

Two fundamental investigations with practical implications

- 1. on the size of APC nanoparticles**
- 2. on the formation of APC nanoparticles**

The size of APC nanoparticles matters

The roles of refined grains and nanoparticles

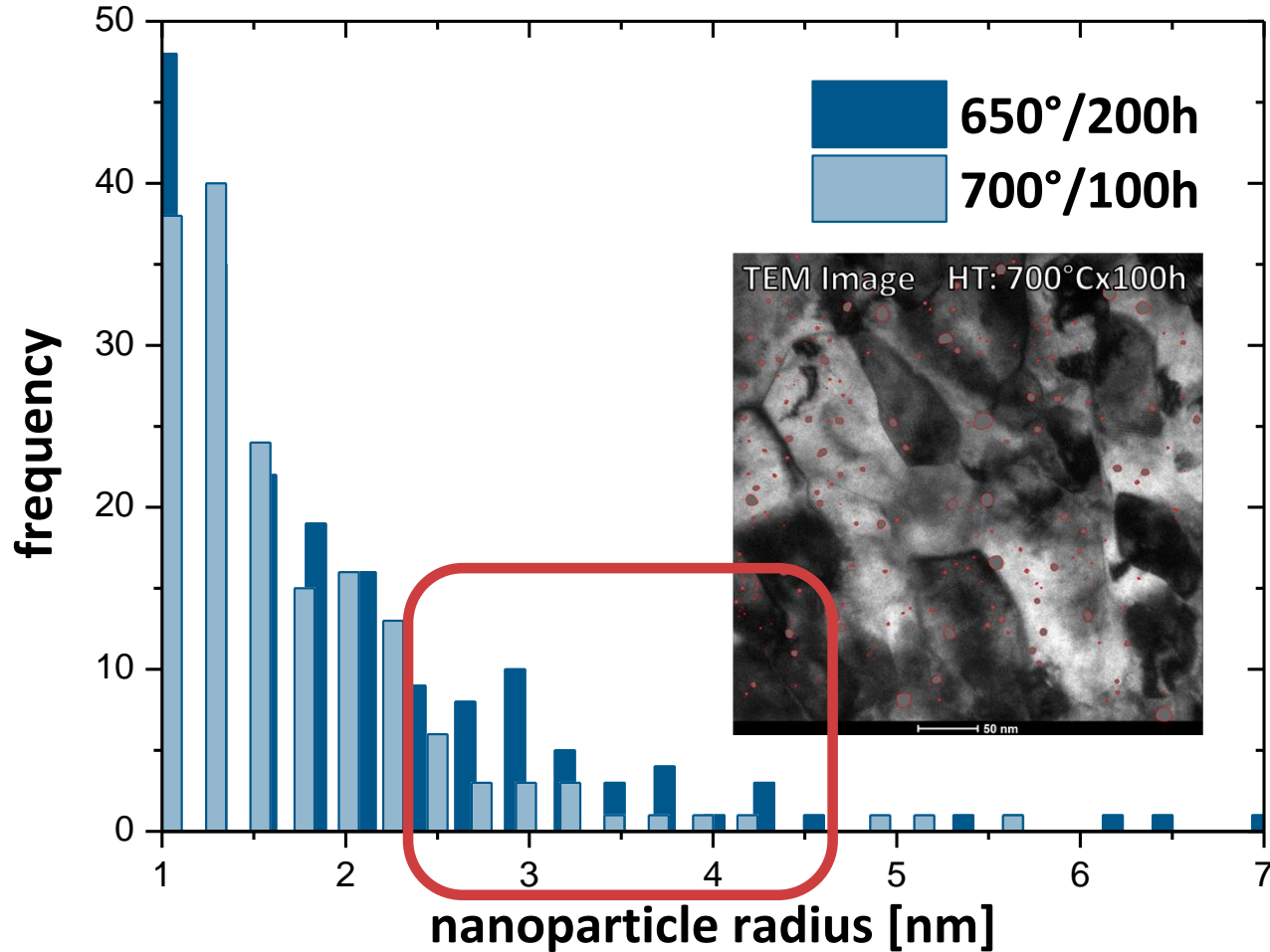


Shift produced by APCs

APC shift vanished

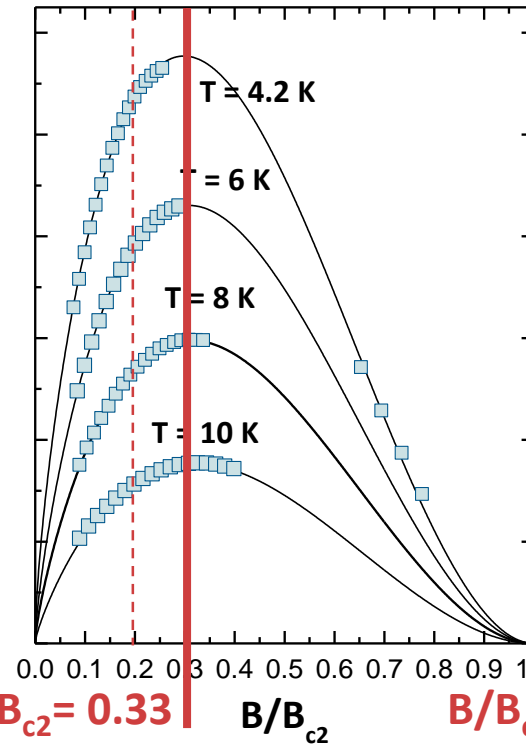
The size of APC nanoparticles matters

The roles of refined grains and nanoparticles



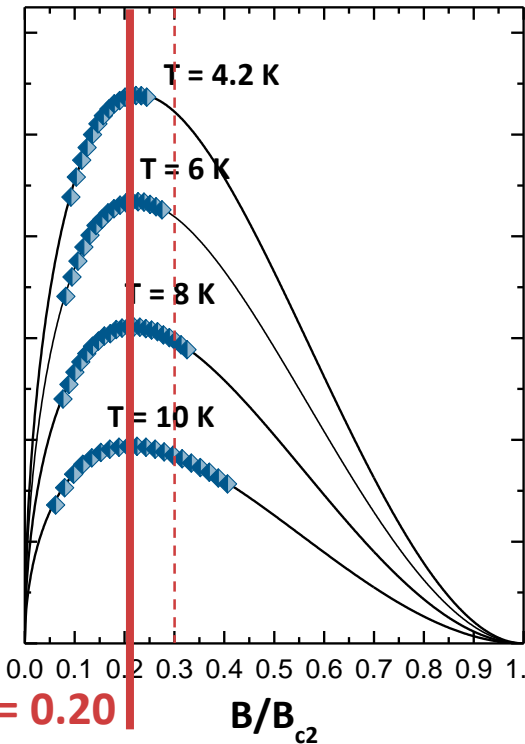
Less APC nanoparticles matching the vortex size in the wire reacted at 700°C/100h

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



Shift produced by APCs

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

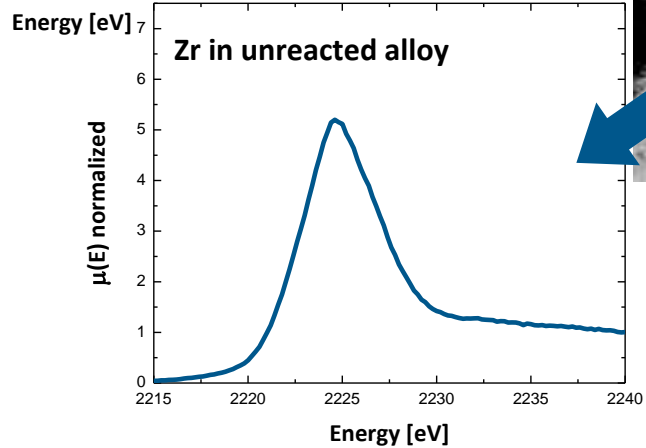
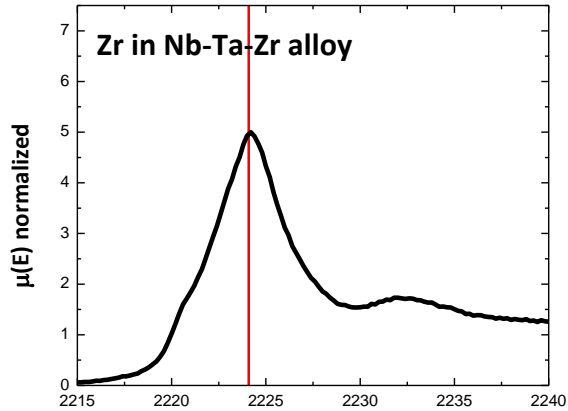


APC shift vanished

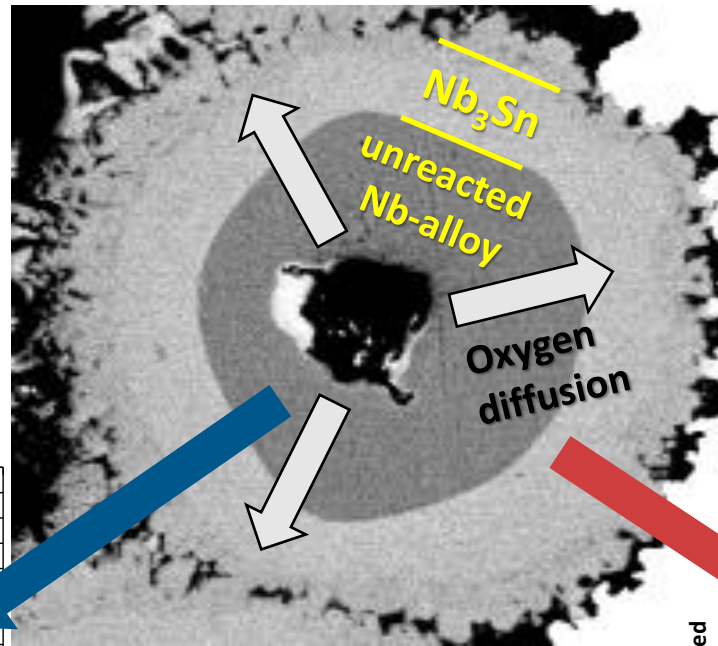
APC nanoparticles are formed along with Nb_3Sn

Spatial distribution of the nanoparticles by X-ray Absorption Spectroscopy

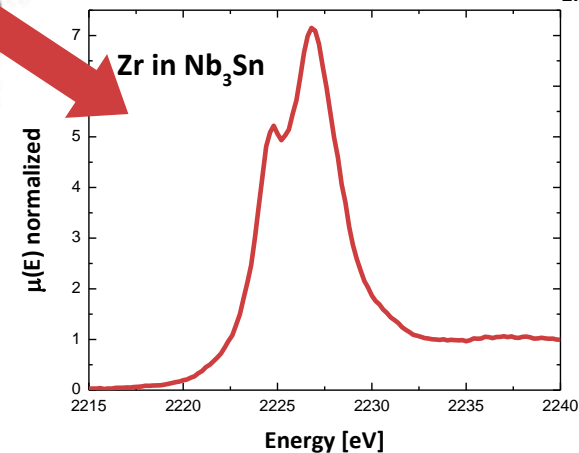
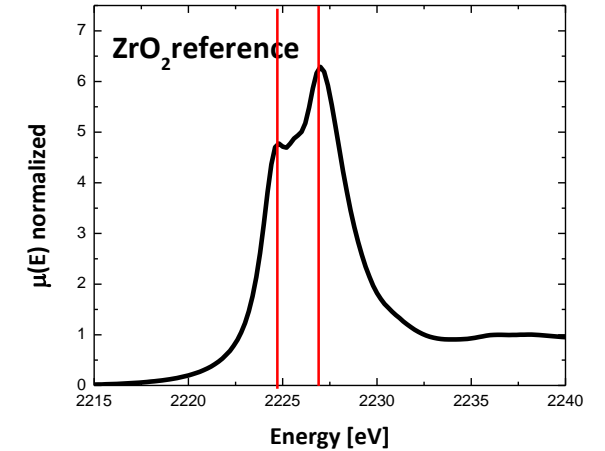
REFERENCE #1
XAS spectrum of Zr in Nb-Ta-Zr alloy



Reacted Monofilamentary Wire



REFERENCE #2
XAS spectrum of Zr in ZrO_2



ZrO_2 -like spectrum found only in Nb_3Sn !

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

... and now back to the wire technology

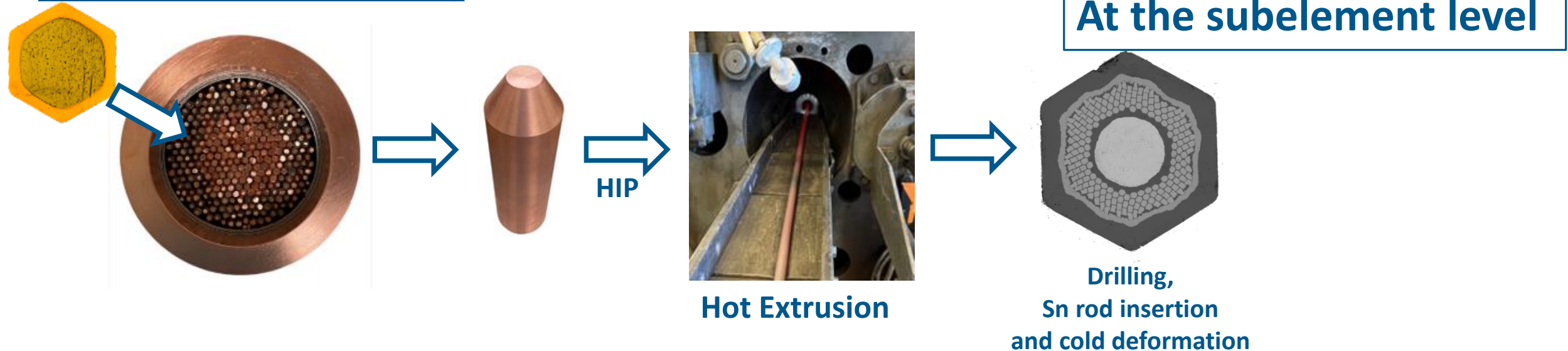
How to implement Internal Oxidation in RRP wires

Two options are being explored

1. Filament processing

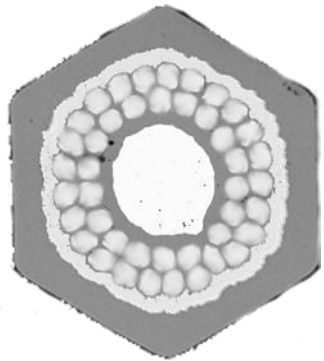


2. Subelement processing

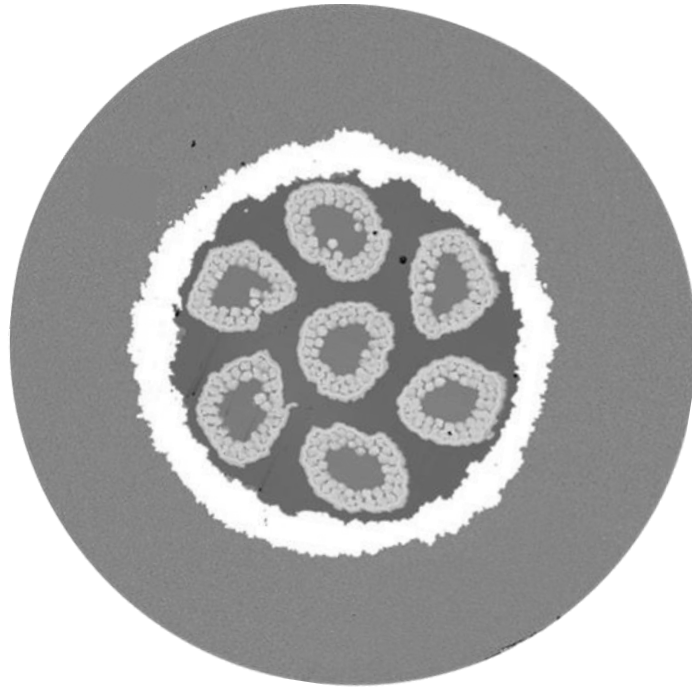


Cold-deformed subelement and 7/7 wire

First results with obtained with Option #1

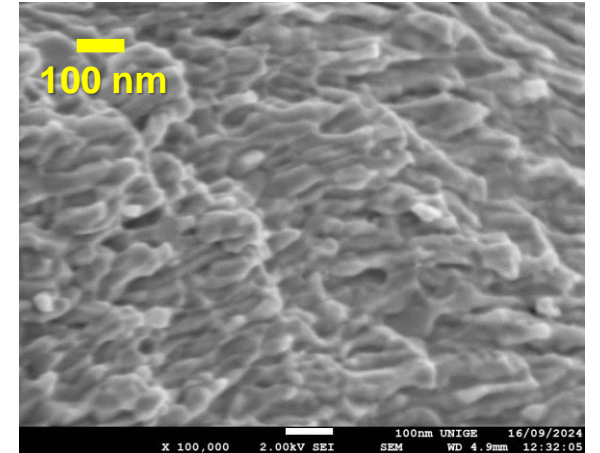
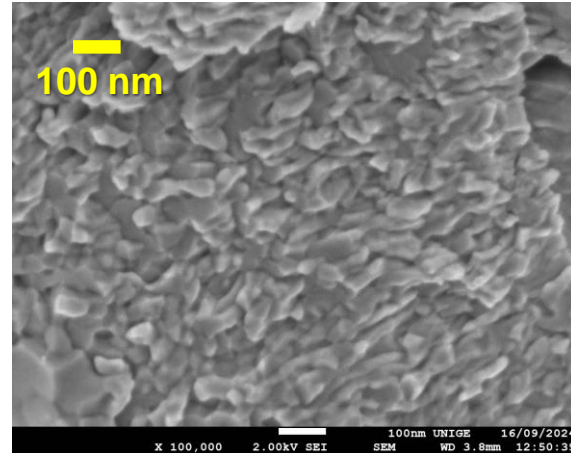


43 Nb-Ta-Hf filaments
Cold Deformed
Oxygen source at the filament level



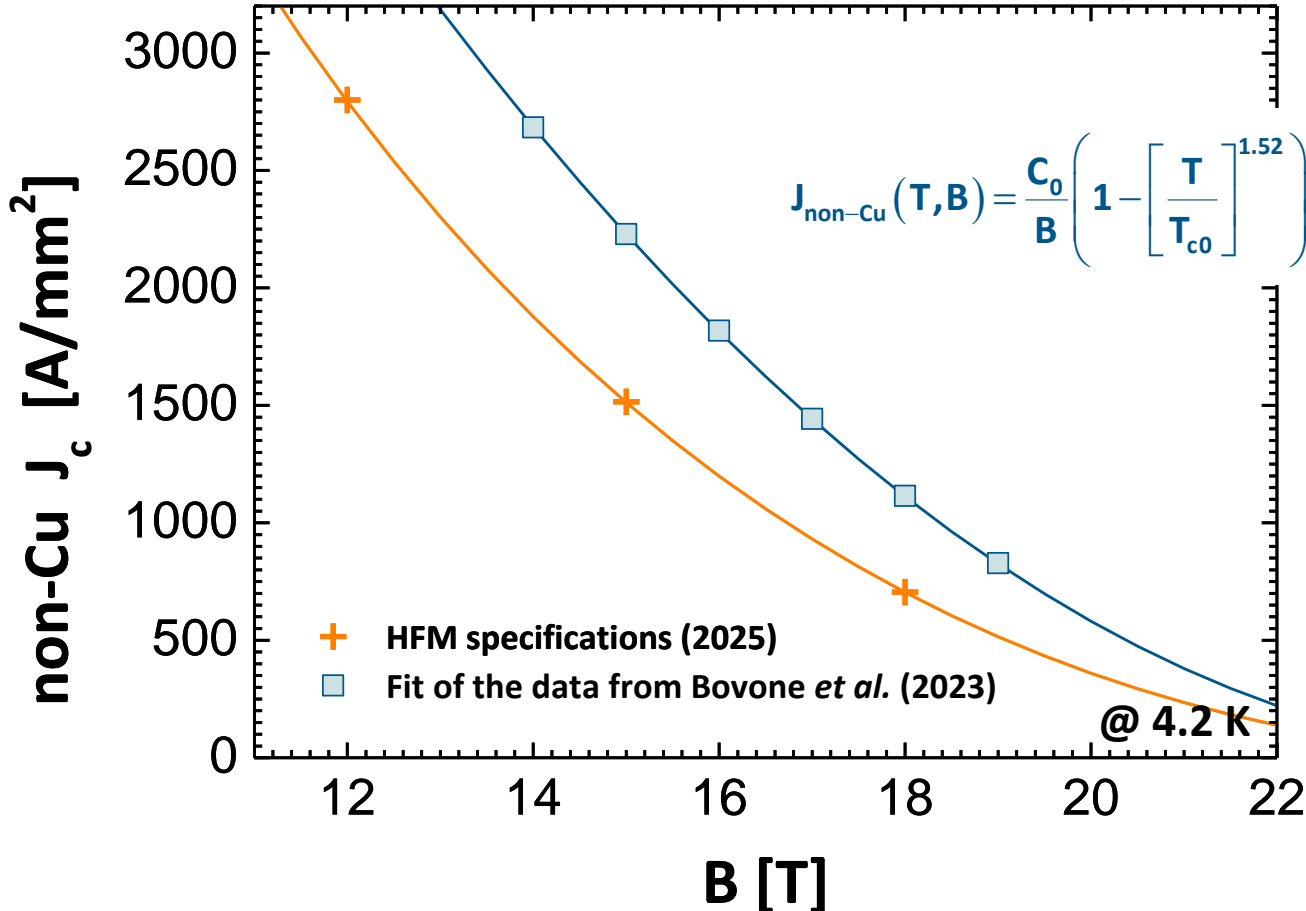
7/7 wire, $\phi = 1.1$ mm
Subelement size = ~ 120 μm

AFTER REACTION



Nb₃Sn grains refined down to 60 nm

J_c(B) fit: HFM specs vs UNIGE APC wire



$$J_{\text{non-Cu}}(T, B) = \frac{C_0}{B} \left(1 - \left[\frac{T}{T_{c0}} \right]^{1.52} \right)^{0.96} \left(1 - \left[\frac{T}{T_{c0}} \right]^2 \right)^{0.96} \left(\frac{B}{B_{c20} \left(1 - \left[\frac{T}{T_{c0}} \right]^{1.52} \right)} \right) \left(1 - \frac{B}{B_{c20} \left(1 - \left[\frac{T}{T_{c0}} \right]^{1.52} \right)} \right)^2$$

Nb-Ta-Hf alloy, Internal Oxidation, APC

$T_{c0}=16$ K, $B_{c20}=29.05$ T, $C_0= 420000$ A T/mm²

non-Cu J_c calculated for a HL-LHC wire layout from the measured layer J_c. – non-Cu J_c = 0.6 layer J_c. Data from:

Bovone *et al.*, Supercond. Sci. Tech. **36** (2023) 095018

DOI: [10.1088/1361-6668/aced25](https://doi.org/10.1088/1361-6668/aced25)

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HFM specs: improved HL-LHC conductor

$T_{c0}=16$ K, $B_{c20}=29.38$ T, $C_0= 214000$ A T/mm²

Todesco, HFM Forum (2025)

URL: indico.cern.ch/event/1501797/

Summary and outlook

- **With Internal Oxidation** it is possible to produce Nb_3Sn with **enhanced J_c** by refining the grain size and introducing APC nanoparticles
- Practical solutions to **implement this technology** in the subelement of **RRP wires** are being developed at UNIGE
- Materials science and wire technology are advancing hand in hand
- A natural follow-up to the activity could further **expand the scope** and involve the fabrication of sufficiently **long demonstration wires** to validate the results in short **Rutherford cables** and model coils.



Swiss National
Science Foundation



Thank you for the attention !

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