WireDev Advanced Niobium-Tin superconductors for next generation particle colliders

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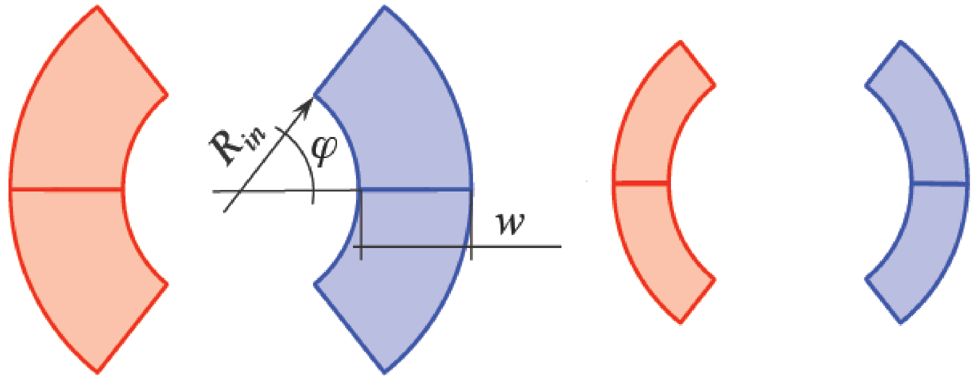
Outline

- **Motivation of the work**
  - Challenges and perspectives in the development of accelerator magnets based on Nb_3Sn conductors for a Future Circular Collider
- **Towards the ultimate performance of Nb_3Sn**
  - The internal oxidation process to increase the critical current and possible strategies to further enhance B_{c2}
  - Basic material science, development of novel wire architectures and test of manufacturing processes scalable for industrial production
- **Summary and outlook**

Targets for a future 100 TeV hadron collider

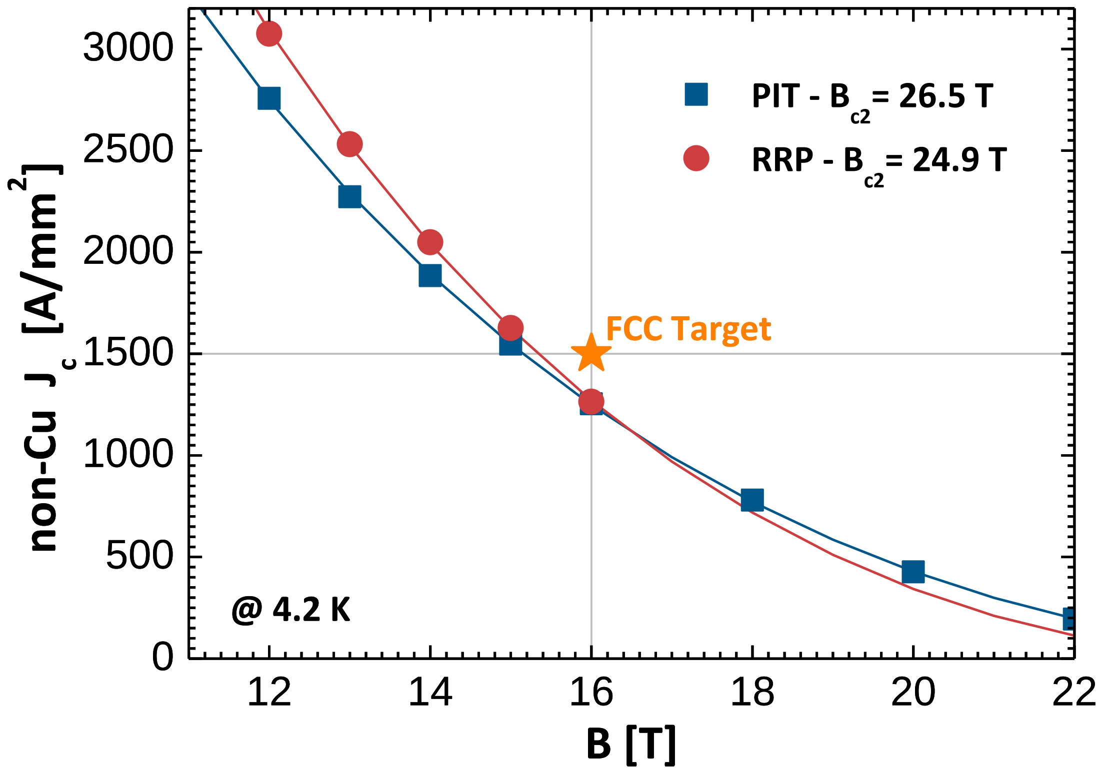
Dipoles at B = 16 T based on Nb_3Sn with a non-Cu J_c(4.2K, 16 T) = 1'500 A/mm^2



		2x	
B [T]	16		16
J_{op} [A/mm^2]	300	→	600
w [mm]	76		38
A_{coil} [mm^2]	20'000		7'000

Doubling the operating current density brings a reduction of the superconductor area to one third

$A_{coil} \propto SC\ mass \propto$ 



The most promising route to fill the performance gap is the Internal Oxidation

Parrell et al., AIP Conf. Proc. 711 (2004) 369
Boutboul et al., IEEE TASC 19 (2009) 2564
Xu et al., APL 104 (2014) 082602

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

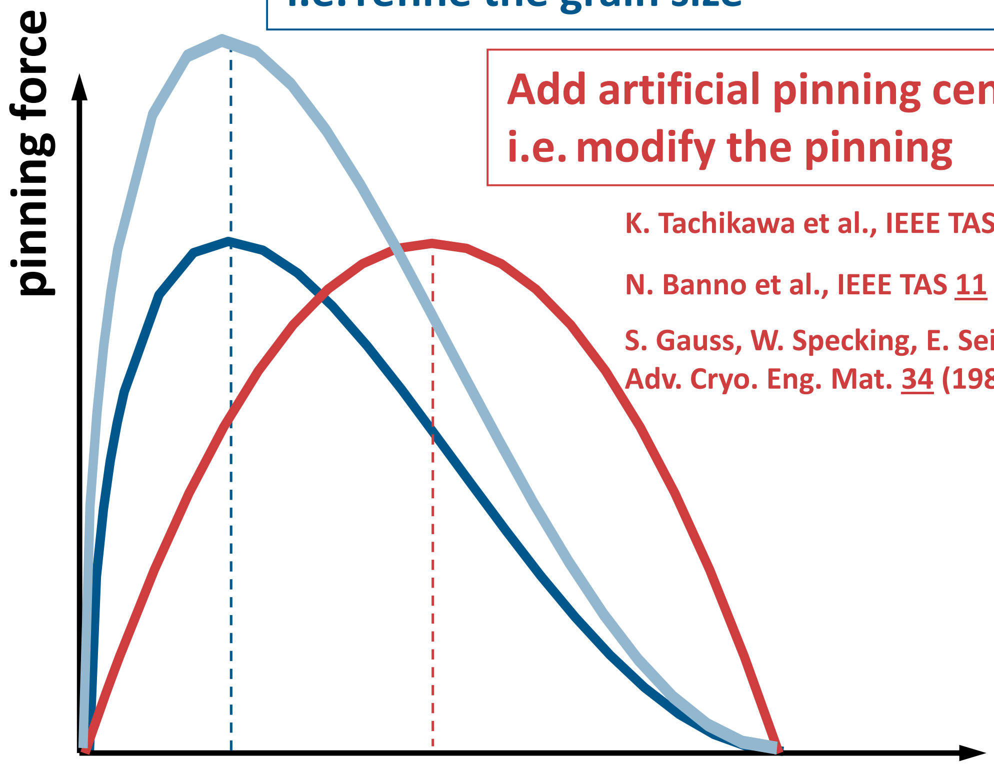
Increase the grain boundary density
i.e. refine the grain size

Add artificial pinning centers
i.e. modify the pinning

K. Tachikawa et al., IEEE TAS 13 (2003) 3438

N. Banno et al., IEEE TAS 11 (2001) 3696

S. Gauss, W. Specking, E. Seibt and R. Flükiger, Adv. Cryo. Eng. Mat. 34 (1988) 843



magnetic field

max at B = 0.2 B_{c2}
Grain boundary pinning

max at B = 0.33 B_{c2}
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)

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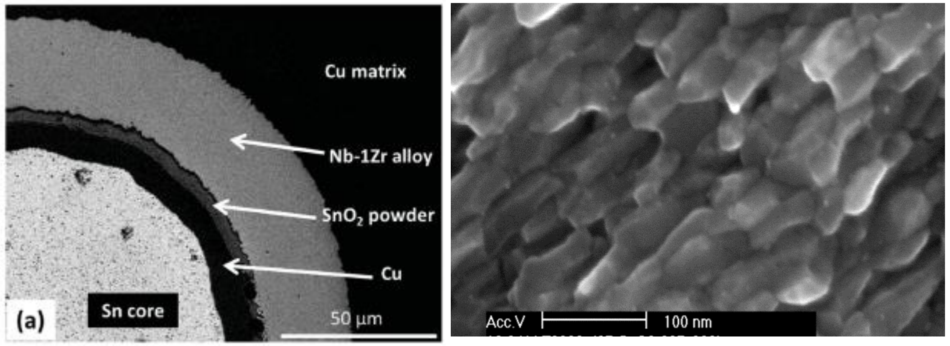

The first evidence of average grain size reduced down to ~ 50 nm (vs ~ 100 nm in regular wires)

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

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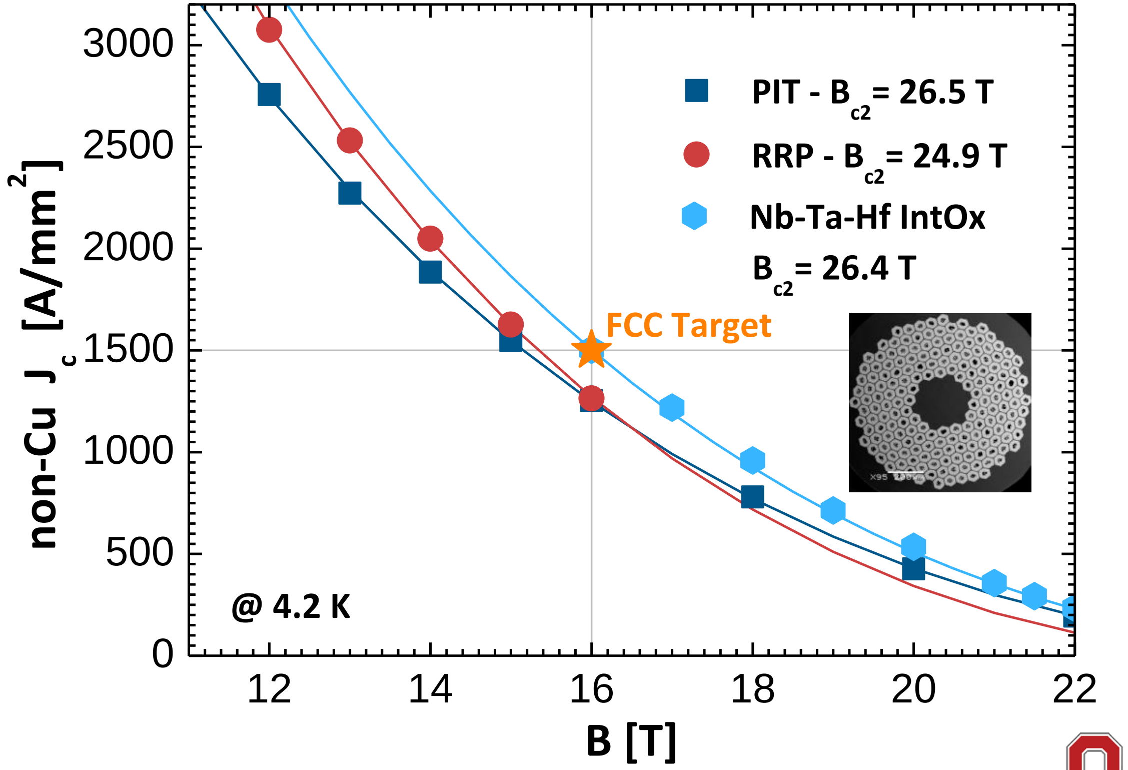

First report on a multifilamentary wire that reaches the FCC specifications

Sumption et al., US-MDT meeting, March 2021

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Hyper Tech

Fermilab

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

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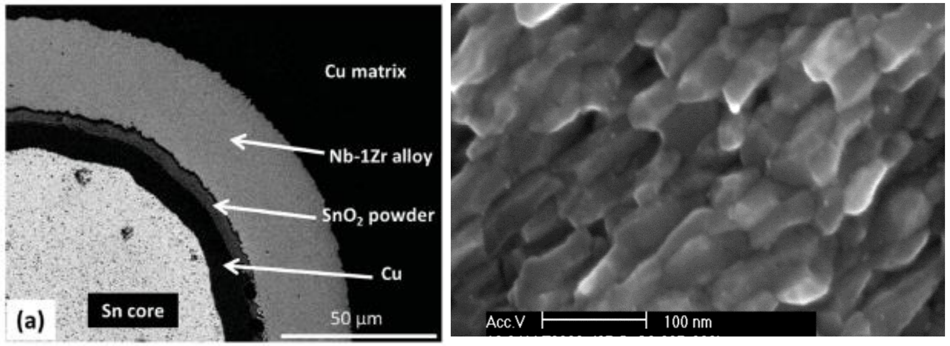
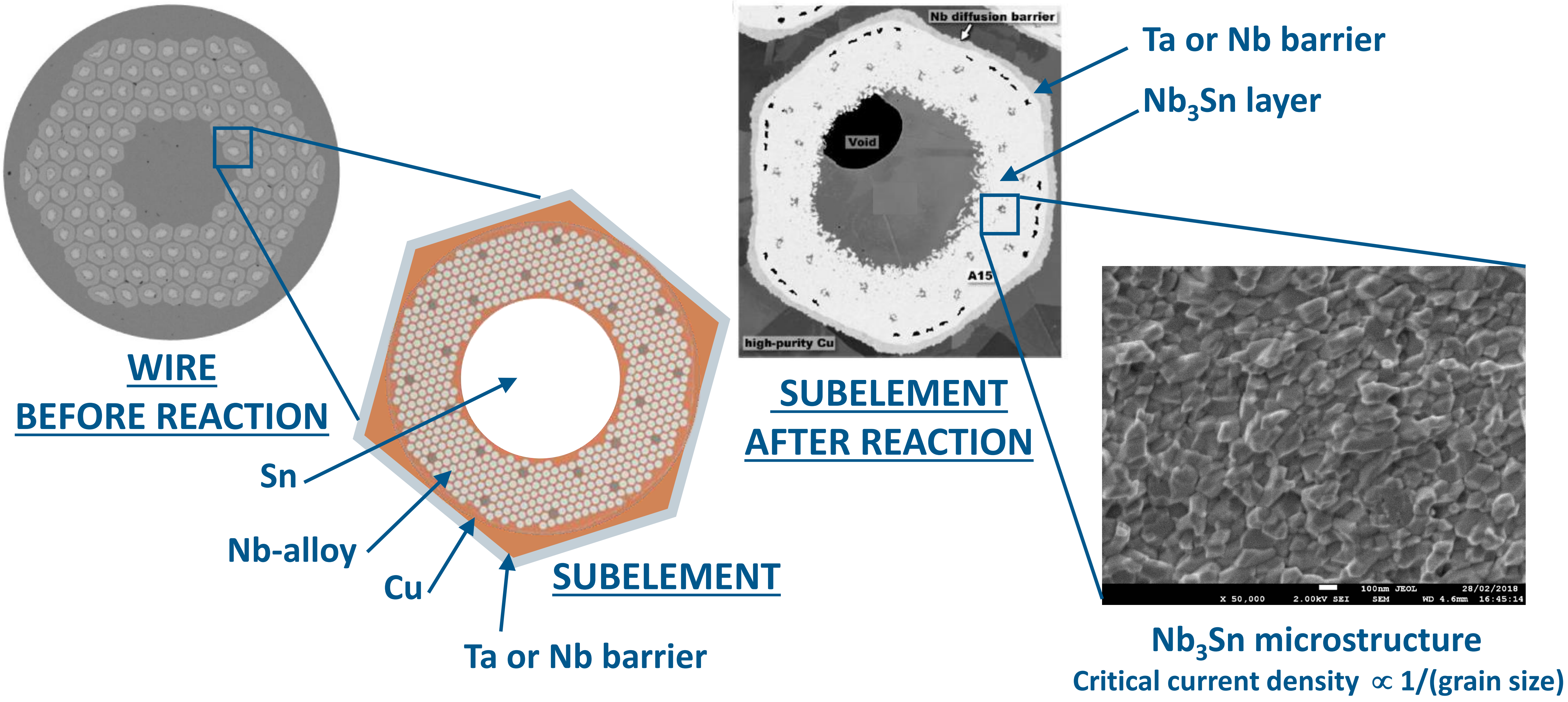


The first evidence of average grain size reduced down to ~ 50 nm (vs ~ 100 nm in regular wires)

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

How is made a high-performance Nb_3Sn wire



The defined goals of WireDev in CHART-2

- Obtaining and optimizing a method for refining grains in Nb_3Sn and enhancing its in-field critical current density

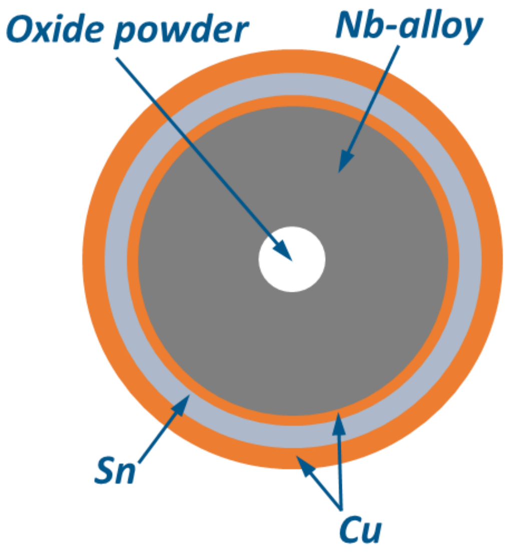
- Producing sufficiently long (unit lengths of the order of 20 m) prototype Nb_3Sn wires, matching the FCC targets for critical current density with a process that can be adopted for an industrial production

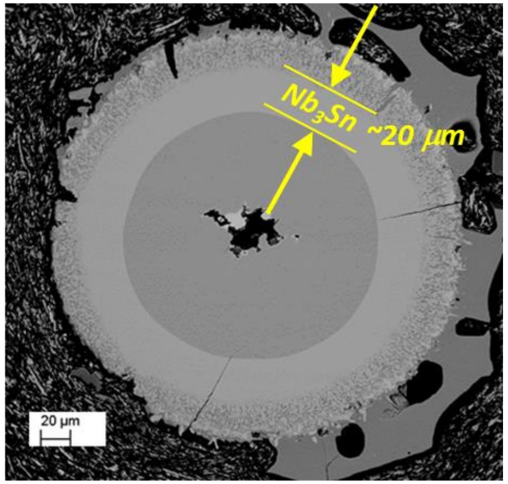
The three steps to get there:

1. Monofilamentary wires: Material study
   Test of various alloys and oxides (and their combinations)
2. Development of test-bed subelements
   Deformation, filaments arrangement and oxygen source configurations
3. Development of multifilamentary wires

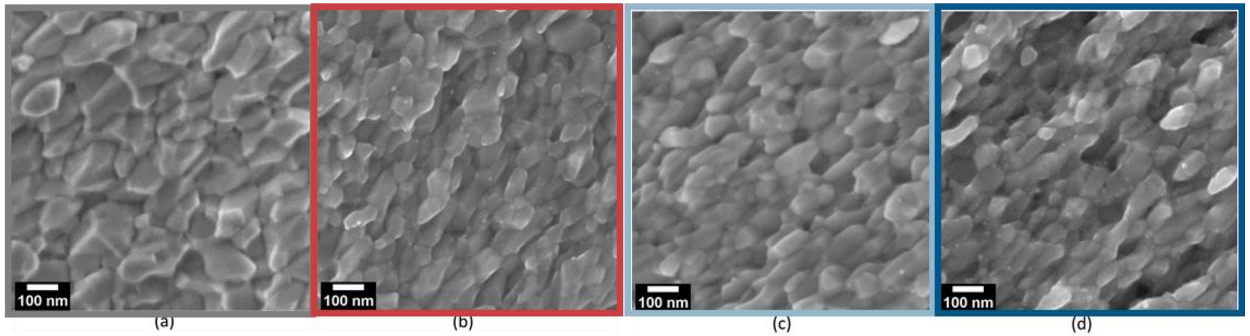
Internal Oxidation of monofilamentary wires

Florin BUTA | Gianmarco BOVONE | Francesco LONARDO





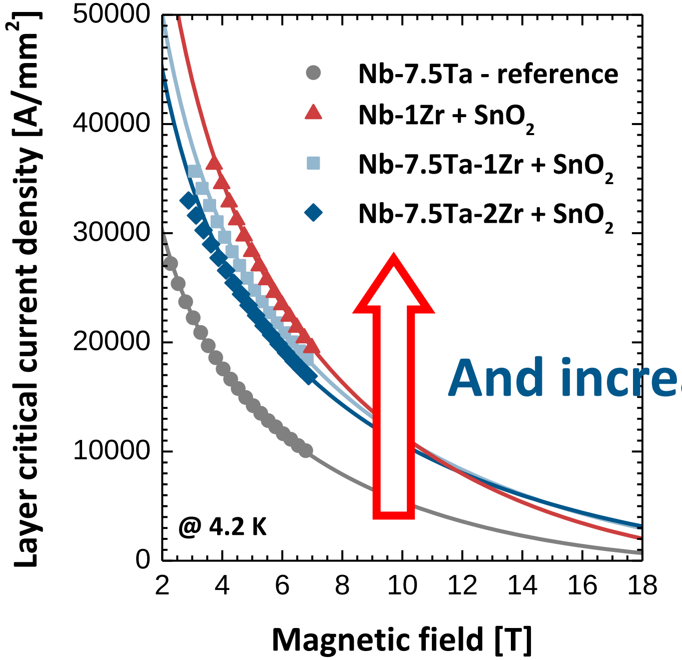
Nb-Ta (ref) | Nb-Zr | Nb-Ta-1Zr | Nb-Ta-2Zr



F. Buta *et al.*, J. Phys. Mater. 4 (2021) 025003
DOI: 10.1088/2515-7639/abe662

Wire configuration	Median grain size, short axis [nm]	Median grain size, long axis [nm]
Nb-7.5wt%Ta (REF.)	85 nm	108 nm
Nb-1wt%Zr + SnO_2	53 nm	86 nm
Nb-7.5wt%Ta-1wt%Zr + SnO_2	55 nm	82 nm
Nb-7.5wt%Ta-2wt%Zr + SnO_2	51 nm	85 nm

Pronounced grain refinement in Zr containing samples

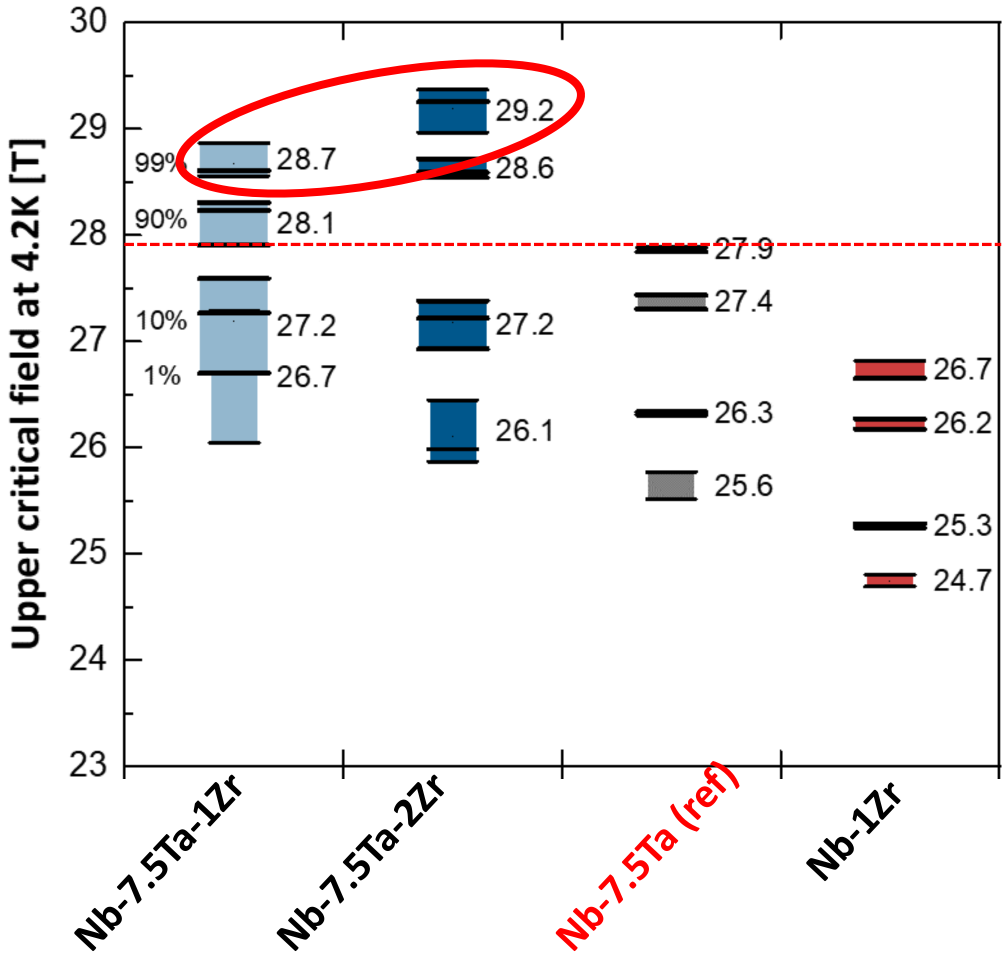


And increased layer J_c

Internal Oxidation of monofilamentary wires

Xavier CHAUD
David LEBOEUF

Critical fields from R(B) performed at LNCMI Grenoble under fields up to 33 T



The combined presence of Ta and Zr further increases the upper critical field up to ~29 T , i.e. to higher values than obtained for Nb7.5Ta

The result is technologically relevant but the reason behind is still unclear:

- Is the presence of Zr and/or O affecting the diffusion of Sn?
- Is the non-oxidized Zr contributing with Ta to increasing B_{c2}?
- Are the ZrO_2 nanoparticles playing a role?

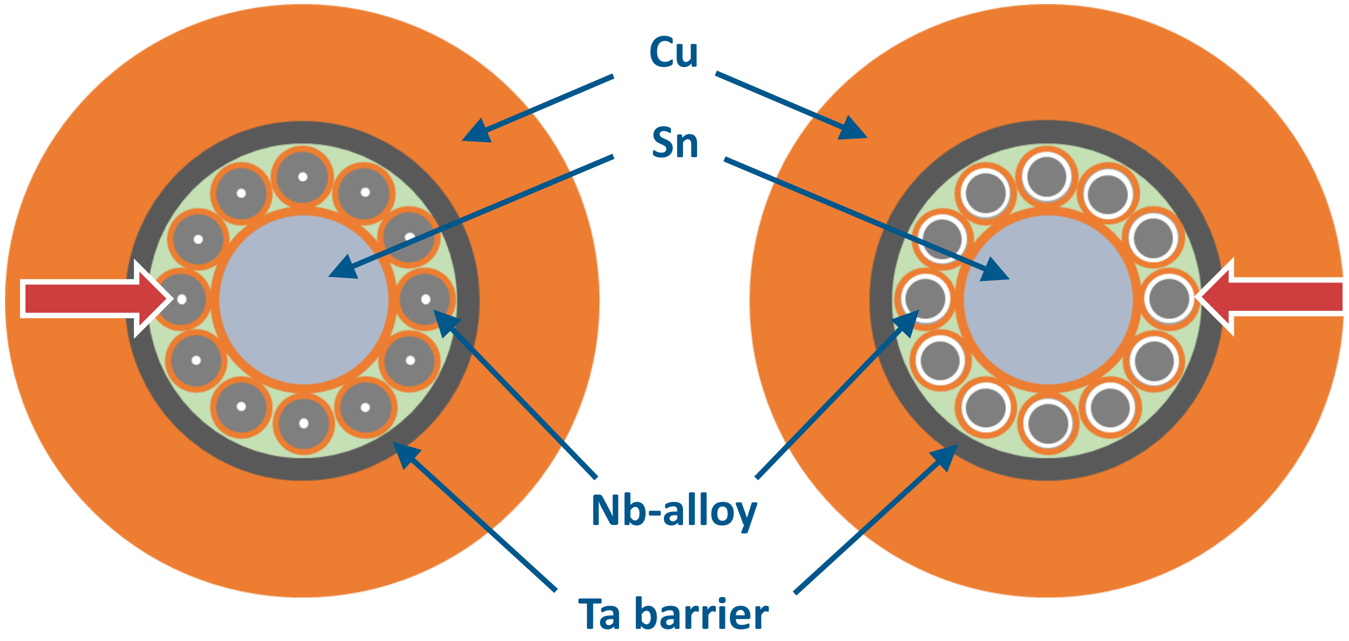
PAUL SCHERRER INSTITUT

X-ray Absorption Spectroscopy (XAS) experiments are planned in August 2022 at the PHOENIX X07MA/B beamline of PSI to shed light on the mechanism
Scientific contact: Thomas HUTHWELKER

Internal Oxidation of test-bed subelements

12-filament wires with an internal Sn source

Two possible configurations for the oxygen source

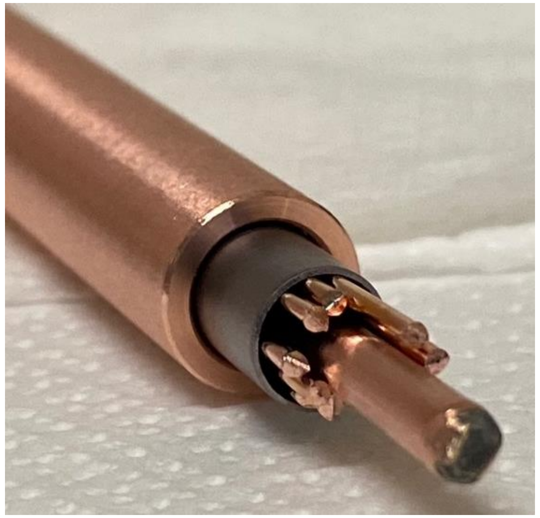


SnO_2 Core
SnO_2 powder inside the Nb-alloy filaments

SnO_2 Annular
SnO_2 powder between the Nb-alloy filaments and the Cu tube

Nb-alloy	Oxide configuration
Nb-7.5wt%Ta (REF.)	None
Nb-7.5wt%Ta-1wt%Zr	None
	SnO_2 Core
Nb-7.5wt%Ta-2wt%Hf	None
	SnO_2 Core
	SnO_2 Annular

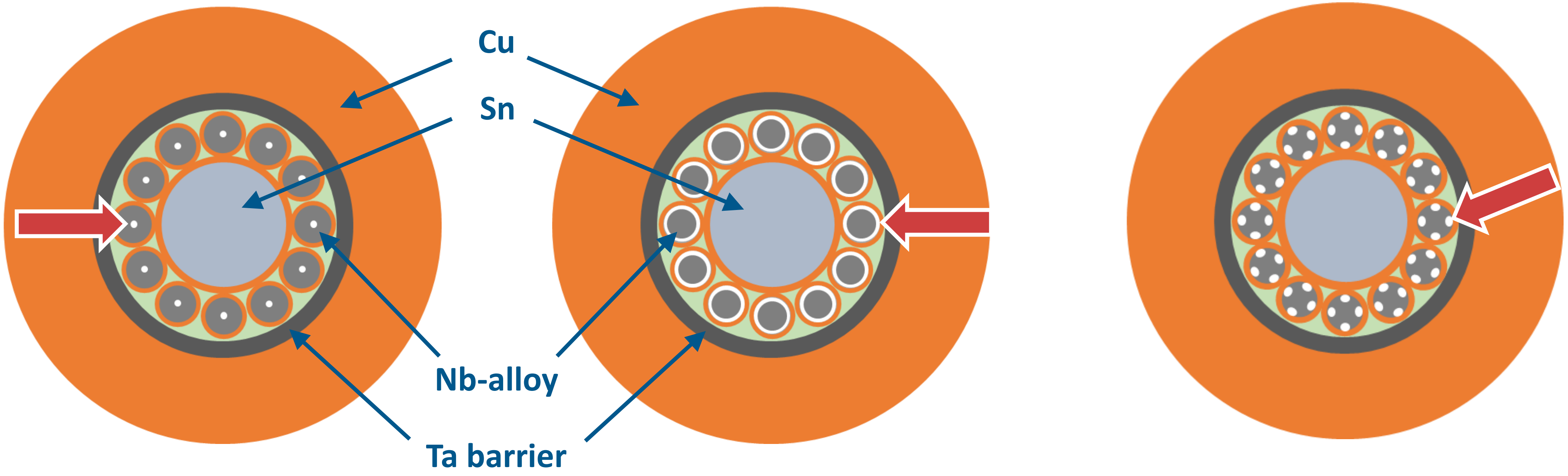
Two commercial ternary alloy were tested with 1wt%Zr and 2wt%Hf



Internal Oxidation of test-bed subelements

12-filament wires with an internal Sn source

Three ~~Two~~ possible configurations for the oxygen source



SnO_2 Core	SnO_2 Annular	SnO_2 Groove
SnO_2 powder inside the Nb-alloy filaments	SnO_2 powder between the Nb-alloy filaments and the Cu tube	Grooves machined in the Nb-alloy filaments and filled with SnO_2 powder

HT: 550°C x 100h + 650°C x 200h

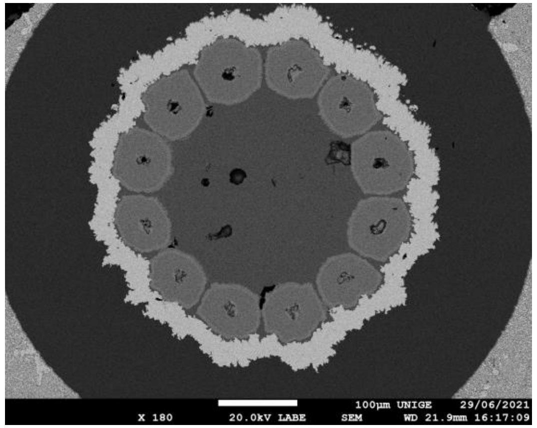
Internal Oxidation of test-bed subelements

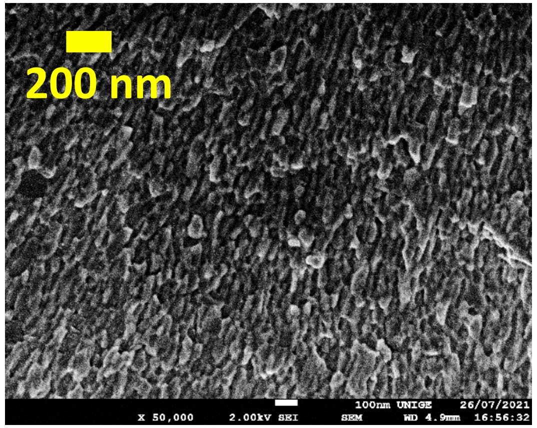
12-filament wires with an internal Sn source

Reference wire w/o oxidation

Average grain size ~ 110 nm

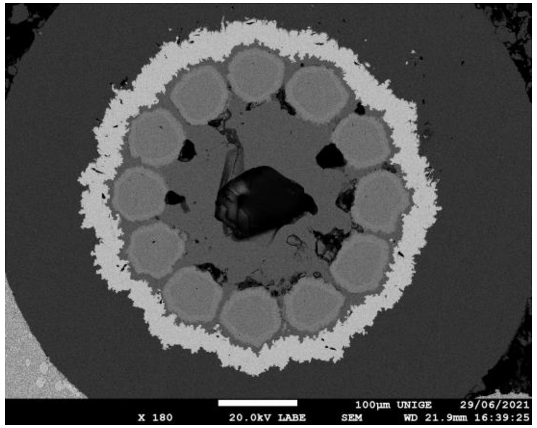
Nb-7.5Ta-2Hf + SnO_2 Core

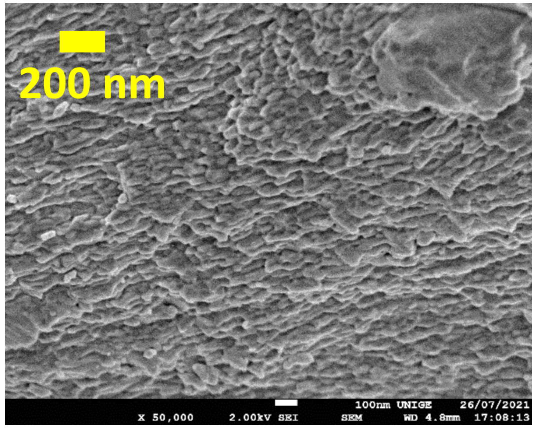




Average grain size ~ 47 nm

Nb-7.5Ta-2Hf + SnO_2 Annular

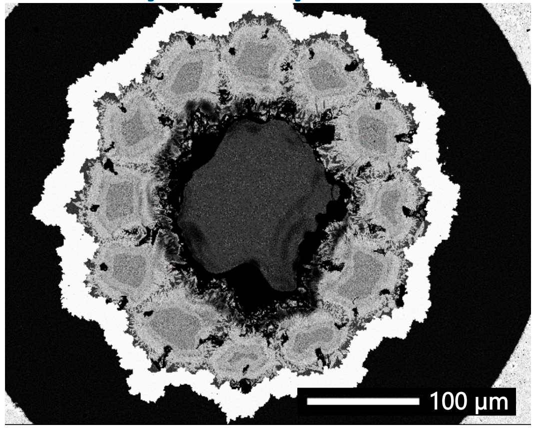


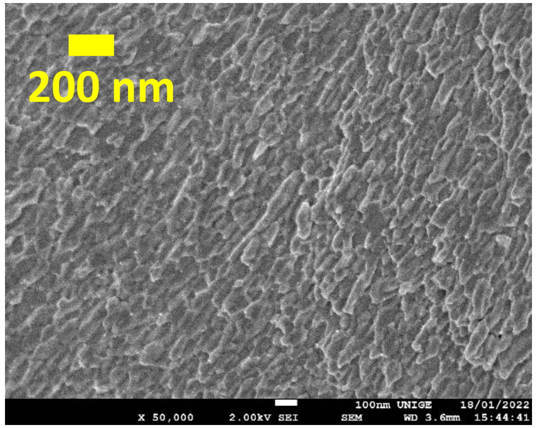


Average grain size ~ 45 nm

Nb-7.5Ta-2Hf + SnO_2 Groove

very first experiment

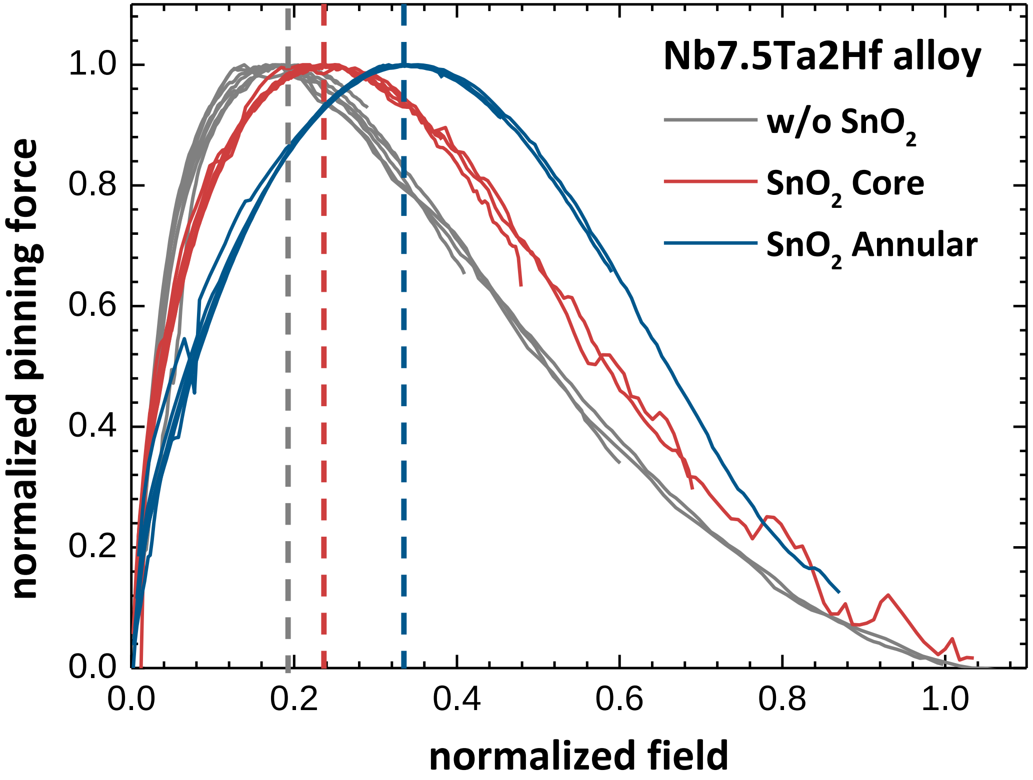


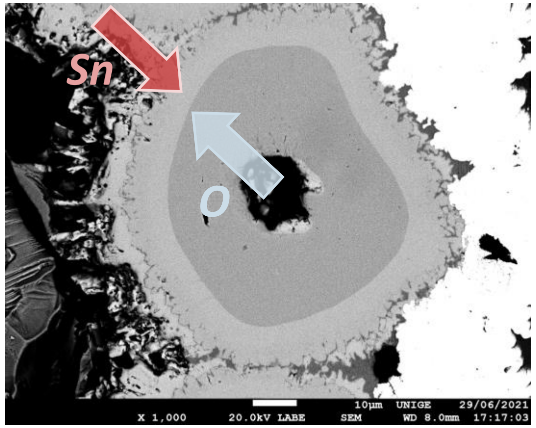


Average grain size ~ 50 nm

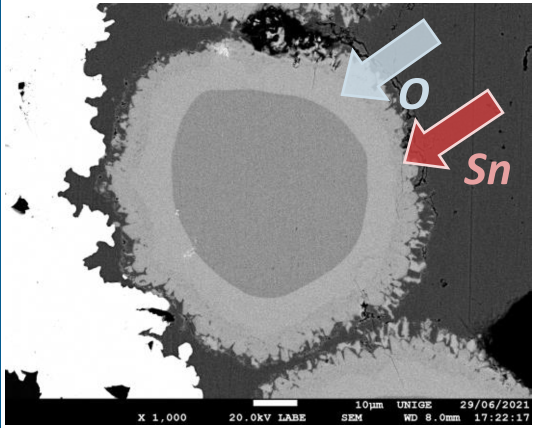
Is the oxygen source configuration making any difference?

Scaling of the pinning force





SnO_2 Core
Sn from the outside
O from the inside



SnO_2 Annular
Both Sn and O from the outside

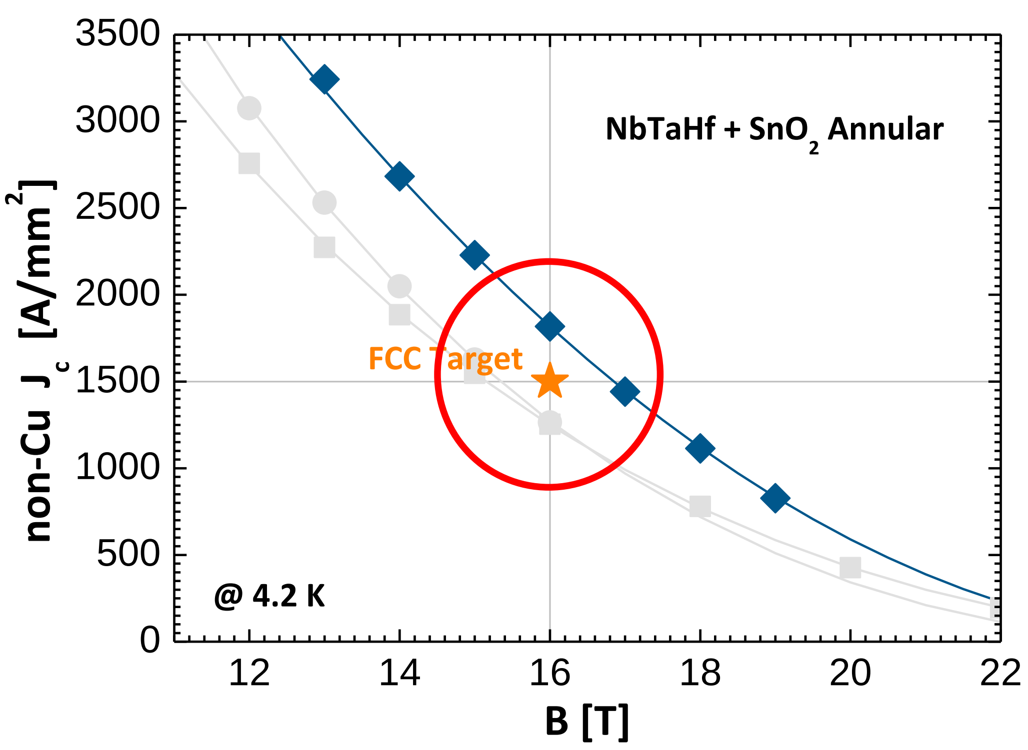
Wire w/o oxidation, $b_{max} = 0.2 \Rightarrow$ grain boundary pinning

Wire with SnO_2 Core, $b_{max} = 0.24 \Rightarrow$ mixed pinning, grain boundary and point pinning

Wire with SnO_2 Annular, $b_{max} = 0.33 \Rightarrow$ mixed pinning, point pinning dominant

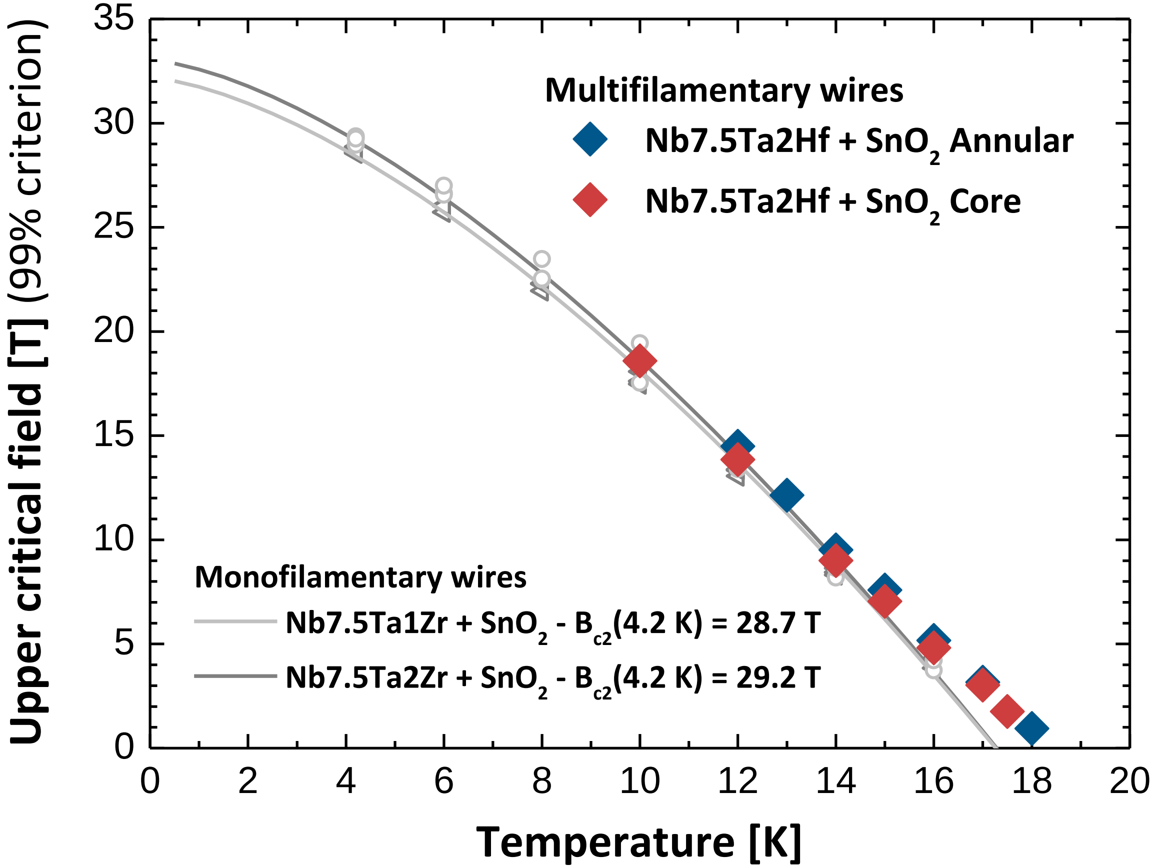
Internal Oxidation of test-bed subelements

Transport I_c and B_{c2} measurements



Layer J_c determined from transport measurements

Equivalent non-Cu J_c for a RRP wire, considering 60% of Nb_3Sn in the non-Cu area



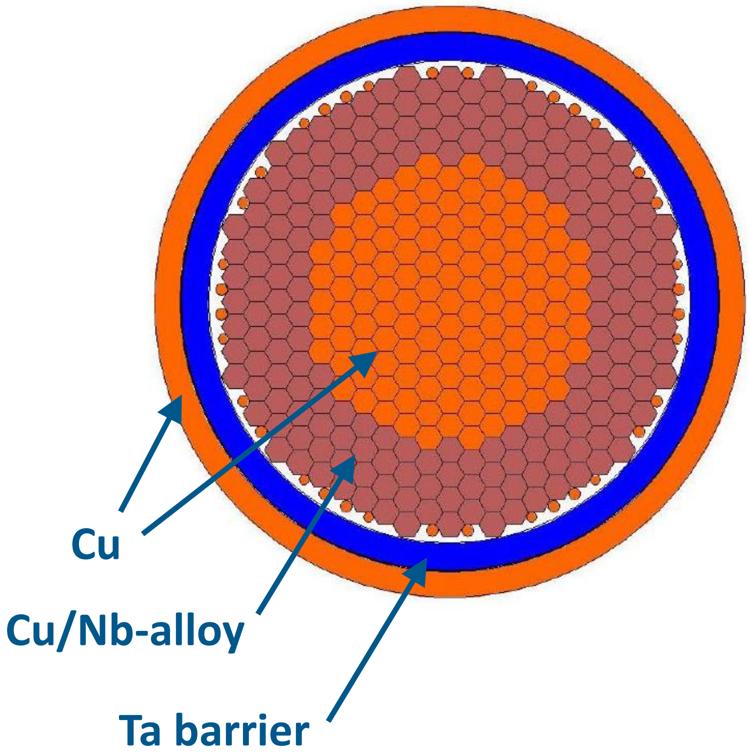
R(B) tests performed up to 19 T suggest that the record high B_{c2} values are achieved also in the test-bed subelements

LNCMI

High field experiments (up to 33 T) are planned in July 2022 at LNCMI-Grenoble

Towards the development of multifilamentary wires

From test-bed to fully-structured subelements

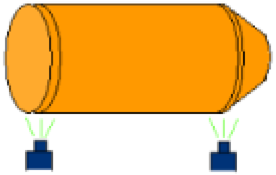


192 Cu/Nb-alloy filaments surrounding 121 Cu filaments

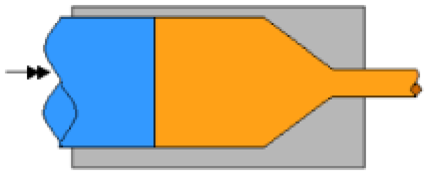
First billet based on Nb-7.5Ta to validate the layout and the following ones to test solutions for including the oxide powder

- Billet preparation and assembly at UNIGE

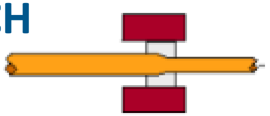
- e-beam welding at CERN
  sealing of the billet



- Hot Isostatic Pressing (HIP) at Deloro HTM, Bienne, CH
  densification of the billet
- Hot extrusion at
  - INGWERK GmbH, Berlin, D
    indirect extrusion, Ø 84 mm
  - Unipress Extrusion, Celestynów, PL
    hydrostatic extrusion, Ø 70 mm



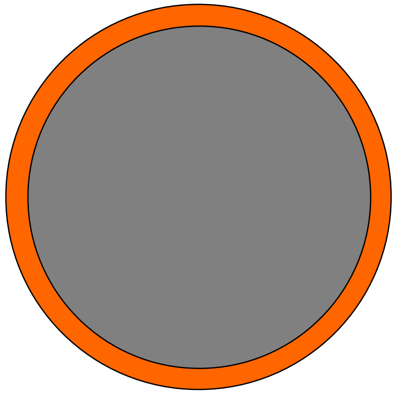
- Drawing of large diameter bars at Zwahlen et Mayr SA, Aigle, CH



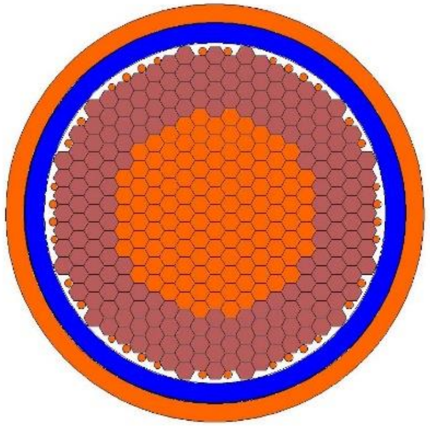
- Long drilling of bars at E. Grütter AG, Roggwil, CH
  to insert the Sn core

Towards the development of multifilamentary wires

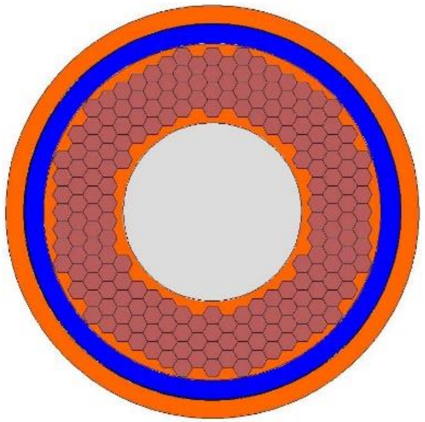
An overview of the entire process



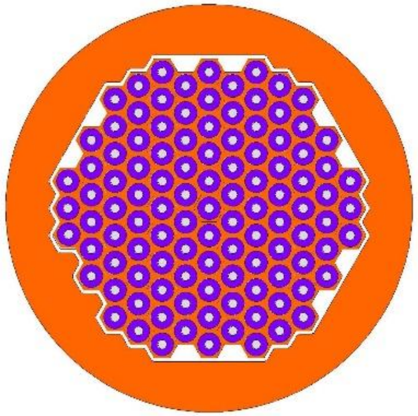
Cu/Nb-alloy rod



Subelement bundle



Subelement with pure Sn core



Final wire with 100-200 subelements

Oxide powders introduced either in the Cu/Nb-alloy rods or at the subelement level

Only cold deformation is possible till the final wire diameter

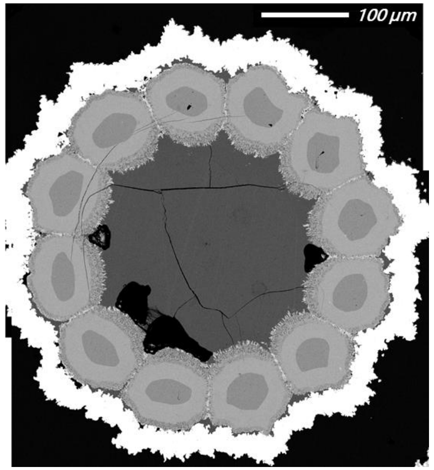
Summary and outlook

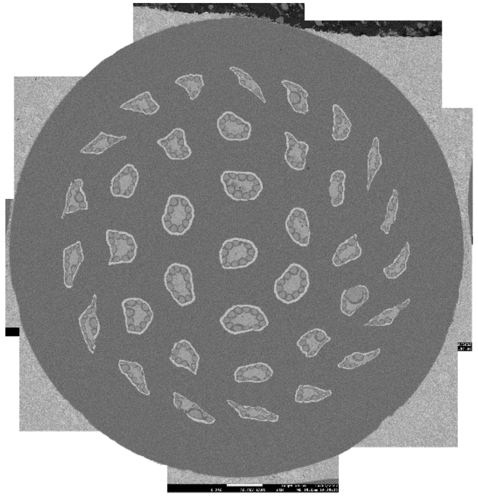
The goal of obtaining accelerator dipoles at 16 T for a Future Circular Collider is driving the development of Nb_3Sn towards its ultimate performance

- it is possible to produce routinely material with enhanced J_c by refining the grain size with the internal oxidation
- The combined presence of Ta and Zr or Hf leads to B_{c2} values that exceed by up to 1.3 T the values obtained at 4.2 K on standard Ta-doped Nb_3Sn
- practical solutions to implement this technology in industrial wires are being developed

In view of the phase 3 of CHART the scope of the activity could further expand with concrete goals and improving the Nb_3Sn R&D capability at UNIGE

- Developing multifilamentary Nb_3Sn wires with enhanced critical current density and able to withstand the mechanical loads imposed during the magnet assembly and by the electromagnetic forces during operation
- Aiming at the fabrication of sufficiently long (unit lengths <u>of the order of 100 m</u>) demonstration Nb_3Sn wires, as required for validation of the results in short Rutherford cables and model coils





Thank you for the attention !

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