Introduction to the activities of the WP1.3 at UNIGE

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Department of Quantum Matter Physics, University of Geneva, Switzerland
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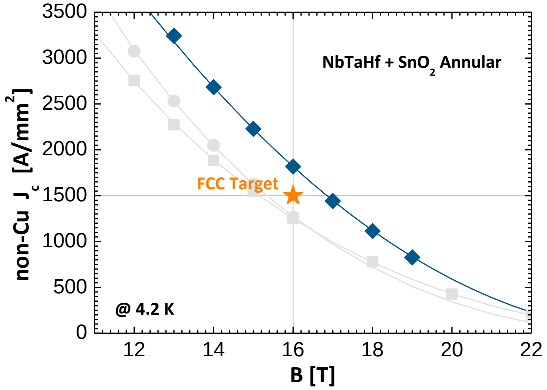
Jose FERRADAS-TROITINO, Simon HOPKINS, Thierry BOUTBOUL, Amalia BALLARINO
CERN, Switzerland

Advanced LTS Nb_3Sn superconductors for next generation particle colliders

Wire R&D and investigations of the properties



Towards the ultimate performance of Nb_3Sn

UNIVERSITÉ DE GENÈVE
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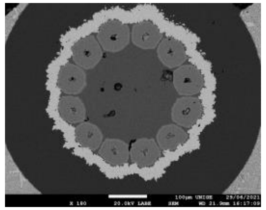
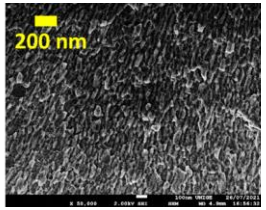
CERN
Swiss National Science Foundation

Producing sufficiently long prototype Nb_3Sn wires, matching the FCC targets for critical current density with a process scalable for industrial production

Wire development – high field tests – advanced analytical tools





Stress limits in Nb_3Sn-based accelerator magnets

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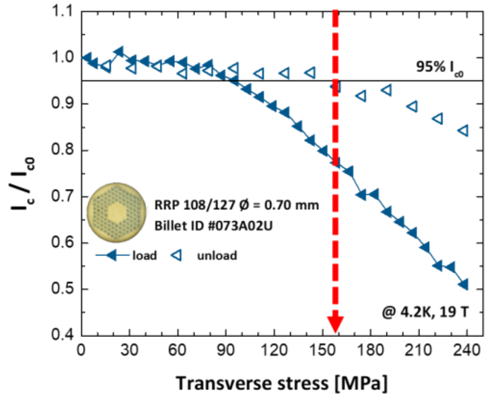
Assessing the electromechanical limits of the conductor at cryogenic temperatures (4.2 K) and high fields (up to 19 T) reproducing the operating conditions in an accelerator magnet

Electromechanical tests – Microtomography – FE simulations



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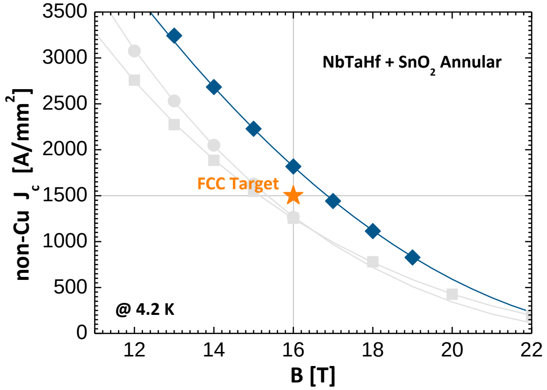

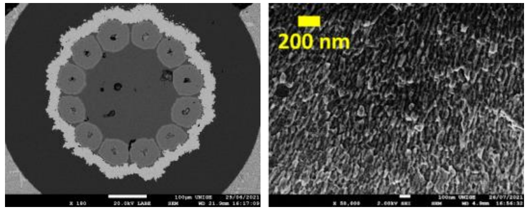

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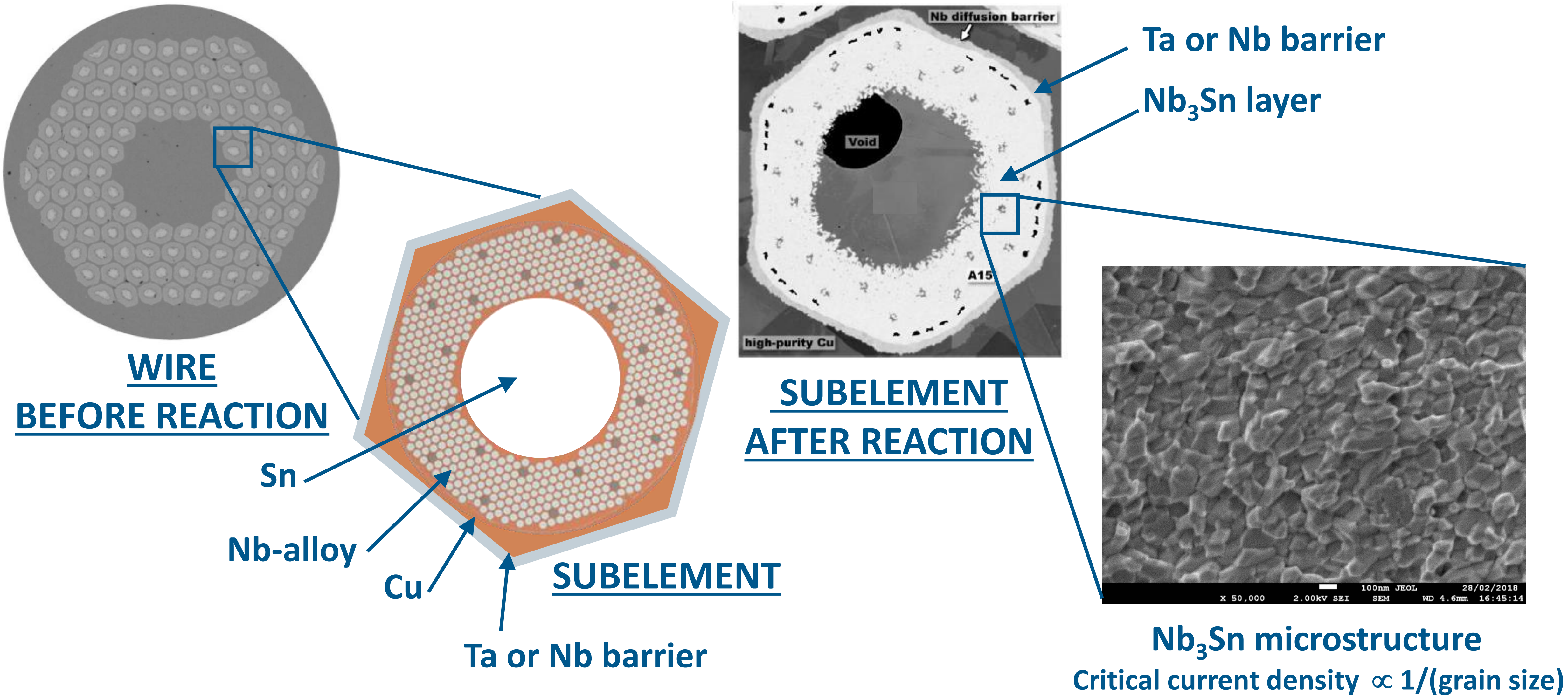
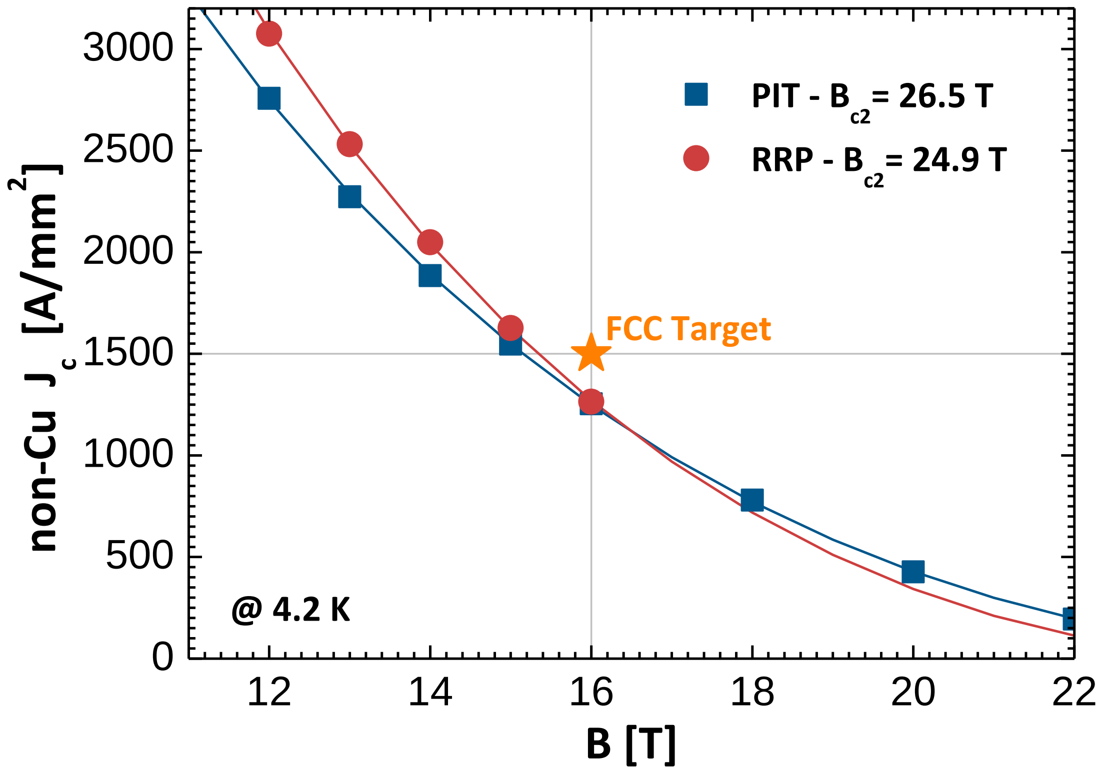
How it's made: high-J_c internal Sn Nb_3Sn wire



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



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

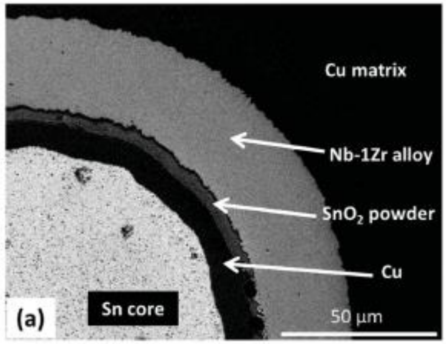
Parrell et al., AIP Conf. Proc. 711 (2004) 369
Boutboul et al., IEEE TASC 19 (2009) 2564

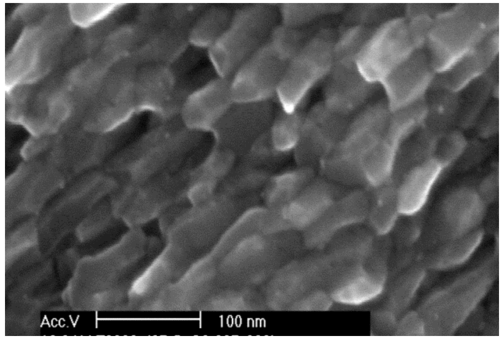
Idea from Benz (1968) of an Internal Oxidation to form fine precipitates in Nb to impede the Nb_3Sn grain growth Benz, Trans. Metall. Soc. AIME, 242 (1968) 1067-1070

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 Ohio State University





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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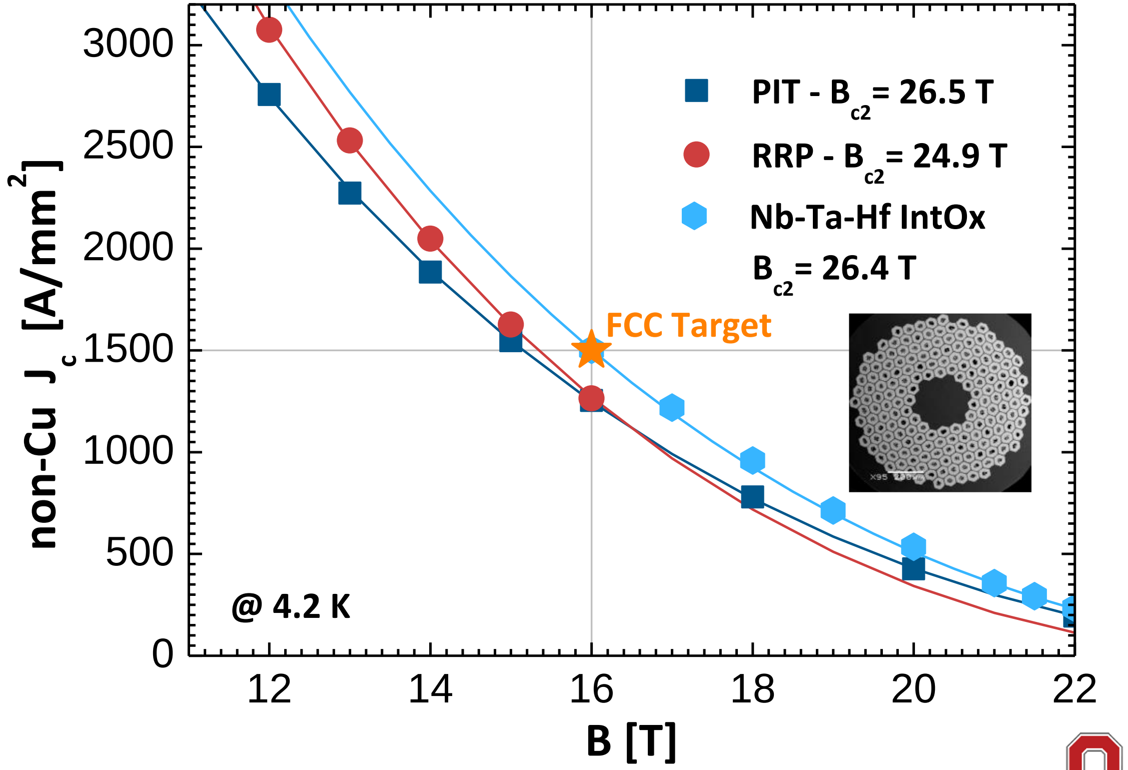

First report on a multifilamentary wire that reaches the FCC specifications

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

THE OHIO STATE UNIVERSITY

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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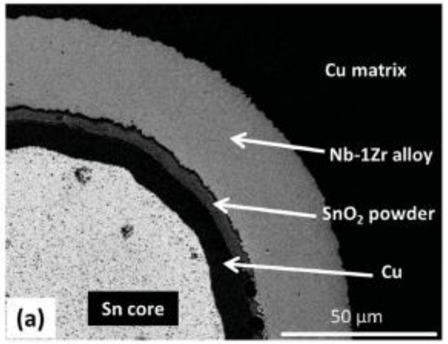
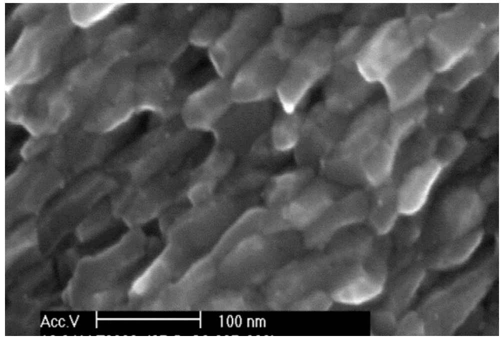
THE OHIO STATE UNIVERSITY





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The goals of the Wire Development Program at UNIVERSITÉ DE GENÈVE

FACULTÉ DES SCIENCES

- 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

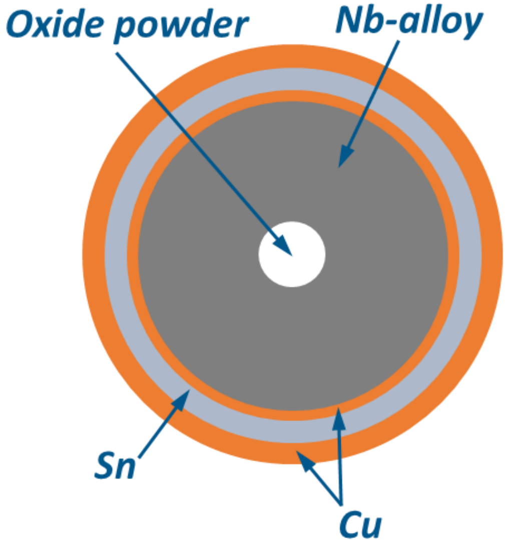
The three steps to get there:

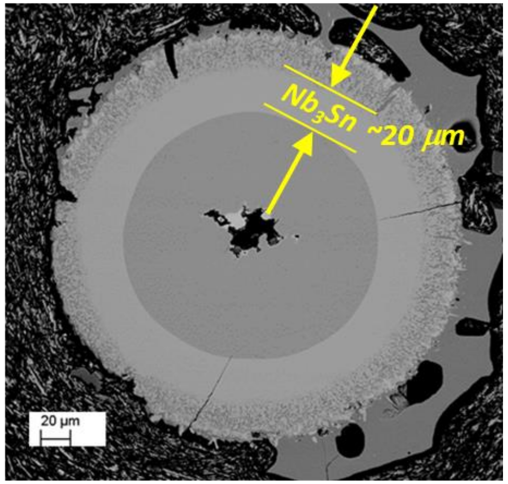
1. Monofilamentary wires: Material study
   Test of various alloys and oxides (and their combinations)
2. Development of test-bed subelements
   Deformation, filaments arrangement and oxygen source configurations
3. Development of multifilamentary wires

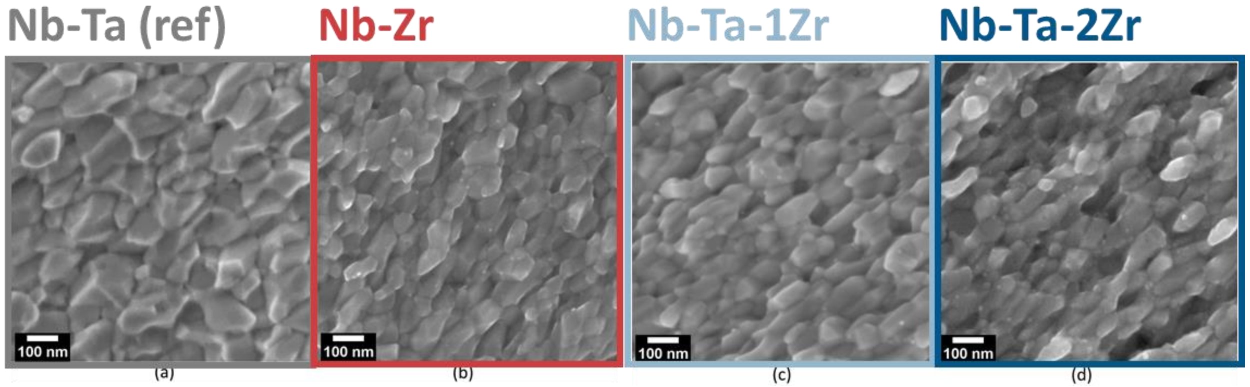
Internal Oxidation of monofilamentary wires



Florin BUTA
Gianmarco BOVONE
Francesco LONARDO



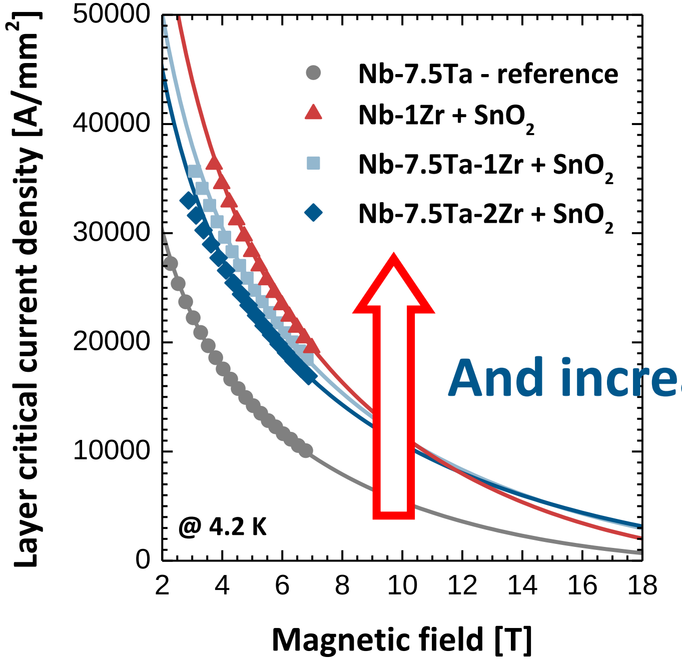




F. Buta *et al.*, J. Phys. Mater. 4 (2021) 025003
DOI: 10.1088/2515-7639/abe662

Wire configuration

Nb-7.5wt%Ta (REF.)
Nb-1wt%Zr + SnO_2
Nb-7.5wt%Ta-1wt%Zr + SnO_2
Nb-7.5wt%Ta-2wt%Zr + SnO_2



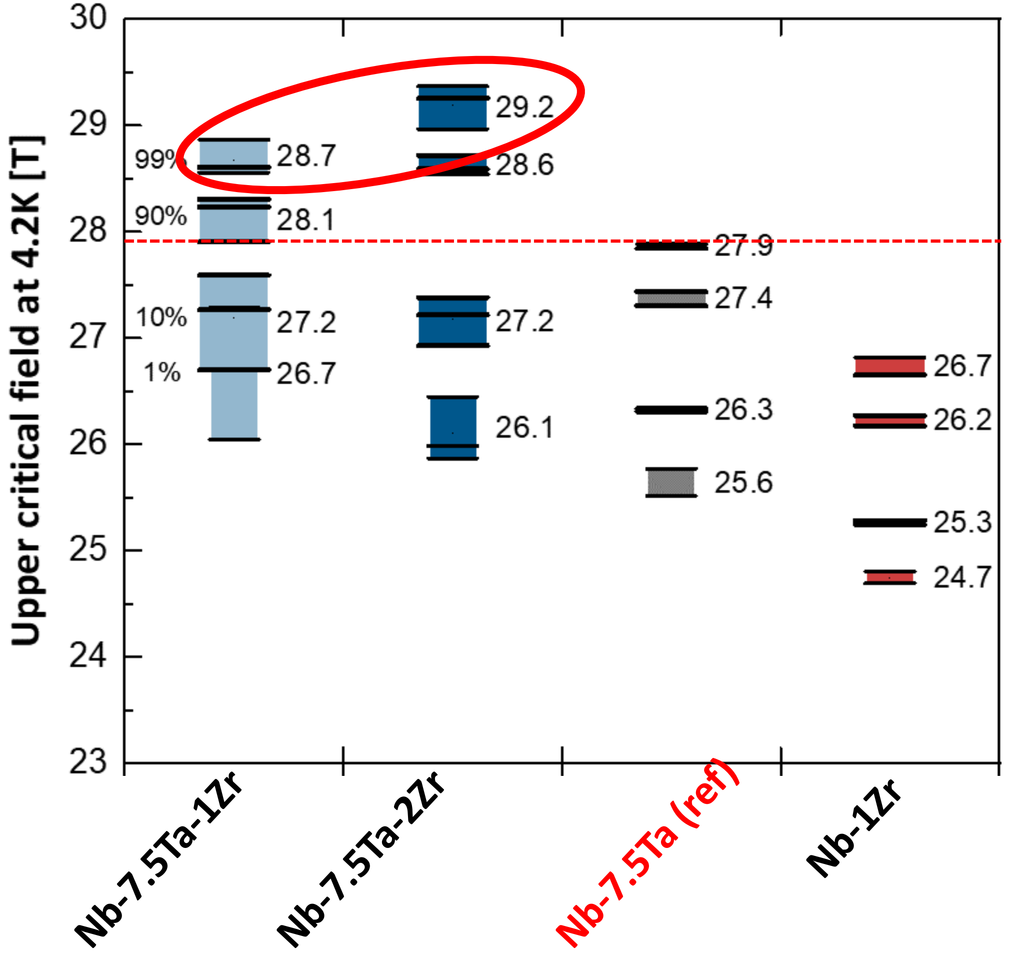
And increased layer J_c

Pronounced grain refinement in Zr containing samples

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 being investigated:

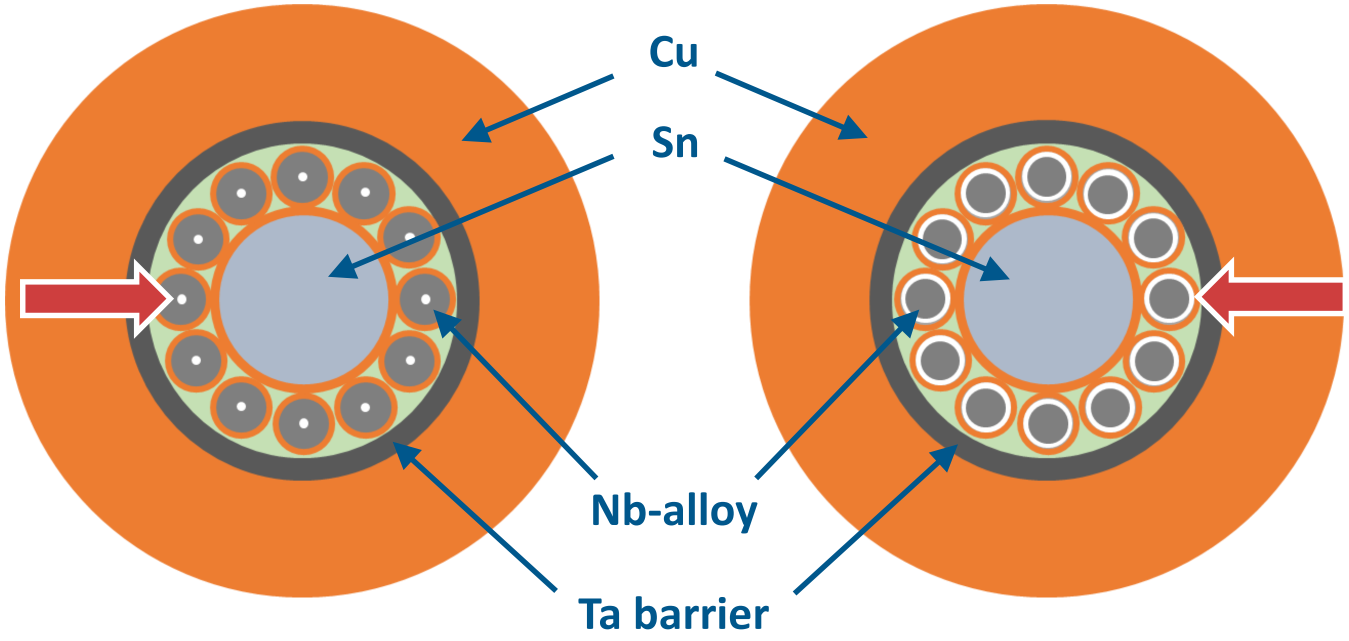
- Is the presence of Zr and/or O affecting the diffusion of Sn?
- Is the non-oxidized Zr contributing with Ta to increasing B_{c2}?
- Are the ZrO_2 nanoparticles playing a role?

More in the following on this topic, with high field measurements and X-ray absorption spectroscopy (XAS) experiments on multifilamentary wires

Internal Oxidation of test-bed subelements

12-filament wires with an internal Sn source

Two possible configurations for the oxygen source

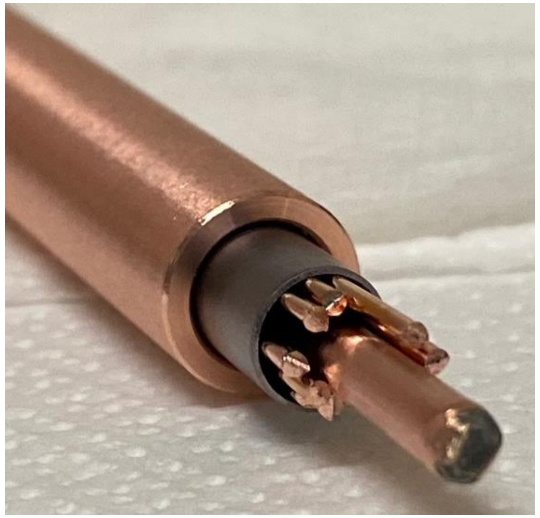


SnO_2 Core
SnO_2 powder inside the Nb-alloy filaments

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

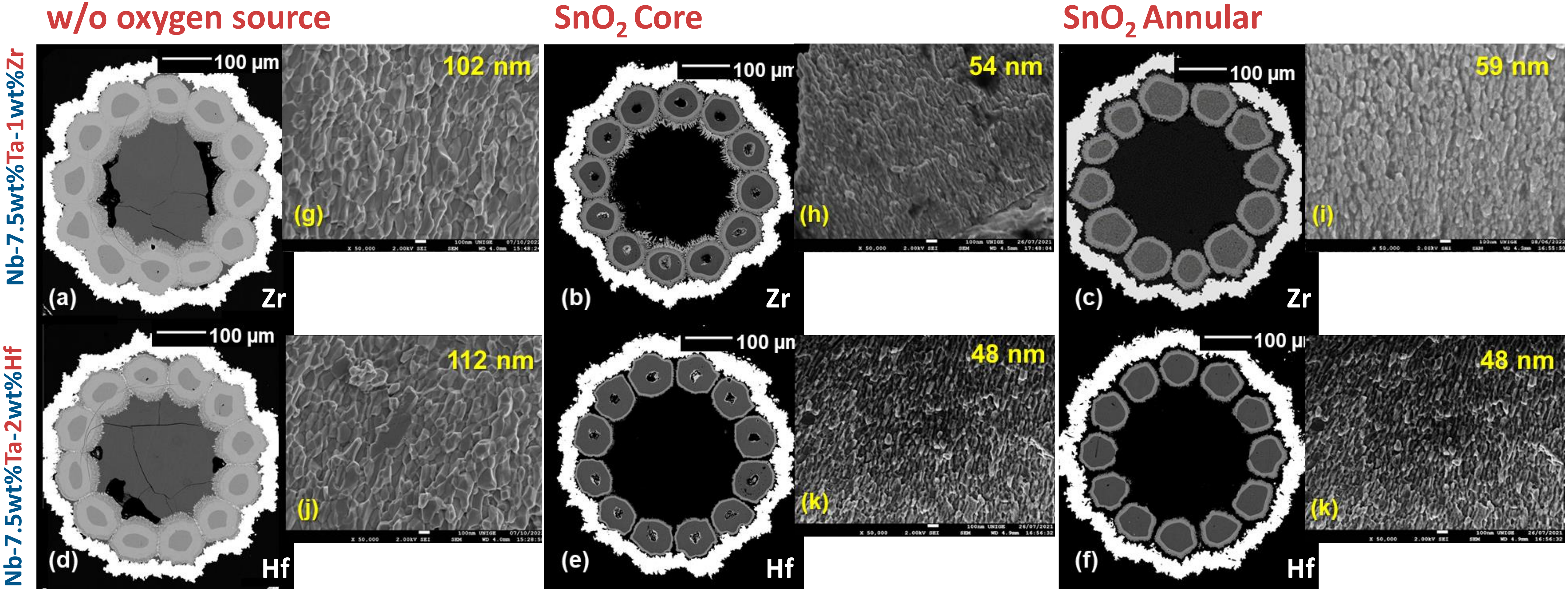
Two commercial ternary alloy were tested with 1wt%Zr and 2wt%Hf



HT: 550°C x 100h + 650°C x 200h

Internal Oxidation of test-bed subelements

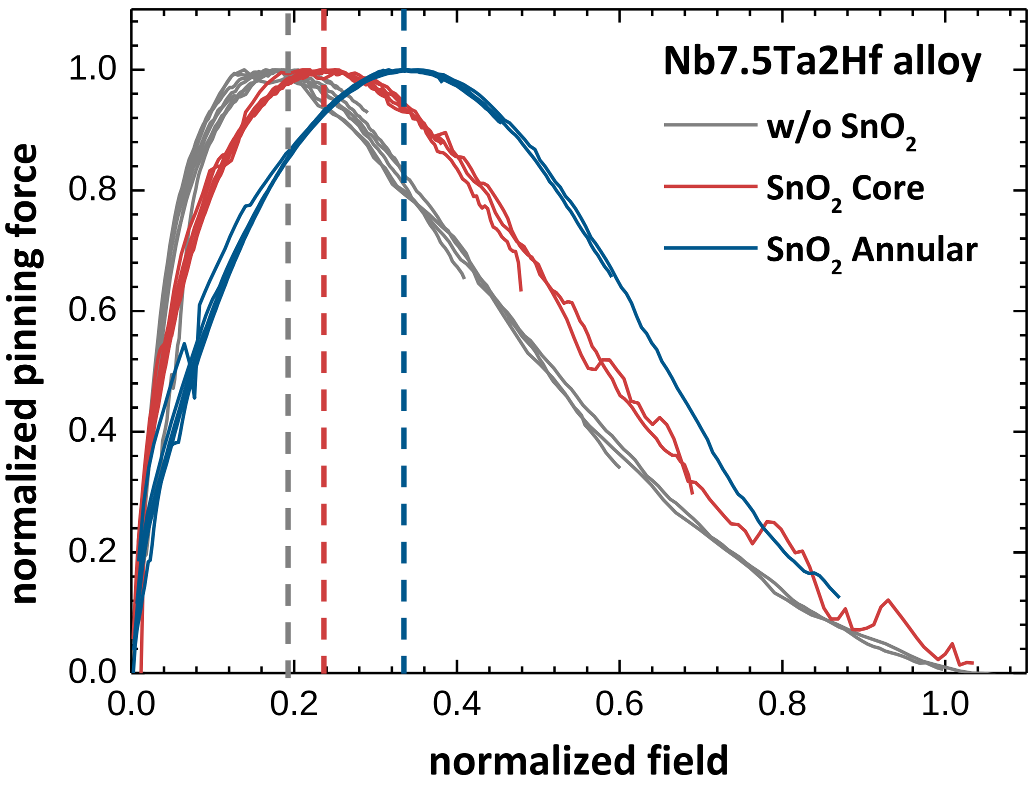
12-filament wires with an internal Sn source

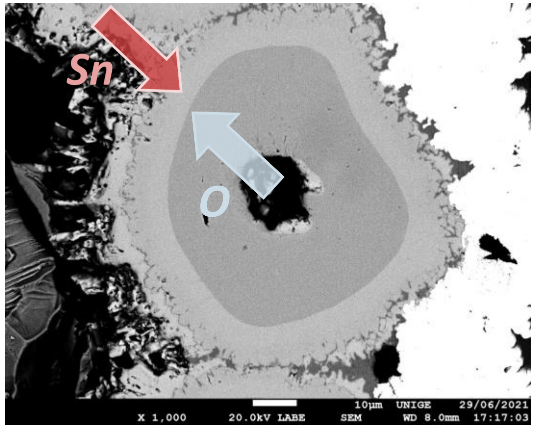


Internal oxidation leads to a refinement of the grain size from ~100 nm to ~50 nm regardless of the oxygen source configuration

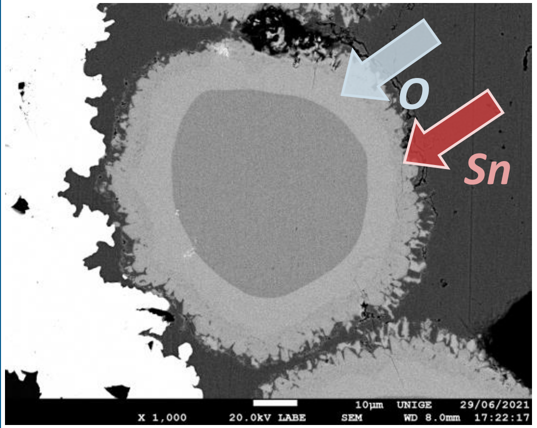
Is the oxygen source configuration making any difference?

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

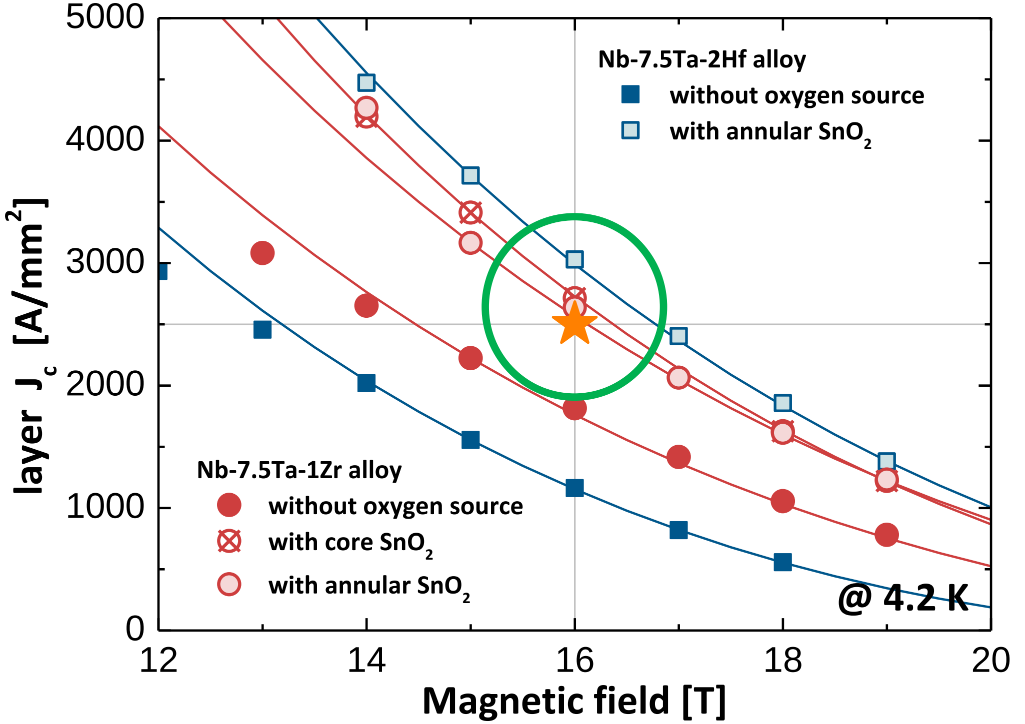
Wire w/o oxidation, b_{max} = 0.2 ⇒ grain boundary pinning

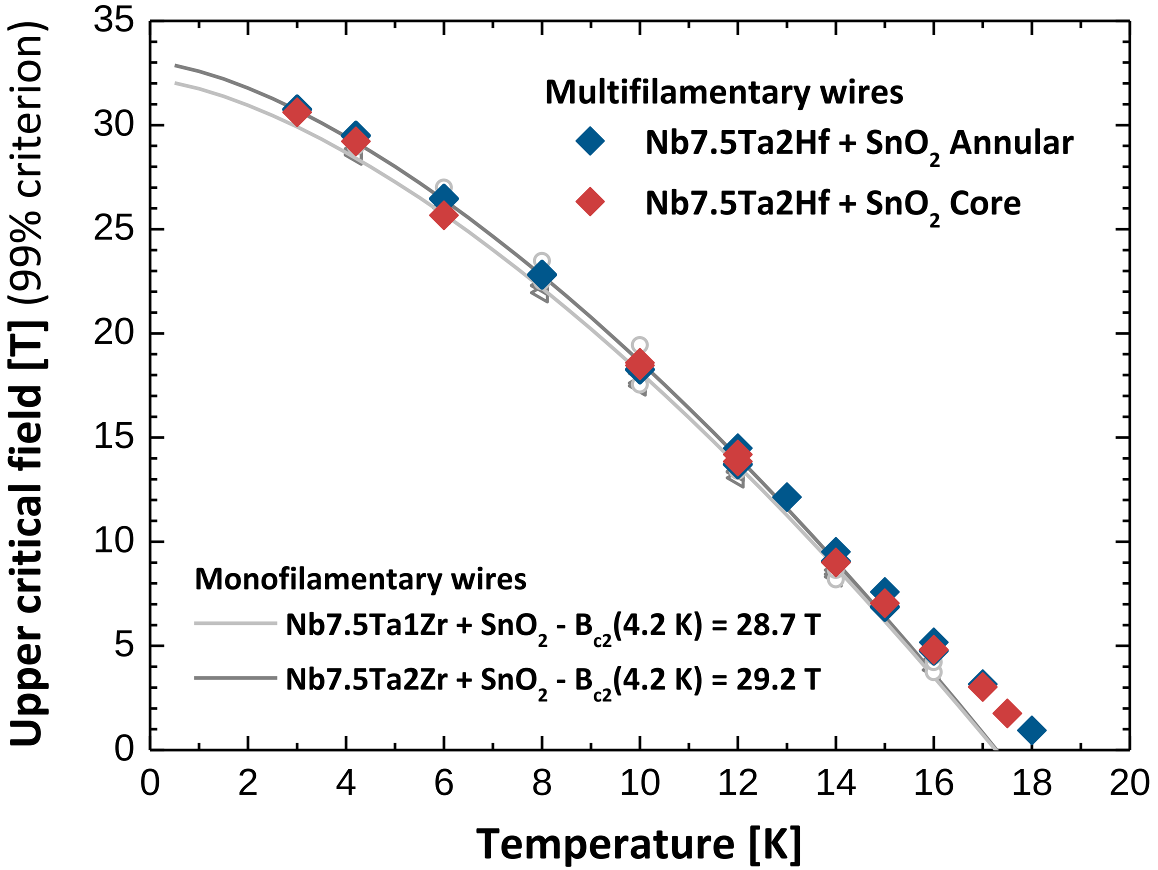
Wire with SnO_2 Core, b_{max} = 0.24 ⇒ mixed pinning, grain boundary and point pinning

Wire with SnO_2 Annular, b_{max} = 0.33 ⇒ mixed pinning, point pinning dominant

Internal Oxidation of test-bed subelements

Transport I_c and B_{c2} measurements





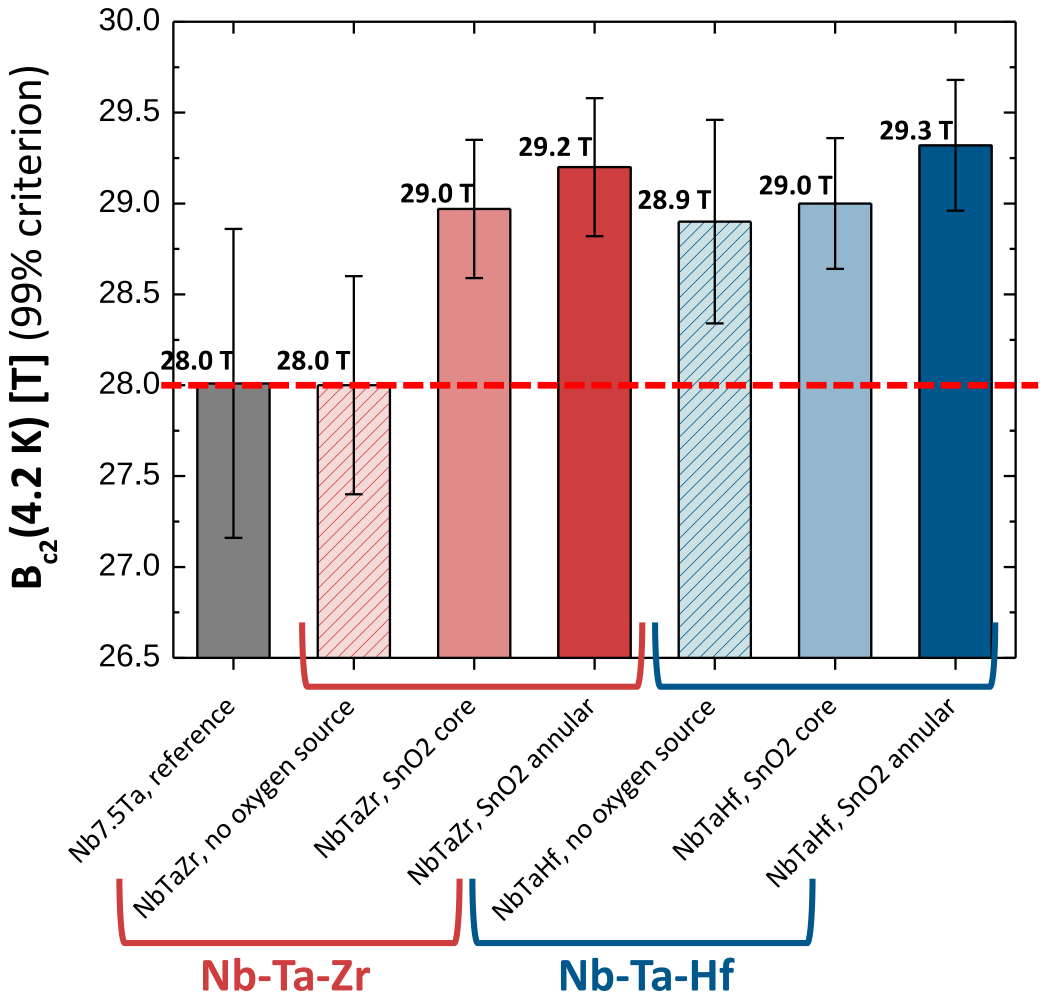
Layer J_c determined from transport measurements

FCC layer J_c (4.2K,16T) = 2'500 A/mm^2 considering 60% of Nb_3Sn in the non-Cu area

R(B) tests performed up to 33 T at LNCMI-Grenoble confirm that the record high B_{c2} values are achieved also in the test-bed subelements, both with Hf and Zr

Enhancement of the Upper Critical Field

Ternary alloys and internal oxidation

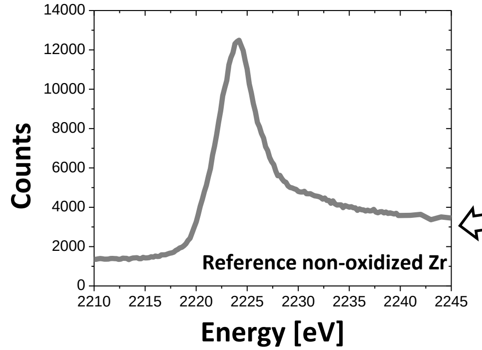


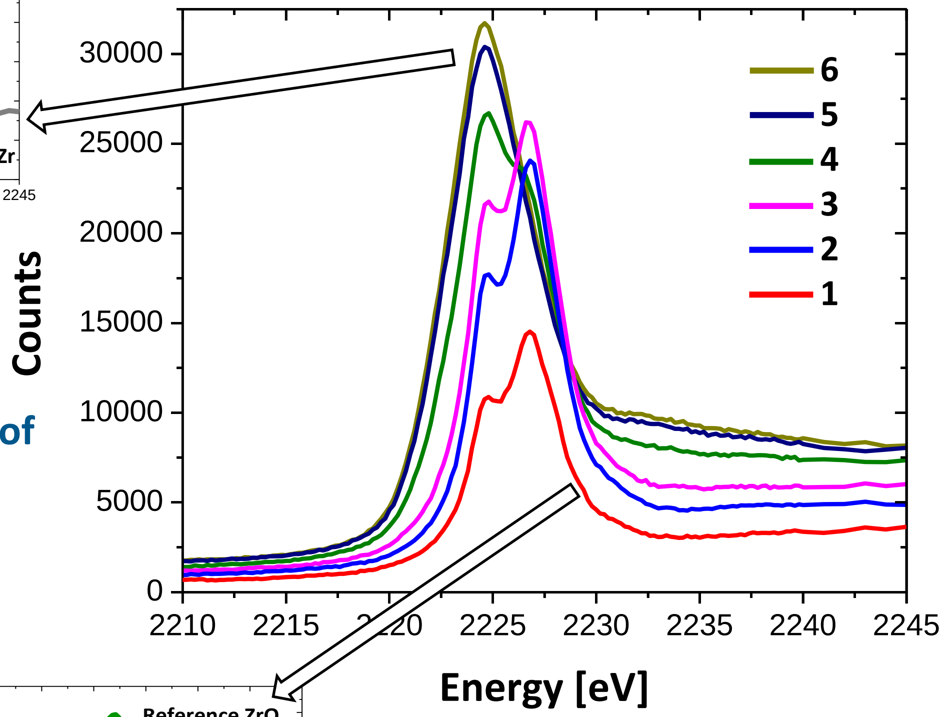
Nb alloy	B_{c2} (T=4.2 K) [T] No Oxygen	B_{c2} (T=4.2 K) [T] Core	B_{c2} (T=4.2 K) [T] Annular
Nb-7.5wt%Ta (REF.)	28.0 ± 0.8	n/a	n/a
Nb-7.5wt%Ta-1wt%Zr	28.0 ± 0.6	29.0 ± 0.4	29.2 ± 0.2
Nb-7.5wt%Ta-2wt%Hf	28.9 ± 0.5	29.0 ± 0.3	29.3 ± 0.2

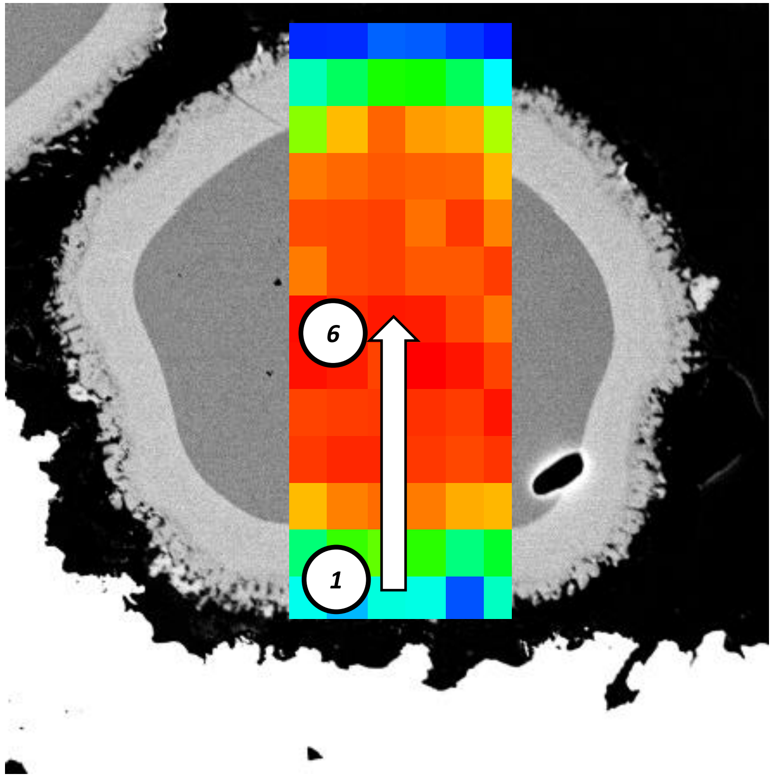
- Values of B_{c2}(4.2 K) reaching and exceeding 29 T are confirmed in the test-bed subelements with internal oxidation
- The Nb-Ta-Hf ternary alloy leads to an increase of B_{c2} also when no oxygen source is present in the wire

XAS experiments at PAUL SCHERRER INSTITUT PSI – preliminary analysis

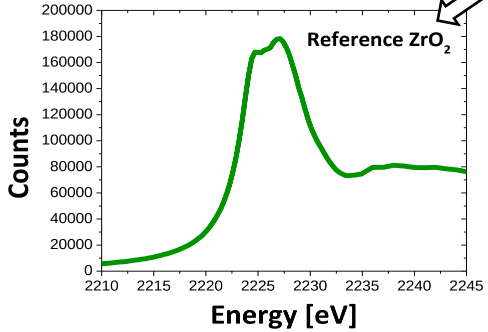
Spatial distribution of the oxide nano-precipitates







Spectra in the unreacted alloy resemble to those of metallic Zr



Spectra acquired in the Nb_3Sn layer appear similar to those of ZrO_2

X-ray Absorption Spectroscopy is used to probe the oxidation state of Zr

Acknowledgements to Thomas HUTHWELKER and Camelia BORCA, PSI

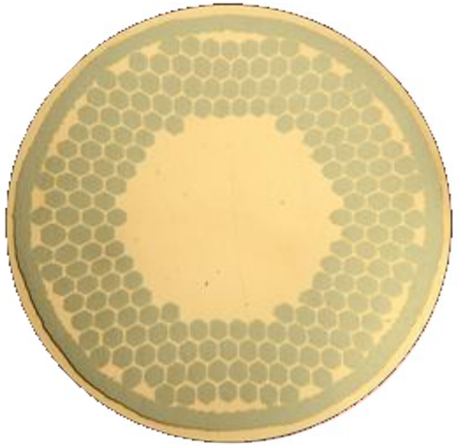
Towards the development of multifilamentary wires

From test-bed to fully-structured subelements

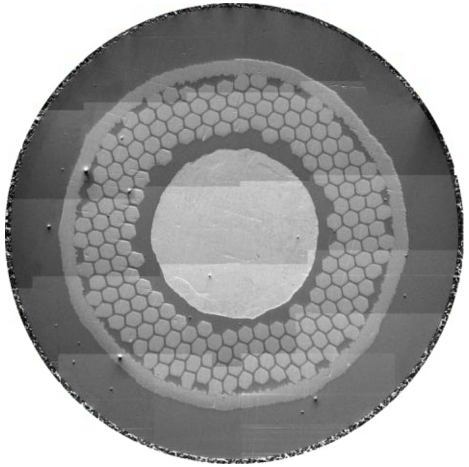
192 Cu/Nb-alloy filaments surrounding 121 Cu filaments

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

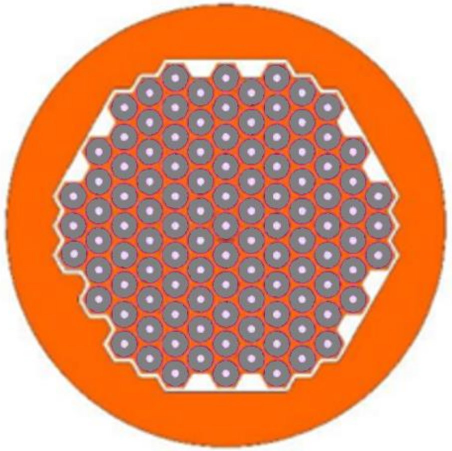
Cu/Nb-alloy rod



Subelement bundle

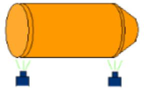


Subelement with pure Sn core

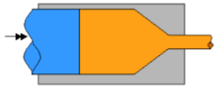


Final wire with 100-200 subelements

Inhouse billet preparation and assembly



e-beam welding at CERN



Hot Isostatic Pressing and Hot extrusion, outsourced

Long drilling of bars, outsourced

A subelement billet with oxygen source is ready for extrusion

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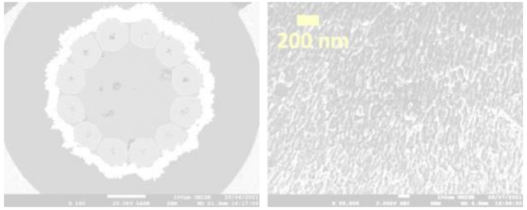

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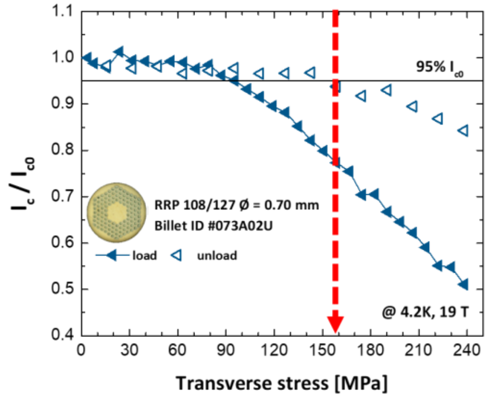
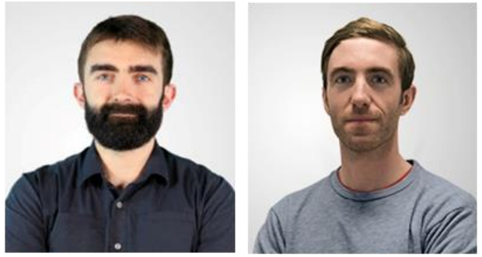
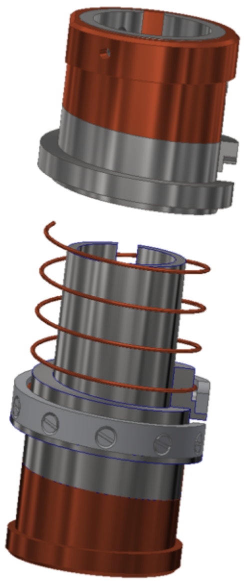


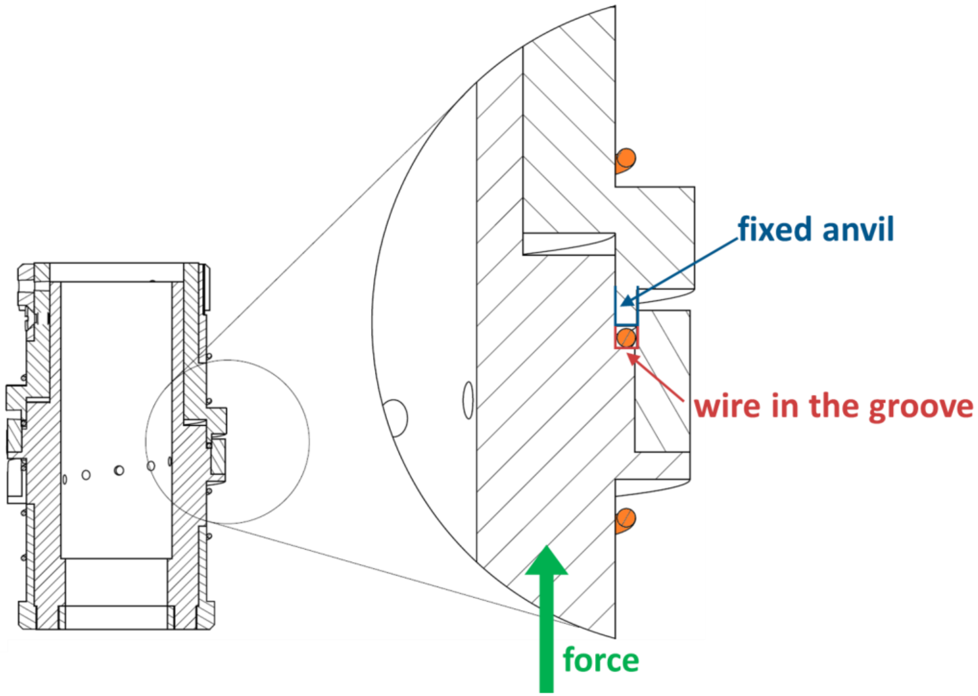
Tolerance to transverse stress of a single wire

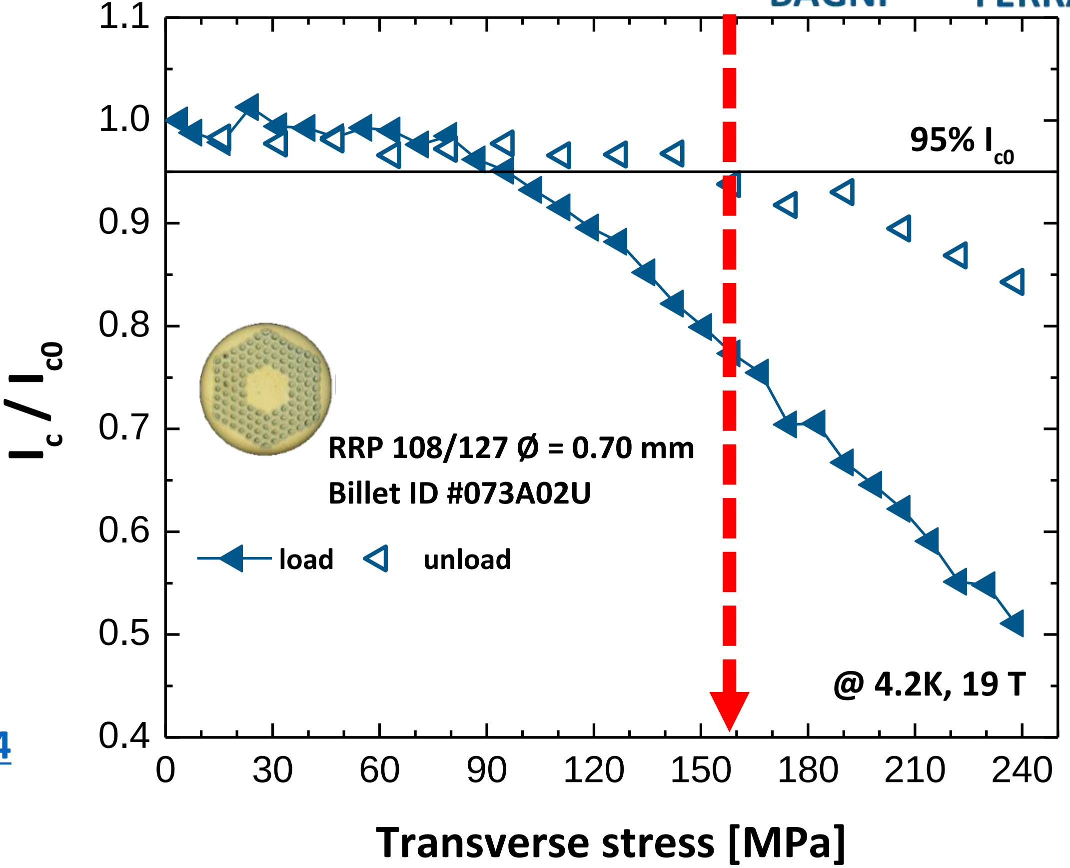
Electromechanical tests on Nb_3Sn wires impregnated with epoxy



Tommaso BAGNI
José FERRADAS







The WASP concept was adapted to transverse loads by
B. Seeber et al., IEEE TAS 17 (2007) 2643, DOI: 10.1109/TASC.2007.897934

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

Here the irreversible stress limit is σ_{irr} (B=19T)= 155 MPa (force dived by groove area)

What has been tested

A comprehensive campaign of electromechanical tests to gain knowledge on some very practical aspects

- **Probed the impact of the impregnation scheme on the transverse stress tolerance**
  Quantified the effect of the rigidity of the impregnation on the irreversible stress limit of PIT wires
  L. Gämperle, *et al.*, Phys. Rev. Research 2 (2020) 013211 DOI: 10.1103/PhysRevResearch.2.013211

- **Assessed the effect of the longitudinal strain state on the response to transverse stress**
  Investigated RRP wires under longitudinal and transverse loads
  J. Ferradas Troitino, *et al.*, Supercond. Sci. Technol., 34 (2021) 035008 DOI: 10.1088/1361-6668/abd388

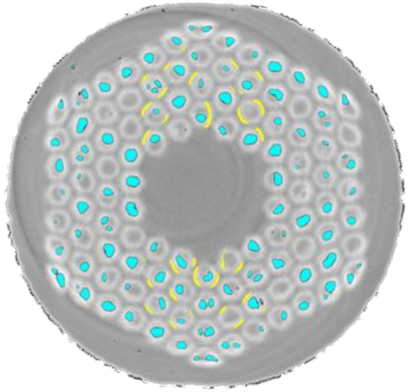
- **Assessed the basic mechanism behind the degradation of the critical current under transverse loads**
  C. Senatore, *et al.*, submitted to Supercond. Sci. Technol. (2023)

- **Investigated the impact of the wire deformation during cabling on the transverse stress tolerance**
  Performed measurements on PIT and RRP wires, round and 15%-rolled to simulate the effects of cabling
  T. Bagni, *et al.*, in preparation

Degradation mechanisms and irreversible reduction of I_c

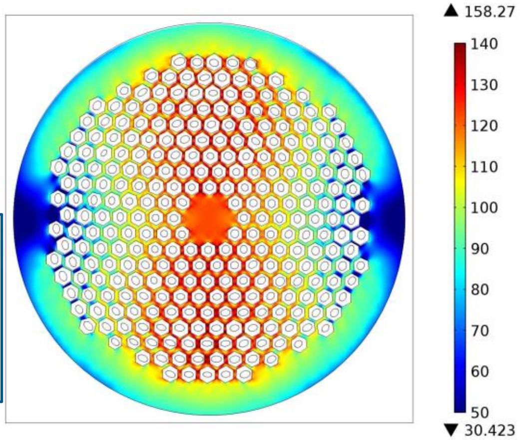
Two mechanisms govern the irreversible reduction of the critical current

- Formation of cracks in the Nb_3Sn filaments due, for instance, to the stress concentration at the voids



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

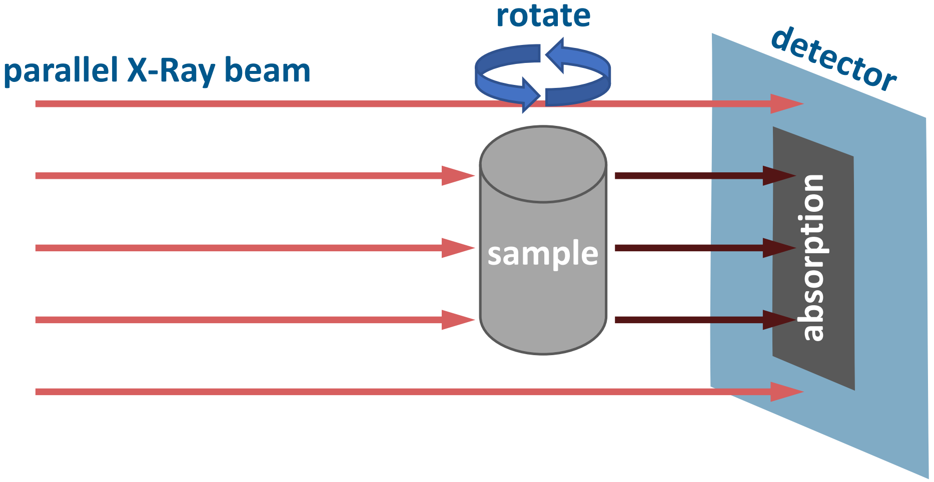


Residual stress induces a permanent reduction of B_{c2} after unload ⇒ I_c^{unload}/I_{c0} depends on of the magnetic field

X-ray tomography and Neural Networks for crack detection


Tommaso BAGNI

Diego MAURO

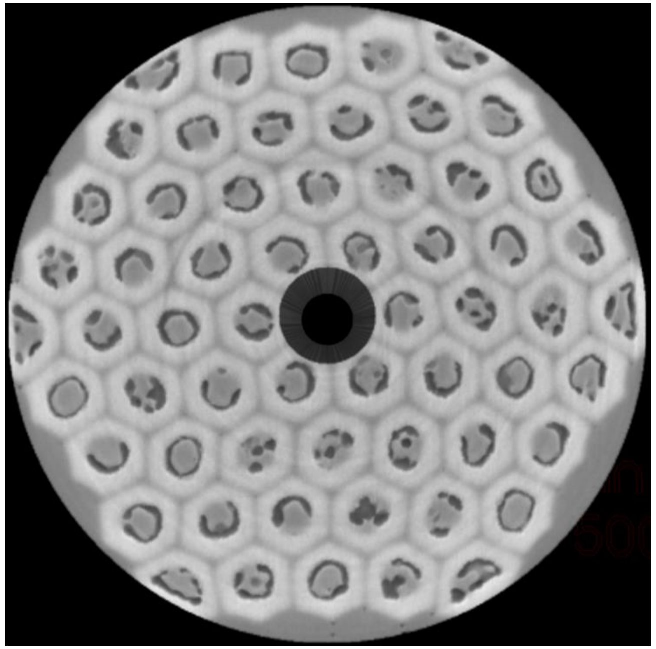


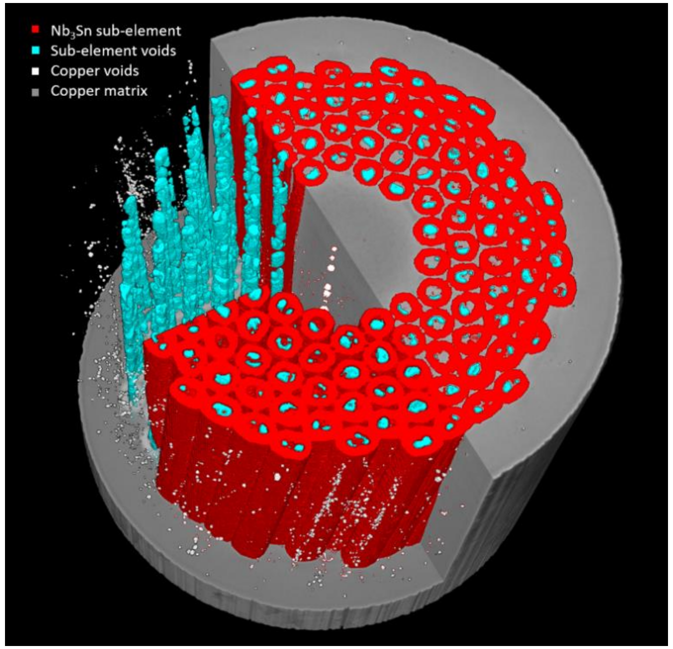
- X-ray photon energy = 80 keV
- 360° rotation of the sample
- 10’000 projections
- 2560 x 2160 pixels
- 0.57 μm/pixel resolution

ESRF
The European Synchrotron

Marta MAJKUT

Alexander RACK





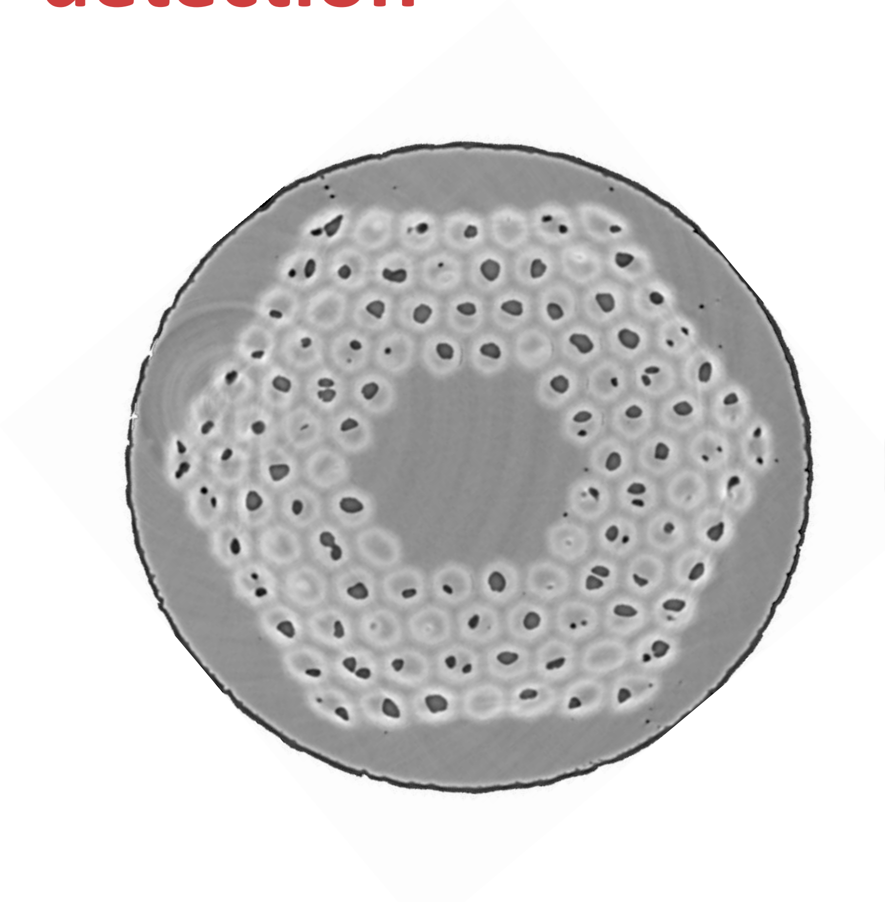
A novel, non-destructive and non-invasive method to investigate the internal structure of high-performance Nb_3Sn wires combines X-ray microtomography with machine-learning algorithms

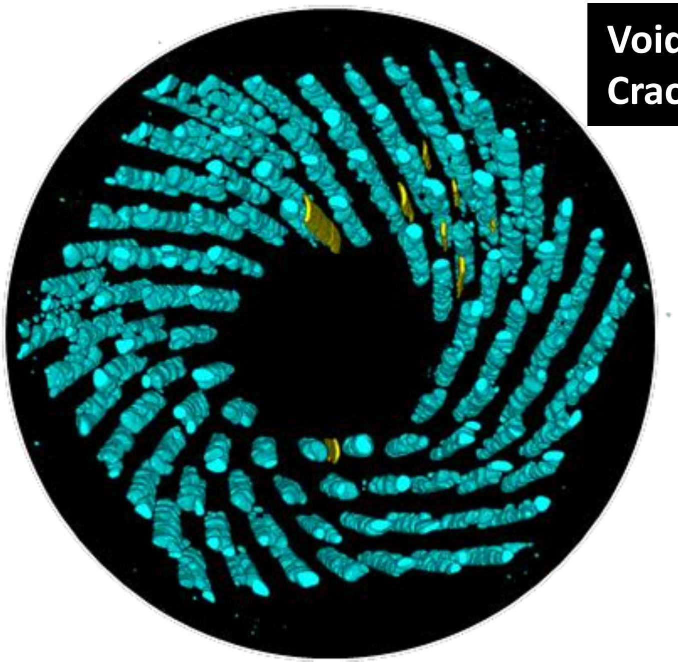
T. Bagni *et al.*, Sci. Reports 11 (2021) 7767 DOI: 10.1038/s41598-021-87475-6

X-ray tomography and Neural Networks for crack detection

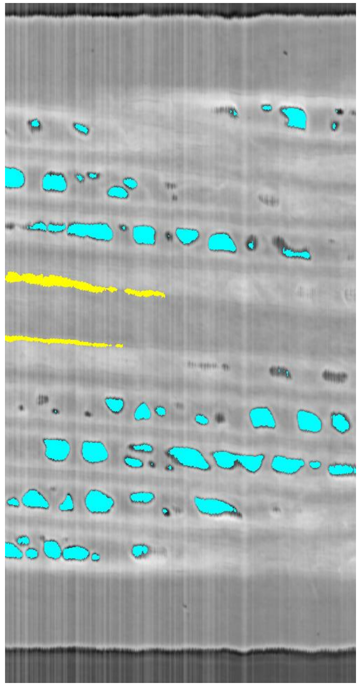
Tommaso BAGNI

Diego MAURO





Voids in cyan
Cracks in yellow



An analysis based on Convolutional Neural Networks was performed on the tomographic scan of the exact same sample used for the I_c vs σ test, after unload from 240 MPa

Very few cracks were detected, none of them interrupting the subelements and thus responsible for the measured degradation by 15% of I_c

Conclusions

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

Tolerance to stress is an issue as important as high critical current density for the conductors to be used in Nb_3Sn-based accelerator magnets

- experiments show that up to 240 MPa the permanent degradation of I_c is dominated by the residual stress *in the examined wires*. Surprisingly, the effect of cracks seems negligible
- with the goal of providing new insights into the electro-mechanical modelling of the wires, a tool combining tomography and machine learning was developed to investigate the internal structure of the wires
- next step will include the integration of the outcome of the tomography studies into FE models to foster the development of wires with enhanced mechanical properties

Swiss Accelerator Research and Technology

Swiss National Science Foundation

HFM High Field Magnets

Thank you for the attention !

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Acknowledgments: This work was done under the auspices of CHART (Swiss Accelerator Research and Technology Collaboration, https://chart.ch). Financial support was provided by the Swiss National Science Foundation (Grant No. 200021_184940), by the European Organization for Nuclear Research (CERN), Memorandum of Understanding for the FCC Study, Addendum FCC-GOV-CC-0175 (KE 4663/ATS) and Addendum FCC-GOV-CC-0176 (KE4612/ATS).