CERN

The FCC Conductor Development Programme

Characterisation at CERN

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FCC Week 2018

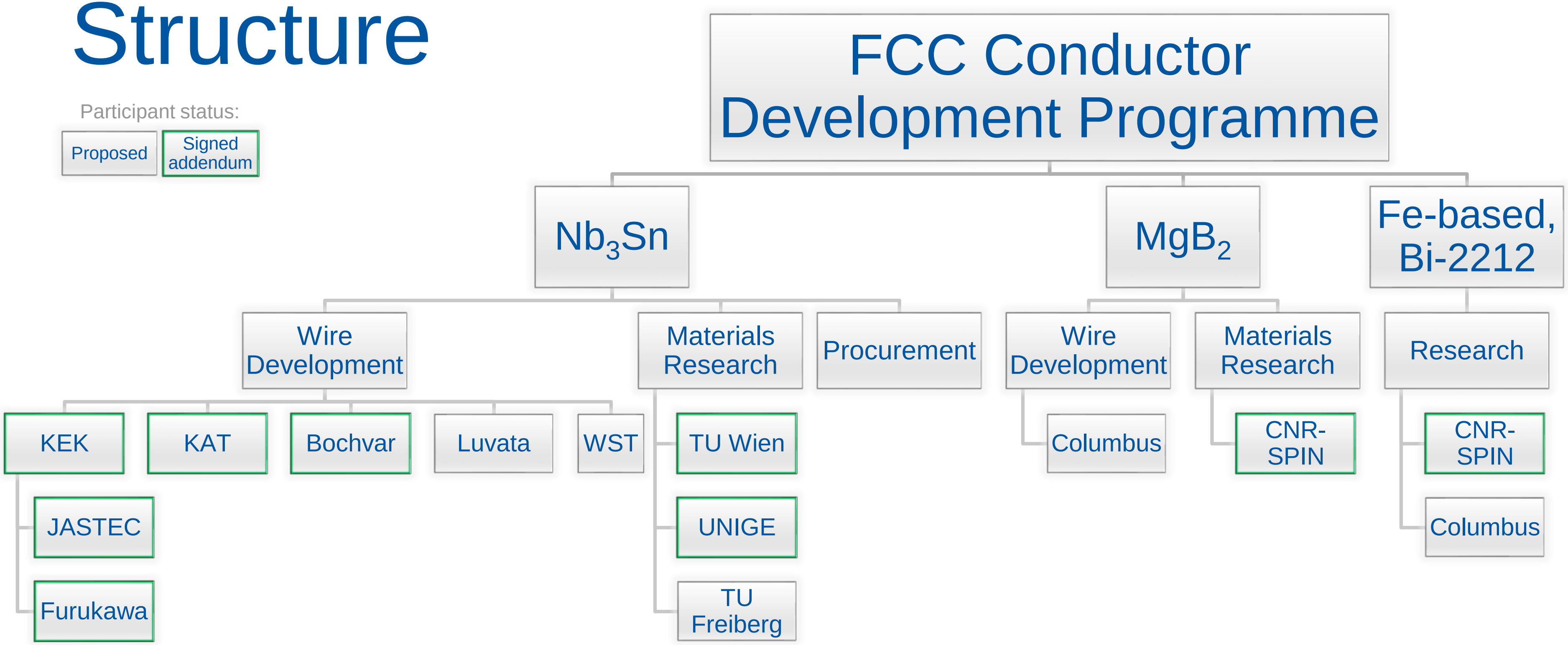
FCC Conductor Development Programme

- Conductor development, evaluation and procurement in support of the Magnet Development Programme
- Context:
  - Baseline FCC design: 100 TeV, 100 km machine with **16 T** dipoles based on **Nb_3Sn**
  - Demanding cost and performance targets significantly exceeding those of HL-LHC
  - For HL-LHC, currently one qualified Nb_3Sn supplier

Programme Goals

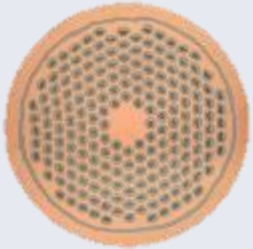
- Evaluate feasibility of achieving target J_c with Nb_3Sn, for compact, cost-effective 16 T dipoles
- Promote industrial development and supply of suitable Nb_3Sn conductor
- Perform collaborative R&D to increase performance towards the FCC performance targets
- Procure Nb_3Sn conductor for the magnet development programme
- Investigate the potential of other superconductors

Structure



Participant status:
Proposed
Signed addendum
FCC Conductor Development Programme
Nb$_3$Sn
MgB$_2$
Fe-based, Bi-2212
Wire Development
Materials Research
Procurement
Wire Development
Materials Research
Research
KEK
KAT
Bochvar
Luvata
WST
TU Wien
Columbus
CNR-SPIN
CNR-SPIN
JASTEC
UNIGE
Columbus
Furukawa
TU Freiberg

Nb_3Sn: The HL-LHC Conductor

Type	Layout	Sub-element size (µm)	J_c (4.2 K) / A mm^{-2}		Cross-section
			12 T	16 T	
RRP 0.7 mm	108/127	46	2676	1098	
RRP 0.85 mm	108/127	55	2835	1289	
PIT 0.85 mm	192 (bundle barrier)	39	2323	1093	

Nb_3Sn Development Targets

Parameter	Ultimate Target
Wire diameter / mm	~1
Cu:non-Cu ratio	~1
Non-Cu J_c (16 T, 4.2 K) / A mm^{-2}	≥ 1500
$\mu_0 \Delta M$ (1 T, 4.2 K) / mT	≤ 150
d_{eff} / µm	≤ 20
RRR	≥ 150

- Scalable to large-scale production, 5 km unit lengths
- **Cost: 5 EUR / kA m** (16 T 4.2 K)

Nb_3Sn Development Targets

Parameter	Ultimate Target	Interim Target
Wire diameter / mm	~1	~1
Cu:non-Cu ratio	~1	~1
Non-Cu J_c (16 T, 4.2 K) / A mm^{-2}	≥ 1500	≥ 1500
$\mu_0 \Delta M$ (1 T, 4.2 K) / mT	≤ 150	
d_{eff} / µm	≤ 20	≤ 60
RRR	≥ 150	≥ 150

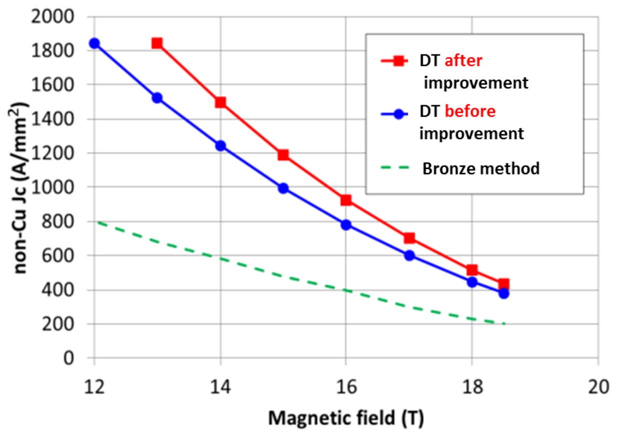
- Initial focus: J_c
  - Magnetisation/d_{eff} targets relaxed where necessary

Characterisation at CERN

- Characterisation of superconducting properties
  - Transport I_c (currently up to 15 T; 4.3 and 1.9 K)
  - RRR
  - VSM (up to 10 T), e.g. for d_{eff}
- Additional analysis
  - SEM and FIB at CERN
  - TEM with partners, e.g. TU Wien

JASTEC

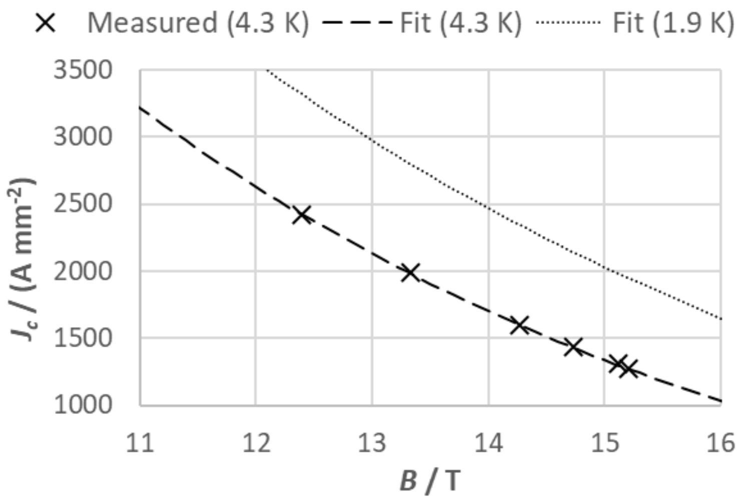
- Development of distributed tin Nb_3Sn wires
  - First trial samples produced at ϕ 0.6 – 1.2 mm
  - Non-Cu J_c reaches 1000 A mm^{-2} (16 T, 4.3 K)
  - Next steps:
    - Increasing Nb fraction
    - Optimising Ti doping
    - Increasing Cu/non-Cu ratio



Measurements from JASTEC

JASTEC, 1st trial (1)

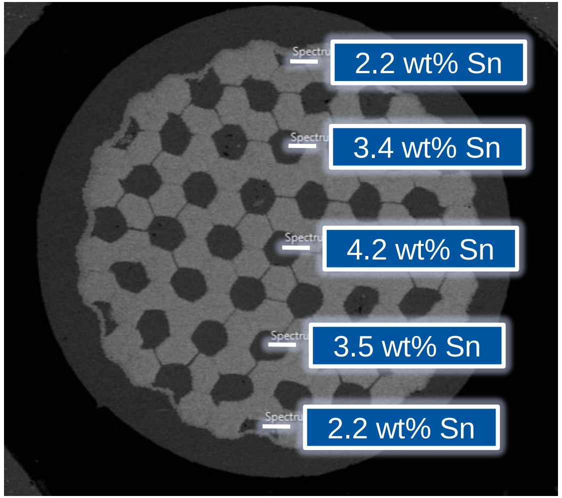
- Transport I_c measured at CERN (15 T, 4.3 K)
  - Non-Cu J_c consistent for 0.6 and 0.7 mm wires
  - Comparable with JASTEC data at 0.8 mm
- RRR: 135
- d_{eff} large for 0.6 mm wires

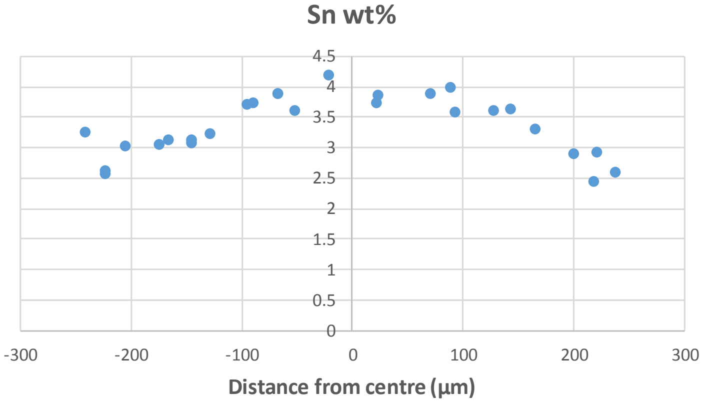


Non-Cu J_c from measurements at CERN: 0.7 mm wire diameter, after self-field correction

JASTEC, 1st trial (2)

- SEM analysis at small wire diameters:
  - Matrix composition gradients



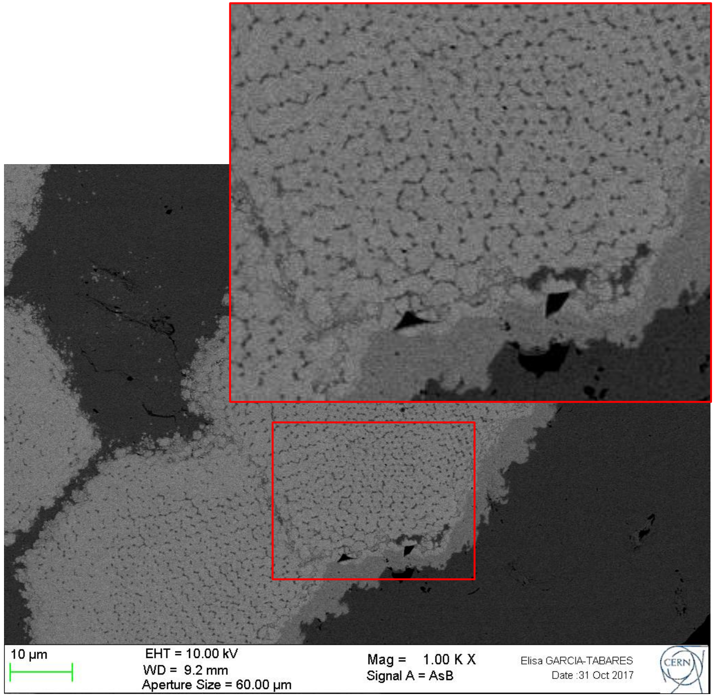


Cu-Sn matrix composition gradients by EDX (SEM)
0.6 mm wire diameter

JASTEC, 1st trial (3)

- SEM analysis: key results
  - Incomplete reaction and local tin depletion
  - Some sub-element bridging

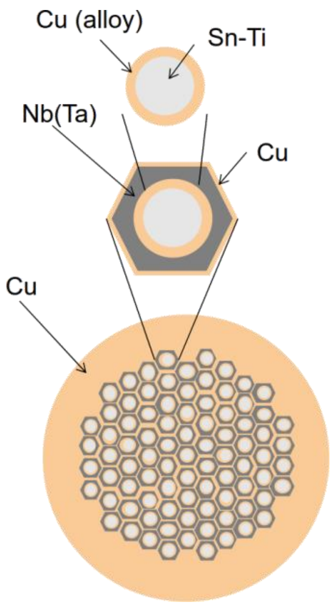
→ opportunities for design and heat treatment optimisation



SEM after reaction (BEI)
0.6 mm wire diameter

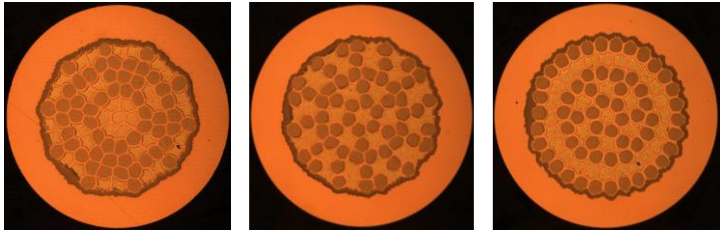
Furukawa

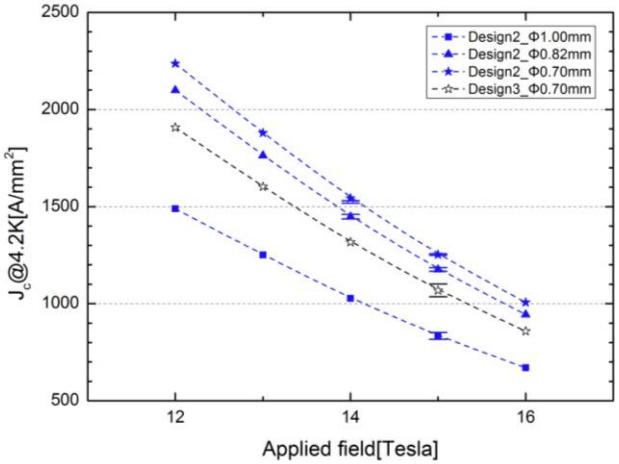
- Developing Nb tube and distributed Nb_3Sn wires
  - Currently focusing on Nb tube design
  - Fabrication of trial 85 sub-element wire in progress
  - Initial results expected in the next few weeks



Kiswire (KAT)

- Developing distributed tin wires
  - Three trial conductors have been produced at ϕ 0.7 – 1.0 mm
  - Hydrostatic extrusion applied with high yield
  - Good J_c progress

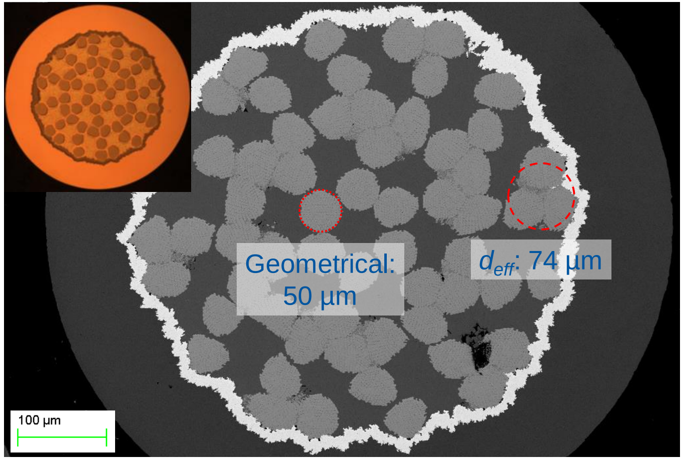


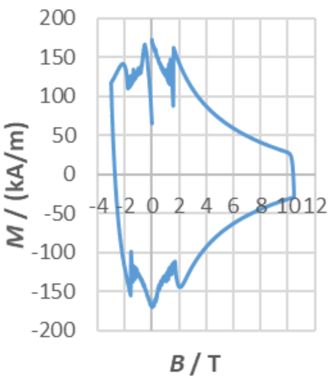


Non-Cu J_c measurements from KAT

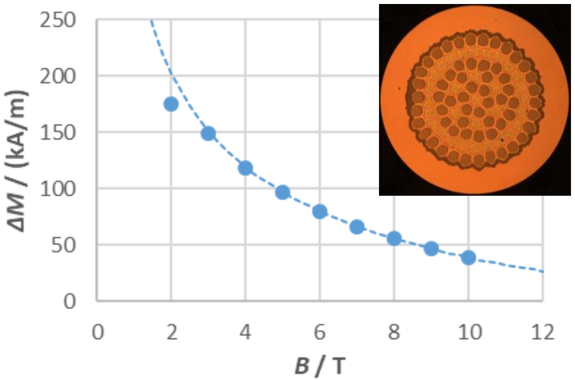
KAT: VSM and d_{eff}

- Effective sub-element size close to the geometrical value and the interim development target





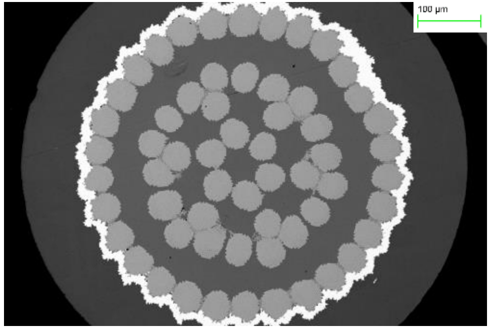
Design 2: Magnetisation and d_{eff}
VSM measurements of ϕ 0.7 mm wire, courtesy of D. Richter



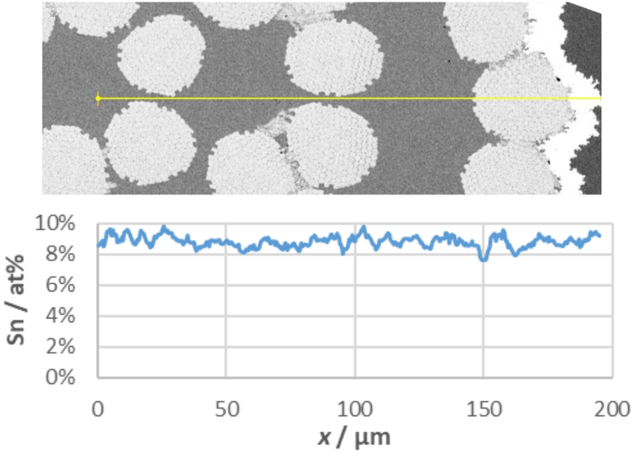
Design 3 (transport I_c not yet available)
ϕ 0.7 mm, B_{c2} ~ 25.3 T

KAT: SEM

- High residual tin content after heat treatment
  → scope for performance increase
  - Increased Nb fraction, thinner barrier, heat treatment optimisation



Design 3 at ϕ 0.7 mm (BEI)



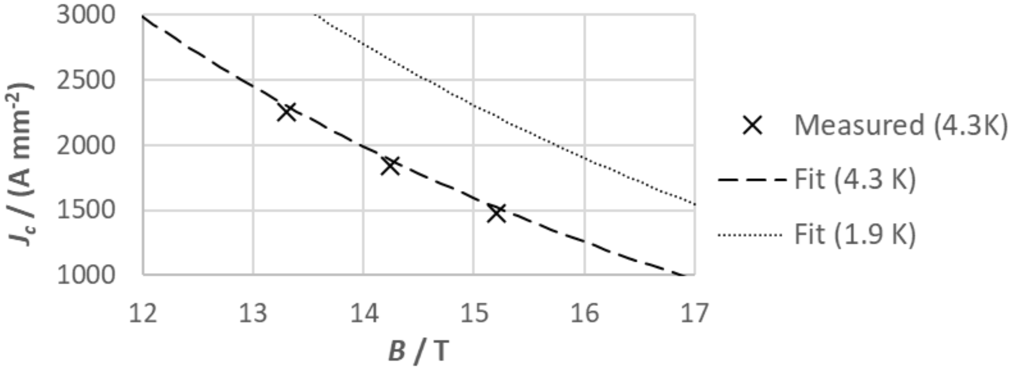
Design 3: Sn concentration in Cu-Sn ~ 9 at%
EDX and BEI; ϕ 0.7 mm wire

Bochvar Institute (1)

- Several layouts of Nb_3Sn internal tin wire developed at 0.7 – 1.0 mm diameter
  - J_c ~ 2700 A mm^{-2} achieved (12 T, 4.2 K)
- Demonstration at production scale:
  - 12 km wire delivered; average piece length > 1 km
  - Typical J_c: 2450 A mm^{-2} (12 T, 4.2 K)

Bochvar Institute (2)

- Initial I_c measurements at CERN:
  - 1 sample each from two billets
    - Both exceed expected J_c at 12 T (based on nominal Cu/non-Cu ratio)



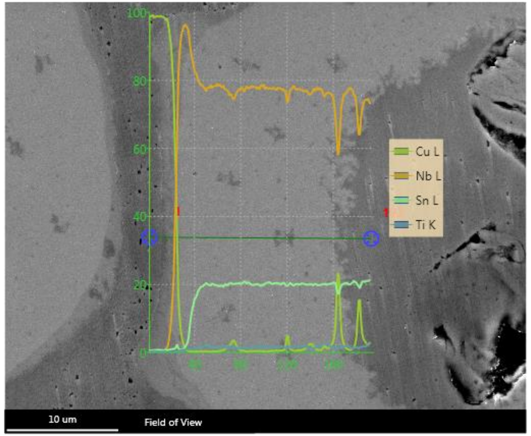
Measured I_c at 4.3 K	
B_{appl} / T	I_c / A
13	804, 703
15	529, 508

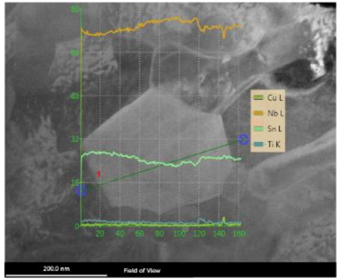
Scaled non-Cu J_c at 4.22 K	
B_{appl} / T	J_c / A mm^{-2}
12	2766, 2581
16	1201, 1162

Non-Cu J_c from measurements at CERN:
1.0 mm wire diameter, nominal Cu/non-Cu, after self-field correction

TU Wien: Microstructural Analysis

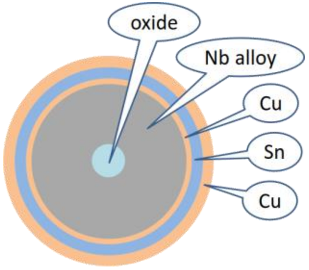
- Detailed analysis of RRP and PIT wires to guide wire optimisation
  - Sn concentration gradients across Nb_3Sn and within grains (TEM, T-EBSD, EDX)
  - Correlations with superconducting properties
  - Irradiation studies, including TEM of induced defects
    - Model system for artificial pinning

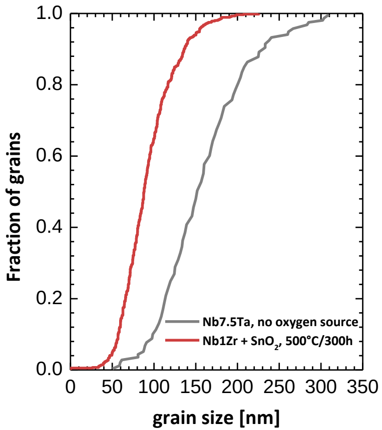


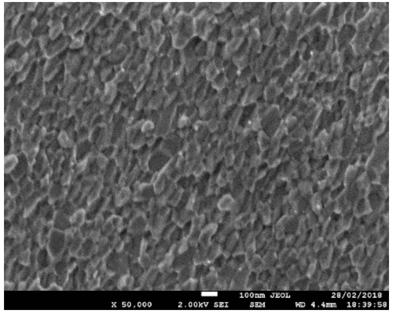


UNIGE: Internal Oxidation

- Studies in progress at the University of Geneva:
  - Simplified geometry (powder core), with several Nb-Zr and Nb-Zr-Ta compositions and alternative oxides
  - Initial confirmation of grain refinement



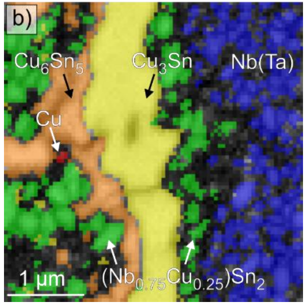


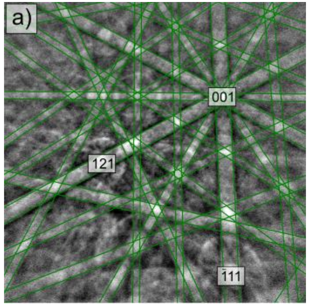


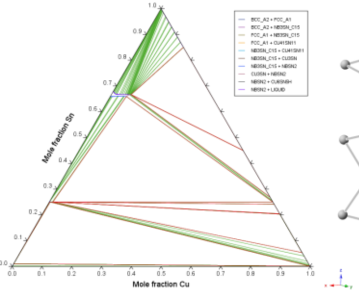
Reduction of median grain size to 88 nm in Nb-1% Zr + SnO_2, with oxidation step at 500 °C (300 h)

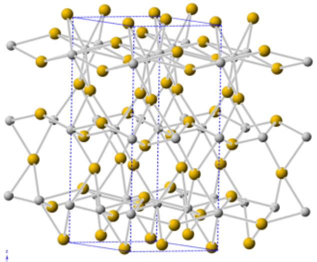
TU Bergakademie Freiberg

- New project to investigate phase formation in the ternary Cu-Nb-Sn system
    - Also including the influence of Ti and O, etc. → towards practical wires and internal oxidation
    - Building on previous work characterising Nausite





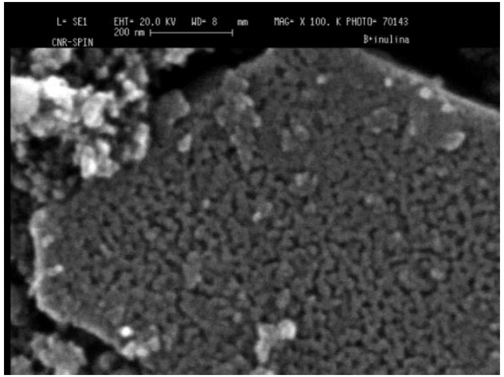




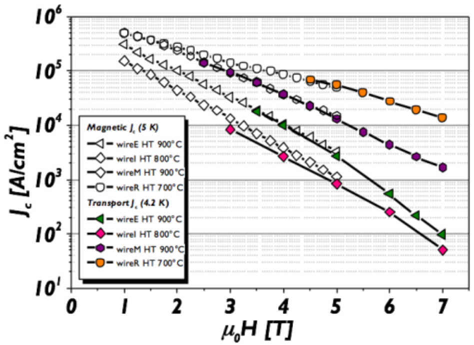
Previous work involving
Prof. A. Leineweber and CERN
A. L. Martin et al., *Intermetallics* **80** (2017) 16

Other Materials (1)

- MgB_2
  - Boron nano-powder synthesis and doping
    - Freeze-drying process for fine nanoparticles at modest cost, incorporating doping additions
    - First MgB_2 trial wires recently produced
    - ~250 m prototype wires to be produced by Columbus Superconductors
  - Targets: grain size ~20 nm, B_{irr} > 35 T, APCs



Starch-doped boron



J_c results for first wire samples

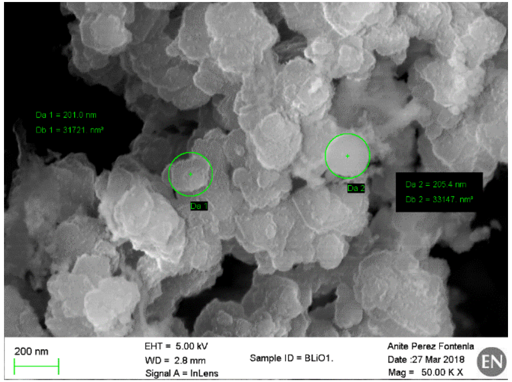
Columbus Superconductors

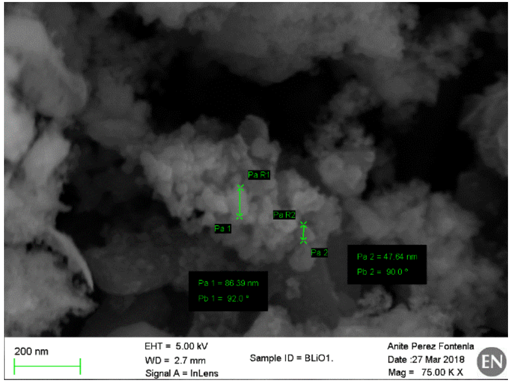
SPIN

CERN

Other Materials (2)

- Characterisation at CERN of nano-boron and MgB_2 produced at CNR-SPIN
  - SEM and compositional analysis of nano-boron
  - TEM planned with external partners

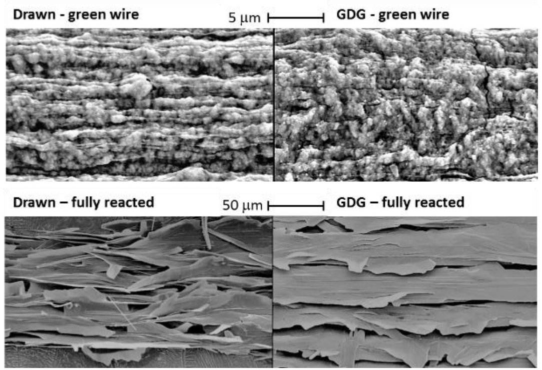




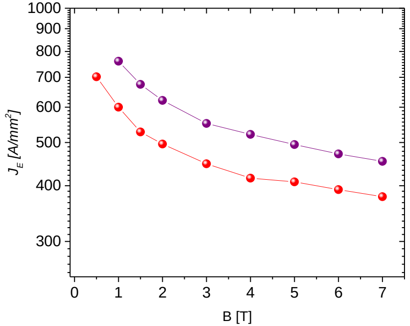
SEM micrographs of boron powder produced by freeze-drying process (SEI) Imaged by A. Pérez

Other Materials (3)

- BSCCO 2212
  - Alternating groove rolling and drawing with ambient pressure heat treatment at CNR-SPIN
    - Close to
    - Scalability to be assessed at Columbus
  - Target J_c: >500 A mm^{-2} (16 T, 4.2 K)
- Iron-based superconductors at CNR-SPIN
  - Longer-term potential for high field applications
    - $FeSe_xTe_{1-x}$ ('11') coated conductors
    - $BaFe_2As_2$ ('122') powder-in-tube wires
  - Target J_c: 10^3 A mm^{-2} (16 T, 4.2 K)



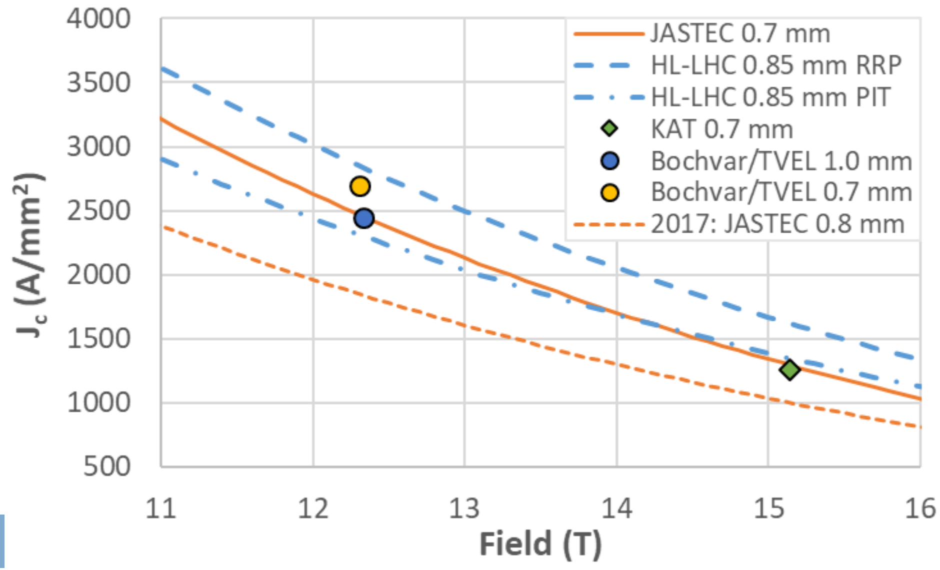
Groove rolling of 2212 achieves sufficient densification to avoid bubbles etc.



Promising J_e progress in 2212 with layout, deformation and heat treatment optimisation

Nb_3Sn J_c Progress

- Non-Cu J_c approaching HL-LHC specification at 12 and 16 T
  - Significant increase in ~ 1 year
  - Other targets not always met
    - d_{eff}, Cu/non-Cu…



Non-Cu J_c from CERN and partners, after self-field correction

Next Steps

- Manufacturing of the latest trial conductors under way:
  - Nb_3Sn wire samples expected in the next few weeks from JASTEC, Furukawa, KAT
  - MgB_2 wire samples to be produced at Columbus Superconductors
- Characterisation of 12 km of wire from TVEL/VNIINM in progress
- New partners/projects expected soon:
  - Nb_3Sn wire development (Luvata, Bruker, TVEL) and materials studies (TU Bergakademie Freiberg)
  - Open to new partnerships, and to receiving samples for characterisation