Homogeneity of Nb_3Sn wires with artificial pinning centres

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Introduction

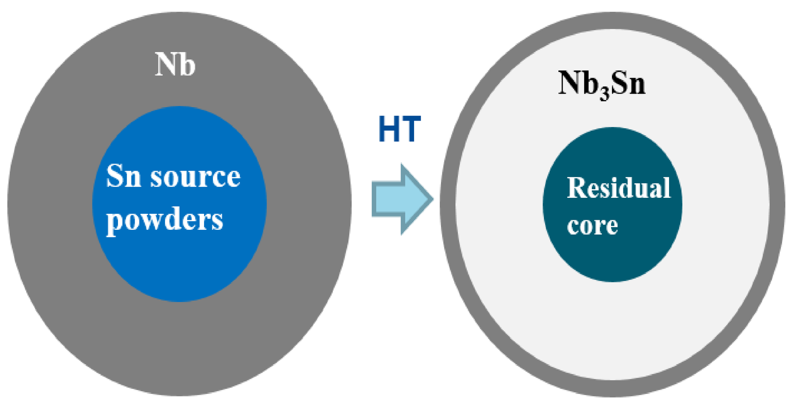
Nb_3Sn is experiencing a renaissance thanks to the high performance required for the Future Circular Collider (FCC-hh) 16T dipole magnets. One of the most promising technologies for improving the conductor performance is the introduction of artificial pinning centers (APC). Here we present the characterization of prototype PIT Nb_3Sn wires with 4at.%Ta-1at.%Zr and 4at.%Ta-1at.%Hf additions, manufactured by Hyper Tech Inc.(USA). SQUID magnetometry was used to assess Jc, benchmarking the high field results obtained by resistive measurements; local inhomogeneities were evaluated by means of AC susceptibility (SQUID) and scanning Hall probe microscopy (SHPM). These results were then related with the microstructure for investigating possible relations between radial-Tc distribution and Sn % content.

Technology and motivation

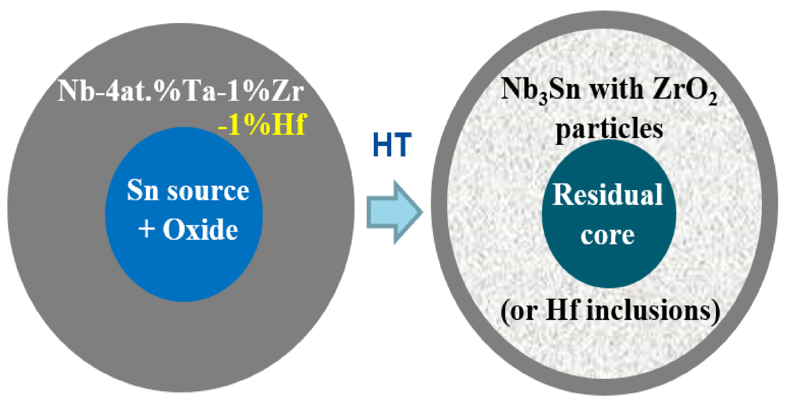
APC Doping

Nb_3Sn APC wires rely on the internal oxidation technique: O diffuses into a Nb-Zr solid solution, selectively oxides Zr forming ZrO_2 particles ⟶ new generation samples also include 4at.%Ta and 1at.%Hf in place of Zr

Standard PIT manufacturing



APC-PIT manufacturing

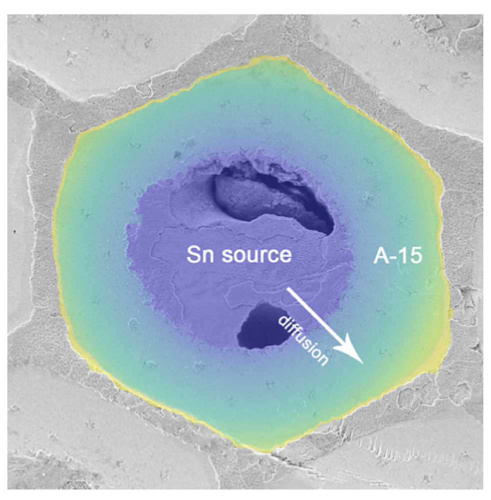


Expected improvements

- A-15 grain size refinement ⟶ J_c ⇈ ($J_c = f(1/d_{grain})$)
- Ta in the lattice ⟶ B_{c2} ⇈
- ZrO_2 particles as additional pinning centres ⟶ J_c ⇈

Problems

A radial gradient in stoichiometry is always present, in particular in compounds doped with Ta



Spatial variations of the superconducting parameters are expected:

- what changes from binary to ternary Nb_3Sn?
- does Hf change the gradient?
- grain size variation?

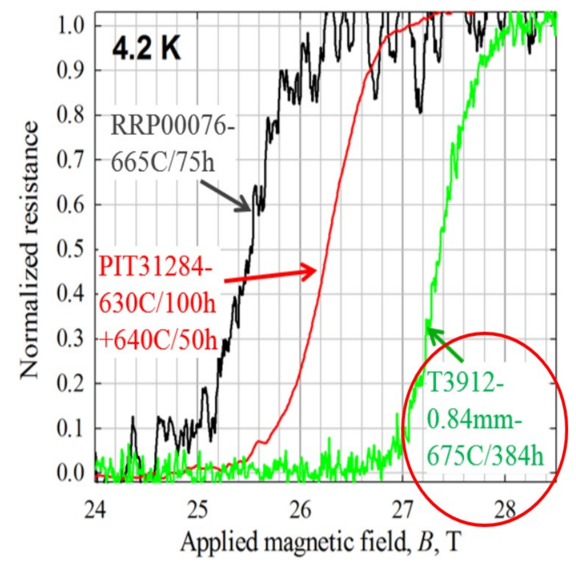
Detailed characterization required ⟶ J_c, B_{c2} and T_c-distribution to be assessed and related to microstructure

Results

B_{c2} and J_c

- In-field B_{c2} values measured at NHFML reveal a boost from binary generation (20-35%)

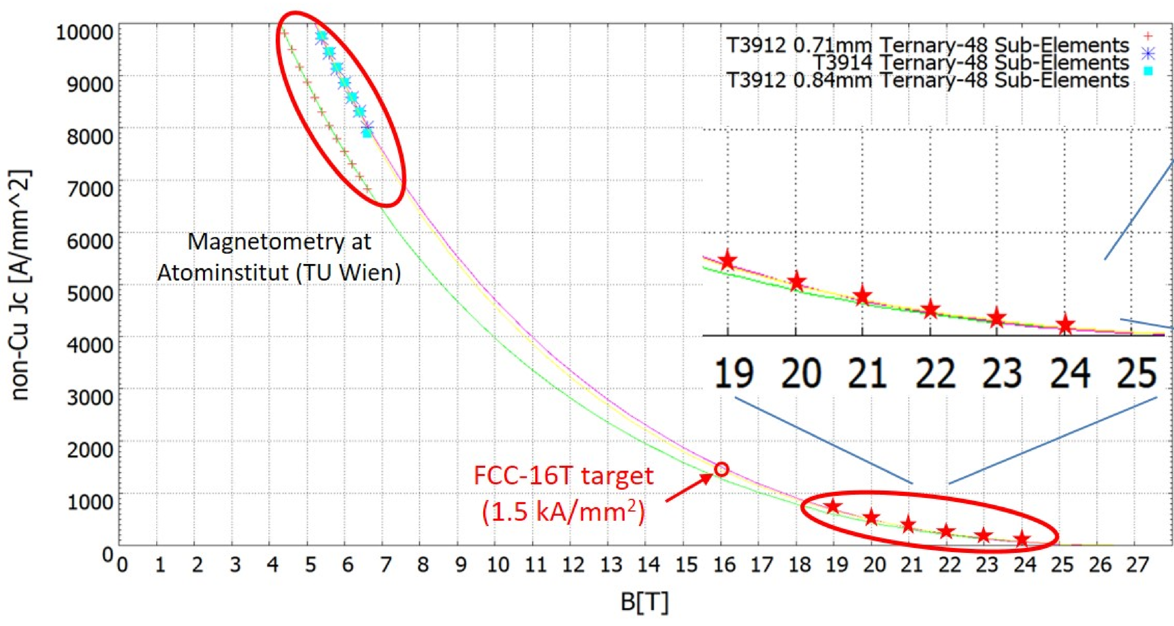
Diameter [mm]	Characteristics	B_{c2} [T]
0.71	1at.%Zr tube + Sn/Cu/SnO2 powders	27.2
0.71	1at.%Hf tube+ Sn/Cu/SnO2 powders	26.7
0.84	1at.%Zr tube + Sn/Cu/SnO2 powders.	27.3

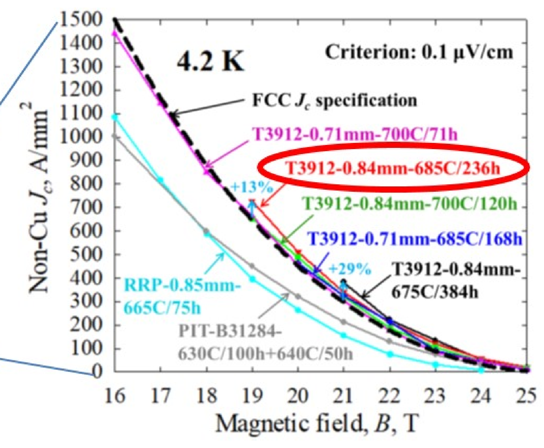


B_{c2}: 4at.%Ta-1at.%Zr compared with commercial wires

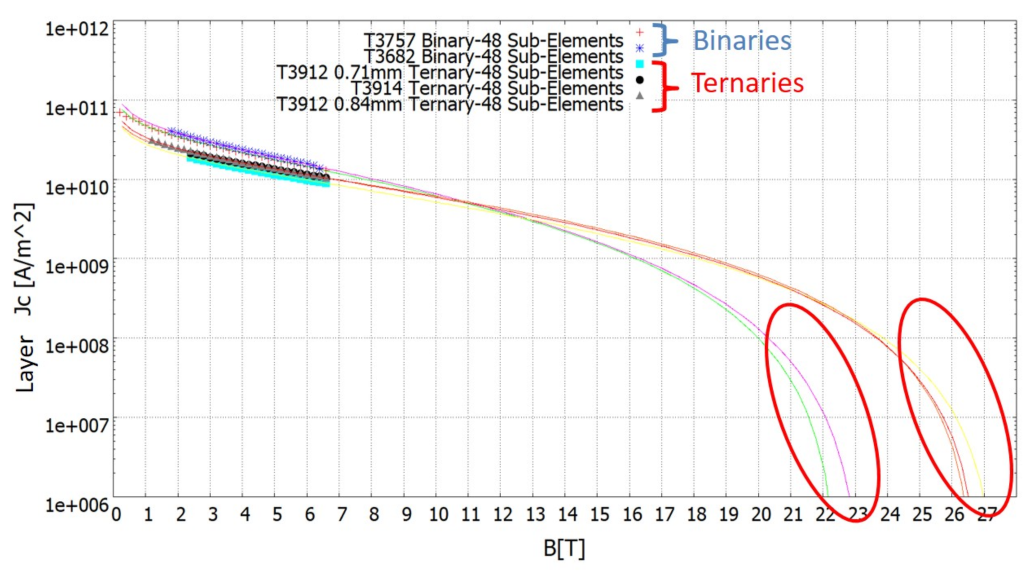
Values used for high-field J_c extrapolations

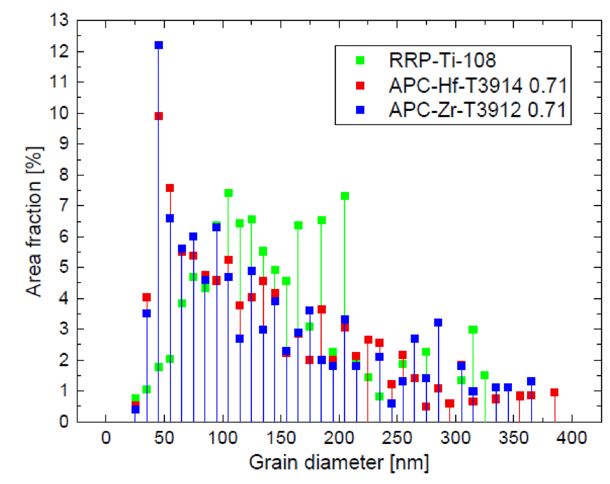
- SQUID magnetometry (up to 7T) extrapolations are benchmarked by resistive measurements: FCC-16 T J_c is reached





- Ta-additions drastically improved high-field behaviour whereas microstructure did not change from binary generation





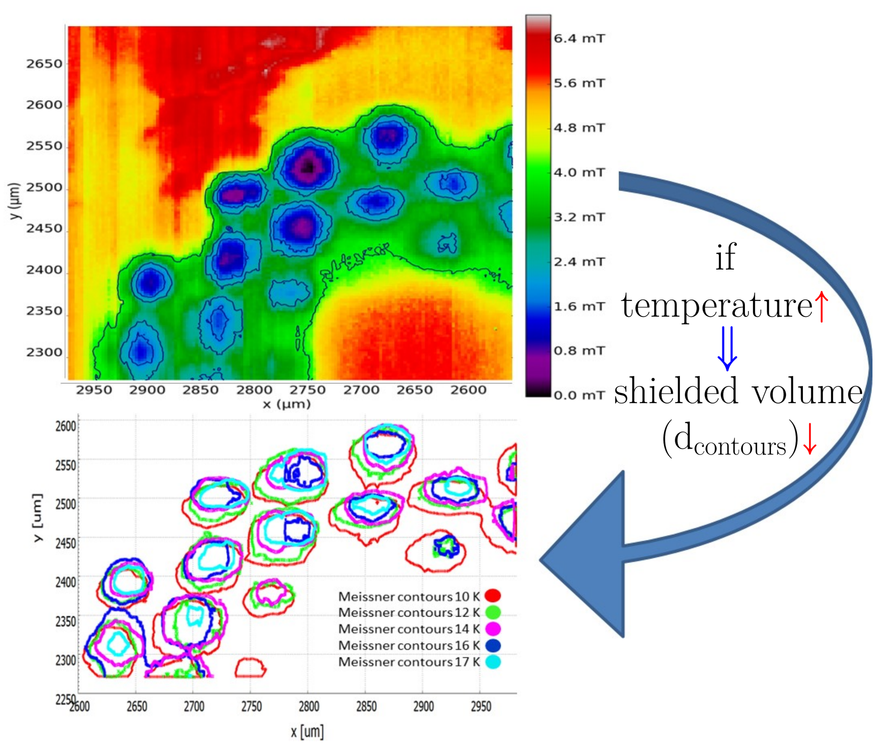
Comparison of grain-size distributions: APC samples show a peak below 50 nm

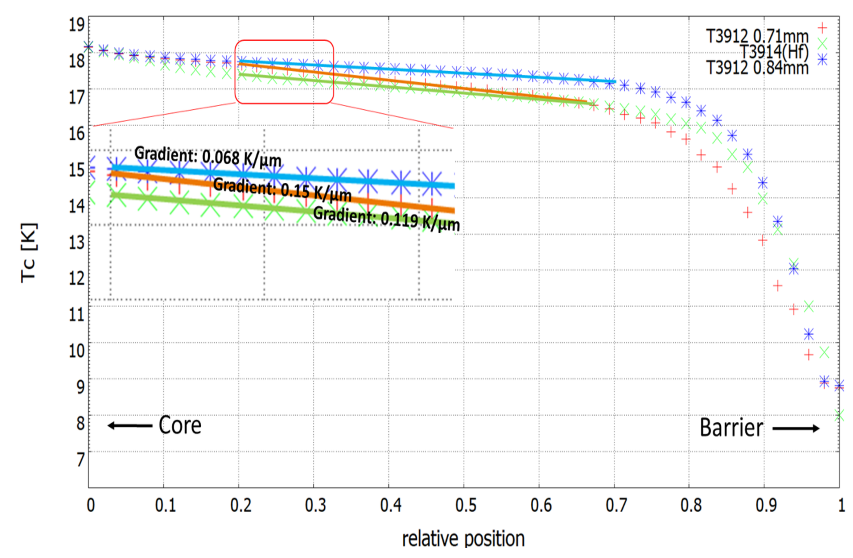
Radial inhomogeneities

AC-susceptibility method (SQUID) was used to identify the Meissner shielding contours

Ingredients:

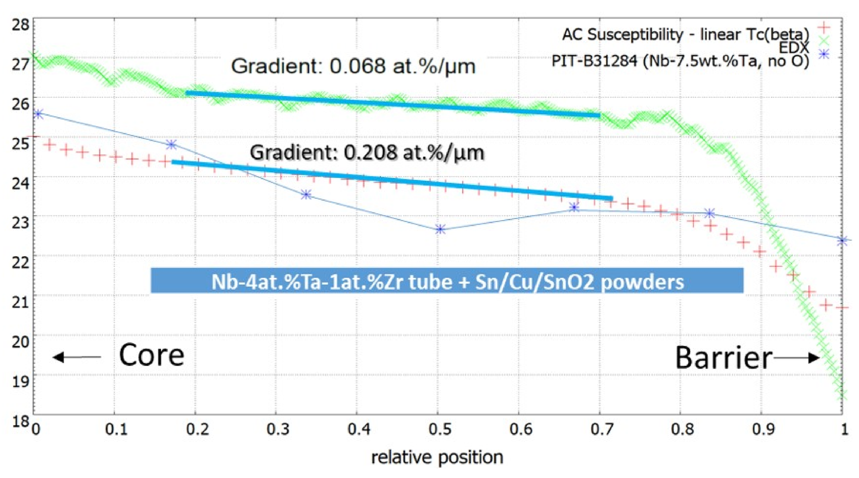
- Magnetometer: SQUID or SHPM ✓
- $B_{app} < B_{c1}$ (Meissner state) 30 μT
- Low frequencies 30 Hz
- Temperature sweep 5 ⟶ 20 K
- Thin and flat sample for SHPM Best achievement: Thickn.=15 μm; Flatness= 7%



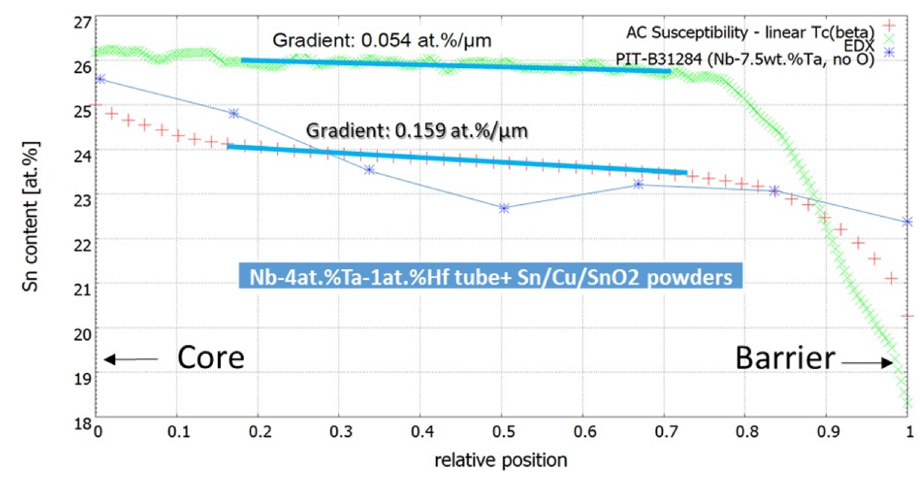


Simulation runs on a single sub-element by changing its radial T_c distribution until the computed $m(T) = m_{exp}(T)/N$

$$T_c(\beta) = \frac{T_{c,min} - T_{c,MAX}}{1 + e^{(\beta - \beta_0)}} + T_{c,MAX}$$



EDX and magnetic evaluations show similar behaviour but different absolute values



Acknowledgments

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Summary and Outlook

- The high J_c performance (beyond FCC-goals) of APC-Nb_3Sn wires produced with 4at.% Ta additions was confirmed as well by means of magnetometry (same behaviour also for Hf-samples);
- Inhomogeneities are an issue: a more accurate investigation of the model (inter-granular gradient to be raised/lowered) or of the Tc-Sn% relation (still referring to binary compounds) is needed;
- Further SHPM-T_c distribution analysis coming: difficult to perform but with less restrictions than AC-susceptibility

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