



U.S. MAGNET
DEVELOPMENT
PROGRAM

Mechanism of flux pinning for APC Nb₃Sn

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How to enhance flux pinning of Nb_3Sn

Enhanced flux pinning → boost in Nb_3Sn J_c . How?

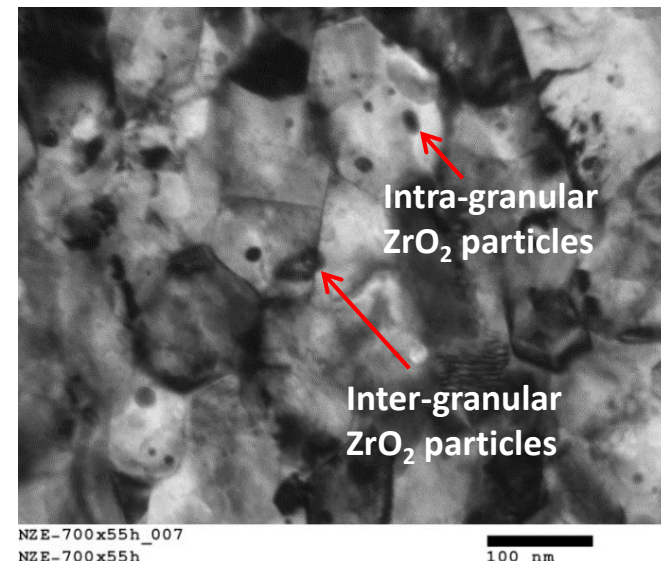
Internal oxidation approach:

- A long history. First made a success in Nb_3Sn wires: 2014.
[X. Xu, M. Sumption, X. Peng, *Appl. Phys. Lett.* 104, 082602 \(2014\).](#)
- Late 2014: proposed to be applied to several wire types, including PIT.
[X. Xu, M. Sumption, X. Peng, *Adv. Mat.*, 27, 1346-1350 \(2015\).](#)
- PIT design: no change in the manufacturing process, but two modifications in raw materials:
 - Powder: $\text{NbSn}_2 + \text{Cu} + \text{Sn} \rightarrow \text{Sn} + \text{Cu} + \text{SnO}_2$
 - Tube: $\text{Nb-4at.\%Ta} \rightarrow \text{Nb-4at.\%Ta-1\%Zr}$ (or Hf)
- Present: developing wires with 61-217 filaments, a HyperTech-FNAL-OSU collaboration.

Non-oxidation approach:

- Hf itself is a grain refiner: found at FSU.
[S. Balachandran et al., *Supercond. Sci. Technol.* 32, 044006 \(2019\).](#)
- $\text{Nb-4at.\%Ta} \rightarrow \text{Nb-4at.\%Ta-1\%Hf}$.

This talk is mainly about pinning mechanism of the internal oxidation route.

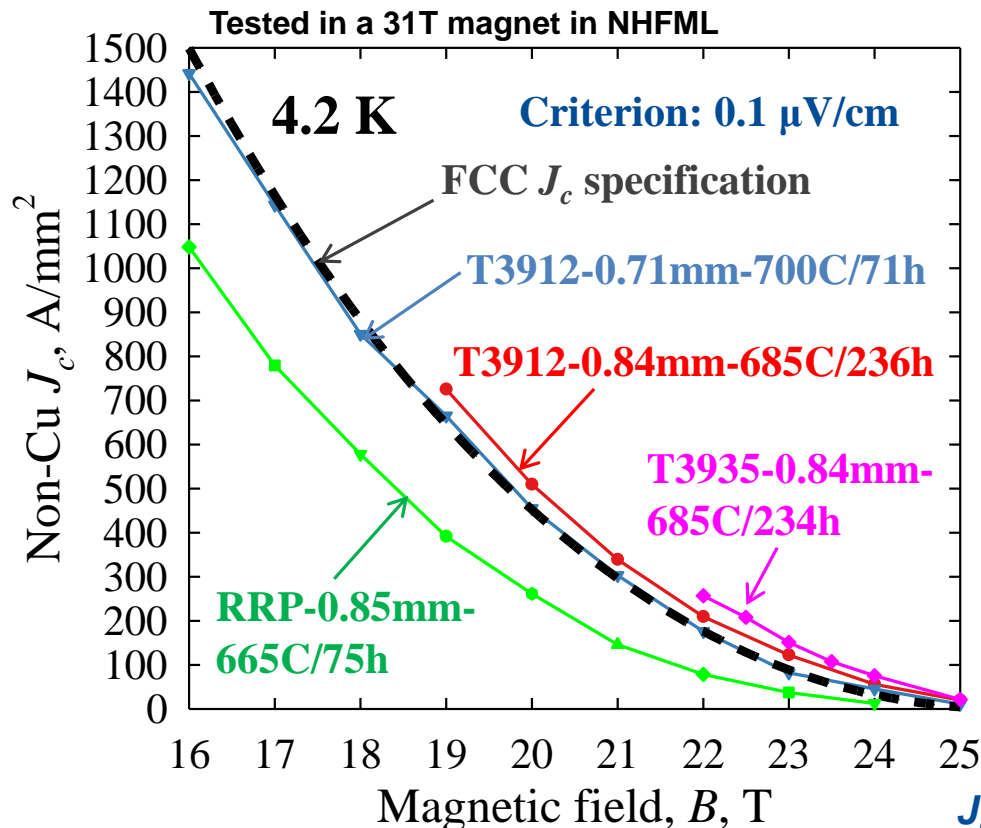




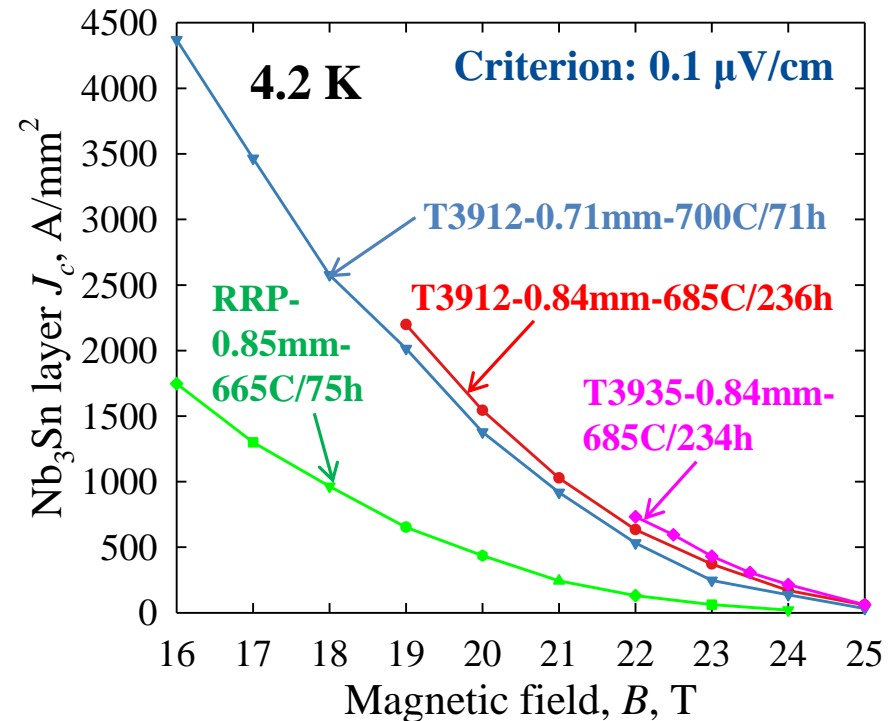
APC can significantly enhance J_c

Non-Cu J_c of recent APC wires (made in Hyper Tech):

Wire	Composition	O amount in filaments	Tested by
T3912	4%Ta, 1%Zr+O	Insufficient in some	FNAL, OSU
T3935	4%Ta, 1%Zr+O	Enough in all	FSU



The Nb₃Sn layer J_c is even much higher:



- Non-Cu J_c of APC can still be much higher by:
- (1) Forming more Nb₃Sn in filaments (32%→40%)
 - (2) Improving filament quality
 - (3) Heat treatment optimization (lower HT T)

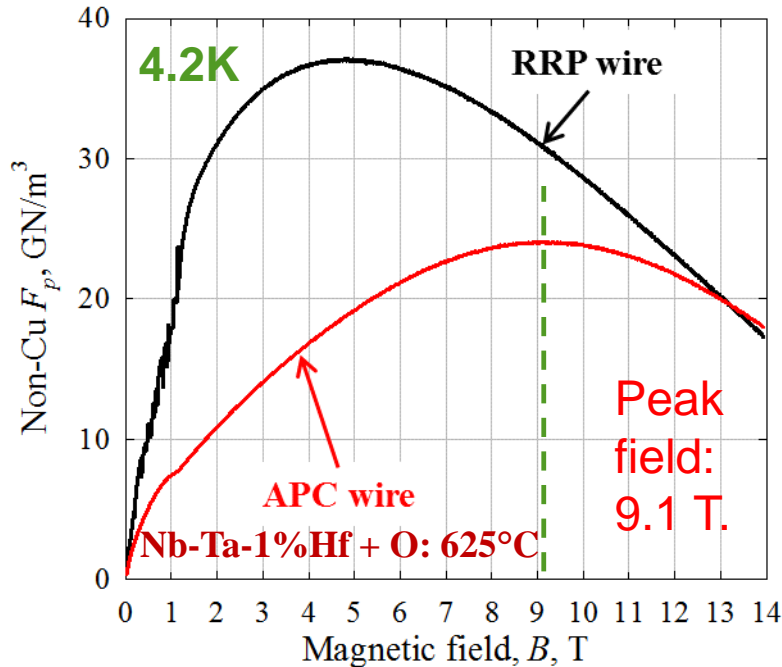
J_c boost in Hf w/o O: see talks by FSU colleagues



What causes enhanced J_c : Factor 1 – point pinning

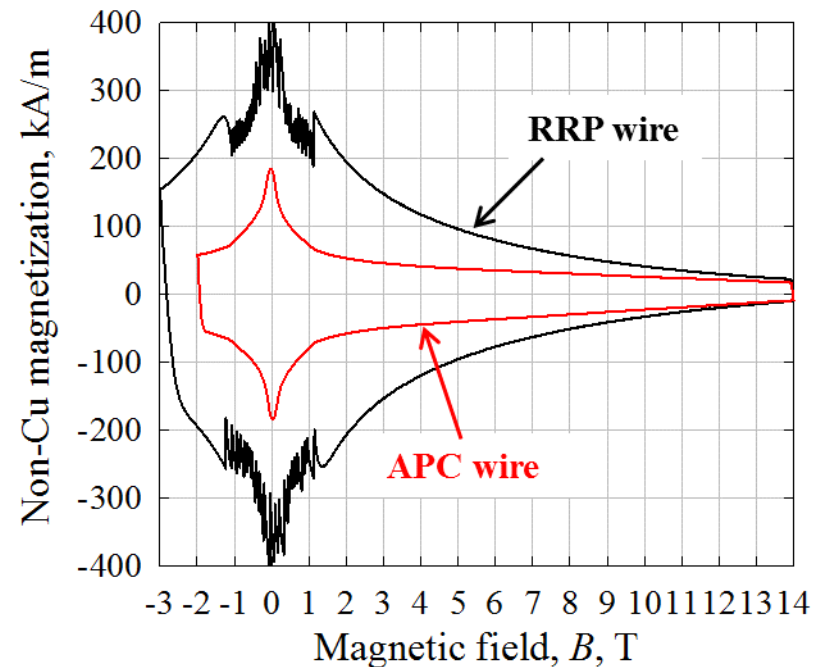
What causes the enhanced J_c ? (1) Zr(Hf)O_2 particles as point pinners, (2) refined Nb_3Sn grain size.

Added point pinning: (1) boosts $F_{p,max}$, (2) causes F_p - B peak shift: $0.2B_{irr}$ (grain boundary) $\rightarrow 1/3B_{irr}$



Thanks to Van Griffin for measuring the M - B loops for us, using the 14 T VSM in ASC/FSU.

Shift in F_p - B curve peak \rightarrow much flatter J_c - B curve



Lower magnetization at low fields reduces low-field instability, field errors, and a.c. losses.

The Nb-Ta-1%Hf wire +O wire had thin Nb_3Sn layer due to under-reaction.

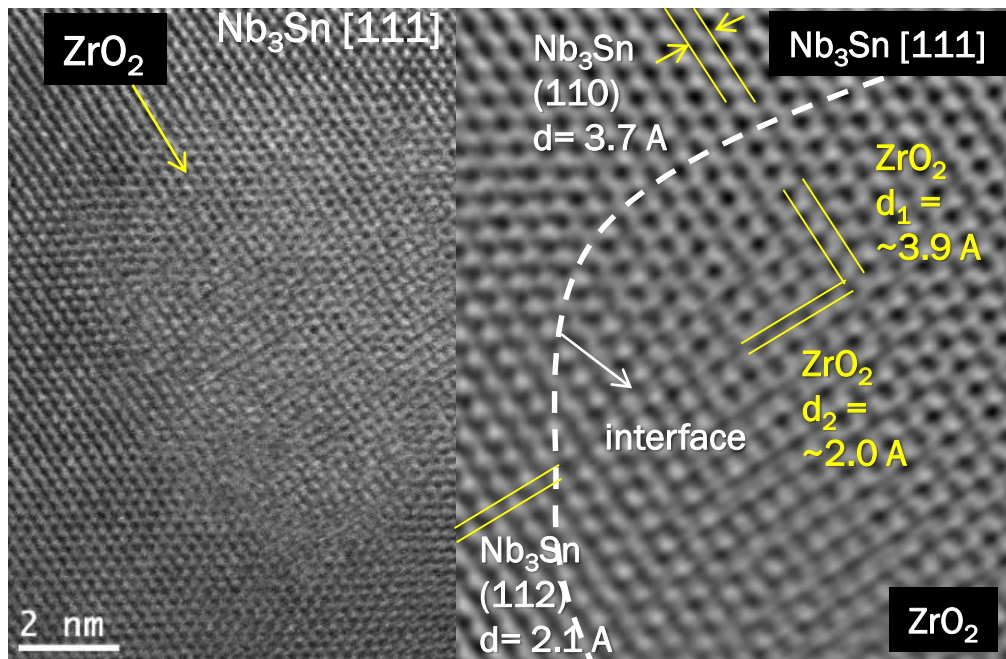
Wire	F_p - B curve peaks at
Standard RRP	5 T, $\sim 0.2B_{irr}$
Nb-Ta-1%Hf + O	9.1 T, $\sim 0.34B_{irr}$
Nb-Ta-1%Hf, no O	5.4 T, 0.21 - $0.22B_{irr}$



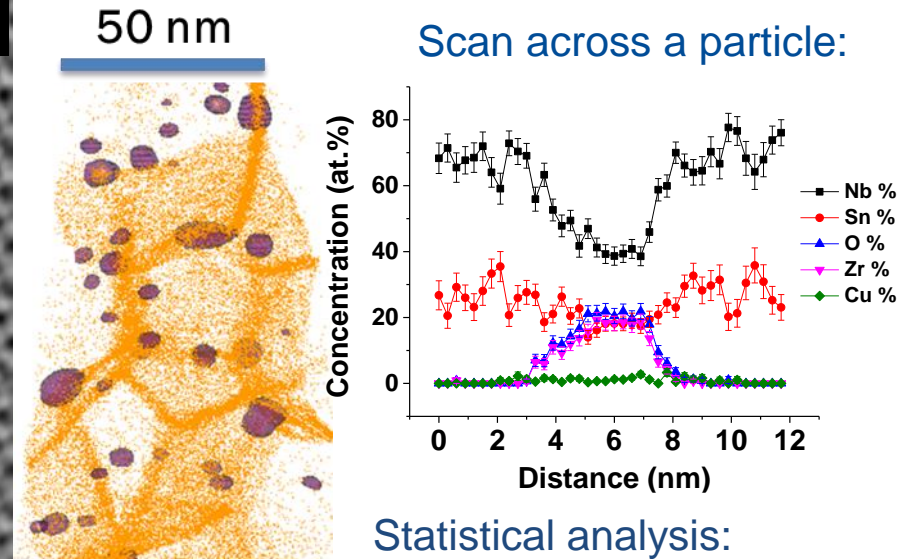
Point pinning: what causes it?

Microscopy studies by Jae-Yel Lee on a wire T3912 (Nb-Ta-1%Zr + O), reacted at 650 °C:

1. HR-STEM study



2. Atom Probe Tomography (APT) study:



From these results, we can verify that:

- The particles seen in TEM images are ZrO₂.
- ZrO₂ particle density is high.
- Particles have diameters similar to grain boundary width, suitable as point pinners.



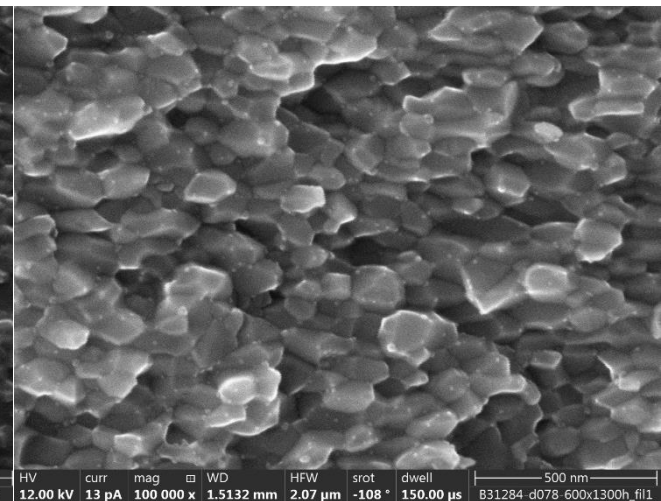
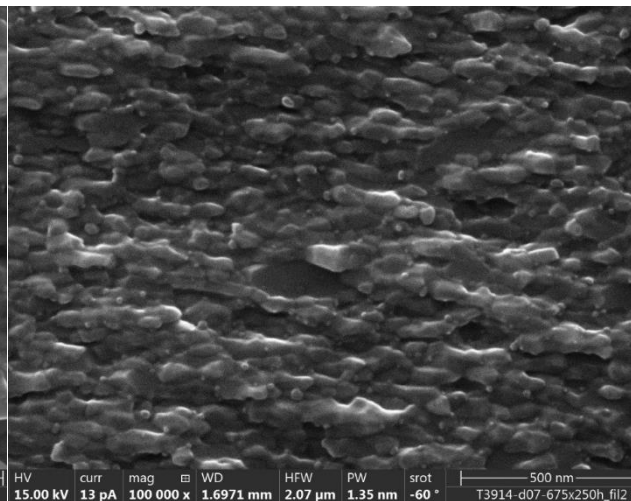
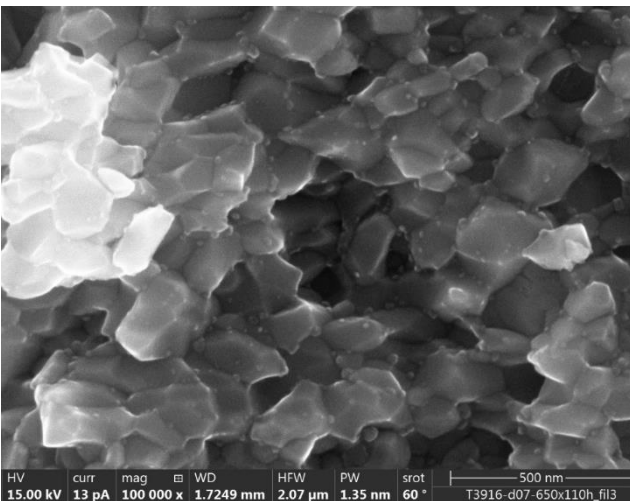
Factor 2 – Grain size refinement: what causes it?

- Grain sizes of internally oxidized wires are ~ half of standard wires. Mechanism?
- To understand its mechanism, we need to answer one question first: what role does O play?
- Both Hf (or Zr) w/ and w/o O → refined grain size: is O really needed?

T3916 (Nb-4at.%Ta-1at.%Hf,
no O): HT at 650 °C:

T3914 (Nb-4at.%Ta-1at.%Hf,
with O): HT at 675 °C:

B31284 (Bruker PIT): HT
at 605 °C (ultra low T):



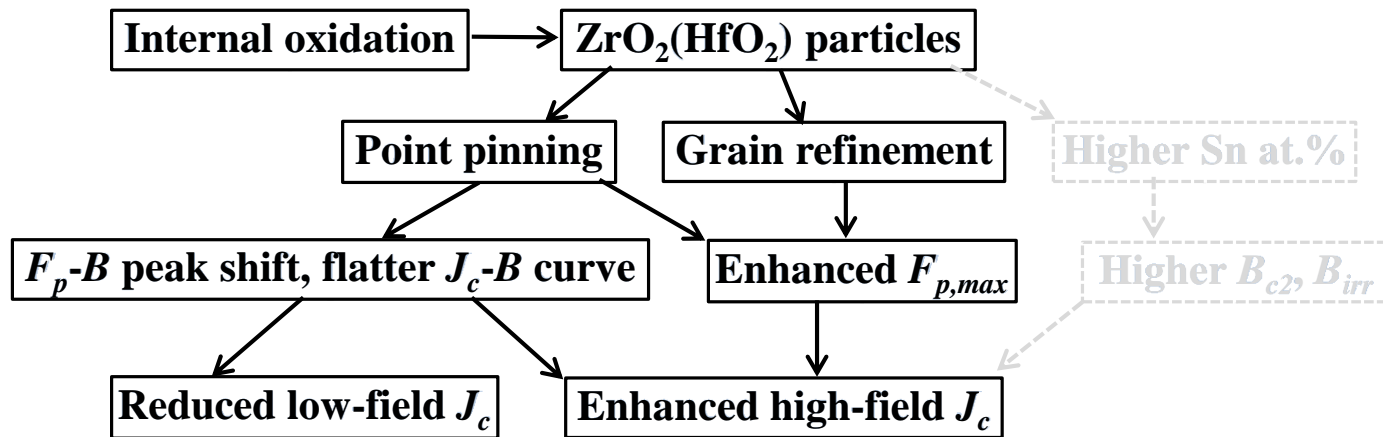
Similar thing was seen in Nb-Ta-1%Zr wires: 675 °C, 70 nm (~2 at.% O) vs 110 nm (~0.5 at.% O).

- Hf (or Zr) itself refines Nb₃Sn grain size. See talks by FSU Colleagues.
- However, adding O makes Nb₃Sn grain size significantly smaller. Possible mechanisms:
ZrO₂ particles (1) serve as Nb₃Sn nucleation centers, (2) inhibit Nb₃Sn grain growth (Zener pinning).



Summary

- Nb_3Sn J_c can be significantly boosted by enhancing flux pinning:
 - The internal oxidation approach forms ZrO_2 (or HfO_2) particles.
 - Hf (or Zr) itself has effect to refine Nb_3Sn grain size.
- Summary of how the internal oxidation affects the properties:



- Further understanding still needed:
 - Point pinning vs enhanced GB pinning: which dominates?



Acknowledgement

- Some very helpful discussions with FSU Colleagues.
- Some tests were performed at the NHMFL, which is supported by National Science Foundation Cooperative Agreement No. DMR-1644779 and the State of Florida.
- The tests were greatly helped by Jan Jaroszynski and Griffin Bradford.
- Magnetization-field (M - B) measurements using a 14 T VSM in the FSU by Van Griffin.
- Ian Pong for providing the RRP and PIT wires for HL-LHC that were used as references.
- Some helpful discussions in the MDP collaboration meetings.

Thank you for your attention!