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Update on the APC Nb_3Sn project

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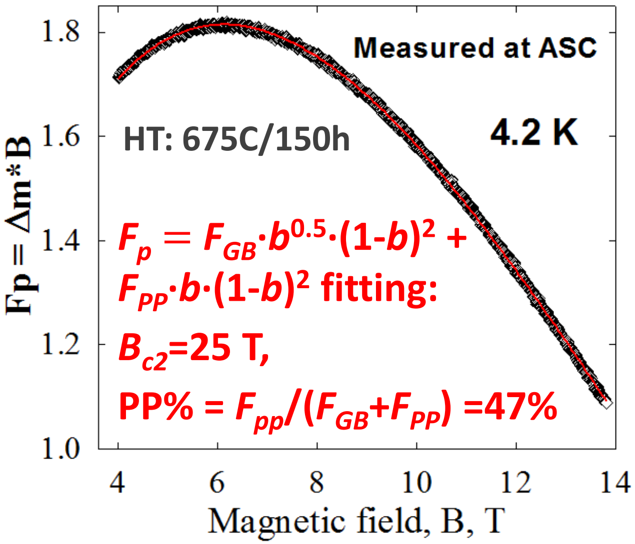
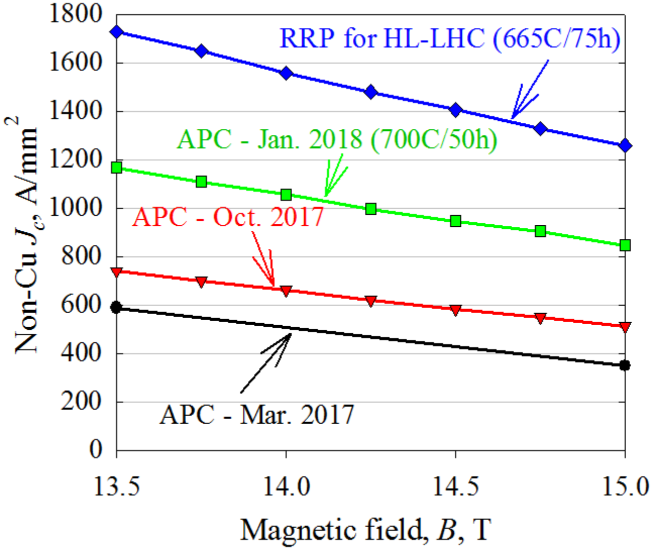
May 9th, 2018

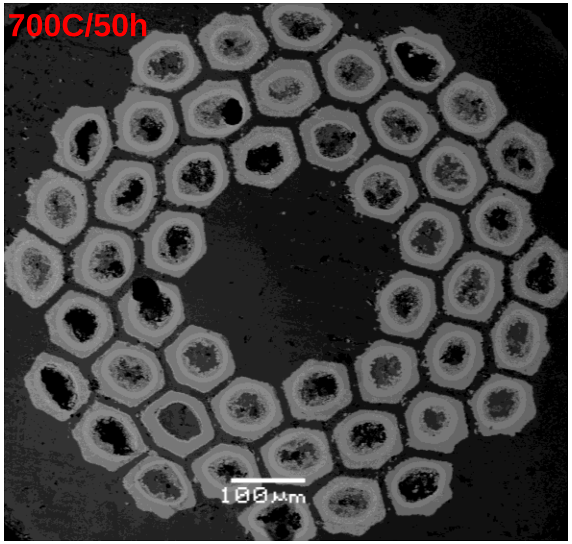
The work is supported by an Fermilab LDRD.

Summary of LTSW talk and what has been done since then

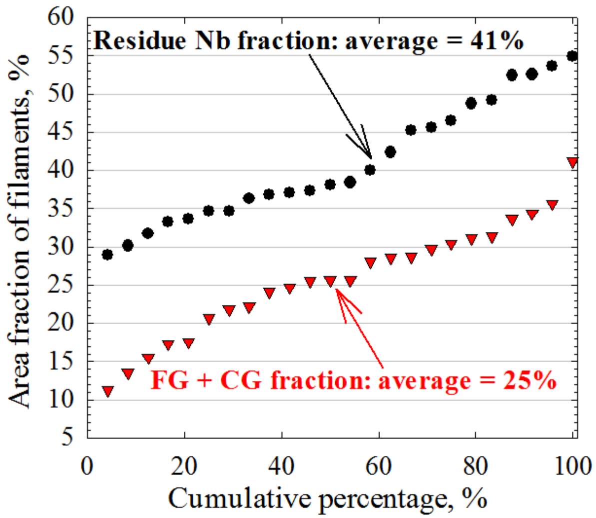
In 2017 a lot of work was done to optimize wire recipe and improve wire quality, and ternary doping was introduced. Below show the results of the wire made just before the LTSW:







Area fraction analysis of the 70C/50h sample: sorted in ascending order.
CG fraction: 5-10% here.



What has been done since LTSW:

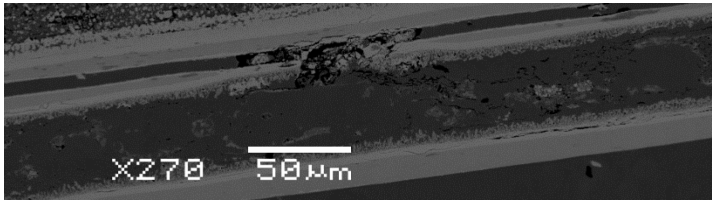
1. Closer analysis of this wire to understand why its non-Cu Jc is not high: bad wire quality issue
2. A non-APC control wire was made to see if the bad wire quality was due to use of APC technique
3. Based on these analyses, new recipe has been determined, and the wire is being made

Why this non-Cu Jc is not high: cause analyses – I

Issue 1: low Nb3Sn fraction

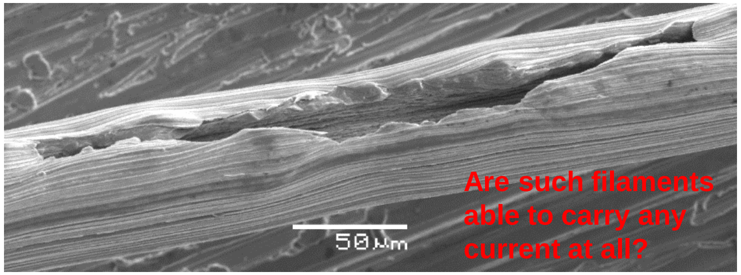
This low Nb3Sn fraction is not because Sn is insufficient, but is really due to Sn leakage into Cu matrix.

A cause for Sn leakage: improper wire design (too large core):



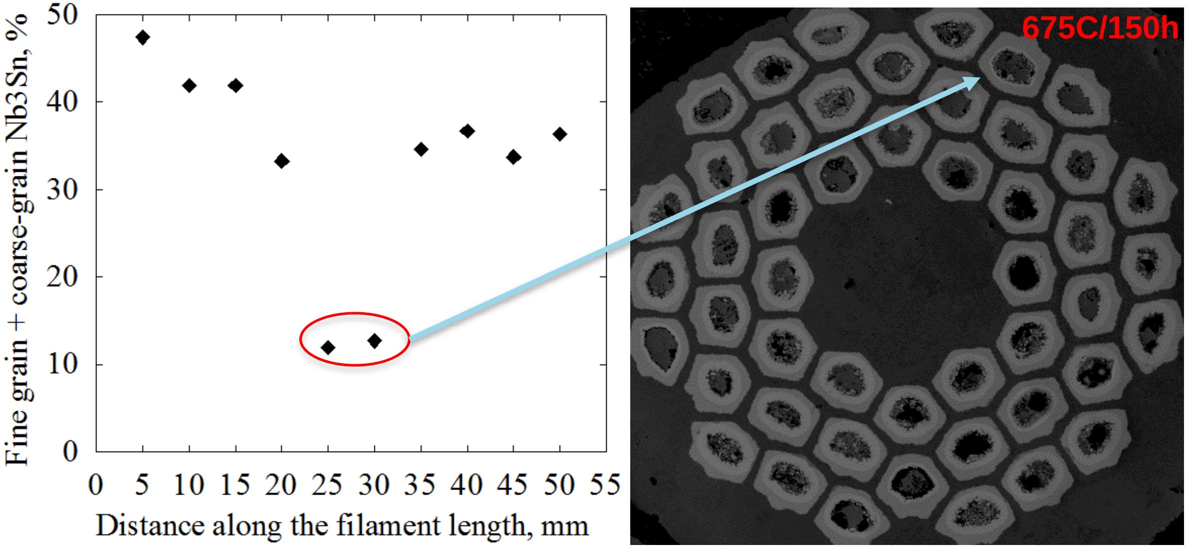
Other causes: see later discussions.

A study: etching the <u>unreacted</u> wire and extracting each filament for SEM:

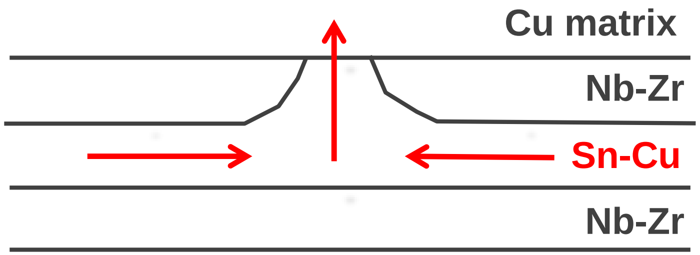


Issue 2: serious non-uniformity (among filaments and in each)

A study: 10 sections polished in a 5-cm long wire, to track the change of Nb3Sn layer every 5 mm along the length:



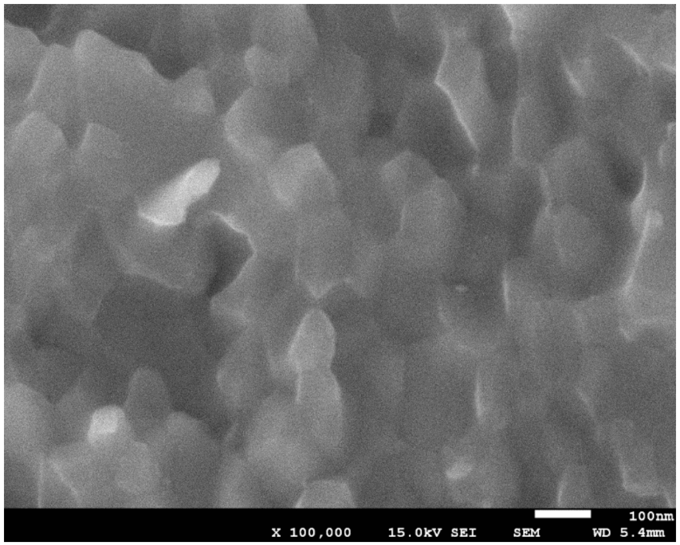
Likely cause: big hard particles cut the tube open during wire drawing



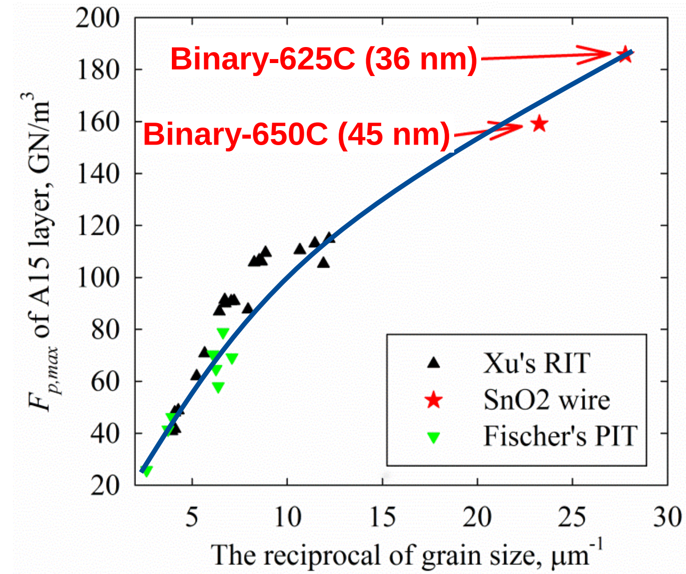
Each leakage spot can cause a long Sn-deficient zone along the length.

Why this non-Cu Jc is not high: cause analyses – II

Grain size of the sample is not really small: ~80 nm. Why so big:
(1) This wire was reacted at 700C/50h.
(2) Used Nb-7.5%Ta-0.6%Zr alloy. Lower Zr content ➔ fewer ZrO_2 ➔ less grain refinement



80 nm grain size is smaller than present RRP (120-150 nm), but not small compared with previous 1%Zr wires (binary):



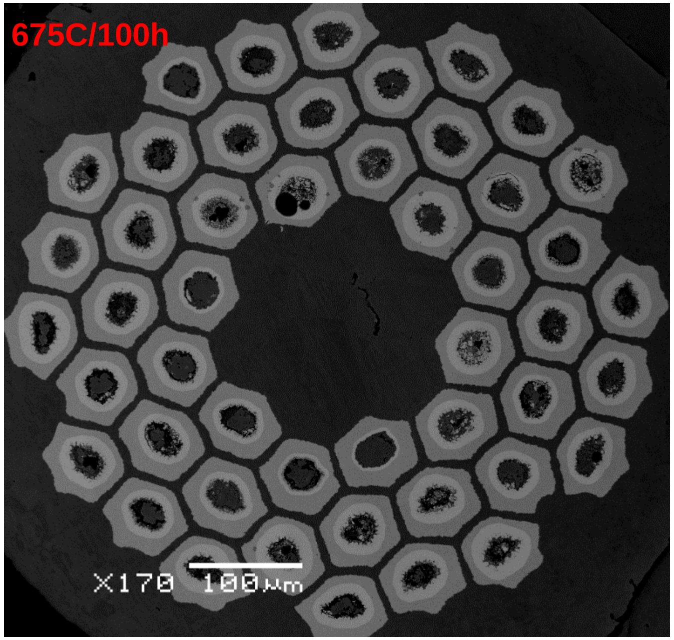
However, even with this 80 nm grain size, the layer Jc is already very high.

- **Due to the bad non-uniformity, estimation of the accurate layer Jc is difficult.**
- **First, forgetting the non-uniformity, based on the non-Cu Jc (850A/mm^2 at 15 T) and the average area fraction, the 15 T layer Jc is estimated to be around 5 kA/mm^2, about doubling that of RRP.**
- **If the non-uniformity really severely limits the Ic, then the true layer Jc could be much higher.**

Next, will use Nb-7.5%Ta-1.0%Zr + 675°C heat treatment ➔ grain size ~55 nm ➔ much higher layer Jc.

How to solve the Sn leakage issue?

Question: Could this issue be due to the APC technique (i.e., use of Nb-Zr tube or addition of oxide)? A control wire was made using Nb-7.5%Ta tube and Sn+Cu powders – a totally regular PIT wire.



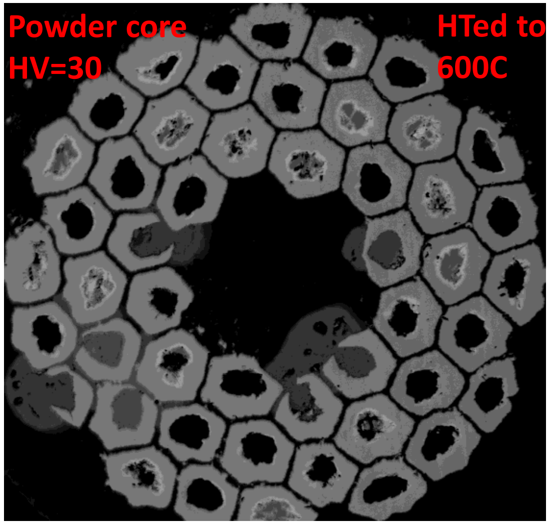
The Sn leakage issue is still there: it is not due to APC technique.

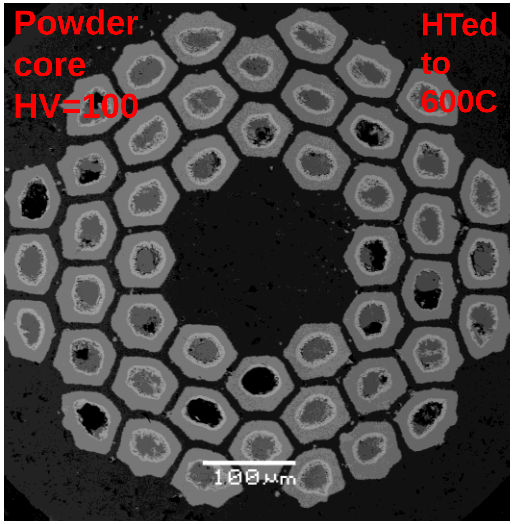
How to solve the Sn leakage issue?

Task 1: improve PIT wire quality during fabrication

- Maybe handling of powders is not proper (e.g., big particles)?
- Maybe powder mixing is not uniform?
- Maybe issue with wire drawing
- ……

Task 2: optimize wire design and recipe. For example, need to adjust powder recipe to make powder core hard: soft core ➔ eccentric cores ➔ Sn leakage. Another example: too large core ➔ easier for Sn leakage. Optimizing wire design and recipe is a process that takes time.





Task 3: need more work to find out if there are other causes.

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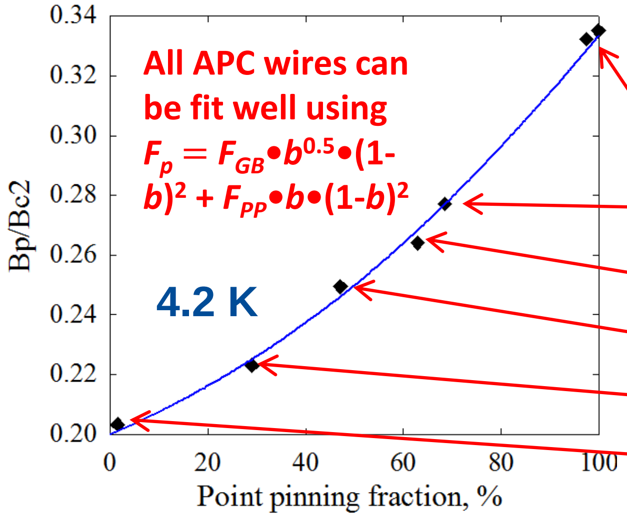
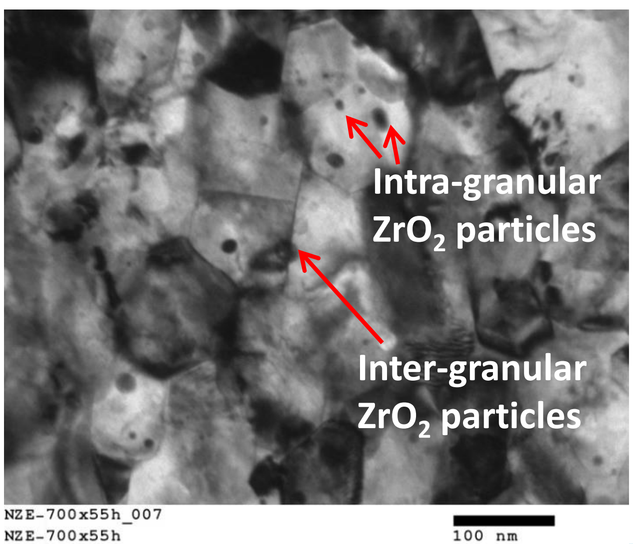
A discussion about point pinning

I believed the peak shift in Fp-B curves of APC wires was due to smaller grain size. This is wrong.

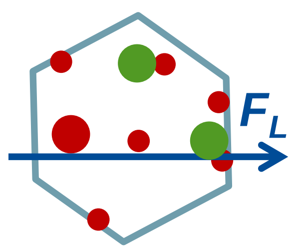


Zr% in Nb-Zr	HT T, °C	Grain size
1%	630	36 nm
0.6%	625	53 nm
1%	675	55 nm
0.6%	675	70 nm
0.6%	720	90 nm
0%	625	105 nm

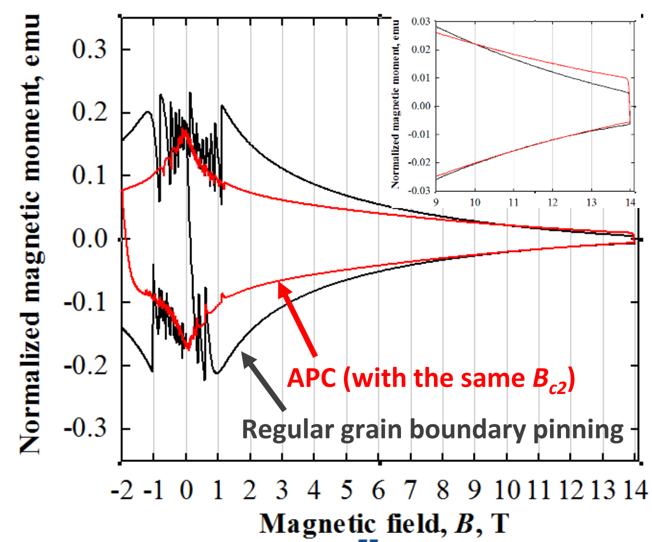
- Even with 90 nm, the PP% is still ~30%, so grain size is irrelevant with peak shift.
- Instead, the point pinners should be ZrO_2 particles (1-10 nm for HT at 700C).
- Total F_p is a sum of GB and ZrO_2 contributions.
- Then why point pinning becomes weaker as HT temperature is higher? Higher HT T or lower Zr% ➔ ZrO_2 particles fewer (sparser) ➔ less effective in point pinning



As point pinning increases from 0 to 100%, F_{GB} drops to 0. How can this happen? Maybe enough ZrO_2 sitting on GBs? If so, F_{pp} should be much stronger than F_{GB}.



Extra benefit: point pinning ➔ Jc-B curve flatter



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Summary

1. Despite bad wire quality, the non-Cu Jc of present APC PIT wires is not far from that of RRP now.
2. Room for further improving the non-Cu Jc is huge:
   1) This wire: 0.6%Zr + 700 °C ➔ 80 nm GS + 40% PP ➔ doubling of 15 T layer Jc. Next, 1%Zr + 675 °C ➔ 55 nm + 60% PP ➔ tripling of 15 T layer Jc or more. Eventually, 1%Zr + 630-640 °C ➔ ~40 nm + 100% PP.
   2) This wire: very low Nb3Sn fraction, with significant non-uniformity also limiting Jc. Next, need to completely solve Sn leakage issue ➔ to reach 40% uniformly.
3. The Sn leakage issue is due to bad wire quality, which has nothing to do with the APC technique, but most likely due to improper wire design/recipe, powder handling, wire fabrication process, …. Making high-quality wires requires a wire manufacturer to have a decent technique level of wire fabrication.
4. It was found that the point pinning behavior is caused by ZrO2 particles. Due to their higher volumetric density, they can provide higher pinning force than grain boundaries. Point pinning makes Jc-B curves flatter, increasing high-field Jc but reduces low-field Jc.
5. Present status of APC: no showstopper, but still needs R&D, needs to make good wires.

Thank you for your attention