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Update on the APC Nb_3Sn project

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A brief history review of the APC project

History review, just to answer a question: “It’s been 4 years, still no wires are ready. Why it takes so long?”

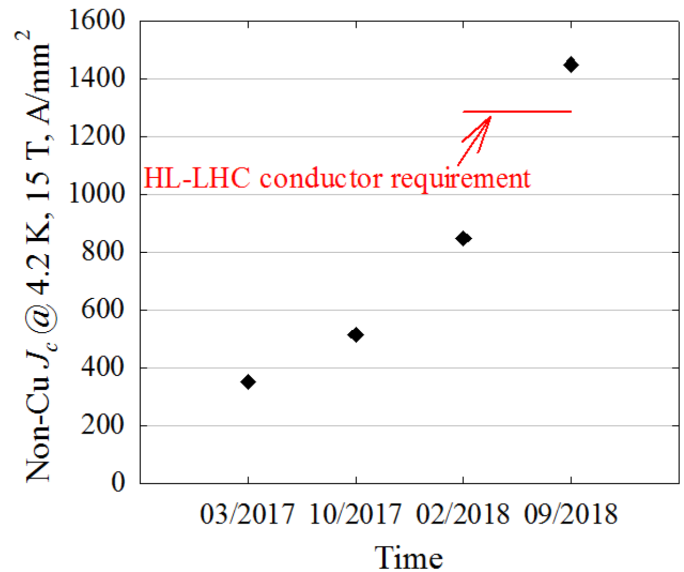
- **2014:** demonstrated the idea in monofilaments: 35-45 nm grain size, doubled layer J_c. But no multi plans.
- **2015:** discovered that direct contact is not needed between oxide and Nb for O to transfer, suggesting PIT design should work. Then managed to persuade Lesh and HyperTech to start making APC-PIT multi wires. Lesh first made it: poor wire quality, but proved the design.
- **2016:** Lesh dropped out. HyperTech: learning to handle powders, no uniform wires.
- **2017:** FNAL LDRD started – development on APC-PIT wires jointly with HyperTech truly started.

So, although the APC idea started in 2014, real development of “APC wires” in fact started from 2017. Progress has been fast:

The APC project: led by HyperTech, FNAL, and OSU.

- So far all wires start with 0.75” billets based on 48/61 design, drawn to 0.5-1.0 mm diameters, 100-200m total length per billet.
- Breakages in early 2017. No breakage in the past 15 billets.
- 114/127 design is in preparation.

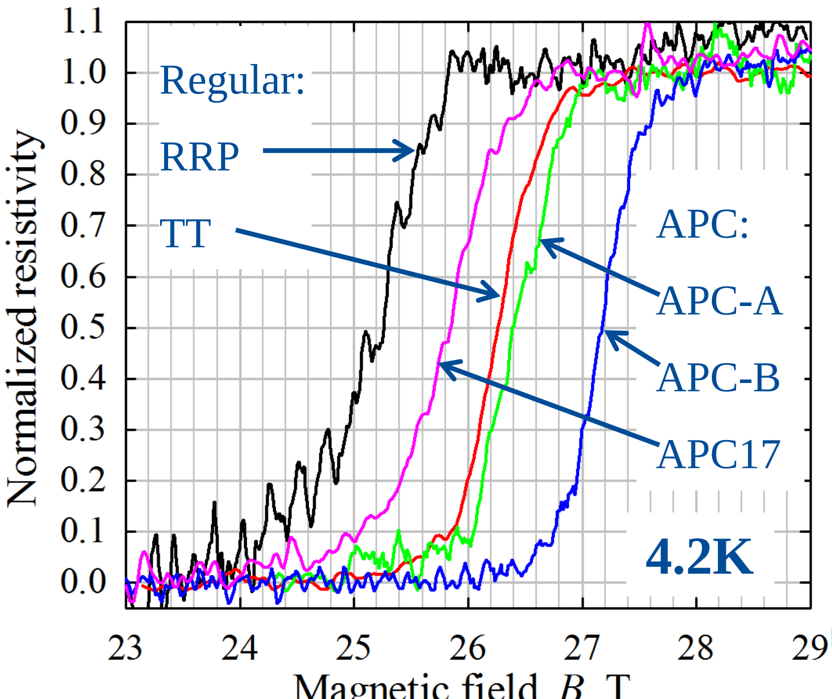
Improvement of APC wires since the development started:



The B_{c2} (B_{irr}) issue of APC conductors

The early monofilaments by HyperTech and multifilaments by Lesh showed low B_{irr}, raising concerns. To see if this is true, in Sept. 2018, 2 reference and 3 APC wires were tested in a 31 T DC magnet in NHMFL.

		Nb alloy	O amount	Design	Heat treatment
Reference	RRP (for HL-LHC)	Pure Nb + Nb-Ti	-	0.85mm, 108/127	210/48+400/48+665/75
	Tube type	Nb-4at.%Ta	-	0.7mm, 192/217	625C/400h (50C/h)
APC	APC-A	Nb-0.6%Zr-3at.%Ta	Sufficient	0.7mm, 48/61	675C/152h (30C/h)
	APC-B	Nb-1%Zr-4at.%Ta	Insufficient	0.84mm, 48/61	675C/300h (30C/h)
	APC17 (poor quality)	Nb-0.6%Zr-3at.%Ta	Sufficient	0.7mm, 48/61	675C/150h (30C/h)



APC17 (made in 2017) had low quality: just to show wire quality effect.

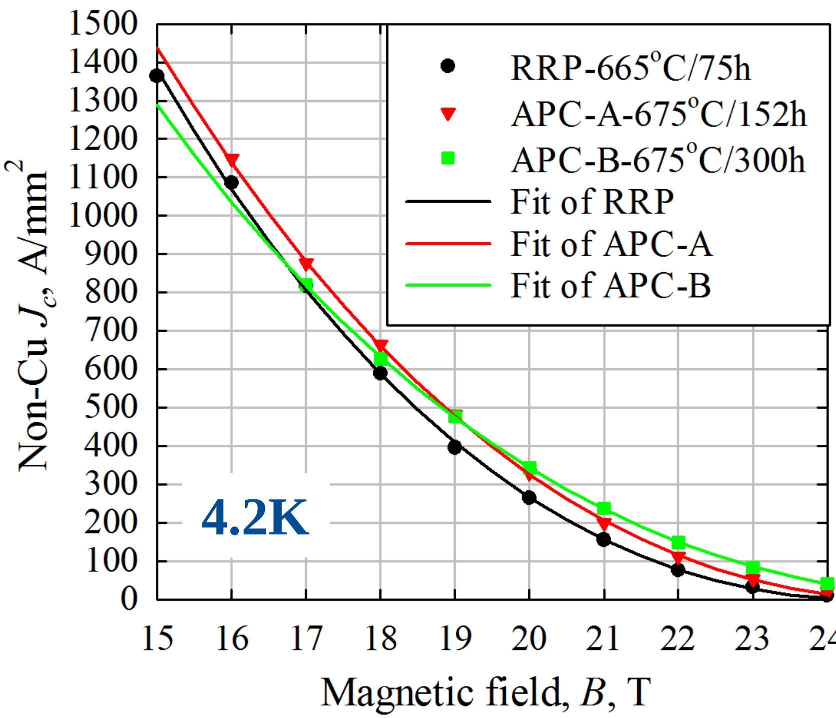
	RRP	TT	APC-A	APC-B	APC17
B_{c2}-10%	-*	25.9	26.0	26.8	25
B_{c2}-50%	25.2	26.3	26.4	27.2	25.8
B_{c2}-90%	25.8	26.7	26.9	27.6	26.3

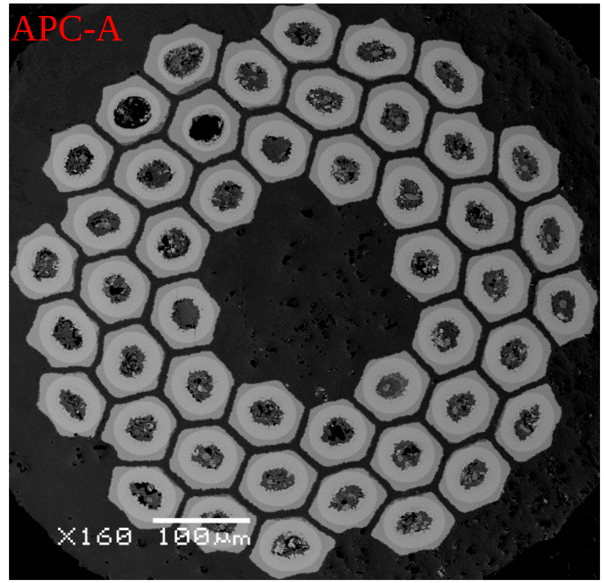
*: The B_{c2} at 10%R cannot be defined accurately due to noise.

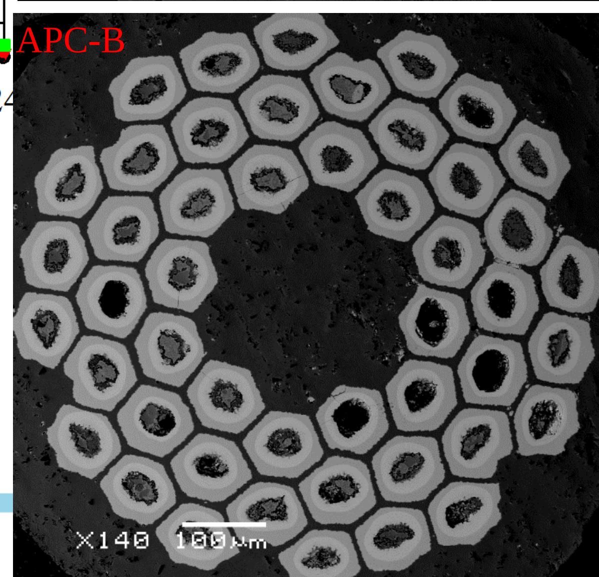
- From APC17: wire quality has big influence on B_{c2}.
- Maybe APC B_{c2} will be higher as quality is in improvement.
- Why early APC wires had low B_{irr}? Dopant-free, low quality.

Non-Cu J_c and Layer J_c

First, many thanks to David and ASC especially Griffin Brandford and Yavuz Oz for the help in the J_c tests in NHMFL. Almost all the tools were from ASC.





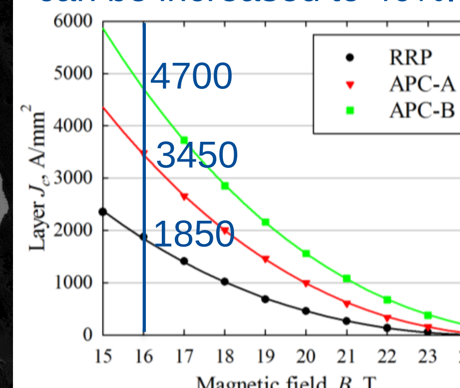


	APC -A	APC -B	Reg. PIT
FG %	33%	22%	40%
Nb %	36%	45%	25%
CG %	13%	13%	12%

PIT data: Segal, ICMC17 paper.

The small FG % is mainly due to high residual Nb %, due to unoptimized recipe and a few bad filaments.

By optimizing recipe, the residual Nb% can be reduced to 25%, the FG% can be increased to 40%.



The fitted B_{irr}s: RRP=24.6 T, APC-A=25.2 T, APC-B=26.2 T, similar to fields at 1% of R-B.

All wires are above HL-LHC specification.

APC-B had low non-Cu J_c due to low fine-grain (FG) Nb_3Sn fraction.

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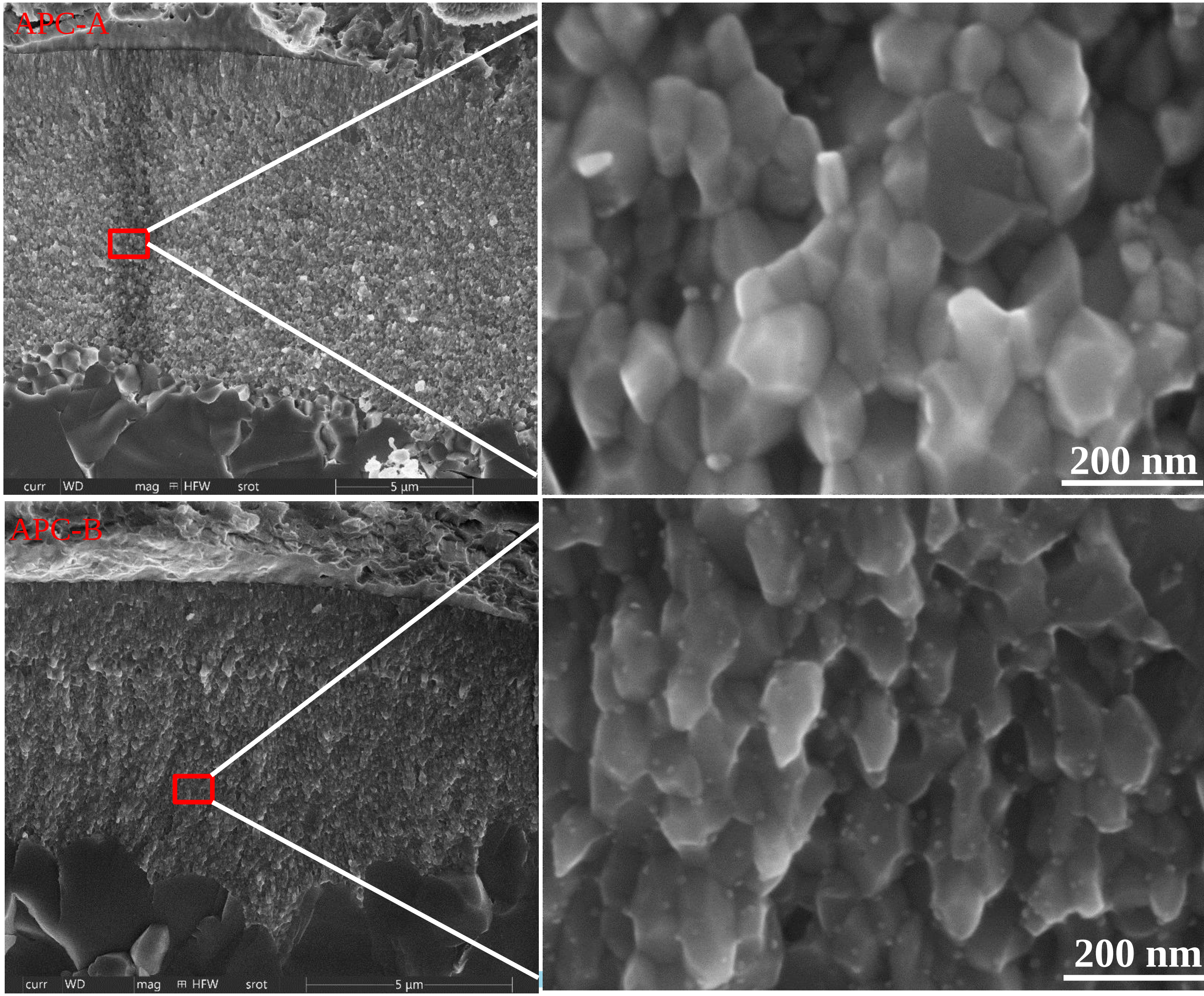
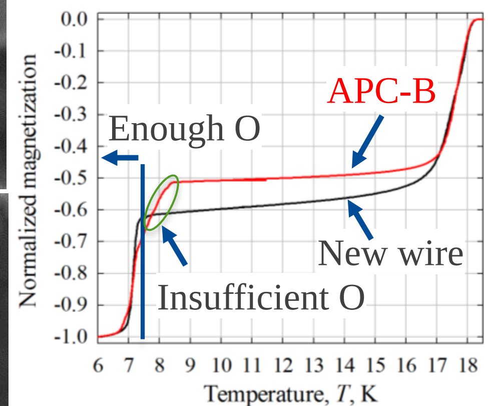
Grain size and Layer J_c



Average grain size:
APC-A = 81 nm,
APC-B = 72 nm.
Early APC = 35-45 nm.

Why GS so big?
APC-A: 675°C, 0.6% Zr.
APC-B: 675°C, short of O.



Projections:
1%Zr + enough O ➔
675°C GS ≤ 65 nm.
650°C GS ≤ 50 nm.
16T layer J_c = 5-7 kA/mm^2

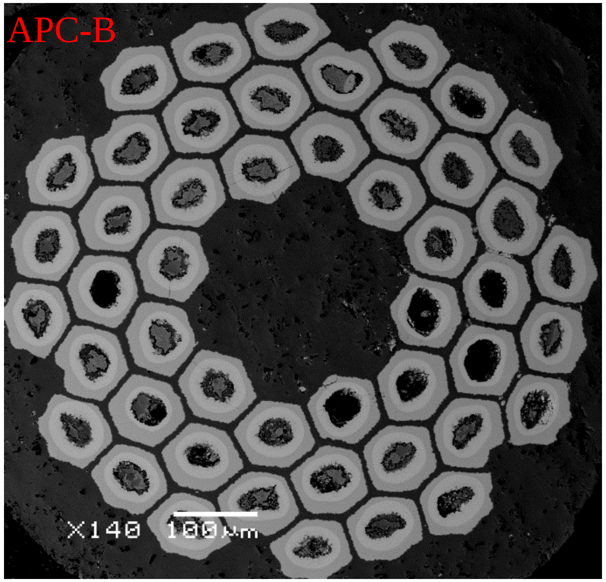
A wire fabricated after NHMFL tests

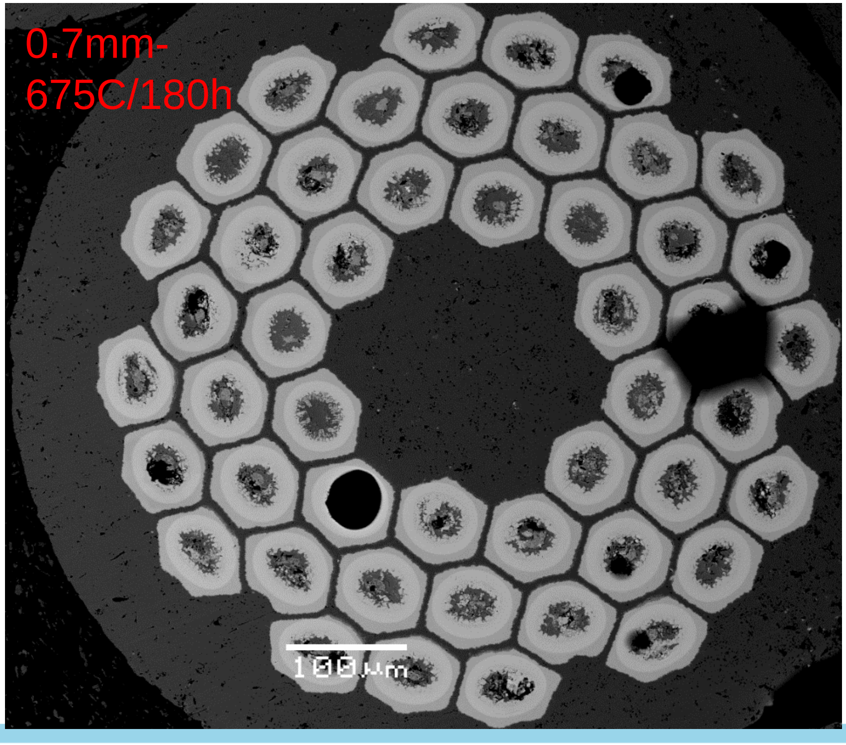
A new wire was fabricated after the NHMFL tests:

- Still used Nb-1%Zr-4at.%Ta tube.
- O amount is sufficient (see *M-T* in previous page).

The grain size should also be smaller and the layer J_c should be higher (>5000 A/mm^2 at 16 T).

The wire (0.7mm-675C/180h) was also much more fully reacted than APC-B. FG %: ~30%.





Its 16 T non-Cu J_c may have reached FCC spec.

Summary

1. Development of APC-PIT wires started in 2017. Since then the progress has been fast.
2. Tests up to 31 T show that B_{c2} is 26-28 T, slightly higher than RRP.
3. R&D work in the past two years has led to significant improvement of wire recipe and quality. The non-Cu J_c is on similar level with present RRP wires, in spite that the Nb_3Sn % is still low and grain size is still big due to unoptimized wire recipe and heat treatment.
4. Room for further improving the non-Cu J_c is big:
   1) By improving conductor recipe and quality and heat treatment, the fine-grain Nb_3Sn fraction can be increased to ~40%.
   2) By optimizing O content and heat treatment, the grain size can be reduced to 50-65 nm or less, which leads to a Nb_3Sn layer J_c of 5000-7000 A/mm^2 for 16 T.

   This means the 16 T non-Cu J_c can reach >2000 A/mm^2. This will surpass the FCC spec and also provide >30% margin (e.g., to counteract degradation under stress).

   Above 16 T, the APC conductors should give extra J_c gain due to higher B_{irr} and shift in F_p-B curve peak to higher fields.
5. Still needs more work.

Thank you for your attention

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