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Recent progress with APC Nb_3Sn conductors

Xingchen Xu, Fermilab
Xuan Peng, Hyper Tech Research, Inc.
Jacob Rochester, Mike Sumption, OSU

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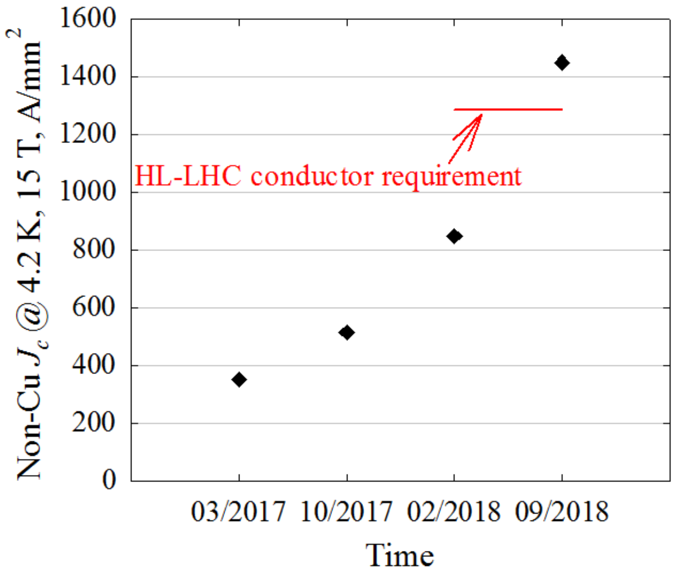
Introduction

Brief History review

- 2014: started on monofilaments.
- Late 2015 and 2016: learning curves towards PIT wires.
- Development of "real" APC multifilamentary wires in fact started from 2017, supported by Fermilab LDRD and HyperTech SBIR from US DOE.
- Progress has been fast since then.



Current status:

- ❑ All wires made in HyperTech. Start with 0.75" billets based on 48/61 design, drawn to 0.5-1.0 mm diameters, 100-200 m total length per billet. 114/127 design is in preparation.
- ❑ Breakages in early 2017. Problem solved after improvement in wire recipe and quality. No breakage in the past 15 billets.
- ❑ Still working to improve wire recipe, which led to great performance improvement, but ongoing.

What is in this talk:

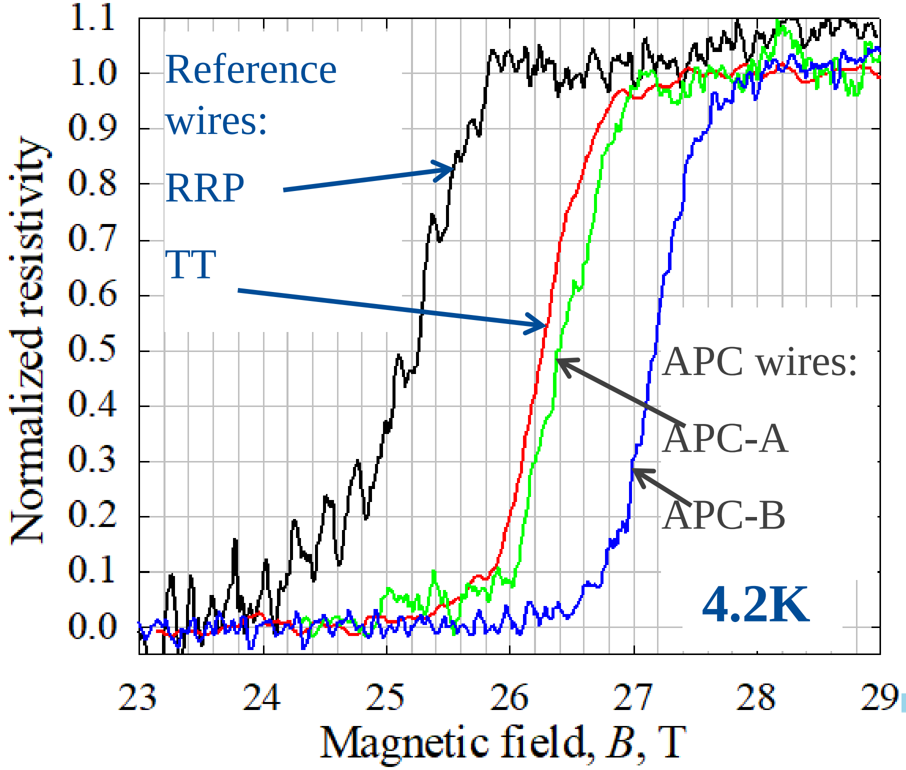
Tests of recent APC wires at NHMFL, including B_{c2}, non-Cu J_c, real estate, layer J_c, prospects.

X. Xu et al., "Ternary Nb_3Sn superconductors with artificial pinning centers and high upper critical fields", in review. Preprint URL: https://arxiv.org/abs/1810.10569

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

- Early monofilaments by HyperTech and multifilaments by Lesh showed low extrapolated B_{irr}, raising concerns.
- To see their real B_{c2}s, in Sept 2018, 2 reference and 2 APC wires were tested in a 31 T DC magnet at NHMFL.

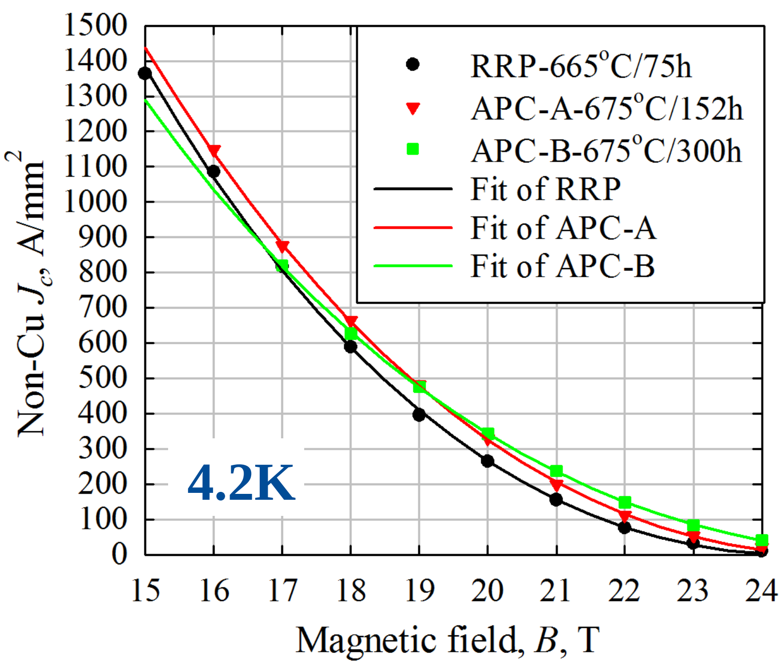
		Nb alloy	O amount	Design	Heat treatment
Reference	RRP (for HL-LHC quad)	Pure Nb + Nb-Ti rods	-	0.85mm, 108/127	210/48+400/48+665/75
Reference	Tube type (T1505)	Nb-4at.%Ta	-	0.7mm, 192/217	625C/400h (50C/h)
APC	APC-A (T3851)	Nb-0.6%Zr-3at.%Ta	Sufficient	0.7mm, 48/61	675C/152h (30C/h)
APC	APC-B (T3882)	Nb-1%Zr-4at.%Ta	Insufficient	0.84mm, 48/61	675C/300h (30C/h)

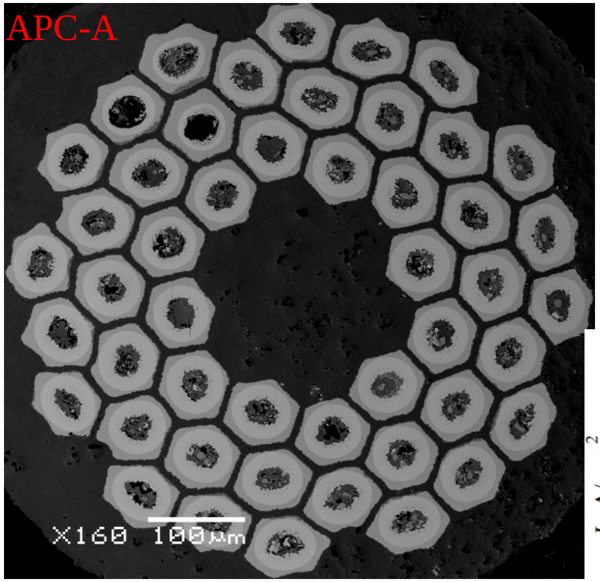


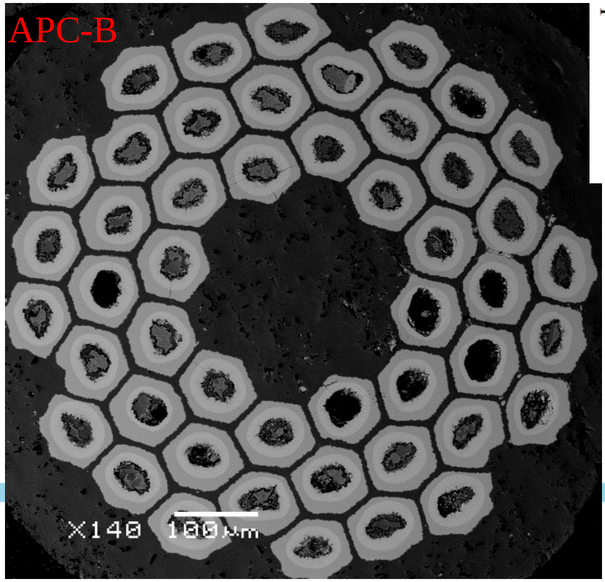
- RRP: B_{irr} = 24.6 T, B_{c2} = 25.8 T at 4.2K.
- APC-A: ~1.2 T higher than RRP, despite insufficient Ta level ➔ reduced B_{c2}.
- APC-B: B_{c2} and B_{irr} about 2 T higher than RRP.

Non-Cu J_c and Nb_3Sn Layer J_c

First, many thanks to David and ASC especially Griffin Bradford and Yavuz Oz for the help in the J_c tests. All the tools (*e.g,* probe, system) were from ASC.



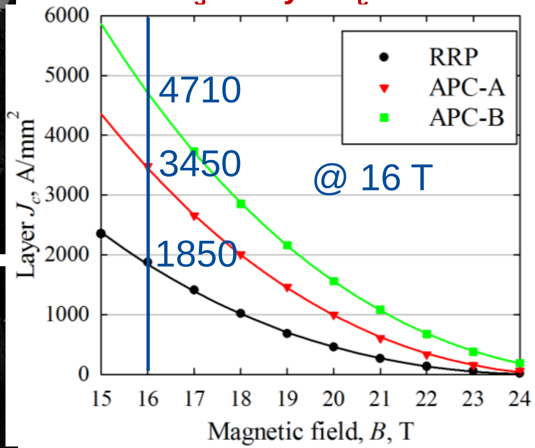




	APC -A	APC -B	Reg. PIT
FG %	33%	22%	40%
Nb %	36%	45%	25%
CG %	13%	13%	12%

PIT data: Segal, ICMC17 paper.

Nb_3Sn layer J_c-B:



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* curves.

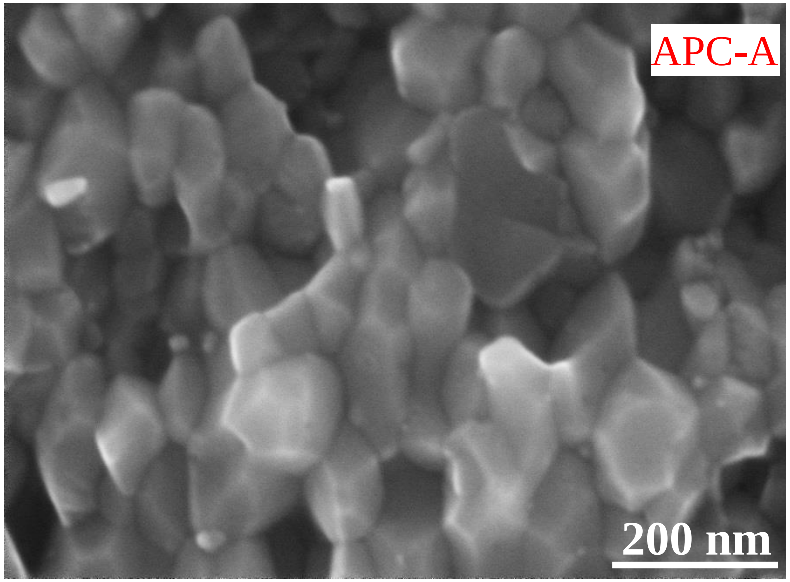
All wires are above HL-LHC specification.

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

The small FG % is mainly due to high Nb %, due to unoptimized recipe.

By optimizing recipe, the Nb% can be reduced to 25%. Expect: FG% reaches ~40%.

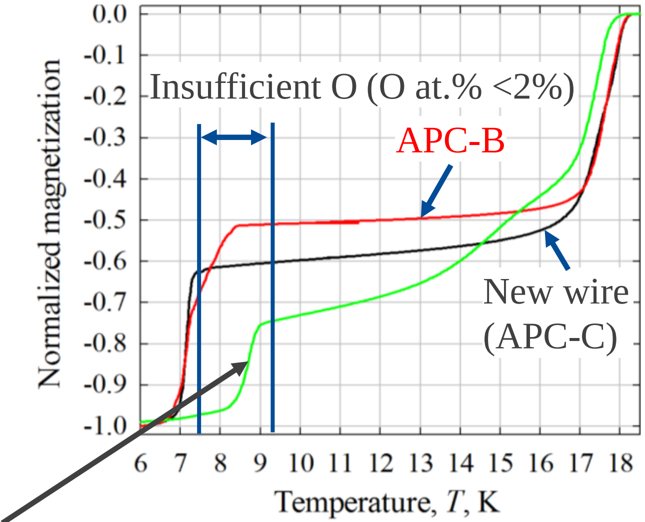
Grain size and Nb_3Sn layer J_c



Average grain size:
APC-A = 81 nm,
APC-B = 72 nm.
RRP (665 °C) = ~150 nm.
Early APC = 35-45 nm.

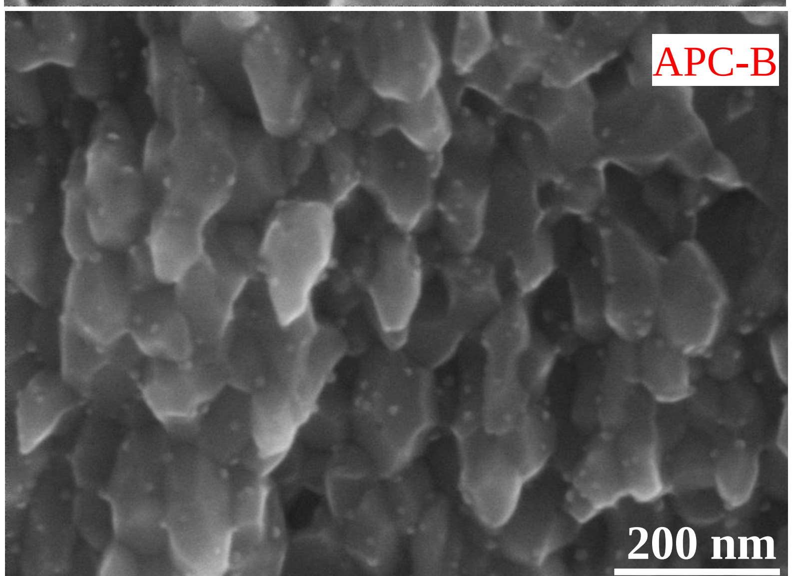
Why GS so big?
APC-A: 675°C, 0.6% Zr.
(Less Zr ➔ fewer ZrO_2).
APC-B: 675°C, short of O.

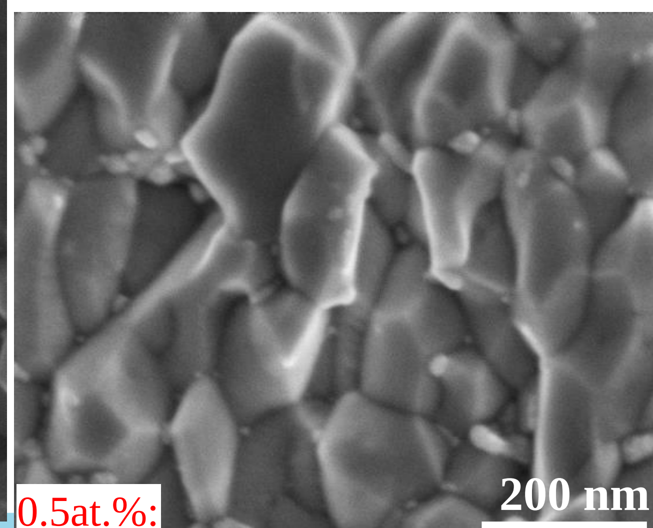
1%Zr needs 2 at.%O.



A 1%Zr wire w/ ~0.5 at% O: 675 °C HT ➔ average GS=110 nm.

GS is sensitive to O at.%. Insufficient O ➔ big GS.





Expectations:
1%Zr + enough O ➔
675°C: GS ≤ 65 nm.
650°C: GS ≤ 50 nm.
(based on previous data).

APC-B: 72nm➔ 4710@16T.
With GS of 50-65 nm, the expected 16T layer J_c = 5000-6000 A/mm^2.

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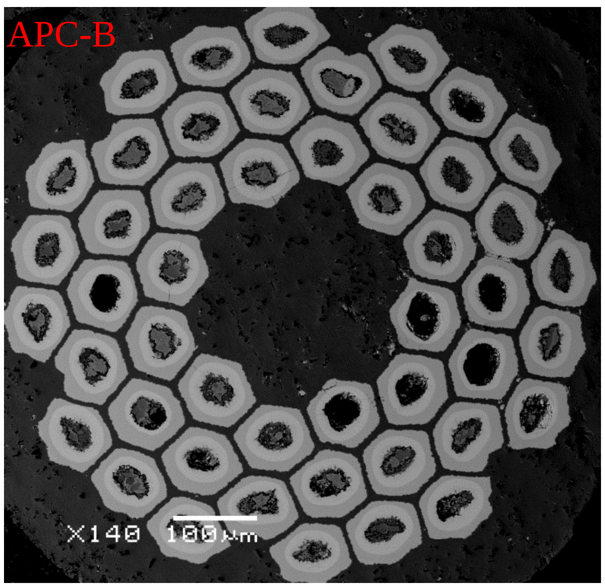
A wire fabricated after NHMFL tests

A new wire was fabricated after the NHMFL tests (let's call it APC-C).

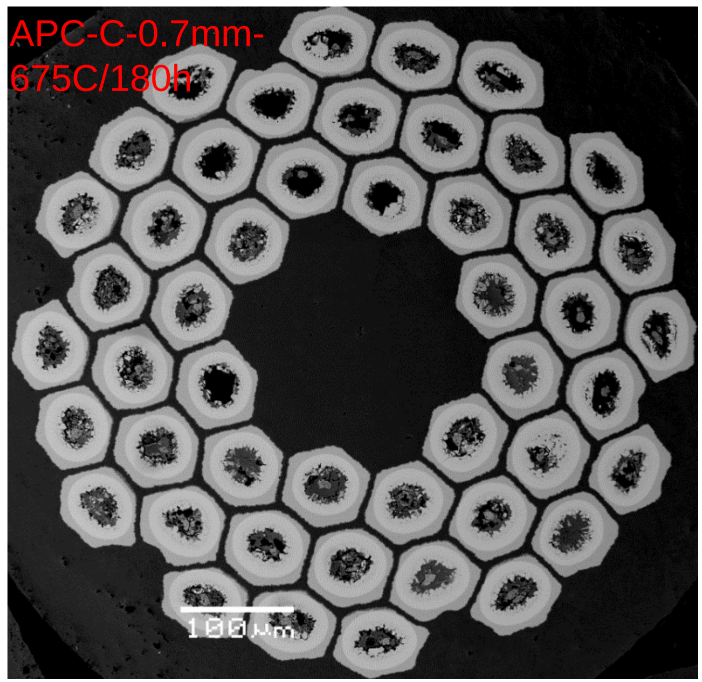
- Still used Nb-1%Zr-4at.%Ta tube.
- O amount is sufficient (see *M-T* in previous page).

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

APC-C-0.7mm-675C/180h was much more fully reacted than APC-B. FG fraction is ~31%.



V.S.



FG fraction (~31%) multiplied by layer J_c (~5000 A/mm^2 at 16 T), it is possible that its 16 T non-Cu J_c may have reached FCC spec.

But when tested at our maximum field, 15 T, it quenched, perhaps due to higher J_c and large D_s (70 µm). To 114/127 design to reduce D_s.

Summary

1. Development of APC-PIT multi wires started in 2017. Since then progress has been fast.
2. Tests up to 31 T at 4.2 K show that B_{irr} is 26-27 T, B_{c2} is 27-28 T, ~1-2 T higher than RRP.
3. R&D 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 not fully refined due to unoptimized wire recipe and heat treatment.
4. The Nb_3Sn layer J_c at 16 T is ~2.5 times of RRP despite grain size not fully refined.
5. The improvement is still ongoing. The following levels are expected.
    1) By improving conductor recipe and quality and heat treatment, the fine-grain Nb_3Sn fraction can be increased to ~40%, as in standard tube type and PIT wires.
    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 5000-6000 A/mm^2 for 4.2 K, 16 T.

    If so, this means the 4.2 K, 16 T non-Cu J_c can reach 2000-2400 A/mm^2. This will surpass the FCC spec and also provide >30% margin.

    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.

Thank you for your attention

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