# Recent progress on APC multi-filamentary $Nb_3Sn$ wires

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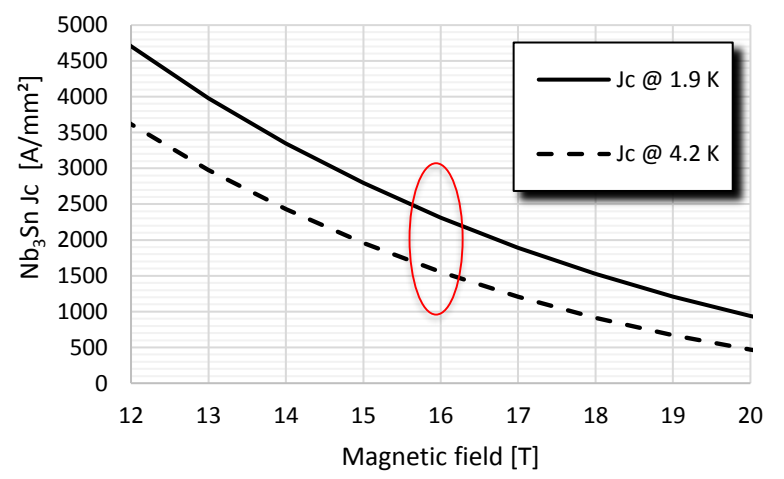
# Outline of this Talk

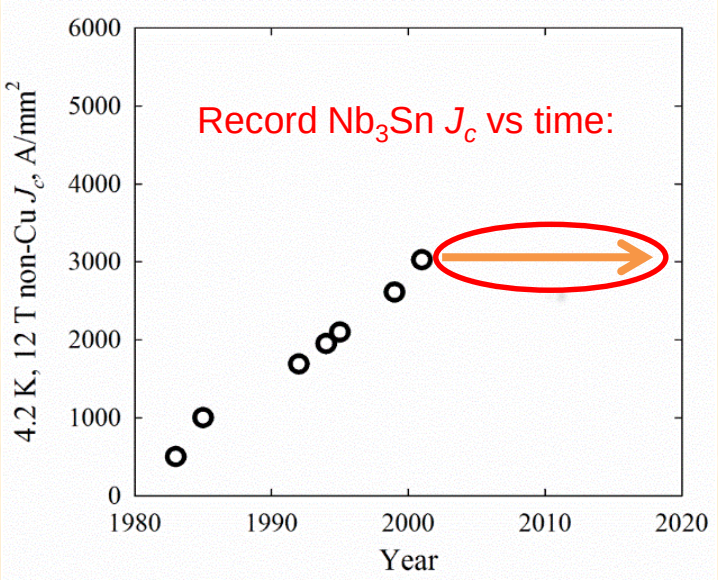
- Motivation of this Project
- Brief History Review of APC wire
- Report the fabrication and properties of the recent Ta doped APC wires
- Further Optimization
- Fabrication of APC wires and their Price Projection
- Sumary

# Motivation of this Project

FCC conductor specification:




EuroCirCol-P1-WP5 report, CERN, 2016.




**J. Parrell et al., *IEEE Trans. Appl. Supercond.* 13 3470-3, 2003:**

Need nearly 40% improvement of $J_c$.

**Create Artificial Pinning Center (APC)**

There is still a lot of room for improving pinning:

1. $J_c \propto$ 1/grain size;
2. Small pinning center spacing -> shift in $F_p$-$B$ peak to improve $B_{c2}$.
3. Doping

The highest $J_c$ has plateaued for nearly two decades, in spite of efforts to:

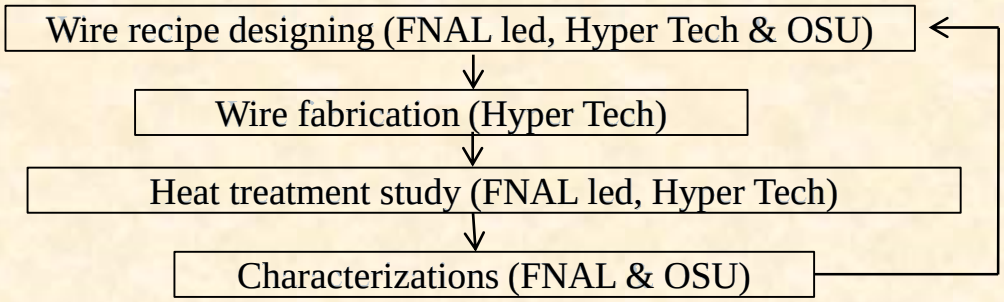
- adjust Nb/Sn/Cu ratio
- adjust LAR (0.13, 0.2, 0.23, hybrid, etc.)
- adjust doping (7.5%Ta, 1.5%Ti, 2.0%Ti, 3.2%Ti, 7.5%Ta+0.9%Ti, etc.)
- adjust heat treatment (FSU)
- adjust barrier composition (pure Nb, Nb-7.5%Ta)

# Brief History Review of Hyper Tech APC wire

**A lot of efforts on APC $Nb_3Sn$ since the 1980s: only became possible recently**

- 2014: started on making APC $Nb_3Sn$ monofilaments by internal oxidation in Hyper Tech through collaboration with OSU, and got great layer $J_c$ in monofilaments.

  X. Xu, M. Sumption, X. Peng, E. Collings, Appl. Phys. Lett. 104, 082602 (2014)."
- Late 2015-2016: made binary PIT multi-filament wires, with high layer $J_c$ but low $B_{c2}$.
- From 2017: Develop Ta-doped Ternary APC PIT multi-filament wires through collaboration with Fermilab and OSU. Great progress has been made since then. This is a joint effort.




- First Ta-doped wire tested at NHMFL in 09/2018: proved high $B_{c2}$, $J_c$ over HL-LHC spec.
- Recent wires tested at NHMFL in Jan 2019, $J_c$ over FCC spec.
- Latest wire tested by FSU group in NHMFL in April 2019, confirmed the $J_c$ over FCC spec at high field.
- Also inspired other groups to pursue the APC approach:

  ASC/NHMFL: explore Hf doping without oxygen.

  U. Geneva & CERN: work on monofilaments, similar to what we started with.

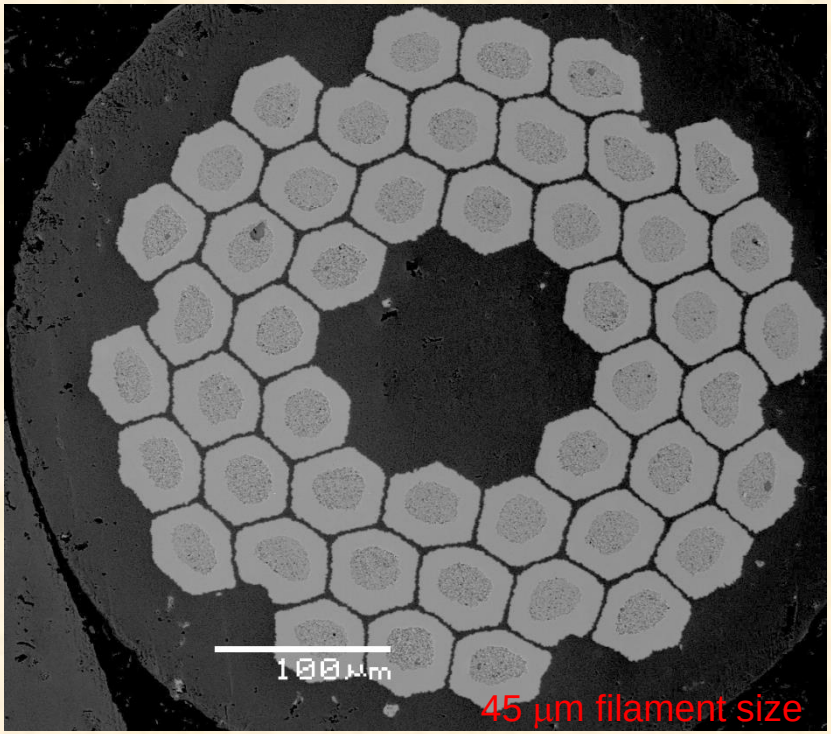
# Fabrication and Properties of the Recent Ta Doped APC Wires

U.S. Patent No. 9,916,919

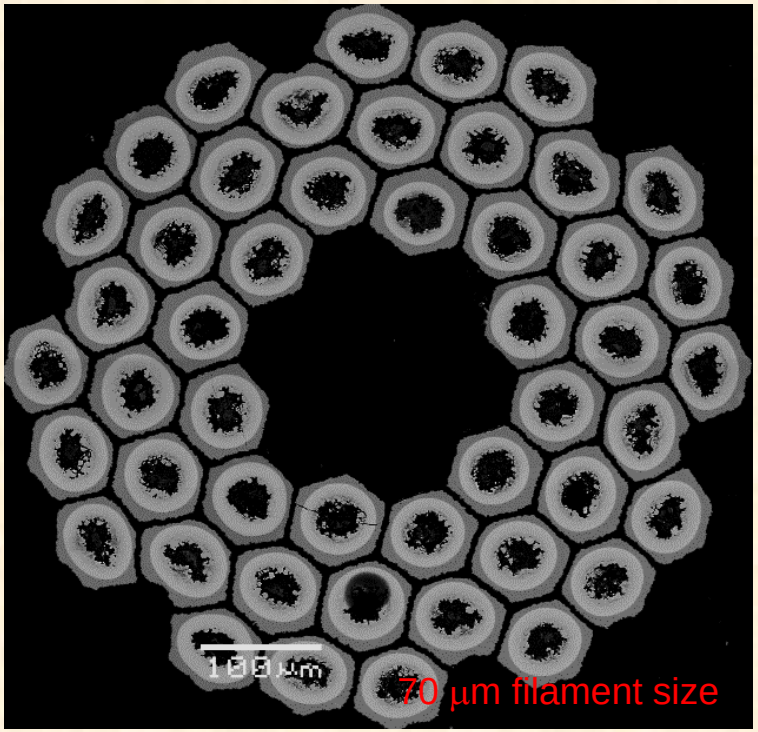
# Ta-doped APC wires have Good Drawbility

About 25 wires of 48/61 design has been made using Nb-Ta-Zr tubes, none had any breakage during wire drawing (100-200 meters of wire at 0.5mm-0.84 mm per billet).

T3912-0.5mm-unreacted




T3912-0.71mm-700C/71h

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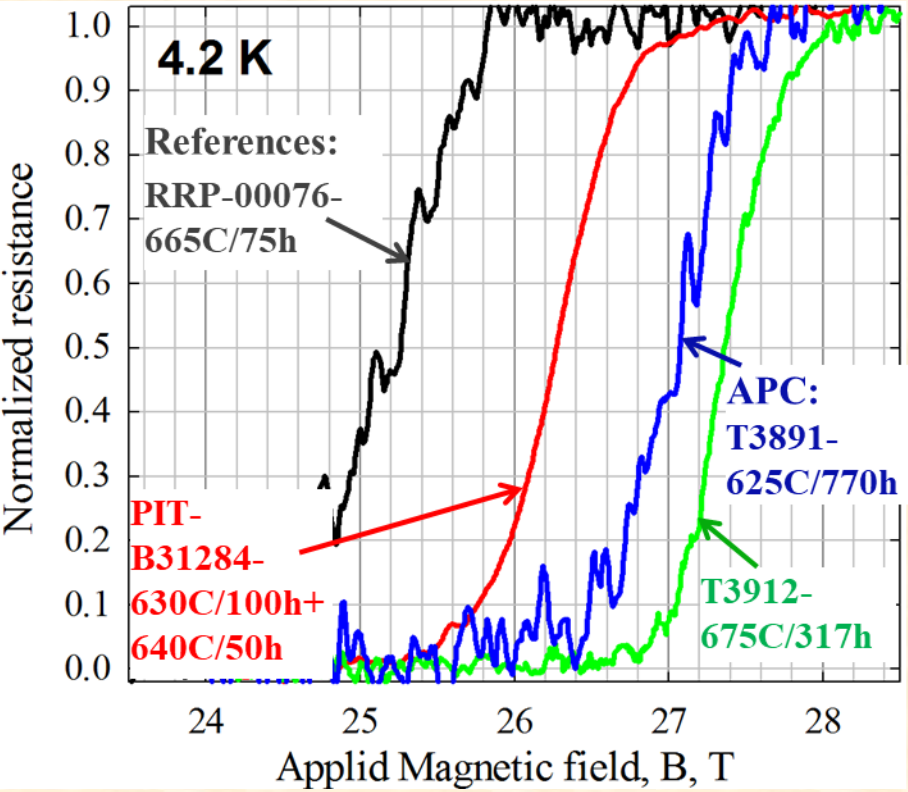
# Ta-doped APC wires have higher $B_{c2}$ than present wires




Transport *R-B* tests, done by X. Xu and M. Sumption in NHMFL, a 31T magnet. **Many thanks to Jan Jaroszynski for the help.**

| Wire | D, mm | Design | Composition |
|---|---|---|---|
| RRP-00076 | 0.85 | 108/127 | 1.5at.% Ti doped |
| PIT-B31284 | 0.78 | 192/217 | 7.5 wt.% Ta |
| APC-T3891 | 0.84 | 48/61 | 7.5% Ta, 1%Zr + O |
| APC-T3912 | 0.84 | 48/61 | 7.5% Ta, 1%Zr + O |

*Data provided by X. Xu, Fermilab*

- Ternary APC wire T3891: tests in 09/2018 showed $B_{irr}$ ($B_{c2}$) of 26-27 T at 4.2K, higher than present-day wires.
- Further confirmed by the tests of new wires T3912 in 01/2019.

Courtesy X. Xu etal. 1. https://arxiv.org/abs/1903.08121
*2. Supercond. Sci. Technol.* **32** 02LT01

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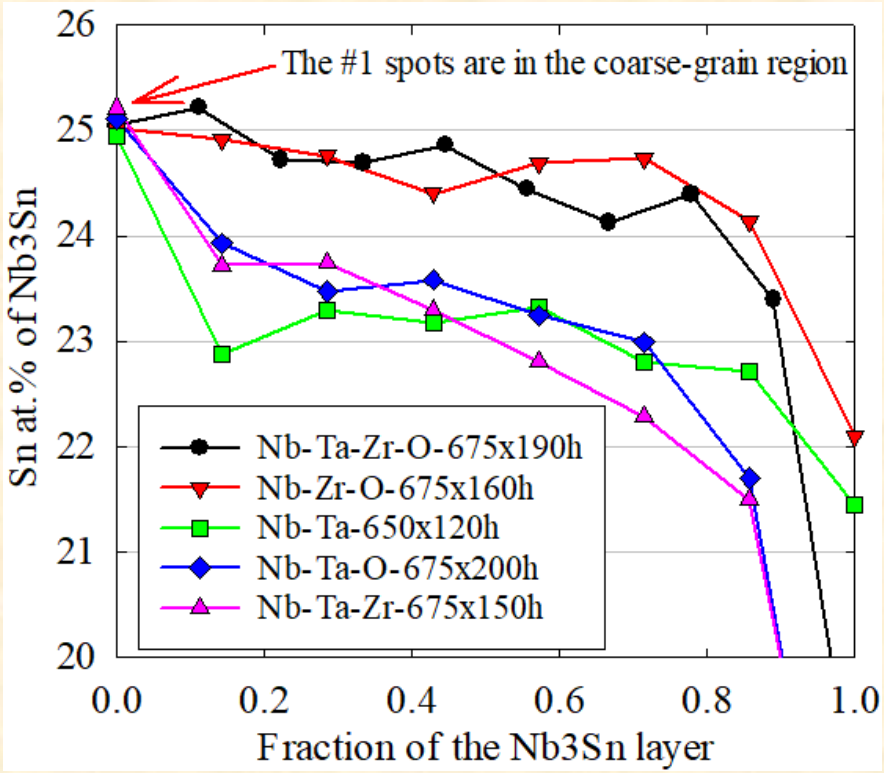
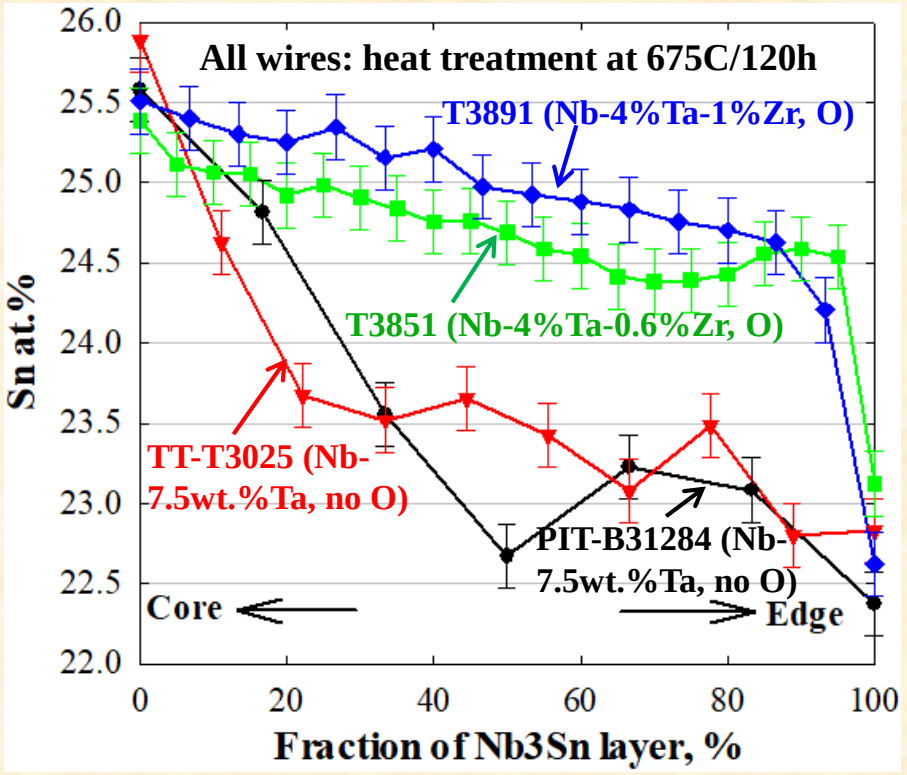
# A unique feature of APC $Nb_3Sn$: high Sn content in A15

**What accounts for the high $B_{irr}$ ($B_{c2}$) in the APC wires?**
**better stoichiometry ➔ higher $B_{c2}$ ($B_{irr}$)**

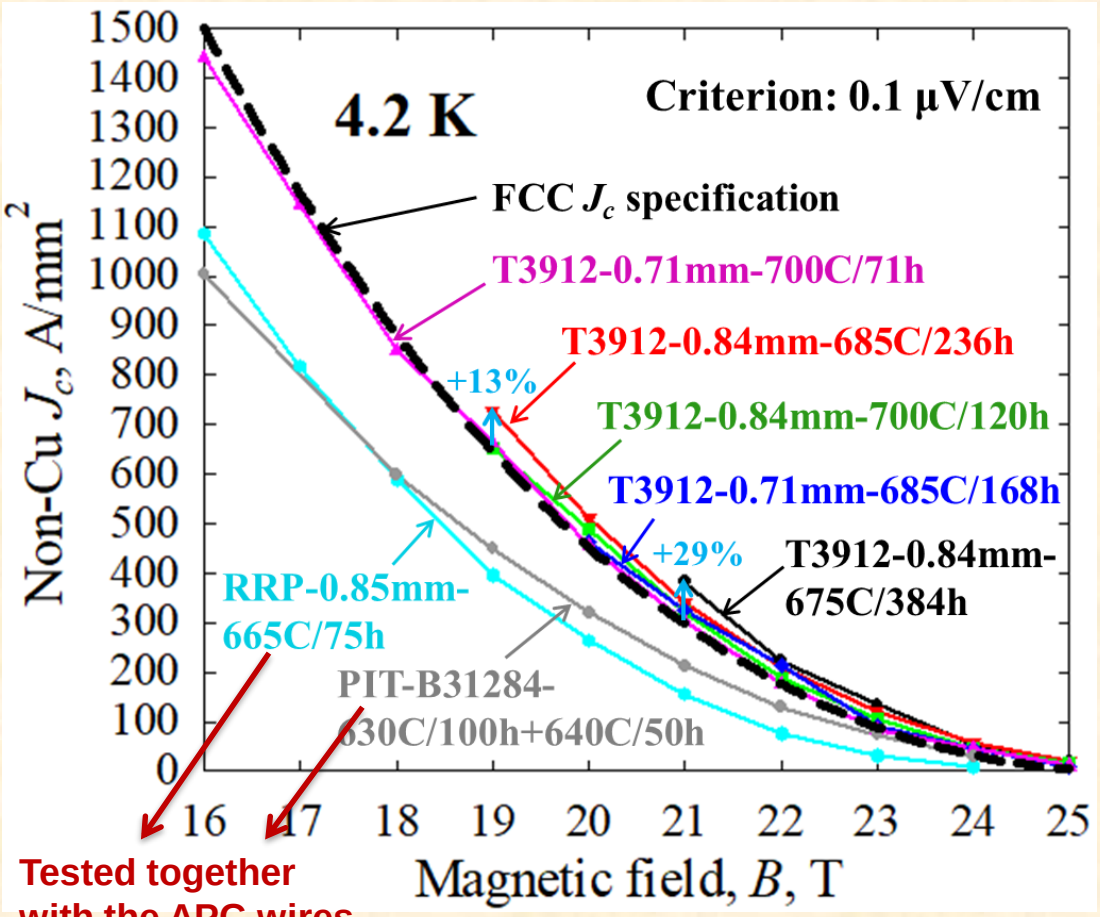
1st measurement by X. Xu at FNAL




Confirmation measurements by I. Pong at LBNL: EDS line scans



# Ta-doped APC wires have non-Cu $J_c$ above FCC SPEC




| Wire | Design | Composition |
|---|---|---|
| RRP-00076 | 108/127 | 1.5at.% Ti doped |
| PIT-B31284 | 192/217 | 7.5 wt.% Ta |
| APC-T3912 | 48/61 | 7.5% Ta, 1%Zr + O |

*Data provided by X. Xu, Fermilab*

**Observations**

1. Wires of 0.71 and 0.84mm have similar $J_c$s ($D_s$: 70 vs 83 μm).
2. Lower HT temperature leads to higher $J_c$ (700→ 685→ 675 C).
3. $Nb_3Sn$ record $J_c$ began to grow again after a 2-decade plateau.
4. Need HT optimization for RRR.
5. Need to reduce the filament size by making higher count restack.

**Tested by X. Xu and M. Sumption in a 31 T magnet at the NHMFL in January 2019.**
**Many thanks to ASC/FSU for the $I_c$ rig, PS, DAQ, program, etc., for the $I_c$ tests in NHMFL.**

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Courtesy X. Xu etal. 1. https://arxiv.org/abs/1903.08121

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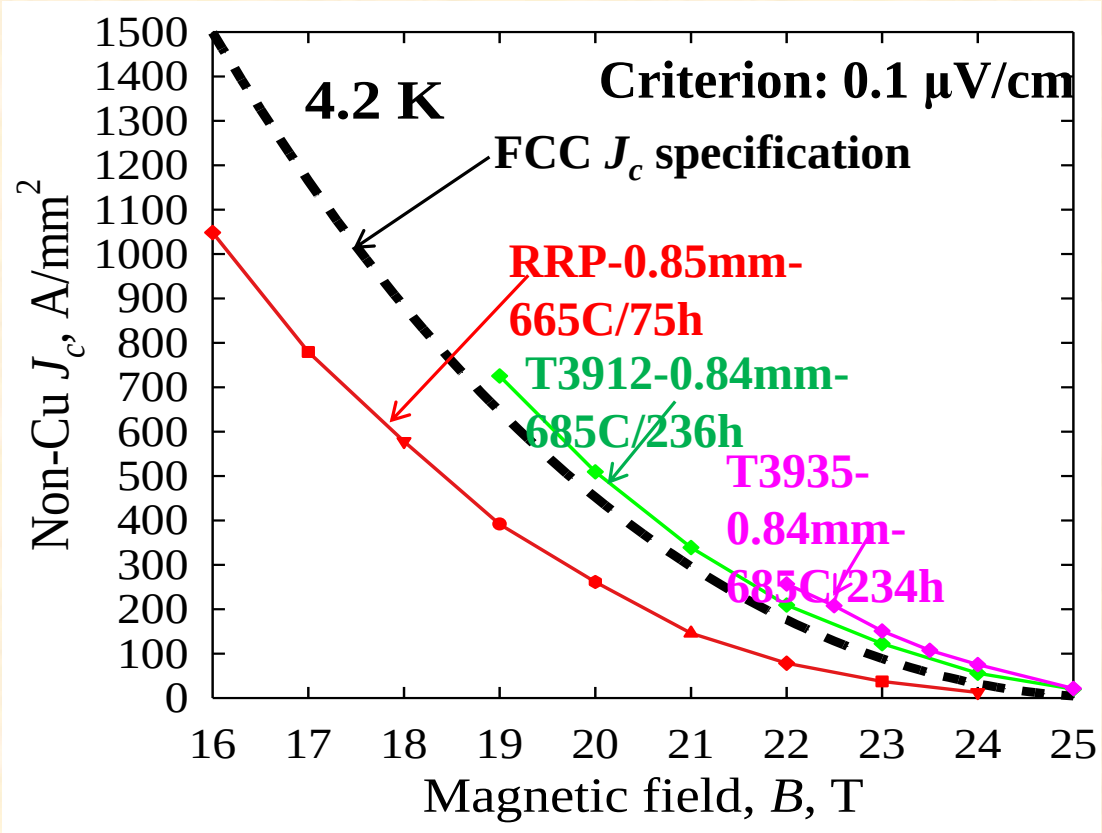
# Latest Ta-doped APC wire has non-Cu $J_c$ above FCC Spec

**A new wire (T3935) was made recently. Tested independently by S. Balachandran from ASC/NHMFL/FSU in April 2019.**

| Wire | Wire description | Tested |
|---|---|---|
| RRP | Standard RRP for HL-LHC | by FSU in Apr. |
| T3912 | 1at.%Zr + oxygen. But O is insufficient for some filaments. | by FNAL and OSU in Jan. |
| T3935 | 1at.%Zr + oxygen. Oxygen is sufficient for all filaments. | by FSU in Apr. |




*Data provided by X. Xu, Fermilab*

**Observations**

1. The recent T3935 has 15% higher Jc than previous T3912, perhaps due to more oxygen.
2. The Jc above FCC spec is verified by independent tests by FSU.
3. Need to make filaments smaller to make the wire stable in the lower field.

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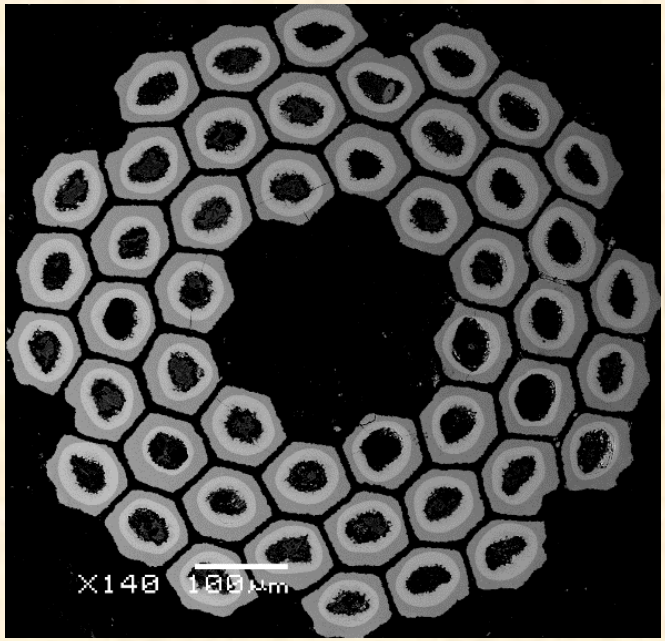
# Why high non-Cu $J_c$ in Ta doped APC wires

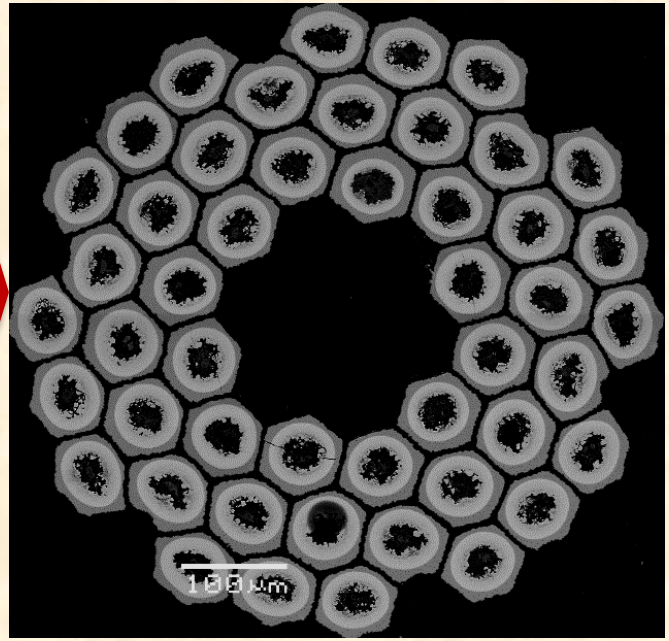
**Sept. 2018: T3882-0.84mm-675C/330h**




1040 A/mm$^2$ at 16T

| FG $Nb_3Sn$ % | Residual Nb% |
|---|---|
| 22% | 45% |

**Jan. 2019: T3912-0.71mm-700C/71h**




1500 A/mm$^2$at 16T

| FG $Nb_3Sn$ % | Residual Nb% |
|---|---|
| 32% | 33% |

**Development is still ongoing: further optimization of recipe.**

**The goal: similar to standard PIT wires.**

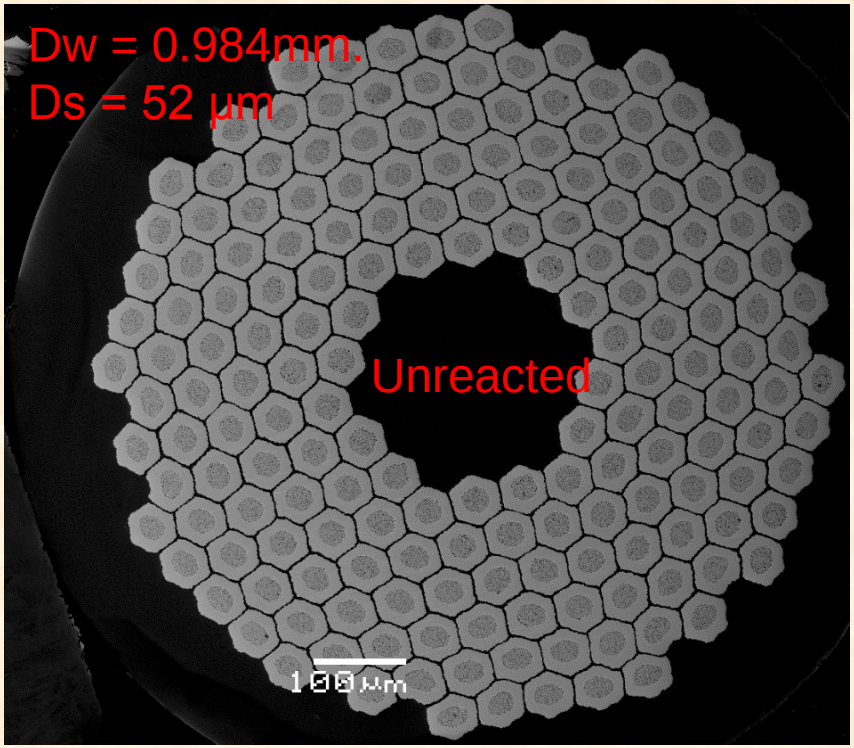
| FG $Nb_3Sn$ % | Residual Nb% |
|---|---|
| 40% | 25% |

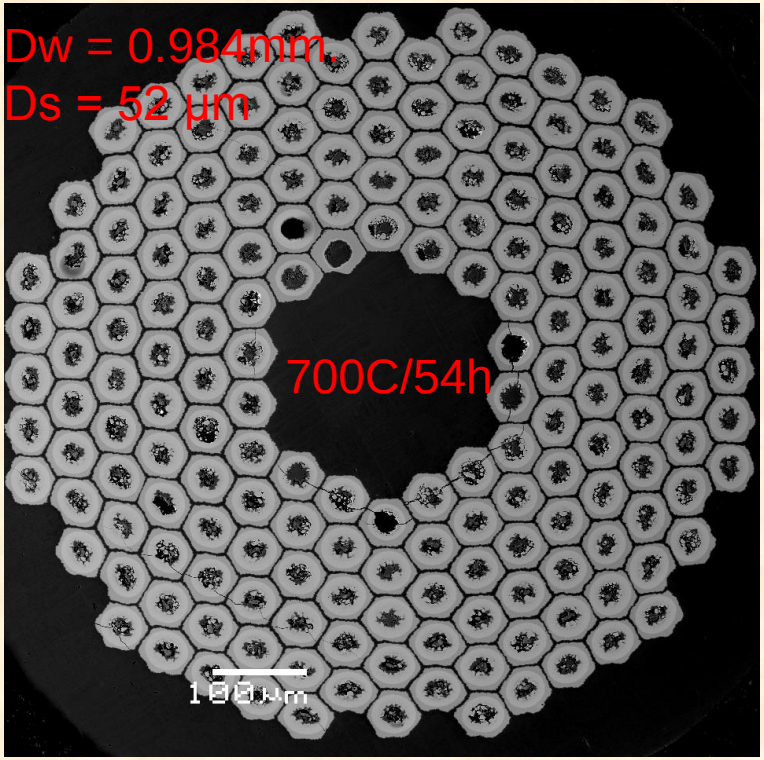
## Observations

- Compared with the $J_c$ obtained in T3882, the $J_c$s of T3912 are ~50% higher.
- This increase was due to higher A15 fraction, driven by improvement of wire recipe.
- $Nb_3Sn$ layer $J_c$ stayed similar, around 4700 A/mm$^2$ at 16T.
- T3912 still has too high Nb/Sn ratio and there is no enough Sn for a full reaction. It is improved in T3935, but the characterization is still going on.
- Other factors for $J_c$ improvement: Filament uniformity; Heat treatment optimization (lower HT temperature).

# Fabrication of 217-restack APC wires turned out good

217-pattern (180 filaments +19 Cu in the middle) restack wire was made and drawn down to 1.2 and1.0 mm diameters with filament size of 63 μm and 52 μm respectively.




- No breakage, about 100-200 meter of different diameter wires per billet.
- $J_c$ has not been measured yet, but SEM images shows promising.
- T3912 recipe was used here and will further be optimized based on the smaller filaments.

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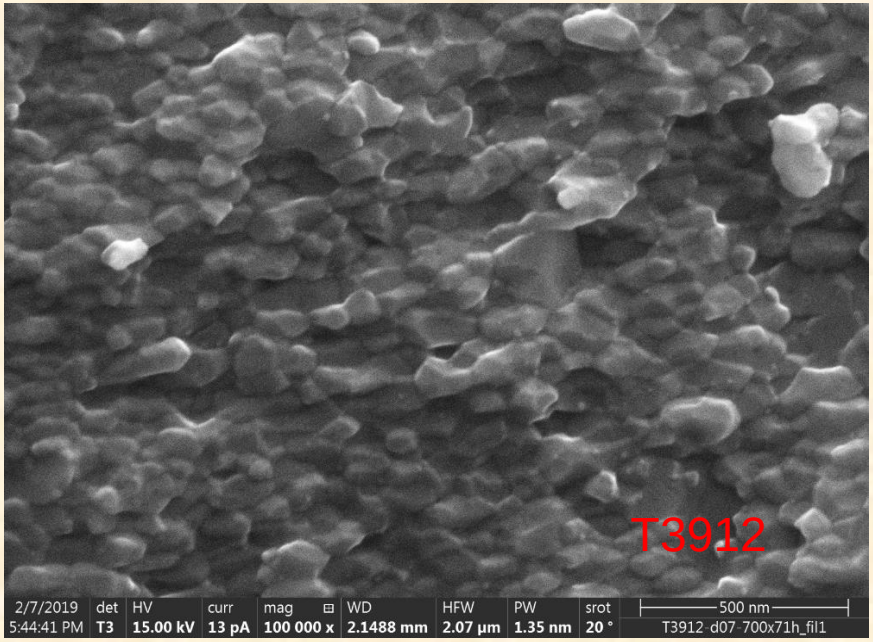
# Work related to Nb-Ta-Hf with Internal Oxidation

FSU group: Ta, Hf doped without internal oxidation.

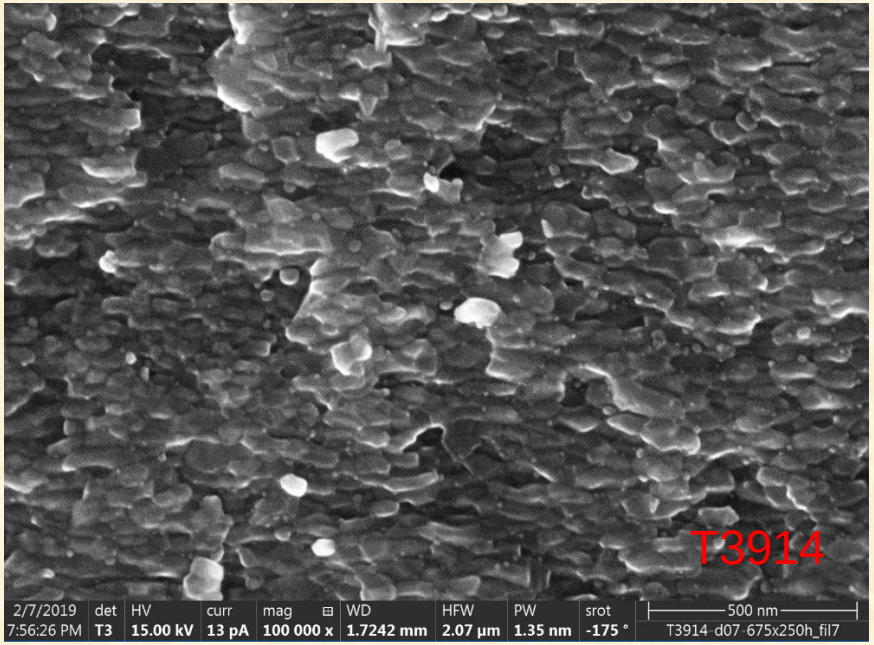
See Dr. S. Balachandran's talk next

Hf is a Hc2 enhancer as well as a prospective oxidizer

**Hyper Tech selected the 1 at% Hf, and made the Nb-Ta-Hf alloy into tubes and made a wire T3914 using internal oxidation.**




Champion wire with Nb-Ta-1Zr tube




Wire with Nb-Ta-2Hf tube

Ta-Hf additions also look promising and deserve more investigation with and without oxidation.

New SBIR Phase I Fund from DOE: DE-SC0019816

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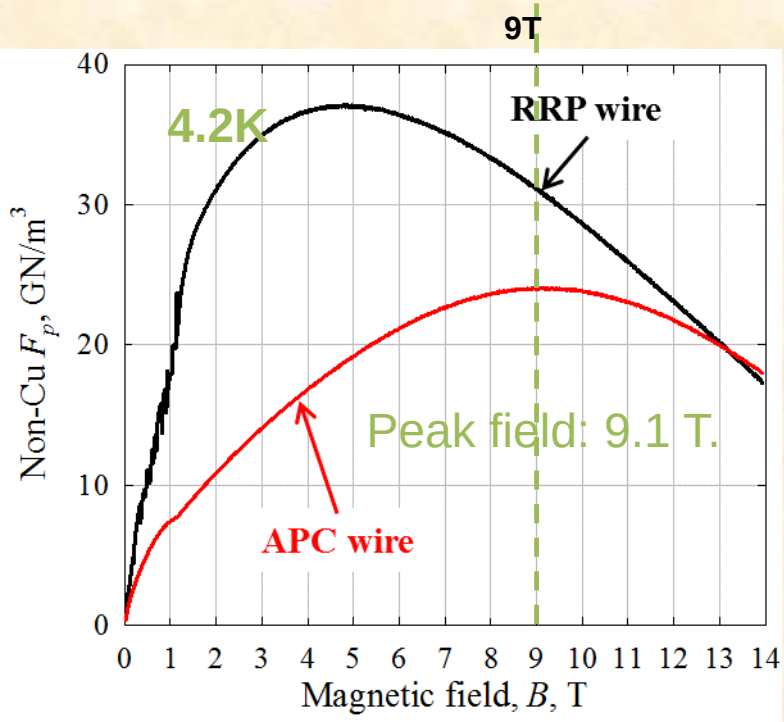
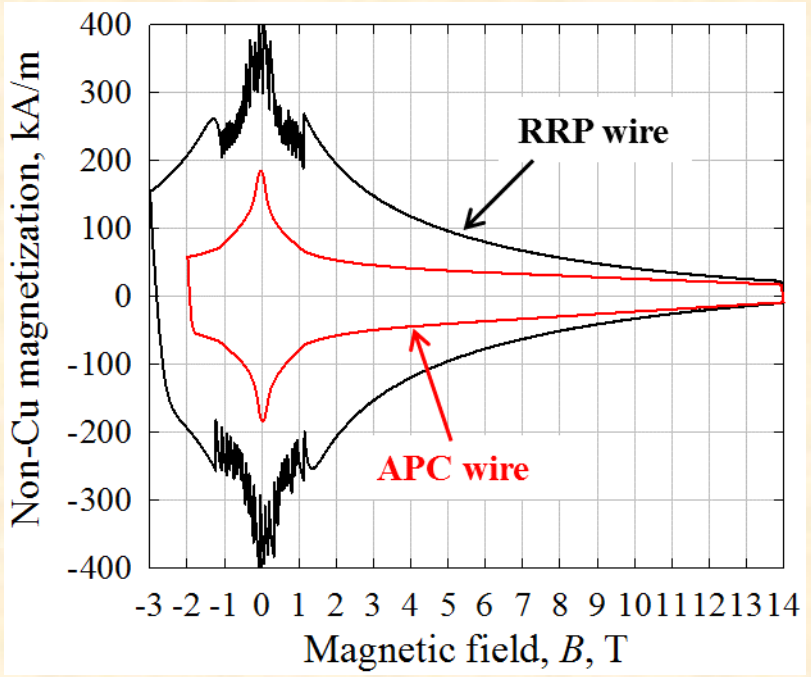
# Extra benefit of internally oxidized APC wires – flatter $J_c$-$B$ curve

Apart from the much higher $J_c$, the internally oxidized APC wires have an extra benefit: $ZrO_2$ or $HfO_2$ particles serve as point pinning centers, causing $F_p$-$B$ curve shift to higher fields.

An example: T3914 (Hf + O), reacted at 625C.

*Data provided by X. Xu, Fermilab*




The $F_p$-$B$ curve of the standard RRP wire peaks at ~4.9 T, while that of the T3914 wire peaks at **~9.1** T.

As a result, the $J_c$-$B$ curve of the APC wire is much flatter, causing much lower magnetization at 1-2 T. This reduces flux jumps, field errors, and a.c. losses.

Note: this APC layer has thin $Nb_3Sn$ layer due to insufficient reaction, causing low non-Cu $J_c$.

# Further Optimization Next

**These results of the prototype wires demonstrate improved $J_c$, but they are still far away from maturity. Much more work is required.**

(1) Further optimization in recipe ➔
- Higher $Nb_3Sn$ % ➔ higher $J_c$
- Higher wire quality ➔ higher RRR

(2) Further optimization in HT ➔
- Lower HT temperature ➔ higher $J_c$
- Optimized reaction time ➔ higher RRR

(3) 217-restack wires ➔ smaller $D_s$ ➔ better conductor stability.

(4) Other better designs, e.g., bundle-barrier (or other barrier) ➔ high RRR

(5) Better bonding, larger billet (2”), round filament ➔ cabling

(6) Other necessary tests, e.g., uniaxial tensile, transverse pressure, etc.

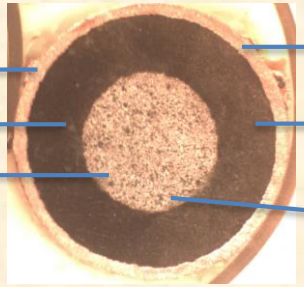
(7) Wire quality control: eddy current device to check the wire quality along the length..

# Fabrication of APC wires and their Price Projection

APC PIT wire

Purchase Materials (Nb-Ta-Zr tube, Cu tube, Sn/oxide/Cu powder)

Make Subelement (fill the tube and then draw)




Regular PIT wire

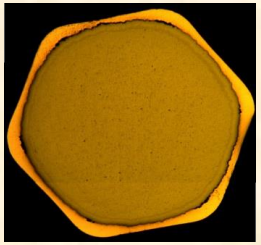
Purchase Materials (Nb-Ta tube, Cu tube, Jet milled and classified $NbSn_2$ or $Cu_6Sn_5$ powder)

Make Subelement (fill the tube and then draw)

RIT wire (RRP)

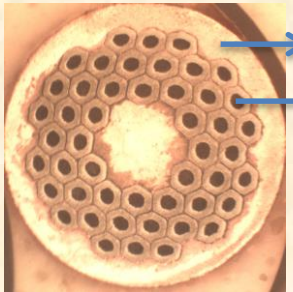
Purchase Materials (Nb rod or ingot, Cu tube, Sn rod)

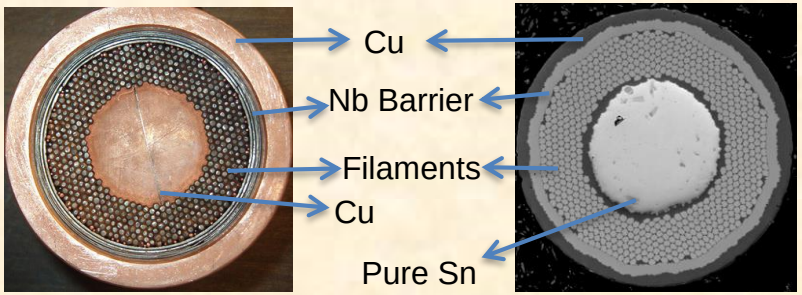
Make filament (stack the Nb rod in Cu tube and draw it down; or extrude and shape it to make better shapes)



Make Subelement (Cut the filaments and restack a few hundreds filaments around Cu filaments in a Cu can, EB weld the end, then extrude the billet down, gundrill the hole in the middle, insert Sn, then draw it to the size for restack)

Make restack (Cut Subelement, restack in multi, and draw it down)



# Fabrication of APC wires and their Price Projection

- Comparing to regular PIT process, APC PIT has similar procedure, but use much cheaper commercially available powder instead of costly intermetallic NbSn2 or Cu6Sn5 plus jet mill and classification.
- Comparing to RIT (RRP) process, APC PIT has much simpler process and avoid the cost of the various processes and also reduces the labor cost although the Nb alloy tube material used is a little expensive than the rod material, it will reduce if high quantities are ordered at one time.
- Rough estimation shows the APC wire price is comparable or even less than RIT wires (RRP).
- Very fast turnaround, considerably less in process time and inventory.

# Summary

1. Development of Ta doped ternary APC-PIT multi wires started in 2017 and great progress has been made.
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 present wires.
3. R&D in the past two years has led to significant improvement of wire recipe and wire quality. The non-Cu $J_c$s have broken the $Nb_3Sn$ $J_{c,non\text{-}Cu}$ record that stood for nearly two decades and have achieved the $J_{c,non\text{-}Cu}$ specification required by the Future Circular Collider (FCC),.
4. The $Nb_3Sn$ layer $J_c$ at 16 T is 4700A/mm$^2$ which is ~2.5 times of the present wires despite grain size not fully refined.
5. 217-restack wire has been made and draw down to about 1 mm with filament size of 52 μm.
6. While these wire properties have been obtained with Ta-Zr additions, Ta-Hf additions also look promising and deserve more investigation with and without oxidation.
7. 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!