# Development of a $(Nb,Ti)_3Sn$ multifilamentary wire with $ZrO_2$ APCs for high $J_c$, high $B_{c2}$, and low AC loss

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## Introduction

$Nb_3Sn$ performance improvement is needed for projects like the Future Circular Collider (FCC)

- Maximize $J_c$ at 16 T
- Maximize pinning force $F_p$ at high B

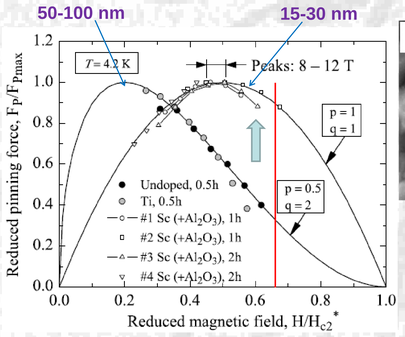
Refinement of grain size increases $F_{p,max}$

- Add $ZrO_2$ particles to prevent grain coarsening during heat treatment [1]

Next step is to produce a Ti-doped ternary wire to increase $B_{c2}$

**Table 1.** Current state of $Nb_3Sn$ strands from various production routes

| | Internal Sn, RRP | Tube | ITER | PIT | Bronze |
|---|---|---|---|---|---|
| 12 T Jc, A/mm2 | 2500-3000 | 2000-2500 | 1000-1200 | 2000-2500 | 600-800 |
| Stability | Low | medium | high | medium | high |
| Loss | High | medium | low | medium | low |



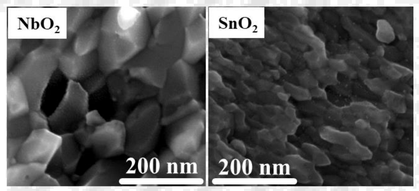
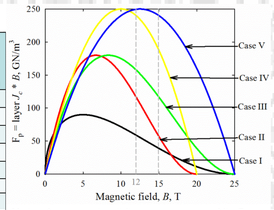




**Table 2.** "Naïve" look at the theoretical limits of $J_c$ in $Nb_3Sn$

| | | I. Present state-of-the-art RRP strands | II. The wire with $SnO_2$ - 625 C / 800h | III. Only improve $B_{irr}$ to 25 T by Ti doping, etc. | IV. Only refine the grain size to 25 nm | V. Both improve the $B_{irr}$ to 25 T and refine the grain size down to 25 nm |
|---|---|---|---|---|---|---|
| Grain size, nm | | 100 - 120 | 36 | 36 | 25 | 25 |
| $F_p$-B peak | | $0.2B_{irr}$ | $0.34B_{irr}$ | $0.34B_{irr}$ | $0.5B_{irr}$ | $0.5B_{irr}$ |
| $F_{p,max}$, GN/m³ | | ~90 | 180 | 180 | ~250 | ~250 |
| $B_{irr}$, T | | 25 | 20 | 25 | 20 | 25 |
| 12 T | Layer $J_c$, A/mm² | 5,000 | 9,600 | 16,400 | 20,000 | 20,800 |
| | Non-Cu $J_c$, A/mm² | 3,000 | 5,760 | 9,840 | 12,000 | 12,480 |
| | Engineering $J_c$, A/mm² | 1,600 | 3,050 | 5,200 | 6,360 | 6,600 |
| | $I_c$, A | 800 | 1,530 | 2,620 | 3,200 | 3,320 |
| 15 T | Layer $J_c$, A/mm² | 2,700 | 3,800 | 7,800 | 12,500 | 16,000 |
| | Non-Cu $J_c$, A/mm² | 1,600 | 2,280 | 4,680 | 7,500 | 9,600 |
| | Engineering $J_c$, A/mm² | 850 | 1,210 | 2,480 | 4,000 | 5,100 |
| | $I_c$, A | 430 | 610 | 1,250 | 2,000 | 2,560 |



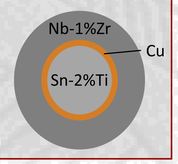

**Note:** Assumes in all five cases: same $Nb_3Sn$ area fraction with state of the art RRP strands, 60% $Nb_3Sn$ area fraction in subelement, non-Cu fraction of 0.53, and wire diameter of 0.8 mm.

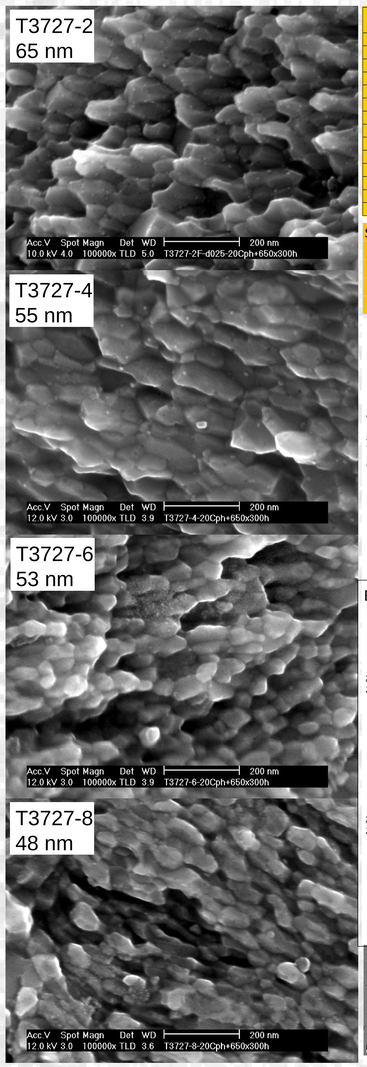
## Externally-Oxidized Subelement

We started with a proof-of-concept ternary strand consisting of a Cu-Sn-Ti rod inside a Nb-1%Zr tube. The wires were heat treated in a vacuum-sealed quartz tube containing varying amounts of CuO pellets.

Observations:

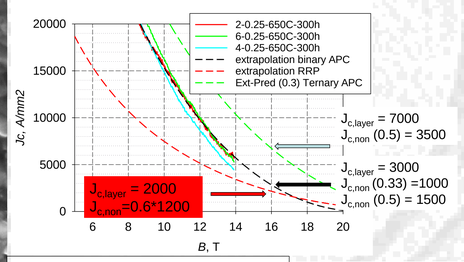
- Grain refinement to ~50 nm
- Ti incorporation in $Nb_3Sn$ layer
- Improvement of $J_c$ (calculated from PPMS M-H curve)

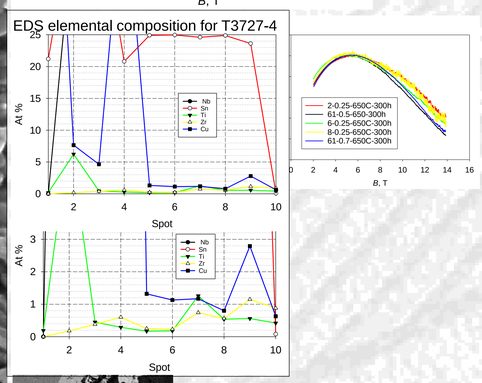



| Sample Number | CuO content (mg, ±0.1) | Heat treatment |
|---|---|---|
| 1 | 1.6 | 20 C/h + 700Cx100h |
| 2 | 1.6 | 20 C/h + 650Cx300h |
| 3 | 2.6 | 20 C/h + 700Cx100h |
| 4 | 2.3 | 20 C/h + 650Cx300h |
| 5 | 5.1 | 20 C/h + 700Cx100h |
| 6 | 4.2 | 20 C/h + 650Cx300h |
| 7 | 9.0 | 20 C/h + 700Cx100h |
| 8 | 9.1 | 20 C/h + 650Cx300h |
| 9 | 12.1 | 20 C/h + 700Cx100h |
| 10 | 11.9 | 20 C/h + 650Cx300h |
| 11 | 17.4 | 20 C/h + 700Cx100h |
| 12 | 17.5 | 20 C/h + 650Cx300h |
| 13 | 31.0 | 20 C/h + 700Cx100h |
| 14 | 30.4 | 20 C/h + 650Cx300h |

| Sample | Grain size (nm) | Ave Ti % | Bc2 (T) | bmax | bmax/bc2 |
|---|---|---|---|---|---|
| 2 | 65 | 1.9 | 22.6 | 5.6 | 0.247345 |
| 4 | 55 | 1.6 | 20.3 | 5.5 | 0.247345 |
| 6 | 53 | 1.1 | 21.3 | 5 | 0.234858 |
| 8 | 48 | 0.25 | 21.7 | 5.25 | 0.242308 |

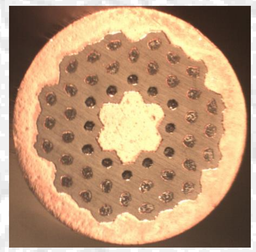


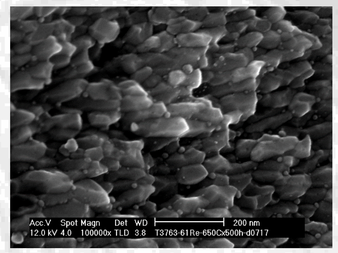



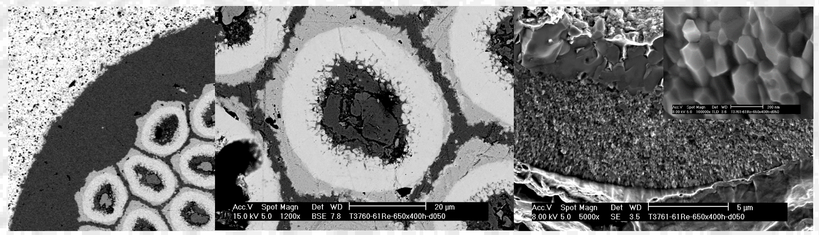

## Initial Multifilament Development

Trying out several designs:

- T3763: ternary hybrid wire
  - Inner ring of filaments contain $Sn/SnO_2$ powder
  - Remainder contain Sn-2%Ti rods
- T3761: Densely packed $Sn/SnO_2$ powder in Cu tube in Nb-1%Zr tube
- T3775: Another externally oxidized subelement containing 6%Ti
- Additional wire architectures are currently in production






## Conclusions

- We have demonstrated grain refinement by a factor of 3 and a doubling of 12 T Jc in monofilaments
- Internal oxidation can be used in many Nb3Sn strand types, including Tube (demonstrated) PIT (proposed), RRP/RIT (proposed) etc.
- Ternary strands under development: Possible to inject Ti into internally oxidized Nb3Sn layers
- Sn contents remain high with Ti additions, but Bc2 increase not yet seen – may need to add more Ti
- Multifilamentary strands have been demonstrated with refined grains and enhanced Jc values.
- New designs which have push non-Cu fraction to above 50% and reaction fraction to above 30% are demonstrated (measurements underway) These need (1) To be optimized, and (2) To be demonstrated for a ternary alloy with the ternary alloy Bc2
- This route is very promising for future Nb3Sn development

### References

[1] Xu, X., Sumption, M. and Peng, X. (2015). Internally Oxidized Nb3Sn Strands with Fine Grain Size and High Critical Current Density. Advanced Materials, 27(8), pp.1346-1350.

[2] Xu, X., Sumption, M., Peng, X. and Collings, E. (2014). Refinement of Nb3Sn grain size by the generation of ZrO2 precipitates in Nb3Sn wires. Applied Physics Letters, 104(8), p.082602.

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