# High-field $Nb_3Sn$ conductor for future accelerator magnets

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For the realization of the future-generation accelerators, the Particle Physics Project Prioritization Panel (P5) supported the research and development of high field conductors with enhanced performance beyond the ~2012 state-of-the-art strands [1]. Extensive R&D is required to make high-field accelerator magnets for a very high-energy proton-proton collider feasible at a reasonable cost. Considering the high cost of high $T_c$ superconductors, continuing to improve the high-field performance of $Nb_3Sn$ conductors appears still a very viable route. The target conductor specifications for the Future Circular Collider are non-Cu critical current density $J_c$ of 1500 A/mm$^2$ at 16 T and 4.2 K, RRR of the Cu stabilizer over 100 and strand diameter of less than 1 mm. The first challenging target is to achieve the $J_c$.

In today's $Nb_3Sn$ grain boundaries are understood to be the principal vortex pinning mechanism and limiting $Nb_3Sn$ grain growth, largely by lowering the heat treatment temperature, has been the most effective way to increase the in-field $J_c$ performance. Today's conductors typically have 100-150 nm diameter grains. In the last few years the introduction of $ZrO_2$ artificial pinning centers (by internal oxidation of a Nb-Zr alloy with $SnO_2$) has been demonstrated to be a valuable route to shift the pinning force maximum toward higher field with a consequent improvement of the intermediate-field $J_c$ [2], [3], and perhaps most importantly showing that there are still large gains to be made in the $J_c$ performance of $Nb_3Sn$. By performing a systematic investigation of potential new base alloys for $Nb_3Sn$, we have determined that Hf can effectively improve the critical current density in $Nb_3Sn$ wires, which also contain the $H_{Irr}$ enhancing Ta-doping. In a Nb-Ta-Hf monofilament wire we were able to obtain a layer-$J_c$ at 16 T, 4.2 K of 3710 A/mm$^2$, a value that if reproduced in a RRP design would lead to an non-Cu-$J_c$ of 2230 A/mm$^2$, exceeding FCC specs by almost 50%.[4] We found that by incorporating Hf we were able to significantly increase the temperature at which the pure Nb or Nb4at%Ta in today's conductors recrystallizes, significantly refining the $Nb_3Sn$ size to ~50-70 nm and increasing the vortex pinning strength that underlies the greatly enhanced $J_c$. Independent of this $Nb_3Sn$ grain size refinement, internal oxidation to make $HfO_2$ nanoparticles may also increase vortex pinning, rather similar to what occurs when Nb1Zr alloy is used.

In short, driven by the demands of a 100 TeV collider, two new routes to higher $J_c$ have been developed:

1. Internal oxidation that both limits $Nb_3Sn$ grain size and adds additional or artificial (APC) insulating oxide pinning centers
2. Inhibition of the recrystallization of the Nb alloy during the $Nb_3Sn$ reaction so as to generate many more $Nb_3Sn$ nuclei in the reaction.

To determine the best alloy for the fabrication of commercial $Nb_3Sn$ conductors for the next generation of accelerator magnets several key issues have to be addressed:

- High quality demonstration alloys must be fabricated and fully characterized
- The wire fabricability must be determined for different wire architectures
- The cabling performance and mechanical properties need to be determined
- The heat treatment schedule must be optimized to maximize $J_c$ in the 16-20 T range.

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Our laboratory still has the wire fabrication equipment used to understand and optimize Nb-Ti for the SSC [5] and later for the LHC. We can apply it now to the development of new Nb alloys for $Nb_3Sn$ optimization. We do note that industrial scale manufacture of the Nb alloys is needed and that ATI and H.C. Starck have been very collaborative so far in making NbTaHf alloys for us.


[1] Particle Physics Project Prioritization Panel, “Building for Discovery - Strategic Plan for U.S. Particle Physics in the Global Context,” 2014. https://www.usparticlephysics.org/wp-content/uploads/2018/03/FINAL_P5_Report_053014.pdf (accessed Aug. 31, 2020).

[2] X. Xu, M. D. Sumption, and X. Peng, “Internally Oxidized $Nb_3Sn$ Strands with Fine Grain Size and High Critical Current Density,” *Adv. Mater.*, vol. 27, no. 8, pp. 1346–1350, Feb. 2015, doi: 10.1002/adma.201404335.

[3] L. R. Motowidlo, P. J. Lee, C. Tarantini, S. Balachandran, A. K. Ghosh, and D. C. Larbalestier, “An intermetallic powder-in-tube approach to increased flux-pinning in $Nb_3Sn$ by internal oxidation of Zr,” *Supercond. Sci. Technol.*, vol. 31, no. 1, p. 014002, Jan. 2018, doi: 10.1088/1361-6668/aa980f.

[4] S. Balachandran *et al.*, “Beneficial influence of Hf and Zr additions to Nb4at%Ta on the vortex pinning of $Nb_3Sn$ with and without an O source,” *Supercond. Sci. Technol.*, vol. 32, no. 4, p. 044006, Apr. 2019, doi: 10.1088/1361-6668/aaff02.

[5] P. J. Lee and D. C. Larbalestier, “Determination of the flux pinning force of α-Ti ribbons in Nb46.5wt%Ti produced by heat treatments of varying temperature, duration and frequency,” *J. Mater. Sci.*, vol. 23, no. 11, pp. 3951–3957, Nov. 1988, doi: 10.1007/BF01106819.



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