Changes to heat-treatment of LHC particle-accelerator Nb_3Sn magnets proposed for optimal results

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Introduction – Strain Irreversibility Cliff in Nb_3Sn wires and its challenges

Systematic studies of axial-strain properties of Nb_3Sn superconducting wires made by the restacked-rod process (RRP®) enabled us to discover the *strain irreversibility cliff* (SIC) [1, 2], an abrupt change of the intrinsic irreversible strain limit $\varepsilon_{irr,0}$ as a function of heat-treatment (HT) temperature θ for forming the Nb_3Sn phase. The SIC imposes certain restrictions on HT that are conflicting with those for maintaining the conductor's residual resistivity ratio (*RRR*) above a certain value that ensures stability of magnets against quenching. Hence, SIC poses a real challenge for choosing suitable heat-treatment conditions that can optimize the wire's transport, strain, and thermal properties all at once, especially for large, wind and react, magnet systems.

Experimental – Measurements of $\varepsilon_{irr,0}$ and *RRR* dependences on θ

This work combined studies of strain and *RRR* properties, in close collaboration of ASC-NHMFL, University of Colorado at Boulder, and NIST. We investigated how HT temperature θ affects critical-current I_c vs. axial strain, $\varepsilon_{irr,0}$ (and SIC), and *RRR* of Nb_3Sn RRP conductors, and defined the range of θ that is suitable to fulfil the competing requirements on multiple parameters for a given Nb_3Sn RRP conductor design. Temperature θ was varied widely, from 599 to 752 °C, for a dwell time at θ maintained constant at 48 hours.

Results and Discussion

The study led us to introduce an electro-mechanical stability (EMS) criterion that takes into account both $\varepsilon_{irr,0}$ and *RRR* requirements. It is a valuable tool to inspect Nb_3Sn wires *before* their usage in magnets to avoid wasting valuable funds. When applied to RRP standard-Sn Nb_3Sn wires, the EMS criterion requires a strikingly narrow HT window that is impractical, especially for massive magnets. In contrast, reduced-Sn wires offer a significantly wider choice of θ, not only for ensuring that $\varepsilon_{irr,0}$ is located at the SIC plateau while *RRR* ≥ 150 (minimum value required for the high-luminosity upgrade of the Large Hadron Collider—HL-LHC), but also for containing the strain-induced irreversible degradation of I_c beyond $\varepsilon_{irr,0}$, as shown in Fig. 1 for HTs varying from 656 to 695 °C.

The HL-LHC project will use reduced-Sn RRP Nb_3Sn wires, of the same design as the wire presented in Fig. 1. However, HL-LHC current plan is to conduct HTs of dipole and quadrupole magnets at 665 °C. Based on our results, we propose that θ for HL-LHC magnets be in the range of 680 to 695 °C instead [2], to ensure that strain-induced irreversible degradation of I_c, if it occurs during magnet operations, remains limited (Fig. 1).

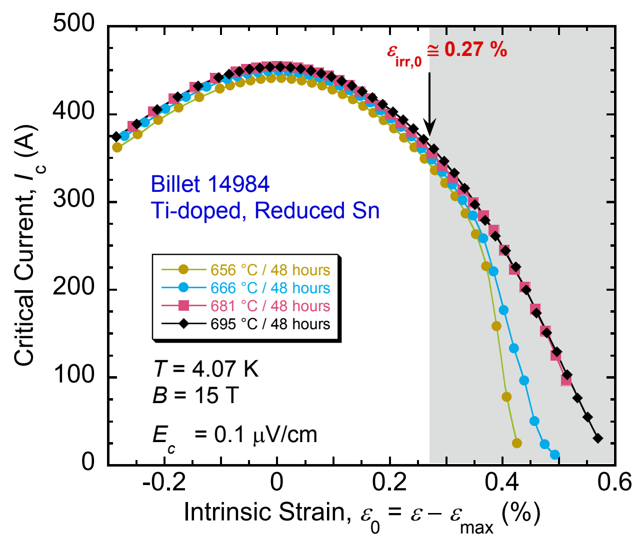

Fig. 1: Comparisons at 4.07 K and 15 T of $I_c(\varepsilon_0)$ curves for RRP reduced-Sn Nb_3Sn samples heat-treated for 48 hours at 656, 666, 681, and 695 °C. Samples reacted at 666–695 °C have practically the same I_c values for any given intrinsic strain ε_0, even beyond $\varepsilon_{irr,0}$, until the sample reacted at 666 °C starts showing a severe drop of I_c. This drop is more pronounced for the sample reacted at 656 °C, indicating its gradual evolution with lowering temperature θ. The area shaded in gray on the right corresponds to the irreversible strain regime ($\varepsilon_0 > \varepsilon_{irr,0}$).

Acknowledgements

This work was supported by the US Department of Energy, Office of High Energy Physics, Grants DE-SC0010690, DE-SC0017657, and partially through the U.S. LHC Accelerator Research Program (LARP). A portion of this work was also supported by the Lawrence Berkeley National Laboratory (LBNL), subcontract No. 7216283 and by the State of Florida.

The National High Magnetic Field Laboratory is supported by the National Science Foundation through NSF/DMR-1157490/1644779 and the State of Florida.

References

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