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Viewpoint

More time for Nb_3Sn magnet conductors

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This is a viewpoint on the letter by X Xu *et al* (2018 *Supercond. Sci. Technol.* 31 03LT02).

The ability of a superconducting wire to tolerate thermal disturbances increases in direct proportion to its heat capacity C. In view of the recent letter by Xu *et al* [1], addition of even modest amounts of materials with high heat capacity to a prototype Nb_3Sn magnet conductor significantly improves the response of the conductor to instabilities. This success is meaningful because their key modification, addition of GdO_3 powder, was incorporated with a modern, high-current conductor design that can be scaled to production. The design of Xu *et al* extends earlier work by Keilin *et al* [2] for additions of PrB_6 in bronze-route wire, so other materials and design options are available. When taken together with other advances that affect the flux-pinning mechanism [3, 4], the possibility of new high-current, disturbance-tolerant conductors could extend Nb_3Sn magnet technology toward new possibilities and higher fields.

Nb_3Sn magnet conductors have been essential for magnet technology above 10 T field for decades. The present status of production is defined by the ~600 tons of conductors procured for ITER [5], ~30 tons for the High-Luminosity Upgrade of the Large Hadron Collider (HL-LHC) at CERN [6], and several tons delivered annually for solenoids. Medical imaging magnets have not taken a serious bite into Nb_3Sn production [7], which makes large science projects the present driver of conductor technology. The HL-LHC conductors [8, 9] have roots in the development period between 1995–2005, when the critical current density within the non-copper wire area J_c was pushed from ~2000 to above 3000 A mm^{-2} at 12 T and 4.2 K and the manufacturing cost was driven down. An additional decade was required to understand different performance trade-offs related to magnet technology and optimize production [8]. The present conductor is routinely capable of J_c above 1000 A mm^{-2} at 16 T, 4.2 K, and, if pushed aggressively, can achieve J_c close to 1400 A mm^{-2} at 16 T and 4.2 K [10], which is just shy of targeted needs for possible future particle accelerators [11]. HL-LHC conductors are also made with very high yield in continuous lengths, typically 2–3 km and sometimes >9 km. Yield is an important benchmark, because it affects the cost of the conductor doubly, first by increasing the price from the supplier, and second by increasing the downstream losses for cabling remnants.

Research toward future accelerator magnets often defines the technical challenges at the conductor level. Since high-current density in Nb_3Sn conductors cannot, so far, be maintained down to an effective filament diameter where magnetization instabilities can be suppressed [8], magnets are wound with conductors that experience instabilities at low fields. These instabilities can trigger quenches of the magnet. A key factor in the decision [9] to use a conductor with 55 μm sub-elements (the conductor dimension which determines effective filament diameter) was the observation that the amplitude of flux jumps was greatly reduced when at 1.9 K [12]. Magnet tests [13] confirmed the reduction of risk. The magnetization data presented by Bordini *et al* in [12] is very similar to that presented by Xu *et al* in their letter, although Xu *et al* carried out their experiment at 4.2 K. Evidently, the high-C additive absorbs the energy released by local instabilities faster than the time required to expand the instability across many sub-elements. Since extraction of heat to superfluid helium has a similar effect, and since accelerator magnets at very high field will likely be operated with cooling by superfluid He, it is worth some thought whether the conductor area devoted to a high-C additive will be effectively used. Tests of wires with high-C additives at 1.9 K will be illuminating.

The larger impact of the advance by Xu *et al* is to reduce magnet training. Training of Nb_3Sn accelerator magnets is a rather lengthy, helium-intensive, and expensive process, and one that has been almost impossible to predict. Generally >20 quenches are required to reach acceptance criteria for Nb_3Sn accelerator magnets [14, 15], where typically the slope of improvement in maximum field with quench number is weak after the first five to ten quenches. Yet, acoustic analyses [16] identify a torrent of pre-cursor emissions that have been attributed to a variety of sources, including motion of coil turns, cracking of epoxy, and relaxation of the magnet support structure. Accumulation of energy from many such events is clearly occurring, which couples to an initial temperature rise ahead of the quench signal. Adding heat capacity should allow additional accumulation to occur and make the training process more efficient. Xu *et al* show a factor of three higher minimum quench energy than conductors without a high-C additive, so the effects on training could be profound. They also propose further tailoring of the conductor design to optimize this advantage. As further progress is made in developing the mechanical structure of accelerator magnets, strands with added heat capacity should also allow operating margins to squeeze closer to short-sample limits.

The longer term impact of the advance by Xu *et al* is more difficult to evaluate. The development of new production Nb_3Sn conductors with high-C additives will require a sustained investment by a major manufacturer with the backing of a large science organization. The development process must not only achieve the high standards of the existing HL-LHC conductor and its logical innovations, but it has to also provide sufficient extra benefits to pay back the investment above. Reduced magnet training is one potential benefit that could sway a decision to invest in high-C conductor development, so it is imperative for magnet development programs to incorporate high-C wire into cable and coil tests to fully understand the potential benefits as soon as possible.

But the time window for these activities may be less than a decade. Model accelerator magnets wound from $REBa_2Cu_3O_{7-x}$ (RE = rare earth element, REBCO), $Bi_2Sr_2CaCu_2O_{10+x}$ (Bi-2212), and $Bi_2Sr_2Ca_2Cu_3O_{14+x}$ (Bi-2223) are progressing quickly on this time scale [17–20], where the higher temperature margin of these materials provides, in principle, 'built in' stability and mitigation of training. One result [20] identifies a Bi-2212 magnet that achieves highest field upon first quench and retains this field after thermal cycling. Magnet programs are carefully monitoring conductor cost and manufacturing scale in contemplation of a paradigm shift [21]. This dynamic situation will continue to evolve as new developments in magnets emerge, wherein future achievements like that by Xu *et al* will be needed to keep emphasis on Nb_3Sn.

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