The Need for Ongoing Advances in Superconducting Materials for Particle Accelerators

M.D. Sumption (Sumption.3@osu.edu)
CSMM, MSE, The Ohio State University
Columbus, OH 43210

Introduction and Motivation

The high energy frontier is one of the key areas to explore for High Energy Physics [1]. There are a number of novel methods that are being developed which may, at some point, allow much more compact exploration of this area, including new forms of particle acceleration. However, at present the surest route to explore this frontier is advanced proton colliders, e.g., the proposed FCC. These accelerators require beam steering magnets which use superconducting wire. The next generation of accelerators at the energy frontier are considered beyond the reach of NbTi, for which reason Nb3Sn and the HTS materials YBCO coated conductors and Bi:2212 strands are considered the most viable candidates. Nb3Sn has been around and in use for some 50 years, and has been considered mature. Even YBCO and Bi:2212, while much younger, are considered more or less "mature" by some, with further development to be done in terms of engineering and test.

It is, however, important to continue to invest in the development of superconducting materials (wire) as key enabling materials, whose properties have huge leverage on the final costs and capabilities of the accelerators they inhabit. While materials development for its own sake is of no use to DOE-HEP, it is important to continue investing at an appropriate level in conductors, both those considered "mature", and those that are not ready yet for prime time. This is because at both ends of the spectrum, this important research is not being undertaken with a long view by anyone else. For conductors like Nb3Sn, only programs with a direct for very high field magnets (< 15 T) are appropriate places for development, and these are rare. For HTS and even now pnictide conductors, the initial excitement and early development has pushed them only so far. The HTS conductors are technically viable, but not yet affordable. The pnictide conductors are in a no-man's land, where they are not yet quite technically viable, but hold promise as much more affordable versions of HTS conductors.

Support for conductor development is important, but must be in balance with all other elements of the portfolio, and the program should take the long view. Below the conductors are considered in turn.

Nb3Sn Conductors

While Nb3Sn conductors had been presumed to be optimized over the previous 50 years, a 2014 work showed that layer J_c values could be doubled using an internal oxidation route [3]. Further work has shown this in more technically viable conductors [4] -[6], and then as ternaries [6]. An alternative mode is also being explore which uses Hf to refine the grains with no internal oxidation [7], which is also quite promising. Further improvements are being made [8][9]. Such efforts may be very important for allowing vital improvements in conductor performance just at the point where future colliders need them, at reasonable cost.

HTS: YBCO Coated Conductors and Bi:2212

YBCO conductors have gone from discovery to technical viable conductors. They now are available in various cable forms, including CORC [10-11], Roebel [12-14], and Twist Stack [15]. Very impressive work continues in coated conductor development [16][17], although it is unfortunate

that none of it seems to be able to address the conductors most pressing issue of cost. Nevertheless, every jump in performance does reduce the effective cost of the conductor, and further work on making this technically viable conductor actually cost-effectively useful for a machine is important.

Bi:2212 Conductors are also seeing continuing improvements [18]. These conductors, while not having the same scale of production and operating infrastructure as YBCO conductors at this point, are also technically viable for accelerator applications [19], and have the benefit that they do not require the same level of infrastructure. They in some ways represent a balance to the risks of long term HTS coated conductor availability.

Pnictide and Other Conductors

The new pnictide conductors hold exciting promise for allowing high field operation like HTS, but at costs closer to that of LTS [20]-[22]. However, these conductors certainly fall in the category of not-ready for prime time. In fact, the jury is out on whether these materials (with many different classes and materials opportunities/ limitations) will ever be suitable, for instance if the grain boundary problems are as limiting and pernicious as for HTS. But, of course, both YBCO and Bi:2212 fell into this category before the advent of the coated conductor and melt growth processing approaches, respectively. Excellent work is ongoing, but some level of continued exploration is important for these materials as well.

Summary

The relatively long frame that has been required for useful superconducting "conductors" is unfortunate, but such time scales are in fact mirrored across many classes of materials, from LEDs to structural composites, and merely reminds us of the need to continue to invest at some level on an ongoing basis for the materials which have so much impact on accelerator cost and performance.

References

1. "High Energy Colliders", Report of the Particle Physics Project Prioritization Panel (P5), May 2014, p. 43
2. X. Wang, S. A. Gourlay, and S. O. Prestemon, "Dipole Magnets above 20 Tesla: Research Needs for a Path via High-Temperature Superconducting REBCO Conductors", *Instruments* 2019, 3(4), 62; https://doi.org/10.3390/instruments3040062
3. X. Xu, M.D. Sumption, X. Peng, E.W. Collings, "Refinement of Nb3Sn grain size by the generation of ZrO2 precipitates in Nb3Sn wires", Appl. Phys. Lett. 104 (2014) 082602.
4. X. Xu, M.D. Sumption, X. Peng, "Internally Oxidized Nb3Sn Strands with Fine Grain Size and High Critical Current Density", Adv. Mater. 27 (2015) 1346-50.
5. 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 Nb3Sn by internal oxidation of Zr", 31 (2017) 014002.
6. X. Xu, J Rochester, X Peng, M Sumption and M Tomsic, "Ternary Nb3Sn superconductors with artificial pinning centers and high upper critical fields", Supercond. Sci. Technol. 32 (2019) 02LT01
7. S. Balachandran, C. Tarantini, P.J. Lee, F. Kametani, Y. Su, B. Walker, W.L. Starch, D.C. Larbalestier, "Beneficial influence of Hf and Zr additions to Nb4at%Ta on the vortex pinning of Nb3Sn with and without an O source", Supercond. Sci. Technol. 32 (2019) 044006.

8. X. Xu, X. Peng, J. Rochester, J-Y Lee, M. Sumption, “High critical current density in internally-oxidized Nb3Sn superconductors and its origin”, *Scripta Materialia* 186 (2020) 317–320
9. X. Xu, M.D. Sumption, J. Lee, J. Rochester, X. Peng, “Persistent compositions of non-stoichiometric compounds with low bulk diffusivity: A theory and application to Nb3Sn superconductors”, Journal of Alloys and Compounds 845 (2020) 156182
10. D.C. van der Laan, X.F. Lu, and L.F. Goodrich, “Compact GdBa2Cu3O7-δ Coated Conductor Cables for Electric Power Transmission and Magnet Applications”, Supercond. Sci. Technol. 24 042001 (6 pp) (2011) doi:10.1088/0953-2048/24/4/042001
11. D.C van der Laan, P.D. Noyes, G.E. Miller, H.W. Weijers and G.P. Willering, “Characterization of a High-Temperature Superconducting Conductor on Round Core Cables in Magnetic Fields up to 20 T”, Supercond. Sci. Technol. 26 045005 (9 pp) (2013)
12. W. Goldacker, R. Nast, G. Kotzyba, S.I. Schlachter, A. Frank, B. Ringsdorf, C. Schmidt, and P. Komarek, “High Current DyBCO-ROEBEL Assembled Coated Conductor (RACC)”, J. Phys. Conf. Ser. 43 901-904 (2006)
13. R.A. Badcock, N.J. Long, M. Mulholland, S. Hellmann, A. Wright, and K.A. Hamilton, “Progress in the Manufacture of Long Length YBCO Roebel Cables”, IEEE Trans. Appl. Supercond. 19 3244-3247 (2009)
14. N.J. Long, R.A. Badcock, K. Hamilton, A. Wright, Z. Jiang, and L. S. Lakshmi, Development of YBCO Roebel Cables for High Current Transport and Low AC Loss Applications”, Journal of Physics: Conf. Ser. 234 022021 (8 pp) (2010)
15. M. Takayasu, F.J. Mangiarotti, L. Chiesa, L. Bromberg and J.V. Minervini, “Conductor Characterization of YBCO Twisted Stacked-Tape Cables”, IEEE Trans. Appl. Supercond. 23 4800104 (4 pp) (2013)
16. R. Pratap, G. Majkic, E. Galstyan, G. Mohanasundaram, S. Chakradhar and V. Selvamanickam, "Growth of High-Performance Thick Film REBCO Tapes Using Advanced MOCVD," in IEEE Transactions on Applied Superconductivity, vol. 29, no. 5, pp. 1-5, Aug. 2019, Art no. 6600905, doi: 10.1109/TASC.2019.2899244.
17. G. Majkic, R Pratap, M. Paidpilli, E Galstyan, M Kochat, C. Goel, S. Kar, J. Jaroszynski, D. Abraimov and V. Selvamanickam, “In-field critical current performance of 4.0 μm thick film REBCO conductor with Hf addition at 4.2 K and fields up to 31.2 T”, Supercond. Sci. Tech. 33 (2020) 07LT03
18. J. Jiang et al., "High-Performance Bi-2212 Round Wires Made With Recent Powders," in IEEE Transactions on Applied Superconductivity, vol. 29, no. 5, pp. 1-5, Aug. 2019, Art no. 6400405, doi: 10.1109/TASC.2019.2895197.
19. Shen, T.; Garcia Fajardo, L. Superconducting Accelerator Magnets Based on High-Temperature Superconducting Bi-2212 Round Wires. Instruments 2020, 4, 17.
20. H. Hosono, et al, Materials Today 21, 278–302 (2018).
21. H. Huang, et al, Superconductor Science and Technology 31, 015017 (2018).
22. F. Kametani, et al, WB4-2-INV, ISS2108, Dec 2018