Emanuela Z. Barzi[3], Ernesto S. Bosque[1], Daniel S. Davis[1], Laura Garcia Fajardo[2], Youngjae Kim[1], Vladimir Kashikhin[3], David C. Larbalestier[1], Tengming Shen[2]
[1]National High Magnetic Field Lab, [2]Lawrence Berkeley National Lab, [3]Fermilab

30 T BSCCO solenoids are now in view

The Over-Pressure (OP) process development led by the NHMFL under DOE support, can now produce whole wire current densities, J_E close to 1000 A/mm^2 at 30 T and 4.2 K in Bi-2212 ($Bi_2Sr_2Ca_1Cu_2O_x$), a twisted, multifilament, macroscopically isotropic HTS conductor like LTS Nb-Ti and Nb_3Sn conductors [1]. While the development of strand based Bi-2212 compact research magnets of 25 T is currently underway at the NHMFL and a 28 T NMR magnet project has been proposed to NIH, in collaborations with industry partners including Cryomagnetics Inc. and Oxford Instruments NanoScience, the necessary magnet technologies for 30 T class solenoids are currently being validated, including a new cable-based effort focused towards high energy physics applications.

A particularly well-suited application is muon beam final cooling, where 30-40 T magnets decrease the transverse emittance by an order of magnitude, allowing for high luminosity muon beams [2], [3]. The opportunity for HTS conductors in muon colliders was identified in PAC'07[4], [5] and has continued to be part of the Muon Accelerator Program's research goals. Application to Axion research is also attractive, even if REBCO solenoids have led so far.

No magnet is better than its conductor:

Muon cooling solenoids became clearly feasible with the world-record magnetic field achievements with REBCO and Bismuth conductors at the NHMFL [6], [7] presented in 2012 to the US Muon Accelerator Program. Newly identified limitations in REBCO, including effects of screening current induced field on coil mechanics and difficulties in magnet protection [8], [9], as well as known challenges of temporal and spatial field homogeneity, call for a new evaluation of commercially available HTS, including Bi-2212, for high field quality solenoids.

In contrast to the 100 to 300 m piece lengths of delivered coated-conductor, limited by control of a complex chemical deposition process, Bi-2212 routinely delivers 800 to 1200 m continuous lengths, minimizing the number of resistive joints needed in a magnet. Despite inherent challenges of a Wind-and-React conductor with a weak Ag-matrix, though one with very high conductivity that avoids the need for diffusion barriers, steady progress has been made to improve our understanding of the conductor. Characterizing new powder production sources has led to improved uniformity of stoichiometry and particle size, that, along with greater control of the Over-Pressure process, has resulted in the substantial gains in critical current shown in figure 1. Mechanical strengthening has been incorporated into the conductor's outer silver stabilizer to reach a critical stress of 160 MPa [10], laminated onto the conductor to reach over

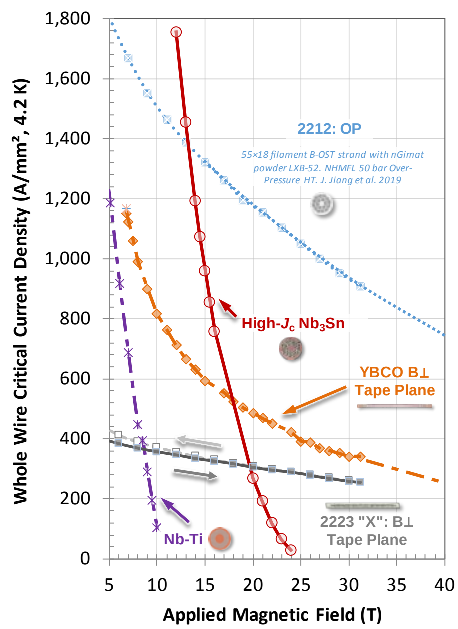

Figure 1: Whole wire current densities, J_E, of commercially available conductors. Note that Nb-Ti, Nb_3Sn and Bi-2212 are isotropic while Bi-2223 and REBCO are anisotropic. In general, the inferior rather than the superior orientation controls magnet properties wound with anisotropic tapes, pushing the critical points towards the end windings with high radial fields for tape conductors. Bi-2212, being macroscopically isotropic, has its critical point in the peak field point at magnet center.

Emanuela Z. Barzi[3], Ernesto S. Bosque[1], Daniel S. Davis[1], Laura Garcia Fajardo[2], Youngjae Kim[1], Vladimir Kashikhin[3], David C. Larbalestier[1], Tengming Shen[2]

[1]National High Magnetic Field Lab, [2]Lawrence Berkeley National Lab, [3]Fermilab

300 MPa [11], and distributed in magnet windings to support 278 MPa of J_E*B*r source stresses, see figure 2. These methods are under active development.

Our unique position to capitalize on Bi-2212

The large bore (50-100 mm) high field (8-20 T) LTS and resistive magnet test beds at the NHMFL enable testing limits of HTS conductors in solenoid inserts, summarized in figure 2, while developing reinforcement strategies to reach the higher stress levels in 30-40 T magnets. In parallel, LBNL has been making Rutherford cables from Bi-2212 into racetrack coils and now canted cosine theta dipoles that, with an added advantage of current sharing, have demonstrated stable and predictable quench properties with no signs of training [12]. Both programs grew from the Very High Field Superconducting Magnet Collaboration (VHFSMC, 2009-2015) and the BSCCo collaboration (2015-2016), and now operate under the US-DOE Magnet Development Program (MDP). Of note, has been the development of an OP furnace with a 25 cm Ø x 1 m long hot zone, funded by MDP, being built by NHMFL based upon experience with the existing furnace (14 cm Ø x 44cm). This allows processing magnets closer to real application volumes for both institutions and collaborators. MDP has recently seen value in subjecting Rutherford cables to stress under higher fields, leading to a Rutherford cable solenoid program, coinciding with a renewed effort at FNAL to optimize the Bi-2212 cabling [13], [14]. Rutherford cable wound solenoids have distinct advantages for Muon Collider cooling, the strongest being that their low-inductance and current-sharing stability makes conventional quench detection straightforward and secure energy extraction viable. An added benefit of cabling is lower sensitivity to conductor variability as current sharing can by-pass low-performing strands. Proposed schemes for muon solenoids will not need rapid charging or discharging, so the inter-strand conductivity can be left at high levels provided by silver matrix fusing during heat treatment to promote current sharing, and AC losses may be controlled by moderate cable and strand level twist pitch, adding a higher resistivity core only if necessary, methods well developed in Nb-based Rutherford cables.

With a short-term plan of focused magnet R&D with industry collaborators, medium term goals of 25 T compact research magnets and 30 T NMR lay the groundwork for long-term reliable 25 T Bi-2212 insert solenoid production for muon accelerator final cooling.

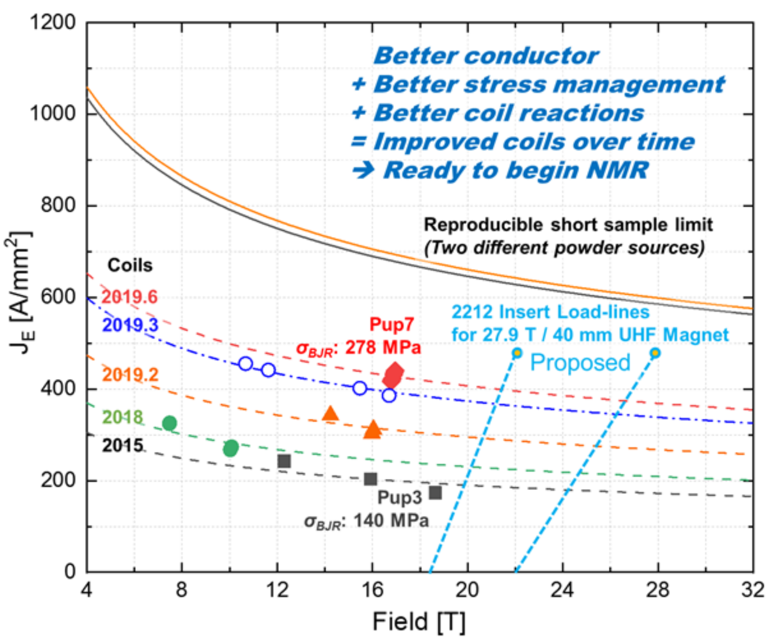

Figure 2: Results of 50 bar OP coil reactions over time are depicted in comparison to limits for single strand reactions. Coils were all reacted in the 130 mm diameter 450 mm long Deltech furnace, whereas strand reactions take place in a smaller OP furnace of smaller thermal mass. We note that we cannot yet achieve the highest possible J_E values in a large coil mass and most recent wires show fluctuations of achievable J_E around 80% of the champion value in figure 1. Coordination of this work with our DOE-supported conductor understanding effort aims to better align the best short sample and coil properties.

Emanuela Z. Barzi[3], Ernesto S. Bosque[1], Daniel S. Davis[1], Laura Garcia Fajardo[2], Youngjae Kim[1], Vladimir Kashikhin[3], David C. Larbalestier[1], Tengming Shen[2]

[1]National High Magnetic Field Lab, [2]Lawrence Berkeley National Lab, [3]Fermilab

[1] J. Jiang, G. Bradford, S. I. Hossain, M. D. Brown, J. Cooper, E. Miller, Y. Huang, H. Miao, J. A. Parrell, M. White, A. Hunt, S. Sengupta, R. Revur, T. Shen, F. Kametani, U. P. Trociewitz, E. E. Hellstrom, and D. C. Larbalestier, "High-Performance Bi-2212 Round Wires Made With Recent Powders," *IEEE Trans. Appl. Supercond.*, vol. 29, no. 5, pp. 1–5, Aug. 2019, doi: 10.1109/TASC.2019.2895197.

[2] R. B. Palmer, J. S. Berg, R. C. Fernow, J. C. Gallardo, H. G. Kirk, Y. Alexahin, D. Neuffer, S. A. Kahn, and D. Summers, "A complete scheme of ionization cooling for a muon collider," in *2007 IEEE Particle Accelerator Conference (PAC)*, Jun. 2007, pp. 3193–3195, doi: 10.1109/PAC.2007.4440712.

[3] D. Kaplan, "Overview of Muon Cooling," *Proc. Workshop Beam Cool. Relat. Top.*, vol. COOL2015, p. 9 pages, 2.929 MB, 2016, doi: 10.18429/JACOW-COOL2015-MOWAUD03.

[4] S. A. Kahn, M. Alsharo'a, R. P. Johnson, M. Kuchnir, R. C. Gupta, R. B. Palmer, E. Willen, and D. J. Summers, "A high field hts solenoid for muon cooling," in *2007 IEEE Particle Accelerator Conference (PAC)*, Jun. 2007, pp. 446–448, doi: 10.1109/PAC.2007.4440240.

[5] V. V. Kashikhin, E. Barzi, V. S. Kashikhin, M. Lamm, Y. Sadovskiy, and A. V. Zlobin, "Study of High Field Superconducting Solenoids for Muon Beam Cooling," *IEEE Trans. Appl. Supercond.*, vol. 18, no. 2, pp. 928–932, Jun. 2008, doi: 10.1109/TASC.2008.921946.

[6] U. P. Trociewitz, M. Dalban-Canassy, M. Hannion, D. K. Hilton, J. Jaroszynski, P. Noyes, Y. Viouchkov, H. W. Weijers, and D. C. Larbalestier, "35.4 T field generated using a layer-wound superconducting coil made of (RE)Ba2Cu3O7−x (RE = rare earth) coated conductor," *Appl. Phys. Lett.*, vol. 99, no. 20, p. 202506, Nov. 2011, doi: 10.1063/1.3662963.

[7] D. C. Larbalestier, J. Jiang, U. P. Trociewitz, F. Kametani, C. Scheuerlein, M. Dalban-Canassy, M. Matras, P. Chen, N. C. Craig, P. J. Lee, and E. E. Hellstrom, "Isotropic round-wire multifilament cuprate superconductor for generation of magnetic fields above 30 T," *Nat. Mater.*, vol. 13, no. 4, pp. 375–381, Apr. 2014, doi: 10.1038/nmat3887.

[8] X. Hu, L. Rossi, A. Stangl, J. W. Sinclair, F. Kametani, D. Abraimov, A. Polyanskii, J. Y. Coulter, J. Jaroszynski, and D. C. Larbalestier, "An Experimental and Analytical Study of Periodic and Aperiodic Fluctuations in the Critical Current of Long Coated Conductors," *IEEE Trans. Appl. Supercond.*, vol. 27, no. 4, Art. no. 4, Jun. 2017, doi: 10.1109/TASC.2016.2637330.

[9] D. Park, J. Bascuñán, P. C. Michael, J. Lee, Y. H. Choi, Y. Li, S. Hahn, and Y. Iwasa, "MIT 1.3-GHz LTS/HTS NMR Magnet: Post Quench Analysis and New 800-MHz Insert Design," *IEEE Trans. Appl. Supercond.*, vol. 29, no. 5, pp. 1–4, Aug. 2019, doi: 10.1109/TASC.2019.2901026.

[10] L. Ye, P. Li, J. Jaroszynski, J. Schwartz, and T. Shen, "Strain control of composite superconductors to prevent degradation of superconducting magnets due to a quench: I. Ag/Bi2Sr2CaCu2Oxmultifilament round wires," *Supercond. Sci. Technol.*, vol. 30, no. 2, p. 025005, Dec. 2016, doi: 10.1088/0953-2048/30/2/025005.

[11] M. D. Brown, E. S. Bosque, D. M. McRae, R. P. Walsh, J. Jiang, E. E. Hellstrom, Y. Kim, U. P. Trociewitz, A. Otto, and D. C. Larbalestier, "Tensile properties and critical current strain limits of reinforced Bi-2212 conductors for high field magnets.," *IOP Conf. Ser. Mater. Sci. Eng.*, vol. 279, 2017, doi: 10.1088/1757-899X/279/1/012022.

[12] T. Shen, E. Bosque, D. Davis, J. Jiang, M. White, K. Zhang, H. Higley, M. Turqueti, Y. Huang, H. Miao, U. Trociewitz, E. Hellstrom, J. Parrell, A. Hunt, S. Gourlay, S. Prestemon, and D. Larbalestier, "Stable, predictable and training-free operation of superconducting Bi-2212 Rutherford cable racetrack coils at the wire current density of 1000 A/mm 2," *Sci. Rep.*, vol. 9, no. 1, p. 10170, Jul. 2019, doi: 10.1038/s41598-019-46629-3.

[13] E. Barzi, V. Lombardo, D. Turrioni, F. J. Baca, and T. G. Holesinger, "BSCCO-2212 Wire and Cable Studies," *IEEE Trans. Appl. Supercond.*, vol. 21, no. 3, pp. 2335–2339, Jun. 2011, doi: 10.1109/TASC.2011.2106106.

[14] E. Barzi, V. Lombardo, A. Tollestrup, and D. Turrioni, "Study of Effects of Transverse Deformation in BSCCO-2212 Wires," *IEEE Trans. Appl. Supercond.*, vol. 21, no. 3, pp. 2808–2811, Jun. 2011, doi: 10.1109/TASC.2011.2106105.