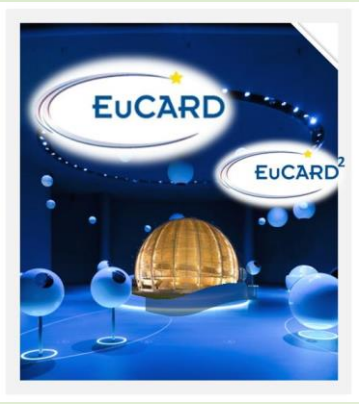

Bi-2212 Conductor Technology in BSCCo – Bismuth Strand and Cable Collaboration overview talk of the collaboration to working group 10 of EUCARD2

David C. Larbalestier

Applied Superconductivity Center
National High Magnetic Field Laboratory,

Florida State University,
Tallahassee, FL 32310, USA

More detail at:
16:00 M. Rikel: "BSCCO 2212 precursor at Nexans: Current Status and Further Development within EuCARD2"
16:20 L. Cooley: "FNAL work on BSCCo"
16:40 D. Dietderich: "LBNL work on BSCCo and US-CDP actions"
17:00 D. Larbalestier "NHMFL and OST work on BSCCo, and interfaces to EuCARD2"

June 14, 2013 CERN

BROOKHAVEN NATIONAL LABORATORY

Fermilab

BERKELEY LAB AFRD ACCELERATOR & FUSION RESEARCH DIVISION

THE APPLIED SUPERCONDUCTIVITY CENTER NHMFL • FSU
NATIONAL HIGH MAGNETIC FIELD LABORATORY FSU • UF • LANL
FLORIDA STATE UNIVERSITY 1851

Key points on Bi-2212 for EUCARD2

- J_E of long length wires has improved by 3-7 times (depending on baseline) and now exceeds the J_E of SuperPower REBCO CC
- This requires reaction under an overpressure (OP) of 25-100 bar so as to:
  - Prevent 2212 dedensification due to Ag expansion driven by internal gas pressure
  - Compress the Ag sheath to achieve full 2212 density
- OP processing delivers a round wire, multifilament, well stabilized conductor suitable for both cabled and single strand magnets (i.e. both accelerator and high field lab (e.g. NMR) magnets)
- The present US focus is intensely collaborative, uniting drivers in the DOE-HEP labs and the NHMFL
  - MAP
  - EUCARD2
  - High field science magnets in the 30-40 T range
- A supportive industrial base is in place too
  - Powder production at Nexans (EUCARD2 contribution of CERN)
  - Strand at OST (new Nexans powder will be made into billets using CDP (US Conductor Development Program) funds for EUCARD2 evaluation)

BSCCo – Bismuth Strand and Cable Collaboration

- Unites efforts at BNL, Fermilab, LBNL and NHMFL,
- Key persons:
  - NHMFL Principals: David Larbalestier, Eric Hellstrom, Jianyi Jiang, Fumitake Kametani, and Ulf Trociewitz (coils)
  - FNAL Principals: Lance Cooley and Tengming Shen
  - LBNL Principal: Arno Godeke
  - BNL Principal: Arup Ghosh
- Affiliates:
  - Dan Dietderich (CDP and LBNL) and Ken Marken (CDP and DOE-HEP)
  - OST manufacturing collaborators – Yibing Huang, Hanping Miao, Seung Hong and Jeff Parrell

Global goals of BSCCo

- To make round wire Bi-2212 a viable magnet technology in both single strand and cable form
  - Establish material compatibility, strength, quench and insulation solutions relevant for magnets
  - Longer, stronger and cheaper!
- Demonstrate capability of 2212 in high field magnets relevant to important end use applications
  - DOE-HEP drives MAP and LHC upgrades
  - NHMFL – very high field magnets for users for which recommendations of the new National Research Council panel on High Magnetic Field Science are explicit and important:

    http://www.nap.edu/catalog.php?record_id=18355

http://www.nap.edu/catalog.php?record_id=18355
High Magnetic Field Science and Its Application in the United States: Current Status and Future Directions
The recommendations

- Consider regional 32 T superconducting magnets at 3-4 geographic locations optimized for easy user access.
- Establish at least 3 US 1.2 GHz NMR instruments (planned commercial) for broad access and plan for ~1.5 GHz class system development
- Establish high field facilities at neutron and photon scattering facilities
- A 40 T all-superconducting magnet should be designed and constructed,
- A 60 T DC hybrid magnet that will capitalize on the success of the current 45 T hybrid magnet at the NHMFL-Tallahassee should be designed and built.

Very strong synergy with HEP goals for high field use – needs strand AND cable development

Principal foci at NHMFL

- Deconstruct, improve and simplify the process used to presently optimize high Jc in Bi-2212
- Develop a flexible Overpressure Process (OP) for reaction of Bi-2212 in short sample and coil form and make available to partners
- Understand the key architectural choices of 2212 multifilament conductor design
- Develop suitable insulation for at least single strand applications
- Prove out Bi-2212 in high field solenoid form
  - All superconducting layer wound REBCO (2013) and 2212 (2014) coils for NMR use are in construction (Ulf Trociewitz)

The 32 T all superconducting user magnet is driving REBCO technology at the MagLab (Weijers and Markiewicz)

Developing OP furnace capability at the NHMFL (2013)

Diameter	Length	Max pressure	Comments
25 mm	15 cm	100-200 bar	Today's workhorse
48 mm	15 cm	25 bar	Commissioning now
45 mm	25 cm	75-120 bar	On order, June delivery
170 mm	50 cm	100 bar	On order, July delivery

- Capabilities are available to all in BSCCo and many samples have been shared with LBNL, FNAL and OST
- FNAL is designing a 100 bar capability for straight Rutherford Cables suitable for reacting 2212 cable designed for test in FRESCA at CERN

Principal foci at FNAL

- Fermilab's program is driven by future energy frontier facilities: the Muon Accelerator Program (MAP) and participation in HE-LHC
- MAP plans development of 30-50 T solenoids for muon cooling, and other magnets, starting FY16
- To avoid overlap with programs at NHMFL, BNL, and CERN, and in view of resource limits, Bi-2212 round wire is the present material focus
  - 2010-2011 work demonstrated 4 double-pancakes YBCO insert reaching 21.5 T in 14 T background.
- Present Bi-2212 work targets readiness for FY16 MAP development
  - Adaptation of OP-process to Rutherford cables FY13-14
  - Understand materials science (T Shen – early career grant)
  - Test straight Rutherford cables, e.g. at BNL, Fresca, FY14
  - Develop insulation and strengthening strategies
  - Explore small solenoids as demonstration of long-length properties, FY14
  - Explore Rutherford cable pancake coils, FY15?
  - Develop coil-sized OP facility, FY15?

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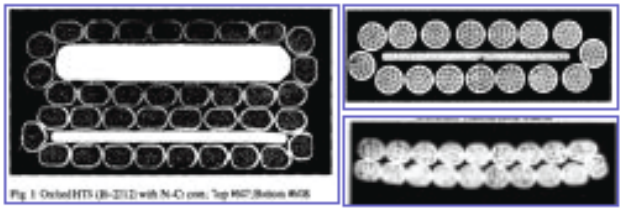
Bi-2212 @ LBNL

U.S. DEPARTMENT OF ENERGY

1998 → 1999 → 2000 → 2001 → 2002 → 2003 → 2004 → 2005 → 2006 → 2007 → 2008 → 2009 → 2010 → 2011 → 2012



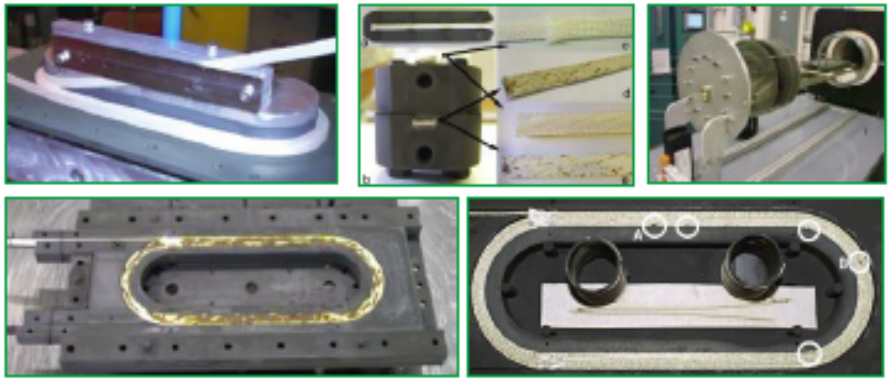
Rutherford cable developments
(with IGC, OST, Showa > 4.5 km SMES cable)

Beyond 16 T dipole fields

- Optimize and refine Nb_3Sn
- Develop W&R Bi-2212
  - Collaborations
    - **SWCC** Showa Cable Systems Co. Ltd.
    - **OST** Oxford Instruments
    - **VHFSMC** U.S. National Program on Bi-2212
      - » BNL, FNAL, FSU, LBNL, NCSU, NIST, TAMU
    - **BSCCo** U.S. collaboration on Bi-2212
      - » BNL, FNAL, FSU, LBNL
- Side path: YBCO, Bi-2223, …

2009 → 2010 VHFSMC

2011 → 2012 BSCCo



W&R Bi-2212 racetracks with Showa and OST
Reach 85% of RW along loadline => **Technology OK**

2006 – 2012: Bi-2212 subscale coils

- Purchase wire, make and insulate cable
- Coil on Inconel 600 former, react, pot, test
- 2 Ag dummies & 11 Bi-2212 coils to-date

2013 onwards: Bi-2212 dipole inserts

- Low strain, high Je insert for HD3

Principal foci at BNL

- Were an essential partner in VHFSMC activities and have become partner in BSCCo too
- Liquid nitrogen transverse pressure capabilities for cable evaluation

Conductor Development Program (CDP) Role

- Bi-2212 round wire is now a significant focus of the effort and is planned to grow as Nb_3Sn problems are resolved and Nb_3Sn emphasis moves to production
- CDP has contract in place for fabrication of 3 most recent Nexans powders (Standard, granulate of smaller and large particle distribution) into 3 billets of 0.8 mm 37 x 18 conductor
- Fermi and LBNL are ready to make cable from this wire for evaluation in support of both the US and EUCARD2 programs
- NHMFL will lead the single strand optimization

Principal foci at OST funded by CDP task I

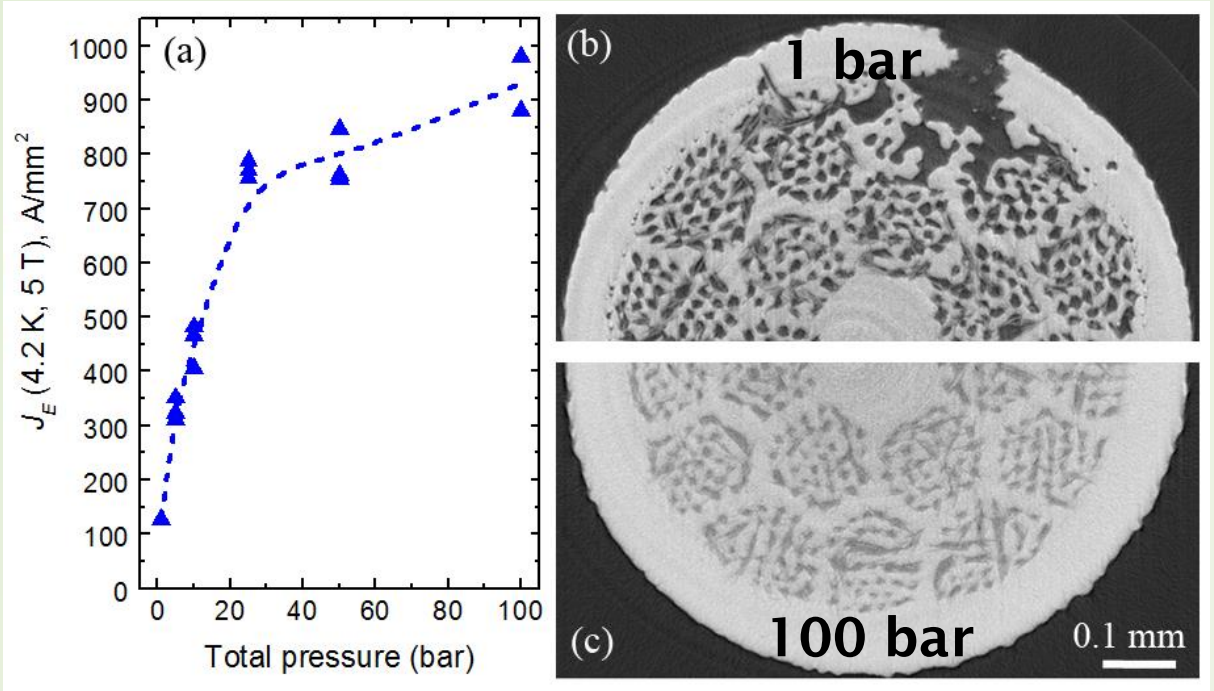
To be completed by Sept. 2013

OXFORD INSTRUMENTS
The Business of Science®

- Fabricate three 37 x 18 filament billets using following three powders (powder is in transit to OST now):
  - Standard ultra-fine powder (d_{50} ~ 1 μm),
  - Standard granulate powder with particle size of 200-500 μm
  - Special granulate powder with narrower particle size range of 100-200 μm.
- Optimize HT for 0.8 mm diameter wire
- Optimize wire diameter (filament size and Ag web thickness) for maximum J_E value
- Draw all billets down to the optimized size
- Deliver green wire (approximately 300 m or equivalent in ~ 0.8 mm wire for each billet) to LBNL (planned for Sept. 2013)

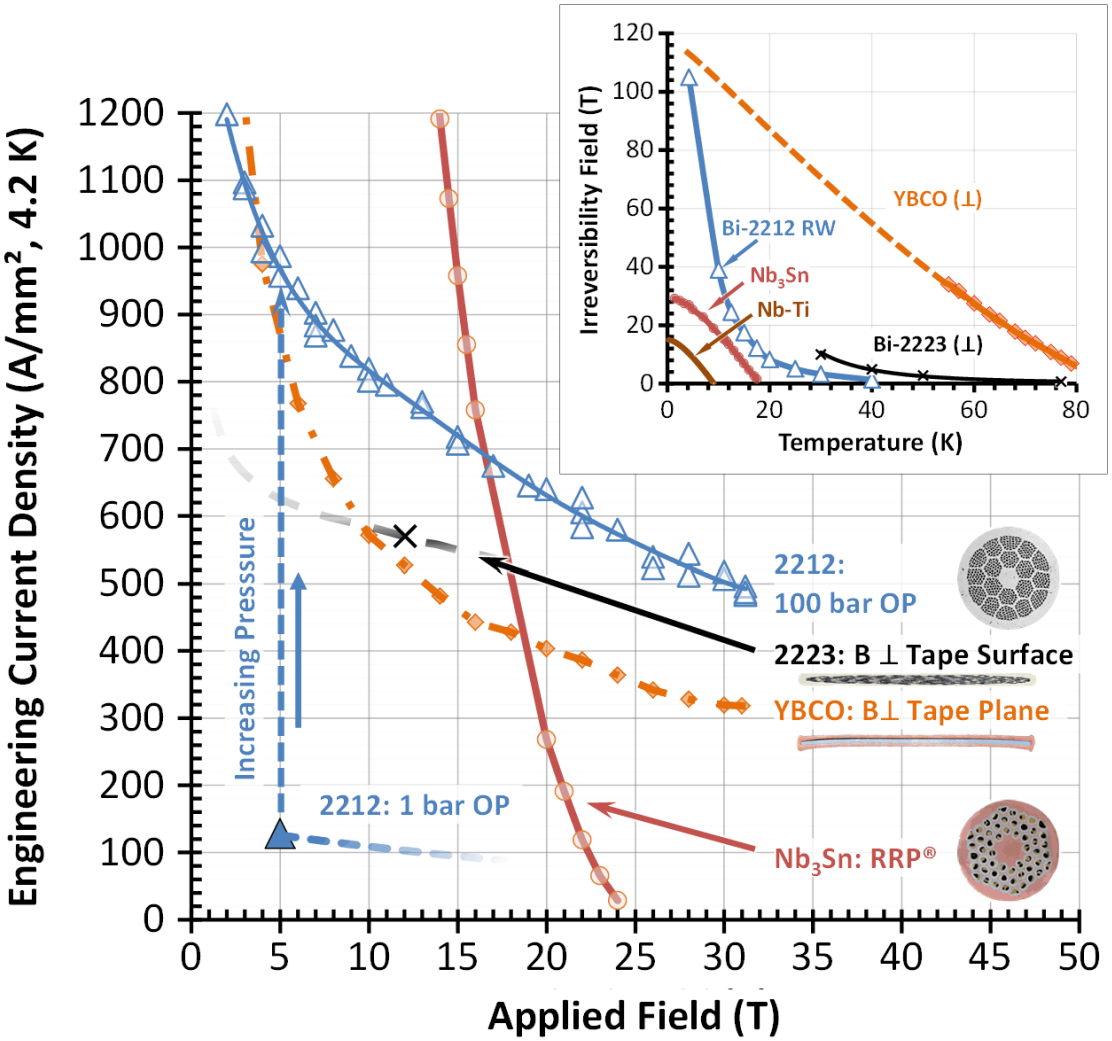
Where are we now with OP 2212?

- A good understanding of how to reliably attain high J_E has been developed and published
- Demonstration of high J_E has been shown in both short sample AND coil form
- Immediate task is to bring on suitable OP facilities to allow more coil demonstrations
- Need to understand whether lower pressures are possible, e.g. with cleaner wires



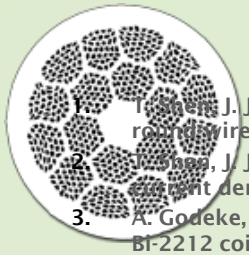
OP evaluation on short samples by Maxime Matras and Jianyi Jiang (NHMFL)
X-ray tomographs by Christian Scheuerlein (CERN) at ESRF

J_E of 2212 and REBCO CC are fully comparable



- Isotropic OST wire with ~25% 2212 is compared to c-axis J_E of good SuperPower REBCO tape with 1 μm REBCO and 40 μm Cu thickness in conductor with total thickness of 0.1 mm
- J_E of RW 2212 now exceeds REBCO CC

Some recent relevant 2212 papers



1. T. Shen, J. Jiang, A. Yamamoto, U. P. Trociewitz, J. Schwartz, E.E. Hellstrom, and D.C. Larbalestier, "Development of high critical current density in untextured round wire, multifilamentary $Bi_2Sr_2CaCu_2O_x$ round-wire by strong overdoping", Appl. Phys. Letts., 95, 152516 (2009).
2. T. Shen, J. Jiang, U. P. Trociewitz, D.C. Larbalestier, J. Schwartz and E.E Hellstrom, "Filament to filament bridging and its influence on developing high critical current density in multifilamentary $Bi_2Sr_2CaCu_2O_x$ round wires", *Supercon. Science and Technology*, 23, 025009, (2010)
3. A. Godeke, P. Acosta, D. Cheng, D. R. Dietderich, M G T Mentink, S O Prestomon, G L Sabbi, M Meinesz, S. Hong, Y. Huang, H. Miao and J. Parrell, "Wind and react Bi-2212 coil development for accelerator magnets", Supercond. Sci. Technol. 23 034022 (2010).
4. Friend, Chris M., Miao, Hangping, Huang, Yibing, Melhem, Ziad, Domptail, Fred, Meinesz, Maarten, Hong, Seung, Yang, Yifeng and Young, Edward A. "The development of high field magnets utilizing Bi-2212 wind & react insert coils." *IEEETransactions on Applied Superconductivity*, 20 (3), 583-586. (2010)
5. Fumitake Kametani, Tengming Shen, J. Jiang, C. Scheuerlein, M. Di Michiel, Y. Huang, H. Miao, J. A. Parrell, E. E. Hellstrom, and D. C. Larbalestier, "Bubble formation within filaments of melt-processed Bi-2212 wires and its strongly negative effect on the critical current density", Superconductor Science and Technology, 24, 075009 (2011).
6. A Malagoli, F Kametani, J Jiang, U P Trociewitz, E E Hellstrom and D C Larbalestier, "Evidence for long range movement of Bi-2212 within the filament bundle on melting and its significant effect on Jc", Superconductor Science and Technology, 24, 075016 (2011).
7. J Jiang, WL Starch, M Hannion, F Kametani, U P Trociewitz, E E Hellstrom and D C Larbalestier "Doubled critical current density in Bi-2212 round wires by reduction of the residual bubble density", Superconductor Science & Technology, 24, 082001 (2011).
8. C Scheuerlein, M DiMichiel, M Scheel, J Jiang, F Kametani, A Malagoli, E E Hellstrom and D C Larbalestier "Void and phase evolution during the processing of Bi-2212 superconducting wires monitored by combined fast synchrotron micro-tomography and x-ray diffraction", Superconductor Science & Technology, 24, 115004 (2011).
9. Tengming Shen, Jianyi Jiang, Fumitake Kametani, Ulf P Trociewitz, David C Larbalestier and Eric E Hellstrom, "Heat treatment control of Ag-$Bi_2Sr_2CaCu_2O_{8-x}$ multifilamentary round wire: investigation of time in the melt", Superconductor Science & Technology, 24, 115009 (2011).
10. Terry Holesinger, Hanping Maio, M. Meinesz, Y. Huang, J. Parrell, J. Kennison, K. Marken and S. Campbell, "Analysis of High Ic and Jc Bi-2212 conductors with Dilute second phase additions" *IEEE Trans. on Appl. Supercon.*, 21, (2011) 2791-2794
11. A. Godeke, D. W. Cheng, D. R. Dietderich, M. G.T. Mentink, S.O .Prestemon, G. L. Sabbi "Heat treatment optimizations for Wind and React Bi 2212 racetrack coils ", Physics Procedia 36(812<817 (2012)
12. M. Dalban-Canassy, D.A. Myers, U.P. Trociewitz, J. Jiang, E.E. Hellstrom, Y. Viouchkov, and D.C. Larbalestier, "Study of the local variation of critical current in Ag-alloy clad, round-wire $Bi_2Sr_2CaCu_2O_{8-x}$ multi-layer solenoids", *Superconductor Science & Technology*, 25, 115015 (2012).
13. H. Miao, Y. Huang, M. Meinesz, S. Hong and J. Parrell "DEVELOPMENT OF Bi-2212 ROUND WIRES FOR HIGH FIELD MAGNET APPLICATIONS "Advances in Cryogenic Engineering Materials, Vol. 58, pp 315-324, (2012)
14. Hanping Miao, Yibing Huang, Seung Hong, J. A. Parrell, "Recent Advances in Bi-2212 Round Wire Performance for High Field Applications", IEEE Transactions on Applied Superconductivity, 23, 6400104 (2013).
15. Jianyi Jiang, Hanping Miao, Yibing Huang, Seung Hong, Jeff A. Parrell, Christian Scheuerlein, Marco Di Michiel, Arup K. Ghosh, Ulf P. Trociewitz, Eric E. Hellstrom and David C. Larbalestier, "Reduction of gas bubbles and improved critical current density in Bi-2212 round wire by swaging", IEEE Transactions on Applied Superconductivity, 23, 6400206 (2013).
16. A Malagoli, P J Lee, A Ghosh, C Scheuerlein, M Di Michiel, J Jiang, U Trociewitz, E E Hellstrom and D C Larbalestier, "Evidence of length-dependent wire expansion, filament dedensification and consequent degradation of critical current density in Ag-alloy sheathed Bi-2212 wires", Supercon. Sci and Tech. 26, 055018 (2013).
17. T. Shen, A. Ghosh, L. Cooley, and J. Jiang "Role of internal gases and creep of Ag in controlling the critical current density of Ag-sheathed $Bi_2Sr_2CaCu_2O_x$ wires", J. of Appl. Physics 113, 213901 (2013).
18. Peng Chen, Ulf P Trociewitz, Matthieu Dalban-Canassy, Jianyi Jiang, Eric E Hellstrom and David C Larbalestier, "Performance of Titanium-Oxide/Polymer Insulation in Bi-2212/Ag-alloy Round Wire Wound Superconducting Coils", Supercon. Sci and Tech. 26, 075009 (2013).
19. 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 "A new superconducting magnet technology for fields well above 30 T using macroscopically untextured, isotropic round wire multifilament $Bi_2Sr_2CaCu_2O_{8-x}$ conductors," submitted to Nature Materials April 2013, arXiv 1305.1269.