U.S. MAGNET DEVELOPMENT PROGRAM

Strategic Goals of the ASC-FSU GARD Conductor Development Program

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DE-SC0010421 (Larbalestier, Eric Hellstrom, Jianyi Jiang, Fumitake Kametani - The Underlying Science of High Critical Current Density in Round Wire Bi-2212
DE-SC0012083 (Larbalestier, Peter Lee, Chiara Tarantini and Shreyas Balachandran co-PIs) Nb_3Sn Superconductors for the LHC and for Accelerators Beyond the LHC
DE-SC0018750 (Kametani, Hellstrom, Tarantini and Larbalestier), The Underlying Science for Realizing High Critical Current Density in $(Ba/Sr)Fe_2As_2$ Fe-based Superconductor Wires.
No contract at FSU since all funds are at LBL: Conductor Development and Procurement Program (CDRP of MDP) – Lance Cooley PI

USMDP Annual Meeting

Virtual by Zoom

March 1-5, 2021

APPLIED SUPERCONDUCTIVITY CENTER
NATIONAL HIGH MAGNETIC FIELD LABORATORY
FLORIDA STATE UNIVERSITY

Driving questions from Soren to the TAC

1. Evaluate the plans and progress in the MDP Research Areas
    a. Does each Research Area have an appropriate assessment of present status?
    b. Are the plans presented for achieving the stated milestones realistic?
    c. Have the teams identified the major challenges?
    d. Are they making effective use of capabilities and infrastructure available within the collaboration?

2. Has MDP adequately identified current bottlenecks to progress, and are the program priorities being addressed by MDP management?

3. Is the MDP encouraging and appropriately engaging with parallel efforts outside MDP that could synergistically advance MDP goals?
    a. University programs and SBIR activities supported by OHEP are two prime examples

4. Is MDP community involvement in the contexts below appropriate? Are there further avenues that should be pursued?
    a. in the US "Snowmass" HEP planning process
    b. in the context of international collaboration
    c. in the context of the industrial ecosystem

- **WRT to Question 3, we at ASC want to point out our long involvement in defining the conditions for making new materials useful, first in prototype conductors and then by working with industry to get conductors in lengths useful for magnets.**
- **More recently as we transitioned to the NHMFL where a central goal was to develop HTS conductors for UHF magnets, we have learned the old story that conductors cannot be developed in isolation from the magnets**
- **As university groups we must connect to the magnet and the industrial programs**
- **True broadly for the earlier university talks in this session too**

A central thrust of the ASC effort has been to support the Nb-Ti Workshop now evolved into the Low Temperature and now High Field Superconductor Workshop (LTSW/HFSW)

- LTSW was imposed on us by Dave Sutter when he funded a program on the underlying science of high current density in Nb-Ti – (1983 to about 1995). Nb47Ti was fully developed before 1990 but exploration of artificial pinning center (APC) Nb-Ti went on for quite some time (PhD theses on Nb-Ti of David Hawksworth, David Moffat, Henry Muller, Bill Warnes (Oregon State ret), Christoph Meingast (KIT), Jim McKinnell, Lance Cooley, George Stejic, Rob Heussner (Intel), Paul Jablonski (TWCA, now Bureau of Mines) and Eric Kadyrov
    - Mike Sumption working on his PhD at OSU with Ted Collings was an early Nb-Ti workshop attendee and may have attended almost as many as Peter Lee and me
- In late 90s, Bruce Strauss in AARD suggested a transition of emphasis to Nb_3Sn conductors because low-J_c bronze conductors were now being challenged by potentially much higher J_c internal tin (IT) conductors – this provided the main emphasis of our program for about the next 15 years (several PhDs: Mike Naus, Matt Jewell, Chad Fischer (MS), Arno Godeke, Jian Zhou, Charlie Sanabria and Chris Segal)
    - Sanabria and Segal pushed RRP and PIT as far as they could but neither route would achieve FCC targets
    - Xingchen Xu and Mike Sumption re-opened the old GE internal oxidation toolbox and showed that it could work in multifilaments
        - This prompted us to rethink the alloy because Chris Segal had conclusively shown that Nb4Ta, just like pure Nb, recrystallized while the A15 reaction was going – this is what led us into prevention of recrystallization and Nb4Ta1Hf
    - David Smathers and Ken Marken also did PhD theses on Nb_3Sn but were funded by DOE-OFES before HEP got into the Nb_3Sn game
    - Good to know that OFES is back in the advanced superconductor game

So what?

- A lot of these PhDs stuck around to drive applied superconductivity to where it is today - and several are here today – to my pleasure!
- A number who did theses on HTS stuck with superconductors but went LTS to be more practical (Jeff Parrell, Mike Field, Michael Brown, all at B-OST, Aixia Xu (REBCO to 2212) at TcSUH and Engi-Mat)
- Charlie Sanabria having done a huge amount of work on damage in the ITER conductors (BS and MS) performed the final optimization of RRP for his PhD
    - Chris Segal (in transition back to the US from CERN) has further tweaked Charlie's HT to get 1640 A/mm^2 at 15 T in a standard inventory AUP wire…
        - Good feed for sub-scale magnets while waiting for APC or Hf-doped Nb_3Sn?
    - Charlie has moved from making AUP cable at LBL to CFS to make Fusion magnets out of REBCO……………

HTS was forbidden/useless for HEP until about 2010

- J_E was far too low to be useful
- The architecture was OK for electric utilities (flat tapes of REBCO or Bi-2223)
- Lengths were a few meters
- We had worked on HTS extensively ourselves – Eric Hellstrom was a big devotee of Bi-2212 (then AND now)
- Just after we moved to Tallahassee, OST published the paper on round wire 2212 at right – it got Eric and my attention!
  - Interestingly Ulf Trociewitz and Andy Twin are part of our ASC-OI-NS collaboration today

2262 IEEE TRANSACTIONS ON APPLIED SUPERCONDUCTIVITY, VOL. 17, NO. 2, JUNE 2007

High Field Insert Coils From Bi-2212/Ag Round Wires

Hanping Miao, Kenneth R. Marken, Maarten Meinesz, Boleslaw Czabaj, Seung Hong, Andrew Twin, Paul Noonan, Ulf P. Trociewitz, and Justin Schwartz

Abstract—Bi-2212/Ag round wire is a promising and practical material for extending high field superconducting magnets beyond the limits of Nb_3Sn. Efforts to develop superconducting magnets in the 25 to 30 T range include fabrication and test of practical size insert coils using this wire. Recent studies have focused on improvements in wire performance, wire insulation, and coil fabrication for wind-and-react coils. Continued improvements in the engineering critical current density (J_E) and the critical current density (J_c) performance have been achieved by optimizing the starting precursor composition, and the heat treatments. The highest J_E of 1580 A/mm^2 at 4.2 K, 0 T and 420 A/mm^2 at 4.2 K, 31 T were obtained in 0.81 mm wire. In particular, significant progress on braided insulation has been made for enabling a robust procedure for wind-and-react Bi-2212 solenoid coils. Performance of three of these coils has been measured in background fields up to 19 T, showing good prospects for high field magnet application of this conductor.

Index Terms—Bi-2212 round wire, high temperature superconductors, superconducting magnets, superconducting materials.

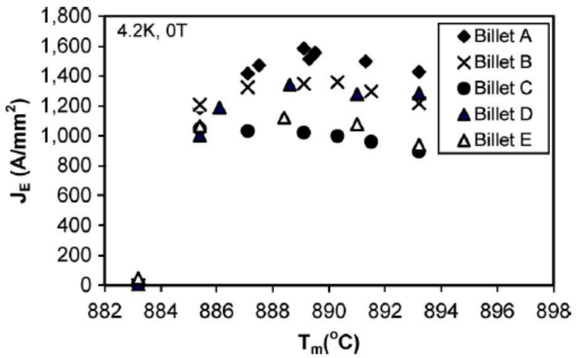


Fig. 1. Optimization of 1.0 $\mu V/cm$ J_E vs. the partial melting temperature for 5 recent billet wires.

Efforts are underway to develop alternate materials with higher B_{c2} values and thus greater high field critical current

An important message – get going but then be flexible: OI 3 years later

- Development takes a long time and has false starts (e.g. the IMPDAHMA 2212 commercialization efforts led by Ziad Melhem at OI and Yibing Huang at OST)
- Bruce Strauss encouraged a proposal on ROUND WIRE 2212 (July 2008 – Very High Field Superconducting Magnet collaboration – VHFSMC – led by DCL and Alvin Tollestrup with FNAL/LBL/BNL/PSU/TAMU collaborators
- Awarded through ARRA stimulus and this has seeded today's MDP 2212 effort

IEEE TRANSACTIONS ON APPLIED SUPERCONDUCTIVITY, VOL. 20, NO. 3, JUNE 2010 583

The Development of High Field Magnets Utilizing Bi-2212 Wind & React Insert Coils

Chris M. Friend, Hanping Miao, Yibing Huang, Ziad Melhem, Fred Domptail, Maarten Meinesz, Seung Hong, Edward A. Young, and Yifeng Yang

Abstract—Wind & react Bi-2212 inserts have been manufactured and tested inside a wide-bore NbTi – Nb_3Sn magnet providing a background field up to 20 T at 4.2 K. A pair of six-layer concentric coils both achieved critical currents of 350 A (J_E = 200 A/mm^2) in a 20 T background field. A thicker 14-layer insert made from 119 m of round wire had a critical quench current I_Q of 287 A (J_E = 162 A/mm^2) at the same field and contributed to a combined central field of 22.5 T. This is a record for a fully superconducting magnet at 4.2 K. The 14-layer coil, equipped with an external protective shunt, was used for an extensive series of quench measurements and endured > 150 quenches without damage. Minimum quench energies were found to be in the range of 200–500 mJ in background fields of 15–20 T when the coil carried 70–95% of its critical quench current.

Index Terms—Bi-2212, high field magnet, high temperature superconductor, quench.

I. Introduction

The last three years has witnessed a marked improvement in the performance of long length $Bi_2Sr_2CaCu_2O_{8-x}$ (Bi-2212) round wires and wind & react coils made with them. In 2008, a combined field of 32.1 T was achieved with a Bi-2212 coil inside a 31 T resistive magnet [1].

This paper demonstrates the current state-of-the-art for Bi-2212 insert coils and how close the technology is to providing wide availability of fully superconducting systems at 25 T and above.

The work was undertaken as part of a UK collaborative project with the acronym "IMPDAHMA" by Oxford Instruments Nanoscience, Cobham Technical Services Vector Fields Software and Southampton University. The aim of this project is to develop a software design module (as an optional addition

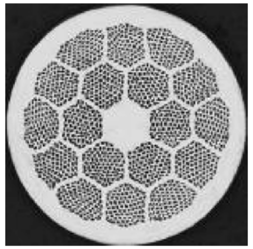
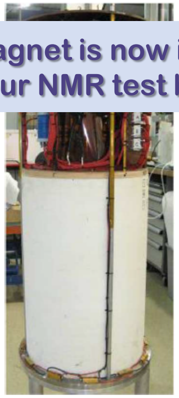


Fig. 1. A cross-section of the 85 × 19 Bi-2212/Ag wire manufactured by OST and used in the insert coils of the IMPDAHMA project.



This magnet is now in ASC as our NMR test bed

Fig. 2. Photo of the Oxford Instruments 20 T/78 mm bore LTS magnet outside its cryostat.

- OI blazed the trail but could not make 1 bar processed J_c values either consistent or high enough
- Great topics for a PhD thesis (Tengming Shen, then Pei Li (GE-Florence, now FRIB, Michael Brown B-OST, and Dan Davis FSU)

A really key insight was to use the small OPHT furnace in which we had earlier proven (EEH, JJ, DCL) higher Jc in Bi-2223 to show that it worked much better for Bi-2212

Test beds are very important – talks yesterday by Ernesto Bosque/Ulf Trociewitz, Dan Davis and Xiaorong Wang on planned MDP (LBL and ACT) tests in the Cryogenic magnet (160 mm/14 T)

- For REBCO we use the 31 T resistive magnet with 38 mm bore
- This is an exquisite damage detector, especially with NI coil construction and operating at J_E = 1400 A/mm^2 at 45.5 T
- To see the damage we need *post mortems*
- Glad to see that Glyn Kirby is planning a pm of FEATHER after its Fresca2 test

Key point: cross-sections of REBCO do not show the REBCO layer easily so cartoons are usually used – their perfection is not what is delivered!

LETTER

https://doi.org/10.1038/s41586-019-1293-1

45.5-tesla direct-current magnetic field generated with a high-temperature superconducting magnet

Seungyong Hahn[1,2], Kwanglok Kim[1], Kwangmin Kim[1], Xinbo Hu[1], Thomas Painter[1], Iain Dixon[1], Seokho Kim[1,3], Kabindra R. Bhattarai[1,4], So Noguchi[1,5], Jan Jaroszynski[1] & David C. Larbalestier[1,4]*

This **hot paper** was published in the past two years and received enough citations in May/June 2020 to place it in the top 0.1% of papers in the academic field of Physics.

Actually now only in top 1%

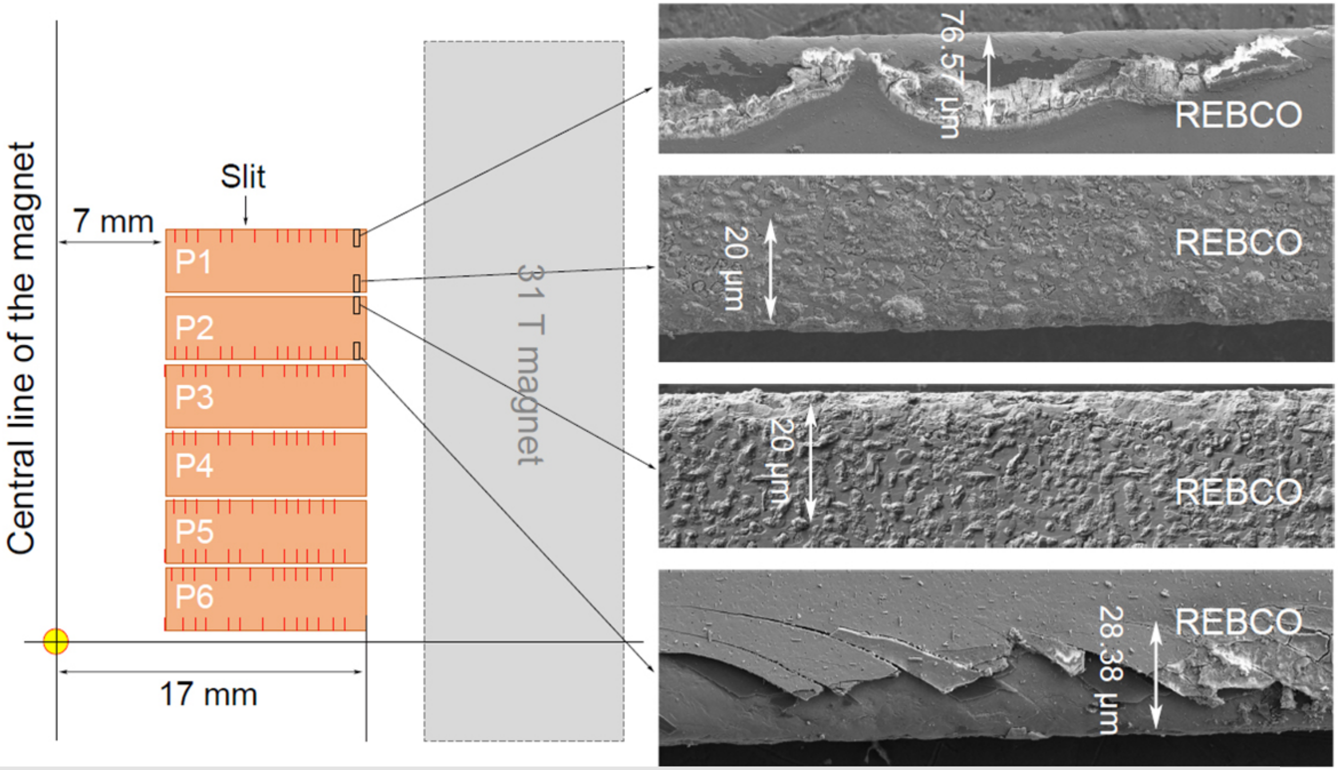
IOP Publishing — Superconductor Science and Technology

Supercond. Sci. Technol. 33 (2020) 095012 (13pp) — https://doi.org/10.1088/1361-6668/aba79d

Analyses of the plastic deformation of coated conductors deconstructed from ultra-high field test coils

Xinbo Hu[1], Michael Small[1,2], Kwanglok Kim[1], Kwangmin Kim[1], Kabindra Bhattarai[1,2], Anatolii Polyanskii[1], Kyle Radcliff[1], Jan Jaroszynski[1], Uijong Bong[3], Jeong Hwan Park[3], Seungyong Hahn[1,3] and David Larbalestier[1,2]

The slit edge is more easily damaged when placed towards the outside of the magnet in highest radial field (45.5 T LBC3) where screening current stress is highest



Delamination on the slit edge

No damage on the not-slit edge

No damage on not-slit edge

Delamination on the slit edge associated with slitting cracks

Paul Hu, Kwanglok Kim and Kwangmin Kim SuST 2020

Although LBC3 operated far beyond the design strains of any user magnet, it shows that the likely long-term behavior of the tape under fatigue and elastic-plastic deformation of the Ag-REBCO-buffer interface needs to be much better understood

Some summary thoughts

- New superconducting materials technology takes a long time – bravo to OHEP AARD/GARD for keeping the faith
- All parties contribute – universities, magnet builders in labs and industry who must manufacture the conductor
  - In general universities are better at basics, discovery, characterization and getting to root cause
  - Magnet building really shows up flaws in conductors if good *post mortems* follow
  - We need to be able to explain to industry how we believe they need to do better
    - LTSW and USMDP are wonderful fora for bring industry/lab magnet builders/universities together
- Dialog and mutual, recursive feedback is vital – the 45^{th} Nb-Ti/LTSW/HFSW is coming this Fall – MDP is already channeling much of its positive spirit

Further ASC presentations on 2212 (Eric Hellstrom), Shreyas Balachandran (NbTaHf) REBCO (Paul Hu and Dima Abraimov) and stability calculations (Dan Davis) are coming