Progress, Problems, and Promise of Bi-2212

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Florida State University

Many collaborators: BOST, Engi-Mat, LBL, FNAL, SMS, OI, CryoMagnetics

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September 1 – 6, 2024, Salt Lake City, UT

What I will cover

- Where Bi-2212 is today and how it got there
- Challenges for Bi-2212 strand, cables, and as a magnet technology
- The promise of Bi-2212 for high-field magnet technology

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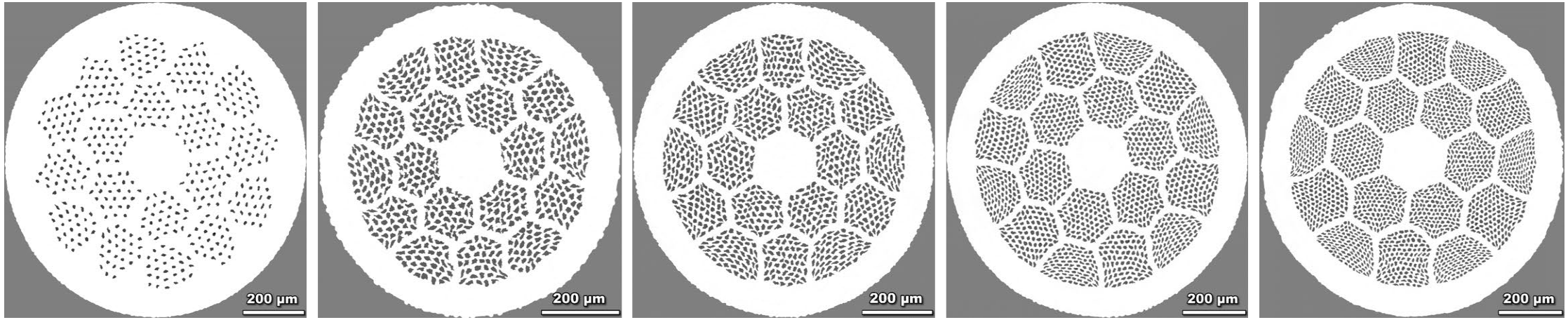
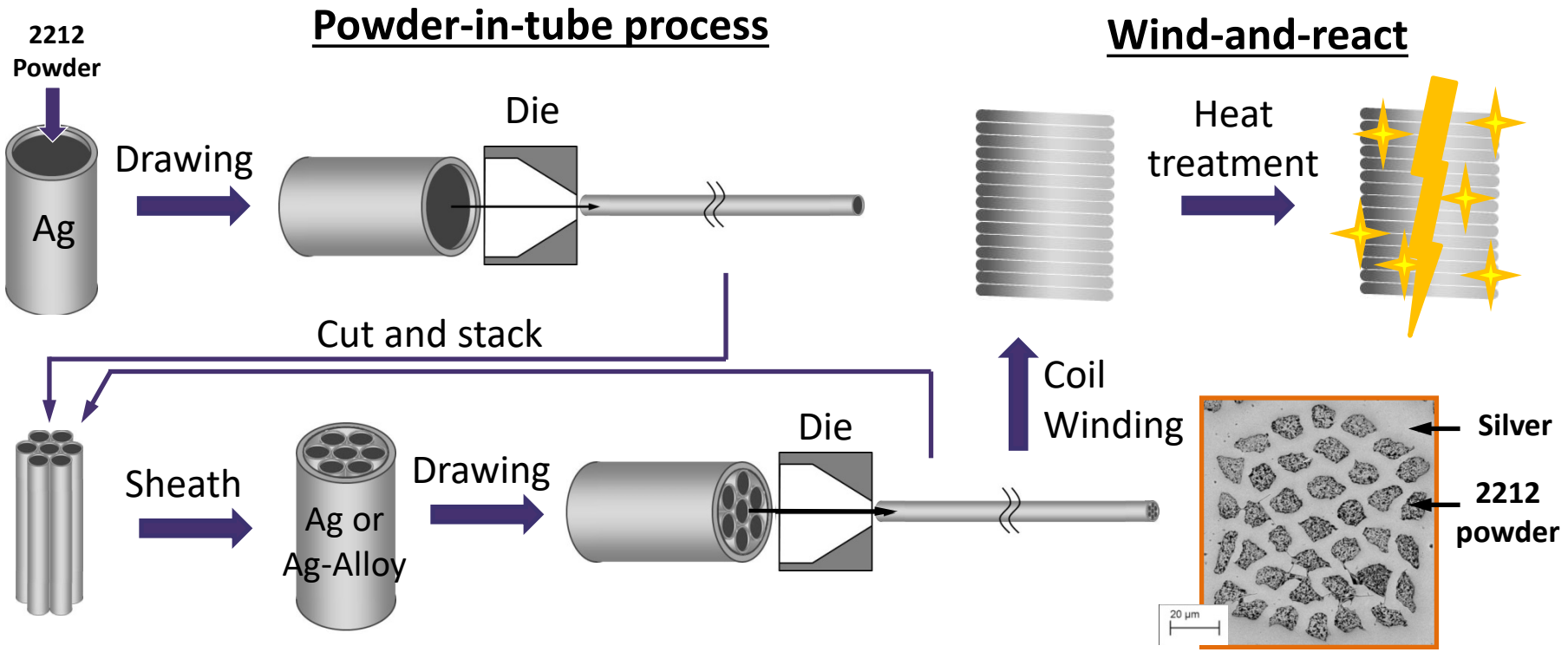
Bi-2212 Wire Technology is Versatile

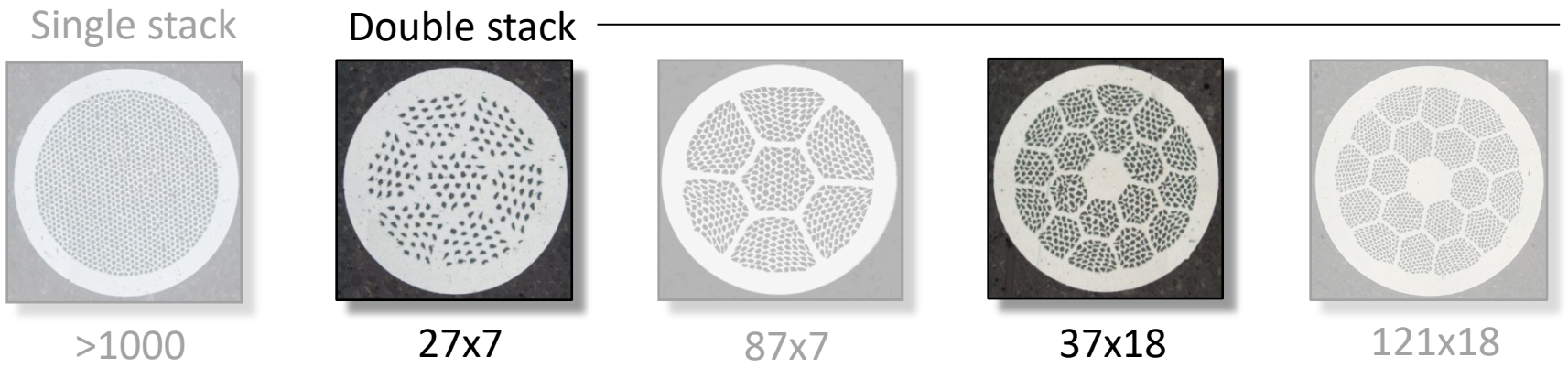


27×18 37×18 55×18 85×18 121×18

- **Optimum Filament Size is in the 10 -15 µm range with complex tradeoffs determined by starting filament uniformity and change of filament shape during heat treatment.**
- **No diffusion barrier is needed because the Ag matrix naturally has high RRR.**
- **Filament bonding occurs during overpressure heat treatment, degrading J_C and increasing the effective filament diameter, typically to about half the sub-bundle diameter – AC losses is about same as ITER but with 2X higher J_C (Oz *et al.* SuST 35, 04004 (2022).**

From powder to high field magnet





Matras

Powder is only 60-70% dense in as-drawn wire – bubbles form on melting

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I am from Salt Lake City - Alta ski area is famous for its very light powder snow

What does snow have to do with Bi-2212 wires?

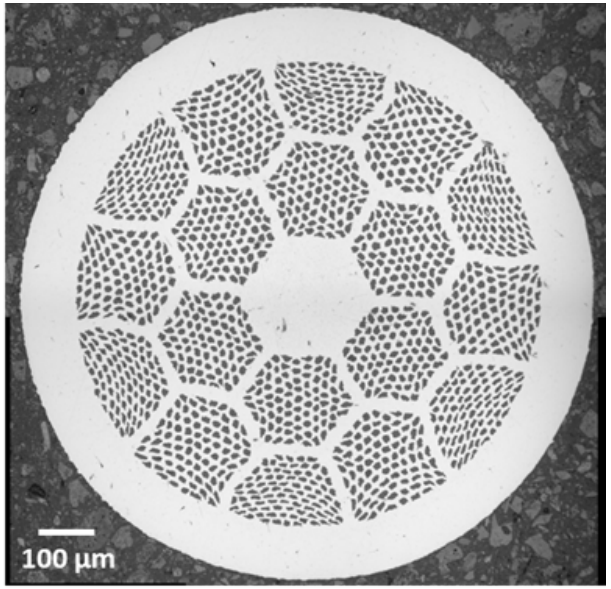
Snow contains ~ 90 % air

Bi-2212 filaments contain gas

Light, deep powder

10 cm snow = ~1 cm of liquid water

- Powder in as-drawn Bi-2212 filaments is only 60-70 % dense
- Filaments contain 30-40 % gas



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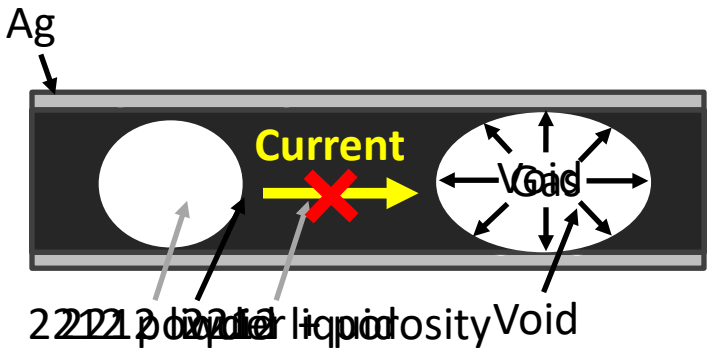
Before 2014 all heat treatments for Bi-2212 wires done in 1 atm O_2

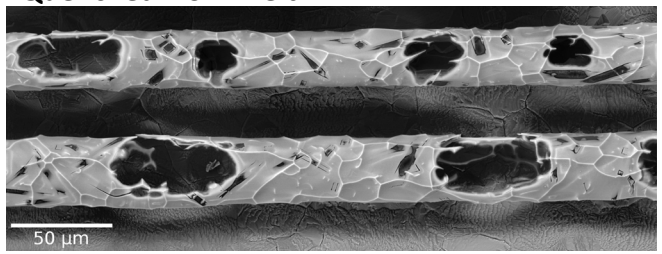
Powder in the filaments in the as-drawn Bi-2212 wire is only 60-70 % dense

What happens when the Bi-2212 melt?



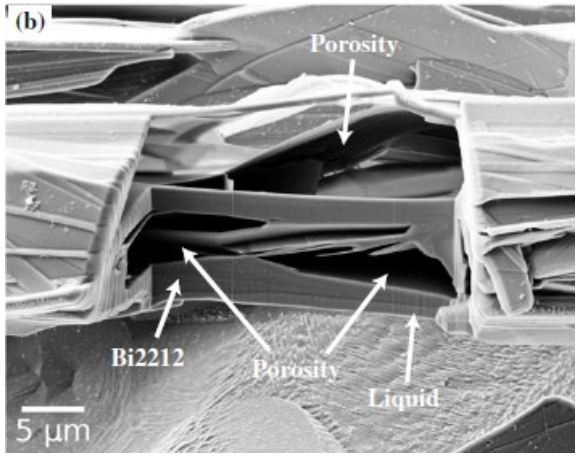
Form filament-sized bubbles in the melt

Quenched from melt



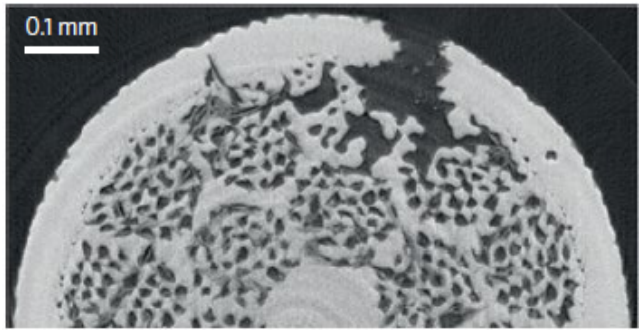
[1] Kametani *et al.*

After 1 atm heat treatment



[1] Kametani *et al.*

Trapped gas (CO_2 and H_2O) on powder causes wire to leak

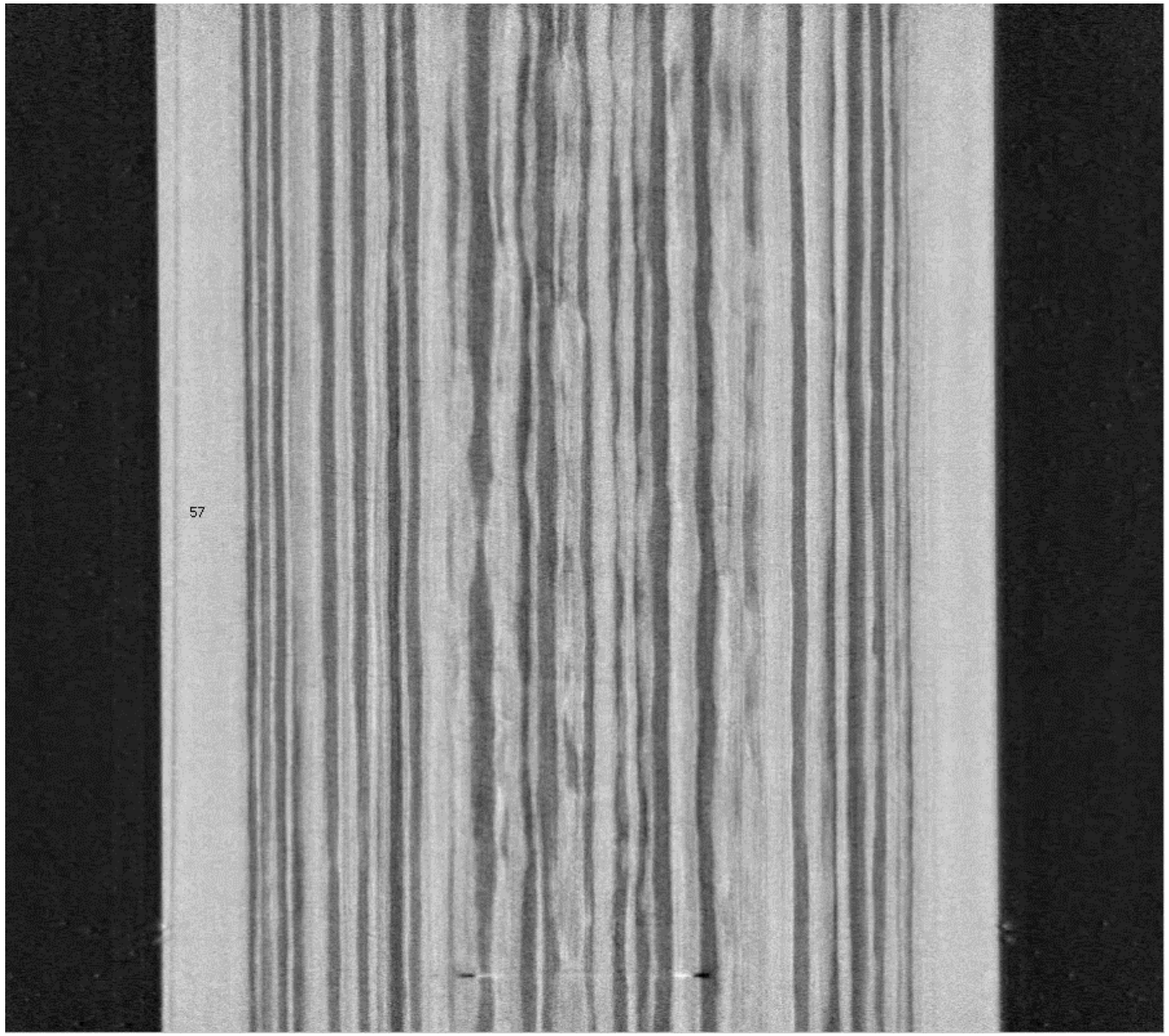


[2] Larbalestier *et al.*

Matras

[1] F. Kametani *et al.*, "Bubble formation within filaments of melt-processed Bi2212 [...] effect on the critical current density," *Superconductor Science and Technology*, vol. 24, no. 7, p. 75009, Jul. 2011.
[2] D. C. Larbalestier *et al.*, "Isotropic round-wire multifilament cuprate superconductor for generation of magnetic fields above 30 T," *Nat Mater*, vol. 13, no. 4, pp. 375–381, avril 2014.

X-ray tomography showing how bubbles develop in Bi-2212 wire with 1 atm heat treatment



Scheuerlein

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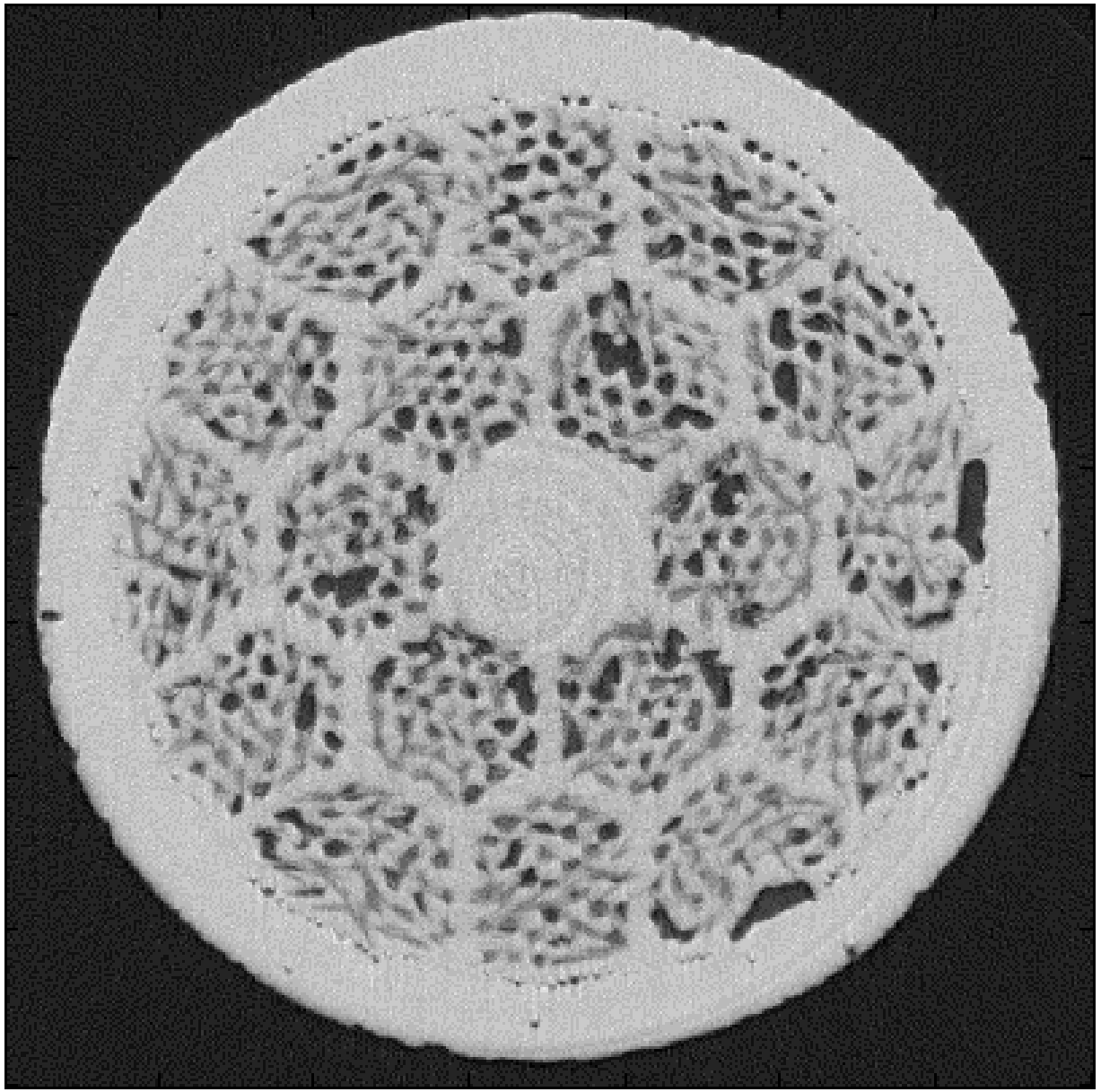
X-ray tomography of bubbles in Bi-2212 wire after 1 atm heat treatment



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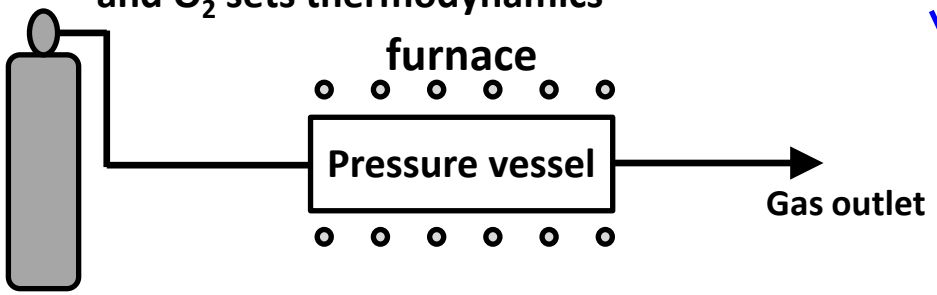
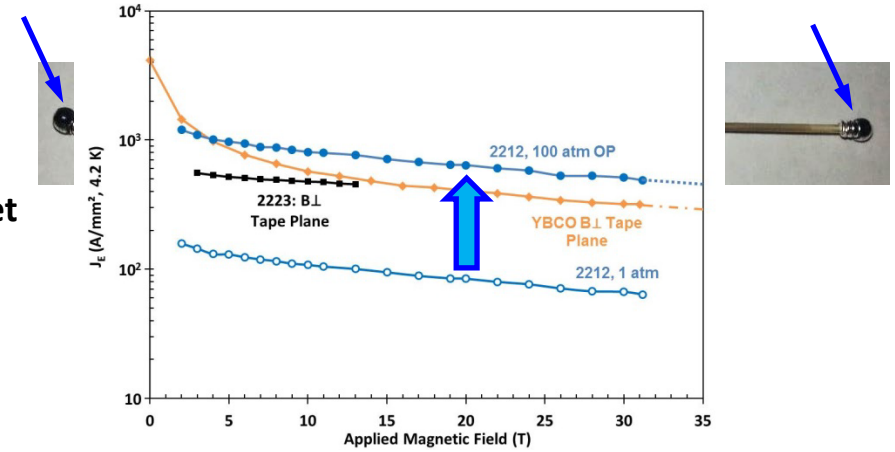
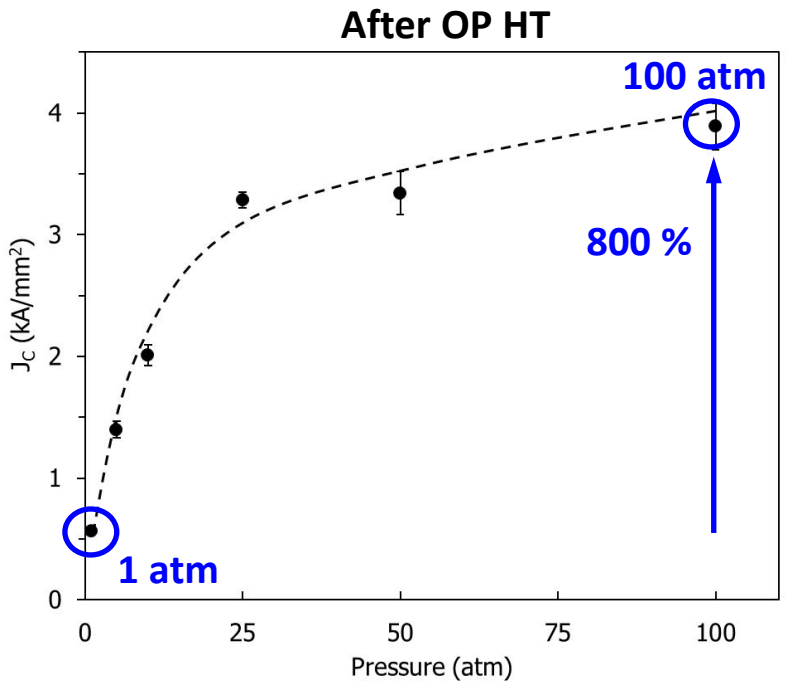
Eliminate bubbles using overpressure processing (OP) increases J_C by 800 %

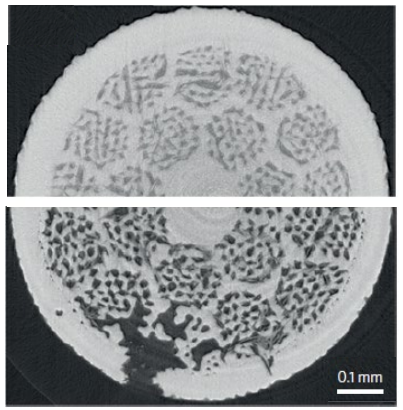
Gas cylinder (Ar-O_2) – Ar compresses wire and O_2 sets thermodynamics





- Cu house wiring





100 atm OP HT

1 atm HT

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[1] Larbalestier *et al.*

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Building progressively larger OP furnaces – newest furnace will have 1 m long hot zone

Large OP furnaces to heat treat large coils

Industrial experience with OP furnace

Research furnace - 100 bar hot wall

Deltech 50 bar cold wall

Renegade (new) 50 bar cold wall

Sumitomo Electric OP furnace for Bi-2223 - 200 bar cold wall – in use for 15 years

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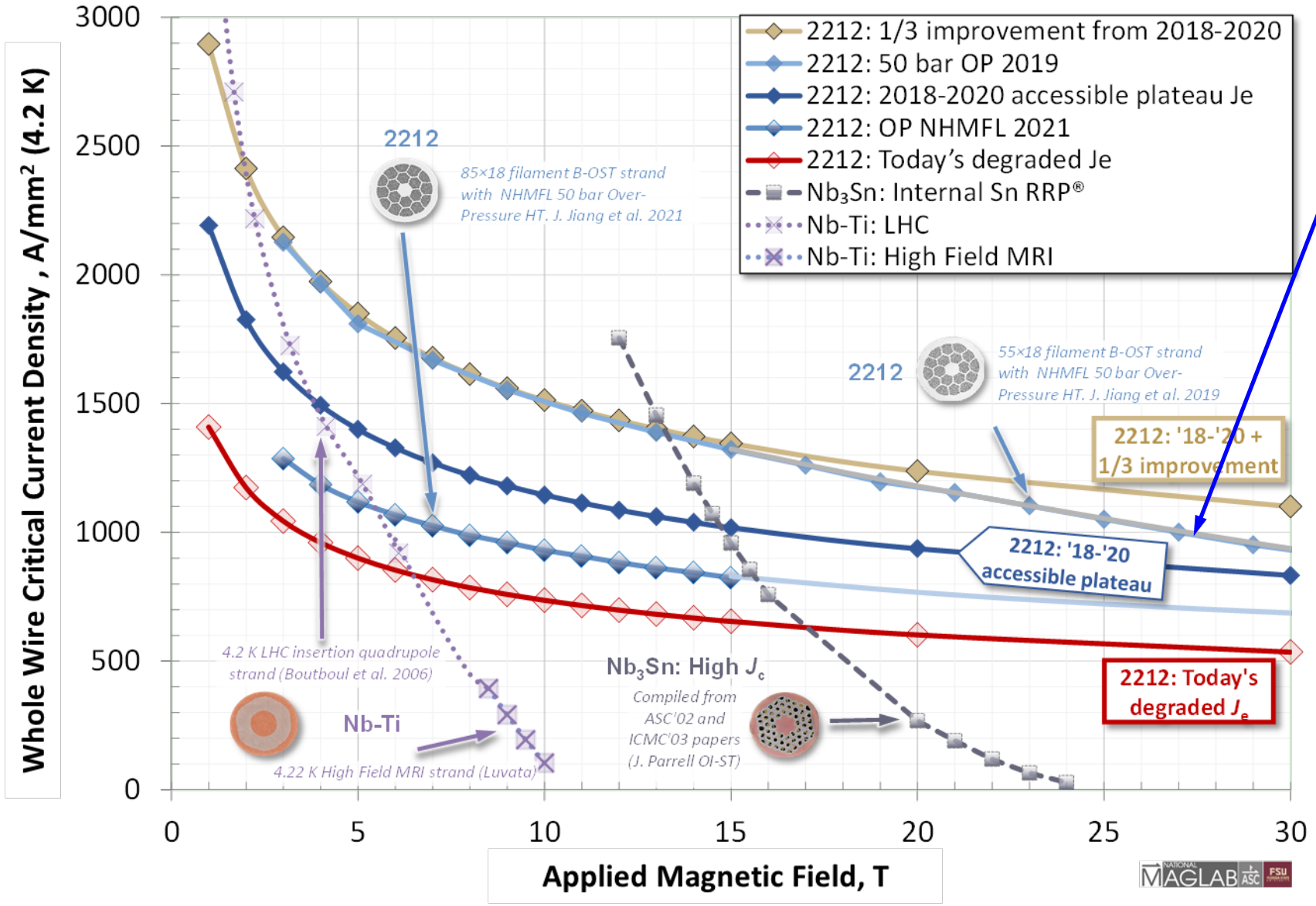

Record Bi-2212 J_E (2017)

950 A/mm² 4.2 K, 30 T

Lee

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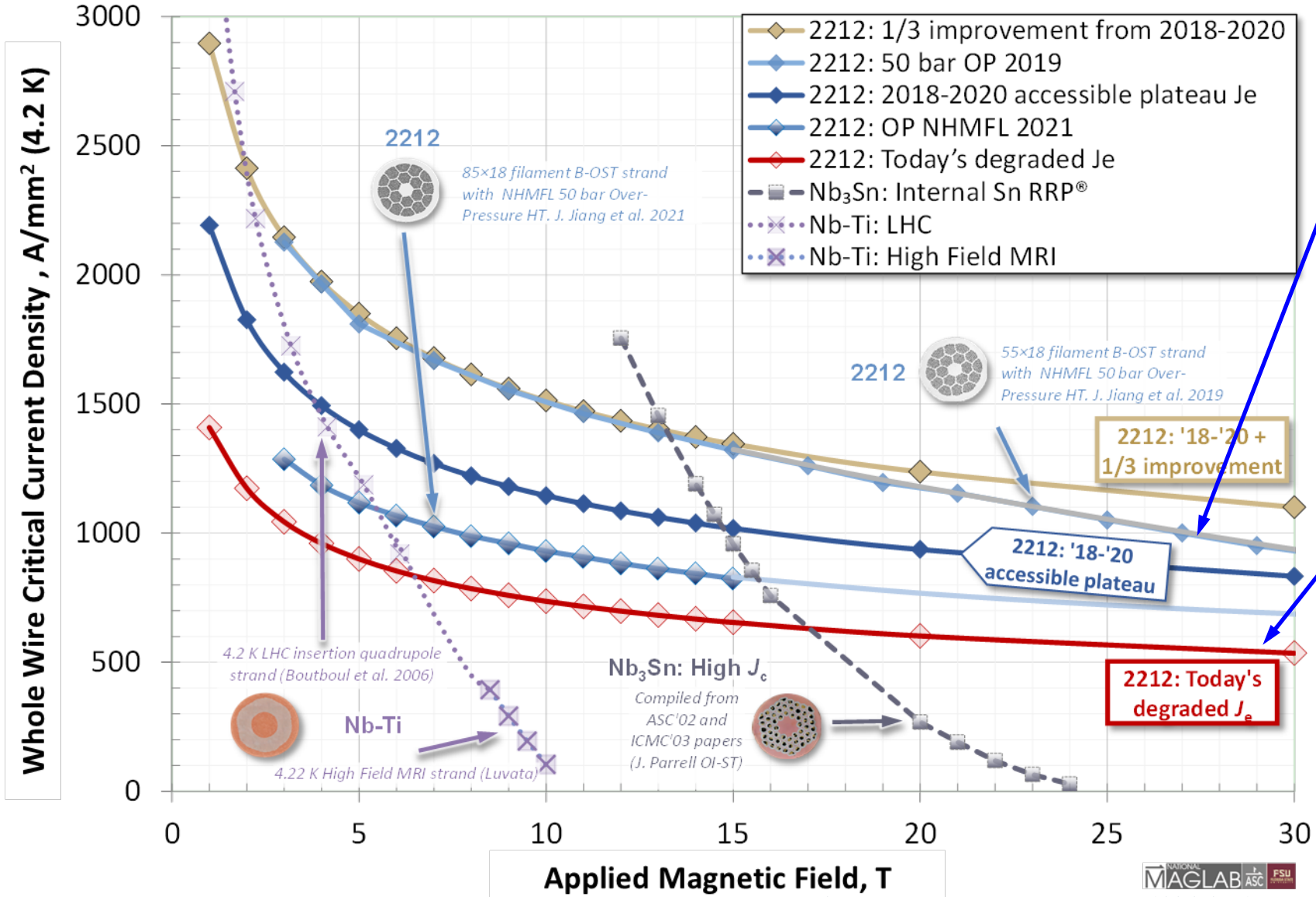
Problem - J_E has degraded since 2017



Record Bi-2212 J_E (2017)

950 A/mm² 4.2 K, 30 T

J_E has degraded since 2017

550 A/mm² 4.2 K, 30 T

Lee

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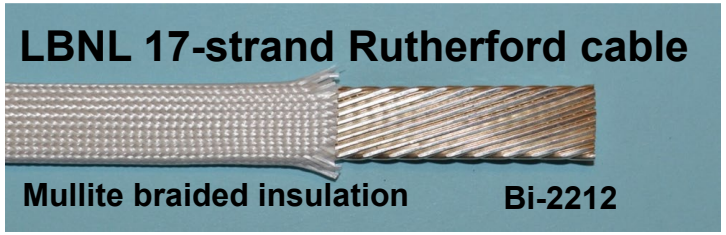
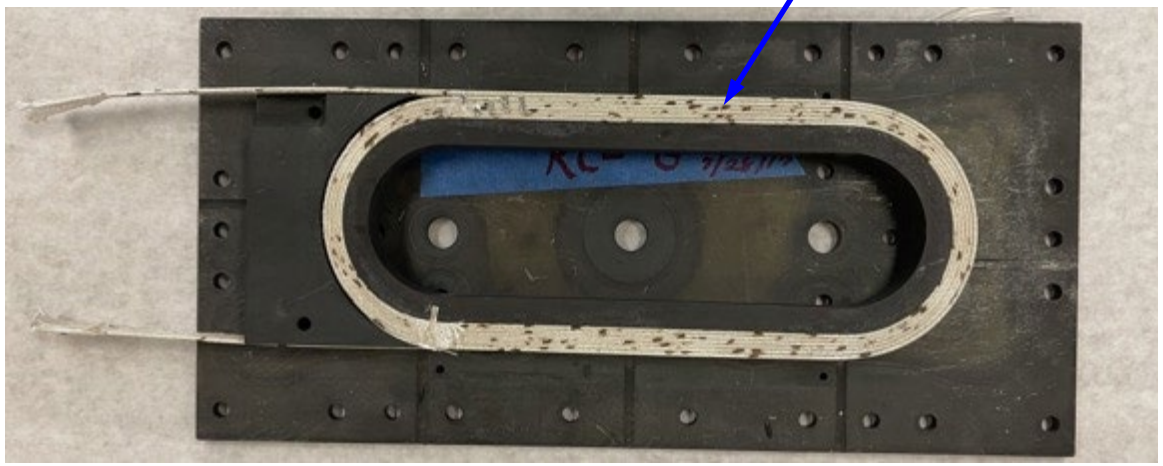
A Key Technology for Bi-22212 is Conductor Insulation:
The problem - leakage

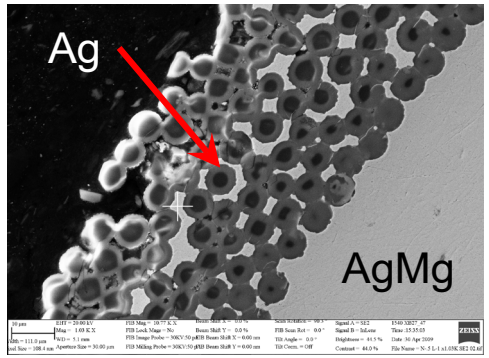


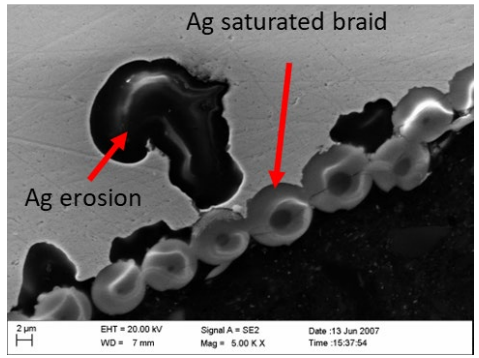
LBL racetrack coil - leakage after OPHT with alumino-silicate braid



Shen

Thermodynamic leakage is a serious issue: Ag dissolves into alumino-silicate fiber degrading the fiber and eroding the Ag matrix





LoSchiavo

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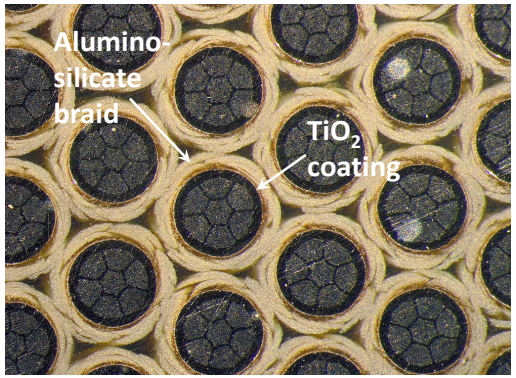
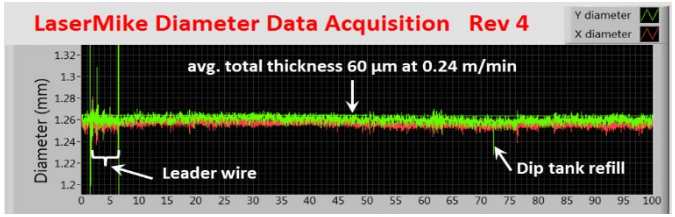
A Key Technology for Bi-22212 is Conductor Insulation: Solutions to prevent leakage

1. introduce a layer of TiO_2 on the conductor to serve as a chemical buffer, which works very well for Bi-2212 strand

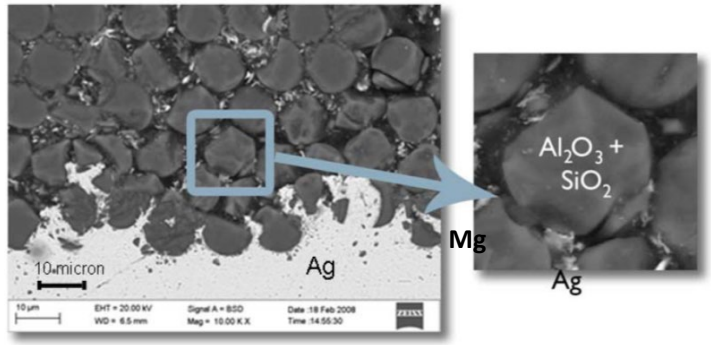




In-house insulation facility (top) and diameter measurement after the process (bottom)

(Jun Lu, NHMFL)

2. New braiding machine allows use of pure alumina fiber as braid; does not react with silver and eliminates need for TiO_2 layer



99% alumina, 12 µm fiber after heat treatment

Kim, Davis, Barua

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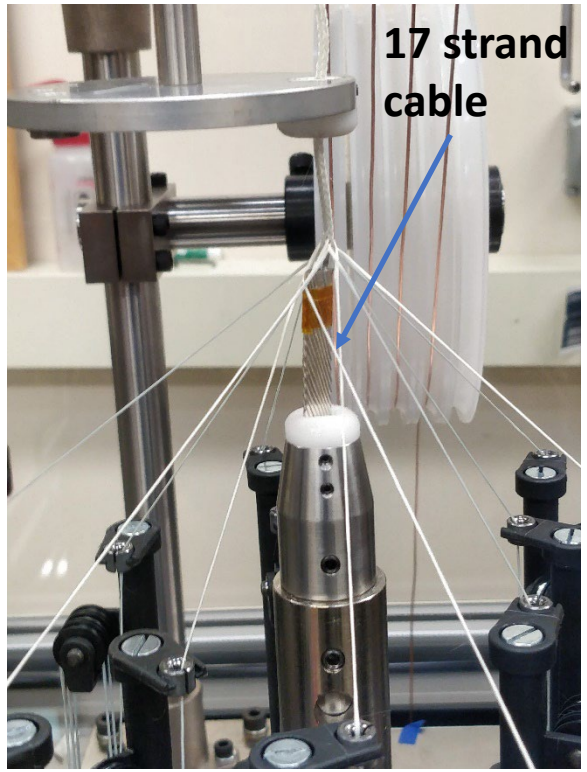
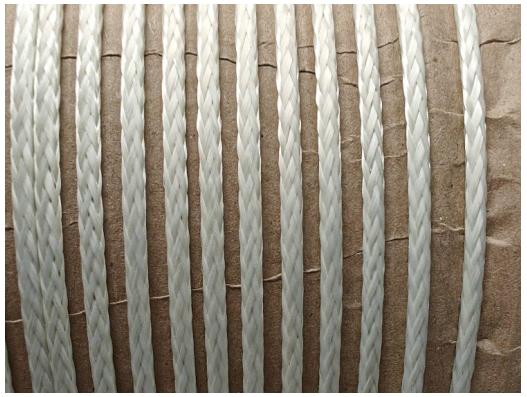
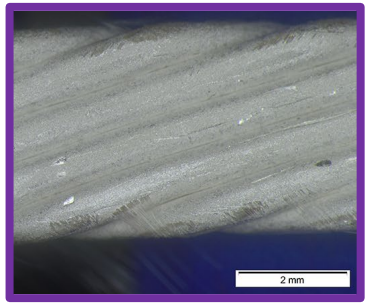
Braiding pure alumina on Rutherford Cable



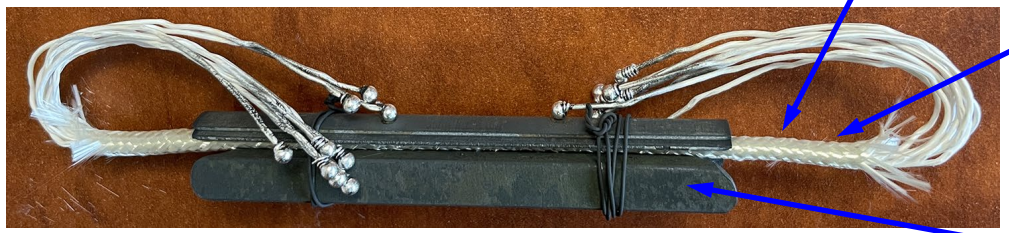
LBNL 2008 with alumina braid



Clean Ag surface after OPHT – no reaction



Rutherford cable with alumina braided after OPHT – no leaks



Pure alumina braid

Inconel compression blocks

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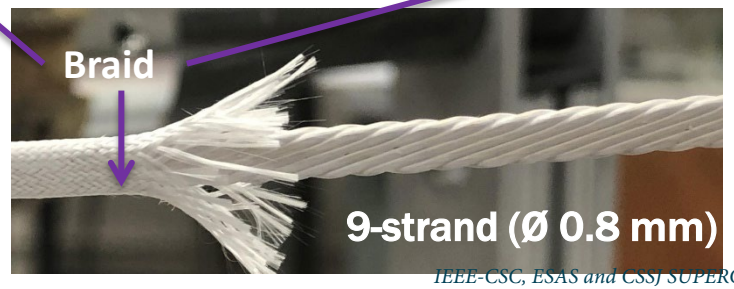
Unexpected leakage with alumina insulation

Problem with Rutherford cable

Alumino-silicate

Alumina



Davis

Teo-BR-1

Teo-BR-2

Alumina – 6 strand 0.7 mm diam

Alumina does not react with Ag, but once leak happens both fiber types will react with liquid Bi-2212

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The promise of Bi-2212 – high-field magnets

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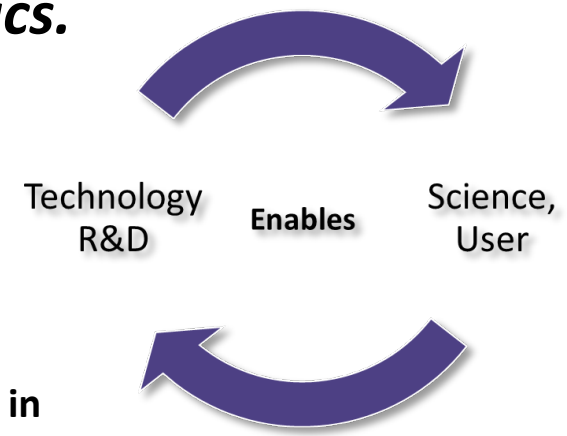
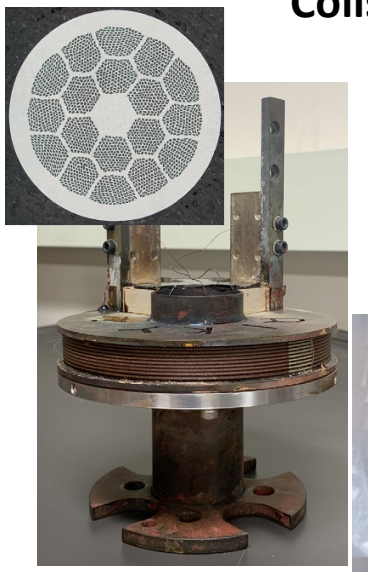
Bi-2212 for High Field Magnets

Bi-2212 is no longer just a conductor technology but a developing magnet technology with support from DOE-HEP, DOE-OFES (INFUSE), NIH, and magnet industry like Oxford Instruments, and Cryomagnetics.

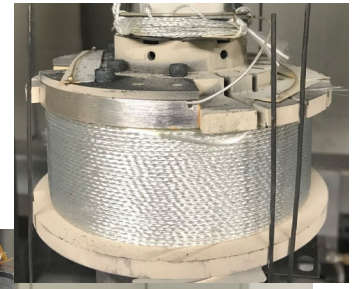
- **Bi-2212 has unique, attractive properties compared to other commercial HTS:**
  - **Round wire, multifilament, macroscopically isotropic**
  - **Can be twisted to reduce charging losses, can be cabled easily.**
- **Bi-2212 conductor technology makes it suitable for use in magnets:**
  - **Very high transport properties (1200 - 1400 A/mm^2 in coil samples and up to 1900 A/mm^2 in short samples).**
  - **Can be produced on 1 + km lengths scale with reproducible performance over these lengths.**
- **ASC is focusing on both, Bi-2212 strand and cable coil technology.**

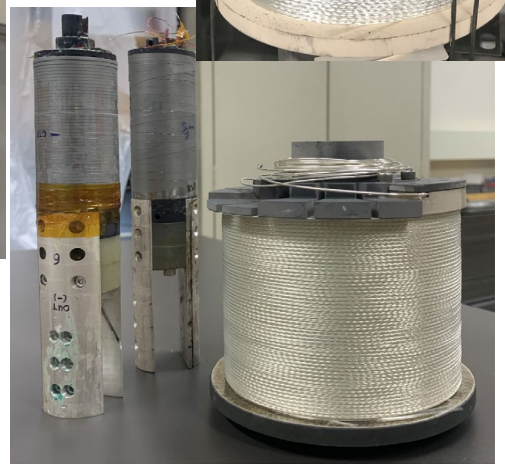


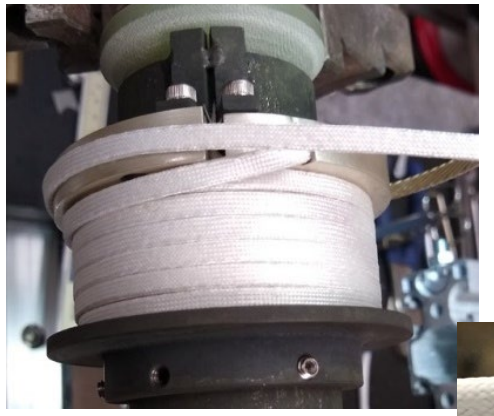
Coils made at ASC:



Bi-2212 strand coils







Bi-2212 Rutherford cable (LBL)

Trociewitz

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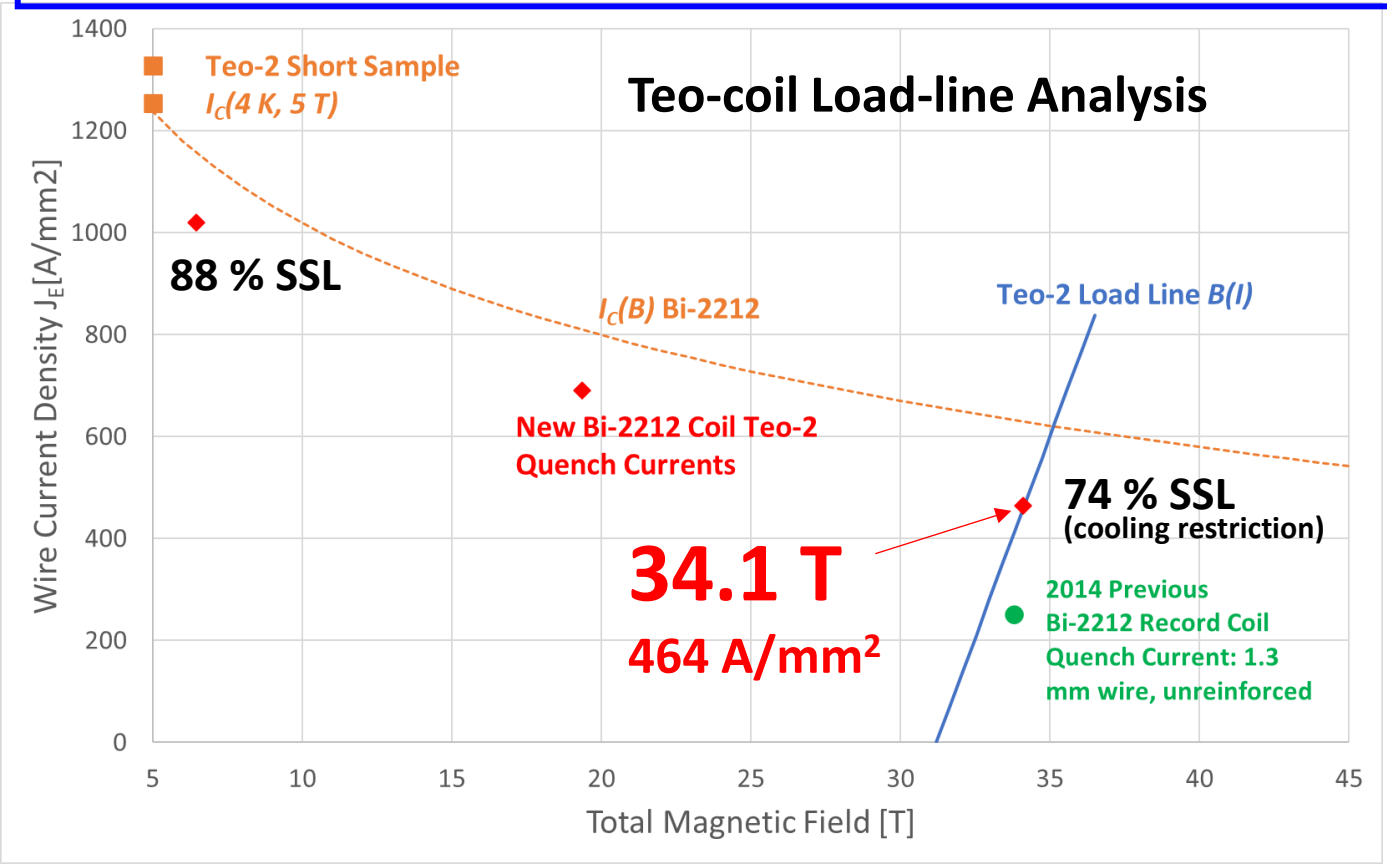
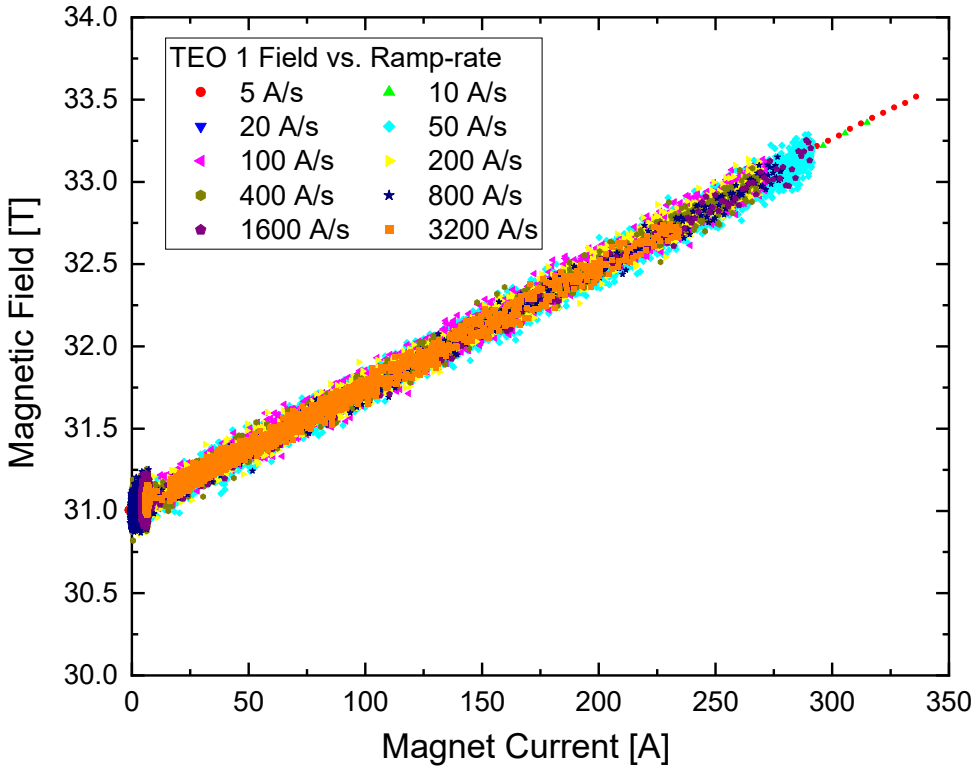
Robust Operation of Bi-2212 Magnets in Highest Fields

This is an important demonstration to our industry and lab collaborators in HEP and fusion (ohmic heating solenoids), as well as to our own high field magnet goals



Field generation is consistent across vastly different ramp rates up to highest ramp rates of > 23 T/s



Trociewitz, Kim, Davis, Martin

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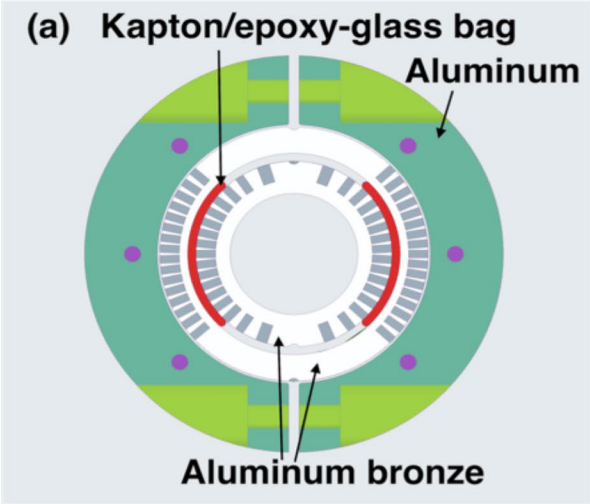
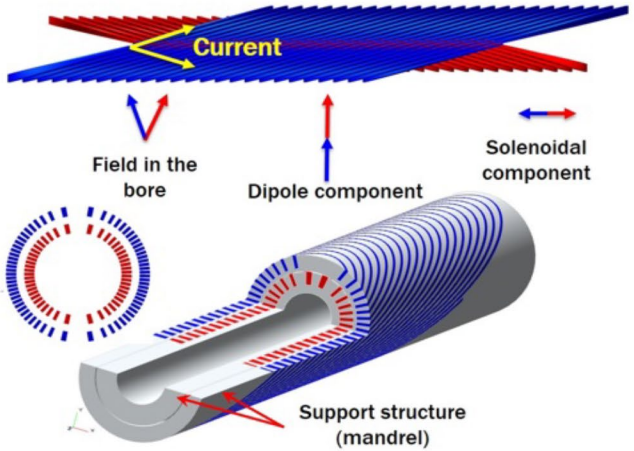
Cable and magnet fabrication expanded to canted-cosine-theta coil prototyping

CCT dipole magnet BIN5, 1.6 T in 30.8 mm bore, 39 cm in length





Shen

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Summary

- Overpressure processing eliminates bubbles, making Bi-2212 a viable high-field conductor
- Early Engi-Mat powder demonstrated high J_E & J_C - but performance has degraded
  - Working to understand degradation and increase performance
- Have solved insulation problem for single strand and cables using pure alumina braid
  - Pure alumina also strengthens the coil pack
  - Unexpected problem with some Rutherford cable leakage – working on this problem
- Demonstrated high-field (34 T) in small coils

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