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Evidence of Excessive Ag-Mg Grain Growth Resulting in Sheath Rupture and Leakage of Bi-2212 Rutherford Cables During Overpressure Processing

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Outline

This work explores the mechanisms of ceramic leakage in Bi-2212 Rutherford cable coils, a limiting factor for the coil performance.

Understanding the mechanisms has important implications for conductor technology and magnet performances.

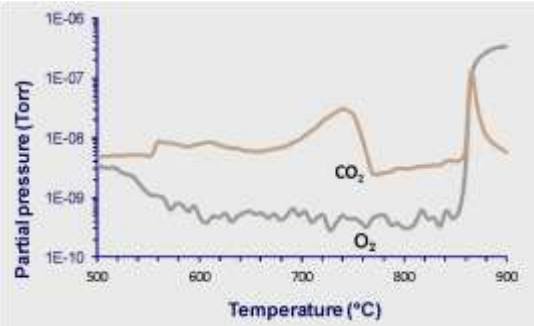
Leakage mechanisms we have understood so far

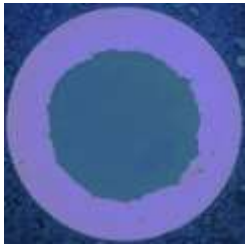
[1] Reaction between Ag/Bi-2212 conductors and oxides. (Wesolowski, Hellstrom, 2005 *Supercond. Sci. Technol.* 18 934)

[2] **Creep rupture** of Ag-Mg sheath due to internal gas pressure.

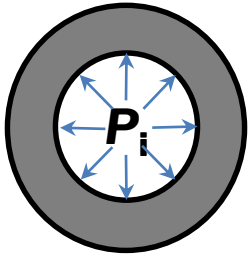
Creep rupture: Shen et al., J. Appl. Phys., **113**, 213901 (2013)
OPHT: (1)J. Jiang, SuST, *Supercond. Sci. Technol.* 24 082001(2011)
(2) D. Larbalestier, Nature Materials 13, 375–381 (2014)

Gas pressure increase with *T*.

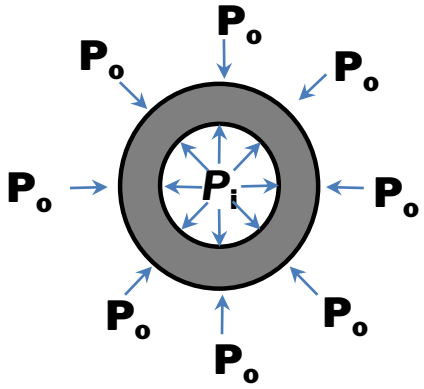




Like a pressure vessel at high-temperatures.



Conventional 1 bar heat treatment
Ag creeps outward -> creep rupture of Ag-Mg



Overpressure processing
Ag creeps inward -> densification

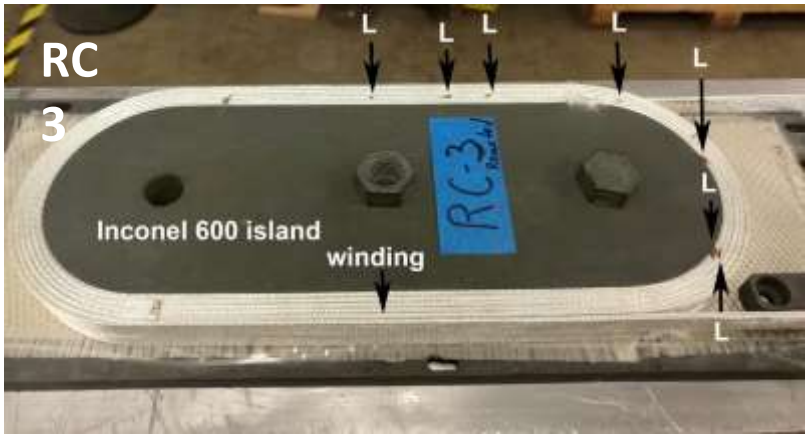
Leakage Observed in OPHT Bi-2212 Rutherford Cable Coils: [1] Why does it occur?

- Leakage frequency is inconsistent. RC4, for example, leaked much more than RC5 despite having the same wire architecture, cable parameters, and heat treatment schedule.
- **Why such variation?**

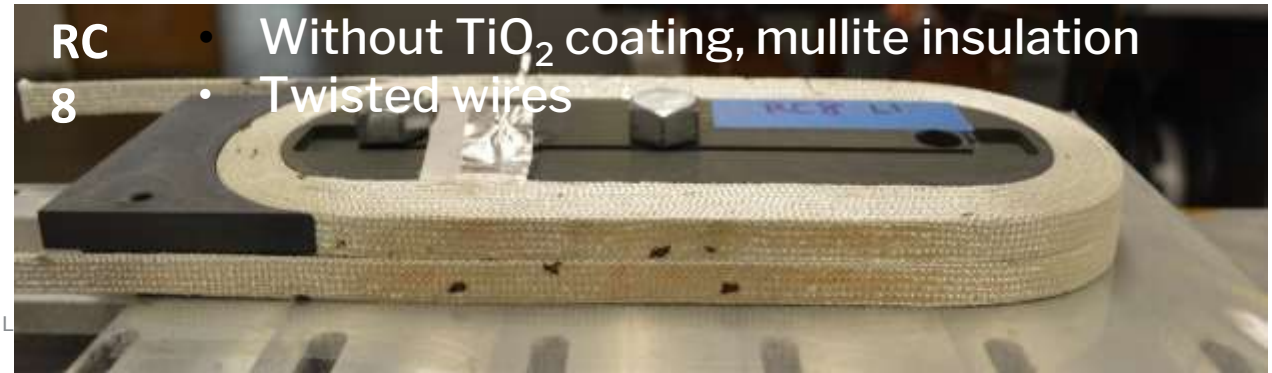
Racetrack Coil 4 (RC4)

Racetrack Coil 5 (RC5)

Leakage Observed in OPHT Bi-2212 Rutherford Cable Coils: [2] Why does it vary?



Mullite + TiO_2
Nearly no leakage



Leakage Observed in OPHT Bi-2212 Rutherford Cable Coils

[1] Why does it occur? Leakage in OPHT round-strand solenoid is largely eliminated.

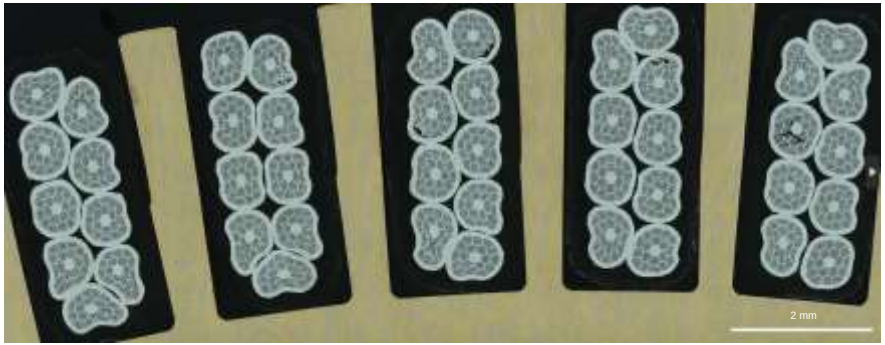
[2] Why does it vary from one coil to another?

[3] Why does it occur only locally?

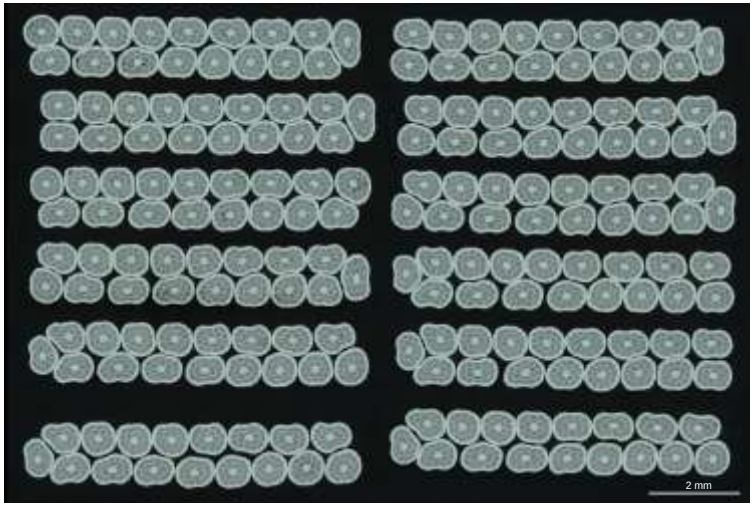
[4] To what degree does leakage affect coil performance in terms of Ic, n-values, and field generation ability?

Postmortem Coil Analysis in three OPHT LBNL coils

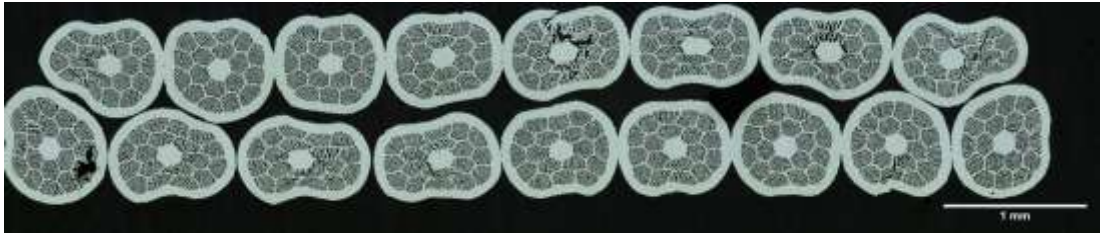
CCT Bin5aOL (50 bar OPHT)



RC5 (50 bar OPHT)



RC4 Cable (50 bar OPHT)

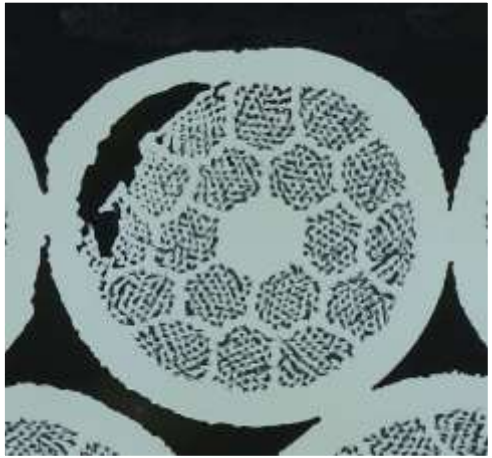


Postmortem analysis revealed two Types of Leakage in OPHT Rutherford Cables and the occurrence of AgMg outer sheath ruptures

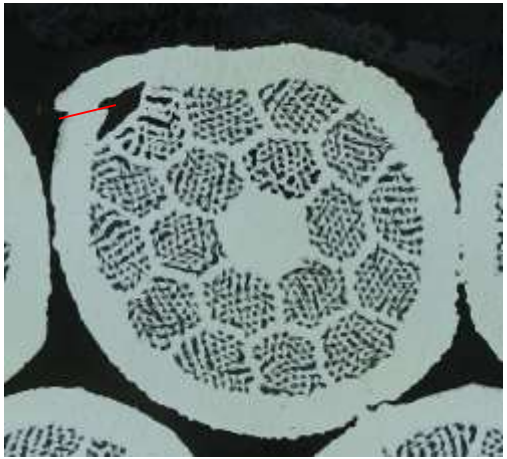
Sheath Debonding and
Internal Leakage

Sheath Rupture resulting
in **external leakage**

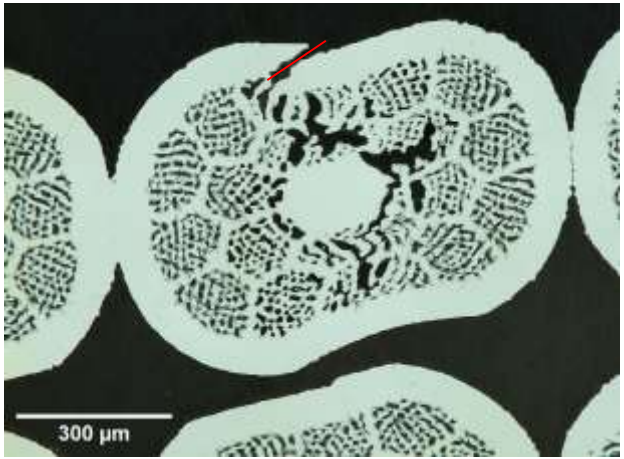
RC5: 3/18 Bundles affected



RC5: 1/18 bundles affected

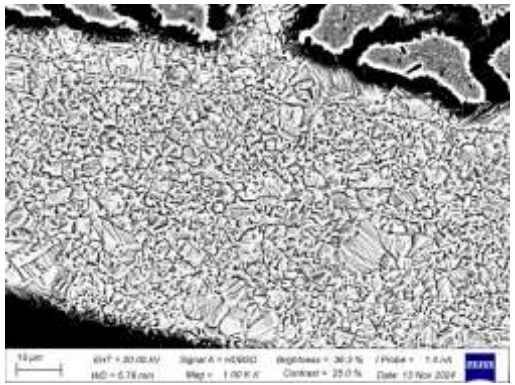


RC4: ~9/18 Bundles affected

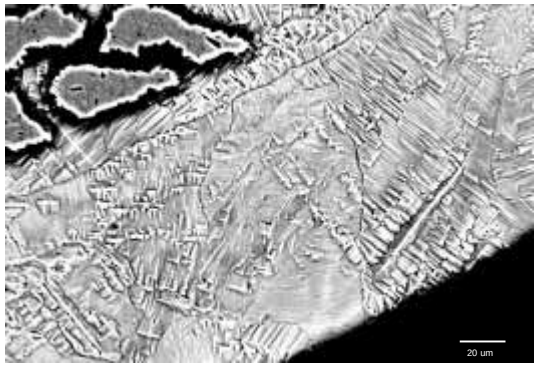


Grain Size and its Relation to Leakage found in ARDAP Round Wires

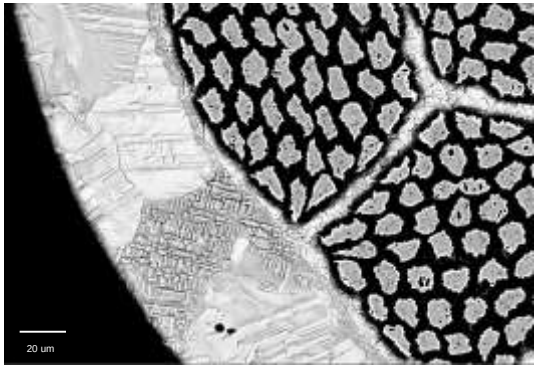
ARDAP Billet Grain Analysis from Dr. Jiang



ARDAP #3: Fine grains. (J. Jiang)



ARDAP #4: Very large grains, no intermediate annealing. Leakage in the OPHT round wires.
(J. Jiang)

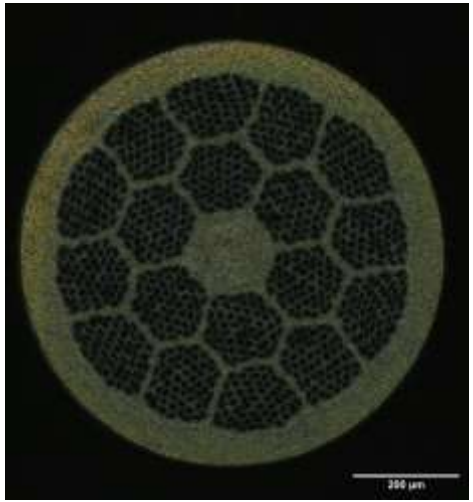


ARDAP #5: Large grains are present, some variance. Leakage in the rolled OPHT ARDAP #5 strands (S. Barua)

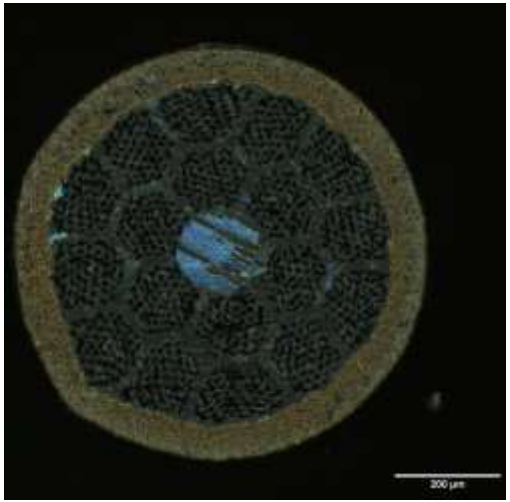
Microstructure of Round Wires vs Cabled Wires indicate AgMg Grain Growths associated with cabling process

- The deformation of the wire during the cabling process spurs grain growth at those boundaries.
  - We hypothesize that these grains are more ductile and densify at different rates, resulting in sheath rupture (indicated by red box).

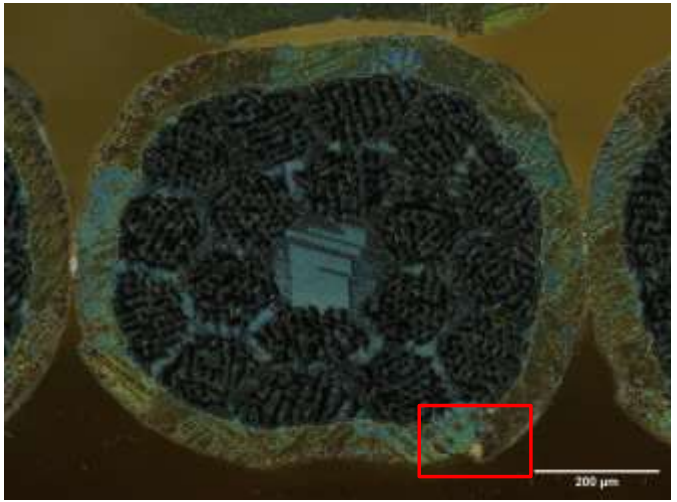
RC5 Wire (PMM170123): Green



RC5 Wire (PMM170123): OPHT

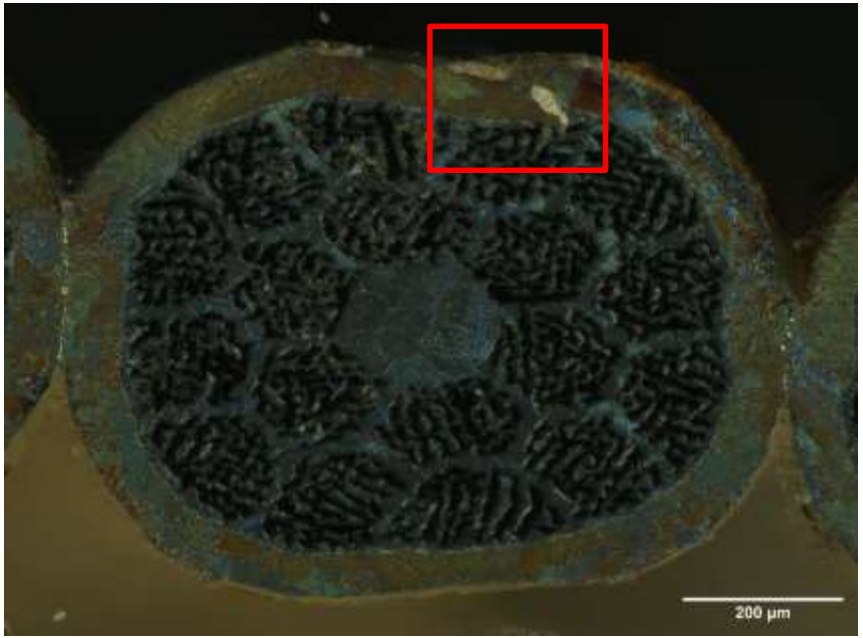


RC5 Strand in Rutherford Cable Coil: OPHT

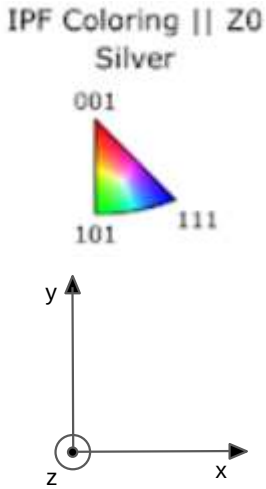


Microstructure of RC4 coil cross-section confirmed large AgMg Grain Growths connected with sheath ruptures

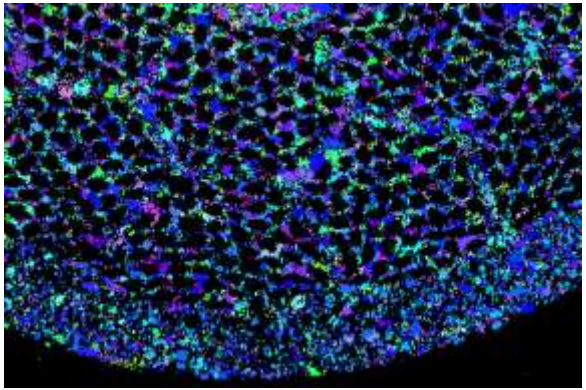
- Grain Size analysis of sheath rupture regions of the RC4 coil strands



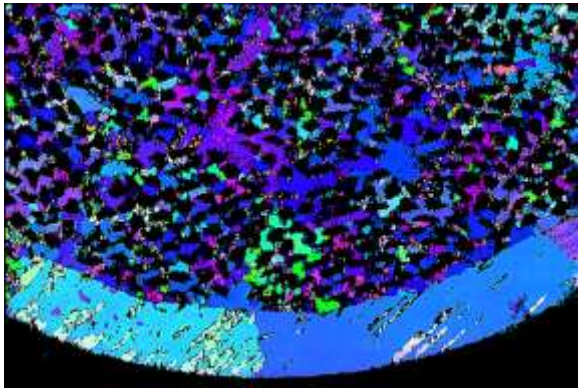
SEM EBSD Maps of Round Wires (IPF-Z) showed that grain sizes in wires from industry varies, perhaps leading to variations in leakage severity in different coils



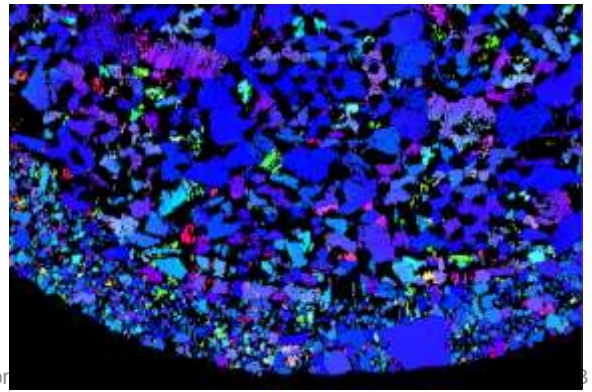
RC5 (PMM170123) Green Wire



RC4 (PMM160913) Green Wire

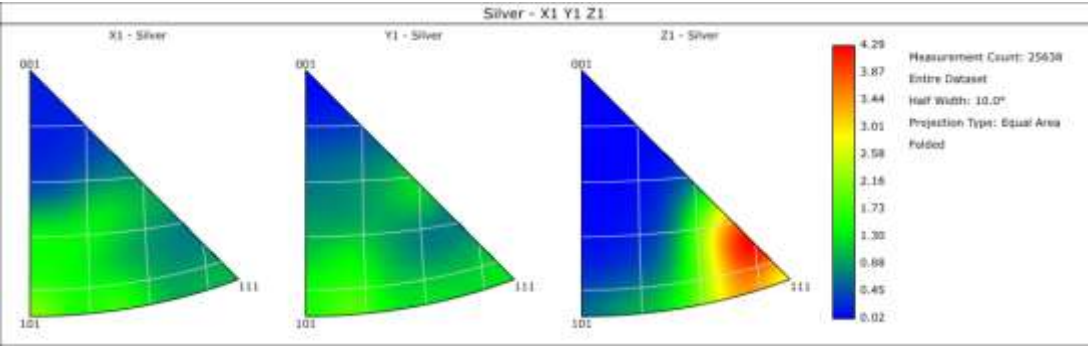


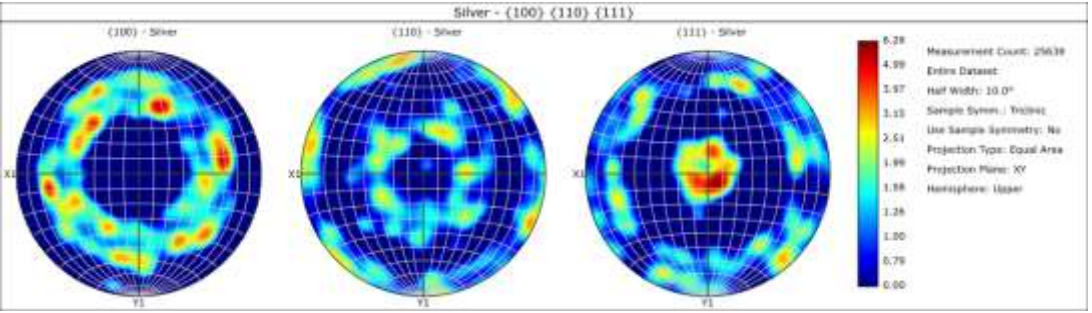
RC5 OPHT Wire

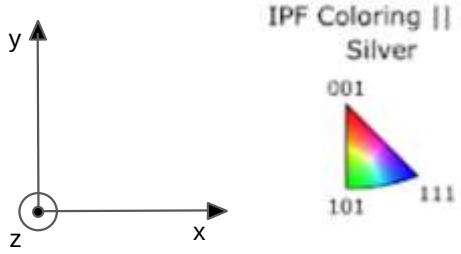


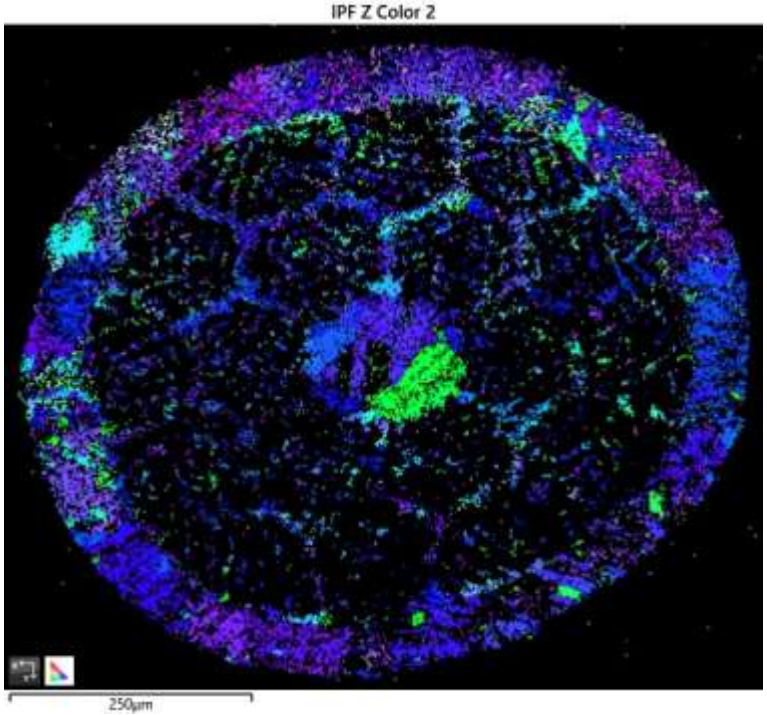
- We hypothesize that the leakage discrepancy is a result of large grains that are formed or already exist in the Ag-Mg sheath.
- RC4 OPHT shown in the next slide

RC4 RW: OPHT Round Wire









Summary

This work first reveals two types of leakage in Bi-2212 Rutherford cable coils and its potential connections to sheath ruptures.

We also suggest that sheath ruptures are connected to the excessive grain growths in Ag-Mg outer sheaths.

- Grain growths are exacerbated by Rutherford cabling process, likely due to the addition of strain energy.
- Grain structure of wires from industry have variations, likely contributing to the differences in severity of leakage found in different coils.

Follow-up questions and Ongoing investigations

Now we know this, so what?

What are implications? Rutherford cable solenoids likely leak (D. Davis with babyRuth coils)

What about RC3 (non twisted) and RC7/RC8 (twisted) strands and their sibling strands?

How to solve the problem?

- Wire manufacturers: Understand how grain growths associated with their raw materials and thermomechanical processing.
- Cabling@LBNL: Can **intermediate annealing** (5% rolled, annealed, then 20% rolled; 10% rolled, annealed, and then 20% rolled.) help remove the strain energy and prevent excessive grain growths and leakage?

Thank You

Thank you your support.