BERKELEY LAB
Bringing Science Solutions to the World

U.S. DEPARTMENT OF ENERGY
Office of Science

Key Results of A DOE-ARDAP Bi-2212 Project

Tengming Shen (LBNL)
Collaborating Institutions: Bruker OST LLC.,
Engi-Mat Co., National High Magnetic Field Lab

U.S. MAGNET DEVELOPMENT PROGRAM

August 27th, 2025
At the US Magnet Development Program Biweekly Meeting

Work supported by U.S. Department of Energy, Office of High Energy Physics, Accelerator Stewardship and Accelerator Development Programs

Overview of the project

- **A 2.5-year project that funds direct industry – national labs – university collaborations (09/2023 – 02/2026)**

BERKELEY LAB

BRUKER

NATIONAL MAGLAB

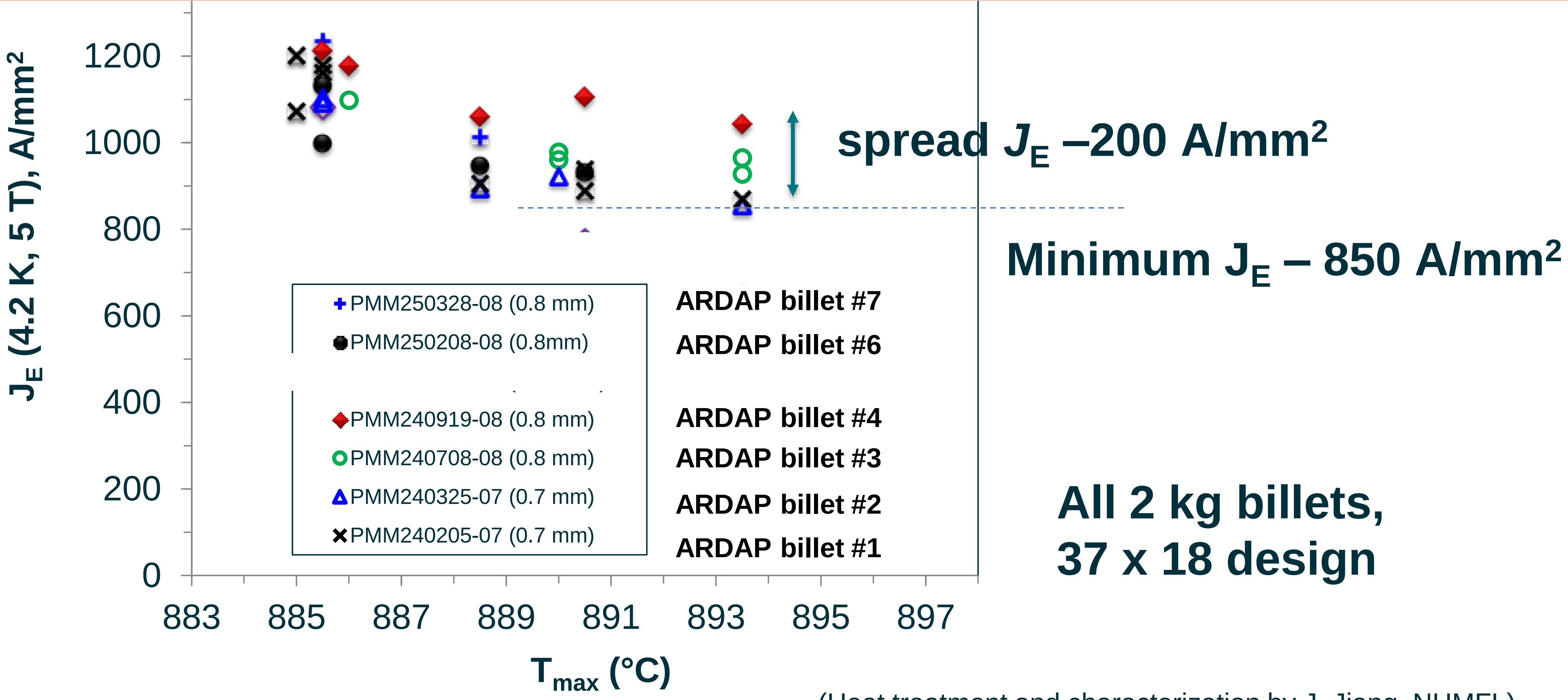
ENGI·Mat NANO ENGINEERED MATERIALS

Work supported by Office of High Energy Physics, Accelerator Stewardship and Accelerator Development Programs

- **Nine 2 kg billets production targeting reproducibility.**
- **Scale up production with a 10 kg billet.**
- **Establish knowledge base and fundamental understanding.**
- **Attempt new insulation on Rutherford cable coils.**

Statistical performance of eight ARDAP Bi-2212 billets and implications

- **Wire uniformity and production consistency are high.**
- **Wire performance needs to be raised by 50% for Bi-2212 to be competitive.**
  - **To raise minimum wire J_E(4.2 K and 5 T) > 1275 A/mm^2 and J_E(4.2 K and 20 T) > 850 A/mm^2**

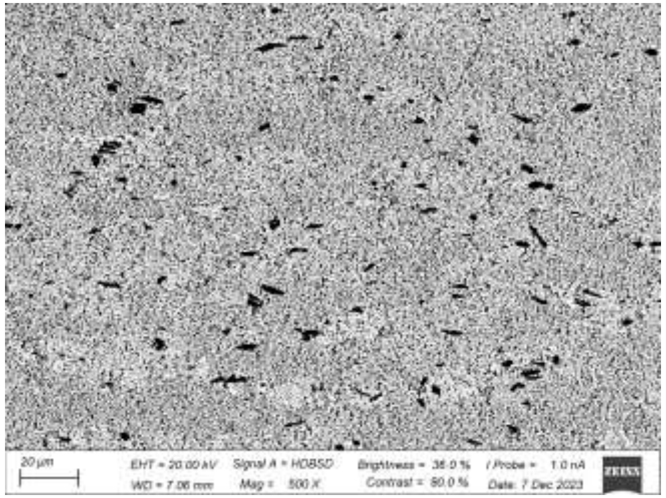


All 2 kg billets, 37 x 18 design

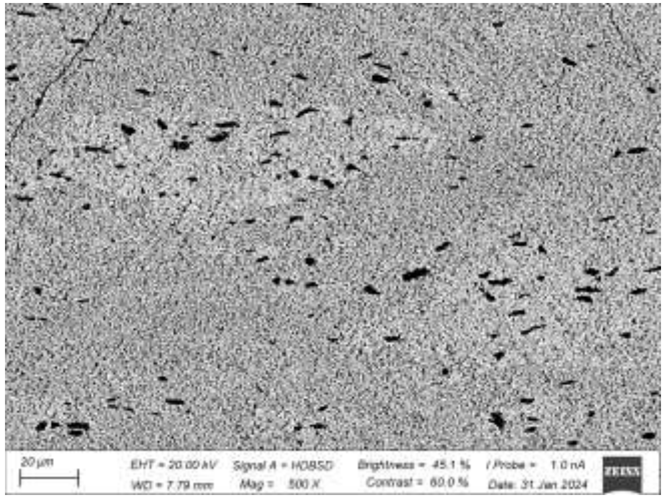
(Heat treatment and characterization by J. Jiang, NHMFL)

Powder characteristics and wire performance

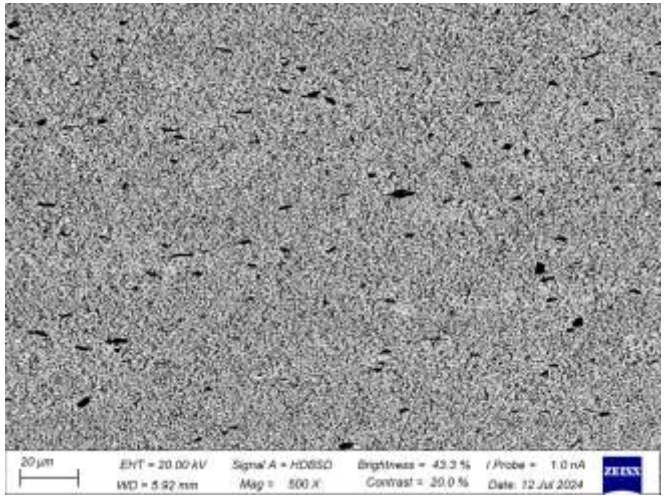
ARDAP billet #1



ARDAP billet #2



ARDAP billet #3

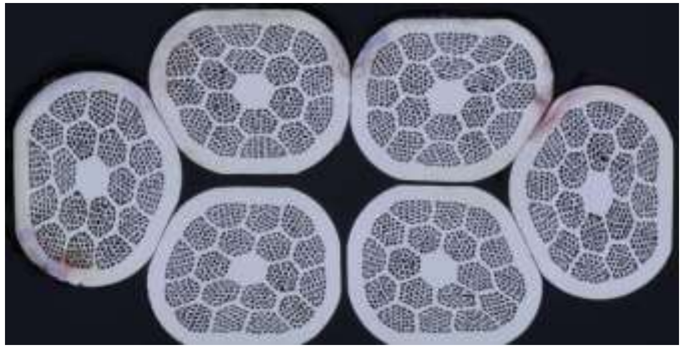


Are there a set of quantitative measures of powder characteristics that correlates to wire performance?

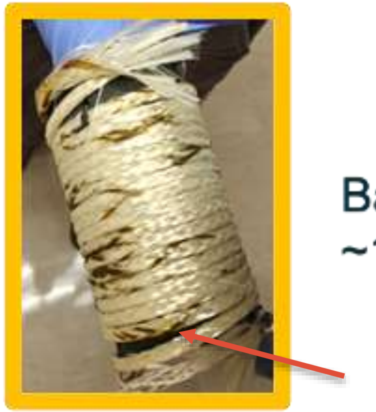
ARDAP billet #1 and #2, when drawn to 0.7 mm and produced as Rutherford cables, showed pronounced leakage in both round barrels and insert coils

~150 m 6-strand cable (strand d = 0.7 mm) fabricated@LBNL

Ian Pong, Andy Lin, Elaine Burron, LBNL, cable production



High-field barrel test



Barrel LBL-2007-B
~1.7 m, ϕ32 mm

Leakage (S. Barua, NHMFL)

Insert solenoid for 31T @ NHMFL

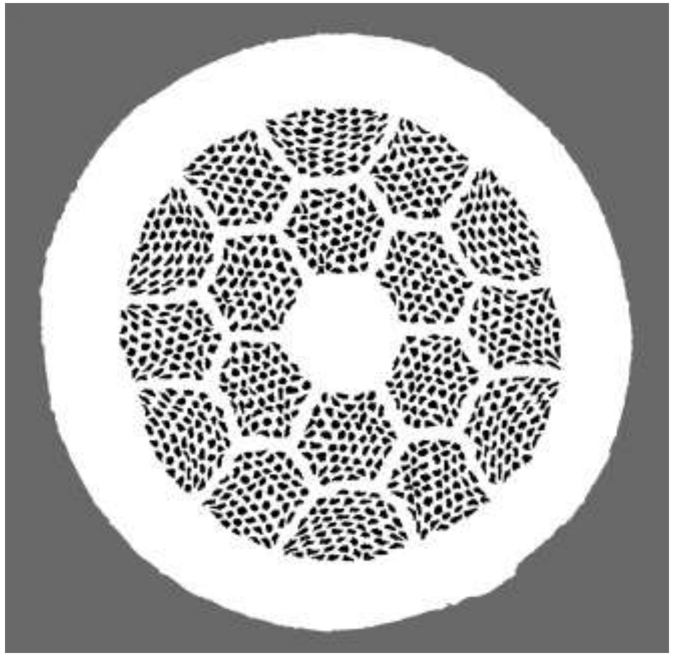
Teo-BR-1 and Teo-BR-2

Teo-BR-2 ramped at 200 T/s to +3.4 T in 31.2 T resistive magnet, despite leakage limited performance.
(D. Davis, Y. Kim, U. Trociewitz et al., NHMFL)

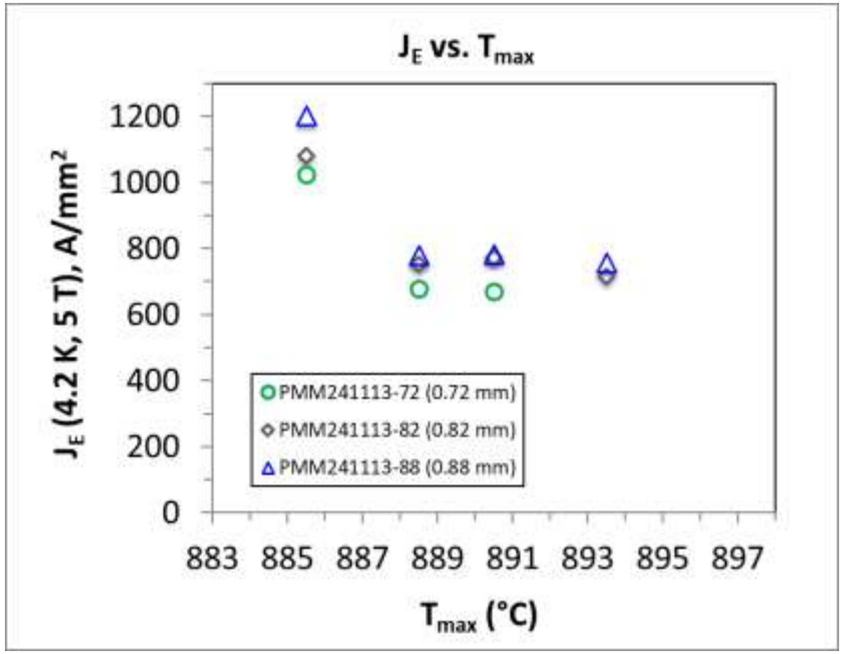
ARDAP billet #5 tests a wire design with thicker Ag-Mg sheath

~25% thicker Ag-Mg sheath.

Ag-0.2wt% Mg is an oxide-dispersion strengthened alloy.

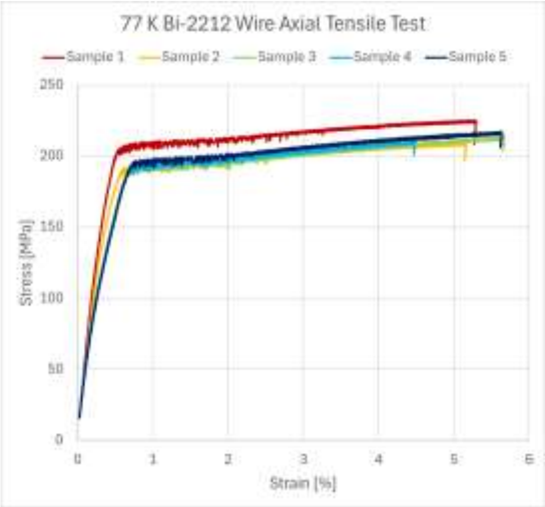


55 x 18 design



Filament uniformity analysis [Ahmed Hasnine Abuzar, Jianyi Jiang, NHMFL] indicates that this billet has poor transverse and longitudinal uniformity.

Billet #5 increases Ag-Mg sheath thickness by 25% to increase wire mechanical strength and minimize leakage during reaction.



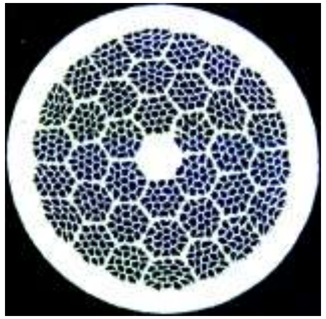
(E. Martin, PhD student, NHMFL)

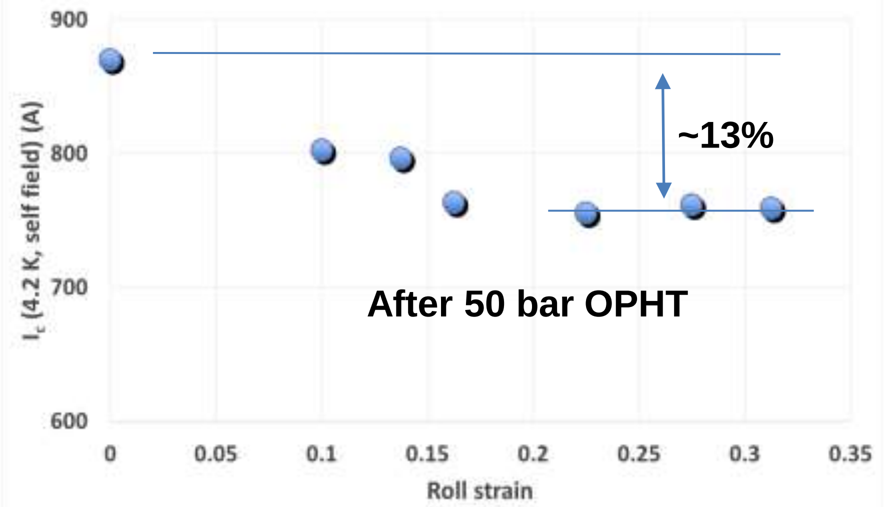
Understanding the cabling effects

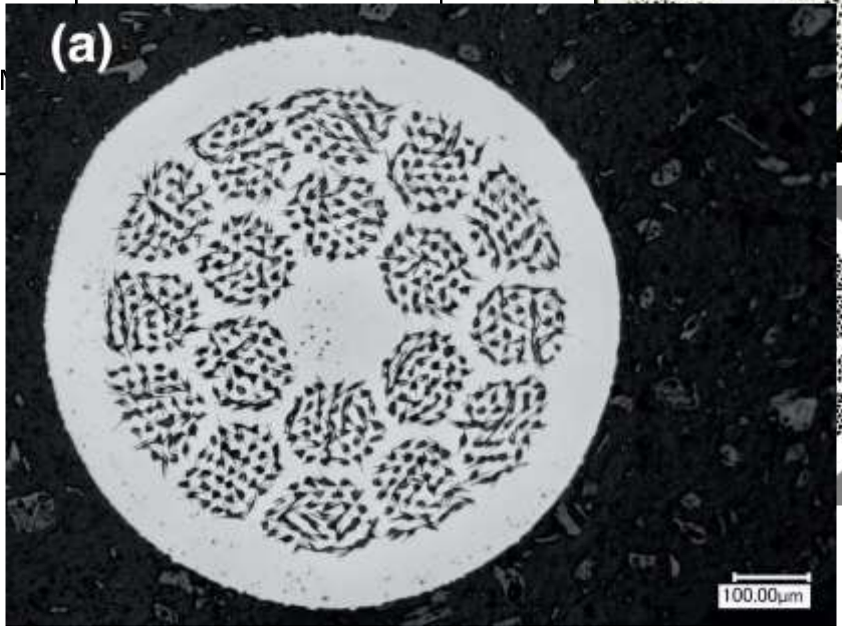
Task 5: Understanding the science and technology of attaining high J_E in Bi-2212 Rutherford cables

Shen et al., Scientific Reports Vol. 9, Art. No.: 10170 (2019)
Zhang et al Supercond. Sci. Technol. 31 105009 (2018)

Strands	Powder	Coils
19 x 36, 0.8 mm strands	Nexans	RC1
37 x 18, 0.8 mm strands.	Nexans	RC2/3
55 x 18, 0.8 mm strands.	Engi-[illegible]	[illegible]





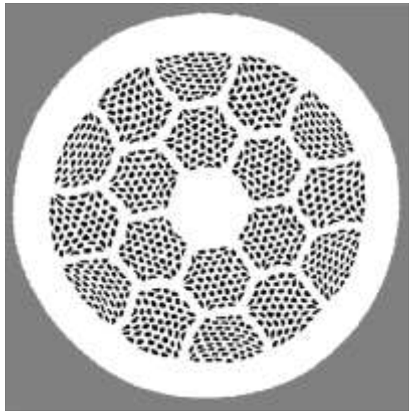


Shen et al., Phys. Rev. Accel. Beams 25, 122401 (2022);

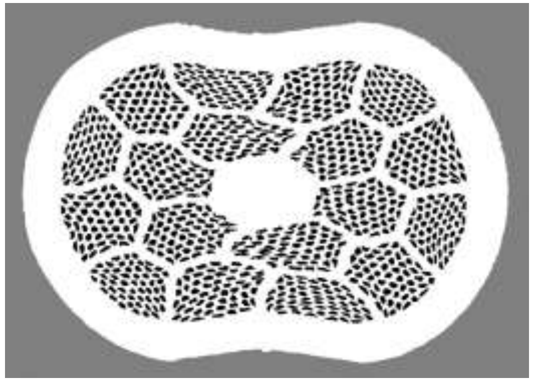
ARDAP study confirmed there is some cabling induced degradation due to filament geometrical changes.

(PMM170725, 55x18, 0.8 mm)

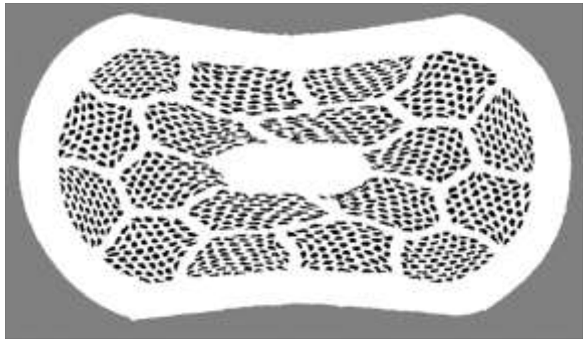
round



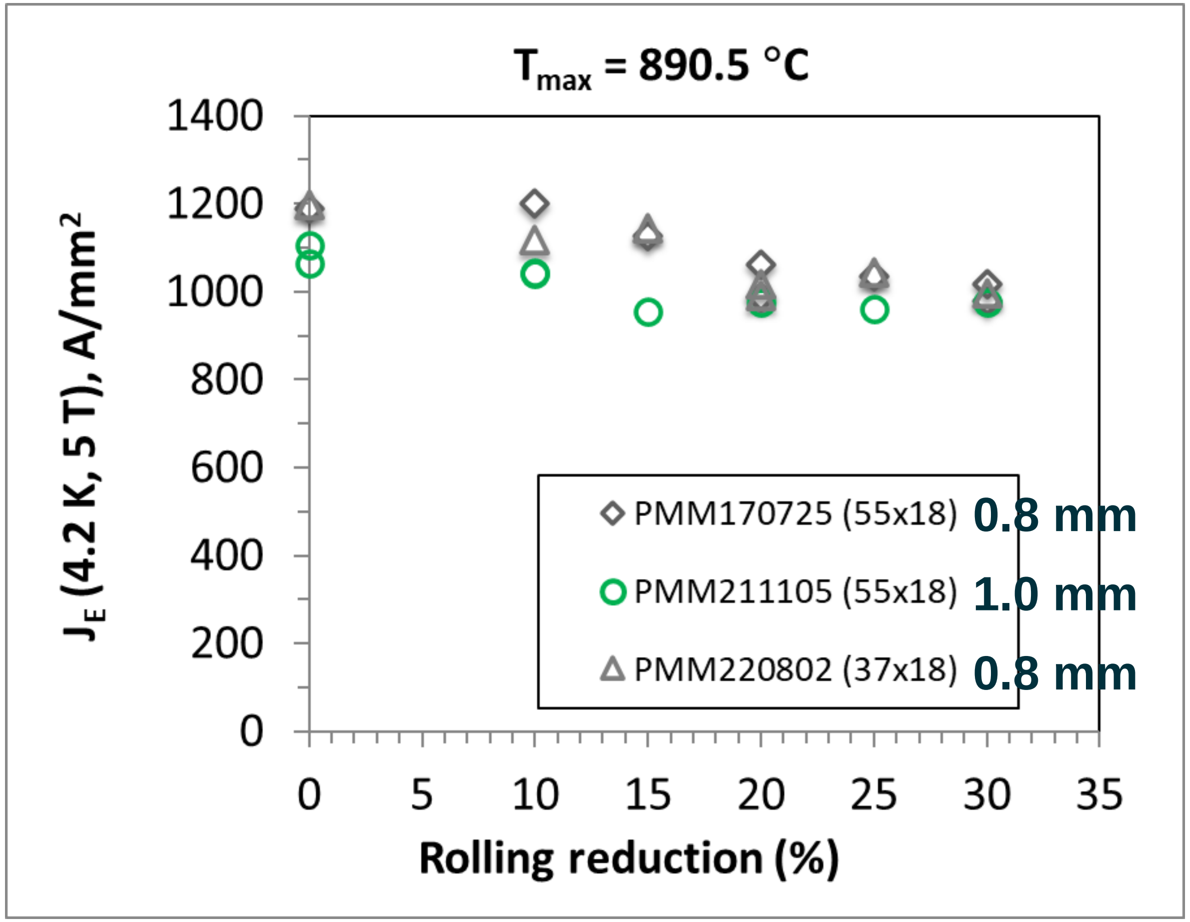
15%



30%



Rolling reduction reduced wire J_E by about 15 %, but the J_E decrease saturated at 15 to 20% thickness reduction.

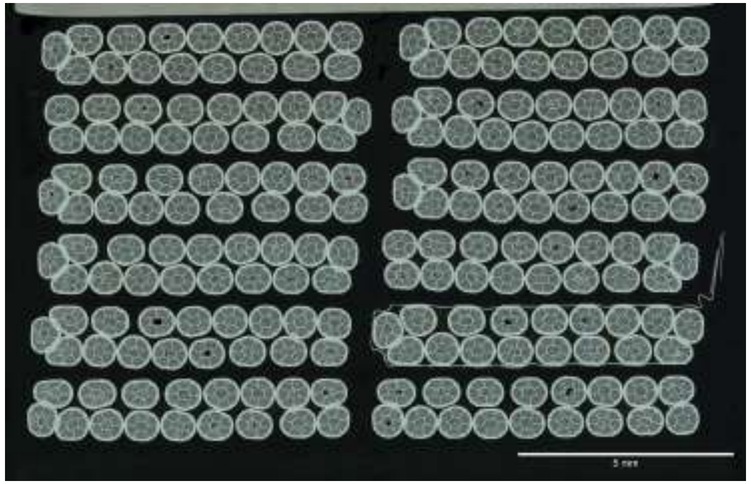


J. Jiang, IEEE TAS 10.1109/TASC.2024.3519083

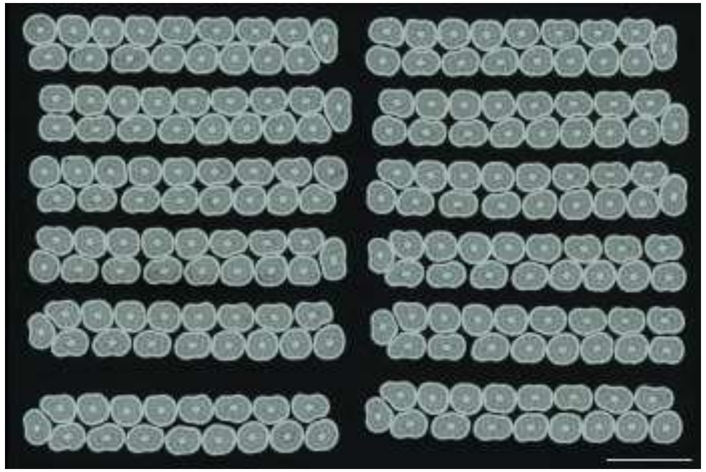
Insulation and leakage reduction for Rutherford cable coils

- **Metallography and post mortem analysis of racetrack and CCT coils (Chris Escobar, UCB/LBNL)**

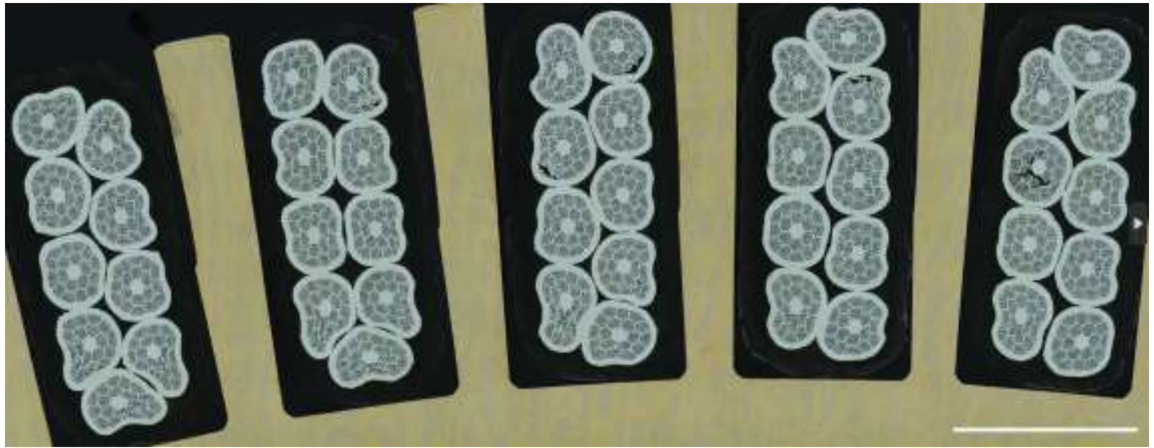
HTS-SC10 (Racetrack coil, 1 bar HT)



RC5 (Racetrack coil, 50 bar OPHT)



Bin5aOL (CCT coil, 50 bar OPHT)



Chris Escobar, UC Berkeley engineering, ME

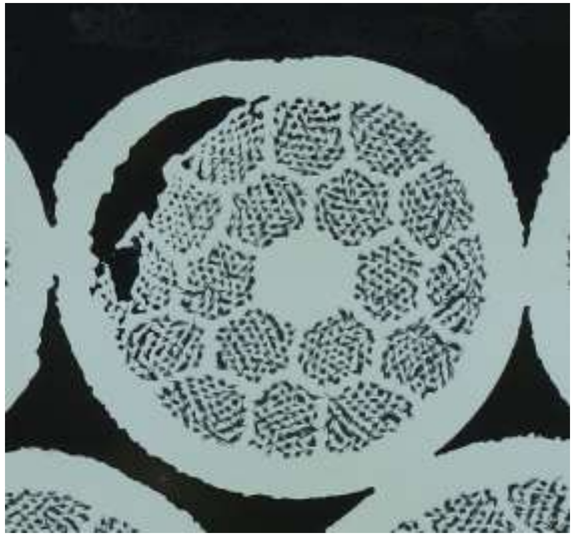
W assistance from JF Croteau

Insulation and leakage reduction for Rutherford cable coils

- **Two types of leakages and mechanisms in OPTH Rutherford cable coils observed.**

[Most commonly observed] Sheath debonding leads to internal leakage.

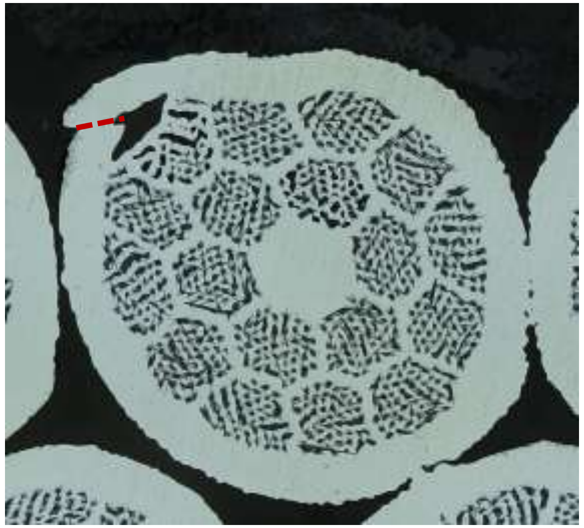
RC5



~3 of 18 bundles affected

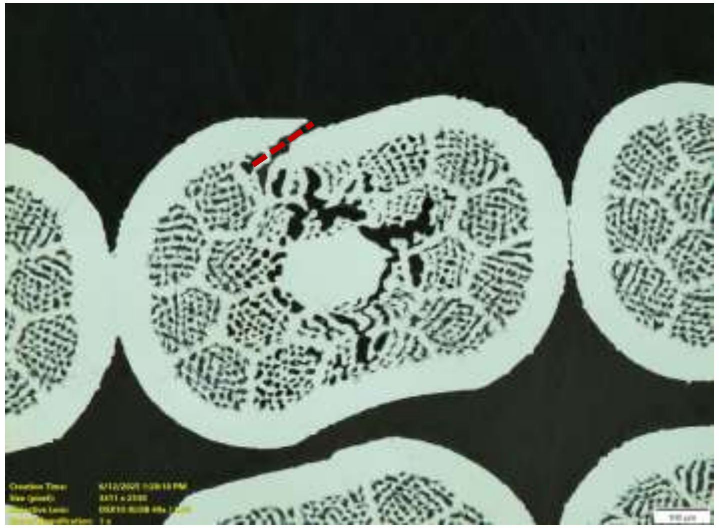
Sheath rupture causes external leakage.

RC5 (the highest performance coil)



1 of 18 bundles affected

RC4 (the most severely leaked coil)

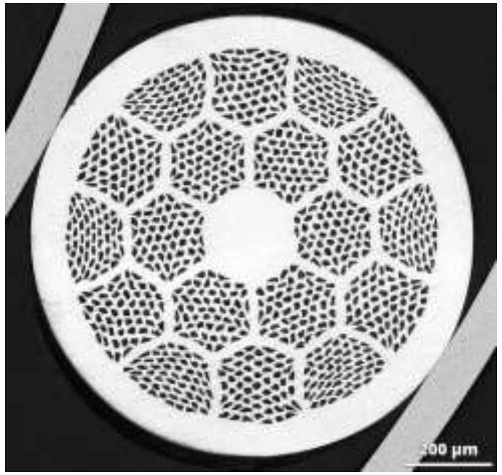


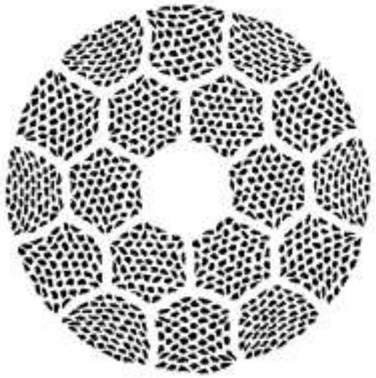
~9 of 18 bundles affected

Summary

- **ARDAP collaboration explores consistency of industrial fabrication, cabling effects, and establishes knowledge base and fundamental understanding**
  - **Conductor uniformity and production consistency are high.**
  - **Wire performance needs to be raised by 50% for Bi-2212 to be competitive as a conductor for accelerator magnet applications. Target is minimum wire J_E(4.2 K and 5 T) > 1275 A/mm^2 and J_E(4.2 K and 20 T) > 850 A/mm^2.**
  - **Rutherford cable fabrication induces J_c degradation (~15%) that saturates at 15 to 20% thickness reduction.**
  - **Two 0.7 mm billets showed pronounced leakage.**
  - **A billet of 0.8 mm with thicker Ag-Mg sheath produced to probe effects of Ag-Mg sheath thickness on leakage.**
  - **Coil postmortem analysis reveals types, mechanisms, and severity levels of leakages.**

Analysis of filament uniformity of ARDAP Bi-2122 wires indicates that achieving high filament uniformities is one of the keys to achieve high J_E

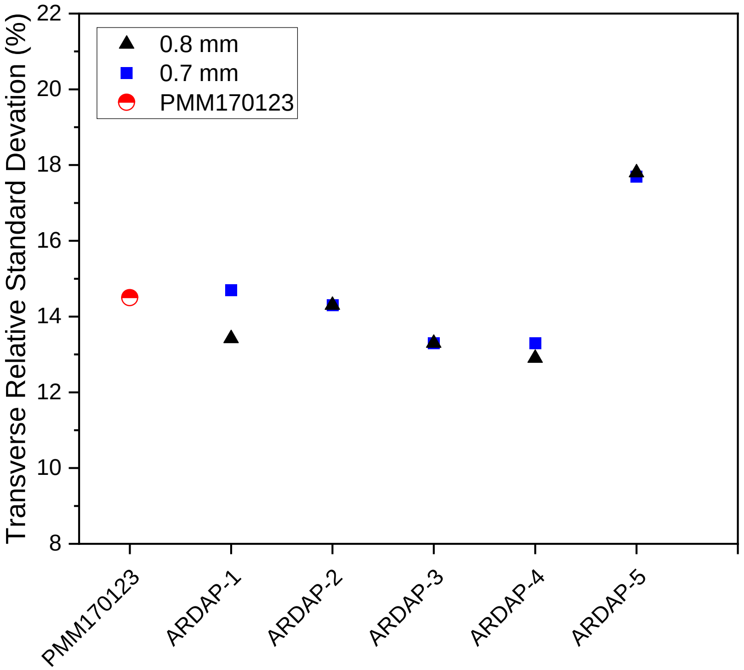




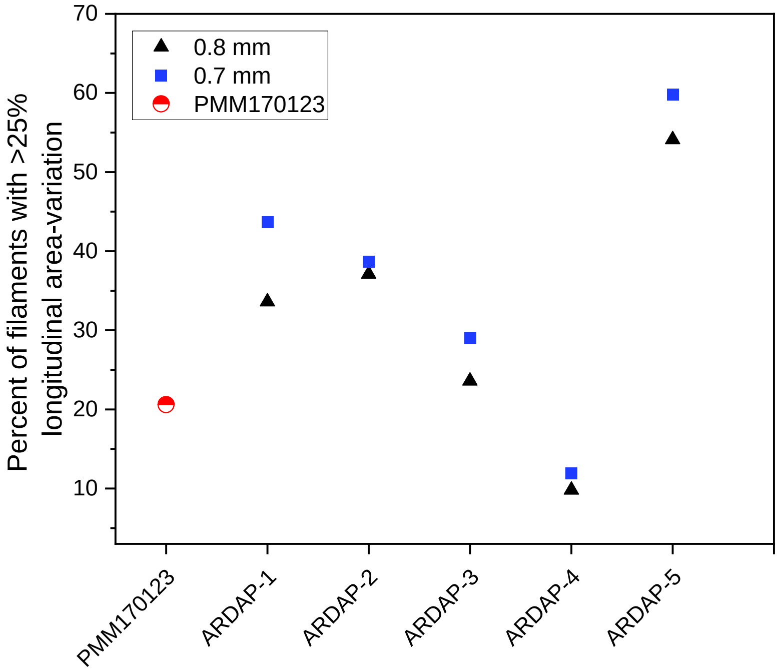
Ahmed Hasnine Abuzar, Jianyi Jiang, NHMFL

$$\frac{Standard\ deviation\ of\ filament\ area}{Average\ filament\ area} x100\%$$

Transverse filament uniformity

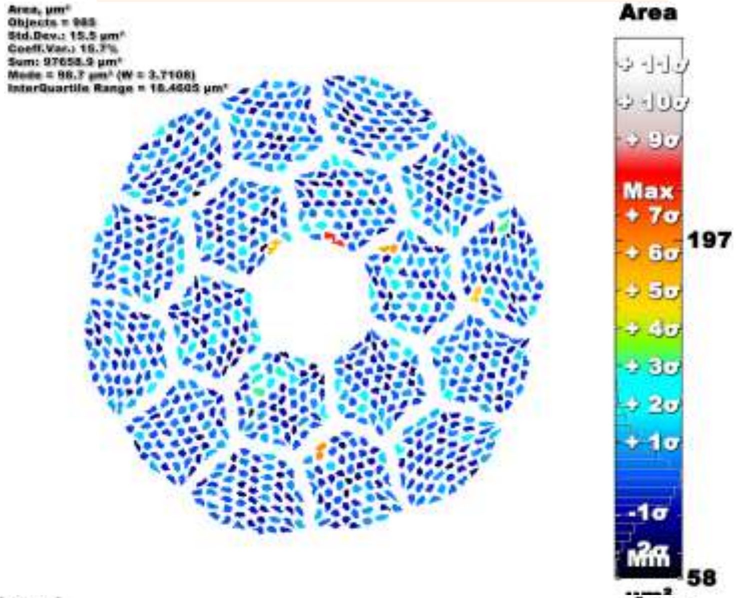


Longitudinal filament uniformity

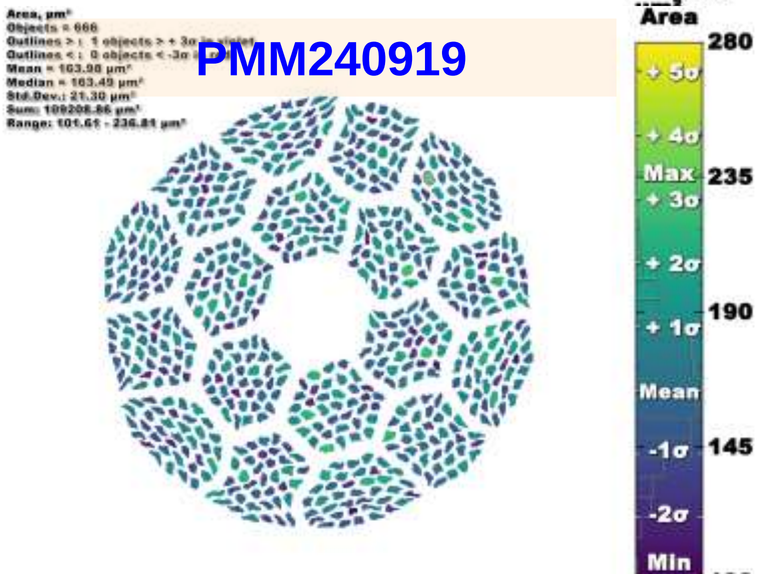


ARDAP wires have higher filling factors and smaller filament distances, indicating that controlling of filling factors, filament size, and spacing of the fully drawn wires may be another key to achieving high J_E

PMM170123



PMM240919



Jianyi Jiang, NHMFL

Billet ID	PMM170123	PMM220802	PMM240919	PMM250328
			ARDAP #4	ARDAP #7
Billet size	2 kg	2 kg	2 kg	2 kg
Wire dia. (mm)	0.8	0.8	0.8	0.8
Wire architecture	55x18	37x18	37x18	37x18
Fill Factor	0.199	0.196	0.232	0.235
Filament size (μm)	12.2	13.3	14.3	14.5
Coef. Var. of Filament size	16.4 %	14.6 %	13.5%	16.7 %

Champion conductor with peak J_E(4.2 K, 5 T) of 1900 A/mm^2.

Collaborators and coauthors

Conductor development through US MDP and ARDAP

Chris Escobar[1], Jean-Francois Croteau[1], Ian Pong[1], Daniel Davis[2], Ahmed Hasnine Abuzar[2], Shaon Barua[2], Eric Hellstrom[2], Jianyi Jiang[2], Youngjae Kim[2], David Larbalestier[2], Emma Martin[2], Ulf Trociewitz[2], Yibing Huang[3], Michael Brown[3], Daniel Bugaris[4], Claudia Goggin[4]

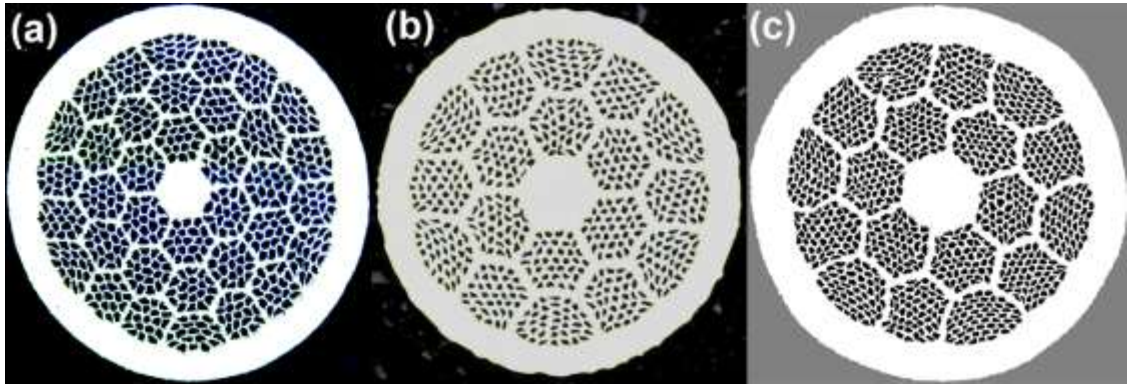
1. *Lawrence Berkeley National Laboratory, Berkeley, CA, 94720*
2. *National High Magnetic Field Laboratory, Tallahassee, FL, 32310*
3. *Bruker OST LLC, Carteret, NJ, 07008*
4. *Engi-Mat Co., Lexington, KY, 40511*

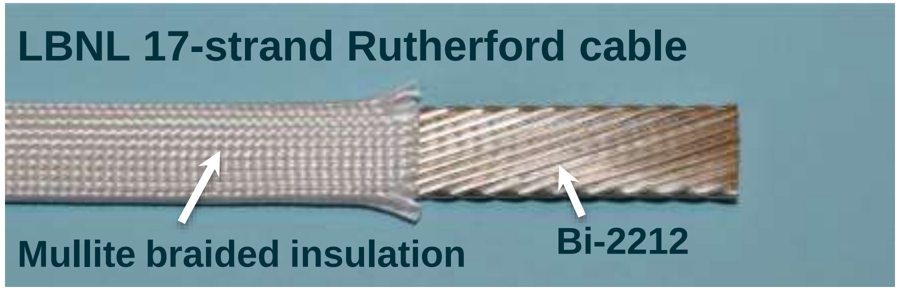
Colleagues at LBNL for **magnet development**: *Laura Garcia Farjardo, Diego Arbelaez, Lucas Brouwer, Jose Luis Rudeiros Fernandez, Paolo Ferracin, Marek Mošať, Soren Prestemon, Xiaorong Wang*

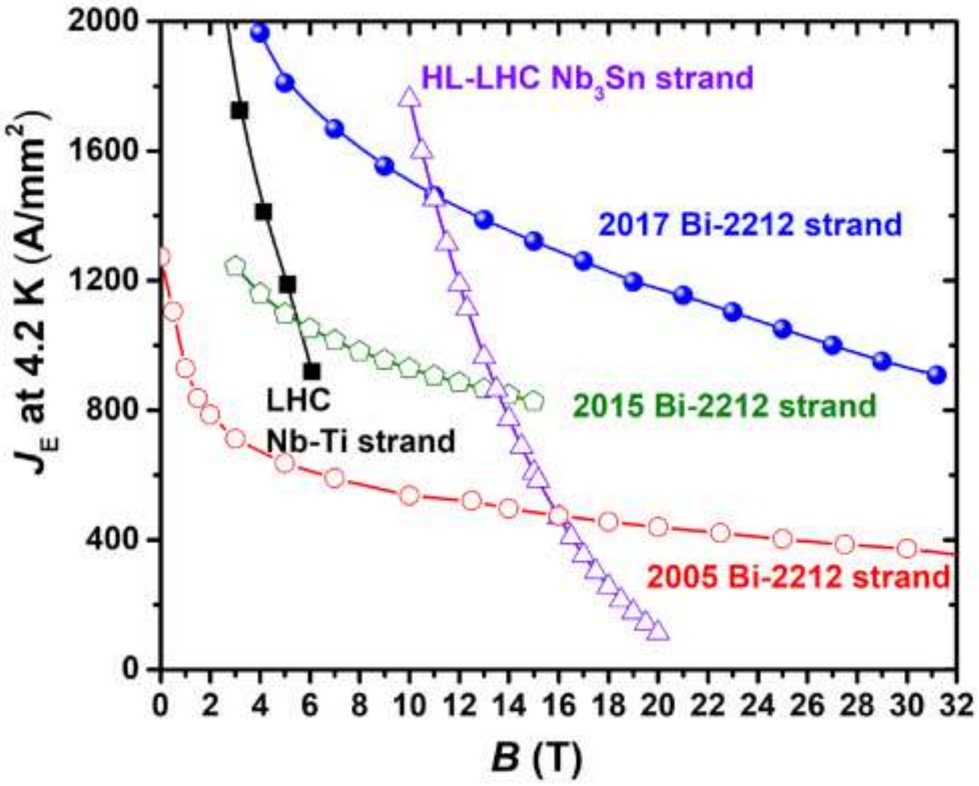
Bi-2212 wires are a round, multifilamentary HTS conductor with J_E of 1000 A/mm^2 at 4.2 K and 27 T and available in long lengths

Bi-2212 is a round, multifilamentary HTS conductor.

T. Shen, L. Garcia Fajardo, *Instruments* **2020**, *4*(2), 17; https://doi.org/10.3390/instruments4020017

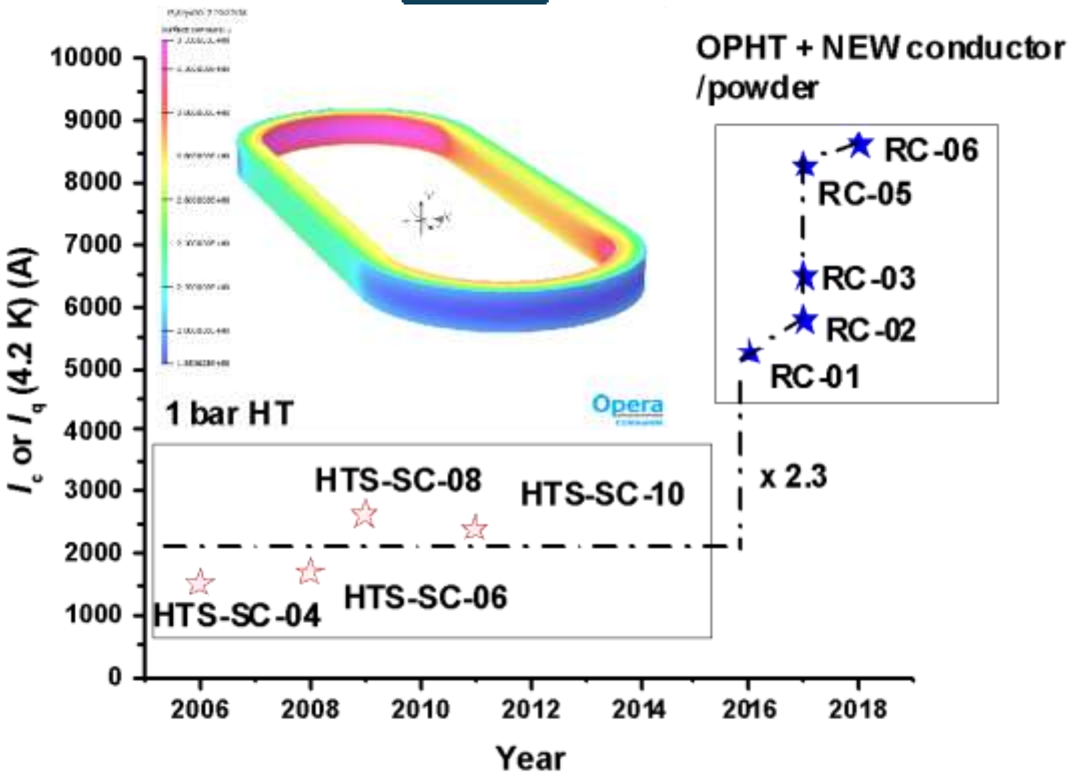




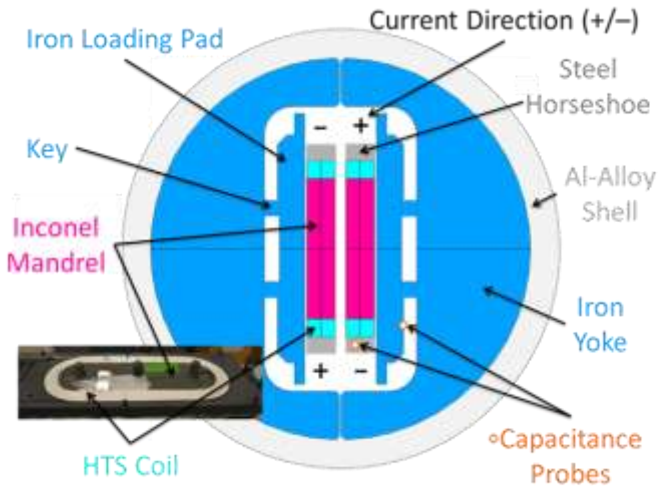


- 2017 strand development funded by DOE-OHEP SBIR by Engi-Mat, Bruker OST, supported by NHMFL and LBNL.
- Strand and racetrack coil heat treatment at NHMFL with DOE-OHEP, additional support from NSF, and state of Florida.

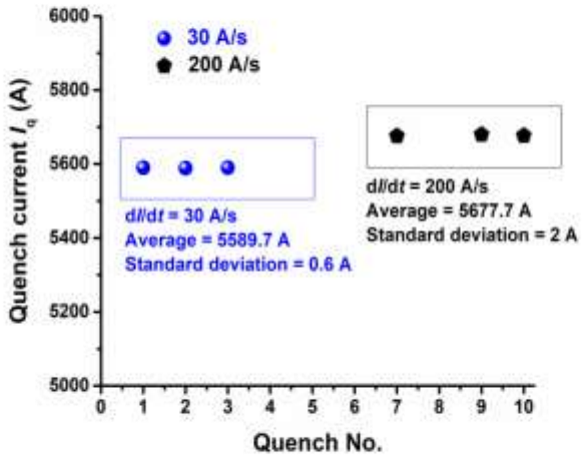
Bi-2212 flat racetrack coils have been made to figure out fabrication and benchmarked performance



RC7n8 common coil dipole magnet, 4.7 T

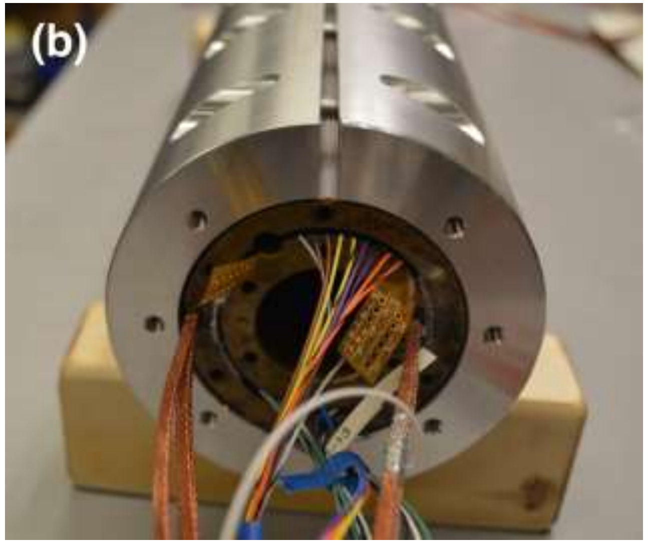


No quench training

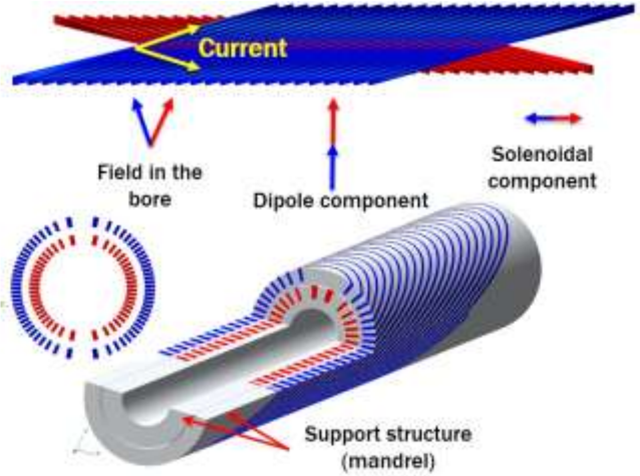


Cable and magnet fabrication expanded to canted-cosine-theta coil prototyping

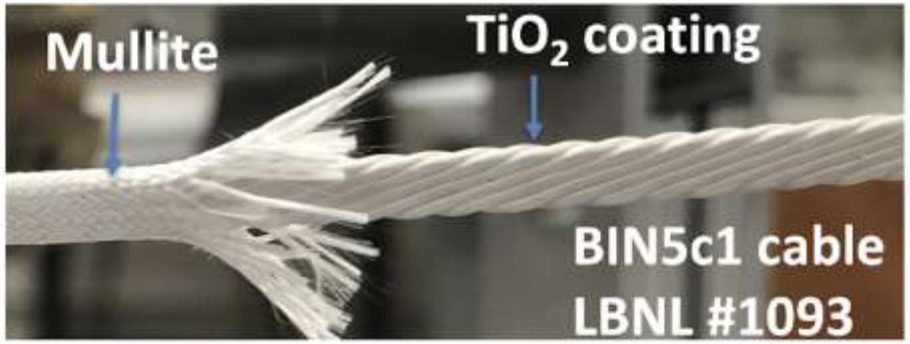
CCT dipole magnet BIN5, 1.6 T in 30.8 mm bore, 39 cm in length



Shen et al., Phys. Rev. Accel. Beams 25, 122401 (2022);



LBNL 9-strand Rutherford cable



From winding to insulation scheme to selection of materials to heat treatment to assembly.

Important for hybrid dipole magnets

US Magnet Development Program is developing 1 m long Bi-2212 magnets for its hybrid magnet program

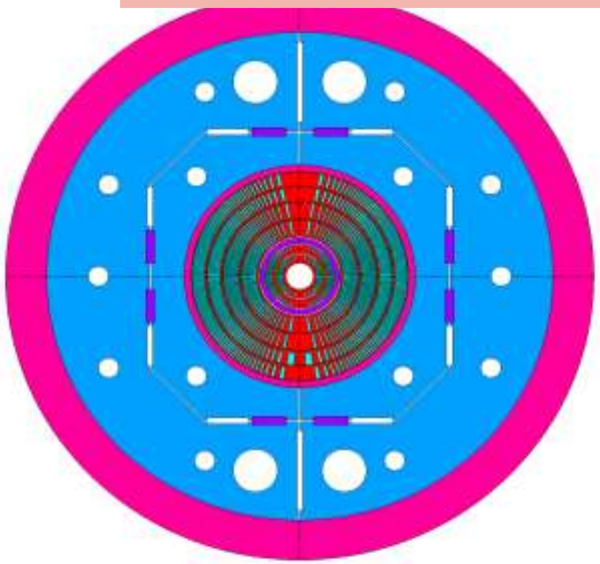
Three coils fabricated.

Heat treatment@NHMFL's RENEGADE furnace

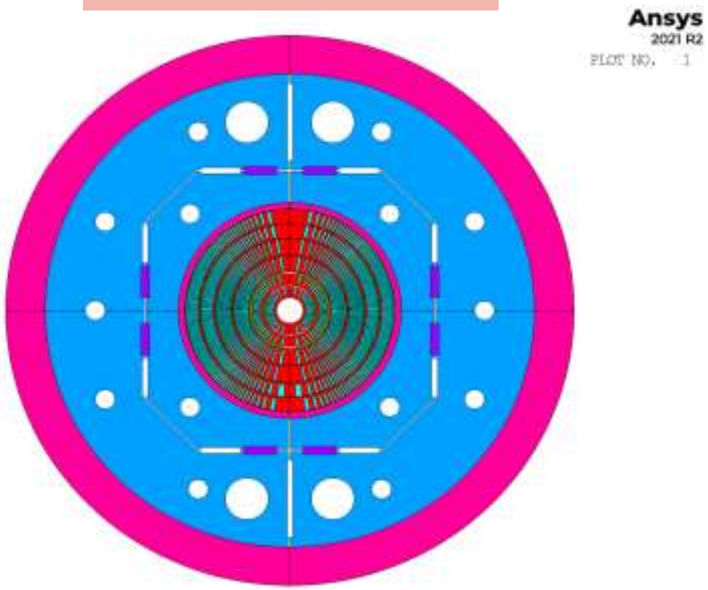
Bi-CCT1

Mandrel	IL (Inner Layer)	OL (Outer Layer)
Material	Aluminum Bronze 954	Aluminum Bronze 954
Mandrel ID (mm)	40	70
Mandrel OD (mm)	66.2	96.2
Mandrel length (mm)	850	850

Bi-CCT1 in Nb_3Sn CCT6



Bi-CCT2 in CCT6



CCT6 is a large aperture (120 mm, >12 T) Nb_3Sn dipole magnet.