Bi-2212 Conductor and Coil Technology at ASC

David Larbalestier

on behalf of the broader ASC conductor and coil efforts with

co-PIs Eric Hellstrom, Jianyi Jiang, Fumitake Kametani (DOE Core Grant)

and

Ulf Trociewitz, Youngjae Kim and Dan Davis (NSF Core and DOE-STTR through Cryomagnetics)

Ernesto Bosque, Tomoka Brady, Lance Cooley, Lamar English, Jozef Kvitkovic, George Miller, and Chiara Tarantini with PhD students Yavuz Oz (now GE Medical), Imam Hossein (now Intel), Abiola Oloye (PhD soon), Shaon Barua (PhD soon), Emma Martin (PhD student), Ahmed Abuzar (PhD student)

Thanks to DOE-OHEP (award no. DE-SC0010421 PIs Larbalestier, Hellstrom, Jiang and Kametani), the NHMFL Core Grant support of NSF (award no. 1157490), DOE-OHEP STTR to Cryomagnetics FSU PI Trociewitz), DOE-SBIR to Engi-Mat (award no. DE-SC0018666, FSU PI Jiang) and Florida State University special allocation (DCL PI) for Bi-2212 commercialization and the US Magnet Development Program Collaboration for much context and many collaborations

U.S. MAGNET DEVELOPMENT PROGRAM

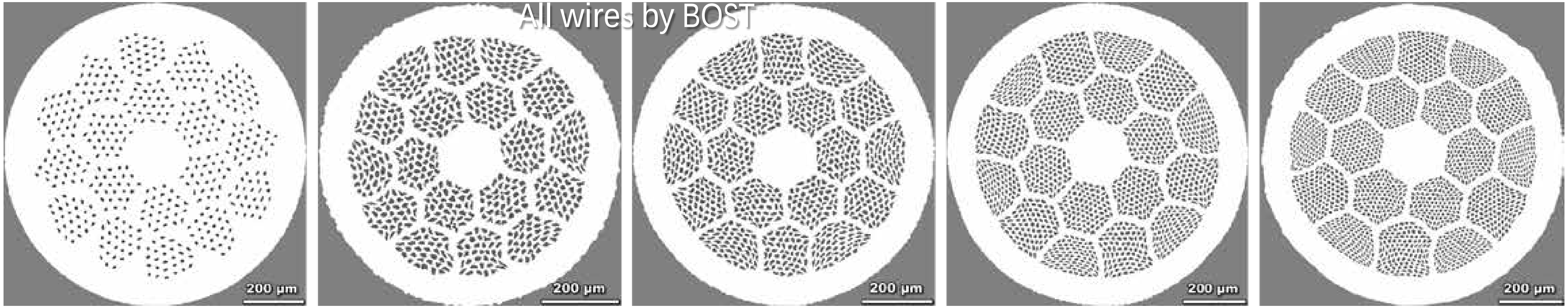
US MDP Annual Meeting Brookhaven National Laboratory, March 21-24, 2023

Messages

- Bi-2212 is becoming a solenoid magnet conductor after more than 10 years of coordinated university-lab-industry support through DOE-OHEP and the CDRP
  - It has great advantages – genuinely multifilament with low AC loss, macroscopically isotropic, round and available in single pieces now > 1 km length in multiple architectures and variable diameters
  - **It has major disadvantages** too – it requires a Wind and React route for HEP and lab magnets at almost 900 C and optimized Jc requires ~50 bar overpressure (1 bar O_2 and balance Ar)
  - Wires have a breaking strength of ~170 MPa, well below the stresses foreseen for many magnets
- Making Bi-2212 into a solenoid magnet technology required addressing these conductor, insulation, force support, and impregnation issues all together

Application to dipoles has thrown up Rutherford cable insulation issues for which we have been developing a solution but CCT force support may be easier than with our single-strand, internal force support techniques

Bi-2212 Wire Technology is Versatile: 10 kg scale is delivering single piece lengths of up to 1.2 km of 55 and 85 x 18 at 1 mm dia.



27×18 37×18 55×18 85×18 121×18

- Optimum Filament Size is in the 10-15 mm range with complex tradeoffs determined by starting filament uniformity, change of shape during heat treatment – tradeoffs becoming clear with more and more coils
- Some filament bonding does occur during OPHT, degrading both J_c and the effective filament diameter, typically half the sub-bundle diameter – AC losses about same as ITER but with 2X higher Jc (Oz et al. SuST 35, 04004 (2022) **– The 2022 Jan Evetts Prize-winning paper**

- No diffusion barrier is needed because the Ag matrix naturally has high RRR
- Although some filament coupling occurs during HT, AC losses are similar to ITER Nb_3Sn wires
- The superconductor fill factor (FF) of present wires is only ~20%, allowing potentially significantly higher J_E just by increasing FF – filament coupling studies (Eric talk) suggest this potential

Tradeoffs of architecture, filament size and resilience to small fluctuations in T_{max} and t_{melt}

IEEE TRANSACTIONS ON APPLIED SUPERCONDUCTIVITY, VOL. 33, NO. 5, AUGUST 2023 6400105

Performance and Microstructure Variation with Maximum Heat Treatment Temperature for Recent Bi-2212 Round Wires

Jianyi Jiang, *Senior Member, IEEE*, S. Imam Hossain, Shaon Barua, T. Abiola Oloye, Jozef Kvitkovic, Fumitake Kametani, Ulf P. Trociewitz, *Senior Member, IEEE*, Eric E. Hellstrom, *Senior Member, IEEE*, David C. Larbalestier, *Fellow, IEEE*, Daniel E. Bugaris, *Member, IEEE*, Claudia Goggin, Yibing Huang, Jeff A. Parrell, and Tengming Shen, *Senior Member, IEEE*

Don't be afraid of 50 bar OP with Bi-2212!

13 billets with less variation than is normally seen in REBCO

TABLE I

SPECIFICATIONS OF THE BI-2212 WIRES USED IN THIS STUDY. THE FIRST TWO DIGITS IN THE WIRE ID DESIGNATE THE YEAR THE WIRE WAS FABRICATED

Billet number	Wire ID	Manufac-ture year	Billet size (kg)	Filament configuration	Wire dimeter (mm)	Filling factor after densification	Average equivalent filament diameter after densification[a] (μm)
1	pmm170123	2017	2	55x18	0.8	0.199	12.2
2	pmm170627	2017	10	85x18	1.0	0.195	11.1
3	pmm170725	2017	2	55x18	0.8	0.236	12.1
4	pmm180207	2018	10	55x18	0.8	0.197	11.1
5	pmm180410	2018	10	85x18	1.0	0.201	11.2
6	pmm180627	2018	10	55x18	1.0	0.217	14.5
7	pmm190118	2019	10	55x18	0.8	0.210	11.4
8	pmm190425	2019	10	85x18	1.0	0.220	11.8
9	pmm191004	2019	10	55x18	0.8	0.219	12.2
10	pmm200222-08	2020	2	55x18	0.8	0.238	12.0
10	pmm200222-09	2020	2	55x18	0.9	0.238	13.4
10	pmm200222-10	2020	2	55x18	1.0	0.238	15.0
11	pmm211105	2021	10	55x18	0.8	0.180	10.4
12	pmm220329	2022	10	55x18	0.8	0.200	11.0
13	pmm220802-08	2022	2	37x18	0.8	0.196	13.3
13	pmm220802-09	2022	2	37x18	0.9	0.196	14.9
13	pmm220802-10	2022	2	37x18	1.0	0196	16.7

[a]Average equivalent filament diameter calculated by measuring the filament area and calculating the diameter of a circle whose area equals the measured area.

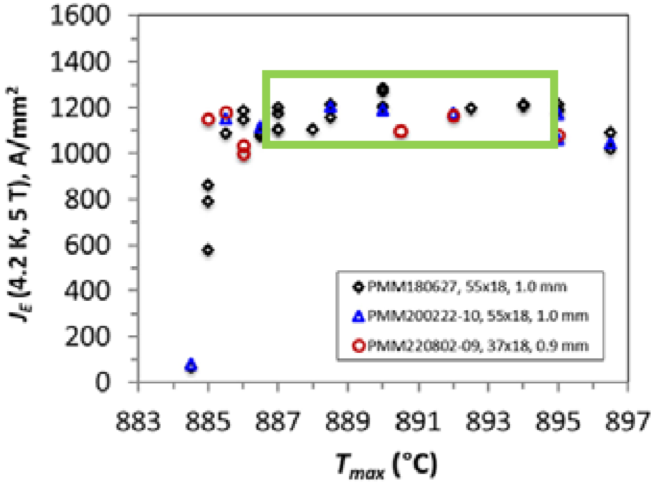
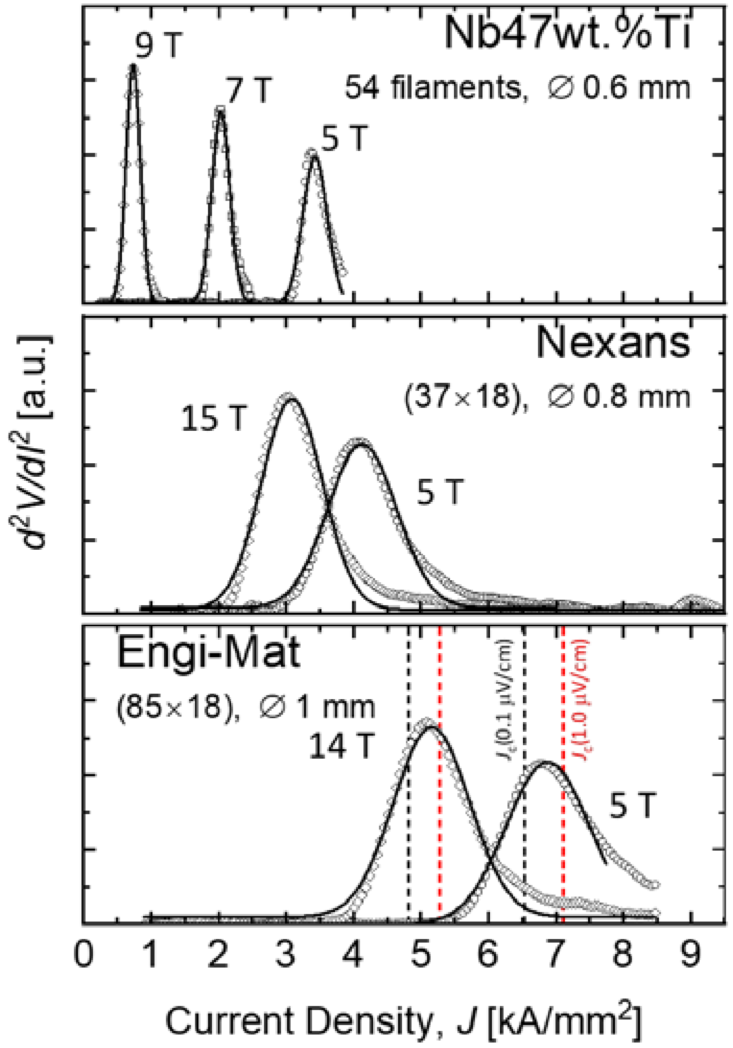
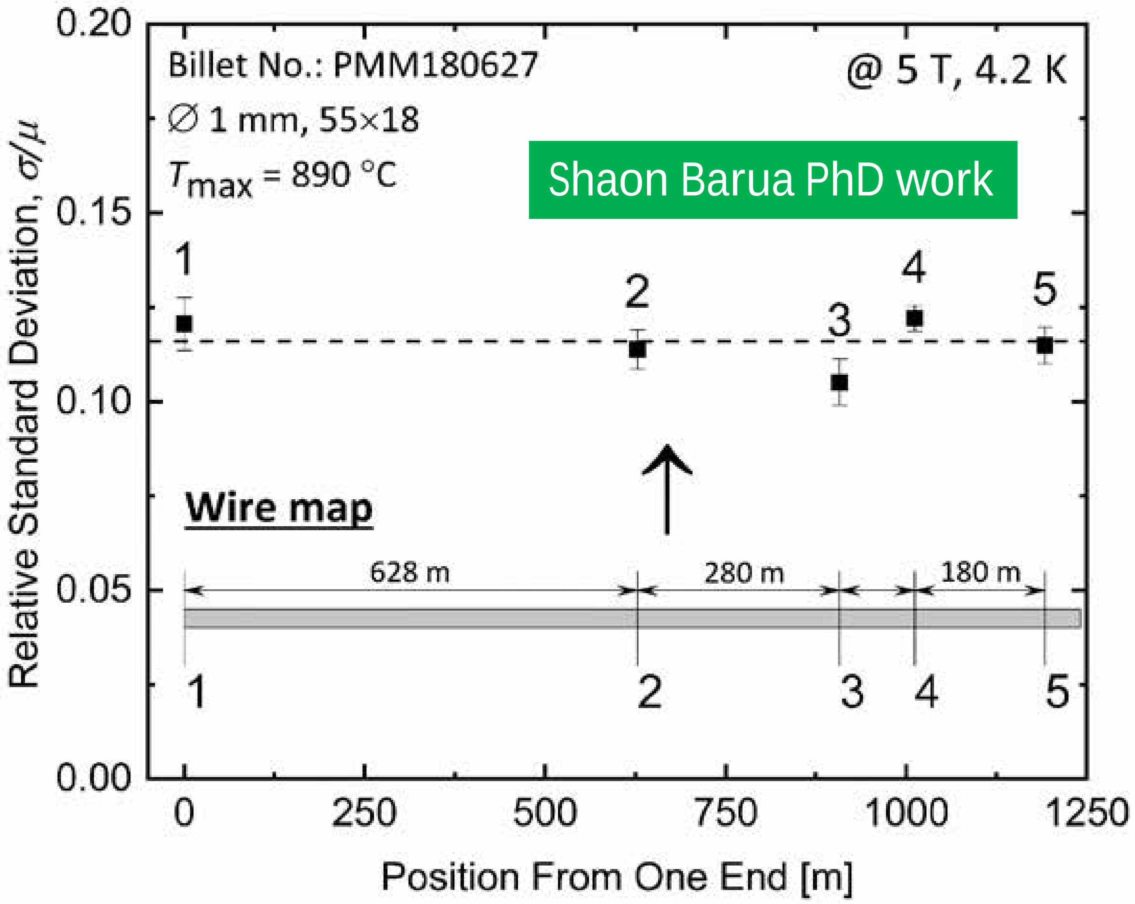


Fig. 5. J_E (4.2 K, 5 T) as a function of T_{max} for wires with very similar filament size, pmm180627 (55 × 18, 1.0 mm) with filament size of 14.5 μm, pmm200222-10 (55 × 18, 1.0 mm) with filament size of 15.0 μm, and pmm220802-09 (37 × 18, 0.9 mm) with filament size of 14.9 μm.

- This study has been central to the theses of several recent PhD students Yavuz Oz (Now GE MRI), Imam Hossain (Now Intel), Shaon Barua and Abiola Oloye (about to graduate)
- They have enabled us to start to separate filament architecture and powder quality effects
  - 10-12 mm filaments have much greater sensitivity to melt conditions than 14-15 mm filaments, allowing T_{max} of 890C which gives good protection from both under- and over-temperature processing

Coil implications: Are short sample properties replicated over km lengths? d2V/dI2 analyses say path to 10 kg coils is open!

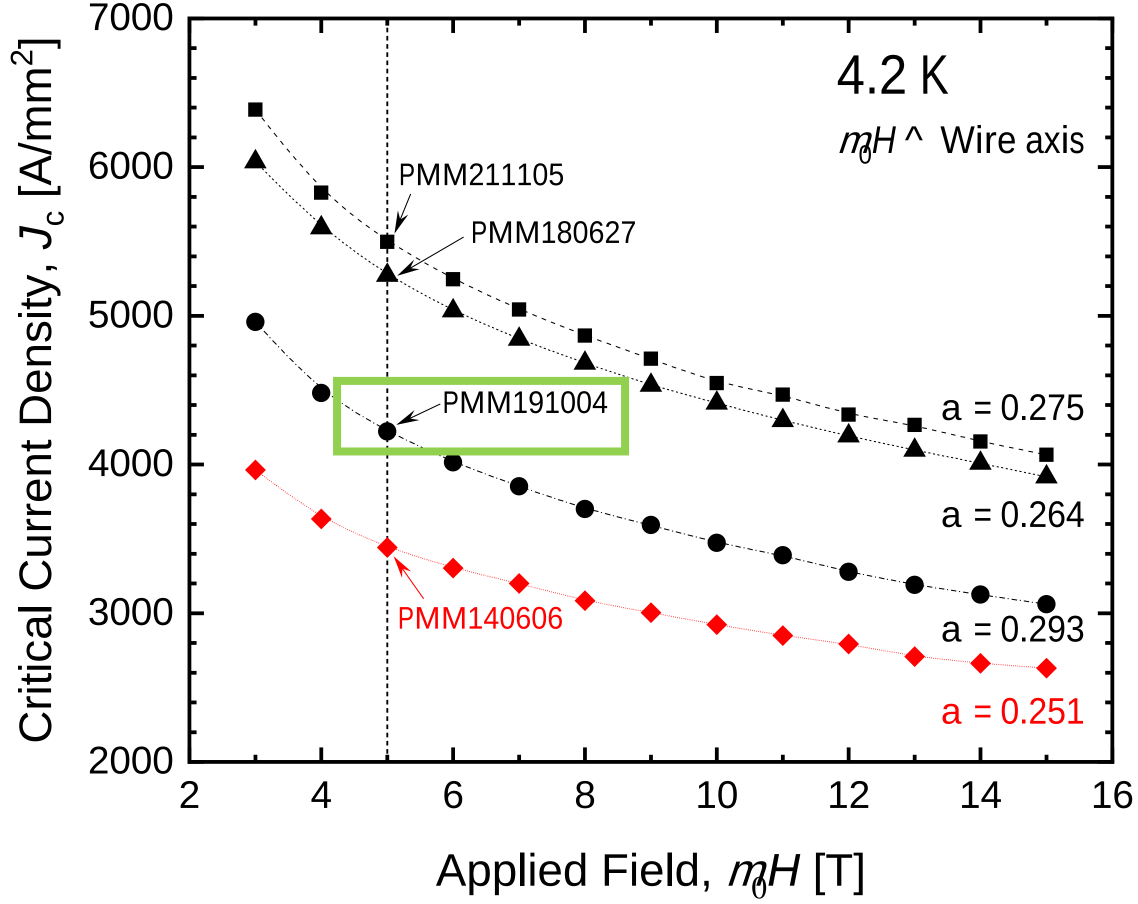




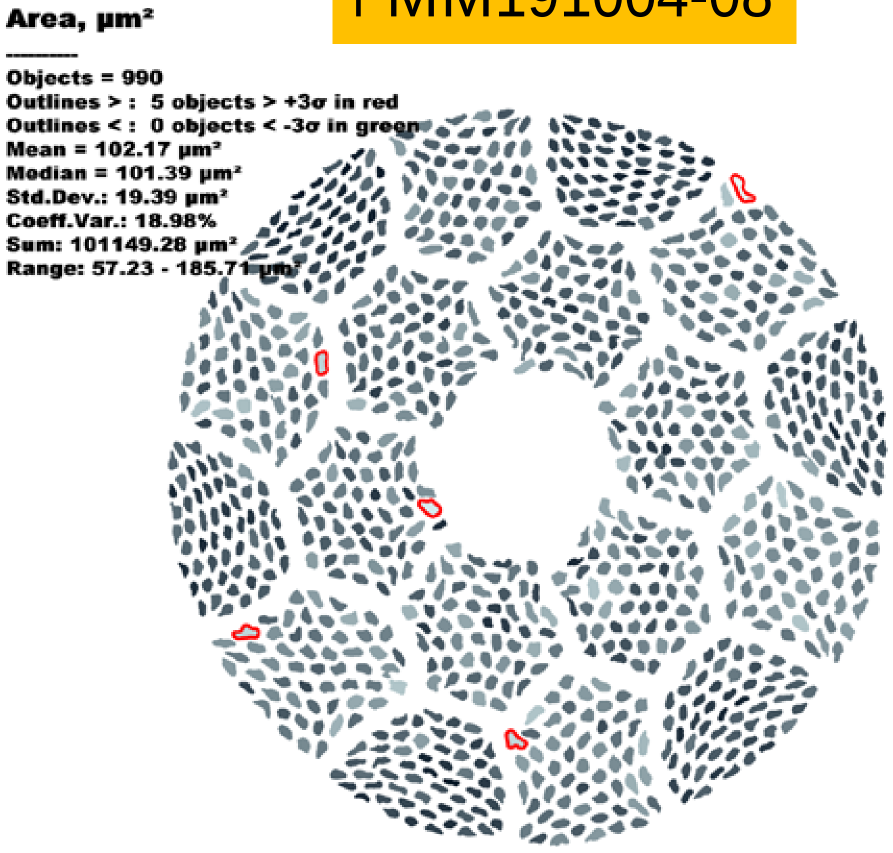
Barua *et al.*, *IEEE Trans. Appl. Supercond.*, vol. 31, no. 5, pp. 1–6, Aug. 2021, doi: 10.1109/TASC.2021.3055479, ASC 2022, PhD 2023

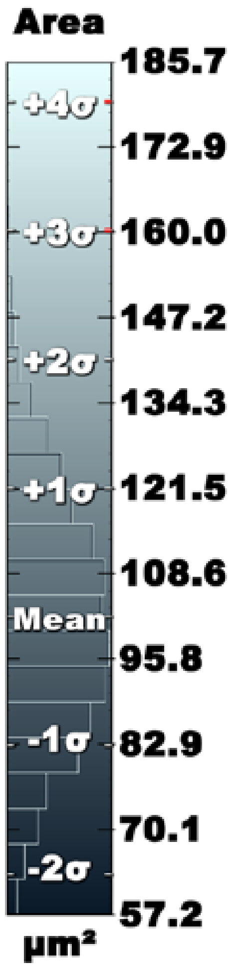
Area s/m of disappointing LBL 0.8 mm billet PMM191004 is higher compared to other Engi-Mat wires

Shaon Barua PhD work (wire from Tengming)



PMM191004-08



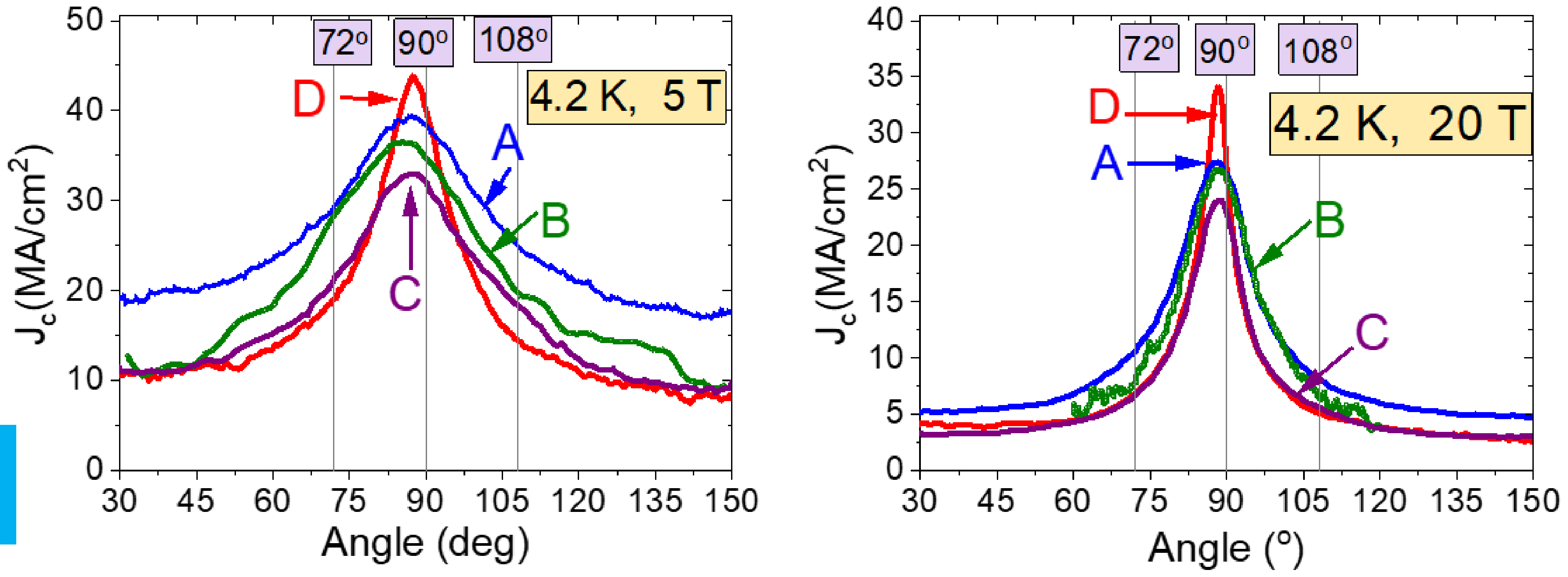


s/m= 18.98 %

Much sausaging is built in to as-delivered 2212 wires and is now worth a campaign to remove

By contrast REBCO CC made to the SAME SPECIFICATION has to deal with large J_c(Q,B,T) variations and large anisotropy

- At all measured *B* & *T*, tapes with higher density of thin BZO have widest peak
  - SP144, with low density of thick nanorods, has narrowest peak
- SP144, with least BZO density and has highest J_c at *ab*-plane
  - J_c drops off quickly away from *ab*-plane due to lack of point pins



Ashleigh Francis unpublished

Effects of nanostructure variations on the field, angular, and temperature dependence of J_c in commercial REBCO Coated Conductors

Ashleigh Francis

PhD thesis defense
Materials Science & Engineering
Florida State University
November 8th, 2022

Now at Commonwealth Fusion Systems working on thse REBCO magnets

Advisor: Dr. David Larbalestier

Committee: Dr. Fumitake Kametani, Dr. Wei Guo (University Rep), Dr. Christianne Beekman, Dr. Theo Siegrist

This work was performed at the National High Magnetic Field Laboratory. The work has been supported by the NHMFL Core Grant of NSF (DMR-1157490) National Science Foundation Cooperative Agreement No. DMR-1644779, DMR-1938789, DMR-2131790, the DOE Office of Fusion Energy Sciences (DE-SC0022011), and the State of Florida.

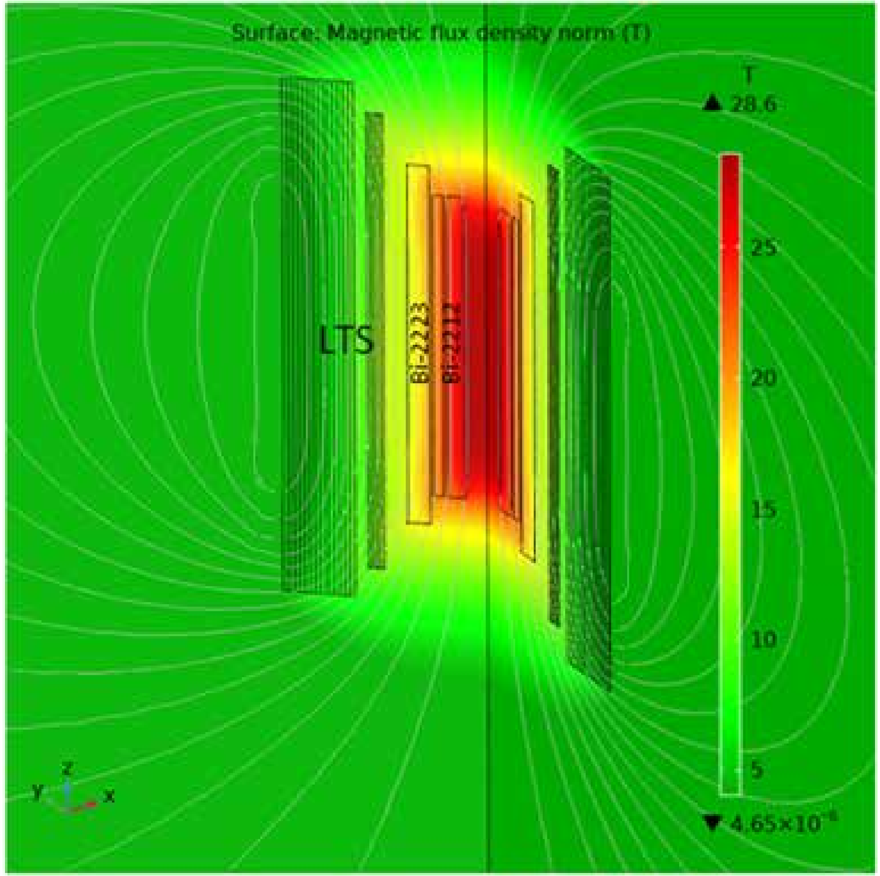
Development of Bi-2212 NMR-type Magnet Technology

- **Since mid 2022 we have collaborated with OI on the development of a 25 T class compact research magnet**
- **And for longer on a 28 T 1 ppm NIH RO1:**
    - uses the modified 12 T, 212 mm bore OI ("IMPDAHMA") LTS outsert magnet 12T/220 mm dia) – formerly 20 T/78mm

Specs:

- Two inner coils with Bi-2212, each with **~800 m of conductor**, 40 mm bore
- One Bi-2223 coil using 2.6 km conductor
- Will have compensation and shim coil sets to correct for field errors
- HTS and LTS coil sets each powered in series (~380 A HTS and ~140 A LTS)

Bi-2212 and Bi-2223 Insert Coil Design for 28.2 T / 40 mm Bore UHF NMR Magnet System		
Bi-2212 Coil #1	a1; a2; z1; z2 [mm]	22.2; 40.5; -178.6; 178.6
	Turns	3920
	Field [T]	5.17
	wire length [km]	0.77
Bi-2212 Coil #2	a1; a2; z1; z2 [mm]	44.45; 55.3; -178.6; 178.6
	Turns	2240
	Field [T]	2.89
	wire length [km]	0.71
Bi-2223 Coil	a1; a2; z1; z2 [mm]	58.5; 81.4; -212.5; 212.5
	Turns	5767
	Field [T]	6.16
	wire length [km]	2.6
HTS Section Current [A]		380.5
Store Energy [MJ]		< 3 (~0.5 MJ in HTS)



OXFORD INSTRUMENTS

Trociewitz, Davis, Kim, Bosque

Goal: Demonstrate 1.2 GHz (28.2 T) 1 ppm NMR; Grand scheme: develop pathway toward 1.5 GHz

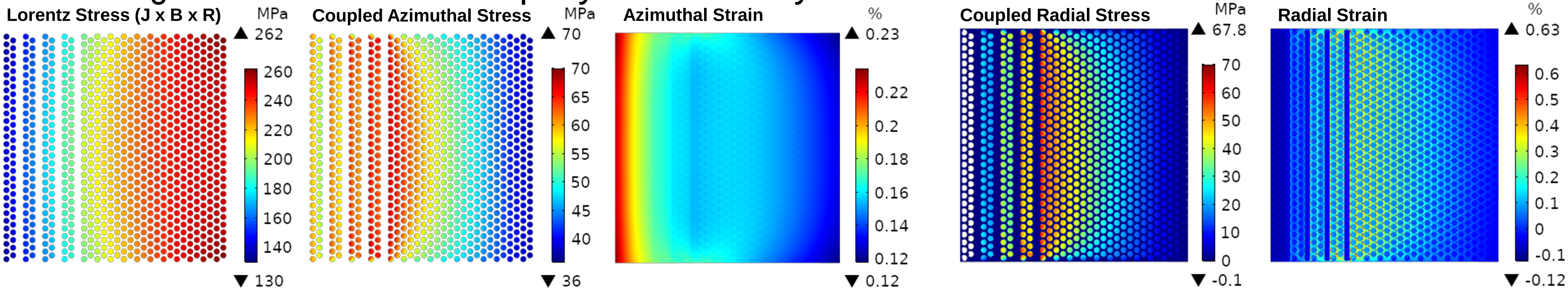
Many test coils, many post mortems: our standard PUP has ~200m 1 mm dia wire

Highest stress case in coil test : I_{op} = 279.6 A, Background = 12 T

- JBr stress up to 260 MPa realized à **Stress redistribution to reinforcement via epoxy confirmed**
- Coil degraded around layer 9
- Coupled azimuthal stress/strain data indicated to be well below conductor's limit
  - But stress map shows elevated stress at Layer 9-12 agrees well with the post-mortem

What about radial stress and strain?

- Highest radial stress on wires at Layer 9 – 12
- Highest radial strain on epoxy between Layer 9 and Band 4

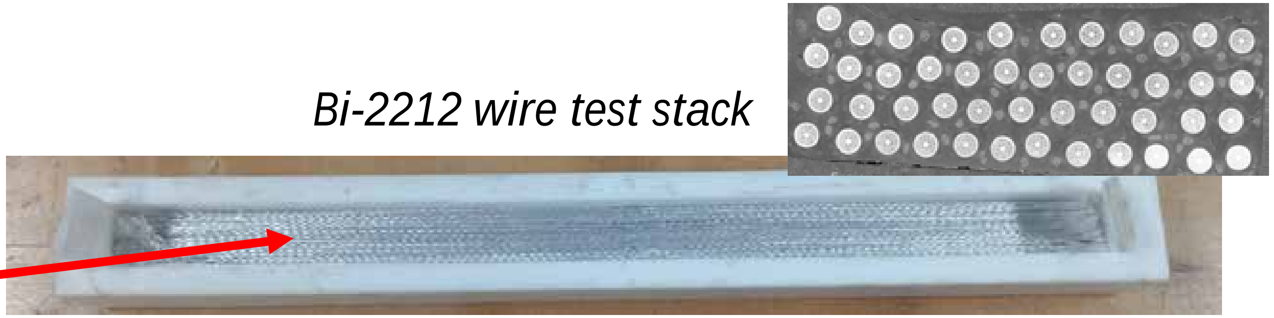


Internal cracking suggests Pup-9 Coil Partially Decoupled

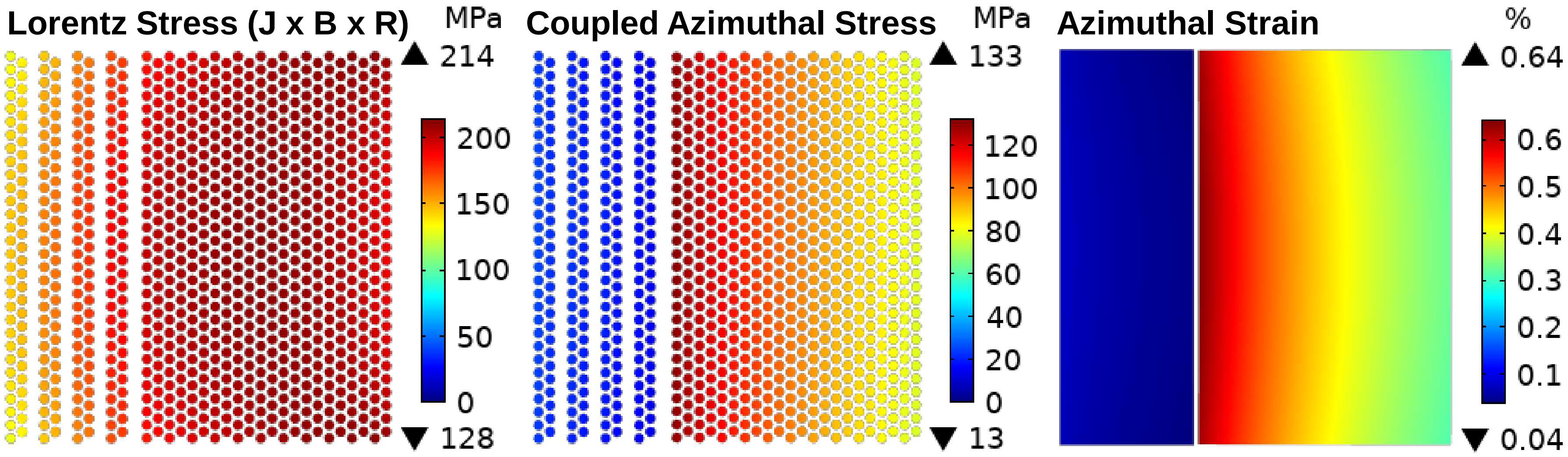
- An assumption: full decoupling between last band and rest of the coil
  - Calculated strain (0.64% at Layer 9) where the cracking occurs makes the outer section of the coil a new free-standing section
  - Layer 1 ~ 8 then become released from the outer coil which shows very low stress
- Possible reasons for the cracks: Interfaces
  - Epoxy bonding to reinforcement cracks near the bands
  - CTE mismatch between components of the winding pack
  - Local stress concentrations

Started series of experiments emulating the mechanical properties of a Bi-2212 winding pack (Emma Martin, 2MPo1A-10)

Bi-2212 wire test stack



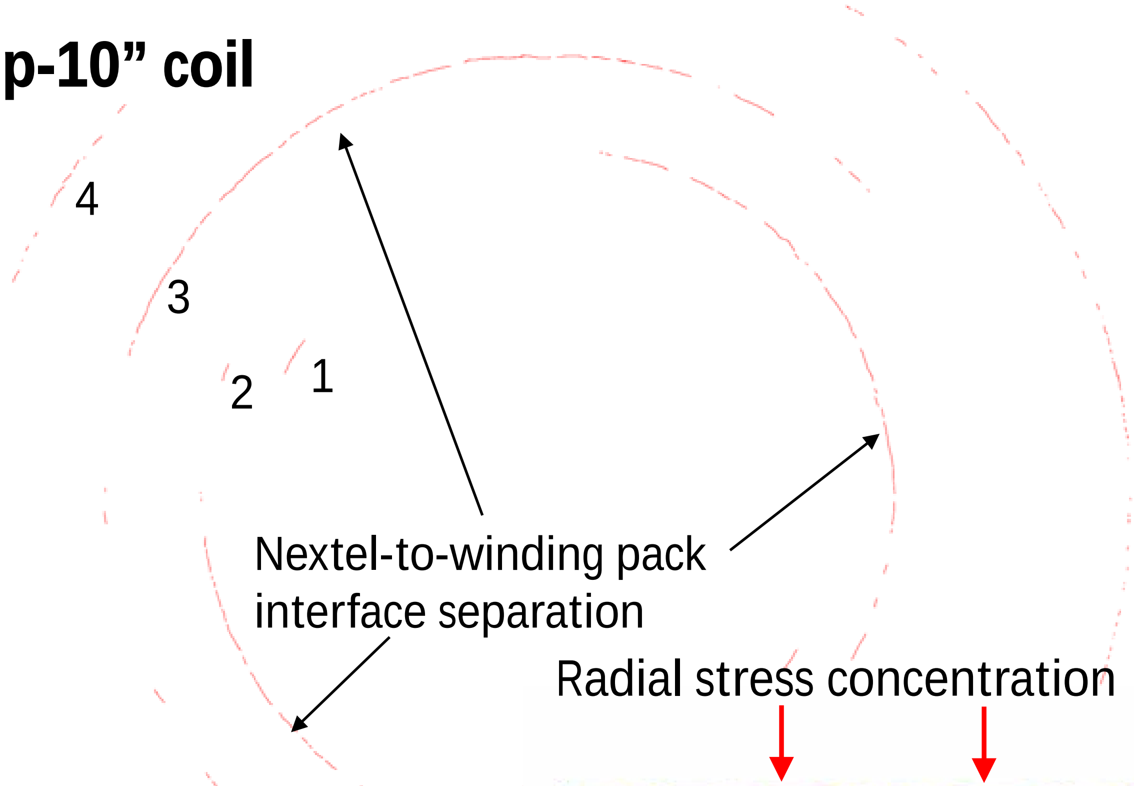
Pup-9 came completely apart at Band 4 after cutting for post mortem



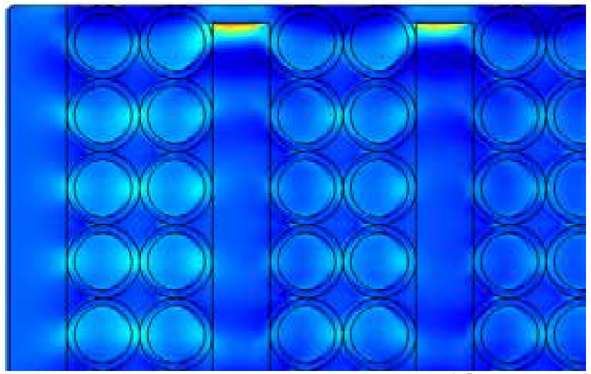
A hypothetical case for separation of Pup-9 into two coil packs

Postmortems are an Important Tool to Understand Coil Mechanics

"Pup-10" coil



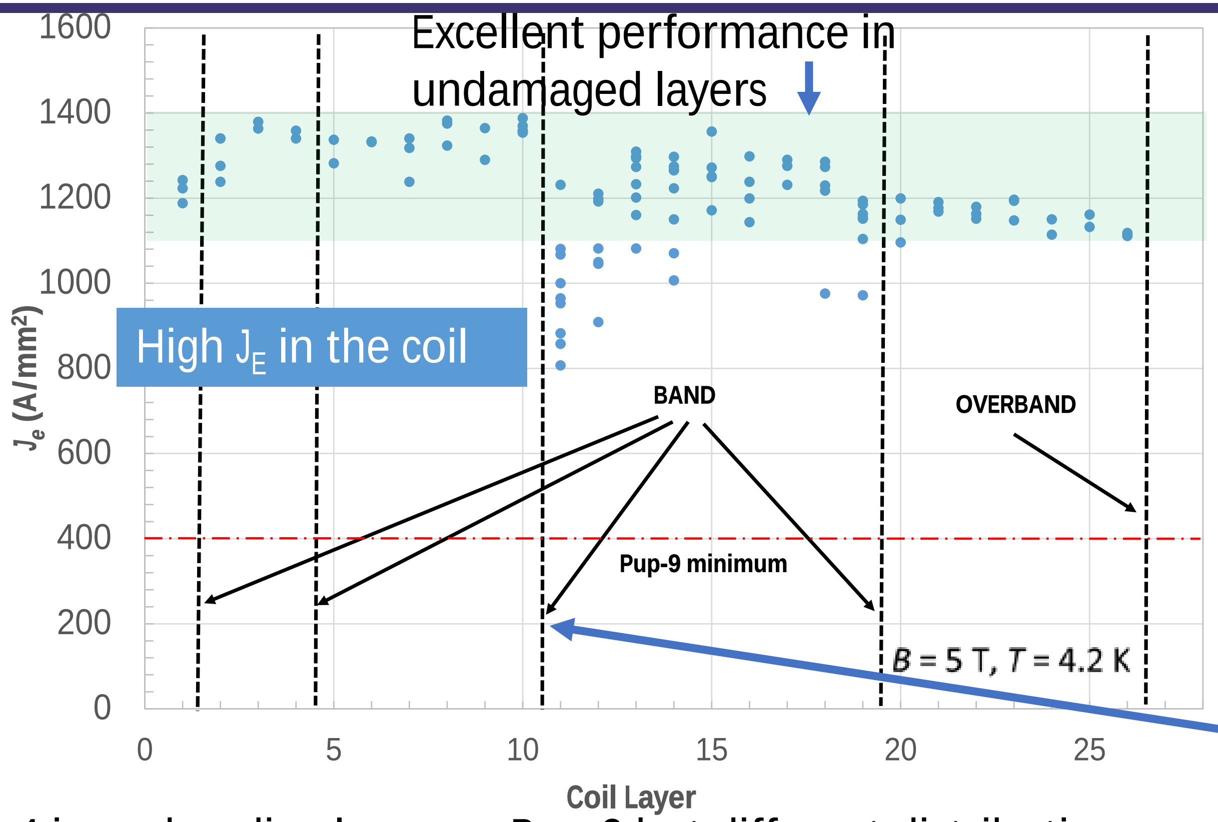
Radial stress concentration

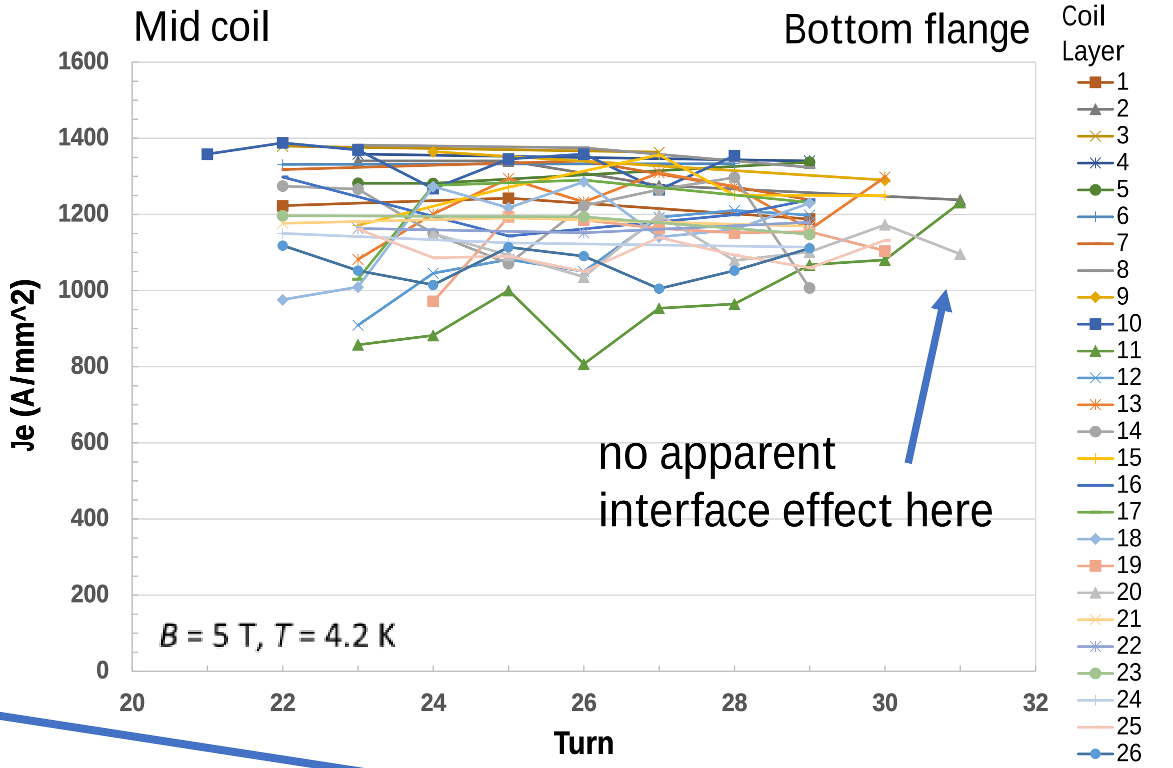


Thermal contraction RT – 4.2 K

In spite of the cracking there is no training in Bi-2212!

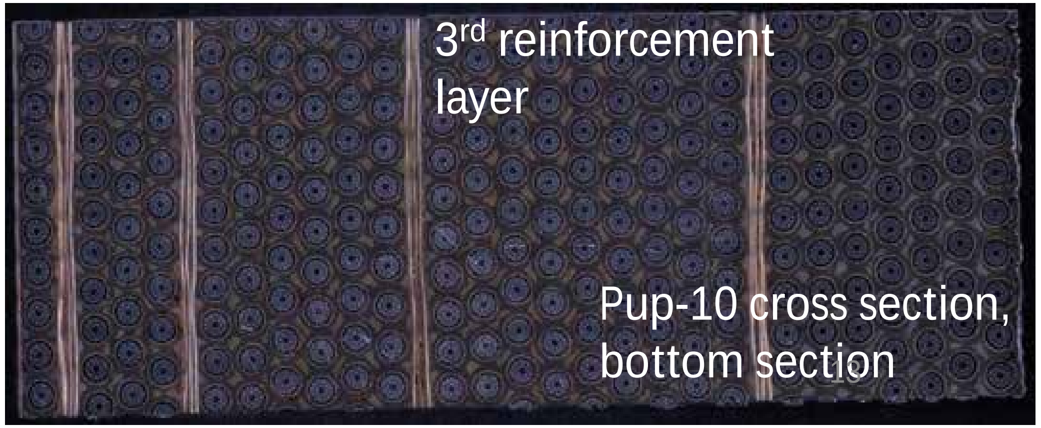
PUP 10 had a more optimum placement of the bands





2 5 11 20

Coil ID



- 4 inner banding layers as Pup-9 but different distribution
- Less degradation than in Pup-9 but some still present around 3rd reinforcement layer
- **Note Jc values from this Deltech reaction above those of Jiang study in smaller furnace and uniform through thick winding**

E. Bosque, Y. Kim, U.P. Trociewitz, C.L. English, D.C. Larbalestier, System and Method to Manage High Stresses in Bi-2212 Wire Wound Compact Superconducting Magnets, U.S. non-provisional patent application, FSU Ref. no. 18-063, 2019.

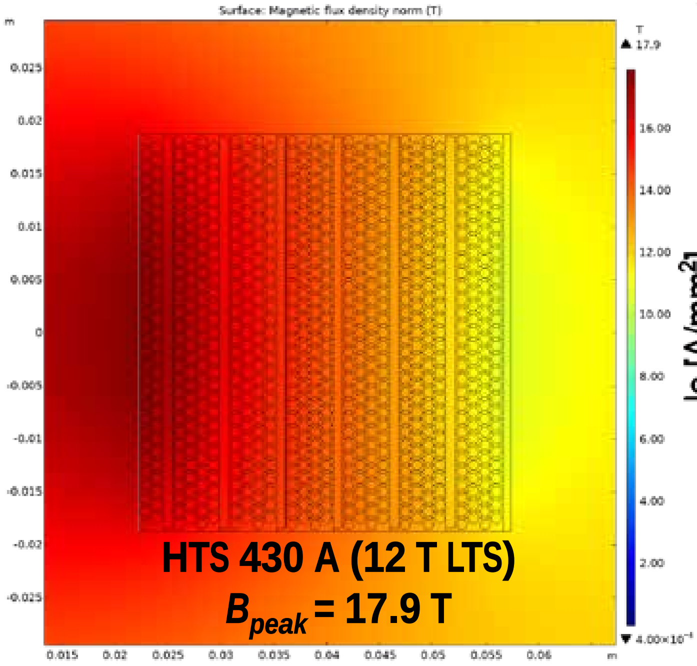
Most Recent Coil "Cryo-4"
current champion coil

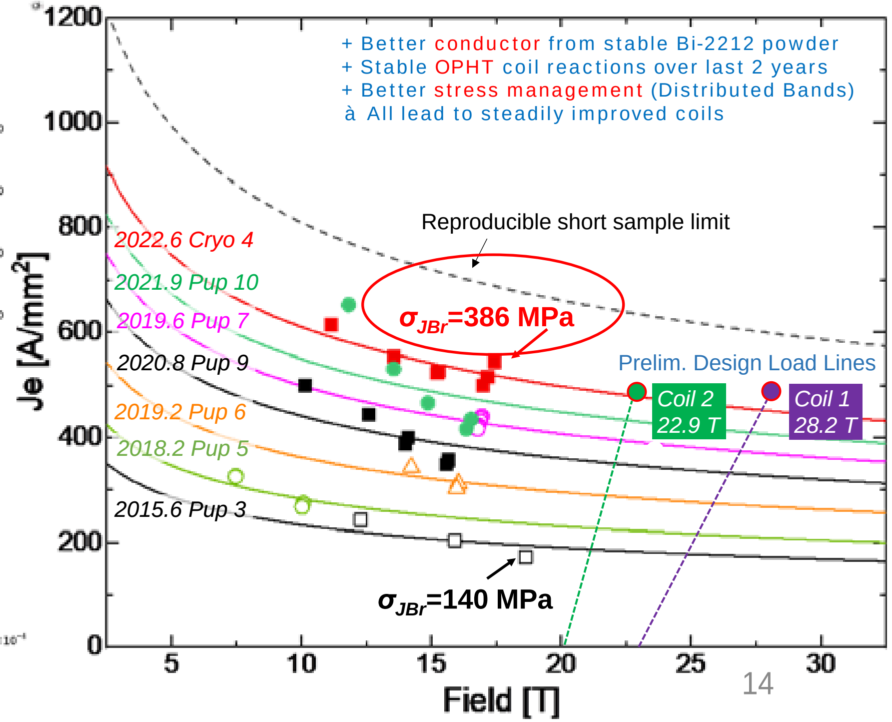
Cryo 4		
Wire	Product No.	PMM180410-1
	Powder	nGimat 116 (85 x 18)
	Insulation	In-house coating+mullite braid
	Diameter [mm]	Φ 1.0 (bare) / Φ 1.22 (ins.)
ID ; OD ; Height [mm]		44.6 ; 115 ; 40.3
Turn ; Layer (Total)		30/29 ; 26 (769)
Magnet constant [mT/A]		11.337
Center field @ 100 A [T]		1.13
Inductance [mH]		31.5
Conductor length [m]		~ 200

~2x breaking stress!

Day	Test	File	B_{ext} Field [T]	B_{center} [T]	Max I_{op} [A]	[A/mm^2]	JBr [MPa]	Trip?	Note
1	T01	1	0	4.5	400	533		No	
	T02	2	5	9.5	400	533		No	
	T03	1	10	14.53	400	533		No	
	T04	1	12	16.9	430	573.3	386	Yes	71% SSL
		3	12	16.6	404	539		Yes	
		5	12	16.5	393	524		Yes	
		6	12	16.4	385	513	347	No	25 Cycles
	T05	1	10	14.7	415	553	310	Yes	
		2	10	14.7	412	549		Yes	
	T06	1	8	12.9	437	582	261	Yes	
		2	8	12.9	437	582		Yes	
	T07	1	5	10.5	484	645		Yes	
		2	5	10.5	484	645		Yes	

- Goal: evaluate uniformly distributed reinforcement
- Stable operation at 70% SSL performance
- Stable in low cycle fatigue
- 726 A/mm^2 matrix current density at quench
- Limited by layers 15-16
- Redistribution of reinforcement layers has significant positive impact on coil mechanics





Defeating “thermodynamic” leaks: A New Braiding Machine at the ASC

- **Allows us to try out various ways of fiber insulation applications and materials**

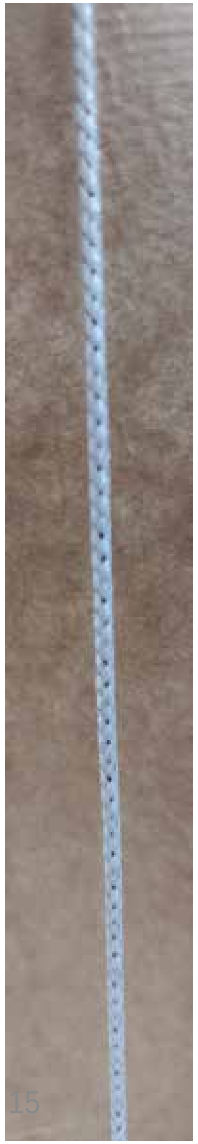
Alumino-Silicate

wrap braid

Pure alumina

wrap braid

See fuller talk by Dan

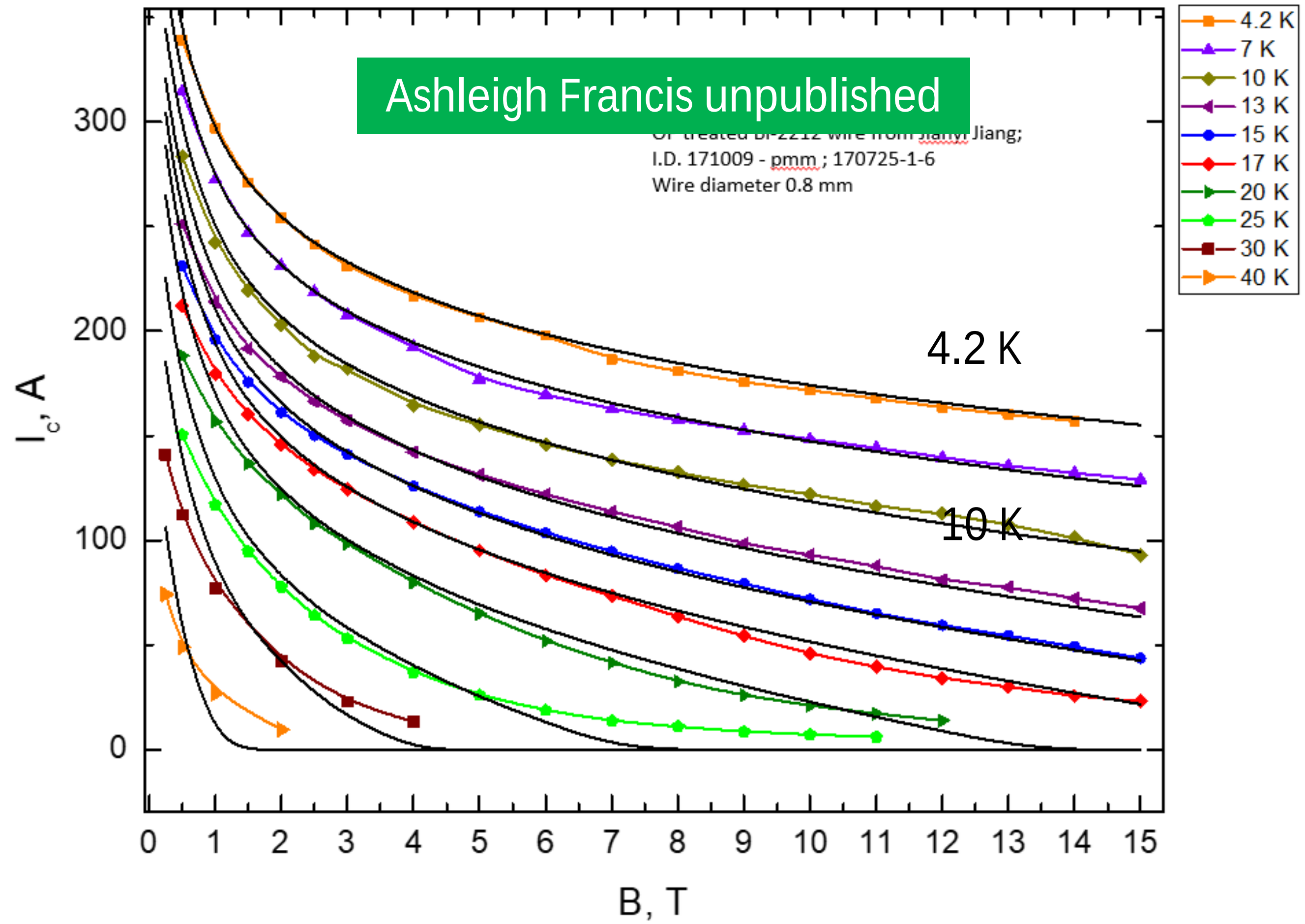


- Wrap reduces fiber insulation thickness of up to 50% compared with braiding
- Pure alumina does not show adverse reaction with the Ag matrix of the conductor
- Fiber dia. alumino-silicate ~7 µm while pure alumina ~10-12 µm and stiffer

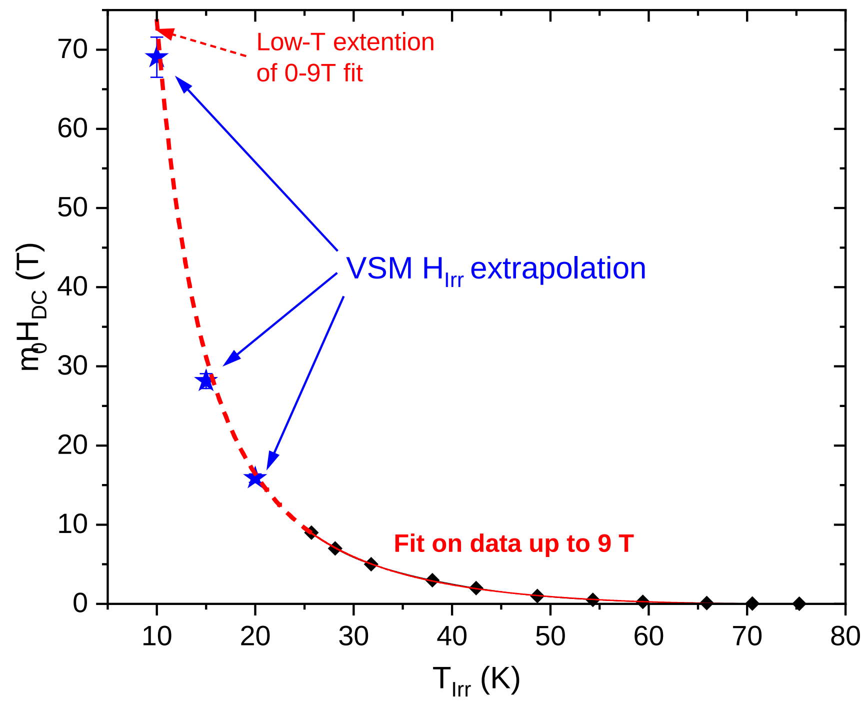
Does 2212 have to be used only at 4.2K?

Comparison experimental data with simple linear fit for OP treated Bi-2212

Fit: $I_c(B,T)=327.85*B^{-0.18439}-(7.89+0.169*B)*T$



Combination of VSM and AC susceptibility is enabling us to sweep out $H_{irr}(T)$ and perhaps better optimize it



Chiara Tarantini unpublished

- Certainly 10 K operation of Bi-2212 at high fields seems possible
- The functional simplicity of an isotropic conductor greatly struck Ashleigh whose thesis was on angular, field and temperature dependence of REBCO

Future Opportunities

- Commercial use of Bi-2212 pulls conductor manufacture and gets us out of present powder woes and high cost of present boutique manufacture
  - The early Engi-Mat powder, not yet replicated, shows us that ~30% higher Jc is available than present wires
- Thesis work of Barua shows us that better filament quality as manufactured benefits both Jc and the distribution (s/m) while thesis of Hossain shows that we must control filament coupling during HT
  - Uniform filament architectures may help Jc greatly
  - R&D billet order from us has been on hold until good (or at least consistent) powder starts to flow again
- Long term DOE support has enabled us to support about 10 PhDs who have been able to work on fundamental aspects of all of Bi-2212 technology
- Special support from FSU for HTS technology has allowed us to invest in wire, a braider, and a new powder capability

Driving questions for Bi-2212

- Do we have a reliable wire technology?
  - What lengths can wire be procured in?
- Do we have a reliable insulation technology?
  - For wires and for cables?
- Do we have a reliable reaction technology?
  - For wires
  - For coils, both solenoids and for dipoles
- Do we understand how to maintain mechanical integrity in coils?

Powder has some warning signs, so we are investing in our own ASP system (Eric talk)

YES!, 1 km of 1 mm wire, ~2 km at 0.8 mm

TiO_2/mullite works for single strand: for cable we are now braiding with pure Al_2O_3 (Dan talk)

50 bar Deltech generally works well but (unnecessary) SiC heating elements are a pain. New 1 m Renegade furnace has Kanthal windings but has been slow to commission (Dan talk)

Internal reinforcement with ceramic fibers and epoxy is enabling JBr stresses of >380 MPa, more than twice the conductor breaking strength

- I am very struck by the recent PSI CCT coil that trained up to full short sample NO DAMAGE
- It took 100 quenches – none of the LBL RT have trained nor have the ASC solenoids
- Bi-2212 may have the right sweet spot to properly current share, remain stable against epoxy cracking and not be too stable and susceptible to local burnout as is quite common in REBCO with present imperfections