



# Bi-2212 Coil Technology Development Efforts at the National High Magnetic Field Laboratory

**Youngjae Kim**

U.P. Trociewitz, E.S. Bosque, D. Davis, L. English, E. Hellstrom, J. Jiang,  
F. Kametani, E. Martin, J. Jones, A. Juliao, G. Bradford, S. Barua, I. Hossain,  
Y. Oz, G. Miller, J. Gillman, J. Lu, J. Levitan, P. Lee, L. Cooley, D.C. Larbalestier

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Mon-Mo-Or2-04

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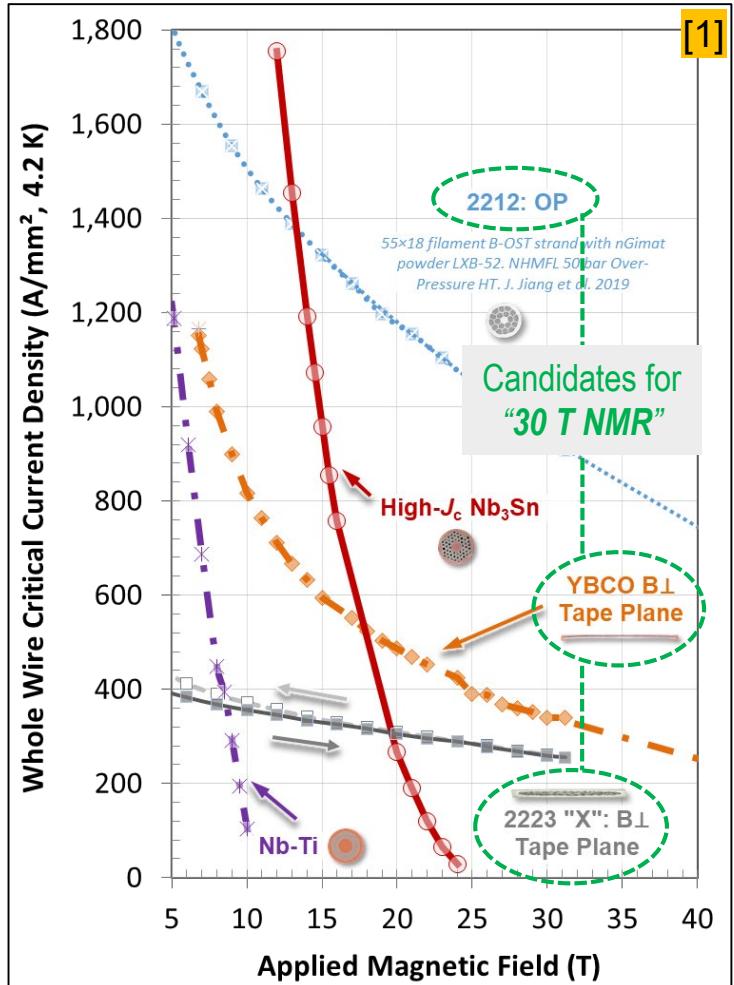
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# **Part 1. Introduction of Bi-2212 Conductor to “Magnet Developers”**

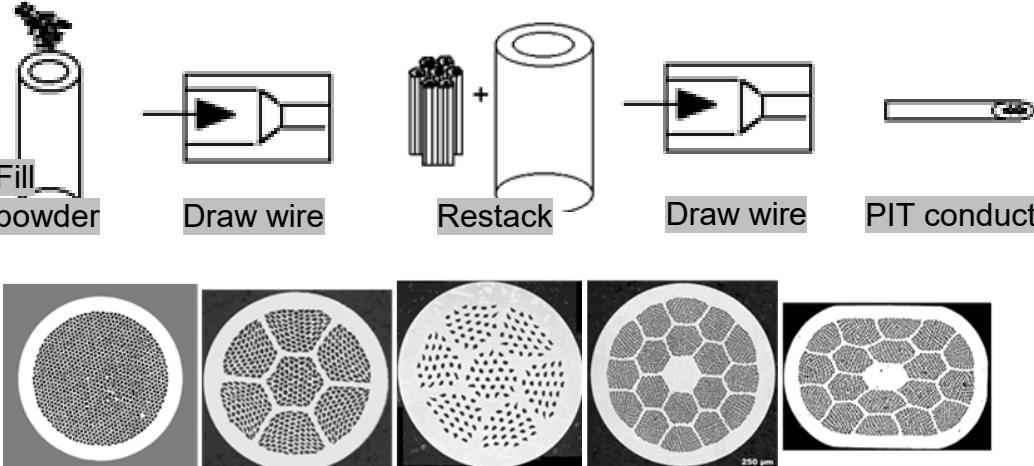
The Inside view from an ex-NI REBCO man to a Bi-2212 man

# Bi-2212 for Magnets; Pros

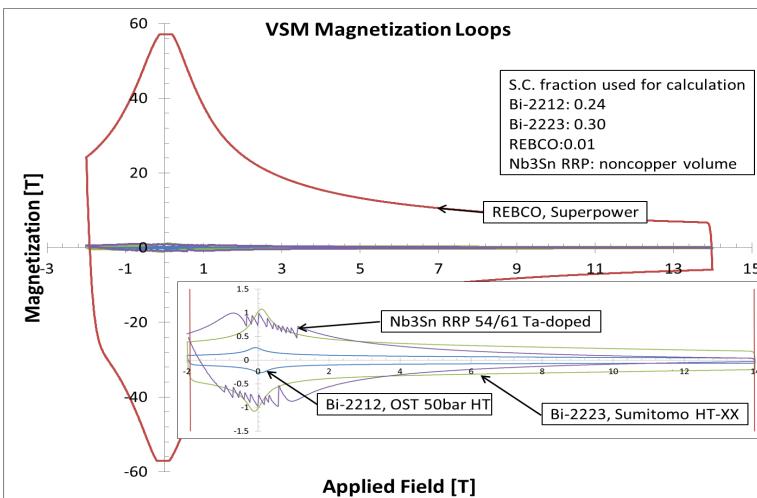


## 1. High and homogeneous $J_E(B)$

*PIT Process is cheap without complex Bi-2223 processing*



## 2. Great architectural wire and size design flexibility

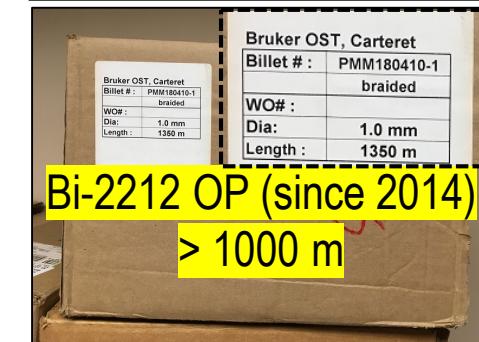


### 3. Low magnetization: no screening current field concerns

**YBCO (since 2000)** Fast high  
current density  
and copper  
can  
superconducting techniques, such as those used  
in the  
substitution  
of yttrium  
with lanthanides  
producing material on buffered metal  
substrates

**~ 300 m** Superior performance in a magnetic field due to  
the large magnetic moment of the lanthanide ions

Bi-2223 (since 2004)  
~ 1500 m (Type H)  
~ 500 m (Type HT)

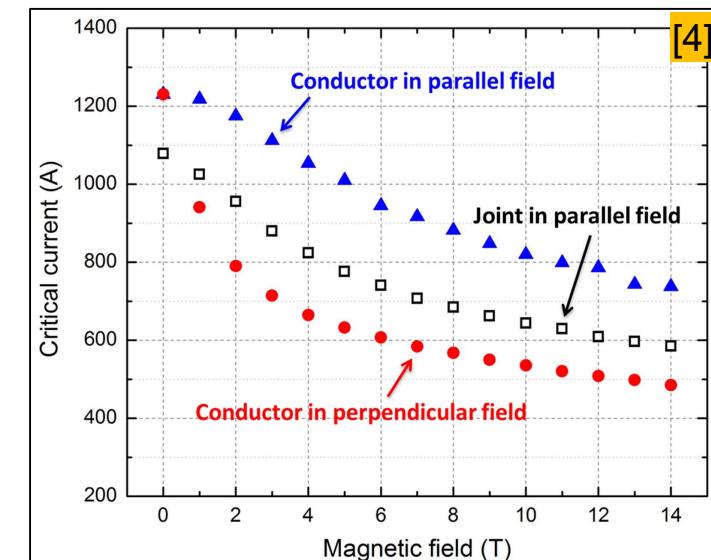
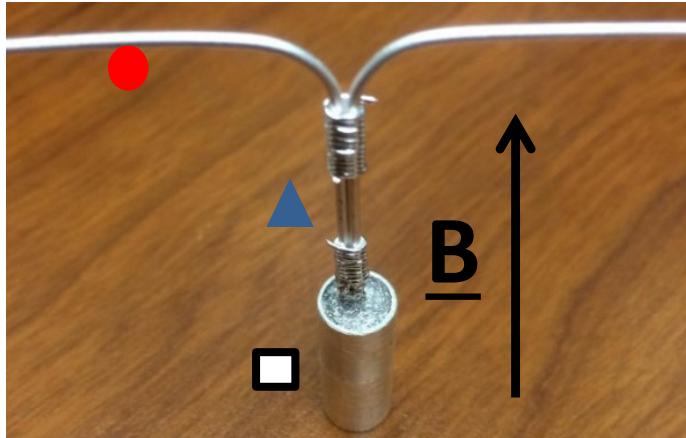


> 1000 m

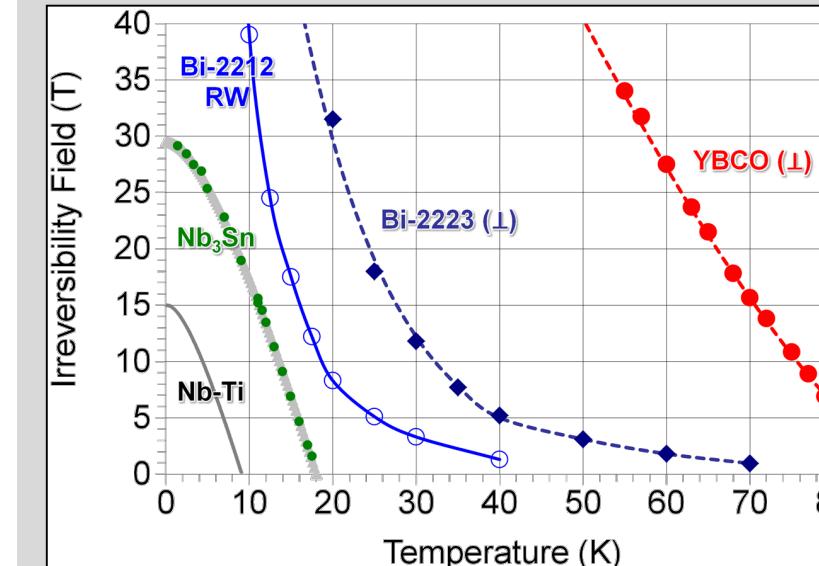
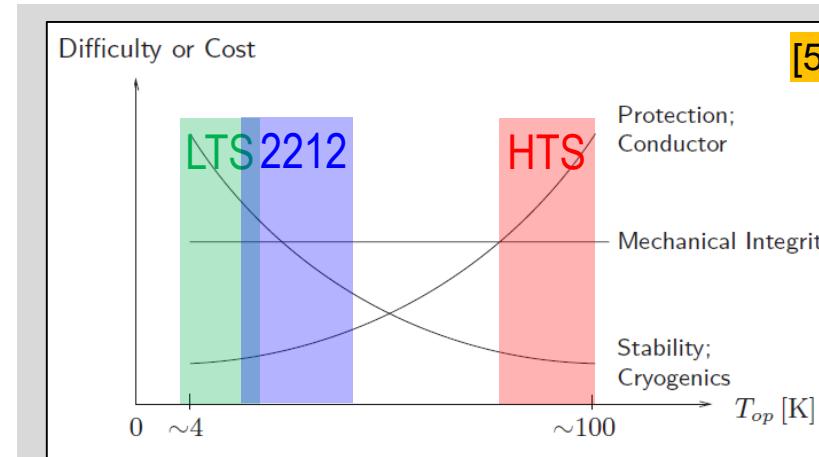
**Bruker OST, Carteret**  
**Billet # :** PMM180410-1  
**braided**  
**WO# :** \_\_\_\_\_  
**Dia:** **1.0 mm**  
 Length: 1360 m

#### 4. Long length capability

# Bi-2212 for Magnets; Pros



5. Bi-2212 Superconducting Joint

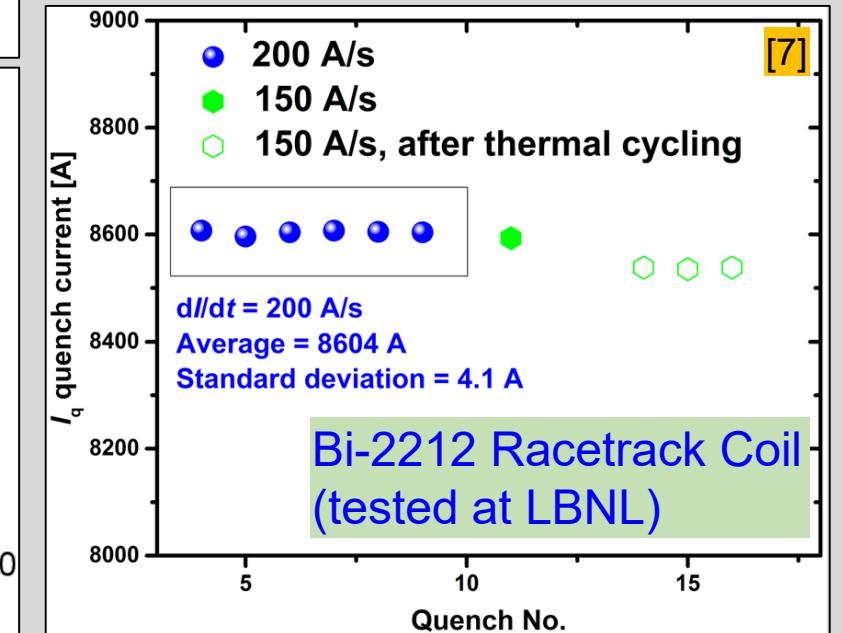


6. Lower  $T_c$ , Easier to Protect

TABLE I  
COMPARISON OF REBCO AND Bi-2223 INNER COIL PERFORMANCE FOR HIGH-RESOLUTION NMR MAGNET

[6]

	REBCO	Bi-2223
Hoop stress tolerance	Very high (e.g. 469 MPa [12])	High (e.g. 370 MPa [7])
Screening current to interfere with obtaining field homogeneity and stability	Large (e.g. 1.51 ppm/h* [5])	Relatively small (e.g. 0.05 ppm/h* [5])
Degradation due to electromagnetic force	Frequently [3],[9],[10],[12]	Rare



We need more experiments and studies.  
(D. Davis, Wed-Af-Or13-03)

# Bi-2212 for Magnets; Cons

## HTS Conductors Mechanical Properties

[2,3,8,9]

Conductor	$\varepsilon_{\text{critical}}$ [%]	$\sigma_{\text{critical}}$ [MPa]	$E_{\text{ave}}$ [GPa]	Winding strain?	Critical Bend dia. [mm]
Bi-2223	~ 0.20	130	65	Yes	80
Reinforced 2223	~ 0.50	400	91	Yes	40
YBCO	~ 0.45	550	122	Yes	11
Bi-2212 (OP)	~ 0.50	160	32	No	< 10
Reinforced 2212	~ 0.40	325	> 70	No	< 10

1. Low modulus → requires strong reinforcement  
...like other HTS conductors



Reinforcement technologies used for HTS magnets  
Left : YBCO coil with SS cowind (NHMFL)  
Right : Bi-2223 standard (top) and reinforced (bottom)

+Price

→ Price breakdown of Bi-2223 and Bi-2212

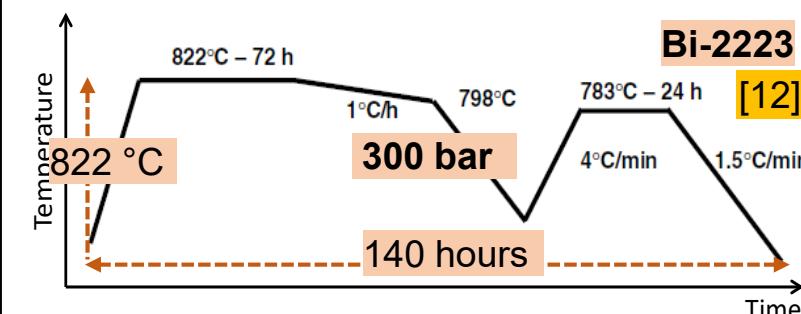
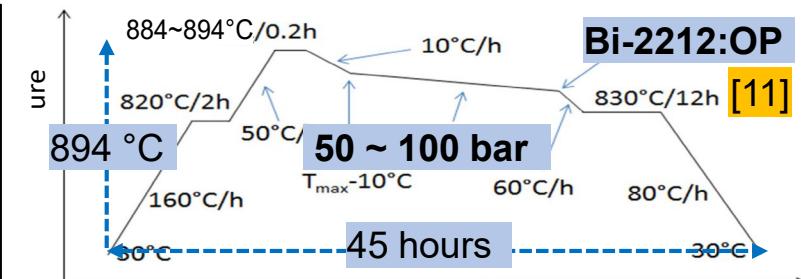
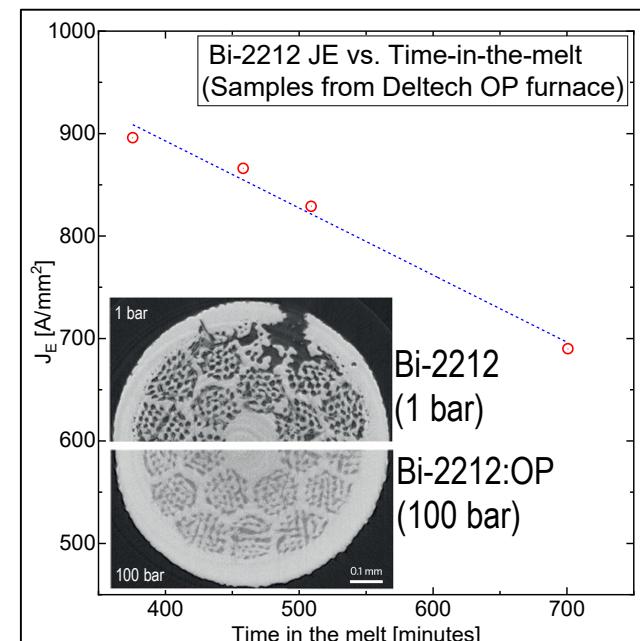
Price [\$/m]	Reacted?
-	Yes
30~40	Yes
40~50	Yes
100~120	No
TBD	No

Conductor	Matrix	Silver price*	Manufacture Process	Roll to tape?	React ?	Reinforced ?	Price
Bi-2223 HT	Silver	~\$5.3/m	PIT	Yes	Yes	Yes	~\$35/m
Bi-2212	Silver	~\$4.2/m	PIT	No	No	No	~\$110/m

\* calculated by simple conductor volume, density, and unit price of \$0.52/g (2019.07)

...But Bi-2212 is still a lab-scale product that has much opportunity to reduce costs BELOW Bi-2223 in mass production.

2. Price



3. Complex Heat treatment, but no more than Bi-2223 (E. Bosque, Wed-Mo-PI4-03)

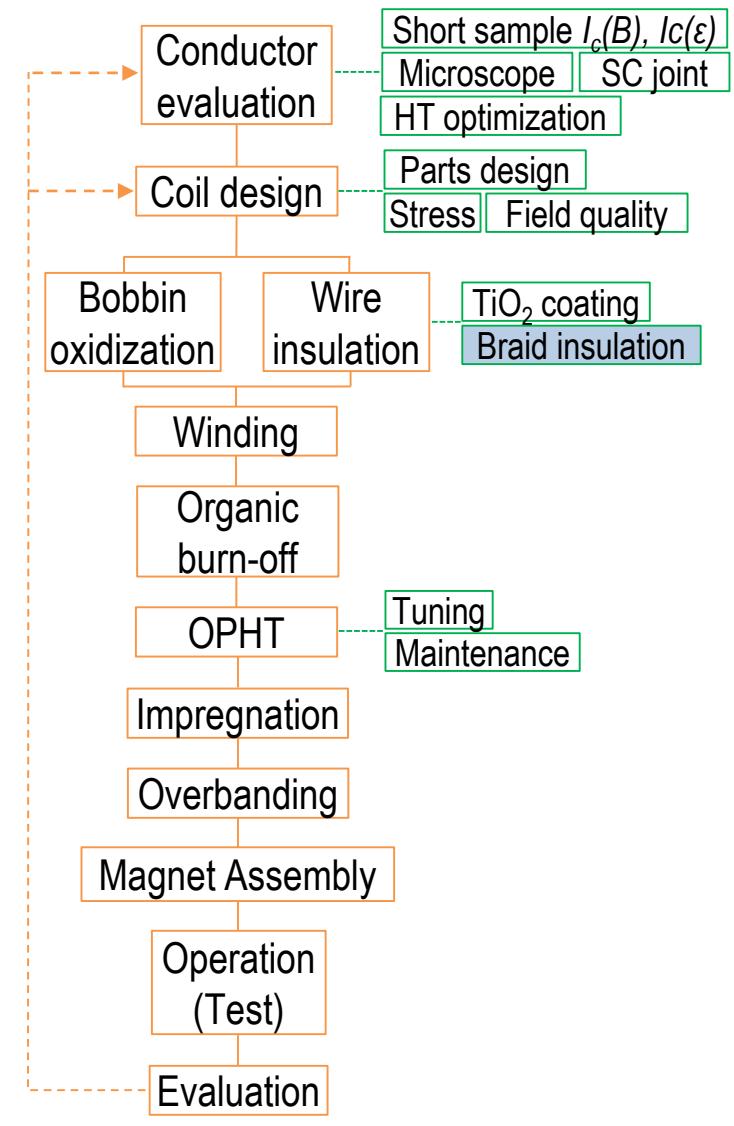
# What's Our Inside View?

- “Hybrid” of Nb<sub>3</sub>Sn and Bi-2223
  - in common: multifilamentary architecture
  - like Nb<sub>3</sub>Sn: wind-and-react, round wire
  - like Bi-2223: silver matrix, similar HT, reinforced for magnet application
- Three big advantages
  - Long length capability: > 1 km spool
  - Low magnetization and negligible SCF
  - Low enthalpy margin makes protection much easier than for REBCO
- Its three principal disadvantages are engineering challenges.
  - Low modulus, price, and complex heat treatment
  - Bi-2223 already conquered similar problems.

## **Part 2. NHMFL's Effort for Bi-2212 Coil Technology**

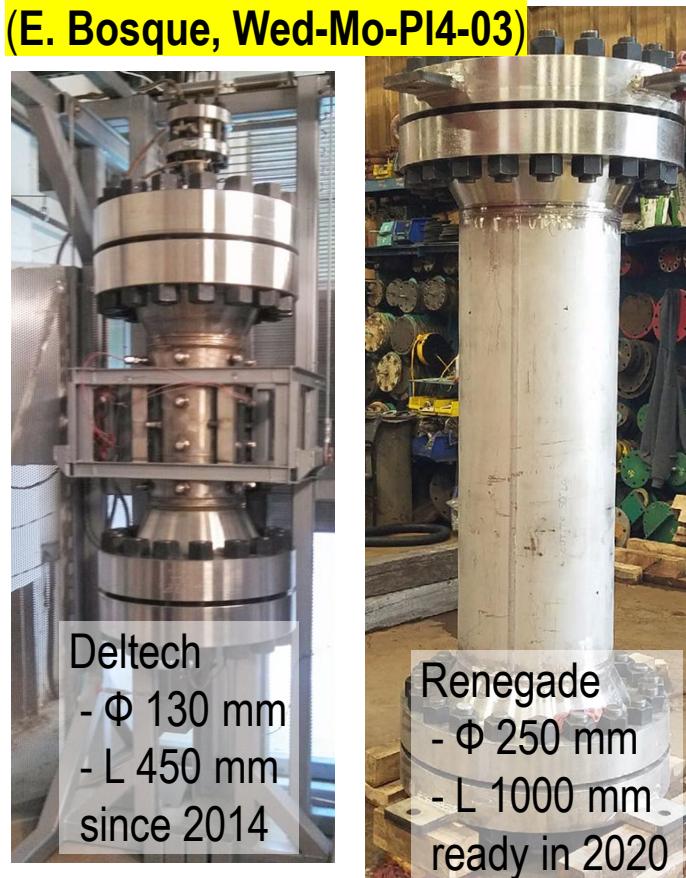
What we have done to improve Bi-2212 coil's performance

# Coil Development at NHMFL

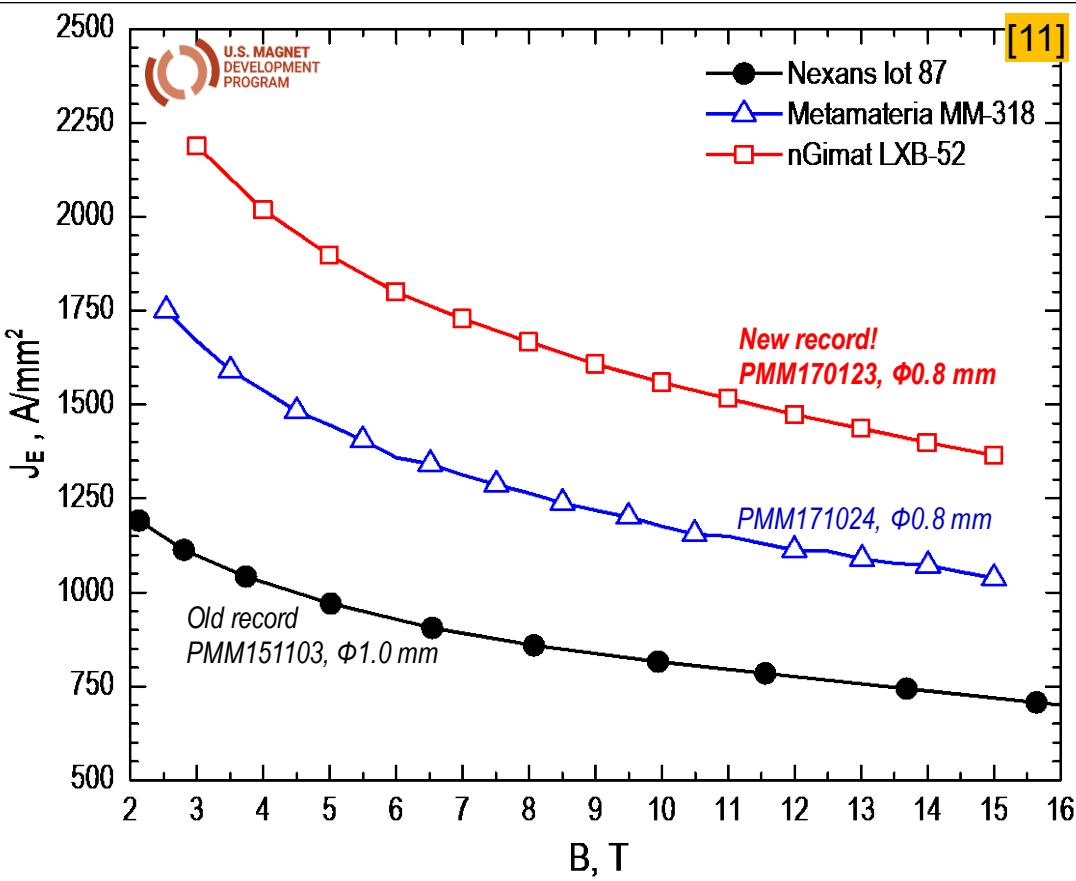


- Bi-2212 coil development at ASC
  - Major R&D activities are carried out internally.
  - Both material and system groups are in ASC.
  - Two main investments: Furnace and Testbed magnet

(E. Bosque, Wed-Mo-PI4-03)

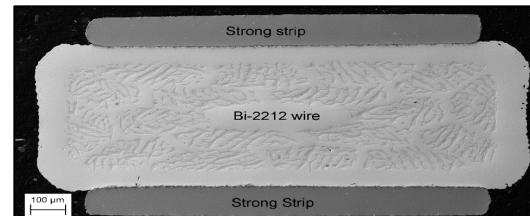


# Improvement of Conductor: $J_E(B)$ and Strength

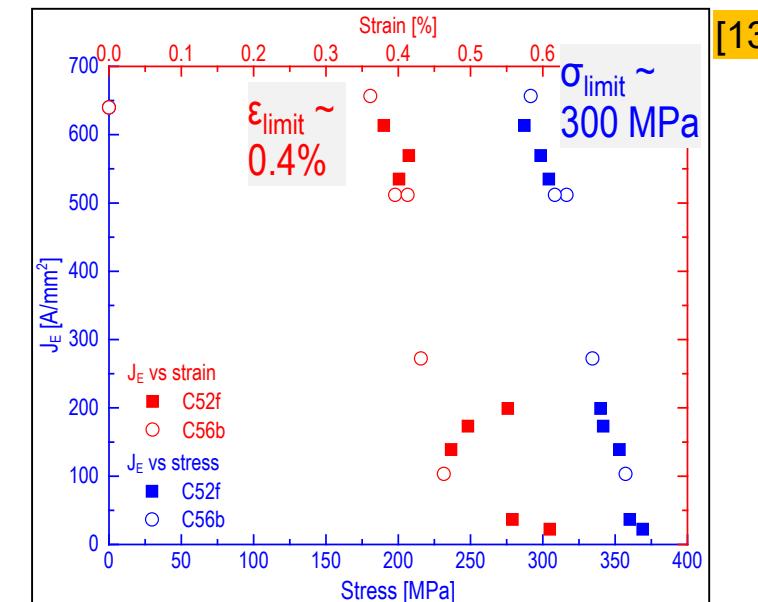


New powders broke the old Nexans powder's record.  
(great success supported by DOE-HEP MDP collaboration.)

SRW (Strengthened Rectangular Wire) by SMS, Alex Otto



Test Coil snapped at  $\sim 175 \text{ MPa}$



$J_E(\varepsilon)$  and  $J_E(\sigma)$  of SRW Samples

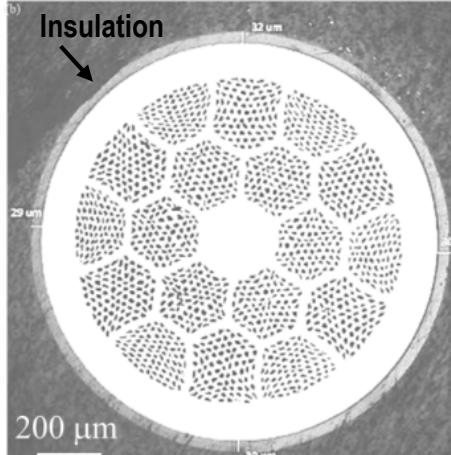
## Notes on the SRW test coil

- The coil didn't quench up to 495 A at 5 T.
- Short sample Ic at 5 T: 527 A
- Calculated BJR stress at the failure was  $\sim 175 \text{ MPa}$ , while the stress created from the conductor was  $\sim 275 \text{ MPa}$ .

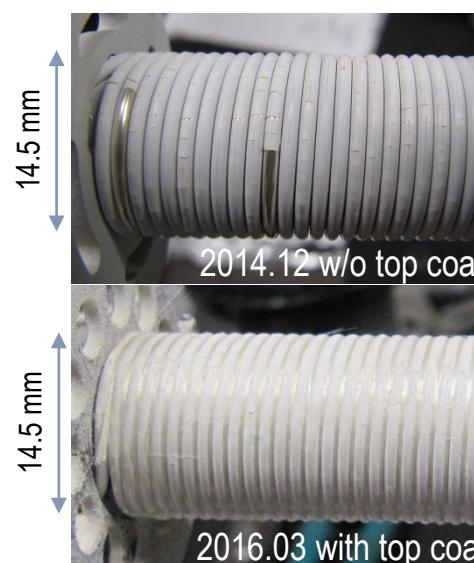
# Insulation of Conductor: Two-Stage Process



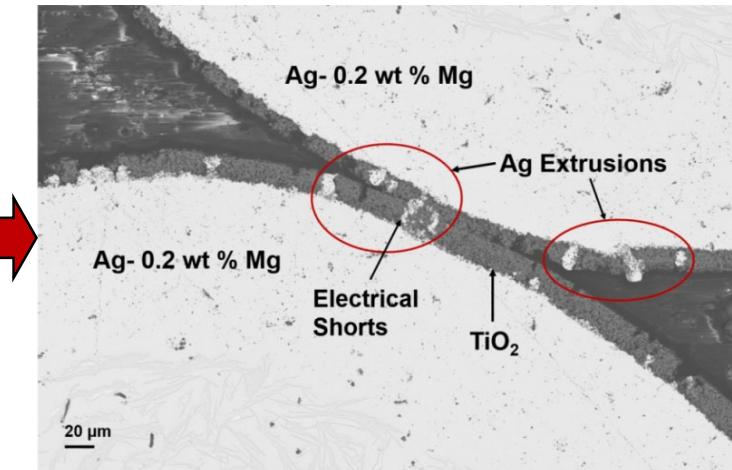
In-house insulation facility (top) and diameter measurement (bottom)



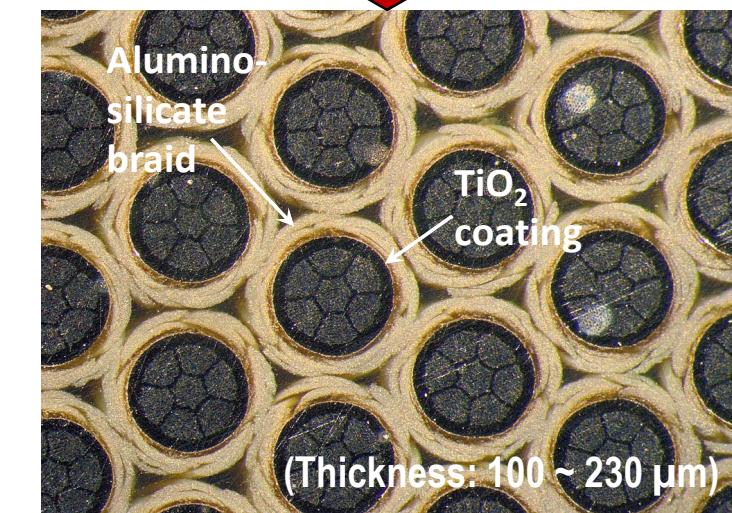
25 µm TiO<sub>2</sub> coating



Improved Insulation Quality



Ag droplets extrusion through TiO<sub>2</sub> coating



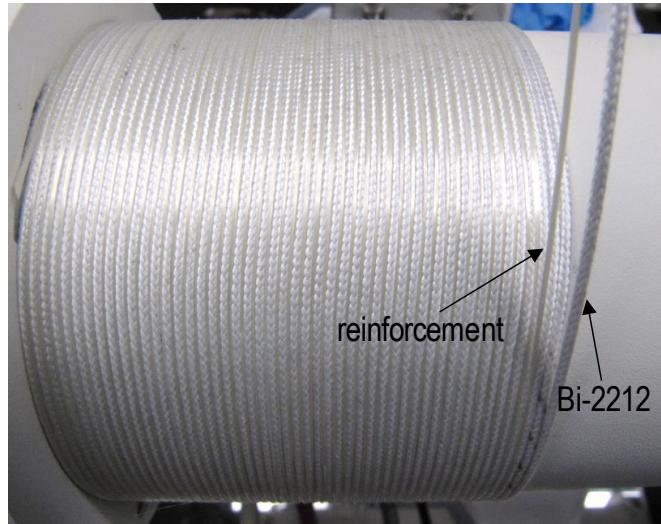
(Thickness: 100 ~ 230 µm)

TiO<sub>2</sub> + Mullite braid: reliable, thermally resilient, and chemically compatible Insulation

# Coil Winding

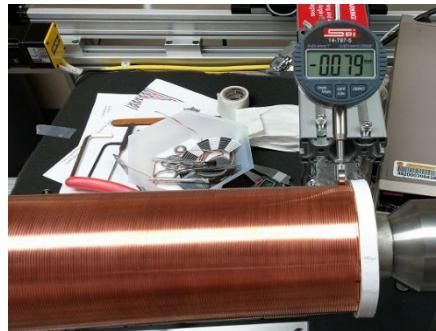


In-house Winding Machine



Bi-2212 and reinforcement co-winding

Mock-up coil (2014)



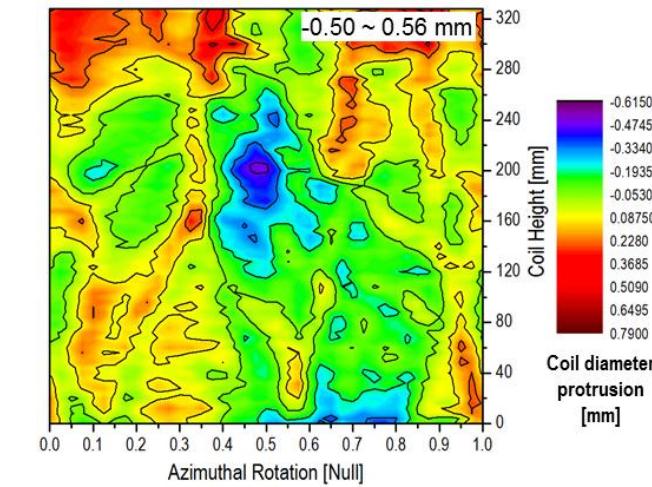
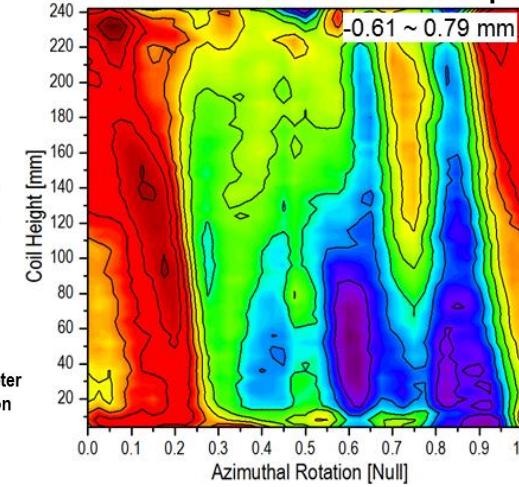
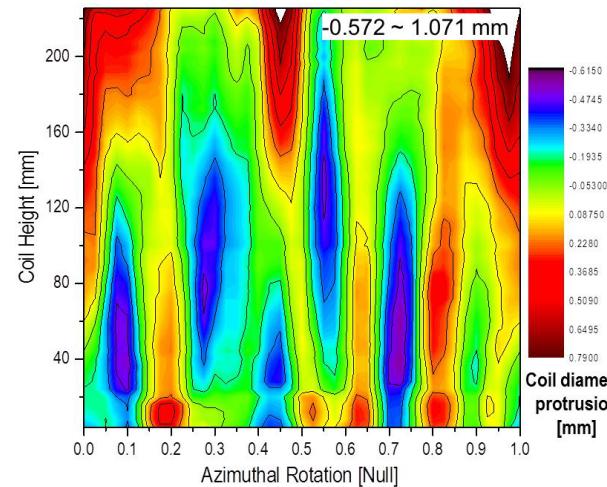
Platypus-I solenoid (2015.08)



Riken-I solenoid (2016.08)

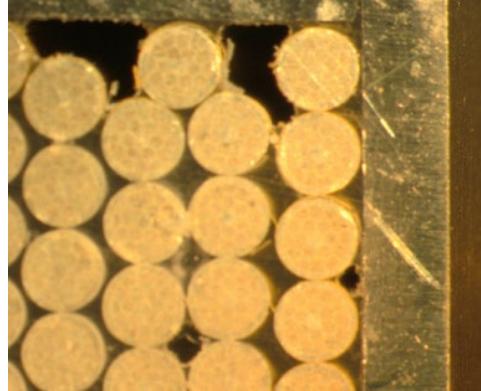
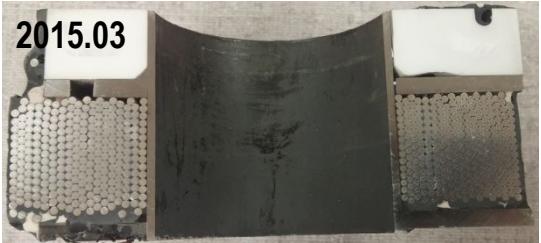


Surface Protrusion Maps

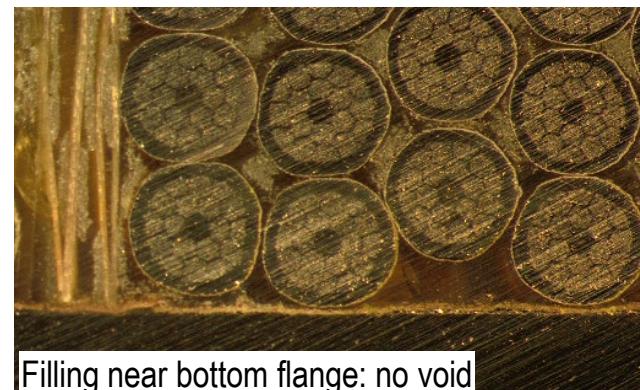
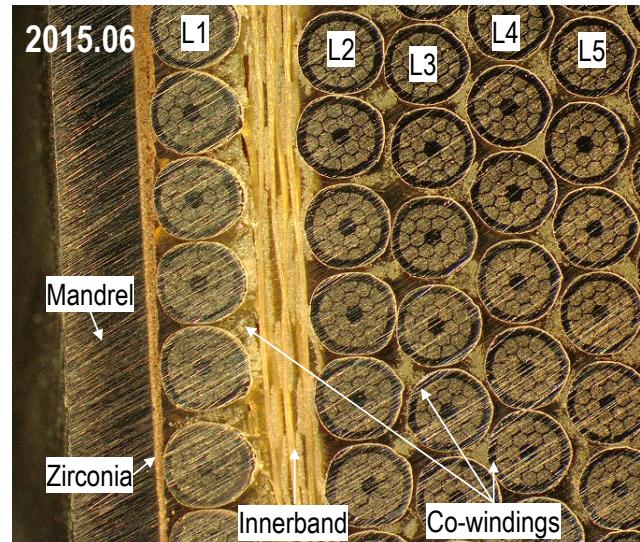


- Coil winding technique has been modified to improve winding pack uniformity and to apply reinforcement co-winding.

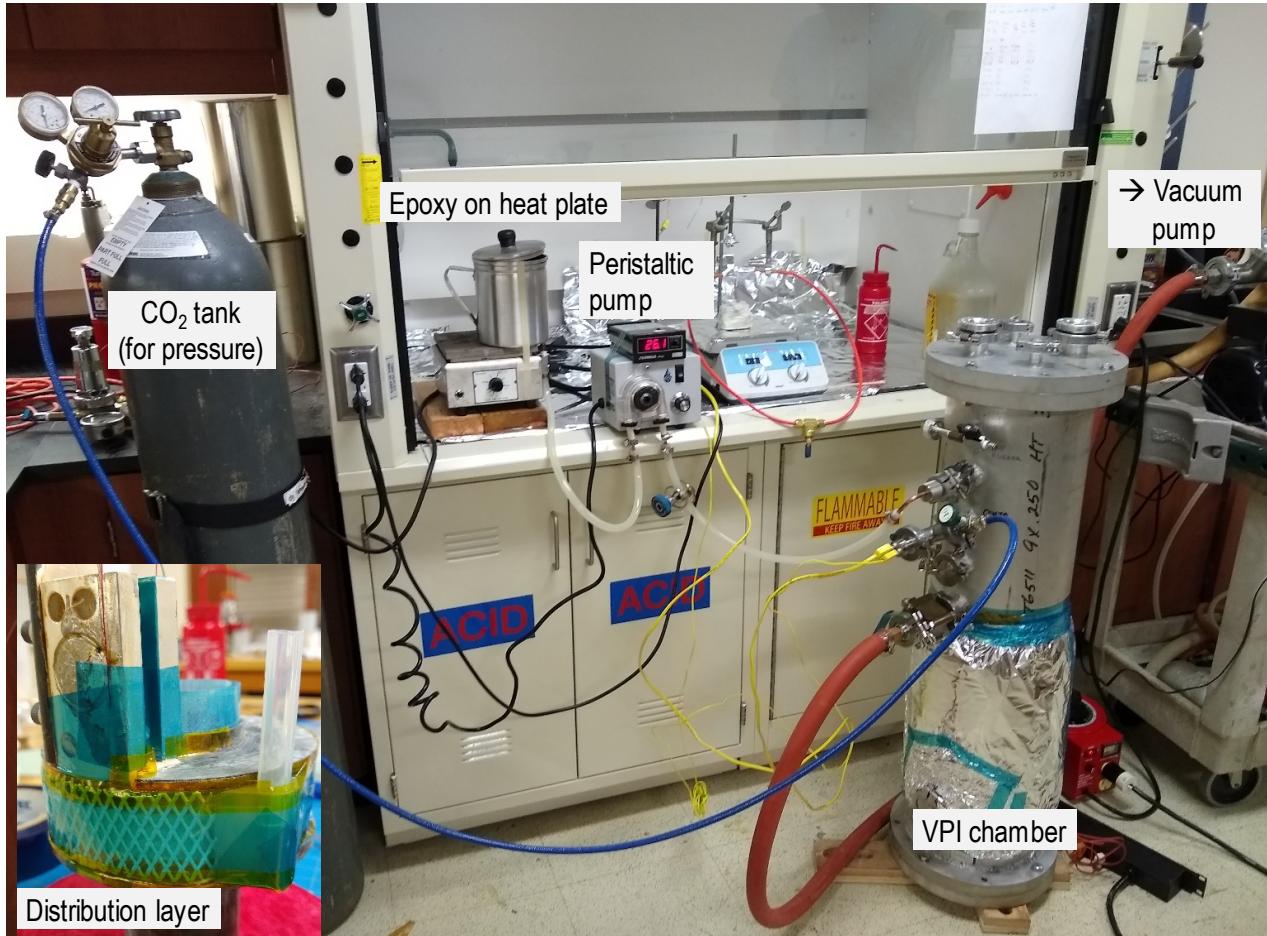
# Impregnation (VPI)



Cross sections of a Test coil  
(impregnated in epoxy bath)



Cross sections of Pup-3  
(2<sup>nd</sup> trial of VPI using NHMFL61)



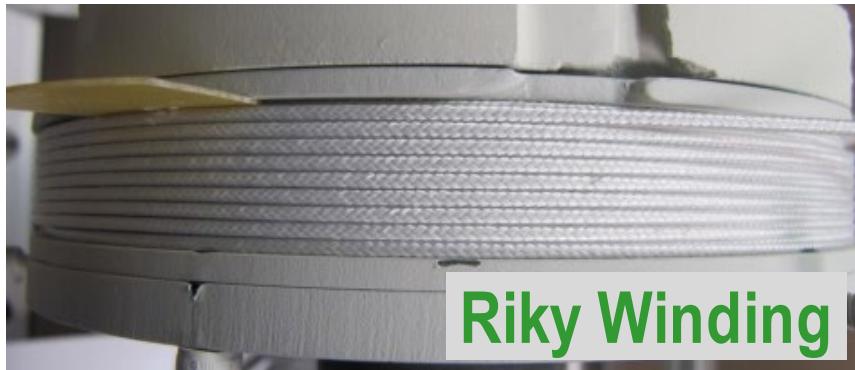
Current Vacuum Pressure Impregnation Process Setup  
(revised from the setup in 2015 for better epoxy fill)

## **Part 3. Progress of Bi-2212 Test Coils**

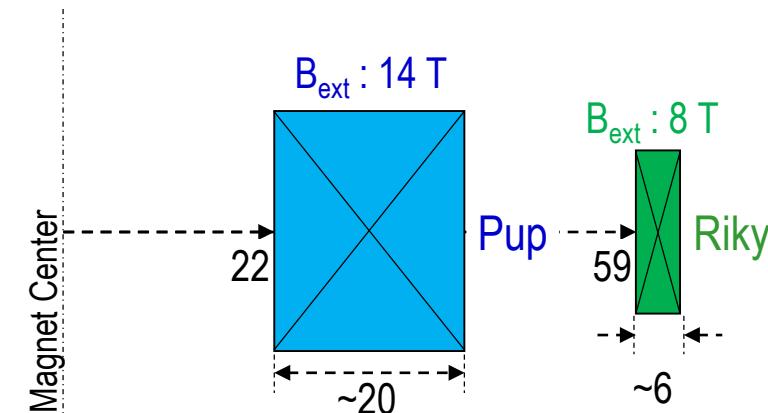
# Two Test Coil Design: Riky and Pup

## □ Two Test Coils for Bi-2212 Coil R&D

1. Riky : Large bore + Thin Coil ← reinforcement technique
2. Pup : Small bore + Thick Coil ← high field insert

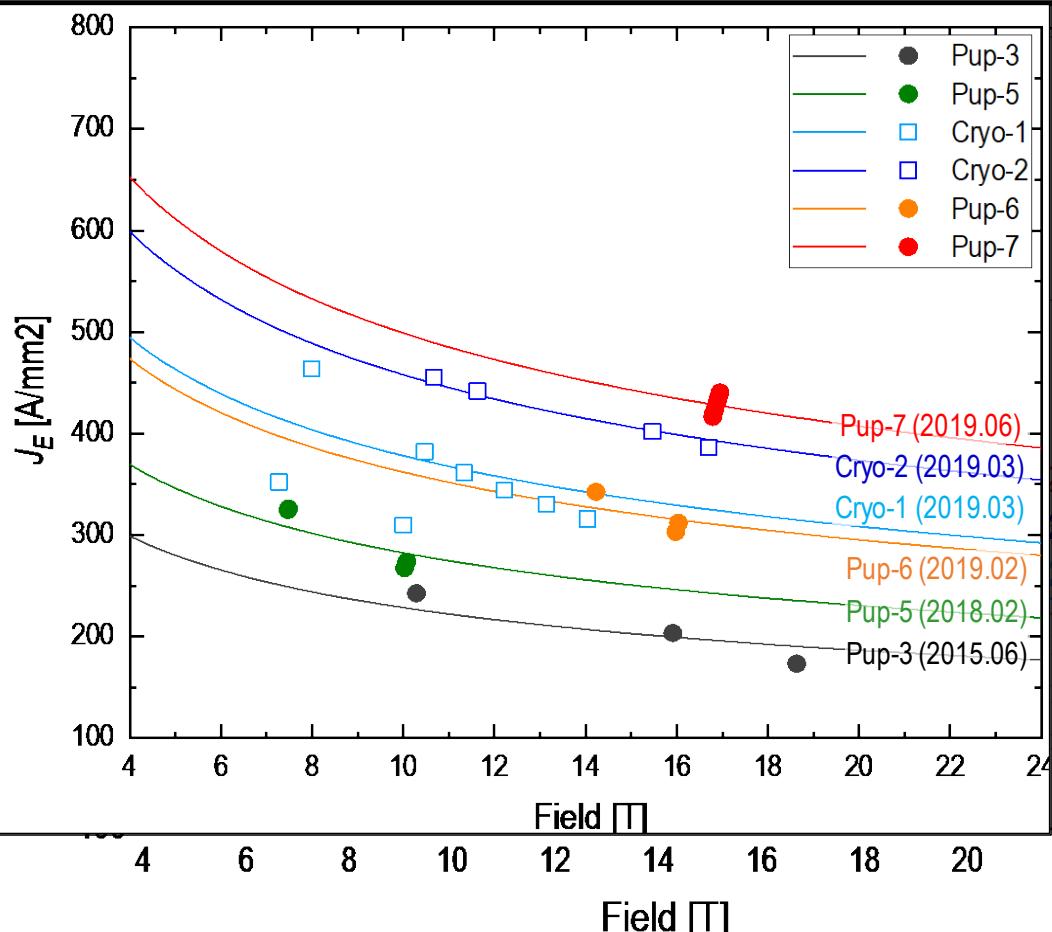


<To-scale Cross-section of Pup and Riky>



Specifications	Pup	Riky
ID ; OD ; Height [mm]	44.0 ; 83.3 ; ~ 25.0	118.0 ; 127.0 ; 12.5
Turn ; Layer (Total)	~ 20 ; 18 (350)	10 ; 4 (38)
Magnet constant	6.58 mT/A	0.39 mT/A
Conductor length	> 70 m	15 m
Test bed	14 T Cryogenic Magnet (LHe cooled)	8 T Cryomagnetic Magnet (Cryogen free)
BJ <sub>E</sub> R ( $I_{op} = 300$ A)	137 MPa	226 MPa
Features and Purpose	High field insert coil Hard to make Expensive to test Real Stress ≠ BJR	Stress test coil Easy to make Cheap to test Real Stress ≈ BJR

# Progress of the Pup Coils



	Pup-3	Pup-5	Pup-6	Cryo 1	Cryo 2	Pup-7
Test Date	Jun 2015	Feb 2018	Feb 2019	Mar 2019	Mar 2019	Jun 2019
Wire Diameter [mm]	Φ 1.3	Φ 1.0	Φ 1.0	Φ 0.9	Φ 0.8	Φ 1.0
PMM #	PMM131203-2	PMM140606	PMM160909-b	PMM181004-2	PMM181004-1	PMM180410-1
Powder	Lot 82 (Nexans)	Lot 82 (Nexans)	Lot 87 (Nexans)	LXB-43 (nGimat)	LXB-43 (nGimat)	LXB-116 (nGimat)
Architecture	121 x 18	55 x 18	121 x 18	55 x 18	55 x 18	85 x 18
ID ; OD ; Height [mm]	44.6 ; 91.6 ; 20.3	44.6 ; 86.6 ; 22.8	44.5 ; 86.2 ; 25.5	40.6 ; 70.5 ; 45.0	40.5 ; 68.5 ; 53.8	44.6 ; 84 ; 25.2
Total Turns	270	370	333	504	712	334
Max. $I_{op}$ ( $B_{ext}$ )	230 A (17 T)	215 A (8 T)	245 A (14 T)	201 A (12 T)	191 A (14 T)	345.8 A (14 T)
Max $J_E$	190 A/mm <sup>2</sup>	299 A/mm <sup>2</sup>	342 A/mm <sup>2</sup>	316 A/mm <sup>2</sup>	417 A/mm <sup>2</sup>	440.3 A/mm <sup>2</sup>
Total Field at Max $J_E$	18.00 T	9.48 T	15.5 T	13.8 T	16.2 T	16.25 T
Max. $B_JE R$ stress	140 MPa	99.2 MPa	199 MPa	-*	191 MPa	278 MPa
Max. Stress	69 MPa	65.7 MPa	74.8 MPa	-	70.4 MPa	102.0 MPa
Max. Strain	0.22 %	0.26 %	0.26 %	-	0.27 %	0.39 %

\*not calculated because it is less than Cryo-2.

- Pups consistently advanced Bi-2212 coil technology.
- Cryo-1 and 2: from Cryomagnetics, Inc. **(S. Minter, Mon-Mo-Or2-05)**
- Pup-7: a new champion. **(E. Bosque, Tue-Mo-Or8-08)**
- New powders are beneficial to coil technology.
- Pup-7 also recorded the highest stress and strain.

# **Part 4. Future of Bi-2212 Coil Development**

Pup-8

27.5 T Design / 40 T Design

# What's Next? Pup-8

- Pup-8 design was fully modified and designed to generate higher field.



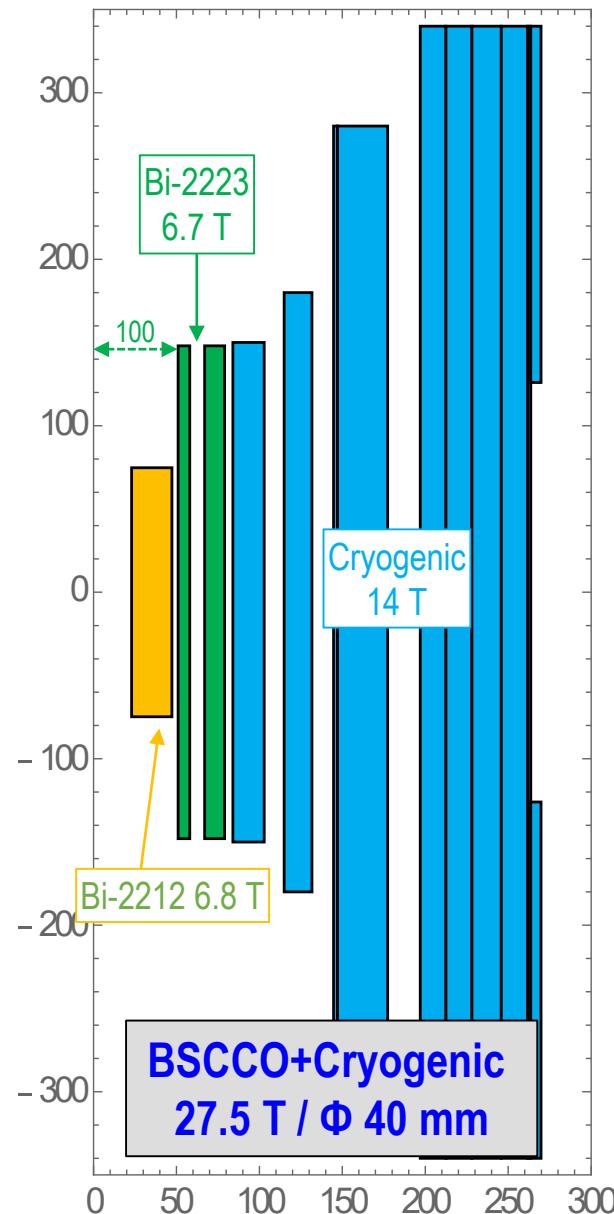
Pup-7 (tested)



Pup-8 (after OPHT)

Specs.	Pup-7	Pup-8
Wire	PMM180410-1 (nGimat) Φ 1.0 mm (bare) / Φ 1.2 mm (ins.)	
ID ; OD ; Height [mm]	44.6 ; 84 ; 25.2	44.5 ; 115.9 ; 40.1
Turn ; Layer (Total)	19 ; 18 (334)	30 ; 28 (859)
Conductor length [m]	~ 70	~ 216
Magnet constant [mT/A]	6.21	12.49
Inductance [mH]	5.92	39.2
Overband	Metal strip	TBD
Status	Tested (+ 2.3 T)	Heat Treated

# What's after Pups? 27 T and 40 T



Total field / cold bore		27.5 T / 40 mm bore
Bi2212	Size [mm]	Φ 1.3 (insulated)
	Powder	nGimat record
Bi2223	Size [mm]	W4.6 x Th0.36
	Type	HT-NX
Coil 1	Conductor	Bi2212
	a <sub>1</sub> ; a <sub>2</sub> ; 2b [mm]	23.0 ; 48.6 ; 149.5
	Layer x Turn	20 x 115
	Self field [T]	6.88
	Length [m]	496
	Innerbands	2
	Strain at I <sub>op</sub> [%]	0.41
	Conductor	Bi2223
	a <sub>1</sub> ; a <sub>2</sub> ; 2b [mm]	51.0 ; 58.0 ; 296.0
Coil 2	Layer x Turn	26 x 62
	Self field [T]	2.54
	Length [m]	564
	Conductor	Bi2223
	a <sub>1</sub> ; a <sub>2</sub> ; 2b [mm]	67.0 ; 79.0 ; 296.0
Coil 3	Layer x Turn	44 x 62
	Self field [T]	4.11
	Length [m]	1285
	I <sub>op</sub> / Field	396.0 A / 27.53 T
	Total Inductance [H]	9.71
Homo. [ppm]		~ 375

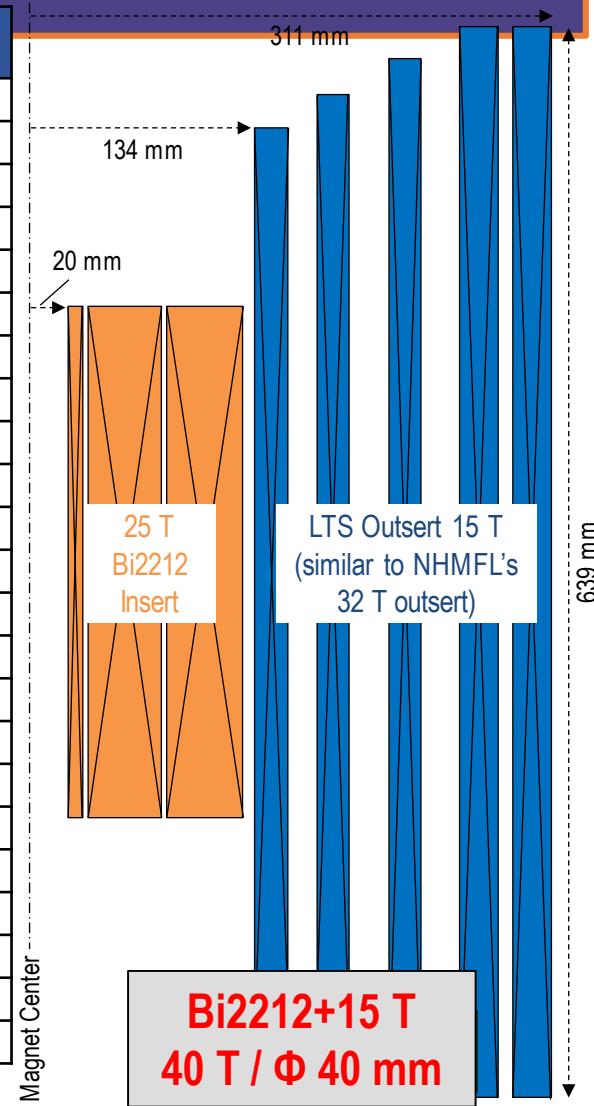
Design based on current equipments

- **Cryogenic 14 T / 160 mm Magnet**
- **Deltech (Φ 130 mm hot zone)**

	Total field / cold bore	40.0 T / 40 mm bore
Bi2212	Size [mm]	Φ 1.2*
	Powder	nGimat record
	a <sub>1</sub> ; a <sub>2</sub> ; 2b [mm]	23.0 ; 31.4 ; 304.8
	Layer x Turn	7 x 254
	Self field [T]	2.9
	Length [m]	300
	I <sub>c</sub> (I <sub>op</sub> /I <sub>c</sub> ) [A]	814.5 (0.49) – <b>40.1T</b>
	Innerbands	1
Coil 1	a <sub>1</sub> ; a <sub>2</sub> ; 2b [mm]	34.4 ; 78.3 ; 304.8
	Layer x Turn	30 x 254
	Self field [T]	11.8
	Length [m]	2,400
	I <sub>c</sub> (I <sub>op</sub> /I <sub>c</sub> ) [A]	832.6 (0.48) – <b>37.3T</b>
Coil 2	Innerbands	13
	a <sub>1</sub> ; a <sub>2</sub> ; 2b [mm]	81.3 ; 127.0 ; 304.8
	Layer x Turn	30 x 254
	Self field [T]	10.4
	Length [m]	4,600
Coil 3	I <sub>c</sub> (I <sub>op</sub> /I <sub>c</sub> ) [A]	936.9 (0.43) – <b>25.4T</b>
	Innerbands	15
	I <sub>op</sub> [A]	399.6
	Field [T]	40.04
	Homo. [ppm]	178

Design based on future equipment

- **15 T / 260 mm Magnet** (similar to NHMFL's 32 T outsert)
- **Renegade (Φ 250 mm hot zone)**



**Bi2212+15 T  
40 T / Φ 40 mm**

# References

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Thank you for Listening!