NATIONAL HIGH MAGNETIC FIELD LABORATORY

Intro: Large Magnet Projects

Laurel Winter
MagLab - LANL

NATIONAL HIGH MAGNETIC FIELD LABORATORY

1:30 PM	**Intro: Large Magnet Projects**	**Laurel Winter, MagLab-LANL**
1:35 PM	**Statuses of REBCO and Bi-2212 solenoid technologies**	Ernesto Bosque, MagLab-FSU
2:10 PM	**Impact of fusion on HTS conductor production, challenges of fusion magnets and need for new test facilities**	David Larbalestier, MagLab-FSU
2:30 PM	**Unstructured Discussion**	DL: Laura Greene
2:50 PM	**BREAK**	
3:10 PM	**Magnets for X-ray & Neutron Scattering, Axion detection**	Mark Bird, MagLab-FSU
3:30 PM	**Beyond 40T at the MagLab & need for Test Facilities (LBR)**	Tom Painter, MagLab-FSU
3:50 PM	**Magnets for muon colliders**	Lance Cooley, MagLab-FSU
4:10 PM	**Pulsed Magnets: The road to 120T**	Ross McDonald, MagLab-LANL
4:30 PM	**Unstructured Discussion and Summary**	DL: Laura Greene
4:50 PM	Break	
5:30 PM	DINNER and Discussion (with UC meeting participants)	
6:15 PM	MagLab Overview	Greg Boebinger
7:15 PM	Adjourn	

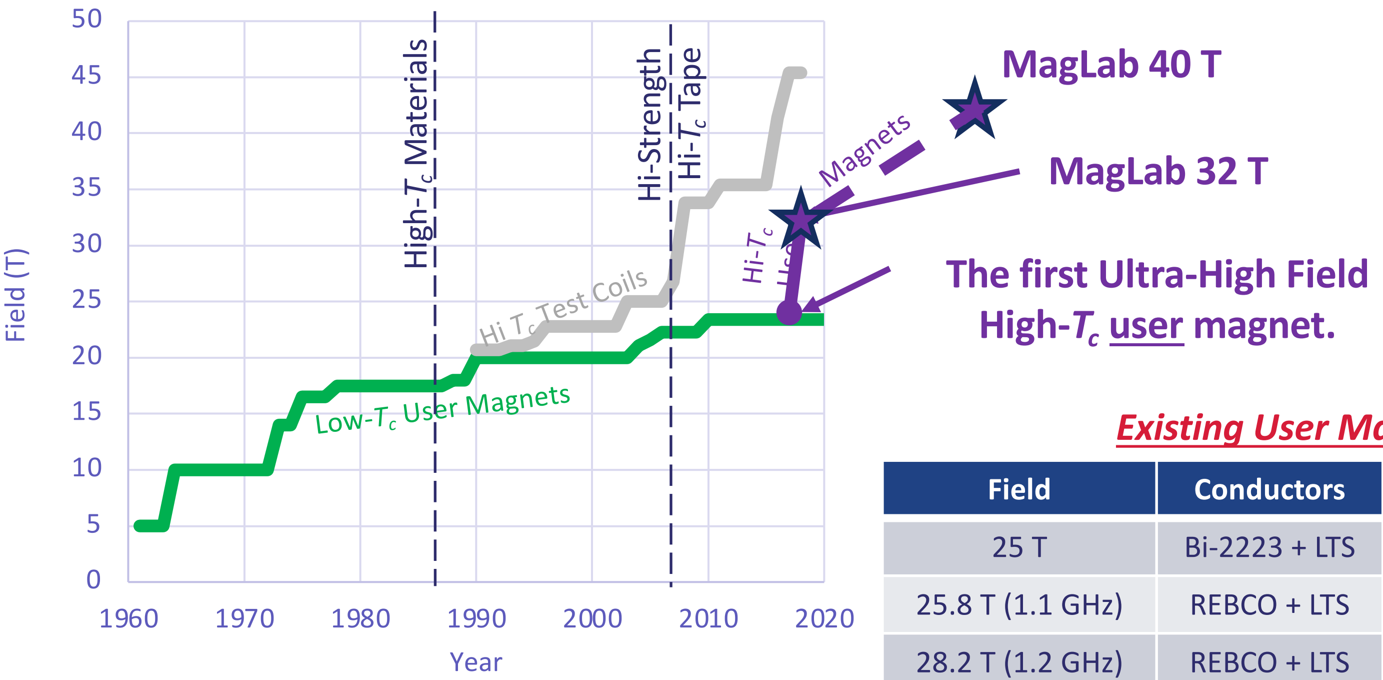
Statuses of
REBCO and Bi-2212 Solenoid Technologies

Ernesto Bosque
National High Magnetic Field Laboratory
Florida State University, Tallahassee, Florida, USA

Presenting slides assembled from M. Bird, U. Trociewitz, and D. Davis

Development of REBCO Superconducting Solenoids

Ultra-High Field (UHF) solenoids means >23.5 T



Many UHF test coils have been built but only a few magnets are in service.

Several Other Projects Underway at labs Worldwide!

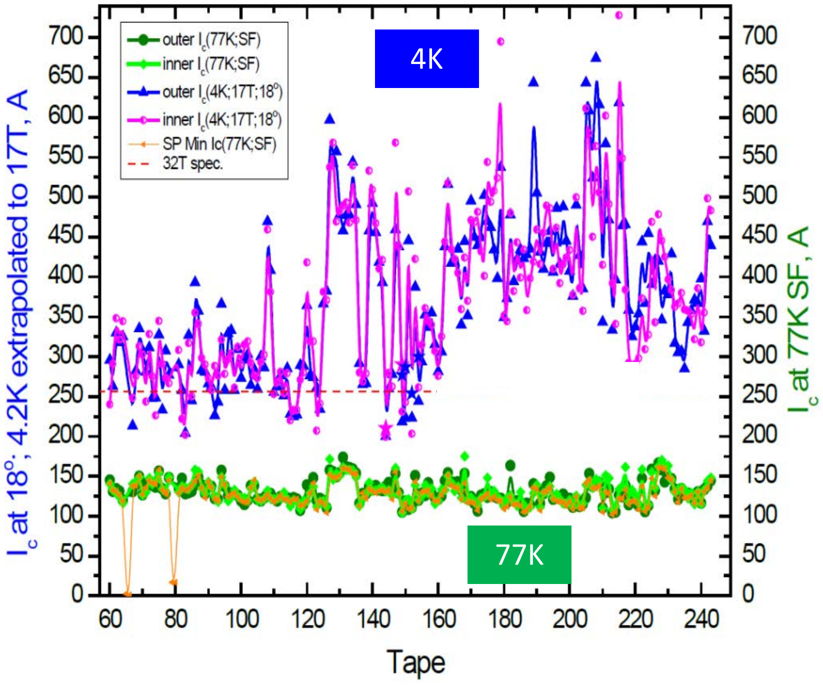
Existing User Magnets > 23.5 T Worldwide

Field	Conductors	Maker	Location	Year
25 T	Bi-2223 + LTS	Toshiba	Sendai	2017
25.8 T (1.1 GHz)	REBCO + LTS	Bruker	Nashville	2019
28.2 T (1.2 GHz)	REBCO + LTS	Bruker	Florence (+6)	2020
32.1 T	REBCO + LTS	MagLab	Tallahassee	2017
30 T	REBCO + LTS	IEE-Beijing	Beijing	2023

Some UHF REBCO Magnet Concepts

Unpredictability of REBCO I_c Tape-to-Tape

32 T Magnet: 2012 – 2014
SuperPower tape



Temp	Ave	St. Dev.	St. Dev.	Min	Max	Ratio
4.2 K	393 A	94 A	24%	200 A	725 A	3.6
77 K	130 A	15 A	12%	100 A	175 A	1.8

There is significant variation in I_c at 4 K between tapes.

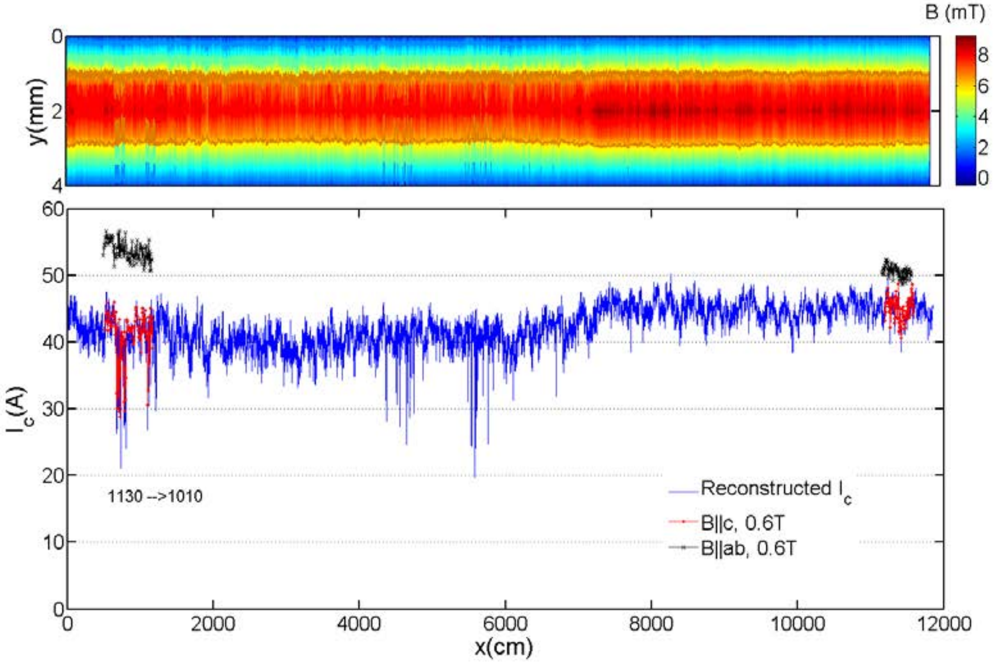
It cannot be predicted from a 77 K measurement.

(Present variation seems to be less than in the past.)

Dima Abraimov

Unpredictability of REBCO I_c Dropouts

<u>YateStar measurement of critical current at 77K of SuperPower tape M4-352-5 0912</u>

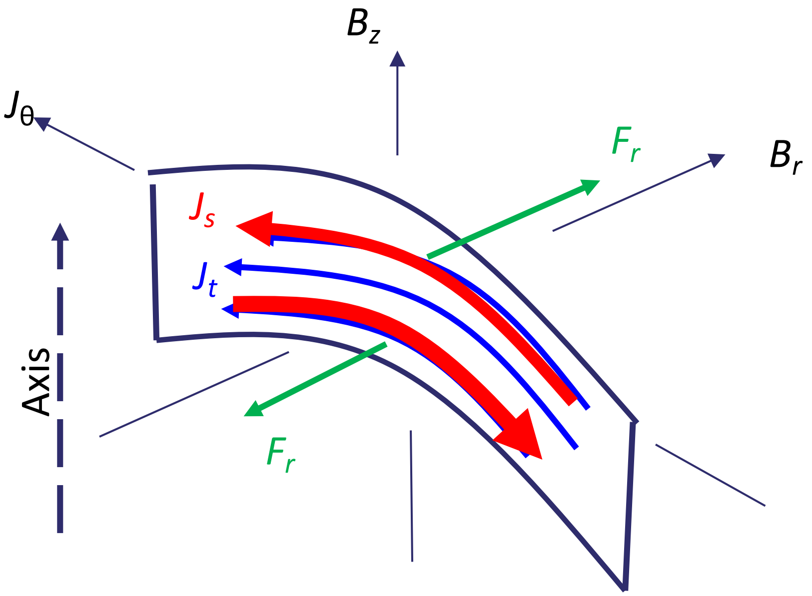


77 K measurements with TapeStar & YateStar indicate there can be spots along a conductor with low critical current.

Similar measurements at 4K have not been made.

Variation at 4K is unknown.

Screening Currents: Tape Conductors



J_t = transport current in θ direction.

- During charging of the magnet, B_r creates screening currents, J_s, in the tape.
- J_s reacts with B_z to give radial forces F_r, in addition to those created by the transport current.
- This gives rise to a bending and strain that is not uniform across the width of the tape.
- <u>Tape removed from test coils can display plastic deformation!</u>

D. Kolb-Bond, M.D. Bird, I.R. Dixon, T.A. Painter, J. Lu, K.L. Kim, K. Kim, R.P. Walsh, F. Grilli, *SuST,* 34, 095004 (2021).

Y. Yan, P. Song, C. Xin, M. Guan, Y. Li, H. Liu, and T. Qu, *SuST.* **34** (2021) 085012 (13pp)

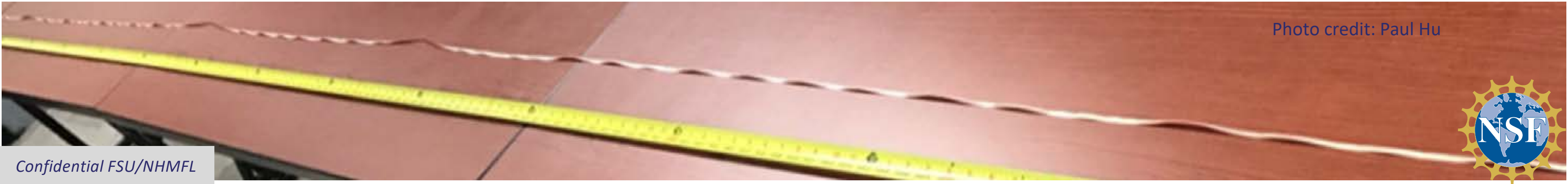


Photo credit: Paul Hu

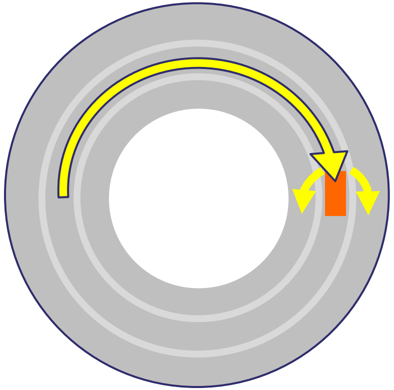
Insulated vs No-Insulation REBCO

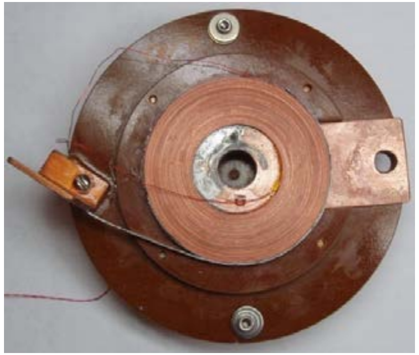
Insulated REBCO

- MagLab 32 T, 2017
- Bruker 28.2 T (1.2 GHz), 2019
- RIKEN 30.5 T (1.3 GHz)
- Sendai 33 T

No-Insulation REBCO

- Resistive (Metal) Insulation
- Partial Insulation
- MIT 30.5 T NMR
- Grenoble/CEA 30 T
- IEE-Beijing: 30 T CMP + 27 T CM NMR





Current Bypasses Quench reducing hotspot temperature.

Less Cu is Required → Smaller Coils [3, 4].

Less Reinforcement Required → Smaller Coils.

- ☐ Coil quench at I_{op}=412 A (1580 A/mm²).
- ☐ No coil damage in 20-s "over-current" operation.

S. Hahn, D.K. Park, J. Bascunan, and Y. Iwasa, *IEEE Trans. On Appl. SC*, **21**, 3, (2011) pp. 1592 – 1595
S. Hahn, D.K. Park, J. Voccio, J. Bascunan, and Y. Iwasa, IEEE Trans. On Appl. SC, **22**, 3, (2012) 4302405

Quench

	LTS	HTS (REBCO, high field, operating at 4 K)
Energy Margin	Small (mJ)	Large (kJ)
Small coils	Self protect Quench propagates quickly Energy distributed uniformly	Frequently burn without active quench protection Quench propagates slowly Energy concentrated in a small volume
		NI-REBCO magnets allow current to bypass quench (with potentially high induced currents and strains)
Large Coils	Require protection system	Require protection system
	1. Diodes allow current to bypass quench (with potentially high induced currents and strains).	1. NI might require controlled inter-turn resistance to control quench dynamics (Metal Insulation, Resistive Insulation, Partial Insulation) [1, 2].
	2. Heaters accelerate quench	2. Heaters accelerate quench
	3. External dump resistor extracts energy	3. External dump resistor extracts energy

[1] P.C. Michael, et al., *IEEE-TAS* **29**, 5, Aug 2019, 4300706
[2] D. Park, et al., IEEE-TAS 29, 5, Aug 2019, 4300804

Operational UHF REBCO Magnets

32 T SC: I-REBCO

NATIONAL HIGH MAGNETIC FIELD LABORATORY

SuperPower Inc. A Furukawa Company

OXFORD INSTRUMENTS

REBCO Unpredictability

I_c of all tapes was measured at 4K, 18° from tape broad surface, and 14 T.

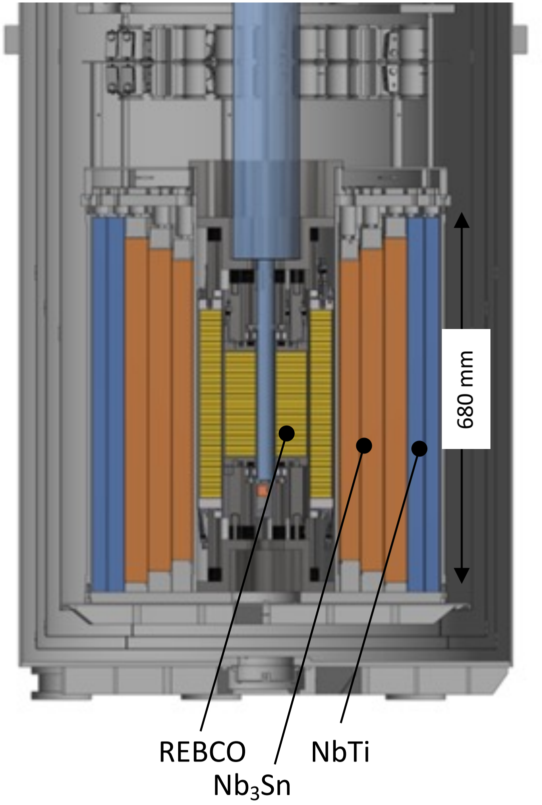
Magnet operates between 20% and 30% of I_c.

Screening Currents

Not fully appreciated at the time.

Quench

Heaters between REBCO double-pancakes (~100 kJ).

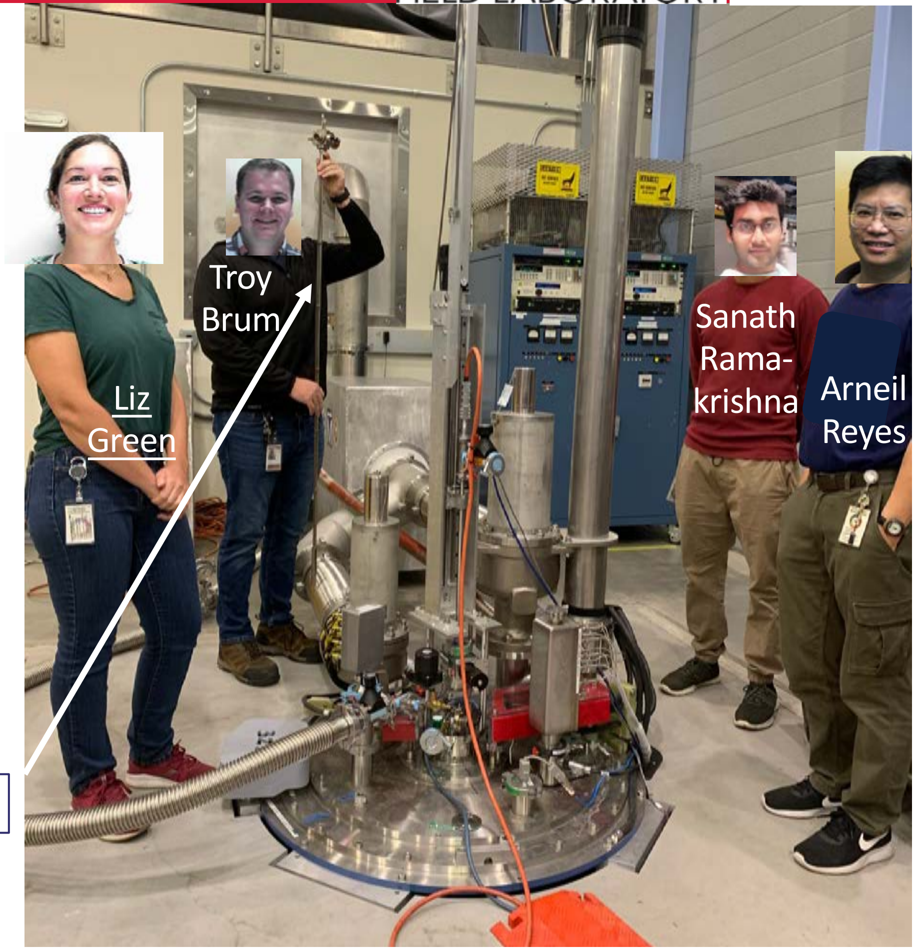


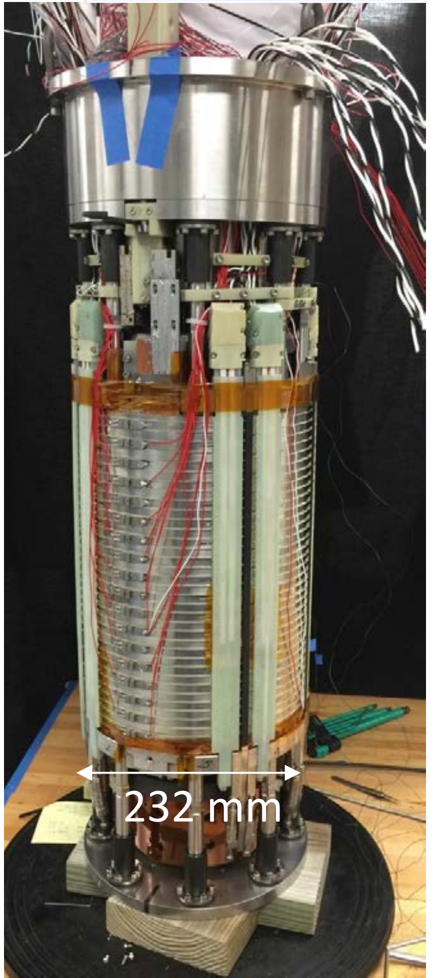
Total field	32 T
Field YBCO coils	17 T
Field LTS coils	15 T
Cold inner bore	32 mm
Current	172 A
Inductance	619 H
Stored Energy	9.15 MJ
Uniformity	5×10^{-4} 1 cm DSV

- Commercial Supply:
  - 15 T, 250 mm bore LTS coils
  - Cryostat (Oxford Instruments)
  - REBCO tape (SuperPower)
- In-House development:
  - 17 T, 34 mm bore YBCO coils

W. Denis Markiewicz, David C. Larbalestier, Hubertus W. Weijers, Adam J. Voran, Ken W. Pickard, William R. Sheppard, Jan J. Jaroszynski, Aixia Xu, Robert P. Walsh, Jun Lu, Andy V. Gavrilin, Patrick D. Noyes, *IEEE TAS*, **22**, 3, 4300704 (2012).

32 T magnet: User Service





Liz Green, a Research Faculty member at the MagLab, leads the 1st User Experiment in the 32 T magnet performing NMR measurements of a frustrated magnet system.

NMR probe

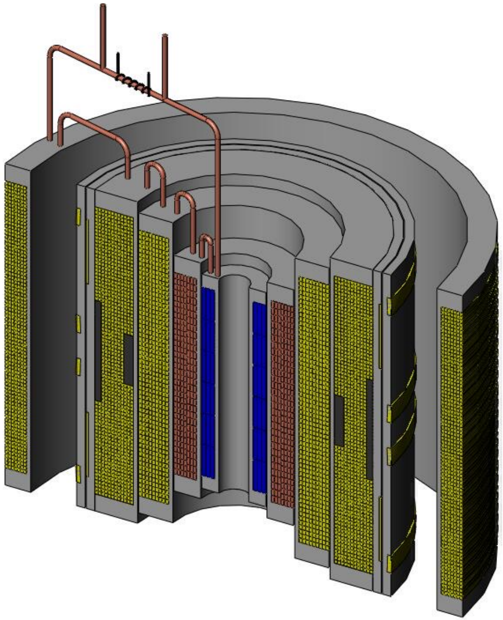
NMR Magnets Beyond 1.0 GHz
High Temperature Superconductors (I-REBCO)

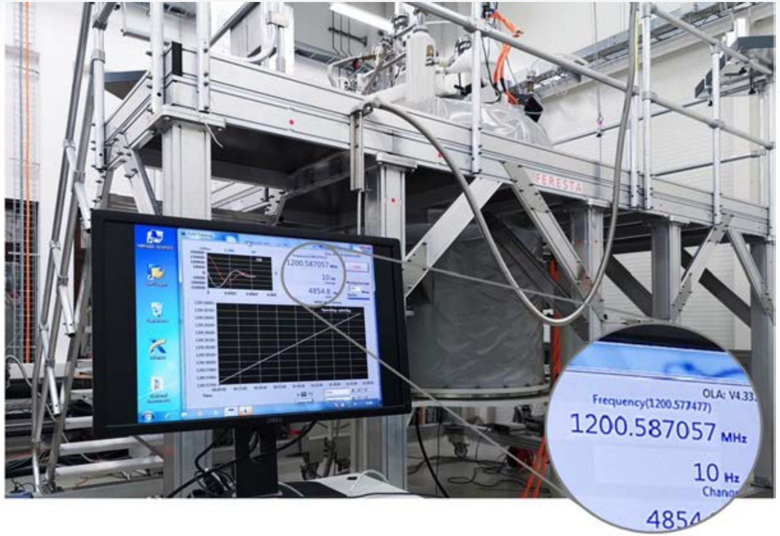
Nuclear Magnetic Resonance is the largest steady market for SC magnets with fields > 3 T.

It requires field uniformity & stability <10 ppb.

Standard magnets are superconducting with compensation, shielding, persistence, and shimming.

To go beyond 1.0 GHz, HTS coil(s) replace inner Nb_3Sn coil(s) and stronger shim coils are needed.

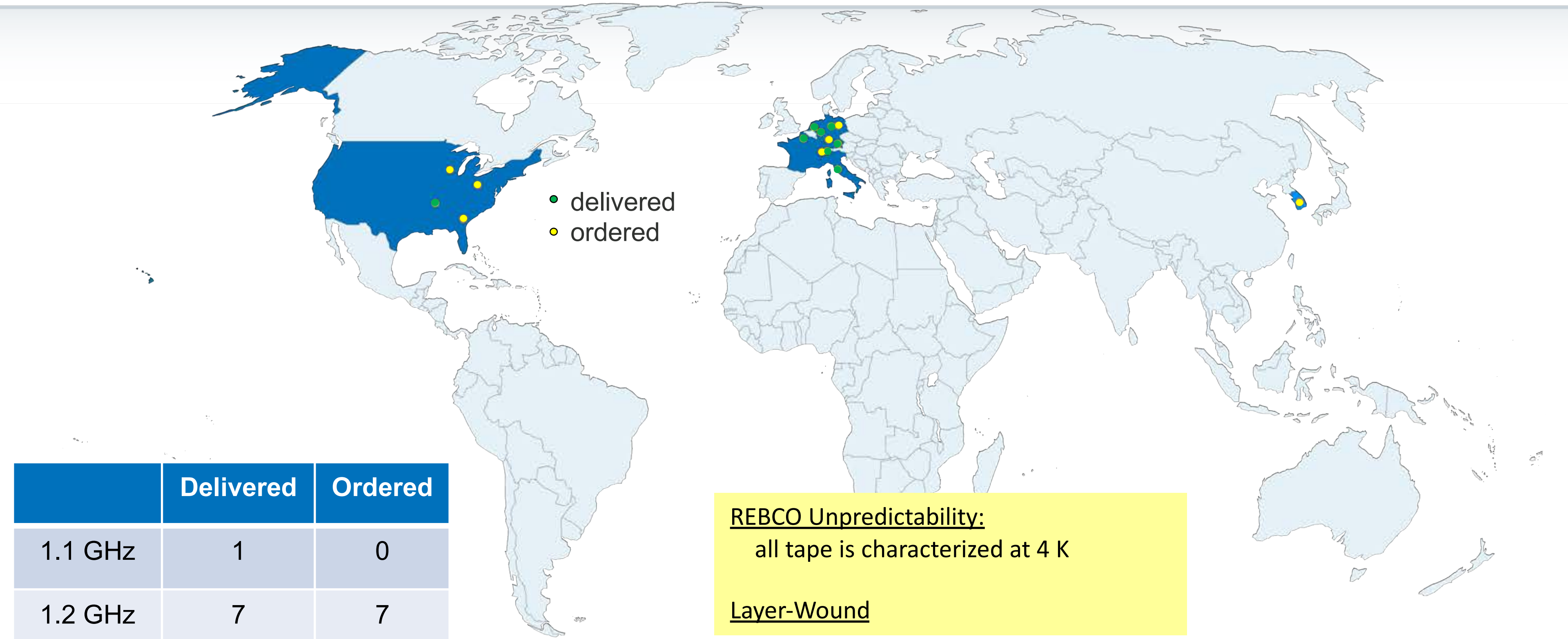




The First 1.2 GHz (28.2 T) NMR Magnet Reached Full Field in 2019

1.1 and 1.2 GHz NMR systems using ReBCO coated conductors ordered and delivered worldwide (Q4 2022)

BRUKER



	Delivered	Ordered
1.1 GHz	1	0
1.2 GHz	7	7

<u>REBCO Unpredictability:</u>

all tape is characterized at 4 K

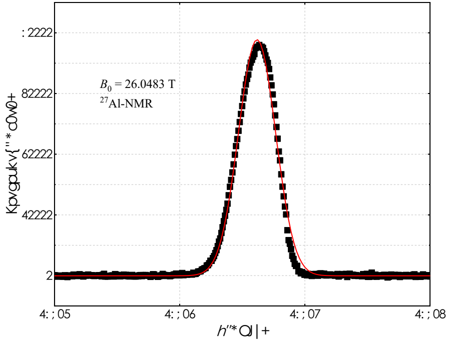
<u>Layer-Wound</u>

Slide courtesy of Patrick Wikus

30T/Φ35mm user magnet at the IEE CAS for SECUF Project : quantum oscillation

Total field	**30 T**
Insert coils	**10.05 T (inner coil)** **4.95 T (outer coil)**
Background coil	**15 T**
Cold inner bore	**35 mm**
Operating current	**140.1 A**
Superconducting tape	**YBCO**
Co-wound tape	**stainless steel tape**
Coil structure	**Double pancake**
HTS conductor length	**9290 m**
Homogeneity	**8 ppm @30 mm**

Magnet in service at 28 – 30 T at SECUF, Huairou, Beijing.



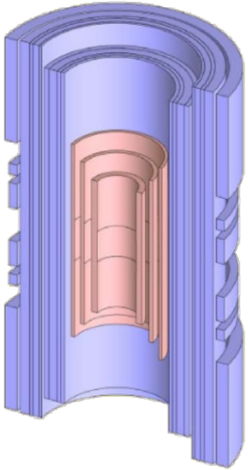
NMR magnet in service at 26 T, with a homogeneity of 13ppm@10mm DSV, at SECUF.

<ins>REBCO Unpredictability</ins>
MI-REBCO
<ins>Quench</ins>
MI-REBCO self-protection.
“Coupling coils” slow dB/dt

content courtesy of Jianhua Liu

UHF REBCO Magnets Underway

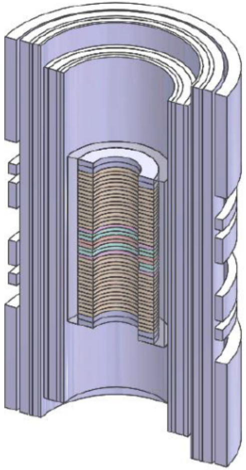
REBCO Insert for MIT 1.3-GHz NMR Magnet



Precedent H800

3-Nested-Coils Design

Quench in standalone test



New H835

Single Solenoidal Design

<u>REBCO Unpredictability</u>

MI-REBCO

<70% I_c

<u>Screening Currents</u>

Narrower tape than earlier version.

Strain <0.7% including SCS.

<u>Quench</u>

MI-REBCO self-protection.

Dump resistor.

Heaters.

- 19.7 T REBCO in 10.93 T LTS NMR Coil
  - for NMR quality 30.5 T (1.3 GHz)
- NI double-pancake windings
- Multi-width REBCO tapes
- Single solenoid to avoid coupling between nested coils
- Metallic insulation to accelerate bypass current relaxation
- Mitigation of Screening Current Induced Strains

Development of a 1.3 GHz (30.5 T) NMR magnet in the JST-Mirai Program

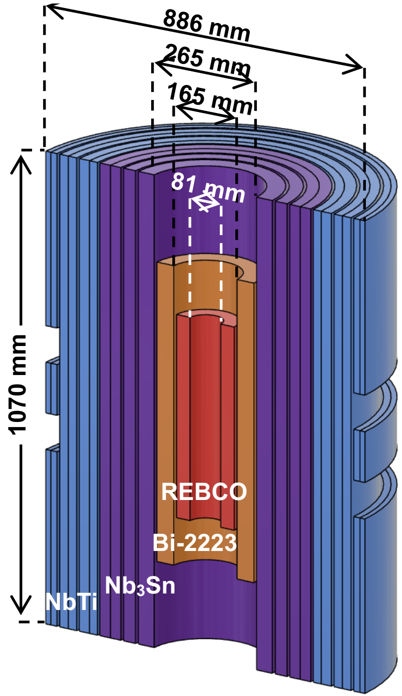
- 15.7 T REBCO & Bi2223 in 15.1 T LTS NMR Coil
- Layer wound
- Persistent mode with superconducting HTS joints

<u>Screening Currents</u>

Stress < 550 MPa (~0.33%) including SCS.

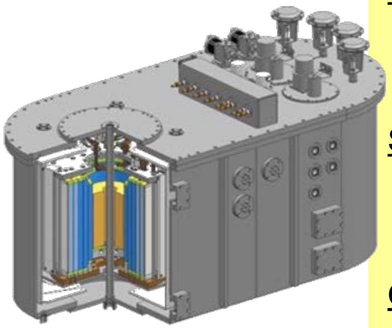
<u>Quench</u>

I-REBCO, single power supply, resistance of LTS coils extracts energy from HTS coils.



33 T Cryogen-Free at Sendai

- High strength Nb3Sn Rutherford Cable
- Robust REBCO conductors



REBCO Unpredictability

Measure I_c of each pancake at 77 K.
Wind 2 conductors in parallel.
50% I_c.

Screening Currents

Epoxy bonds turns to G10 spacers to eliminate strain due to screening currents.

Quench

Assume HTS will not quench.
If LTS quenches, use external resistor to prevent current increase in HTS coil.

- Recent test coil w/ 20 pancakes generated 11 T HTS & 14 T LTS = 25 T
- Two-in-hand winding
- 33 T current estimate is $12M usd.

35 T at Tsinghua University Institute of Plasma Physics Chinese Academy of Sciences

Fig.2 Photo of fabricated 20-T magnet before liquid-helium test.

REBCO Unpredictability

65% of I_c at end of coil.

Screening Currents

Strain 0.68% max including SCS w/o coupling.

Quench

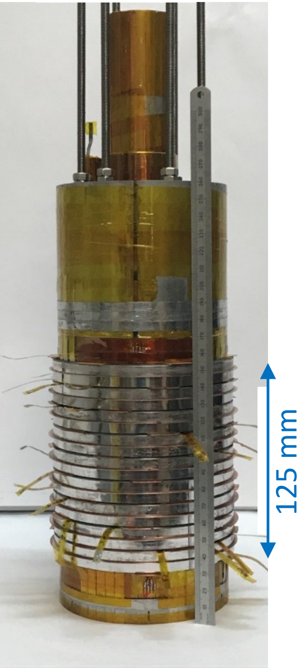
NI-REBCO for inner coil
MI-REBCO for 2nd coil

- 20 T coils quenched 5 times, leading to damage
- Repaired and charged to 23.2 T
- No Background

Grenoble Magnet Lab + CEA, Metal Insulation

LNCMI

Test of the 14 T NOUGAT HTS insert (made of 9 "Metal Insulated" Double Pancakes)



- March 2019
  - System reached 30.1 T (12.1 T HTS + 18 T Resistive).
  - System reached 29 T (10 T HTS + 19 T Resistive) when resistive magnet tripped off, inducing large current in HTS coil.
  - HTS coil worked well despite discharge of resistive background magnet.
  - HTS coils re-energized in self-field successfully.
  - System reached 32.5 T (14.5 T HTS + 18 T resistive) when Quench occurred.
- Significant damage seen in HTS coil.
- All 9 double-pancakes were repaired.
- System reached 28.2 T (10.2 T HTS + 18 T Resistive), Oct. 2021.
- Install HTS coil in LTS outsert @ Dresden to provide 30 T SC user magnet.

REBCO Unpredictability
MI-REBCO.
60% of I_c.
Screening Currents
Not included in strain calculations.
Quench
MI-REBCO.
HTS shield between LTS & HTS coils.

➔ **Horizon 2020 study call** for the design of an All Superconducting Magnet (40 T), Jan 2021 – Four years Studies for future hybrids

Philippe Fazilleau, Xavier Chaud, Francois Debray, Thibault Lecrevisse, Jung-Bin Song, *Cryogenics*, 106, March 2020, 103053.
Jungbin Song, Xavier Chaud, Francois Debray, Steffen Kramer, Phillippe Fazileau, & Thibault Lecrevisse,
Thibault Lecrevisse, Xavier Chaud, Philippe Fazilleau, Clement Genot, Jung-Bin Song, *SuST*, **35** (2022) 074004 (18pp).

The 40 T SC Magnet at MagLab

- Developed software to compute screening currents, strains, and field distributions that is being adopted by other labs worldwide.
- Developed quench modelling software for both MTI and RI coils.
- Introduced critical-current graded coils.
- Demonstrated coils survive
  - 50,000 cycles with 125 MPa axial pressure
  - >23,000 cycles at 0.4% strain in small coil
    >700 cycles at 0.5% strain in midscale coil
- Increase in copper current density, J_{cu}, compared with 32 T.
- Introduced Reinforcement grading.
- Demonstrated numerous improvements to quench protection
- Tested 20 different REBCO coils.
- Comprehensive testing of components and process controls

REBCO Unpredictability
Measure each REBCO tape at 4K.
I_{op}/I_c ~ 0.6.
I-REBCO = 2-in-hand

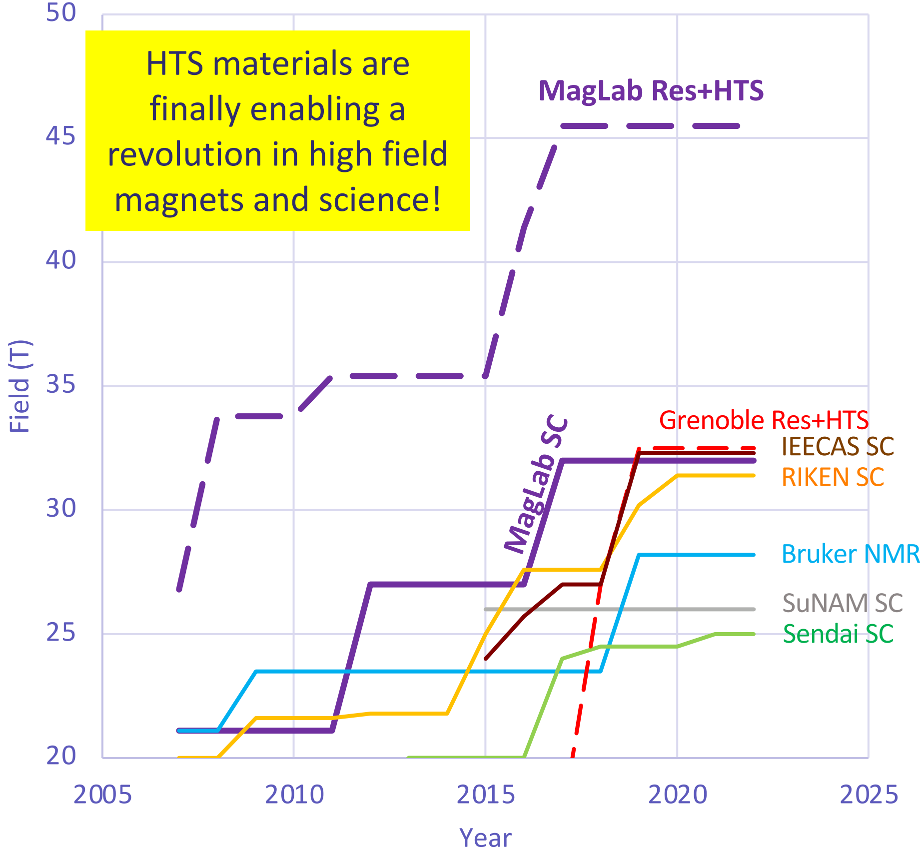
Screening Currents
Strain <0.45% including SCS.

Quench
I-REBCO version uses heaters between modules.

TC2
(August 2022)

Recent REBCO test coils from the 40 T magnet project.

Summary of REBCO Status



NMR = Nuclear Magnetic Resonance.

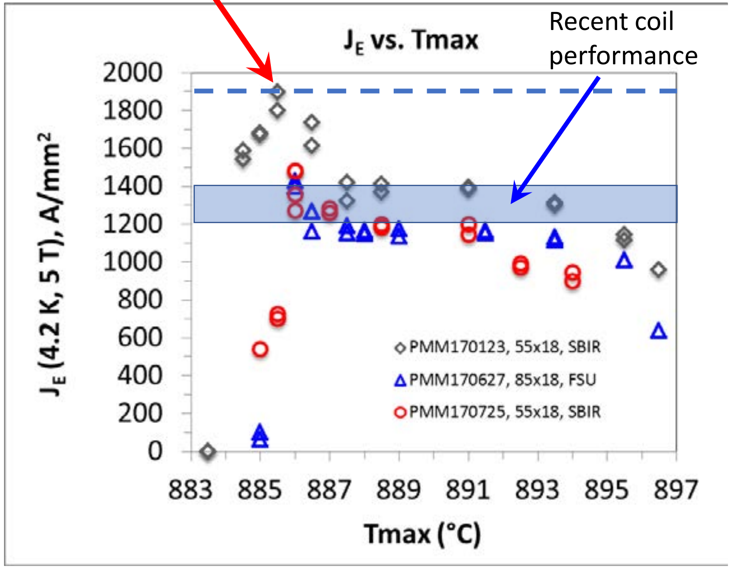
There are now > 7 organizations worldwide developing HTS coils for service at Ultra-High Fields.

- All SC magnets >25 T use REBCO.
  - SC magnets are presently available at 28 – 32 T for condensed matter physics.
  - NMR magnets are operating at 28.2 T (1.2 GHz).
  - >4 groups are pursuing 30 – 35 T SC.
  - 2 groups are pursuing 30.5 T (1.3 GHz) NMR.
  - ~4 labs are pursuing 40 T SC.
- Variability of properties, effects of screening currents, and quench protection remain important challenges.

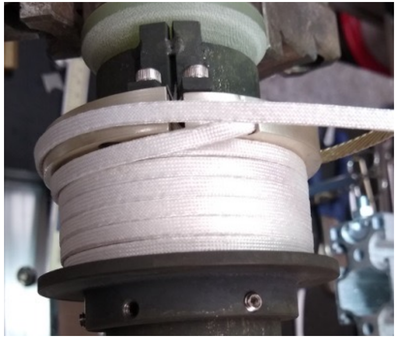
Why Bi-2212 for High Field Magnets

- Bi-2212 is unique among commercial HTS:
  - round, multifilament, macroscopically isotropic, can be twisted to reduce charging losses, just like Nb-Ti and Nb_3Sn
  - and it can be **cabled easily**.
- Bi-2212 conductor technology has come far:
  - **very high transport properties** with even higher possible
  - produced on **1 + km lengths** scale
  - **reproducible performance** over long lengths
  - Insulating technologies exist for **wire and cable**
- Specific to Bi-2212:
  - It must be **heat treated for s/c**
  - All materials in winding pack must be compatible with 890°C and 50 bar HT
- Mechanical reinforcement as in any other s/c high field magnet technology is a challenge (not specific to Bi-2212)

Let's transform peak into plateau



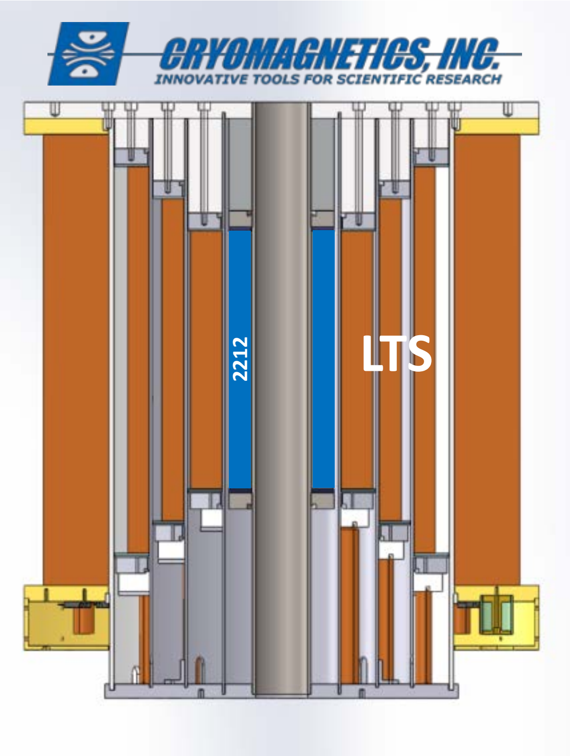
Bi-2212 Strand



Bi-2212 Rutherford cable (LBL)

High Field Bi-2212 General Science Magnets

- ASC currently has a large focus on strand-based magnet development
- Collaborations with industrial magnet builders



ASC has a continuing Phase II STTR with **Cryomagnetics Inc. (Steve Minter and Mike Coffey):**

- **25 T** magnet system,
  8 T Bi-2212 insert inside LTS magnet built be CM
- Cold bore of ~40 mm
- ~100 mm OD of HTS coil
- ~700 m HTS conductor
- Strain mitigated and quench protected

- Series of test coils to be tested at ASC and CM ongoing

Development of Bi-2212 NMR-type Magnet Technology

- **Collaborate with Oxford Instruments since mid 2022 on the development of a 25 T class compact research magnet**
    - Set of test coils made at OI, awaiting OPHT in Renegade furnace
- **Also collaborating with OI-NS on a high homogeneity magnet (RO1 submitted to NIH):**
    - uses the modified 12 T, 212 mm bore OI-NS (“IMPDAHMA”) LTS outsert magnet

The NMR demonstrator will have substantial size:

Two inner coils with **Bi-2212**, each with **~800 m of conductor**, 40 mm bore

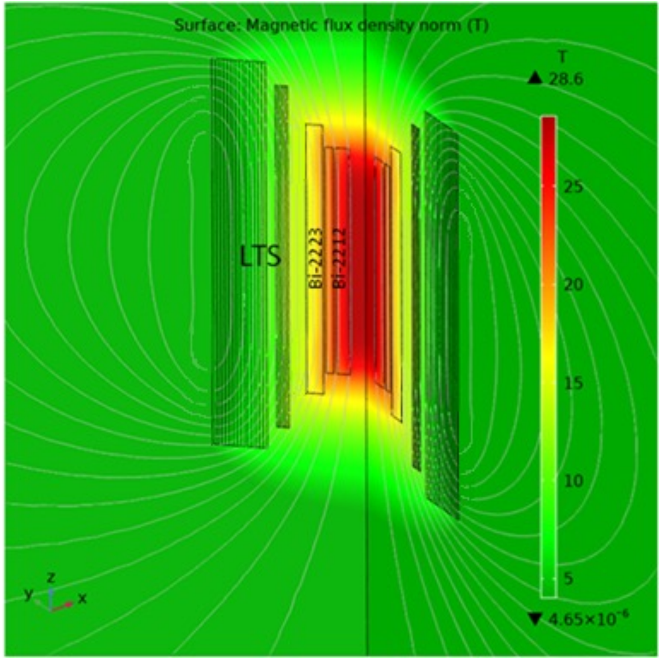
One **Bi-2223** coil of **2.6 km** conductor

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)

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

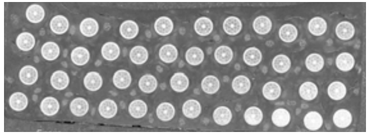
Bi-2212 and Bi-2223 Insert Coil Design for 28.2 T / 40 mm Bore UHF NMR Magnet System		
Bi-2212 Coil #1	a1; a2; z1; z2 [mm]	22.2; 40.5; -178.6; 178.6
	Turns	3920
	Field [T]	5.17
	wire length [km]	0.77
Bi-2212 Coil #2	a1; a2; z1; z2 [mm]	44.45; 55.3; -178.6; 178.6
	Turns	2240
	Field [T]	2.89
	wire length [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)



What happens if Coils Mechanically Decouple? (Pup-9)

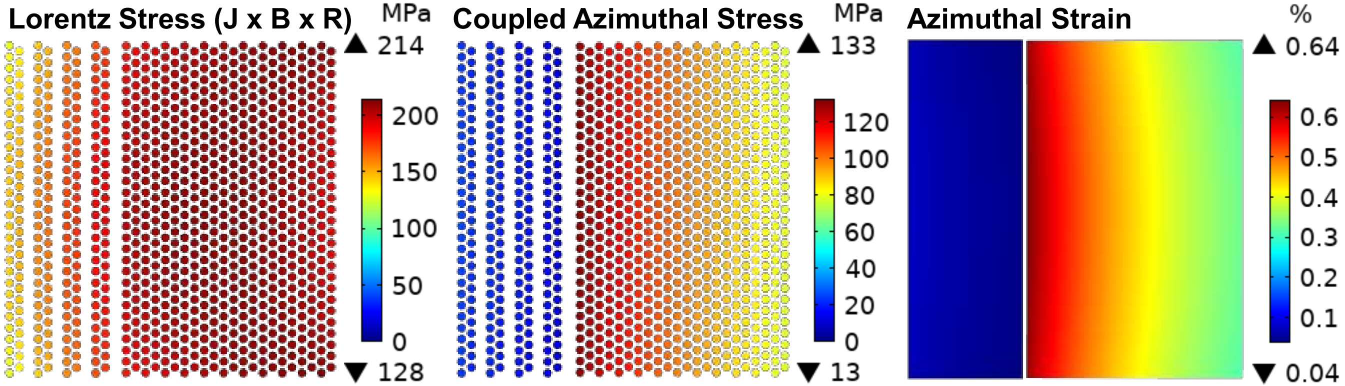
- An FEA assumption: full decoupling between last band and rest of the coil
  - Calculated strain (0.64% at Layer 9) where the cracking occurs makes the outer section of the coil a new free-standing section
  - Layer 1 ~ 8 then become released from the outer coil which shows very low stress
- **Potential critical role in crack formation: Interfaces**
  - Epoxy bonding strength near the bands
  - CTE mismatch between components of the winding pack
  - Local stress concentrations

Bi-2212 wire test stack



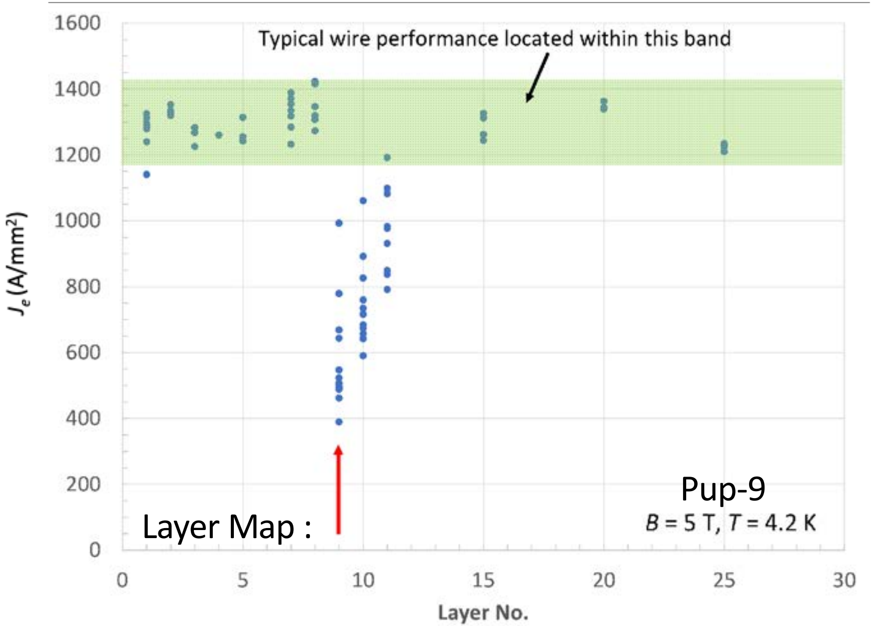
Started series of experiments emulating the mechanical properties of a Bi-2212 winding pack to improve our FEA models (Emma Martin, PhD student)

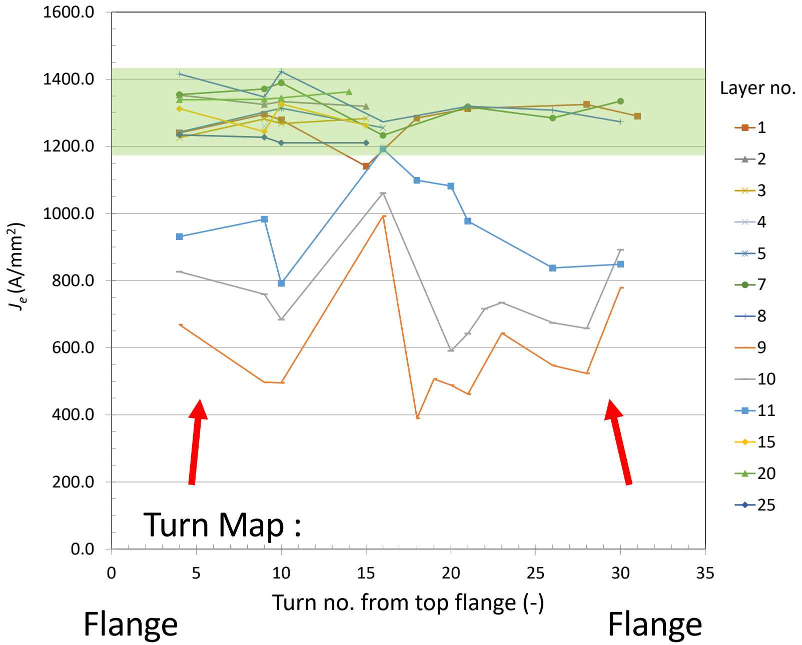
Pup-9 came completely apart at Band 4 after cutting for post mortem



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

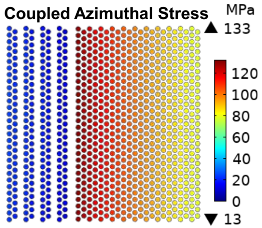
Postmortem of Pup-9 Provides a Clear Picture



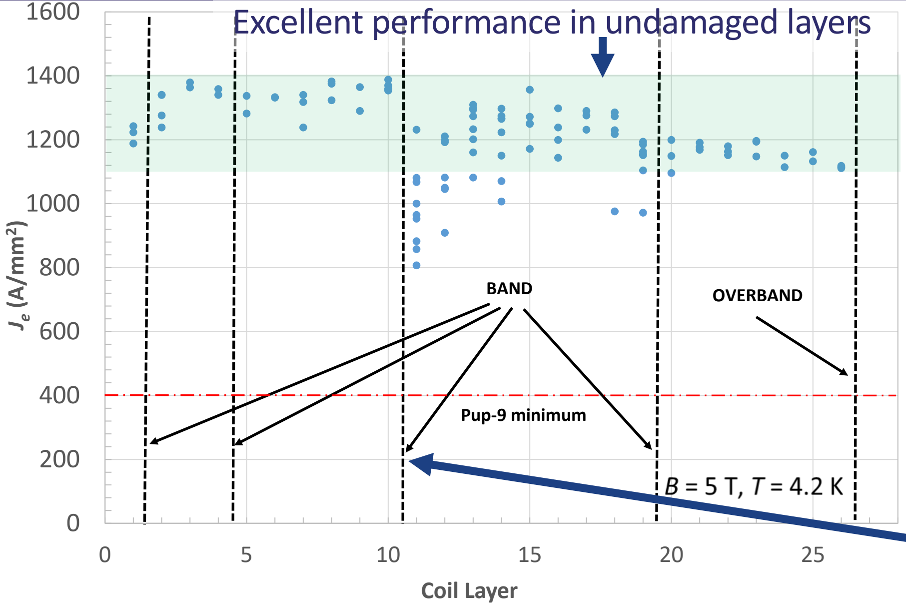


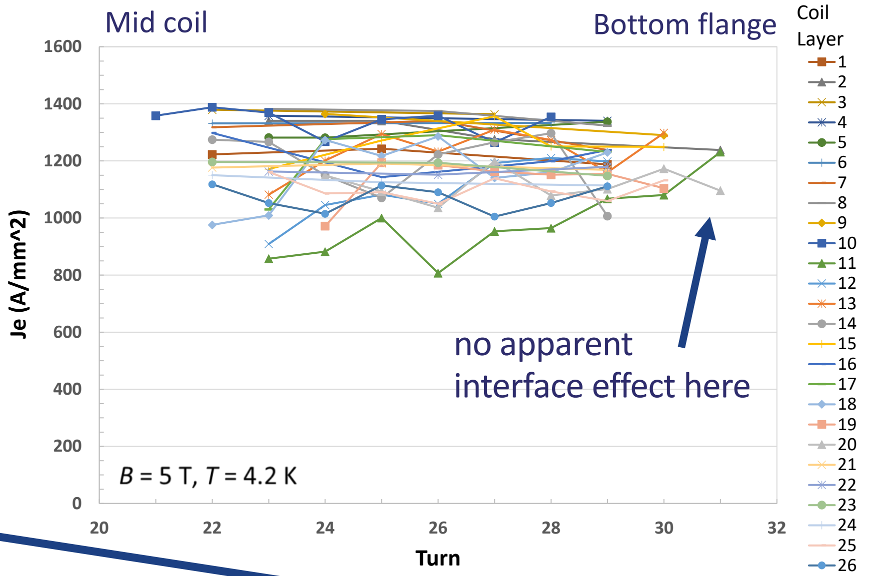
Need to optimize distribution of reinforcement layers

Also seen: Winding pack is not fully decoupled from mandrel and flanges



Pup-10 Postmortem



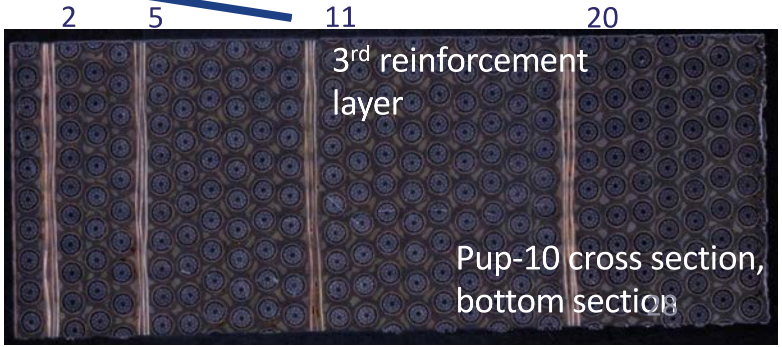


Same number of four inner banding layers as Pup-9 but different distribution

Less degradation than in Pup-9 observed but still present around 3rd reinforcement layer

Optimization of banding layer distribution appears to work

Coil ID



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.

Recent Coil "Cryo-4"

current champion performance 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	

Primary goal: evaluate uniformly distributed reinforcement

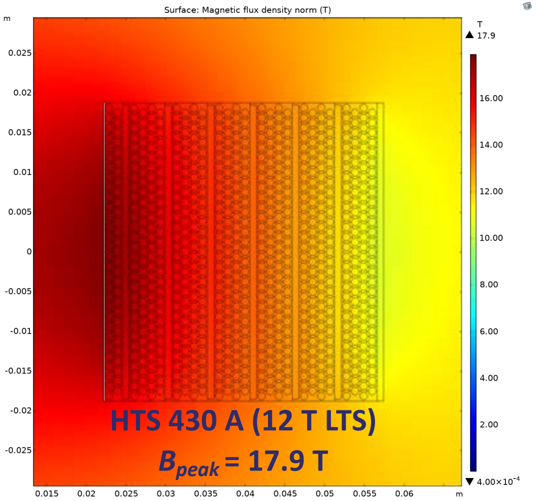
Stable operation at 70% SSL performance

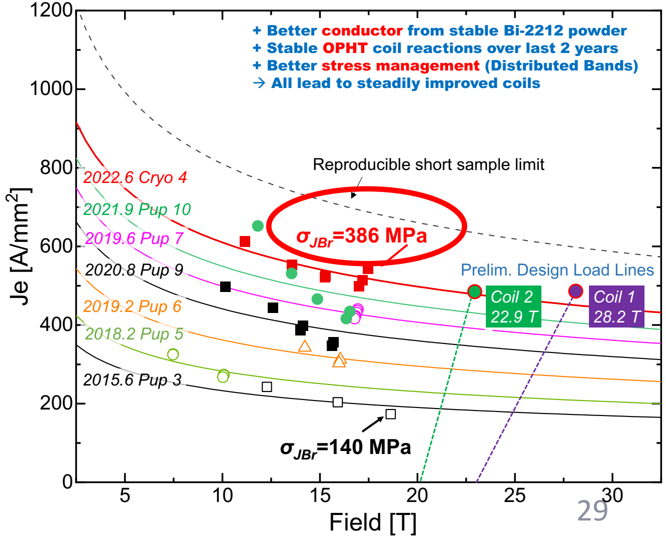
Stable in low cycle fatigue

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

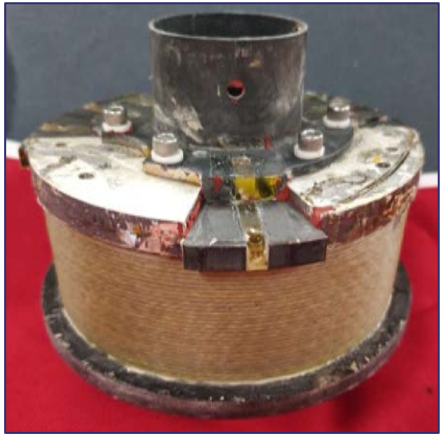




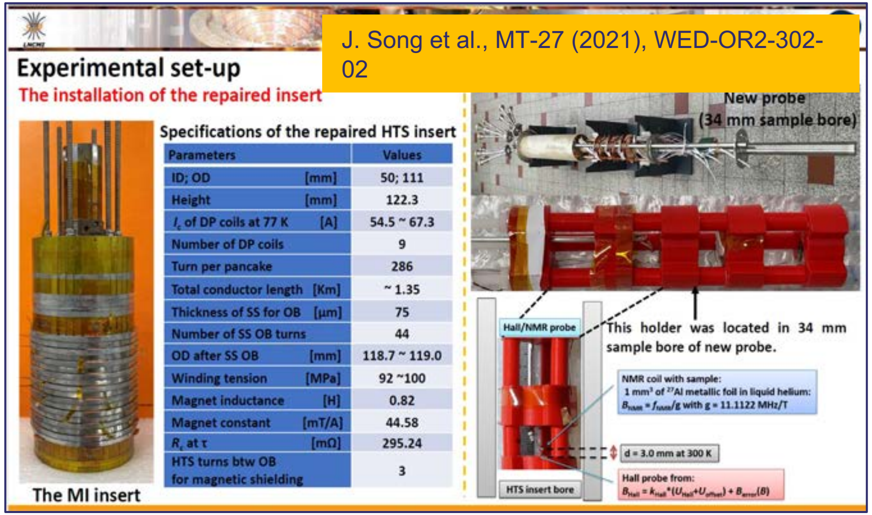
Double Pup : A Mid-Scale Bi-2212 Insert to Explore Field Quality

Motivations

- Cryo-4's successful stress management to withhold ~380 MPa of *JBr* stress
- Rising necessities of stable "Mid-scale" Bi-2212 coil operation
- Need for faster turn out to make and test Bi-2212 coils
- Impressive LNCMI Grenoble's MI insert test using NMR probe at 28.2 T (1.2 GHz)



Cryo-4 (2022)'s Record
- Reached 16.8 T in 12 T test bed
- *JBr* stress up to 386 Mpa
- Operated at 70% of SSP I_c



Experimental set-up

The installation of the repaired insert

Specifications of the repaired HTS insert

Parameters	Values
ID; OD [mm]	50; 111
Height [mm]	122.3
I_c of DP coils at 77 K [A]	54.5 ~ 67.3
Number of DP coils	9
Turn per pancake	286
Total conductor length [Km]	~ 1.35
Thickness of SS for OB [μm]	75
Number of SS OB turns	44
OD after SS OB [mm]	118.7 ~ 119.0
Winding tension [MPa]	92 ~100
Magnet inductance [H]	0.82
Magnet constant [mT/A]	44.58
R_c at τ [mΩ]	295.24
HTS turns btw OB for magnetic shielding	3

J. Song et al., MT-27 (2021), WED-OR2-302-02

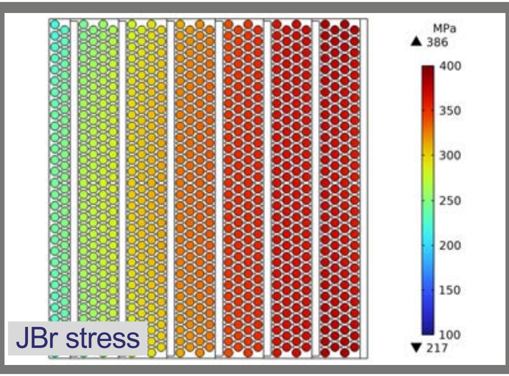
10.2 T MI REBCO insert in a 18 T Resistive background
(7 ppm/min drift measured using NMR probe)

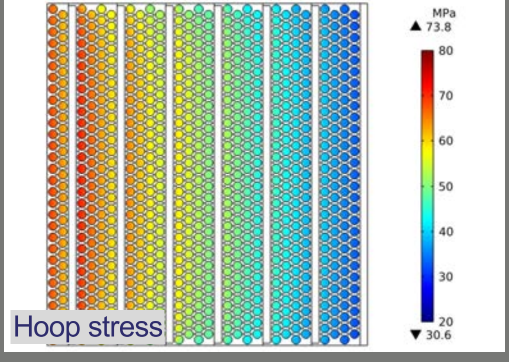
Predicted Stress and Strain Properties od Double-Pup at 18 T

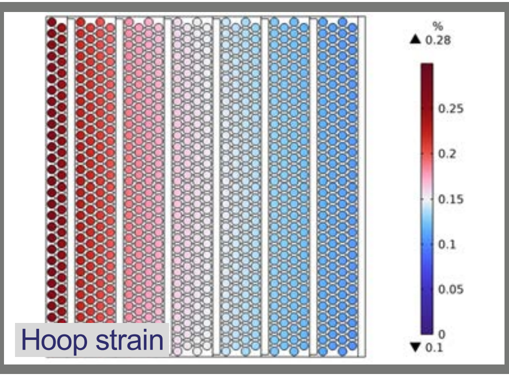
Double Pup-1 should operate in less stressful condition

- From Cryo-4: Epoxy cracking didn't affect stress and strain drastically thanks to uniform distribution of bands

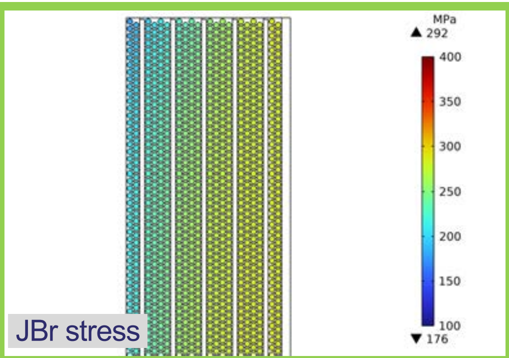
Cryo-4 at Highest Field (16.9 T)

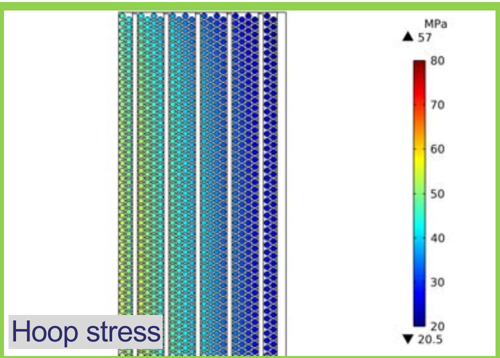


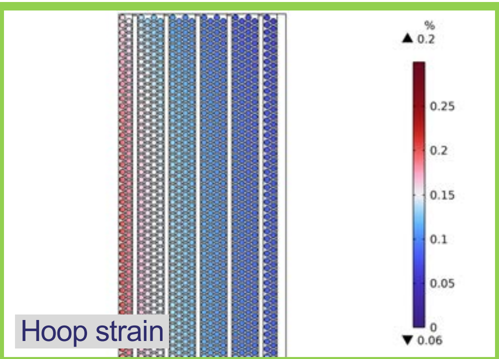




D-Pup-1 at Target Field (18 T)







Design and Operating Target

Double Pup copied many of Cryo-4 except three key features

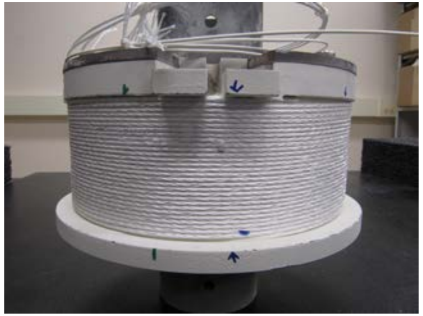
- 3x coil height, 75% radial build (26 → 20 layers), and 2x conductor usage
- Increased field homogeneity and magnet constant + easier stress management

Targeting to reach 18 T in 12 T test bed with less magnetic stress

- Status: ready for testing

Test Coil Specs.		Cryo-4	Double Pup-1
ID;OD;Height [mm]		44.5; 116.0; 40.3	44.5; 98.0; 122.0
Turn ; Layer (Total)		30 ; 26 (769)	91; 20 (1825)
InnerBands		6	5
Conductor [m]		~ 200	~ 412
Field Const. [mT/A]		11.3	16.2
Inductance [mH]		31.5	80.8
Background Field		Max. I_{op}	Target I_{op}
8 T	I_{op}	437 A	370 A (6+8 T)
	Max. *JBr*	213 Mpa	173 Mpa
12 T	I_{op}	430 A	370 A (6+12 T)
	Max. *JBr*	386 Mpa	292 Mpa

Specifications of Cryo-4 and Double Pup-1



Cryo-4 and…

DoublePup-1 in same scale

First Set of Coils Made Applying Mica and Nextel Inner Winding; TEO-1, 2, and 3

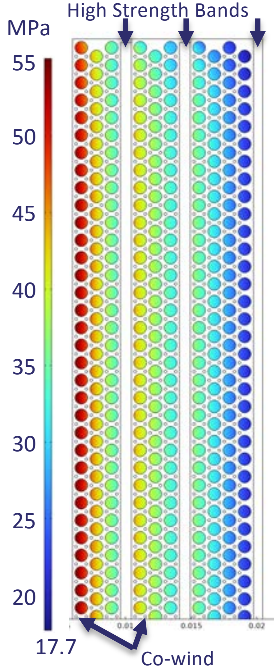
38 mm

Over-banding

TEO-type coils are a cost-efficient vehicle to test materials and processes

Coil Specs:

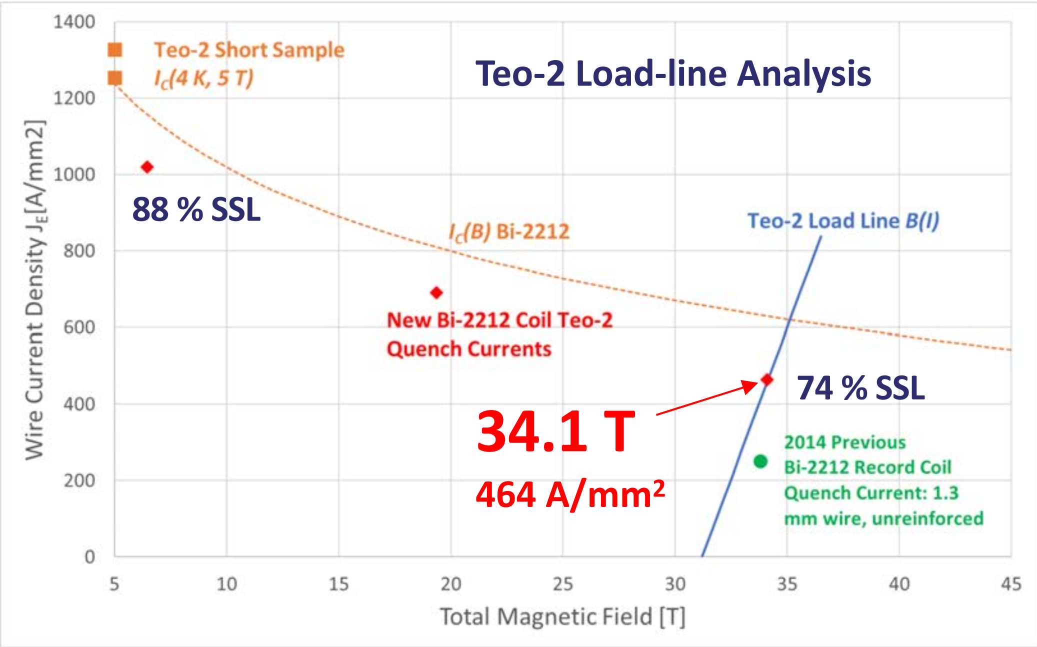
Coil Name		TEO 1	TEO 2	TEO 3
Wire	PMM No.	PMM180928 (Φ1.0 mm)		
	Insulation	TiO2 coat – Mullite Braid (Φ1.3 mm)		
ID; OD; Height [mm]		12.0; 34.2; 80.9	12.0; 37.5; 80.4	12.0; 37.4; 88.6
Turn ; Layer (Total)		60.3 ; 8 (482)	59.2 ; 10 (592)	59.1 ; 10 (591)
Innerbands		2 (Band)	2 (Band)	2 (Wind)
Overband		Hastelloy C276	Hastelloy C276	Inconel X750
Conductor		35 m	45 m	45 m
Field Const.		7.2 mT/A	8.8 mT/A	8.1 mT/A
Inductance		1.0 mH	1.7 mH	1.5 mH
Ic Test at 12 T		> 500 A	> 500 A	270 A

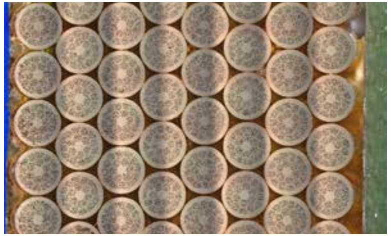


Stress with Reinforcement

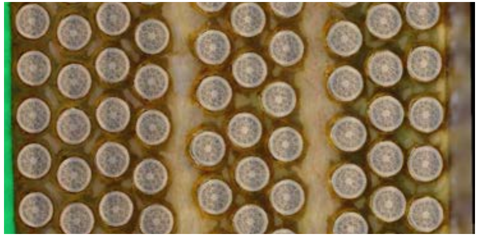
peak source hoop stress (J_E*B*R) between **237 - 273 MPa**

Robust Operation of High Temperature Superconducting Bi-2212 Magnets at 34 T and Ramp Rates Over 23 T/s

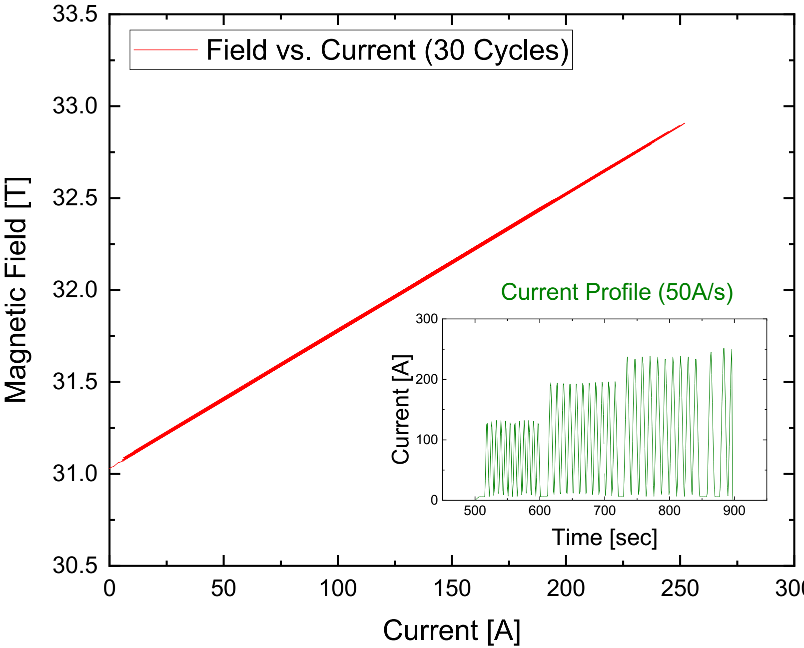




2014
to
2023

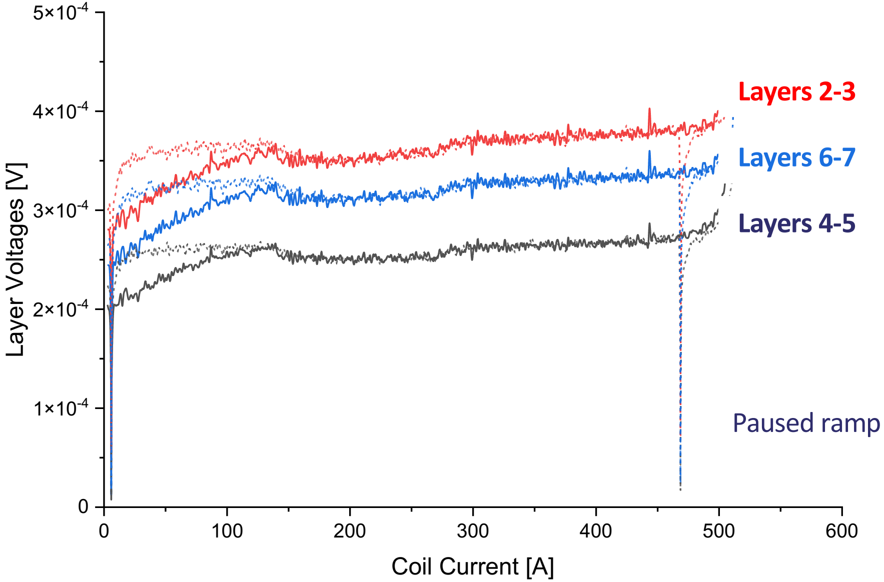


- **Teo-1 Field generation consistent across cycles indicating proper insulation and low hysteresis**

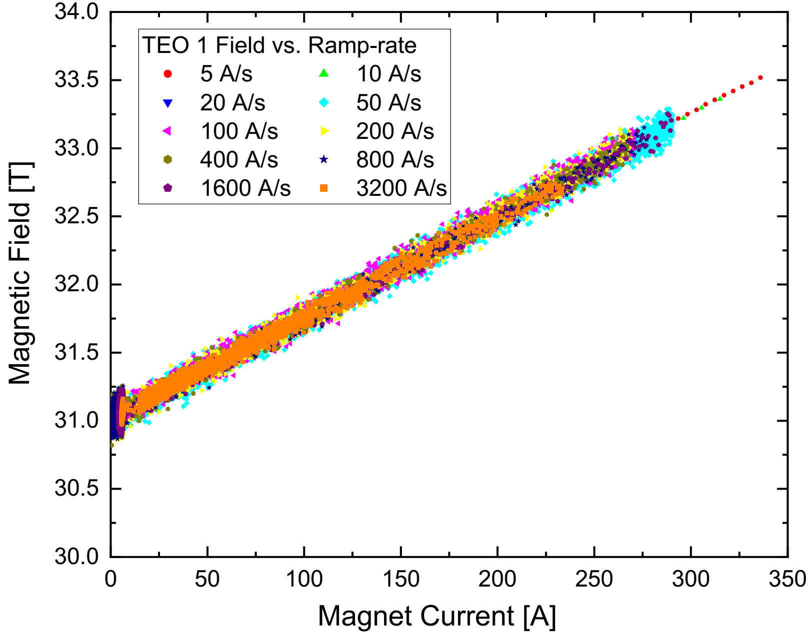


Robust Operation of High Temperature Superconducting Bi-2212 Magnets at 34 T and ramp rates over 23 T/s

- **Teo-1 V-I curves (4 K, 15 T) before (dotted) & after (solid) high-current rate tests at 31 T are essentially the same**



- **Teo-1 Field generation are consistent across vastly different ramp rates**



- This robust operation of multiple coils in fields >30 T is an important demonstration to our industry and lab collaborators in HEP and fusion (ohmic heating solenoids), as well as to our own efforts in pursuing the development of high field NMR and EMR magnets.

Tightly Wound Cable Test Solenoid with Higher Friction Mullite Application Resulted in Substantial TiO_2 Disruption and Leaks

We have no cable dip coating route yet:

- Existing mullite braid removed from cable
- <u>Coating painted and slid into braid by hand</u>
- Cannot apply abrasion resistant top-coat on TiO_2 without inline furnace
- Mullite braid installed by hand

No leaks observed in the terminal region:

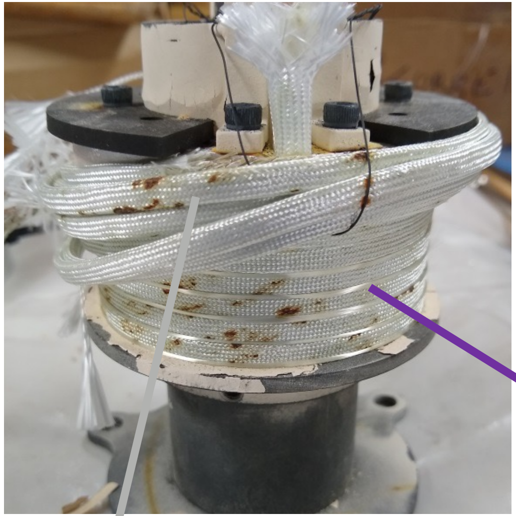
- went through 50 bar OPHT w/out mullite or TiO_2

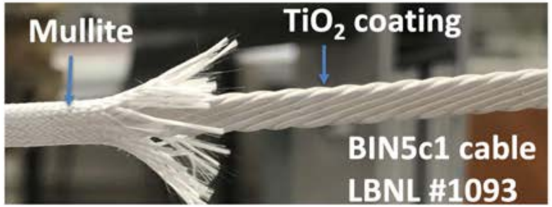
Moderate preference for cable edge leaks

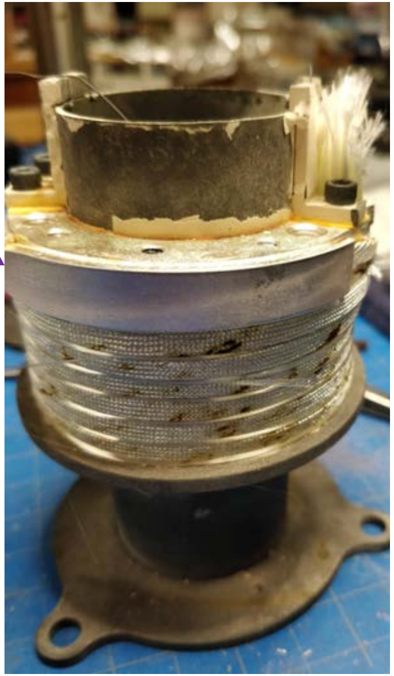
- Removed braid from lead-in/out excess conductor pigtails

Period of leaks is consistent with squeezing cable to manipulate braid onto the cable

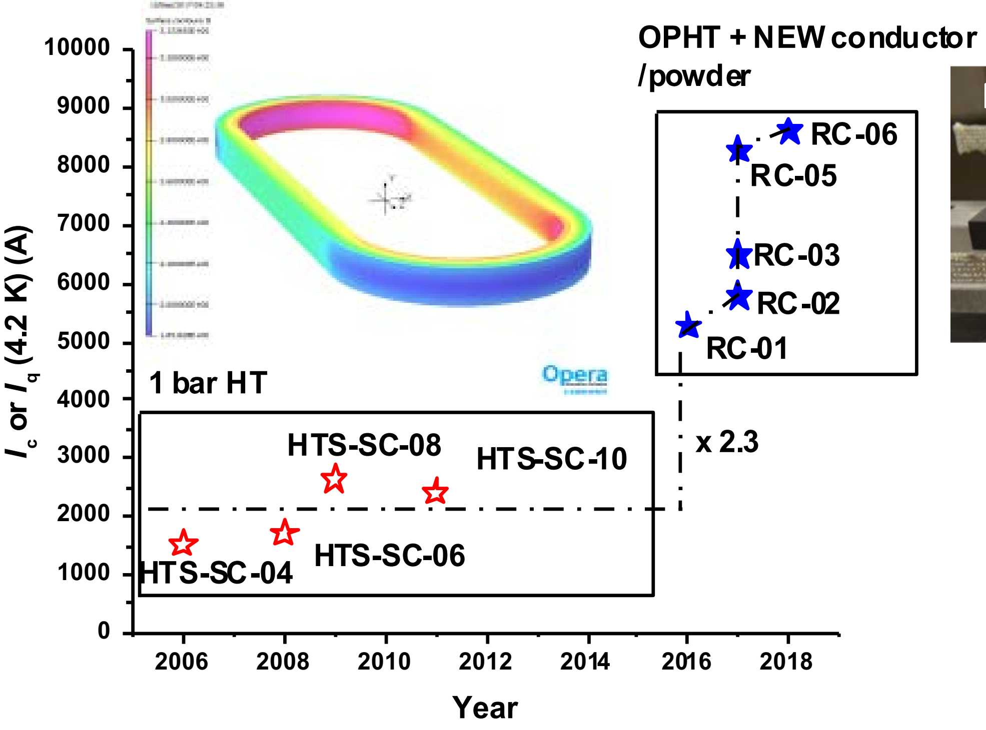
It is likely that installing the braid disrupted the TiO_2 causing the cable to react with the mullite braid allowing for leakage

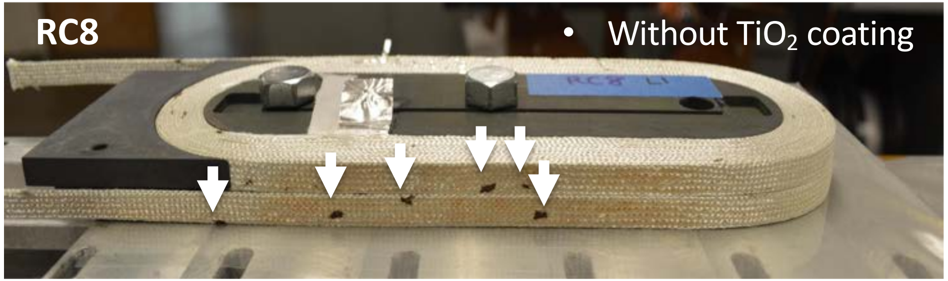


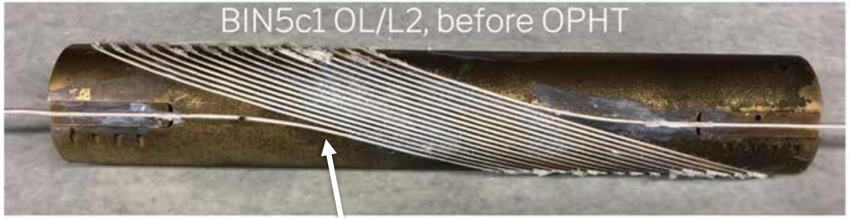




Minor Coil Leakage in RC7 and RC8, CCT Coils, and our own Solenoids







There is another coat of TiO_2 on top of mullite directly for insulation purpose.

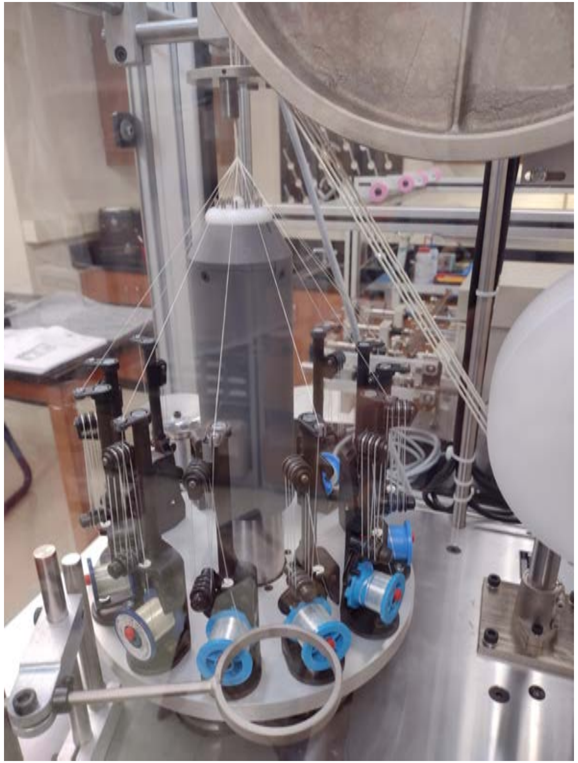
Observation of leakage in CCT coils is very incomplete as only one cable edge can be viewed directly.

ASC has Invested in a Fiber Insulation Facility

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

Alumino-Silicate

wrap braid



Pure alumina

wrap braid

- 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

Implementing New Insulation for Rutherford Cable Solenoids

Motivation:

- **Low inductance ultra high field** magnets, research magnets, Muon collider cooling magnets, **fusion**
- **Accelerator magnet test-beds**
  - Solenoids are a simple and affordable system to evaluate Rutherford cable and material (epoxies, insulation, etc…) limits in high field.

Test coil with new insulstion:

- 30 m conductor, 9-strand, 0.8 mm strand diameter from LBNL, 2013 low-performance strand
- 24 mm ID, 14 layers x 12 turns; Expected 5.7 T Increment in a 12 T BG
- **Goal: validate pure Alumina braid insulation in a magnet OPHT**

Pure alumina braid

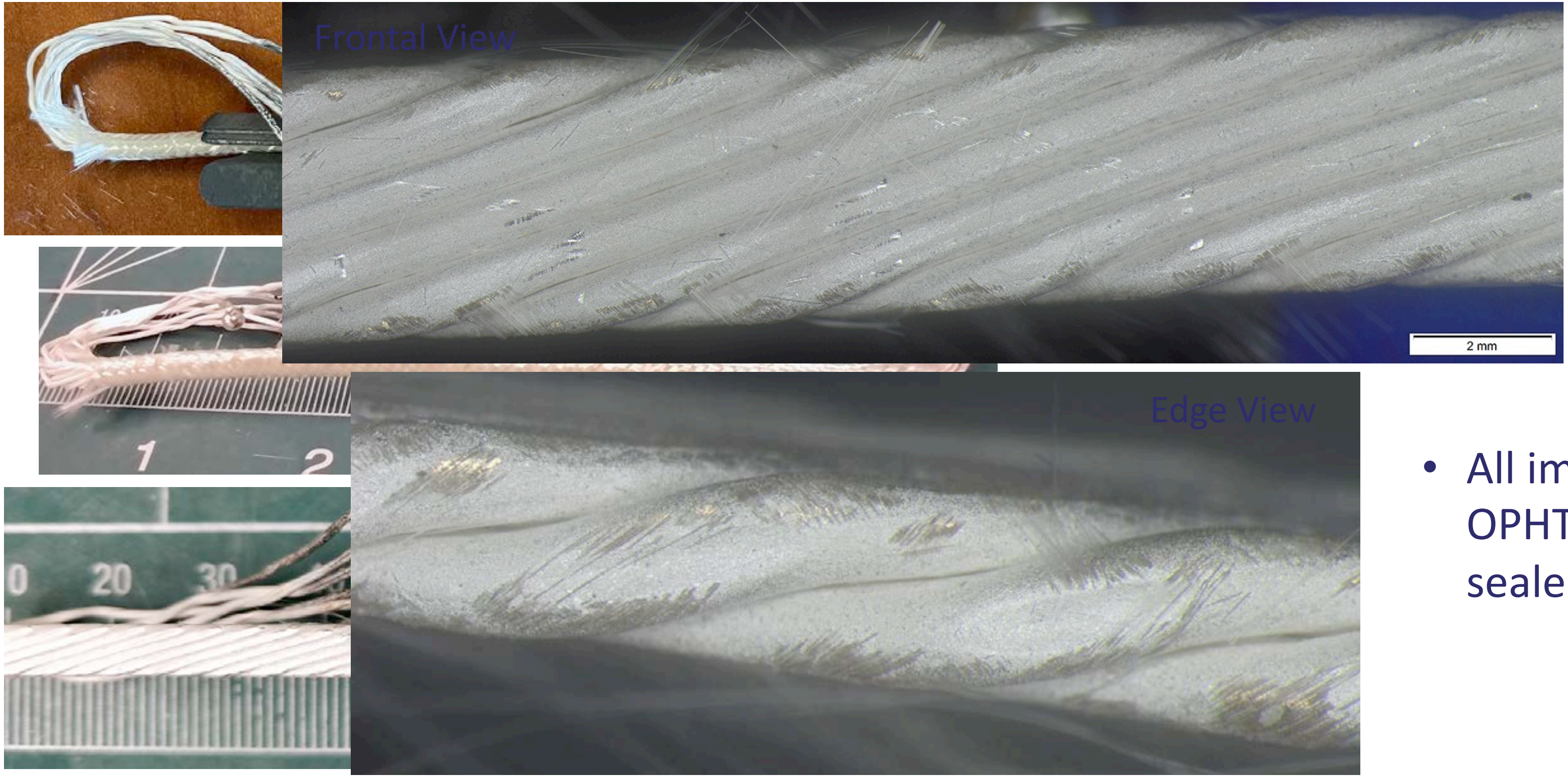
Inconel compression blocks

- **No leakage in fully OPHT'ed Rutherford cable sample with pure alumina braid**
- **Very little, to no embedding of fiber in Ag-matrix**

9-strand Bi-2212 Rutherford cable is a surprisingly flexible and easy to work with conductor

Specs.:
9 strand (4 x 1.44 mm bare)
1500 denier
12-thread, 16 ppi
0.15 mm thick on flat side
0.2 mm thick on edges

No Leaks in OPHT'ed Rutherford Cable with Sealed-ends Insulated with Pure Alumina Braid



- All images post OPHT; fully sealed sample

- **No leakage in fully OPHT'ed Rutherford cable sample with pure alumina braid**
- **Very little to no embedding of fiber in Ag-matrix**

Summary of Bi-2212 Status

Today's Bi-2212 round wire technology is ready for high-field coils.

- 2015 - highest J_E was ~625 A/mm^2 (20 T)
- Today – reproducible plateau J_E is ~845 A/mm^2 (20 T) in long length coils
- Peak J_E is ~1235 A/mm^2 (20 T)

Proper reinforcement can handle the operating stresses and strains.

- Reinforcement shown to support about 390 MPa in recent coil
- Still work ahead to modelling and further optimize coil reinforcement, build, test, and analyze these coils.
- Post-mortems have been extremely helpful in further understanding of coils and will continue

Magnet technology robust in ultra-high-fields above 31 T

- Produced a peak of 34.1 T with 464 A/mm^2
- Ramped at up to 23 T/s
- Fully reinforced and quench protected, showing no degradation after high field operation

Bi-2212 Rutherford cables show great promise

- Very long, continuous cables are possible
- Insulation – leakage issue appears solvable
- Continue to work on robustness of Rutherford cable technology

Though we had to endure supply chain and resource issues affecting our furnace capabilities in the recent past, the 2212 heat treatment is no black magic

An alternative for the mullite insulation using Al_2O_3 fiber material has become available, which eliminates the risk of conductor leakage

Thank You!

NATIONAL HIGH MAGNETIC FIELD LABORATORY