APPLIED SUPERCONDUCTIVITY CENTER
NATIONAL HIGH MAGNETIC FIELD LABORATORY
FLORIDA STATE UNIVERSITY

U.S. MAGNET DEVELOPMENT PROGRAM

Conductor and Cable Challenges and Opportunities: Cable Tests for Fusion

Daniel S. Davis

REBCO Round Table, Fermilab

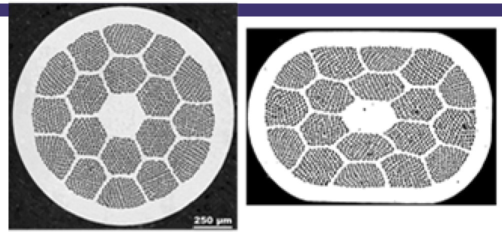
November 2, 2023

Coil Group: U.P. Trociewitz, Y. Kim, G. Murphy, C.L. English, C.T. Brady, J. Kvitkovic, G. Miller, W.S. Marshall
Conductor Group: E.E. Hellstrom, J. Jiang, F. Kametani, J. Lu, J. Levitan, P. Lee
Graduate Students: E. Martin, G. Bradford, S. Barua, A. Oloye
L. Cooley, D.C. Larbalestier

Key Collaborators - LBNL: T. Shen PPPL: Y. Zhai ACT: D.C. van der Laan, J Weiss, Z. Johnson, K Radcliff

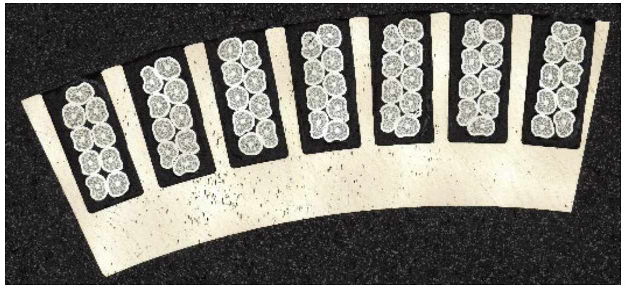
ASC-NHMFL is supported by US DOE-OHEP (DE-SC0010421, DE-SC0018666, DE-SC0018683), NHMFL Core Grant (NSF 2128556), FSU special allocation for Bi-2212 commercialization, the State of Florida, and the US DOE-MDP for much context and many collaborations. LBNL is supported by US DOE-OHEP-MDP under contract No. DE-AC02-05CH11231. PPPL was supported by the U.S. Department of Energy under contract number DE-AC02-09CH11466.

Magnet Testing is The Bottleneck to Ultra-High Field Applications



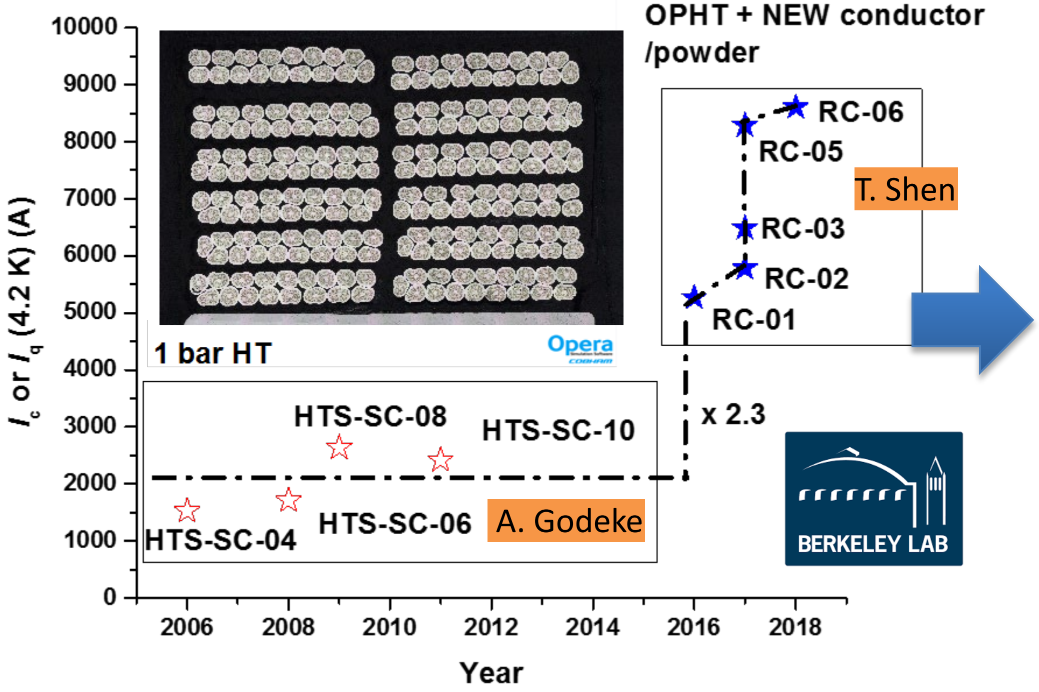
T. Shen-LBL

The recent developments of HTS Bi-2212 round wire and cable are clear examples of rapid progress with test coils

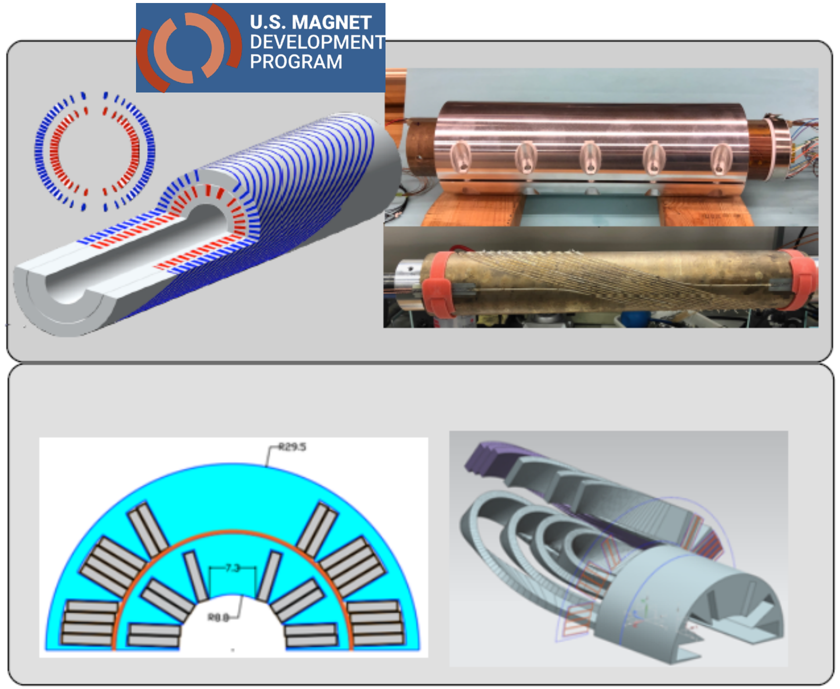


Bi-2212 Canted Cosine Theta Layer Cross Section

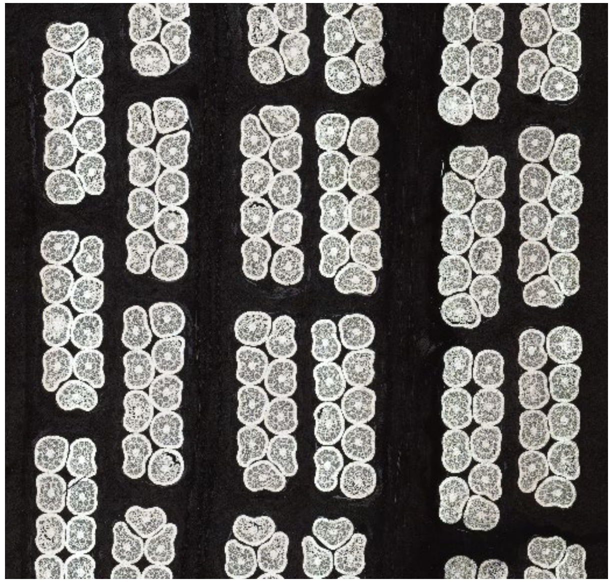
HTS Racetrack Coils



LBL-HTS-RC program: example of a simple-geometry coil series showing progressive performance and developing magnet technologies for 3D dipole geometries

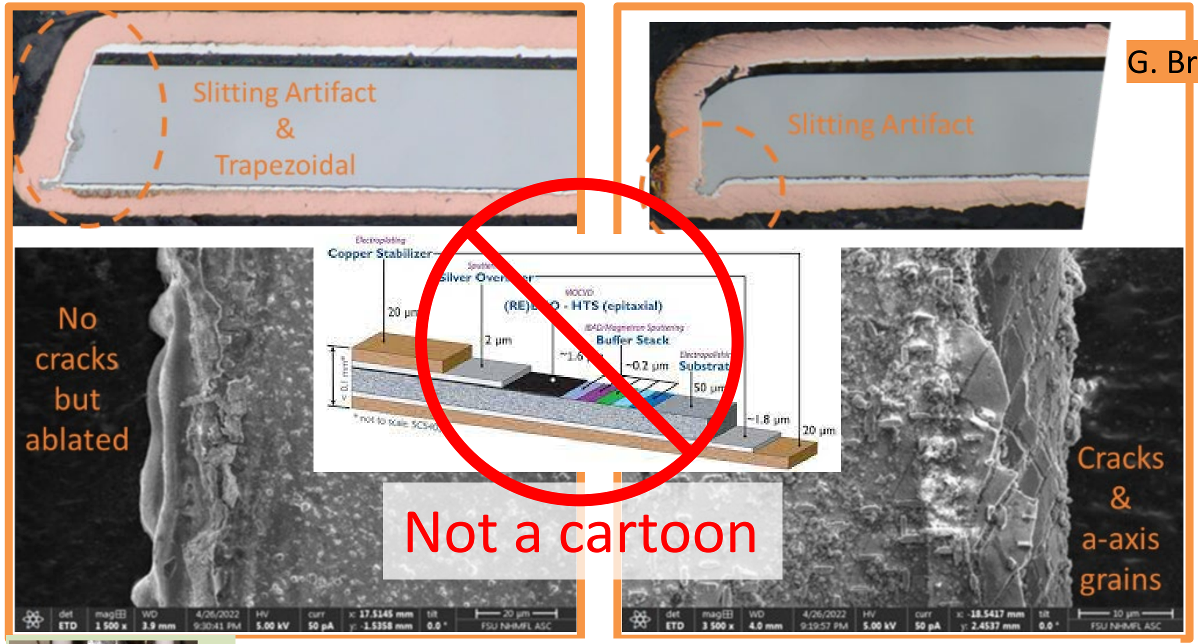


Led to present MDP Bi-2212 program including Bi-2212 cable cosine-theta coils and high field solenoid testing and postmortems

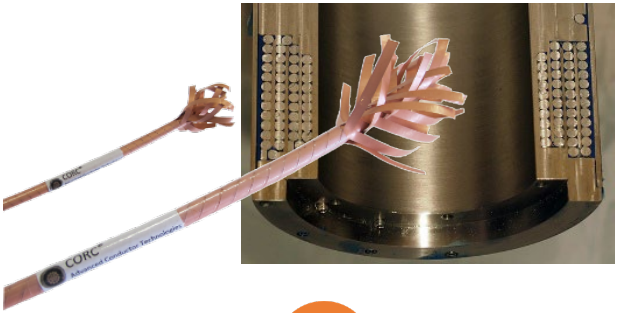


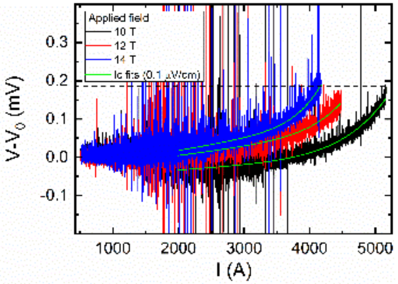
Bi-2212 Cable Solenoid Cross Section

Conductor → UHF →Modelling → Cable/Solenoid → Postmortem Program



G. Bradford

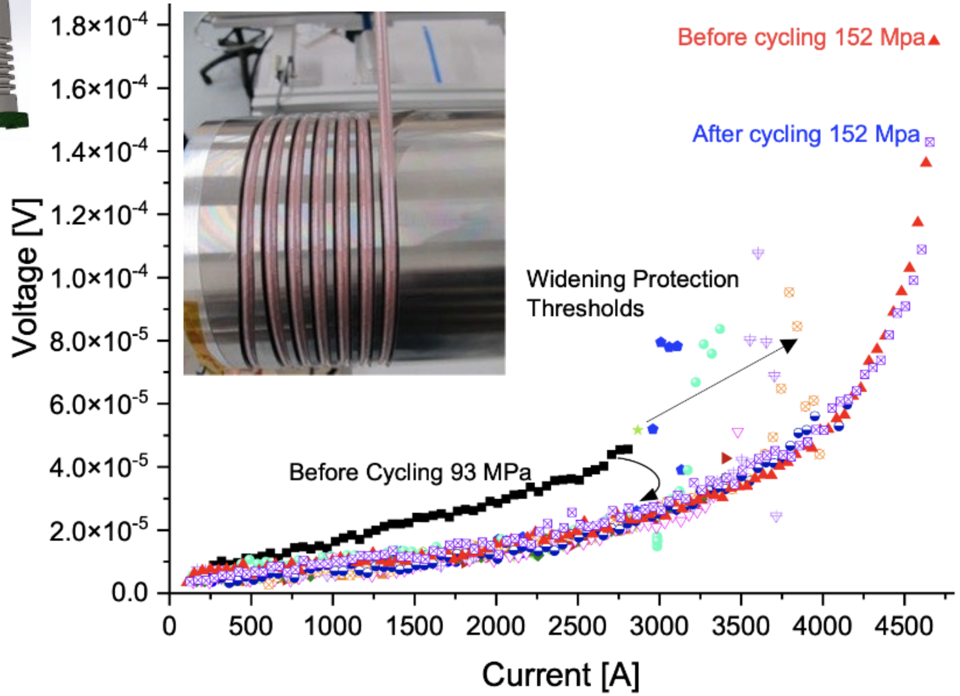




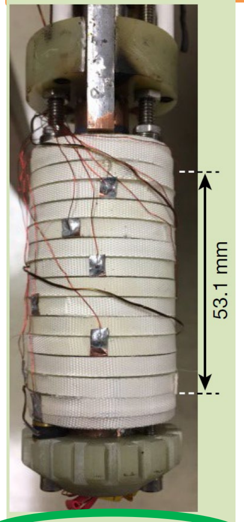
PRINCETON PLASMA PHYSICS LABORATORY

Advanced Conductor Technologies LLC
www.advancedconductor.com

Y. Zhai, D.C. van der Laan, D. Davis, U.P. Trociewitz

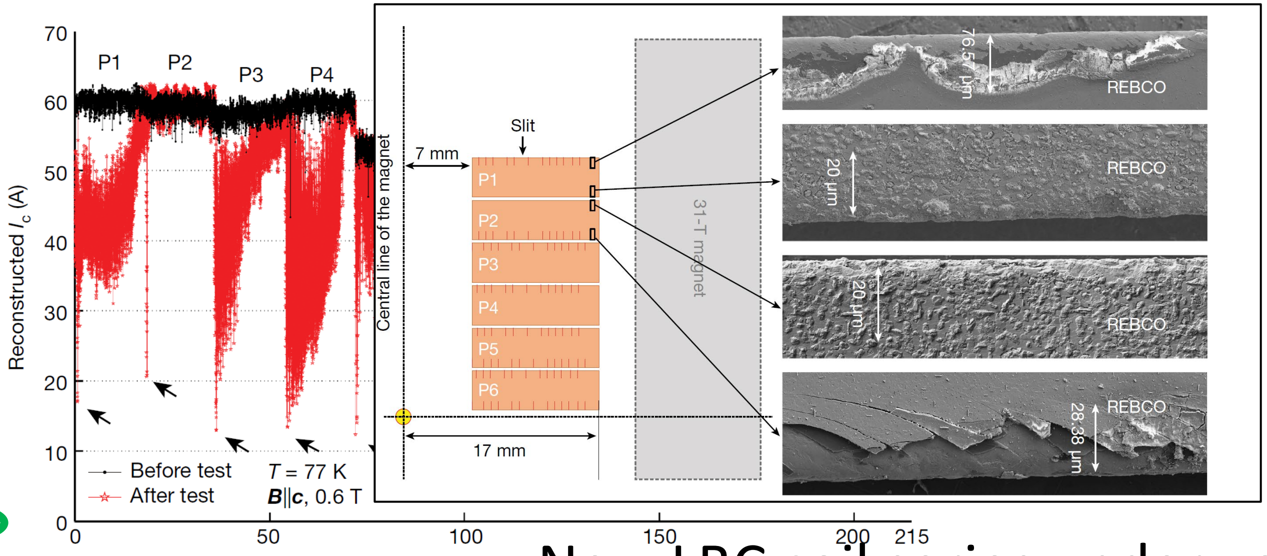


2-Layer CORC® solenoid in grooved mandrel 12 T background field at 4 K



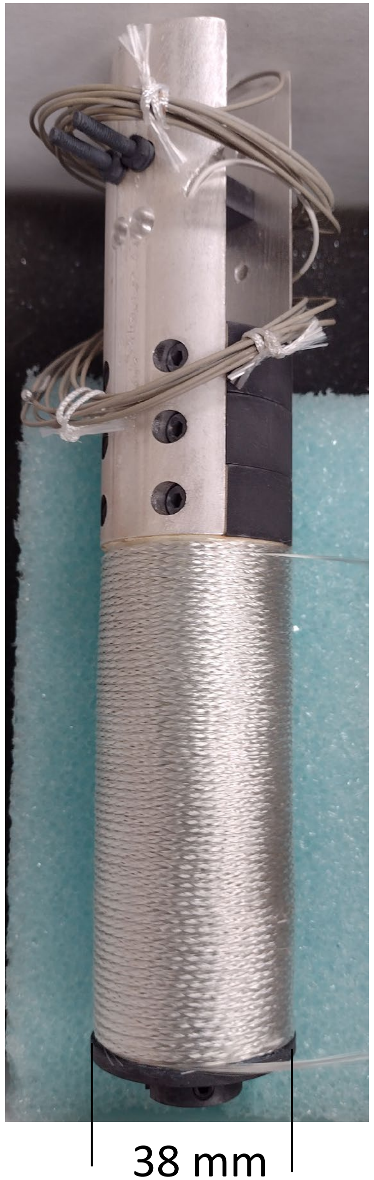
LBC3 after 45.5-T test

Hahn et al.



New LBC coil series underway!

Ultra-High-Field Solenoid Testing in the 31 T Resistive Magnet Demonstrates Conductor Capabilities and Magnet Technology

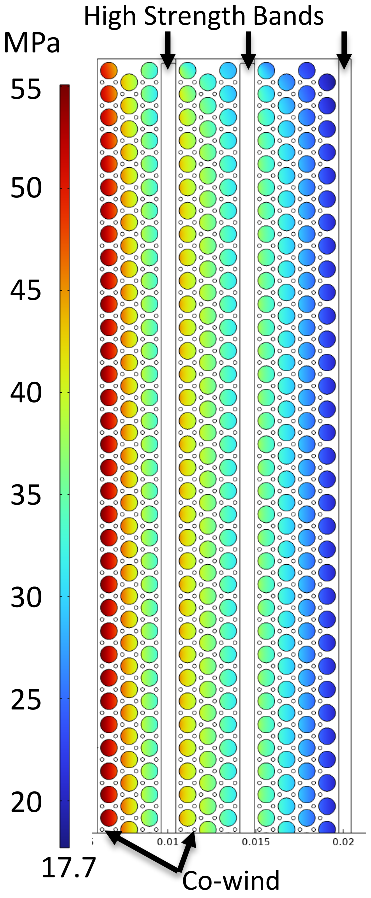

38 mm


Over-banding

Like the LBCs, 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**

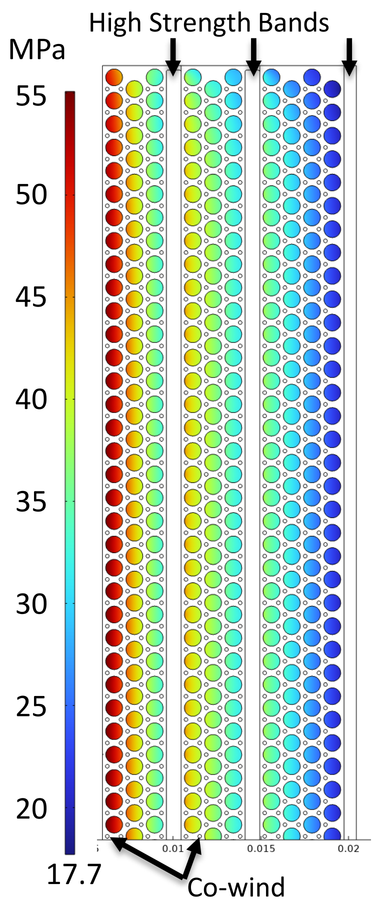
Ultra-High-Field Solenoid Testing in the 31 T Resistive Magnet Demonstrates Conductor Capabilities and Magnet Technology

Next generation scientist, Teo Kim with “Teo-2”

Like the LBCs, TEO-type coils are a cost-efficient vehicle to test materials and processes

Coil Specs:

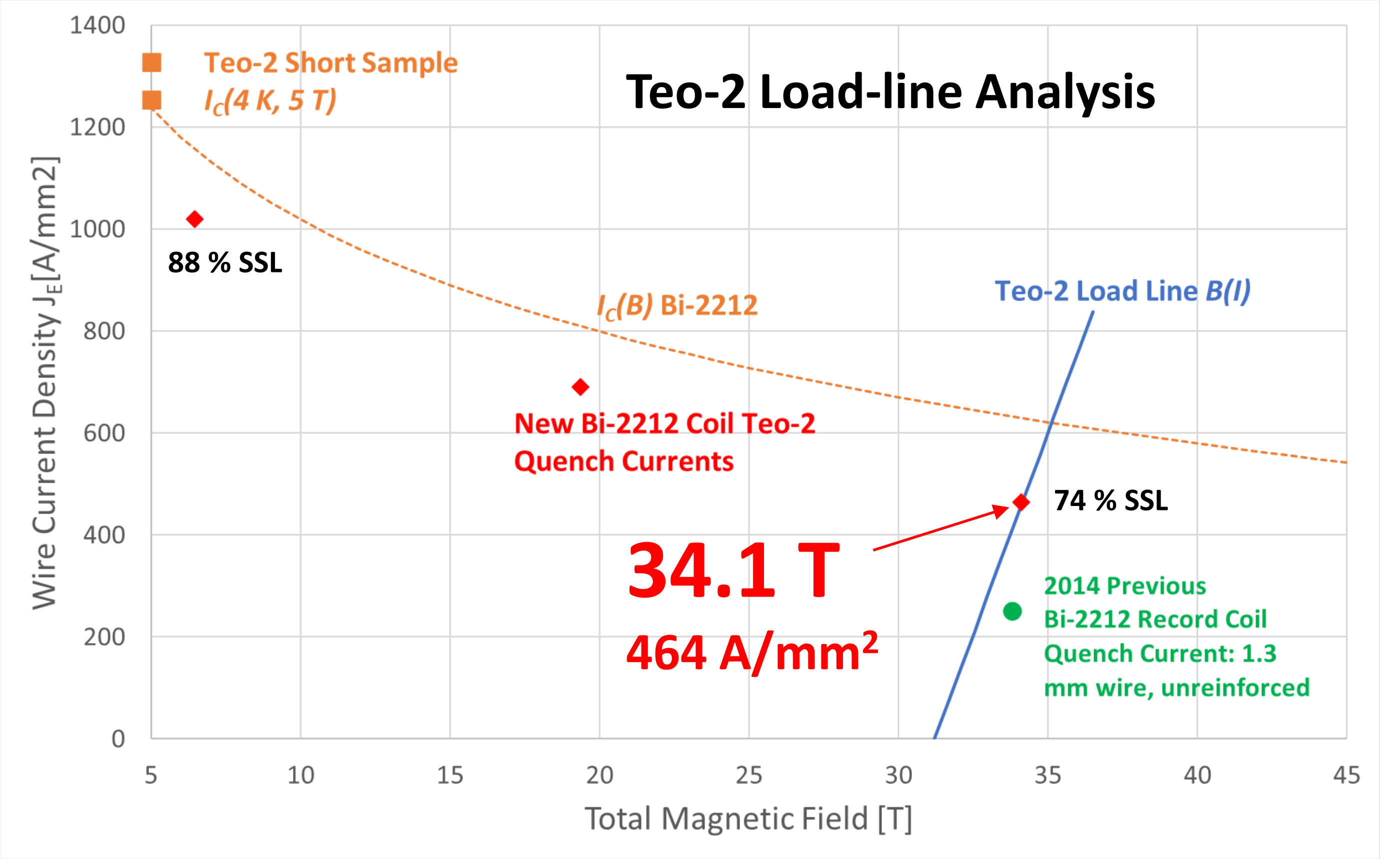
Coil Name		TEO 1	TEO 2	TEO 3
Wire	PMM No.	PMM180928 (Φ1.0 mm)		
	Insulation	TiO2 coat – Mullite Braid (Φ1.3 mm)		
ID; OD; Height [mm]		12.0; 34.2; 80.9	12.0; 37.5; 80.4	12.0; 37.4; 88.6
Turn ; Layer (Total)		60.3 ; 8 (482)	59.2 ; 10 (592)	59.1 ; 10 (591)
Innerbands		2 (Band)	2 (Band)	2 (Wind)
Overband		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



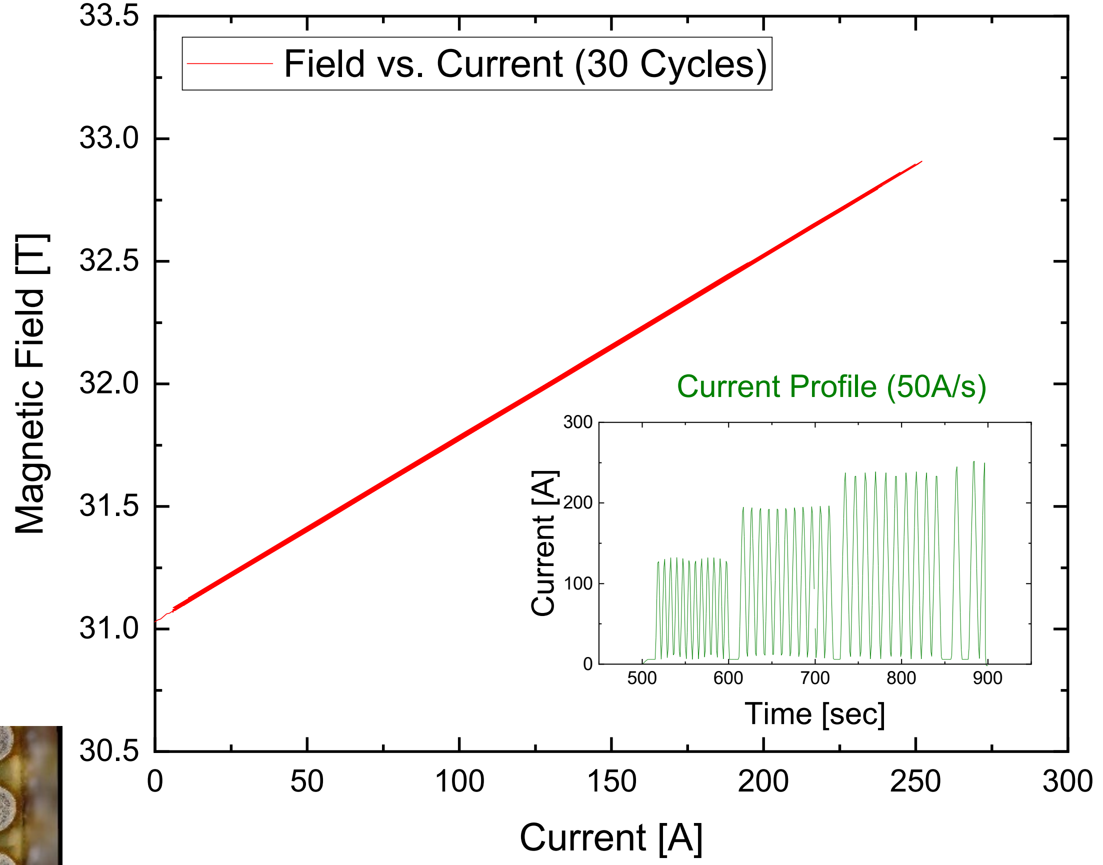
Stress with Reinforcement

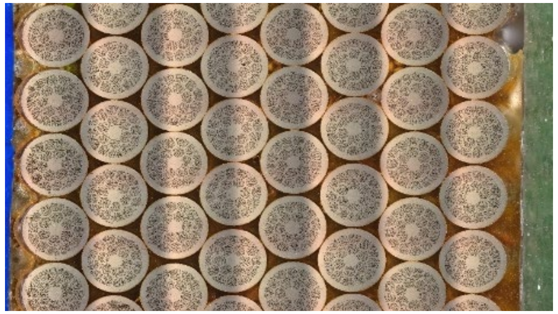
peak source hoop stress (J_E*B*R) between **237 - 273 MPa**

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



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

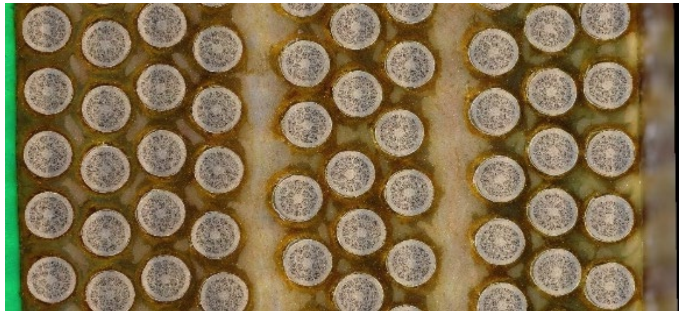




2014

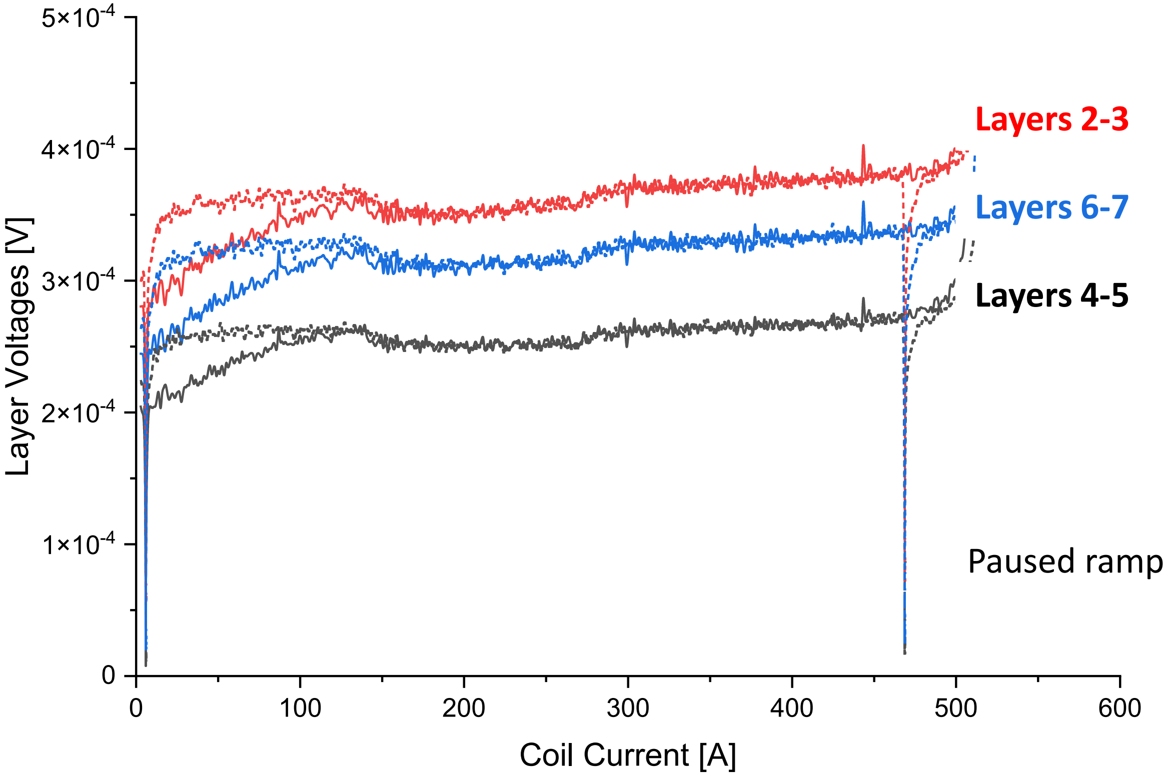
to

2023

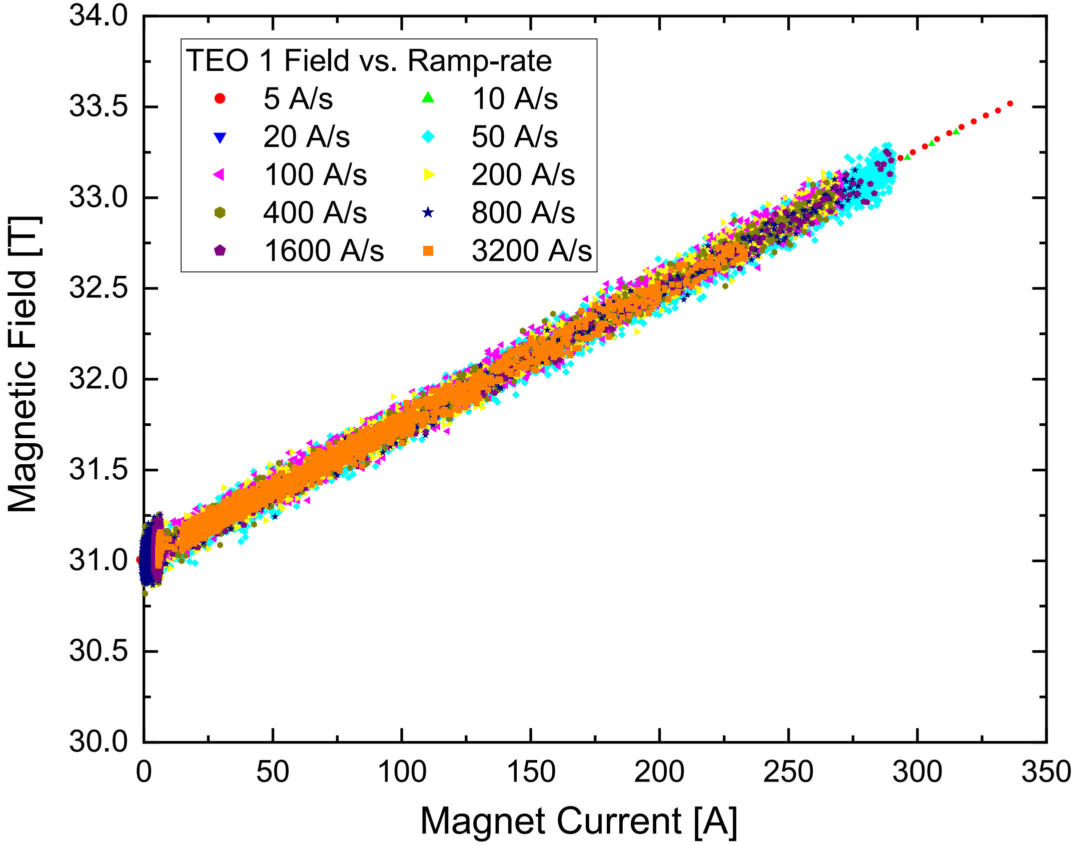


Robust Operation of High Temperature Superconducting Bi-2212 Magnets at 34 T and ramp rates over 23 T/s

Teo-1 V-I curves (4 K, 15 T)
before(dotted) & after(solid) high-rate tests at 31 T

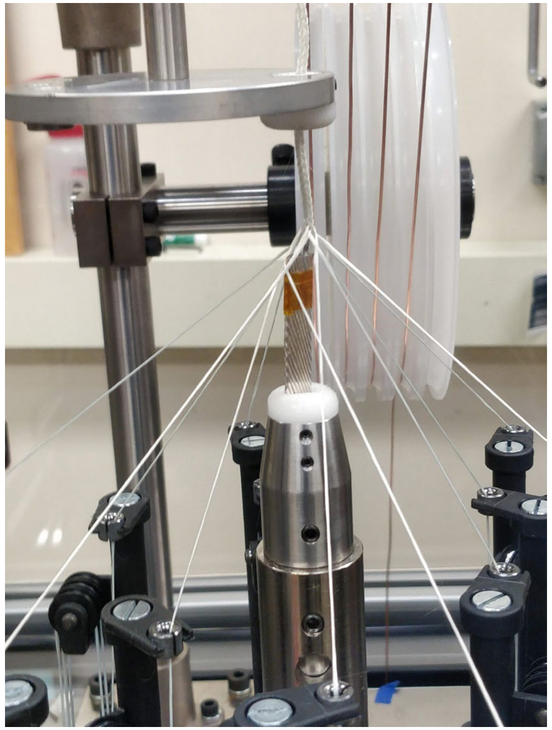


Teo-1 Field generation consistent across ramp rates indicating proper insulation



This robust operation of multiple coils in fields >30 T is an important demonstration to our collaborators including commercial partners Cryomagnetics Inc. and Oxford Instruments (OI) developing compact 25 T class research magnets, the US-DOE Magnet Development Program developing hybrid HTS/LTS 16 T dipoles, and Princeton Plasma Physics Laboratory (PPPL) pursuing fusion ohmic heating solenoids, as well as our own efforts at ASC towards >1.2 GHz NMR with an NIH-R01 submission.

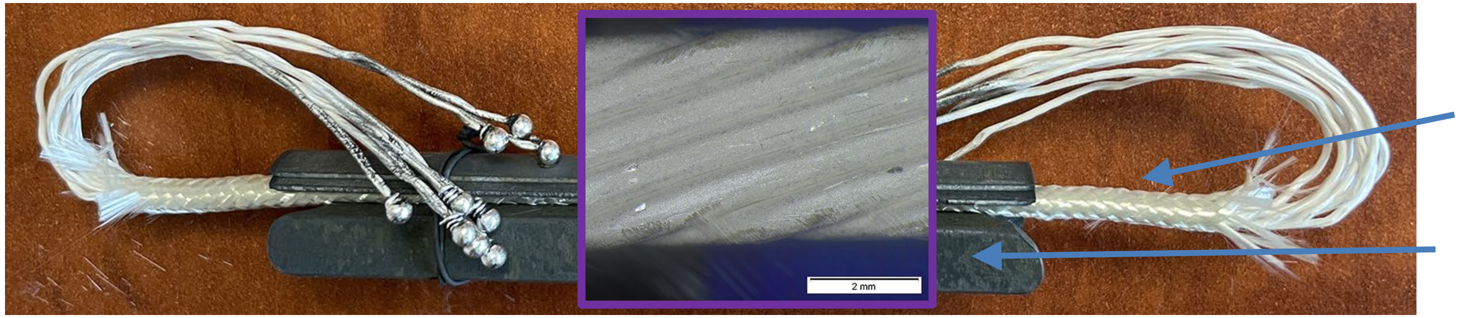
Implementing New Insulation in Rutherford Cables Magnets



First 17 strand cable length insulated with pure alumina

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



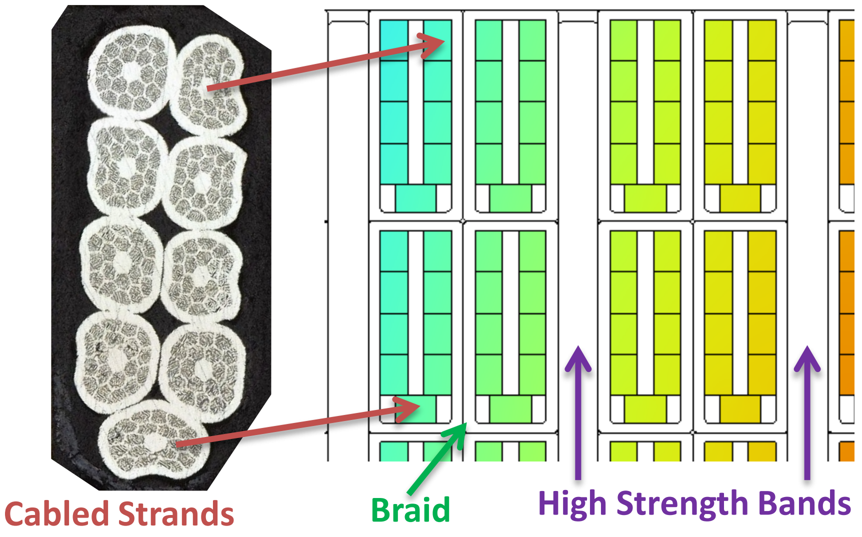
Pure alumina braid

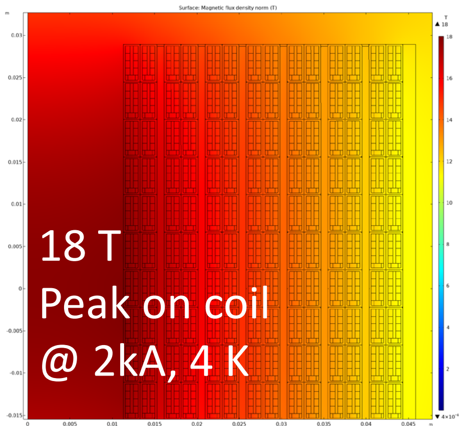
Inconel compression blocks

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

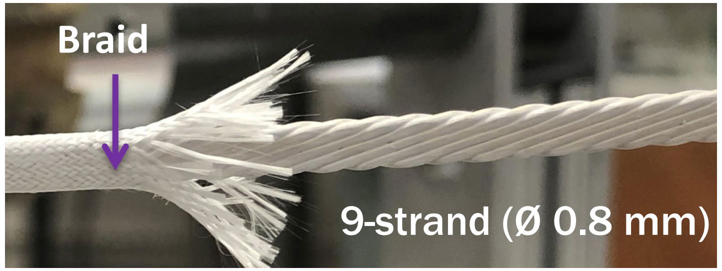
~5 T Rutherford Cable Solenoid to Validate Alumina Braid Insulation

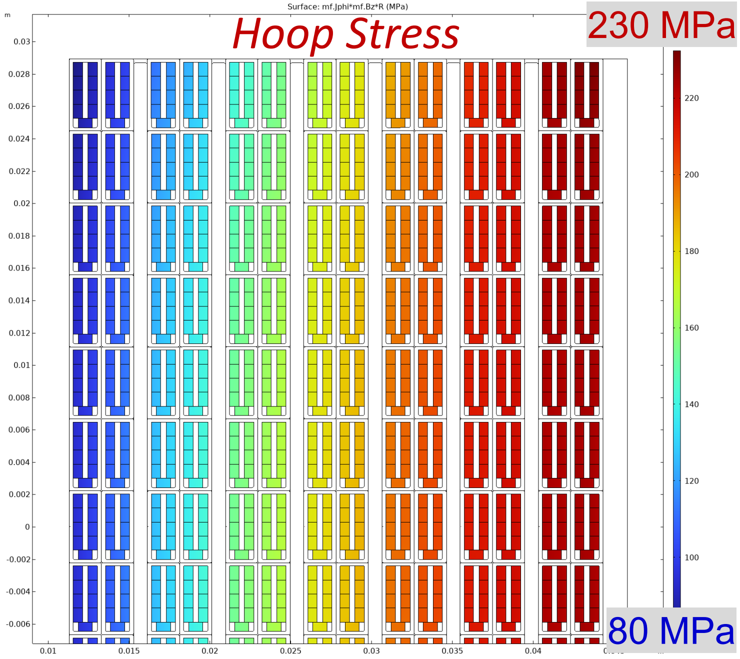
Bi-2212 Rutherford (BR) Cable Solenoids			
		BR-1	BR-2
Wire	Product No.	PMM170725	PMM130723-1
	Powder	nGimat (85 x 18)	Nexans (37 x 18)
	Insulation	In-house coating(no top-coat)+mullite braid	Pure Alumina (Nextel) Braid
	Diameter [mm]	Φ 0.8 (bare)	Φ 0.8 (bare)
Cable	ID	LBNL-1093	LBNL-1075
	Size, uses (length)	9-Strand, CCT leftover (8.5 m)	9-strand, winding/insulation tests (31 m)
	Geometry	4.0 x 1.44 mm (bare) / 4.38 x 1.82 mm (ins.)	4.0 x 1.44 mm (bare) / 4.4 x 1.74 mm (ins.)
ID ; OD ; Height [mm]		44.45 ; 69.67 ; 26.29	24.0; 84.5; 55.0
Turn ; Layer (Total)		6 ; 6 (36)	12.5; 14 (175)
Magnet constant [mT/A]		0.708	2.876
Inductance [mH]		0.064	0.7
Conductor length [m]		6.5	30
Status		Tested	Final Design and Test Winding





18 T
Peak on coil
@ 2kA, 4 K





232 MPa
J_E*B*r
Hoop Stress

Unique HTS Test-bed : 161 mm, 12 T LTS, 10 kA

12 T HTS Coil Test Bed

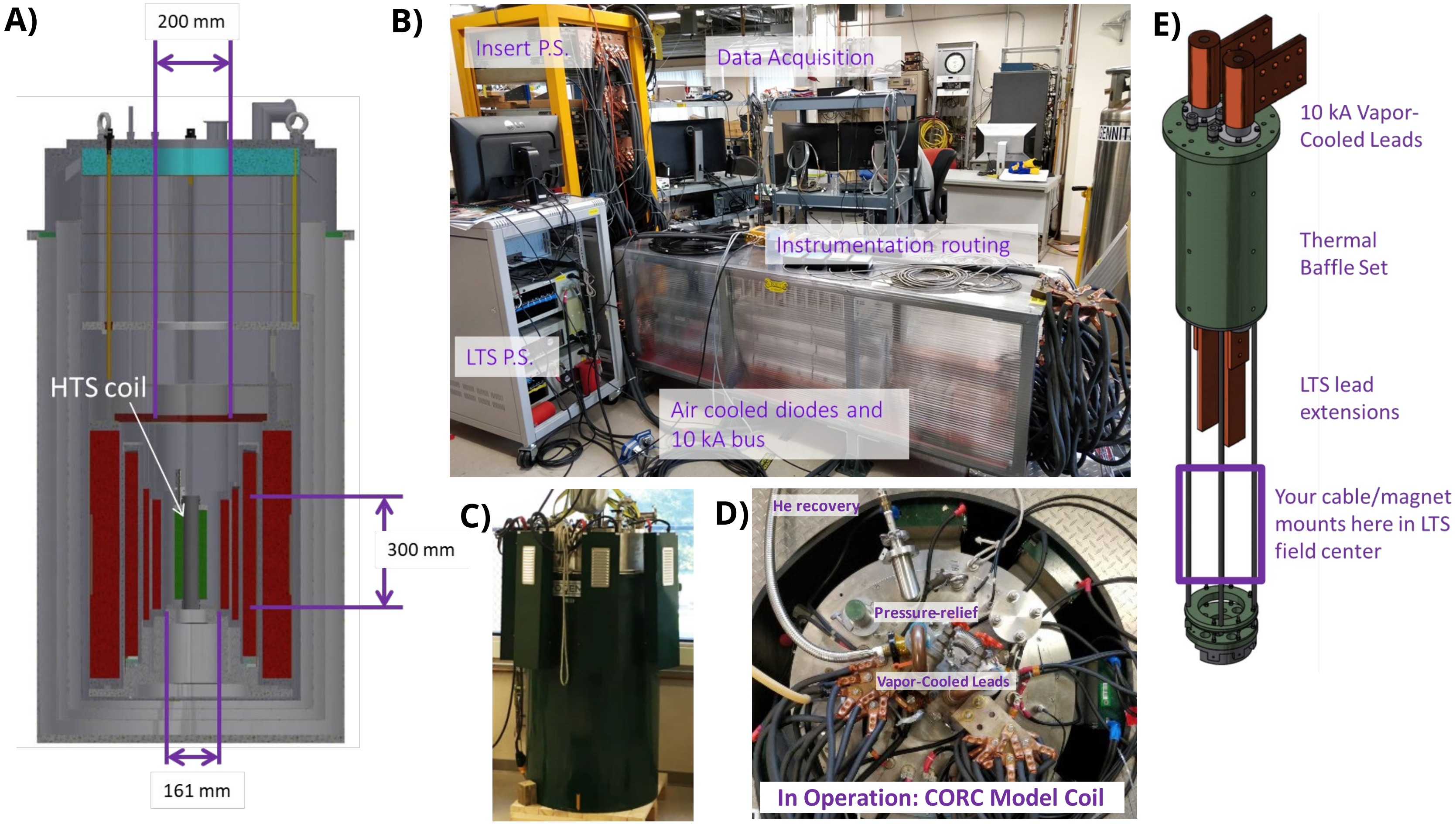
- 10 kA bus, 8 x 1.2 kA power supplies
  - Enables individual cable and cable magnet testing
- Magnet bore 161 mm, 200 mm access bore for leads, 128 ppm uncorrected homogeneity (1 cm DSV)

Large bore enables insert magnets:

- To explore field generation and mechanical limits in strand-wound and cable wound coils
- To add additional means to improve field homogeneity (e.g., compensation coils, shims etc.)
- Implement novel HTS quench management

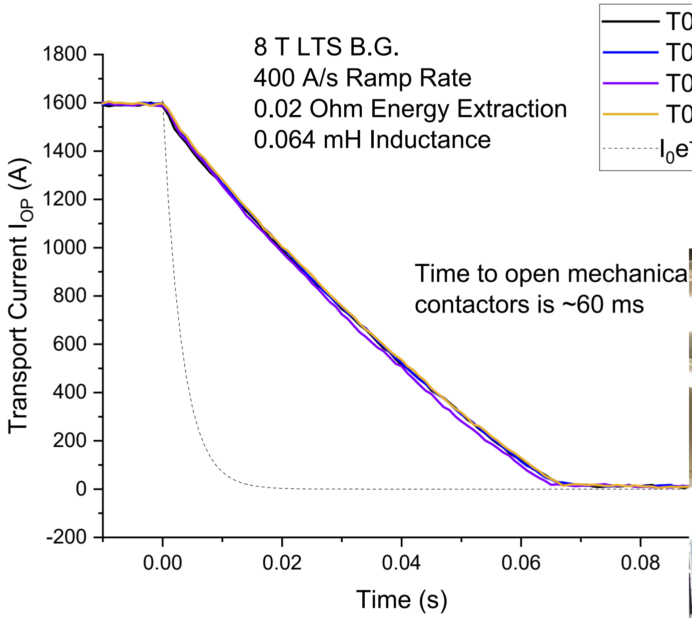
Features

- 1 kA, 7.5 kA, and 10 kA VCL probes
- FPGA control and IGBT quench management
- Variable dump resistors and varistors

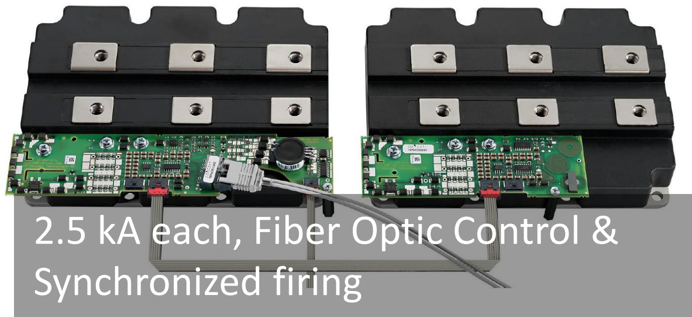


A) Schematic of the 12 T LTS (red) magnet with a 200 mm probe access and a 161 mm cold bore for HTS insert (green); **B)** Picture of the LTS & HTS support systems; **C)** Picture of the 12 T magnet cryostat with external protection elements; **D)** Picture of the top plate of the 12 T magnet during a recent test of an HTS Bi-2212 Rutherford cable solenoid; **E)** Schematic of the 10-kA vapor-cooled-lead probe being prepared

IGBT Quench Circuit Upgrade

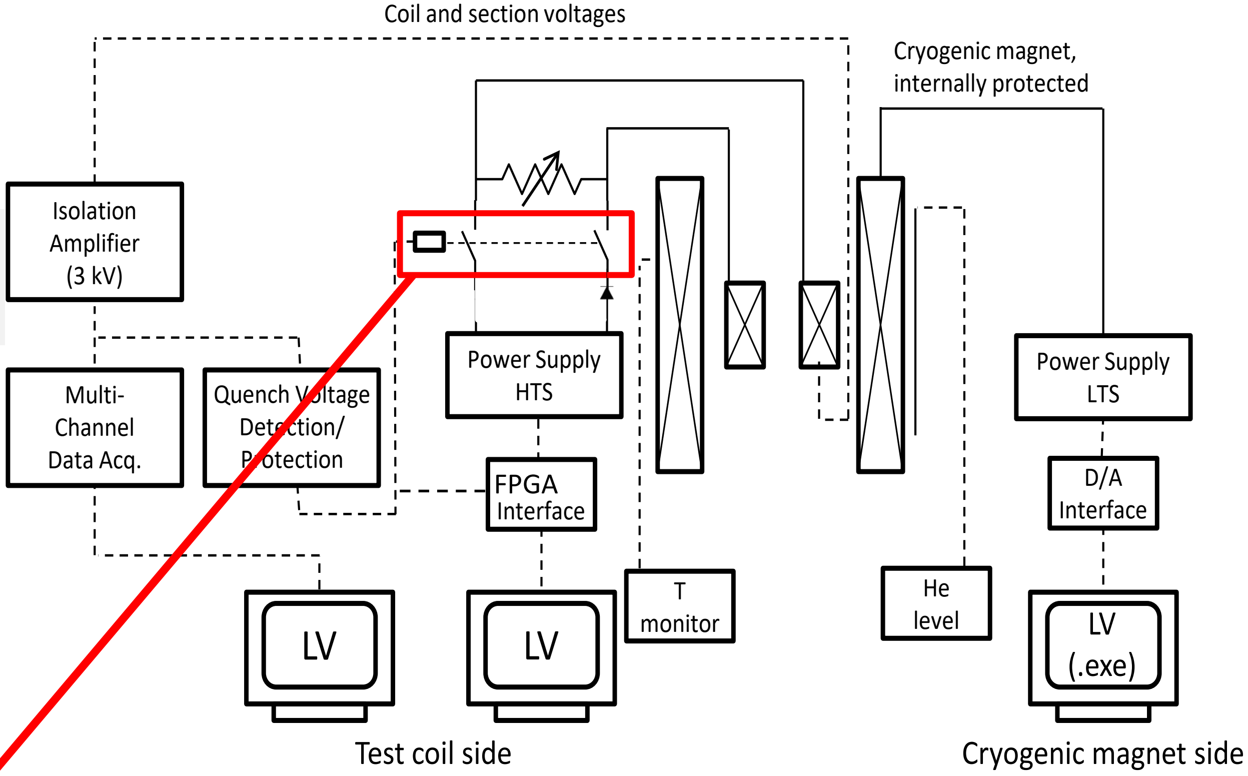


Cable solenoid protection speeds were limited by hardware limits of mechanical contactors rather than the coil inductance or peak voltage.



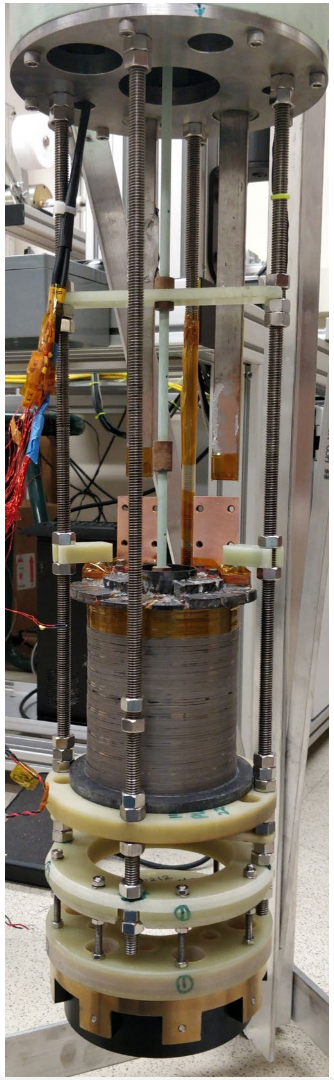
2.5 kA each, Fiber Optic Control & Synchronized firing

Insert Coil Power Supply Rack

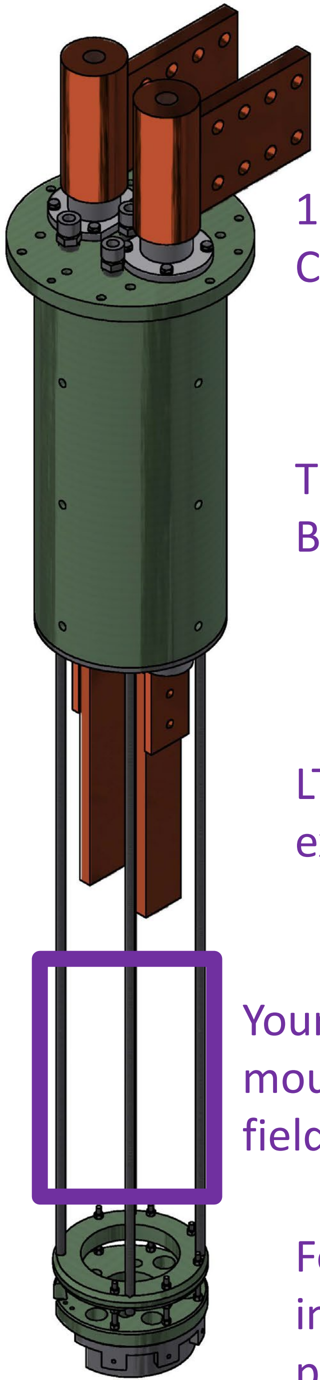


Cable-Coil/Sample Test Platforms

- A probe with 10 kA helium vapor cooled leads is ready to operate inside our 14 T, 161 mm large bore magnet
- Will accommodate Bi-2212 as well as ReBCO cable coils/samples
- We have existing 7.5 kA and 1 kA probes for lower current cables and wires with reduced heat load on the system.



Recent Bi-2212 strand solenoid test



10 kA Vapor-Cooled Leads

Thermal Baffle Set

LTS lead extensions

Your cable/magnet mounts here in LTS field center

Force support interface from probe to LTS

High-field insert solenoid wound from CORC® cables

Addresses main challenges of low-inductance HTS magnets

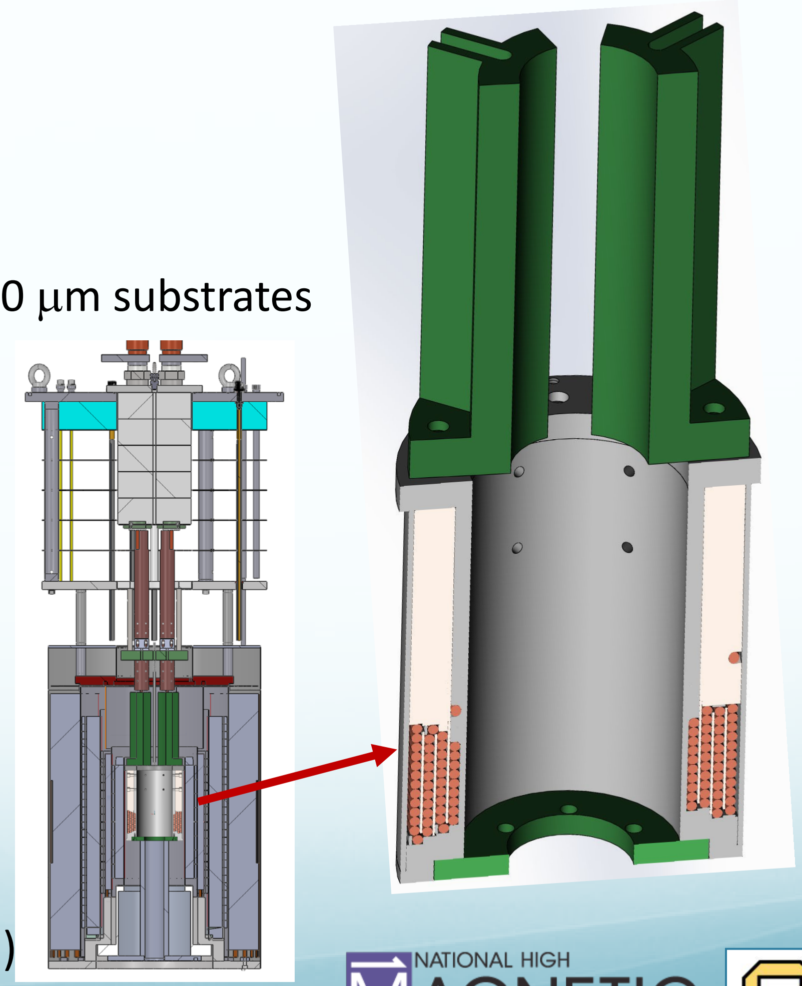
- Operate CORC® insert solenoid in **14 T background field**
- CORC® insert should have meaningful bore: 100 mm diameter
- High operating current: **4,000 – 5,000 A**
- **J_e > 200 A/mm^2**
- Operate at **JBr source stress >250 MPa**

CORC® cable layout

- 28 REBCO tapes of 3 mm width containing 30 μm substrates
- 4.56 mm CORC® cable outer diameter

CORC® insert layout

- 100 mm inner diameter, 143 mm OD
- 4 layers, 45 turns
- 18.5 m of CORC® cable
- Wet-wound with Stycast 2850
- Stainless steel overbanding between layers



14 T LTS
(161 mm bore)

Danko van der Laan et al., CCA21, October 14th, 2021

This work was in part supported by the US Department of Energy under agreement numbers DE-SC0009545, DE-SC0014009 and DE-SC0021710.

Advanced Conductor Technologies
www.advancedconductor.com

UNIVERSITY OF TWENTE.

NATIONAL HIGH MAGNETIC FIELD LABORATORY

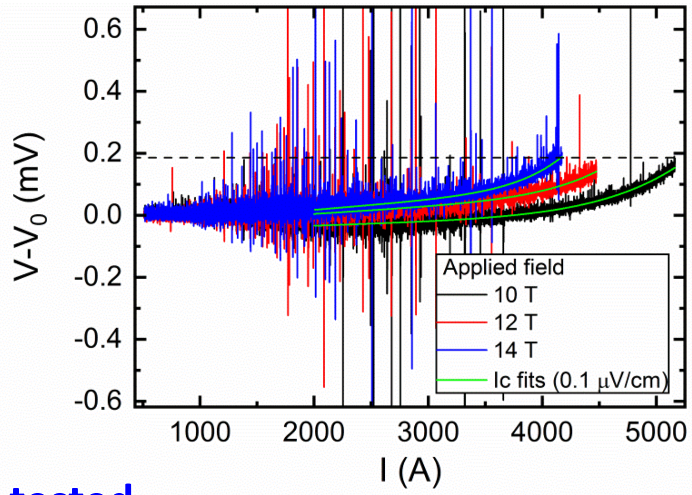
CORC® insert solenoid test: summary

CORC® insert impact

- **First HTS insert magnet tested at high current (>1 kA) in a background field**
- Stable operation likely due to current sharing between tapes in the CORC® cable
- Combination of high *I*, J_w and JBr demonstrated at 16.8 T peak field

Applied field [T]	Central field at I_c [T]	Peak field at I_c [T]	I_c (0.1 μV/cm) [A]	*n*-value [-]	J_w [A/mm²]	J_e [A/mm²]
10	12.25	13.35	5,315	7.9	203.9	340.3
12	14.08	15.09	4,908	9.1	188.3	314.2
14	15.86	16.77	4,404	10.5	168.9	281.9

D. C. van der Laan, et al.,
Supercond. Sci. Technol. (2020)
https://doi.org/10.1088/1361-6668/ab7fbe



First high-current CORC® insert solenoid successfully tested

- Operation at over 4.4 kA in 14 T background field, generating a peak field of 16.77 T
- Operated at 282 A/mm^2 and 275 MPa JBr source stress at 14 T background field

Conductor challenges when going to higher field and larger coil diameters

- A Central Solenoid in a future compact fusion reactor may have a JBr of 200 A/mm^2 x 20 T x 0.2 m = 800 MPa (source stress)
- How to further optimize the CORC® conductor to allow higher hoop stress, but also a higher irreversible strain limit?

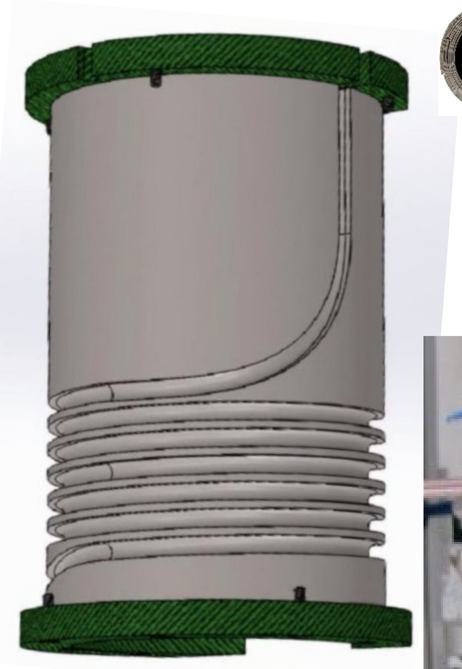
Advanced Conductor Technologies
www.advancedconductor.com

UNIVERSITY OF TWENTE.

NATIONAL HIGH MAGNETIC FIELD LABORATORY

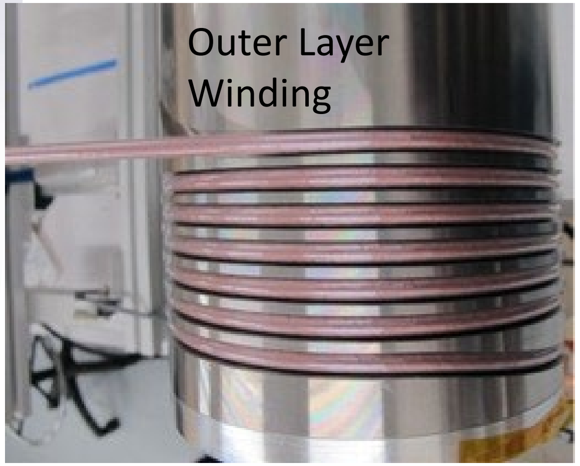
Fatigue testing a Prototype Ohmic Heating (OH) CORC Cable Solenoid

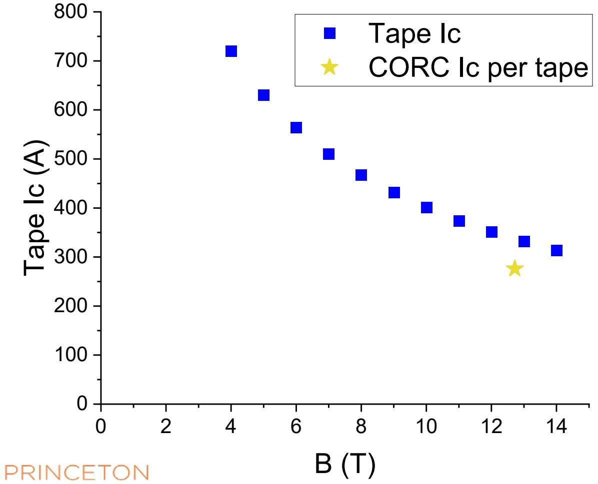
Prototype Ohmic Heating CORC Cable Solenoid		
Cable	Product No.	ACT- CORC, 20191113-3
	Tape	SP M4-534-105 0508
	Insulation	Heat Shrink + Kapton between Cu tape and cable
	Diameter [mm]	5.86
ID ; OD ; Height [mm]		119; 152; 60
Turn ; Layer (Total)		6; 2 (12)
Magnet constant [mT/A]		0.102
Inductance [mH]		~ 0.019
Conductor length [m]		5.1
Status		Tested



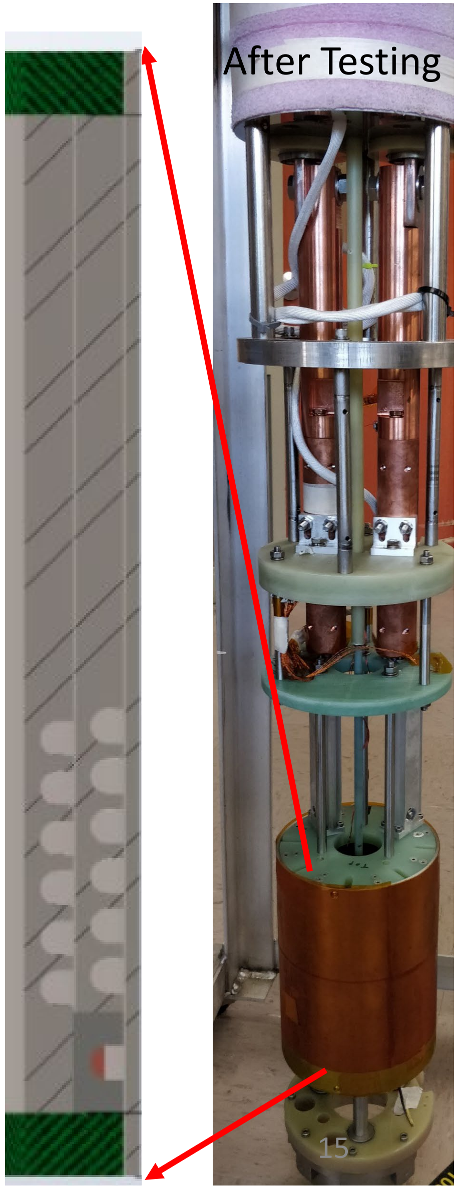
Advanced Conductor Technologies LLC
www.advancedconductor.com

8x2 tapes

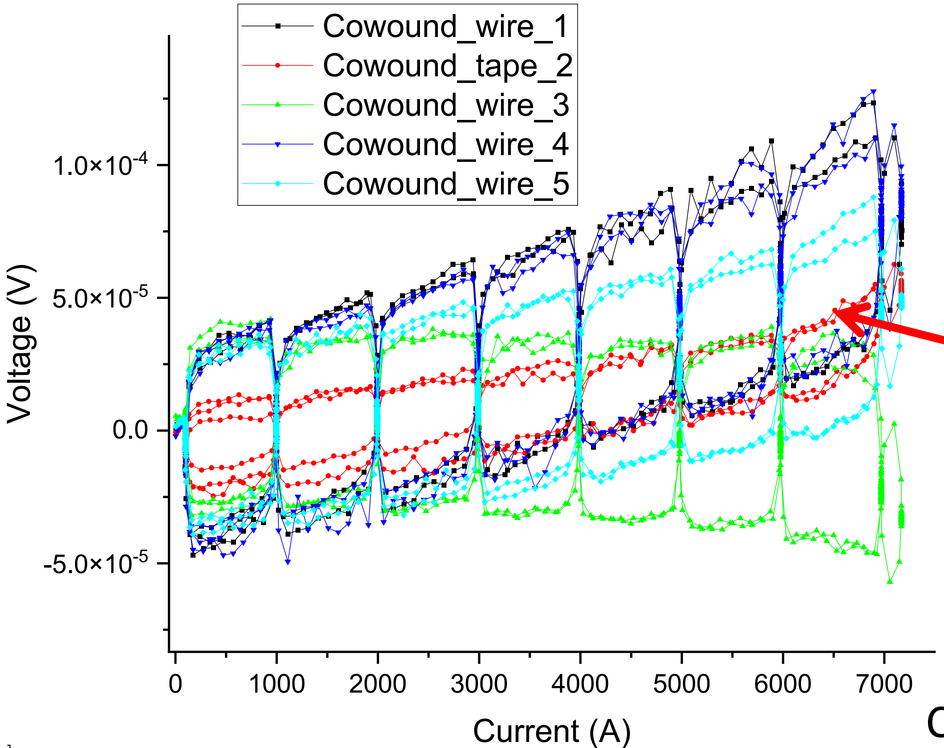




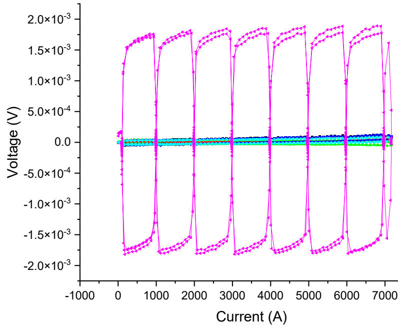
Fatigue Test	Cycles	B_{app} [T]	Peak JBr stress [MPa]	Min cycle I_{op} [A]	Max cycle I_{op} [A]
1	69	5	79	2200	5000
2	50	10	101	2000	3200
3	127	12	107	1600	2800
4	67	12	173	3400	4600



4 K self-field testing demonstrated fast ramp rates with stable operation despite effects of magnetization and motion on voltages

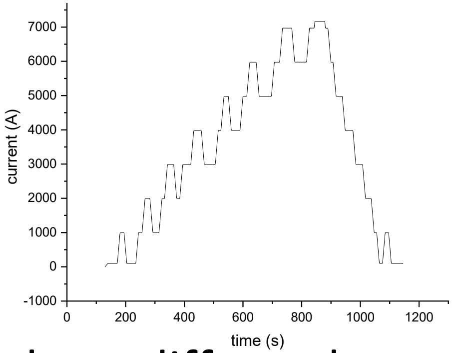


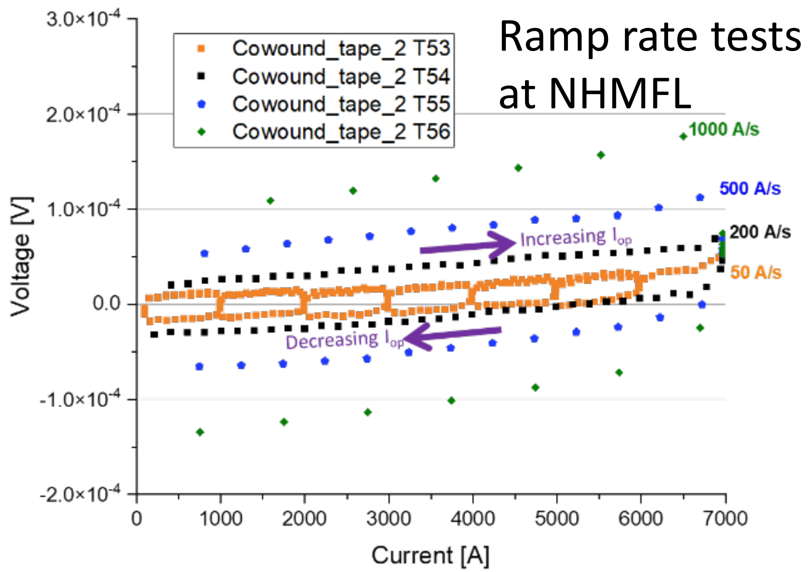
Co-wound Tape-2 provided the best indicator of cable transition



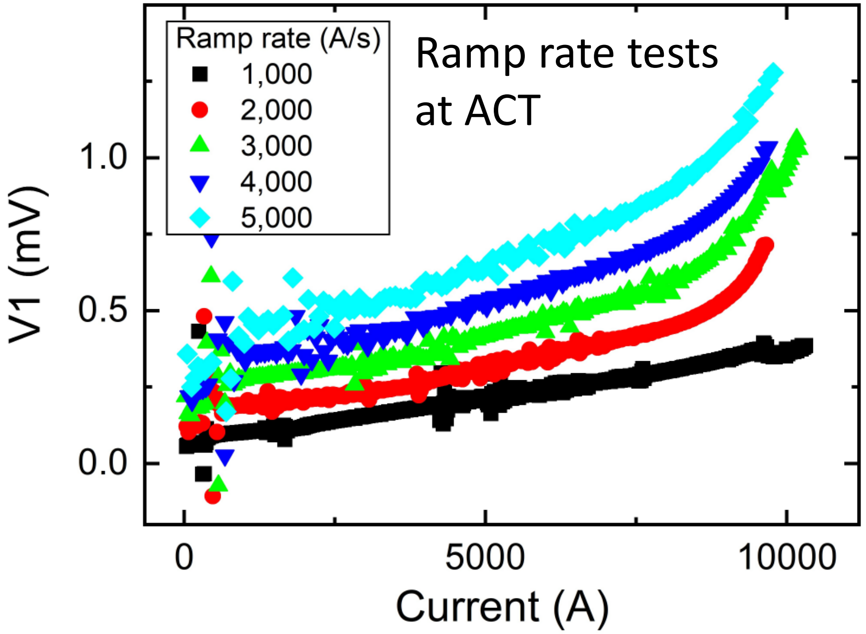
Not co-wound Wire-7: Inductance dominates response

Current - Time





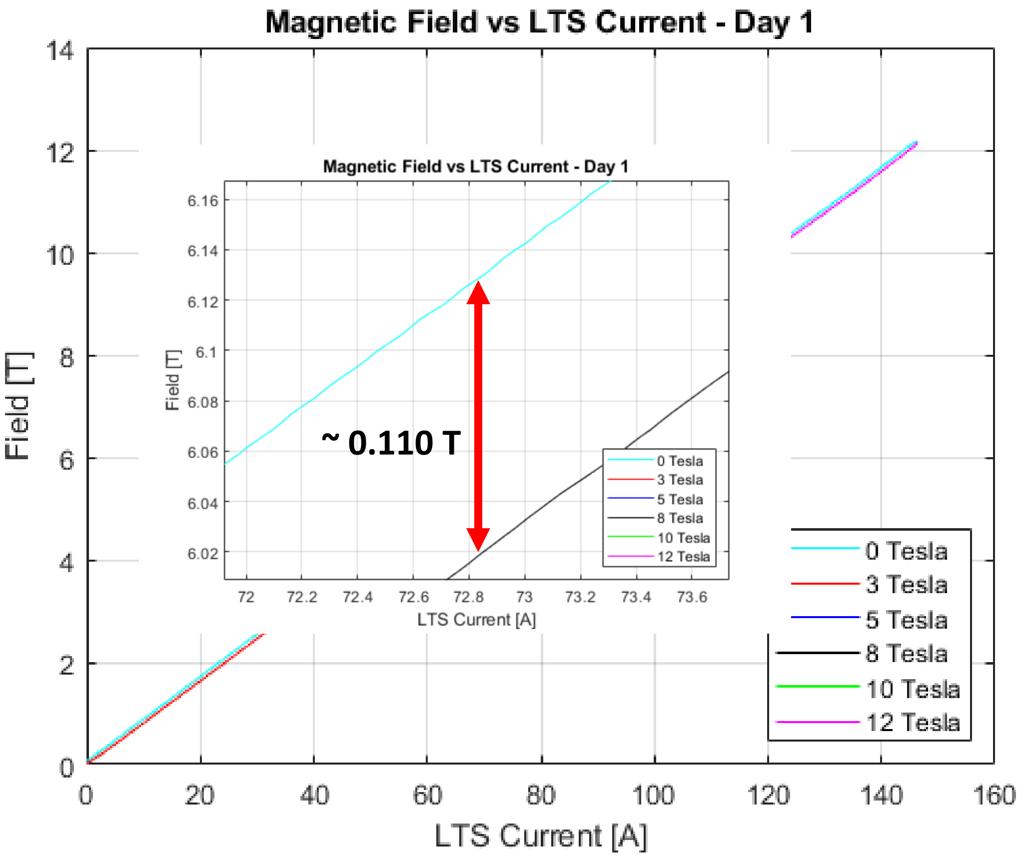
Ramp rate tests at NHMFL



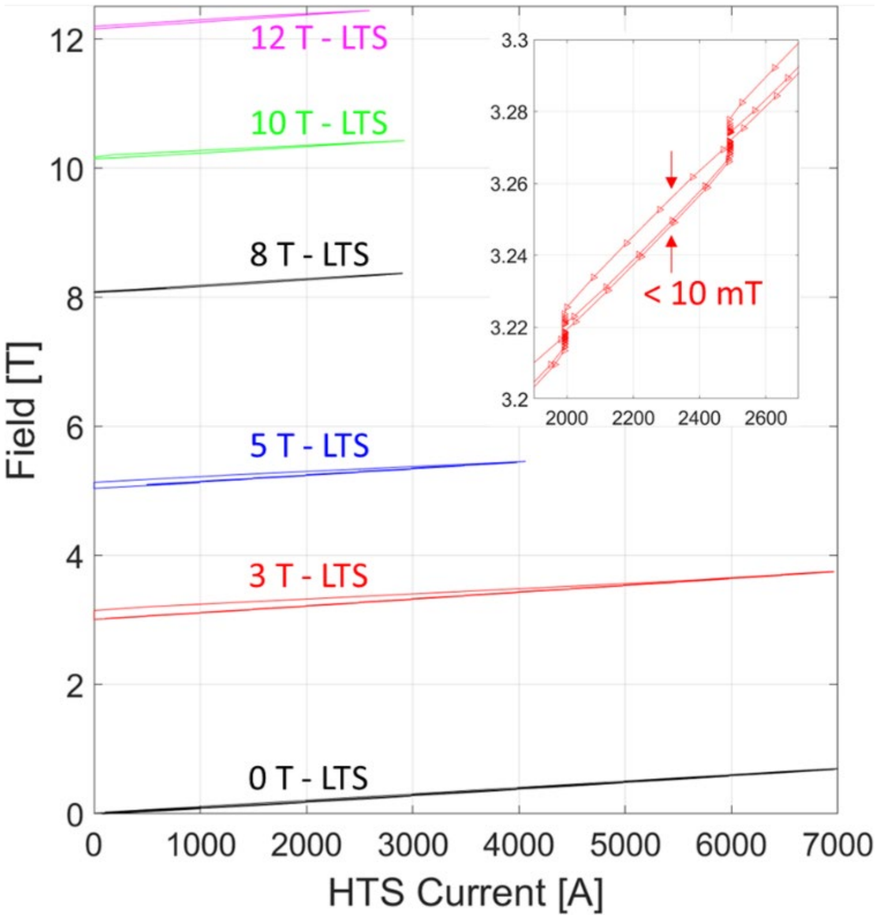
Ramp rate tests at ACT

Voltages nominally at the same location behave differently depending on how inductance and motion are compensated.

Reasonable Screening Current Induced Field

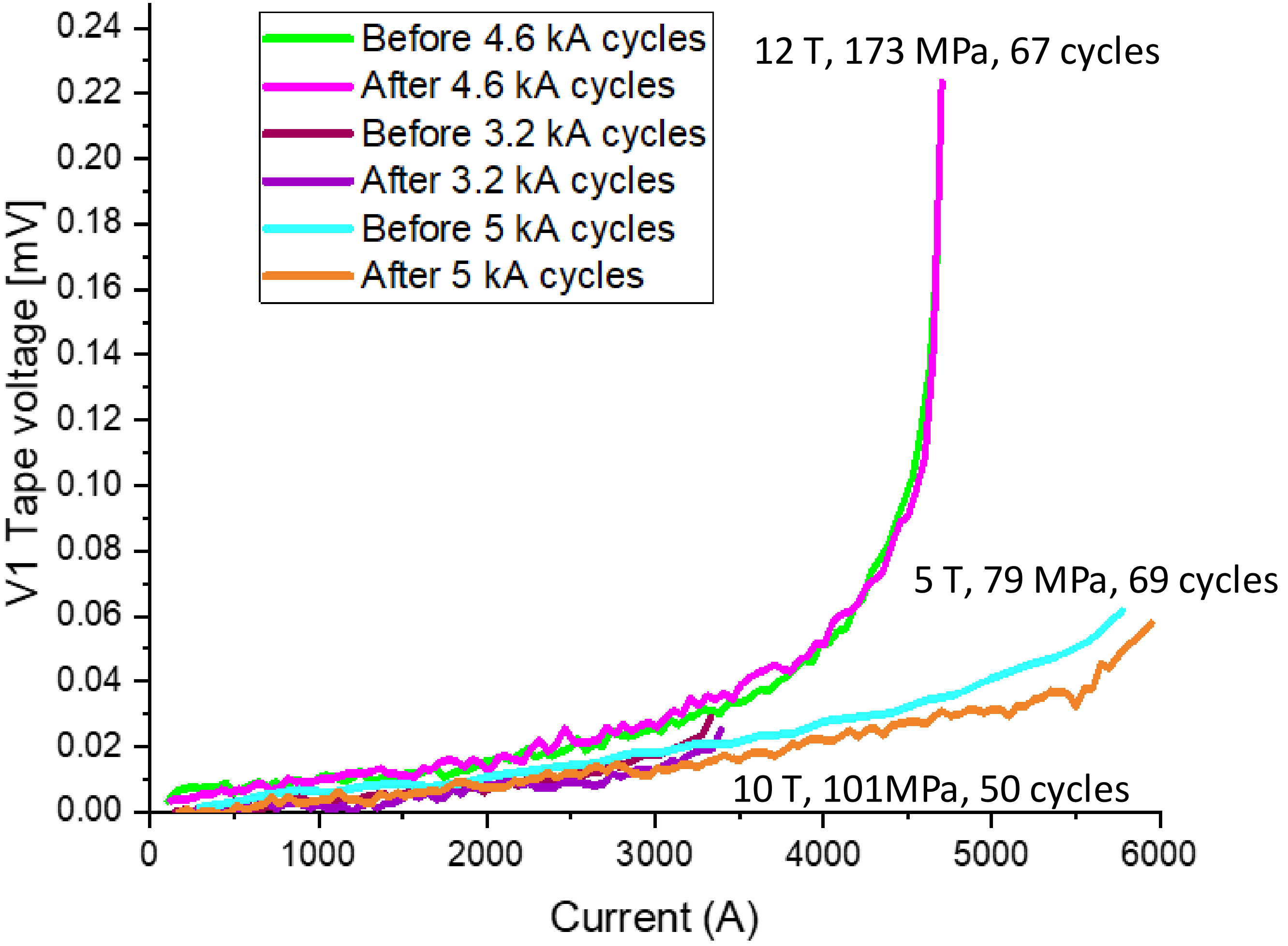


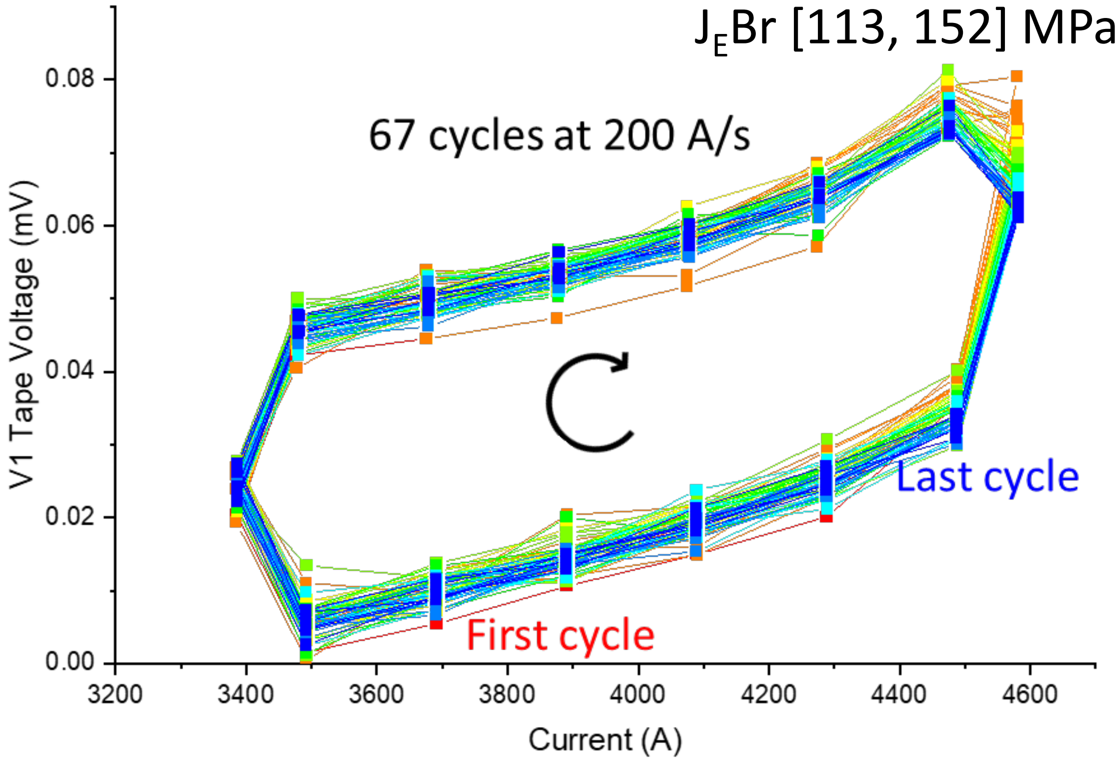
Excess field max is 163 mT
And decays over time of measurements at high field



Expected 0.102 mT/A
Measured range 0.082 to 0.112 mT/A
Median: 0.102   Average: 0.102

No performance change after fatigue cycles





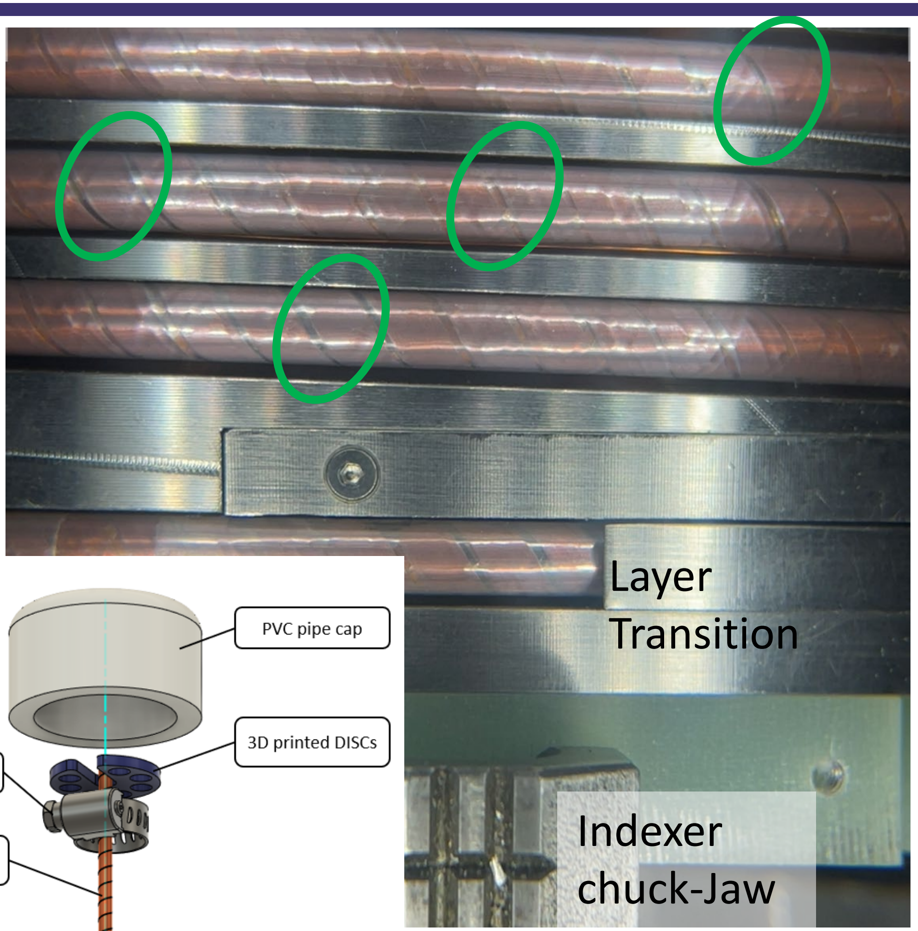
B_{Peak} [12.54,12.73] T

$J_E Br$ [113, 152] MPa

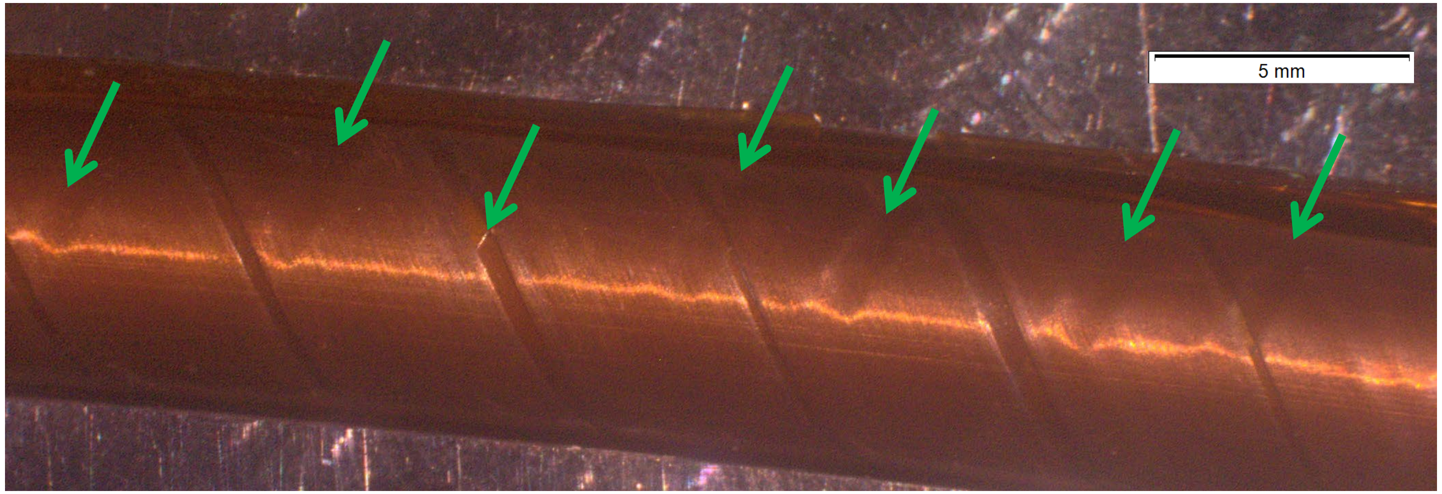
Fatigue Test	Cycles	B_{app} [T]	Peak JBr stress [MPa]	Min cycle I_{op} [A]	Max cycle I_{op} [A]
1	69	5	79	2200	5000
2	50	10	101	2000	3200
3	127	12	107	1600	2800
4	67	12	173	3400	4600

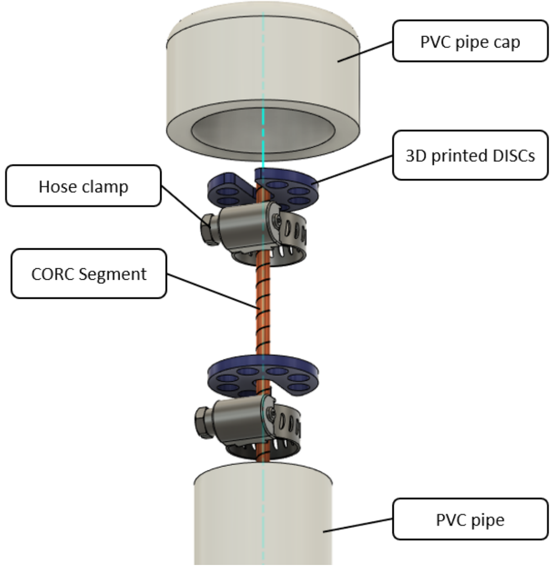
Prototype OH CORC Solenoid Postmortem: So-far So-good

- No visible degradation, pinch points or significant conductor deformation
- Evidence of Lorentz forces by next layer impressions in the copper.
- Conductor removed from each layer without unbending
- Developing postmortem techniques for the next coils with higher stresses:
  - Control coil for comparison
  - Cross section images: secure, diamond wire saw, VPI, polish, tape centroid analysis, tape gap analysis



Inside terminal riser support





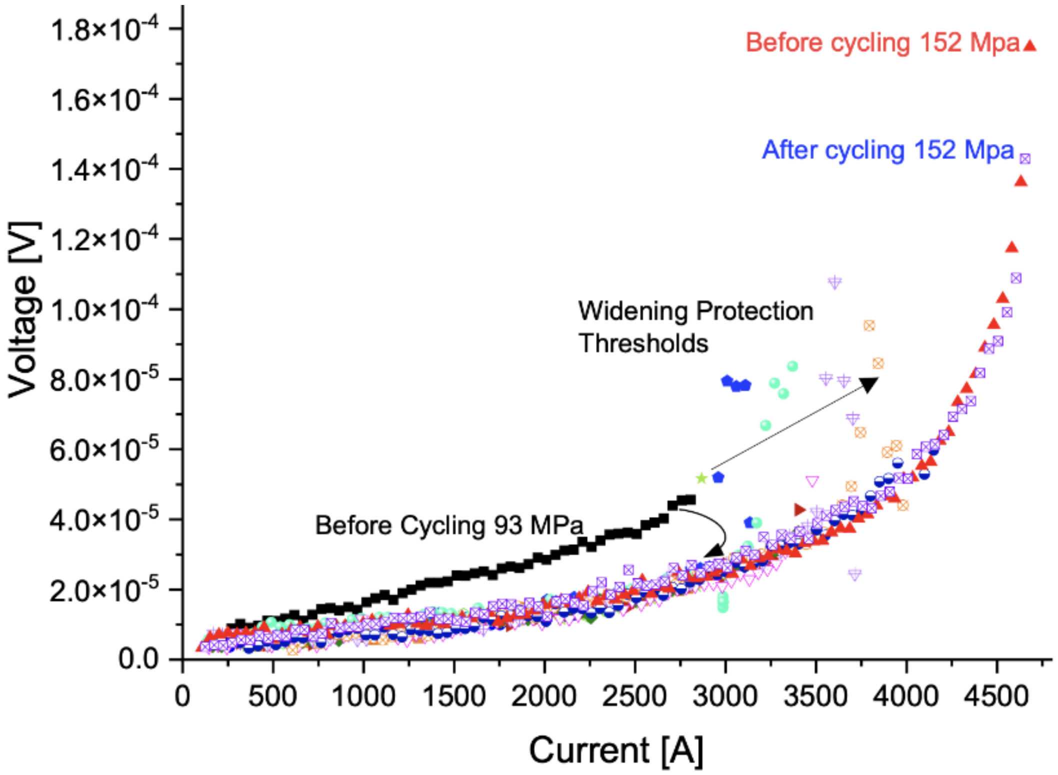
Epoxy VPI fixture for cross sections from bent coil turns (G. Murphy)

Multiple Key Results From Each High Field Coil Test

- **No signs of degradation from low-cycle fatigue**
  - Higher quench currents and apparent I_C after cycling

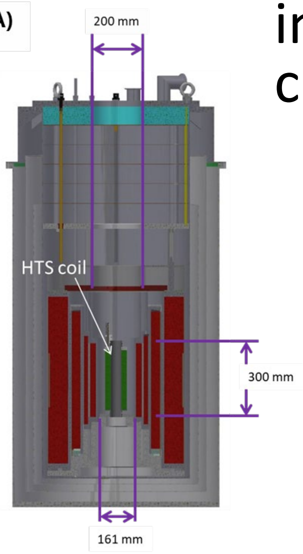
(>50 cycles, > 170 MPa)

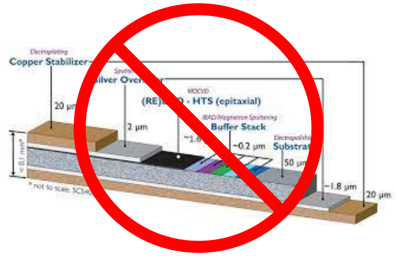
- High ramp rates are manageable
- Complex mix of phenomena in voltages
  - Further analysis needed to identify contributions:
    cable motion, strand motion, screening currents, contact resistance, current sharing, strand degradation, co-wound voltage-tap wire motion
  - Quench detection challenges
    (false positives, transient voltage spikes, change in current sharing dissipation, or local quenches)
    - Must be conservative on quench detection
  - We could benefit from alternative diagnostics to deconvolute behaviors
  - Matched inductance voltage taps significantly improve quench monitoring
  - The cable appears very stable, despite the dynamic behavior of the coil
- Screening currents are manageable
  Affect initial current distributions after background field is ramped and decay as expected
- Demonstrated feasibility of dry-wound cable magnet concept
- **CORC Solenoids solenoid results confirmed by an uneventful postmortem investigation**
  - Developing a control, techniques, and experience for subsequent CORC investigations



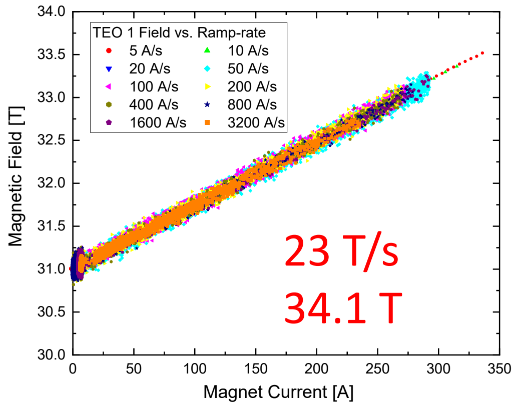
Solenoid Program Opportunities

- Conductor development program into tight loop magnet testing
- Ultra-High-Field tests demonstrate key capabilities and limits of conductor and cable
- Unique large-bore test bed and supporting postmortem investigation cycle demonstrates how cables and solenoids act closer to operation in affordable tests
    - Rapidly test magnet designs and isolate phenomena
    - Low-cycle fatigue test magnets in closer to final operating conditions
    - Dedicated test articles: cables, joints, diagnostics and instrumentation…
    - Validate design and modelling: mechanical reinforcement and constraints, current sharing, screening, quench, etc..
- ASC has extensive postmortem investigation capabilities
    - Material science experts and equipment, Yatestar (Reel-Reel tape evaluation), light/SEM/TEM/MO microscopy capabilities (see Bi-2212 session Postmortem investigation talk for examples)





Not a cartoon



23 T/s
34.1 T