Cable Solenoid Testing in a 14 T, 160 mm LTS with 10 kA Insert Capability

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First Workshop on User Interfaces – Fermilab's Cable Test Facility

November 21-22, 2022

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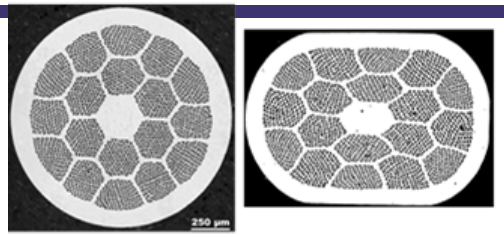
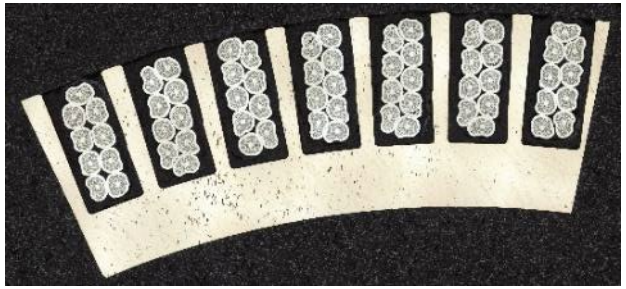
Magnet Testing is The Bottleneck to Ultra-High Field Applications



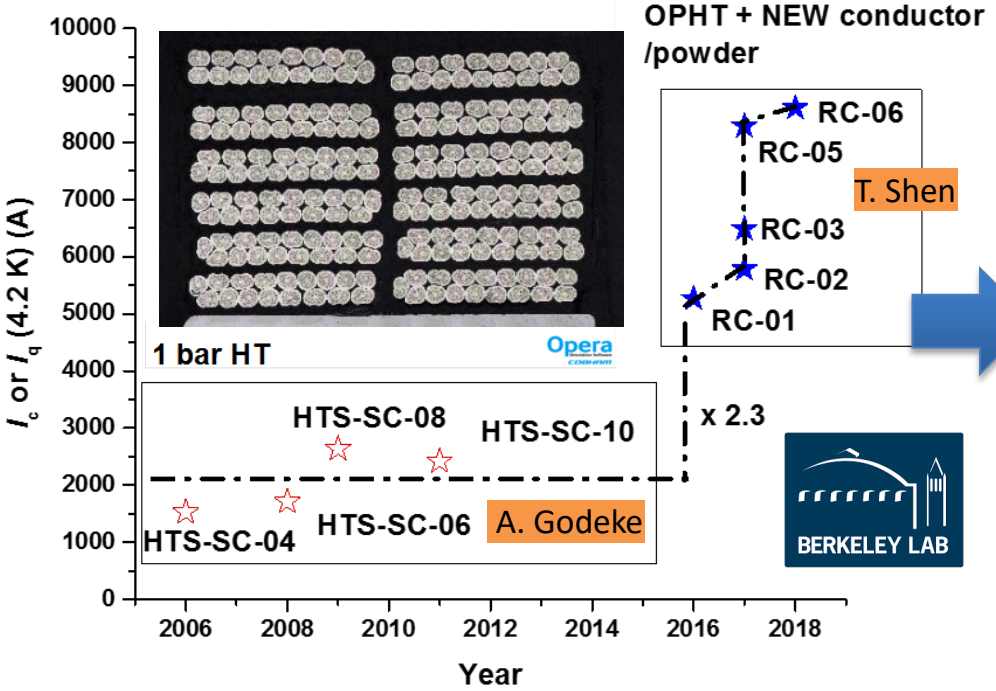
T. Shen-LBL

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

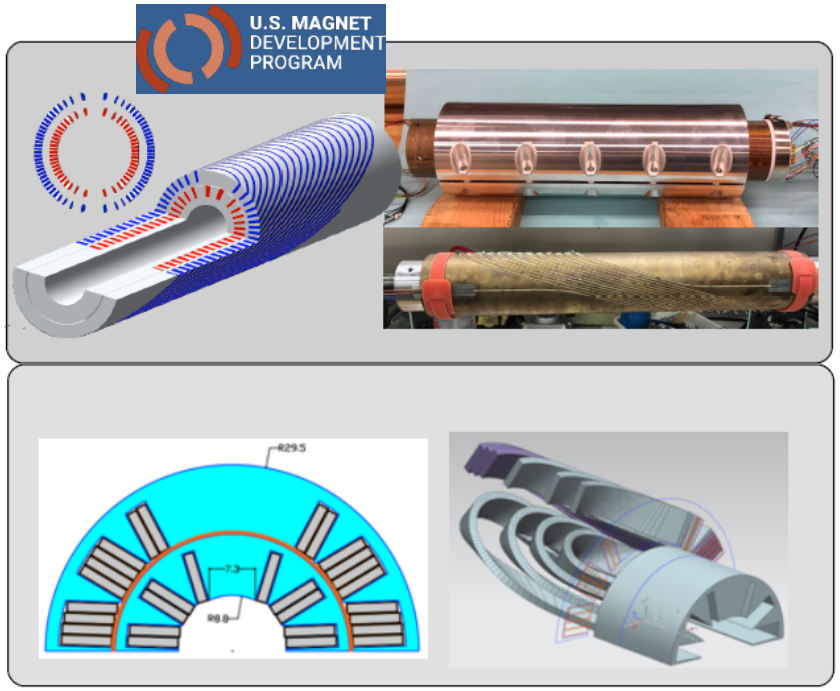


Bi-2212 Canted Cosine Theta Layer Cross Section

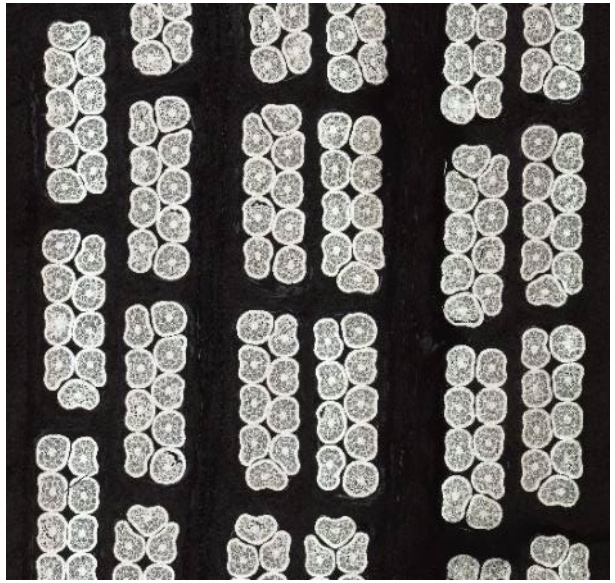
HTS Racetrack Coils



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

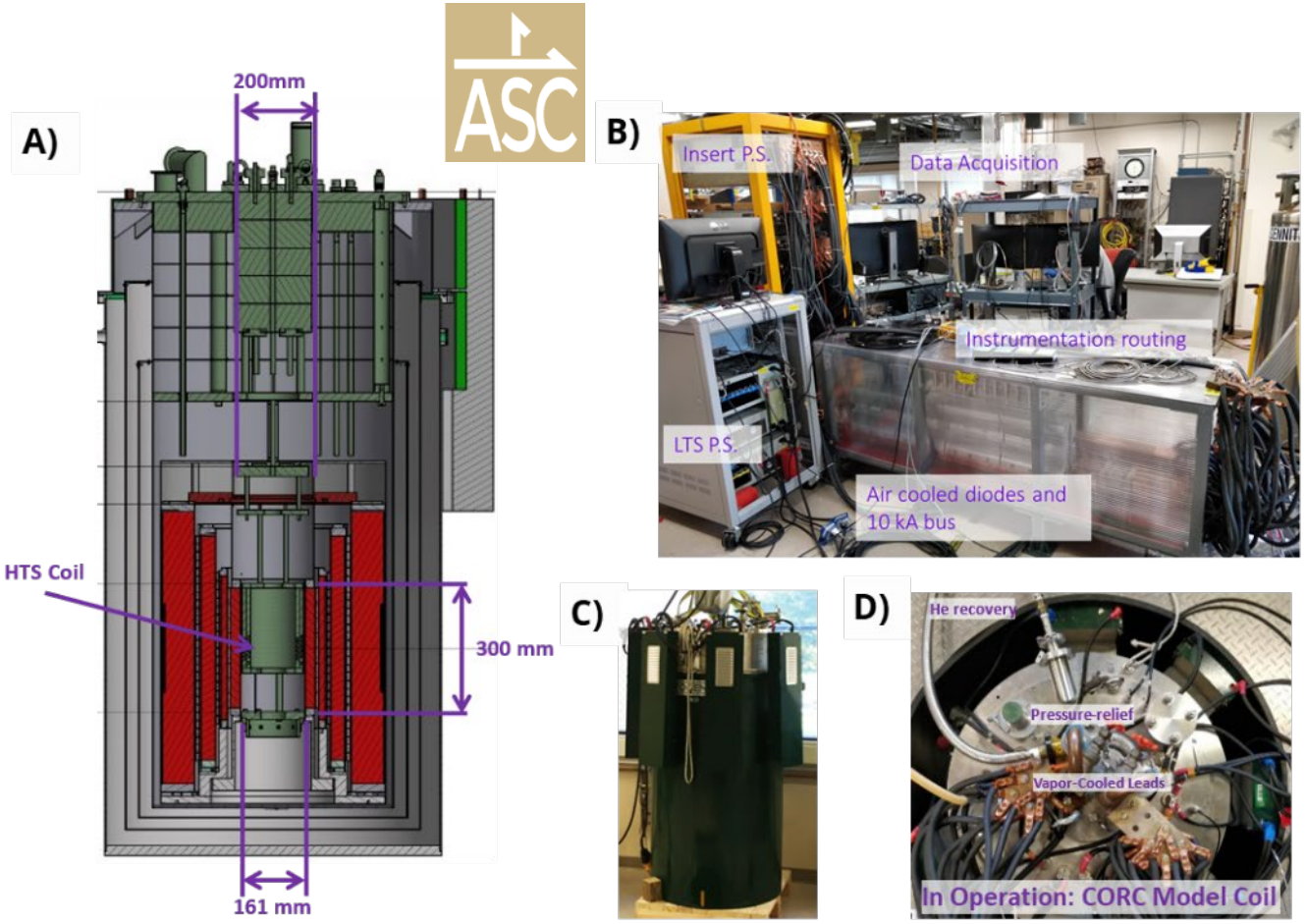
Unique HTS Test-bed : 161 mm, 14 T LTS, 10 kA

14 T HTS Coil Test Bed

- 10 kA bus, 6 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



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.

Upgrades underway: 2 more 1.2 kA supplies, 10 kA VCL, FPGA control, and faster IGBT replacement to mechanical contactors for quench management

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Development of High-strength and High Strain Tolerant CORC® Conductors for High-Field Magnets

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CCA21, October 14th, 2021

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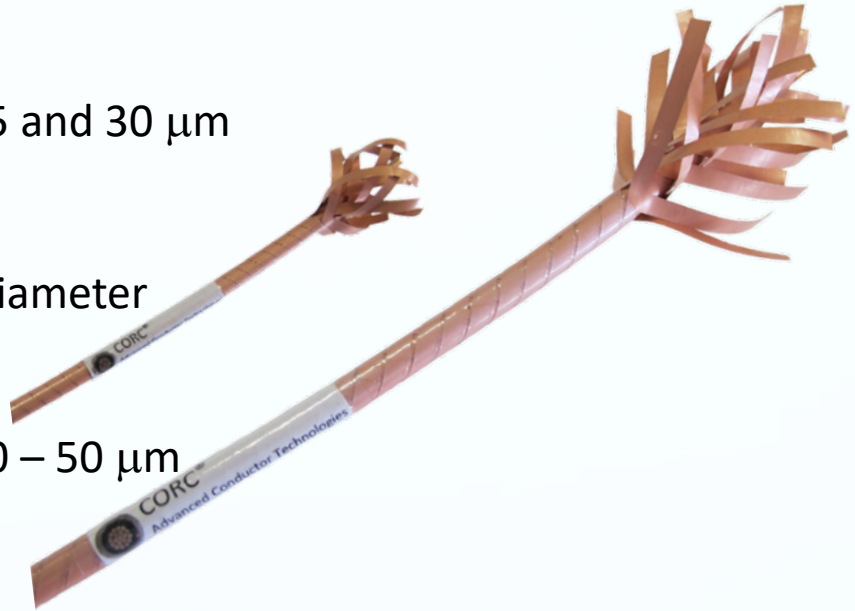
CORC® magnet cables and wires

CORC® wires (2.5 – 4.5 mm diameter)

- Wound from 2 – 3 mm wide tapes with 25 and 30 μm substrate
- Typically no more than about 30 tapes
- Flexible with bending down to < 50 mm diameter

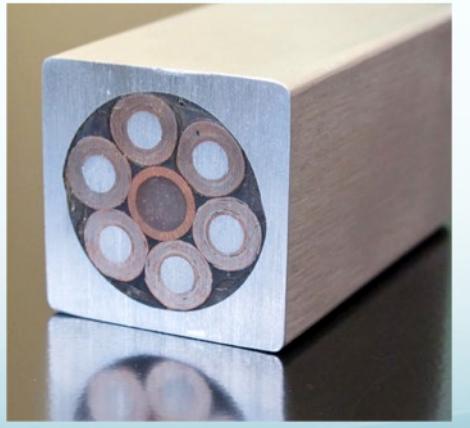


CORC® cable (5 – 8 mm diameter)

- Wound from 3 – 4 mm wide tapes with 30 – 50 μm substrate
- Typically no more than about 50 tapes
- Flexible with bending down to > 100 mm diameter

CORC®-Cable In Conduit Conductor (CICC)

- Performance as high as 100,000 A (4.2 K, 20 T)
- Combination of multiple CORC® cables or wires
- Bending diameter about 1 meter



High-field insert solenoid wound from CORC® cables

Addresses main challenges of low-inductance HTS magnets

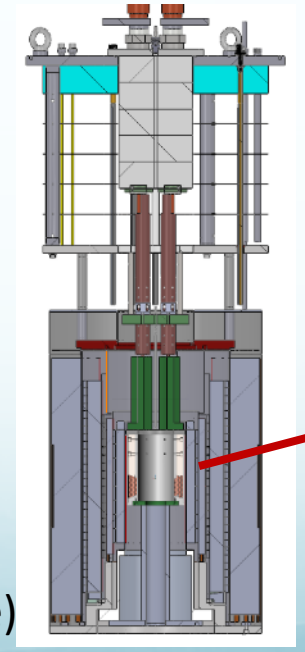
- Operate CORC® insert solenoid in **14 T background field**
- CORC® insert should have meaningful bore: 100 mm diameter
- High operating current: **4,000 – 5,000 A**
- J_e **> 200 A/mm²**
- Operate at **JBr source stress >250 MPa**

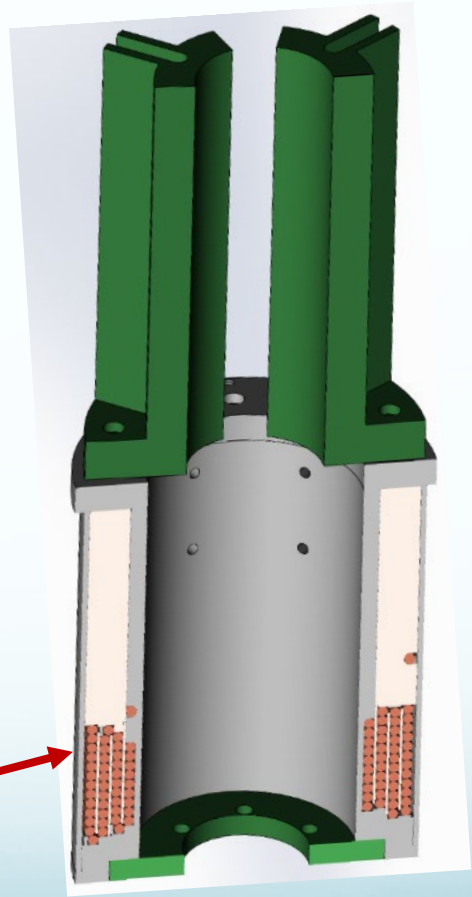
CORC® cable layout

- 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)

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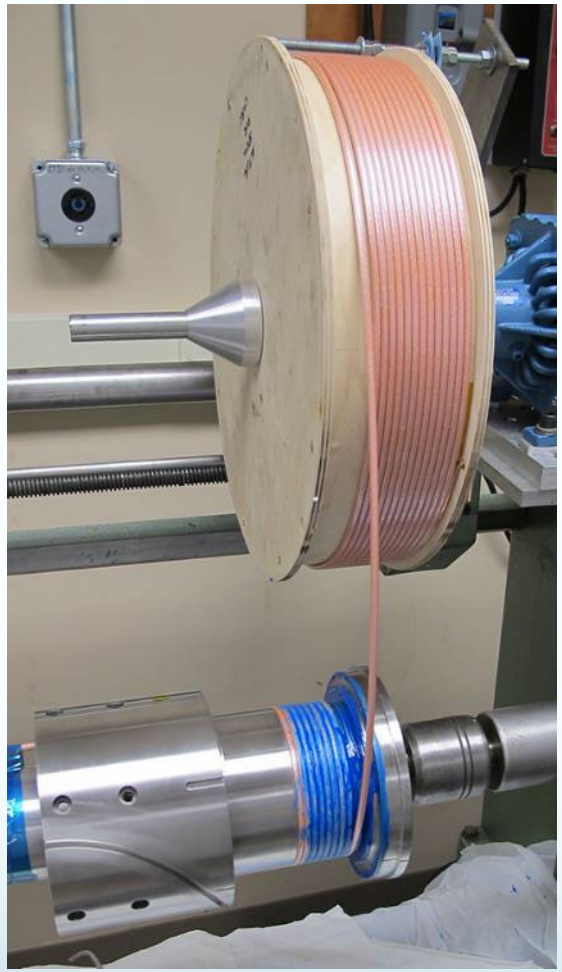
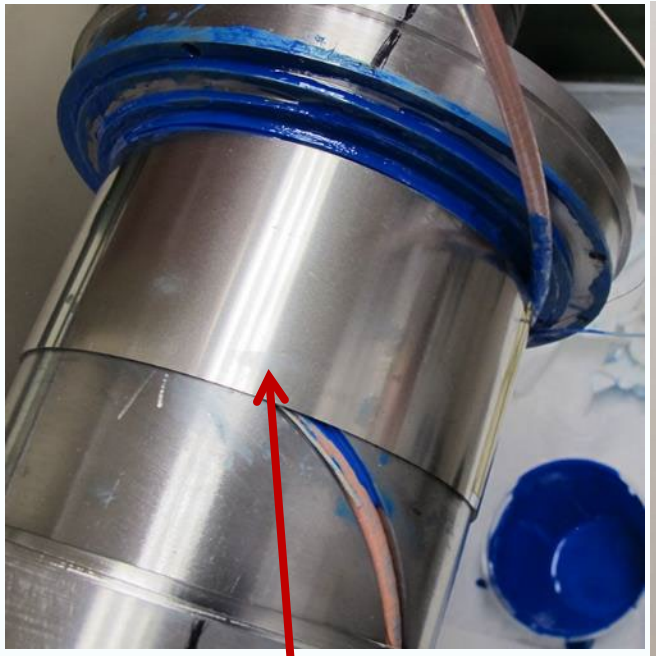
CORC® magnet winding





Interlayer stainless steel overbanding

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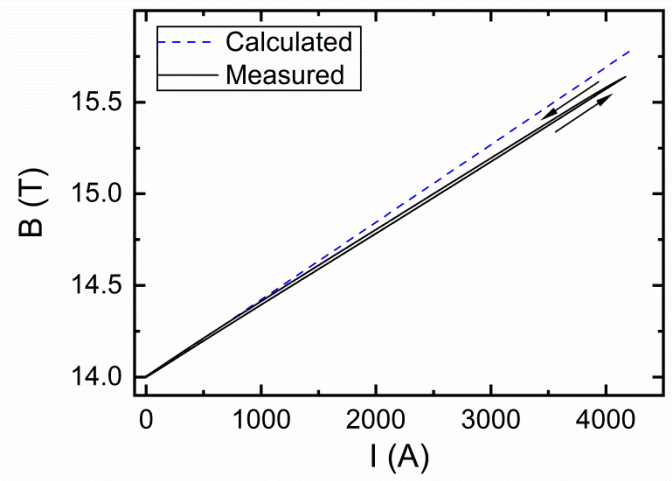
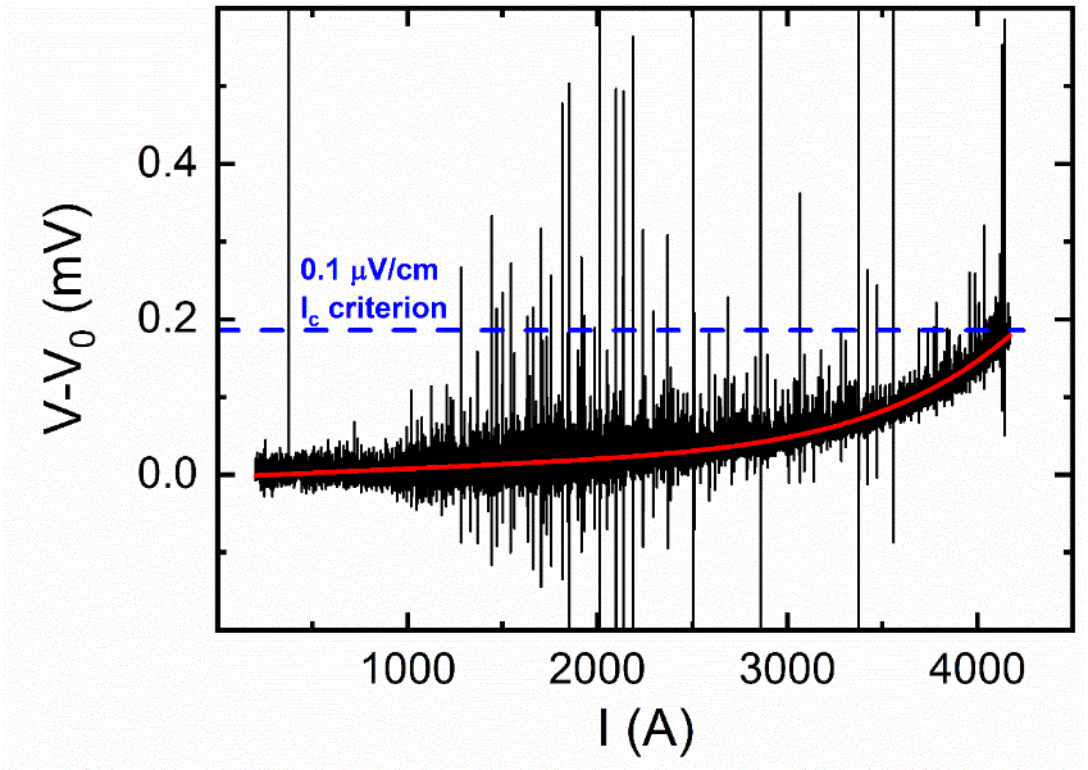
CORC® magnet test: 14 T background field

Results 14 T background field

- Maximum current 4,200 A to avoid quench trigger
- I_c = 4,404 @ 0.1 μV/cm
- Contact resistance 11.1 nΩ
- 15.86 T central field
- 16.77 T on conductor
- JBr source stress 275 MPa





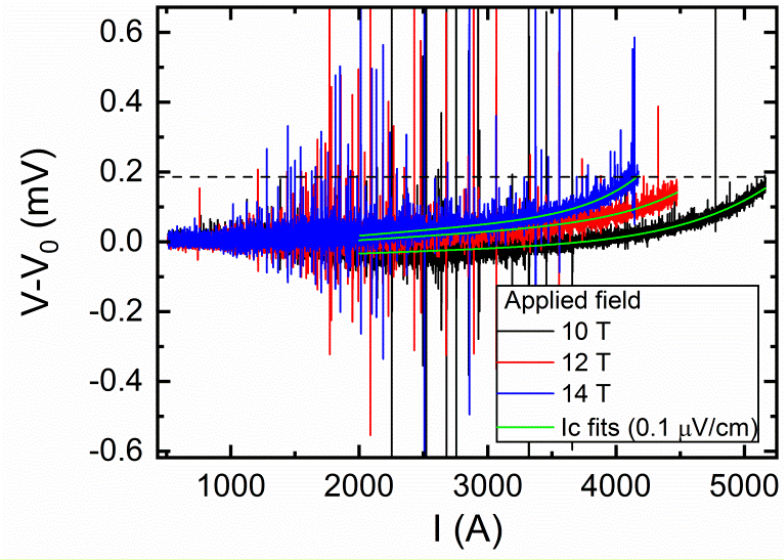
CORC® insert solenoid test: summary

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



Conductor challenges when going to higher field and larger coil diameters

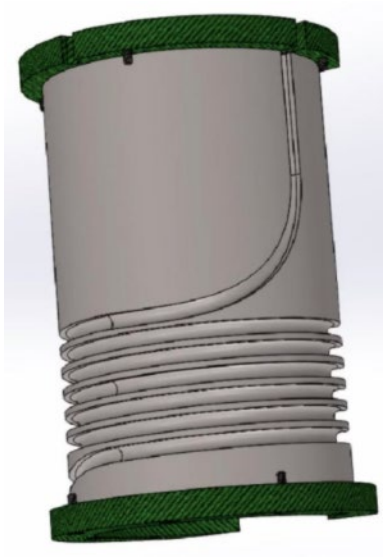
- A Central Solenoid in a future compact fusion reactor may have a JBr of 200 A/mm² x 20 T x 0.2 m = 800 MPa (source stress)
- How to further optimize the CORC® conductor to allow higher hoop stress, but also a higher irreversible strain limit?

Summary

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

High field low-cycle fatigue testing of HTS CORC® insert solenoid with fusion relevant parameters



ASC: **Daniel S. Davis,** U.P. Trociewitz, Y. Kim, M. Small, G. Miller, J. Kvitkovic, A.H. Chapa, L. Cooley, D.C. Larbalestier

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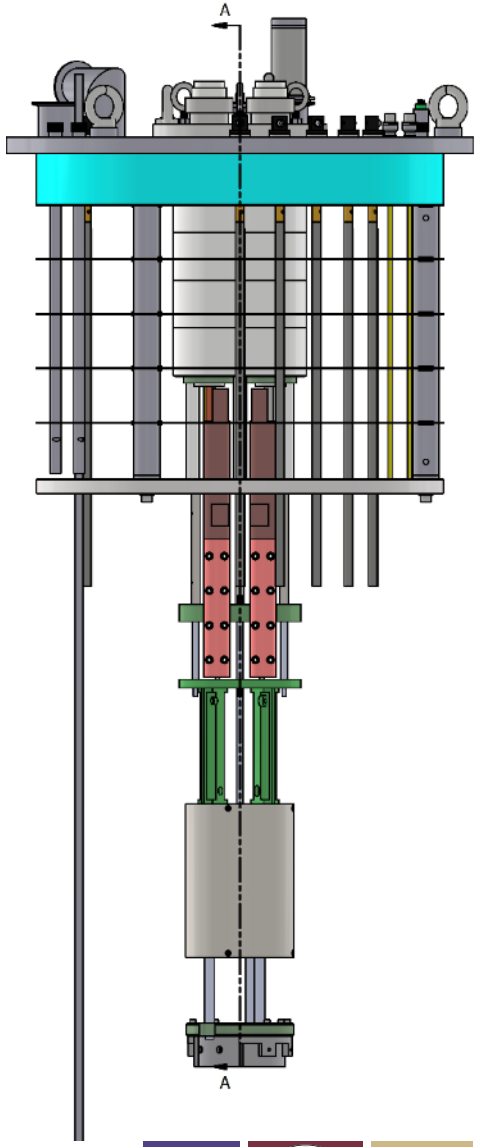
PPPL: Y. Zhai

LTSW 2022



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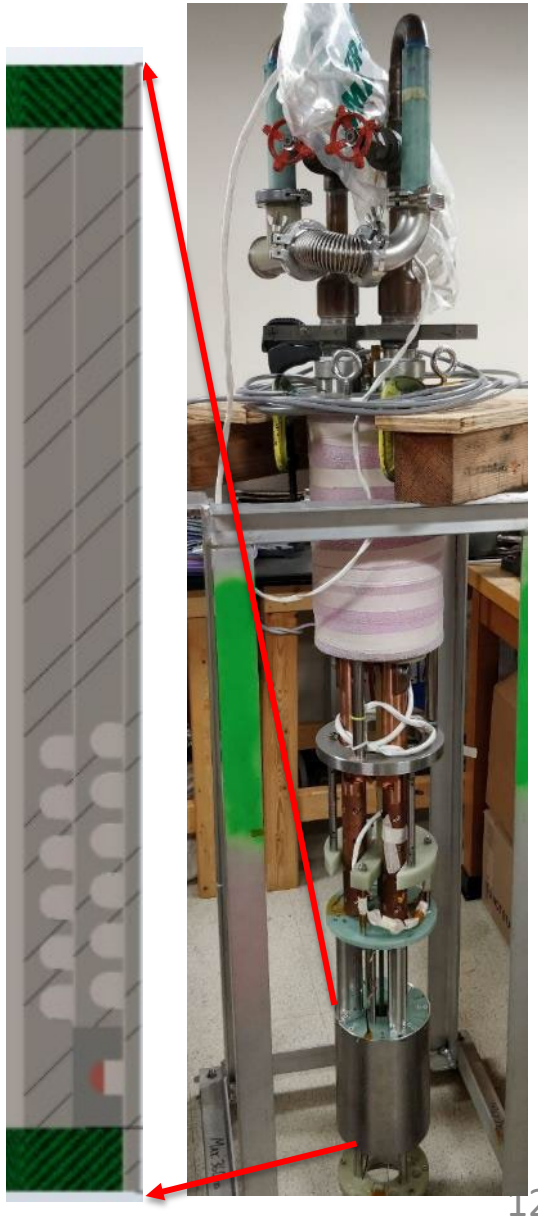
Overview: Coil and Test Parameters

PPPL_CORC		
Cable	Product No.	ACT- CORC, 20191113-3
	Powder	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]		~ 0.0186
Conductor length [m]		5.1
Status		Tested

Day	Test	Nominal Field [T]	B_{ext} Field [T]	HTS Field [mT]	Max I_{op} [A]
1	T2	0	-0.01	725.04	7172
	T7	3	3.00	751.26	6965
	T17	5	5.03	575.63	5507
	T26	8	8.07	300.36	2903
	T36	10	10.14	303.24	2987
	T49	12	12.16	311.00	2761
2	T56	0	-0.01	571.05	6968
	T60	5	5.04	626.83	5984
	T71	10	10.14	339.03	3391
	T88	12	12.16	510.87	4704



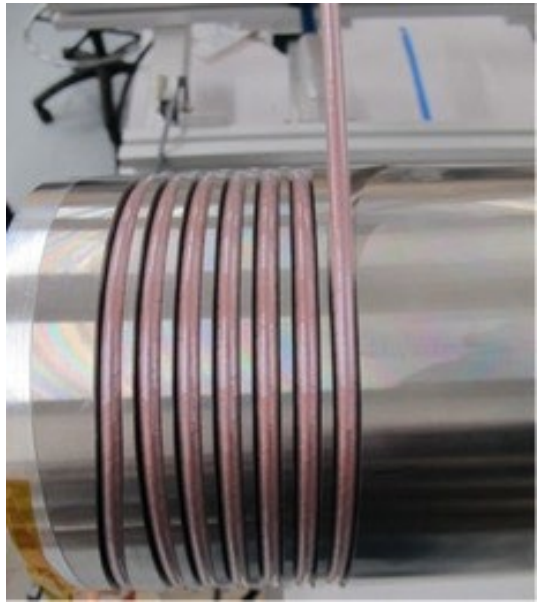
- Primary purpose: Stress cycling and demonstrate fusion relevant magnet technology
- Insulated cable wound in channel inside steel shell.
- No epoxy or other filler

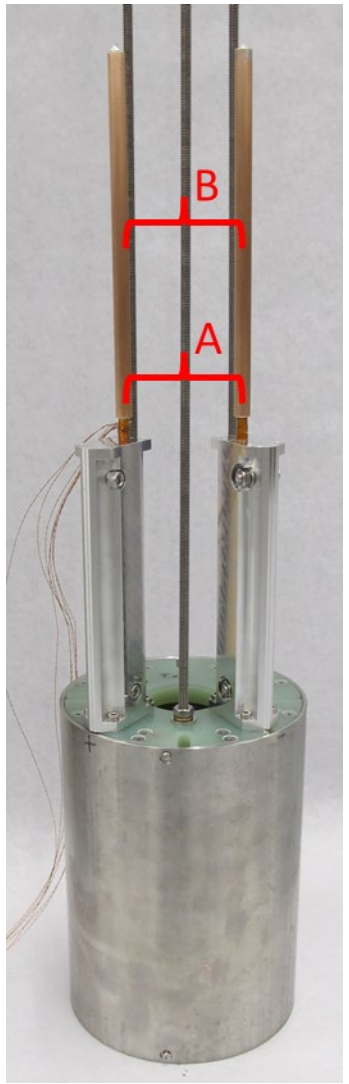
- T66: 69 cycles [2200, 5000] A, [30, 66] MPa
- T70: 50 cycles [2000, 3200] A, [55, 88] MPa
- T73: 127 cycles [1600, 2800] A, [54, 93] MPa
- T87: 67 cycles [3400,4600] A, [113, **152**] MPa

Cable Instrumentation Considerations

V-tap number	Voltage tap location	Description
1	A to A	Cowound Cu Wire
2	A to A	Cowound Cu Tape
3	A to A	Cowound Cu Wire
4	B to B	Cowound Cu Wire
5	B to B	Cowound Cu Wire
6	A to A	Not cowound - broke
7	A to A	Not cowound
Cu-Cu	C-C	Cu terminal extensions
Hall	LHP-NA #2423	50 mA, 41.3 mV/T, offset 23 uV
	X161472	Cernox top plate
CX-1050-SD-4	X20428	Cernox positive Cu bus
	X157000	Cernox bottom plate

8x2 tapes

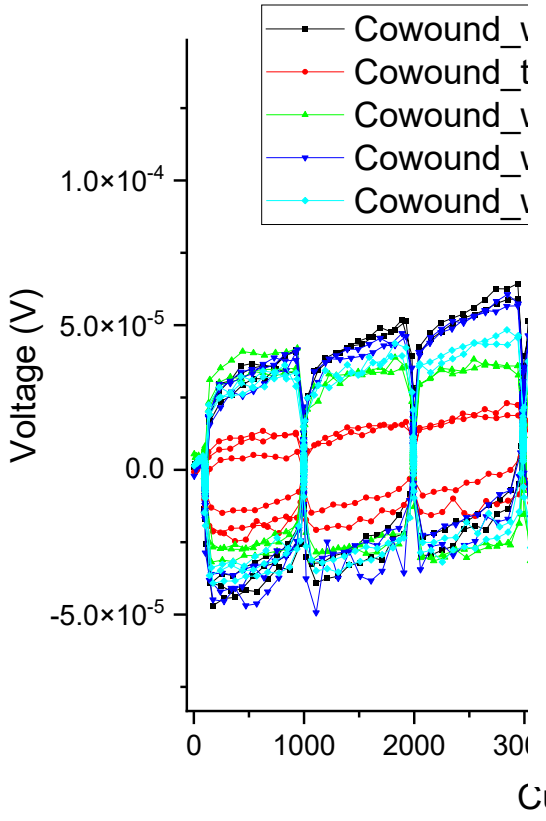


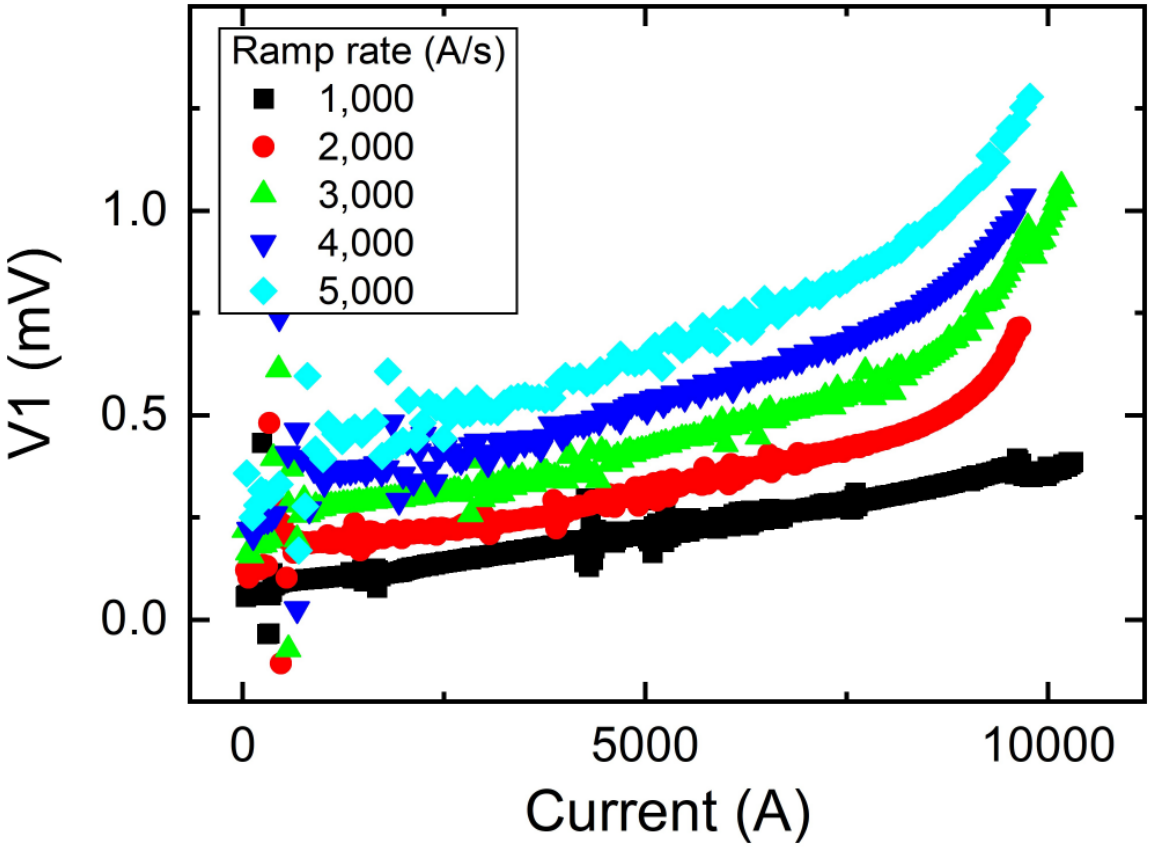


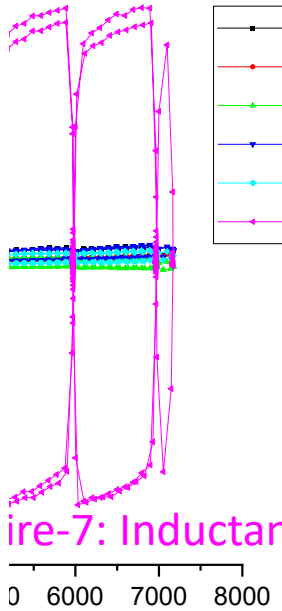
- Novel insulated co-wound copper tape
  - Matches very closely to cable inductance
- Co-wound wires to ensure redundant quench protection
  - For example, wire pair number 6 got pinched in the structure
- Simple wire pairs show inductive voltages and movement

Initial 4 K self field testing shows a stable but evolving behavior

Voltages nominally at the same location behave differently due to inductive sensitivity.

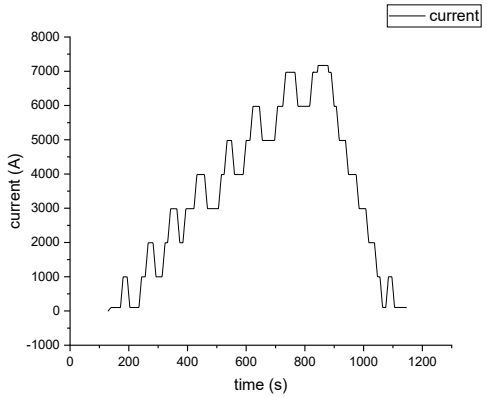


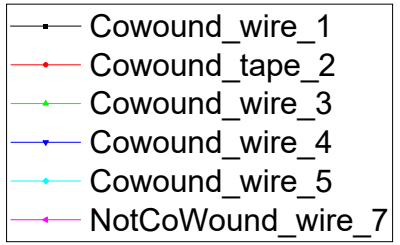




ire-7: Inductance dominates response

Current - Time

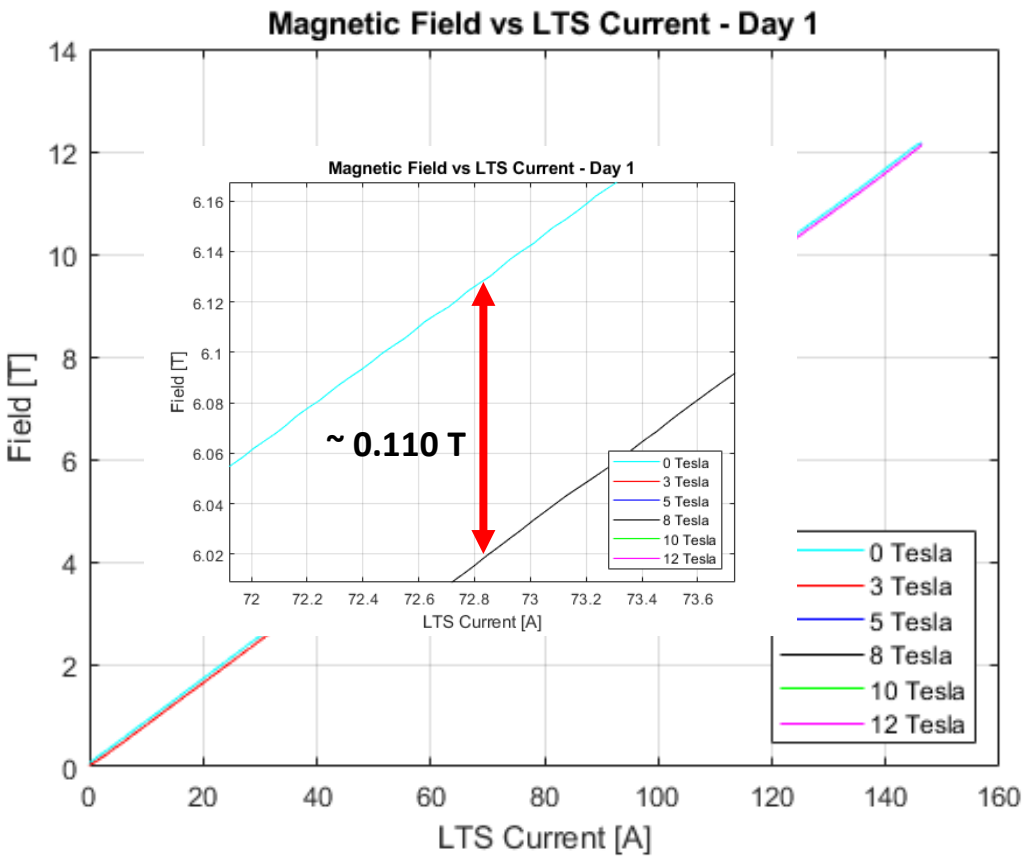


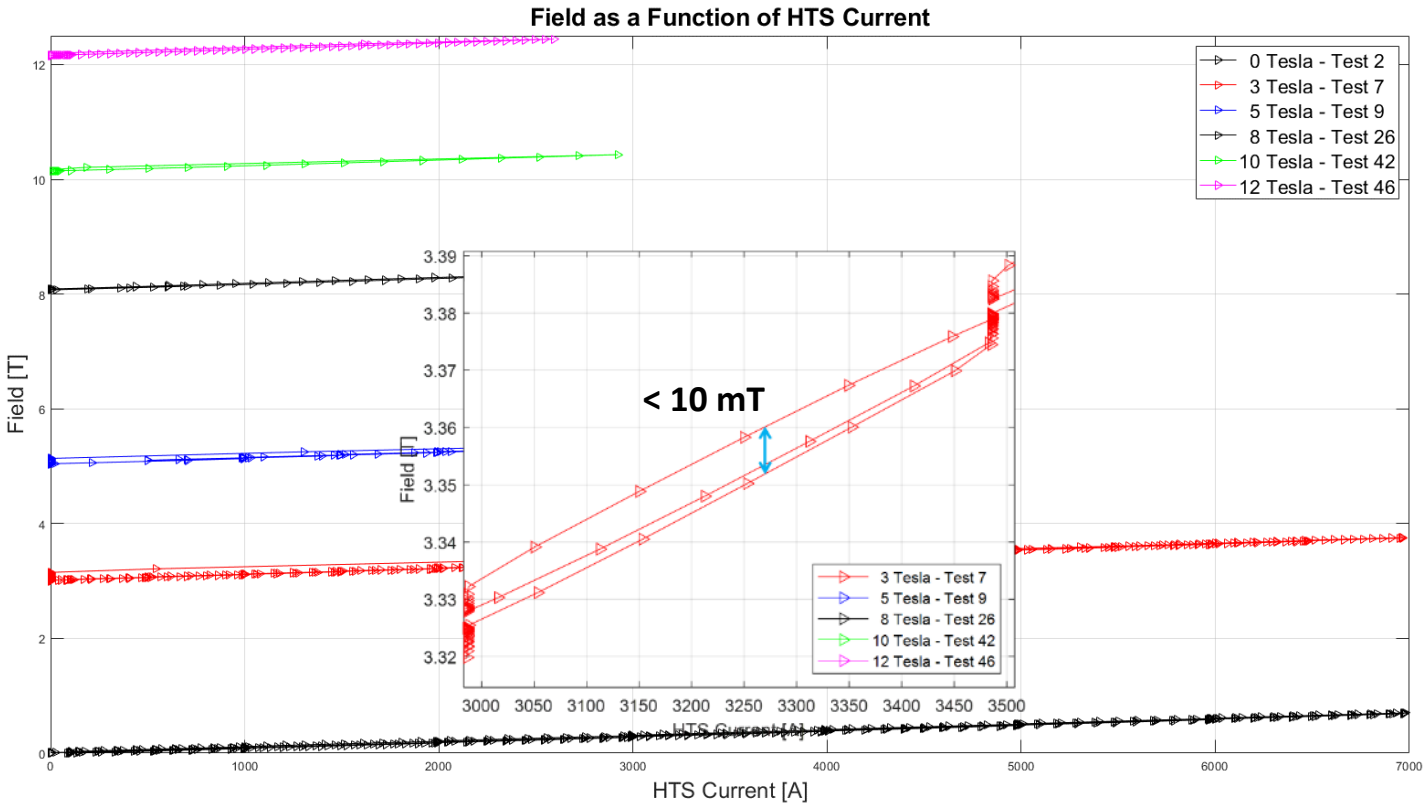


Wire-3: Possibly current redistribution, voltage wire motion, or cable motion

Tape-2: Best indicator of cable transition

Reasonable Screening Current Induced Field



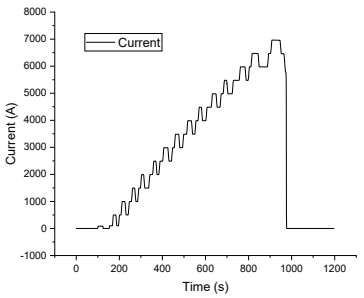


Excess field max is 163 mT
And decays over time of measurements at high field

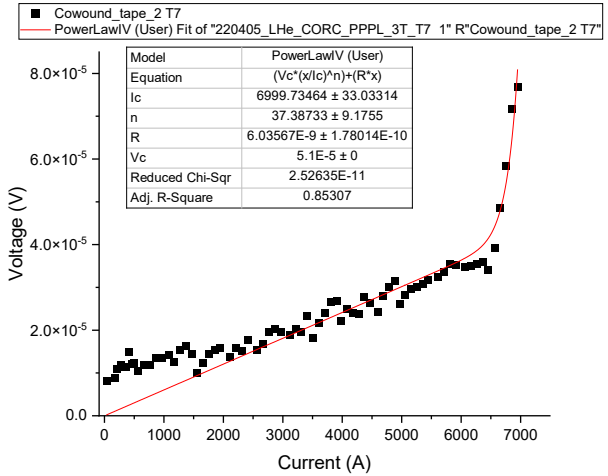
Expected 0.102 mT/A
Measured range 0.082 to 0.112 mT/A
Median: 0.10164 average: 0.10194

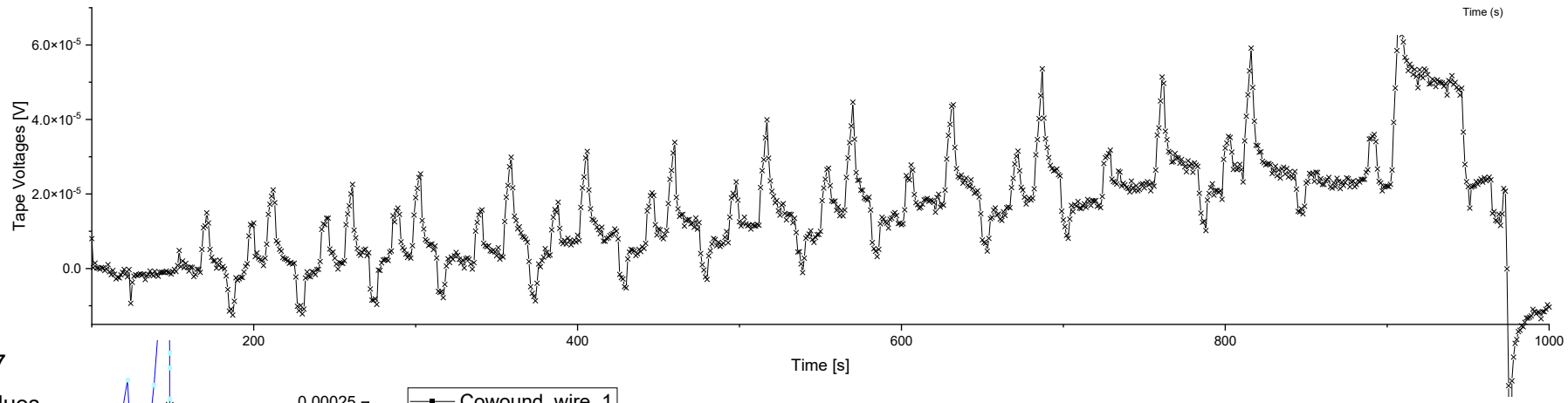
First in-field test 3T: Saw-tooth step-wise current ramp;

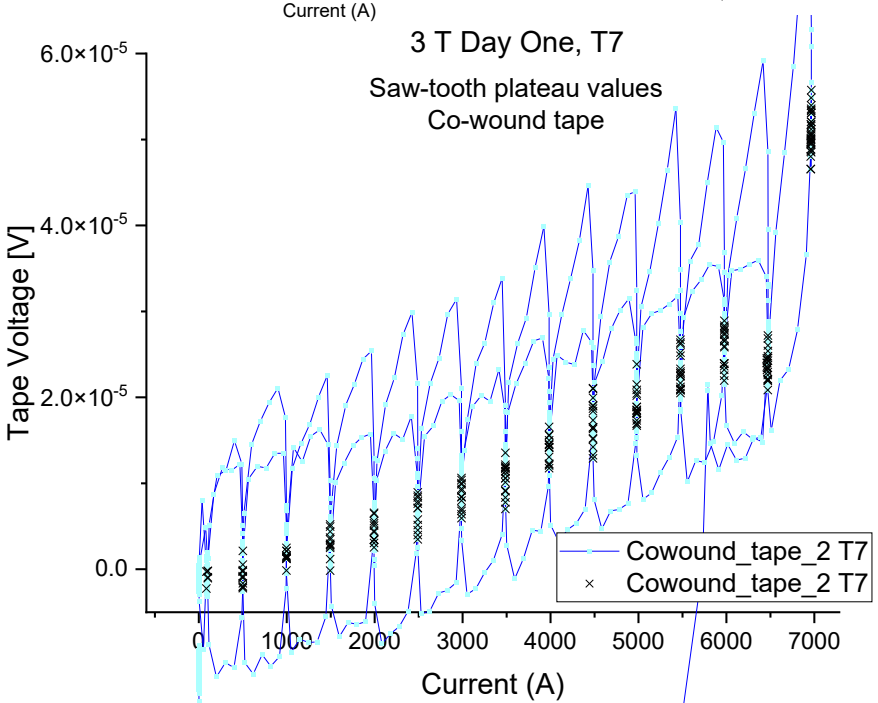
Current - Time

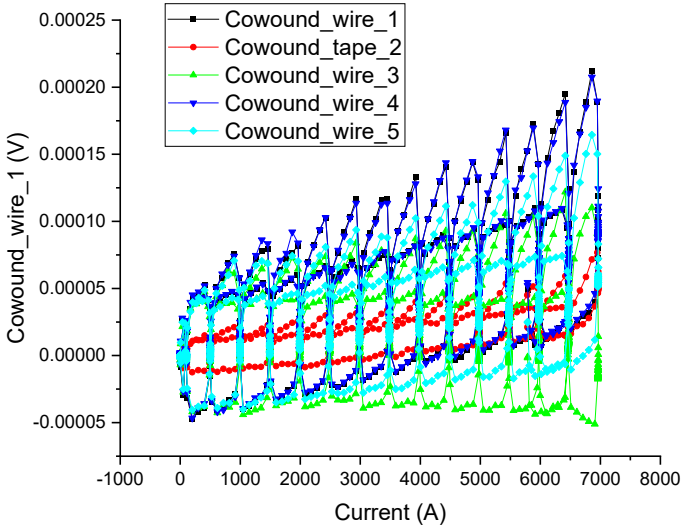


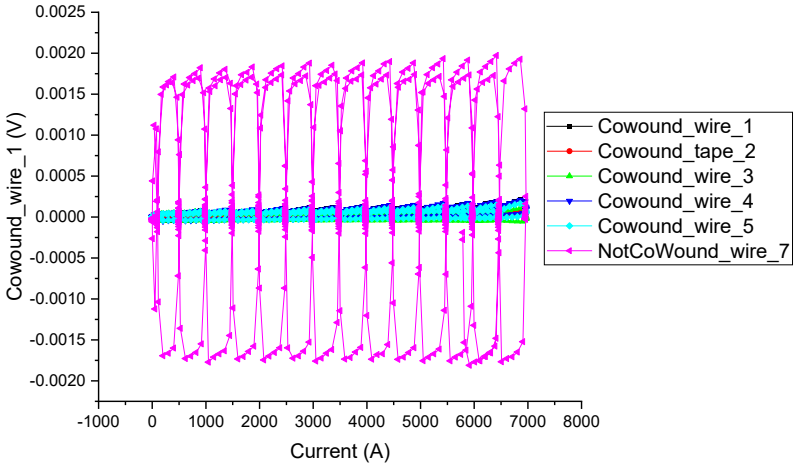
Higher voltages on initial hysteresis current loops



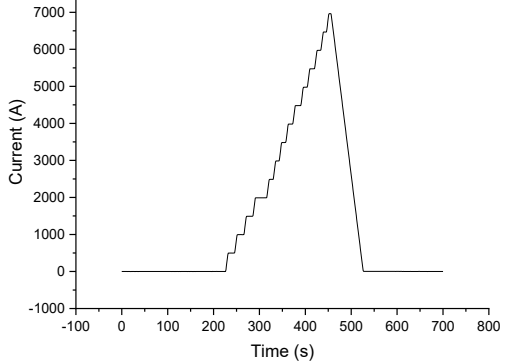


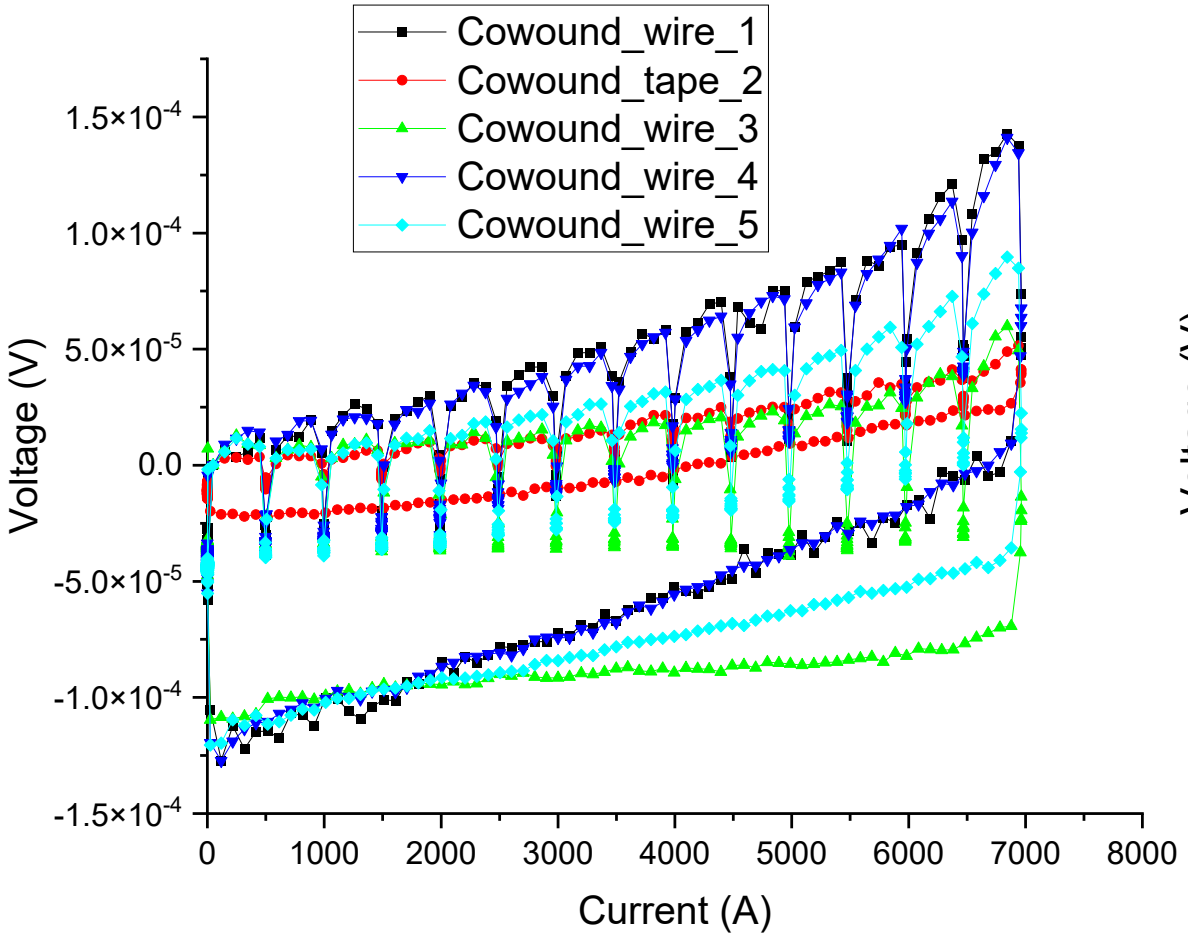


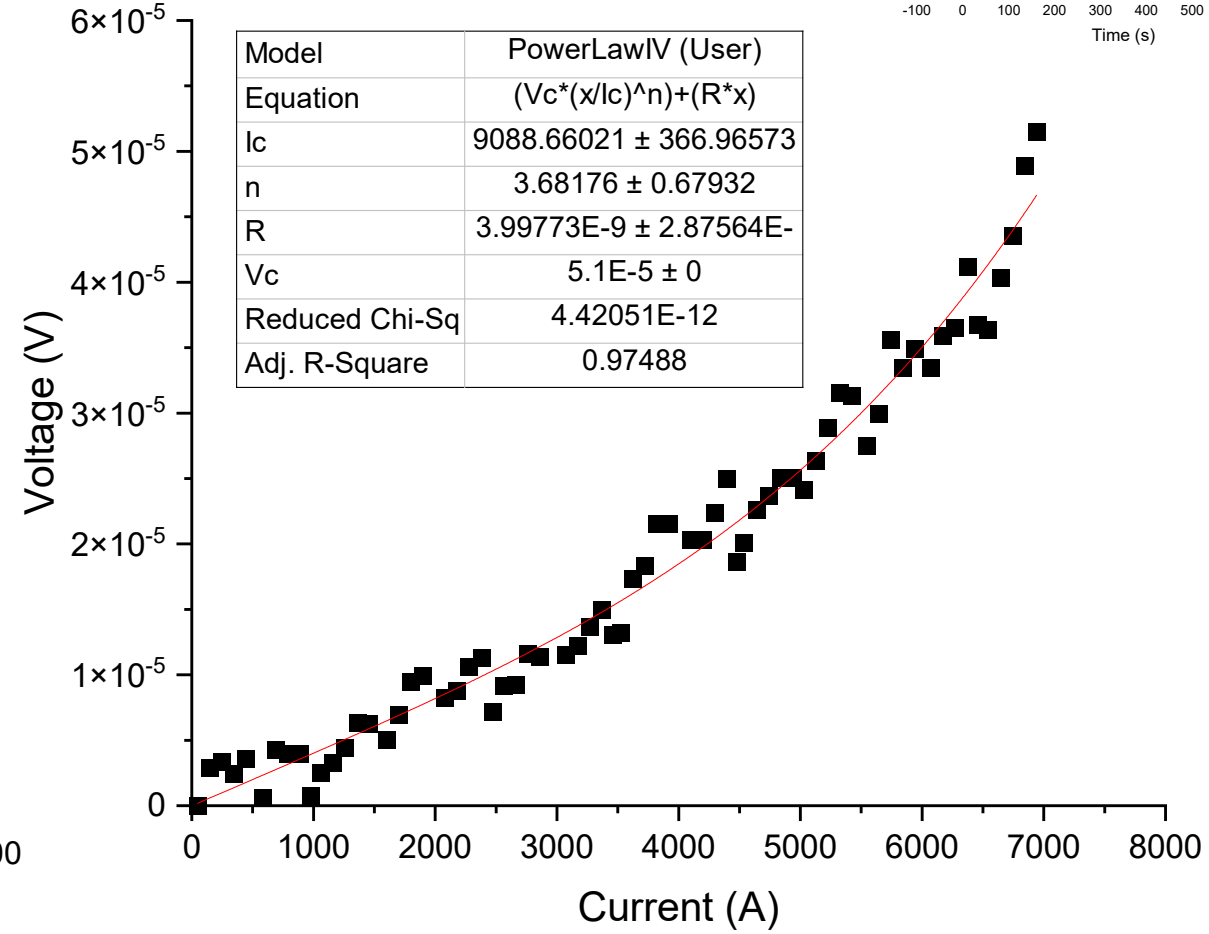




Voltages simpler in second in-field test





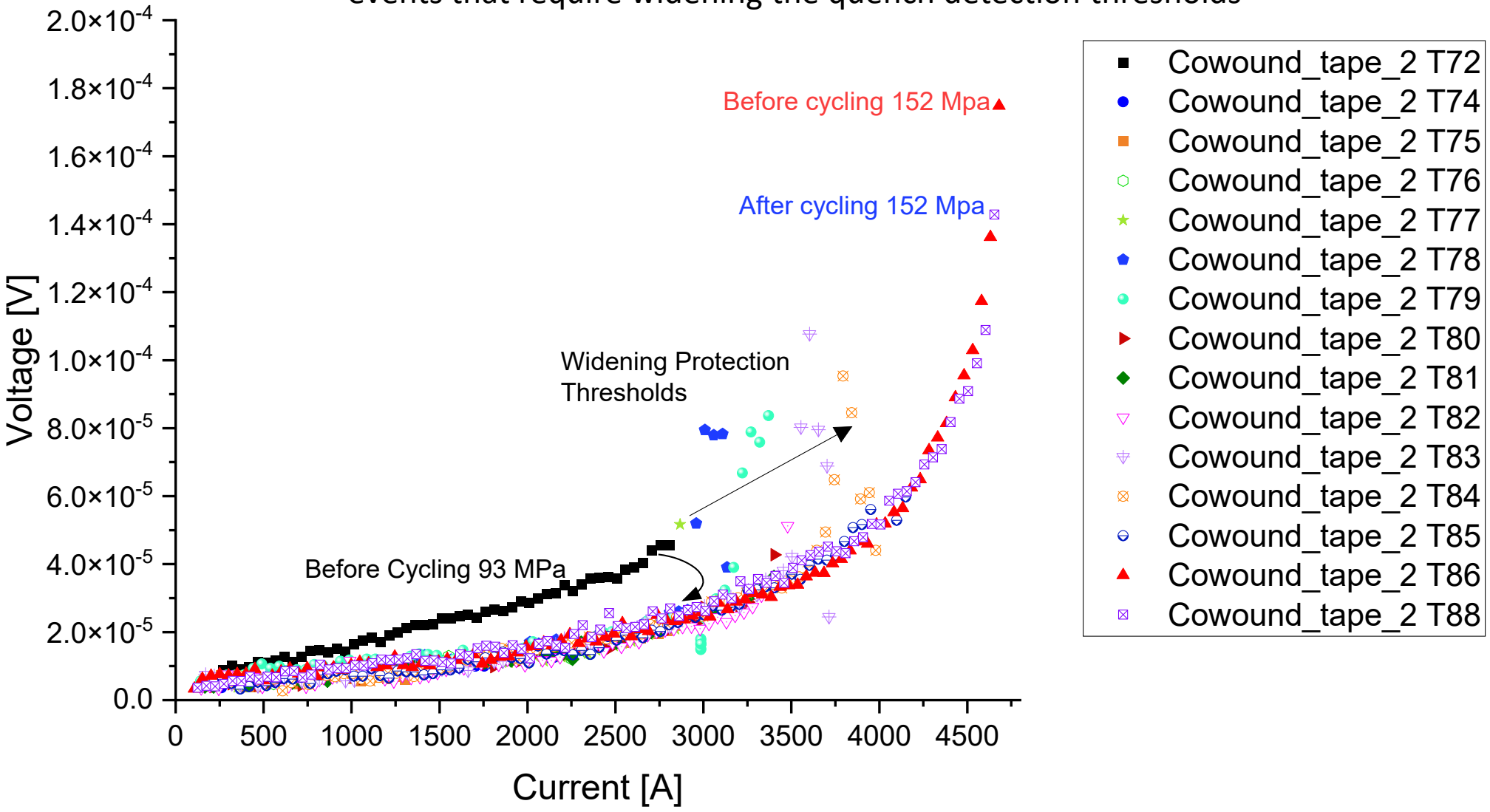


Model	PowerLawIV (User)
Equation	(Vc*(x/Ic)^n)+(R*x)
Ic	9088.66021 ± 366.96573
n	3.68176 ± 0.67932
R	3.99773E-9 ± 2.87564E-
Vc	5.1E-5 ± 0
Reduced Chi-Sq	4.42051E-12
Adj. R-Square	0.97488

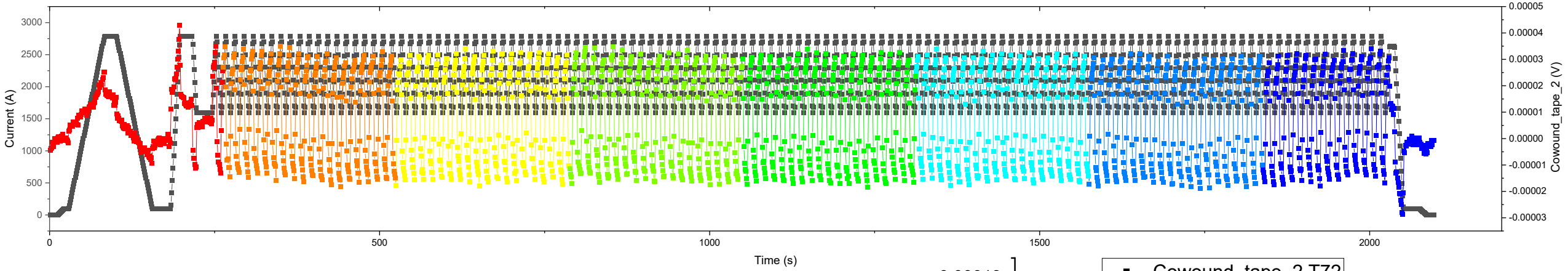
We consistently observed that the first time a current is reached after significant field changes the voltages showed higher nonlinear behavior. The largest factors are likely magnetization effects influencing initial current distributions. Cable and tape motion also play a role, e.g. stick slip. This has implications for operation, such as quench detection decisions.

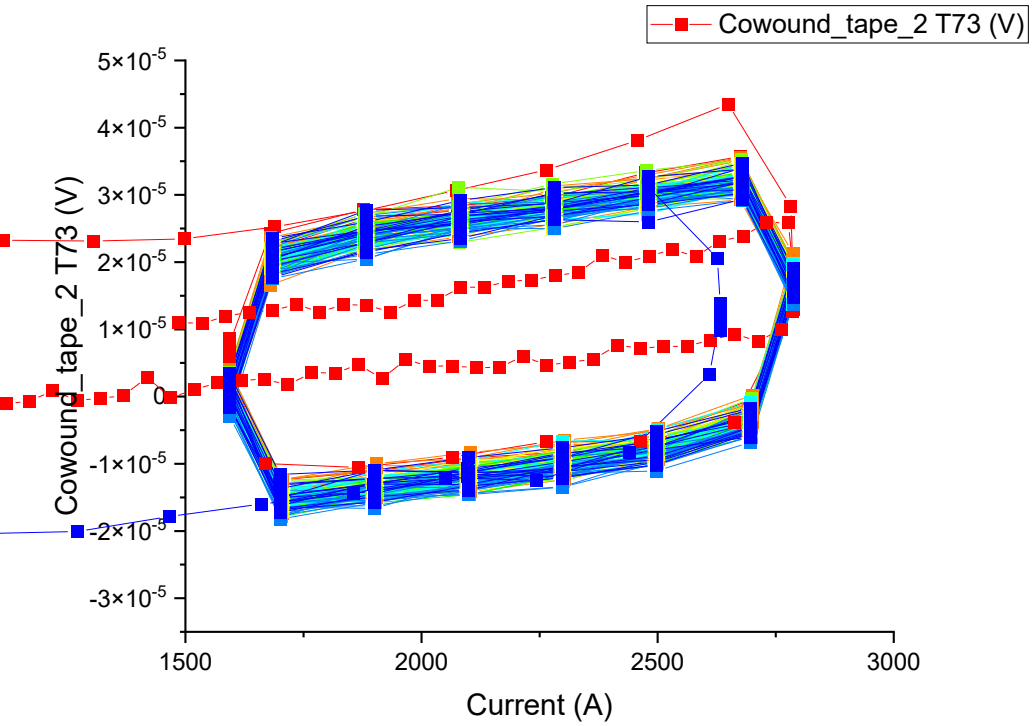
12 T: Complex evolution to stable VI curve

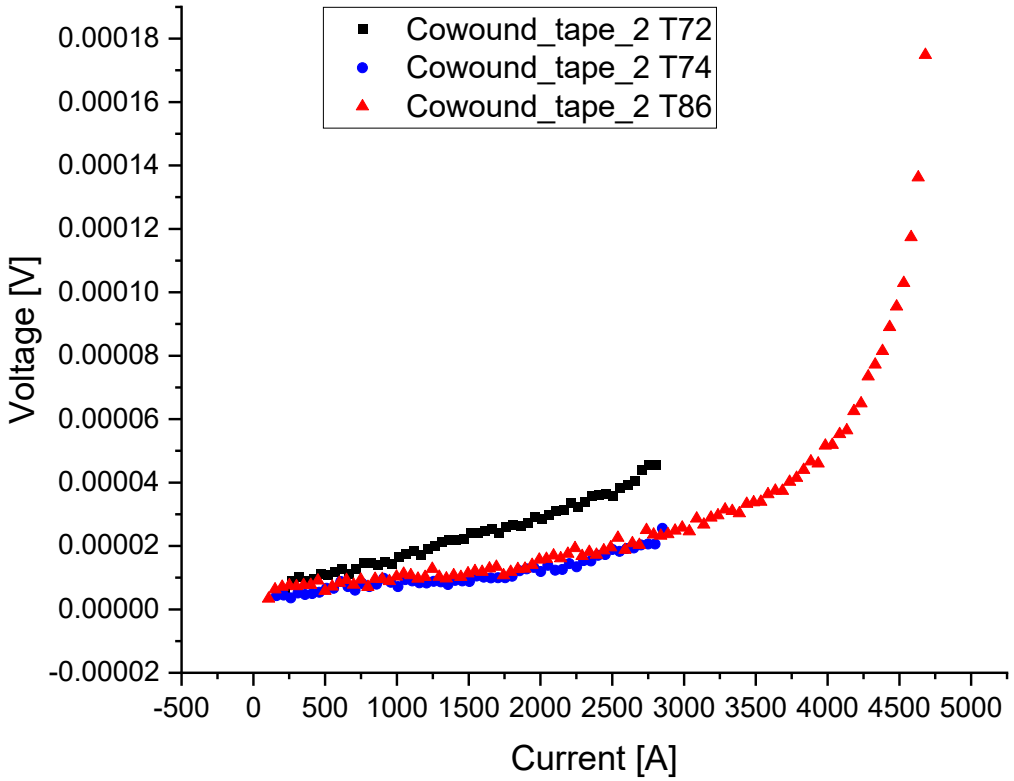
Getting braver post-cycling, we reach further into the transition past extended events that require widening the quench detection thresholds



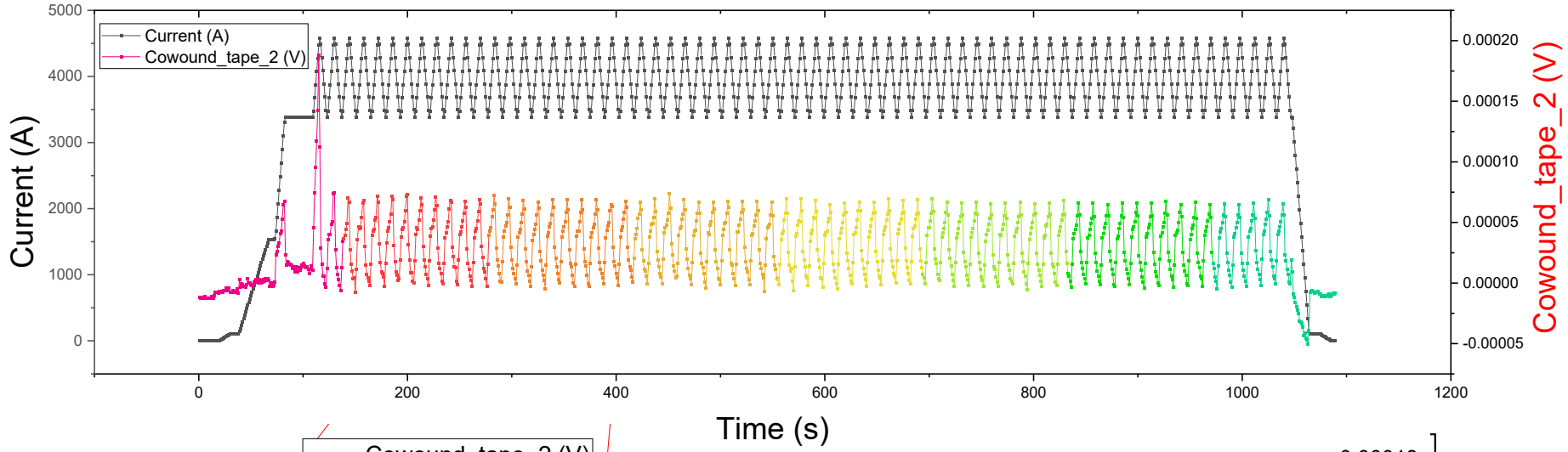
T73: 12 T BG, 127 cycles, [1600,2800] A, B_{Peak} [12.25, 12.44] T, J_EBr [54, 93] MPa



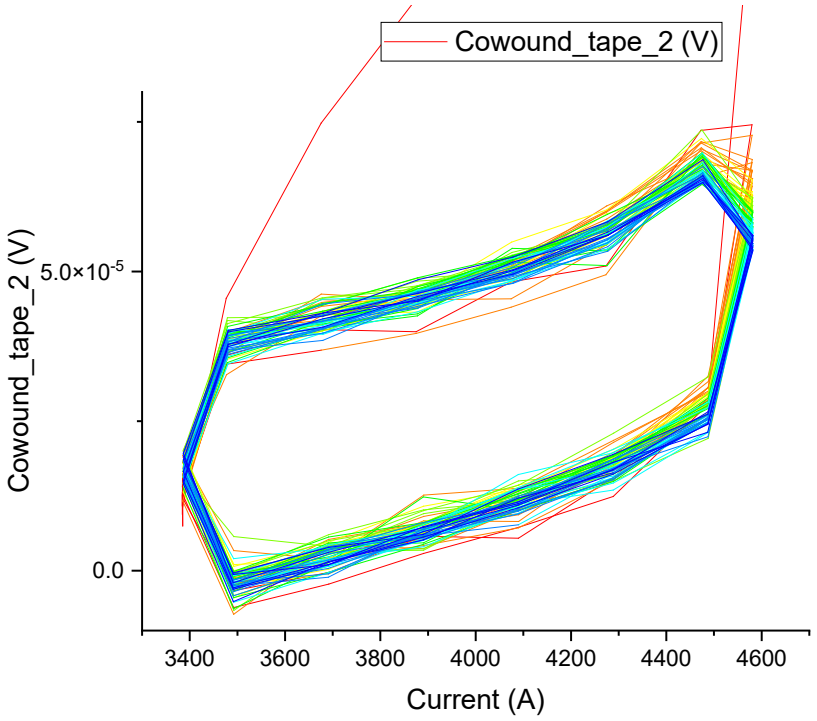


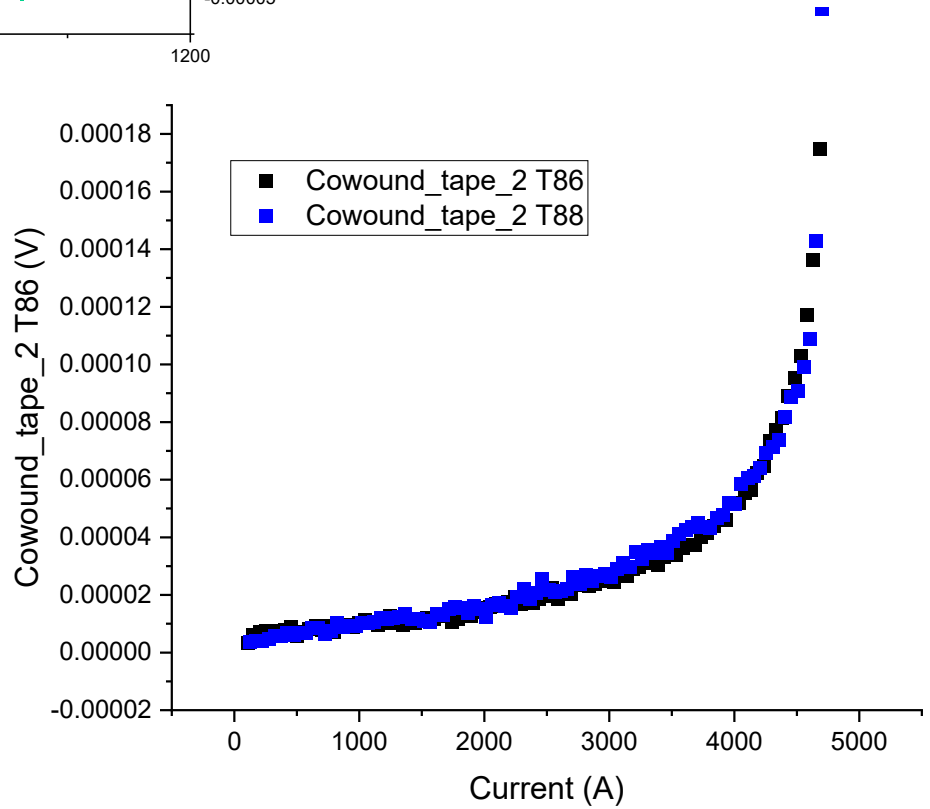


High-Field Fatigue:(T87) 12 T BG, 68 cycles, [3400,4600] A

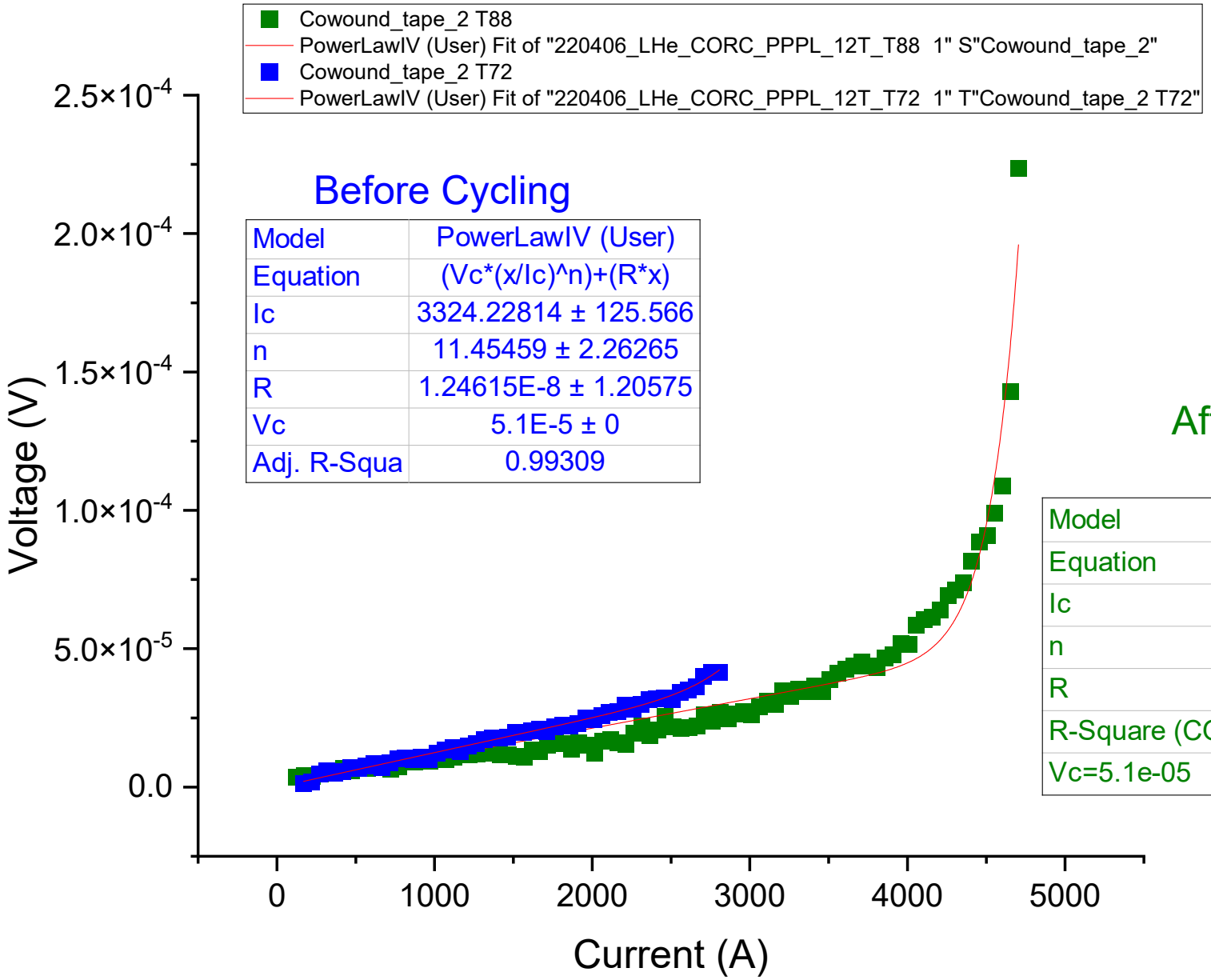


B_{Peak} [12.54,12.73] T,
J_EBr [113, 152] MPa





12 T: Reduced baseline after cycling



Before Cycling

Model	PowerLawIV (User)
Equation	(Vc*(x/Ic)^n)+(R*x)
Ic	3324.22814 ± 125.566
n	11.45459 ± 2.26265
R	1.24615E-8 ± 1.20575
Vc	5.1E-5 ± 0
Adj. R-Squa	0.99309

After Cycling

Model	PowerLawIV (User)
Equation	(Vc*(x/Ic)^n)+(R*x)
Ic	4514.94301 ± 12.21569
n	25.6012 ± 1.77922
R	1.06434E-8 ± 3.18118E-
R-Square (COD)	0.95947
Vc=5.1e-05	

Discussion Points

- Higher quench currents and apparent I_C after cycling
  - **No signs of degradation from low-cycle fatigue**
- Complex mix of phenomena in voltages
  - Current sharing, cable motion, strand motion, screening currents, contact resistance, strand degradation, co-wound voltage-tap wire motion
  - Hard to distinguish true thermal runaway (false positives, transient voltage spikes, change in current sharing dissipation, or local quenches)
    - Must be conservative on quench detection
  - The cable appears very stable, despite the dynamic behavior of the coil
  - We could benefit from alternative diagnostics to deconvolute behaviors
- Screening currents are reasonable, seem to affect initial current distributions after background field is ramped, and decay as expected

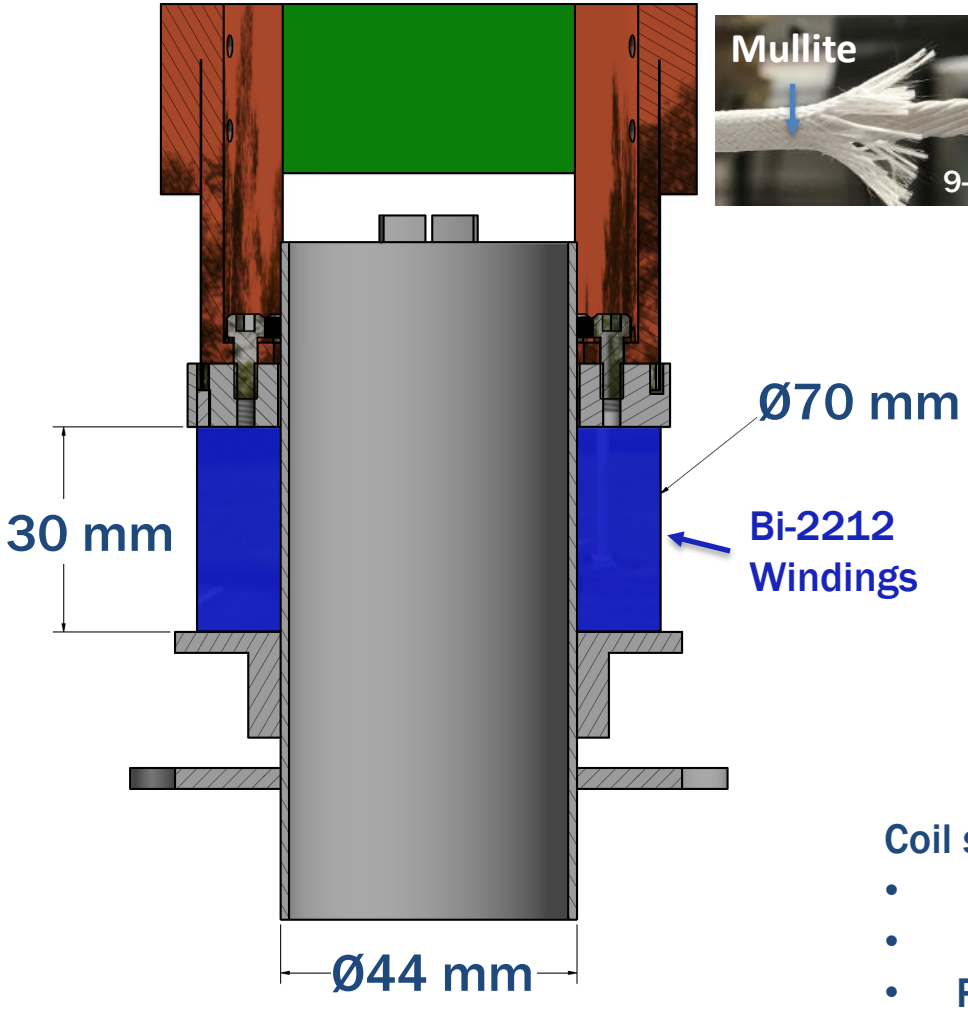
Postmortem Microscopy of Overpressure Processed Bi-2212 Rutherford Cable Magnets with Implications for Performance Improvement

Daniel S. Davis, Michael Small, Ulf P. Trociewitz, Tengming Shen, Youngjae Kim, Jianyi Jiang, David Larbalestier

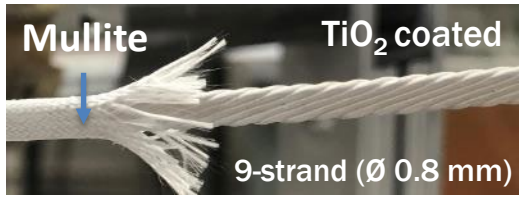
With lots of support from the larger NHMFL and LBNL Bi-2212 groups

Thanks to DOE-OHEP (award no. DE-SC0010421 PIs DCL, 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), the Florida State University special allocation (DCL PI) for Bi-2212 commercialization, the state of Florida, and the US Magnet Development Program Collaboration for much context and many collaborations

First Bi-2212 cable solenoid was wound and tested



Baby Ruth



"Baby-Ruth" test solenoid

- First in a series of Bi-2212 Rutherford cable coils of increasing size
- Similar to Bi-2212 strand (and based on positive experience with LBNL accelerator cable), cable is coated with TiO_2 and braided
- Terminal interface was a challenge due to small footprint
- Enables high field coils of low inductance

Coil Specs:

- 6.45 m conductor, 9-strand, 0.8 mm strand diameter from LBNL
- 45 mm ID, 6 layers x 6 turns
- 2.78 kA (0.75*Ic) at 16.64 T load-line,
- Self Field (1.97 T central field, 2.64 T peak on conductor)

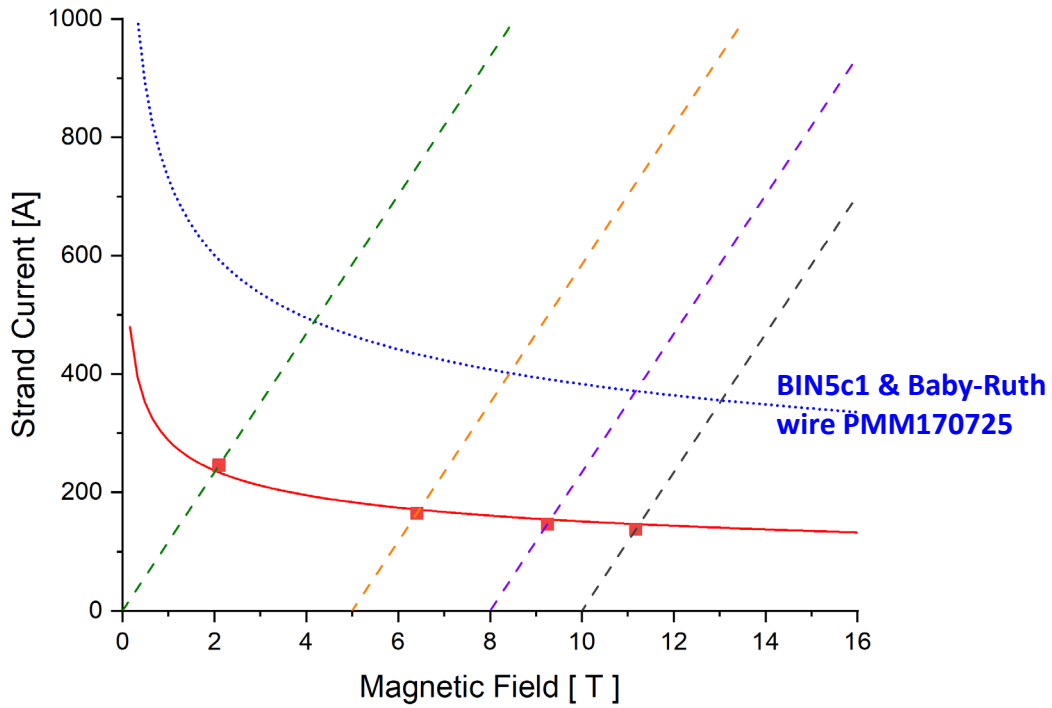
Coil scale-up options contingent upon successful tests – 9 strand cables

- **2-3 T added (17 T total), 8 meter (existing cable) = "Baby-Ruth"**
- **5-6 T added (20 T total), 40 meter needed +back-up**
- **Possible Full-Scale: 100's of meters for full volume (11-18 T added 25-30 T total). Major funding and large furnace required.**

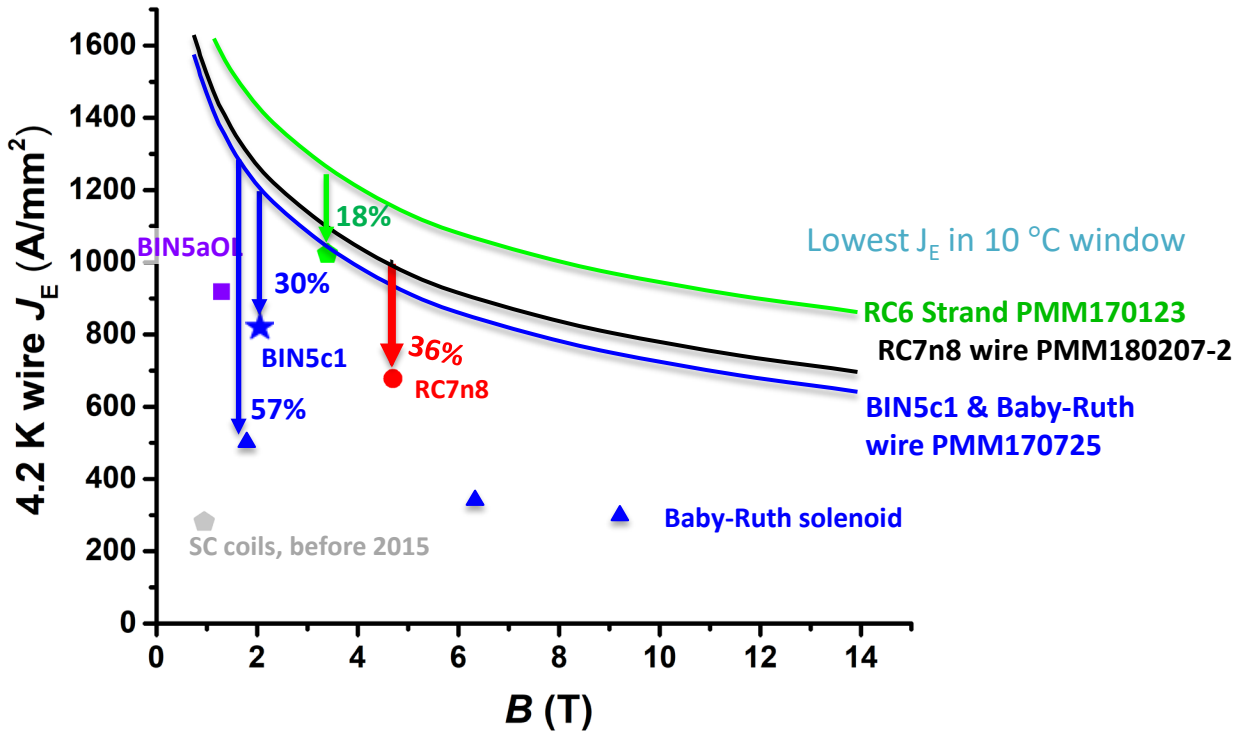
Cable wound Bi-2212 coils haven't achieved short sample I_C yet

- Coil performance is limited by the weakest link
  - This can include thermodynamic leakage, cabling effects, strain limits including local stress concentrations, terminals, and quench degradation.
  - Although, we know how to eliminate leakage, so how much of the gap will we gain back?

Baby-Ruth Test Solenoid

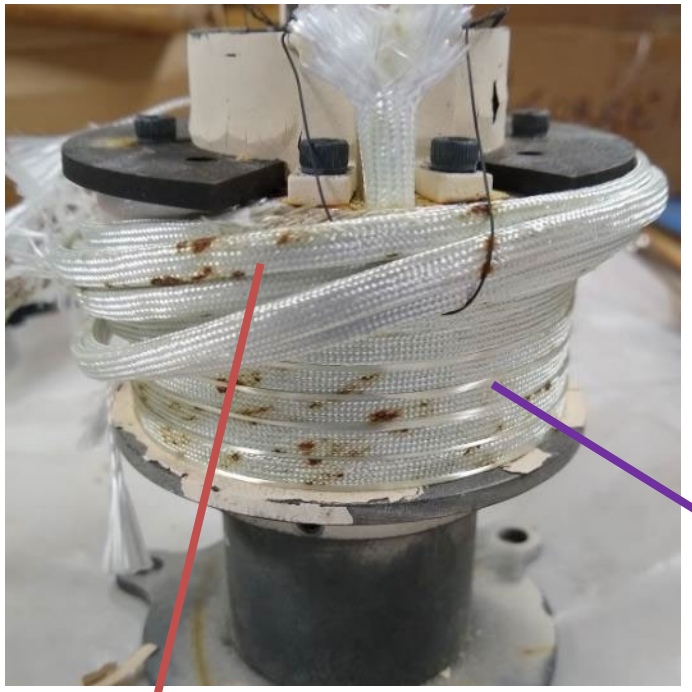


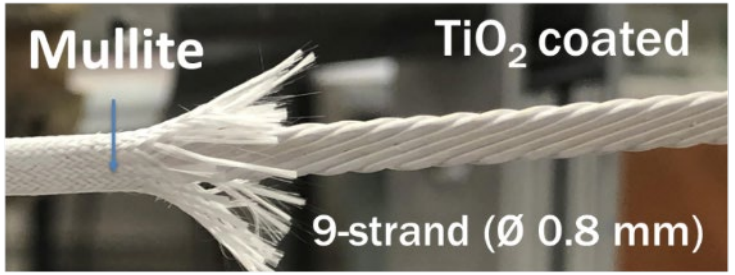
Sub-scale Coils

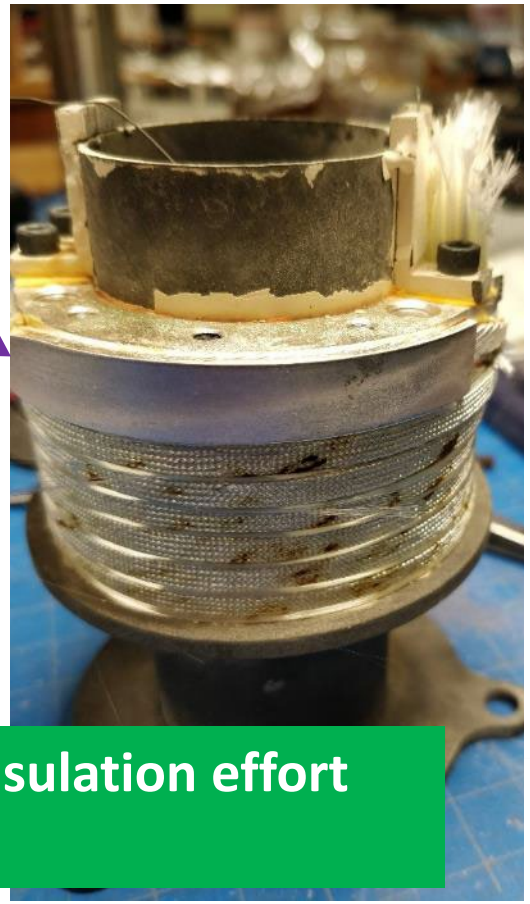


Many Leaks Observed: Could Not Apply Standard TiO_2 Process

- **We have no cable coating route yet:**
  - Existing mullite braid removed from cable
  - Coating painted and slid into braid by hand
  - 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





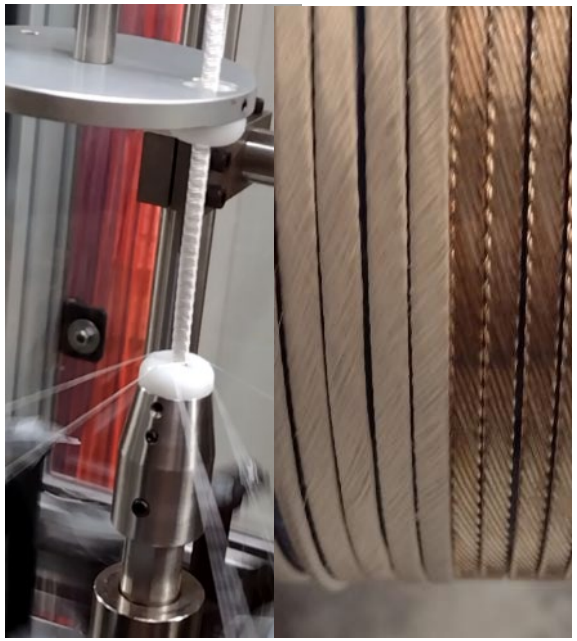


It is likely that installing the braid disrupted the TiO_2 causing the cable to react with the mullite braid allowing for leakage

ASC has recently purchased a braider/wrapping device to seriously pursue the insulation effort on strand-based and Rutherford cable coils

Take-Away: Nat. Labs/Univ. Should Intelligently Damage Test Coils

- **"Intelligent Damage" requires careful postmortem analysis**
- We can eliminate leaks by removing interaction with mullite and gain on the order of 15%
  - TiO_2 and Al_2O_3 are both known solutions but need to be implemented for cables
- We have seen a marked difference between the 9-strand and 17-strand cables
  - Different twist pitch (longer distance away from edges)
- There is a definite and reproducible effect from cabling on the filament merging and strand shape.
  - Is it now time to optimize the architecture for cables?
- The Bi-2212 Rutherford cables are very flexible for winding into a variety of coil types and small diameters (solenoids, racetracks, CCTs, cosine-theta magnets)

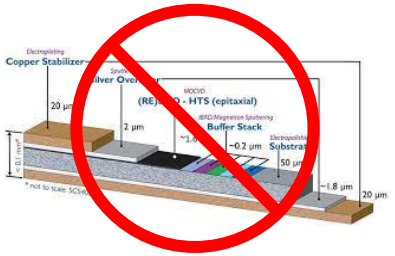


Braiding/wrapping Rutherford Cable at ASC

Benefits of A High-Field HTS Cable Solenoid Program

APPLIED SUPERCONDUCTIVITY CENTER
NATIONAL HIGH MAGNETIC FIELD LABORATORY
FLORIDA STATE UNIVERSITY

- Unique large bore (161 mm), 12 T LTS, 7.2 kA [10 kA upgrade in-progress] test facility
- 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)
- HEP and Fusion would benefit from a sustained testing program
- Smaller relative cost for conductor, engineering, and testing
- Take-Away: Nat. Labs/Univ. Should Intelligently Damage Test Coils



Not a cartoon

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