The NHMFL LBC Program: A design-test-postmortem approach towards a 50 T R&D magnet

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Introduction to the Little Big Coil (LBC) Program

- **Little coil, big stresses, *really really big* field**
  - Operate in 31 T resistive background magnet at NHMFL
  - 12 NI pancakes connected in series via low-resistance inner/outer joints
  - Dry-wound for stress management, for compactness (high J_e), **and to allow *post-mortem* after high-stress coil test**
- **The 9 LBC *post-mortems* (and counting) have revealed many surprising behaviors of REBCO in UHF magnets…**
  …and some of these behaviors might be leveraged to mitigate stresses and eventually break 50 T
- **In this talk we will first discuss SuperPower (LBC1—4, 8), then Faraday (LBC5&9), and lastly Shanghai (LBC6&7)**

LBC1-3 (45.5T) (before 2017)

LBC4 (44.0 T) (Mar. 2023)

LBC5 (😱) (Mar. 2024)

LBC6 (42.7 T) (Feb. 2025)

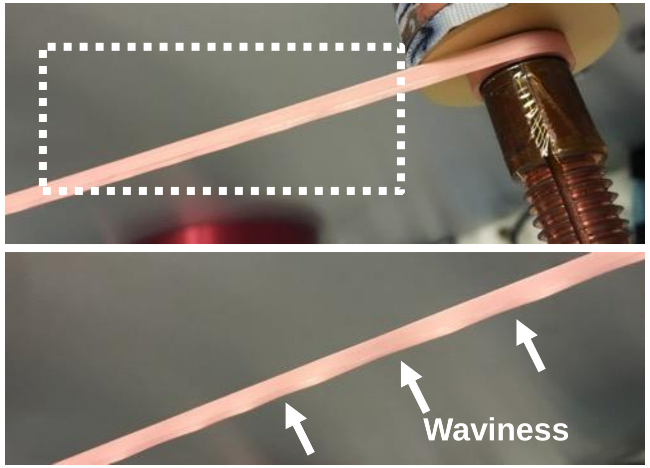
LBC7 (40.9 T) (Aug. 2025)

LBC8 (46.0 T) (Aug. 2025)

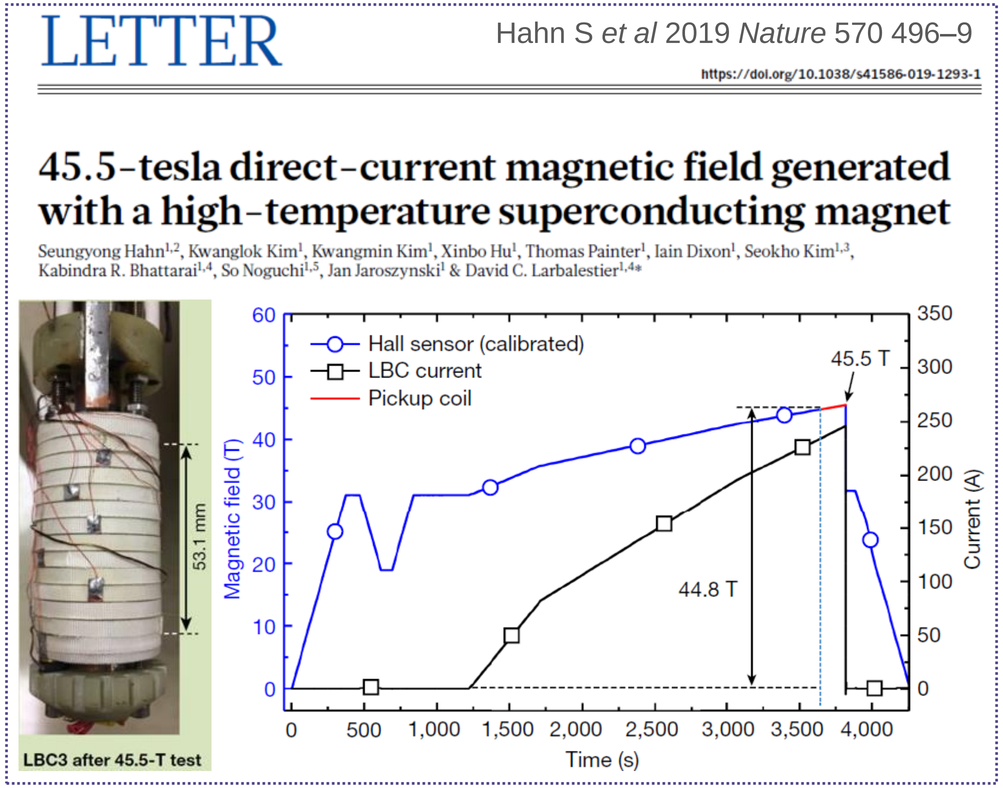
LBC9 (48.7 T) (Aug. 2025)

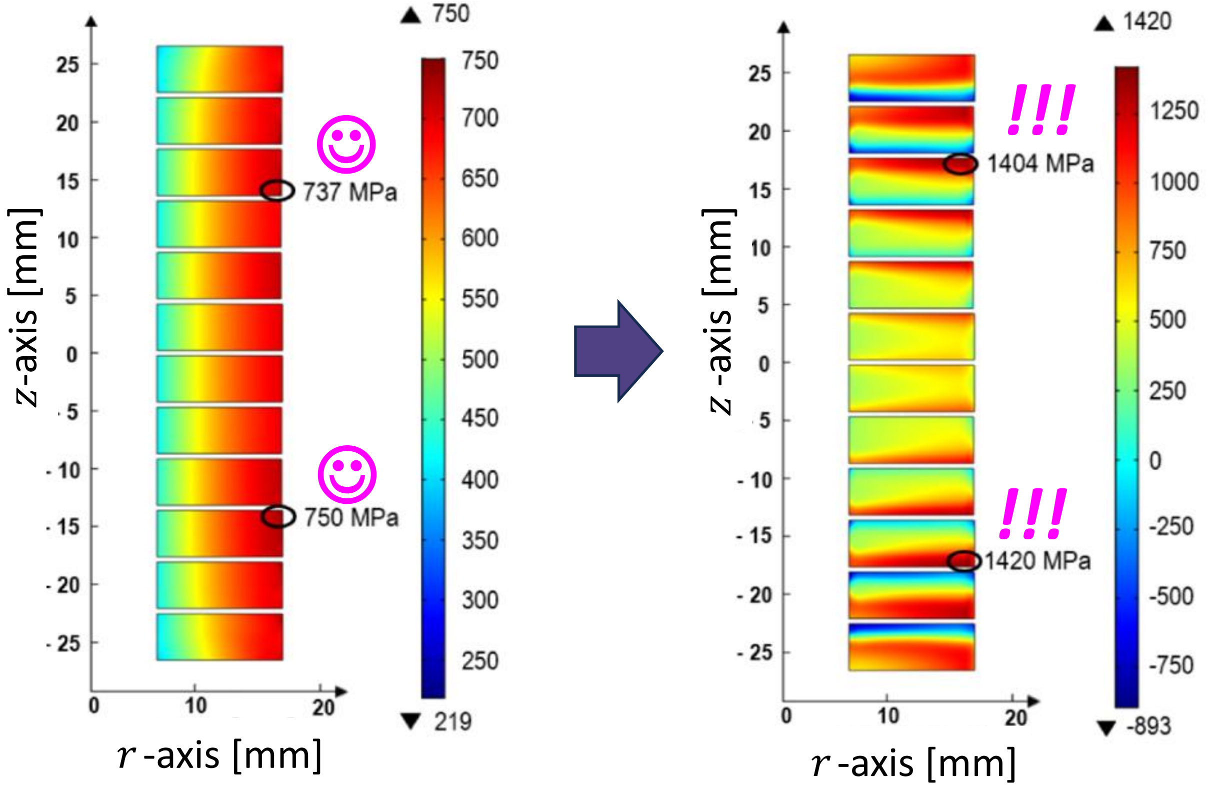
1. The SuperPower LBCs (1, 2, 3, 4, 8)

LBC1—3 introduced us to wavy plastic deformation–the signature damage mode of $J_c B r$ screening current stresses (SCS) and a useful feature for postmortem analysis



- Wavy deformation indicates where the local conditions exceeded σ_y
- Unpredicted features in the inferred SCS distribution reveal important unaccounted-for REBCO behaviors

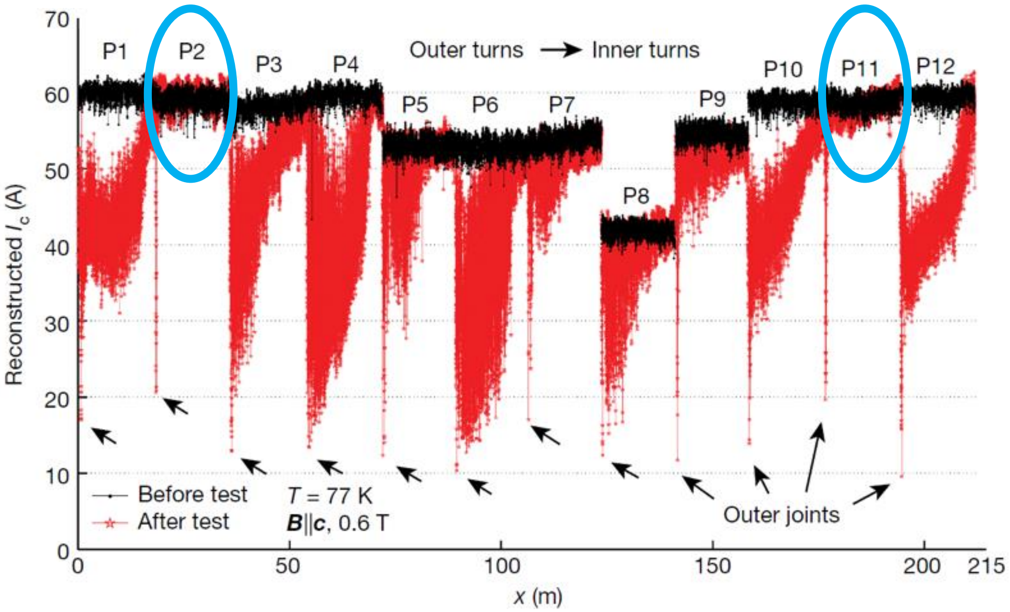




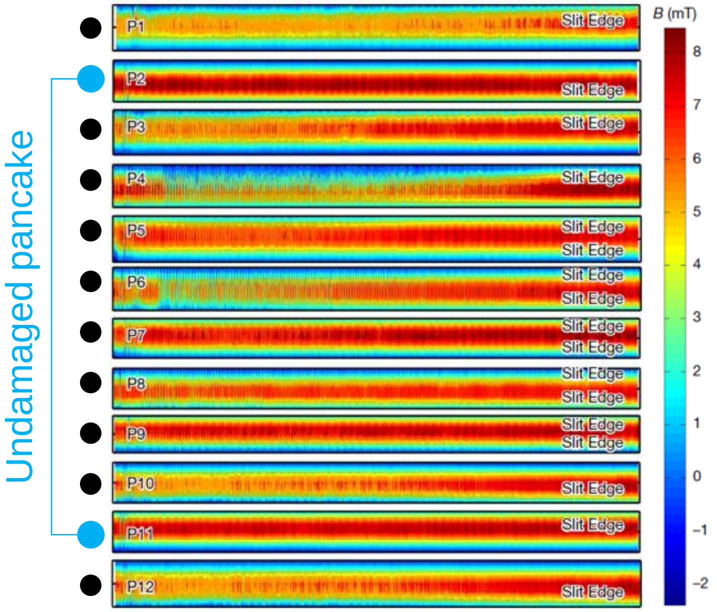
LBC3: Is there a "correct" slit edge orientation to mitigate SCS damage?

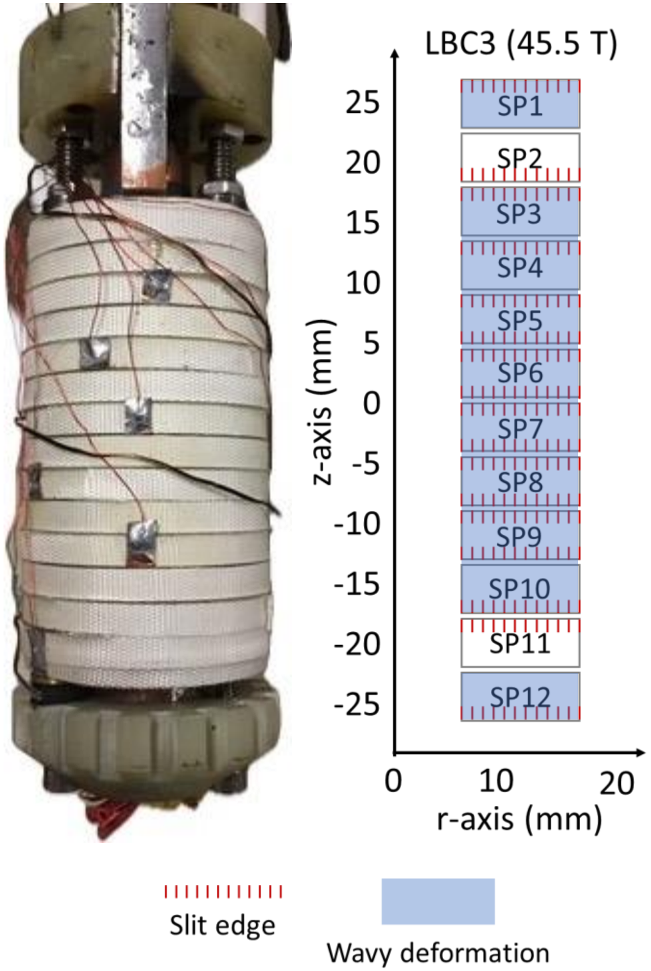
- **A strange result in LBC3 (45.5 T):** Only SP2 and SP11 showed no plastic conductor deformation or I_c degradation
- **Implication:** Significant SCS mitigation occurs when using single-slit SuperPower AP tapes wound with slit edges pointing inward towards the magnet center

Lengthwise I_c scanning results of each pancake (P)



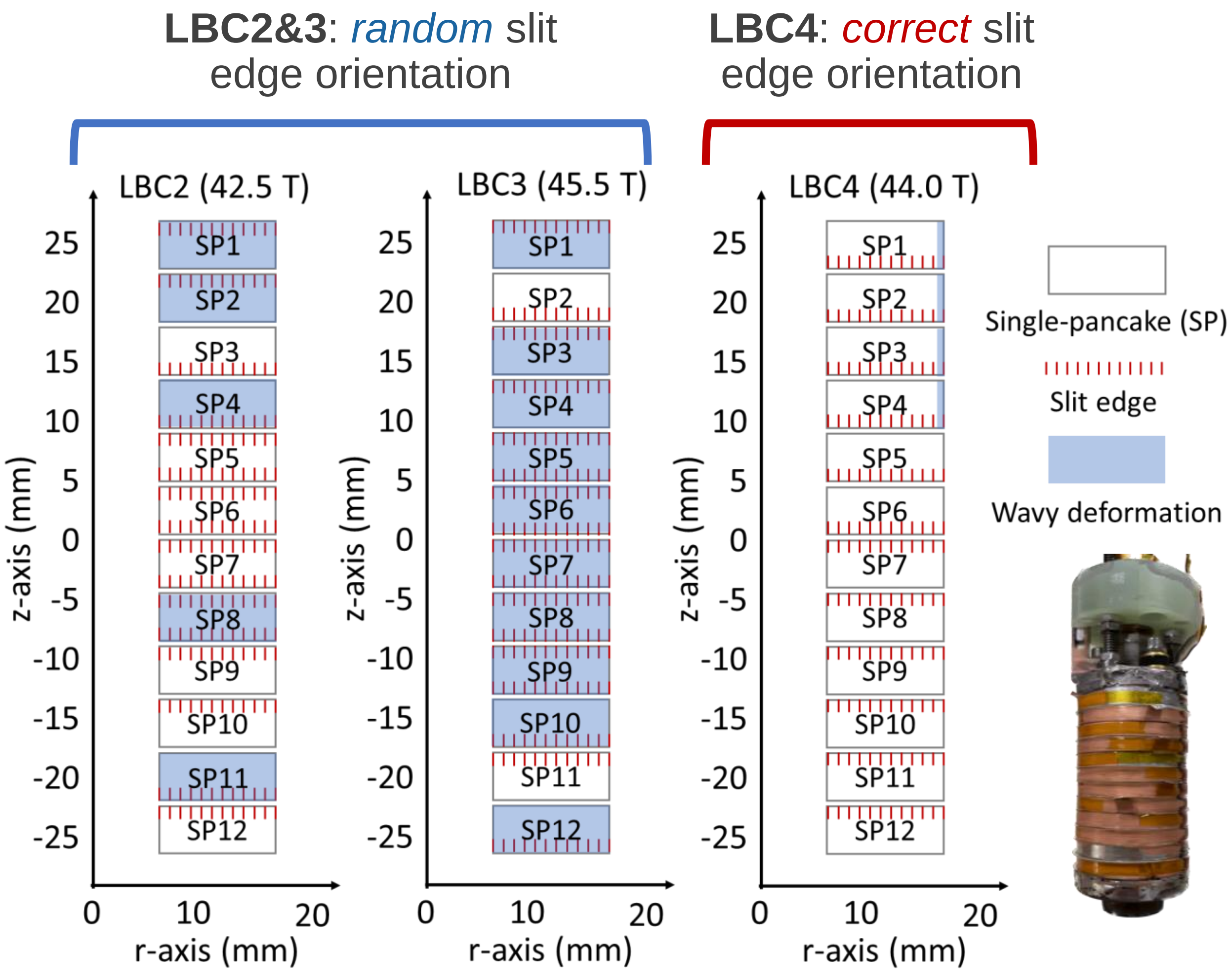
YateStar magnetization scanning results



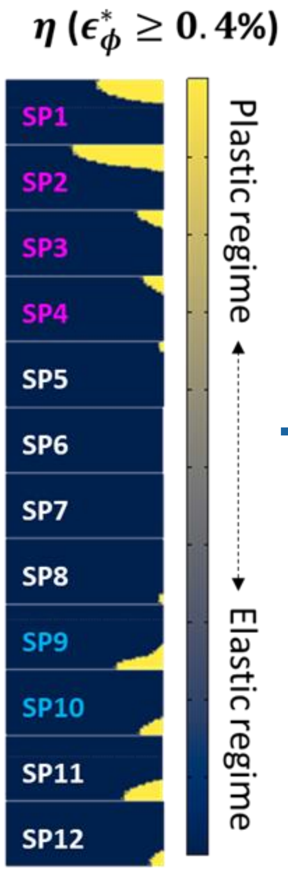


LBC4: Confirmed damage mitigation through slit edge orientation, but…

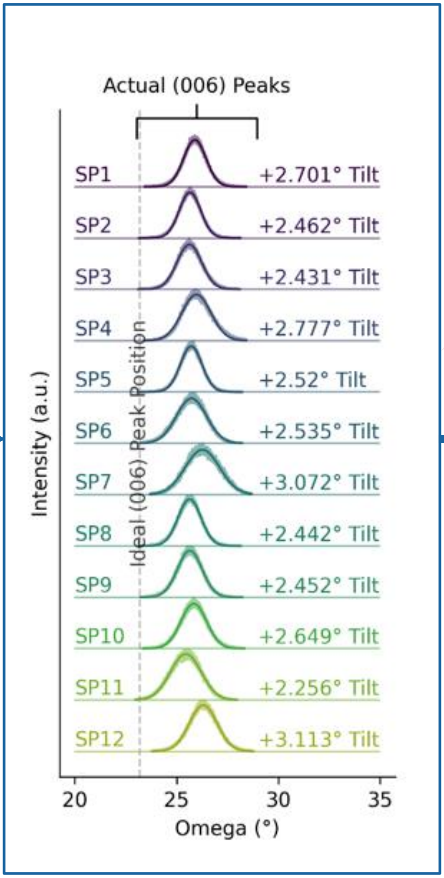
- **LBC4 replicated LBC3 but with the “correct” orientation:** only single-slit tape with slit edge facing the coil midplane
  - Peak 44.0 T at 213.5 A with some dissipation
  - Quench set off by outer joint failure
  - Wavy plastic damage only observed in outer few turns of SP1—4!
- **We concluded that this damage mitigation mechanism is real***…but why?*
  - Simulation predicted massive SCS damage throughout coil irrespective of slit edge orientation!
- **Reconciling simulation with observation revealed the truth…**



LBC1—4: The real damage mitigation mechanism involved crystallographic tilt and transverse J_c variability (slit edge orientation = confounding variable)

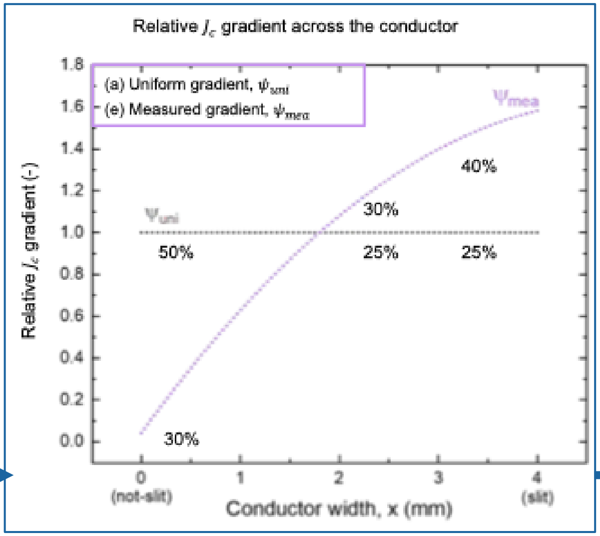


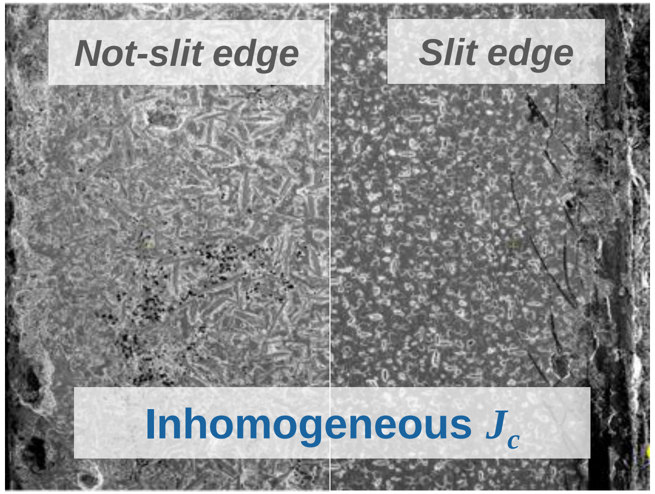
Ideal conductor

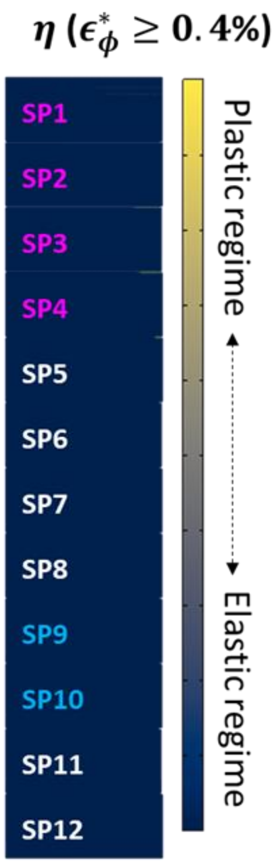


Crystallographic tilt

We are grateful to to Ernesto Bosque (formerly NHMFL 40 T project) and CFS for making us aware of crystallographic tilt!





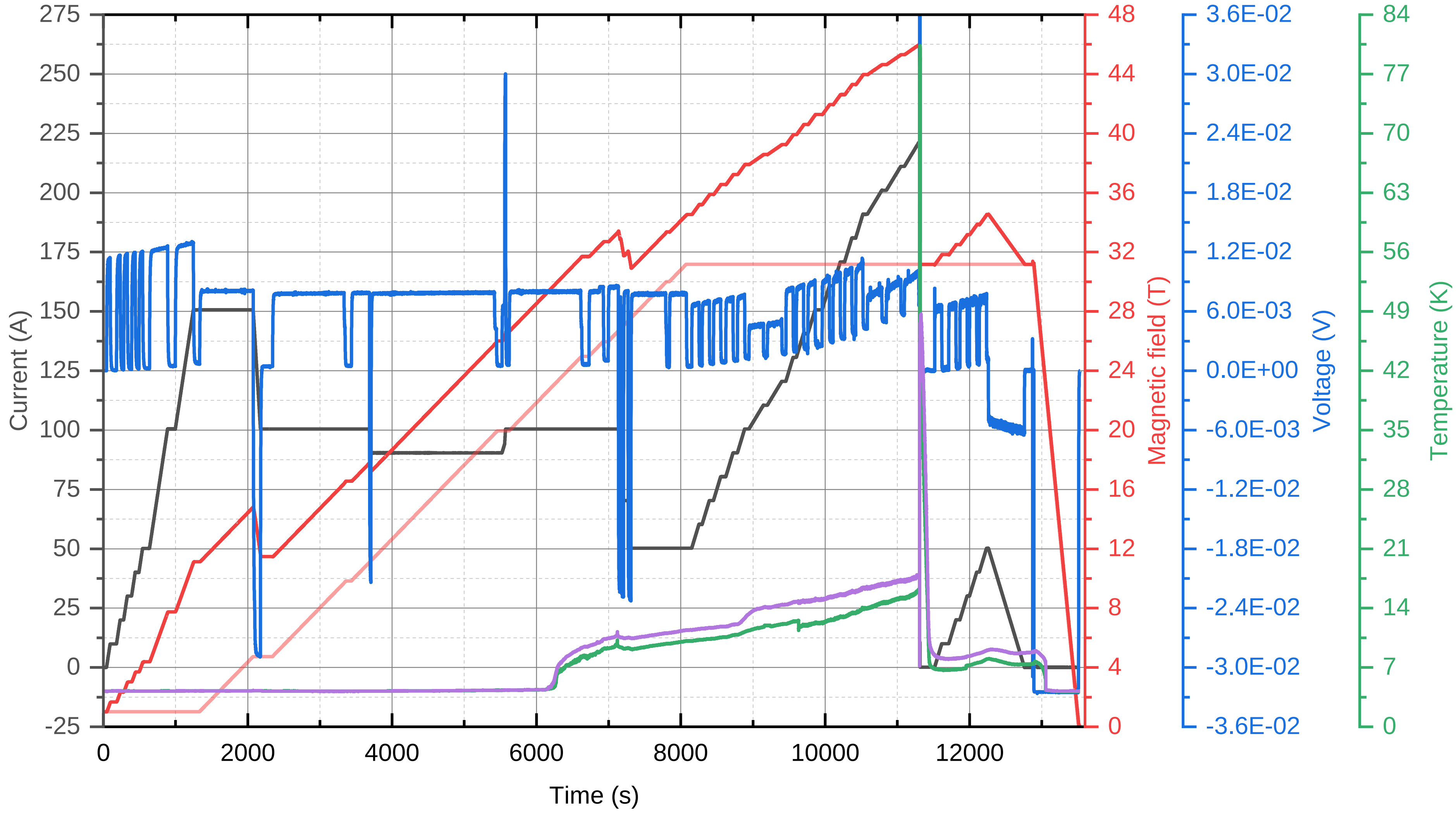


Realistic conductor

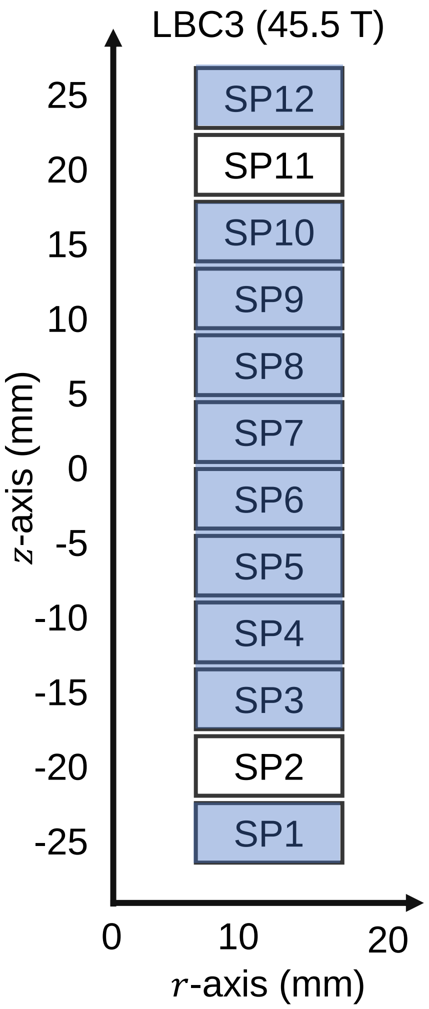
Crystallographic tilt and inhomogeneous J_c produce "high-I_c" and "low-I_c" conductor orientations. The latter can be intentionally chosen to reduce I_c margins and mitigate SCS.

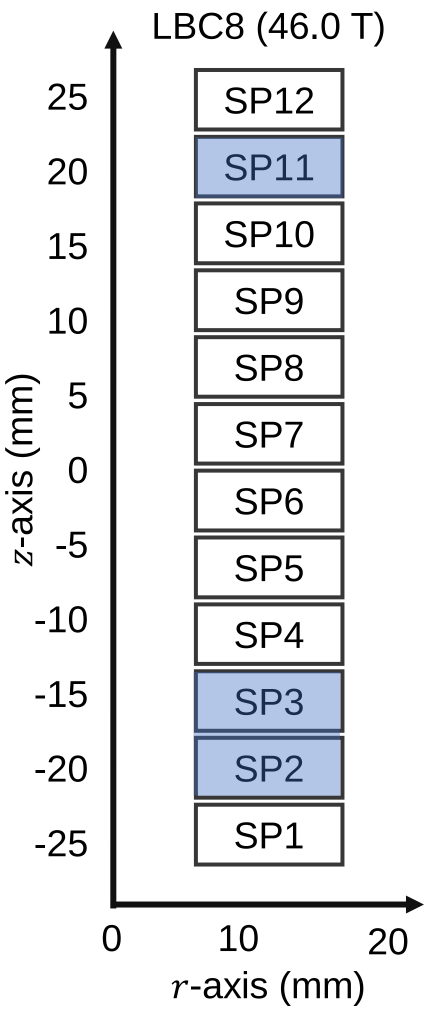
LBC8 (SP-HM): Using Lessons Learned to Surpass LBC1—4 (SP-AP)

Initial characterization suggested only marginal orientation effect on SCS mitigation.
Stainless steel overbanding adopted as additional SCS mitigation measure.



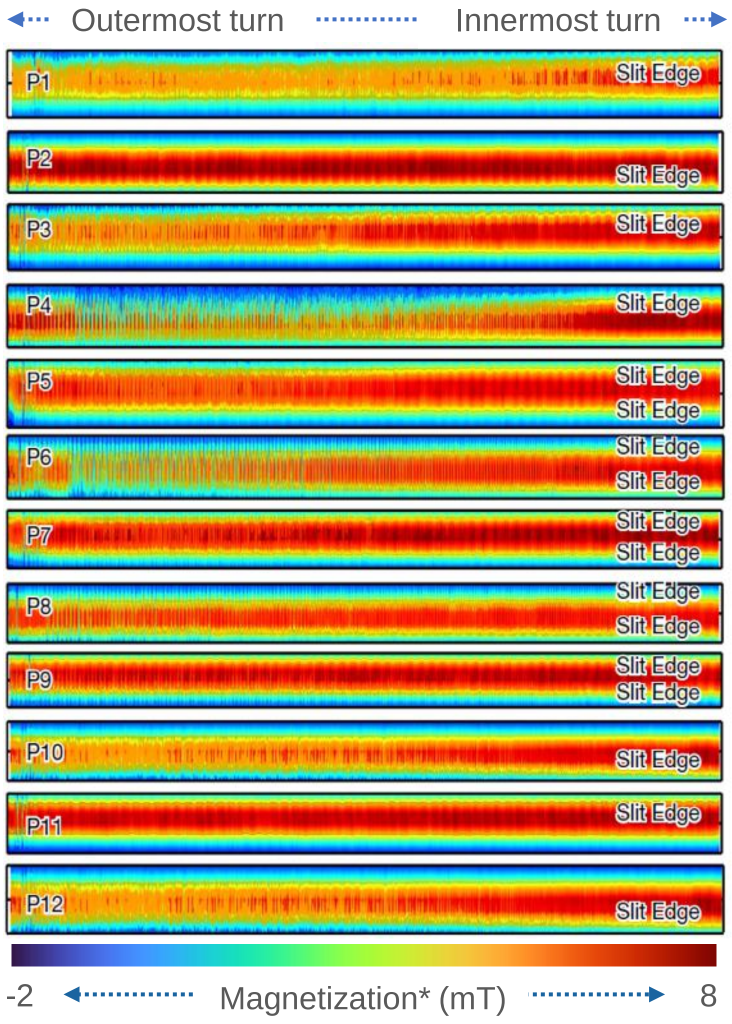
Comparison between LBC3 (SP-AP 45.5 T) and LBC8 (SP-HM 46 T) postmortems



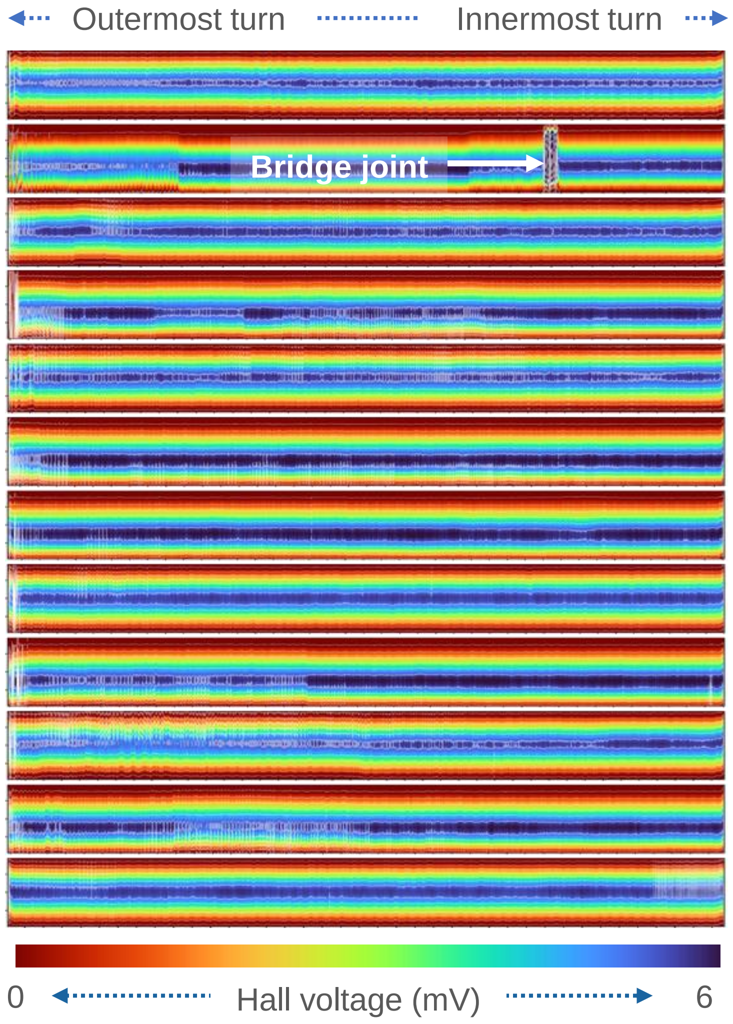


Plastic conductor deformation

LBC3 magnetization scanning results



LBC8 magnetization scanning results

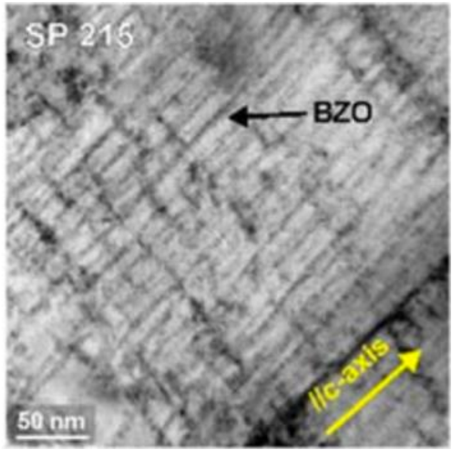


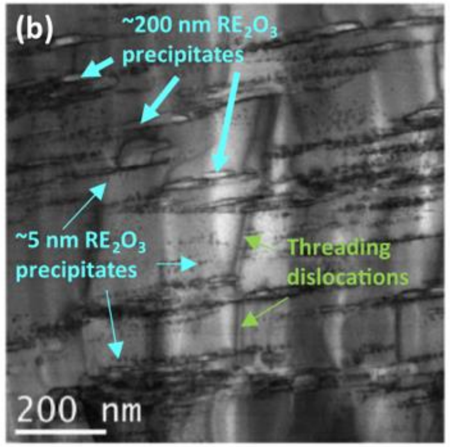
2. The Faraday LBCs (5 + 9)

Key features of fusion-type PLD conductors (Faraday and Shanghai)

Original MOCVD CC:
c-axis oriented nanorods to optimize for B//c performance

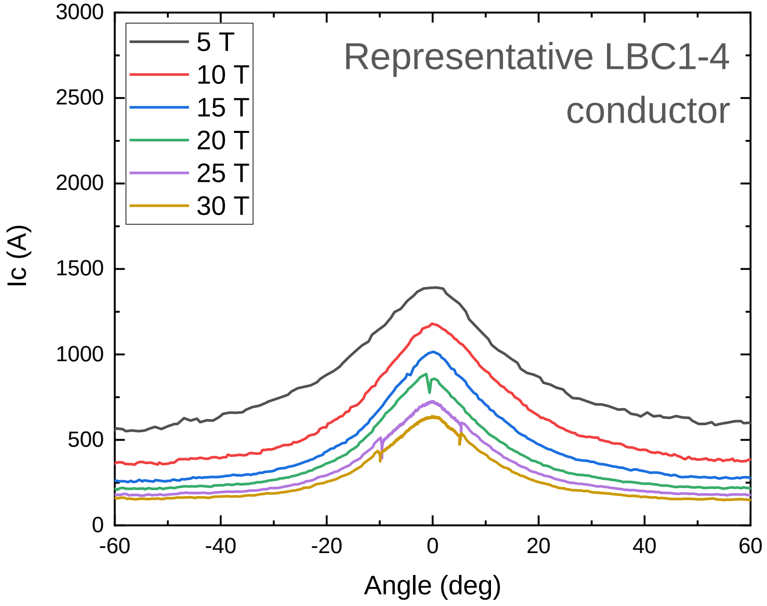
TEM: A. Francis et al., Supercond. Sci. Tech. 2020





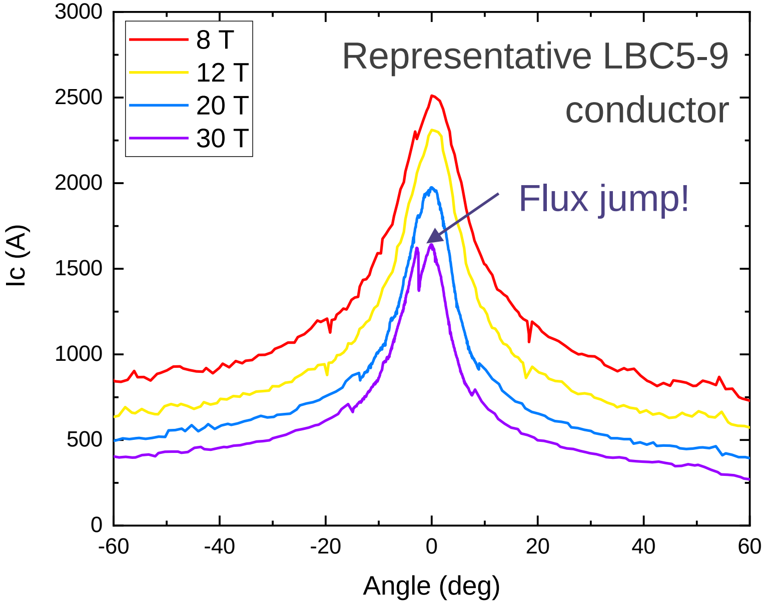
Fusion-type PLD CC:
dense uncorrelated defect network to optimize for performance near B//*ab* at 20K/20T

TEM: A. Xu et al., IEEE Trans. Appl. Supercond. 2025



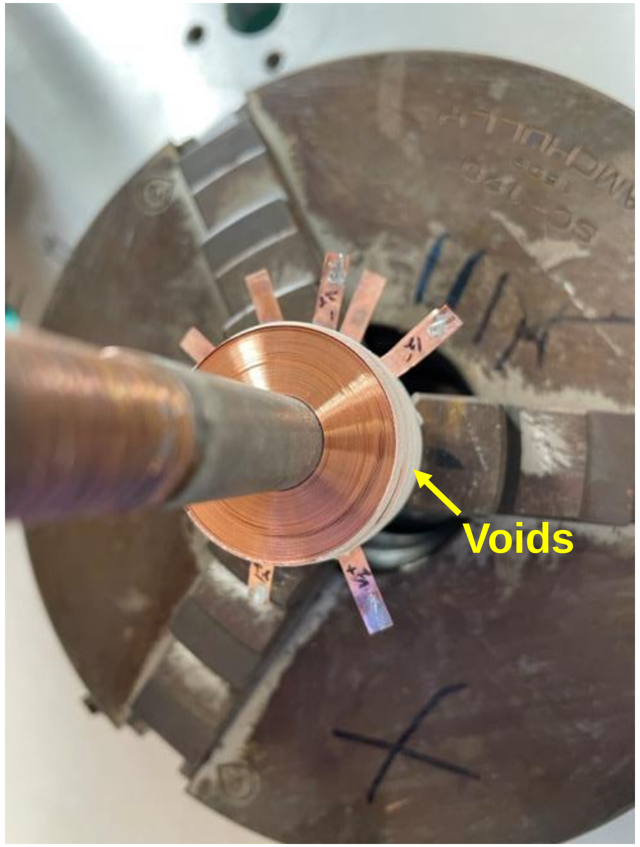
3x the I_c and uniform across the width!

Are we headed for major SCS damage?

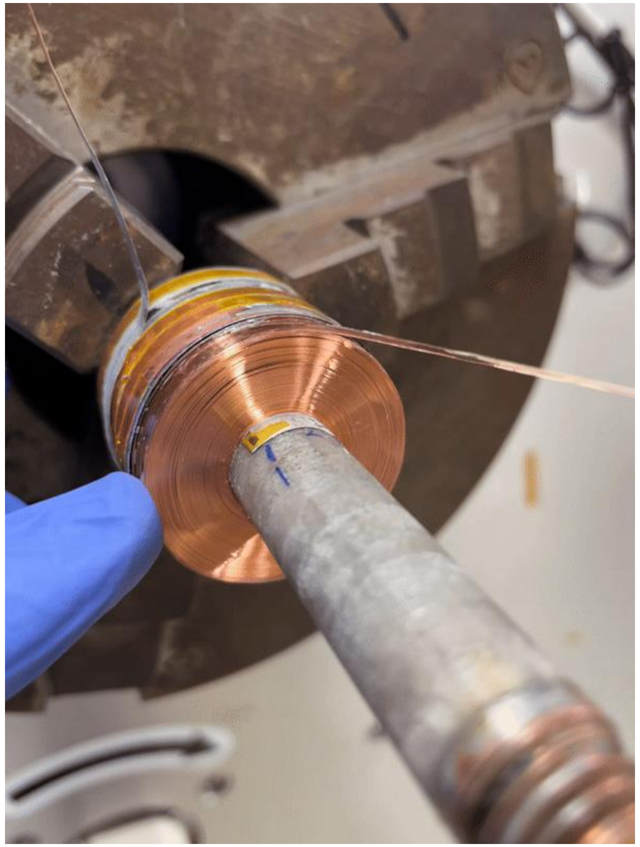


LBC5: Disastrous First Attempt to Use Faraday Conductor

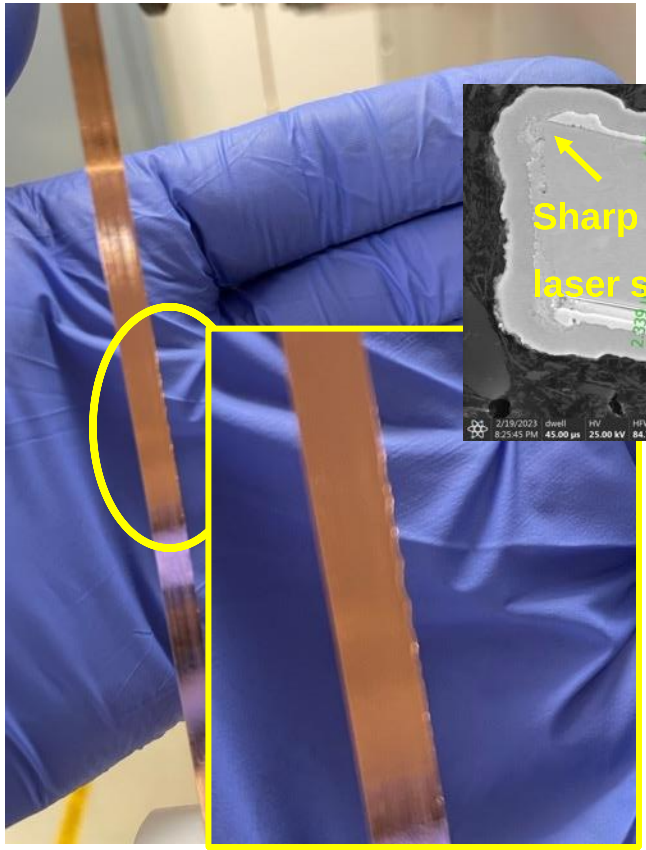
Void space in the winding pack



Large compressibility



Copper delamination



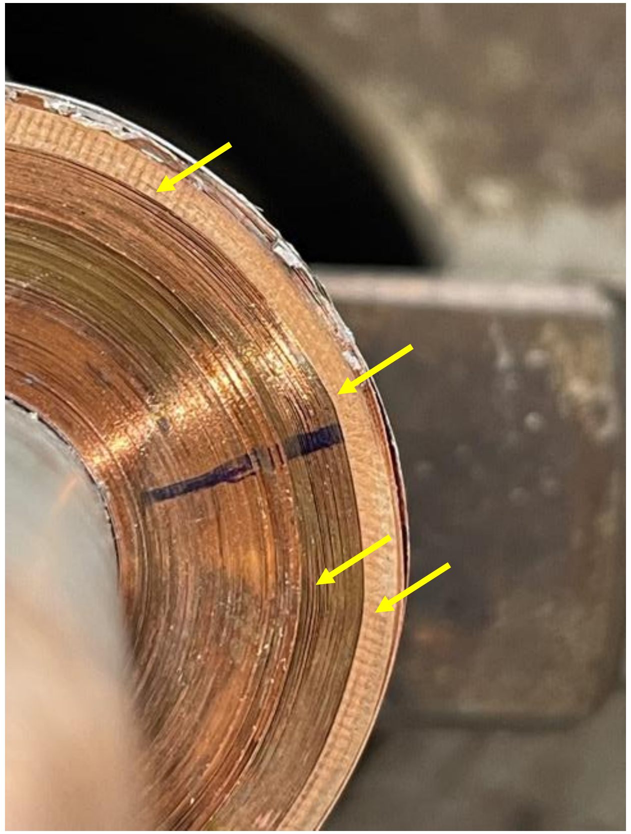
Ph.D. work from Dr. Grififn Bradford (now at ACT)

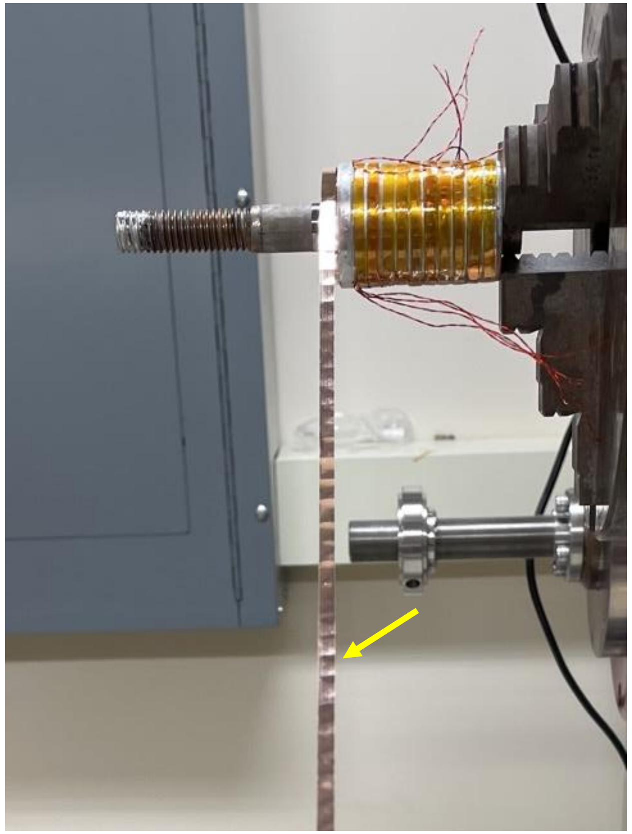
REBCO CCs are not their cartoons!

LBC5: Disastrous First Attempt to Use FFJ Conductor

LBC5 did not survive a background magnet trip (loss of 31 T in ~0.5 s)!

The surface after the background magnet was tripped	Multiple global kinks



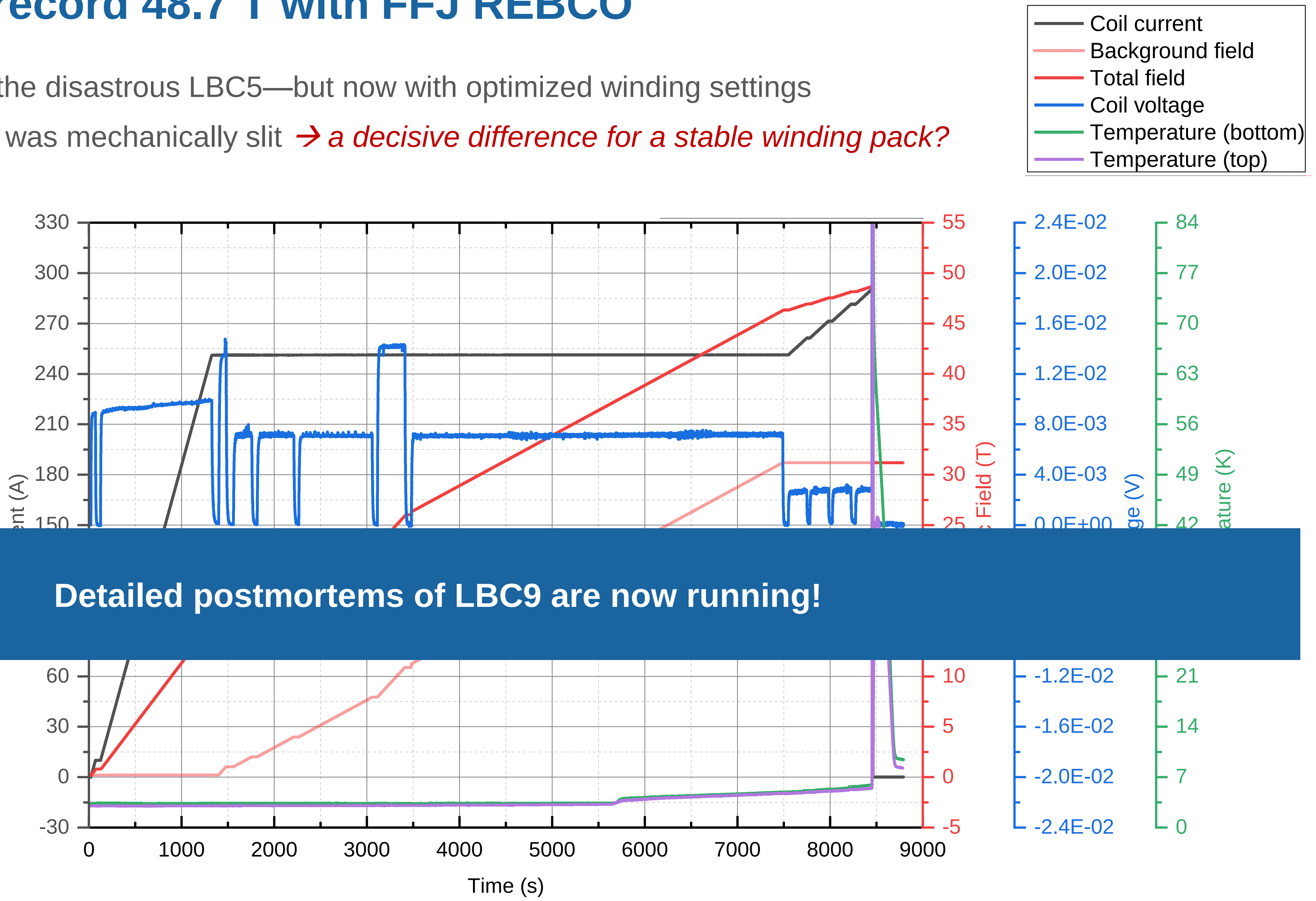


Edge defects = void space = fatal!

Dr. Seungyong Hahn (SNU) and Dr. Yu Suetomi (NHMFL) are two experts who have grappled with this “winding compressibility” issue considerably in recent years

LBC9: New world record 48.7 T with FFJ REBCO

- Similar conductor used in the disastrous LBC5—but now with optimized winding settings
- LBC5 was laser slit; LBC9 was mechanically slit → *a decisive difference for a stable winding pack?*

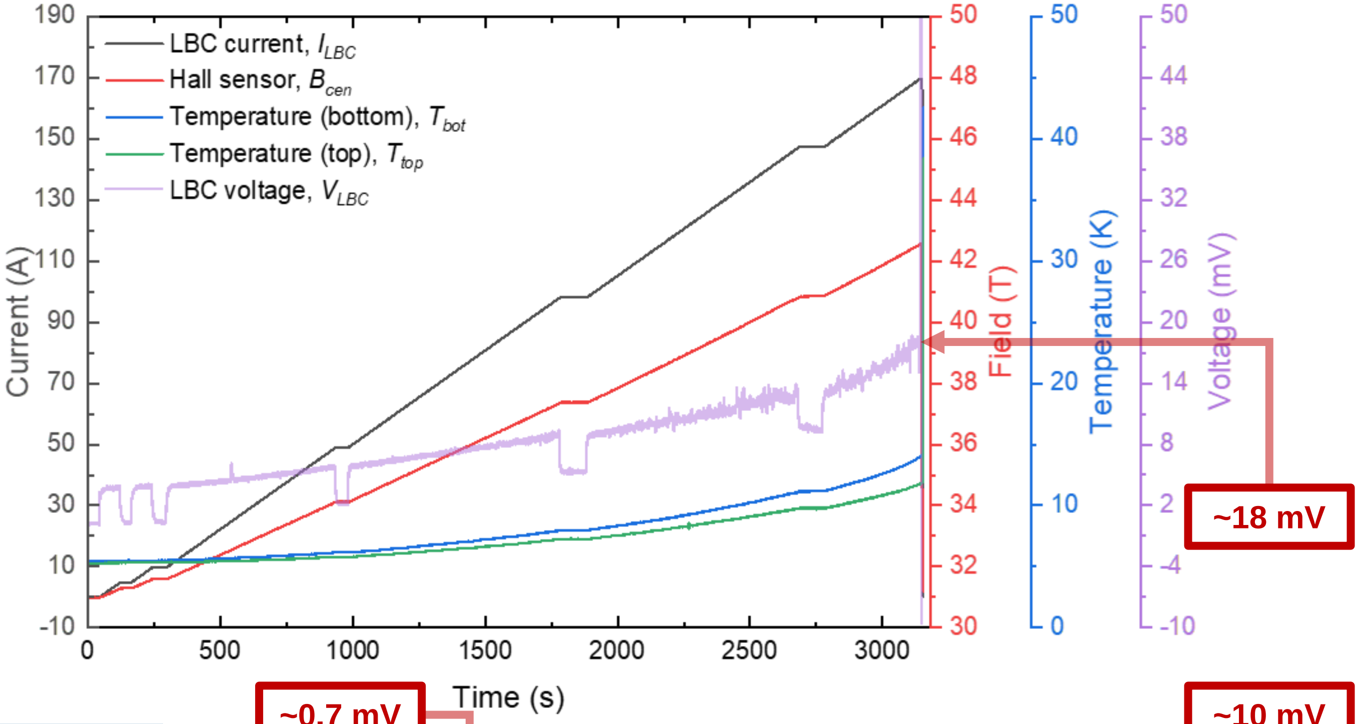


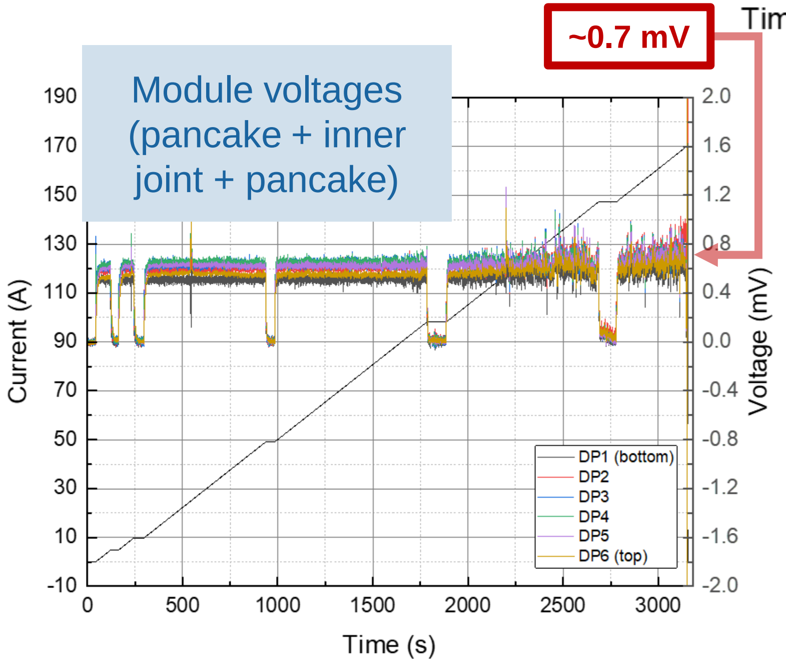
Detailed postmortems of LBC9 are now running!

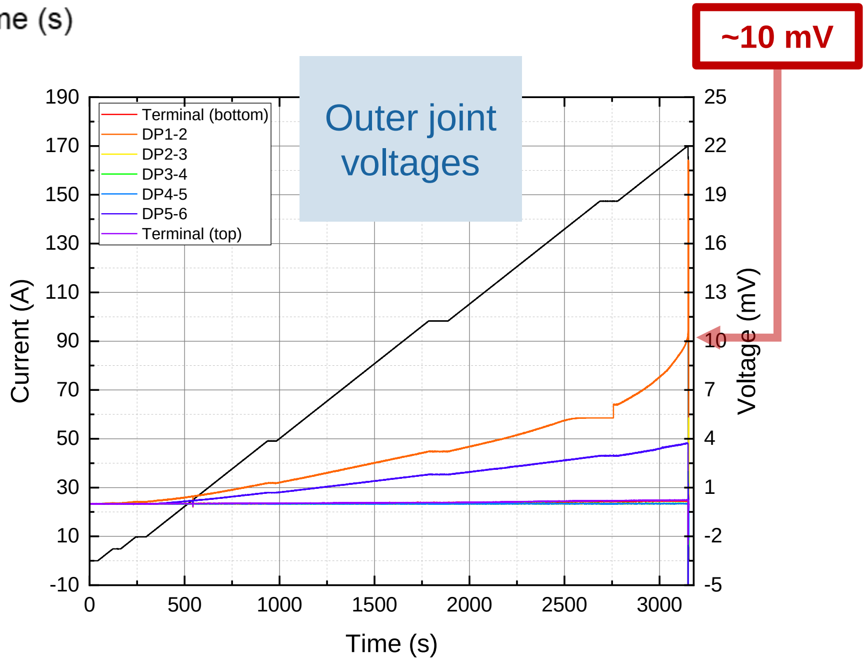
3. The Shanghai LBCs (6 + 7)

LBC6 (SST): The first LBC to survive >40 T quench…

- **Double-laser-slit Shanghai (SST) tape with extensive characterization**
- **Numerous voltage spikes during ramp-up:**
  - Conductor motion? Flux jumps? Something else?
- **Quench initiated by outer joint at 42.7 T but coil still superconducting afterwards!**







LBC6 (SST): The first LBC to survive >40 T quench and cycling…

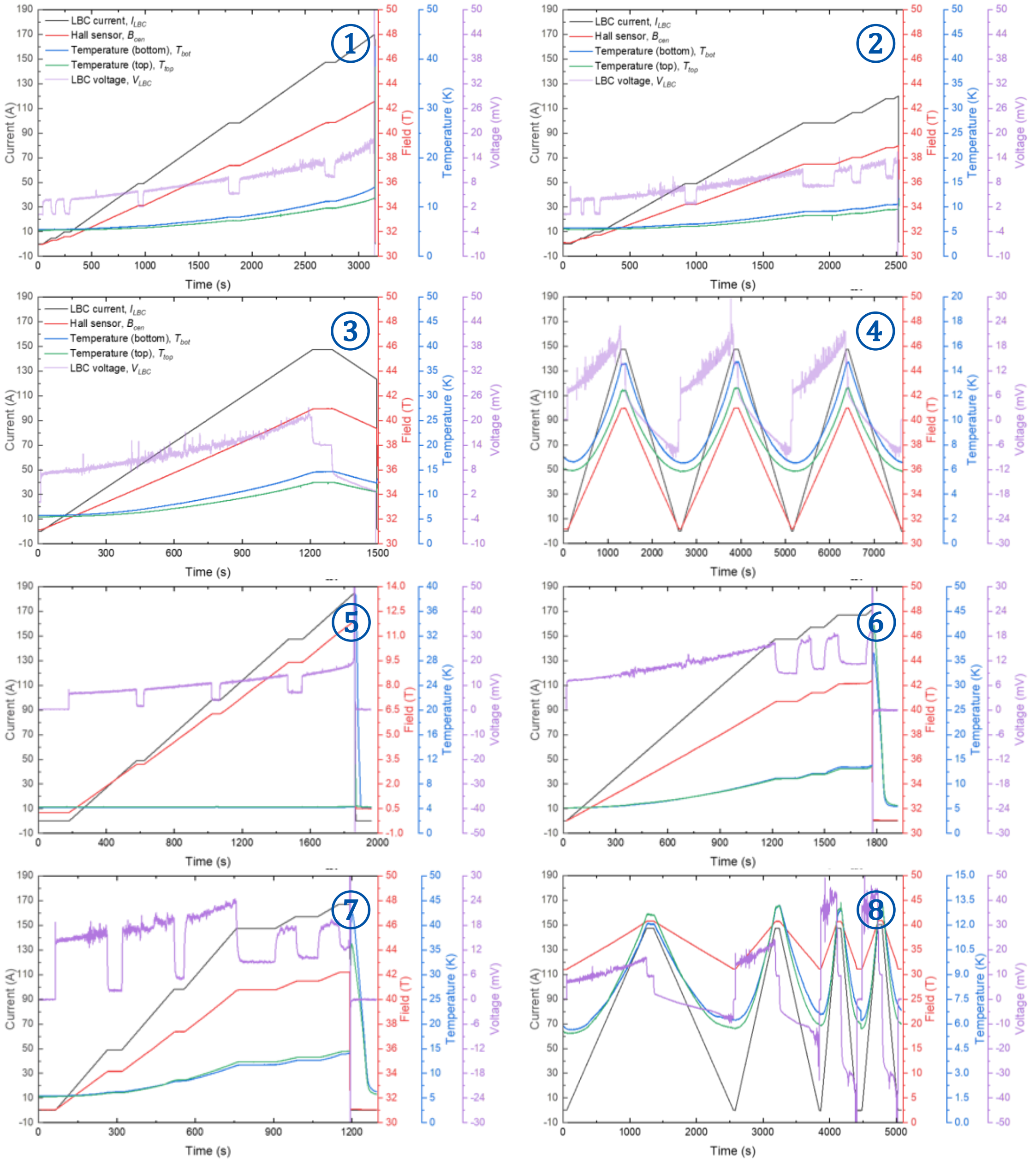
List of all tests performed:

1. Initial quench from 42.5 T/170 A (31 T background)
2. Rapid accidental discharge from 39 T/120 A (31 T background)
3. Ramp to 41 T/150 A, rapid discharge from 120 A due to quench detection error (31 T background)
4. 3 repeated cycles to 41 T/150 A (31 T background)

- *Overnight warm up to 200 K then cooldown back to 4.2 K (31 T background)*

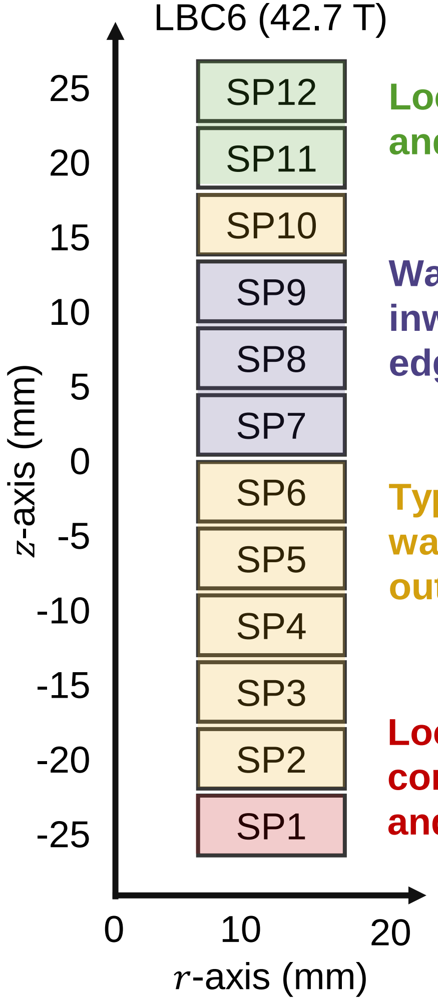
5. Self-field (no background) quench at 185 A/12 T
6. Quench at 42.5 T/173 A (31 T background)
7. Quench at ~42.25 T/170 A (31 T background)
8. 4 cycles to 41 T/150 A at variable rates (31 T background)

Outer joints showed signs of fatigue but we ran out of magnet time without coil failure!



LBC6 (SST): Coil unwinding showed extensive conductor damage!

How could the coil be repeatedly energized when the conductor looked like this?

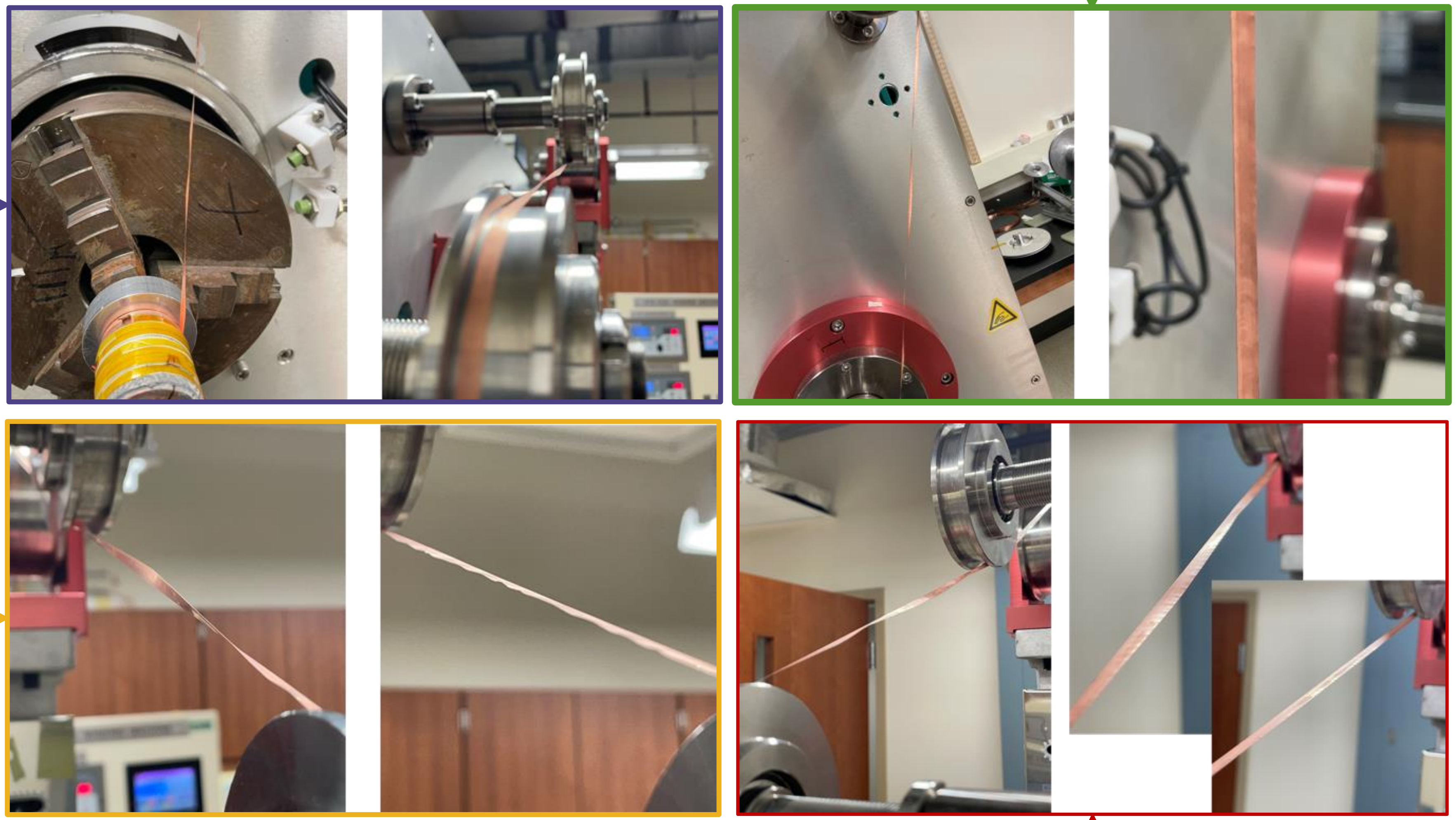


Local kink, and waviness

Waviness at inward(!) edges

Typical waviness at outward edges

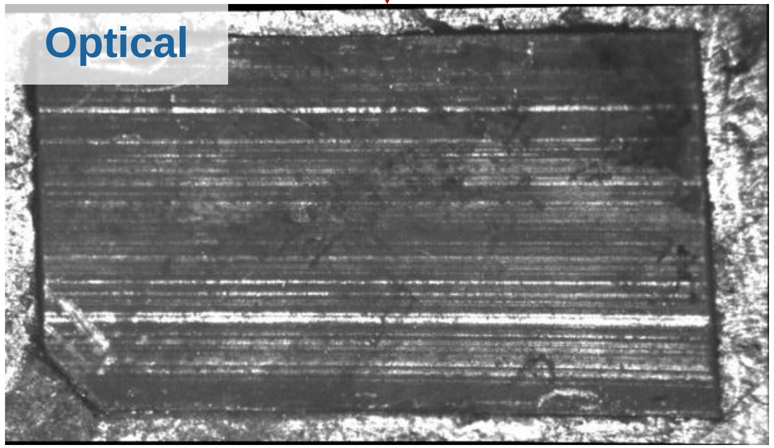
Local kink, corrugation, and waviness



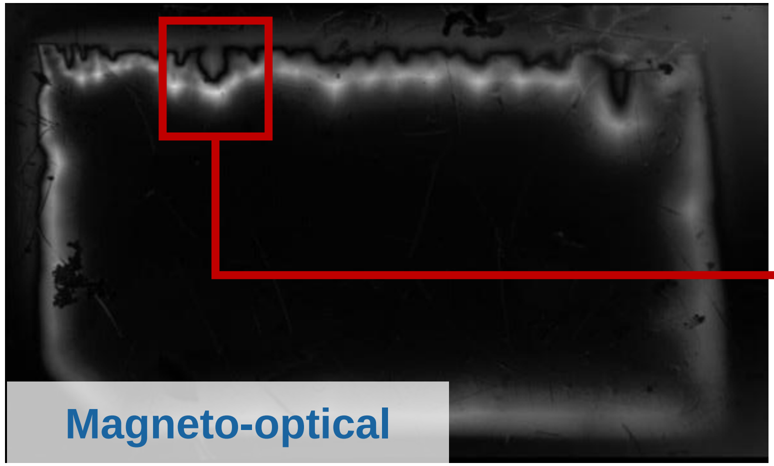
LBC6 (SST): Postmortem indicates damage contained on single edge

Edge facing away from coil midplane

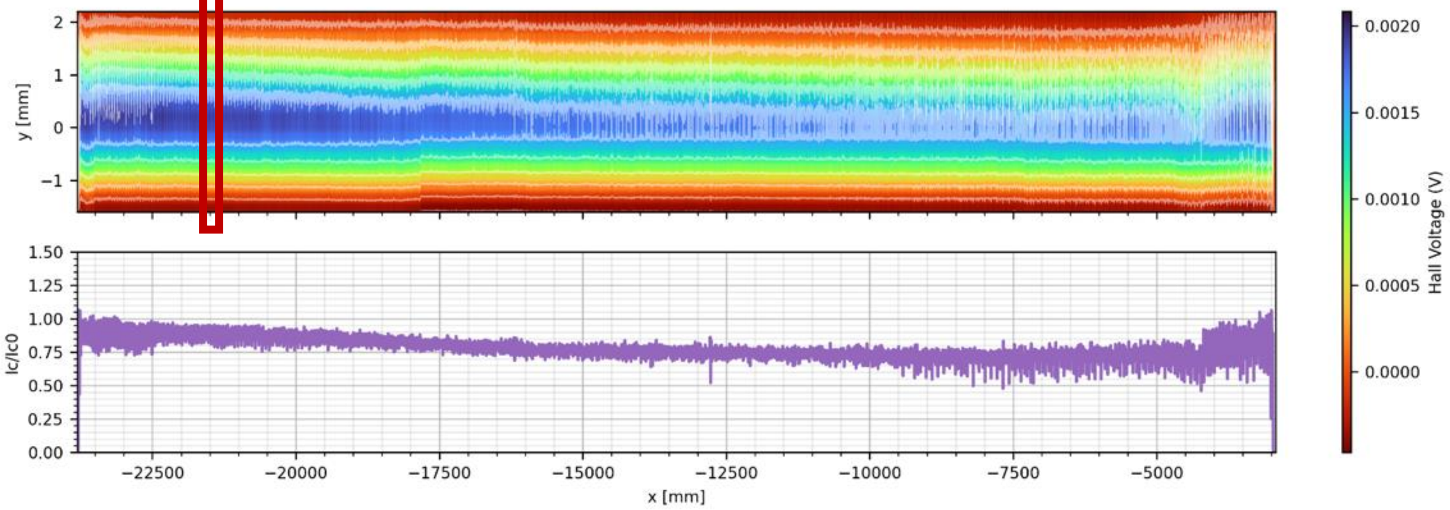
Optical



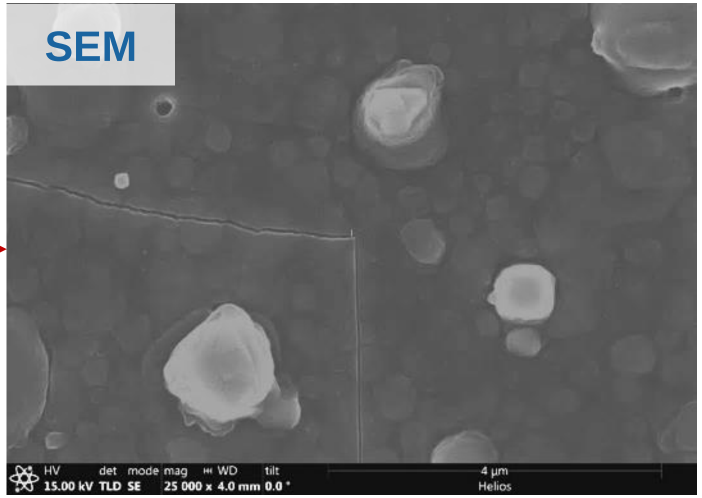
Magneto-optical



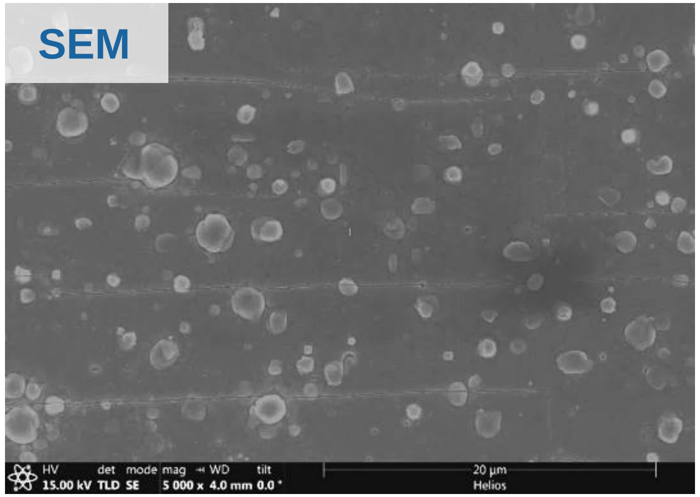
77K Magnetization on SP1 (bottom module)



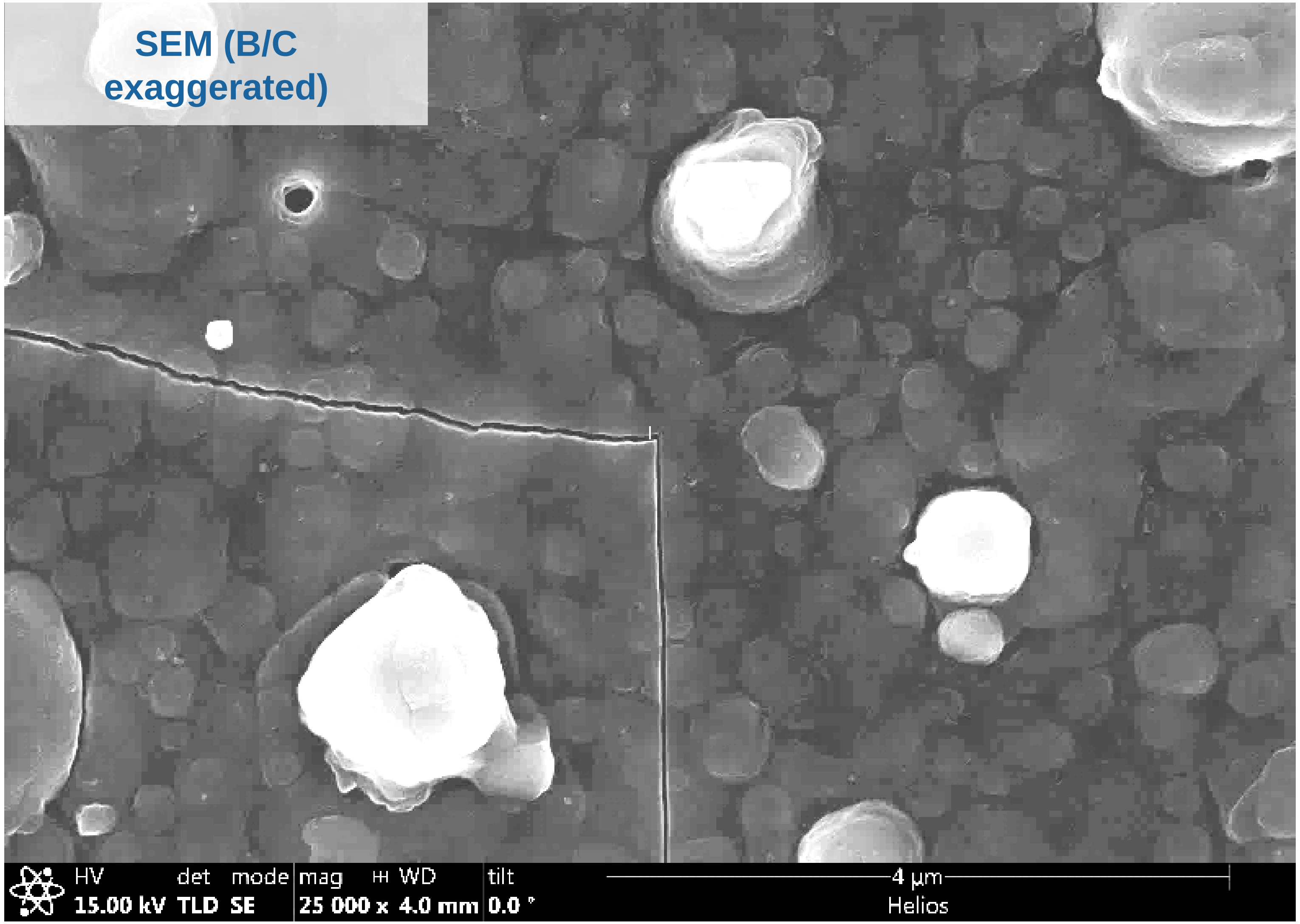
SEM



SEM



LBC6 (SST): Postmortem indicates damage contained on single edge

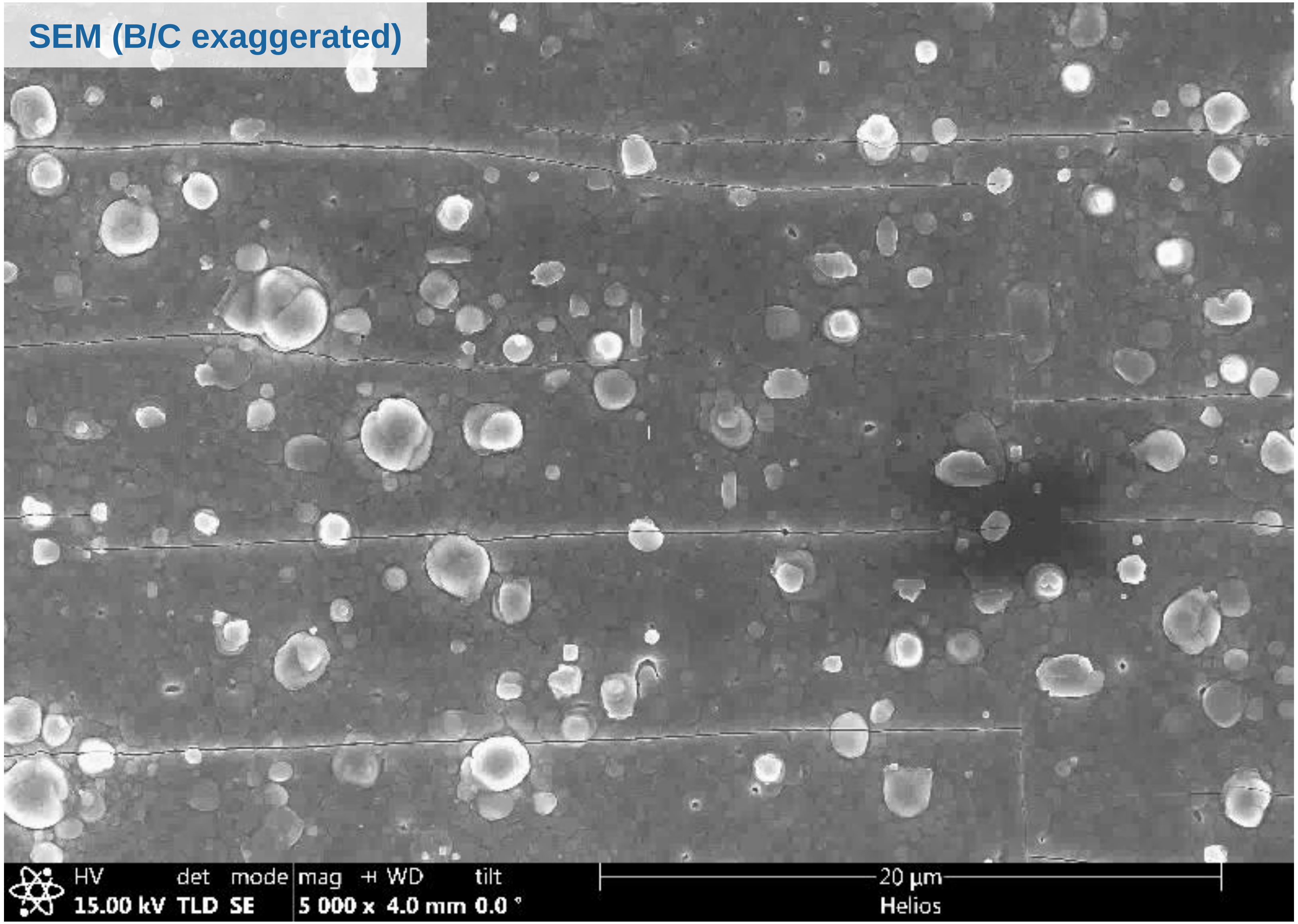


Crack parallel to tape length

Crack parallel to 4 mm tape width

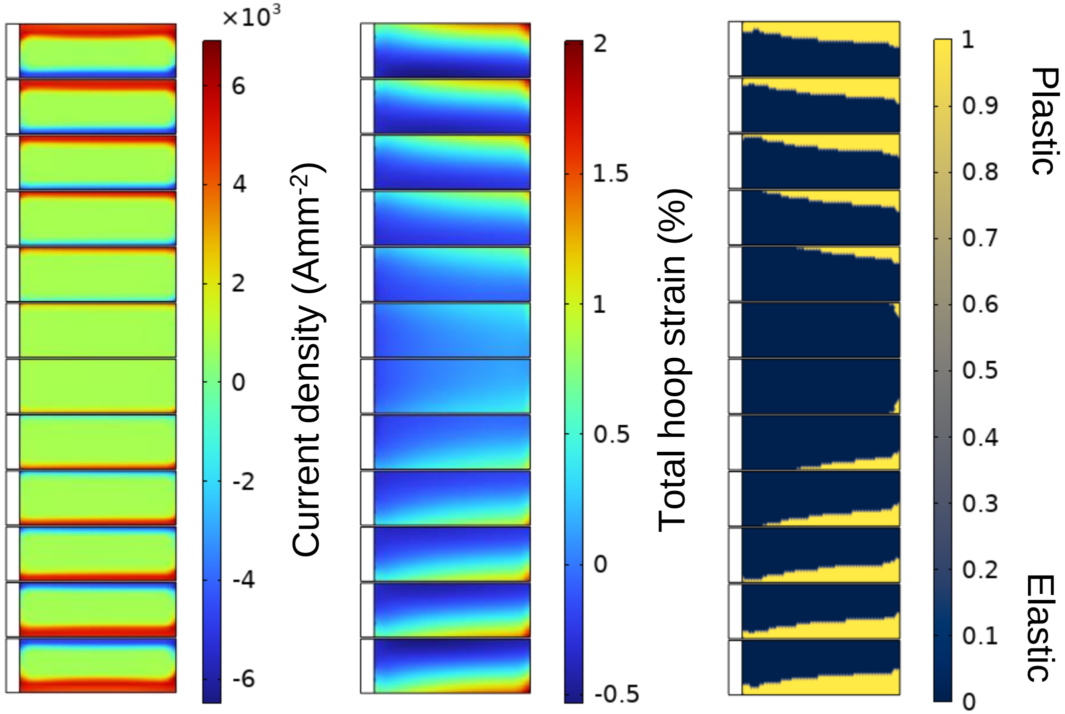
LBC6 (SST): Postmortem indicates damage contained on single edge

Cracks parallel to tape length



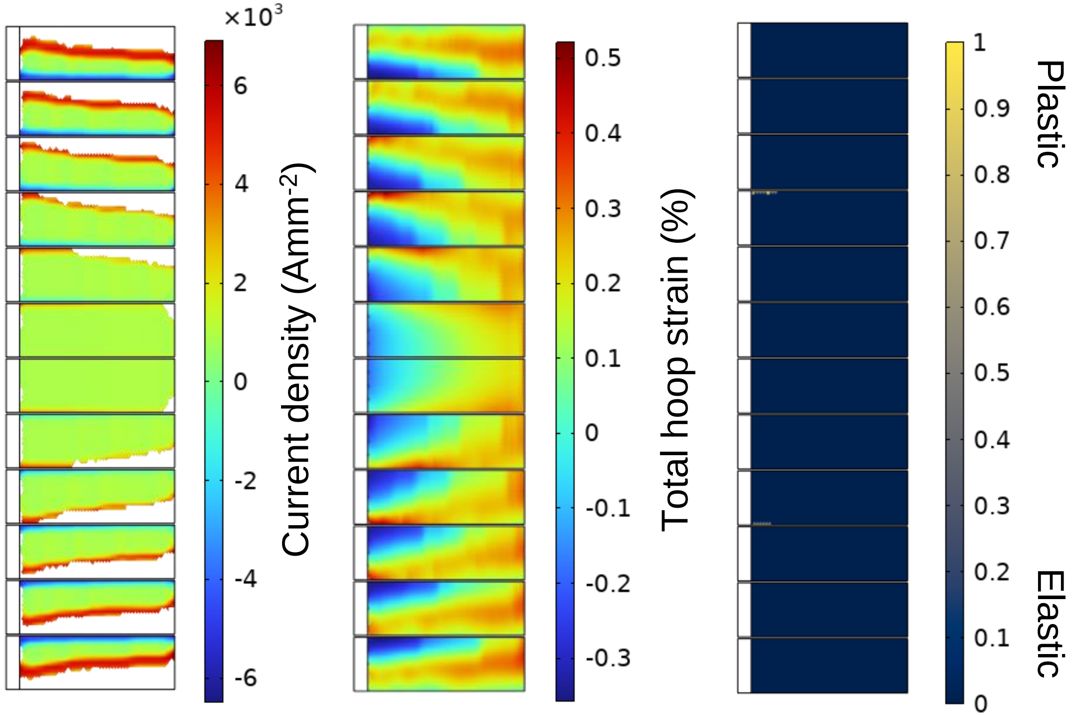
LBC6 (SST): Simulation & observations suggest “*self-performance-limiting*” SCS damage mechanism

Simulation of Undamaged LBC6:
SCS Damage Expected



Set J_c = 0 in plastically deformed regions (ε > 0.4%)

Simulation of Degraded LBC6:
No <u>Further</u> SCS Damage Expected

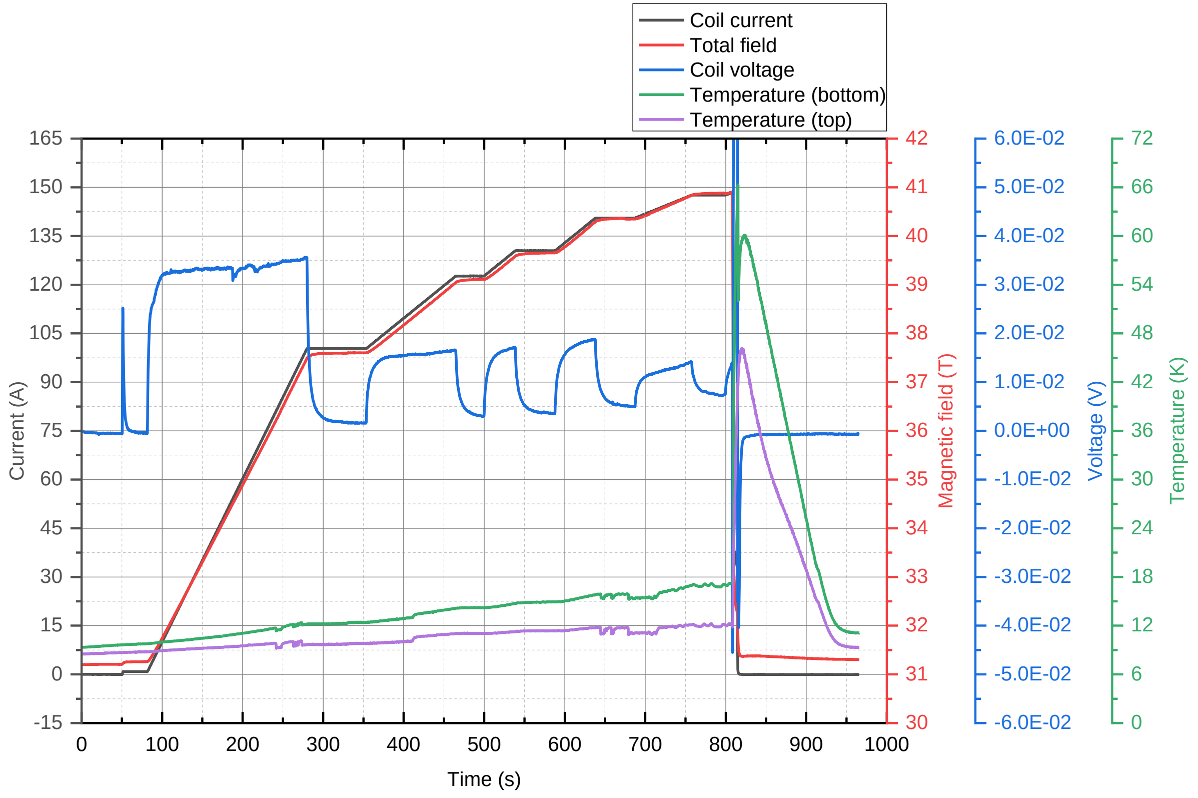


Certain REBCO CCs may be capable of “deformation training.”
If I_c is too high, SCS will progressively destroy one conductor edge, lowering I_c until equilibrium is established.

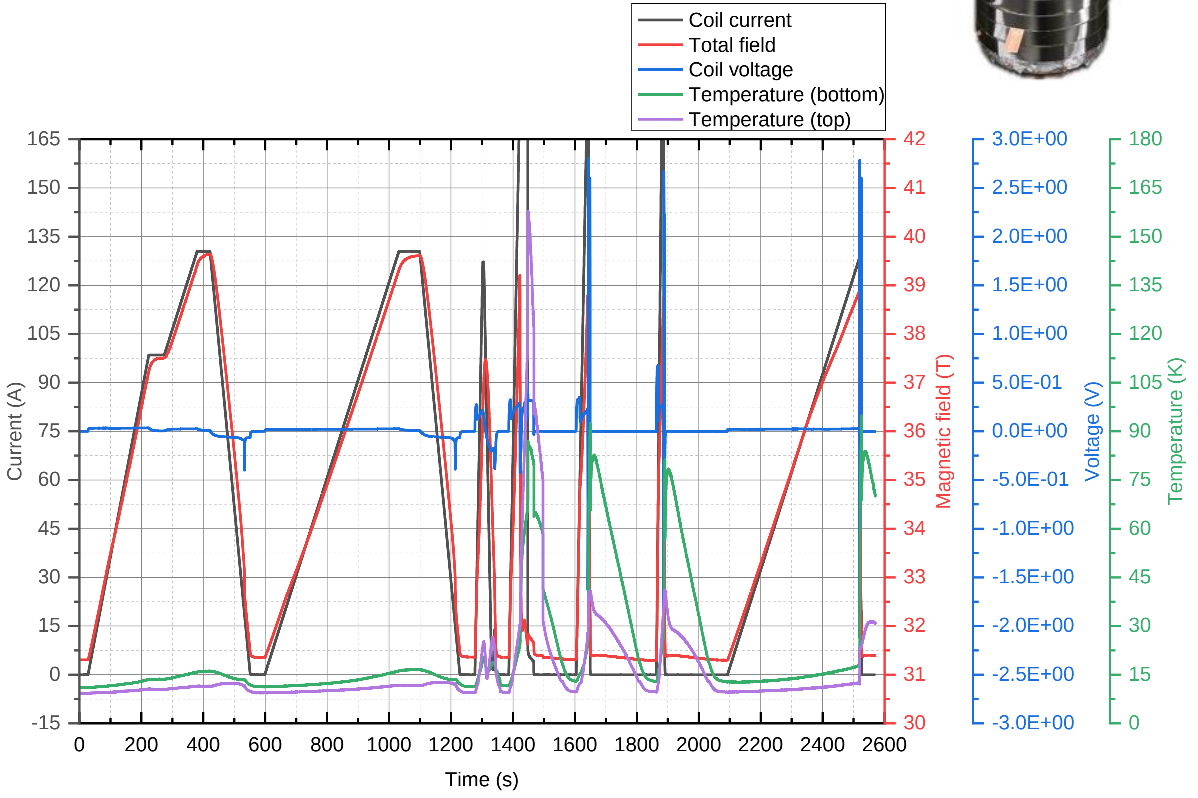
LBC7: A second SST coil with low peak field but high survivability

Unfortunately, overbanding did not allow us to reach higher field.

However, surviving a background magnet trip is a big contrast to LBC5!



Original ramp to 41 T after surviving background magnet trip (19T → 0T in ~0.5s)



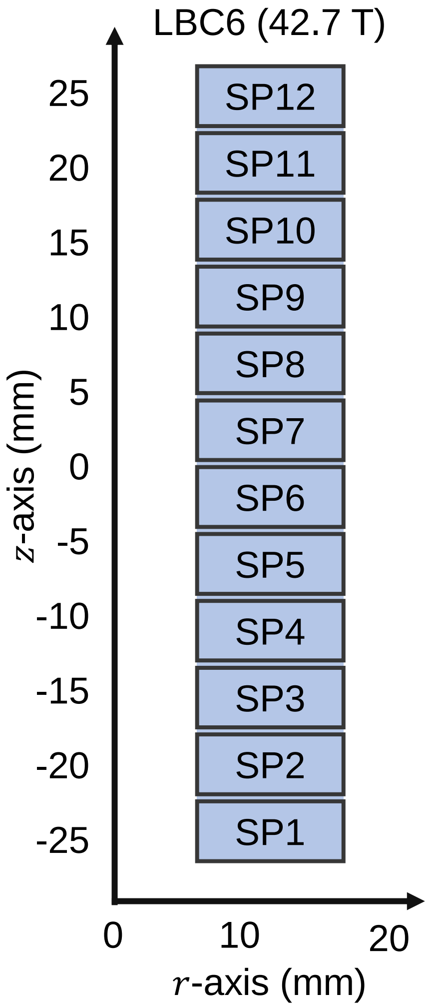
2 post-quench cycles: ① 0.5 A/s, ② 0.25 A/s

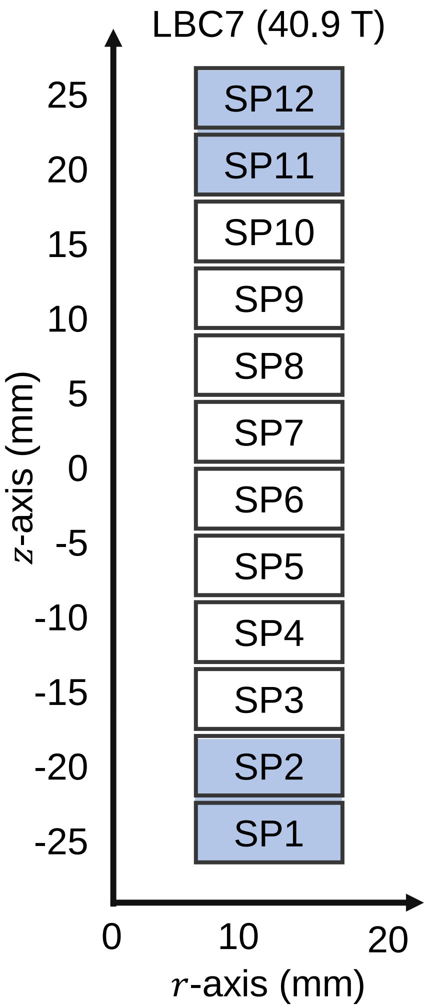
5 quench tests: ③ ④ ⑤ 5 A/s, ⑥ 10 A/s, ⑦ 0.25 A/s

Still survived!

Comparison between LBC6 (SST 42.7 T) and LBC7 (SST 40.9 T) postmortems

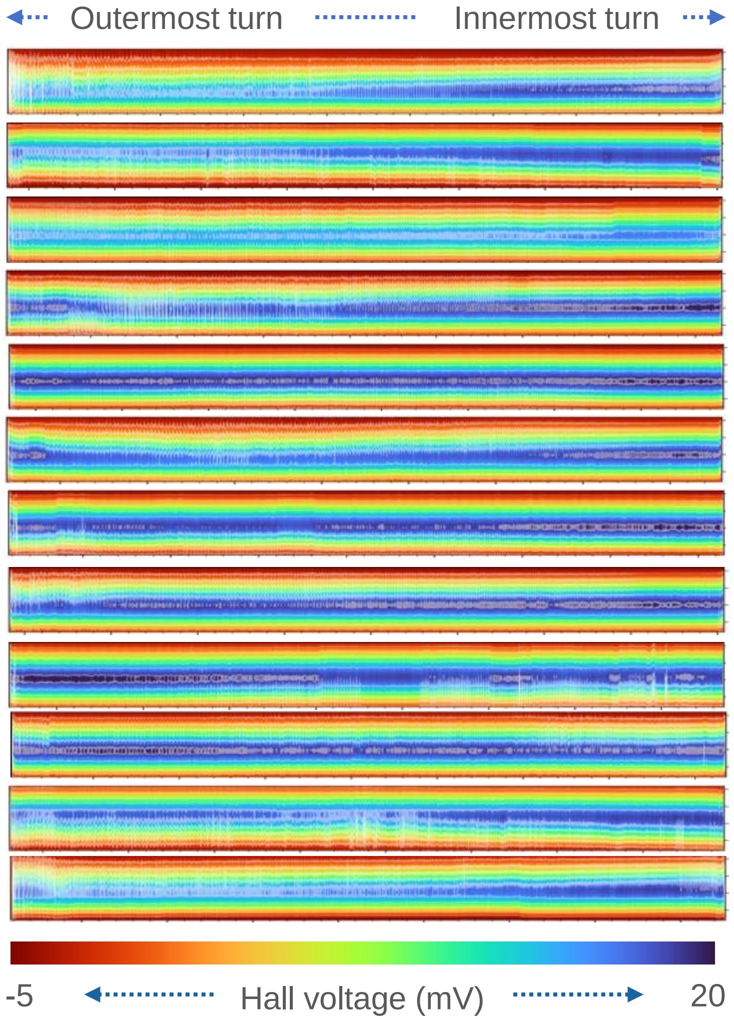
What about SST's REBCO makes it so damage tolerant?



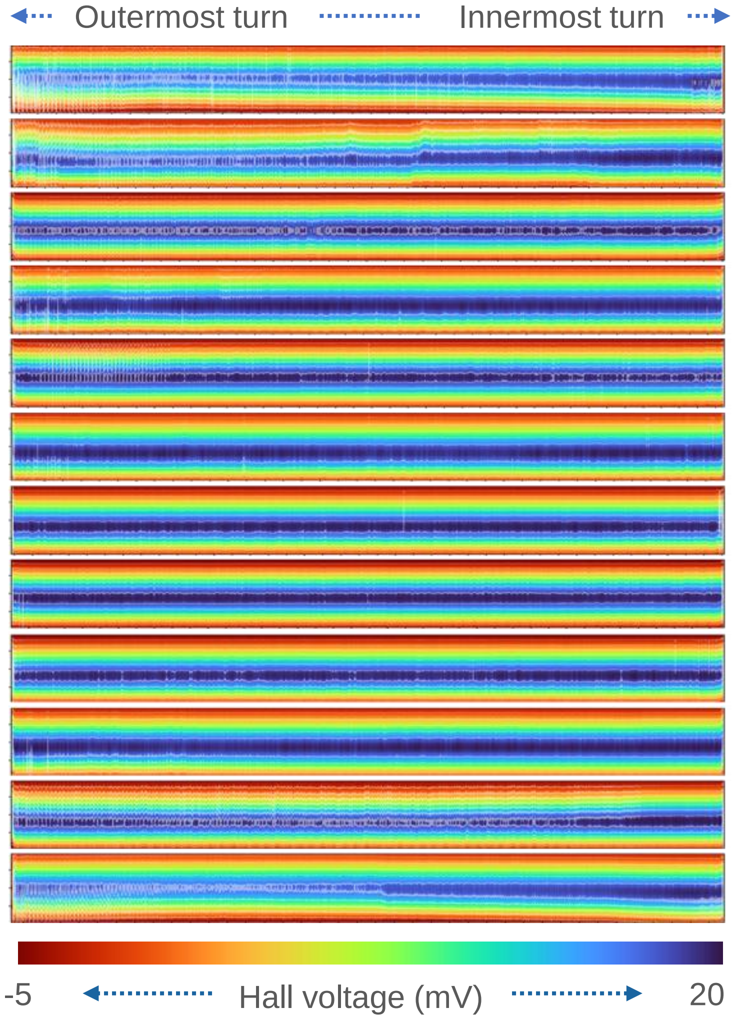


Plastic conductor deformation

LBC6 magnetization scanning results



LBC7 magnetization scanning results



Closing Thoughts

- **The subtle differences among different manufacturers' CCs have outsized impacts on LBC behavior:**
  - **SuperPower**: our "old friend" with good field-generating capability despite (or because of?) its lower I_c
  - **Faraday**: high I_c and exceptional field-generating capability but it is not trivial to control winding compressibility
  - **Shanghai**: lower field-generating capability than would be expected from its high I_c but seems to have inherent damage tolerance and quench survivability
- **There may be two distinct "styles" of NI-UHF REBCO magnet, but which is the way forward?**
  1. "Deformation training:" select a conductor with excess I_c that can be "broken in" by localized edge degradation but still have enough I_c to reach the target field
  2. "No damage:" select a conductor with barely enough I_c for the target field (or dilute with co-winding) to minimize SCS
- **Modern CCs are likely capable of reaching 50 T—the rest depends on the coil itself:**
  - LBC9 reached 48.7 T but we are still far below the theoretical current-carrying capacity of the conductor
  - We are testing different modified LBC designs with improved joints, temperature management, and stress management

"ASC LBC factory is running actively, never stops!," but we need *extensive conductor characterization* for UHF REBCO solenoids

- All these data must be leveraged by a combined electromagnetic-mechanical-thermal simulation which accounts for screening current stresses

The Classic Techniques:

- **Lengthwise magnetization scans** (Yatestar, Tapestar, etc.) to screen all tapes for dropouts
- **Transport measurements** at actual B, T, θ (due to poor correlations across the critical surface)
- **Stress-strain curves** to parameterize the elastic, elastic-plastic, and plastic deformation regimes
- **Strain-transport measurements** to identify the threshold for irreversible I_c degradation
- **Thermal degradation** of all properties if intending to make a solder-potted coil

Important Active Areas of Research:

- **"Degradation resistance:"** What allows conductors to be "broken in" by SCS in a controlled manner?
- **RRR:** Can flux jumps occur in NI magnets?

The Contemporary Technique:

- **Torque magnetometry** to parameterize $I_c(B, T, \theta)$ and lengthwise variations thereof (anchored by transport measurements)

Unexpectedly Necessary:

- **Widthwise I_c inhomogeneities** via MOI or bridged transport measurements (useful to juxtapose with microstructure via plan-view SEM)
- **Winding practice** to find appropriate techniques for generating a stable coil pack (including preconditioning/flattening by repeated respooling)
- **Torque measurements at variable T** since even 4.2 K coils will run hot
- **Lengthwise ab-plane offset measurements using** torque or XRD combined with careful orientation tracking

Thank you for your attention!