20 K test of ExoCable epoxy impregnated coils

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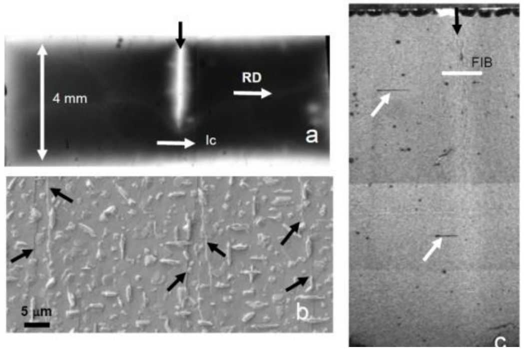
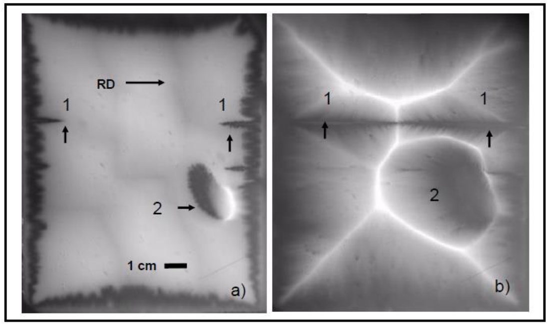
Motivation: we need defect tolerant cable

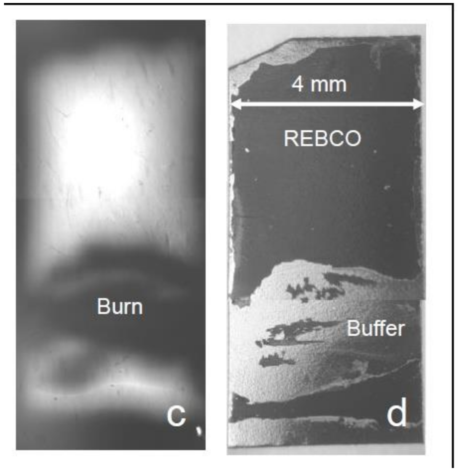
Across-tape defects



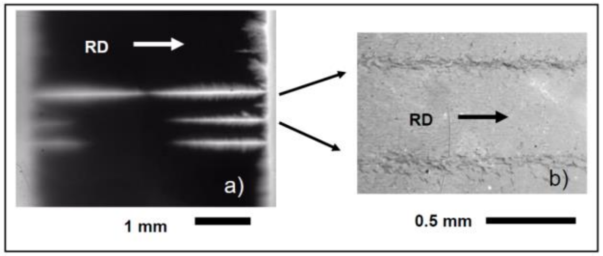
Deposition malfunction



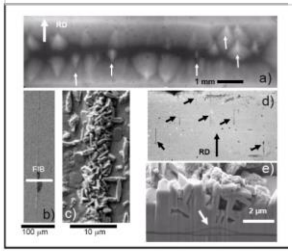
Some defects emerge during coil operation



Along-tape defects



Epitaxy failure



Courtesy of Anatolii Polyanskii
NHMFL

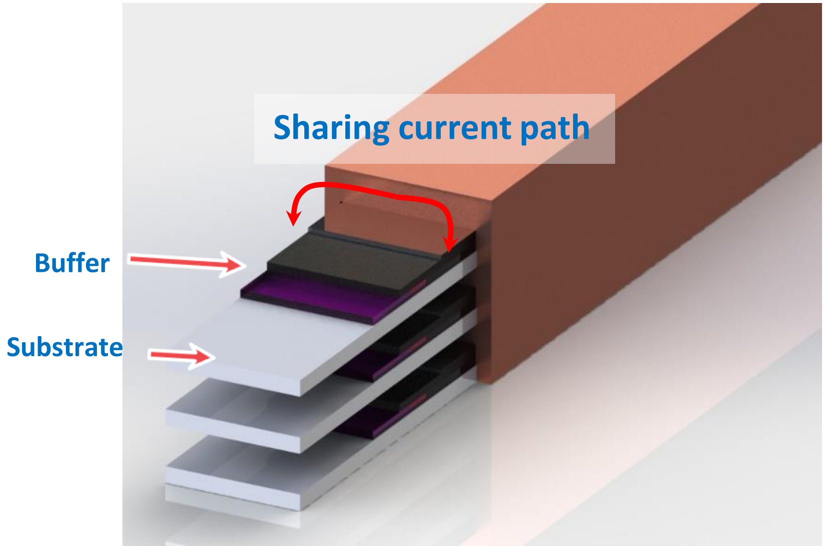
- ✓ Avoiding defects in YBCO layers is difficult
- ✓ Some defects are hidden, get revealed only after coil tests

Solution: electrically coupled cable

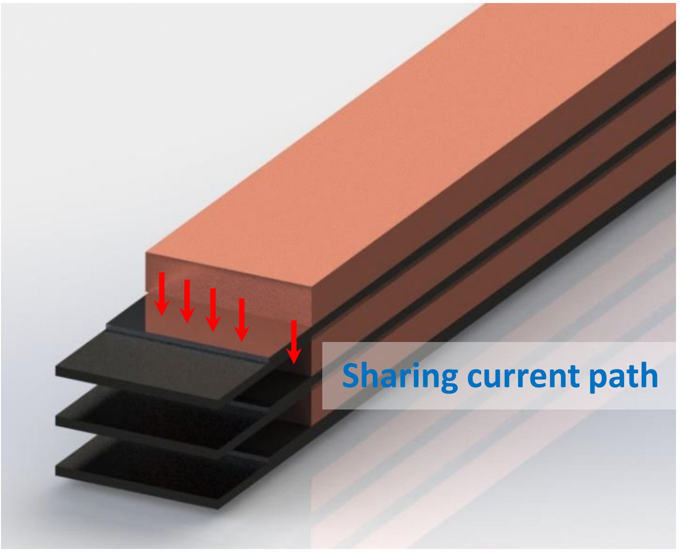
We are solving the following problems:

- Single-filament magnets proven difficult to protect against burnout
- Substrate prevents efficient current sharing
- Multifilamentary cable is far more expensive than a single tape
- Not compatible with epoxy impregnation

2G wire stack



BTG exfoliated filament stack



Timeline of the exfoliated YBCO development

Irradiation enhancement

Double sided tape

Trapped field coils

EERE AMO BAA: AMSC, BTG, BNL

10 cm coupons

2 m coupons

2.5 mm laser sliced

1 mm filaments

15 m cable
20 K coil tests

YBCO on insulator

Current leads

Signal lines

Cables

Transposed cable
Distributed splices

Phase I HEP

Phase II HEP

Phase I HEP

Phase I Fusion

2015

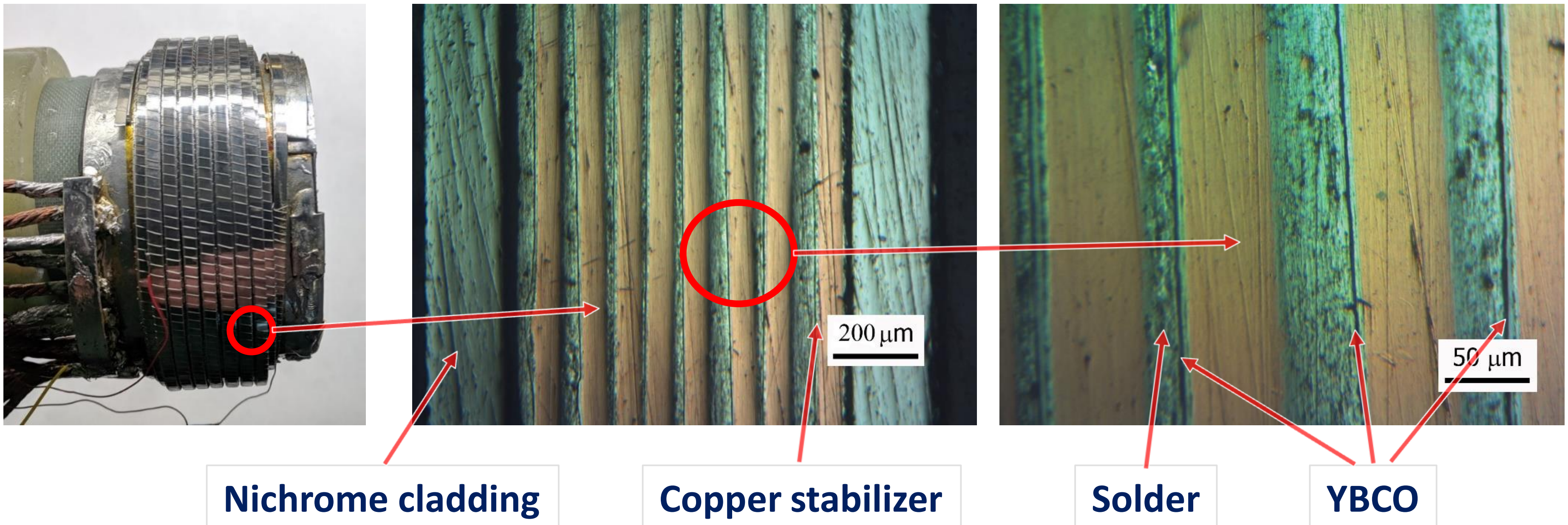
2016

2017

2018

2019

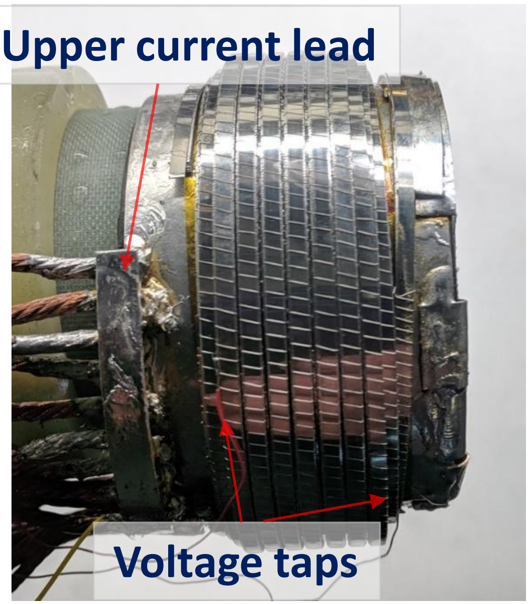
Multi-filamentary cable architecture



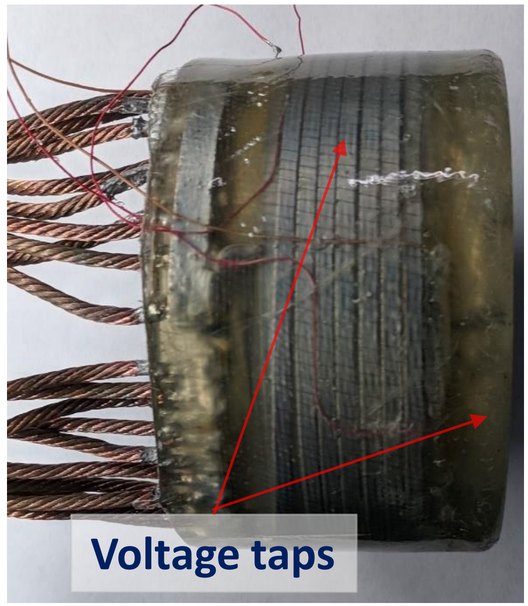
- ✓ **Electrically connected filaments are the key element for a stable cable structure**

Test coil manufacturing process

Dry wound



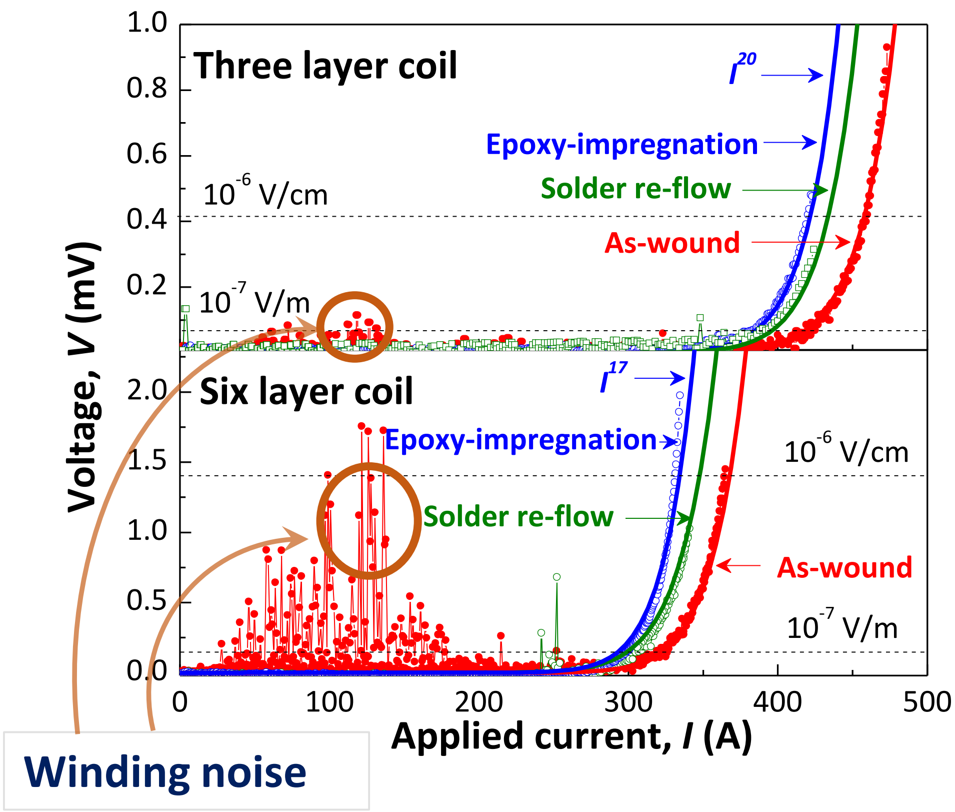
Vacuum impregnation, Stycast 1266

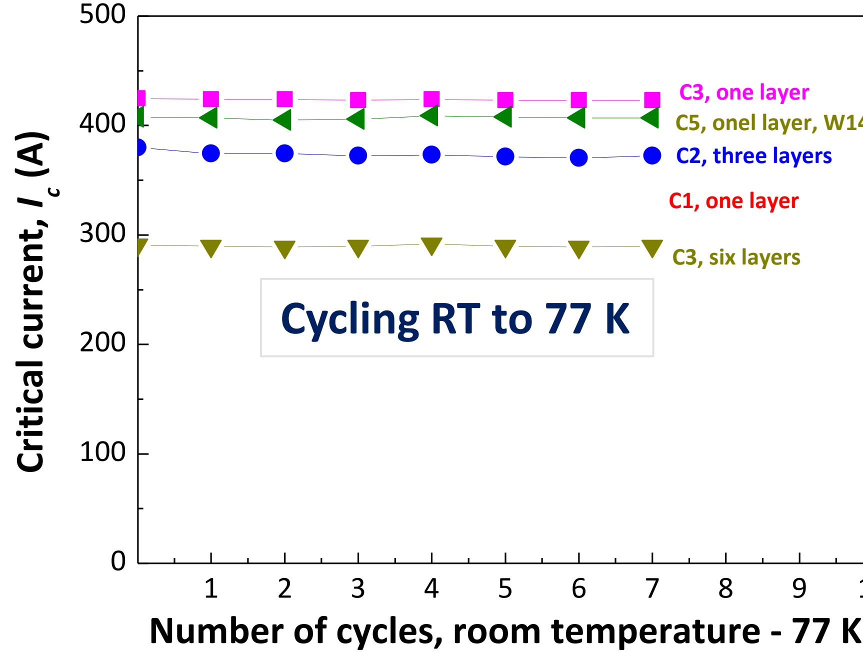


Cooling collar attached

12 coils, over 100 meters of cable tested

77 K performance after re-flow and impregnation

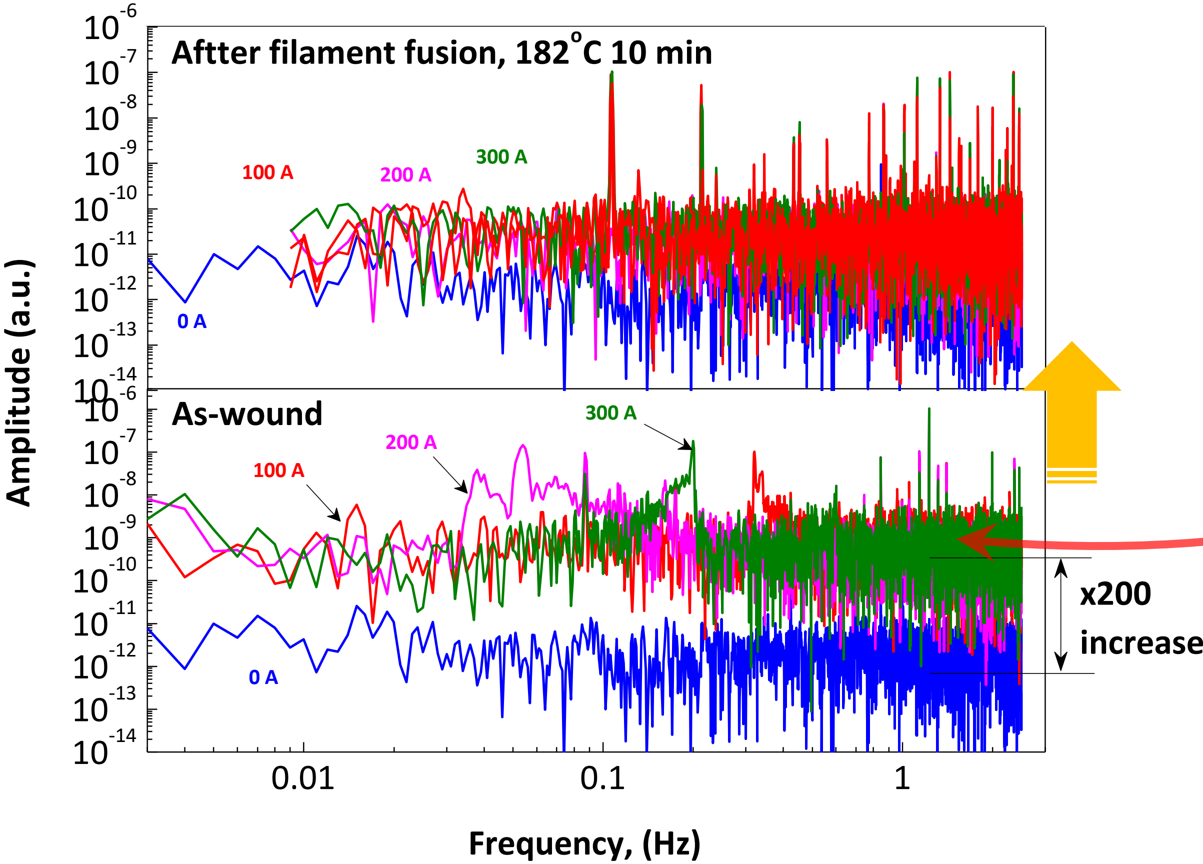


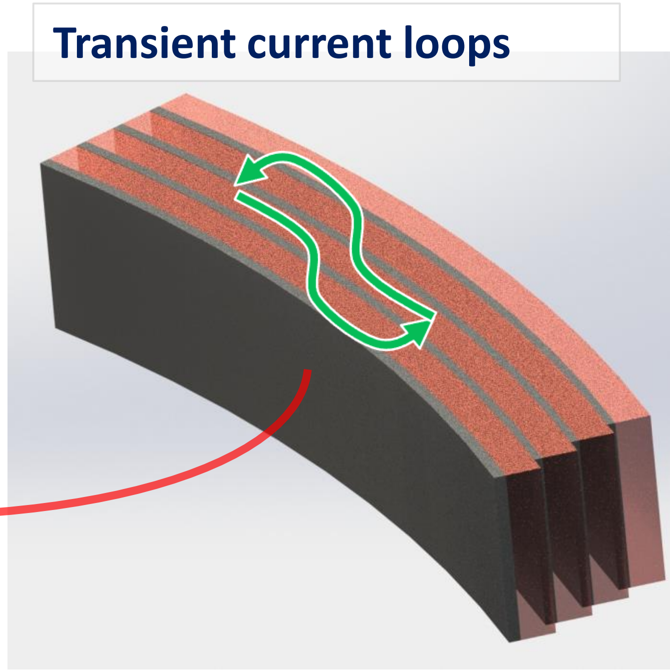


✓No Ic and n-value degradation after multiple rapid cool-downs to 77 K

✓Solder reflow significantly reduces the winding noise, but reduces I_c by 8%

Effect of solder re-flow on the winding noise: FFT of coil signal

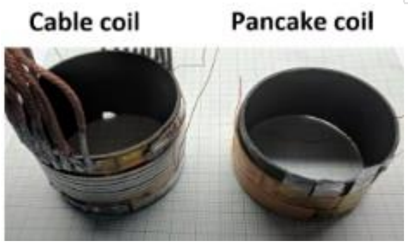


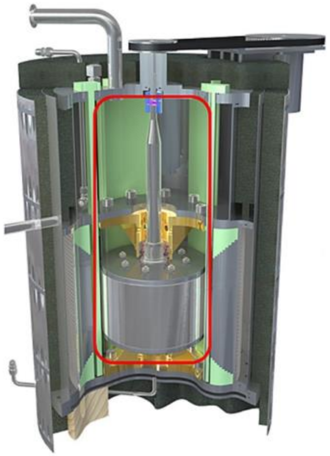


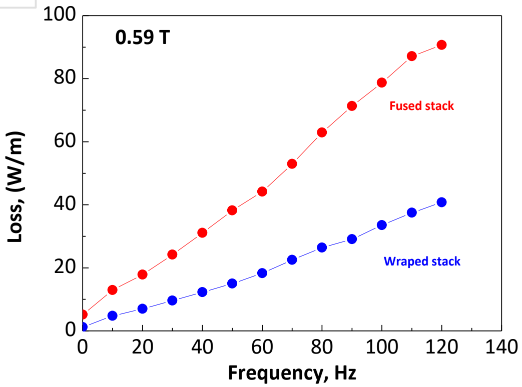
- ✓ Winding noise is most likely originates by collapse of inter-filament current loops
- ✓ Reliable electrical connection between the filaments is essential in suppressing the winding noise

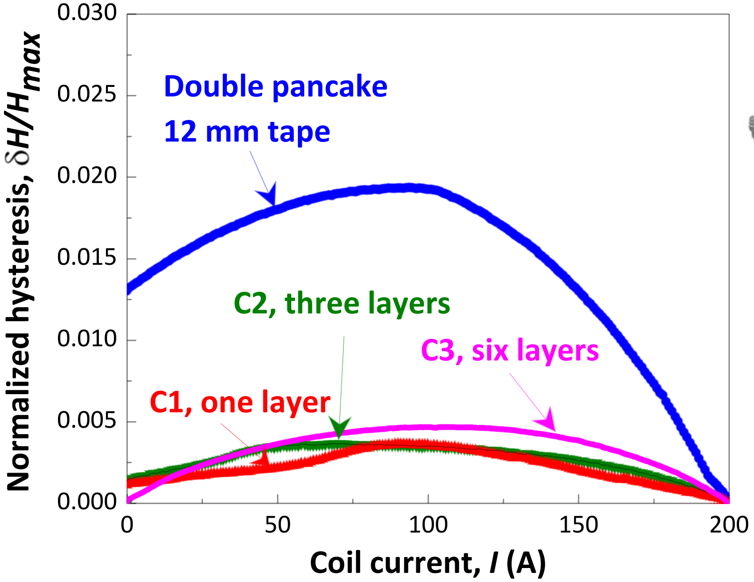
High field AC loss and field error (winding magnetization)

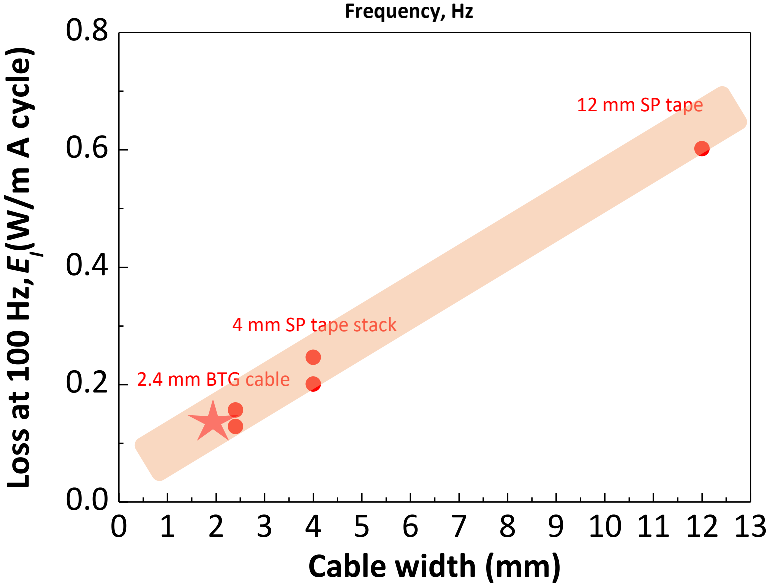
0.6 Tesla AC loss measurement





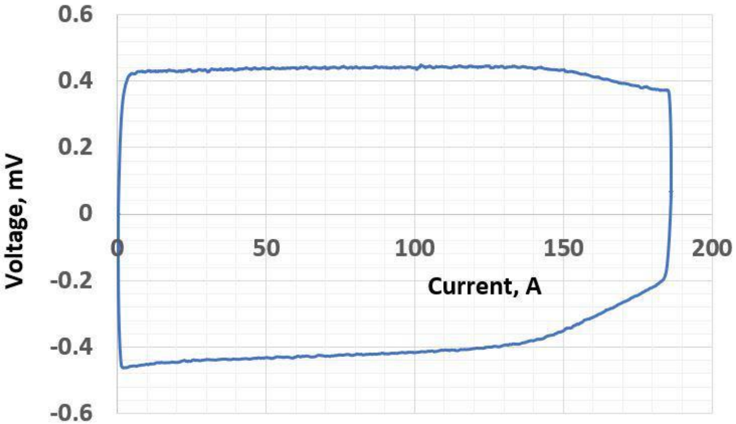


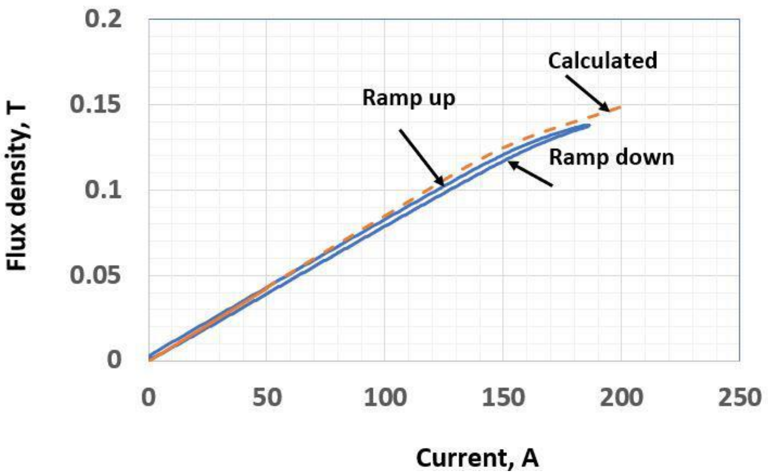




- AC los and field error is reduced proportionally to the filament width

Technology deployment: quadrupole coil for Fermilab

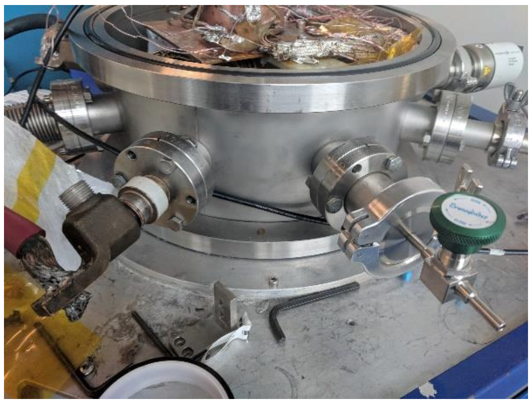




- ✓ **Layer-wound, epoxy impregnated Exocable coil was tested independently in a quadrupole structure by FermiLab**

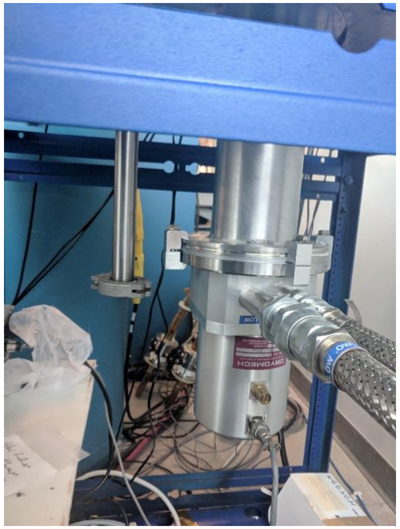
25 K testing-conduction cooled

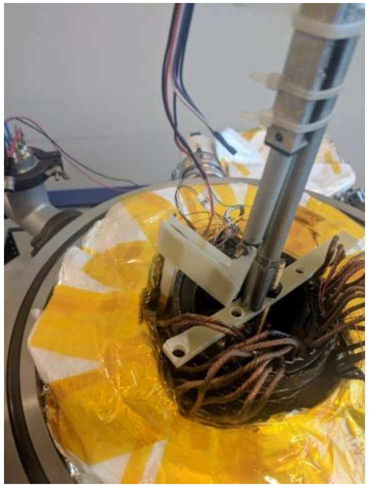
12” chamber



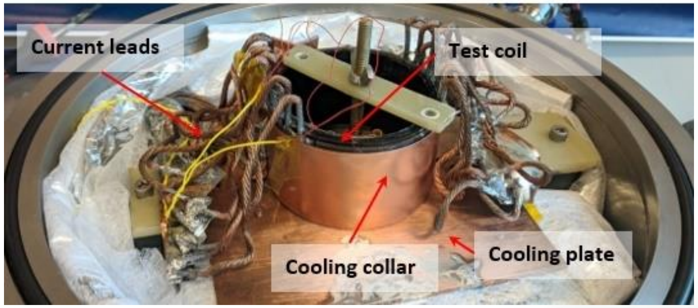
Cryomech compressor

Cryomech coldhead



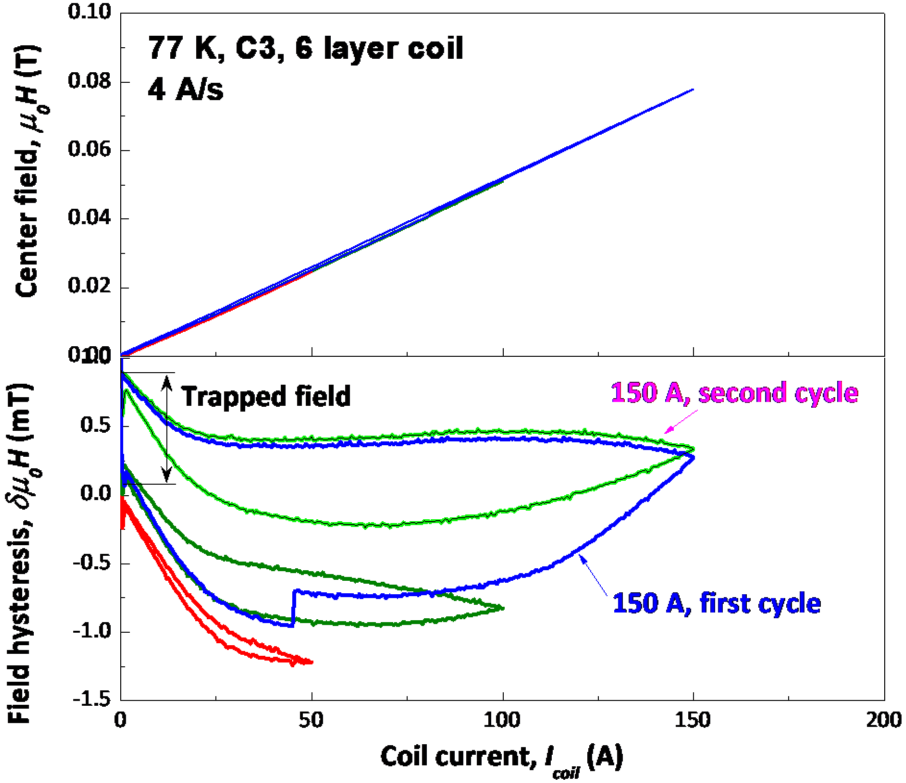


Mounted coil
With scanning Hall probe

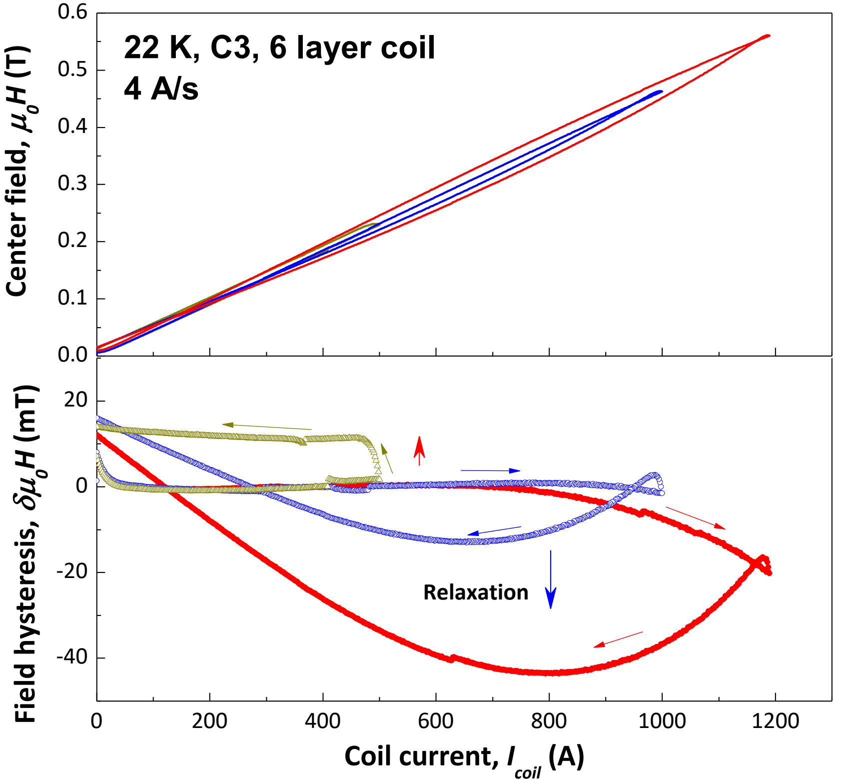


Central field hysteresis at 77 and 25 K

77 K



22 K



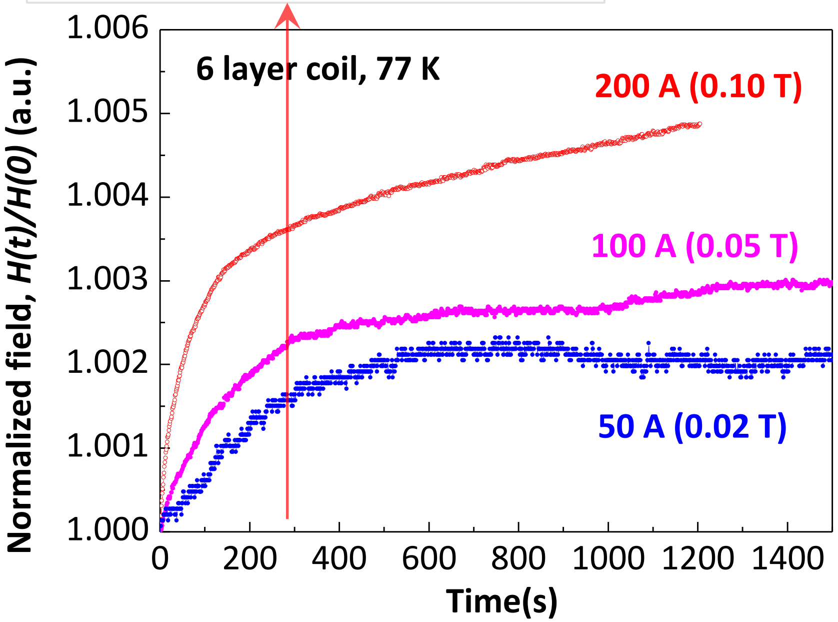
✓At 22 K field dynamics is defined by relaxation at high currents

✓The coil excited up to **1,300 A, generation 0.7 T in the center**

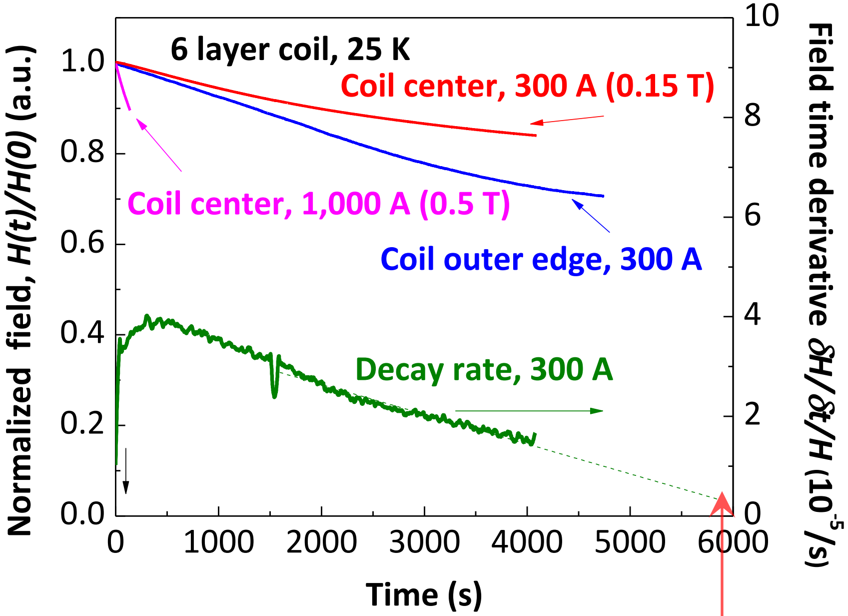
Flux dynamics at 77 and 25 K

77 K

Settling time 3 min at 0.1 T



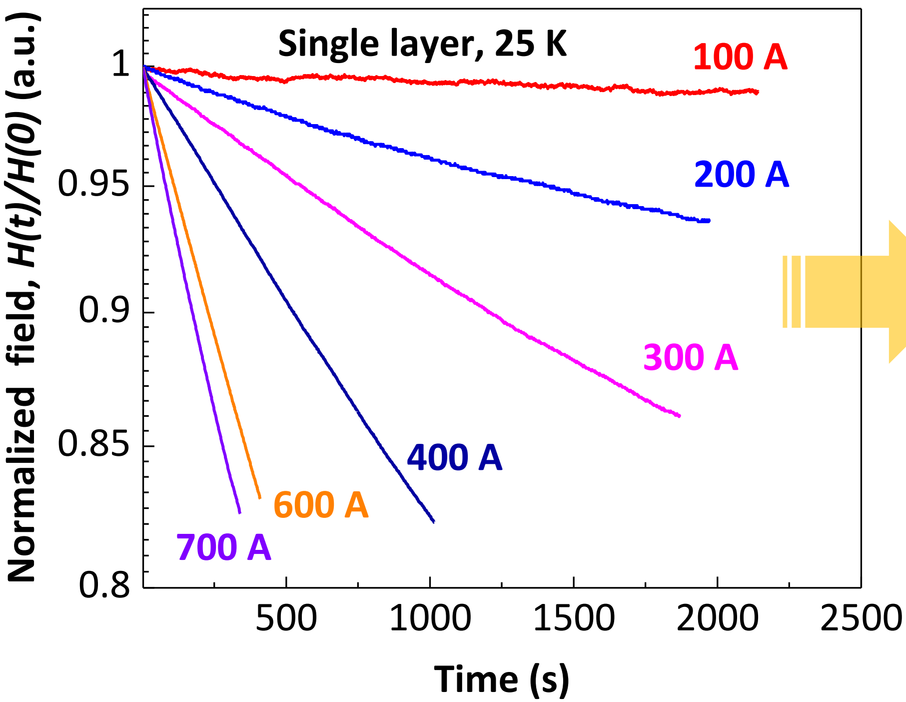
25 K

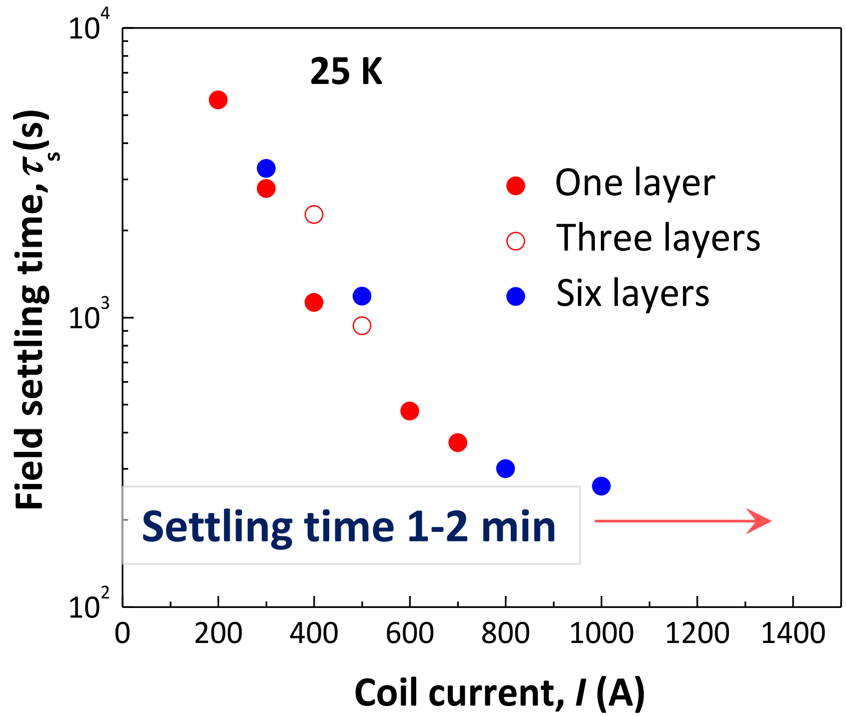


Settling time 2 hrs at 0.1 T

- ✓ Completely different field settling profile at 77 and 25 K
- ✓ The field increases at 77 K and decreases at 25 K

Field settling time for flat cable coils

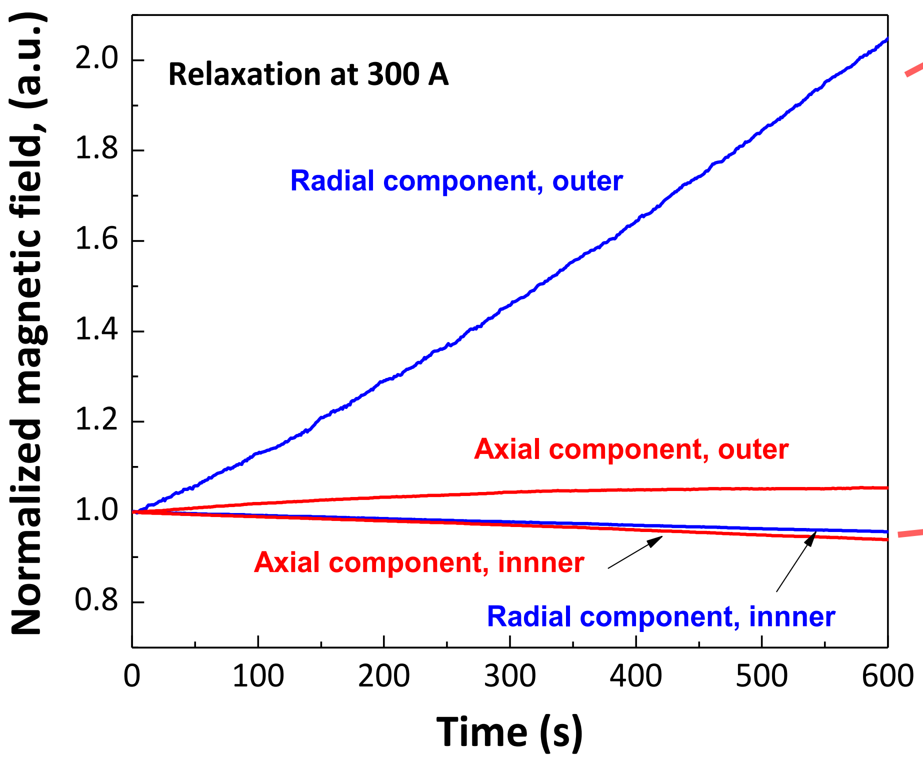


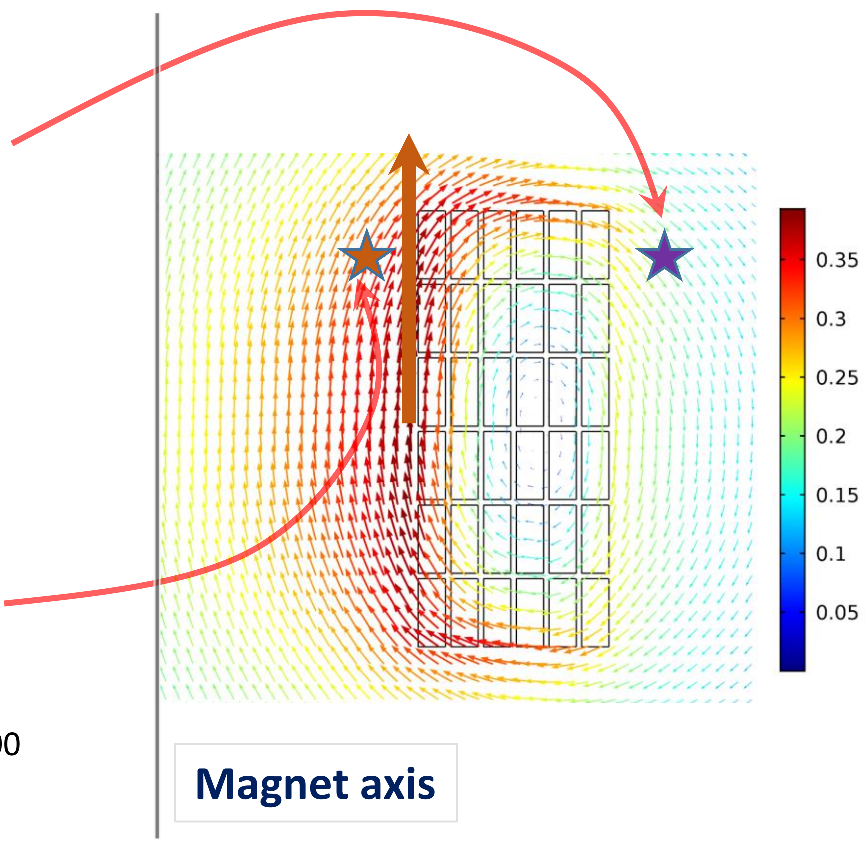


✓Field settling time strongly depends on current: not just coupling

✓The time does not depends on the cable length: coupling loops are not global

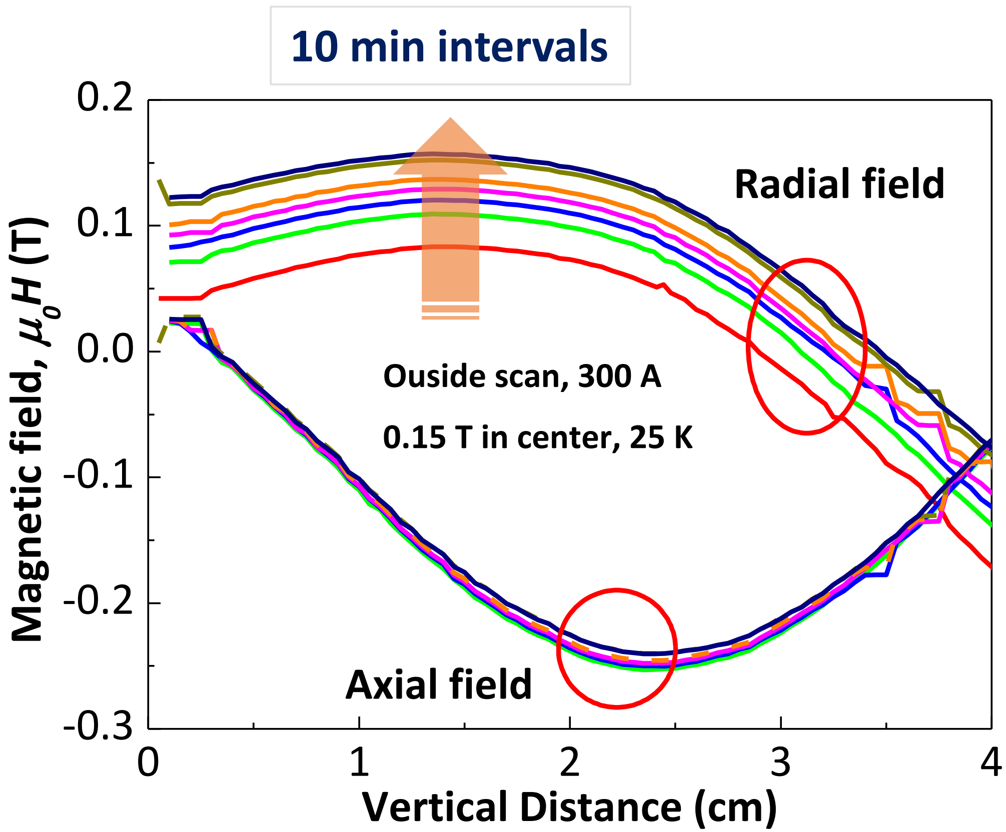
Time profile of magnetic field inside and outside the bore

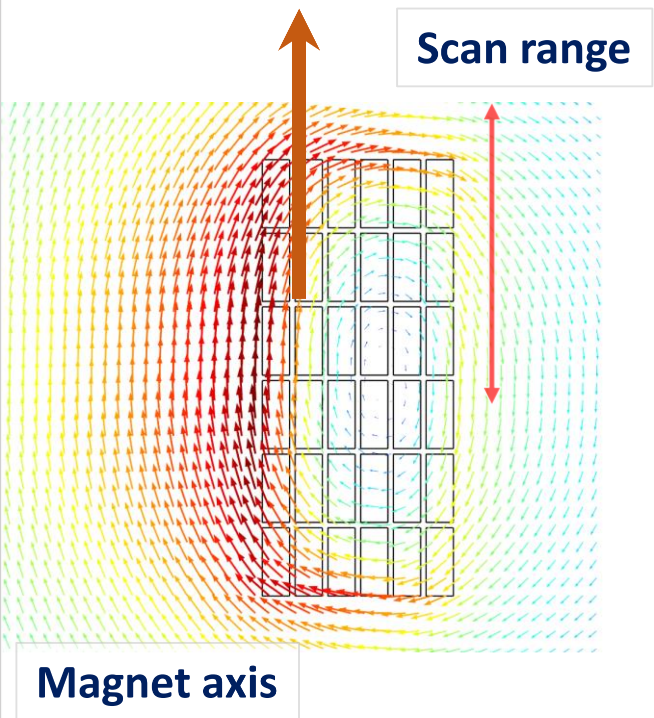




✓ The central field reduction is probably explained by the flux diffusion through the winding

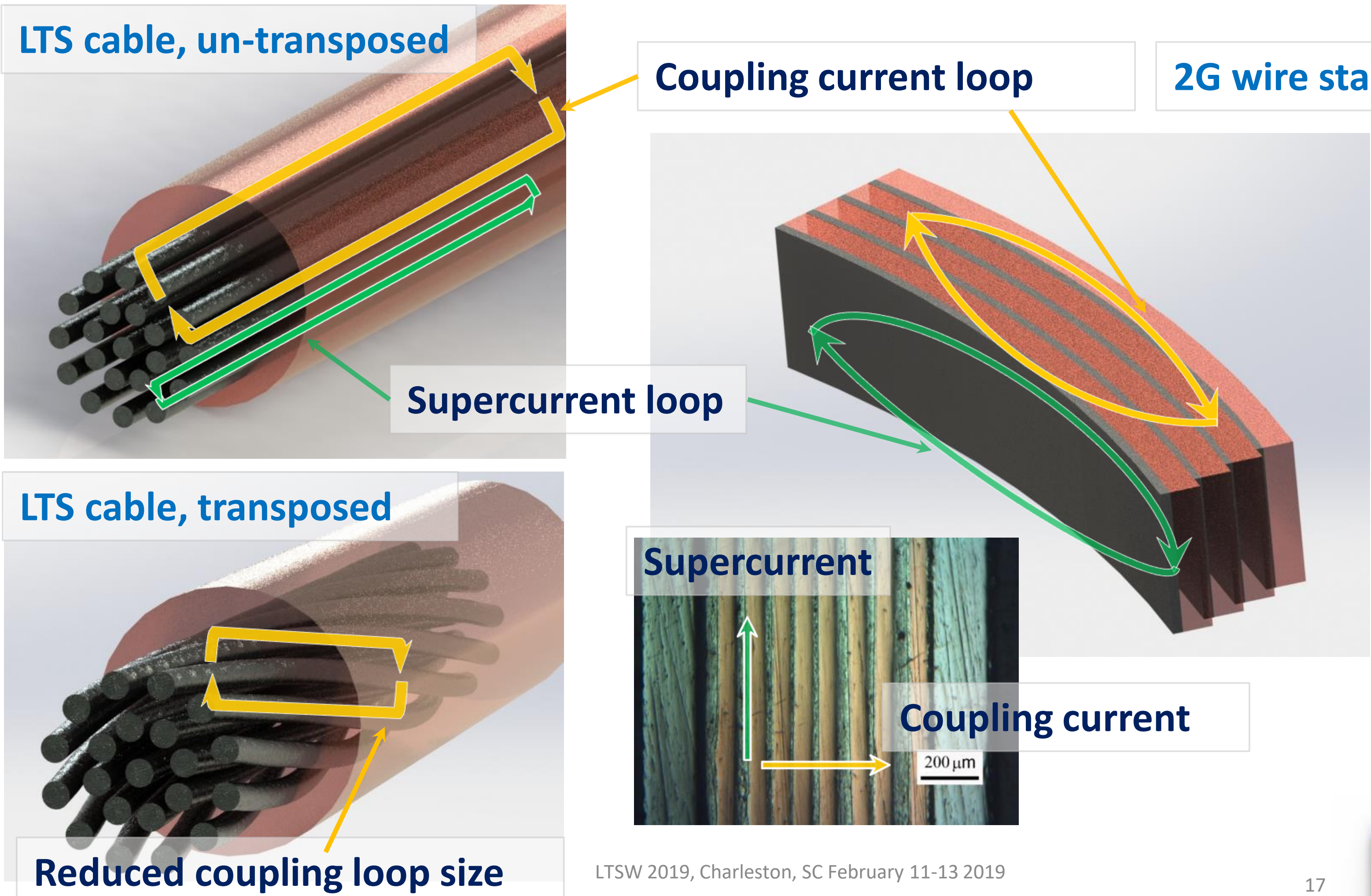
Vertical Hall probe scan: field penetration into the winding



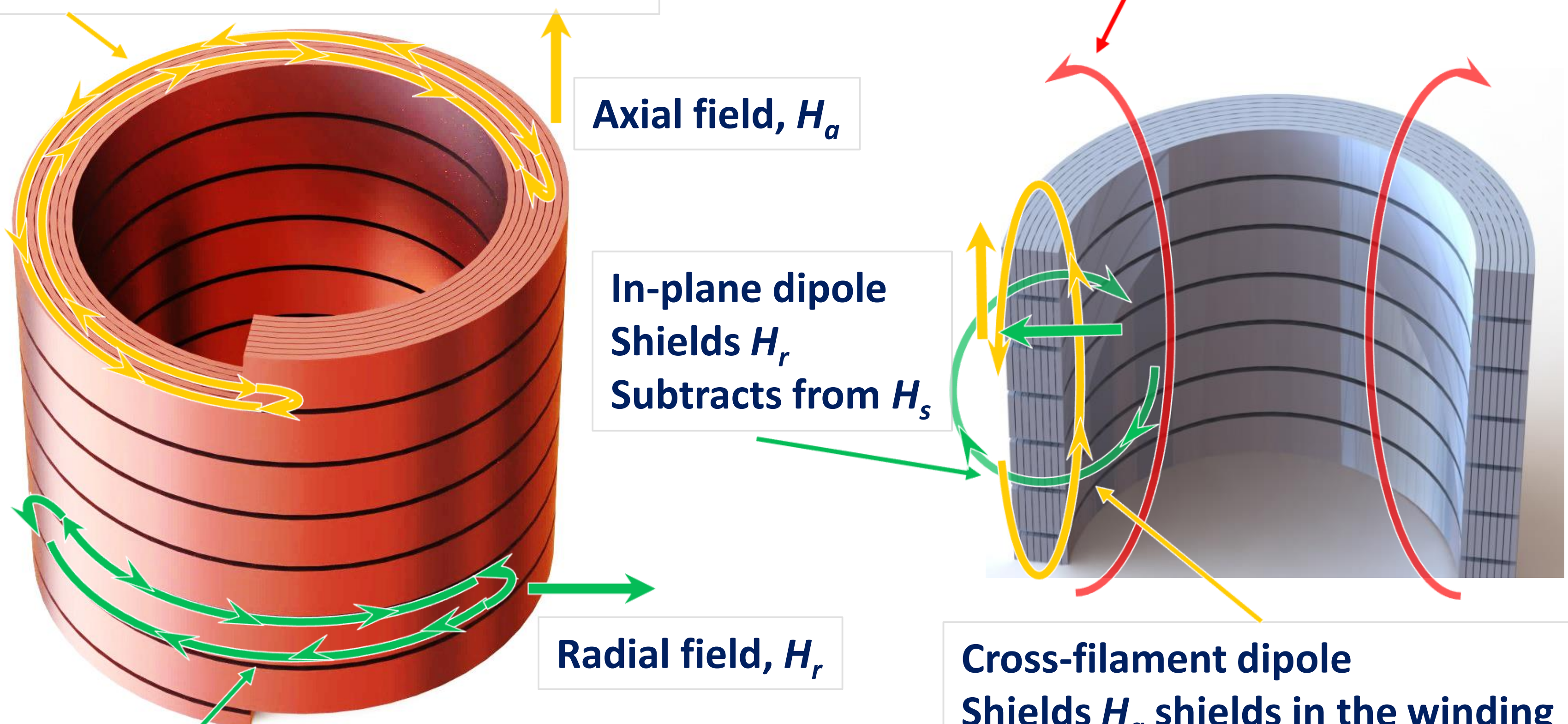


✓ **Magnetization is determined by the radial component penetrating the winding**

Coupling and supercurrents in LTS and HTS

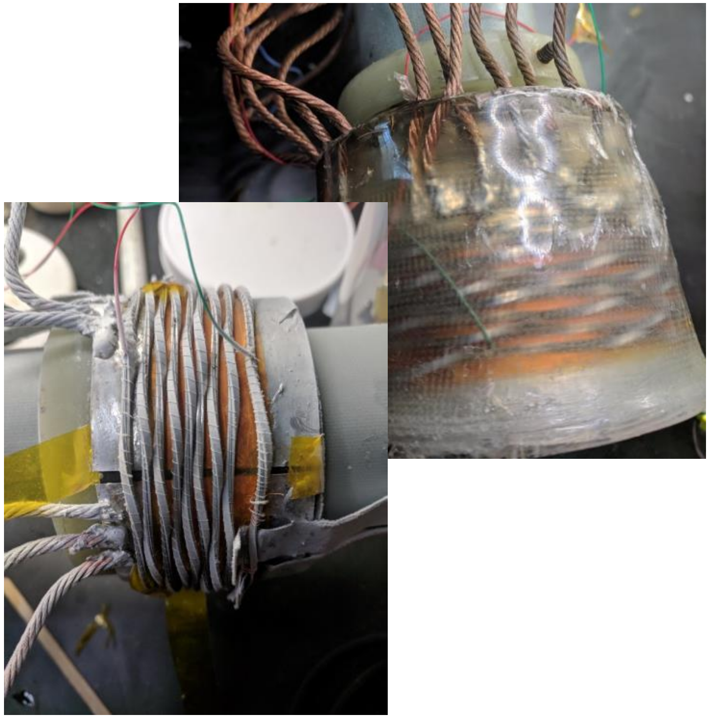


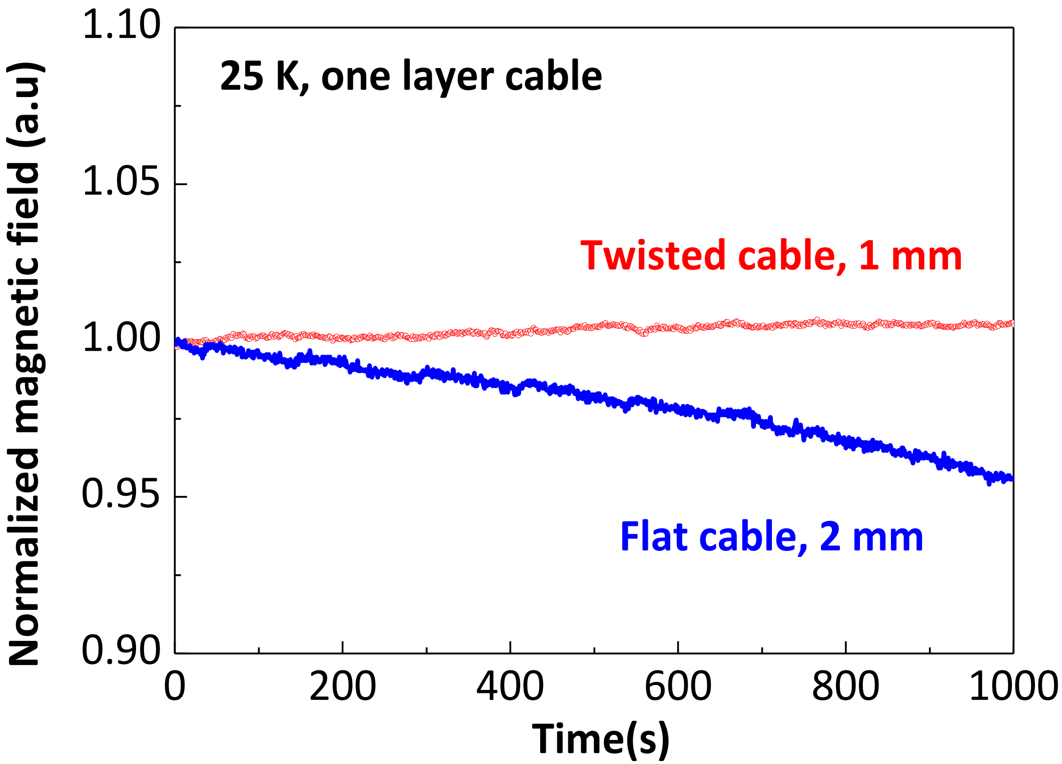
Simplified flux penetration model into a coupled cable, highly anisotropic filament



Transposition: Twisted 1 mm vs. flat 2.4 mm, 240 A at 25 K

Twisted cable coil





✓Twisting seem to improve the field stability: more tests needed

Conclusion

- Demonstrated operation of epoxy-impregnated multi-filamentary cable in conduction cooled mode
- Transposition is non-essential at 77 K: coupling current play a minimal role at 77 K
- Generated maximum 0.7 T in conduction cooled regime at 25 K
- Winding magnetization at 25 K is not well understood, transposition maybe needed due to possible coupling effects
- Testing coils at low temperature is critical
- Flux behavior at 77 K and < 30 K seems to be very different!

Acknowledgement

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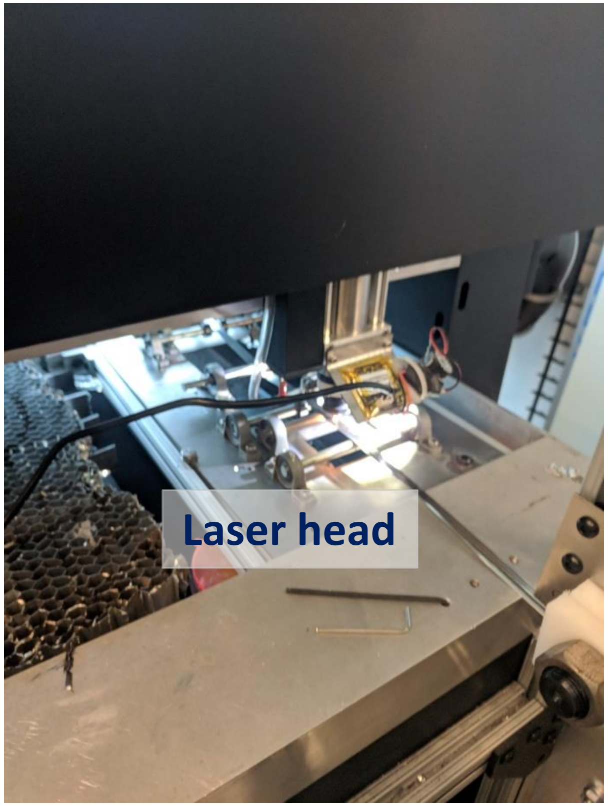
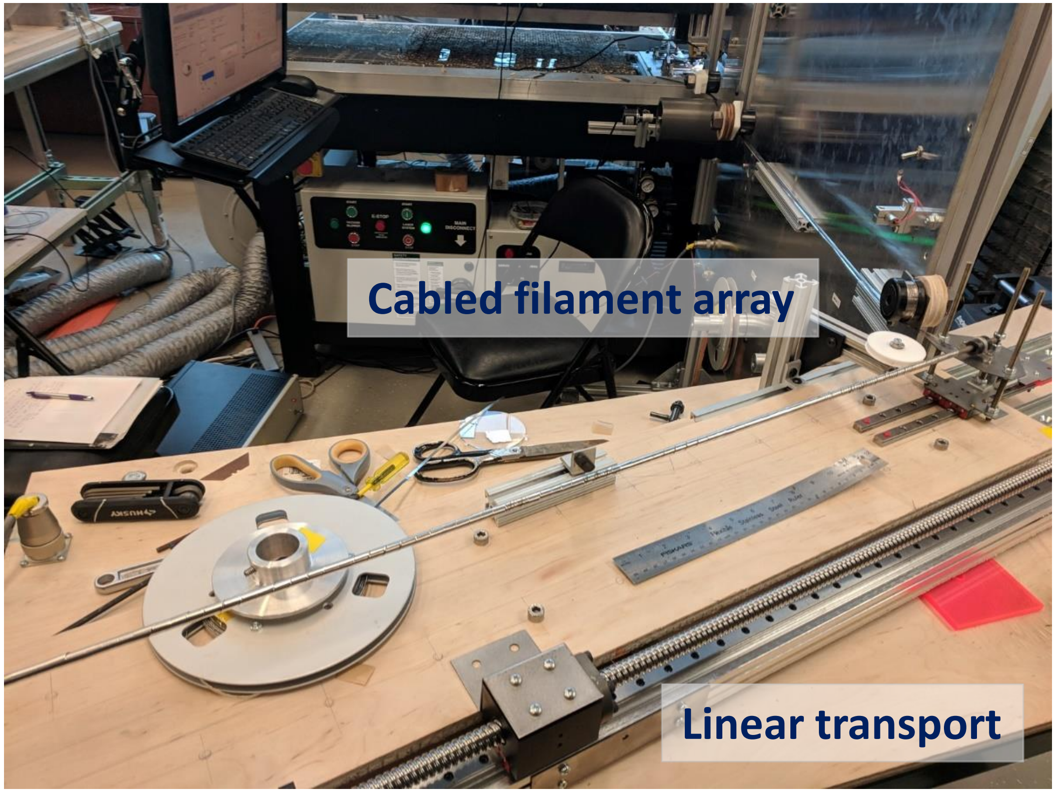
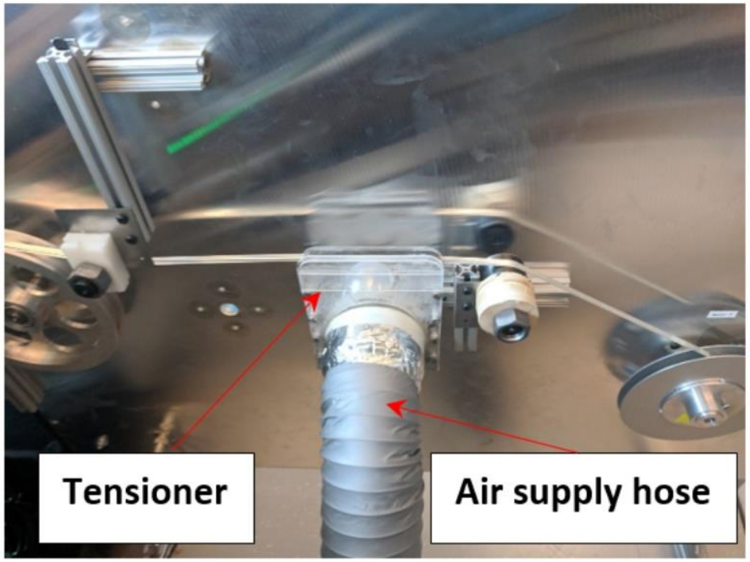
- American Superconductor Corporation
- Wright-Patterson Air Force Lab
- Fermi National Accelerator Facility
- Advanced Energy Center incubator at Stony Brook University
- Office of Strategic Partnership for Industrial Resurgence at Stony Brook University

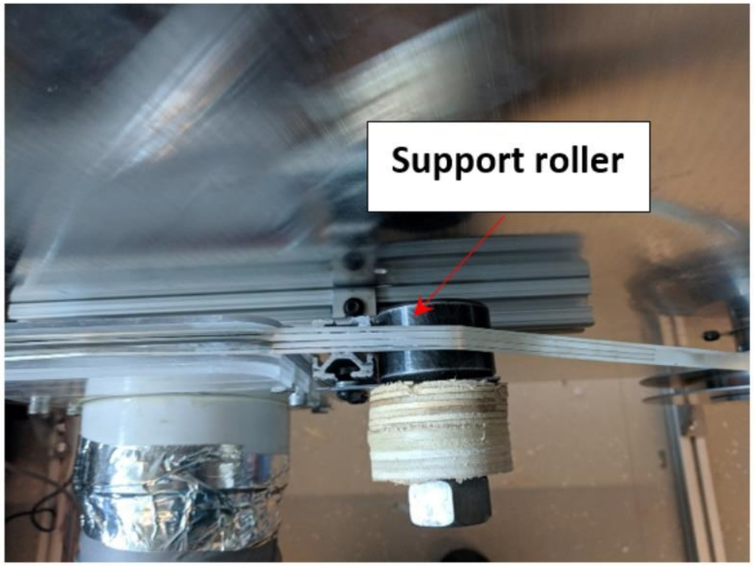
Continuous slicing and cabling: Phase I funded by Fusion Science

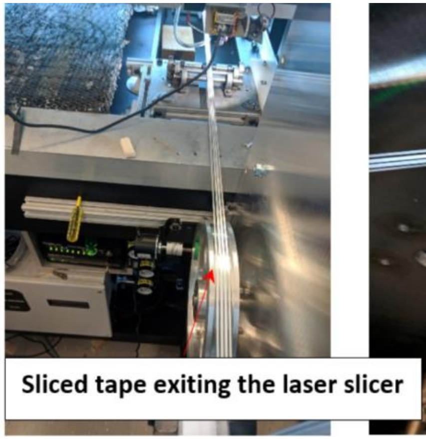


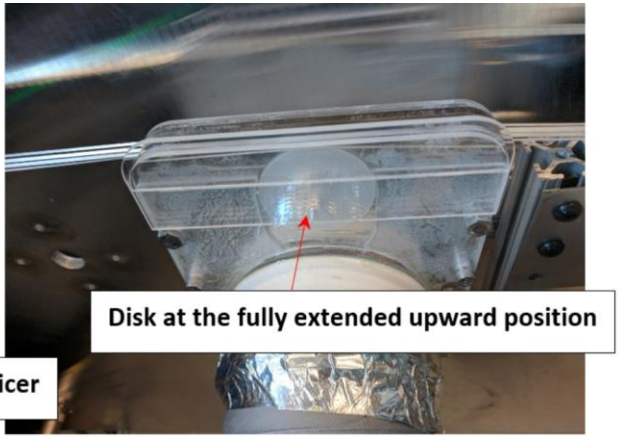


Tape tensioner operation



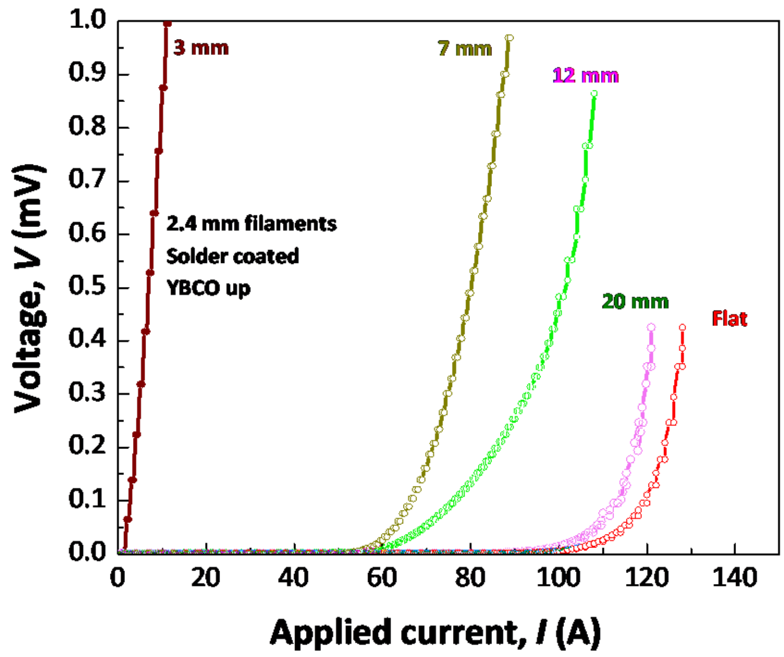


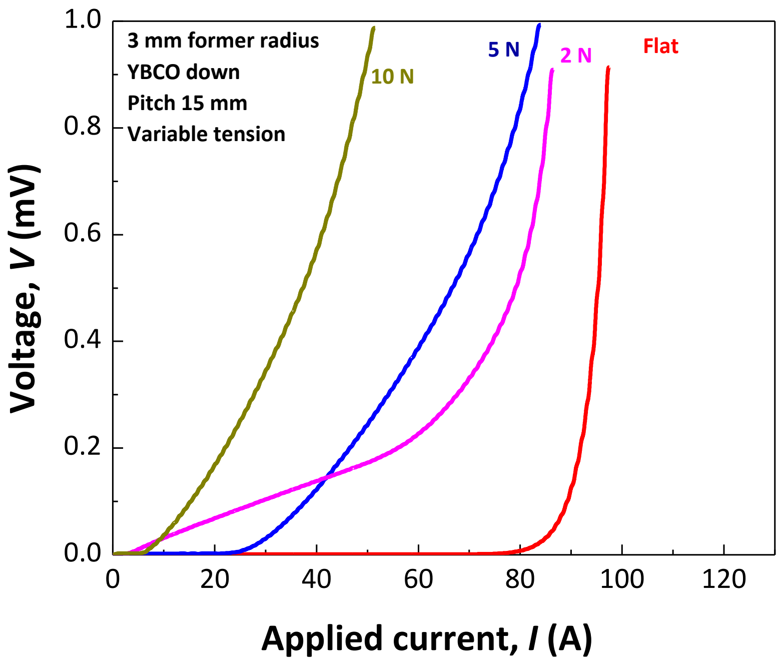




- ✓ **Tensioner tested**

Cabling of solder-coated superconducting filaments

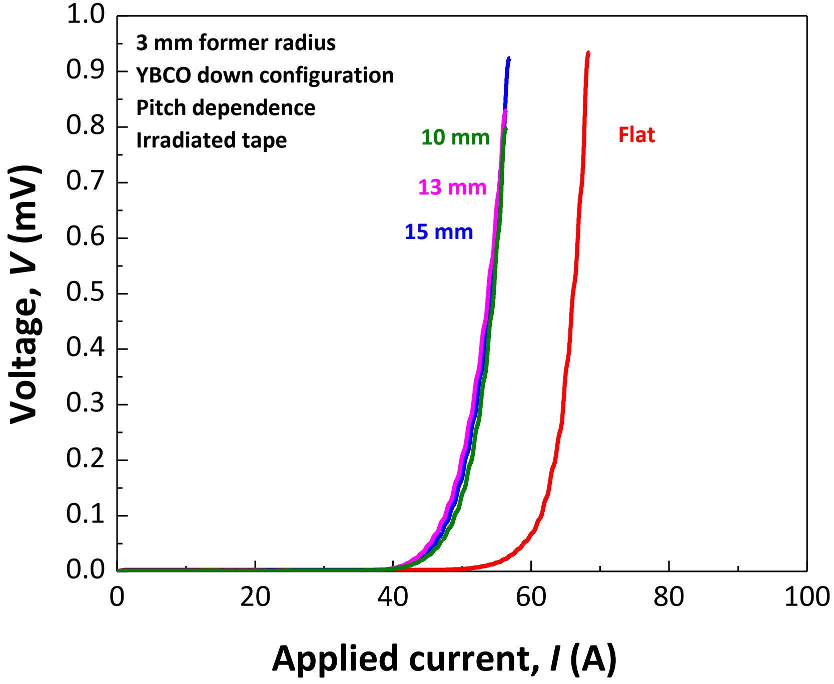




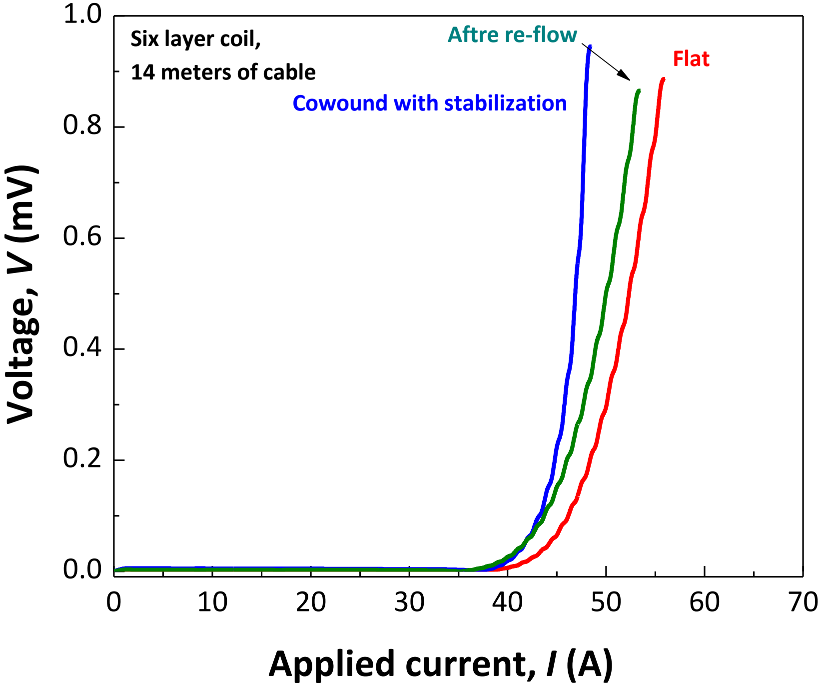
✓ **Critical bending radius of the solder-coated filaments is too large**

Uncoated tape cabling test

Cabling pitch dependence



Co-wound stabilizer



- ✓ Co-winding the stabilizer allows reducing the effect of cabling degradation
- ✓ Even narrower filaments are needed