How we torture High Temperature Superconductors at University of Twente

Anna Kario, Jeroen Boerma, Jorick Leferink, Herman ten Kate, Thomas Nes, Simon Otten, Sander Wessel

CERN: Gijs de Rijk, Glyn Kirby, Amalia Ballarino

LBNL+NHFML: Tengming Shen, Ernesto Bosque, Ulf Trociewitz, Daniel Davis

Outline

Bi-2212 Rutherford cable

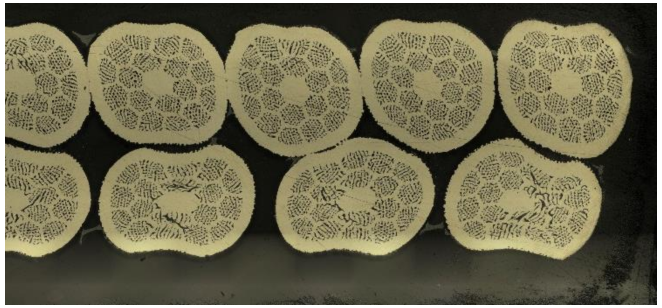
- Transverse stress examination

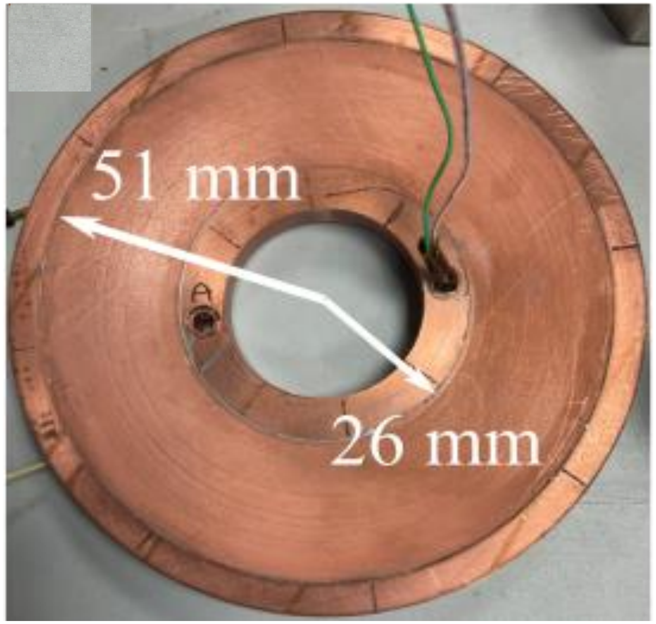
*Re*BCO pancake coils and cloverleaf

- Electromagnetic characterization at 4.2 and 77 K, self-field
- Electromagnetic, mechanical and microstructural post-mortem study of *Re*BCO material

Plans for future torturing

- Electromagnetic, mechanical and microstructural study of *Re*BCO tapes





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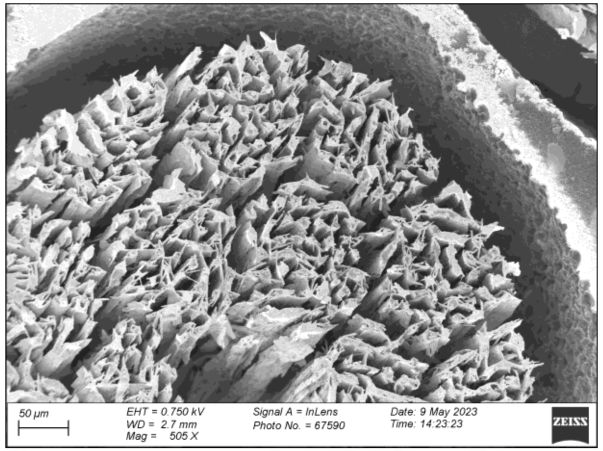
Rutherford BSCCO-2212 cable samples

- **Sample 3:** LBNL1109, 17-strand subscale magnet and CCT magnet cable, nominal 7.8 mm x 1.4 mm, non-twisted PMM180207_4, 5, 6, 7, 55 x 18, 0.8 mm, Engi-mat powder LXB103

- **Sample 4:** LBNL2002, 17-strand subscale magnet cable, nominal 7.8 mm x 1.4 mm, PMM190118, 55 x 18, 0.8 mm, Engi-mat LXB156



Transverse pressure measurement: two BSCCO-2212 Rutherford cables

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Sample comparison

- **Sample 3:** LBNL1109, tested **Dec 2022**
- **Sample 4:** LBNL2002, tested **June 2023**

- **Sample 3:** LBNL1109, I_c of **2.70 kA**
- **Sample 4:** LBNL2002, I_c of **4.07 kA**

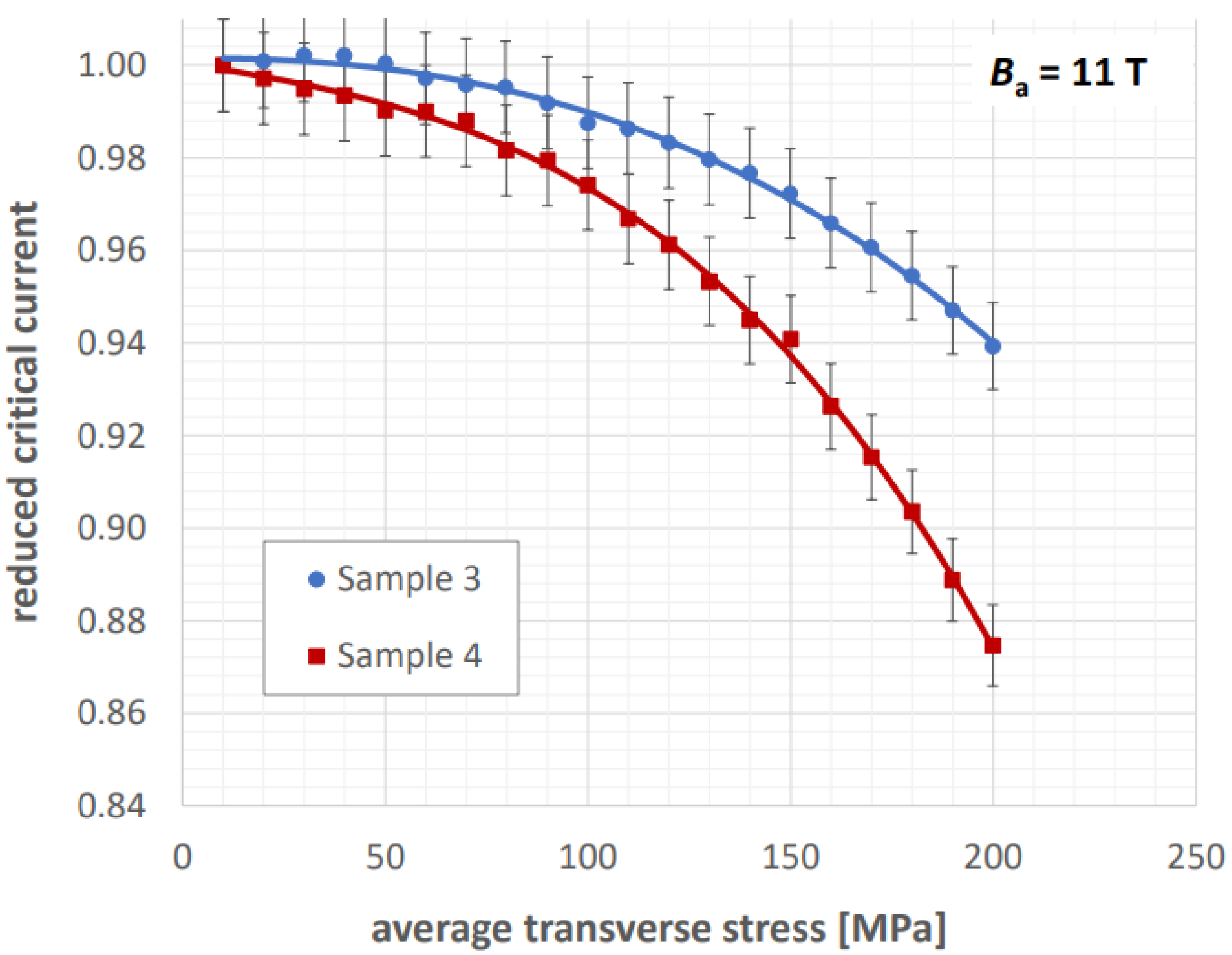
Stronger stress dependence observed in sample 4, at 150 MPa:

- **Sample 3** has **3%** degradation, whereas
- **Sample 4** has **6%** degradation

- No reversible I_c change observed

- **Globally, from a magnet application point of view, the samples behave practically the same.**

Critical current as function of transverse stress



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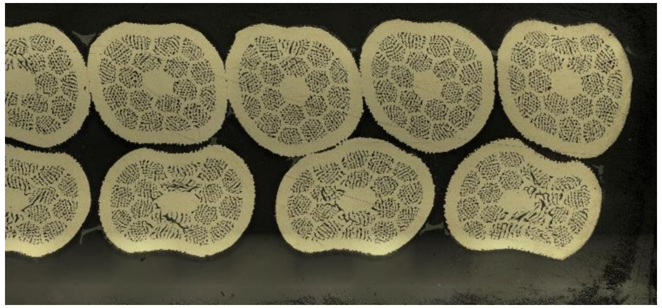
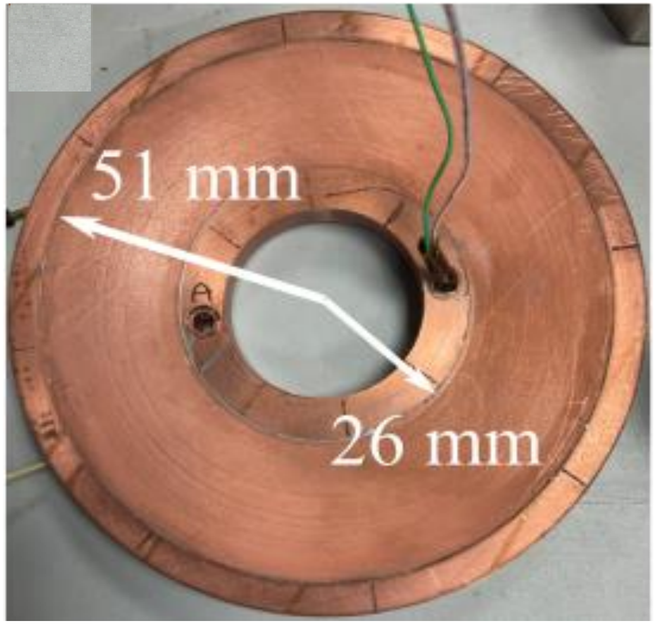
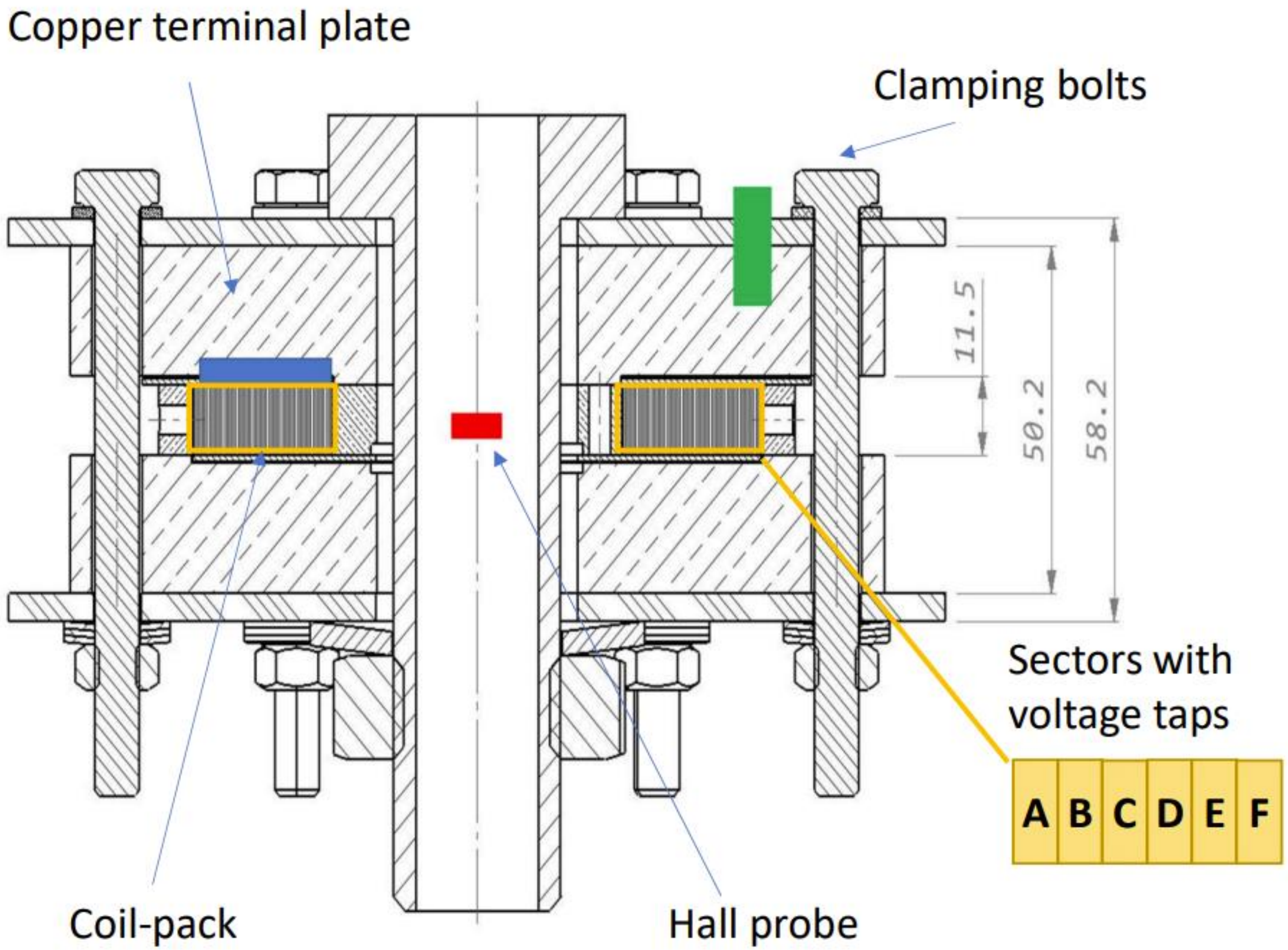
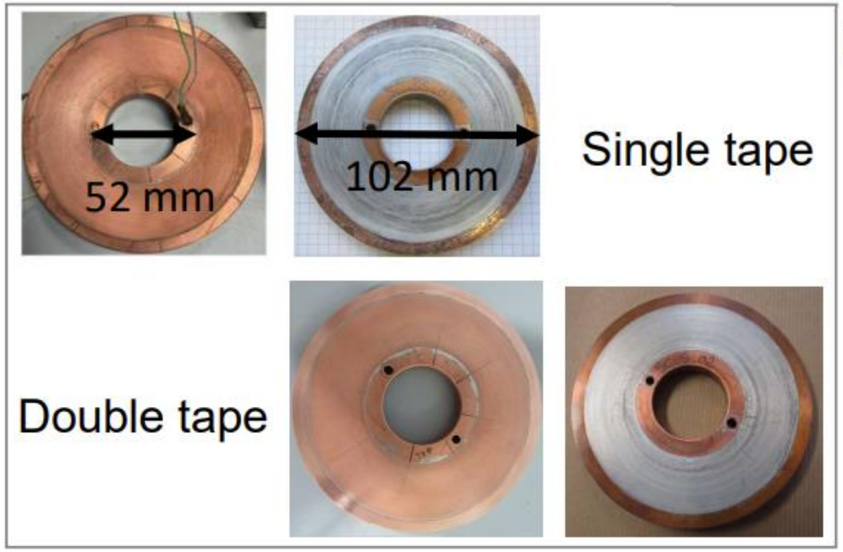




*Re*BCO coil in external magnetic field at 4.2 K

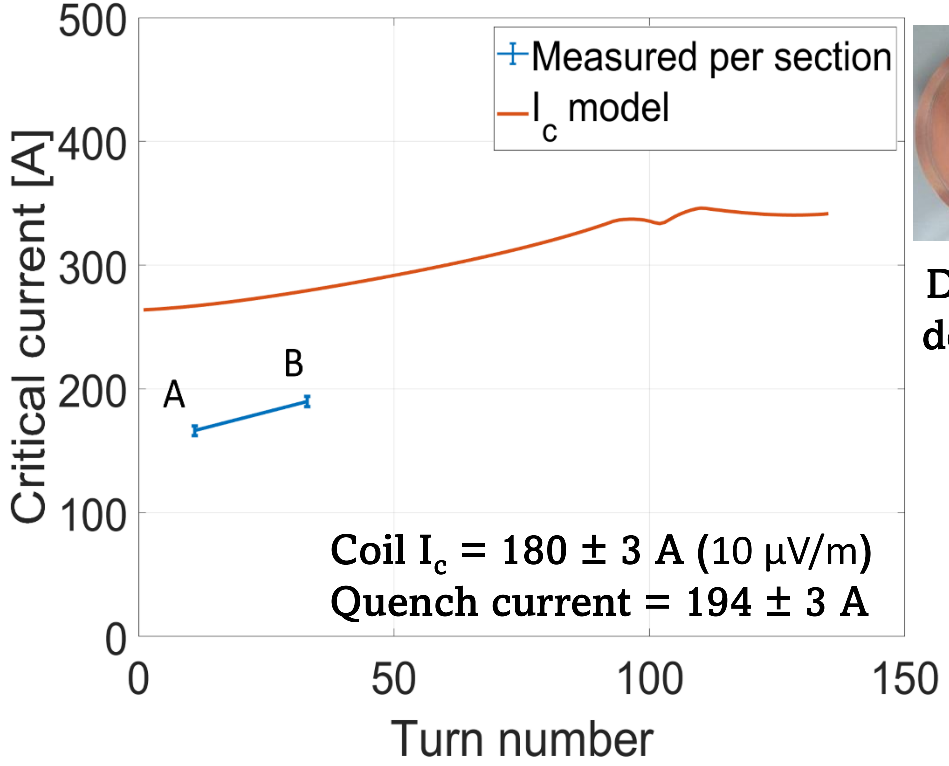


- T. H. Nes et al, IEEE TAS 32 (4), 1-6, 2022

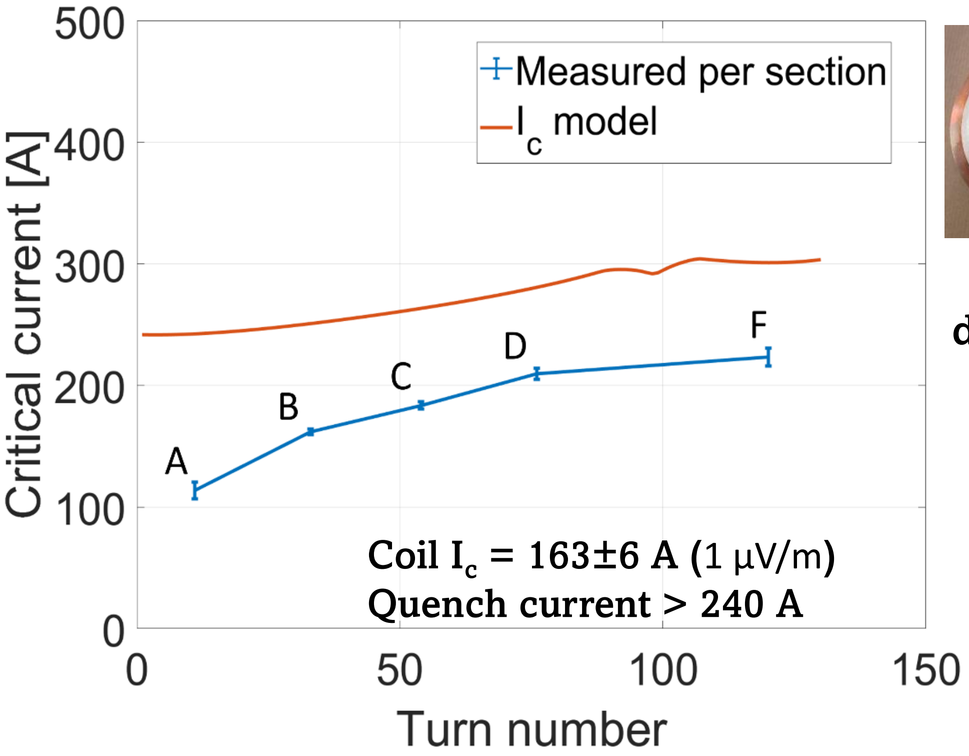


- Tape from Shanghai Superconductor
  - 10 mm wide, 0.1 mm thick
  - Tape Ic = 380 A at 77 K
- Critical surface estimated using fit of data from Wellington University:
  - http://htsdb.wimbush.eu/
  - data range between 20-90 K
  - < 20 K Ic extrapolated using fit

Critical current of the double-tape wound pancake coils at 77 K, self-field



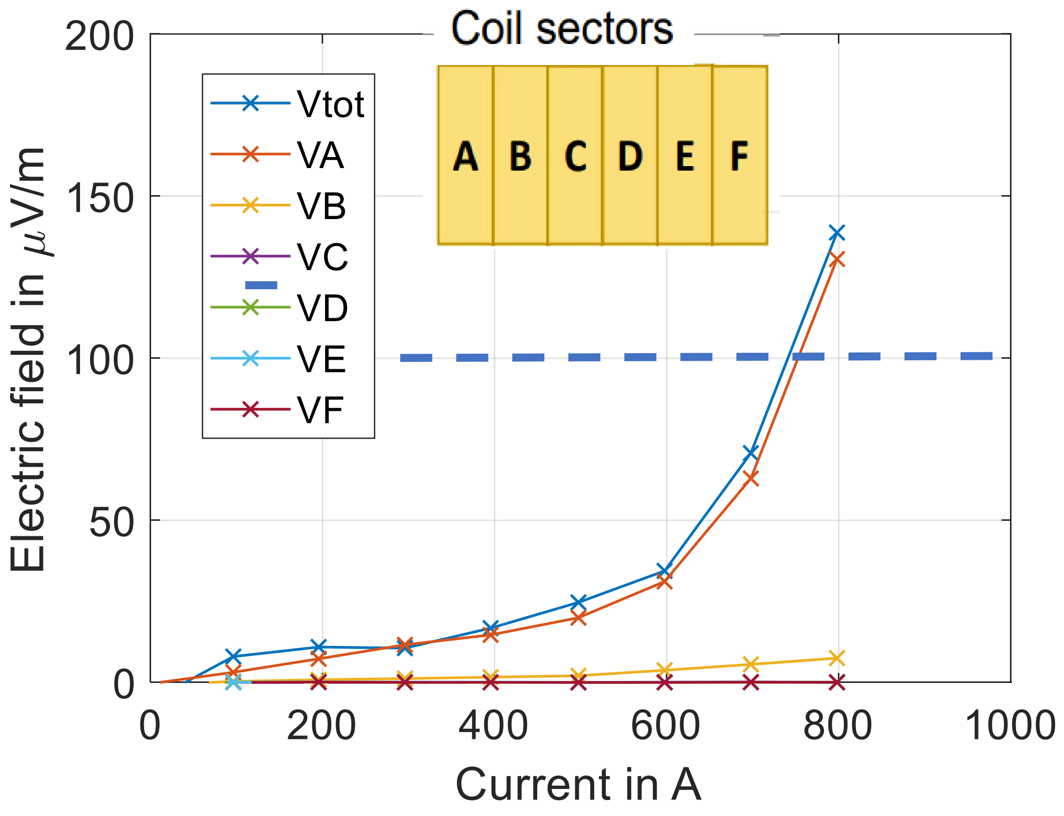
Dry-wound double tape

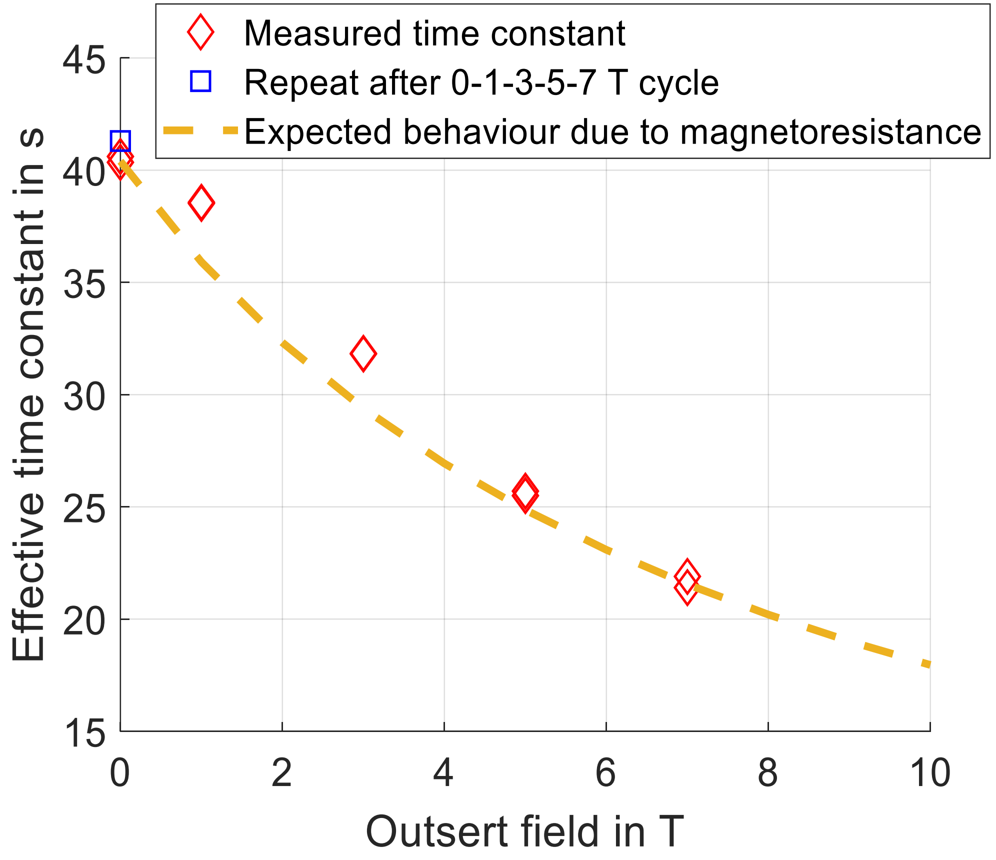


Soldered double tape

- Model seems to overestimate I_c, may be due to difference in tape properties in model and coil
- Soldered coils seem to have low performance in the inner sections
- Performance is lower than for the dry-wound coils

Lower coil performance at 4.2 K than expected from calculations





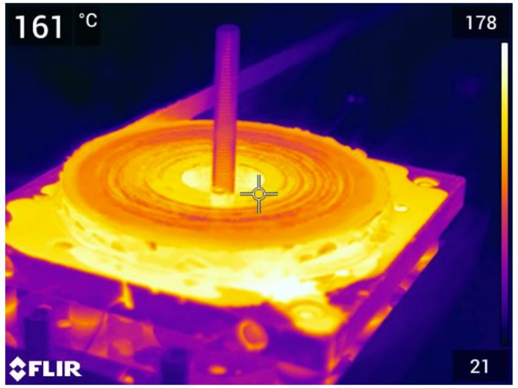
VI curve in self field:

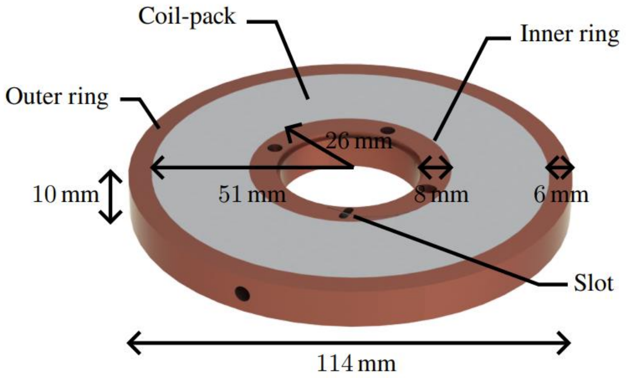
- I_c = 750 A, expected from model 2.7 kA!
- Inner section turns of the coil define the coil current

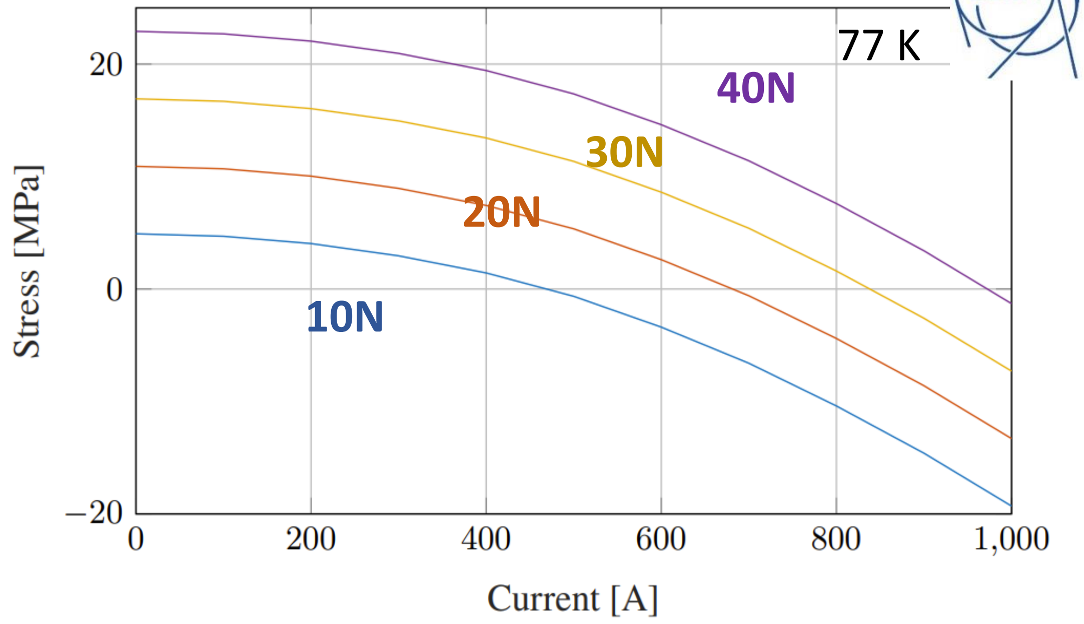
Time constant:

- decreases in applied magnetic field due to magnetoresistance

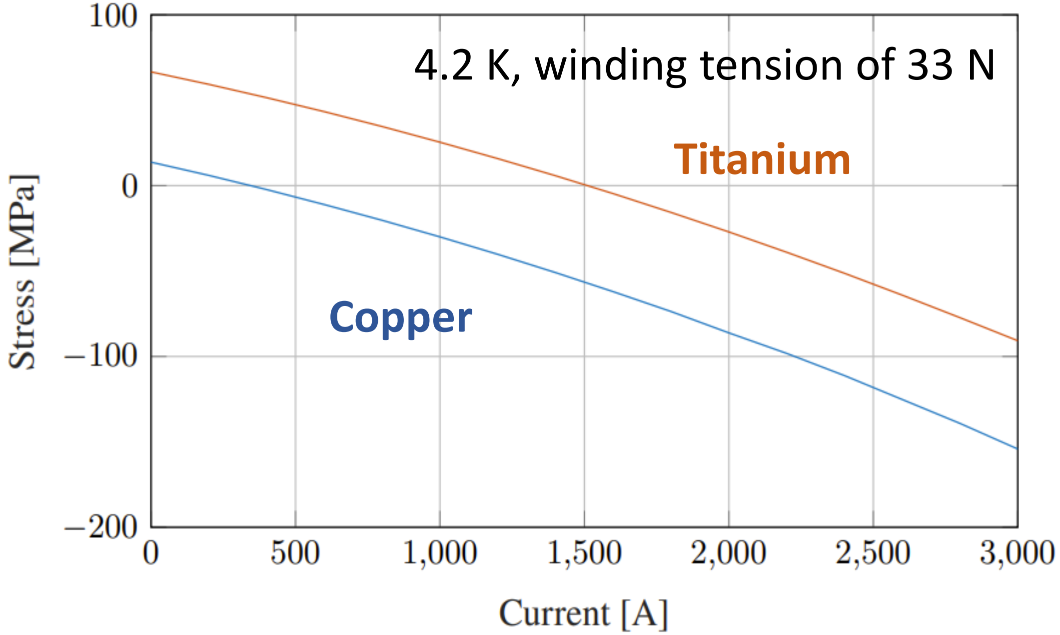
Possible degradation reasons for lower pancake performance

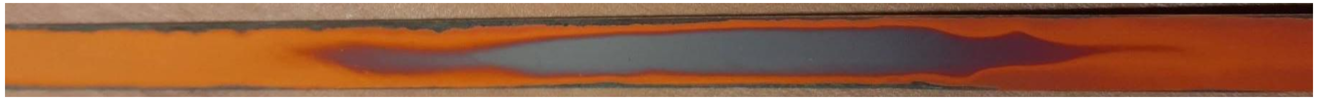






- Tape I_c(B, T, angle) and homogeneity along the length
- Winding tension and soldering - mechanical and temperature dependent degradation
- Thermal expansion of core of the coil material influence on stress in winding pack
- Coil quenches leading to permanent lowering of the coil performance





Cloverleaf-racetrack *Re*BCO accelerator type magnet

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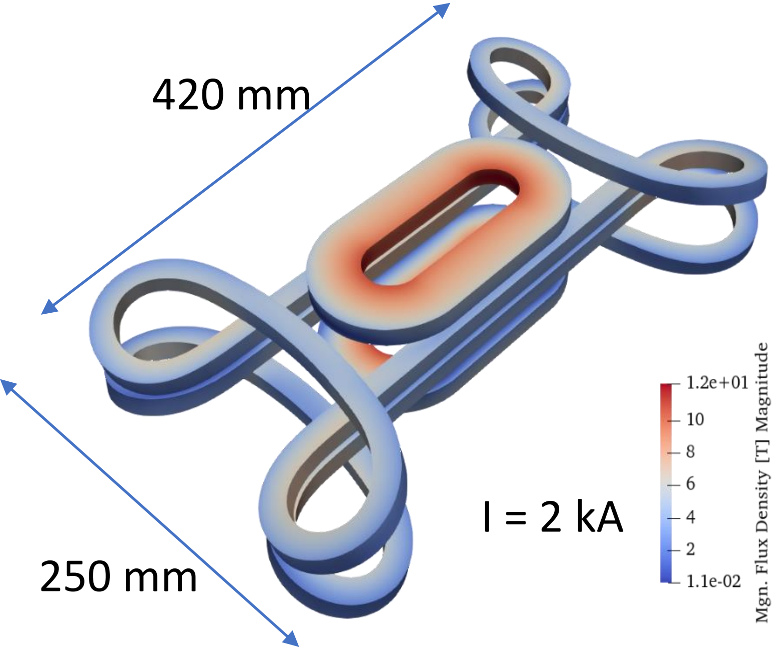
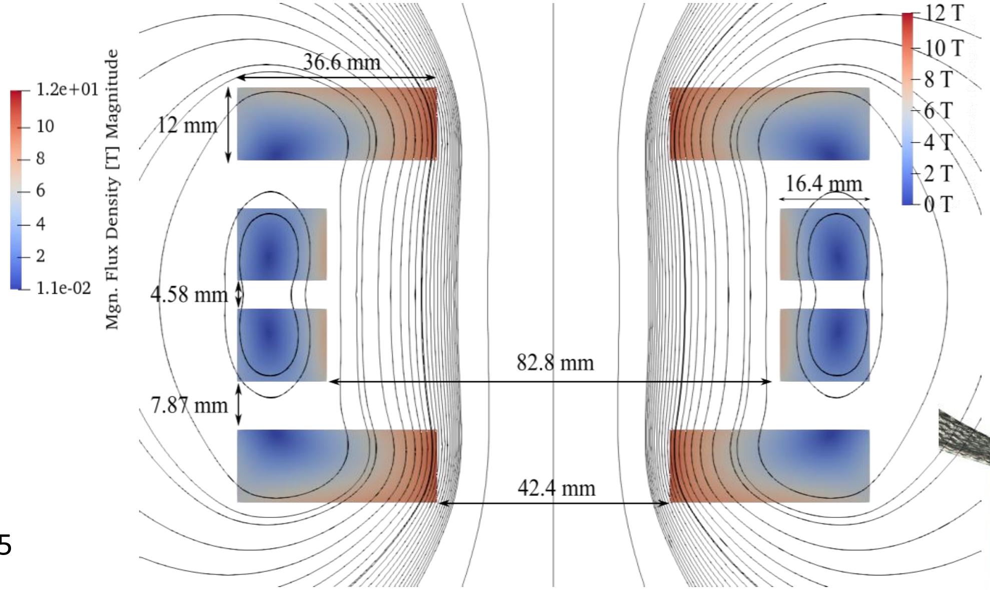


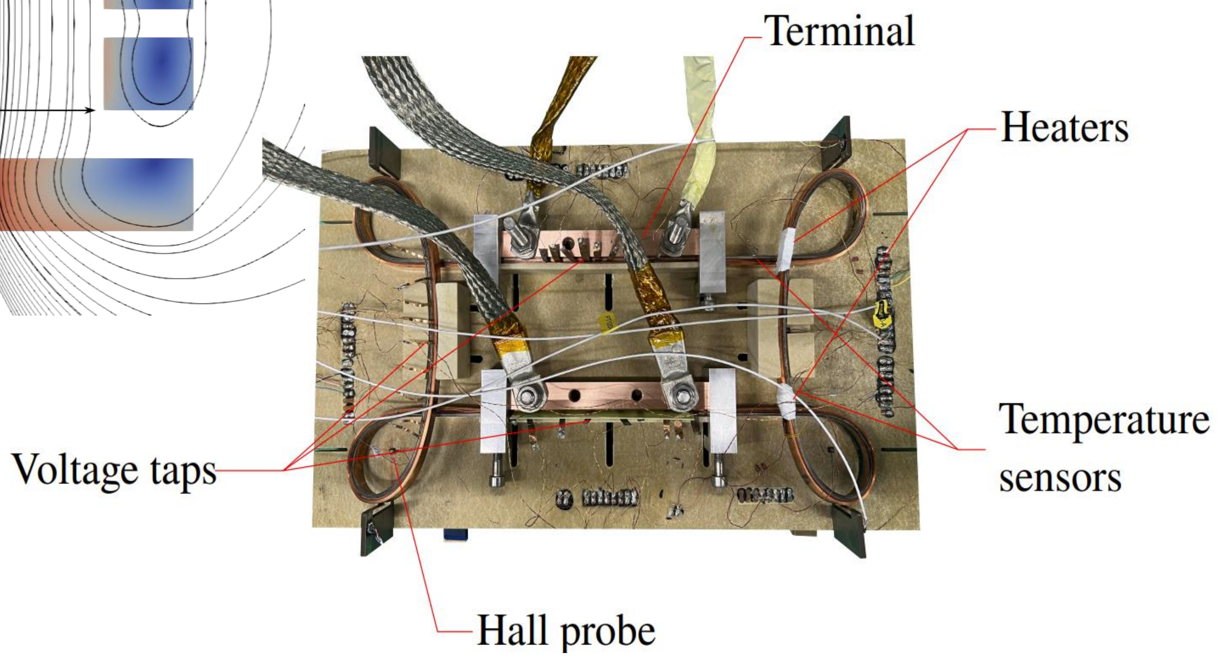


- T. H. Nes, DOI:10.1088/1361-6668/ac8e39
- T. H. Nes, DOI:10.1109/TASC.2022.3155445

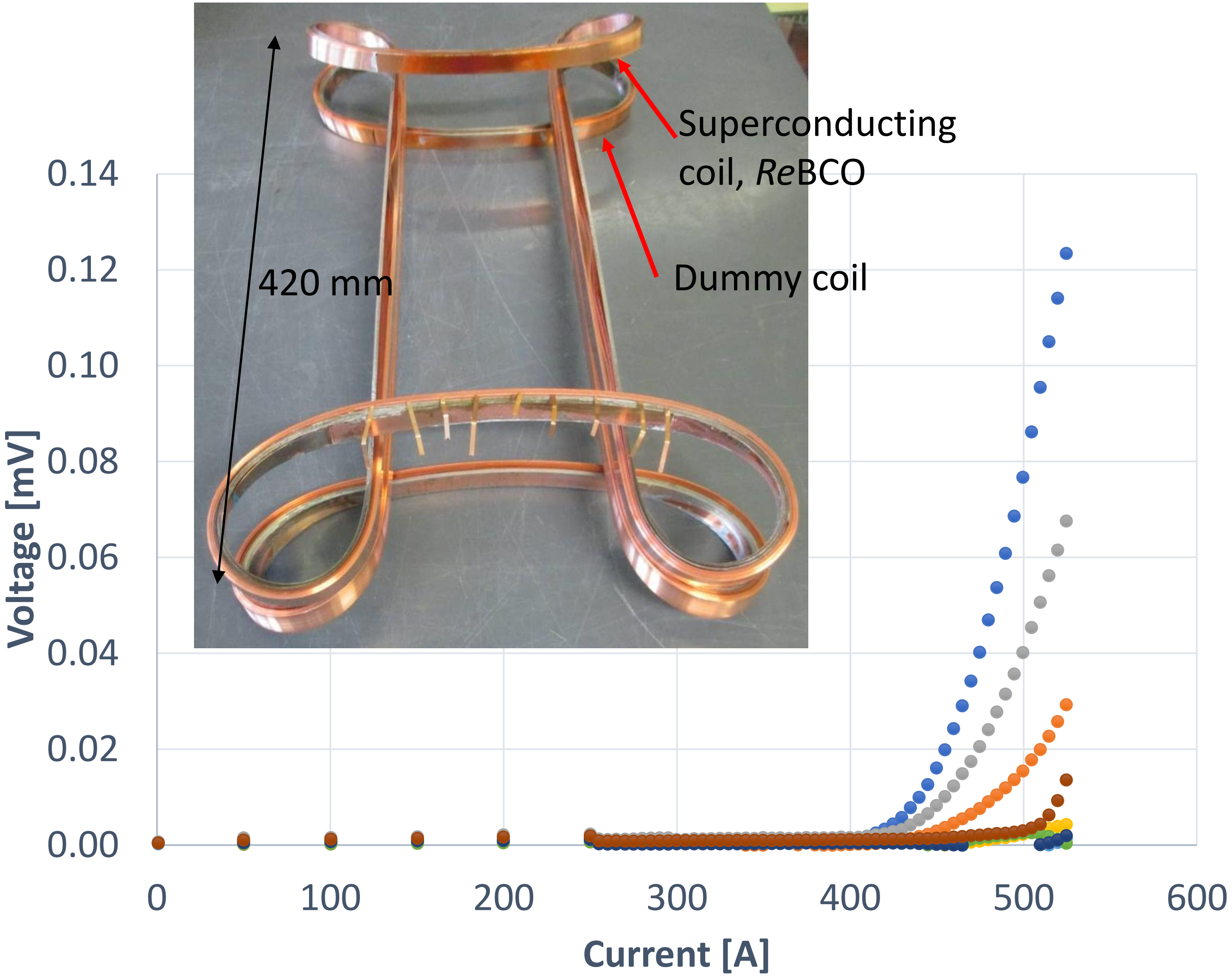
- Demonstrator as a first step towards a 20 T accelerator coil
- Cloverleaf shape is solution to the hard-way bent problem
- 12 mm double *Re*BCO tape used as conductor
- Full HTS magnet with 8 turns

Test in Liquid Nitrogen, 77 K:

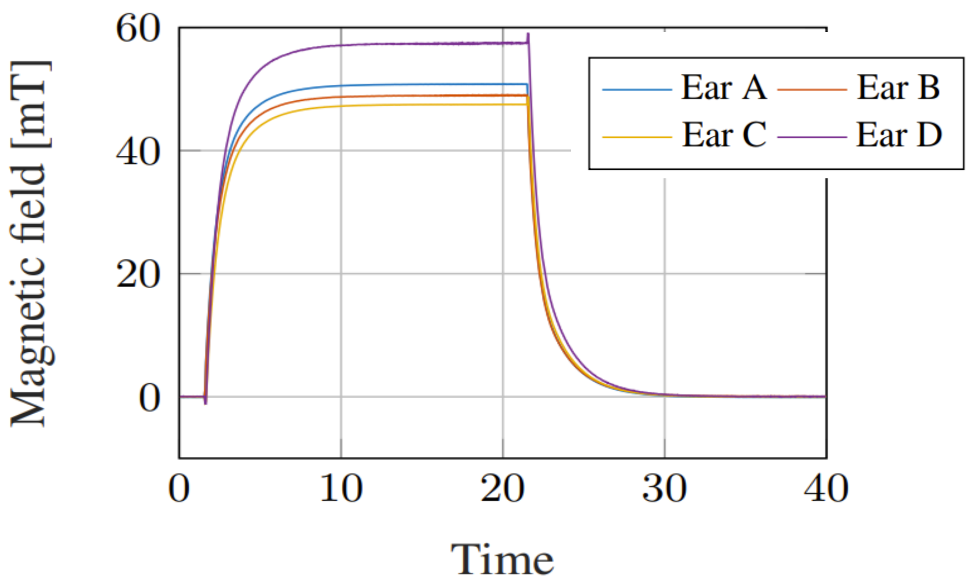
- measurement of the critical current
- linear and stair ramp
- multiple thermal cycles
- instrumentation: hall probes, extensometers, voltage taps.



Cloverleaf *Re*BCO coil test at 77 K in self-field



- Smooth VI curves
- Expected coil critical current of 400 A reached, estimated from tape properties
- No degradation due to coil winding
- Time constant estimated from magnetic field decay - approximately 2.7 s



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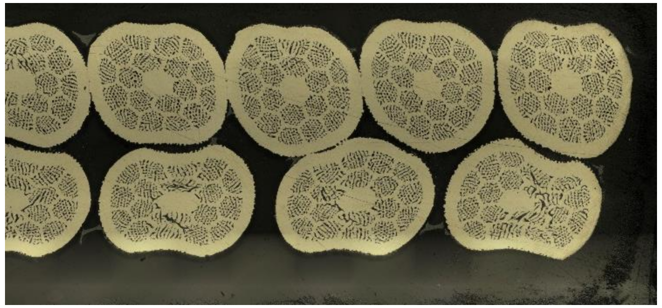

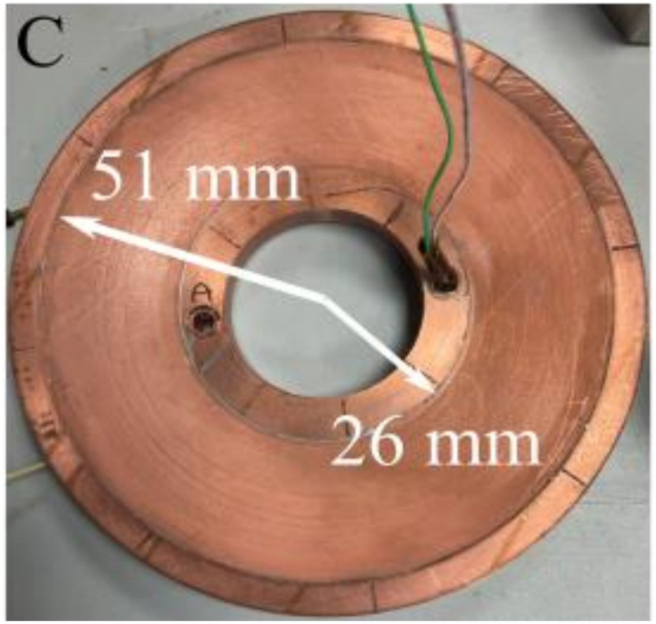

Characterization of mechanical properties of *Re*BCO tapes

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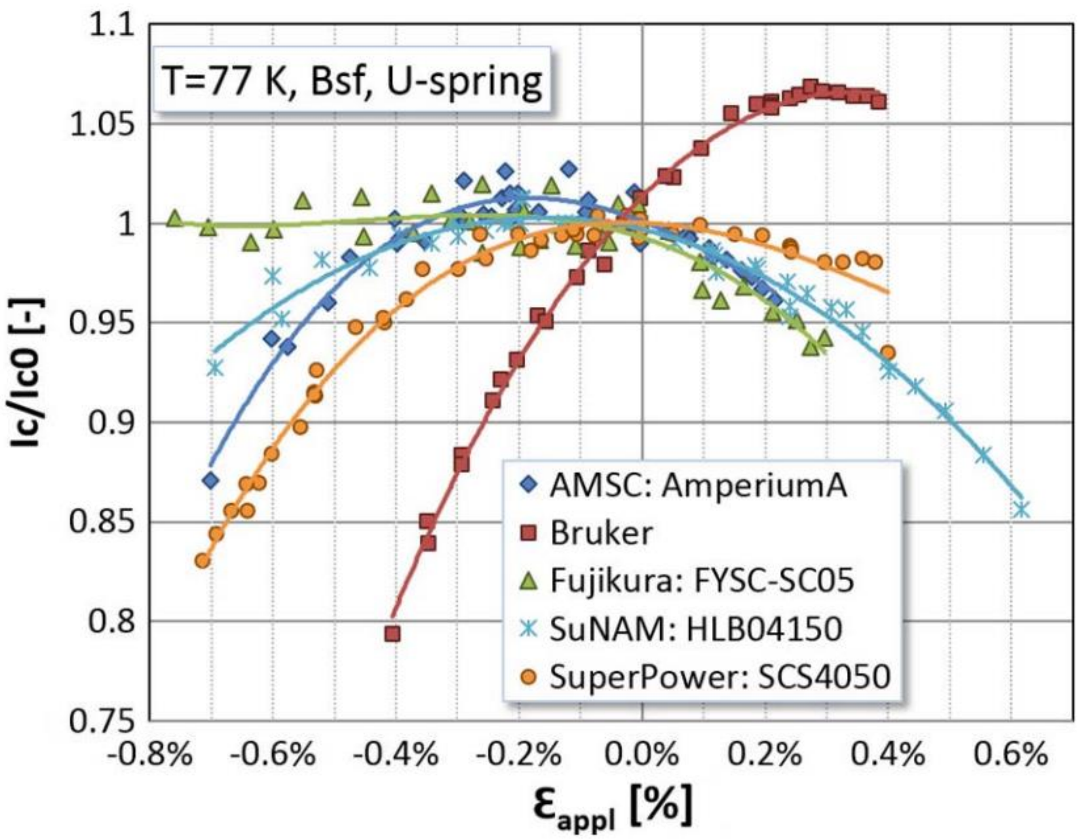

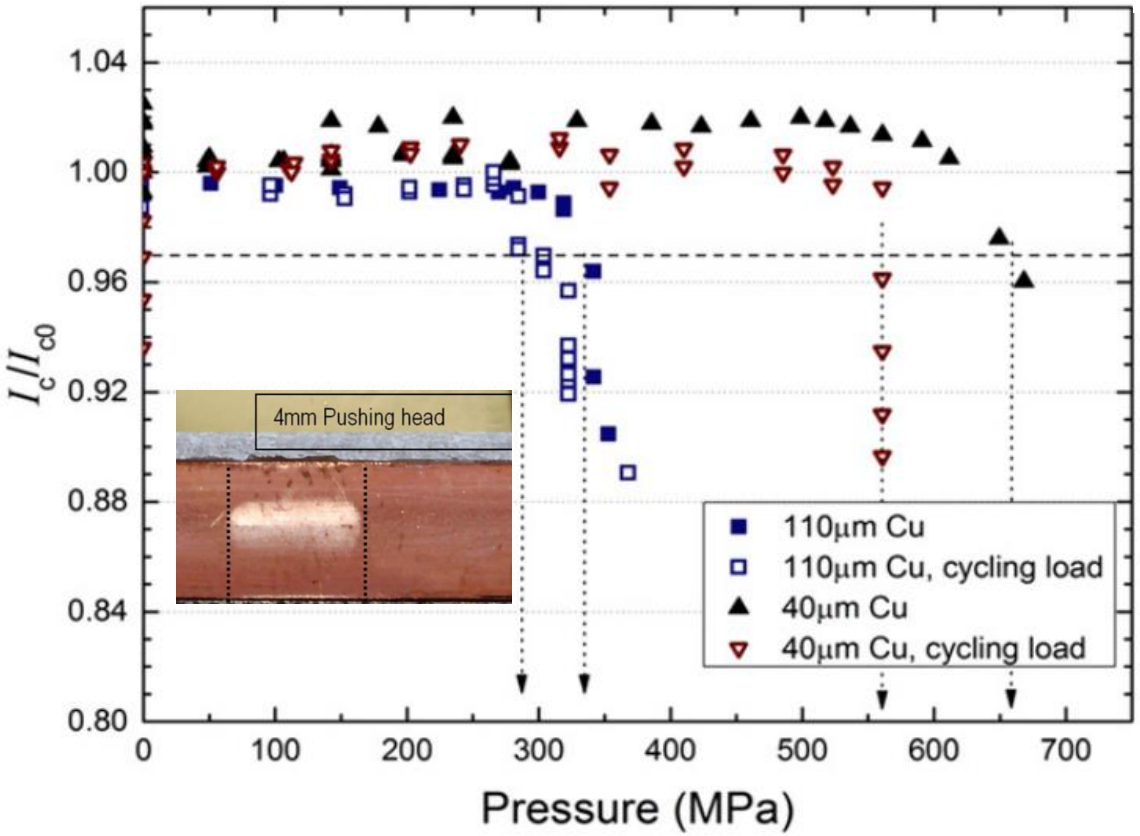

- C. Zhou et al., IEEE Transactions on Applied Superconductivity, Vol. 26, No. 4, June 2016.
- K Ilin et. all, Supercond. Sci. Technol. 28 (2015) 055006 (17pp)

- Importance of study *Re*BCO tape mechanical properties, together with simulations, for understanding limits in high-current cables for future high-field magnets.
- Measuring ReBCO tapes and stack limits with Ic in self-field and under cycling conditions: tension, transverse,

Summary

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Bi-2212 Rutherford cable

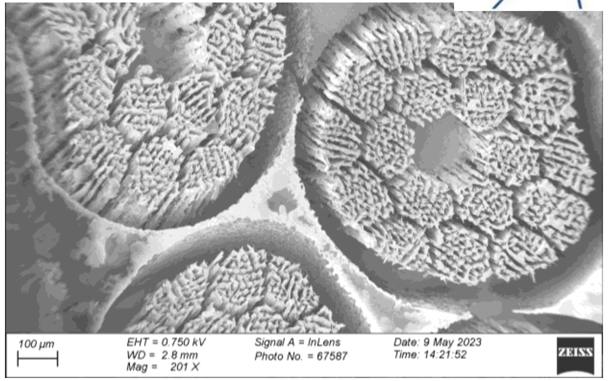
- Unique results obtained on two Bi-2212 Rutherford cable samples, another two to be tested
- 5% critical current decrease reached at an average transverse stress of 170 to 200 MPa in sample 3 (LBNL1109) and at 120 to 150 MPa in sample 4 (LBNL2002)
- All changes in critical current were irreversible

*Re*BCO pancake coils and cloverleaf

- Soldered coils show a higher margin between critical current and quench current
- The time constant is 50 times higher in soldered compared to dry wound coils
- Dry wound coil predicted critical current was 2.7 kA but only 750 A was reached
- First cloverleaf sub-demonstrator was wound and successfully tested at 77K, self-field

Plans for future torturing

- *Re*BCO tape mechanical properties study for understanding limits for future high-current cables and high-field magnets



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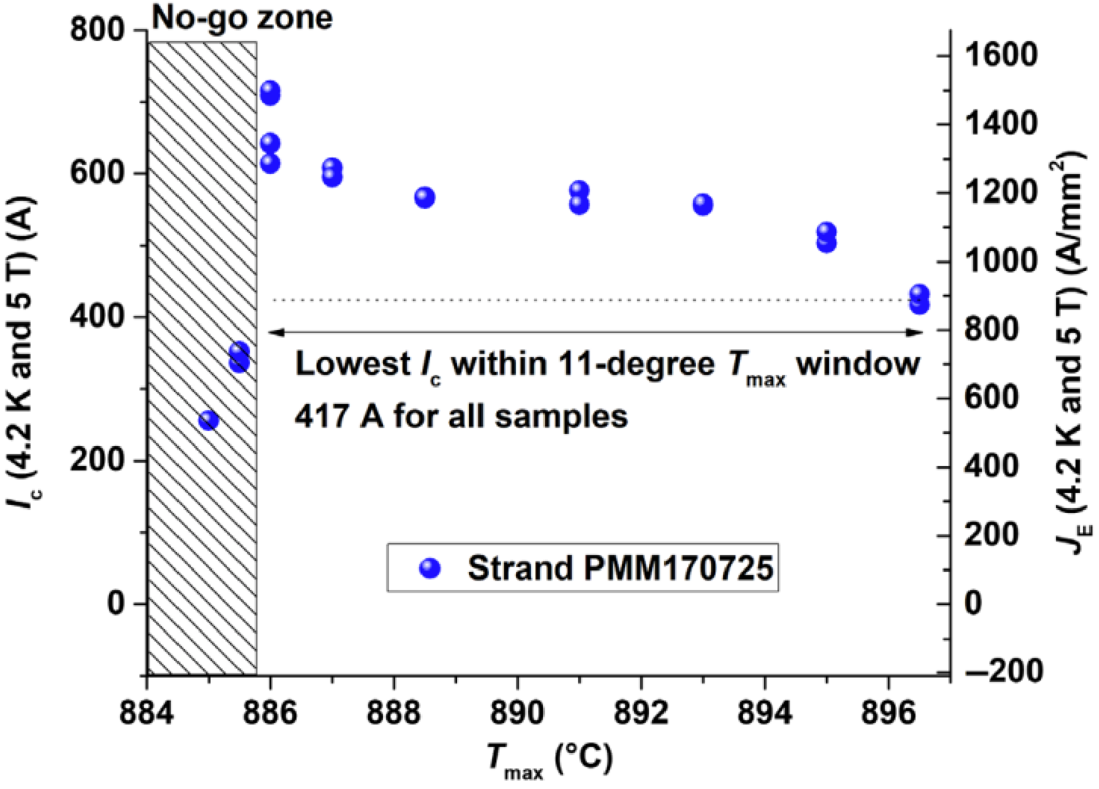
BSCCO-2212: heat treatment and deformation



- Heat treatment window for BSCCO-2212 material

- Pre-deformation mimicking Rutherford cable

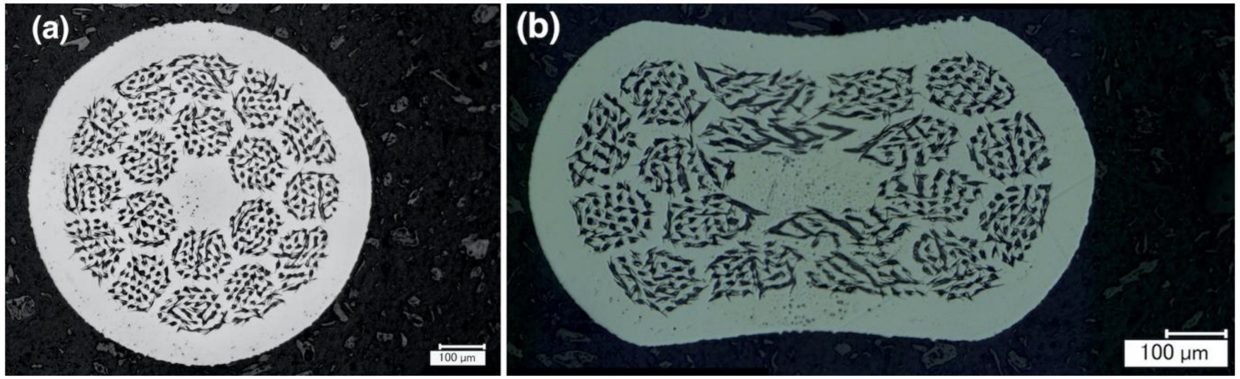


FIG. 11. The strand on the left is a round, 37 × 18, 0.8 mm Bi-2212 wire after a 50 bar overpressure processing heat treatment, after which it is still a round wire despite that its diameter d is reduced to ~0.78 mm. The strand on the right is the same wire rolled to a thickness t of 0.580 mm and reacted with a 50 bar overpressure processing heat treatment, after which the strand has a peanut shape with its width at 0.957 mm and its thickness varying from 0.502 to 0.550 mm. The four bundles of the rolled strand near the vertical central line are more deformed than others and show a larger degree of filament bonding and bridging. The 4.2 K, self-field I_c of the rolled strand (rolled strain: $(d-t)/d = 0.275$) is ~13% lower than that of the round strand.

- Tengming Shen et al, Design, fabrication, and characterization of a high-field high-temperature superconducting Bi-2212 accelerator dipole magnet, PHYSICAL REVIEW ACCELERATORS AND BEAMS 25, 122401 (2022)