Measurements of the Effects of Compressive Loading on the Narrow Side of the HTS TAPE

S. Joshi, J. Cozzolino, W. Sampson, R. Gupta

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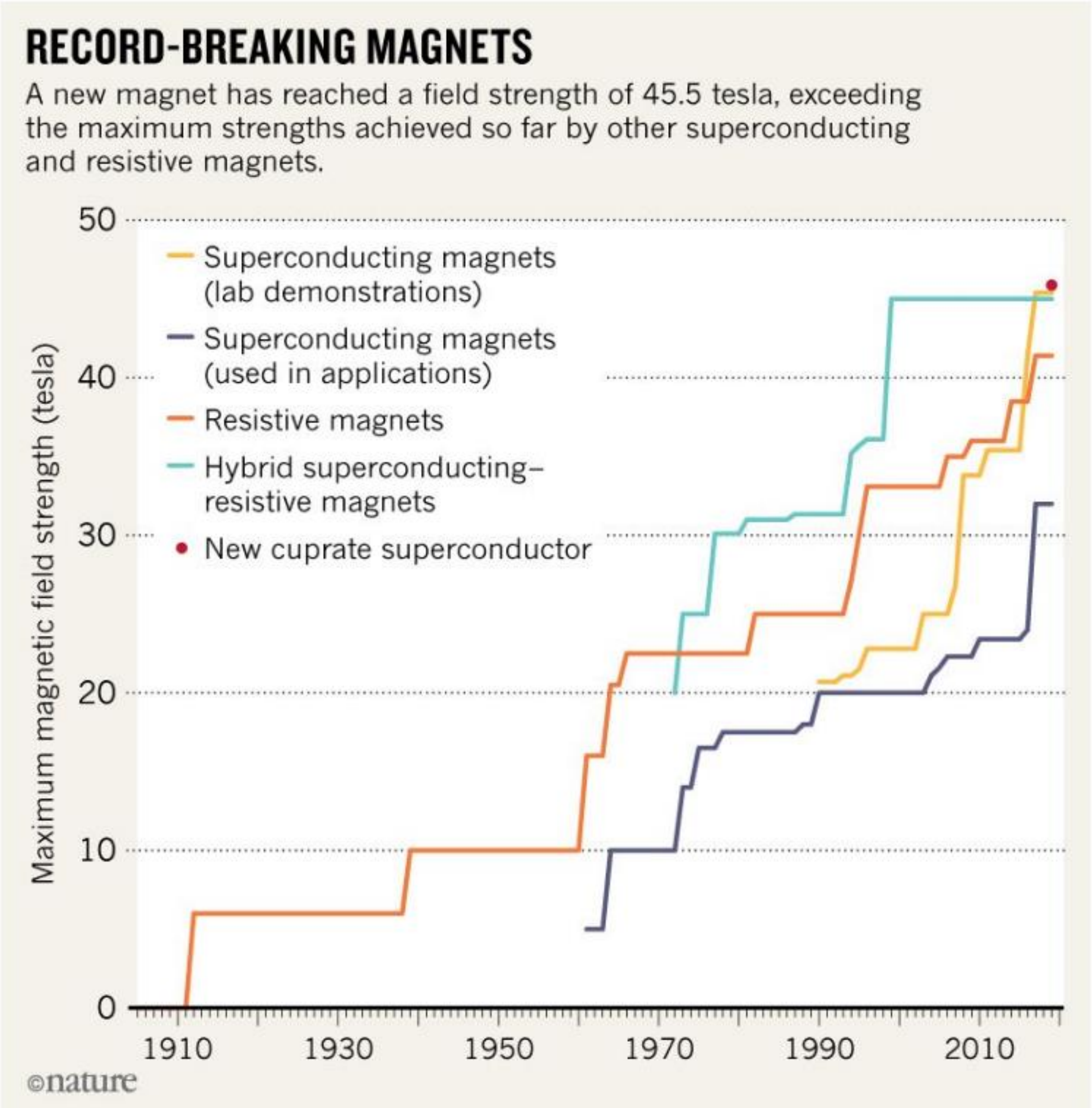
INTRODUCTION

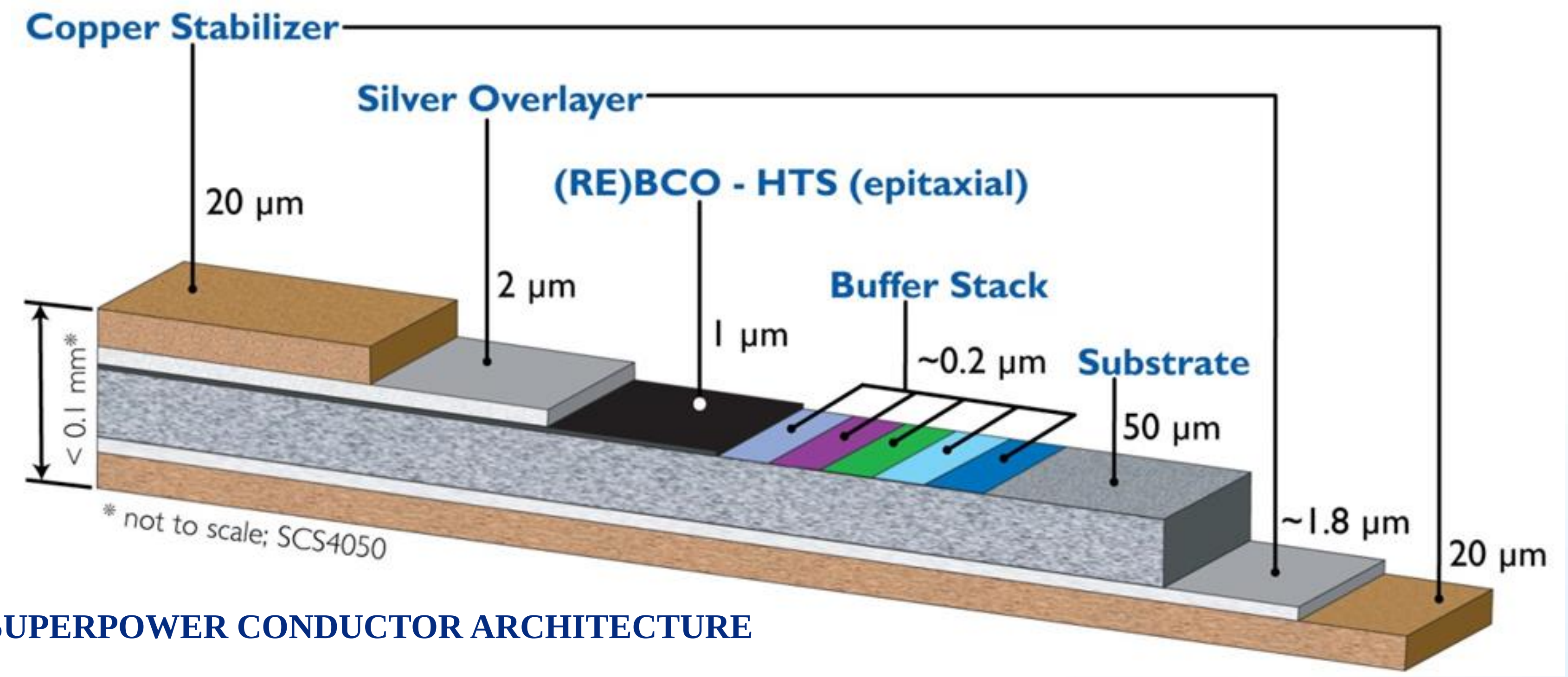
MAGNET FIELD STRENGTH



Source: Mark Bird, National High Magnetic Field Laboratory

- Magnets (HTS/HTS-Hybrid) with fields exceed 20 Tesla are imminent
- Magnitude of the resulting Lorentz forces in a large bore solenoid at **20+ Tesla approaches the limits of the HTS conductor**.
- Dealing with large electro-magnetic stresses is the biggest challenge **in high field, as the mechanical properties of the conductors limit the electrical performance of the coil**.

CONDUCTOR ARCHITECTURE

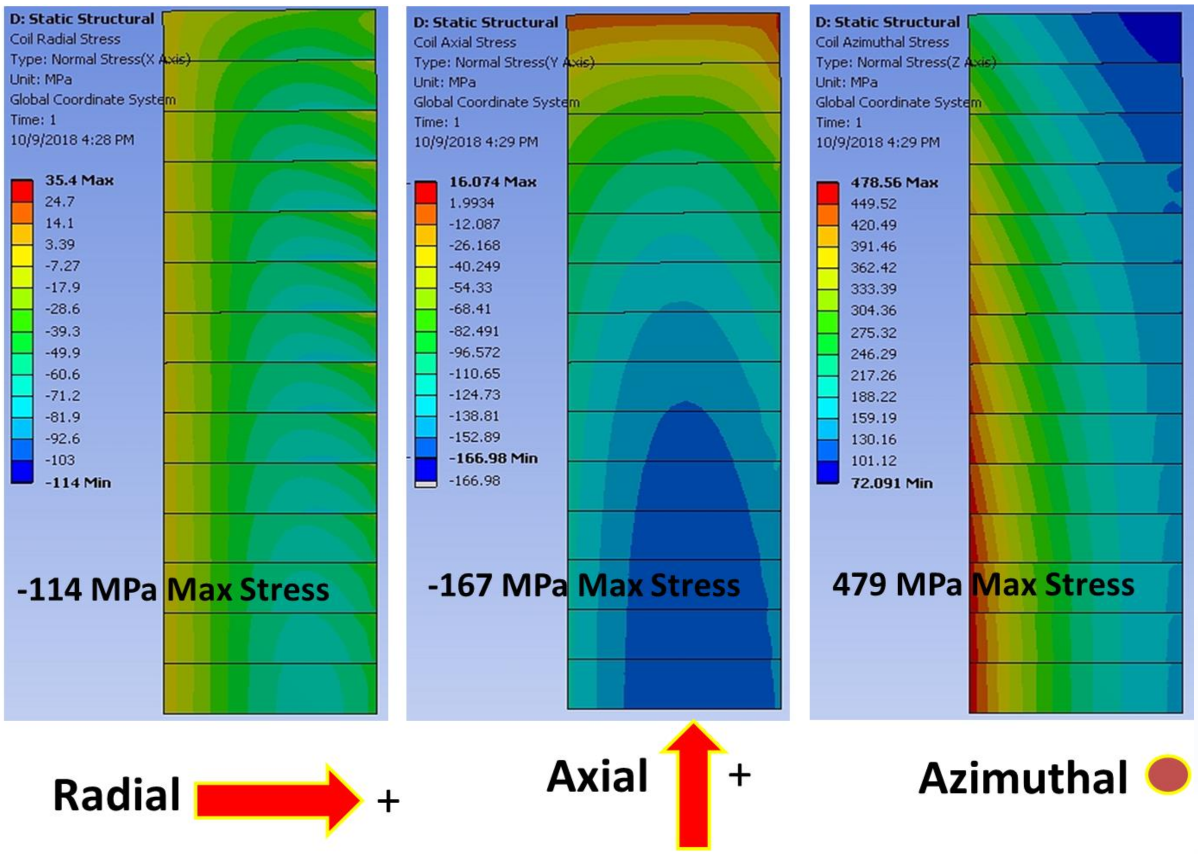


SUPERPOWER CONDUCTOR ARCHITECTURE

Reference:
http://www.superpower-inc.com/system/files/SP_2G+Wire+Spec+Sheet_2014_web_v1_0.pdf

- The **mechanical characteristics of the Conductor are predominantly dependent on the Hastelloy substrate**
- 12mm wide 2G HTS tape architecture shown above is available in varying amount of Copper Stabilizer layer (65 µm, 40 µm, and 20 µm, etc)

LORENTZ FORCE ISSUES



- The ANSYS Maxwell magneto-static FE model of a **14 double-pancake coils** in a single layer arrangement (**I.D = 100mm, O.D = 200 mm**) wound using 70 µm thick HTS conductor (~50 µm Hastelloy, **20 µm Copper**) corresponding to a **25 T central flux density**.
- The resulting Lorentz forces:
  - **Axial** (narrow side of conductor) = **167 MPa**
  - **Radial** (wide side of the conductor) = **114 MPa**
  - **Azimuthal** (wide side of the conductor) = **479 MPa**

LORENTZ FORCE ISSUES

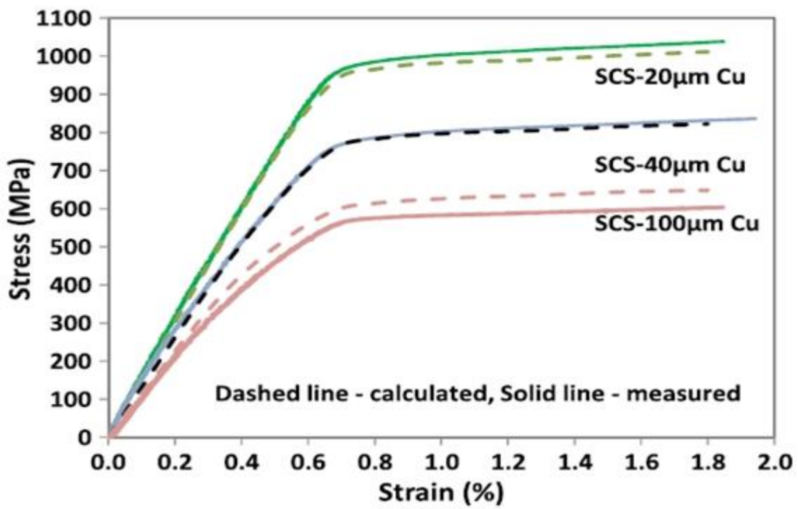


Fig. 3. Calculated (dashed line) and measured (solid line) stress–strain curves at 77 K for 2G HTS wires on 50-μm-thick Hastelloy substrate and with variation in electroplated Cu stabilizer thickness.

TABLE I
77 K STRESS–STRAIN CURVE FITTING PARAMETERS FOR DIFFERENT TAPES

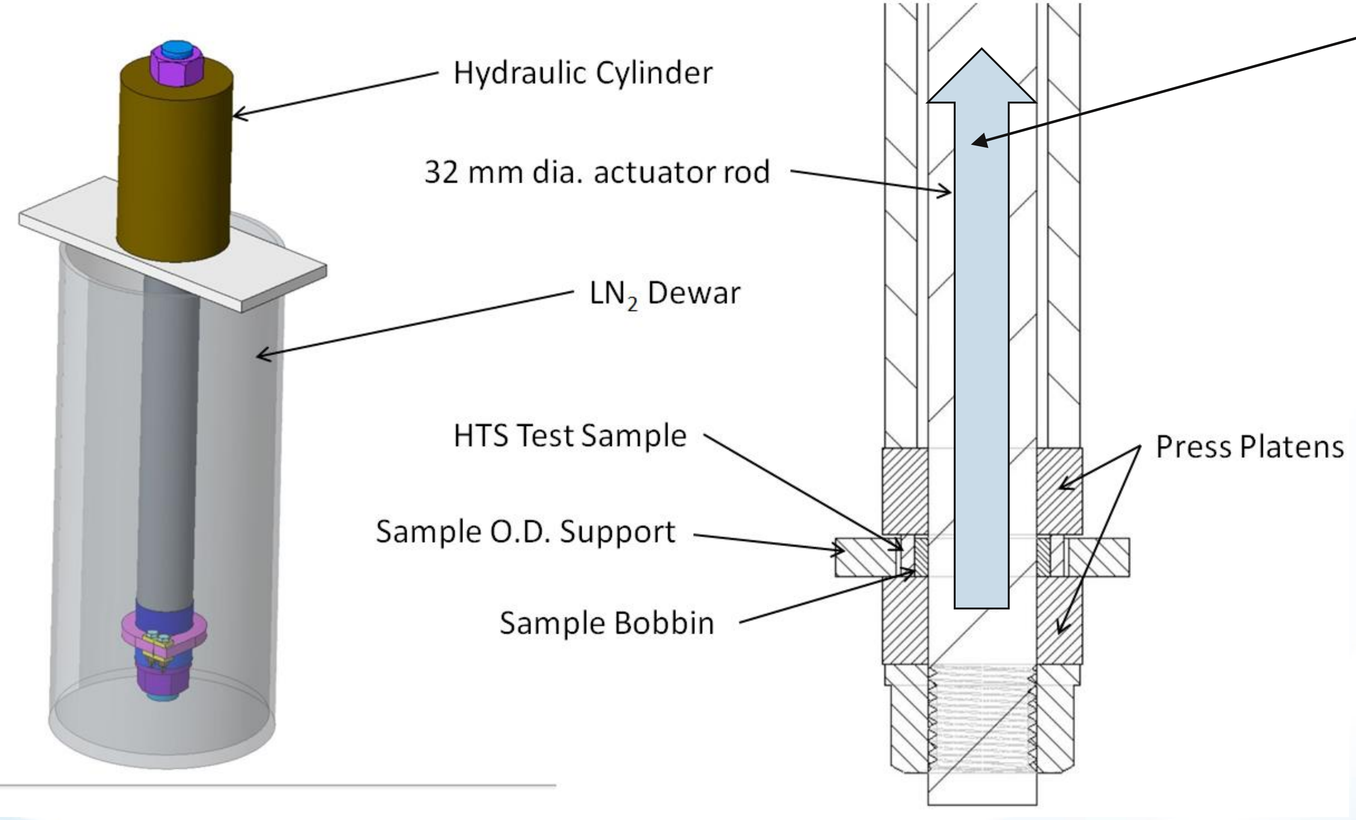
Tape Type	E (GPa)	$\sigma_{0.2}$ (MPa)	α
Bare REBCO Tape	180	1225	56
20µmCu wire	150	998	38
40µmCu wire	125	795	38
100µmCu wire	98	580	38
Cu Stabilizer	85	339	15

- Y. Zhang, et al. show that **SuperPower 2G HTS tape with 20 micron copper and 50 micron Hastelloy can withstand stresses approaching 1000 MPa** - validating the radial (114 MPa) and azimuthal (479 MPa) stress requirements - before reaching its .2% yield limit
- Previously measured safe value, measured at BNL, for coil stresses in the **Axial direction is 107 MPa on 4 mm wide SuperPower 2G HTS tape with 40 micron copper** – not meeting 167 MPa requirement.

Reference: Zhang, Y., Hazelton, D. W., Kelley, R., Kasahara, M., Nakasaki, R., Sakamoto, H., & Polyanskii, A. (2016). Stress-Strain Relationship, Critical Strain (Stress) and Irreversible Strain (Stress) of IBAD-MOCVD-Based 2G HTS Wires under Uniaxial Tension. *IEEE Transactions on Applied Superconductivity*. https://doi.org/10.1109/TASC.2016.2515988

Development of the Test Equipment

TEST EQUIPMENT



As pressure is applied to the Hydraulic Cylinder, the Actuator Rod gets pulled into the Cylinder Housing applying Compressive Loading Forces onto the Sample via the Press Platens

CAD RENDERING OF THE COMPRESSION FIXTURE

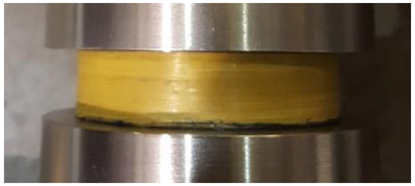
TEST EQUIPMENT

COMPRESSION FIXTURE SETUP

COMPRESSION FIXTURE SETUP IN OPERATION

AXIAL LOADING SAMPLE HOLDER EVOLUTION

10AUG17 – Kevlar Wrap



14AUG17 – Al Outer Ring

25AUG17 – Al Outer Ring and 1 Piston

28AUG17 – Al Extended Outer Ring (25.4 mm) and 2 Pistons

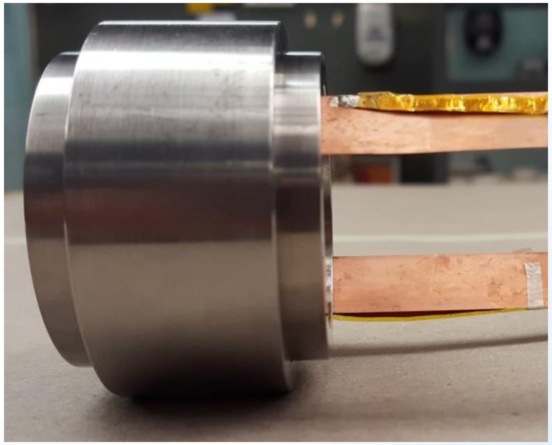
Above: Sample holder evolution from outer Kevlar wrapping to Aluminum rings and pistons.

- **Scaled down coils were wound for Axial load testing**
- Kevlar wrapping was a very time consuming process and the wrapping could not be reused
- Aluminum rings and pistons allowed for a more a even distribution of Axial loading forces on the coils

SAMPLE HOLDER EVOLUTION (continued)

27OCT17 – Stainless Steel Extended Outer Ring with 2 Pistons, Insulated Leads, and Nomex Caps



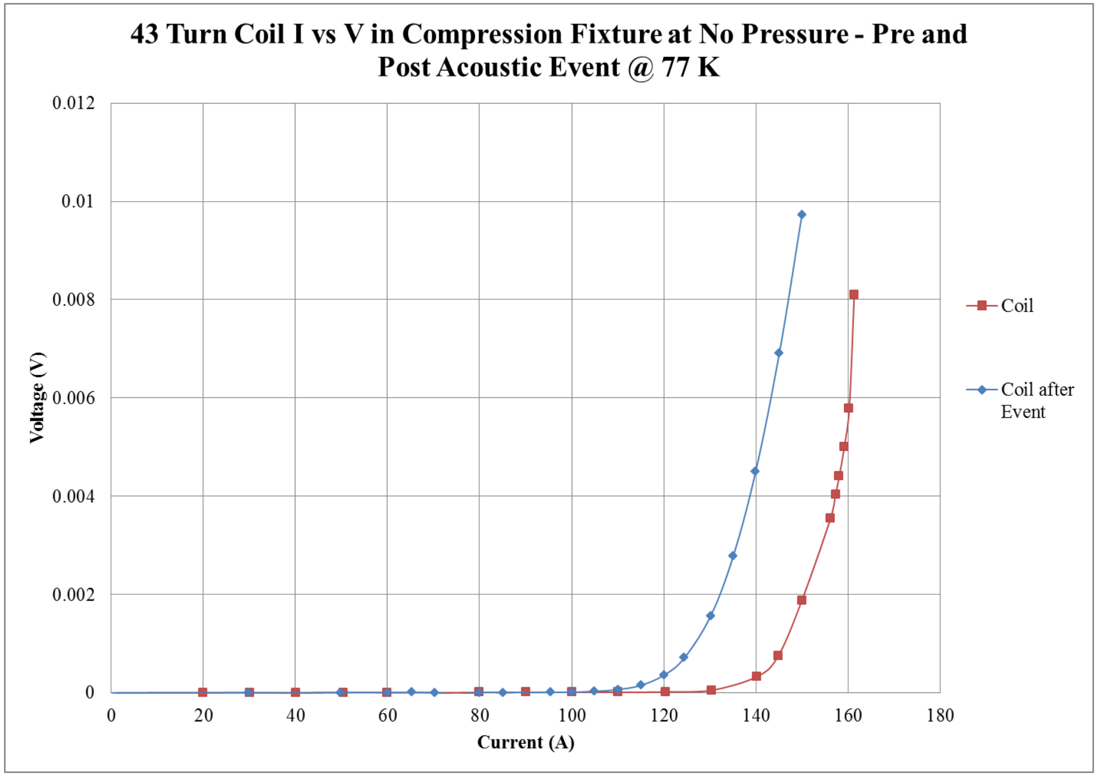


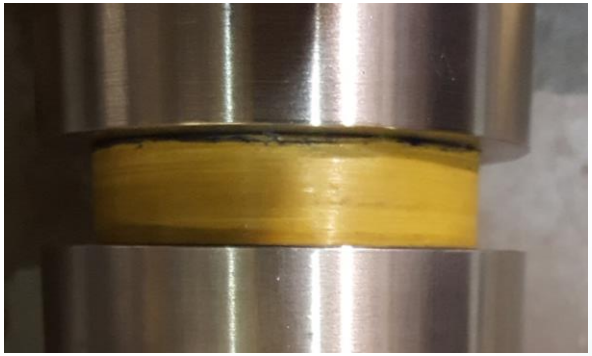
Above: Leads from the coil were insulated to provide for a more accurate signal. A pair of Nomex caps was added to the top and bottoms of the coil for better force distributions.

Test Results

65 µm Cu CONDUCTOR TEST RESULTS

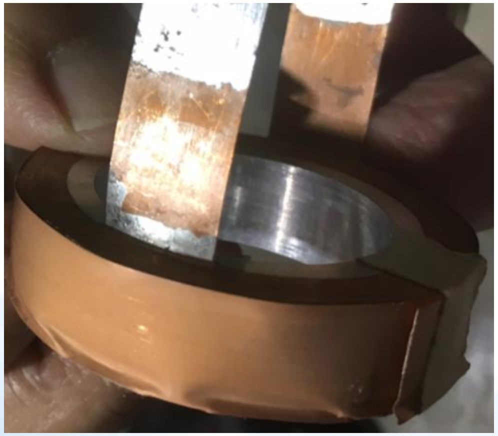
FIRST 77K COMPRESSION TEST

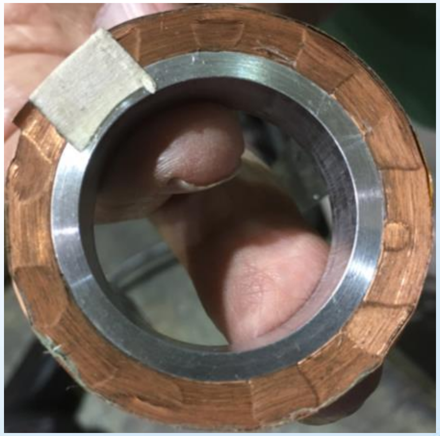




Sample in Kevlar Wrap

- The **Acoustic Event occurred around 200 MPa**
- Ic degradation in coil by ~20A

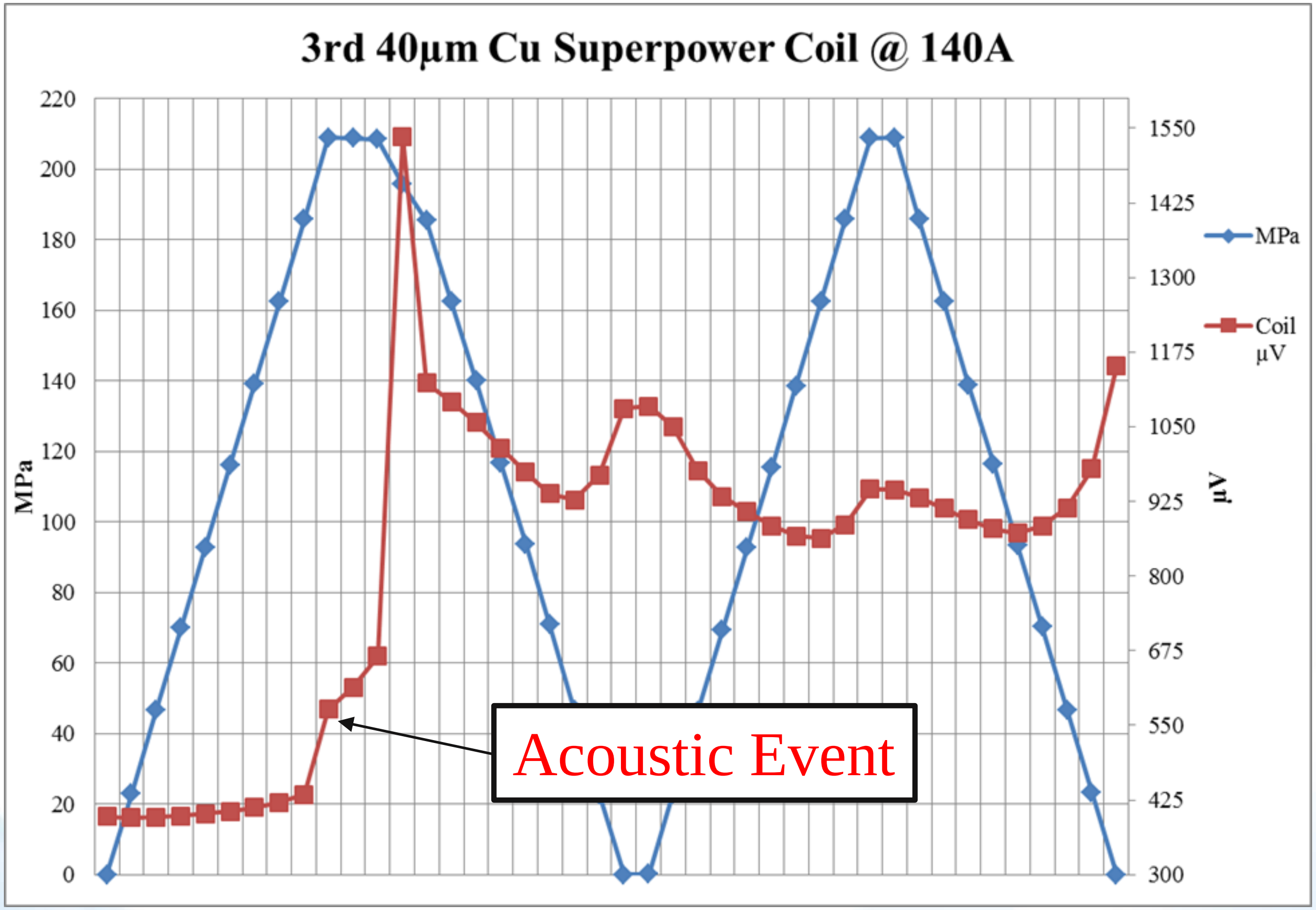




Sample Post Acoustic Event

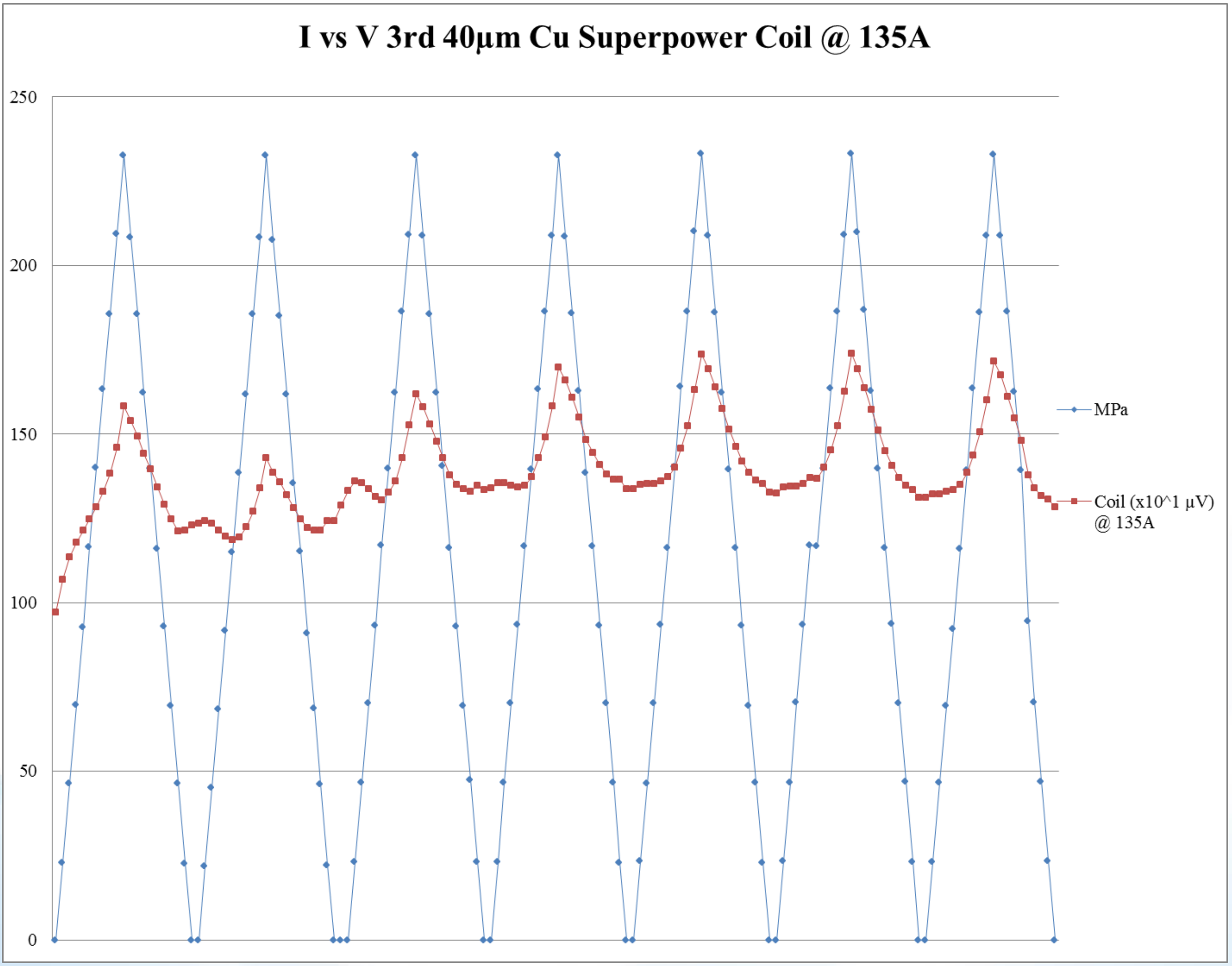
40 µm Cu CONDUCTOR TEST RESULTS

40 µm Cu CONDUCTOR PERFORMANCE LIMIT



- V vs MPa comparison for 3rd 40 µm Coil; I_c = 146A, I_c threshold voltage (according to the 1µV/cm standard) = 700µV.
- **At 140A, the 3rd 40 µm Coil showed no signs of performance degradation under Axial loading until around 200 MPa** (Acoustic Event).
- Stainless Steel Fixture was used.

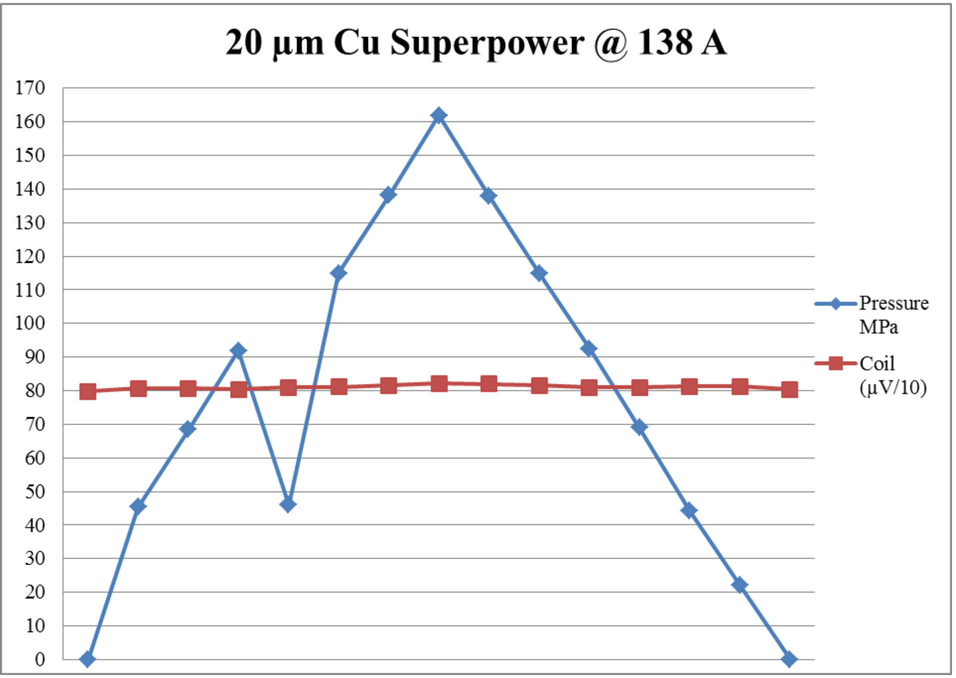
40 μm Cu CONDUCTOR COMPRESSIVE LOAD CYCLING RESULTS

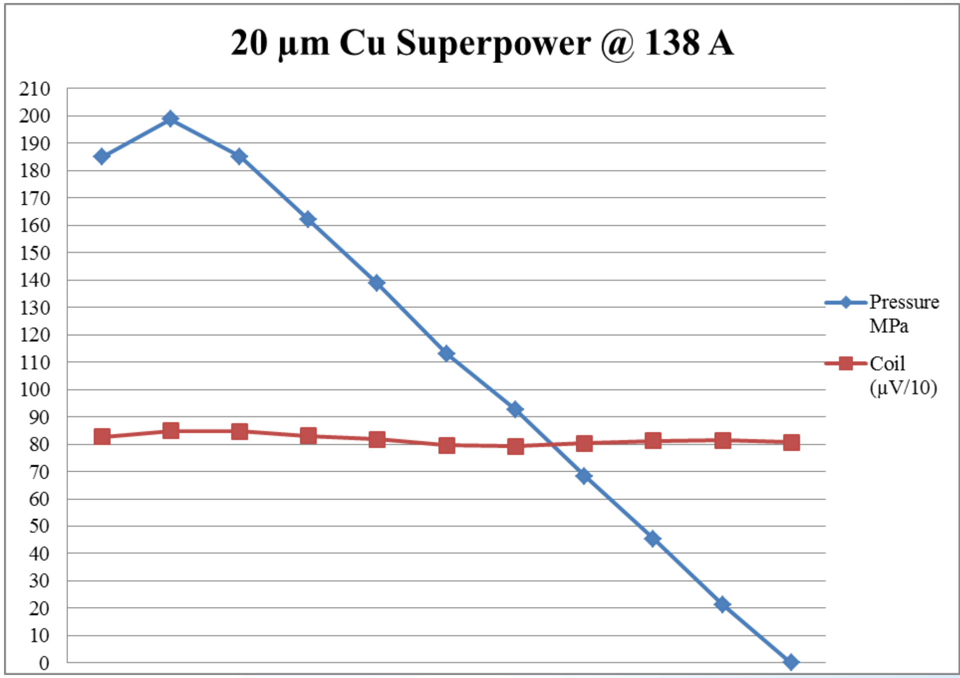


- V vs MPa comparison for 3rd 40 μm Coil. The **3rd 40 μm Coil was cycled multiple times to an Axial loading of 232 MPa at 135A**.
- The sample showed no further performance degradation of any significance.
- Interesting **recovery characteristic of the superconductor once compressive load is removed**

20 µm Cu CONDUCTOR TEST RESULTS

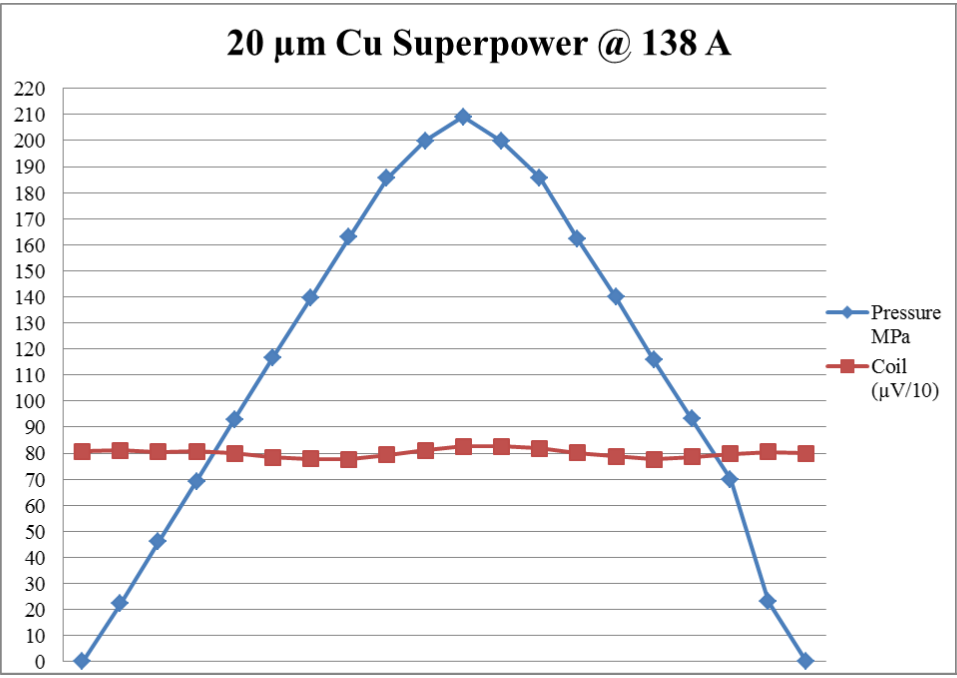
AXIAL LOADING UP TO 200 MPa

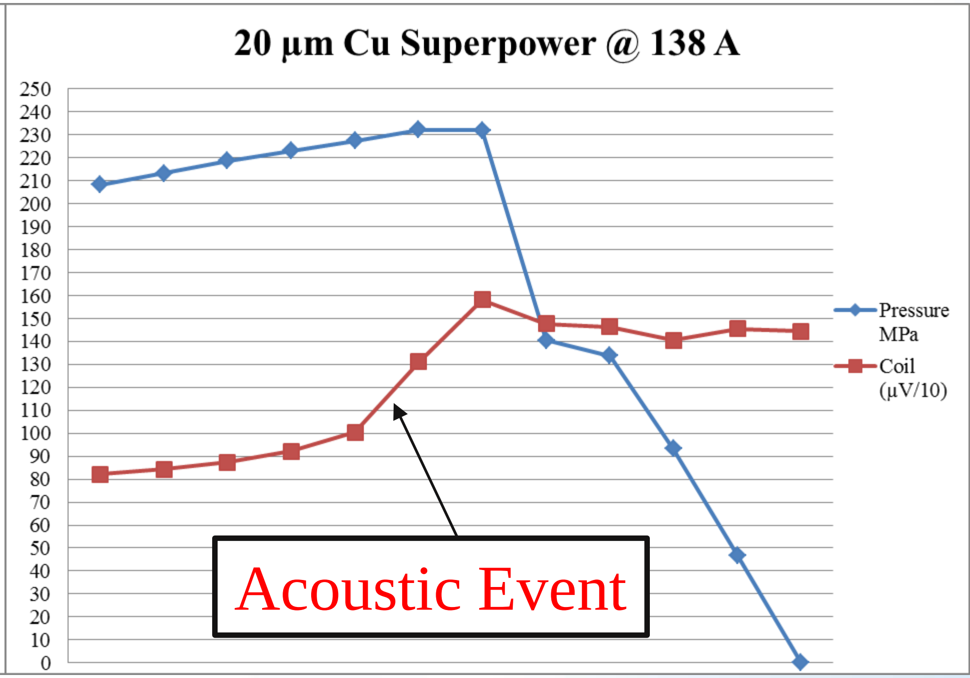




Above: Coil Performance at 138 A (I_c = 141 A; I_c threshold voltage (according to the 1µV/cm standard) = 977µV) up to 200 MPa. Axial loading on the coil was cycled up to 200 MPa. The coil showed no performance degradation throughout the cycle.

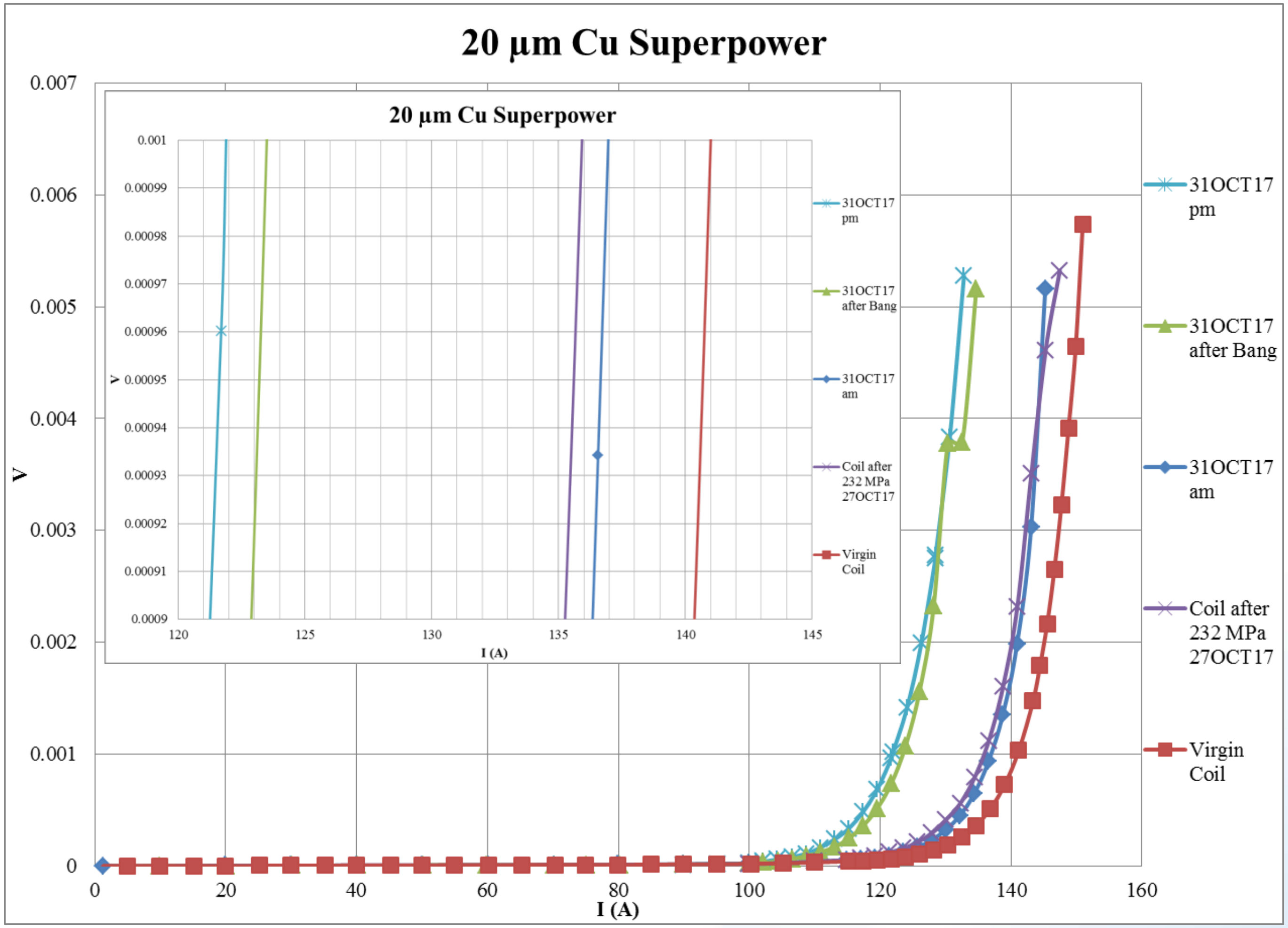
AXIAL LOADING UP TO 232 MPa





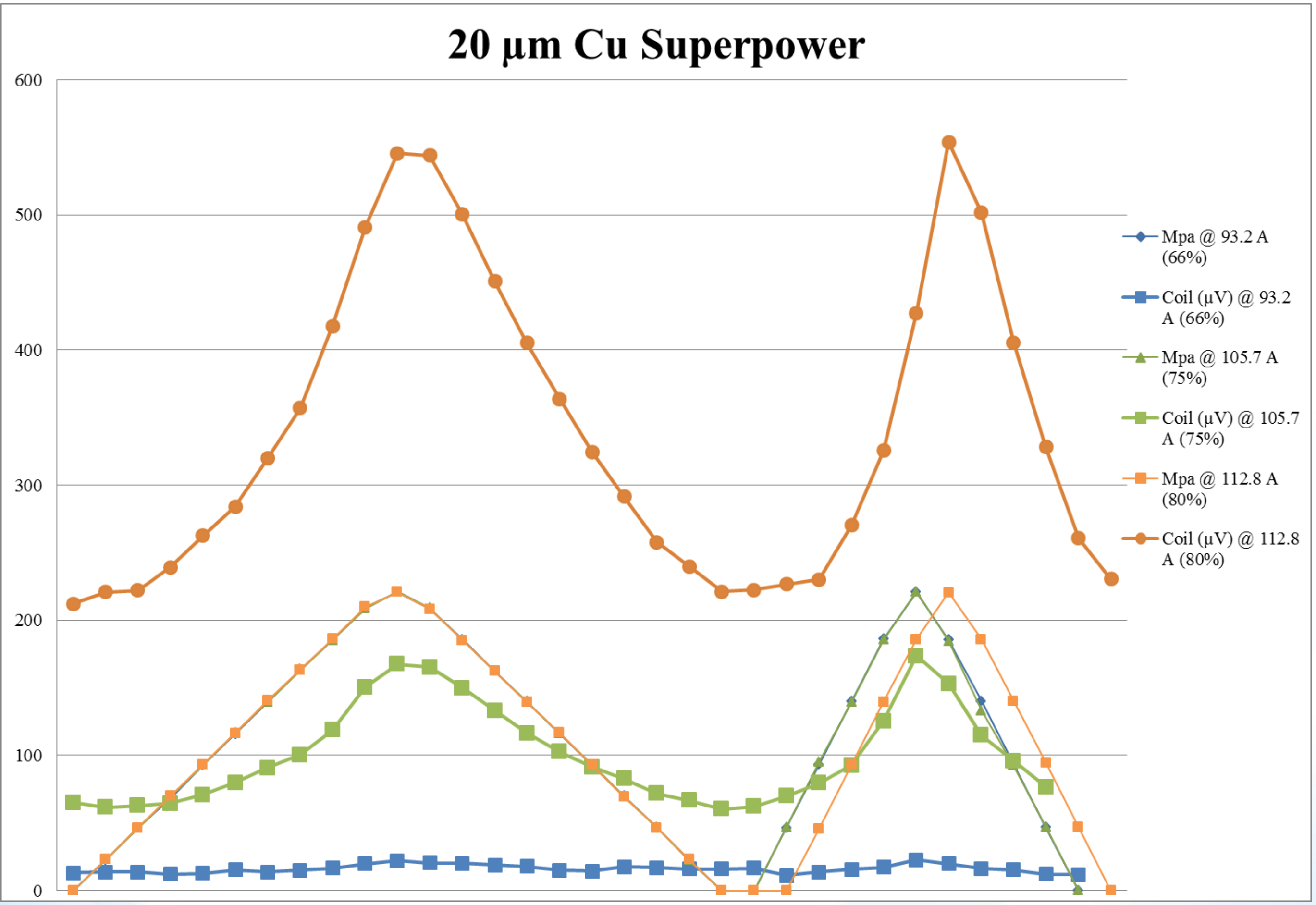
Above: Coil Performance at 138 A (I_c = 141 A; I_c threshold voltage (according to the 1µV/cm standard) = 977µV) up to 232 Mpa. Axial loading on the coil was cycled up to 232 MPa. **The coil started to showed signs of performance degradation as the Axial loading approached 230 MPa. The coil showed performance degradation beyond 232 MPa.**

20 μm Cu OVERALL TEST RESULTS



Above: I vs V Curves for 20 μm Cu Coil. After multiple Axial loading cycles on the 20 μm Cu Coil, the **I_c of the coil dropped form 141A to 122A**.

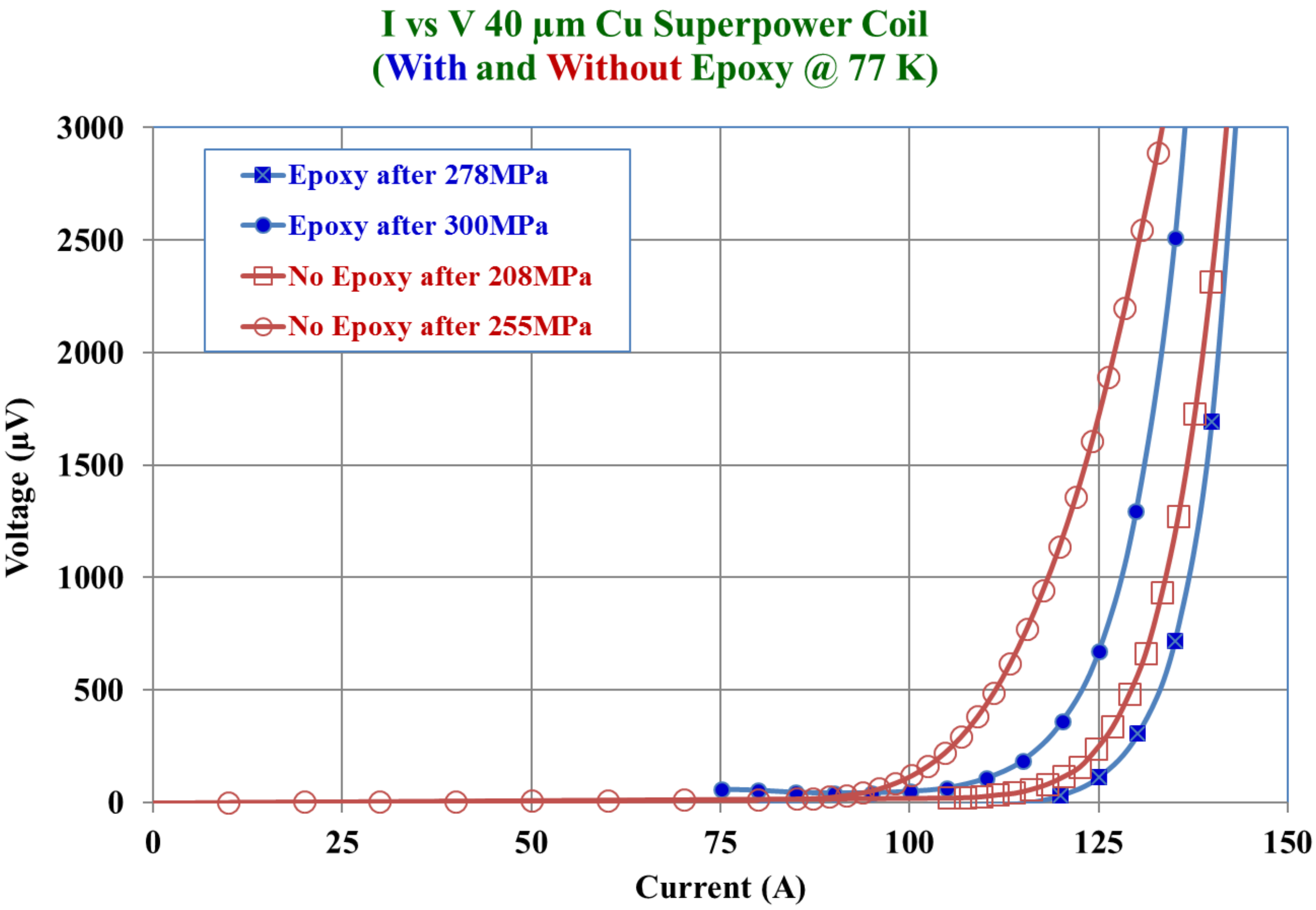
20 µm Cu PERFORMANCE AFTER MECHANICAL DEGRADAGTION



Coil Performance at 66%, 75%, and 80% Virgin I_c (141 A) up to 210 MPa. At this point, the coil's **I_c had degraded from 141 A to 121A. Even so, the coil performed well within limits at** – the coils I_c threshold voltage (according to the 1µV/cm standard) is 977 µV.

Recovery characteristic of the superconductor observed again.

EPOXY vs NO EPOXY



Epoxied coil shows better performance against axial loading in comparison to Non-Epoxied coil.

SUMMARY

SUMMARY

- Testing equipment was developed to perform axial loading tests on the narrow side of the 12 mm wide SuperPower 2G HTS tape – up to 300 MPa (magnet design requires ~170 MPa).
- **For 12 mm wide SuperPower 2G HTS tape, the compressive loading limits were found to be:**
  - **40 µm Cu Stabilizer = 200 MPa**
  - **20 µm Cu Stabilizer = 230 Mpa**
- Superconducting layer exhibits an interesting recovery characteristic – needs further investigation
- Applying Epoxy to the wound coils further increases the compressive loading limits.
- As the **ratio of Hastelloy to Copper in a coil wound with SuperPower 2G HTS conductor increases, the coil becomes more mechanically robust**.