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Transverse stress test of two Bi-2212 Rutherford cables

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In collaboration with

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BERKELEY LAB

NATIONAL HIGH MAGNETIC FIELD LABORATORY

US MDP zoom meeting, 19th of July 2023

Motivation: stress in Bi-2212 dipole magnets

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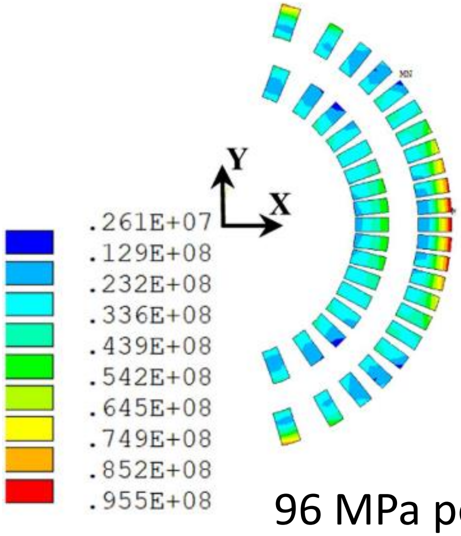
80 to 105 MPa azimuthal stress present in recent high-field Bi-2212 dipole magnet designs

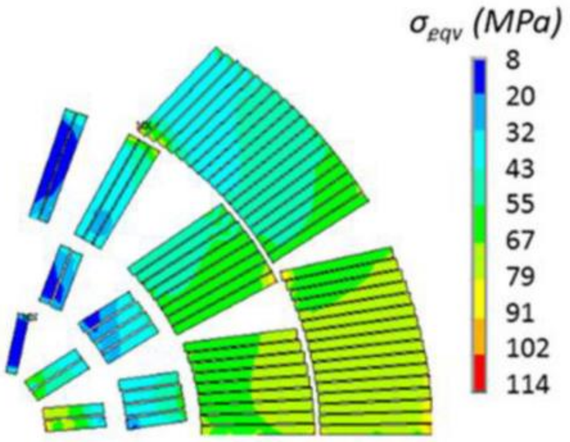
- Apart from one early date test, there are no systematic test data existing on cables
- It would be useful to have experimental data on stress limits for recent Bi-2212 cables

Garcia Fajardo et al. (2022)
https://doi.org/10.1109/TASC.2023.3264788



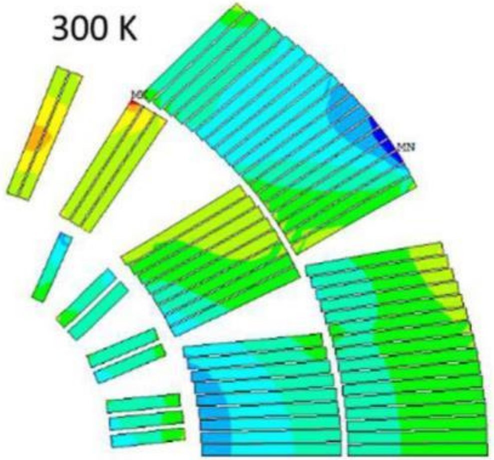
96 MPa peak stress

Zlobin et al. (2022)
https://doi.org/10.1109/TASC.2022.3158635



104 MPa peak stress

Zlobin et al. (2023)
https://doi.org/10.1109/TASC.2023.3264165



80 MPa peak stress

➢ Results are also highly relevant for high-field solenoids under high radial compressive load!

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- <u>Bi-2212 samples and test setup</u>
- Sample preparation
- Transverse stress results
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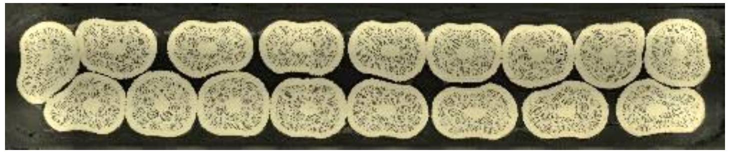
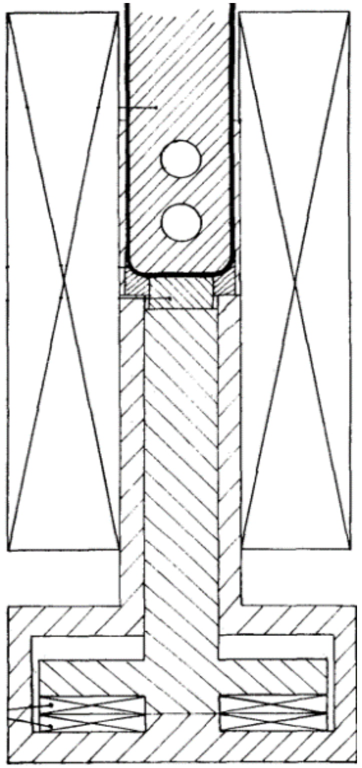
- Conclusion

Bi-2212 Rutherford cable



Cable press in 11 T solenoid



Bi-2212 Rutherford cable samples

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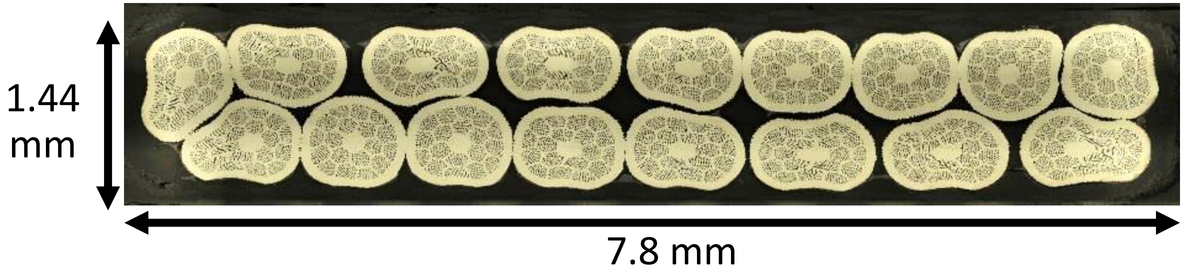
- **Two sample were tested at Uni. Twente in transverse stress set-up:**

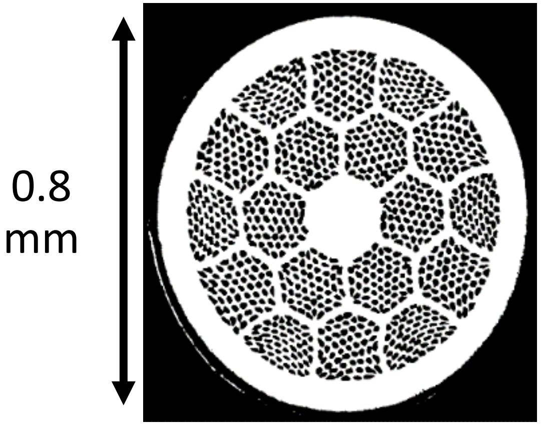
Zhang et al. (2018), https://doi.org/10.1088/1361-6668/aada2f

Cable cross-section



	Sample 3	**Sample 4**
Cable no.	LBNL1109	LBNL2002
Number of strands	17	17
Size excl. insulation	7.8 mm x 1.4 mm	7.8 mm x 1.4 mm
Twist pitch	58 mm	58 mm
Bi-2212 wire	Nontwisted PMM180207_4, 5, 6 ,7, 55x18, 0.8mm, Engi-mat powder LXB103	PMM190118, 55x18, 0.8mm, Engi-mat LXB156
Insulation	Mullite sleeve, 150 µm thick	Mullite sleeve, 150 µm thick
Test date at Uni. Twente	December 2022	June 2023

Wire cross-section (Zhang et al.)



Transverse stress setup

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- 50 kA superconducting transformer
- 11 T solenoid magnet
- 250 kN press
- 4.2 K helium bath

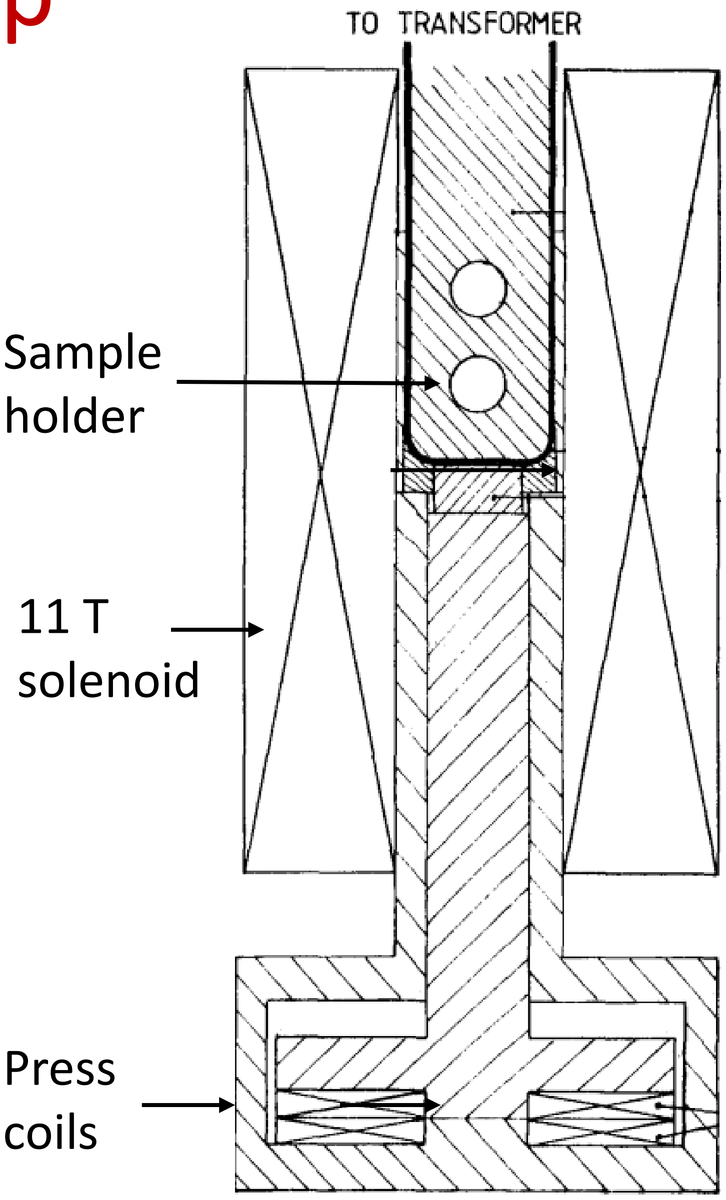

Image by Boschman et al.
https://doi.org/10.1109/20.133551

50 kA trans-former

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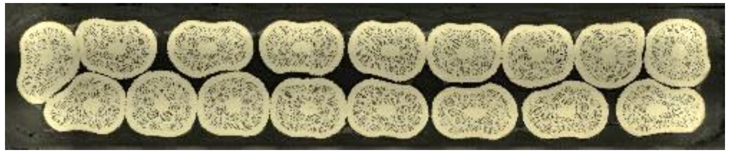
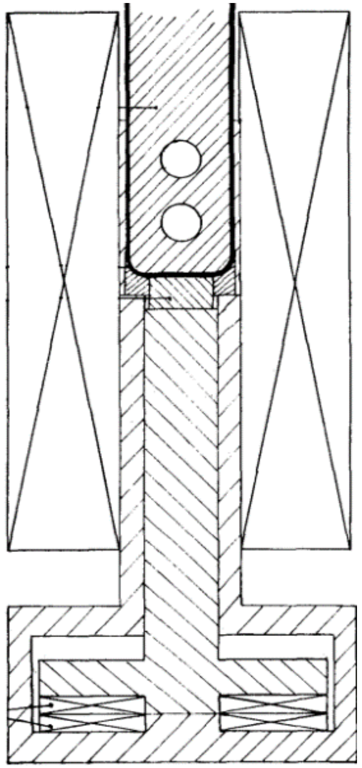
Bi-2212 Rutherford cable



Cable press in 11 T solenoid



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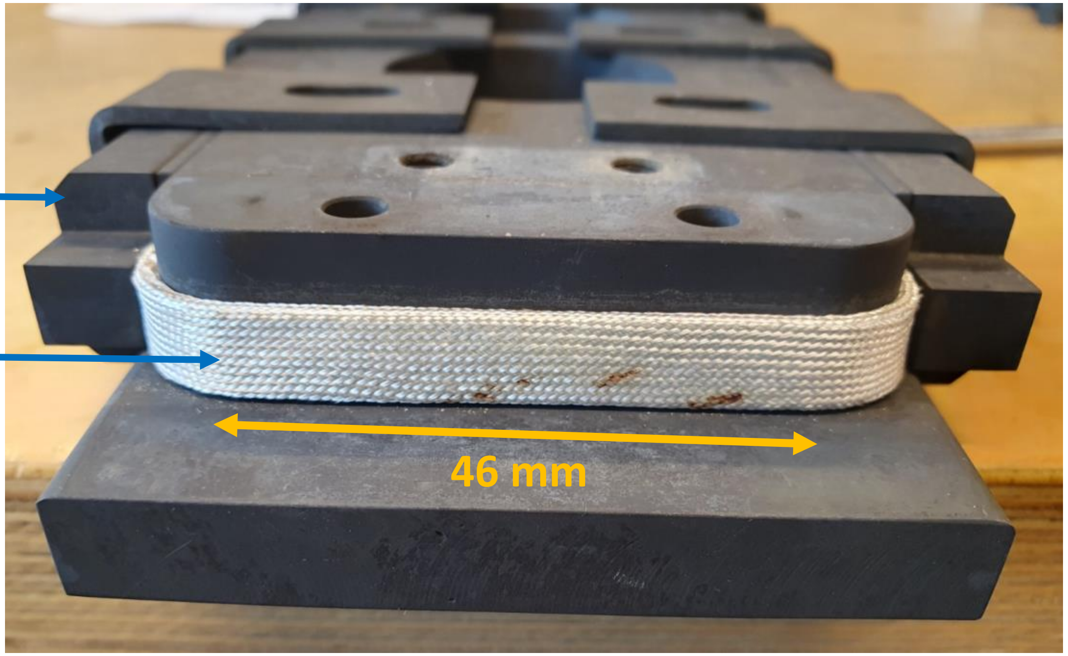
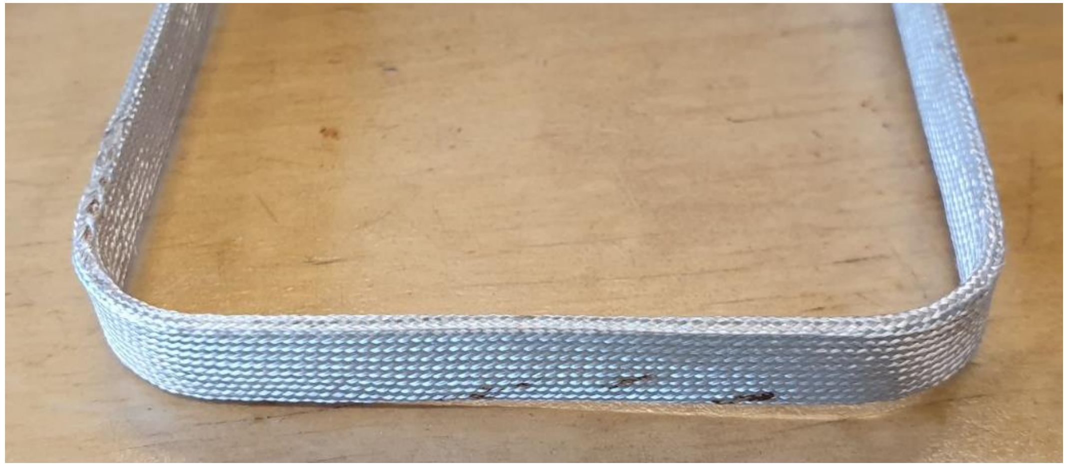
Sample after heat treatment

Pictures of sample 4 after heat treatment

Stainless steel reaction holder

Bi-2212 Rutherford cable in mullite sleeve



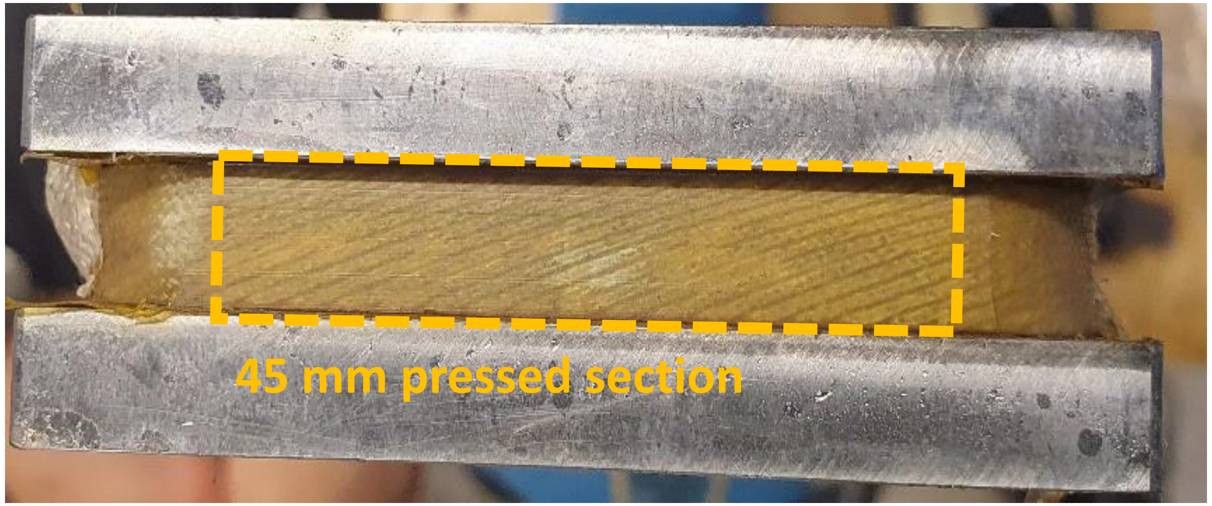


The samples were heat treated at NHMFL in 49:1 mixture of argon and oxygen with a total gas pressure of 50 bar (892°C)

Epoxy impregnation

- Vacuum impregnation with CTD-101k at 60°C, 0.6-0.8 mBar
- Cured for 5 hour at 110°C and 16 hour at 125°C in a furnace

Sample surface after heat treatment



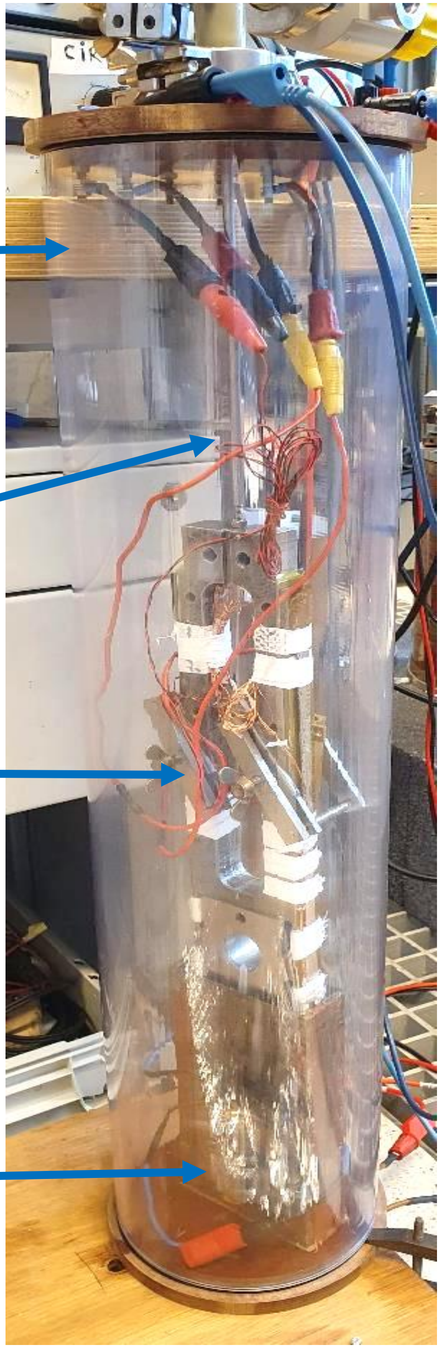
Impregnation setup

Vacuum chamber

Rod for moving the sample

Sample holder

Heated resin container



50 cm

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Pushing block and strain gauges

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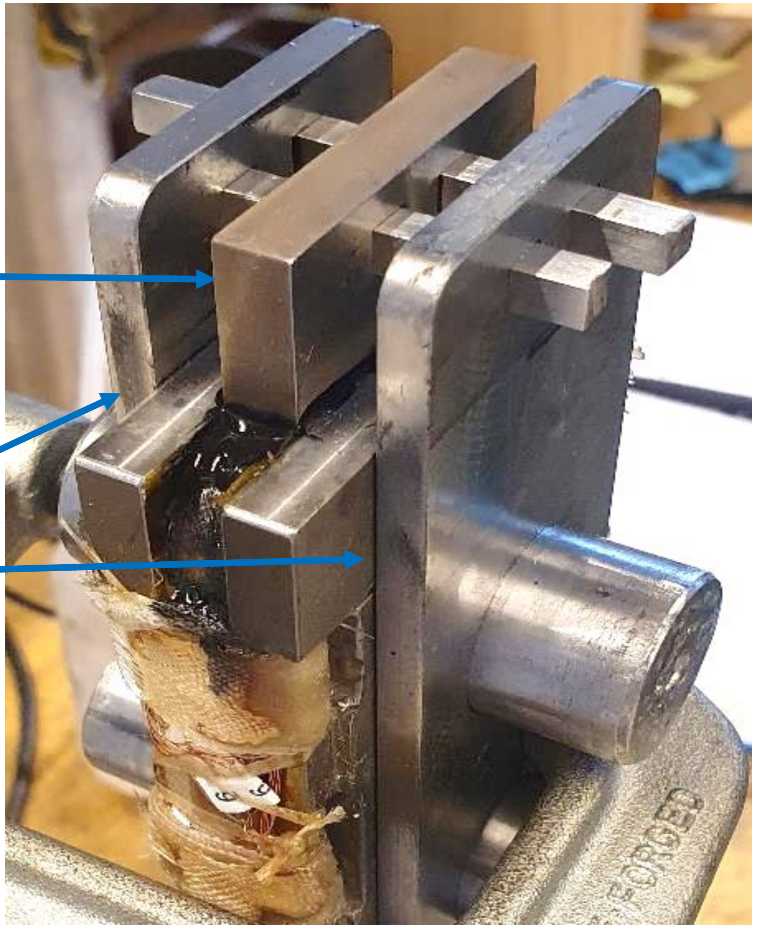
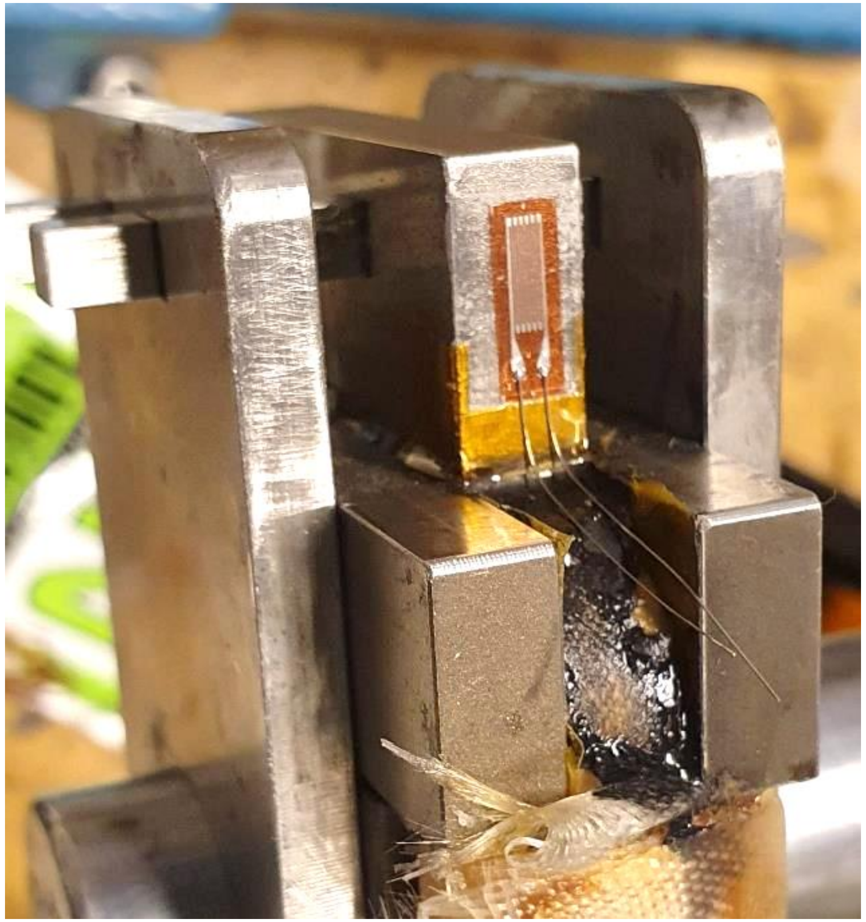
Pushing block

Alignment plates (removed when Stycast cured)



- Block glued onto the sample with Stycast 2850FT/23LV and three layers of glass ribbon
- Pushed area is 8.1 mm x 45 mm = 3.654 cm^2



- Strain gauge (CFLA-6-350-17) on each side of the pushing block
- Attached with cyano-acrylate glue (TMI CN)

Sample connection to the transformer

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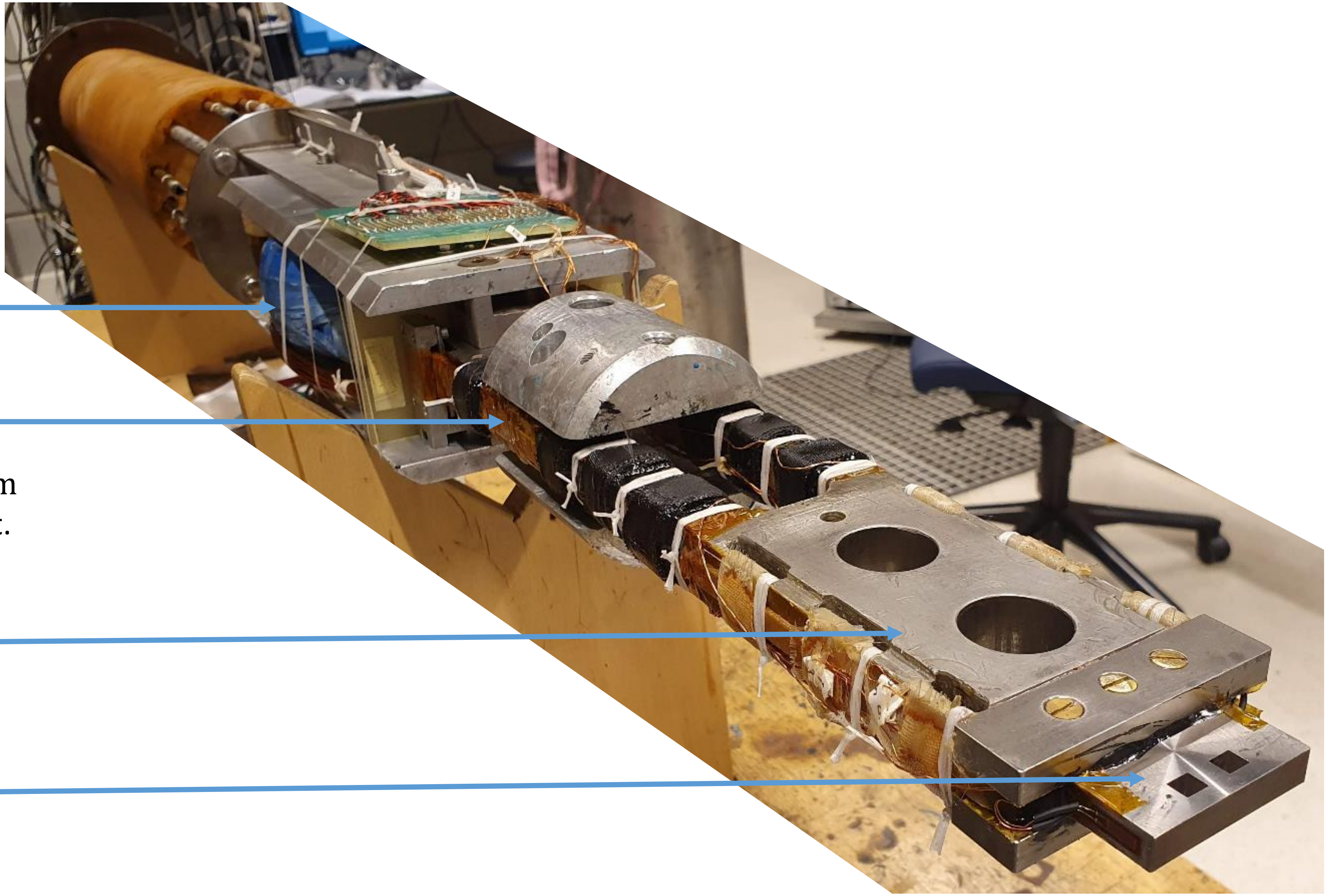

Transformer

Joints

Soldered over $2\ell_t = 116$ mm with SnAg. Fixed with Stycast.

Sample holder

Pushing block

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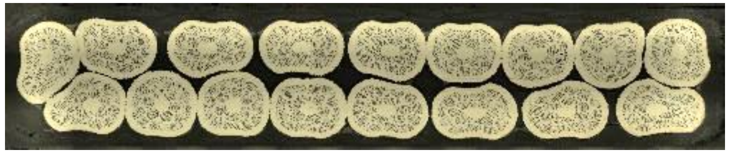

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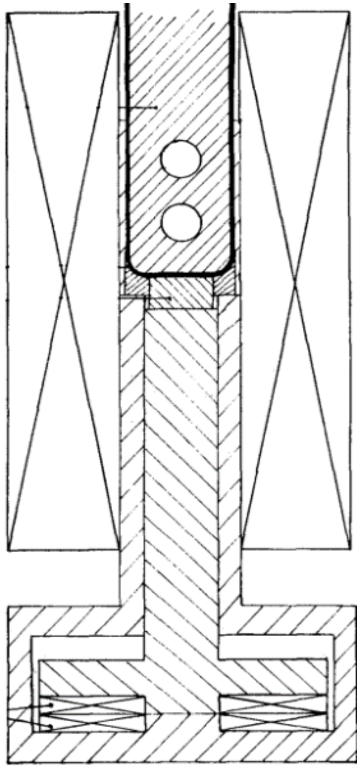
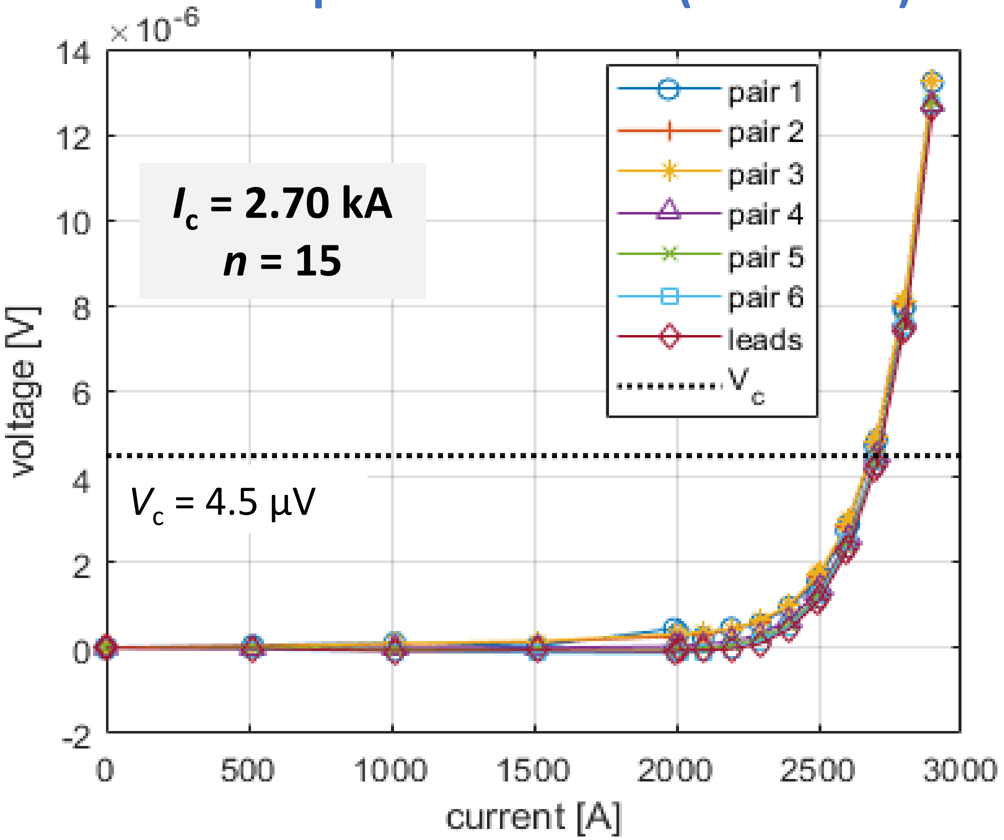


Initial VI curves

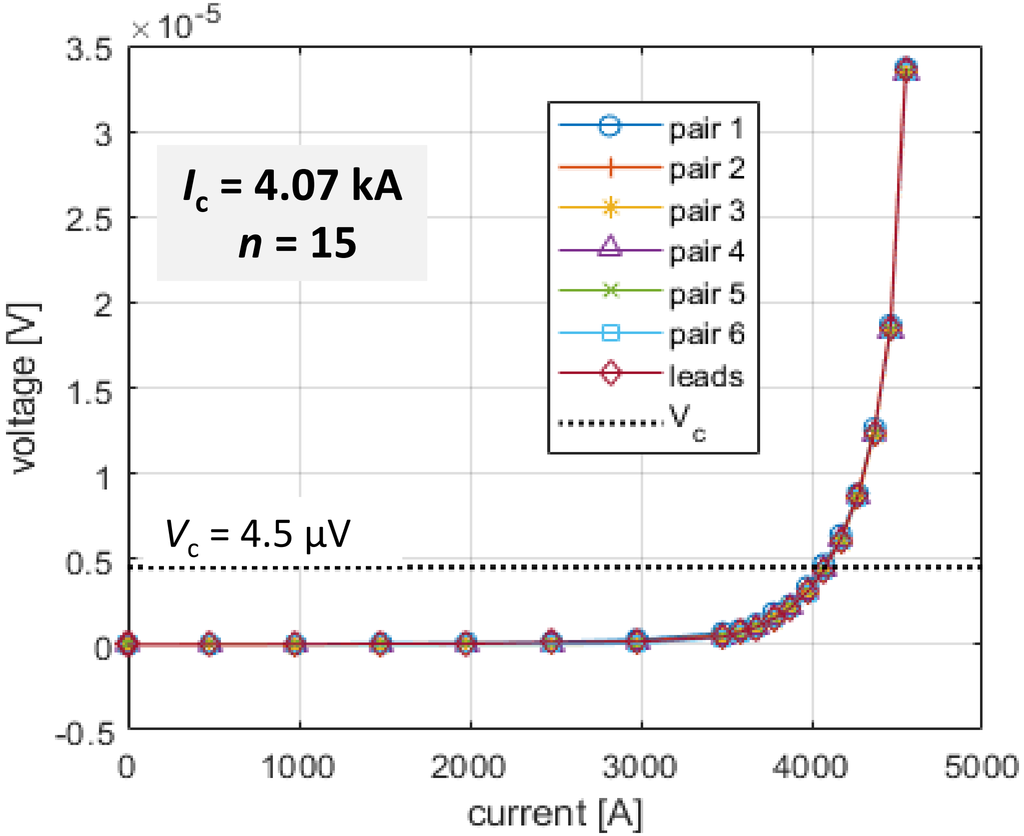
T = 4.2 K, B_a = 11 T, σ = 10 MPa

- Voltage measured on 6 strands and current leads; they all look smooth and consistent
- Voltage criterion of 4.5 μV results from $E_c = 10^{-4}$ V/m and 45 mm pushing block length

Sample 3: LBNL1109 (Dec 2022)



Sample 4: LBNL2002 (June 2023)



Initial $I_c(B)$ curve

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Comparison of samples:

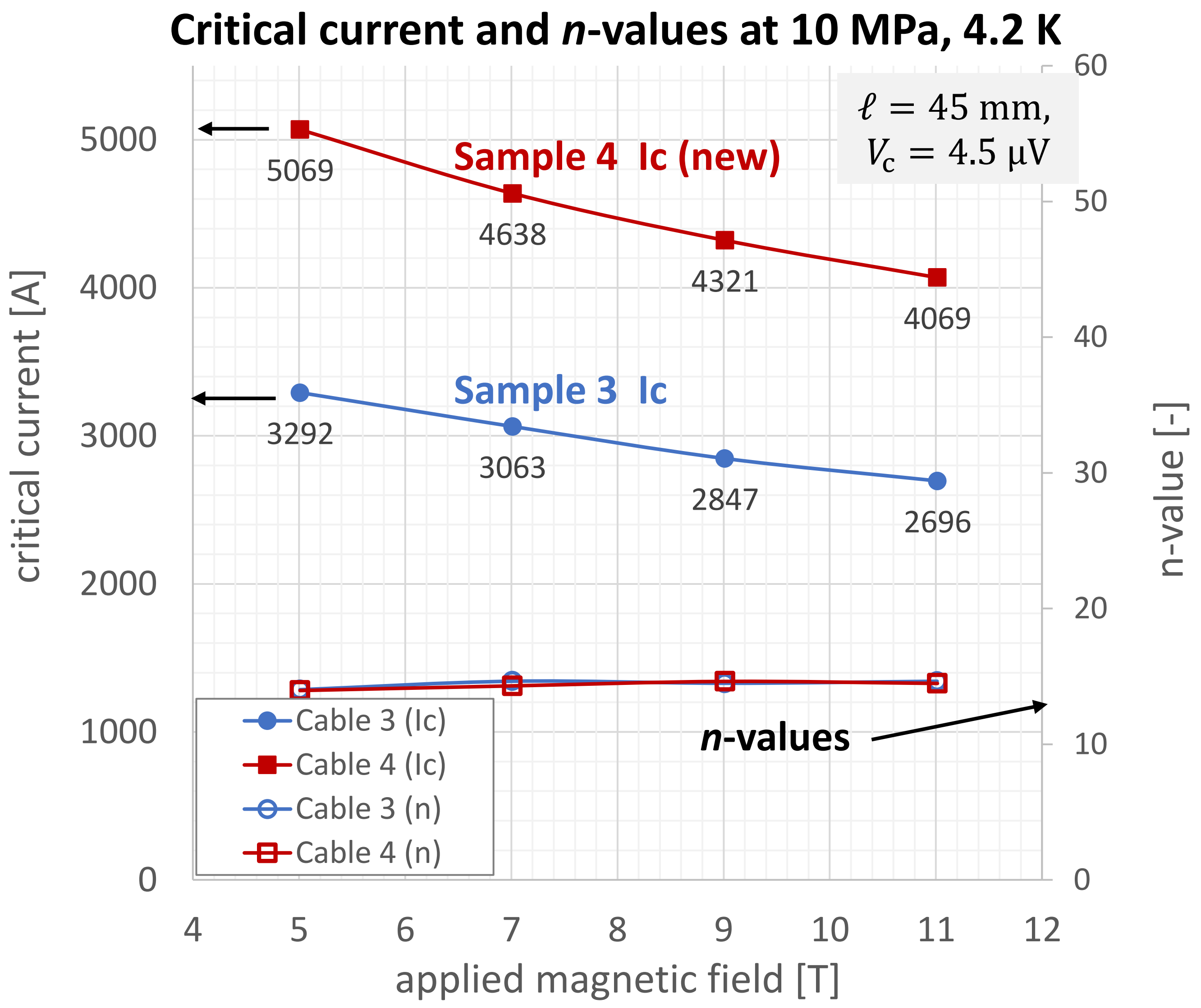
- **Sample 3: LBNL1109, tested Dec 2022**
- **Sample 4: LBNL2002, tested June 2023**

- **Engineering current density at 5 T** applied field using 7.8 mm² cross-sectional area is:

  422 A/mm² for sample 3,

  650 A/mm² for sample 4 (54% increase)

- ***n*-values** are 14 to 15 for both samples and all applied fields in the range 5 to 11 T.



Critical current versus transverse stress

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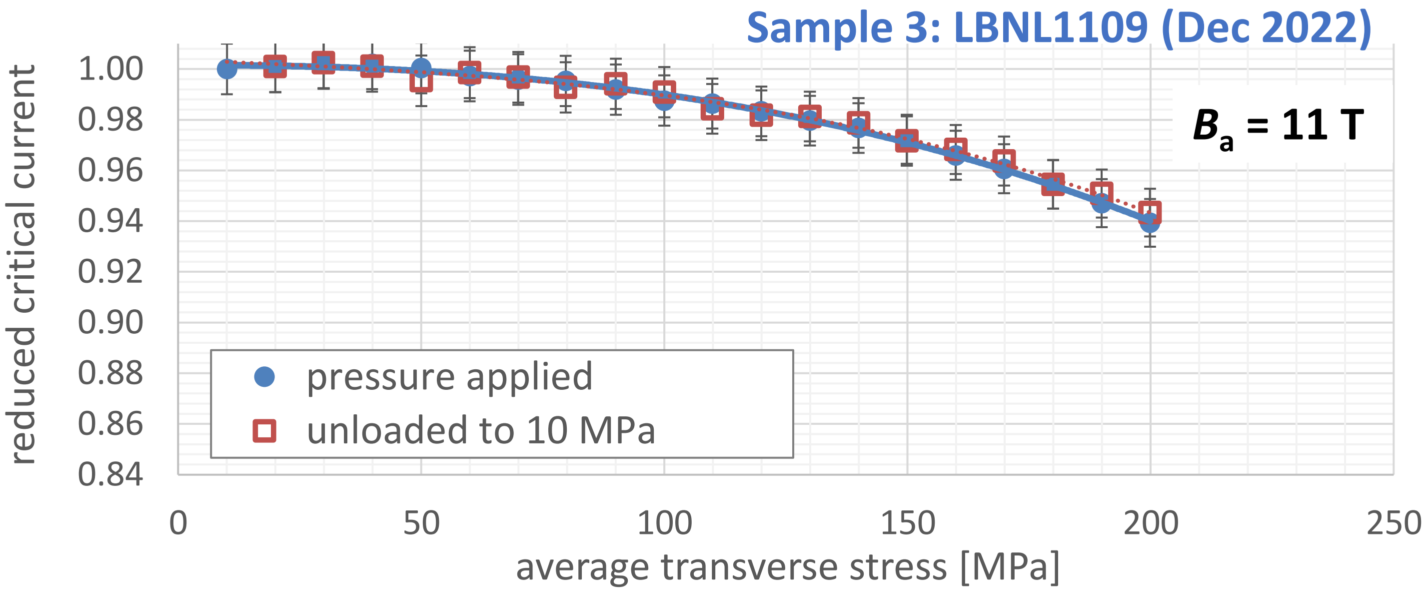
Applied field 11 T, data normalized to initial I_c of 2.70 kA (sample 3), and 4.07 kA (sample 4)

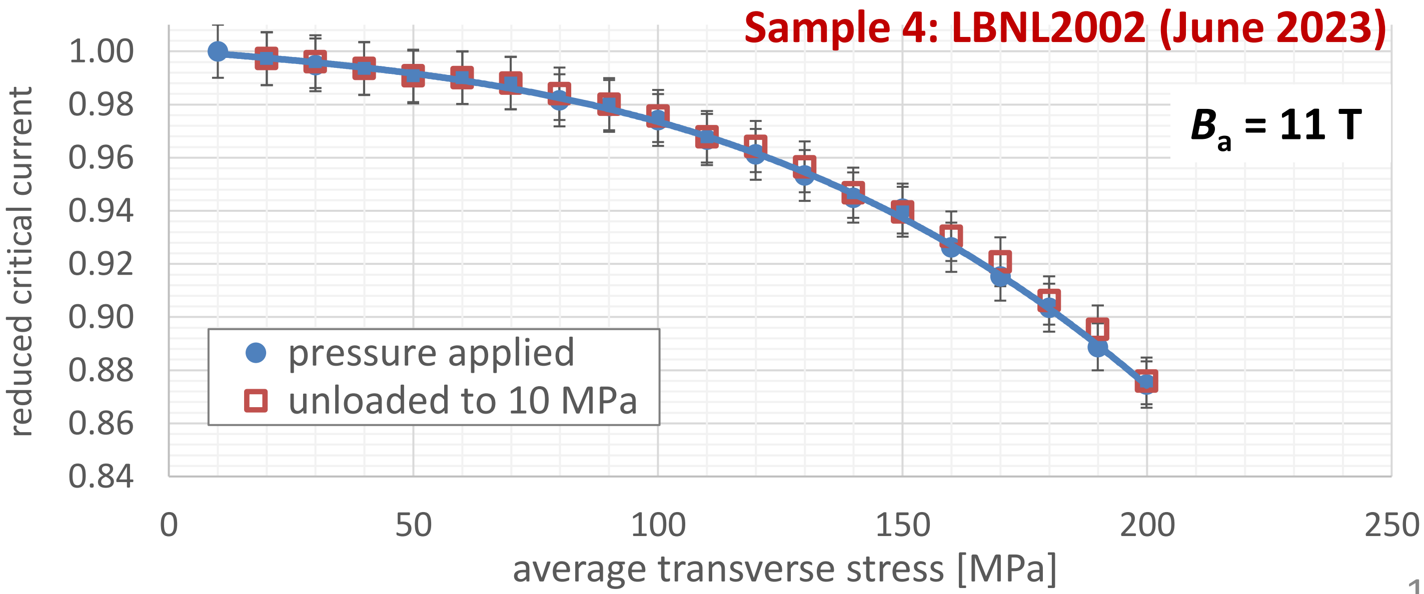
- Measurement sequence:
  - 10 MPa
  - 20 MPa
  - 10 MPa
  - 30 MPa
  - 10 MPa
  - 40 MPa
  - etc.

- **5% degradation reached at:**

  170-200 MPa in sample 3 and

  120-150 MPa in sample 4





Comparison of the two samples 3 and 4

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Sample comparison

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

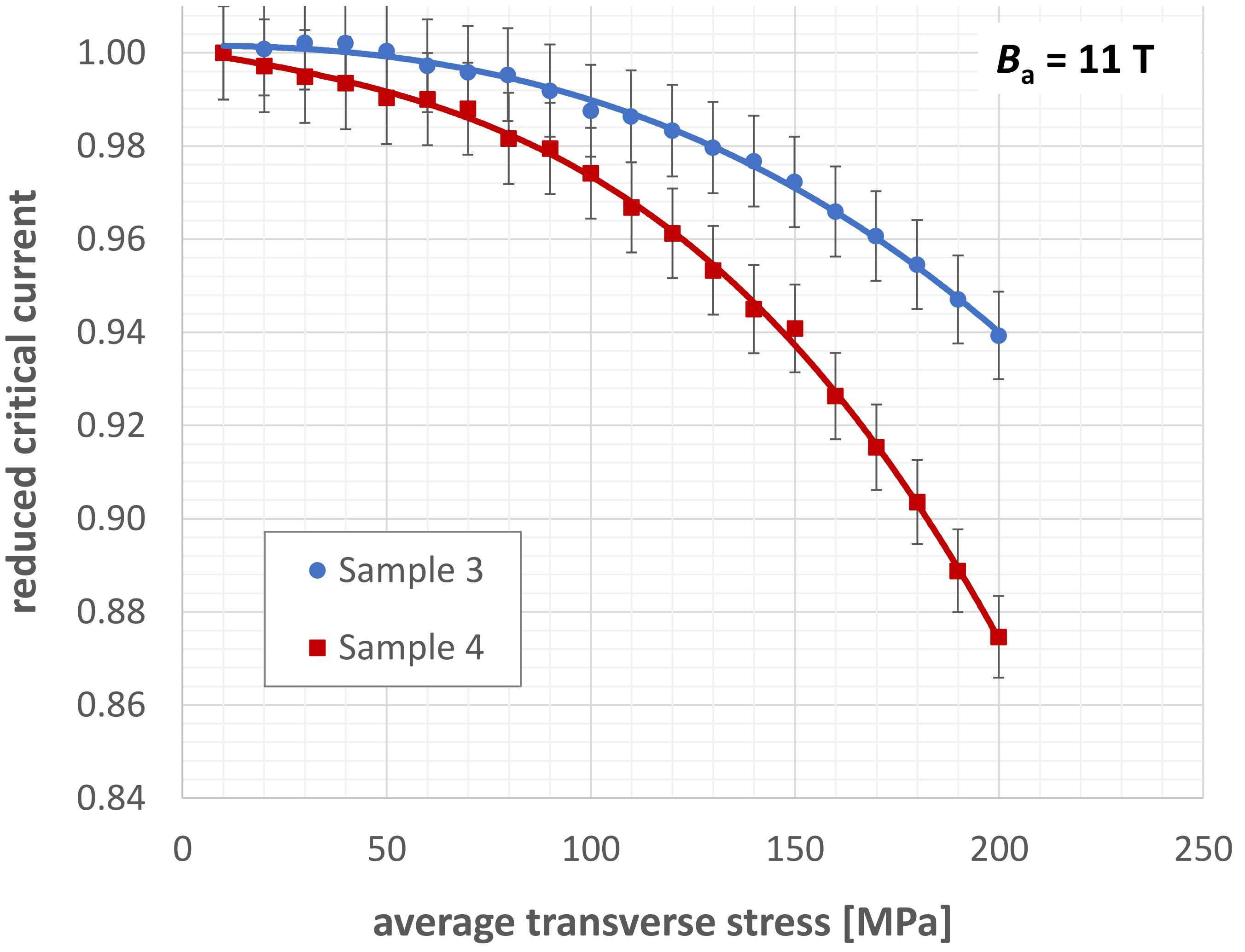
Stronger stress dependence observed in sample 4, at 150 MPa:

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

➢ The difference between the samples at 100 MPa is 1.5% and at 150 MPa is 3% only

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

Critical current as function of transverse stress



$I_c(B)$ curves after applying 200 MPa

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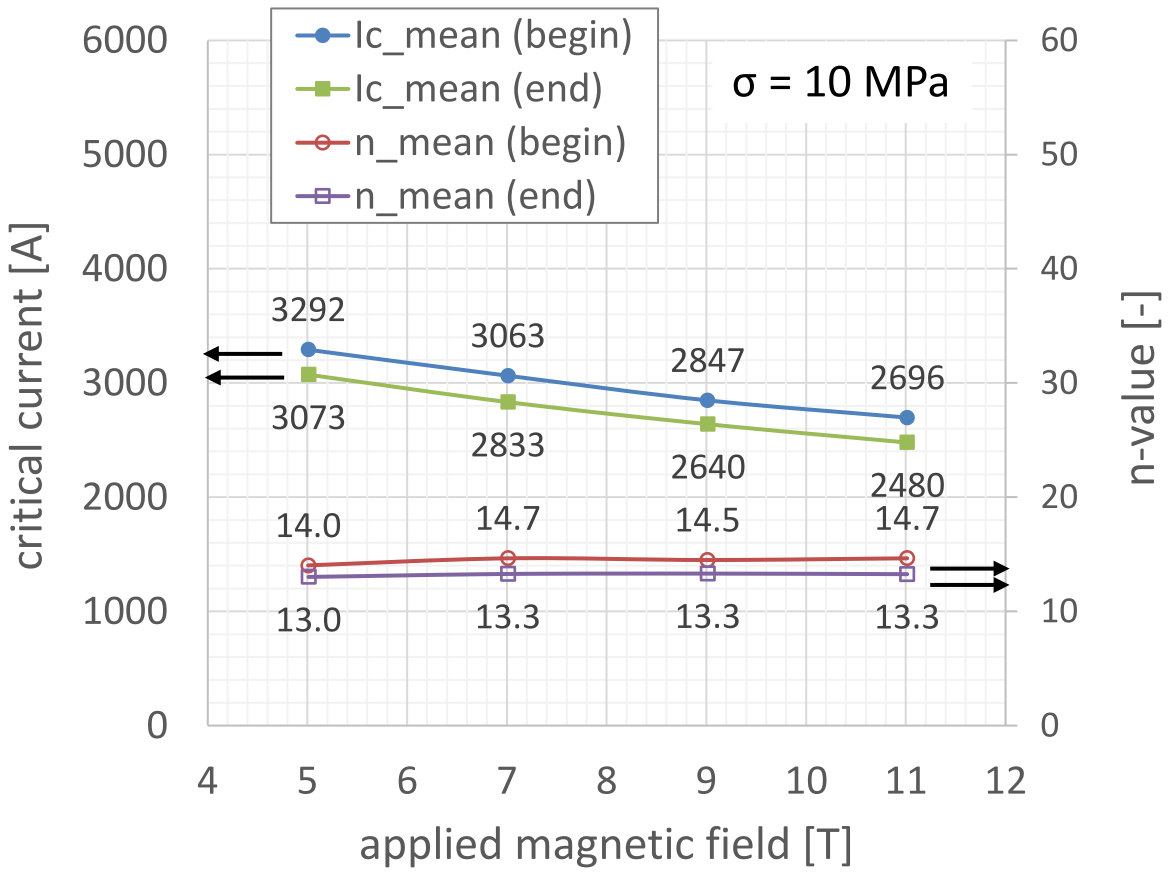
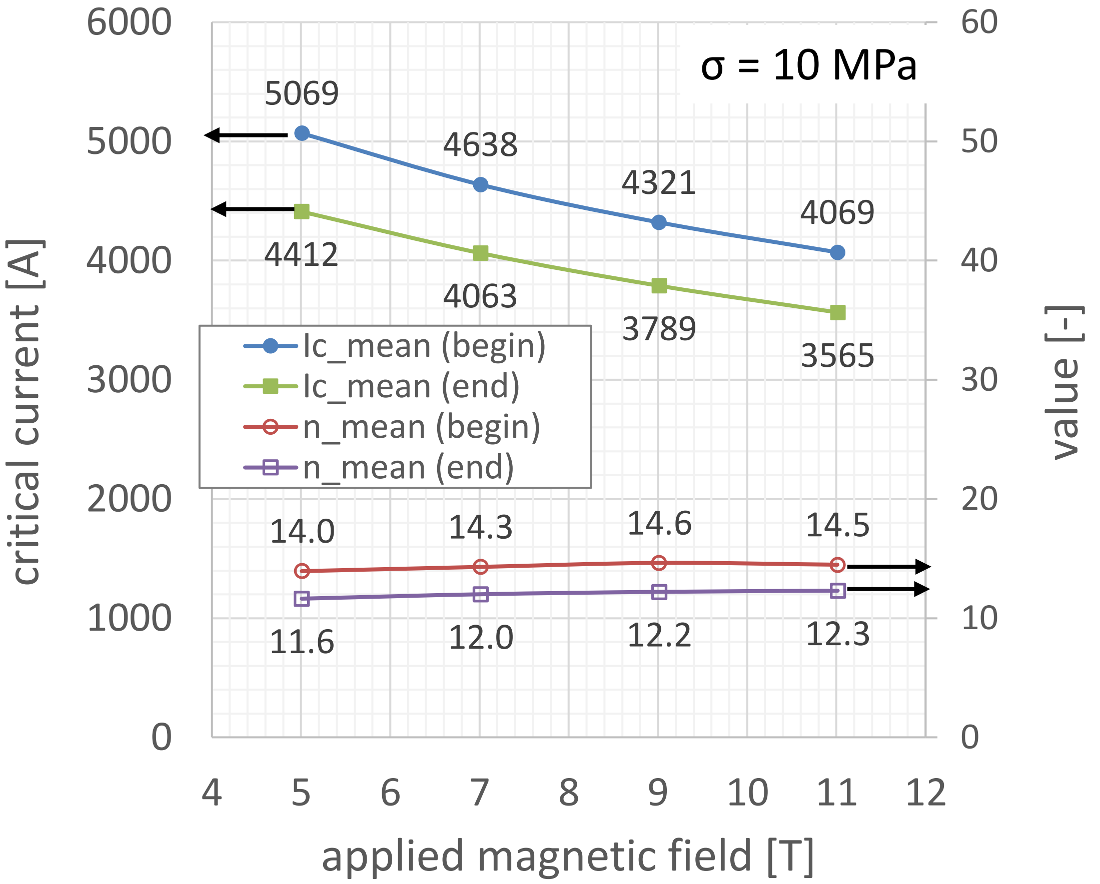
Sample 3: LBNL1109 (December 2022)

- 7 to 8% field-independent I_c reduction
- *n*-value dropped by 1 to 2 points



Sample 4: LBNL2002 (June 2023)

- 12 to 13% field-independent I_c reduction
- *n*-value dropped by 2 to 3 points



Effect of mechanical load cycling 10 to 200 MPa

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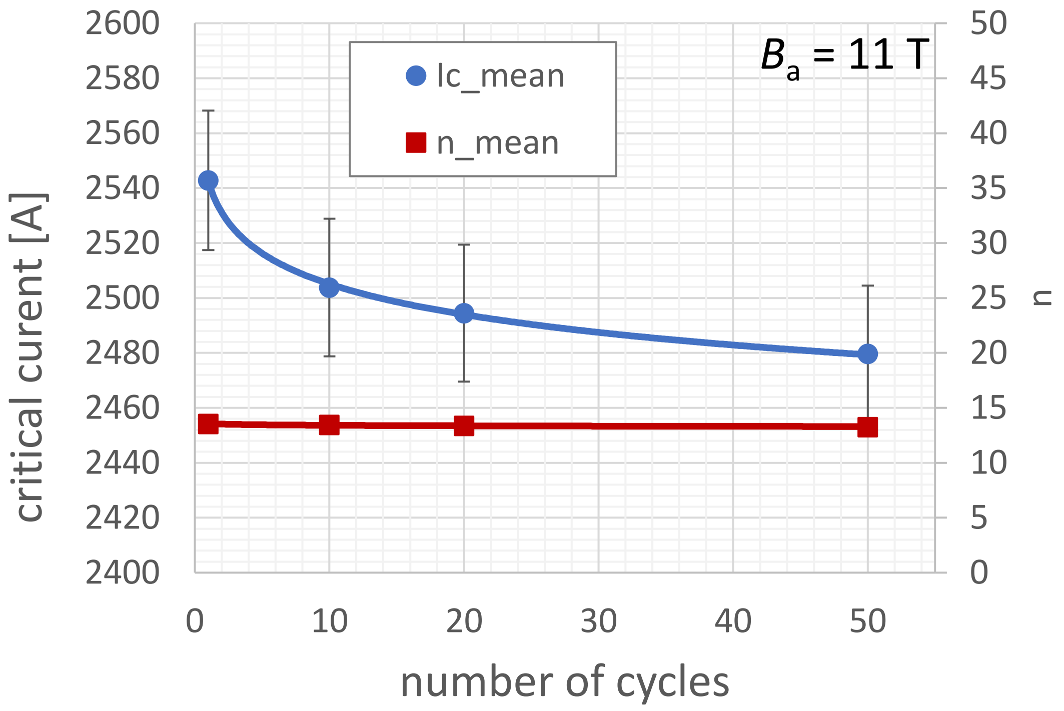
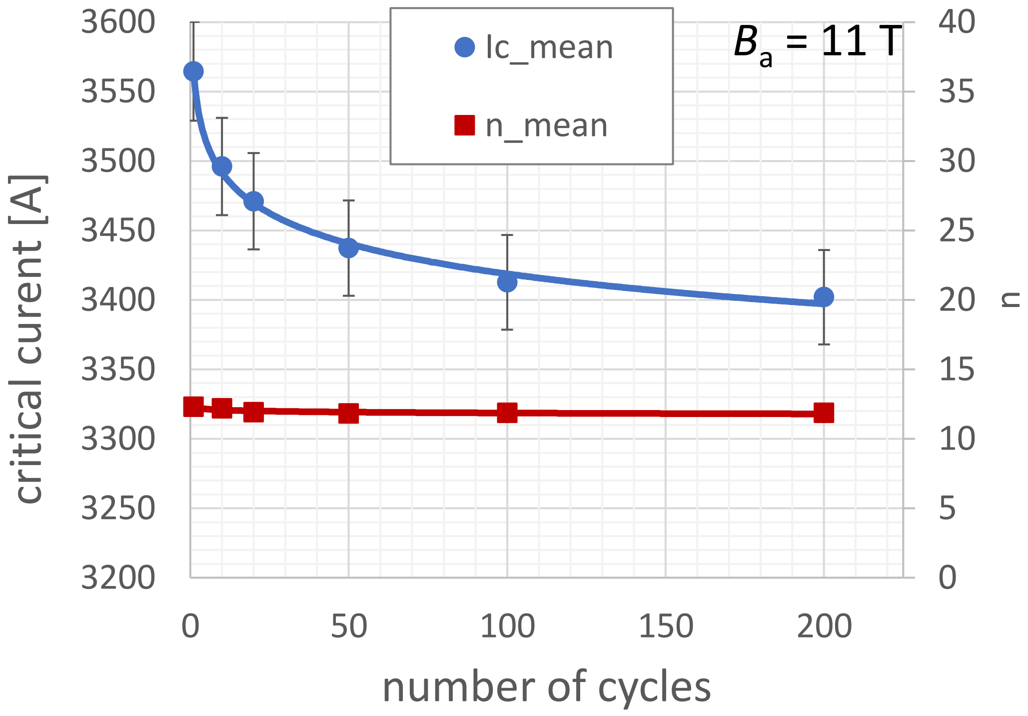
Sample 3: LBNL1109 (December 2022)

- 2.5% I_c reduction after 50 cycles
- No significant change in *n*-value



Sample 4: LBNL2002 (June 2023)

- 3.6% reduction after 50 cycles
- 4.6% reduction after 200 cycles
- No significant change in *n*-value



➢ Load cycling I_c reduction at 200 MPa is modest (some 5 %), and saturating (good) .

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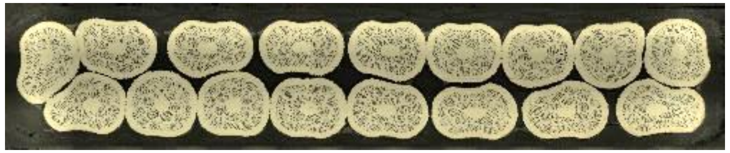

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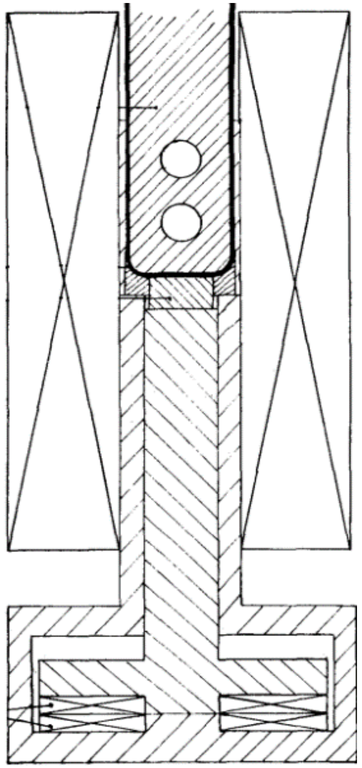

Microstructural analysis cross-sections of sample 3

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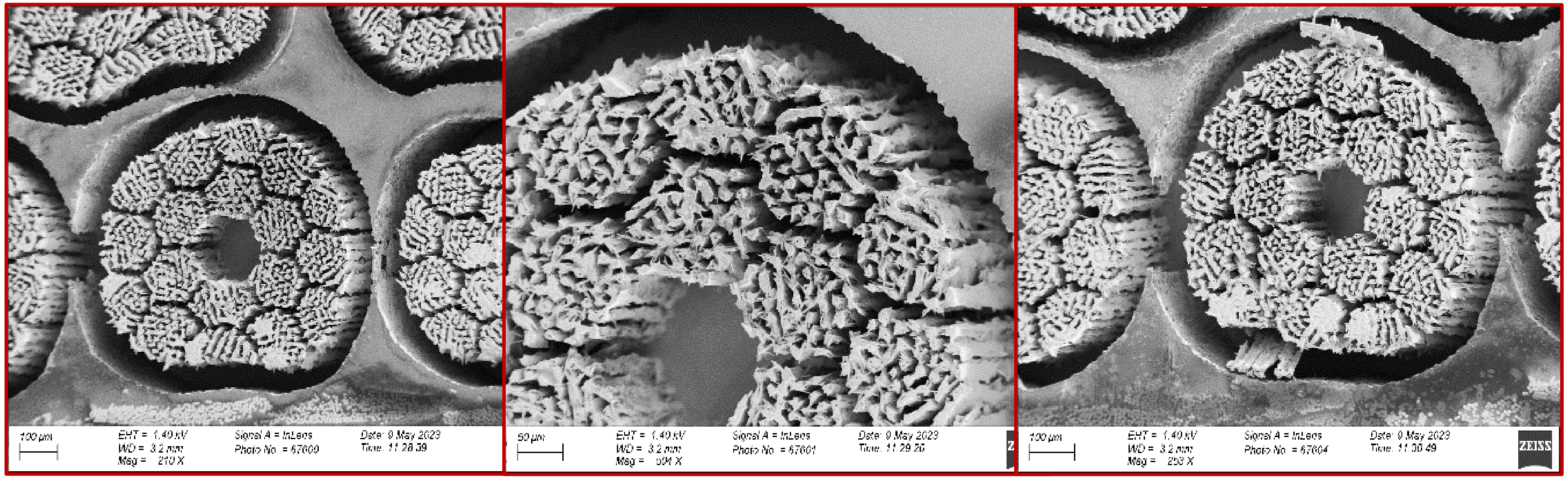
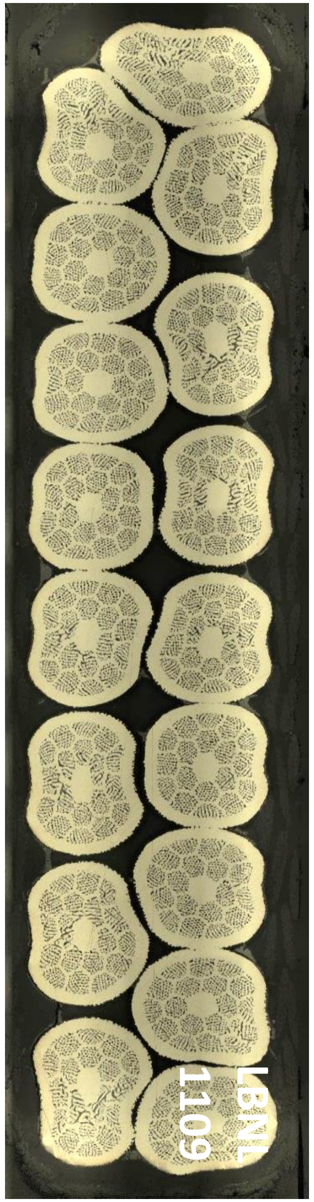


Silver matrix removed with NH_3OH and H_2O_2



- 5 cross-sections examined (200 MPa, 8% I_c decrease)
- **No obvious damage seen yet, main degrading cause not yet identified**
- I_c-degradation = broken current path + some residual stress redistribution effect
- In Nb_3Sn we see filament µm-cracking, current in entire filament interrupted
- May be here (hypothesis, for discussion) we brake with nm-cracking current path at grain boundaries mainly on surface of filaments, not leading to global cracking……
- **Sample 4 has seen 300 MPa and -45%, next to be examined….**

Conclusion

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- Results obtained on 2 Bi-2212 cable samples, another 2 to be tested
- Initial whole cable critical current density at 5 T applied field was **422 A/mm² in sample 3 (LBNL1109)** and **650 A/mm² in sample 4 (LBNL2002)**
- 5% critical current decrease reached at an average transverse stress of **170 to 200 MPa in sample 3** and at **120 to 150 MPa in sample 4**
- **Progressive I_c reduction (but saturating) observed** in both samples when cycling between 10 and 200 MPa
- All changes in critical current were irreversible