# Analyses of the plastic deformation of coated conductors deconstructed from ultra-high field test coils

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**Aug 05, 2020**

ACCEPTED MANUSCRIPT

Analyses of the plastic deformation of coated conductors deconstructed from ultra-high field test coils

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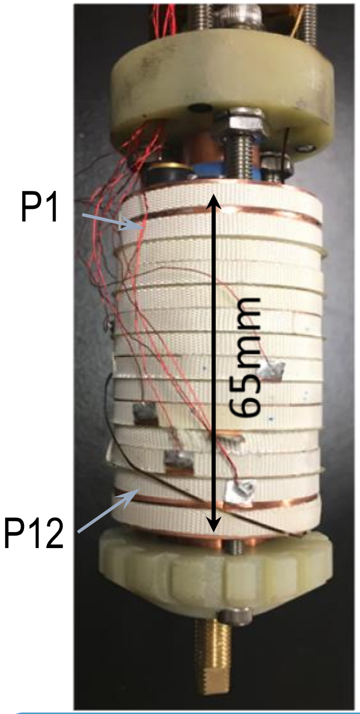
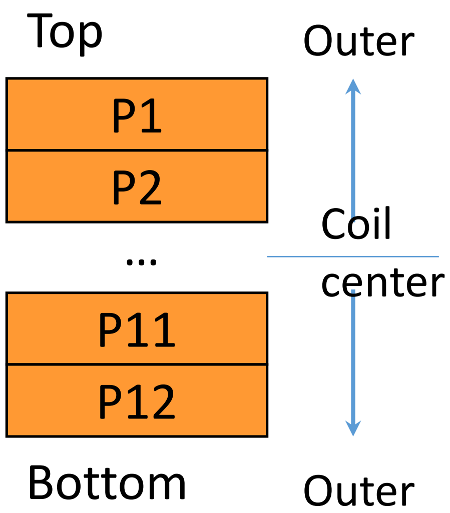
Accepted Manuscript online 20 July 2020 • 

# The Little Big Coil NI coil went through 3 iterations..(LBC1-3)

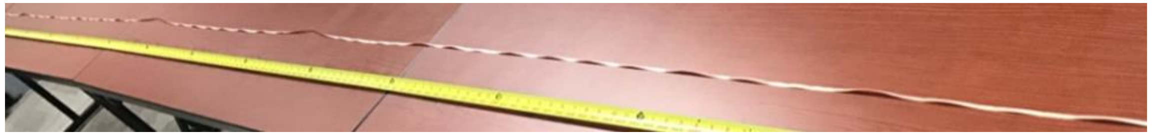
- All consist of 12 pancakes with 7 and 17 mm inner and outer radius
- All tested in a background field of 31 T.
- LBC1 – 40.2 T, LBC2 – 42.5 T, LBC3 – 45.5 T




LBC provides an extreme test bed far beyond user magnet specification

After achieving 45.5 T, we noticed some joint resistance: after unwinding.....



Multiple pancakes showed rippling (permanent plastic deformation of the tape (YS ~ 1 GPa, ~ 2 x nominal JBr stress

- One edge of the tape is stretched longer than the other.

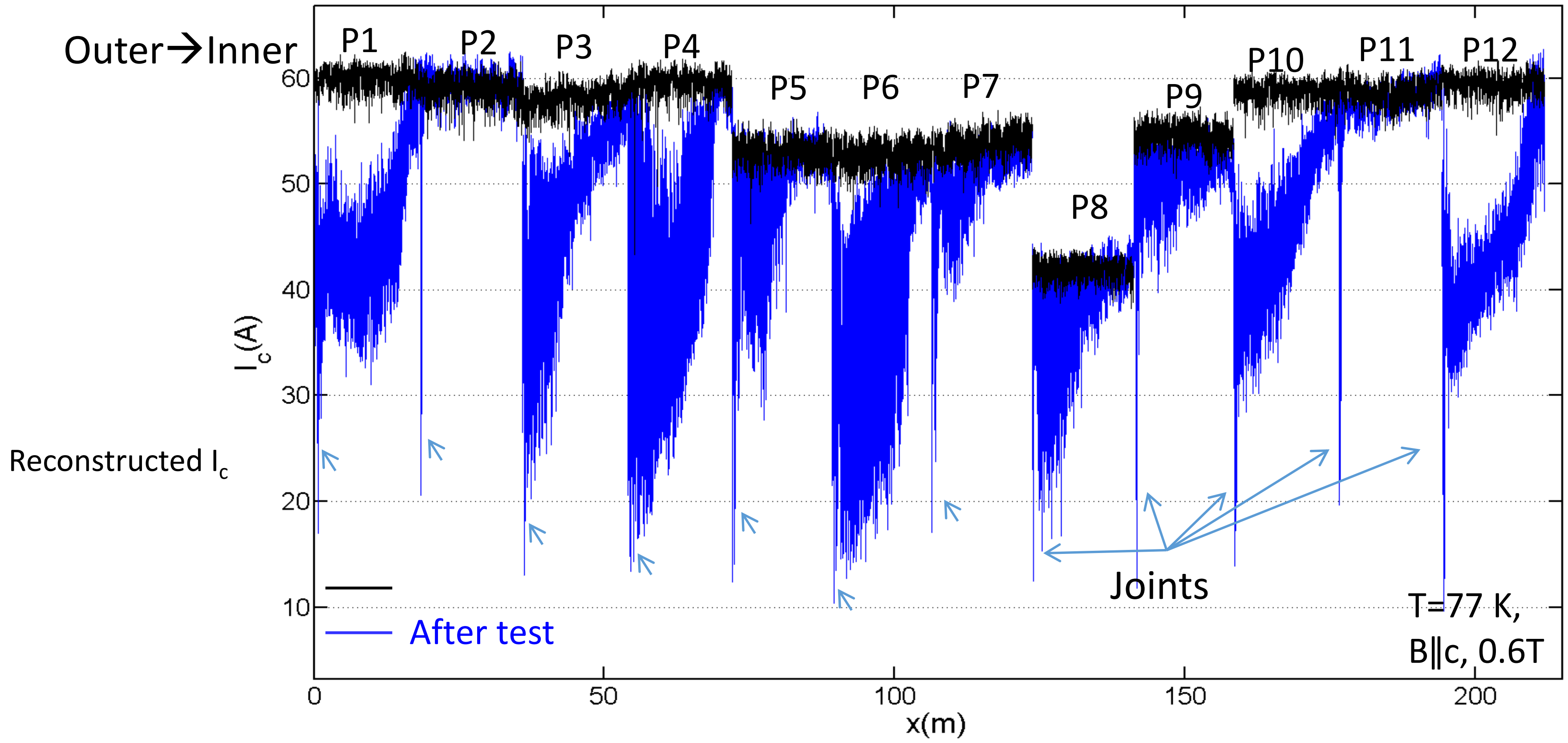
**45.5-tesla direct-current magnetic field generated with a high-temperature superconducting magnet**


Seungyong Hahn[1,2], Kwanglok Kim[1], Kwangmin Kim[1], Xinbo Hu[1], Thomas Painter[1], Iain Dixon[1], Seokho Kim[1,3], Kabindra R. Bhattarai[1,4], So Noguchi[1,5], Jan Jaroszynski[1] & David C. Larbalestier[1,4*]



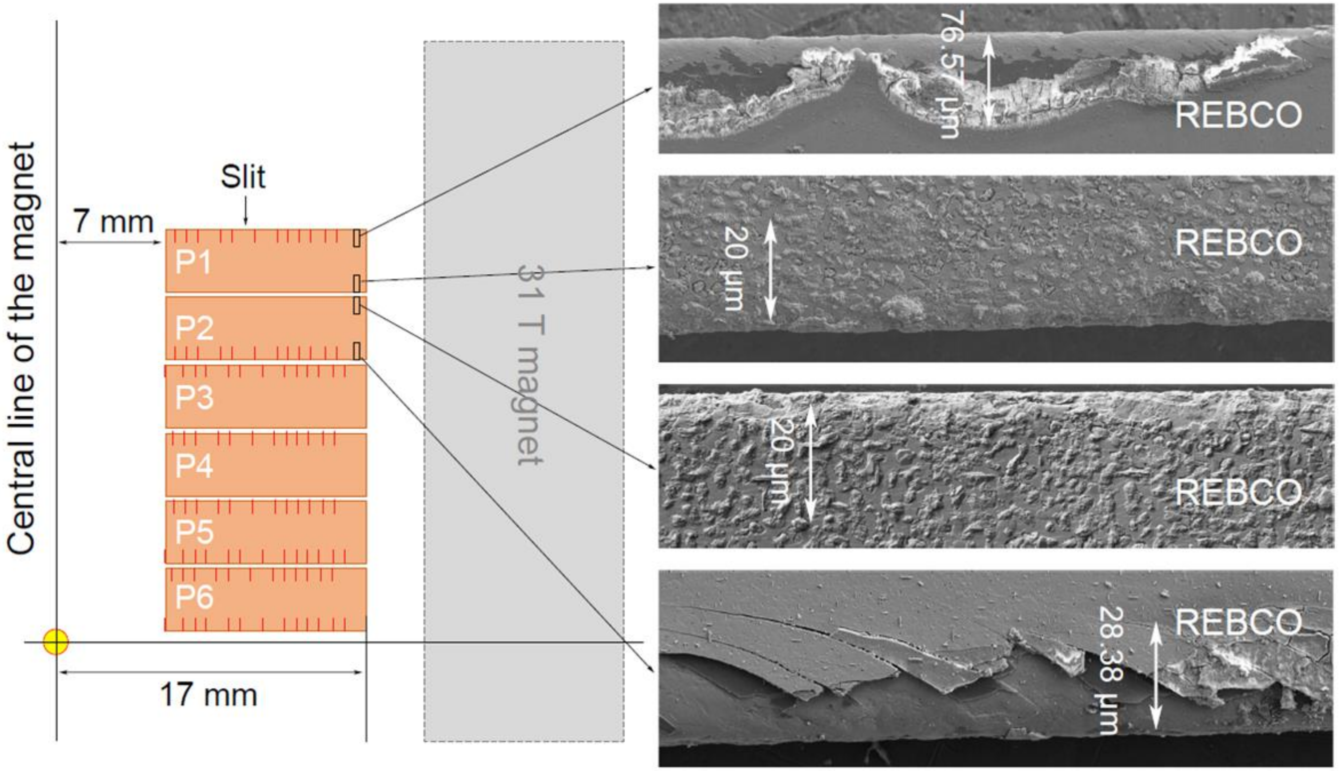
*Nature* 570, 497 June 2019 https://doi.org/10.1038/s41586-019-1293-1

# Using our transport and Hall array in-line measurement system (YateStar) we found clear evidence of conductor damage AFTER test for all pancakes EXCEPT P2 and P11




- The big dropouts on outer turns came from outer solder joints.
- Maximum degradations are close to the outmost turns but not on them.
- Indications of hoop stress occur on outer turns which we believe occurred during quench rather than from energization to field (Note that PC 2 and 11 do NOT have this damage).

# An important observation is that the slit edge is more easily damaged when placed towards the outside of the magnet




Delamination on the slit edge

No damage on not-slit edge

No damage on not-slit edge

Delamination on the slit edge associated with slitting cracks

Although LBC3 operated far beyond the design strains of any user magnet, it shows that the likely long-term behavior of the tape under fatigue and elastic-plastic deformation of the Ag-REBCO-buffer interface needs to be much better understood

# More examinations – why are the *post-mortem* analyses necessary?

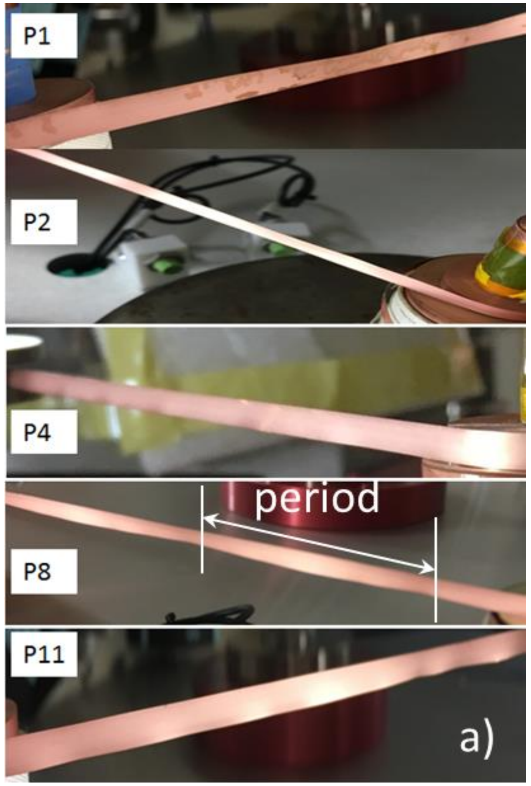
- To understand the failure mechanism of the conductor
- To estimate the stress distribution and magnitude.
- Many of the mechanical issues in REBCO magnets are related to the screening current. Experimental data is the benchmark for any simulation.

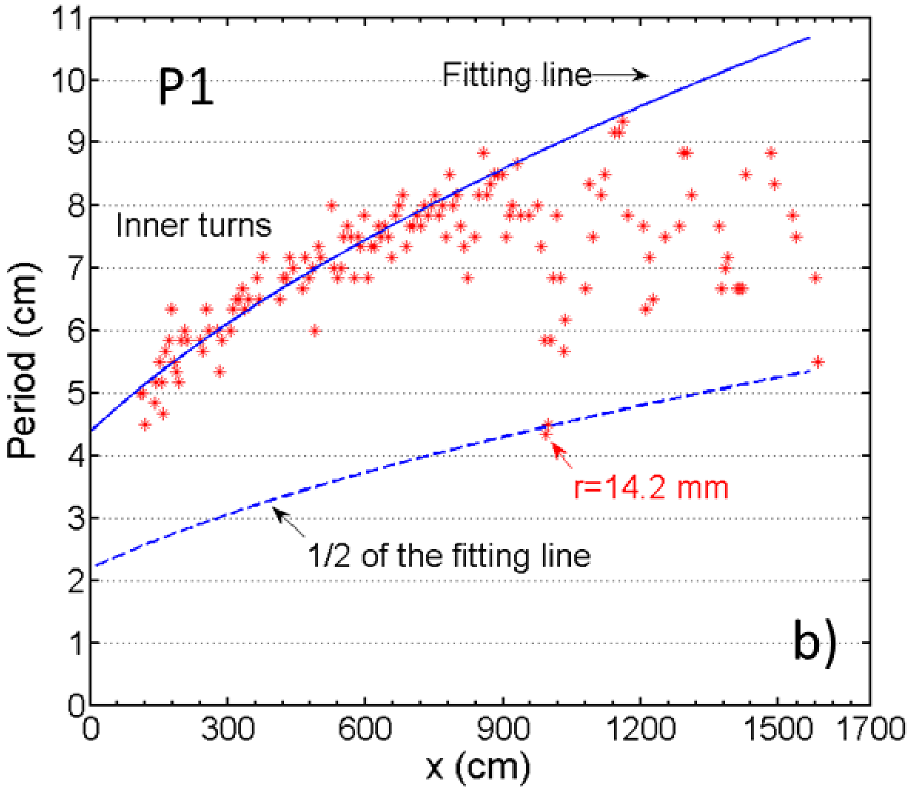
# The plastic deformation is periodic in the middle turns but not the outermost turns

LBC2

top

bottom

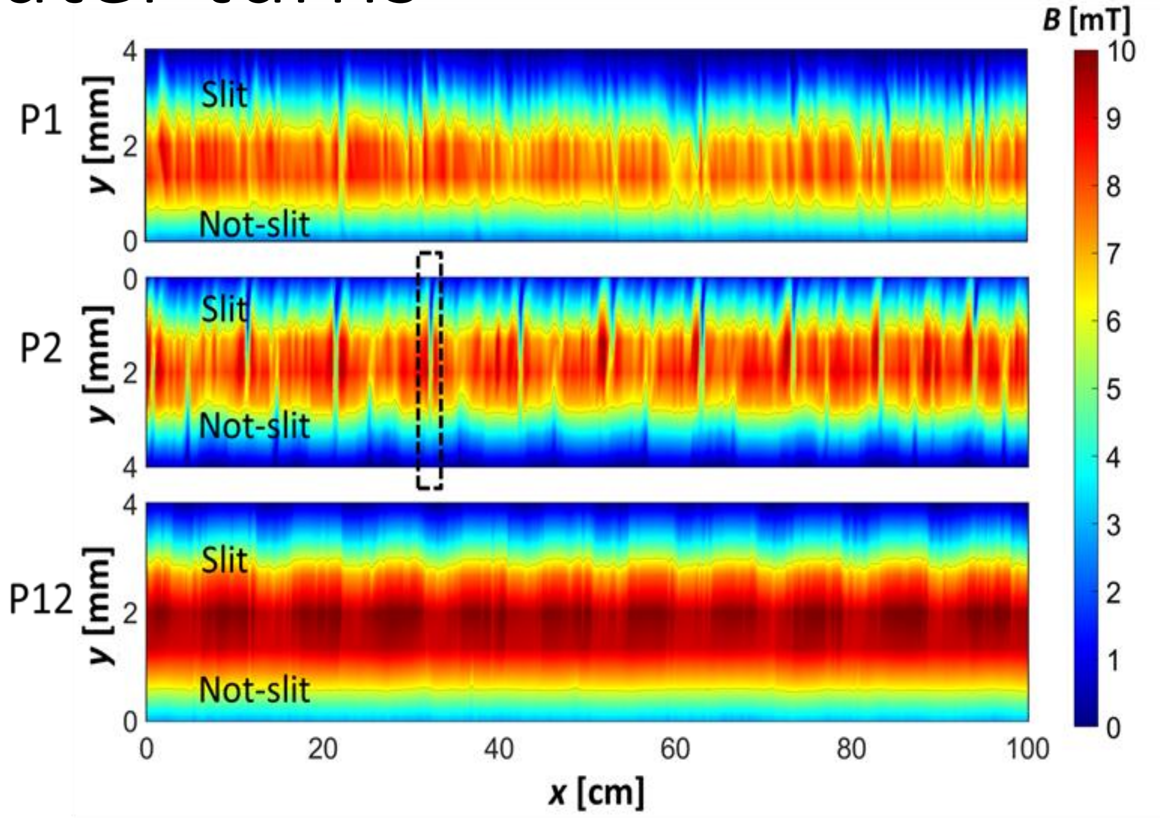



- Ripple period versus tape position from the inner to the outer turns of P1, LBC2. The fitting line is the circumference of inner to outer turns versus tape position.
- Outermost turns have more random ripples. Innermost turns have no rippling. Joint heating is probably not the reason.

# Buckling-like defects are associated with the rippling in outer turns

LBC2



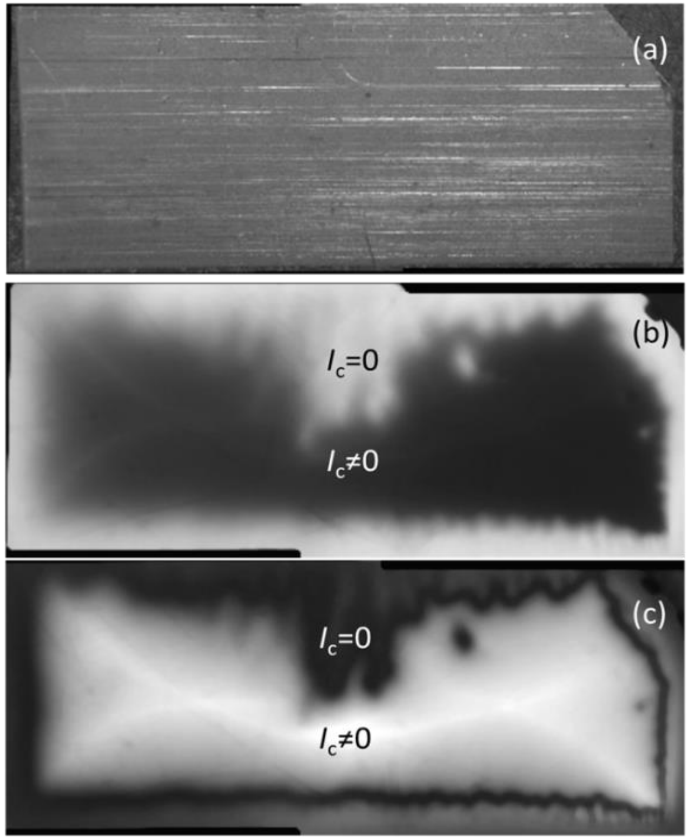

- Two dimensional magnetization maps of one meter lengths of outer turns of pancakes P1 and P2 of LBC2. The dashed rectangular box is the region cut out for Magneto-optical Imaging. Evident transverse and longitudinal damage is present.

# The slit edge has a non-uniform penetration of magnetic flux in MO images

LBC2

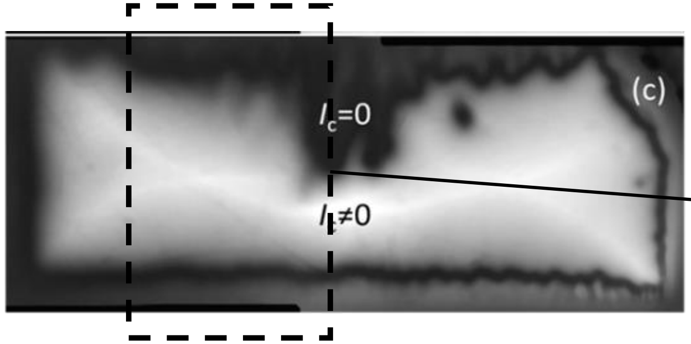
ZFC

FC

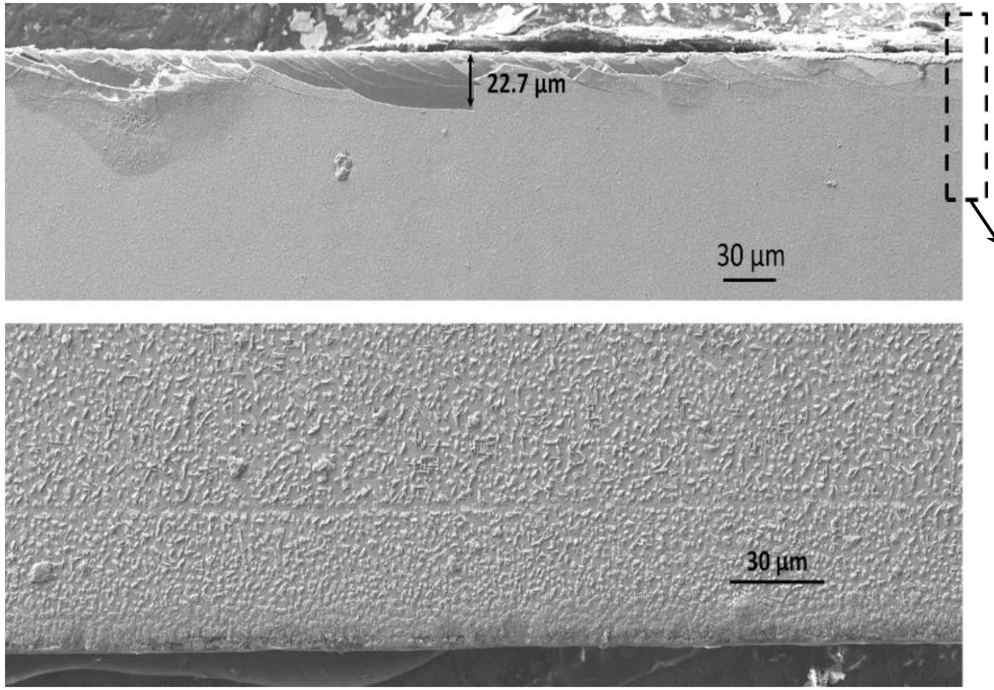


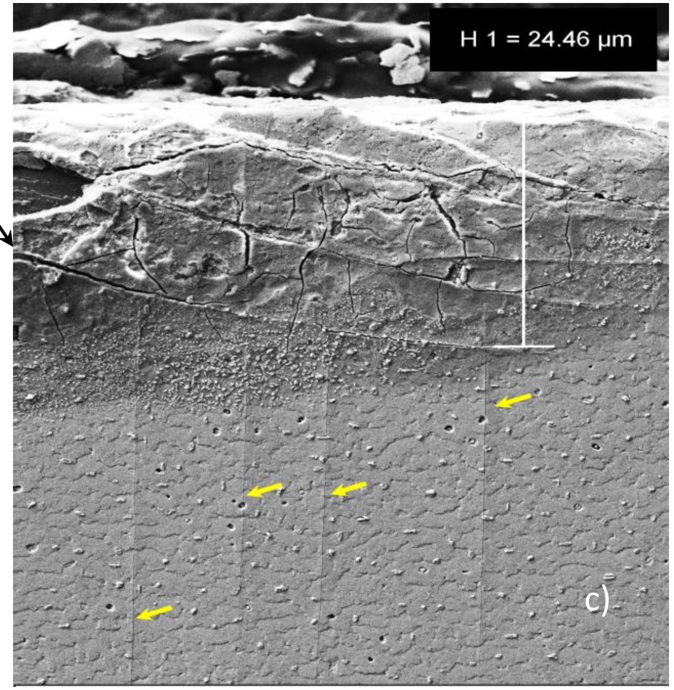

- Magneto-optical (MO) image of the sample shows clear evidence of easy flux penetration at multiple places on the upper edge, which reaches approximately half of the tape width in the central region.

# The transverse cracks may be associated with delamination




LBC2

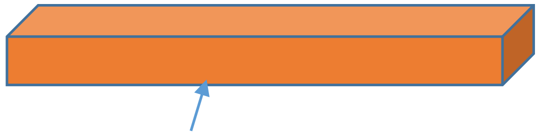


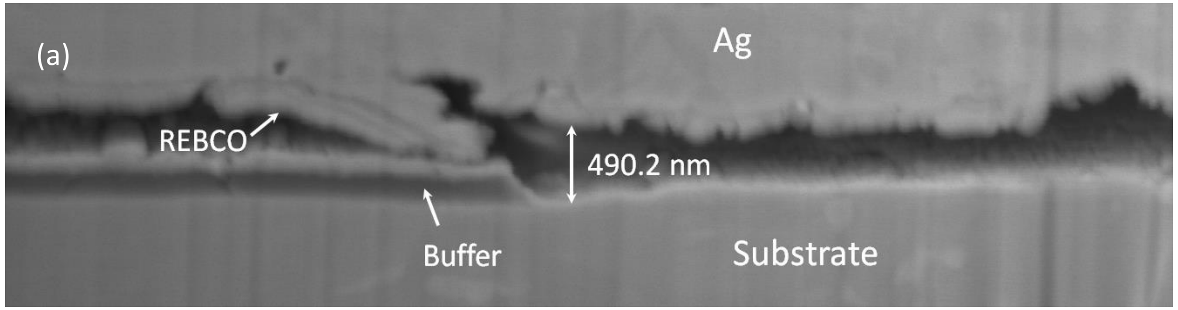

- Top views of the upper (slit) and lower (not-slit) edge of the tape after removing Cu and Ag.
- Transverse cracks on the slit edge which might be caused by stress-concentration. The slitting cracks can be clearly seen in both the REBCO and buffer layers, and are usually 20-25 mm in depth from the edge. The not-slit edge presents large amount of a-axis grains, but no cracks.
- The transverse cracks are only hundreds of microns in SEM image.
- The screening current or the quench current?

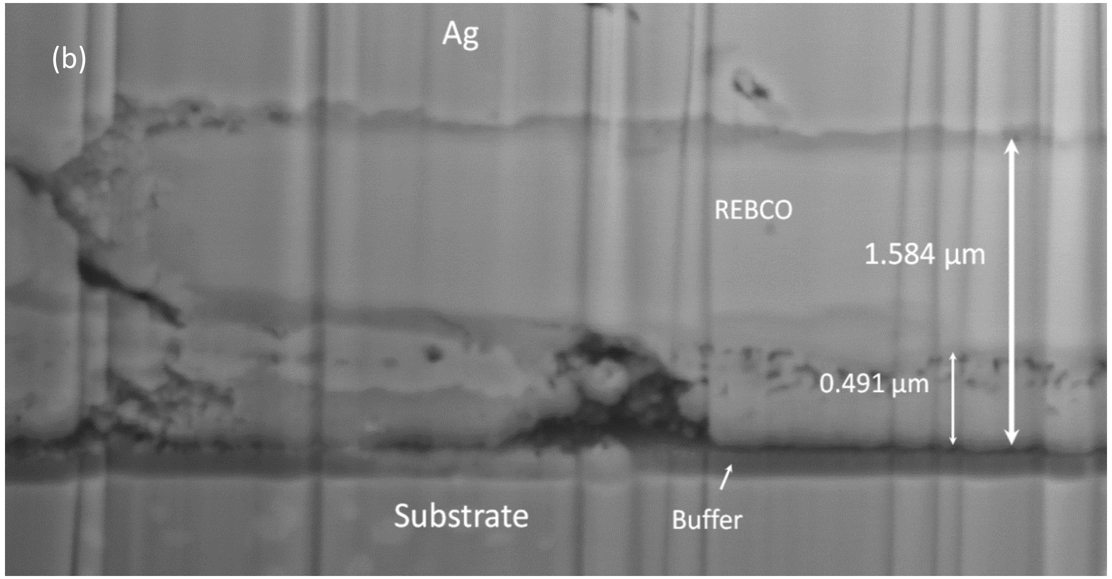
# Delamination is observed in the slit edge of P1

LBC2



Longitudinal cross-section

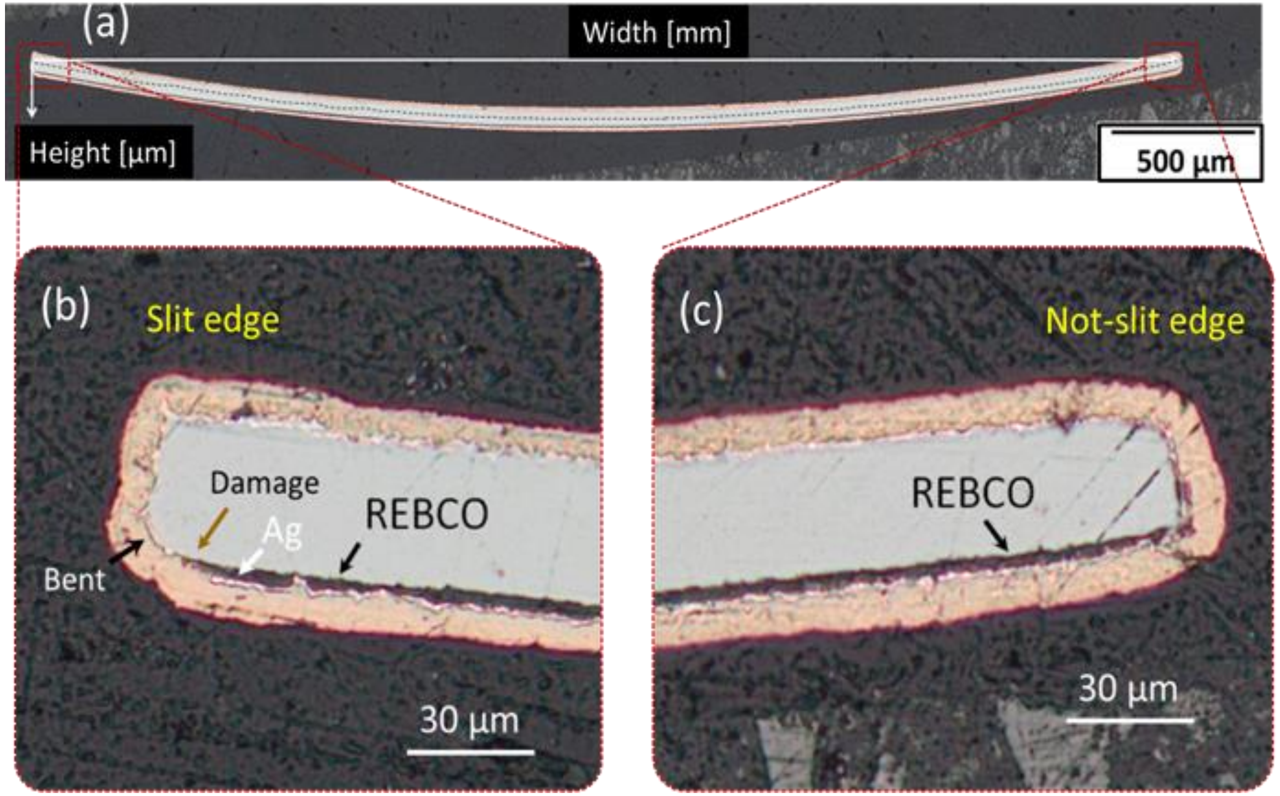



- Longitudinal cross-sectional views (a) 10 µm and (b) 15 µm away from the damaged, slit edge. REBCO is clearly delaminated from the buffer at 10 µm from the edge. The bottom of REBCO layer is porous, while the top is more compact.

# Cross-section of the as-received (AR) tapes for LBC3

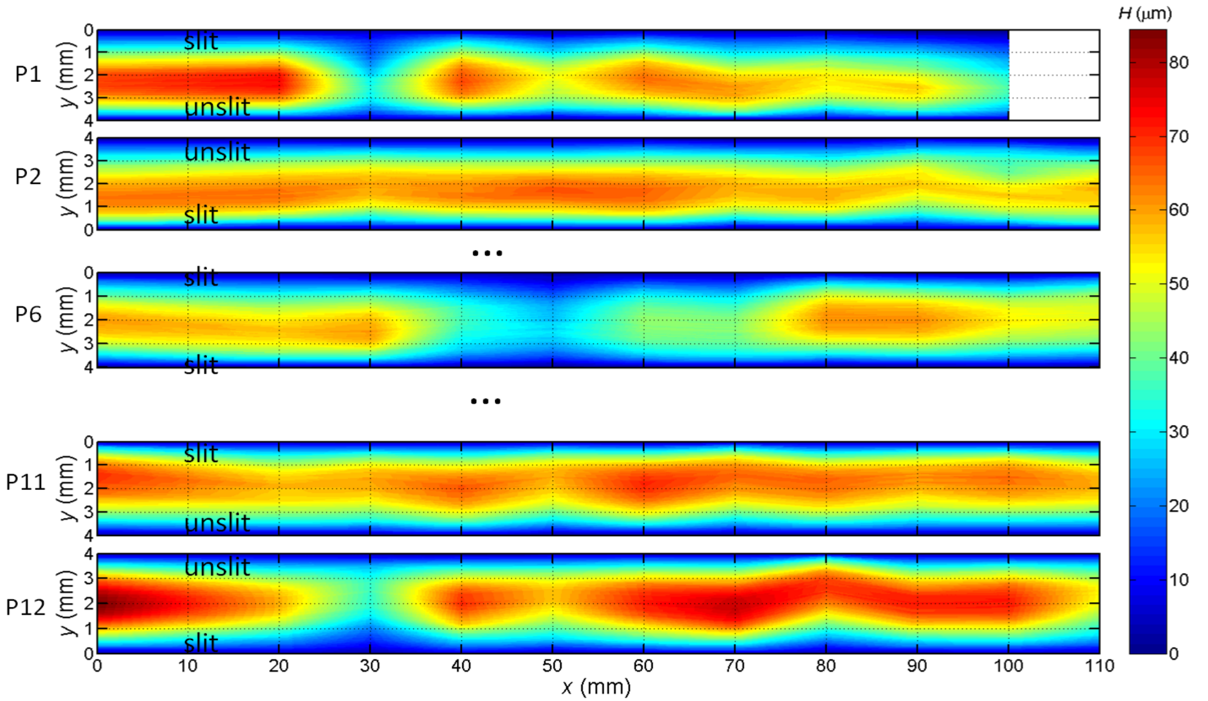
LBC3



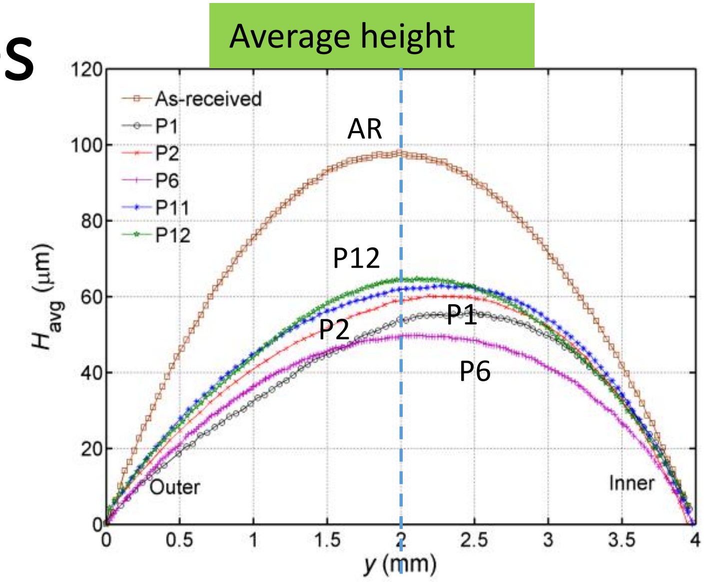

- All the tapes of the LBC series have the same specification.
- The tapes have a camber.
- There is pre-existing damage due to the mechanical slitting.

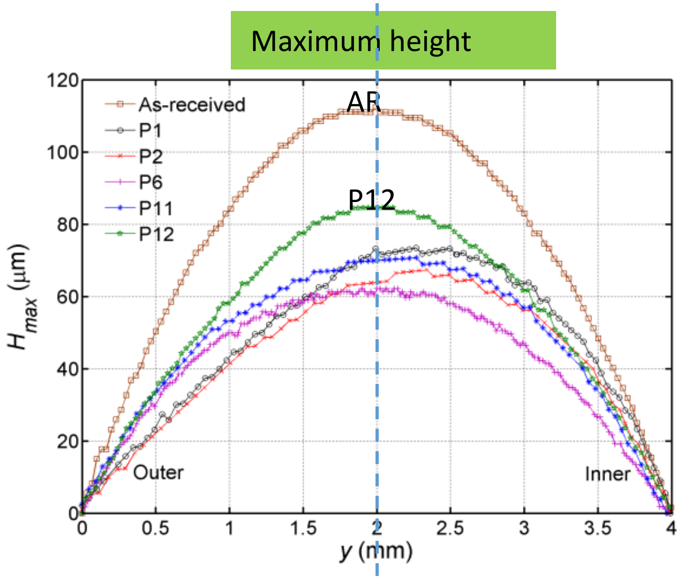
# Geometrical contour map of the deformed tapes

LBC3




Contour map reconstructed from the 10 mm-spaced cross-sectional views



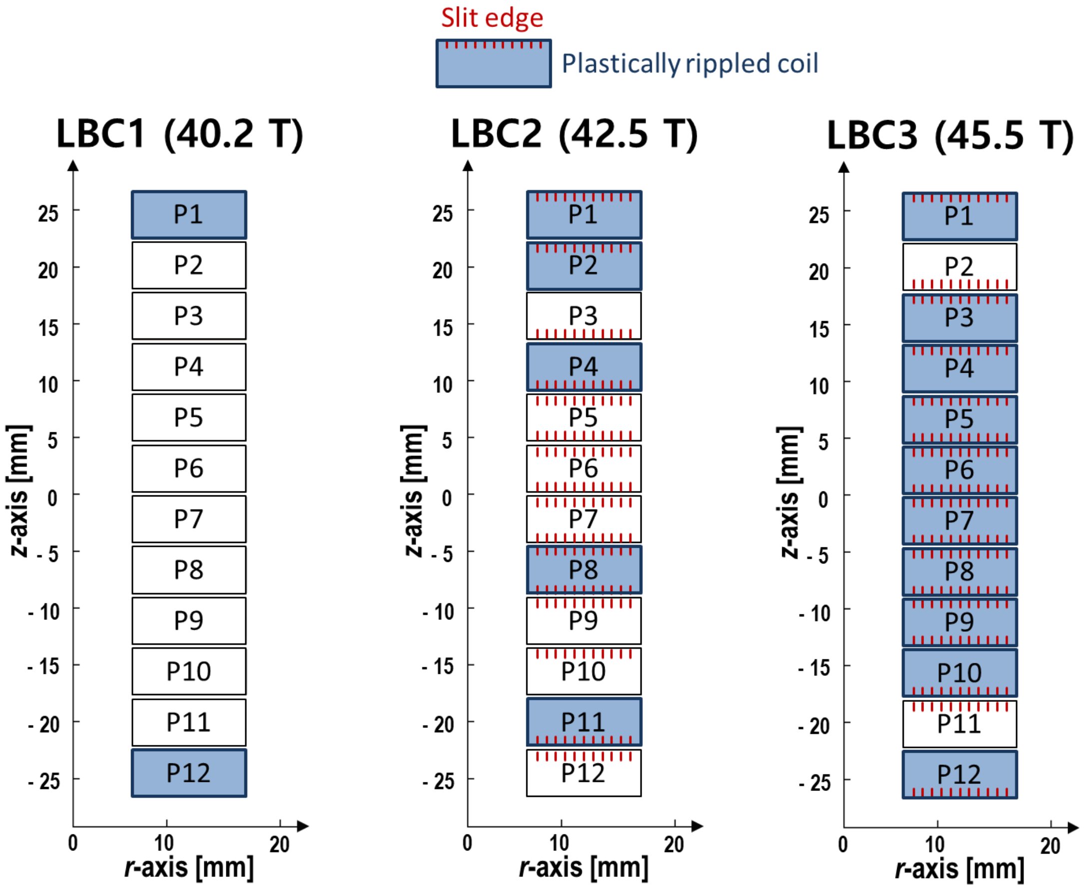



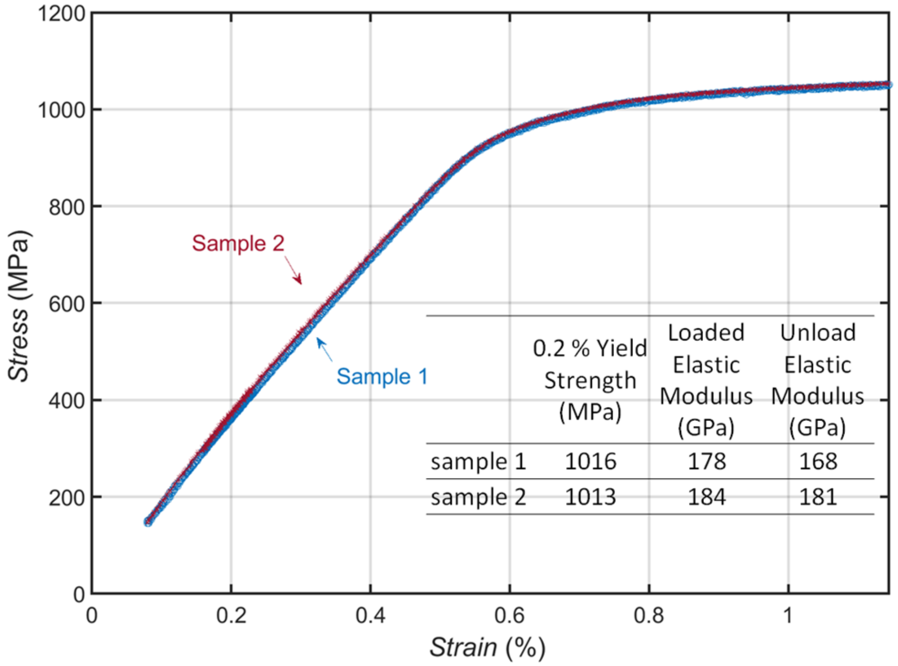

- Tapes were flattened after test, especially the outer edges. Tape centers shifted.
- The middle pancake has been flattened most, but symmetrically.

| Pancake | P1 | P2 | P6 | P11 | P12 |
|---|---|---|---|---|---|
| Standard deviation (σ, μm) | 13.1 | 3.48 | 11.4 | 4.19 | 13.5 |
| Mean value (μ, μm) | 57.0 | 61.5 | 51.0 | 63.9 | 66.0 |
| σ/μ (%) | 23.0 | 5.66 | 22.3 | 6.56 | 20.5 |

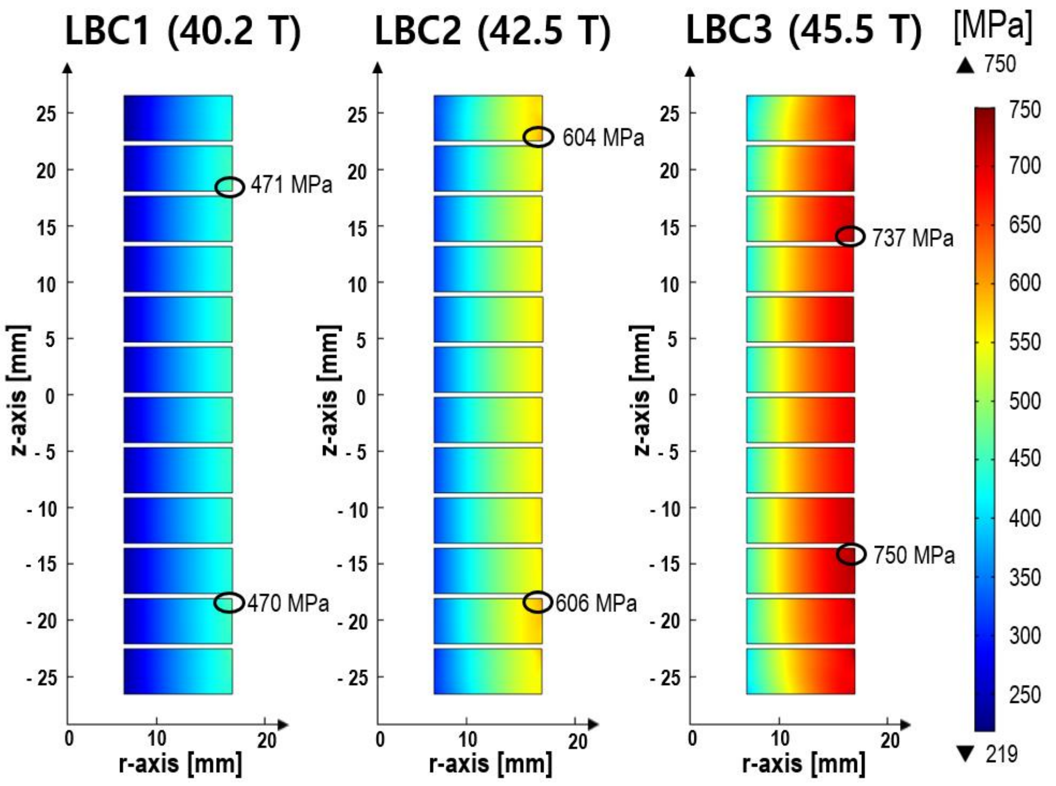
The center has been shifted by the screening current

# A summary of the slit edge orientation and the rippling

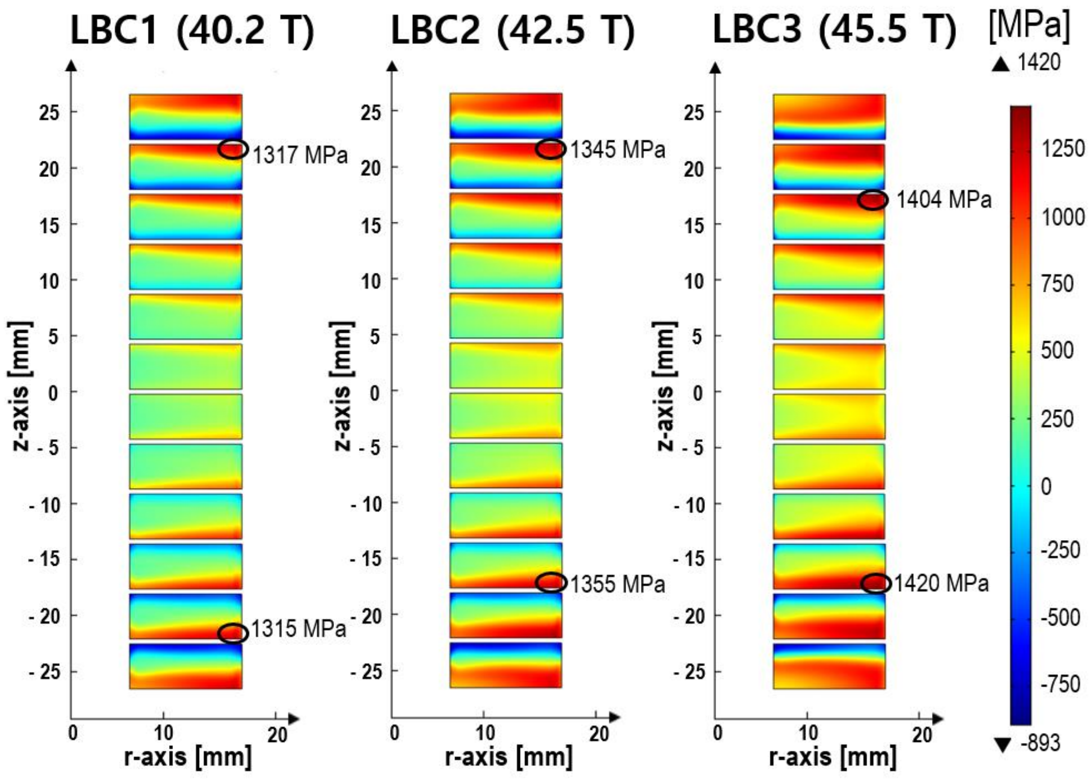


# No simulation yet can explain the survival of some pancakes in LBC series




No screening current




With screening current, $n$=21

- The actual dimensions of the pancakes were taken into account.
- Quench simulation by lumped circuit model was also included in the paper.

# Summary

- Mechanical issues are the major challenges for REBCO magnet.
- The degradation of the tapes includes the rippling caused delamination and the buckling-like cracks.
- All our previous experiments have proved that the slit edge orientation matters. To be more specific, it is the side that the transport current flows matter. The transport current on the slit edge may cause local electrical field rising and other complexity we do not understand at the moment.
- The rippling of the conductor is surely related to the screening current, but how?
- The Bean critical state model may not be 100% applicable in REBCO tapes because of the non-uniform $J_c$ along and across the tape. This non-uniformity may have some randomness even for tapes from the same manufacturer. We are now doing more rigorous measurements to clarify it.