

## Measurement and FE modelling critical transverse loading limits of REBCO round cables for fusion

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# Conductor design optimization



Single tape  $I_c$   
– mech. load  
testing

Axial tensile  
stress,  $I_c$  &  
mech. props.

Axial tensile &  
compressive  
strain,  $I_c$  &  $\epsilon_{irr}$

Transverse  
Stress  $\sigma_{irr}$

Winding  
angle,  $I_c$  &  
min. diam.

Cable cyclic  
load testing  
Twente Press

Critical  
current/load  
 $I_c(F)$

Transverse  
stiffness  $d(F)$

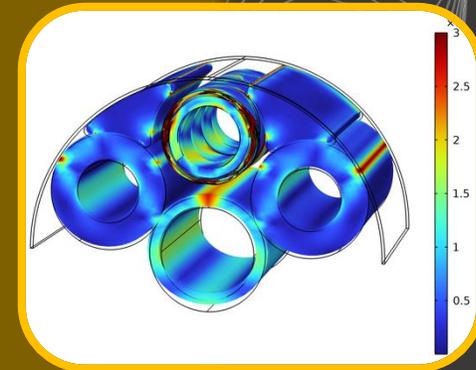
Inter tape  
contact  
resistance  $R_c$



FE cable model

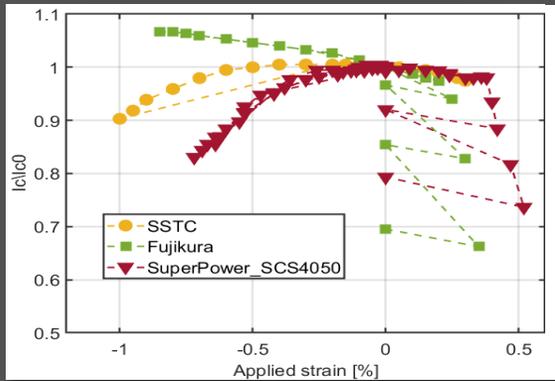
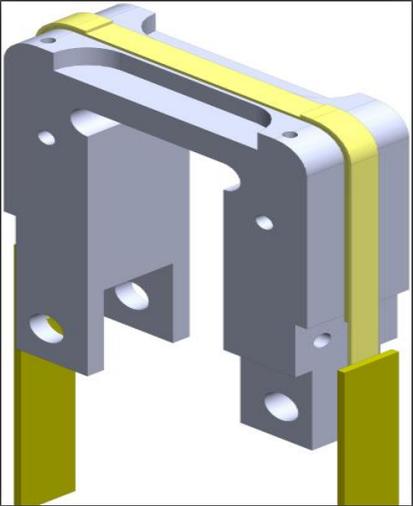
Materials

Design

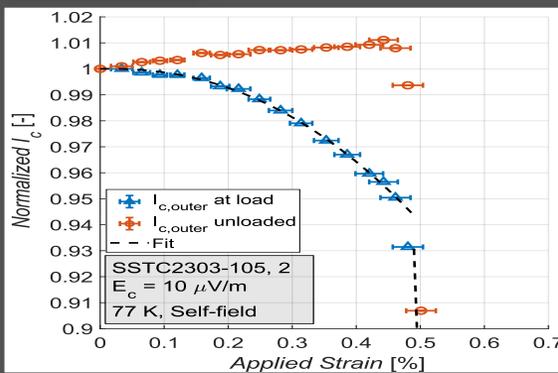
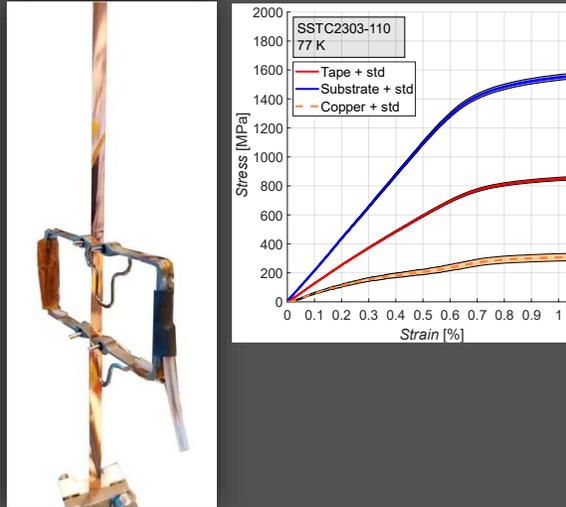


# Single tape: $I_c$ – mechanical testing

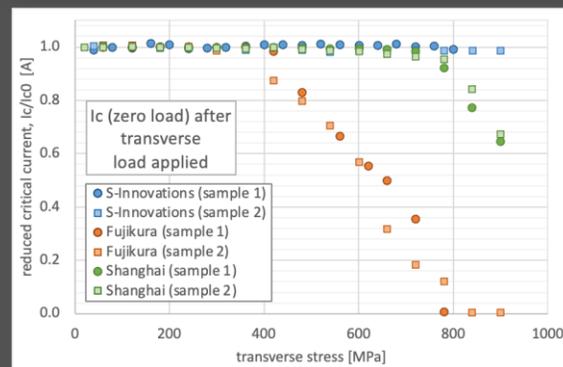
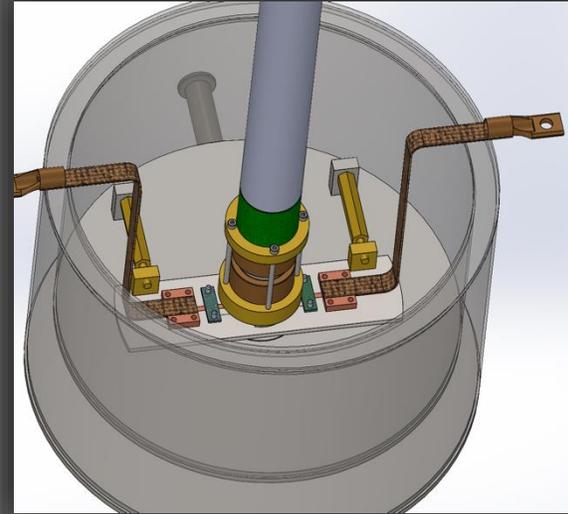
U-Spring axial tensile  
& compressive strain  
 $I_c(B, T, \varepsilon)$



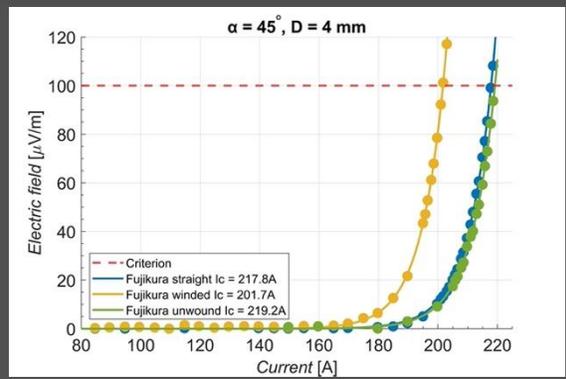
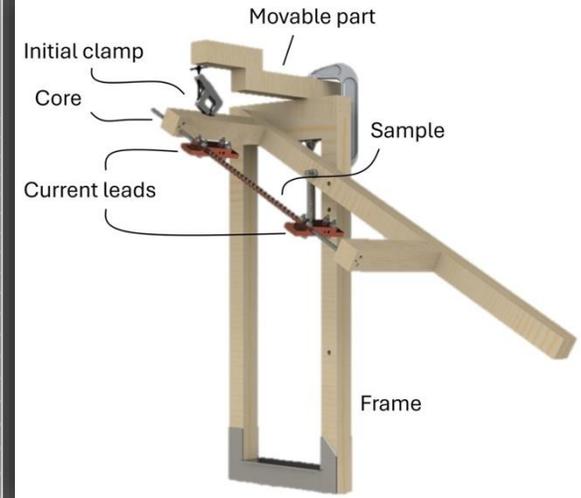
Axial tensile stress,  
mechanical  
properties,  $I_c$  &  $\varepsilon_{irr}$



Transverse stress,  $I_c$  &  
 $\sigma_{irr}$  (77 K)



Winding angle  
 $I_c$  & min core diam.  
(77 K)

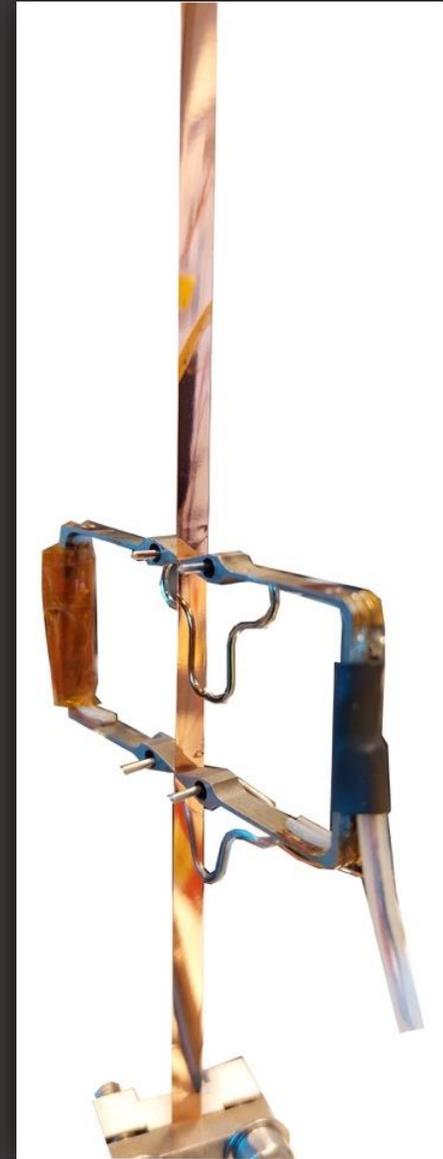
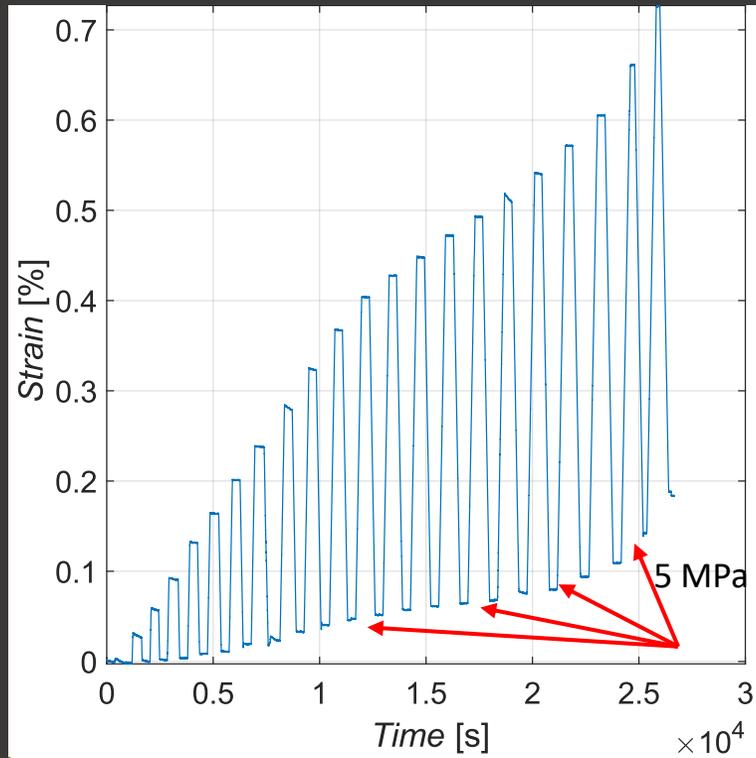


# Axial tensile strain: setup

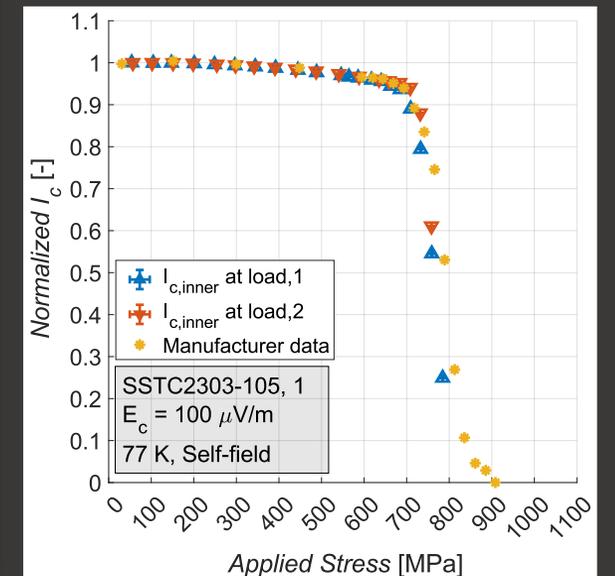
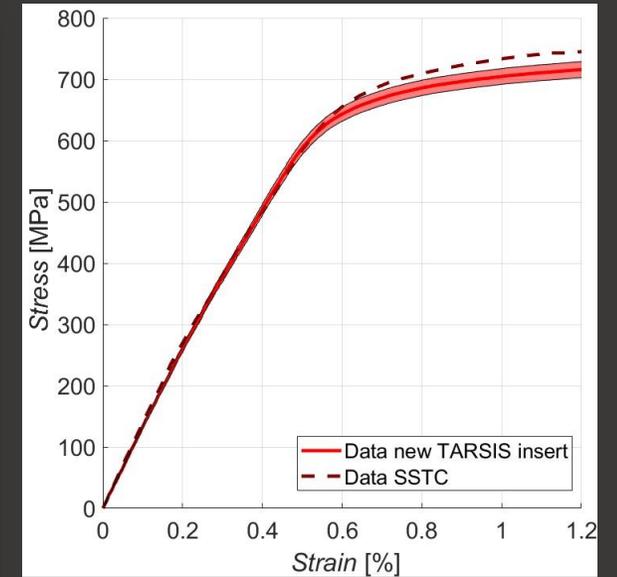
| Tape     | $t_{\text{Substrate}} [\mu\text{m}]$ | $t_{\text{Copper}} [\mu\text{m}]$ | $I_c [\text{A}]$ |
|----------|--------------------------------------|-----------------------------------|------------------|
| SSTC     | 52                                   | 22                                | 186              |
| Fujikura | 49                                   | 25                                | 204              |
| Faraday  | 39                                   | 13                                | 162              |

Substrate : Hastelloy, width = 4 mm

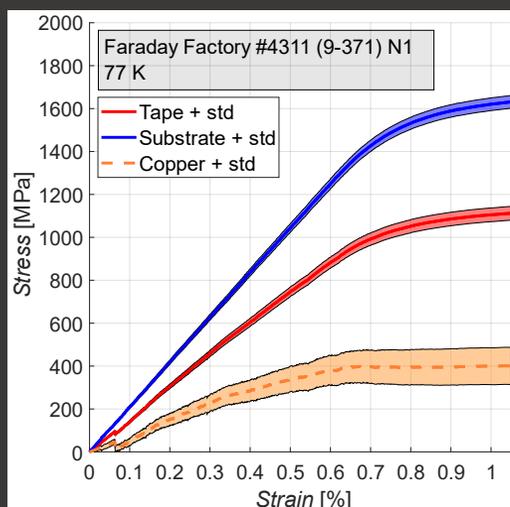
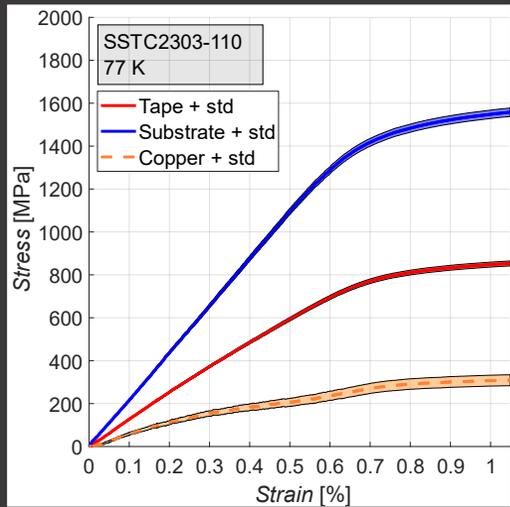
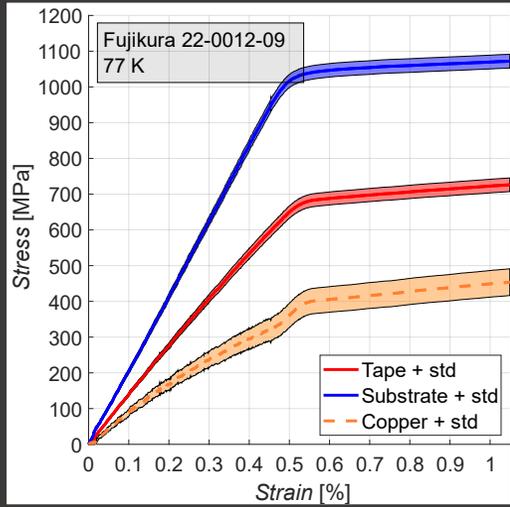
Goal:  
Stress-strain  
properties,  $I_c$  &  
irreversibility  
limit for tensile  
axial strain



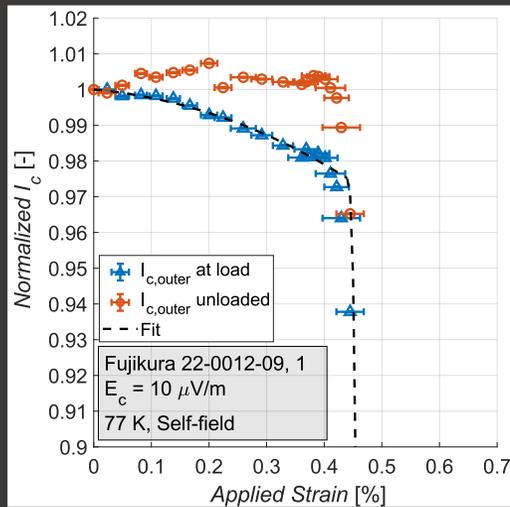
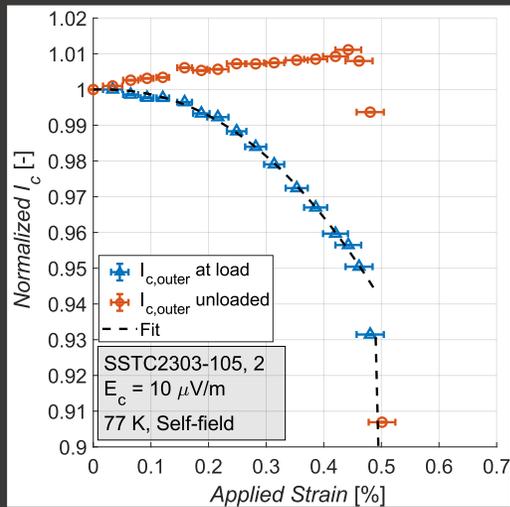
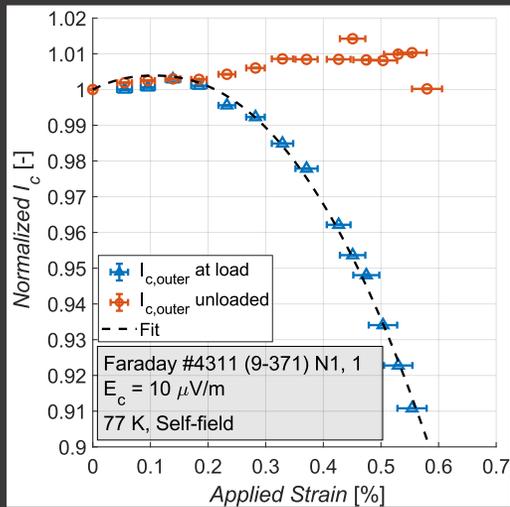
Comparison data  
manufacturer



# Axial tensile Stress-Strain curves & $I_c(\epsilon)$



| Tape     | $E$ [GPa] | $\sigma_{ys}$ [MPa] |
|----------|-----------|---------------------|
| SSTC     | 125       | 600                 |
| Fujikura | 135       | 621                 |
| Faraday  | 150       | 875                 |

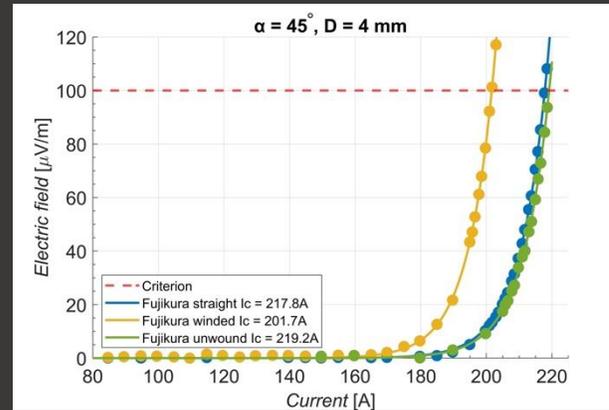
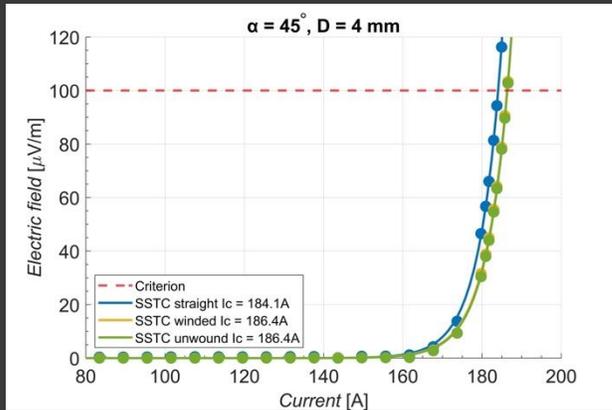
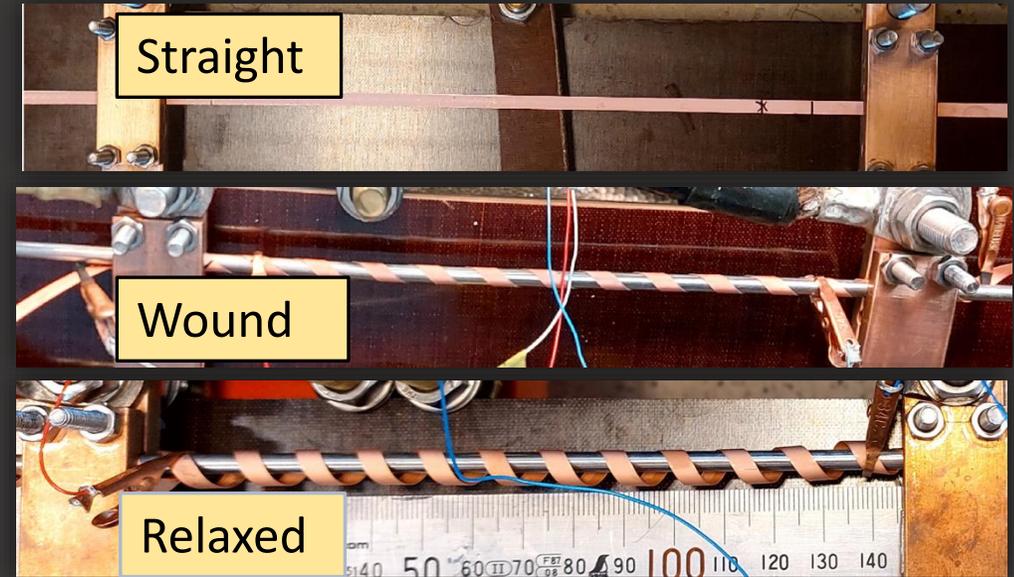


| Tape     | $\epsilon_{irr}$ [%] | $\sigma_{irr}$ [MPa] |
|----------|----------------------|----------------------|
| SSTC     | 0.48                 | 709                  |
| Fujikura | 0.43                 | 626                  |
| Faraday  | 0.58                 | 900                  |

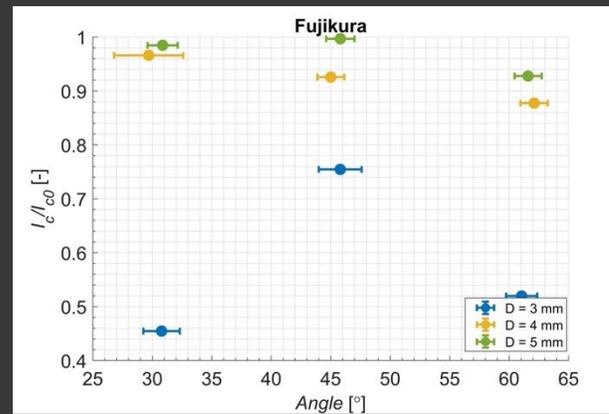
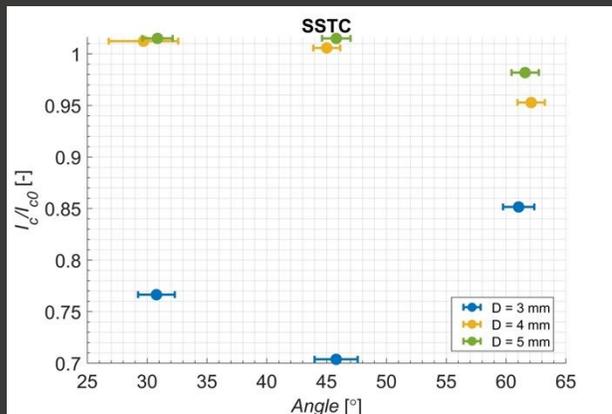
# Winding performance

- 3 winding diameters (3, 4 and 5 mm)
- 3 winding angles (30°, 45° and 60°)
- REBCO layer faces core

Minimum winding radius (irreversibility limits)  
Verification of current retention/reduction

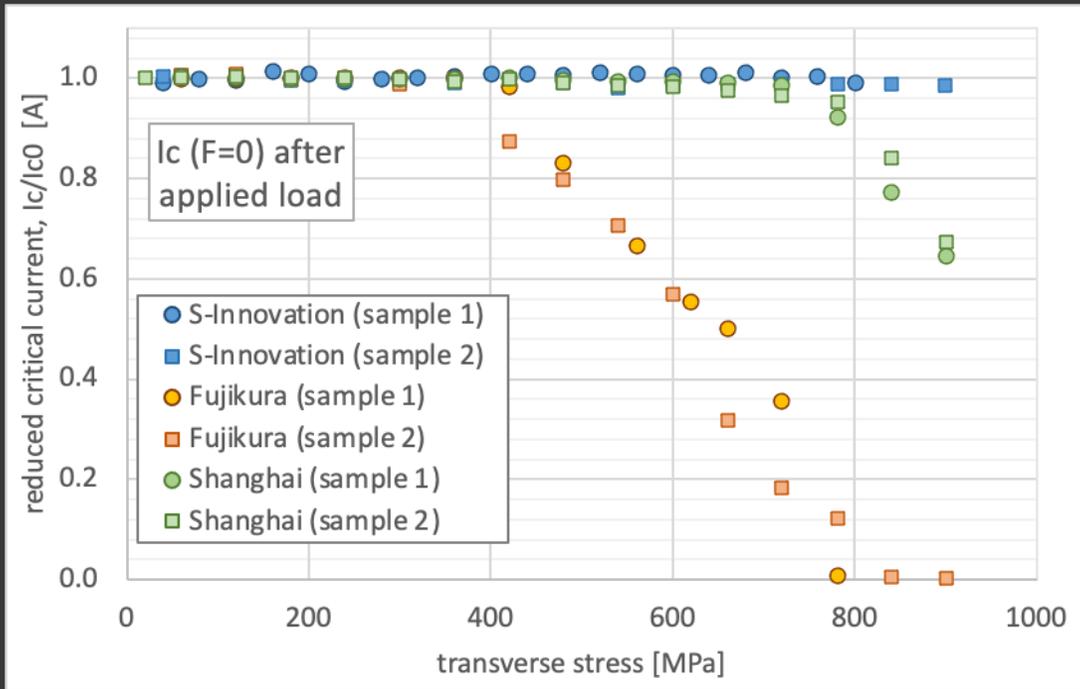


SSTC retains 100%  $I_c$ , wound at 45° on 4 mm former.  
Fujikura shows  $I_c$ -reversible reduction (7%).

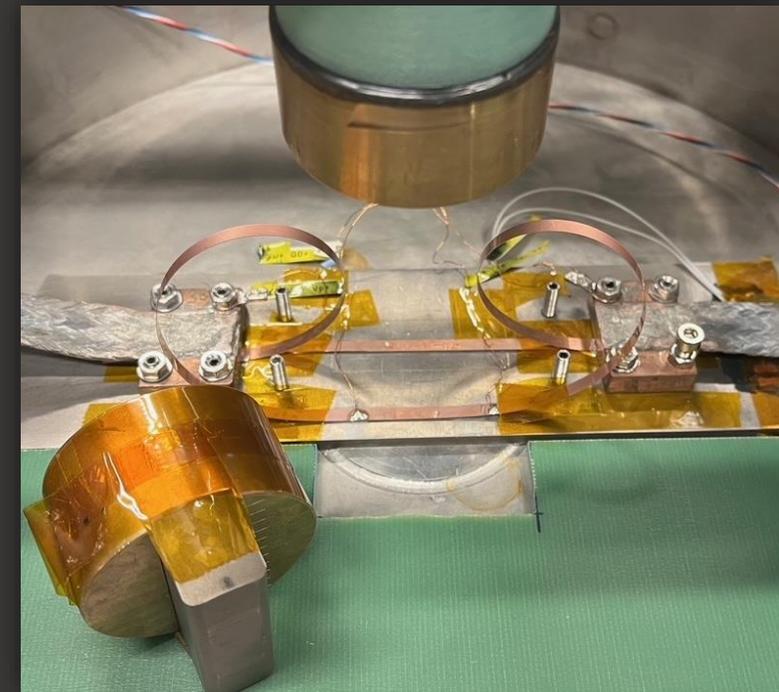
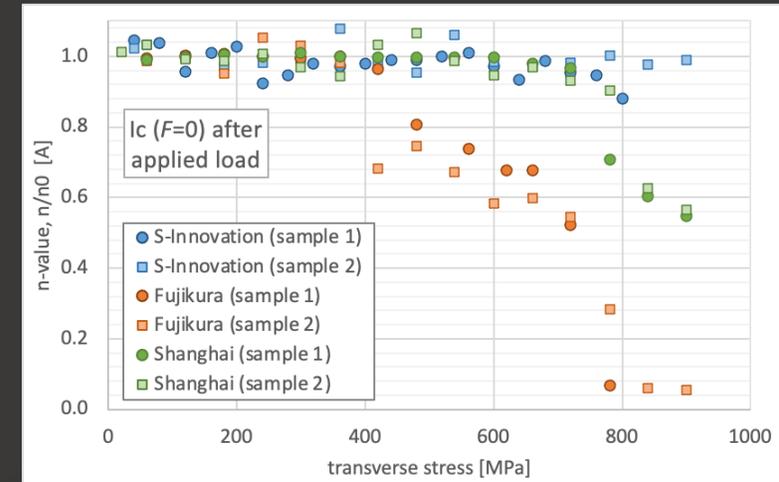


$I_c$  wound is normalized with  $I_{c0}$  of initial straight configuration.  
Critical core diameter >3 mm, critical angle < 60° for standard tape dimensions.

# Transverse load (10 x 4 mm<sup>2</sup>)



$I_c/I_{c0}$  and  $n/n_0$  at zero load after applied stress.



| Tape                 | $\sigma_{irr}$ [MPa] |
|----------------------|----------------------|
| S-Innovation         | > 900                |
| Fujikura, 22-0012-09 | 400                  |
| SSCT, ST2903-105     | 750                  |

# Conductor design optimization



Single tape  $I_c$   
– mech. load  
testing

Axial tensile  
stress,  $I_c$  &  
mech. props.

Axial tensile &  
compressive  
strain,  $I_c$  &  $\epsilon_{irr}$

Transverse  
Stress  $\sigma_{irr}$

Winding  
angle  $I_c$  &  
min. diam.



Cable cyclic  
load testing  
Twente Press

Critical  
current/load  
 $I_c(F)$

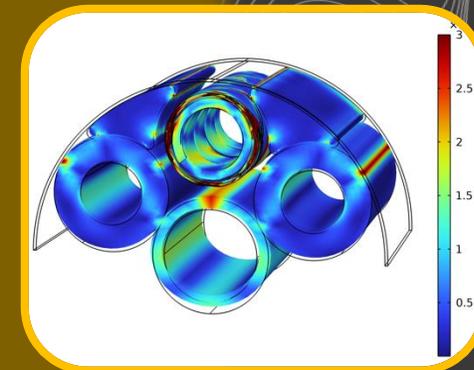
Transverse  
stiffness  $d(F)$

Inter tape  
contact  
resistance  $R_c$

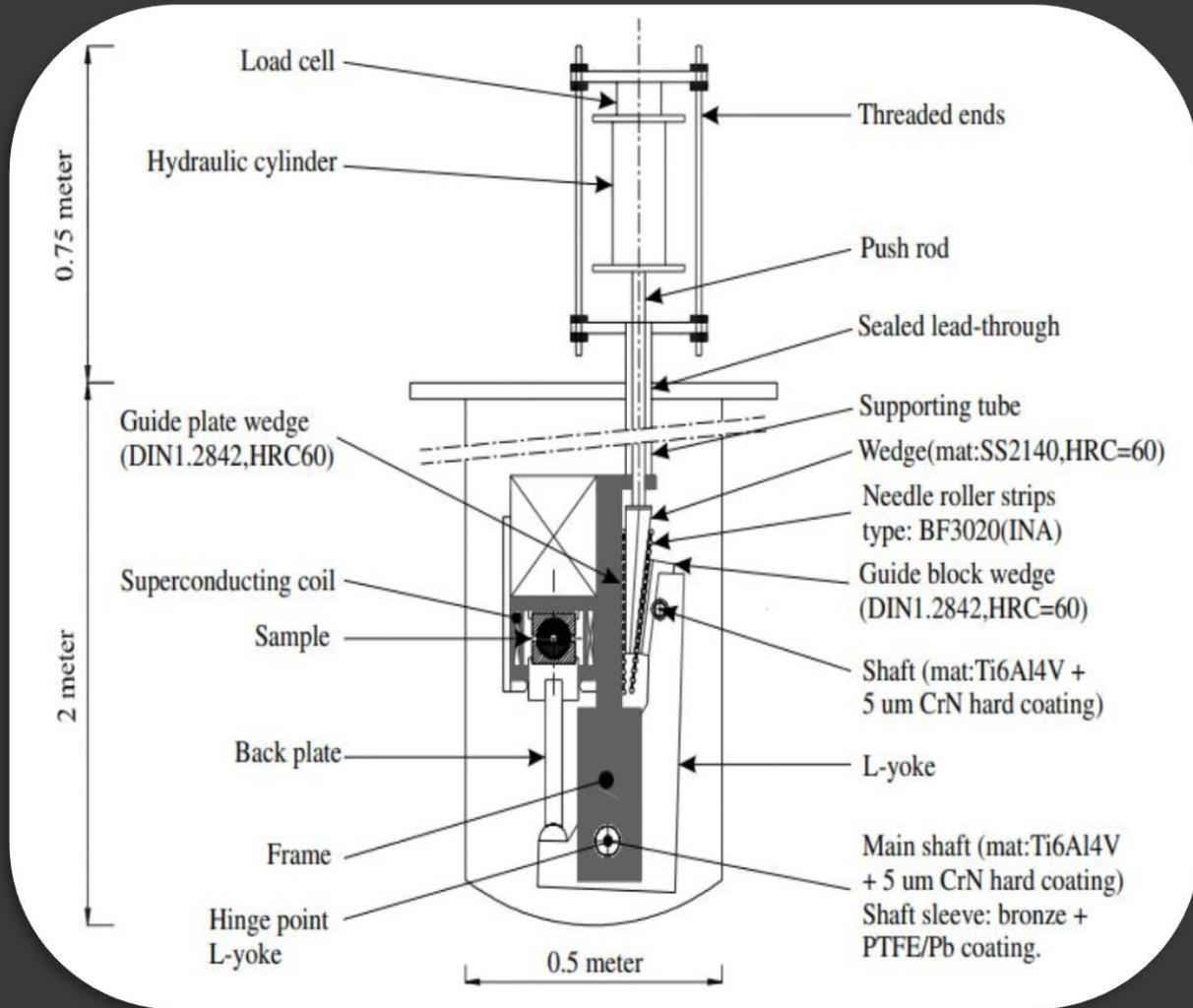
FE cable model

Materials

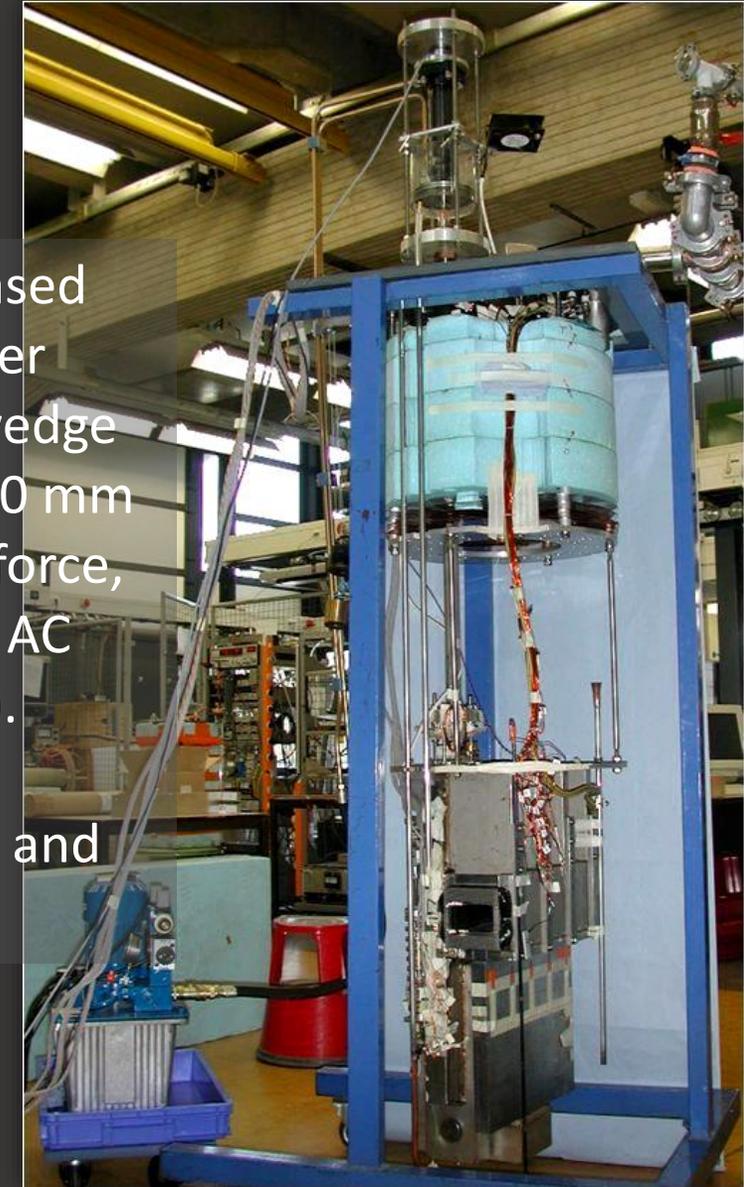
Design



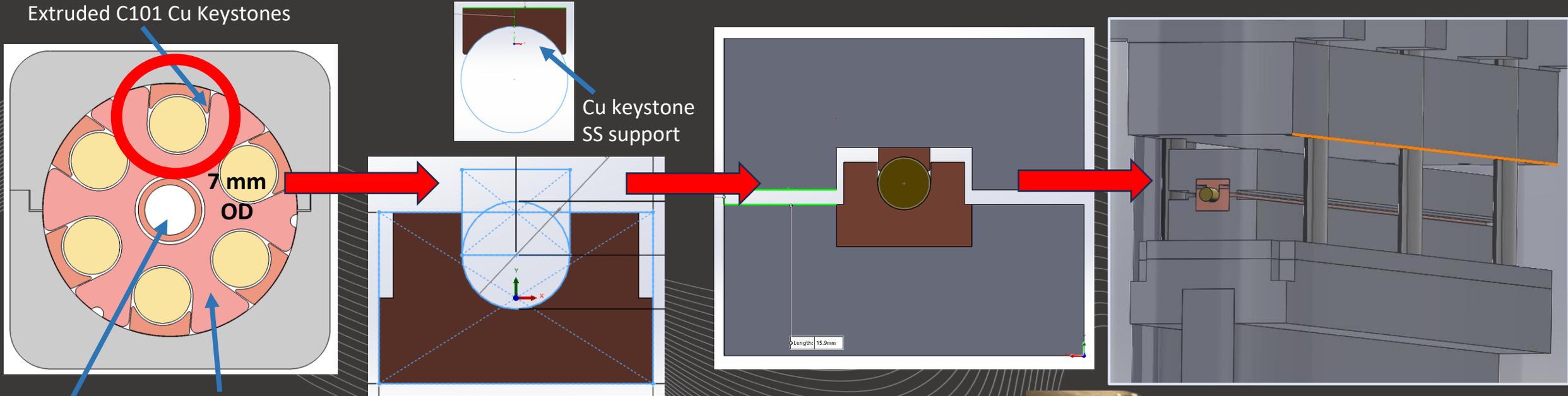
# Transverse load: Twente Cable Press



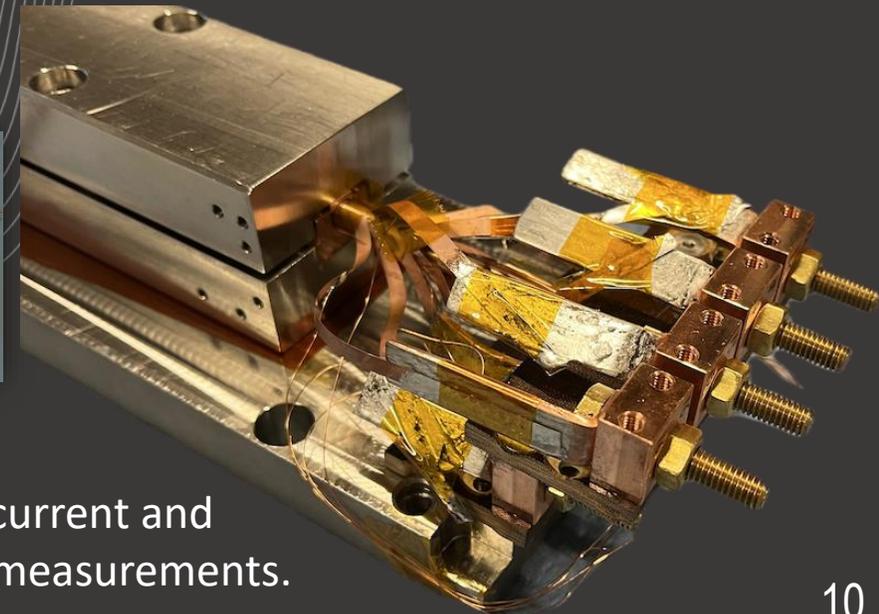
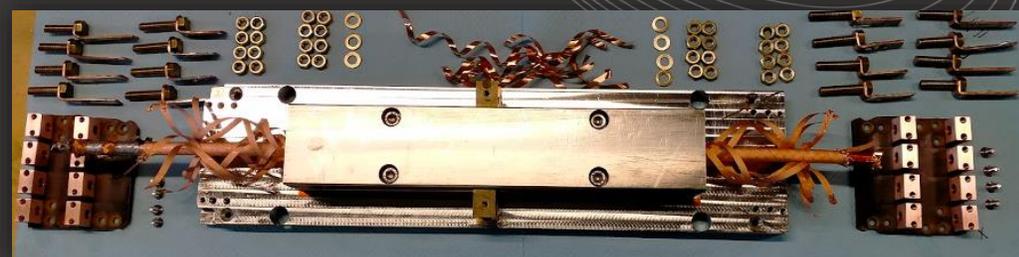
- Hydraulic press based on principle of lever mechanism and wedge
- Sample length: 400 mm
- Measuring:  $I_c$ ,  $R_c$ , force, displacement and AC loss (only at 4.2 K).
- $T$ -operating temperatures: 4.2 and 77 K



# ACT CORC<sup>®</sup>-CICC Twente Press test sample



CORC<sup>®</sup> cable used in ACT Sultan sample with 36 tapes, OD of 7.04 mm (including thin plastic tube) in groove with 7.54 mm.



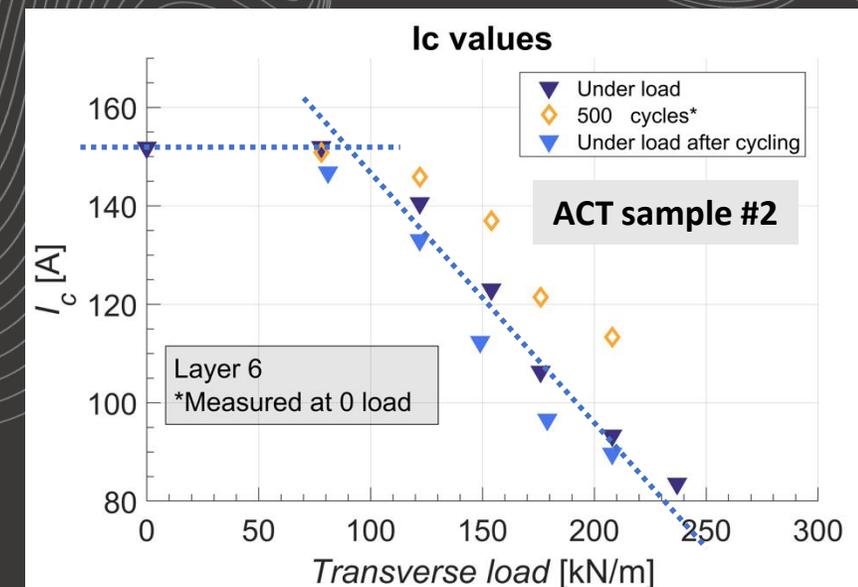
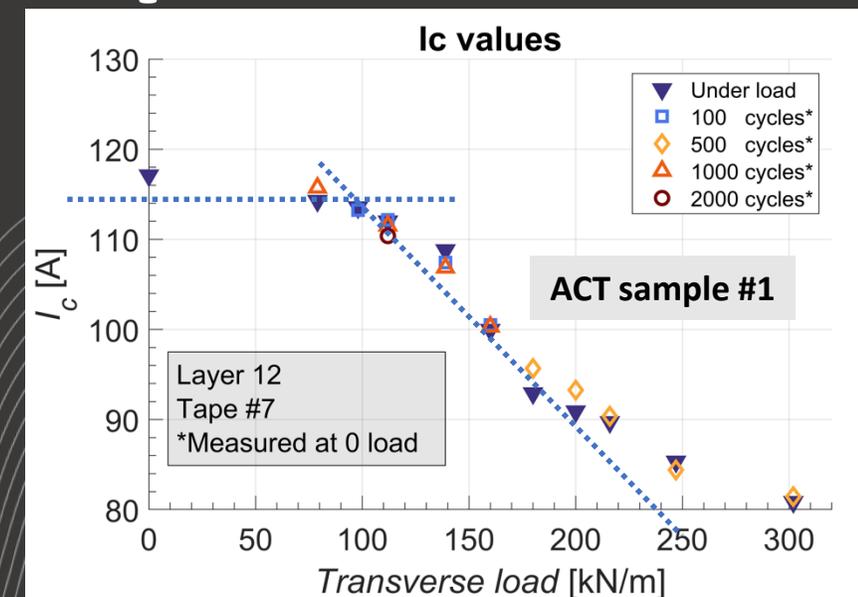
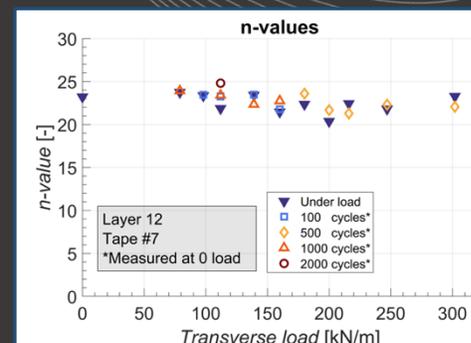
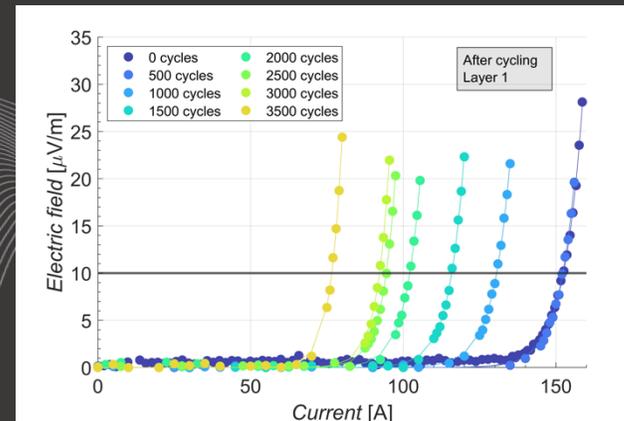
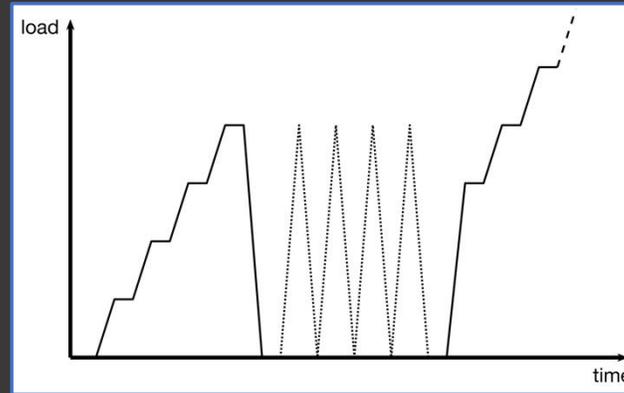
Selected tapes (8) for critical current and inter-tape contact resistance measurements.



# CORC<sup>®</sup> Twente Press ACT samples #1 & 2

## Sub-cable parameters both samples

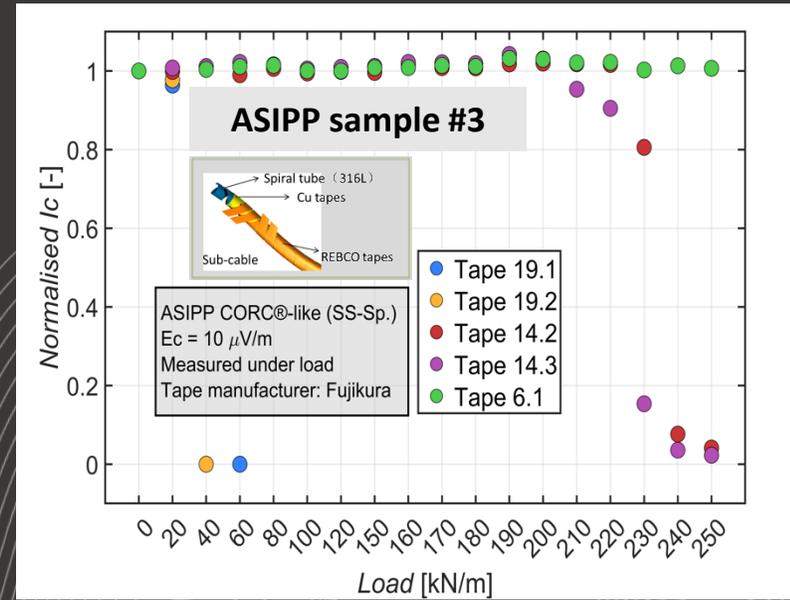
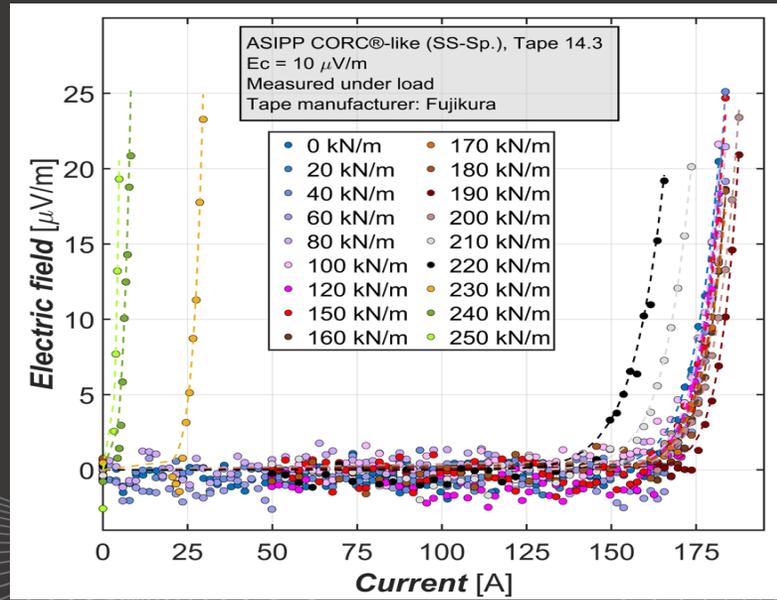
|                     |                  |
|---------------------|------------------|
| Tape Manufacturer   | SuperPower       |
| SC Tapes            | 36               |
| Tape width          | 4 mm             |
| Tape thickness      | 63 $\mu\text{m}$ |
| Substrate thickness | 50 $\mu\text{m}$ |
| Copper thickness    | 5 $\mu\text{m}$  |
| Spacing             | 0.5 mm           |
| Core                | Cu Rod           |
| Core OD             | 5.34mm           |
| Strain window       | [-1.3%, 0.45%]   |



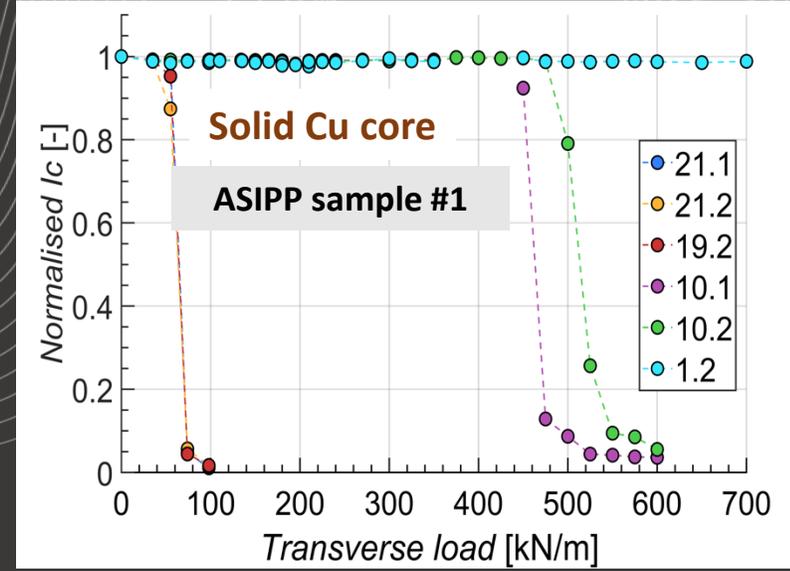
- 9,000 cycles successive  $F$ -increases
- ( $E_c=10 \mu\text{V/m}$ ),  $n$ -value (22-21)
- Irreversible degradation = critical load (CL):
- Both ACT samples **CL $\sim$  100 kN/m**.

# Twente Press ASIIPP sample #1 & #3

| Main parameters ASIIPP  |                                       |                             |
|-------------------------|---------------------------------------|-----------------------------|
| ASIIPP Sultan #         | #3                                    | #1                          |
| tape supplier           | SSTC                                  | SSTC                        |
| Cu Core OD              | 4.0 mm                                | 4.6 mm                      |
| SC tape layer           | 16                                    | 22                          |
| tape No. layer          | 2x3 Cu+<br>SC(2x4+3x8+4x4)<br>+4x2 Cu | SC(2x4+3x7+<br>4x11)+4x1 Cu |
| tape No.                | 48                                    | 73                          |
| winding angle           | 33.5-49°                              | 36.5-56°                    |
| gap                     | ~0.6 mm                               | 0.4 mm                      |
| OD                      | ~8.6 mm                               | 9.6 mm                      |
| width                   | 4 mm                                  | 4 mm                        |
| thickness               | 0.1 mm                                | 0.1 mm                      |
| I <sub>c</sub> @ 77K,SF | 160 -210 A                            | 160-190 A                   |

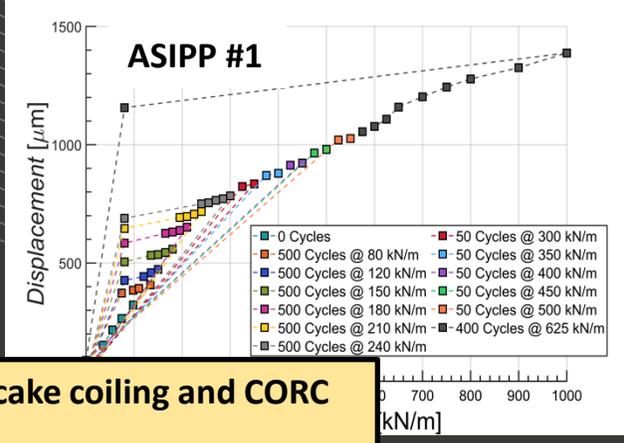
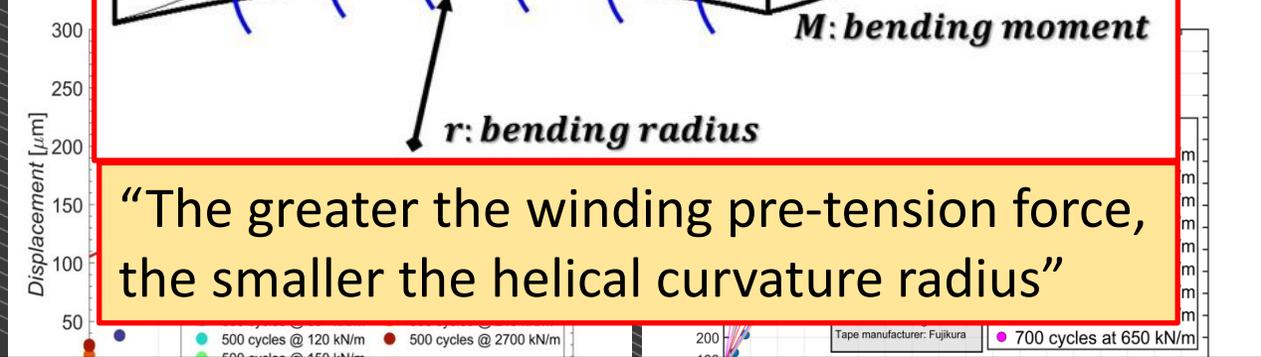
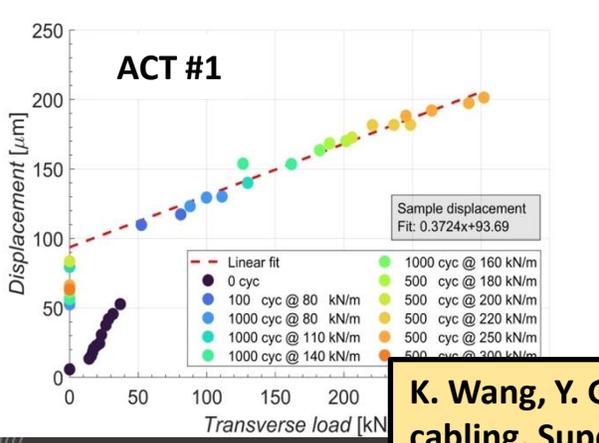
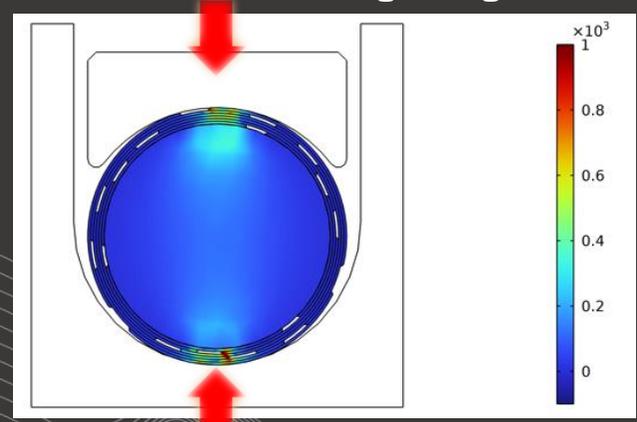
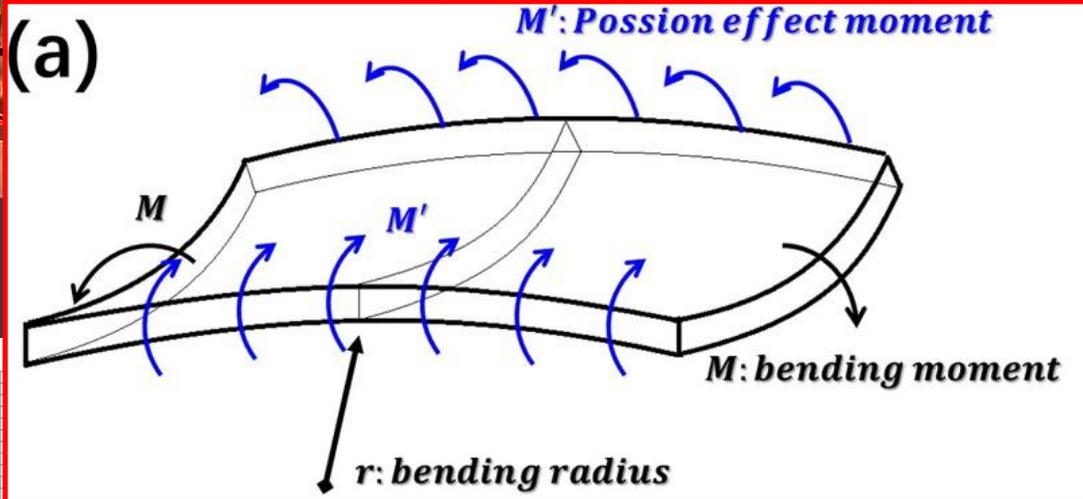
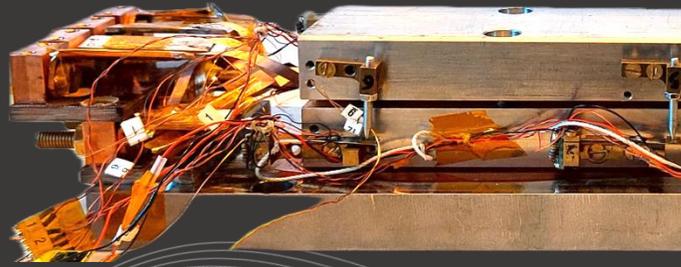


ASIIPP sample #3, degradation for spiral at **210 kN/m (x6 = 1260 kN/m)**. Solid core **450 kN/m (x6=2700 kN/m)**. Degradation ACT samples **~ 90 kN/m < (x6 = 540 kN/m)**.



- Main difference with ATC samples:
- radius Cu profile matches to cable.
  - No plastic tube around cable.

# ACT #1 & 2, ASIPP #1 & 3 (spiral), Press $F(d)$



“The greater the winding pre-tension force, the smaller the helical curvature radius”

K. Wang, Y. Gao, W. Luo, Y. Zhou, A. Nijhuis, Nonlinear contact behavior of HTS tapes during pancake coiling and CORC cabling, Supercond. Sci. Technol. 34 (2021) 075003 <https://doi.org/10.1088/1361-6668/abf710>

- Two stiffness regimes:

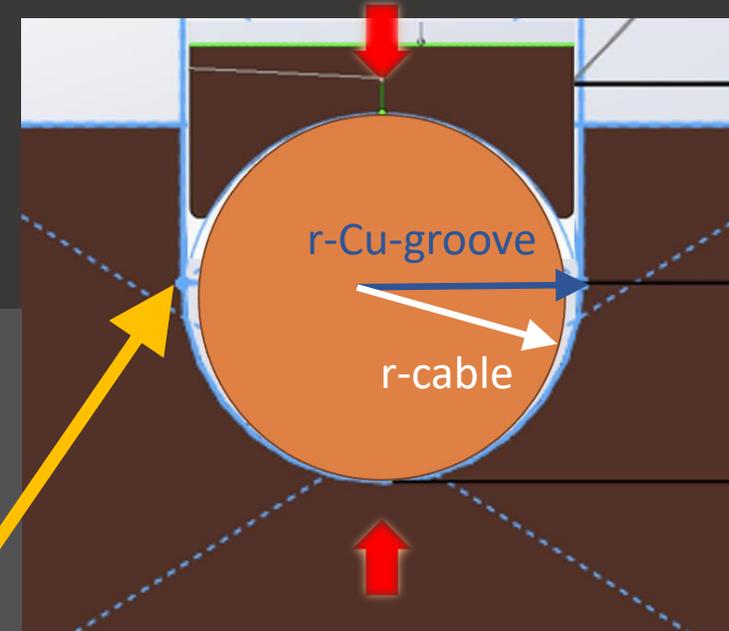
| space/layer - sample                            | ACT #1 | ACT #2 | ASIPP #3 | ASIPP #1 |
|---|--------|--------|----------|----------|
| $(D_{cab} - D_{core})/(2N)-t$ [ $\mu\text{m}$ ] | 11.6   | 11.6   | 48       | 9.5      |
| $d_{meas}/(2N)-t$ [ $\mu\text{m}$ ]             | 5.0    | 6.3    | 31       | 17.0     |

# Outer layer damage Press test

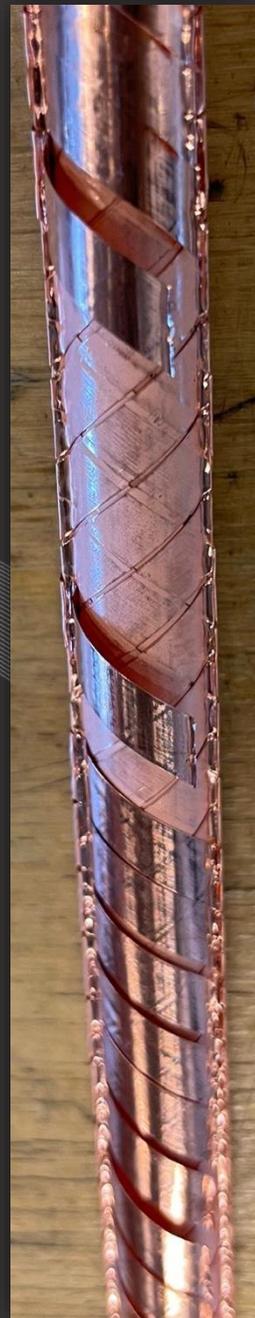
**ACT cables:** tightly wound, less layers than ASIPP, Cu groove and key-stone have larger radius than cable (stress concentration). Thin plastic tube around cable.

**ASIPP cables:** Inner layers withstands 800 kN/m, homogeneous contact.

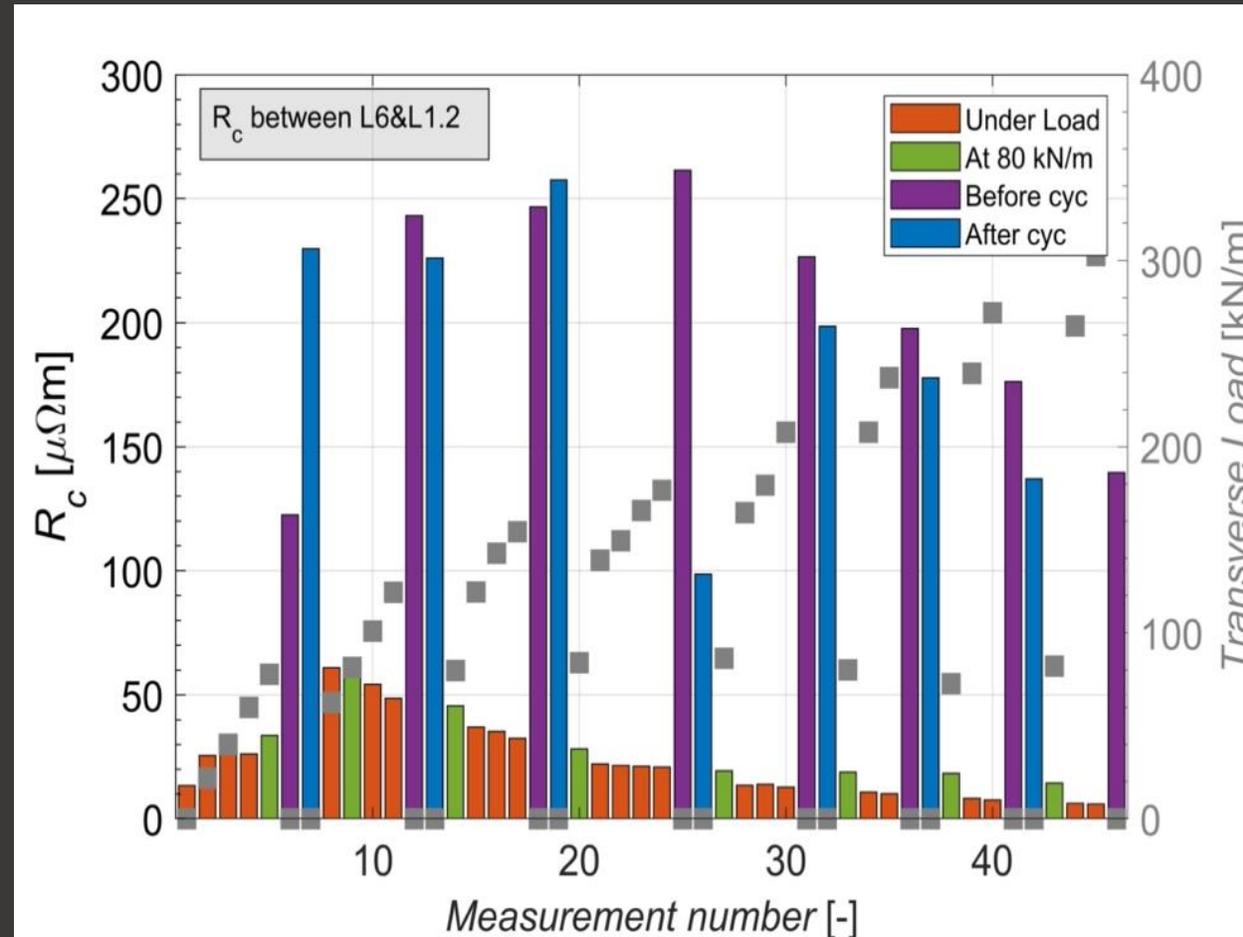
More loosely wound (groove radius matches cable's), early degradation outer squeezed tape layers ( $\rightarrow$  bending).



- Tapes are squeezed towards open space at sides.
- Space needed for cable to “breathe” due to voids from anticlastic winding effect.
- **Remedies:**
- Tighter winding of tapes to reduce voids.
- Outer Cu (ASIPP) or plastic tube (ACT) for tape containment.



# Contact resistance results: $R_c(F)$



- Contact resistance: initial  $R_c$  and after 3,000 cycles, 2 to 10  $\mu\Omega\text{m}$  in all conductors (under load).
- $R_c$  evolution with cycling in qualitative agreement (peak).

# Conductor design optimization



Single tape  $I_c$   
– mech. load testing

Axial tensile stress,  $I_c$  & mech. props.

Axial tensile & compressive strain,  $I_c$  &  $\epsilon_{irr}$

Transverse Stress  $\sigma_{irr}$

Winding angle  $I_c$  & min. diam.

Cable cyclic load testing  
Twente Press

Critical current/load  $I_c(F)$

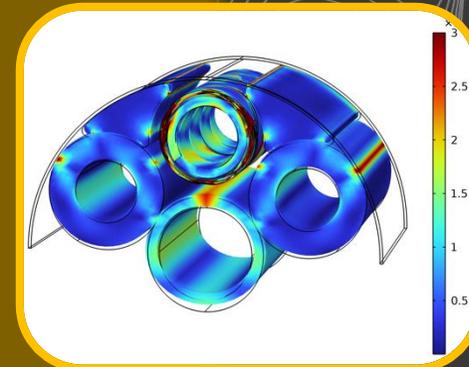
Transverse stiffness  $d(F)$

Inter tape contact resistance  $R_c$

FE cable model

Materials

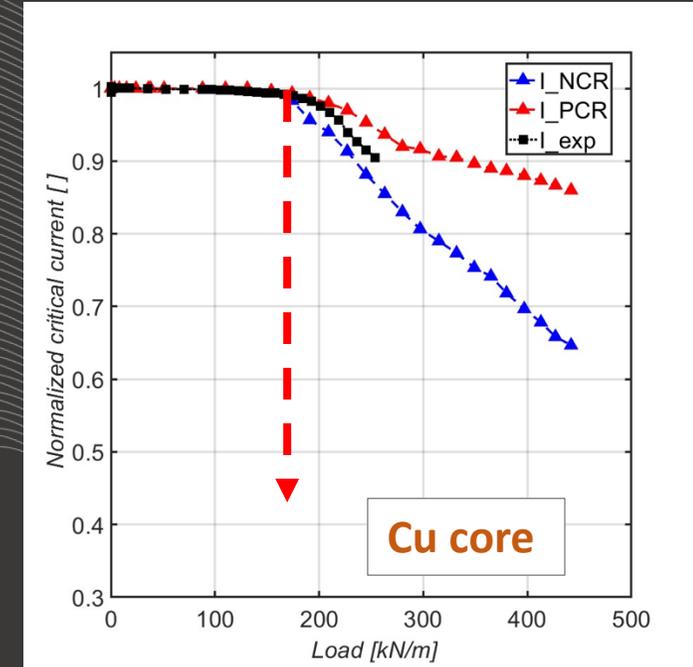
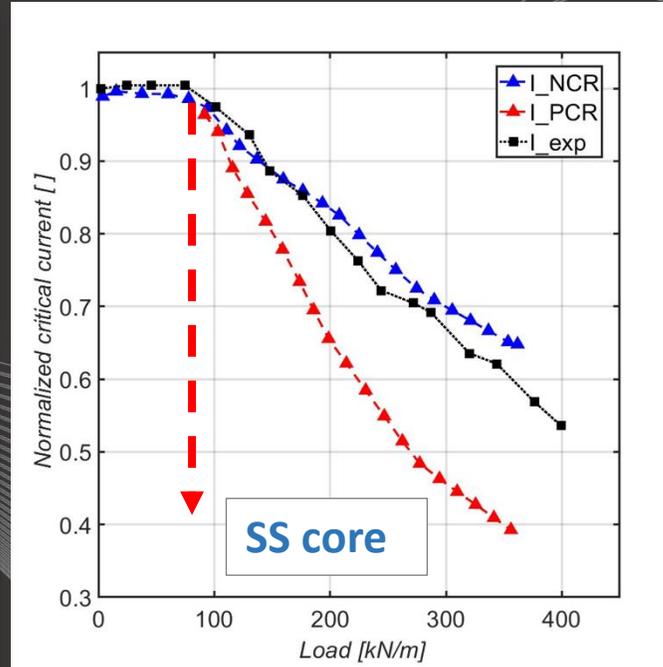
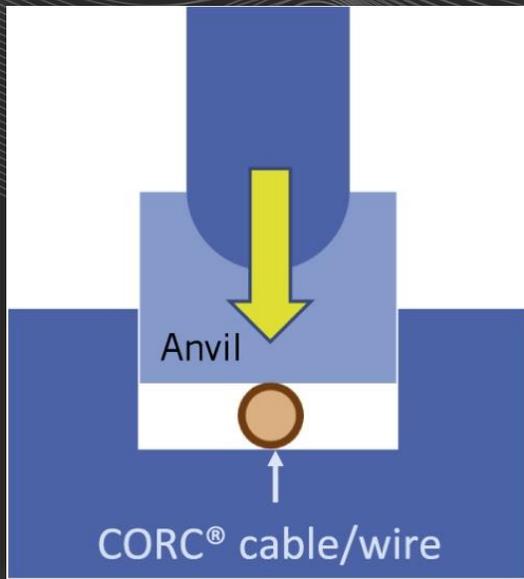
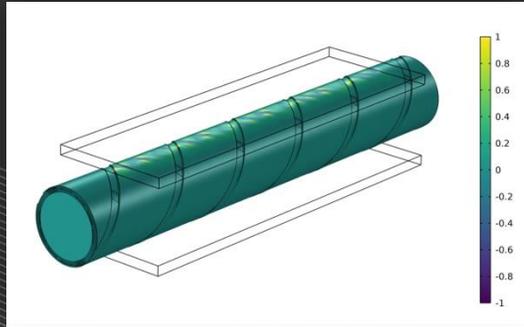
Design



# Model validation – experimental data

ACT single CORC<sup>®</sup> experiment with transverse anvil loading.

| Parameters    |                  |
|---------------|------------------|
| Tapes         | 12               |
| Layers        | 6                |
| Tape width    | 3 mm             |
| d-Tape        | 44 $\mu\text{m}$ |
| d-Substrate   | 30 $\mu\text{m}$ |
| d-Copper      | 5 $\mu\text{m}$  |
| Gap spacing   | 0.5 mm           |
| Core          | Cu/SS rod        |
| Strain window | [-1.3 %, 0.45 %] |

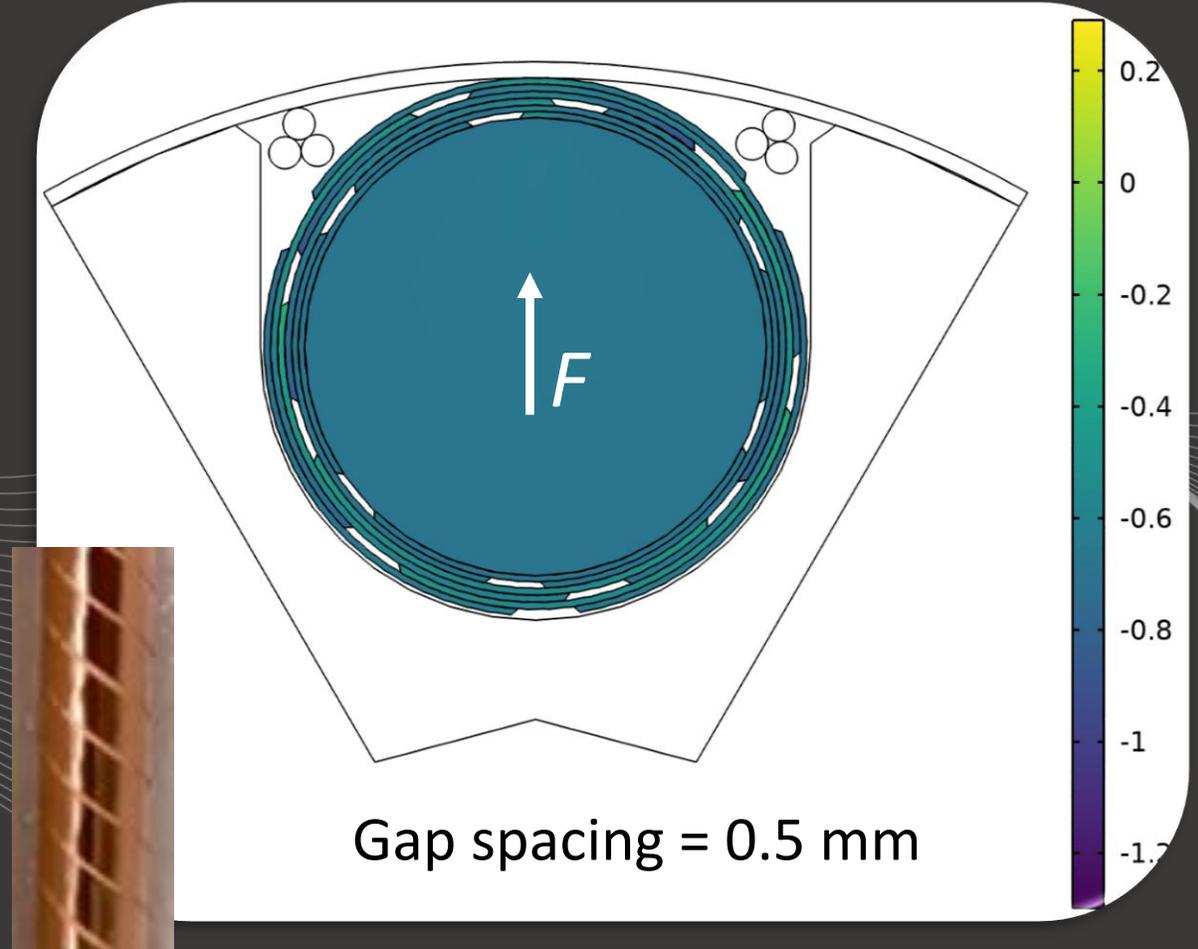
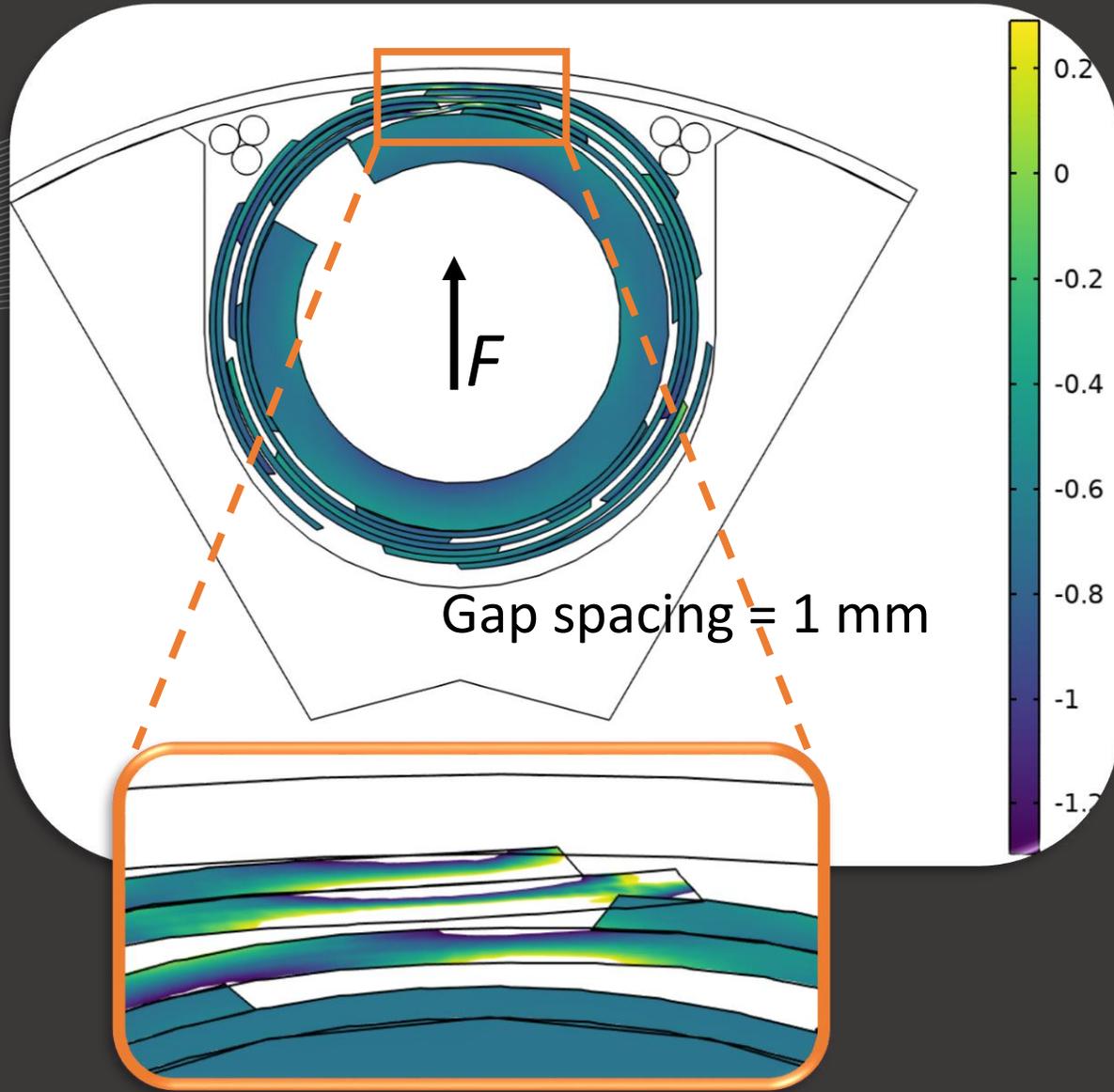


*NCR = no current sharing between tapes.  
PCR = perfect current sharing between tapes.*

**Good match irreversibility limits:  
model versus experiment**

D.C. van der Laan et al, 2018 Supercond Sci Technol 32,  
DOI:10.1088/1361-6668/aae8bf  
D.C. van der Laan et al 2019 Supercond. Sci. Technol. 32 015002  
D.C. van der Laan, private communication.

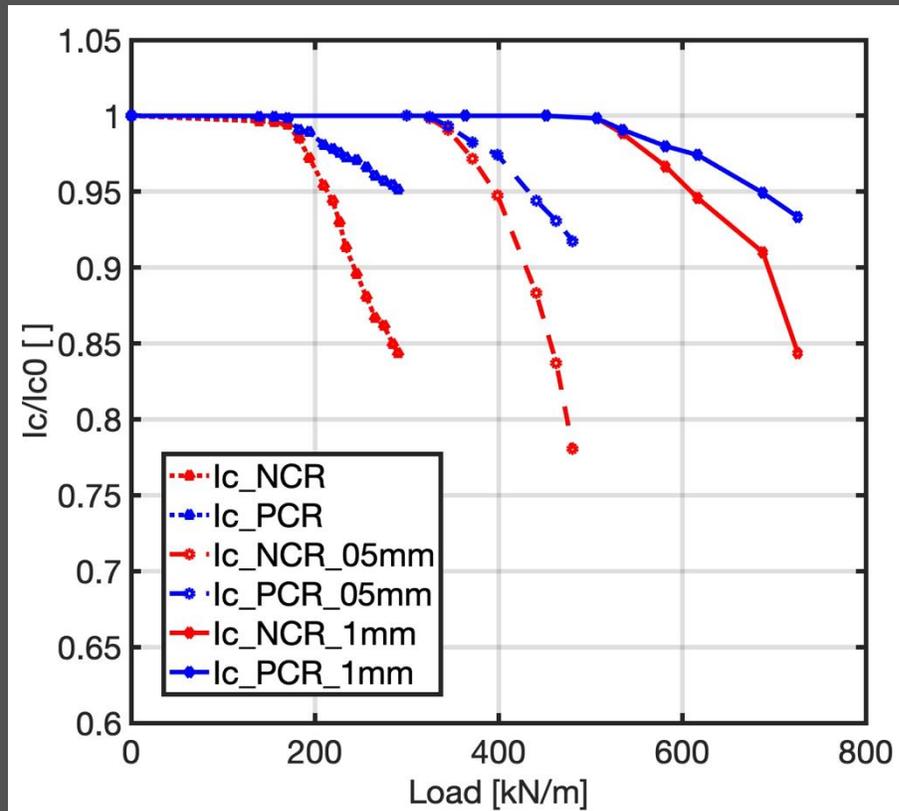
# ASIPP CICC MD; Gap $\sim 1$ and $\sim 0.5$ mm



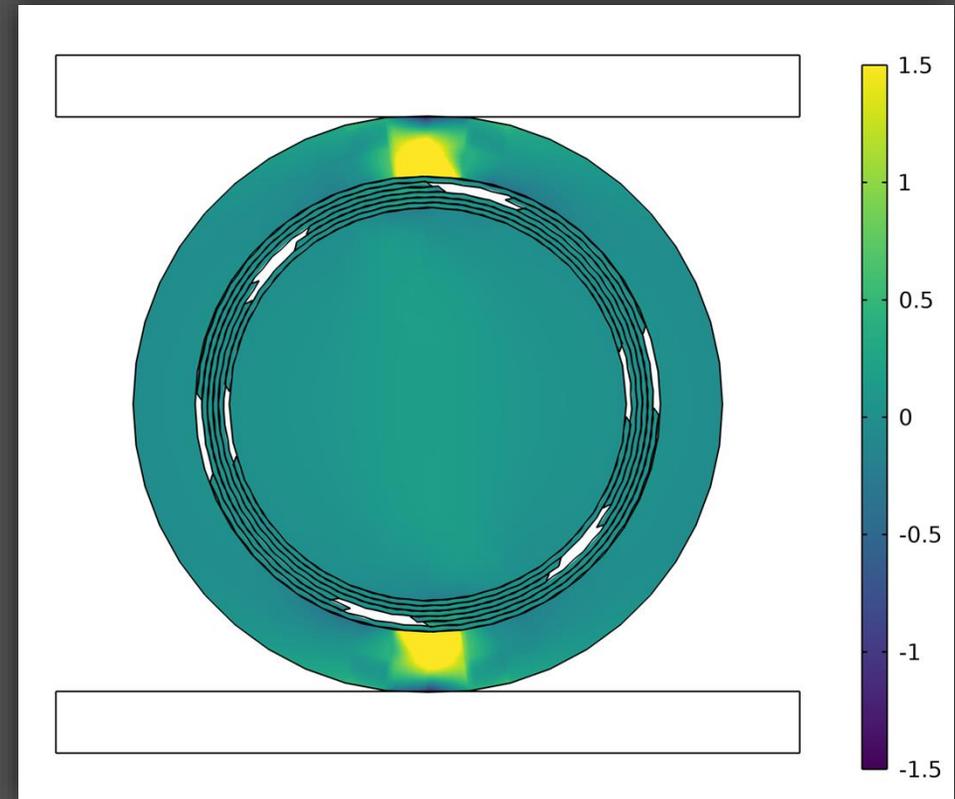
Reducing gap reduces voids and bending - significantly improving performance.

# Model results – ASIPP MC single cable

ACT cable model validation results compared with 0.5 and 1.0 mm Cu tube.

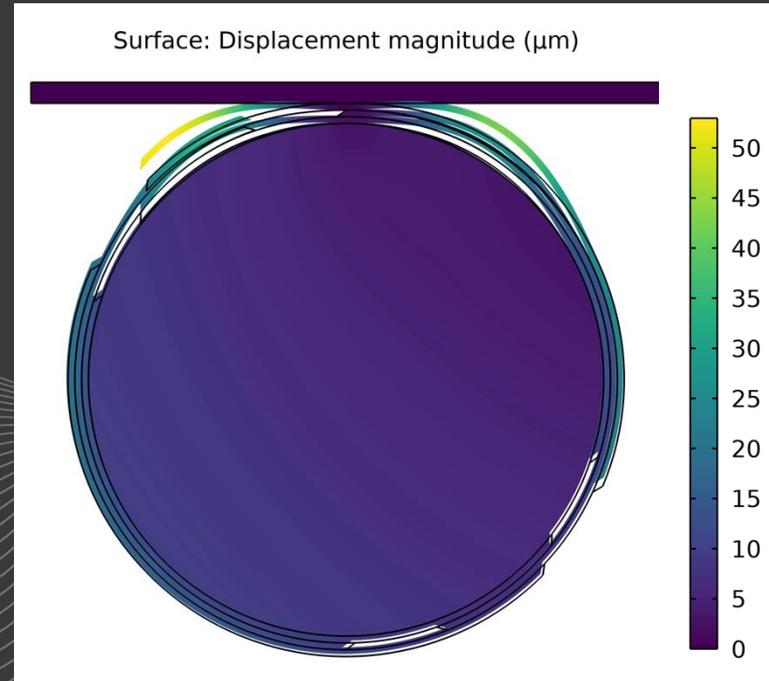
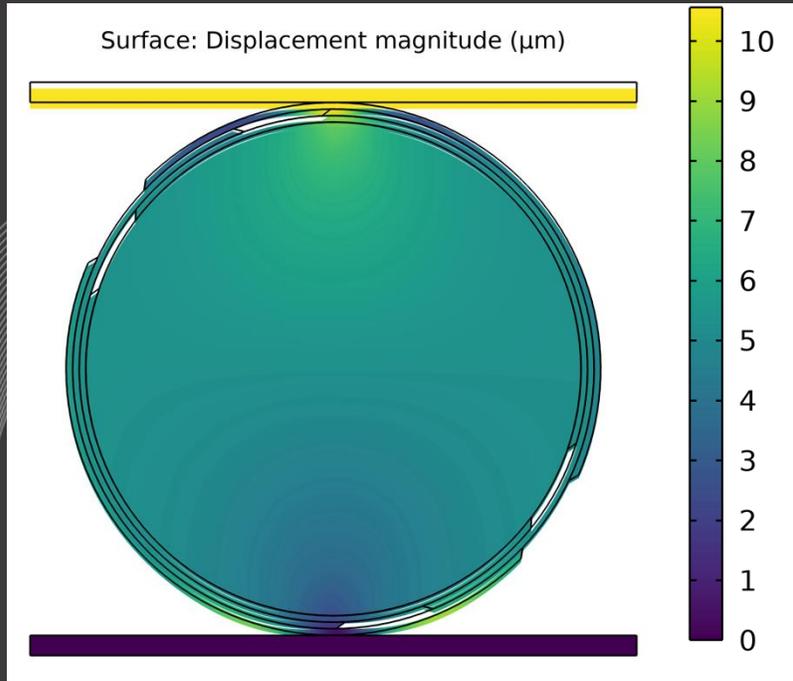


Strain distribution with 0.5 mm Cu-wall thickness.

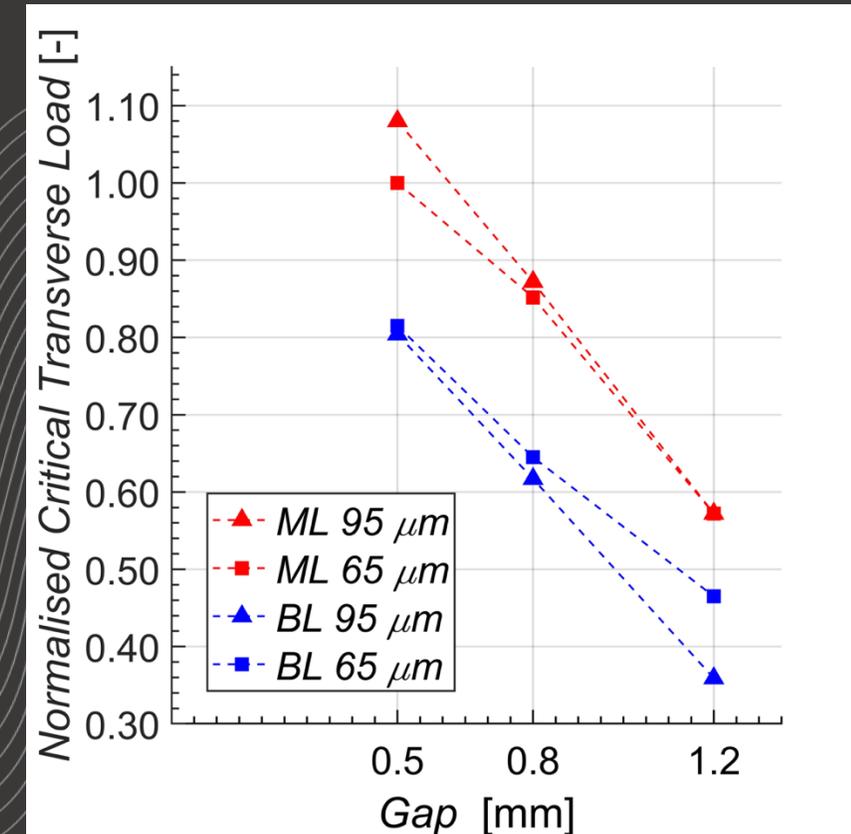


Outer copper tube around cable & solid Cu core: 500 kN/m.

# Mechanical & EM Load (BL)

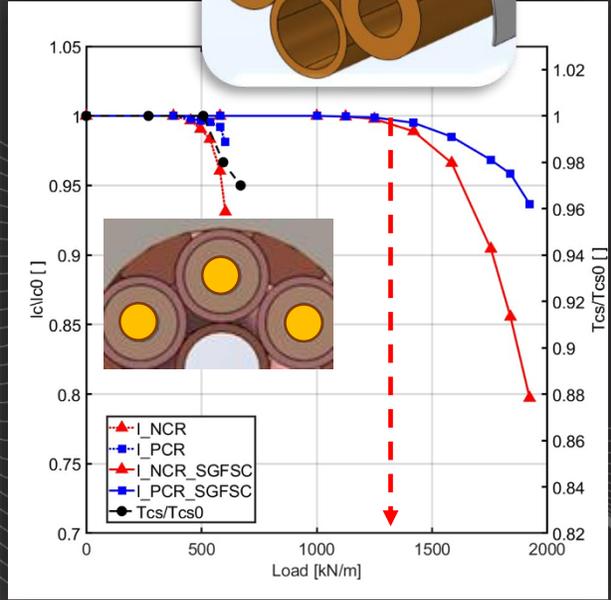
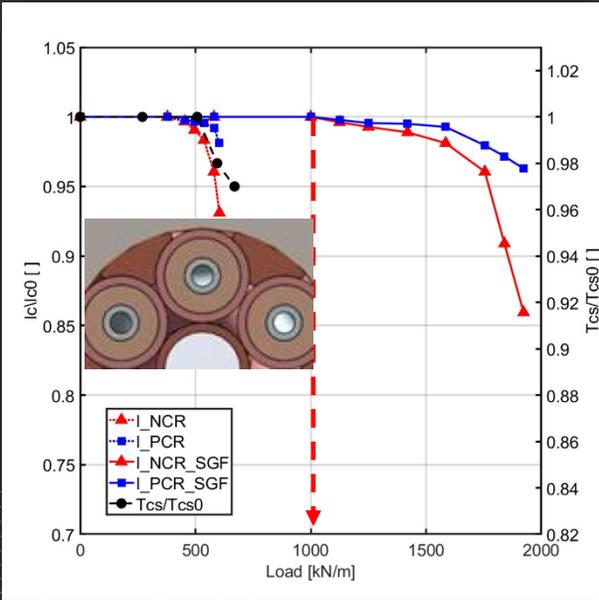
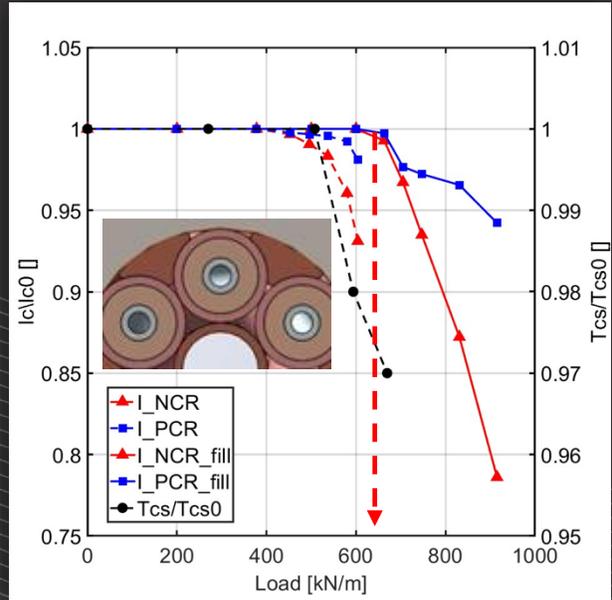
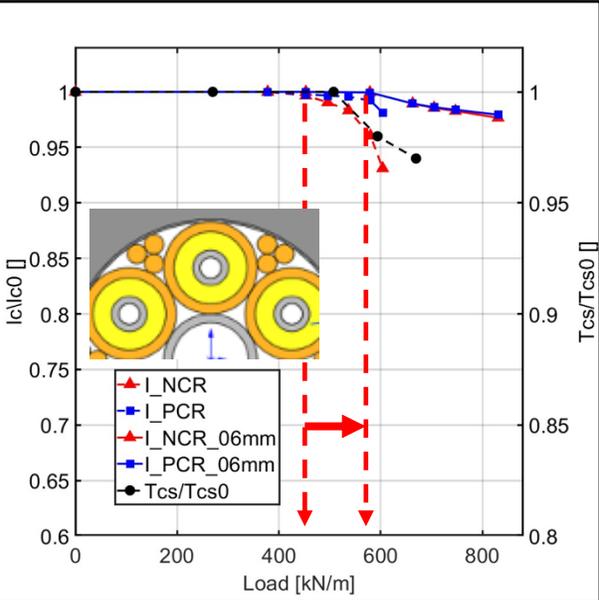
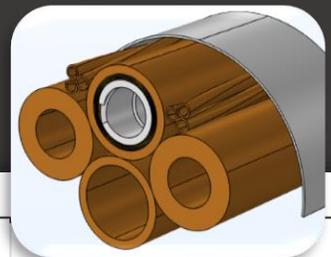


Displacement ( $\mu\text{m}$ ) for Mech Load and Electromagnetic Load at 200 kN/m.



- Difference between body load (EM) and mechanical load (flat anvil) for different tape thicknesses and gap sizes.
- **Critical transverse EM load < mechanical load (30%).**

# Model – ASIPP MC samples

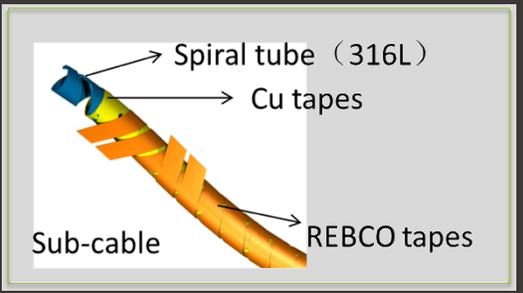


**0.6 mm gap**  
Modest improvement  
SS spiral

**Original gap 1.3 mm**  
**Cu-keystones**  
SS spiral

**0.6 mm gap**  
**Cu-keystones**  
SS spiral

0.6 mm gap  
Cu-keystones  
**Solid Cu core**



Critical force:  
 MC Sultan #1: ~ 400 kN/m  
 MC 1.3 mm gap, Cu-keystones: ~ 600 kN/m  
 MC 0.6 mm gap, Cu-keystones: ~ 1,000 kN/m  
 MC 0.6 mm gap, solid core: ~ 1,300 kN/m



| $I_x B$ CS | $I$ [kA] | $B$ [T] | $F(I_x B)$ [kN/m] |
|------------|----------|---------|-------------------|
| ASIPP      | 42       | 20      | 840               |
| EU-DEMO    | 60       | 18      | 1080              |

# Summary

- (New) setups for characterizing mechanical and electrical properties of REBCO tapes.
- Round cable FE model validated.
- Critical transverse load CORC<sup>®</sup>-like cables after cycling (4 samples) varies from 90 to 450 kN/m.
- Observations to be further optimized for CICC with round cable:
  - *void fraction - winding tension – winding angle - # tape layers*
  - *space for tape bending (breathing) and cable containment*

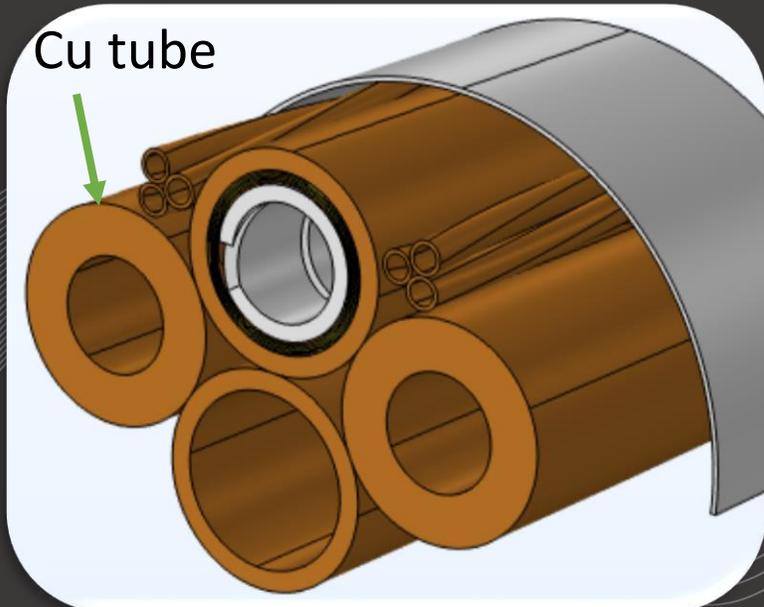
# Short term plans

- Testing mechanical and electrical properties of REBCO tapes different manufacturers.
- Design optimization (number of layers, void fraction, tape bending etc).
- Cable tests ( $I_c$ ,  $R_c$ ,  $d$ ) under cyclic loading in Twente Press:
  - ACT-cable with matching cable and Cu-groove radii.
  - ASIPP-cable within Cu-tube.
  - Stacked tape conductors (+ modeling).

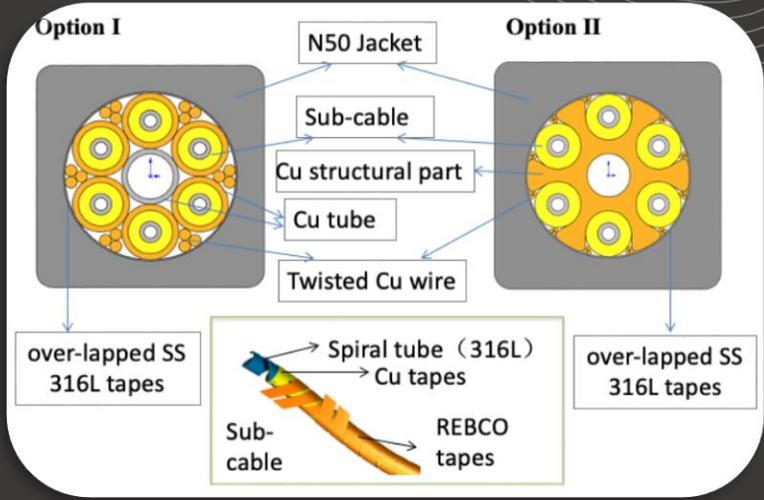
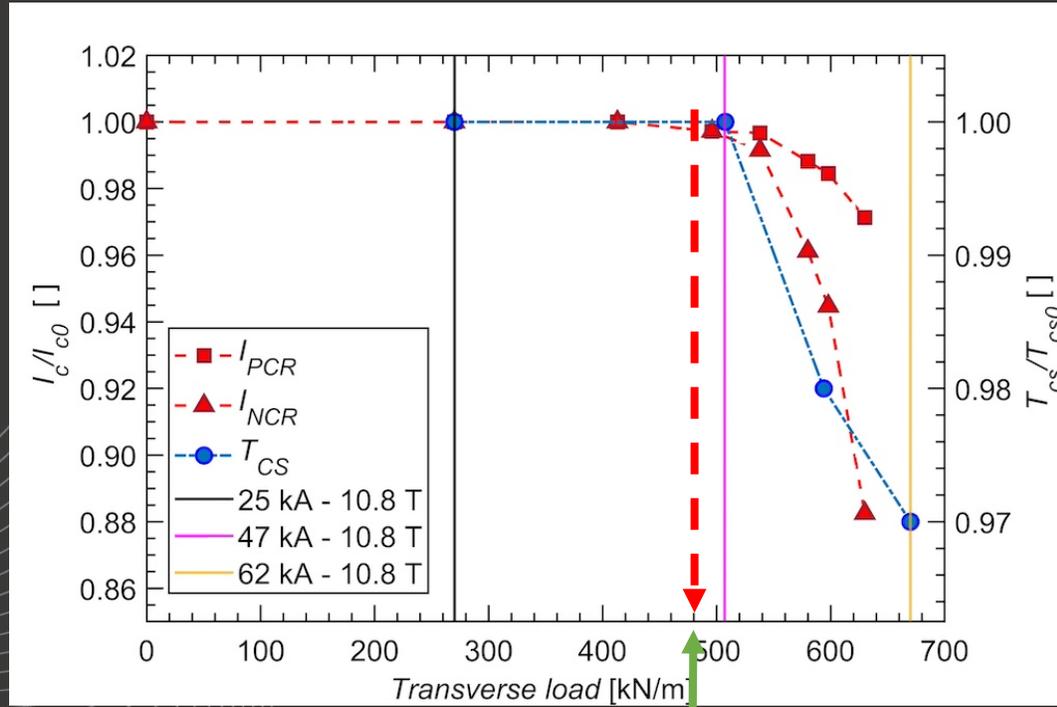
A decorative graphic consisting of numerous thin, white, wavy lines that flow across the slide, creating a sense of movement and depth. These lines are centered behind the main text.

**Thank you!**

# Model results – ASIPP MC sample #1

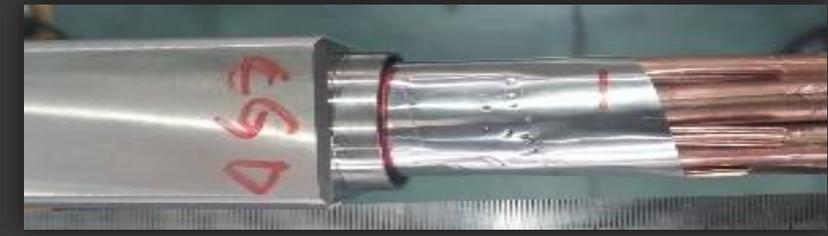


| Sub-cable Parameters |                   |
|----------------------|-------------------|
| Tape Manufact.       | Fujikura          |
| SC Tapes             | 36                |
| Simulated Tapes      | 9                 |
| Tape width           | 4 mm              |
| d-tape               | 110 $\mu\text{m}$ |
| d-substrate          | 50 $\mu\text{m}$  |
| d-copper             | 23 $\mu\text{m}$  |
| Gap spacing          | 1.3/1.6 mm        |
| Core                 | SS Spiral         |
| Strain window        | [-1.3, 0.29 %]    |

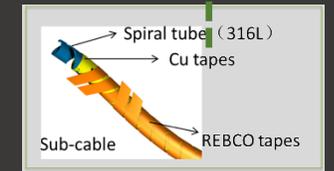
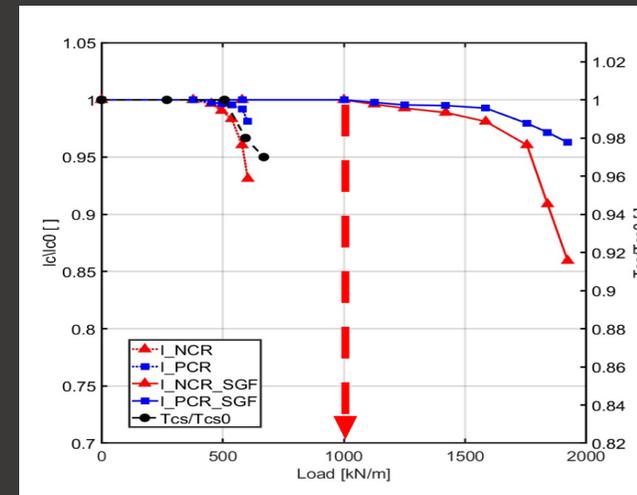
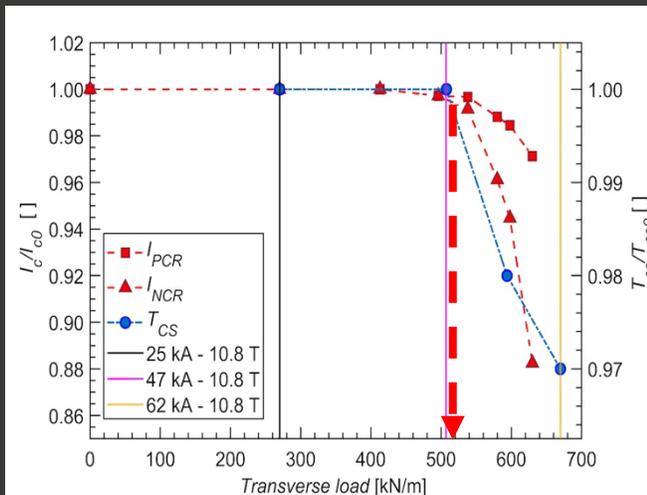
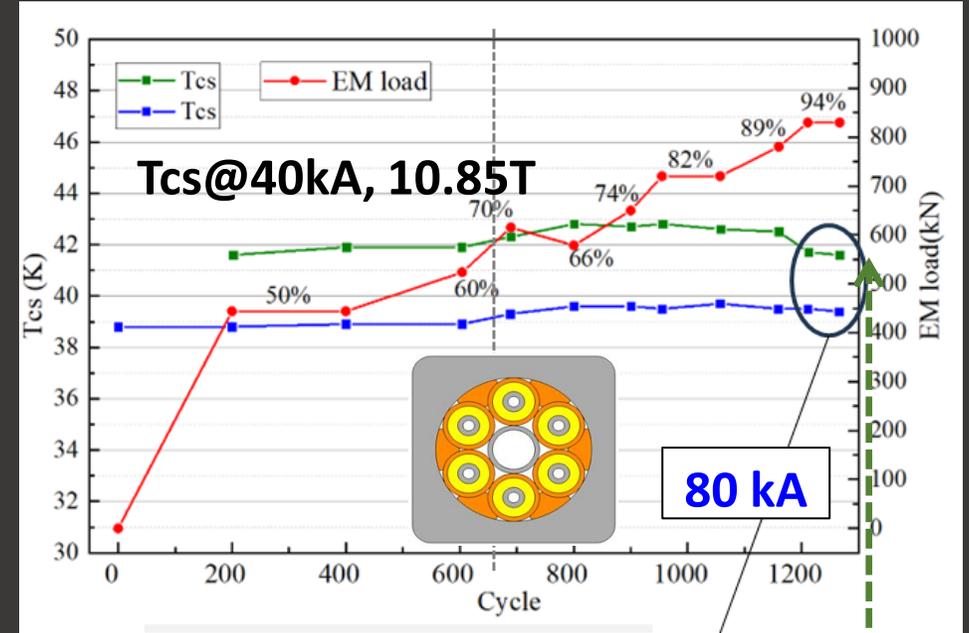
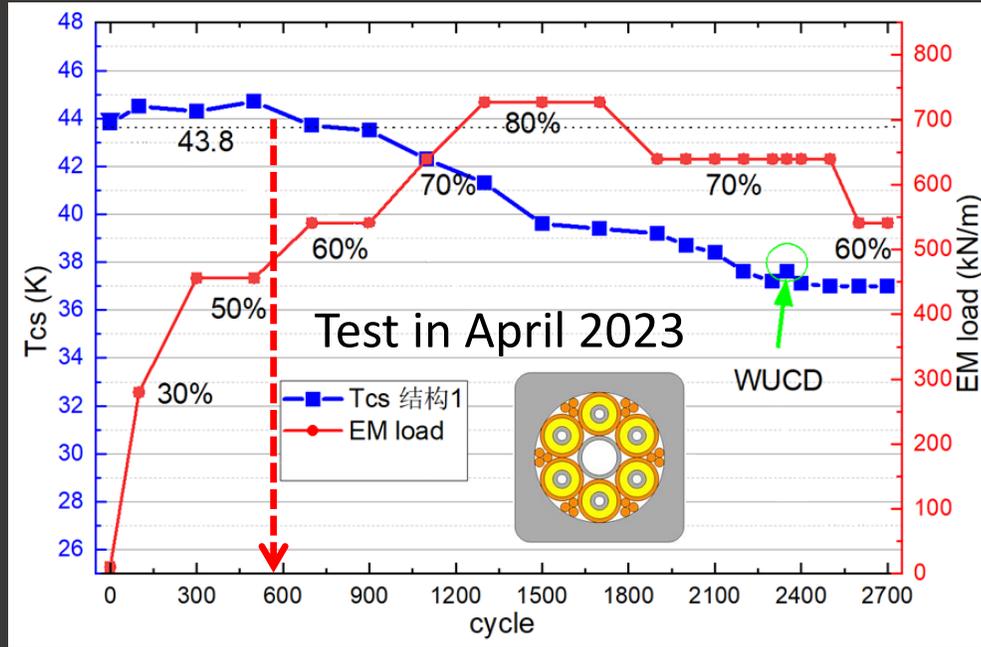


Prediction & SULTAN  $T_{cs}$  reduction coincide.

Irreversibility:  
 MD: ~ 200 kN/m.  
 MC with copper tube: ~ 500 kN/m.



# Model prediction - SULTAN results (ASIPP)



# Inter-tape friction

Axial strain at 1000 kN/m EM load.

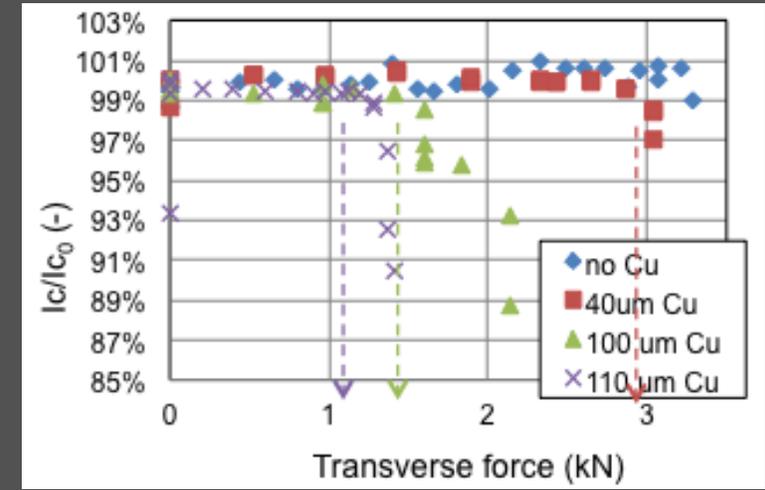
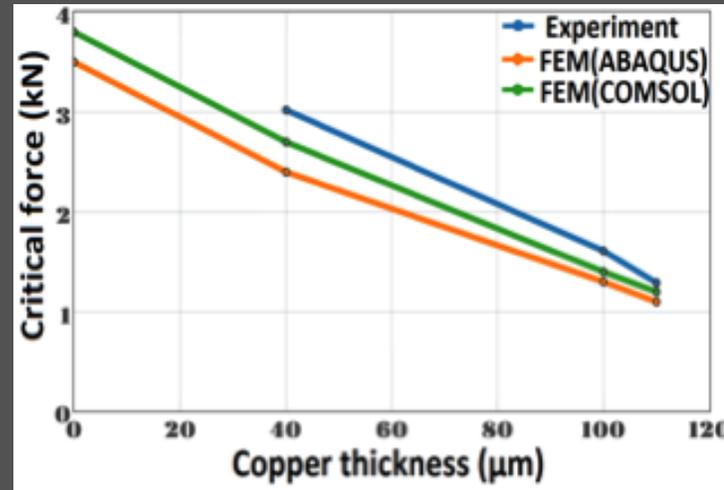
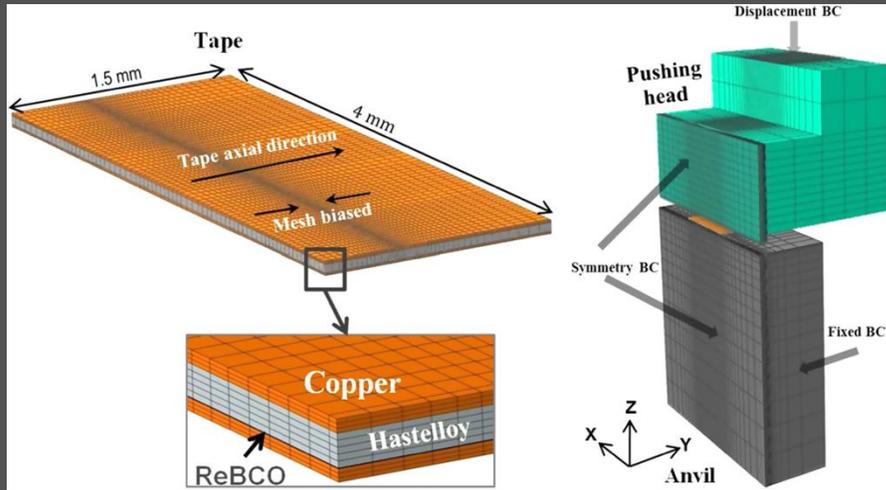
friction factor 0.2

For  $ff=0.2$ , tapes do not move due to contact friction with tapes underneath and above.

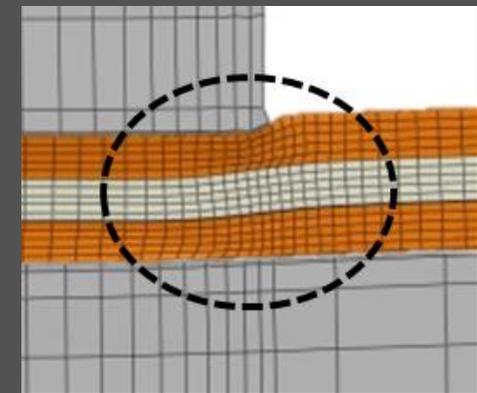
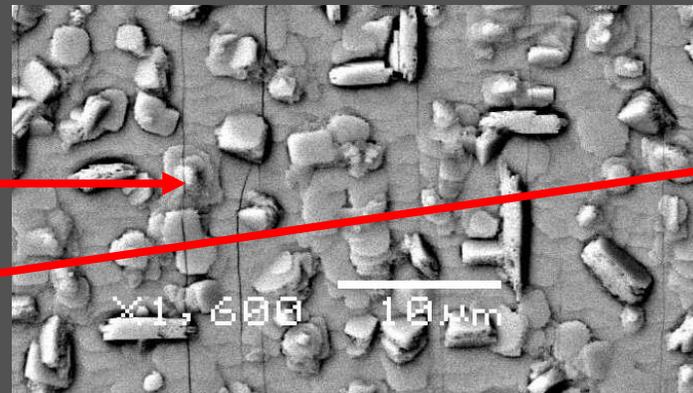
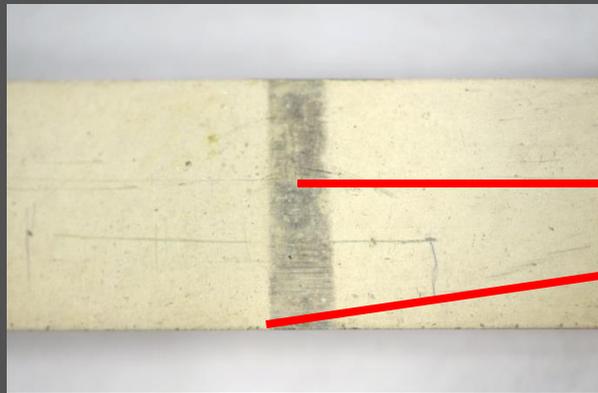
Tapes slide due to EM load. Gap is reduced and near tape edges irreversibility limit 0.3% is exceeded.

friction factor =zero

# Local transverse load and tape Cu-layer thickness



Critical load REBCO tape for different Cu layer thickness: 1 mm anvil width.



K. Ilin, K.A. Yagotintsev, C. Zhou, P. Gao, J. Kosse, S.J. Otten, W.A.J. Wessel, T.J. Haugan, D.C. van der Laan and A. Nijhuis 2015  
 Experiments and FE modeling of stress-strain state in RECO tape under tensile, torsional and transverse load, Supercond Sci Technol  
 28 055006 [10.1088/0953-2048/28/5/055006]

# Press testing profile

