Characterization of electromechanical properties of striated REBCO tapes for TORT cables with reduced magnetization AC losses

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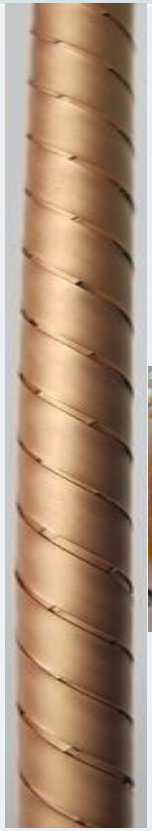
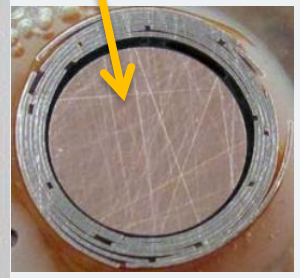
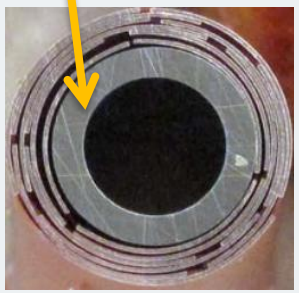
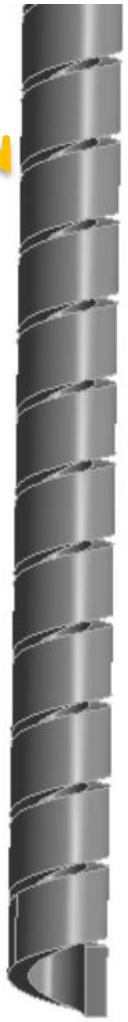
REBCO tape cabling methods

Stacking		Helical winding on a round former	
RACC Roebel Assembled Coated Conductor	**TSTC** Twisted Stacked-Tape Cable	**CORC®** Conductor on Round Core	**TORT** Tapes on Round Tube
		 	 
Tapes in zigzag pattern	Twisting stacked tapes	Winding tightly with a short pitch on a small diameter former	

Former is rectangular spring



Outline

1. Striating of REBCO CC tapes
   - Chemo-mechanical striating
   - DC measurements
2. Bending of the striated REBCO CC tapes - experiments
   - DC measurements
   - AC losses measurements
3. SEM-FIB & ToF-ERDA
   - Gap width
   - Overetching
4. Bending of striated CC tapes - FE analysis
   - Variation in gap width, bending diameter, overetching,...
5. I_c (B, alpha) measurements

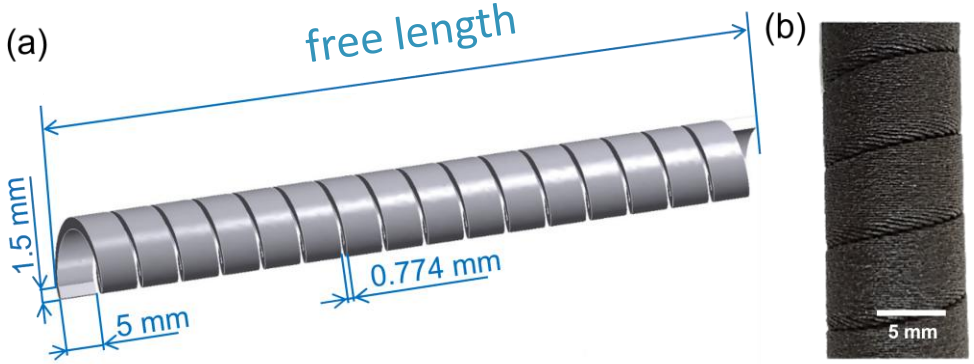
Conclusion

Requirements for central former of TORT cable

- High electrical resistivity
- Dimensional stability during temperature shocks
- Resilience against low diameter bending
- Perforation to improve cooling of REBCO tapes from inside of the former

Promissing technology for production of central former → **3D printing**

Selected geometry of central former



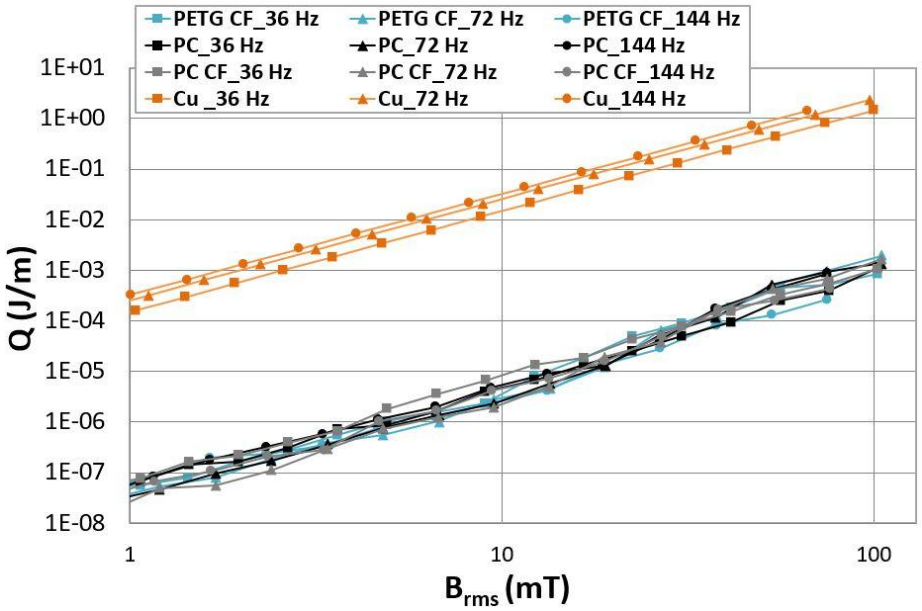
Materials suitable for printing of central former:

- PC CF (polycarbonate carbon fiber reinforced)
- PETG CF (polyethylene terephthalate glycol carbon fiber reinforced)

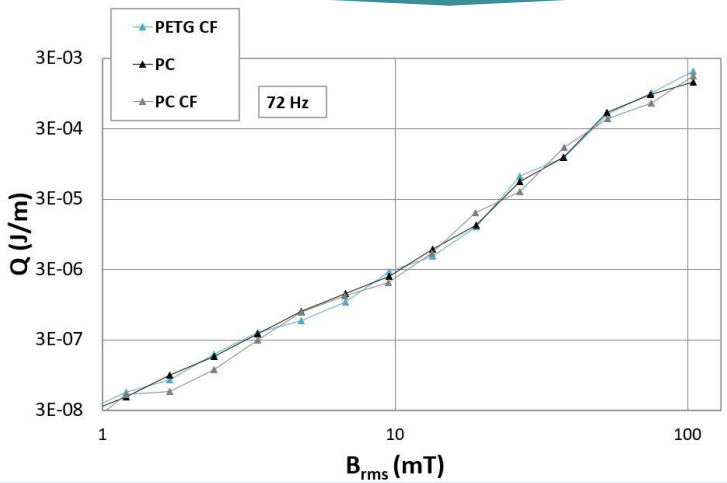
Geometry specification:

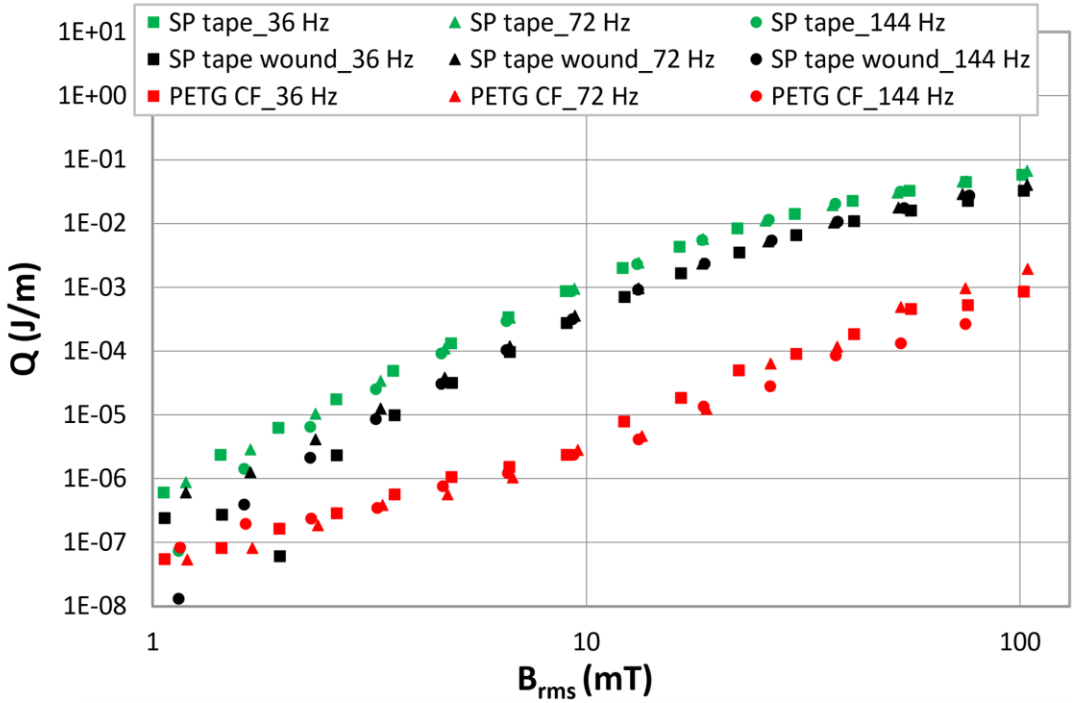
- ✓ Adjustable outer and inner diameter of the former
- ✓ Wall thickness: 1.5 mm
- ✓ Gap between turns: 0.774 mm

AC losses measurements of central former



The presence of carbon fibers does not affect electrical conductivity of the formers





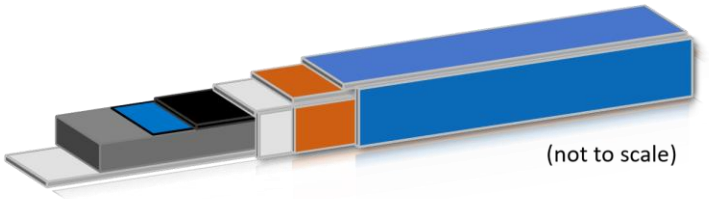
1. Striating of REBCO CC tapes

SuperPower® SCS 2030
2 mm wide tape

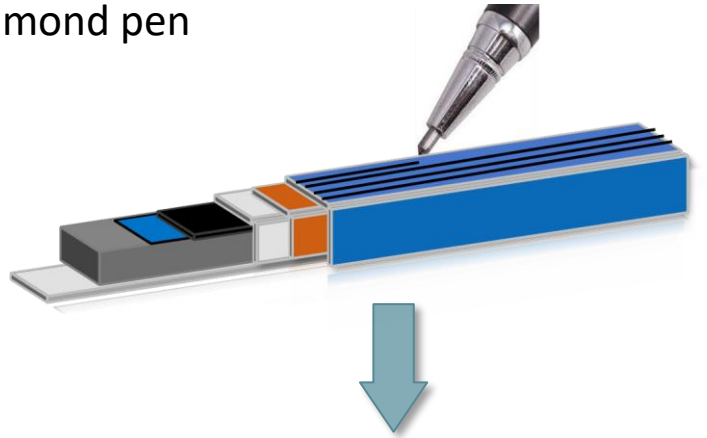
- Cu top: 8.3 µm
- Ag top: 1.3 µm
- REBCO: 1.4 µm
- Buffers: 0.25 µm
- Hastelloy: 30 µm
- Ag bottom: 1.3 µm
- Cu bottom: 7.5 µm

Chemo-mechanical selective etching process

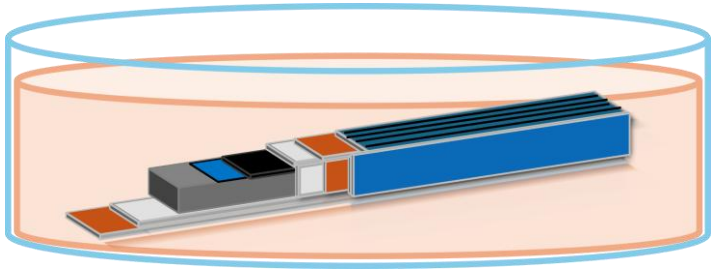
1 Covering of the REBCO tape with a mask throught the spray coating



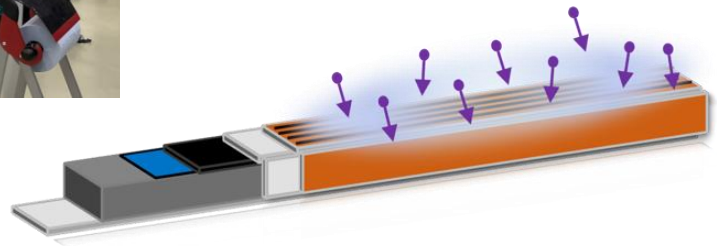
2 Mechanical scribing of a mask with a diamond pen



3 Selective etching of Cu and Ag overlayer together with REBCO layer using KI_3 etchant combined with 6.5 wt.% of aqueous solution of HNO_3

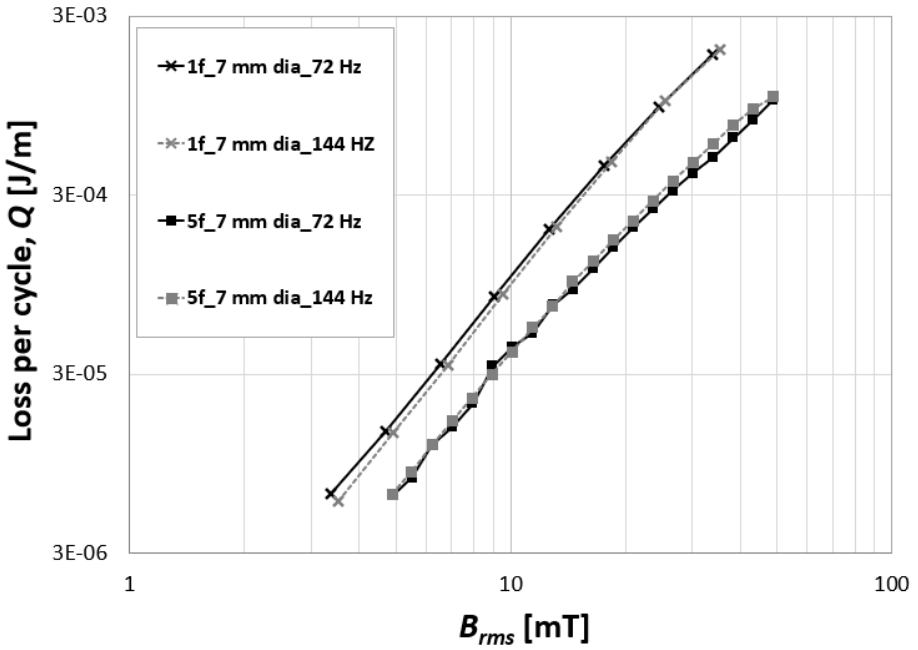


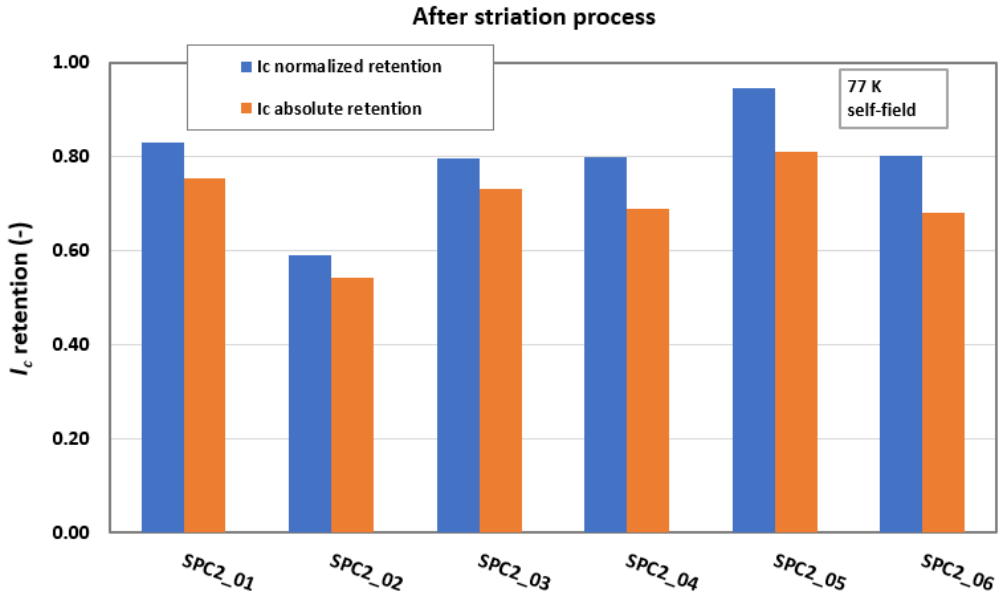
3. Magnetron sputtering of protective layers

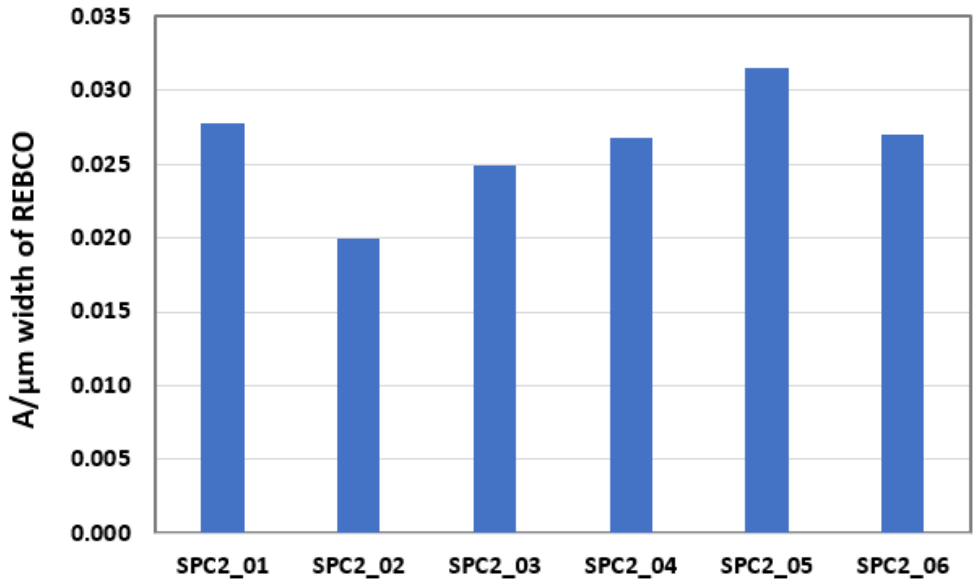


1. Striating of CC tapes

Sample	Etching	No. of filaments	Magnetron sputtering deposition
SPC2_ref	-	1	-
SPC2_01	➢ Cu and Ag layer etched with KI_3 (40 s)	5	30 nm Ti + 200 nm AlN
SPC2_02		5	30 nm Ti + 100 nm AlN
SPC2_03	➢ REBCO and buffers etched with 6.5 vol.% HNO_3 (40 s)	5	30 nm Ti + 300 nm AlN
SPC2_04	KI_3 (80 s)/ 6.5 vol.% HNO_3 (40 s)	5	100 nm AlN
SPC2_05		5	400 nm AlN
SPC2_06		5	700 nm AlN





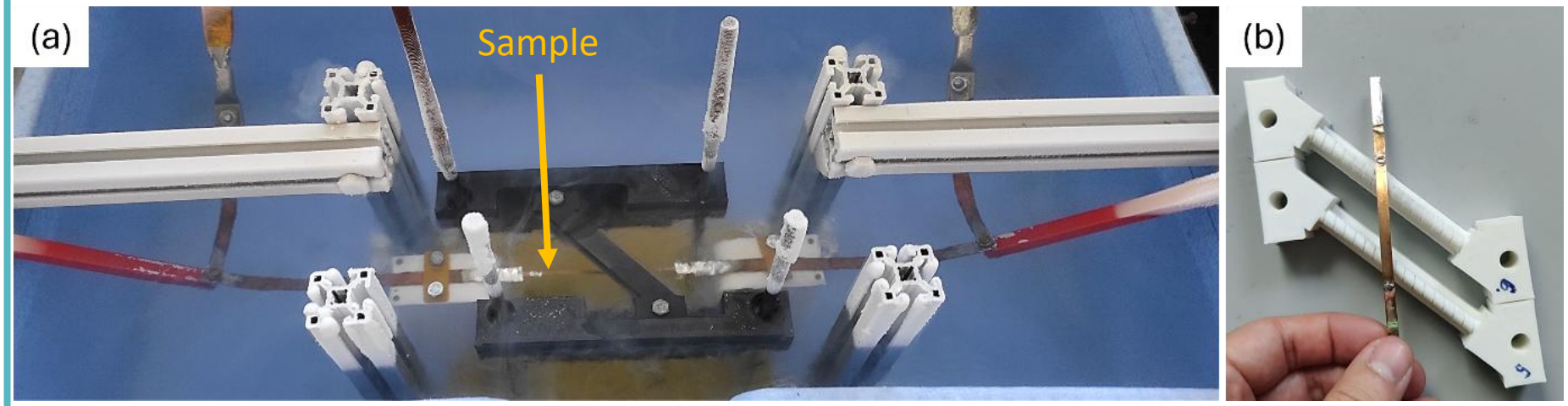


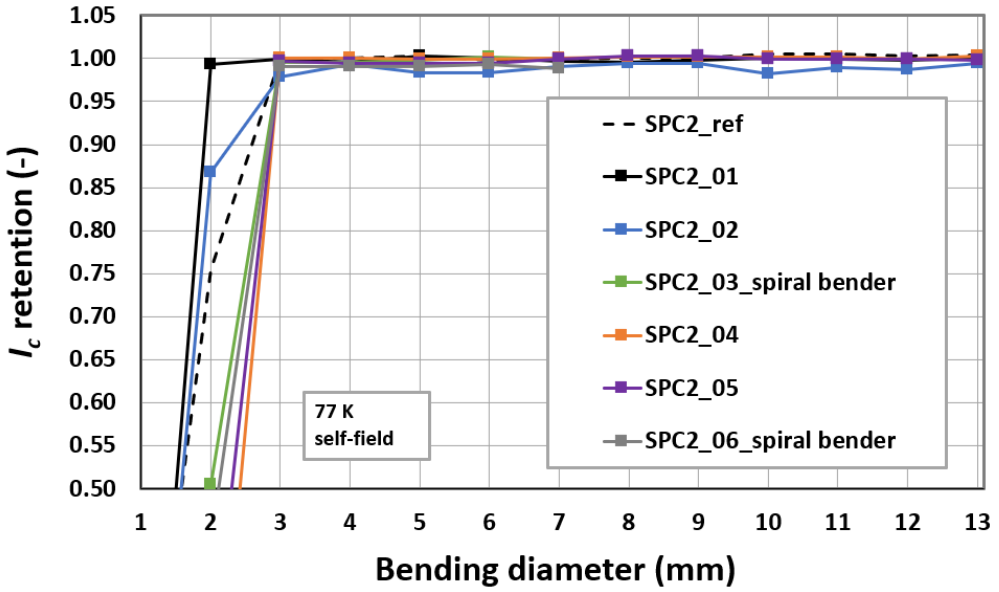
IEEE-CSC, ESAS and CSSJ SUPERCONDUCTIVITY NEWS FORUM (global edition), Issue No. 60, Sept. 2025. Presentation given at MT29, Boston, MA, USA, July 2025.

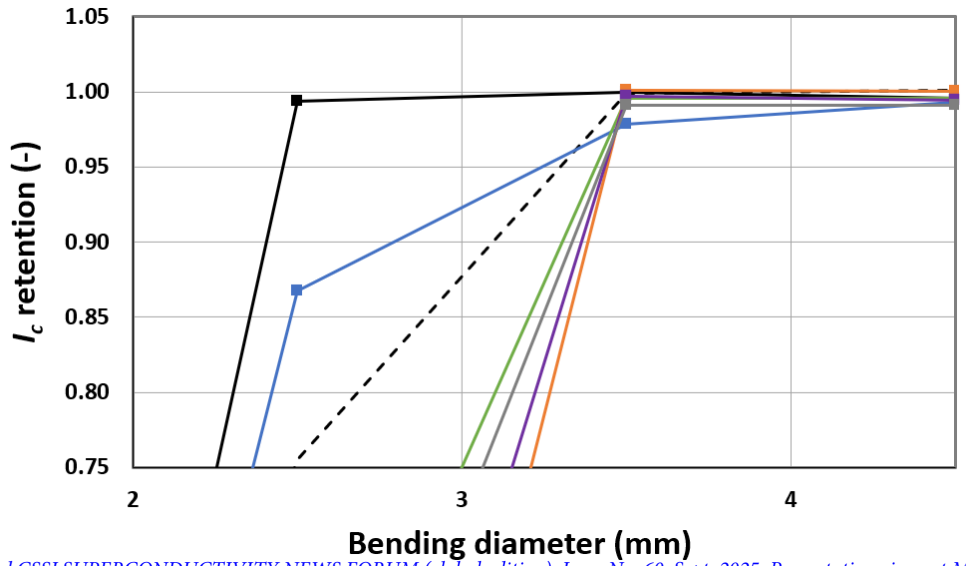
2. Bending of the striated CC tapes - experiments

- DC measurements 77 K, self-field
- REBCO side inwards of the helix
- Benders: PETG CF material with outer diameter in a range from 13 mm to 1 mm; 1 mm step
- Bending angle: 45°
- Tensioning force: 6.5 N

Spiral benders





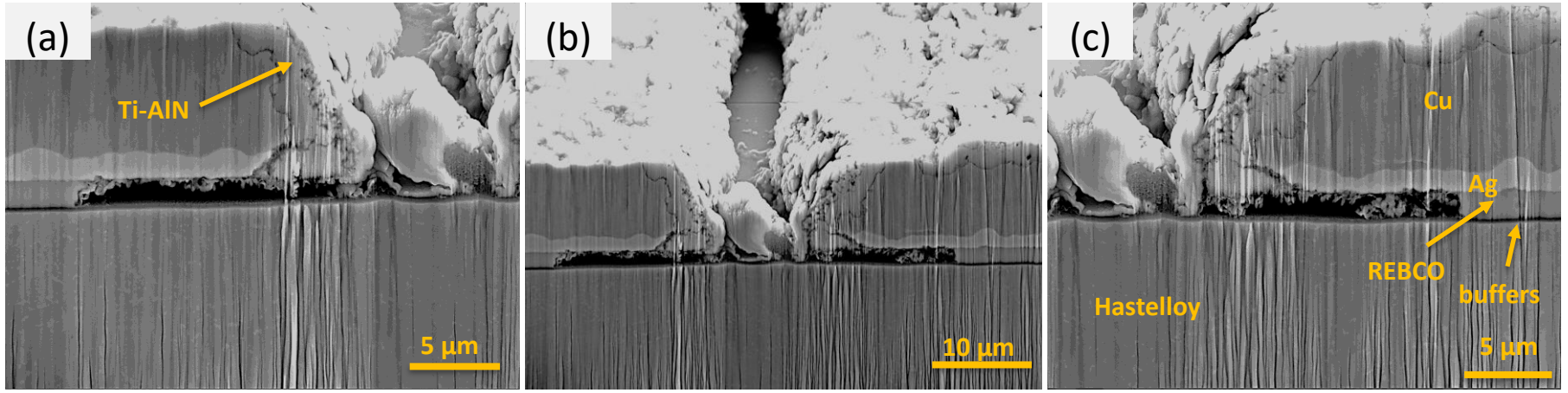


I_c is normalized to I_c of striated tapes

3. SEM-FIB of striated REBCO CC tapes

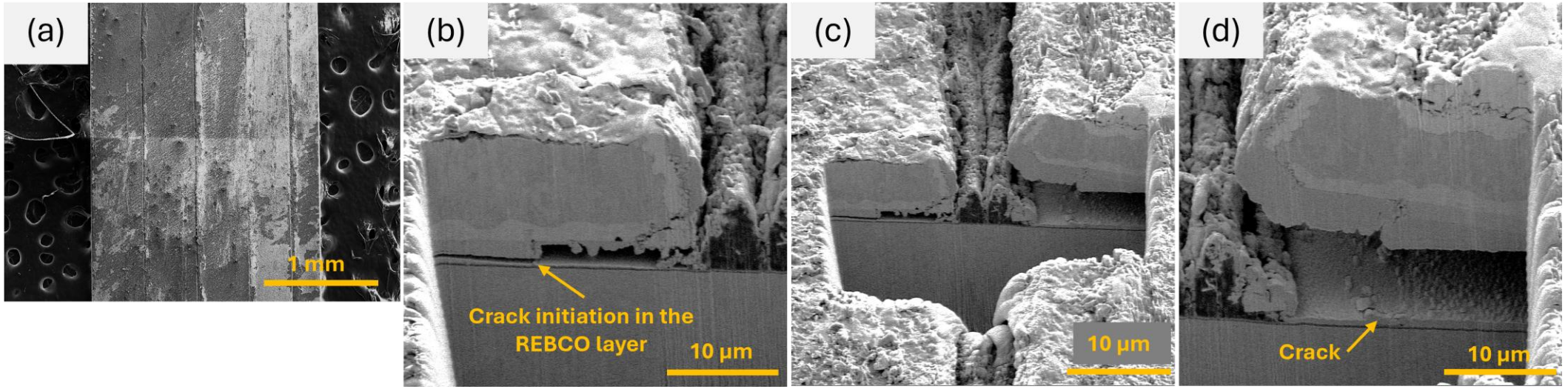
SPC2_01

straight region



Sample	Gap width (µm)	Overetching (µm)
SPC2_01	21	12.5
SPC2_02	22	11
SPC2_03	31	10.5
SPC2_04	54	8
SPC2_05	53	9
SPC2_06	57	9.5

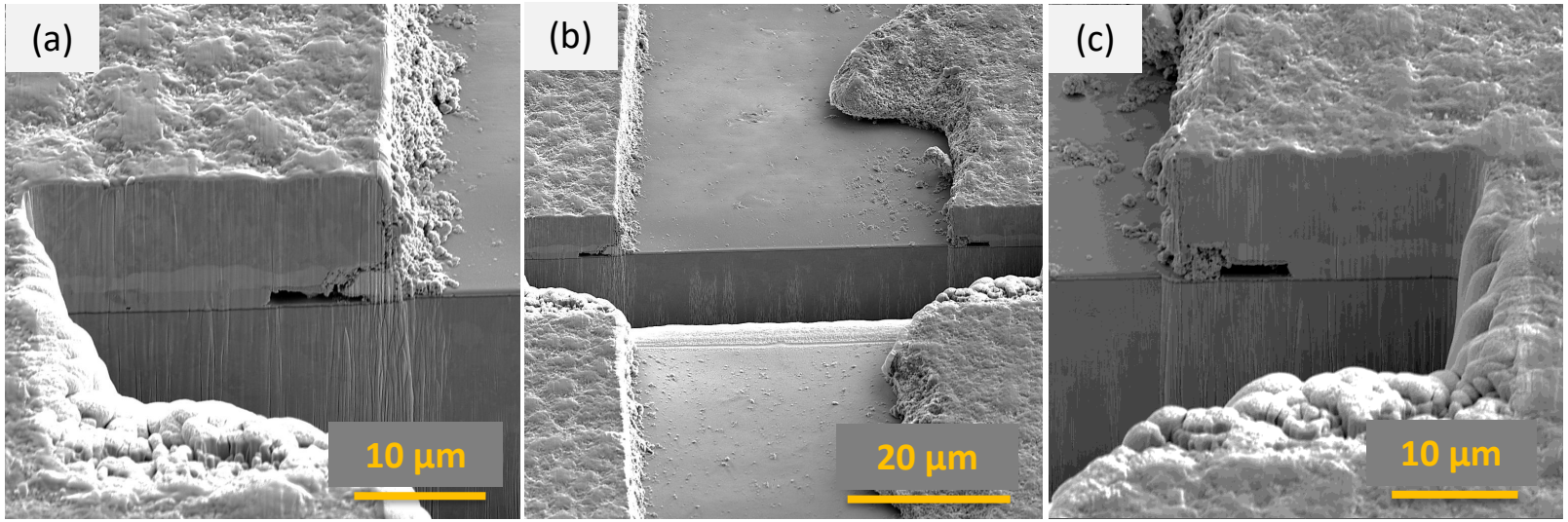
bent region



3. SEM-FIB of striated REBCO CC tapes

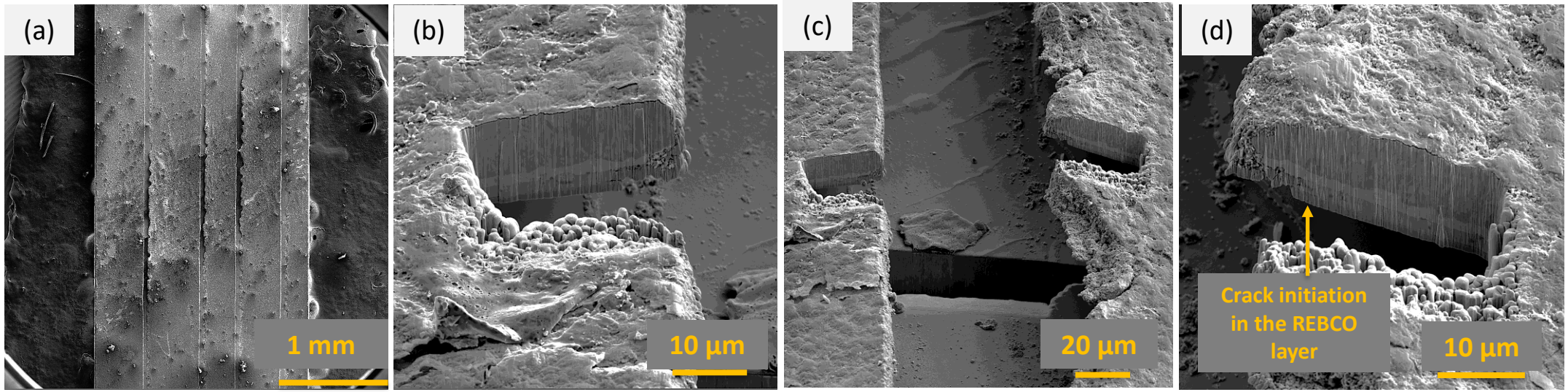
SPC2_04

straight region

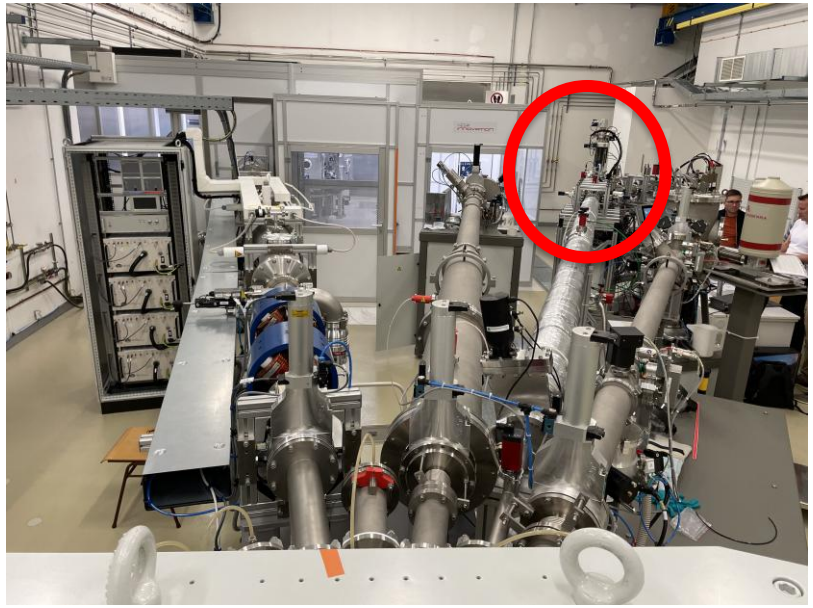


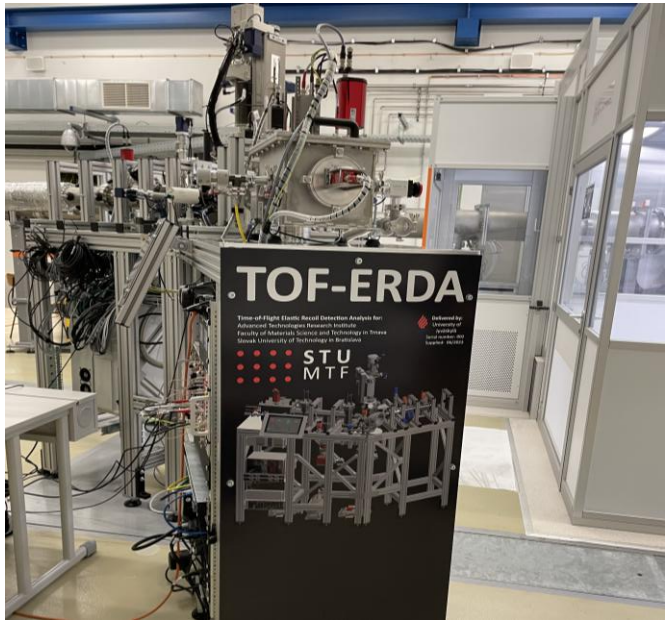
Sample	Gap width (µm)	Overetching (µm)
SPC2_01	21	12.5
SPC2_02	22	11
SPC2_03	31	10.5
SPC2_04	54	8
SPC2_05	53	9
SPC2_06	57	9.5

bent region

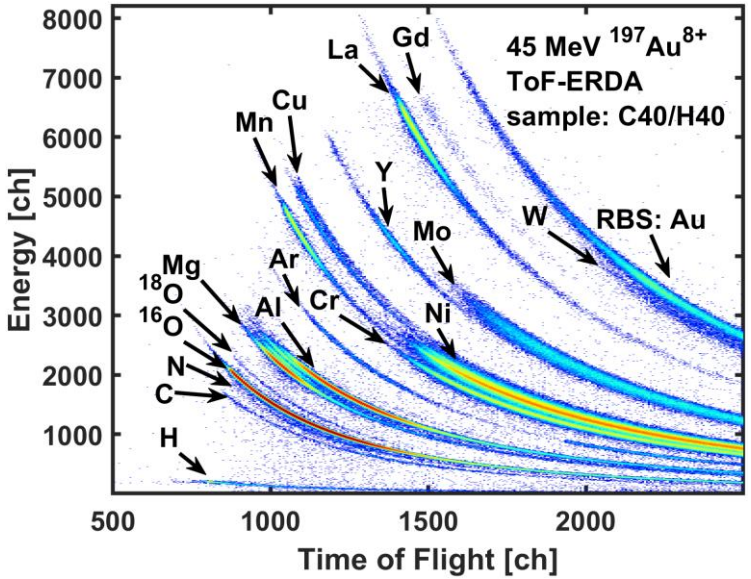


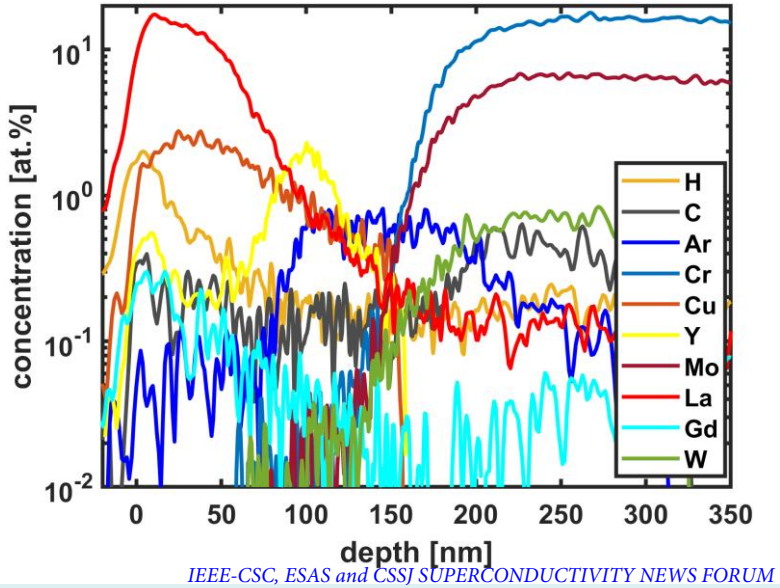
3. ToF-ERDA measurements

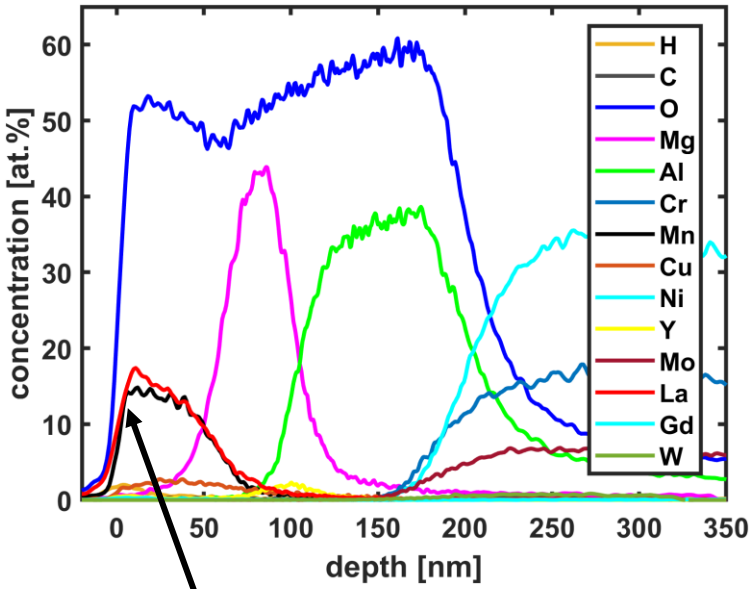




Etched KI_3 (40 s) + HNO_3 (40 s)



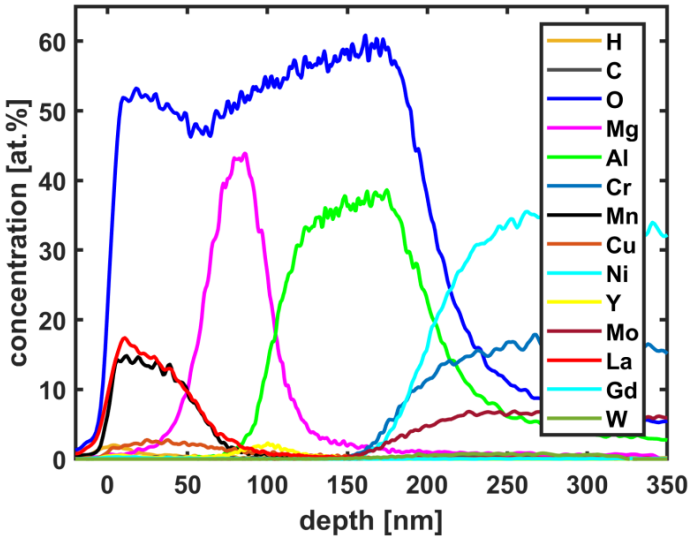




Etching stopped
at the LMO layer

3. ToF-ERDA measurements

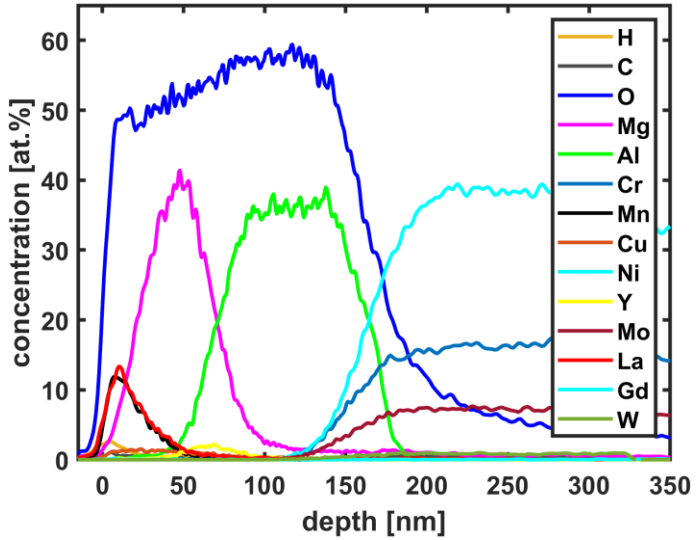
Etched KI_3 (40 s) + HNO_3 (40 s)



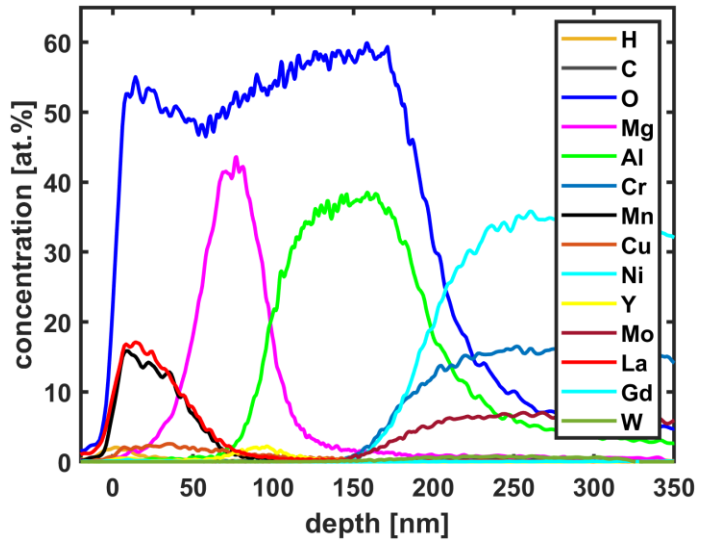
Etching stopped at the LMO layer

Etching stopped at the MgO layer

Etched KI_3 (75 s) + HNO_3 (75 s)

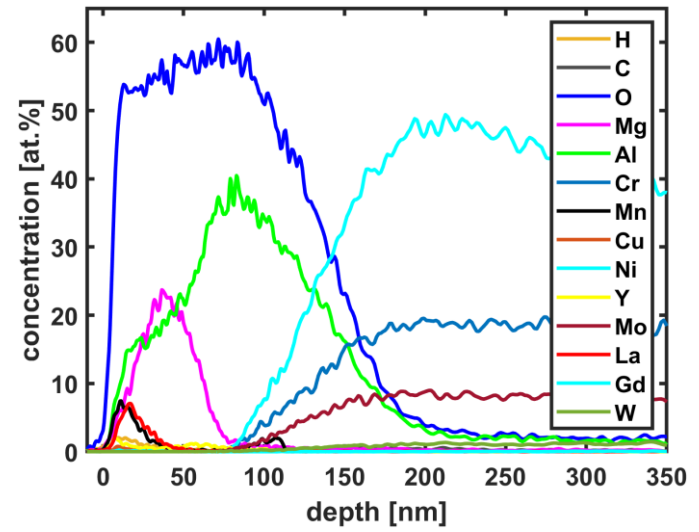


Etched KI_3 (80 s) + HNO_3 (40 s)



Etching stopped at the Al_2O_3 layer

Etched KI_3 (150 s) + HNO_3 (180 s)



4. Bending of striated CC tapes - FE analysis

The identical boundary conditions and tape geometry as in the experiments were applied in the FE analysis (3D, static structural)

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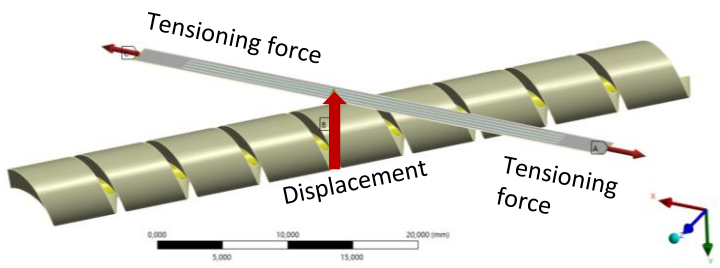
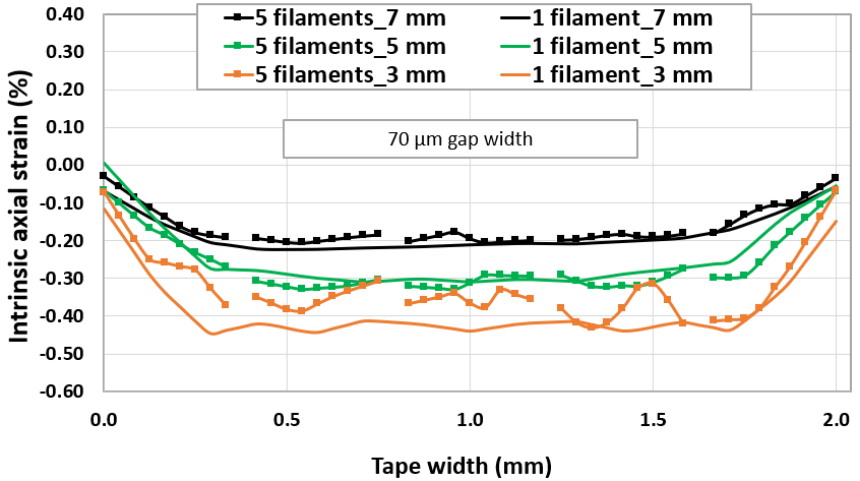
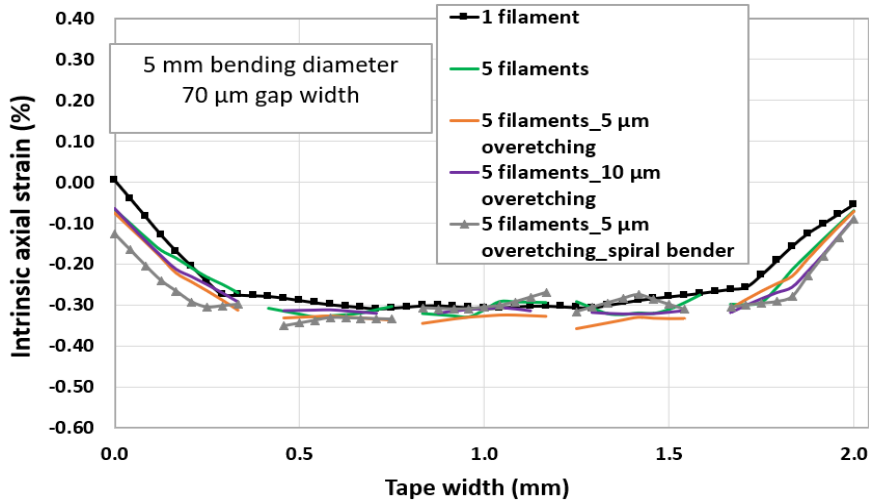


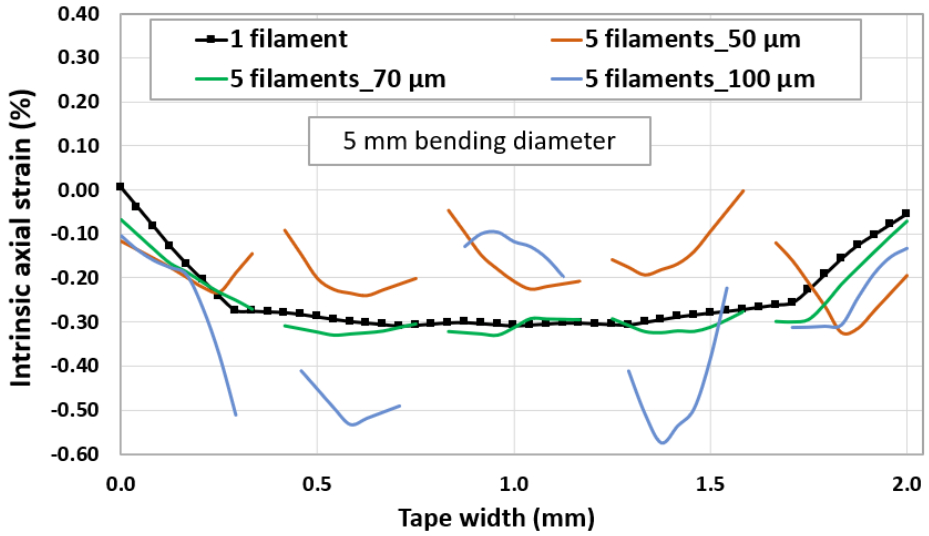
Variation of bending diameter



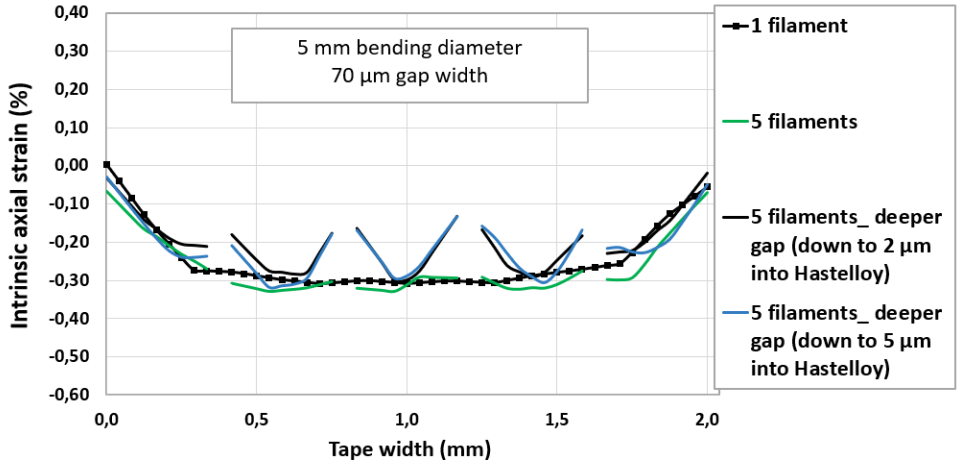
The effect of overetching



Variation of filament width

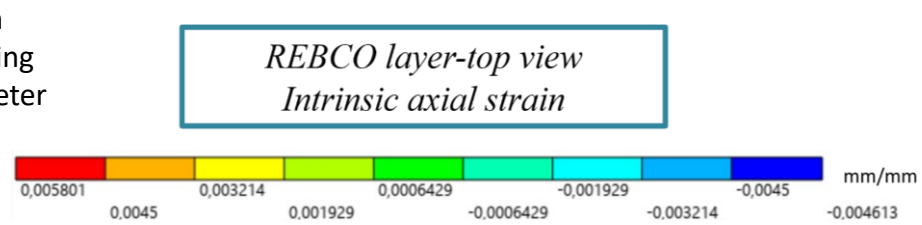


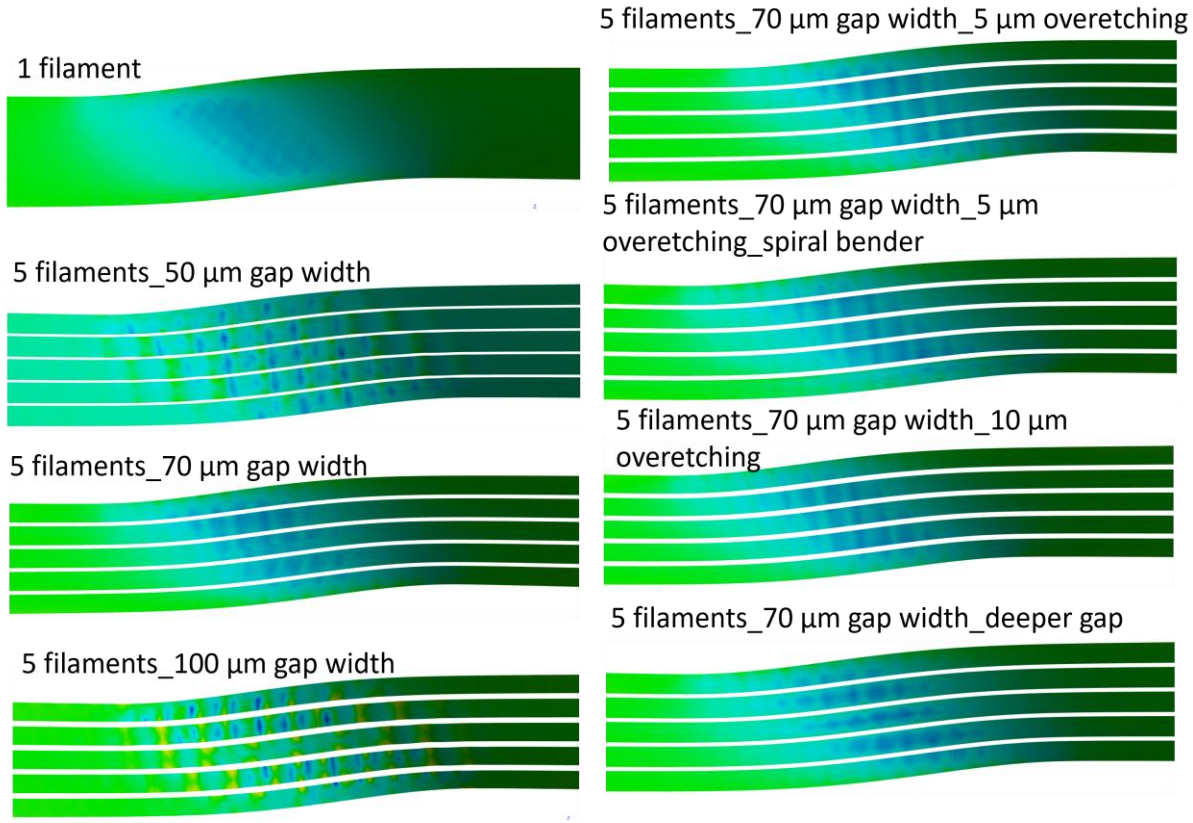
The effect of gap depth

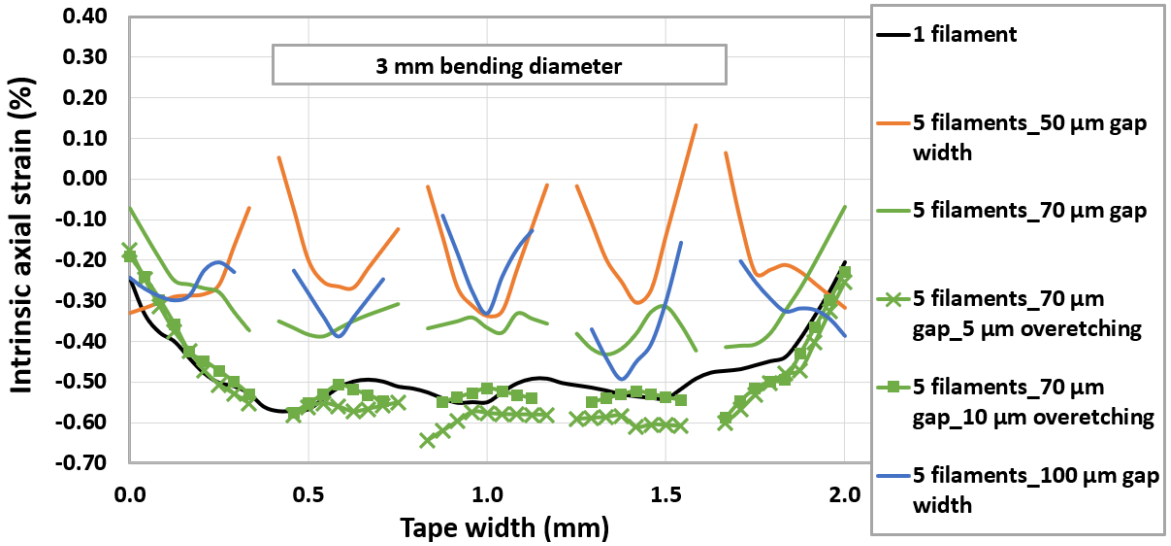


4. Bending of striated CC tapes - FE analysis

5 mm bending diameter

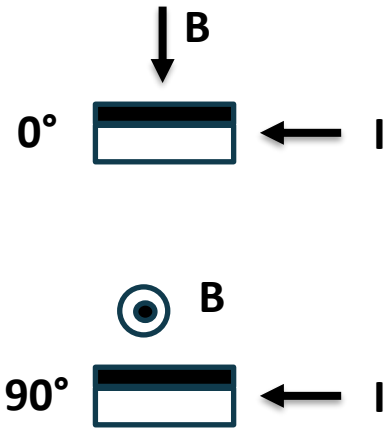


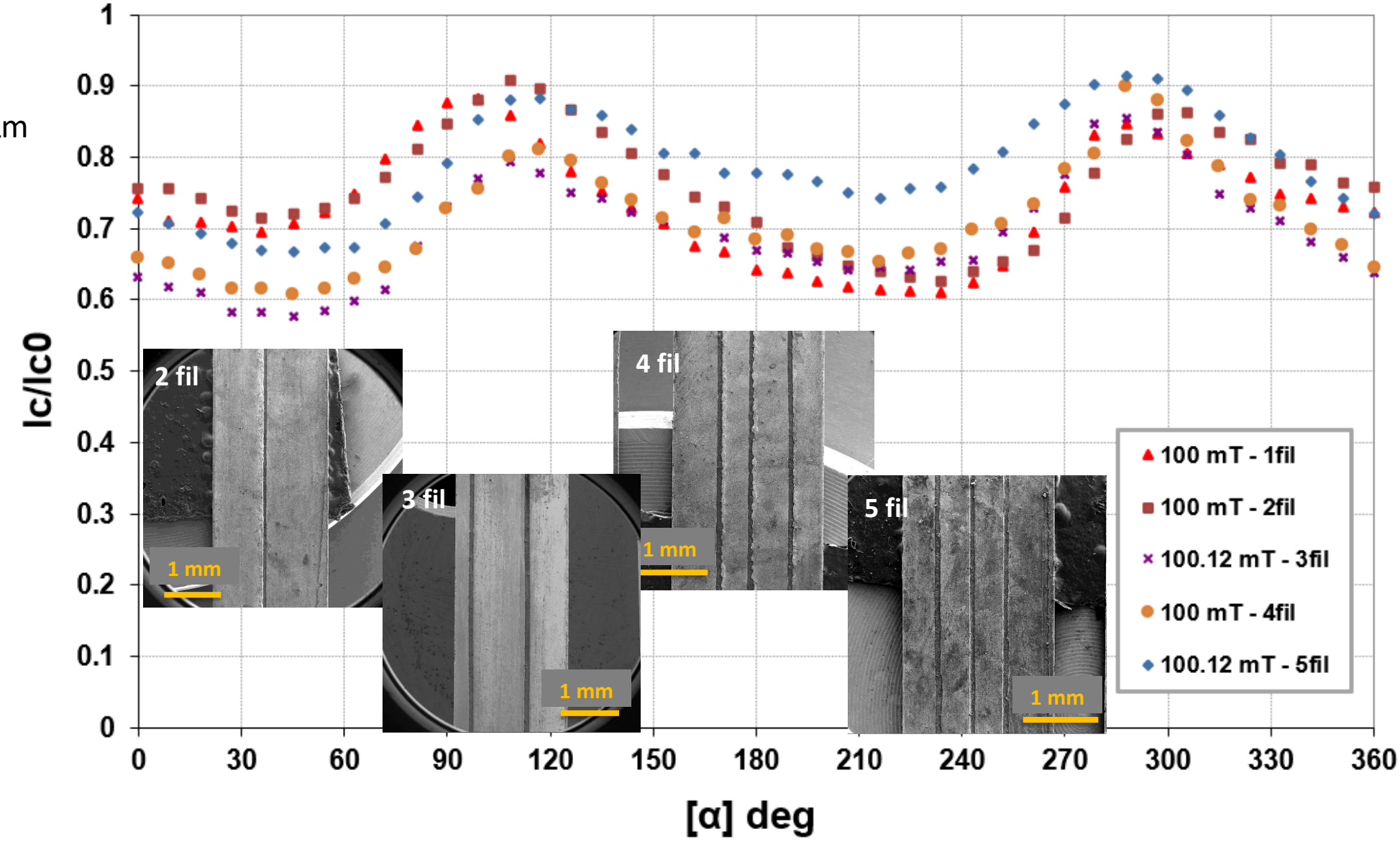




5. I_c (B, alpha) measurements

Width of the gaps: 70 µm





CONCLUSION

AC losses measurements - tapes

- Good reproducibility of the CH-M striating without frequency dependence was demonstrated by the measurements of AC losses. Finding balances between AC losses reduction and I_c reduction is essential.

Bending of striated CC tapes - experiments

- Striated tapes with narrower gaps between each individual REBCO filaments remained without significant I_c reduction to a bending diameter of 2 mm,
- Non-striated tape started to degradate at larger diameter,
- No difference between spiral and tube bender.

SEM-FIB & ToF-ERDA measurements

- The width of the gaps (as well as the overetching) can be changed by varying the etching times,
- The mistmach between I_c absolute and I_c normalised caused by over-etching,
- Delamination and crack formation occurred in the REBCO layer,
- ERDA measurements allow us to precisely determine the depth and material at which we ended etching.

CONCLUSION

Bending of striated CC tapes - FE analysis

- FE analysis of tape bending have shown that overetching does not have a fundamental effect on the strain state of the REBCO superconductor,
- Alternatively, the strain state of the superconductor was more adversely affected by the gap depth and width,
- These interesting preliminary results force us to continue a deeper study of this issue in order to confirm the correctness of the models with experiments.

Thank you for your attention

Acknowledgment

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