Towards energy efficient accelerator magnets: Development of commercial large-scale production of filamentary HTS tapes

A status for the Eurostars project: Filaments 4 Fusion

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Outline

- Introduction to SUBRA
- Motivation for making wrapped & multifilamentized REBCO tapes
- The Filaments 4 Fusion project – towards fast-ramped high field magnets
- Present project status
- Summary & outlook

At SUBRA, we are…

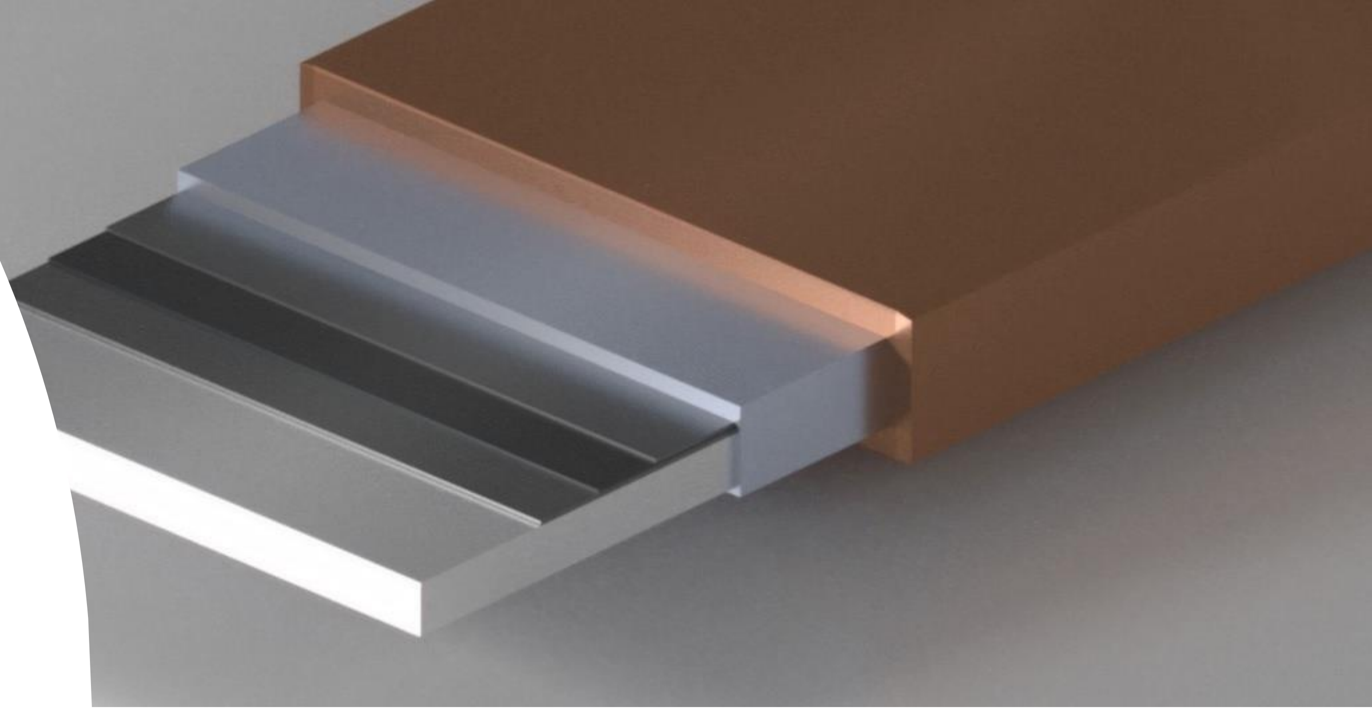
SCIENCE-BASED DEEP-TECH STARTUP
Pioneering the field of superconductivity.

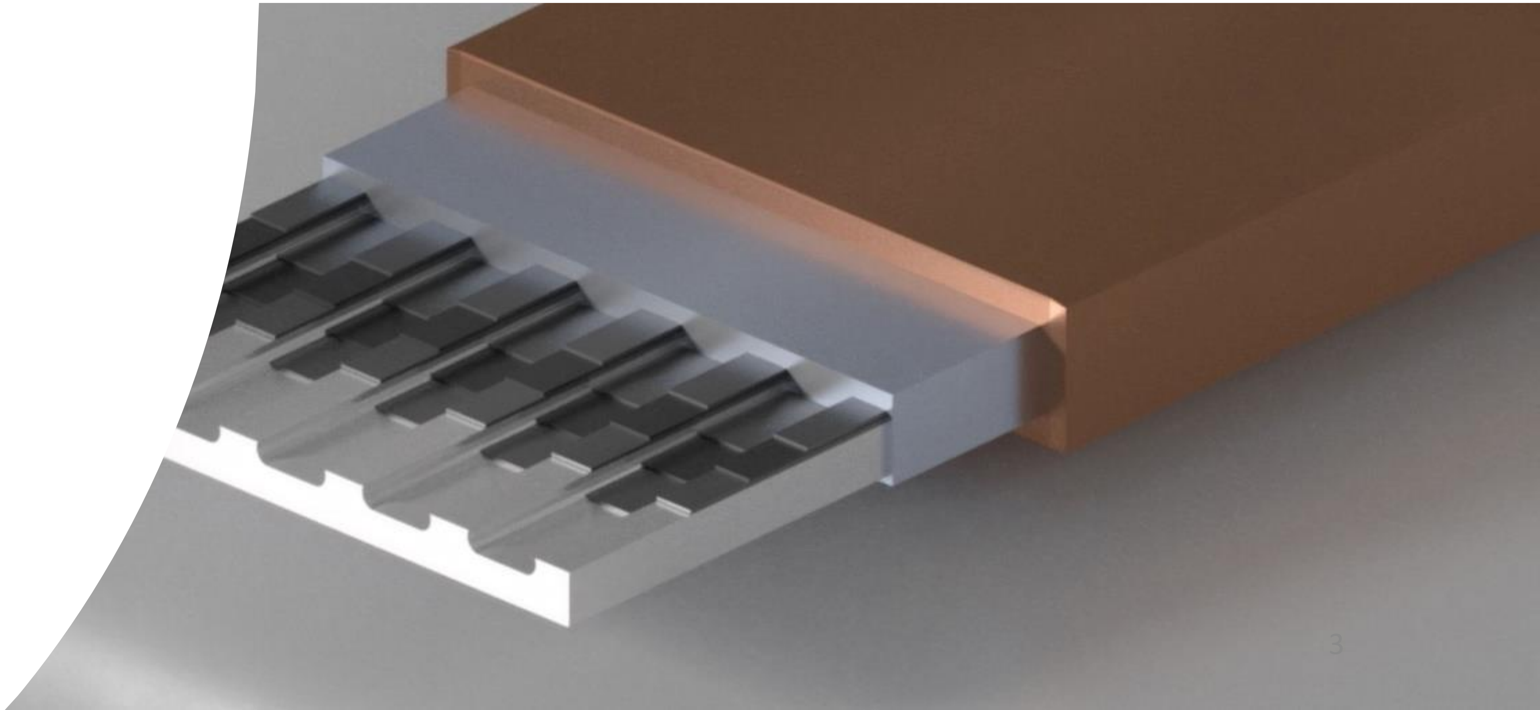
SPIN-OFF FROM DTU ENERGY
With more than 15 years of excellency in superconductor R&D.

ON A MISSION
To “Transform the way we transport electricity”.

STRONGLY COMMITTED
To a sustainable future and to being a key player in the Climate Solution.

GROWING
1000 m^2 of production + R&D facility and 25+ skilled engineers, scientist, technicians and operators.





THERE'S NO GREEN TRANSITION…

…without transforming the way, we transport electricity

CABLES
POWER TRANSMISSION

FUSION
ENERGY PRODUCTION

POWER2X
ENERGY STORAGE

European Innovation Council

European Innovation Council (EIC) established by the European Commission, under the Horizon Europe programme (2021-27)

eurostars™

HORIZON EUROPE

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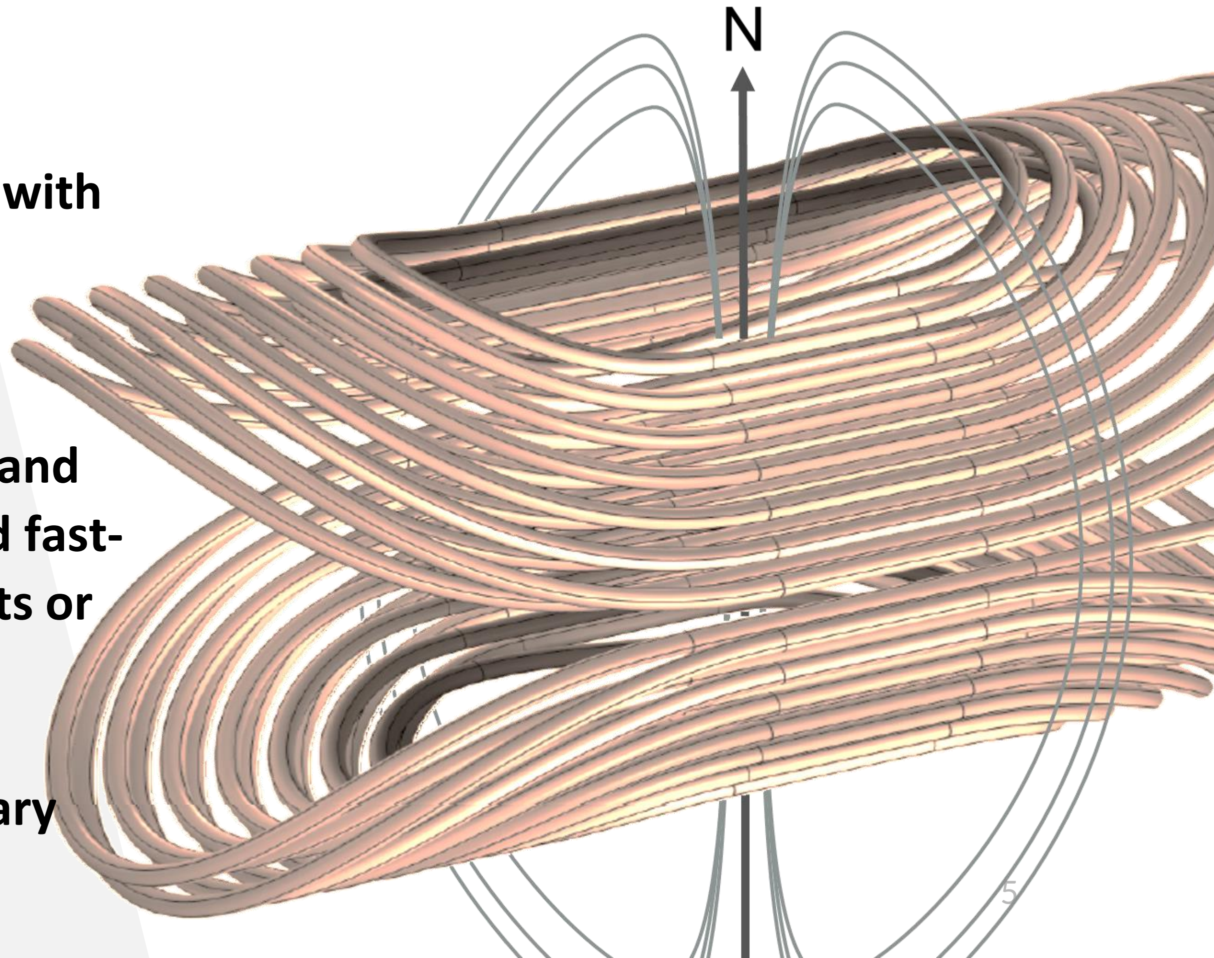
Accelerator magnets or fusion magnets:
- Towards energy efficient magnets

Eurostars Filaments 4 Fusion project goal:
DEMONSTRATE LOW-COST AND LARGE SCALABLE COMMERCIAL PRODUCTION OF MULTIFILAMENTARY REBCO TAPES

- Combine SUBRAs 3D-profile substrate technology with THEVAs Inclined Substrate Deposition and REBCO coatings
- Optimize multifilamentary design w.r.t. AC losses and mechanical stability for operation in high-field and fast-ramped magnets (+10 T/s) e.g. accelerator magnets or fusion tokamak magnets
- Demonstrate +400 m fabrication of multifilamentary REBCO tapes



Why do we need wrapped & filamentized REBCO tape?
- to reduce AC losses in the magnet cable

$Q_{total} = Q_{coupling} + Q_{hysteretic} + Q_{eddy}$

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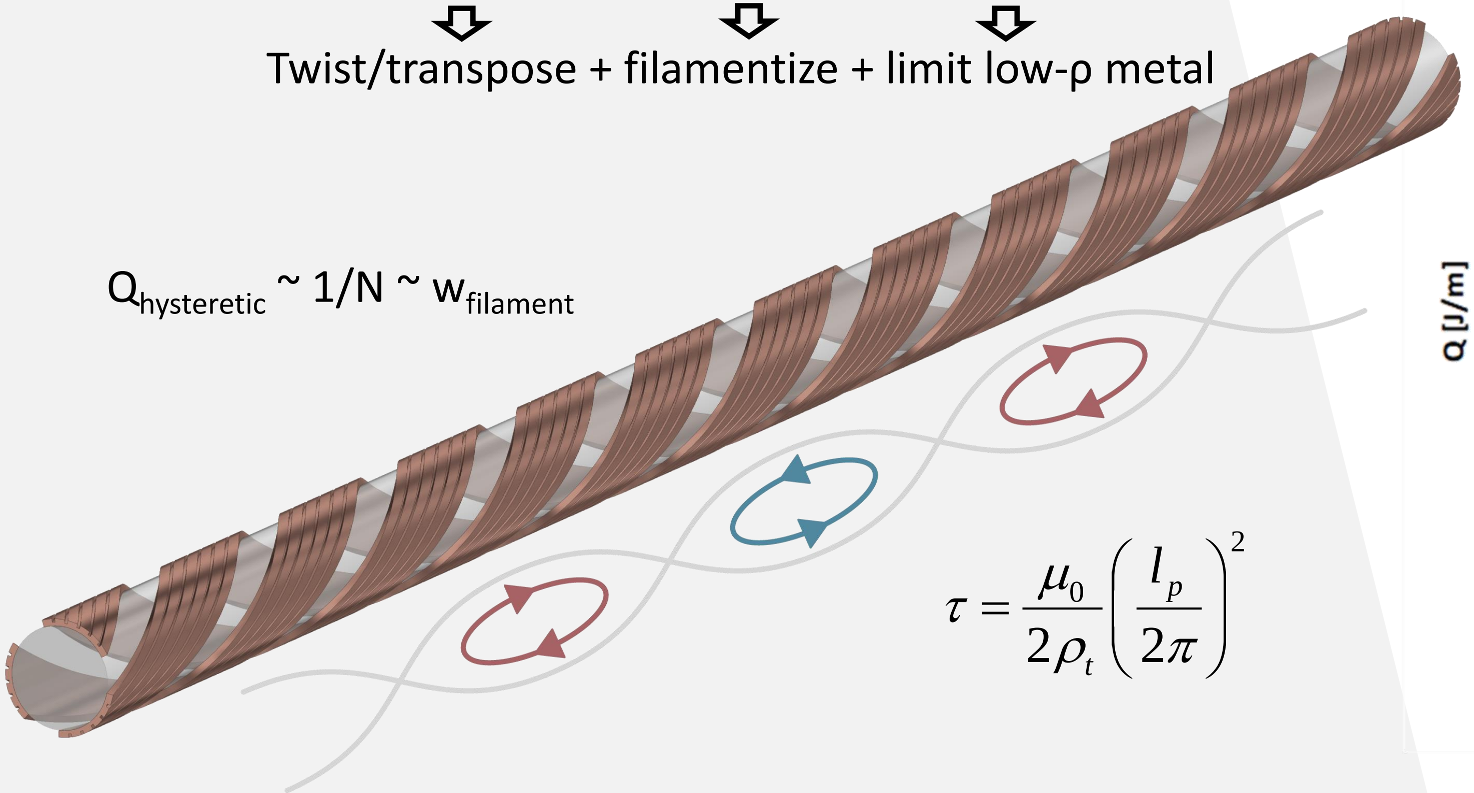
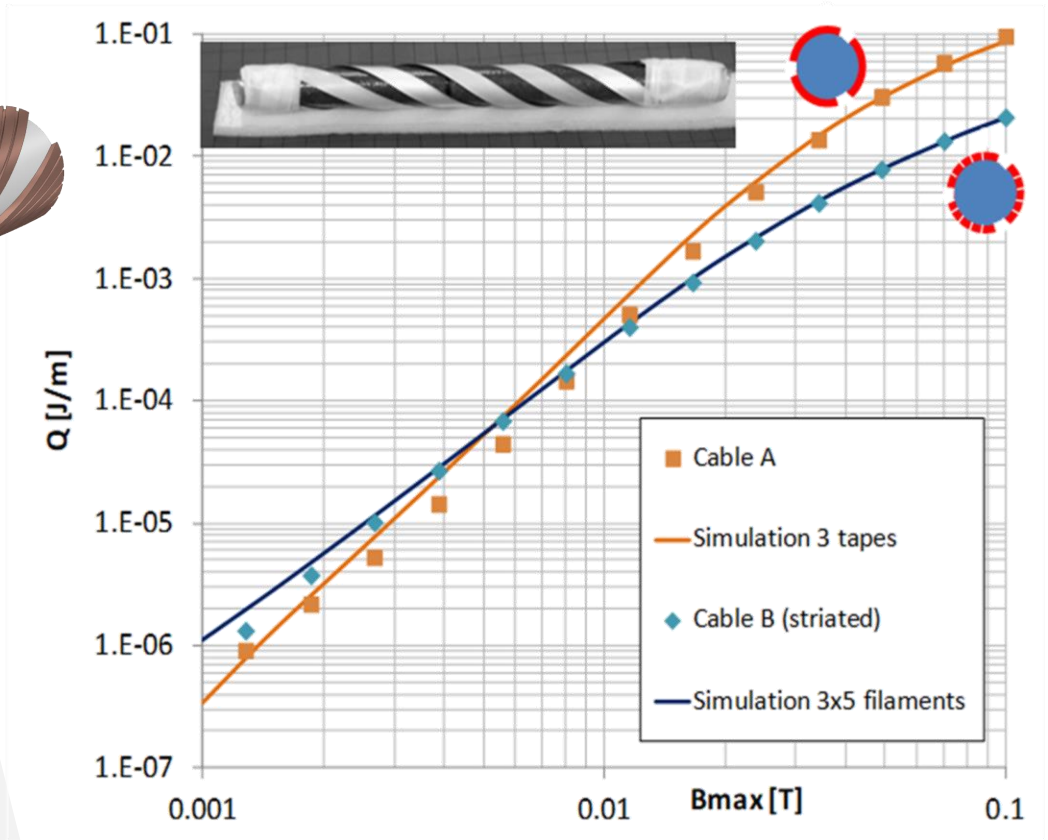
Twist/transpose + filamentize + limit low-ρ metal

$Q_{hysteretic} \sim 1/N \sim w_{filament}$



$$\tau = \frac{\mu_0}{2\rho_t}\left(\frac{l_p}{2\pi}\right)^2$$

Wulff et al., Supercond. Sci. Technol. **34** (2021) 053003 (29pp)



J. Šouc et al. Supercond. Sci Technol. 26 (2013) 075020

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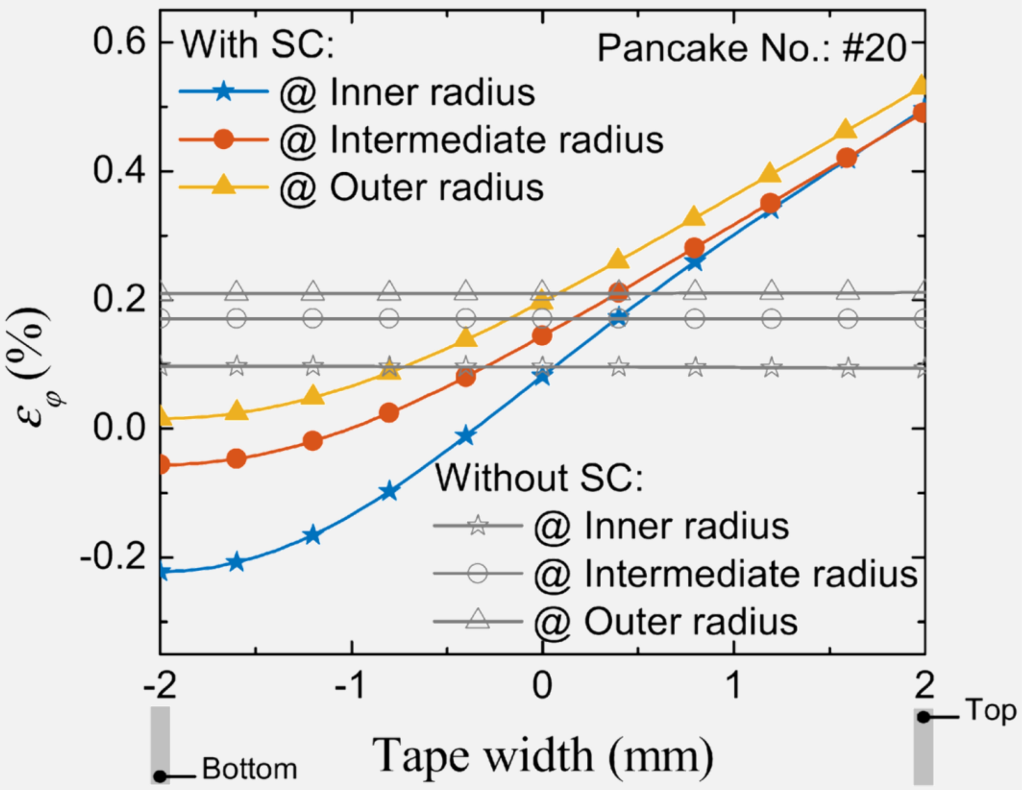
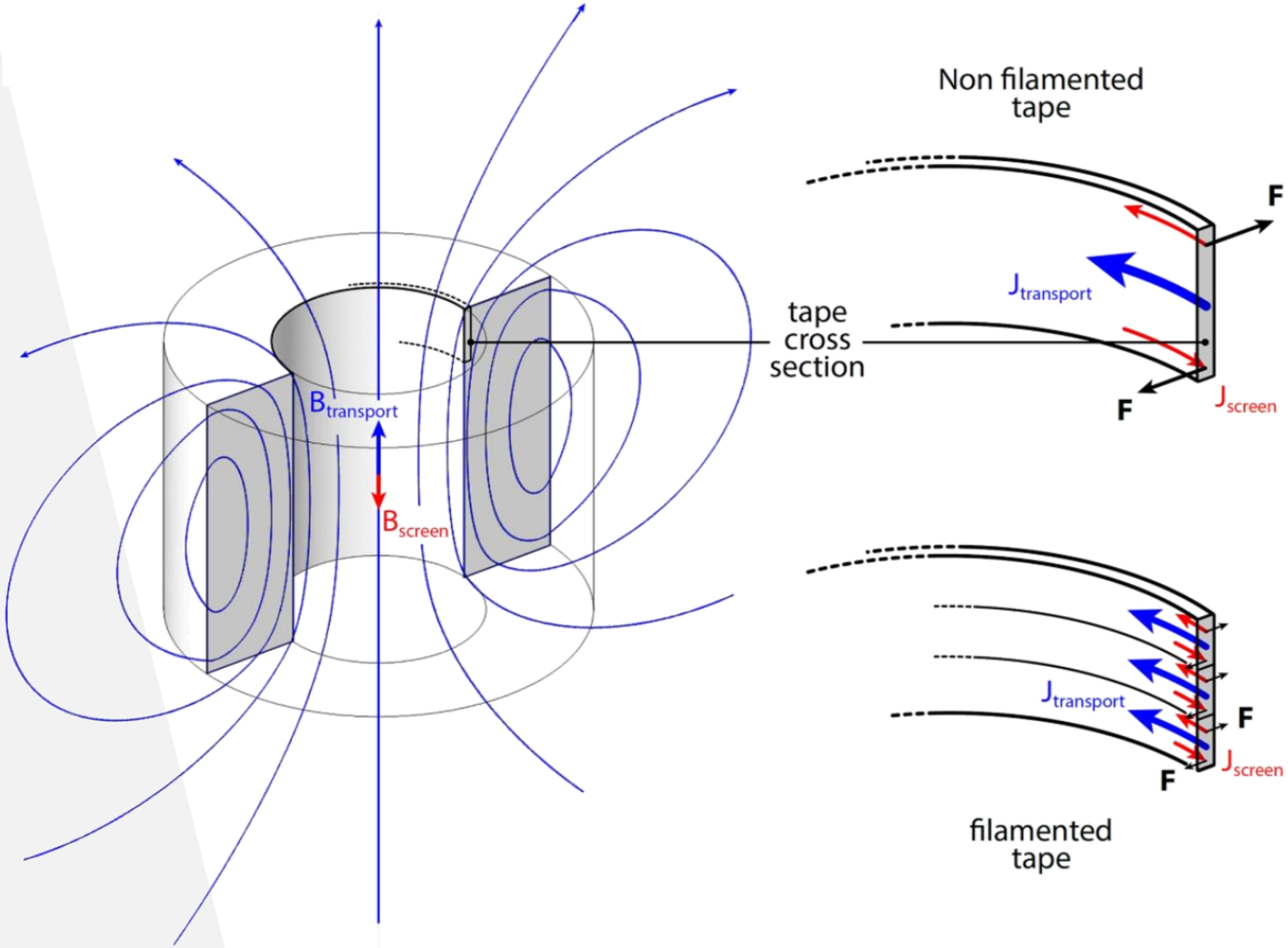
Why do we need wrapped & filamentized REBCO tape?
- reduce screening current induced twist-strain on tape

Lorentz force due to screening currents:

$\mathbf{f}_L = \mathbf{J}\times\mathbf{B} = f_r\mathbf{i}_r + f_z\mathbf{k} = J_\vartheta B_z \mathbf{i}_r - J_\vartheta B_r \mathbf{k}$



Jing Xia *et al* 2019 *Supercond. Sci. Technol.* **32** 095005



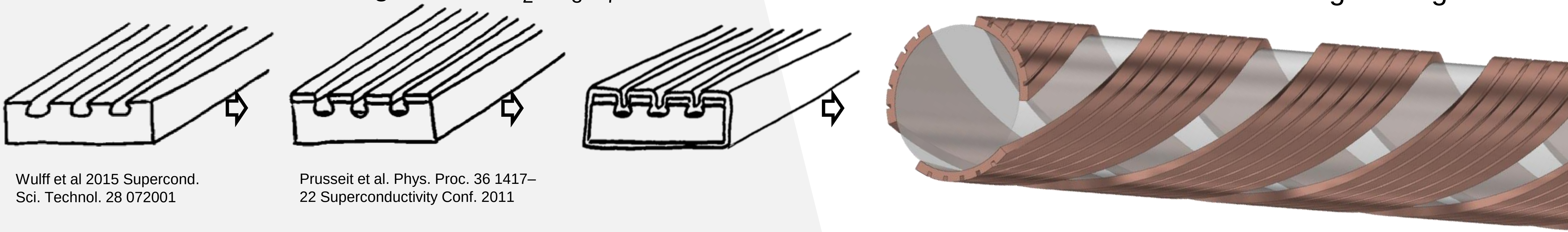
Wulff et al., Supercond. Sci. Technol. **34** (2021) 053003 (29pp)

As stated by Kolb-Bond in 2020: ”Screening current induced strains have historically been ignored”

Filamentized REBCO tape wound on a cylindrical former

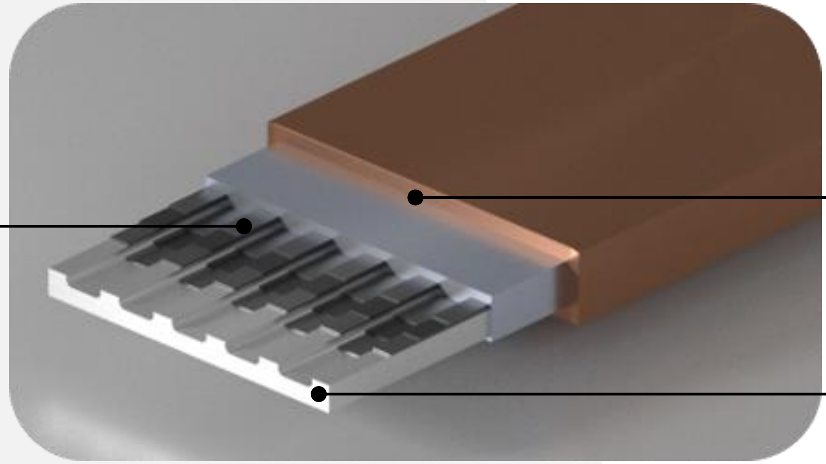
All tape fabrication steps are scalable reel-to-reel processes

3D substrate | ISD/MgO + $GdBa_2Cu_3O_7$ | Metallization | CORT winding/cabling



Wulff et al 2015 Supercond. Sci. Technol. 28 072001

Prusseit et al. Phys. Proc. 36 1417–22 Superconductivity Conf. 2011



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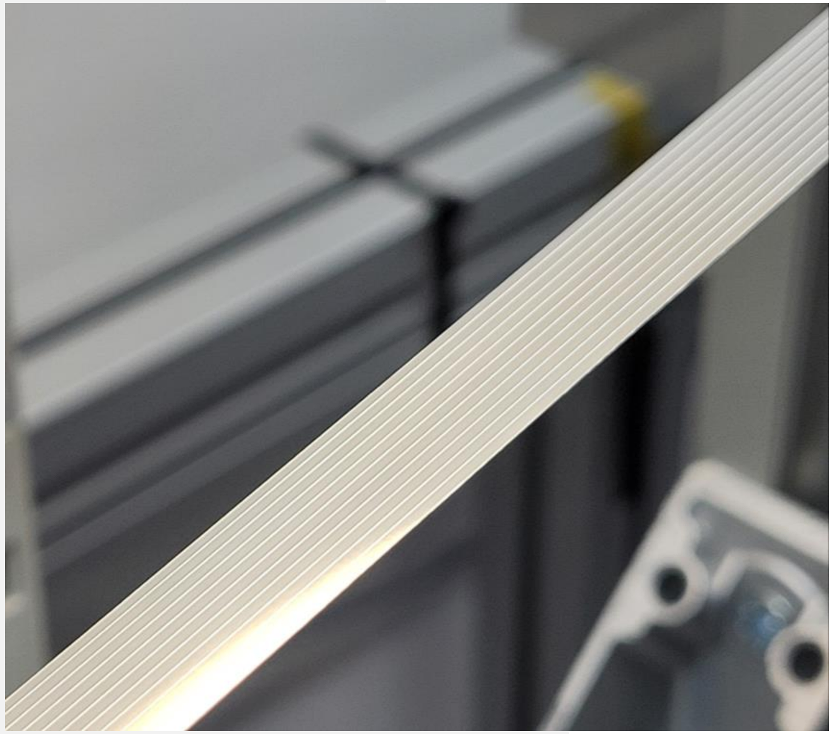
WP3: Test batches (>50 m) completed
WP4: Test batch (+200 m) completed
WP5: Test batches (450 m) ongoing

500/100µm



1000/100µm

2000/100µm

12 MM WIDE, 25-200 m LONG, MULTIFILAMENTARY REBCO TAPES PRODUCED COMMERCIALLY USING LARGE SCALE MANUFACTURING

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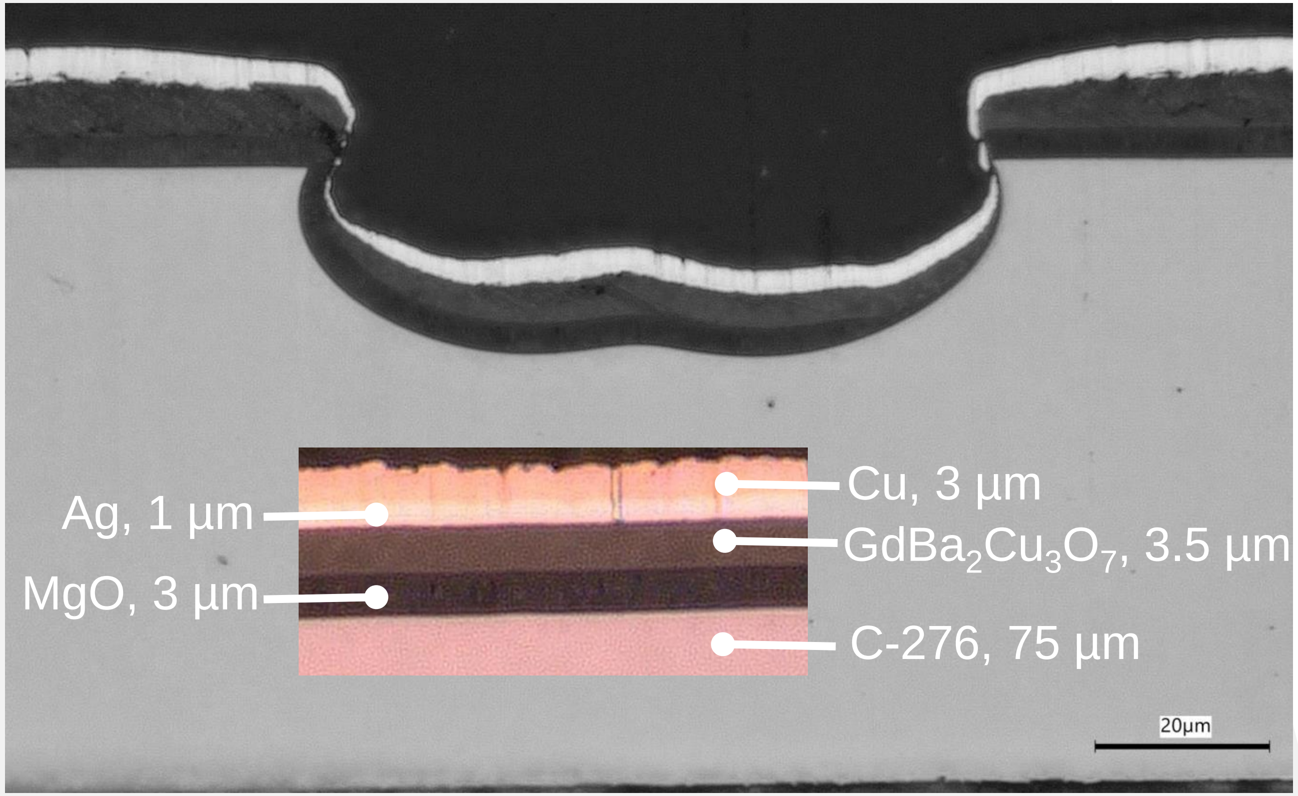
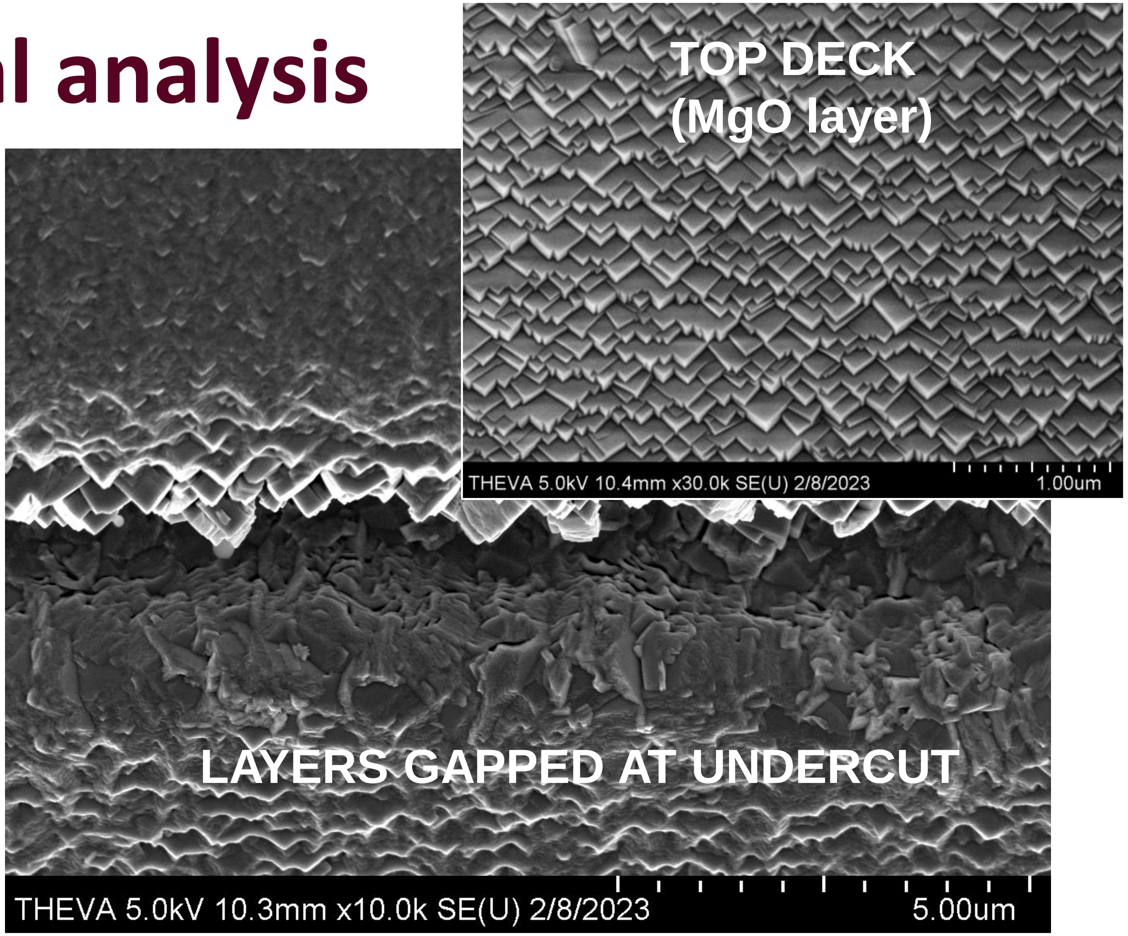
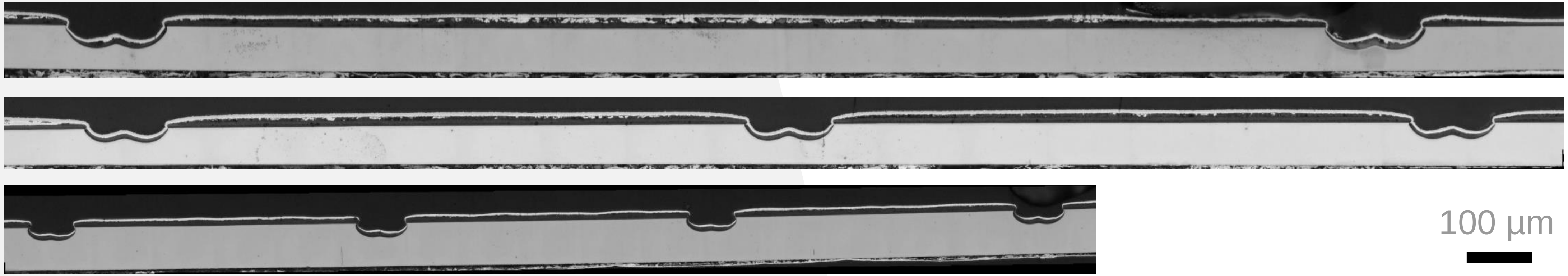
Cross-section and microstructural analysis



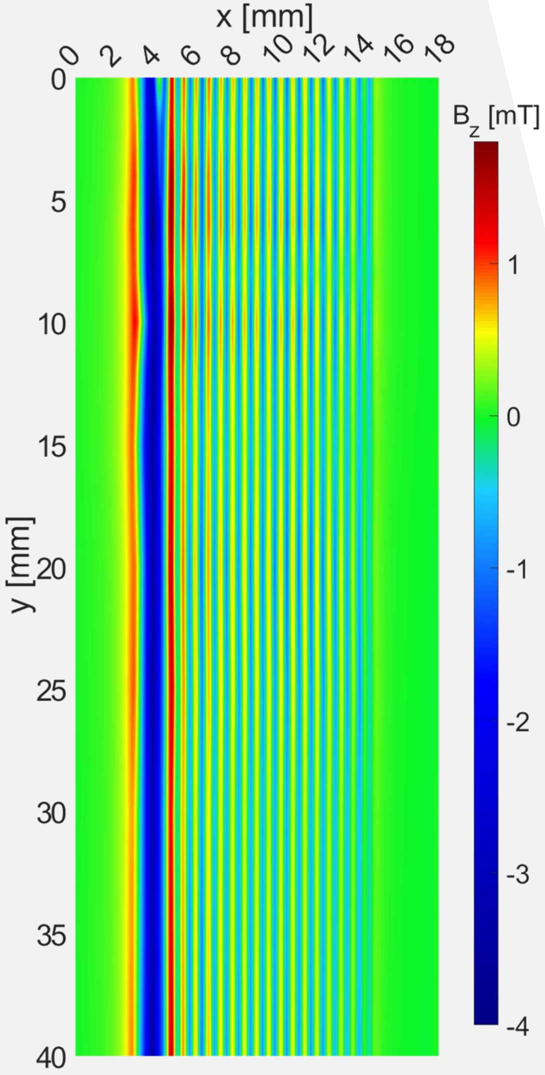


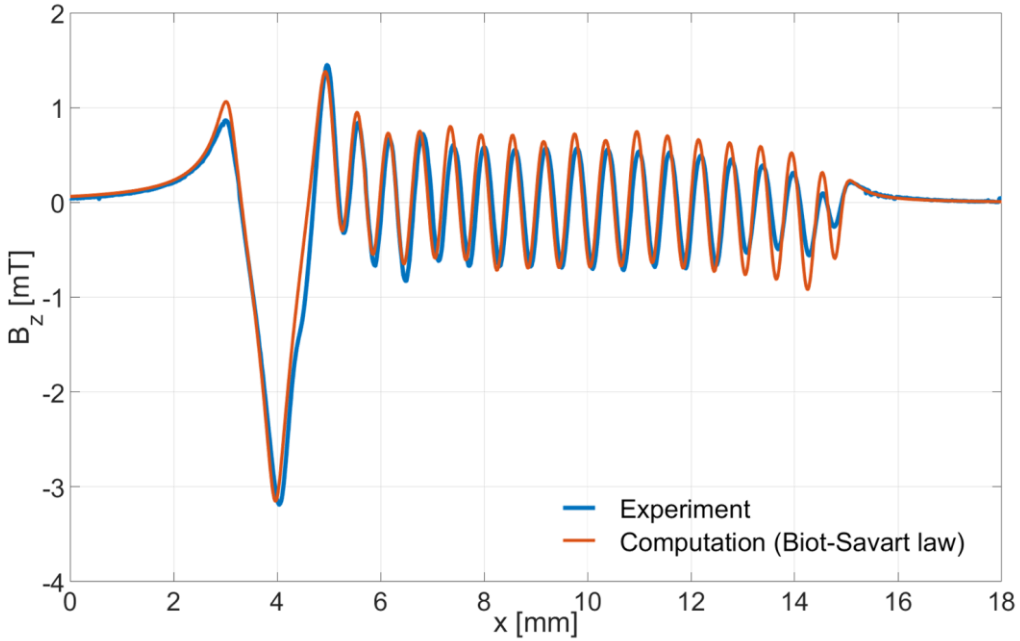


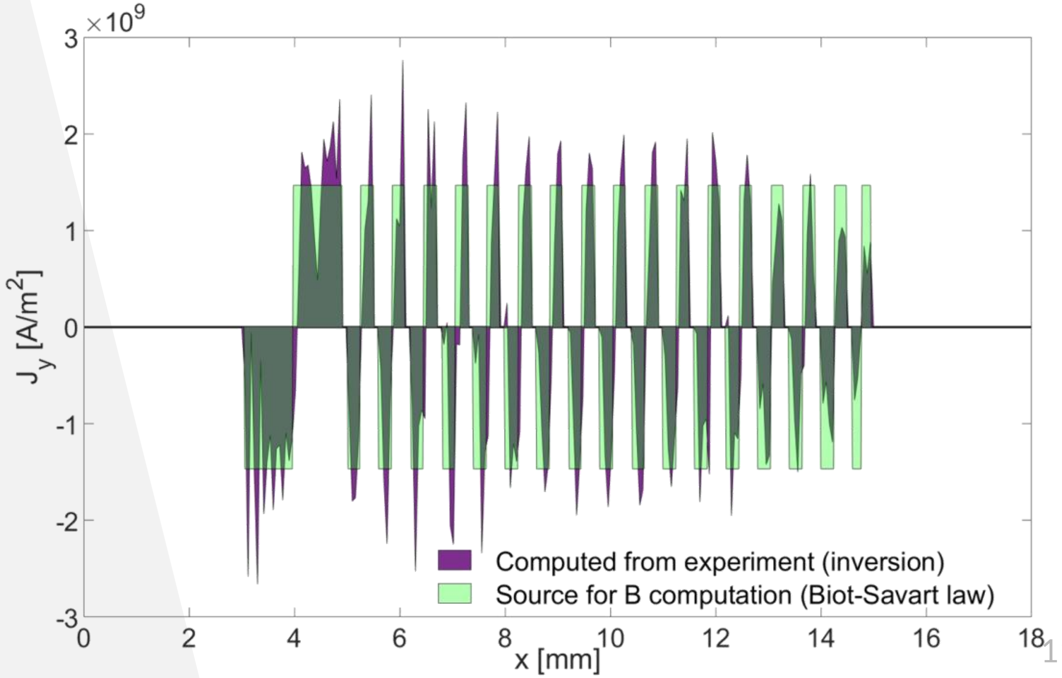
Hall scanning @ 77 K

In-field cooling at B_a = 90 mT (remnant magnetic field map)

- Hall scanning indicates good homogenity for central filaments
- Scan height is a major dominating parameter (z =0.15 mm)
- Current inversion approach requires special attention







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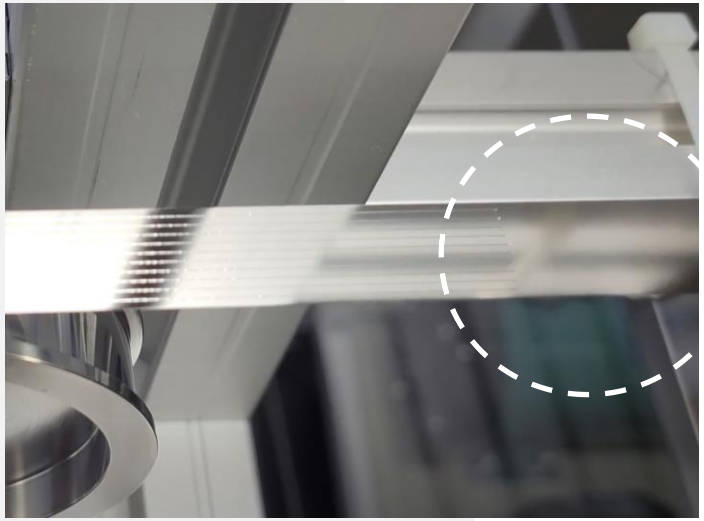
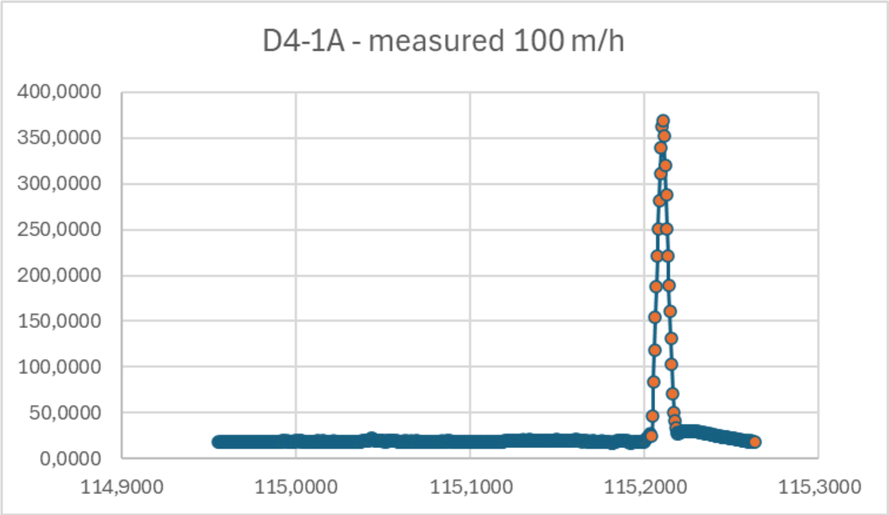
Tapestar^{TM} analysis – introducing bridges



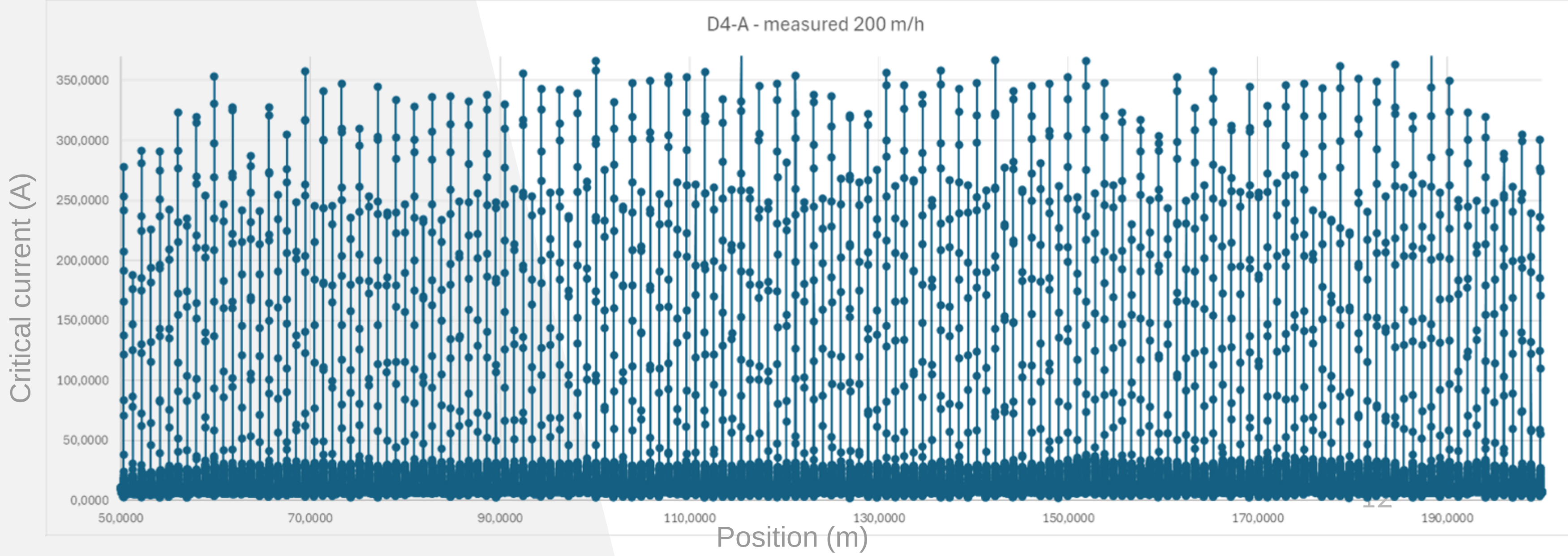


General findings

- Baseline Ic seems reasonable compared to ref-tape (~360 A)
- Difficult to characterize with Tapestar^{TM} below 1 mm filament width - for now (lower z)
- The HTS deposition was not yet run with calibration – ”*deposited as is*”

Introducing ‘bridges’ enables

- current sharing = stability
- ”a window” for Ic measurement via Tapestar reel-to-reel scanning



Breaking the limit of Weibull Statistics for 500/100 µm

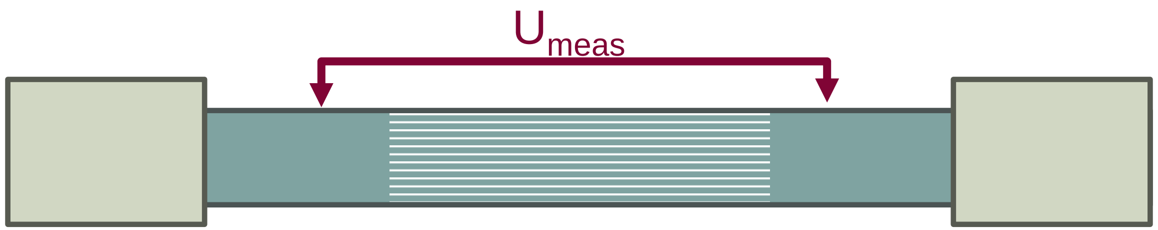
- Current is injected in non-filamentized lengths (measured I_c = 285-311 A) → all filaments see the same current at the front end.
- Reduction expected due to gap between filaments:

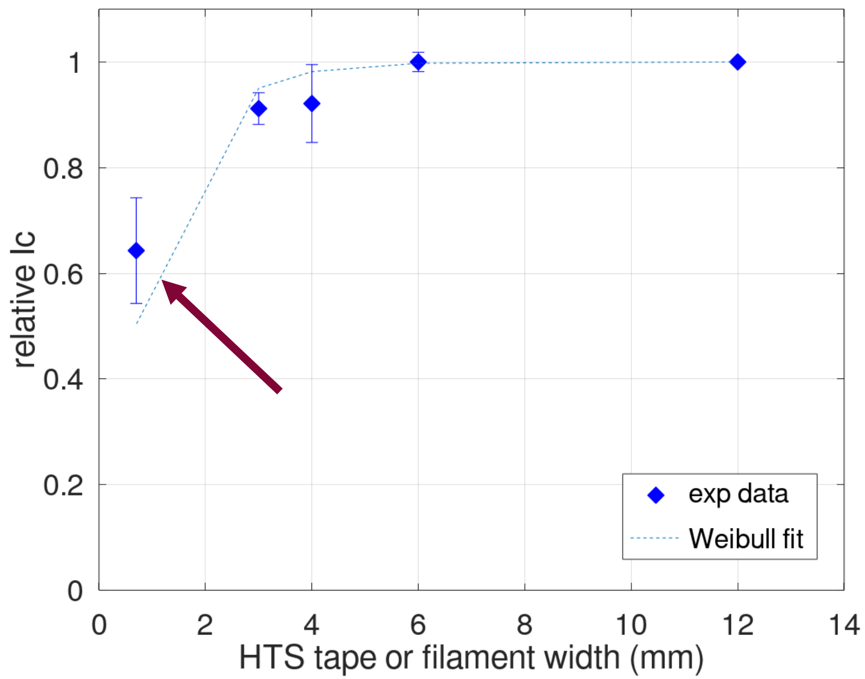
$$285\ \mathrm{A} \cdot \left(1 - \frac{100\ \mu\mathrm{m}}{500\ \mu\mathrm{m}}\right) = 228\ \mathrm{A}$$

- The above does not take into account statistical lowering of I_c due to fabrication errors = Weibull statistics.
- With Weibull statistics the current should be 65% of full 12 mm width I_c → 150 A.
- Seven samples measured, averages showed:

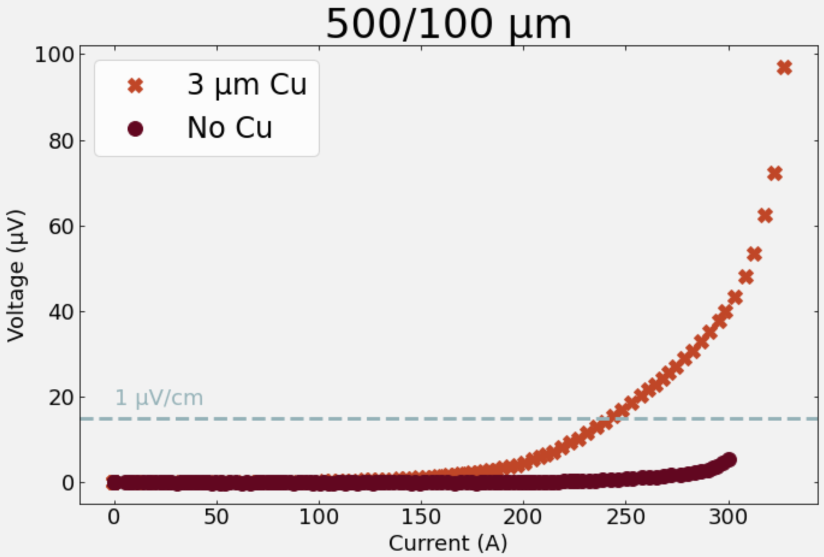
I_c = 229 A	n = 16

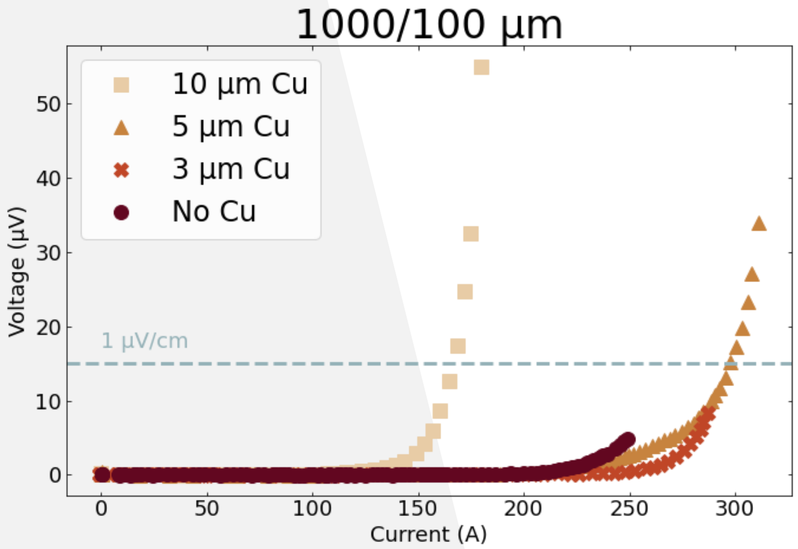
Lowering of I_c due to filament size – not performance loss.

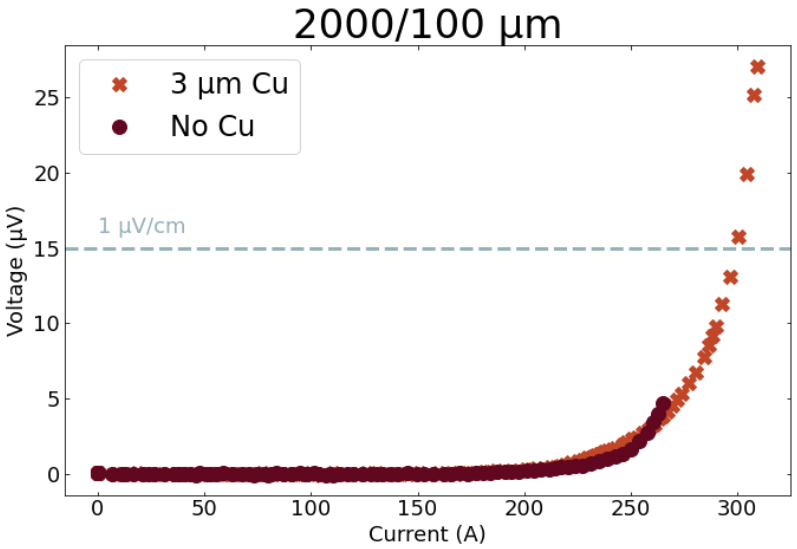


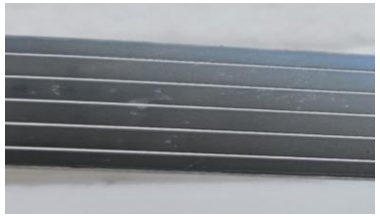


I/V analysis @ 77 K (25-50 m samples)









- I/V values indicate higher level than obtained from Tapestar™
- 3 µm copper greatly improves stability and handling (multiple ramping)
- HTS layer has not been optimized yet

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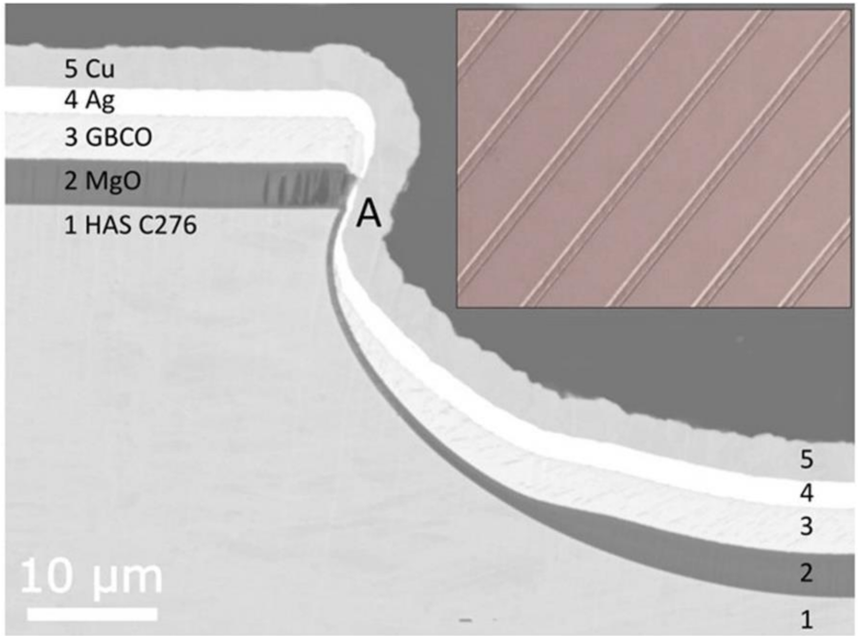
Cable results:

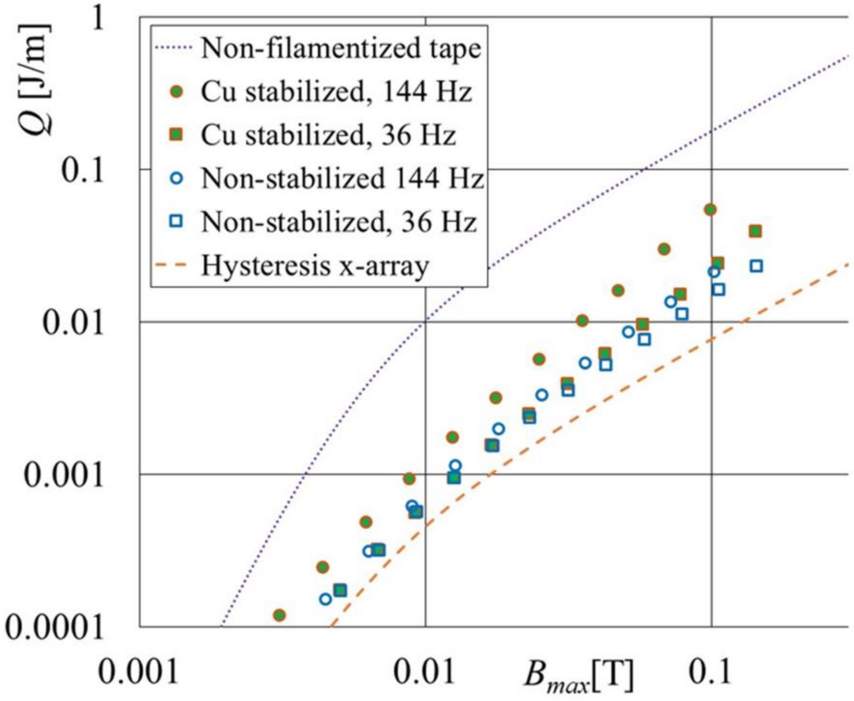
Conductor on Round Tube cable test (single layer tape) made from:

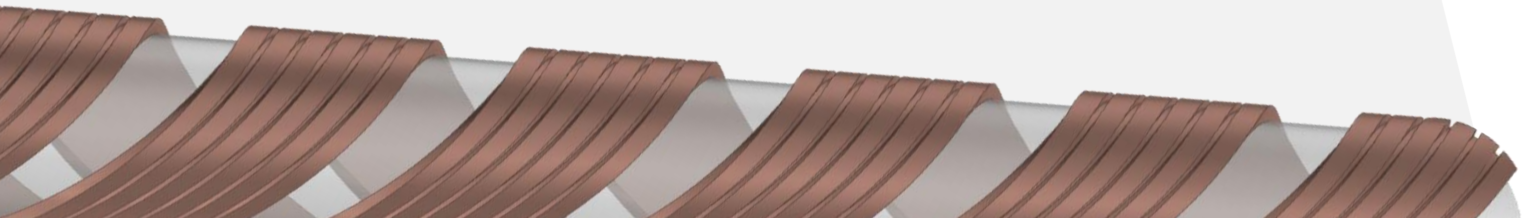
- HTS tape commercially produced using large-scale reel-to-reel systems
- Copper stabilized (5-10 µm)
- CORT cable samples contained 230 mm of 12 mm wide tape with 19 filaments helically laid with the angle of 67^{o} on a Ø10 mm non-conducting tube.
- Test: 36 Hz, 100 mT, equivalent to the field change at the rate of ~14 T/s

The loss in the round cable from filamentized tape is <u>one order of magnitude lower</u> than for the non-filamentized

Gömöry et al. IEEE TRANSACTIONS ON APPLIED SUPERCONDUCTIVITY, VOL. 34, NO. 5, AUGUST 2024







Summary & outlook

- Successful initial validation of combining 3D-profile substrate + ISD/MgO-HTS/REBCO

- Demonstrated of low cost and large-scale manufacturing

- 25-200 m test samples w. acceptable performance level
  Next: 400 m sample qualification

- Commercial (400 m) ordering expected ready by Q3.2024

Thank you for your attention!