I E E S A S INSTITUTE OF ELECTRICAL ENGINEERING SAS

Computing Hysteresis and Coupling AC Losses in Round High-Temperature Superconductor Cable

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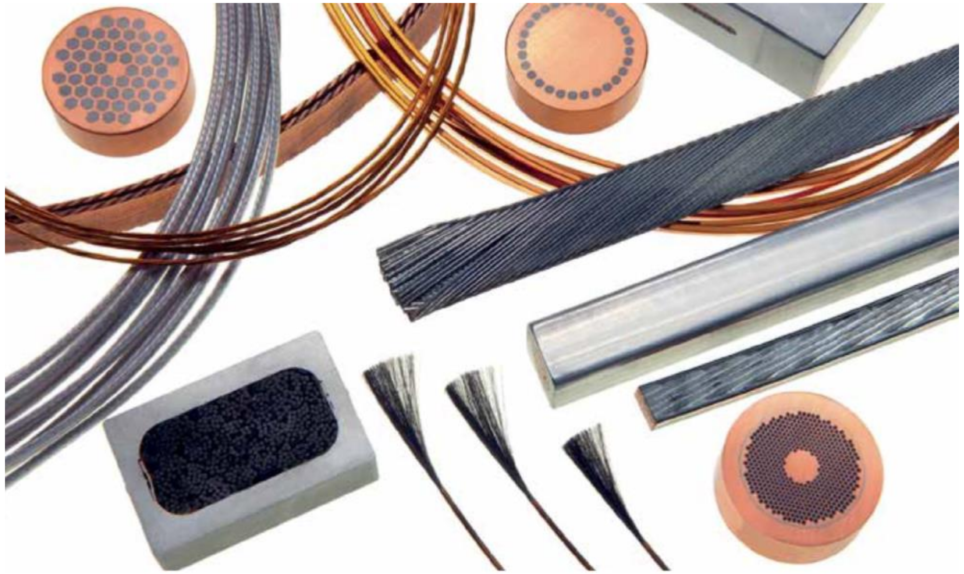
Superconducting wires

Low T_c superconductors:



https://www.luvata.com

High T_c superconductors (gen. II tapes):

https://www.theva.de

600 amps of traditional copper cable vs. the equivalent of 600 amps of High-Temperature Superconducting Wire, Photo: MetOx 2024

https://www.metoxtech.com/superconductors-101

Superconducting cables

ITER TF conductor

ITER CS conductor

Stored magnetic energy of 6.4 GJ in the central solenoid will initiate and sustain a plasma current of 15 MA for durations of 300-500 seconds. Maximum field of 13 tesla will be reached in the center of the stacked modules, making the central solenoid the most powerful of all ITER magnet systems.

https://www.iter.org/machine/magnets

https://nationalmaglab.org/magnet-development/applied-superconductivity-center/image-gallery/nb3sn-image-gallery/

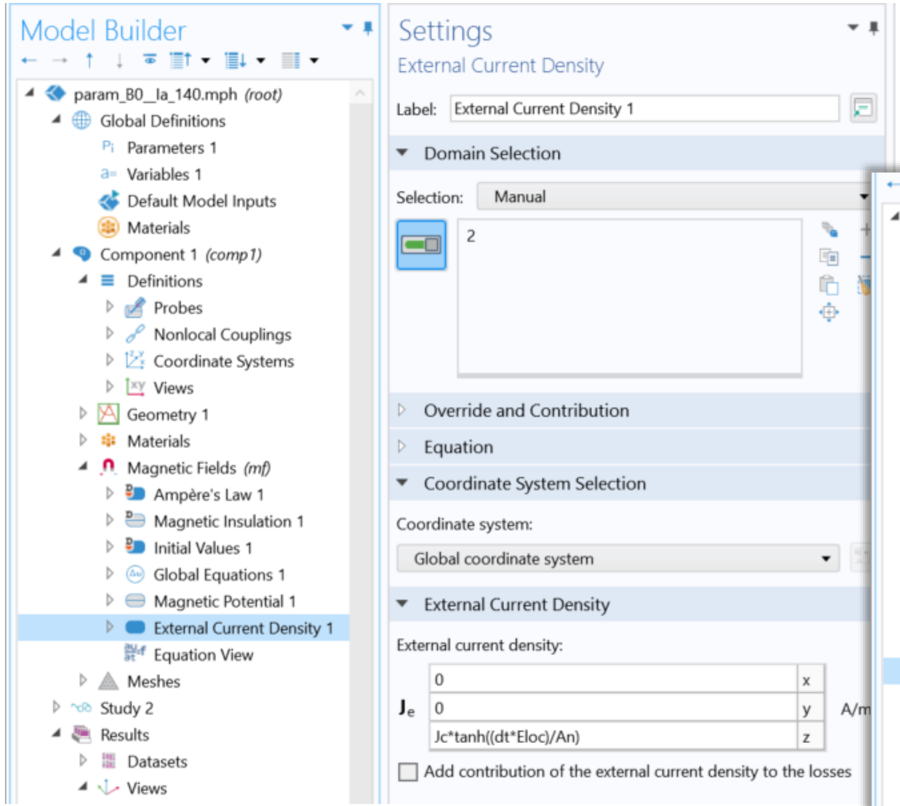
10 T, 60 kA range HTS cable

High Luminosity LHC Project

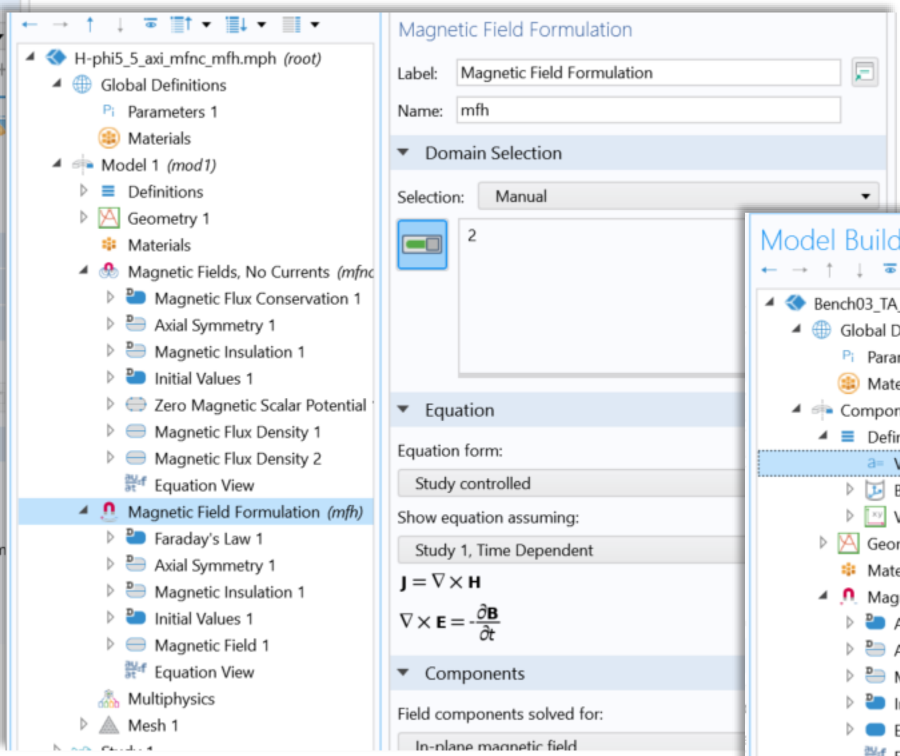
https://hilumilhc.web.cern.ch/article/completion-hts-rebco-cables

Superconductor's modelling in various formulations using the predefined physics

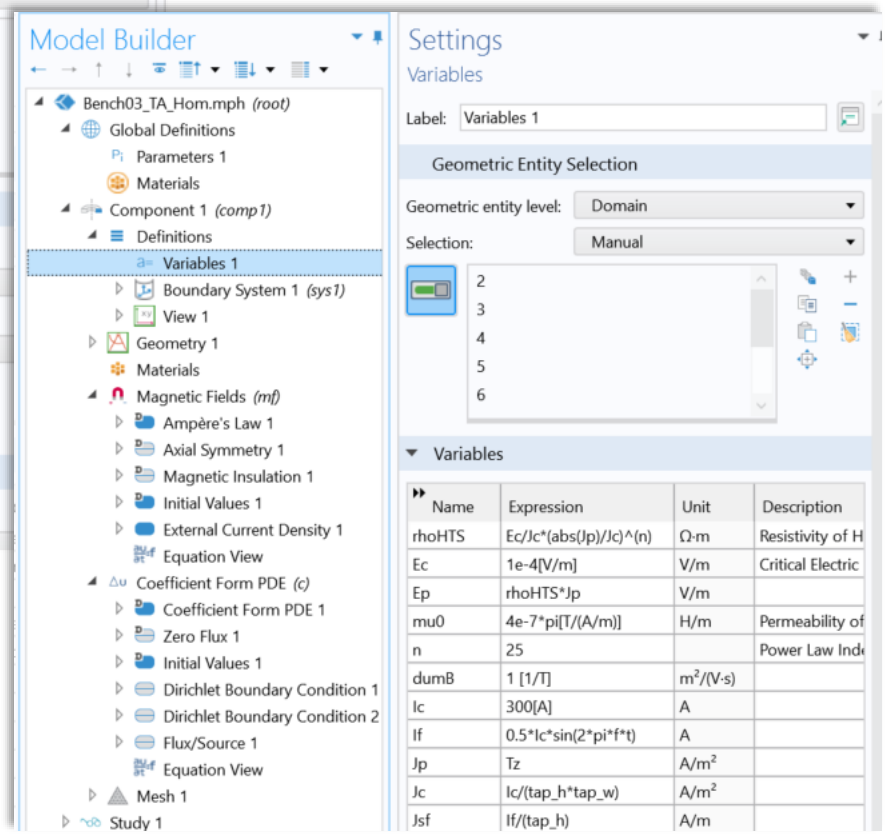
A-formulation



H-formulation

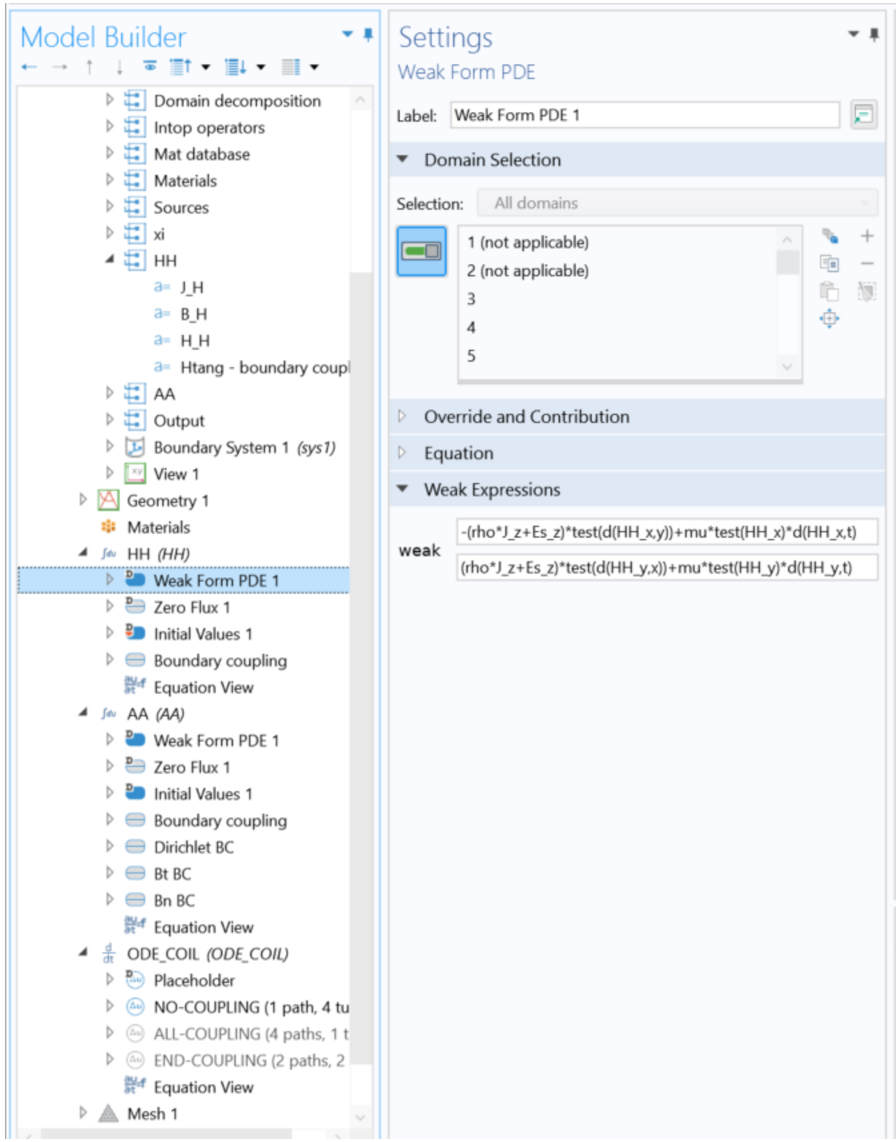


H-A-formulation

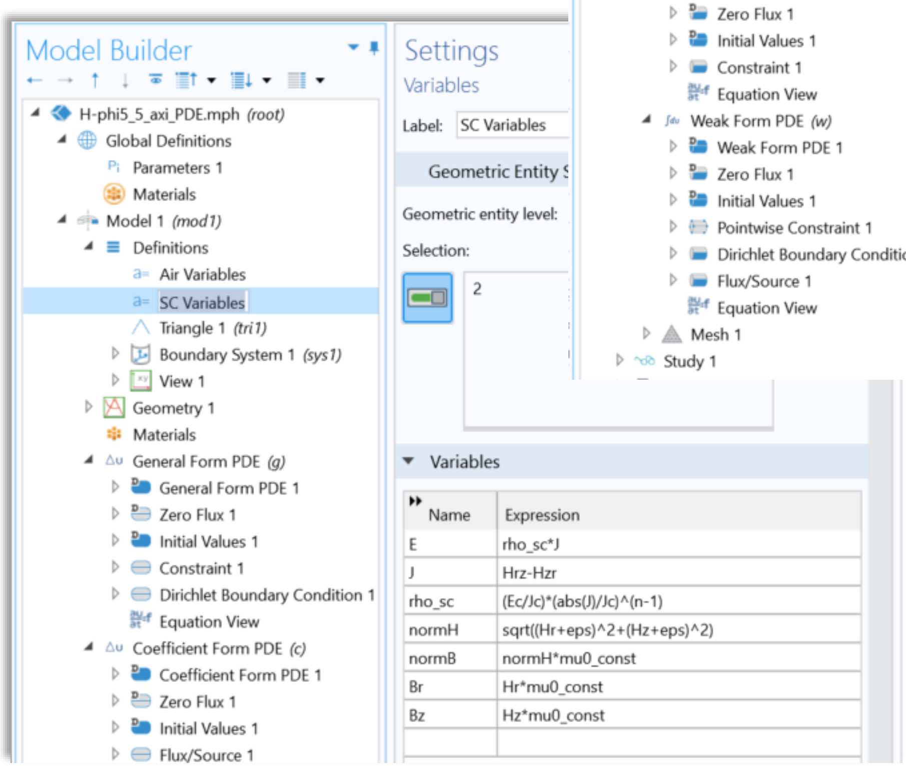


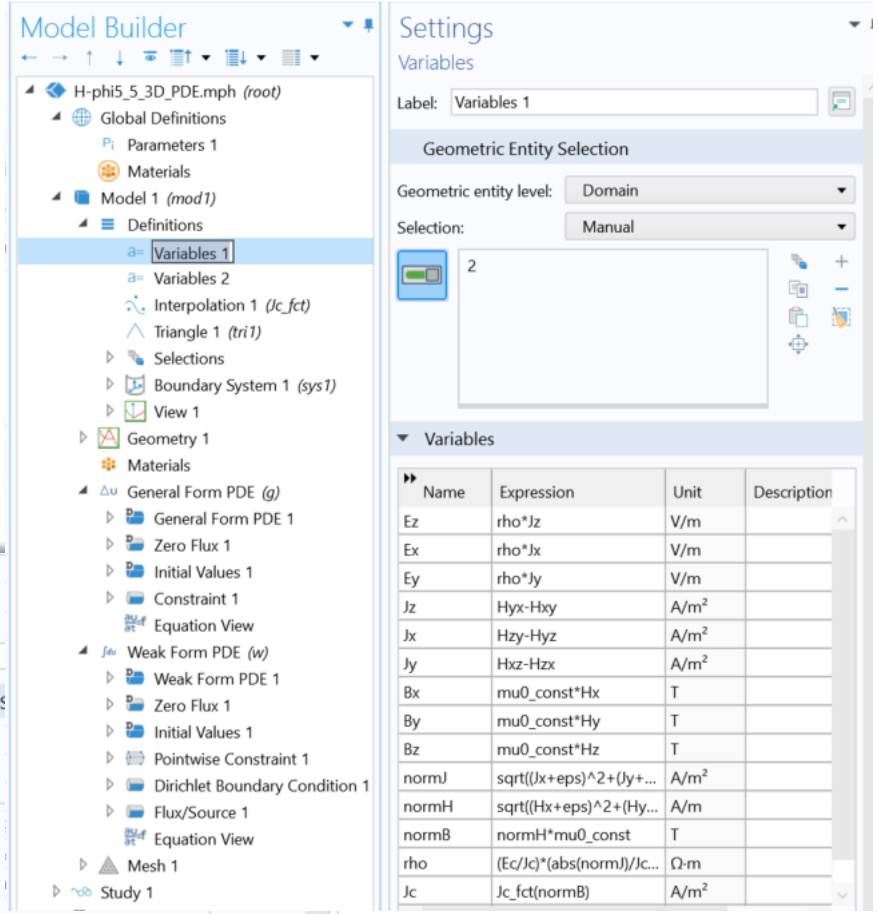
Superconductor's modelling in various formulations using the basic COMSOL capability

T-Ω-formulation



H-ϕ-formulation





A-formulation for time domain in Comsol Multiphysics™ (AC/DC module)

Maxwell equation for time domain: $$\vec{E} = -\frac{\partial \vec{A}}{\partial t}$$

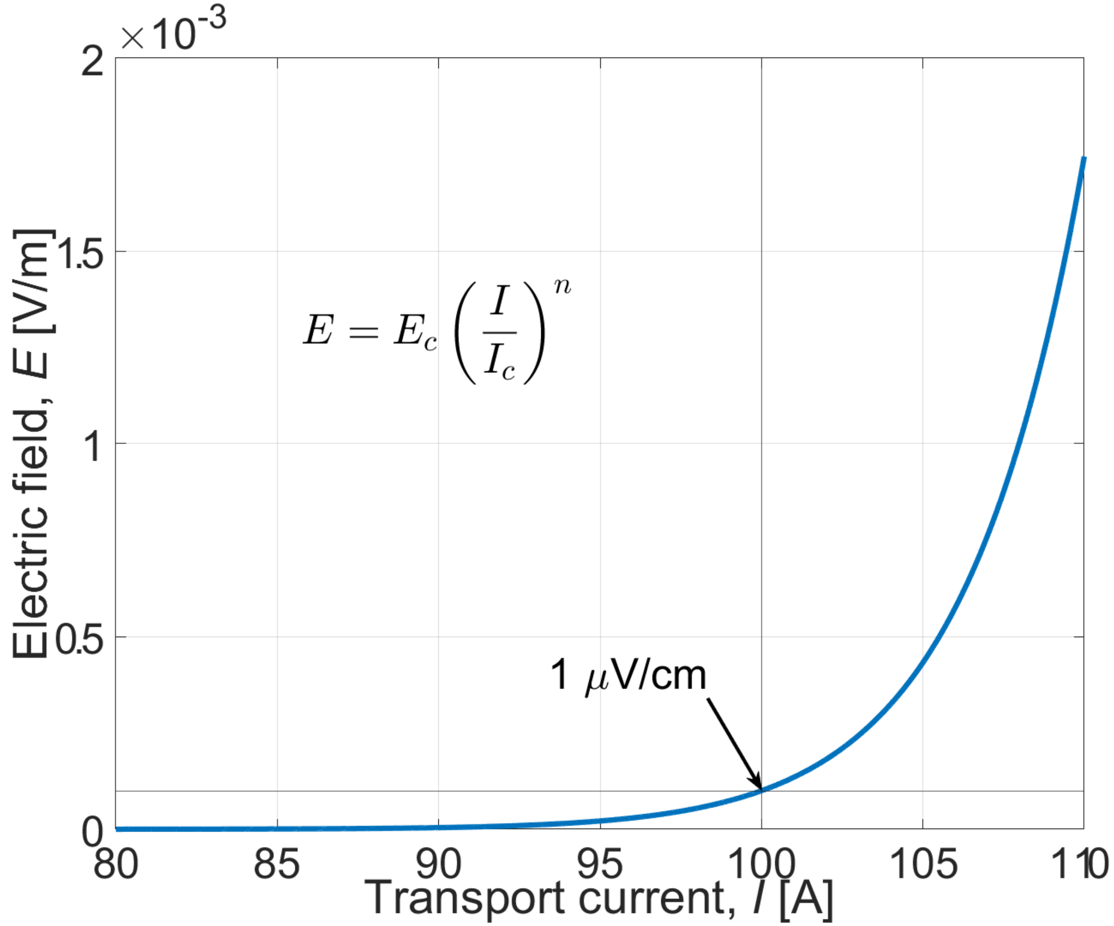
Current in non-superconducting domain: $$J = \sigma E$$

Current in superconducting domain:

1. Bean's model: $$J = J_{c0} sign\left(\frac{E}{E_c}\right)$$

2. Power low: $$J = J_{c0}\left(\frac{E}{E_c}\right)^{\frac{1}{n}}$$

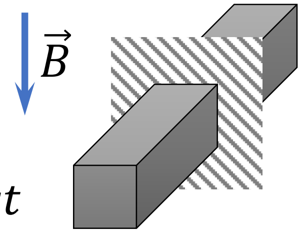
3. Improved convergence: $$J = J_{c0} tanh\left(\frac{E}{E_c}\right)$$

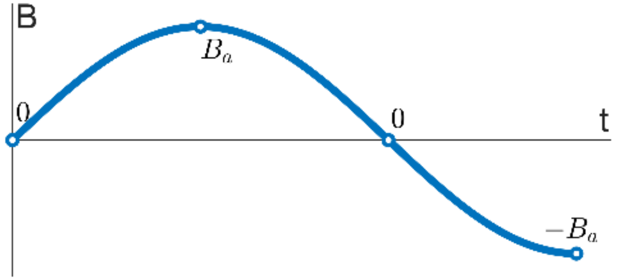


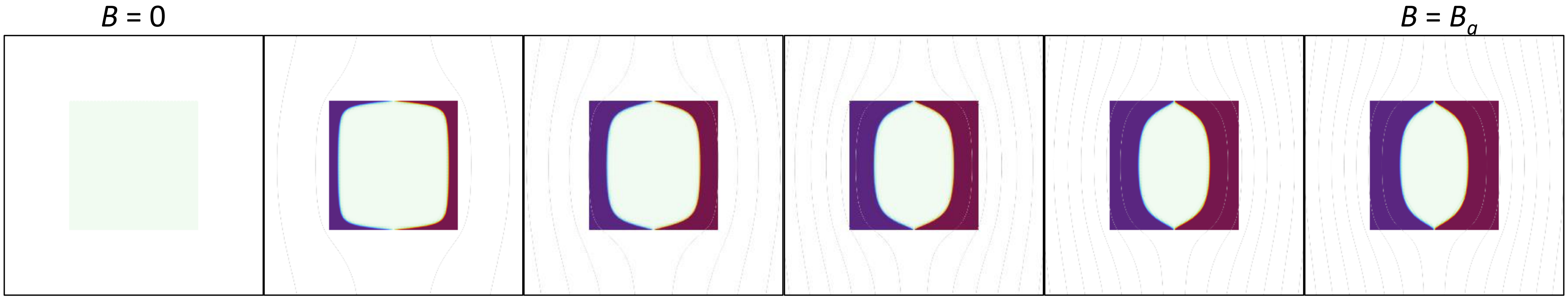
[1] F Gömöry et al 2010 Supercond. Sci. Technol. **23** 034012
[2] M Solovyov and F Gömöry 2019 Supercond. Sci. Technol. **32** 115001

Bean's critical state model [3]

$$\vec{j} = \begin{cases} +J_{c0}, & for \quad {}^{\partial A}/_{\partial t} < 0 \\ -J_{c0}, & for \quad {}^{\partial A}/_{\partial t} > 0 \\ 0, & for \quad t = 0, A = const \end{cases}$$







[3] Bean, C. P. (15 March 1962). "Magnetization of Hard Superconductors". Physical Review Letters. 8 (6). American Physical Society (APS): 250–253.

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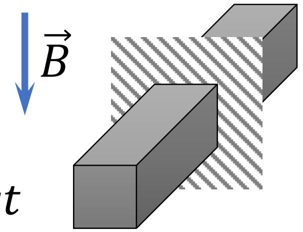
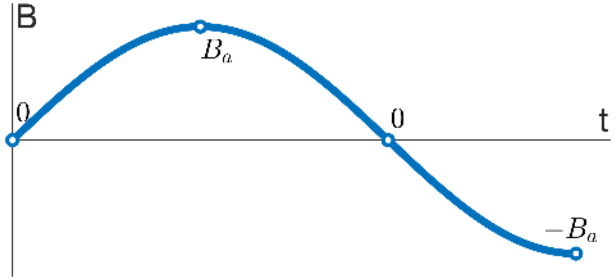
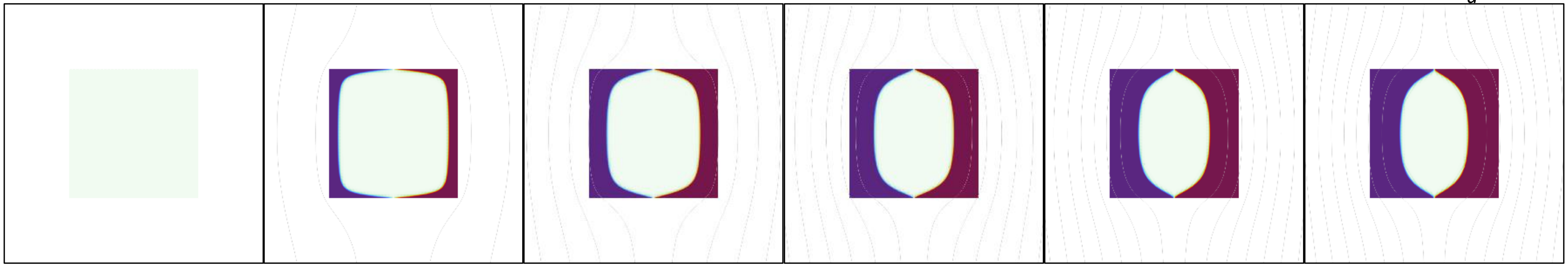
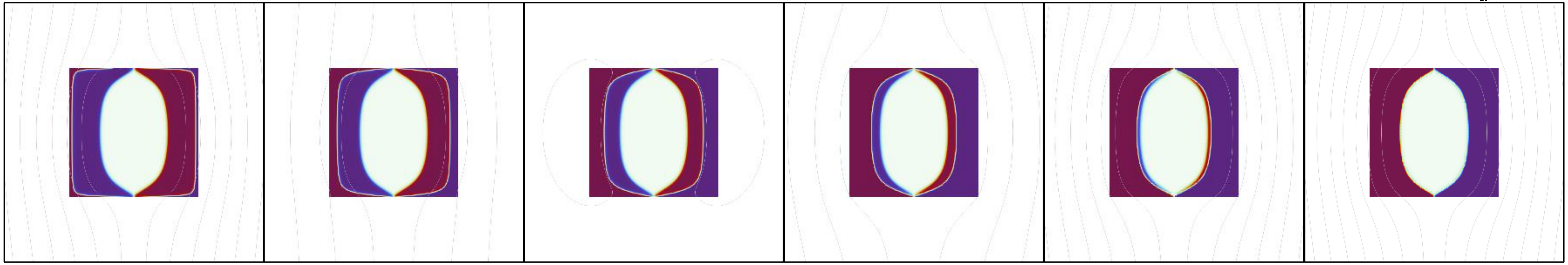




B = 0 B = B_a

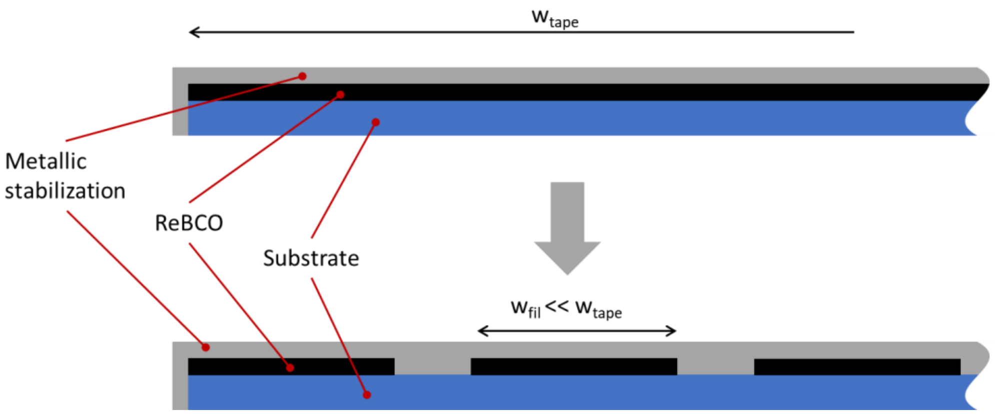


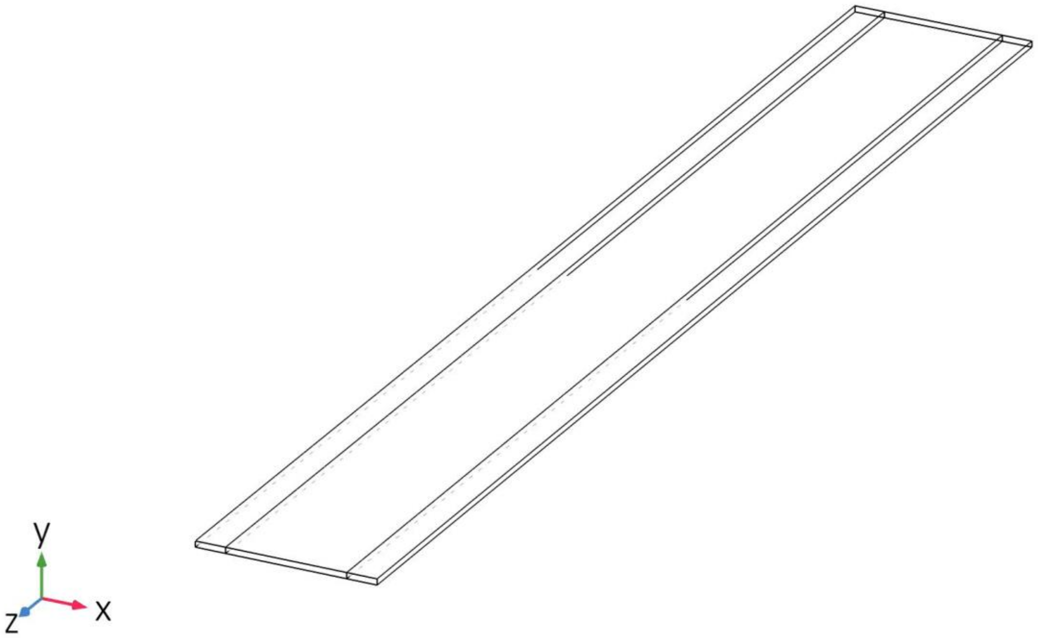
B = 0 B = -B_a

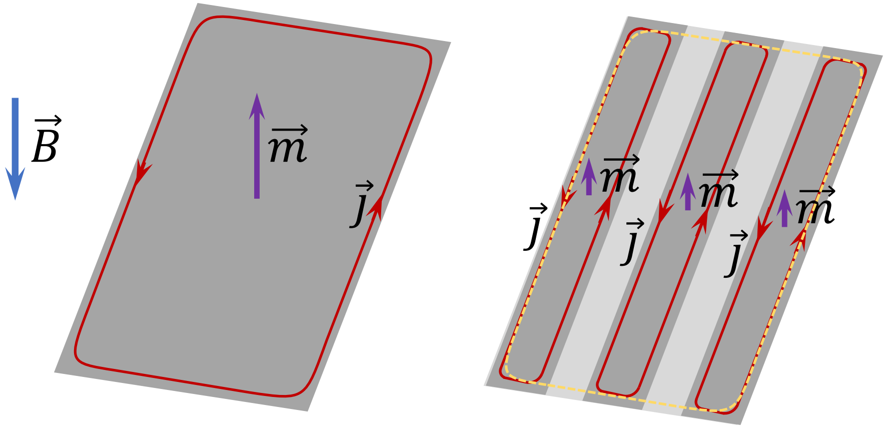


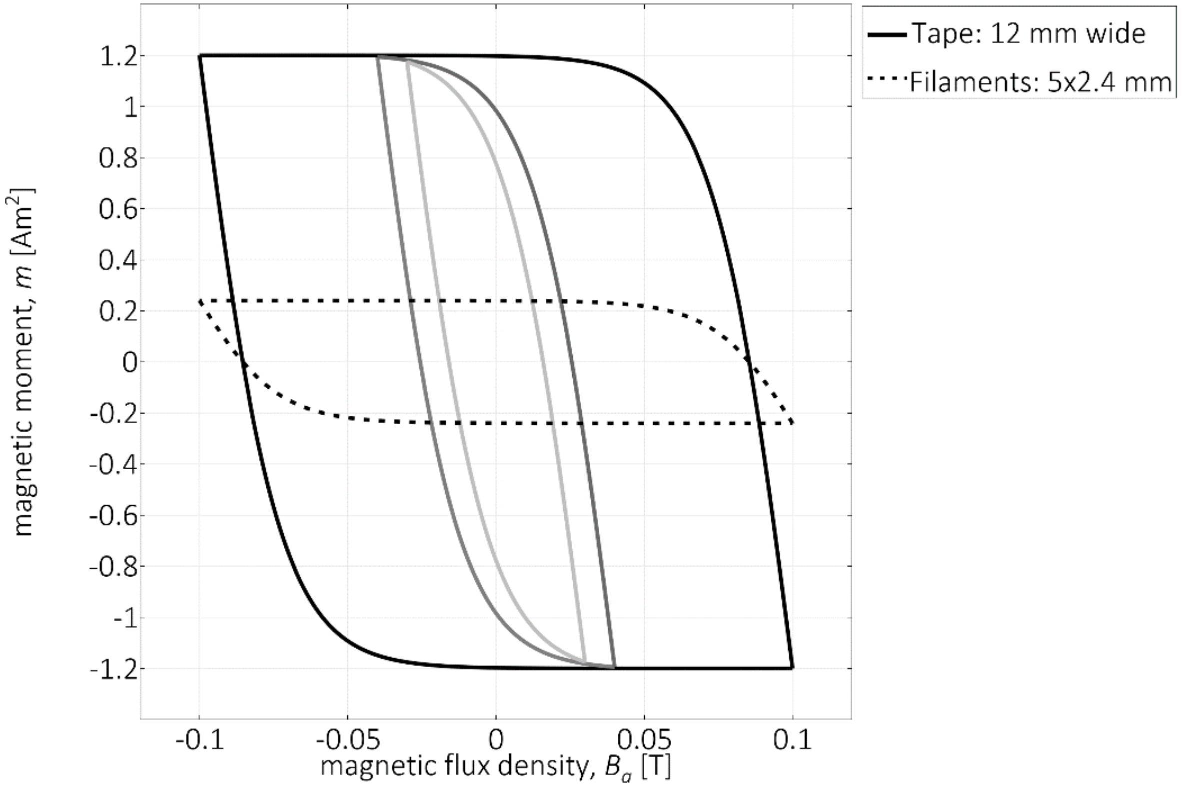
[3] Bean, C. P. (15 March 1962). "Magnetization of Hard Superconductors". Physical Review Letters. 8 (6). American Physical Society (APS): 250–253.

Hysteresis losses reduction by tape filamentization.

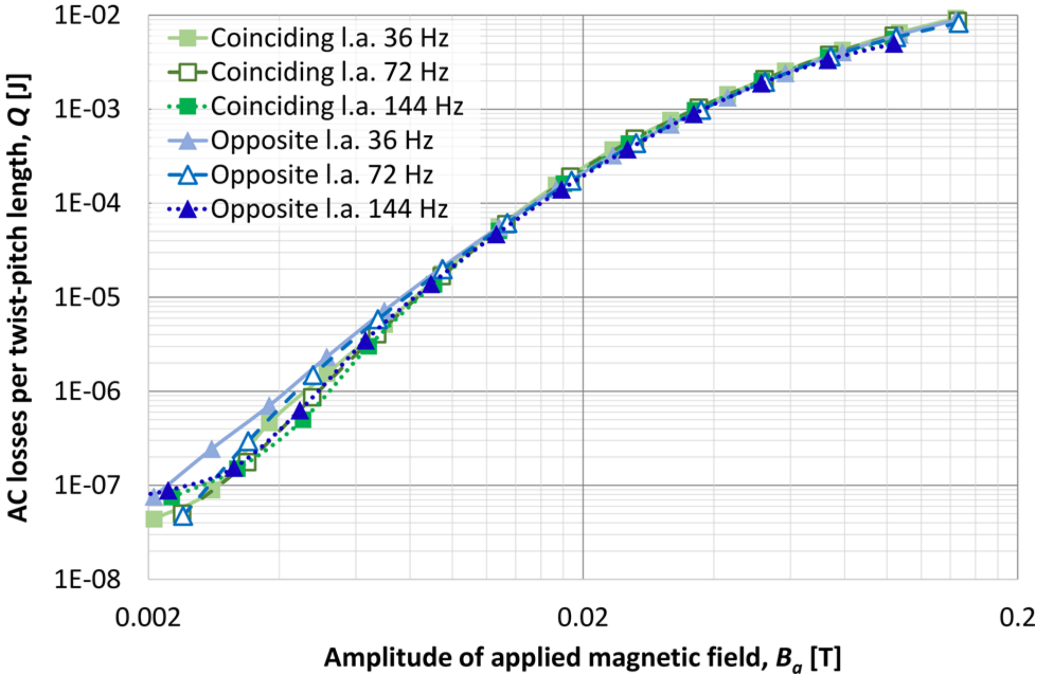






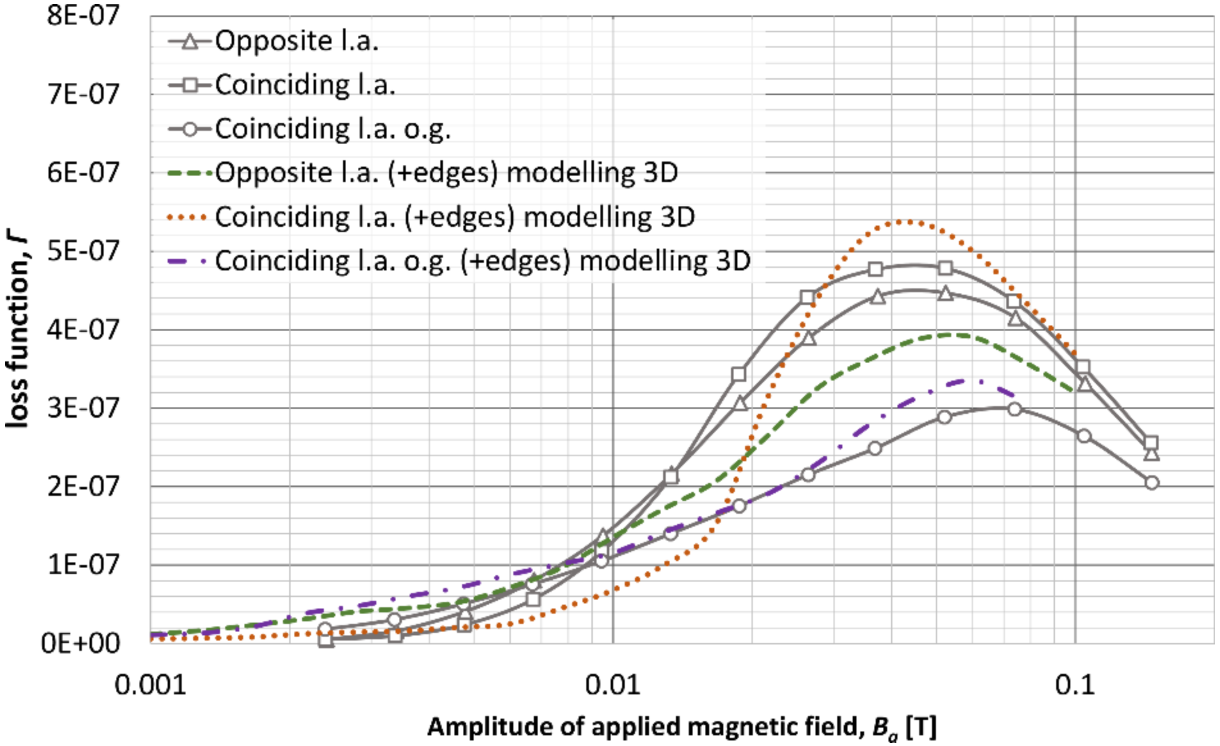


Cables: D_{in} = 7 mm, n_{tapes} = 10, w_{tape} = 3mm; cables differ in terms of the arrangement of the tape in the outer layer.



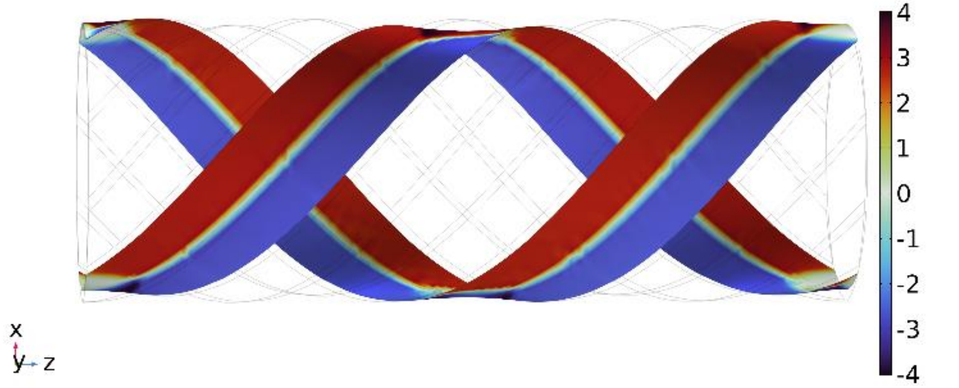
Loss function Γ:

$$\Gamma = \mu_0 \frac{Q}{2B_a^2}$$

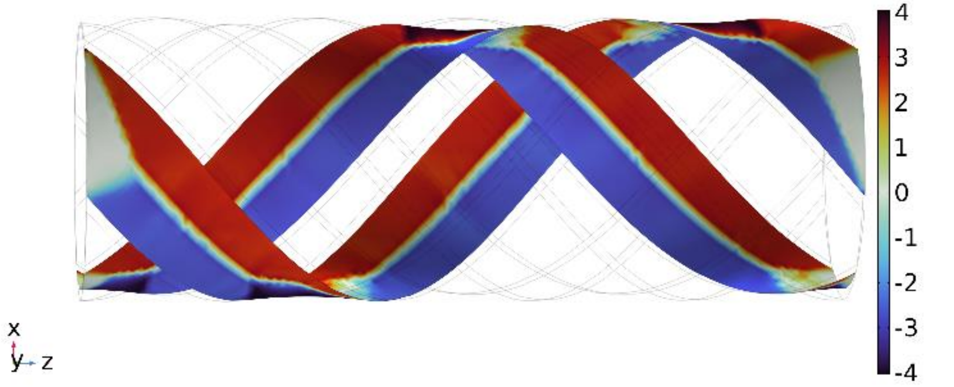


Cables: D_{in} = 7 mm, n_{tapes} = 10, w_{tape} = 3mm, $n_{fil/tape}$ = 5

Opposite lay angles

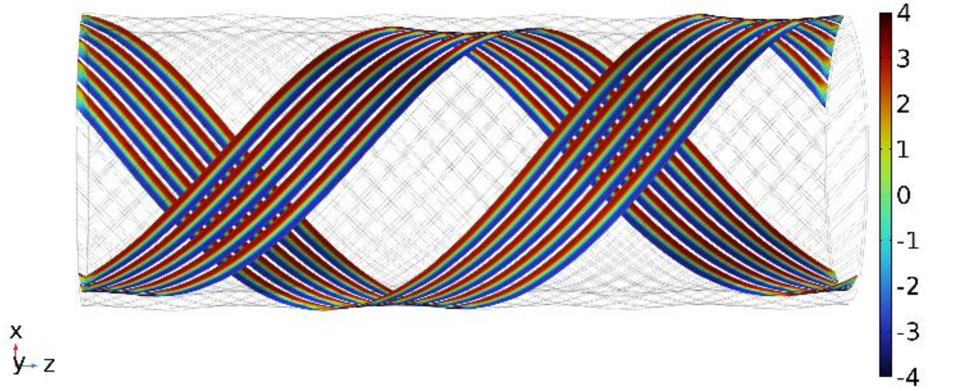


Coinciding lay angles

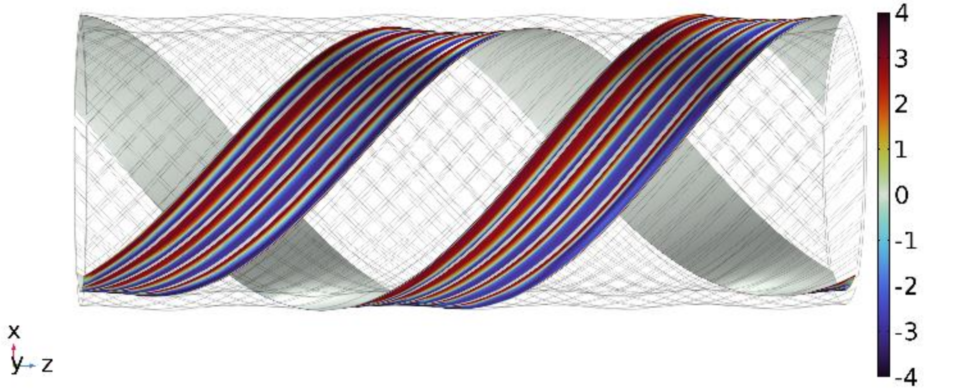


⊕ B_{appl}, 100 mT amplitude

Uncoupled filaments

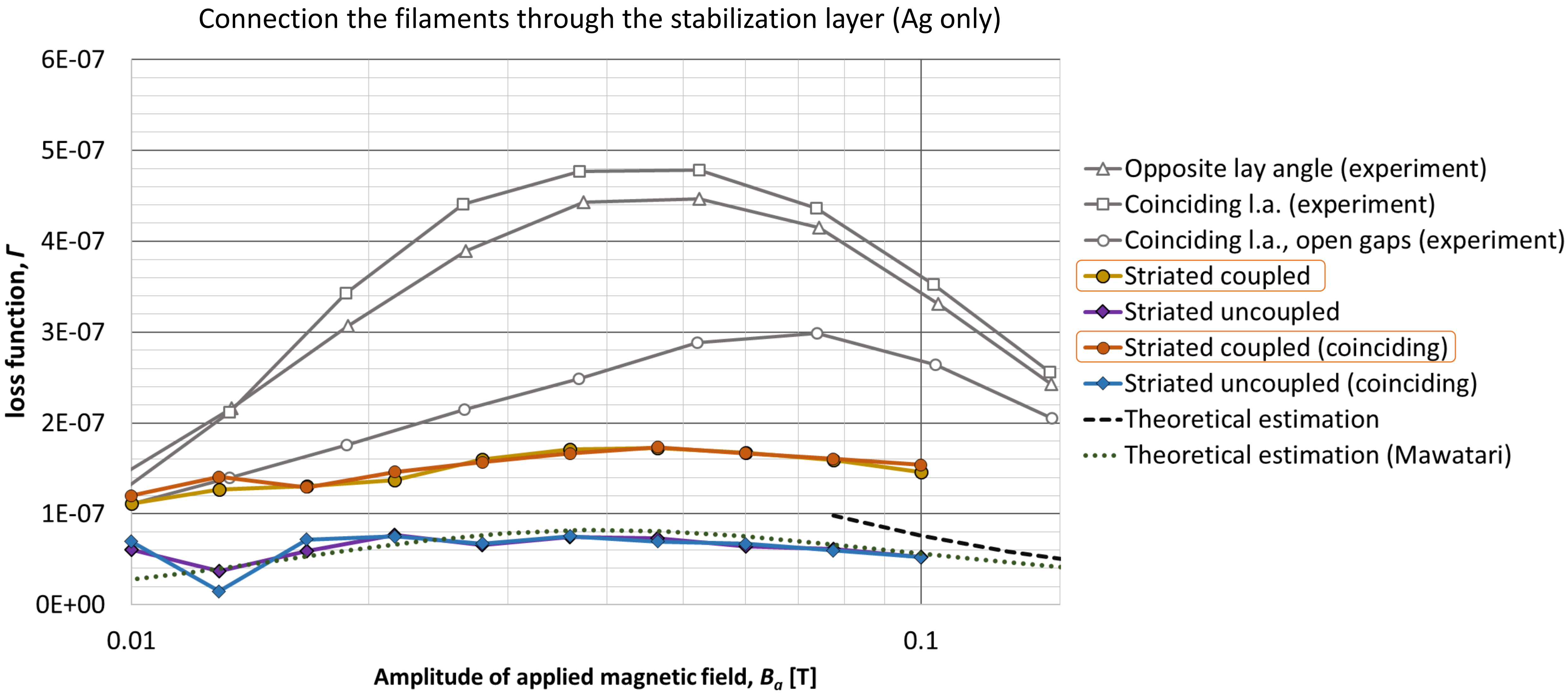


Partially coupled filaments



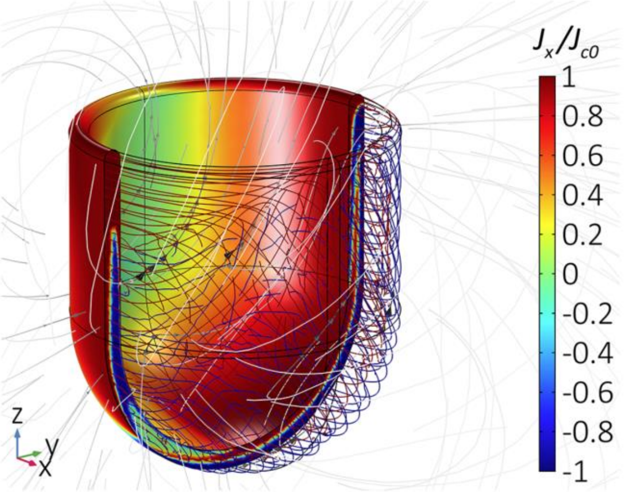
Cable: D_{in} = 7 mm, n_{tapes} = 10, w_{tape} = 3mm, $n_{fil/tape}$ = 5; testing the tapes filamentization impact.

Total computation time ≈ **18 days** (**2 millions** DOF) for 10 appl. field amplitudes on Intel(R) Core(TM) i9-10920X CPU @ 3.50GHz (12-cores) and 64 GB RAM



Conclusions

A-V formulation for numerical modelling of superconductor magnetization in true 3-D geometry

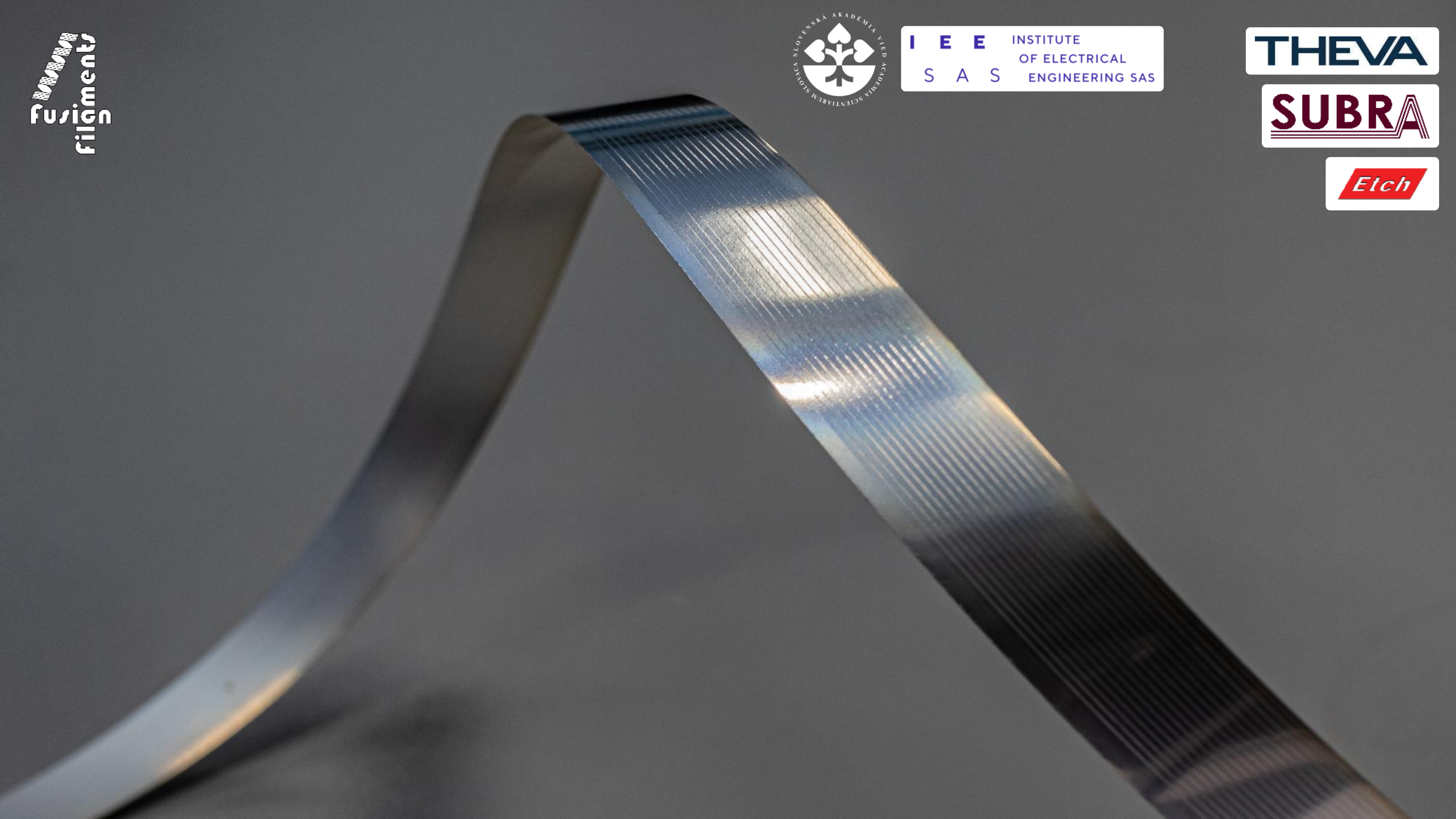


This model was shared by Mykola Soloviov, Institute of Electrical Engineering, Slovak Academy of Sciences.

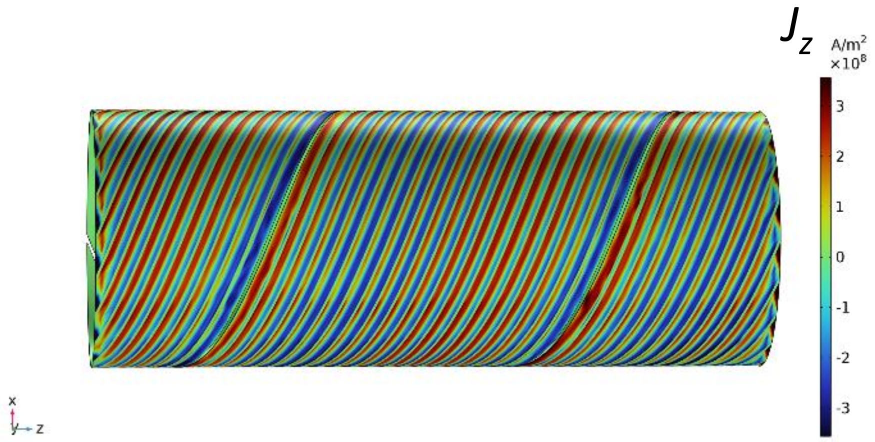
Model file of superconducting cup magnetization in the diagonally oriented external AC magnetic field. The model was saved in the Comsol v. 5.4 without generated mesh and solution to reduce the file size. The solver settings are oriented to speeding up the computation with the cost of precision and stability of the solution output.

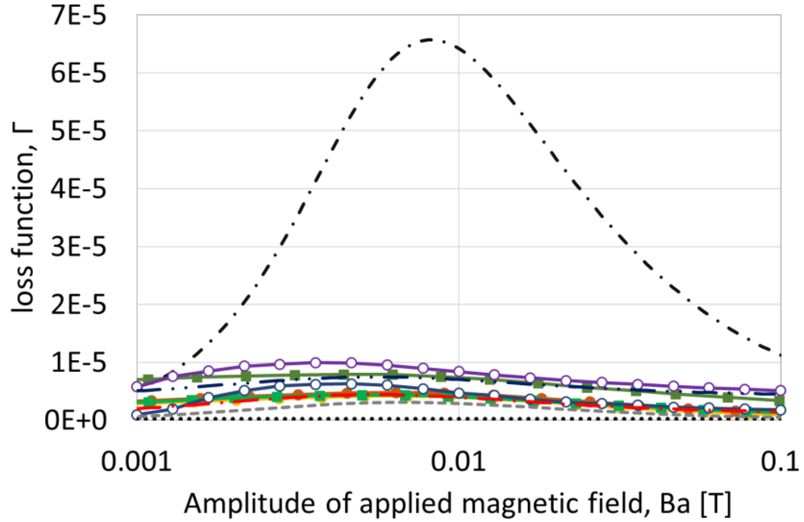
https://htsmodelling.com/model-files/a-v-formulation-for-numerical-modelling

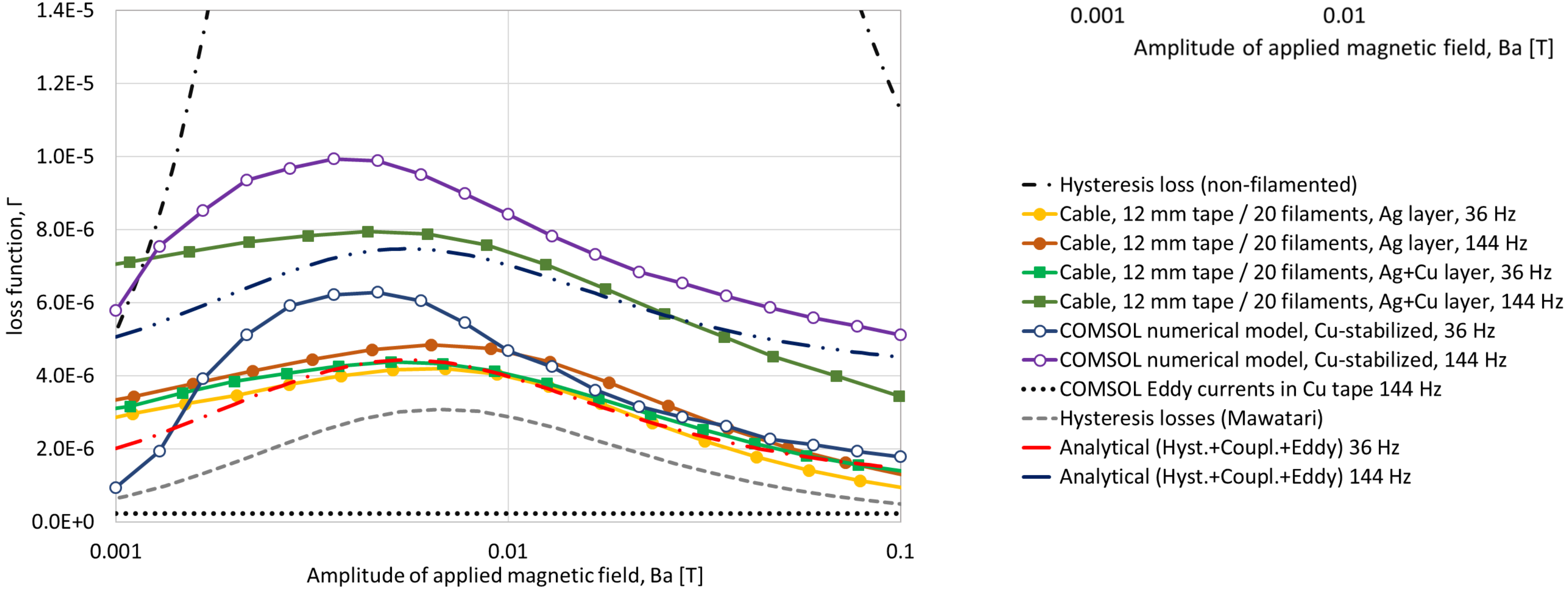
- A numerical model in A-formulation allows computing AC losses in the superconducting cables with a good agreement with the experiment.
- The coupling losses reduce the effect from the filamentization (as expected).
- The coupling losses in typical ReBCO tapes become significant at the higher magnetic field growth rates (0.1 T, 36 Hz ≈ 20 T/s), which are not common for fusion CS magnet – 1.3 T/s is expected.


Fusion filaments
IEE SAS INSTITUTE OF ELECTRICAL ENGINEERING SAS
THEVA
SUBRA
Etch

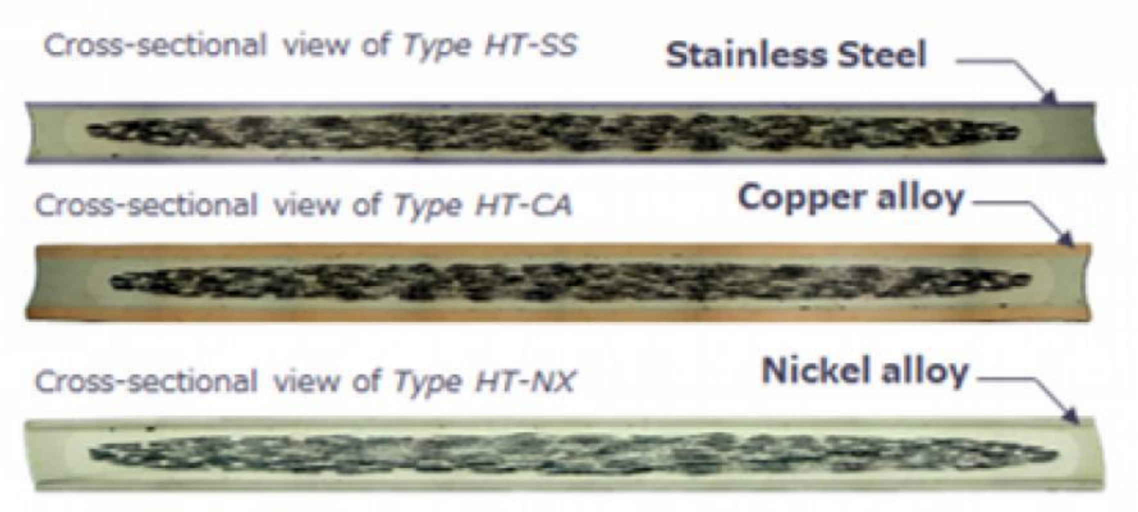
Cable: D_{in} = 10 mm, n_{tapes} = 1, w_{tape} = 12mm, $n_{fil/tape}$ = 20; testing the tapes filamentization impact.







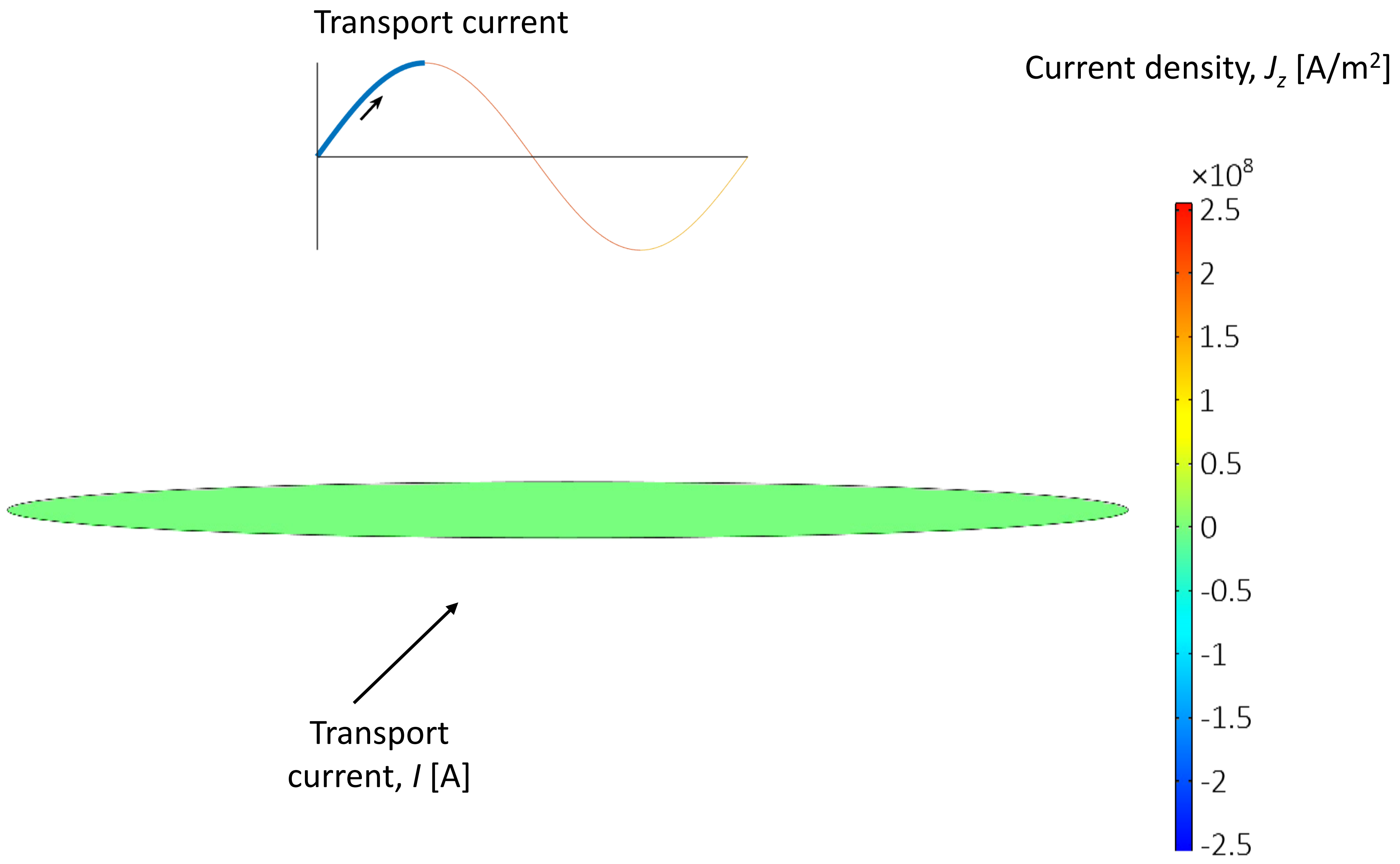
BiSCCO HTS tape (gen I)

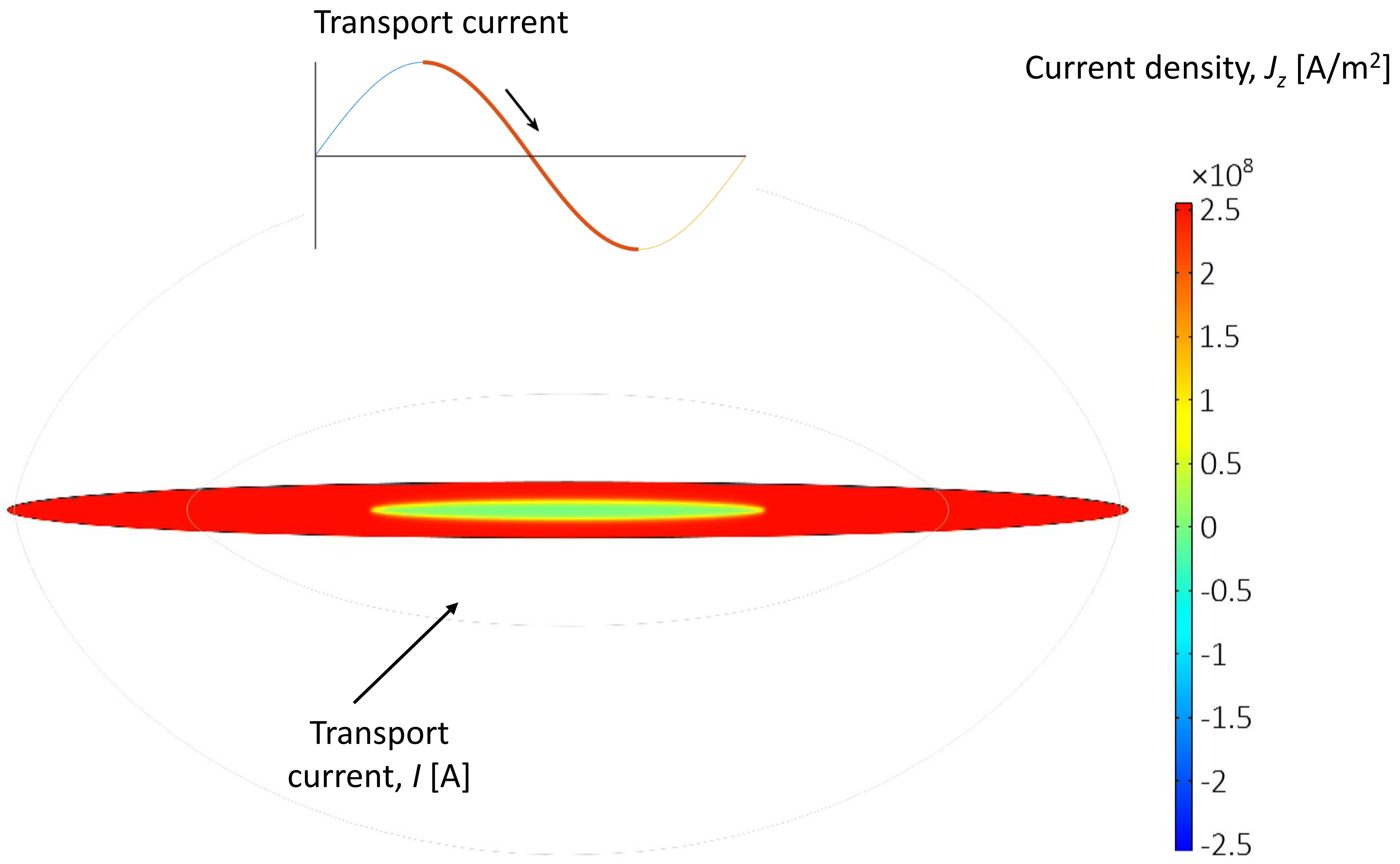


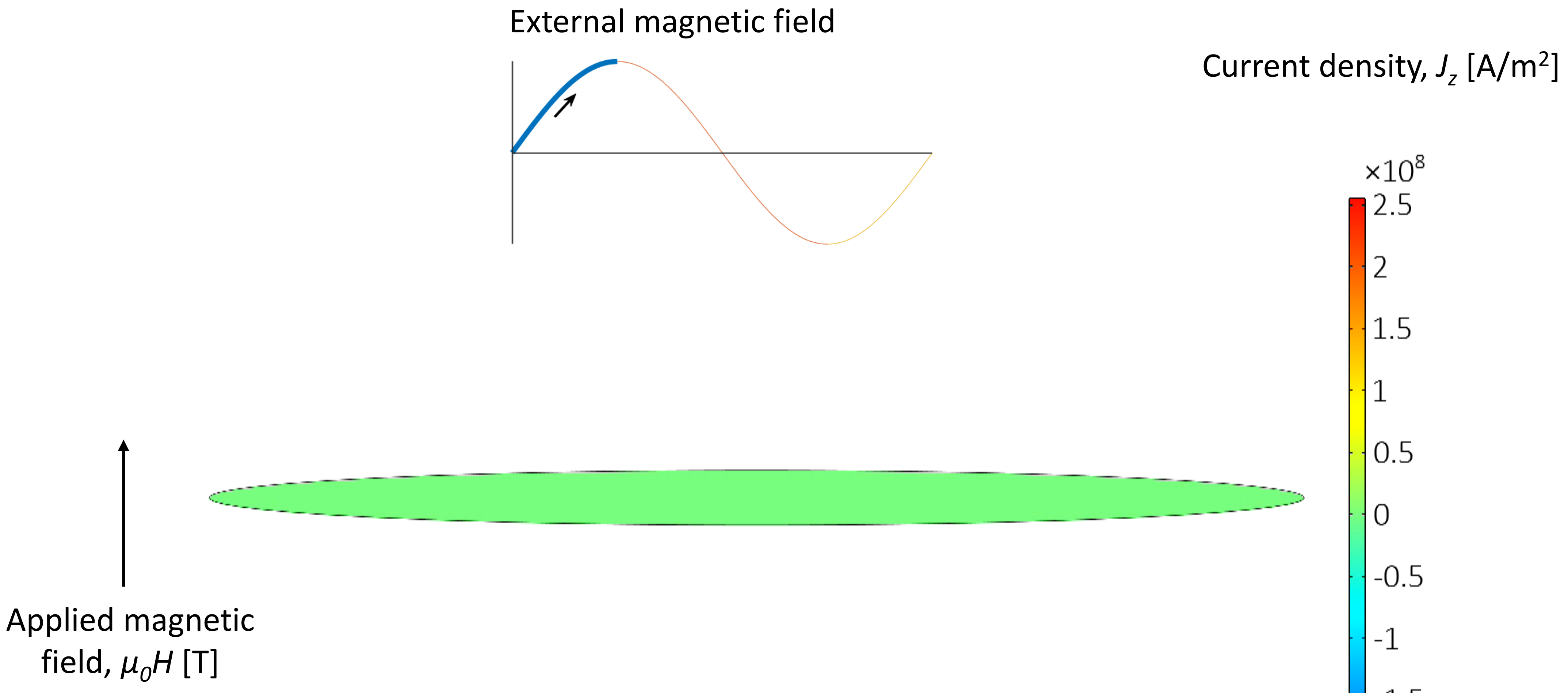
https://sumitomoelectric.com

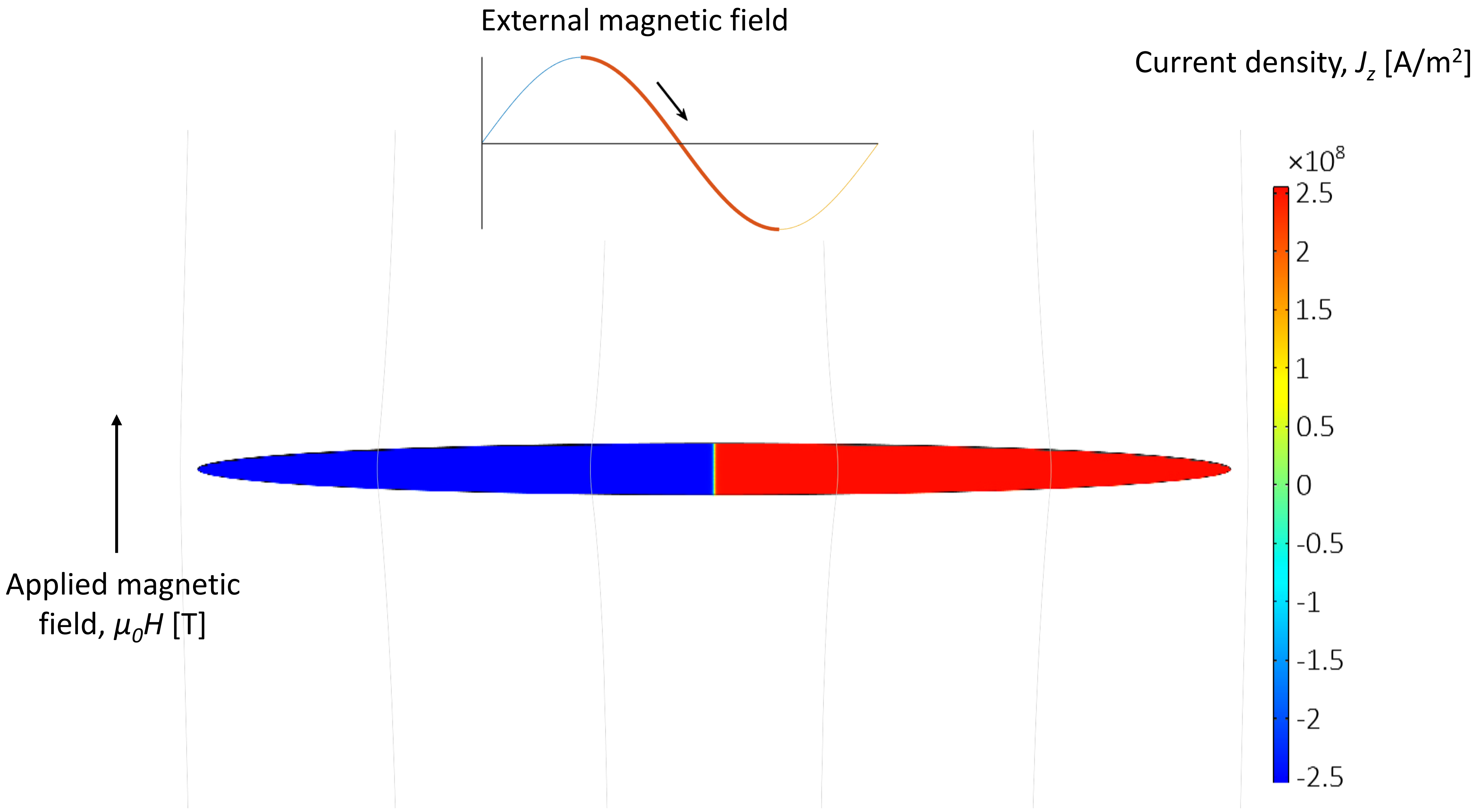
$$j = \begin{cases} +J_c \\ 0 \\ -J_c \end{cases}$$

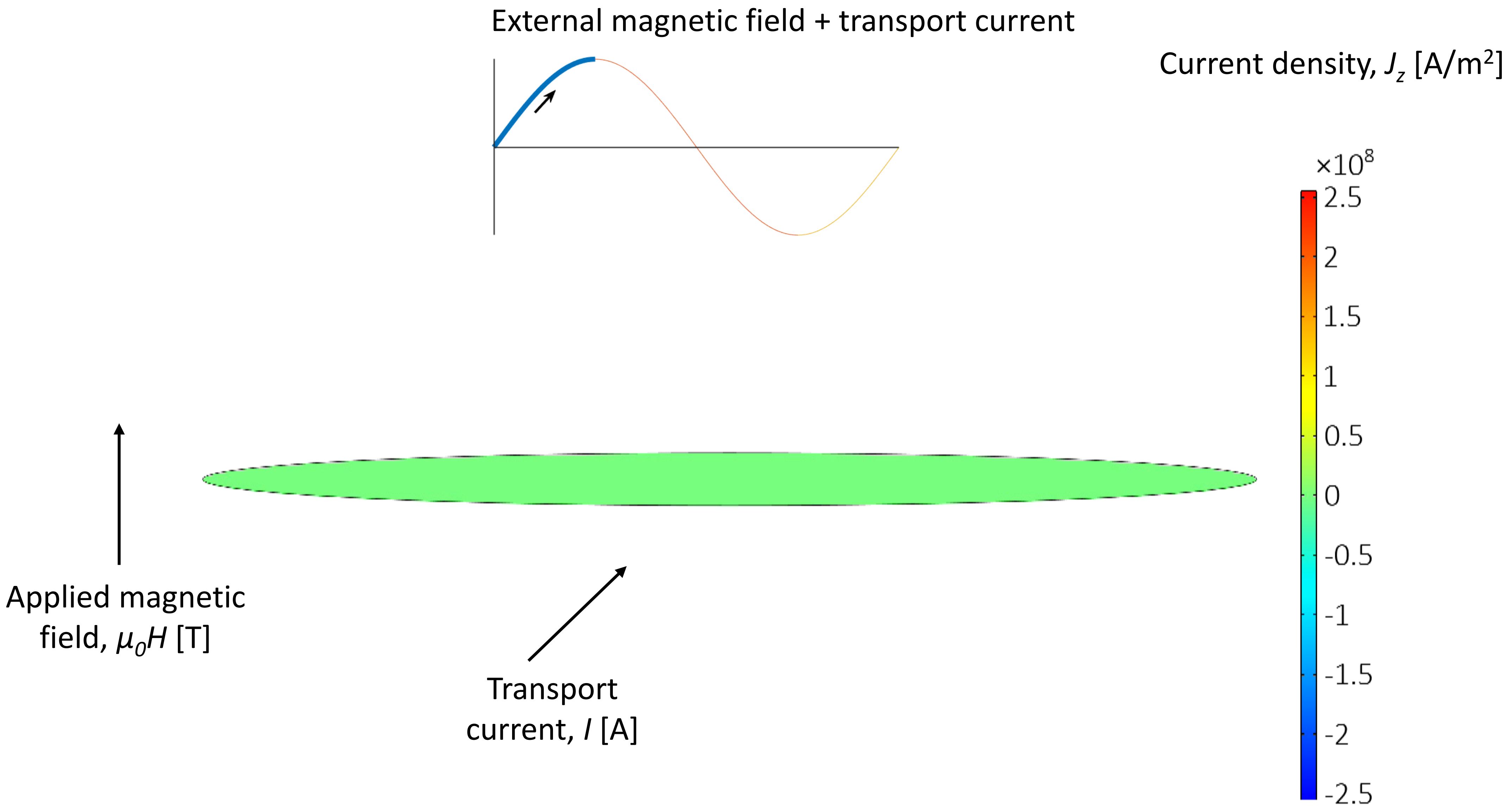
A simple elliptical cross-section


Transport current
Current density, J_z [A/m^2]
×10^8
2.5
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
-2.5
Transport current, I [A]

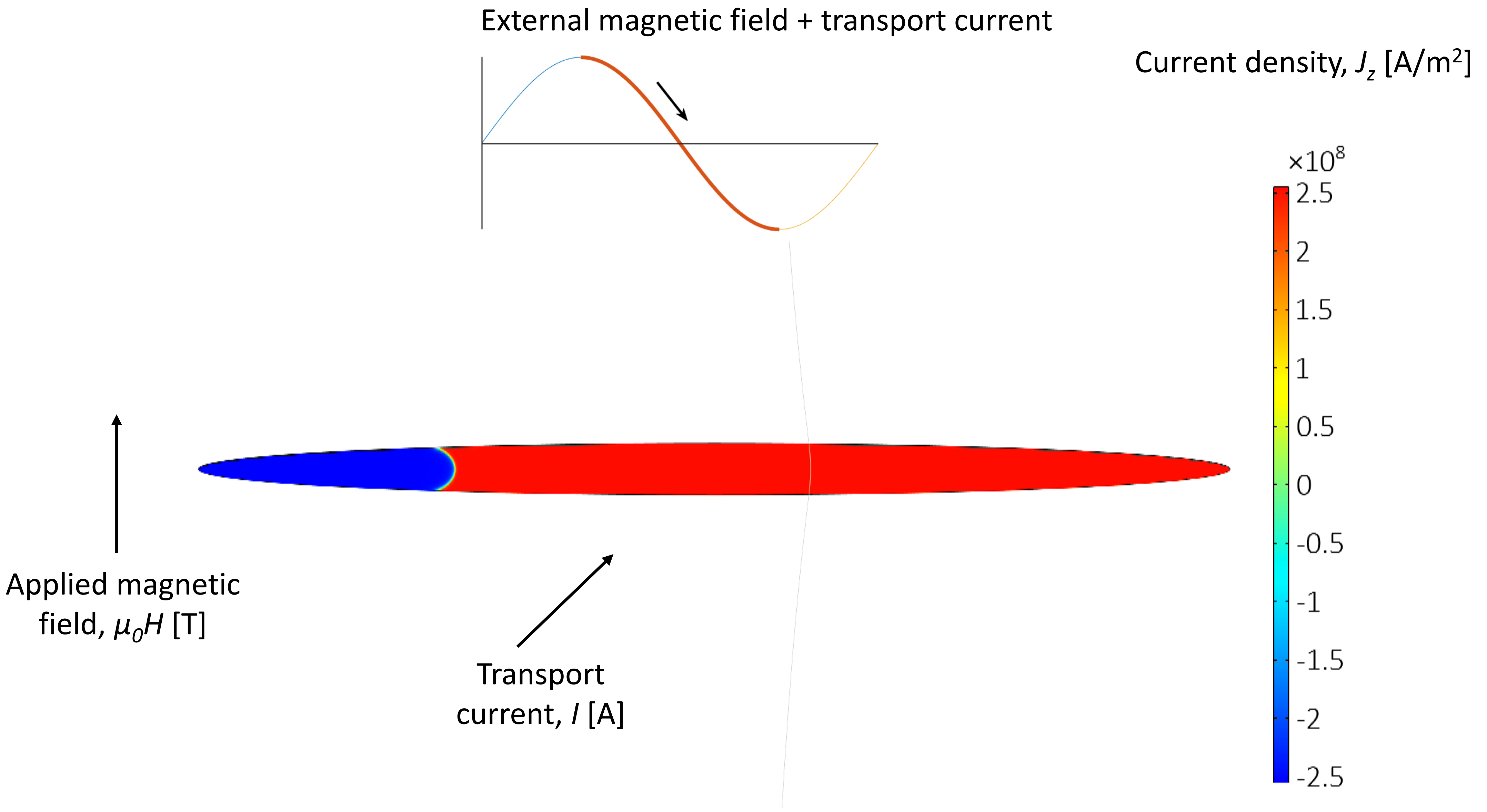

Transport current
Current density, J_z [A/m^2]
$\times 10^8$
2.5
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
-2.5
Transport current, I [A]


External magnetic field
Current density, J_z [A/m^2]
$\times 10^8$
2.5
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
-2.5
Applied magnetic field, $\mu_0 H$ [T]


External magnetic field
Current density, J_z [A/m^2]
×10^8
2.5
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
-2.5
Applied magnetic field, $\mu_0 H$ [T]



External magnetic field + transport current
Current density, J_z [A/m^2]
$\times 10^8$
2.5
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
-2.5
Applied magnetic field, $\mu_0 H$ [T]
Transport current, I [A]



External magnetic field + transport current
Current density, J_z [A/m^2]
$\times 10^8$
2.5
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
-2.5
Applied magnetic field, $\mu_0 H$ [T]
Transport current, I [A]

Motivation. AC losses in round ReBCO cable.

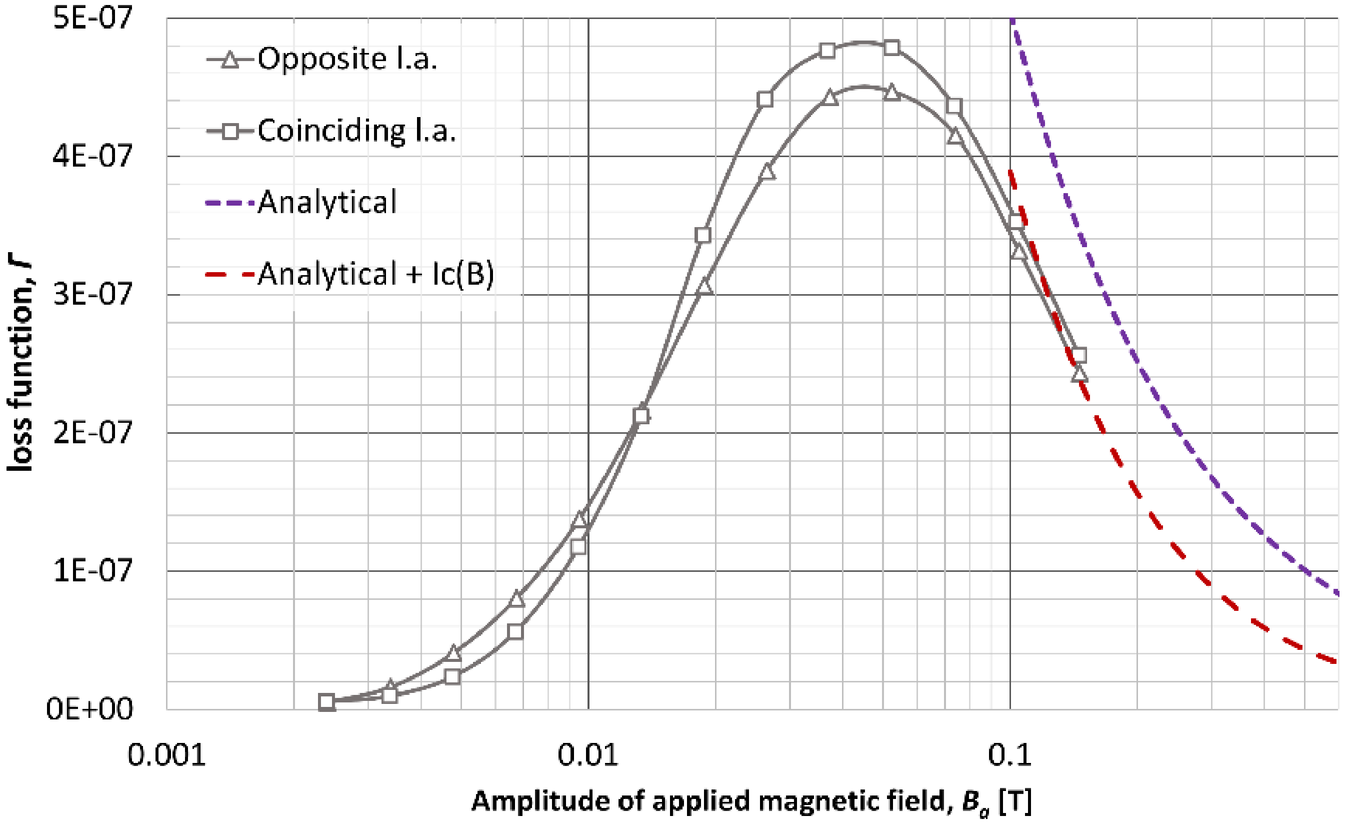
The analytical solution for AC losses in the strip in the perpendicular field is described in [6, 7]. Additionally, the helicity may be included into the formula as the correction factor $2/\pi$ [8, 9].

The sample of length L_s each tape is long $L_s/\cos\alpha$ where α is the lay angle.

Loss function: $\Gamma = \mu_0 \frac{Q}{2B_a^2}$

$$Q = \frac{2\,NI_c}{\pi cos\alpha} B_a w$$

α – is the lay angle
N – total number of tapes
I_c – critical current
B_a – applied magnetic field amplitude
w – the tape width



[6] E Brandt and M Indenbom 1993 *Phys. Rev. B* **48** 17 12893–906
[7] F Gomory et al 2017 Supercond. Sci. Technol. **30** 11 114001
[8] M Majoros et al 2014 Supercond. Sci. Technol. **27** 12 125008
[9] J Souc et al 2013 Supercond. Sci. Technol. **26** 7 075020

Motivation. AC losses in round cable, HTS vs LTS.

In similar way, hysteresis loss in LTS wires, considering the filaments with diameter d_f and critical current per filament $I_{c,fil}$:

$$Q_{LTS} = B_a N_{fil} I_{c,fil} \frac{8}{3\pi} d_f$$

Assuming ReBCO vs. best NbTi wire, w = **3 mm** and d_f = **3 µm**:

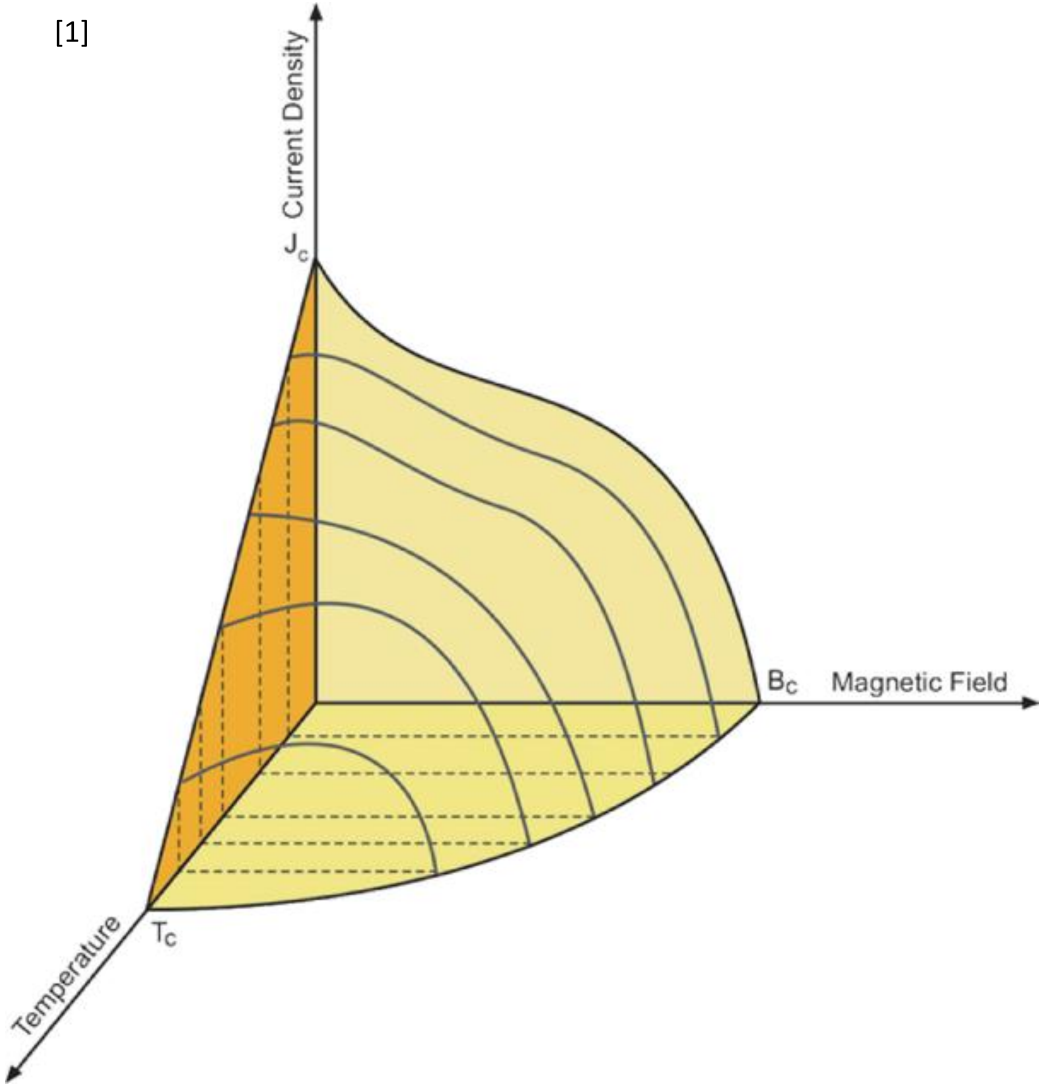
$$\frac{Q_{HTS}}{Q_{NbTi}} = \frac{3}{8cos\alpha}\frac{w}{d_f} \approx \frac{w}{2d_f} = \mathbf{500}$$

The practical Nb_3Sn (filament diameter **50 µm**), still no coupling:

$$\frac{Q_{HTS}}{Q_{Nb_3Sn}} \approx \frac{w}{2d_f} = \mathbf{30}$$

High-Temperature Superconductors (HTS)

[1]

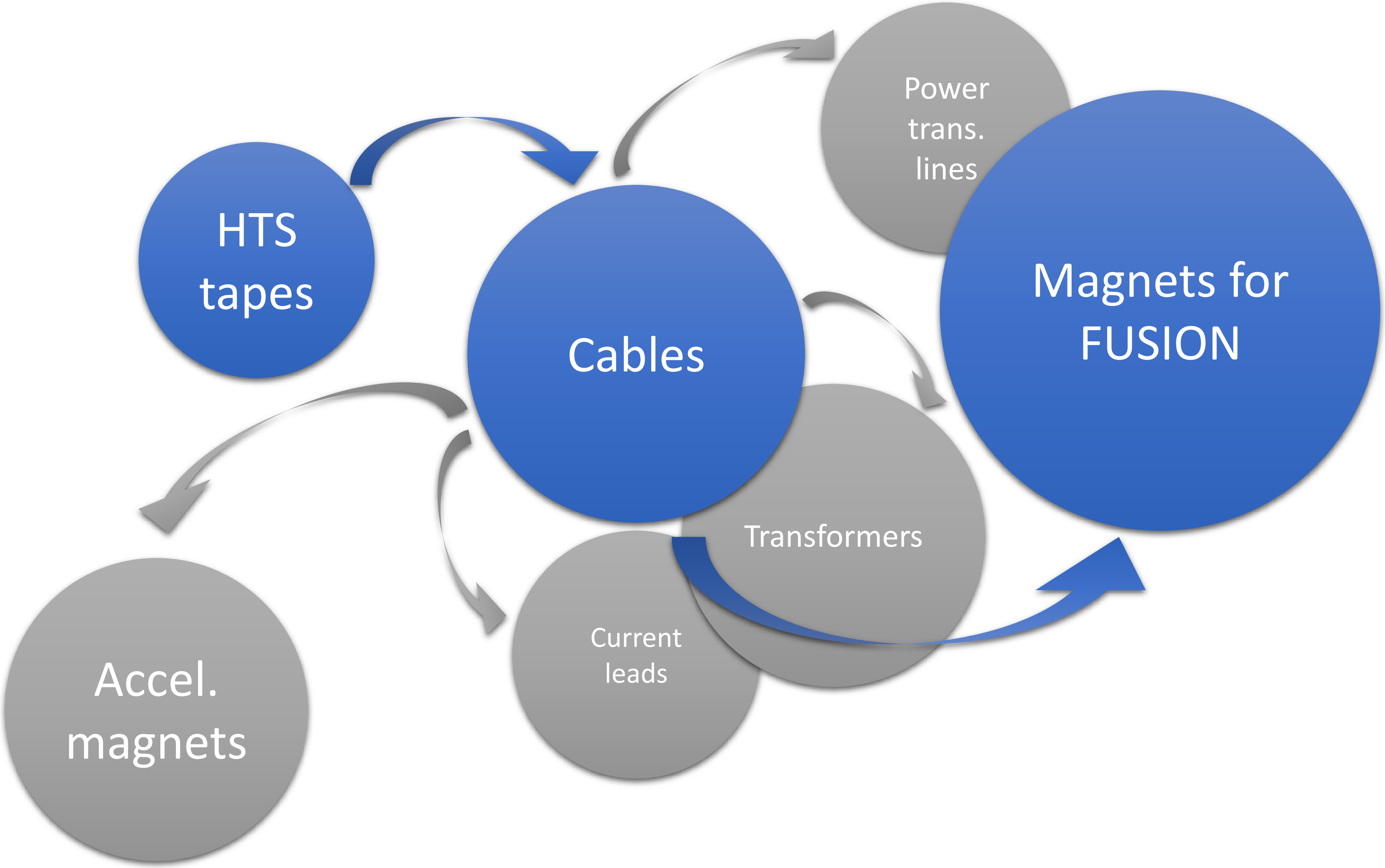


For Rare-earth barium copper oxide (ReBCO):

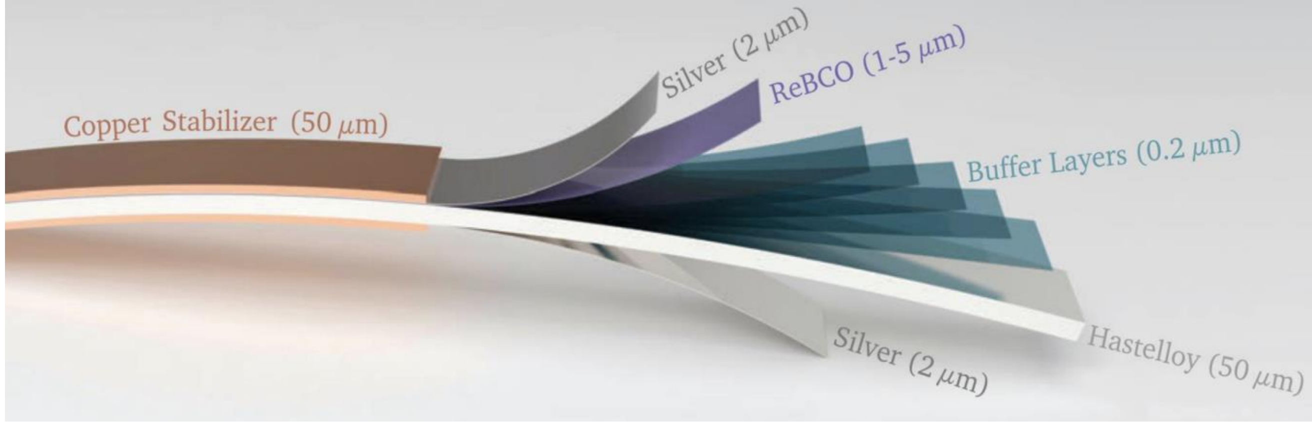
- B_{c2} ~ 110 T (4.2 K)
- T_c ~ 93 K ($YBa_2Cu_3O_{7-\lambda}$; λ~0.16)
- I_c > 1000 A/mm^2 (4.2 K, 20 T)

[1] Sharma, R.G. (2021). The Phenomenon of Superconductivity and Type II Superconductors. In: Superconductivity. Springer Series in Materials Science, vol 214. Springer, Cham. https://doi.org/10.1007/978-3-030-75672-7_2

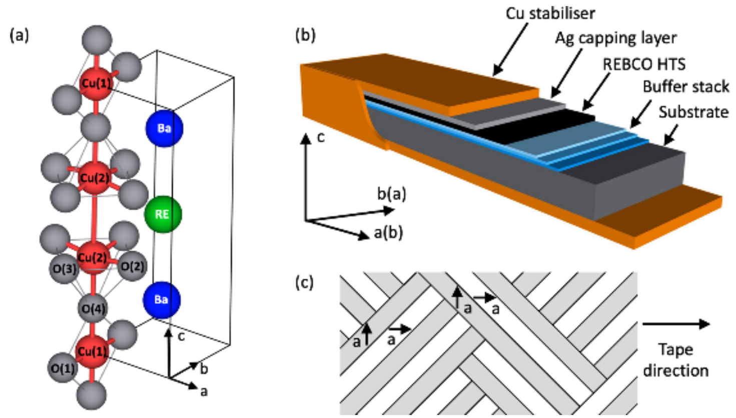
Application of High-Temperature Superconductors (HTS)

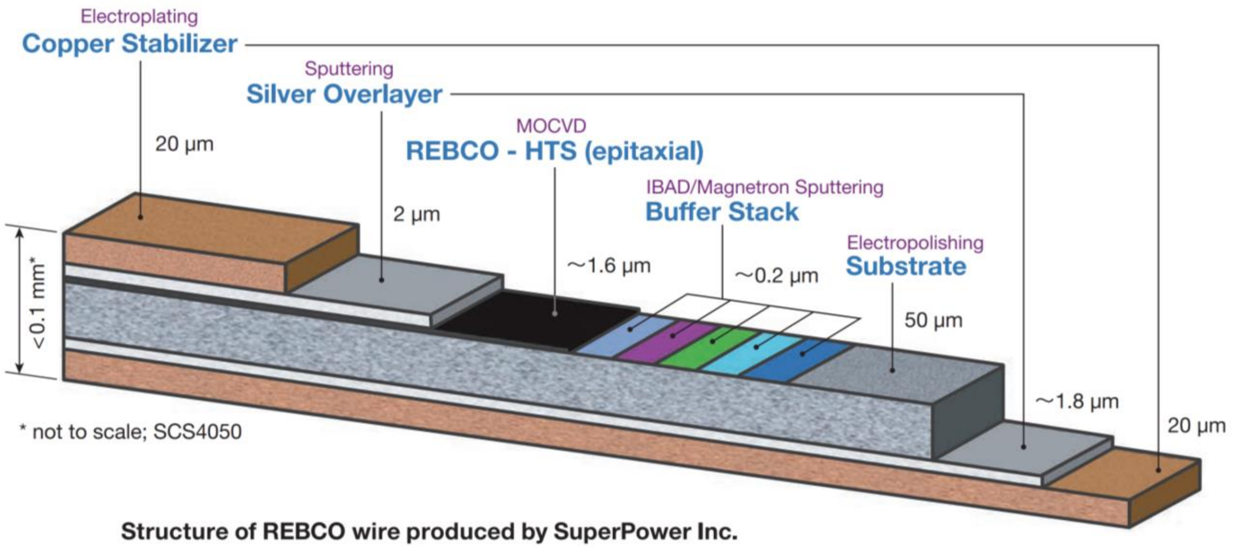


HTS coated conductor (CC) tape architcture



Herman ten Kate, Anna Kario, Simon Otten iFAST-HiTAT workshop at CERN, March 9, 2023





Structure of REBCO wire produced by SuperPower Inc.

Furukawa Electric Review, No. 55 2024

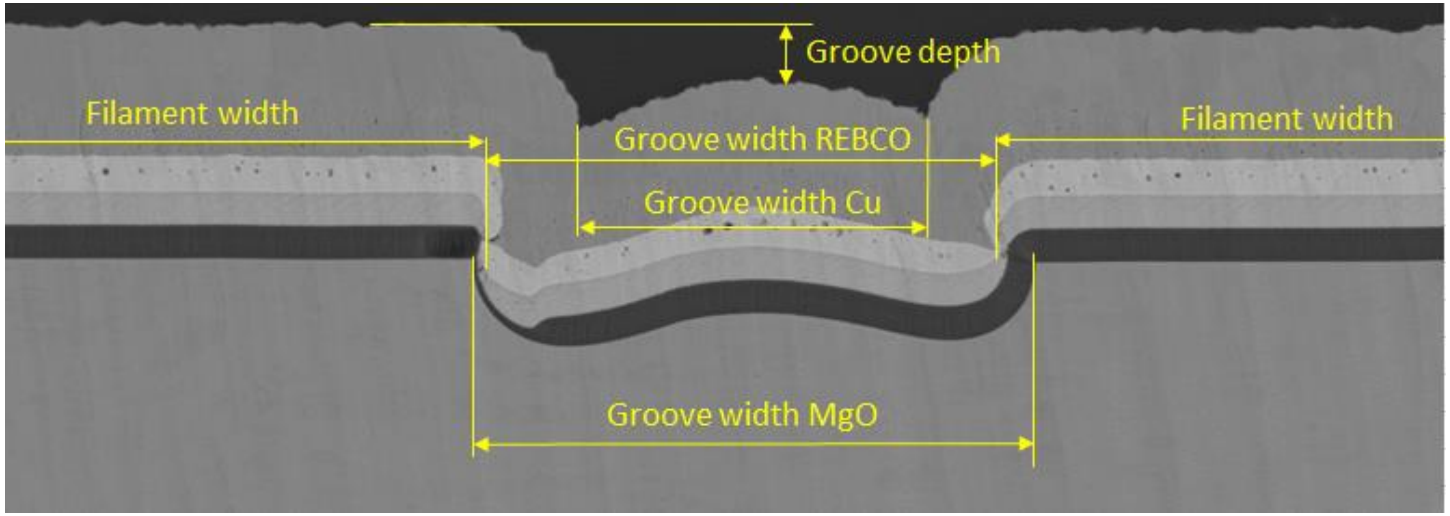
Schematic diagrams of a $REBa_2Cu_3O_{7-\delta}$ (RE = rare-earth element), REBCO, coated conductor.

a) Part of the REBCO unit cell.

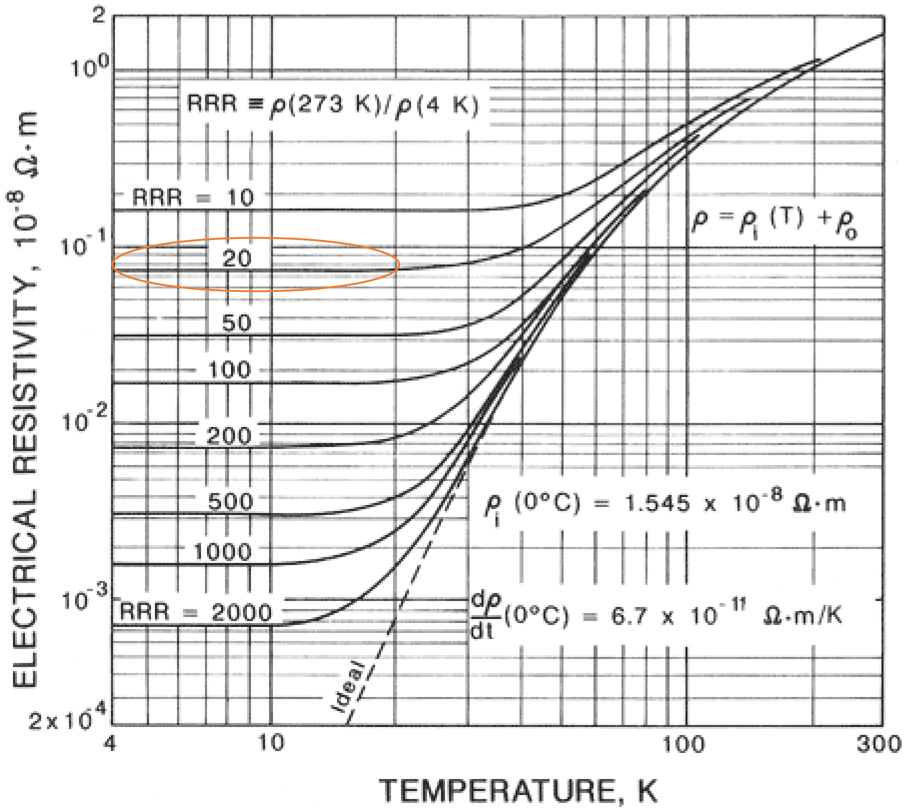
b) Schematic diagram of a generic coated conductor tape.

c) Schematic diagram of the twin structure with arrows representing the direction of the *a*-axis.

Analytical estimation of AC losses in round cable.



Micrographs of cross-sections (performed by Marcela Pekarčíková from STU)



Tape D5-2B-250 parameters:

w_{tape} = 3.81 mm

$w_{filament}$ = 267 µm

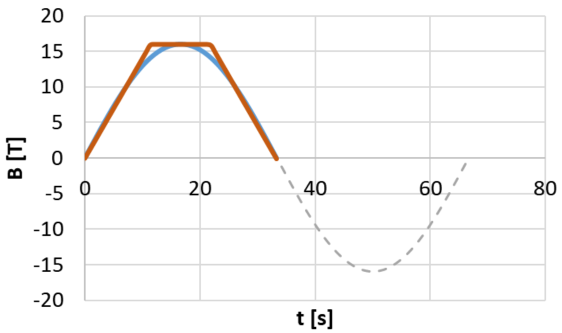
w_{gap} = 55 µm

$n_{filaments}$ = 12

t_{Cu} = 14 µm

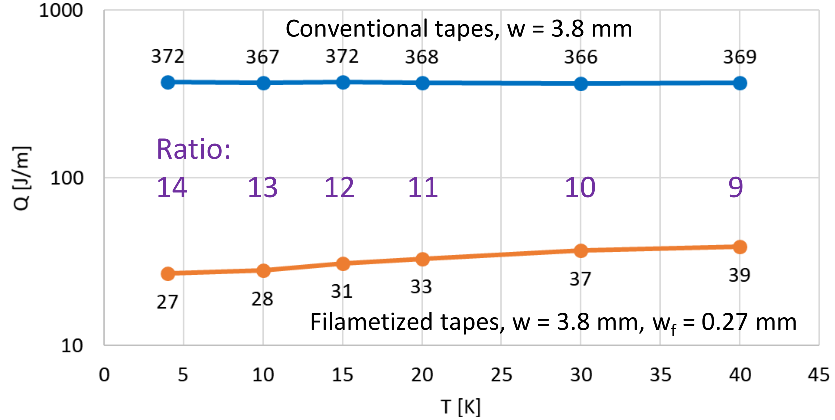
Results. AC losses in 10 KA round cable at temperature range 4 – 40 K.

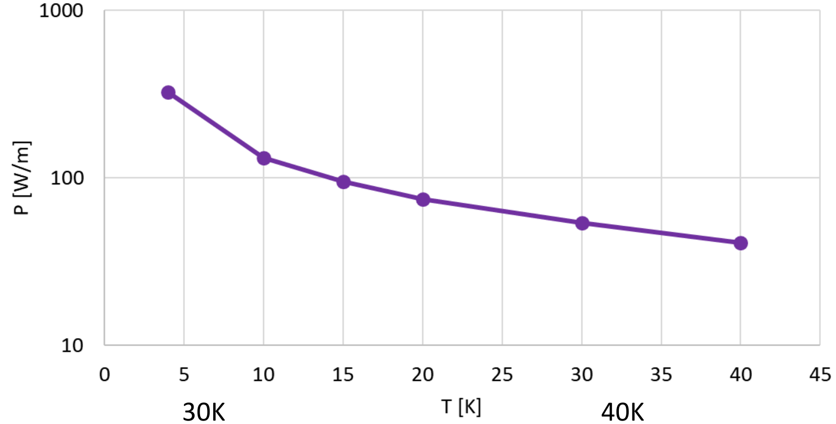
Adaptation the evaluation to non-harmonic operation



Magnetic field ramp = 1.4 T/s
Operation cycle = ½ T = 33.3 s

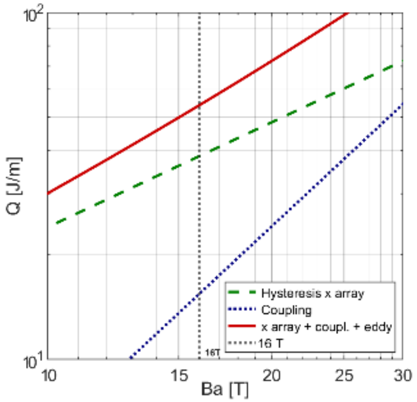
$$R: 3.81/0.267 \approx 14$$



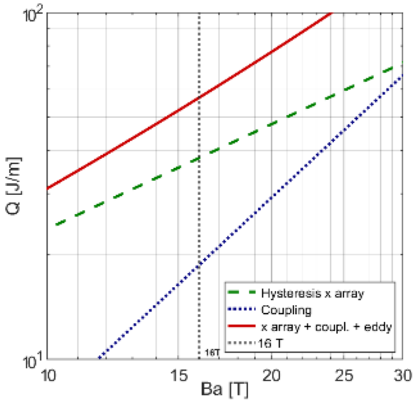


T, K	I_c, A 12 mm tape	I_c, A 3.8 mm tape	N_{tapes}	I_c, A cable	ρ_{Cu}, Ωm RRR=100	Q, J/m conventional	Q, J/m filamentized	Cooling penalty factor	P, W/m Single cycle
4	1671	530	19	10078	8.2E-10	372	27	400	324
10	1362	432	23	9943	8.2E-10	367	28	157	132
15	1132	359	28	10061	8.2E-10	372	31	103	95
20	924	293	34	9972	8.2E-10	368	33	76	75
30	568	180	55	9916	1.0E-09	366	37	49	54
40	315	100	100	9995	1.7E-09	369	39	35	41

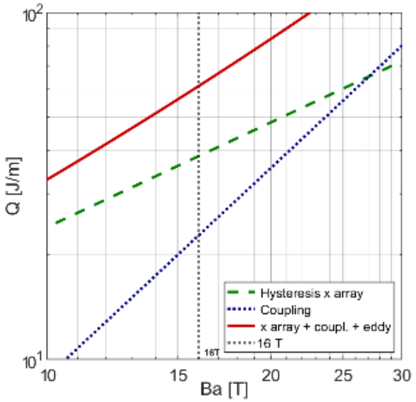
4K



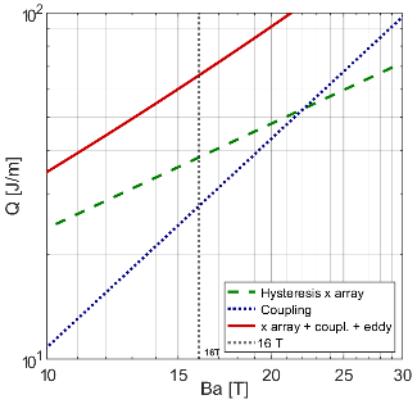
10K



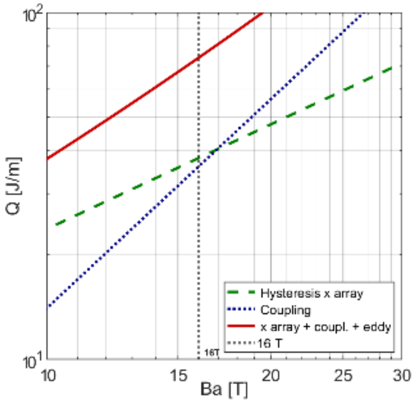
15K



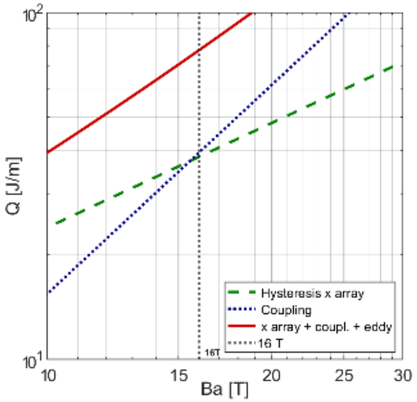
20K



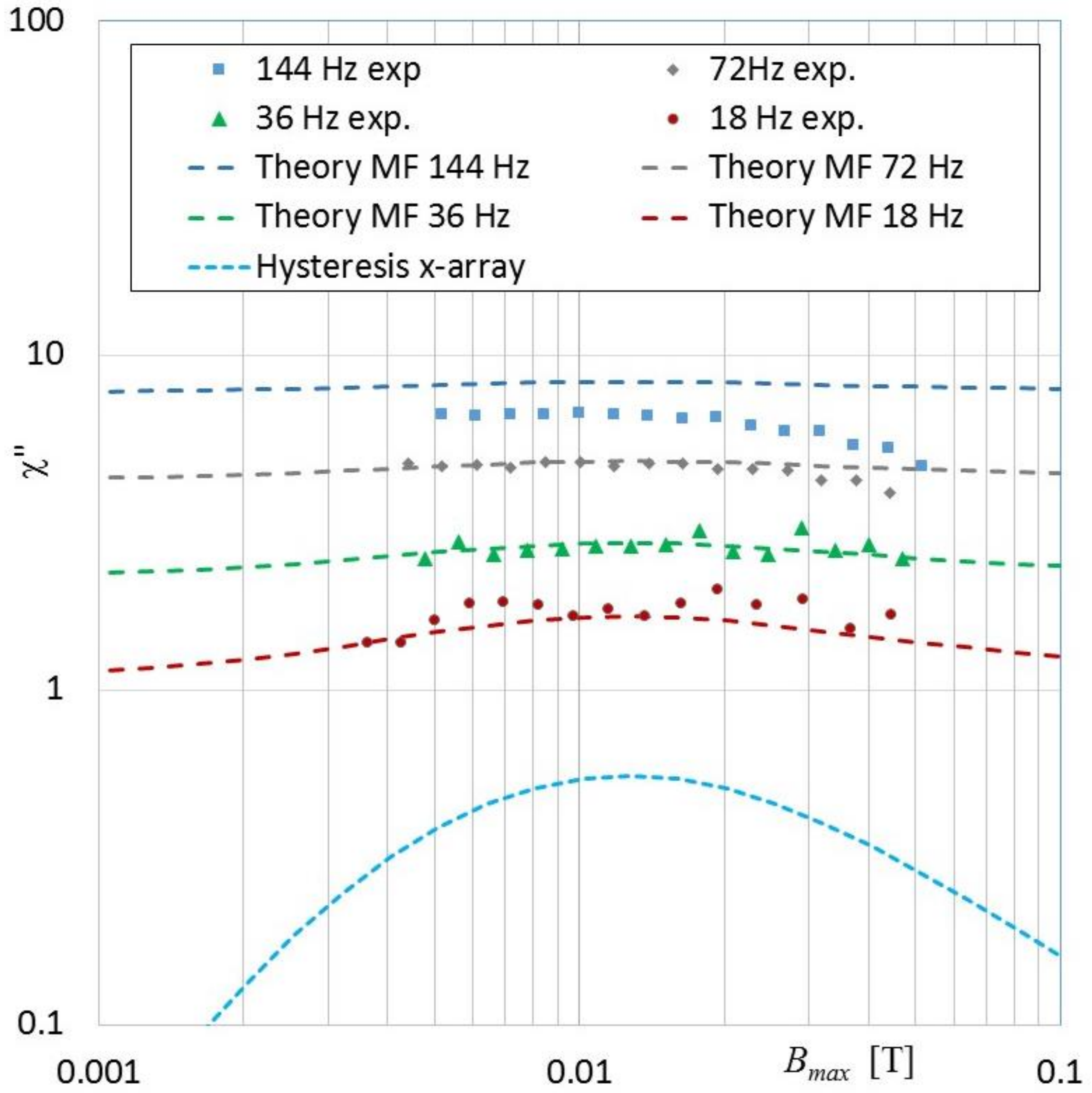
30K



40K



Magnetization AC loss measurements – straight samples 30 mm long



D5-2B-250 (250 µm filaments): $\rho_g = 4.5 \times \rho_{Cu}$