

# Striation for the reduction of AC loss and magnetization of CC tapes and cables

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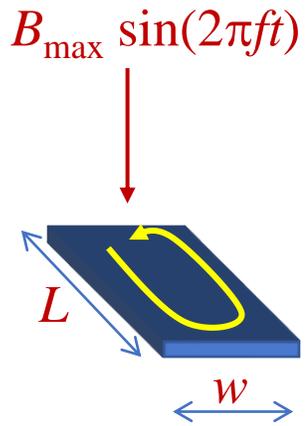
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SUBRA A/S, Farum, Denmark

- 1) Introduction: motivation for CC tape filamentization
- 2) Analytical models for AC loss components
  - comparison with experiments
- 3) Consequences for
  - cable arrangement
  - tape architecture
- 4) Conclusions

# Introduction

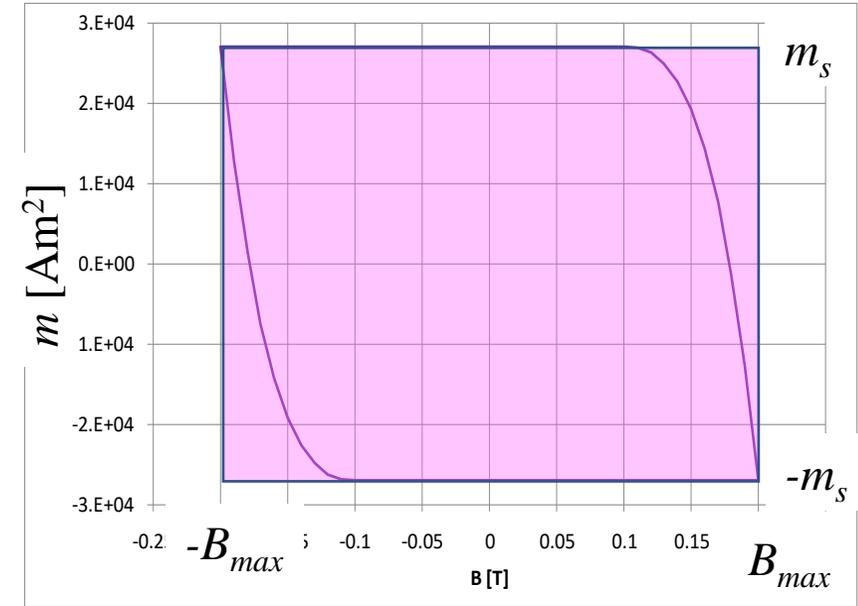
Straight tape (critical current  $I_c$ , width  $w$ ) in perpendicular magnetic field



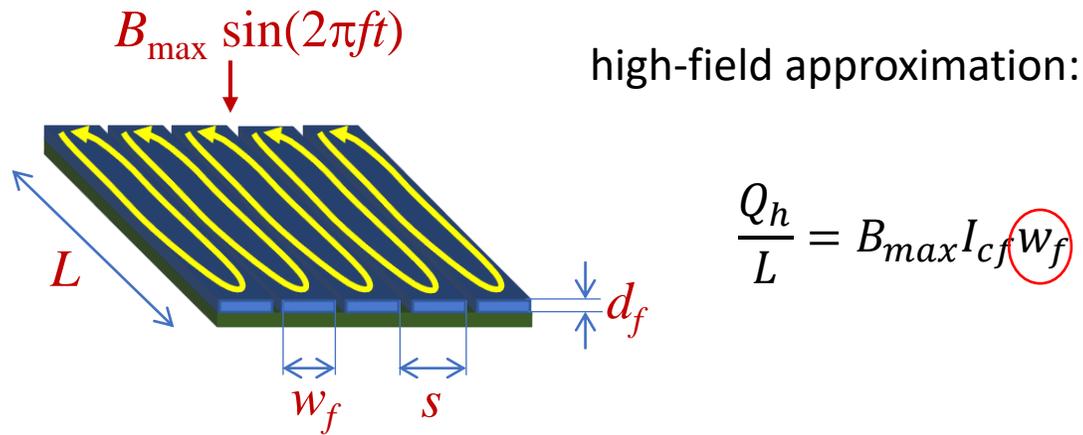
magnetic moment at saturation:  $m_s = \frac{I_c w}{4} L$

hysteresis loss per cycle and unit length:

$$\frac{Q}{L} \approx 4B_{\max} \frac{m_s}{L} = B_{\max} I_c w$$



# AC loss in filamentized tape: hysteresis loss

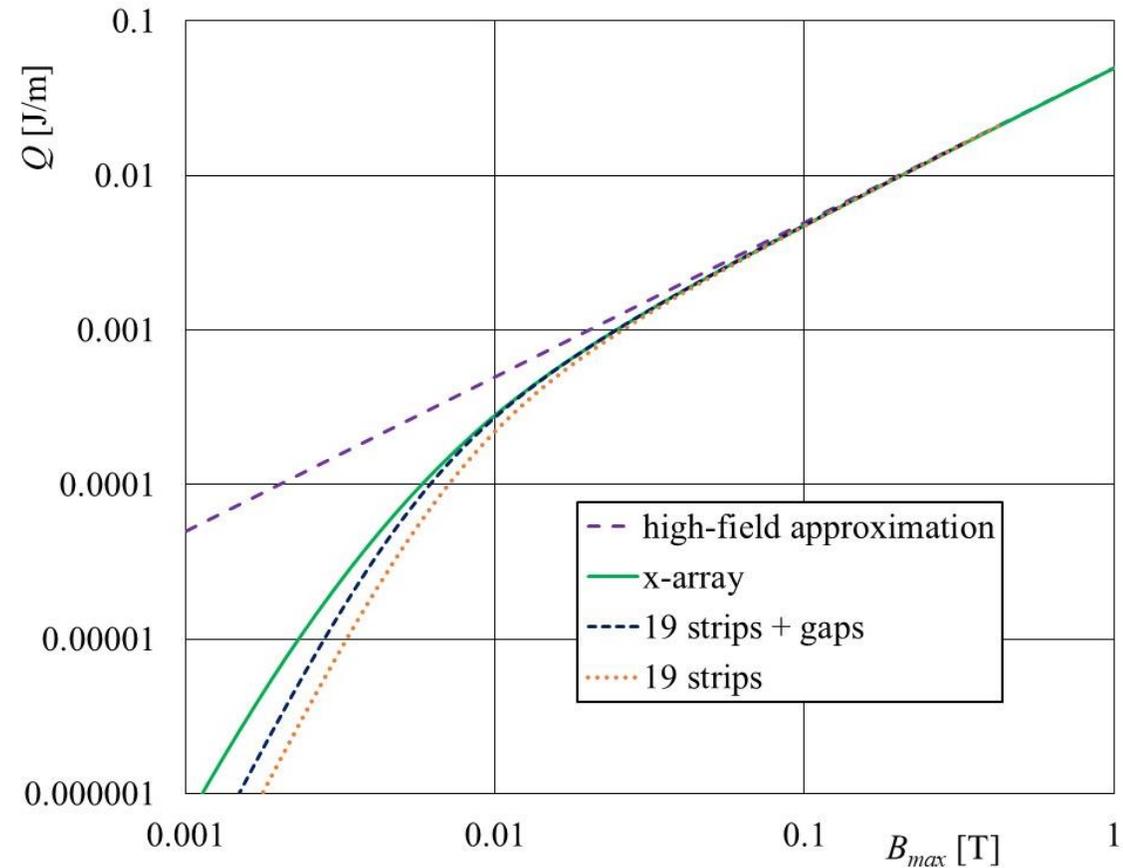


$N_f$  single strips: [E H Brandt and M Indenbom, Phys. Rev. B 48 \(1993\) 12893](#)

x-array of strips: [Y Mawatari, Phys. Rev. B 54 \(1996\) 13215](#)

$$\frac{Q_x}{L} = \frac{-4N_f s^2}{\pi\mu_0} \int_0^{B_{max}} (B_{max} - 2B) \ln \left[ 1 - \frac{X}{\cosh^2(B/B_0)} \right] dB$$

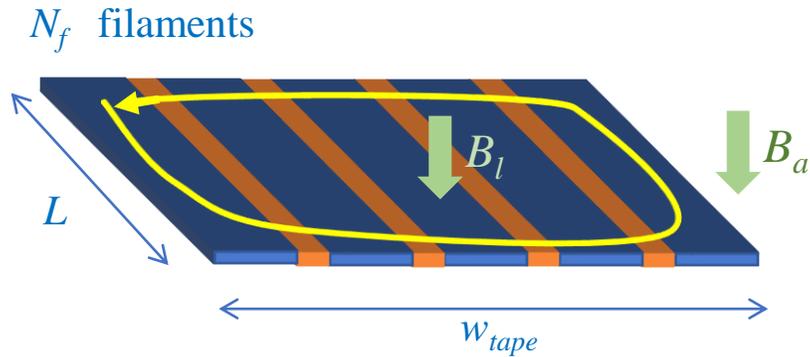
$$B_0 = \mu_0 I_{cf} / \pi w_f \quad X = \left[ \sin \left( \frac{\pi w_f}{2s} \right) \right]^2$$



# Coupling loss in filamentised tape, low frequency

W J Carr Jr, Supercond. Sci. Technol. 20 (2007) 168

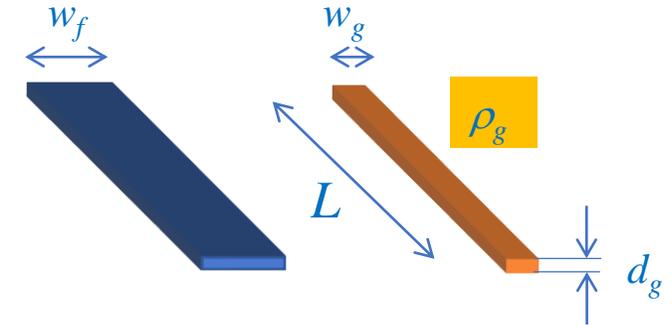
assumption:  $B_l \approx B_a$



$$B_a = B_{max} \sin(\omega t)$$

$$\omega = 2\pi f$$

relevant parameters:  $N_f, L, w_f, w_g, d_g, \rho_g$



$$\frac{Q_c}{L} = \frac{\pi^3}{3} B_{max}^2 w_{tape} d_g \frac{\omega}{\rho_{\perp}} \left(\frac{L}{2\pi}\right)^2$$

$$\rho_{\perp} = \rho_g \frac{(N_f - 1)w_g}{w_{tape}}$$

in reality a fitting parameter

valid only for **low frequencies**: loss is per cycle is directly proportional to frequency

# Coupling loss in filamentised tape, model extension to higher frequencies

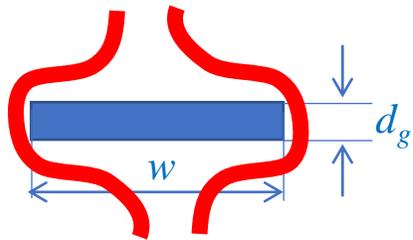
assumption: magnetic field decay from the tape ends is exponential

$$B_l = \frac{B_a}{\cosh(L/2\lambda)} \cosh(z/\lambda)$$

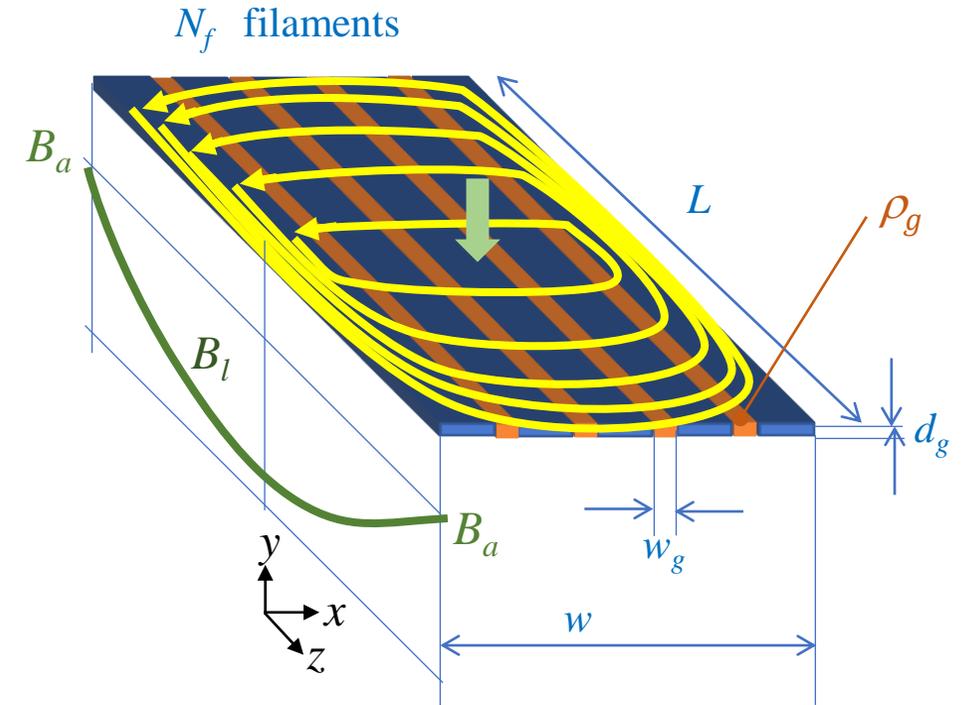
$$M = \frac{\dot{B}_a \lambda^2}{\rho_{\perp}} \left[ 1 - \frac{2\lambda}{L} \tanh(L/2\lambda) \right]$$

$$\rho_{\perp} = \rho_g \frac{(N_f - 1)w_g}{w}$$

penetration depth,  $\lambda$ , determined from the asymptote at perfect screening



$$\lambda^2 = \frac{\pi^2 w \rho_{\perp}}{8 d \mu_0 \omega}$$



# Coupling loss in filamentised tape, model extension to higher frequencies

$$Q_c = wLd \oint B_a dM = - \int_0^T M \dot{B}_a dt$$

$$\frac{Q_c}{L} = \frac{wd}{\rho_{\perp}} \pi \omega B_{max}^2 \lambda^2 \left[ 1 - \frac{2\lambda}{L} \tanh(L/2\lambda) \right]$$

general coupling loss expression: [A M Campbell, Cryogenics 22 \(1982\) 3](#)

$$\frac{Q_c}{L} = wd\pi \frac{B_{max}^2}{\mu_0} \chi_0 \frac{\omega\tau}{1 + \omega^2\tau^2}$$

$$\chi_0 = \frac{\pi w}{4 d_g}$$

$$\lim_{\omega \rightarrow 0} \frac{Q_c}{L} = wd\pi \frac{B_{max}^2}{\mu_0} \frac{\pi w}{4d} \omega\tau$$

then:  $\tau = \frac{\mu_0 d L^2}{3\pi w \rho_{\perp}}$

final formula:

$$\frac{Q_c}{L} = 3\pi^2 w^2 \frac{B_{max}^2}{\mu_0} \frac{\lambda^2}{L^2} \left[ 1 - \frac{2\lambda}{L} \tanh\left(\frac{L}{2\lambda}\right) \right] \frac{\omega\tau}{1 + \omega^2\tau^2}$$

[\*]

$$\lambda^2 = \frac{\pi w \rho_{\perp}}{4 d \mu_0 \omega}$$

$$\rho_{\perp} = \rho_g \frac{(N_f - 1)w_g}{w}$$

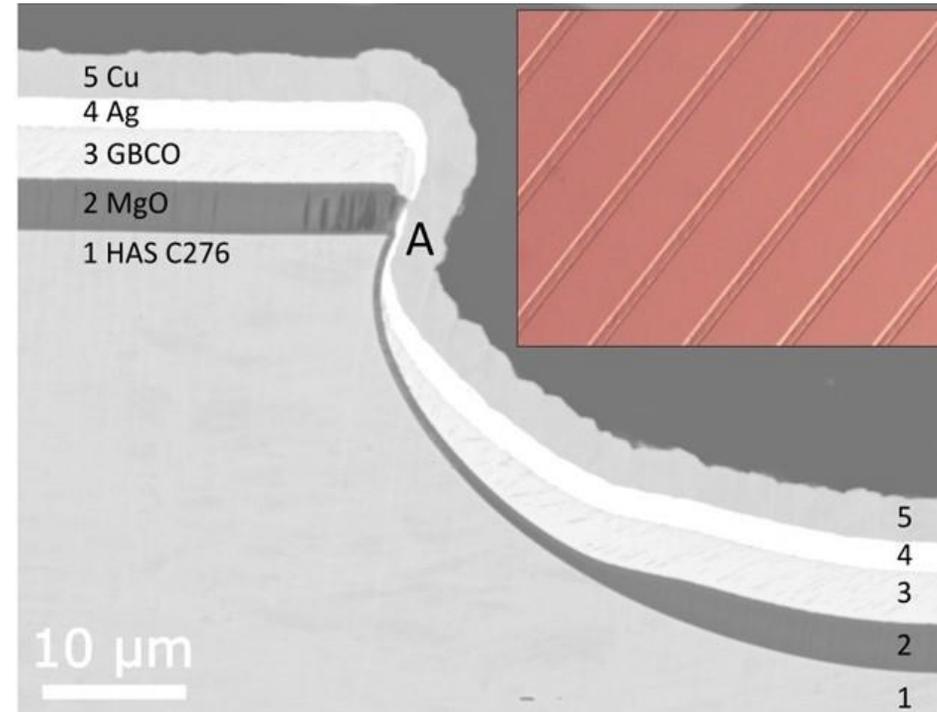
# Model validation by experiments

filamentized tapes produced using large-scale low-cost technology:

- SUBRA produced 3D-patterned Hastelloy
- buffer, REBCO and Ag cap layer are deposited via standard industrial procedures at THEVA
- Cu metallization added by THEVA/SUBRA

[A Wulff et al., Supercond. Sci. Technol. 28 \(2015\) 072001](#)  
[A R Insinga et al., IEEE Trans. Appl. Supercond.. 28 \(2018\) 6601705](#)  
[A R Insinga et al., IEEE Trans. Appl. Supercond.. 29 \(2019\) 8200704](#)

Ag, Cu  
REBCO  
buffer(s)



[F Gömöry et al., IEEE Trans. Appl. Supercond.. 34 \(2024\) 5901605](#)

# Model validation by AC magnetisation experiments

filamentized tapes produced using large-scale low-cost technology:

- SUBRA produced 3D-patterned Hastelloy
- buffer, REBCO and Ag cap layer are deposited via standard industrial procedures at THEVA
- Cu metallization added by THEVA/SUBRA

fixed parameters:

- geometry:  $L, w, w_f, w_g, d_g, d_m$

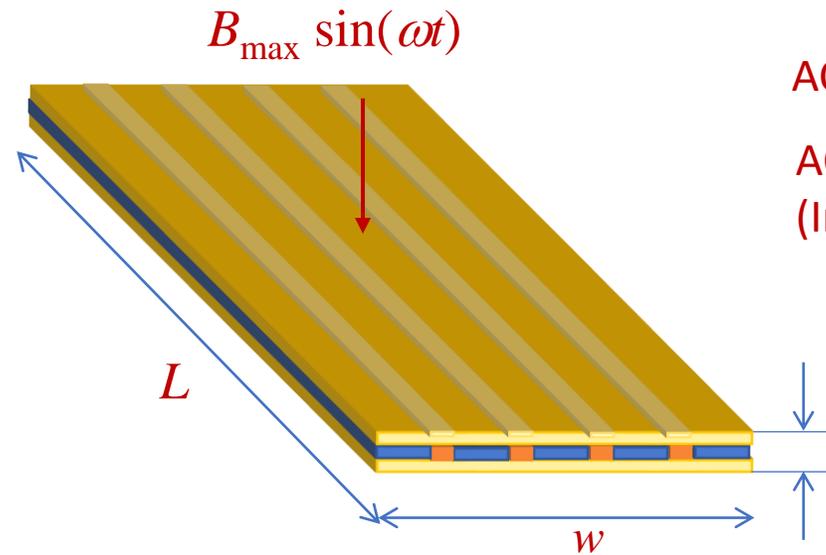
- superconductor: 
$$I_{c,filament} = \frac{I_{c,tape}}{N_{filaments}}$$

fitted:

- gap resistivity 
$$\rho_{\perp} = \rho_g \frac{(N_f - 1)w_g}{w_{tape}} \quad \rho_g = k_g \rho_{Cu}$$

- resistivity of metallic overlayer(s) 
$$\rho_m = k_m \rho_{Cu}$$

$$\rho_{Cu} = 2 \times 10^{-9} \Omega m$$



AC loss:  $Q/L$  [J/cycle/m]

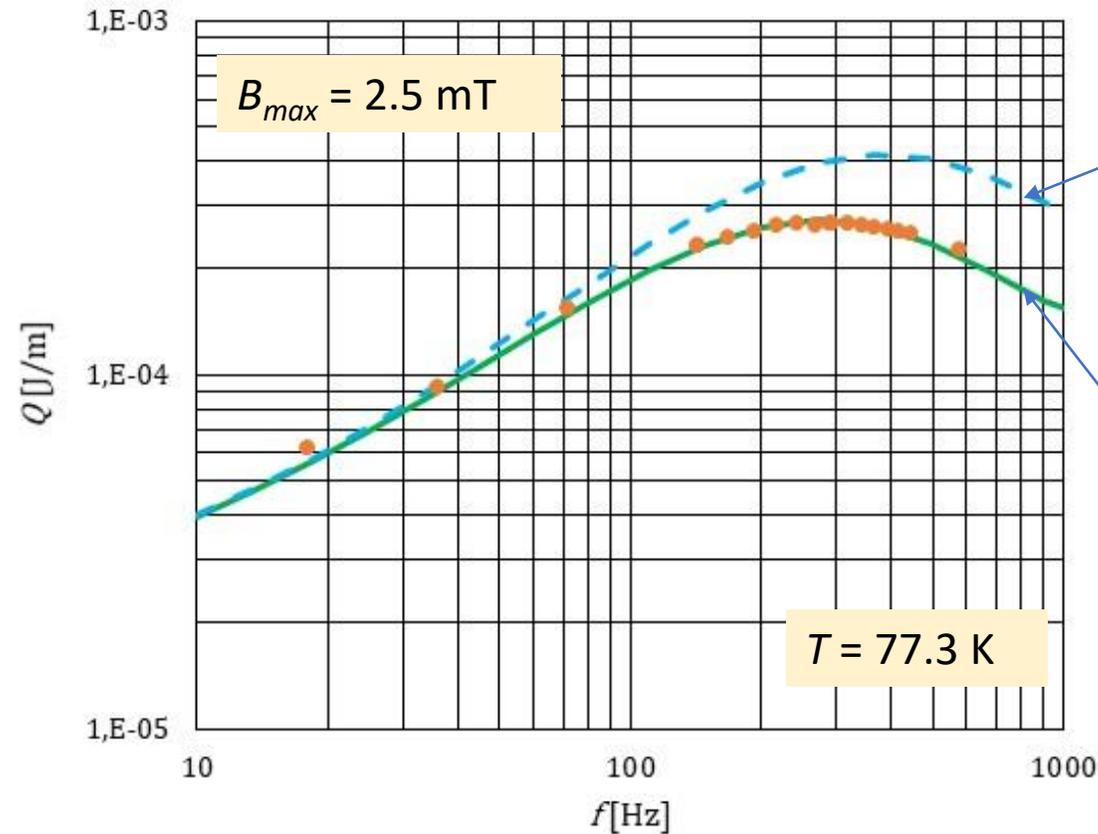
AC susceptibility  
(Imaginary part):

$$\chi'' = \frac{Q}{Lwt} \frac{\mu_0}{\pi B_{max}^2}$$

# Model validation by AC magnetization experiments

Tape 4 mm wide,  $I_c = 90$  A, 7 filaments (500  $\mu\text{m}$ ), 3.5  $\mu\text{m}$  Ag + 14  $\mu\text{m}$  Cu

Sample length: 3 cm



fitting parameter

$$\frac{Q_c}{V} = \textcircled{A} \frac{B_{max}^2}{\mu_0} \frac{\omega\tau}{1 + \omega^2\tau^2}$$

N Amemiya et al., IEEE Trans Appl Supercond 32 (2022) 6602005

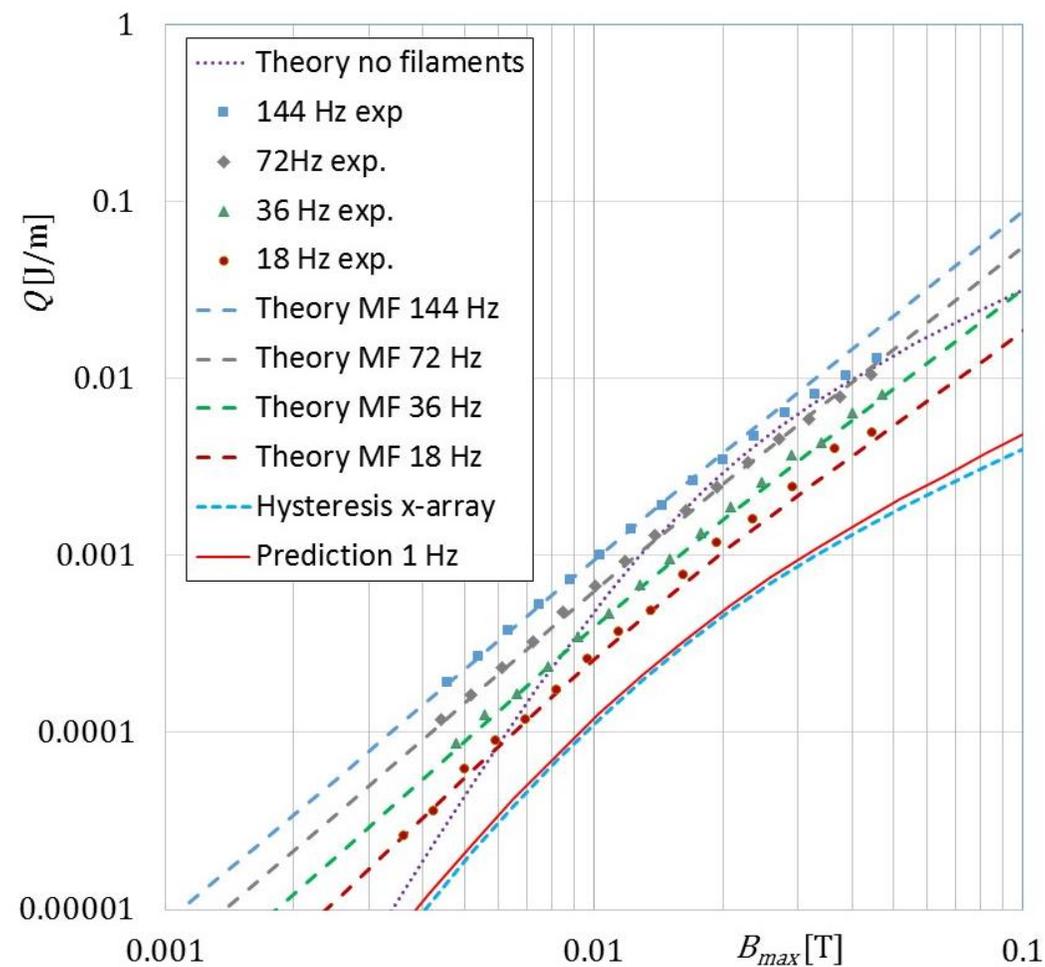
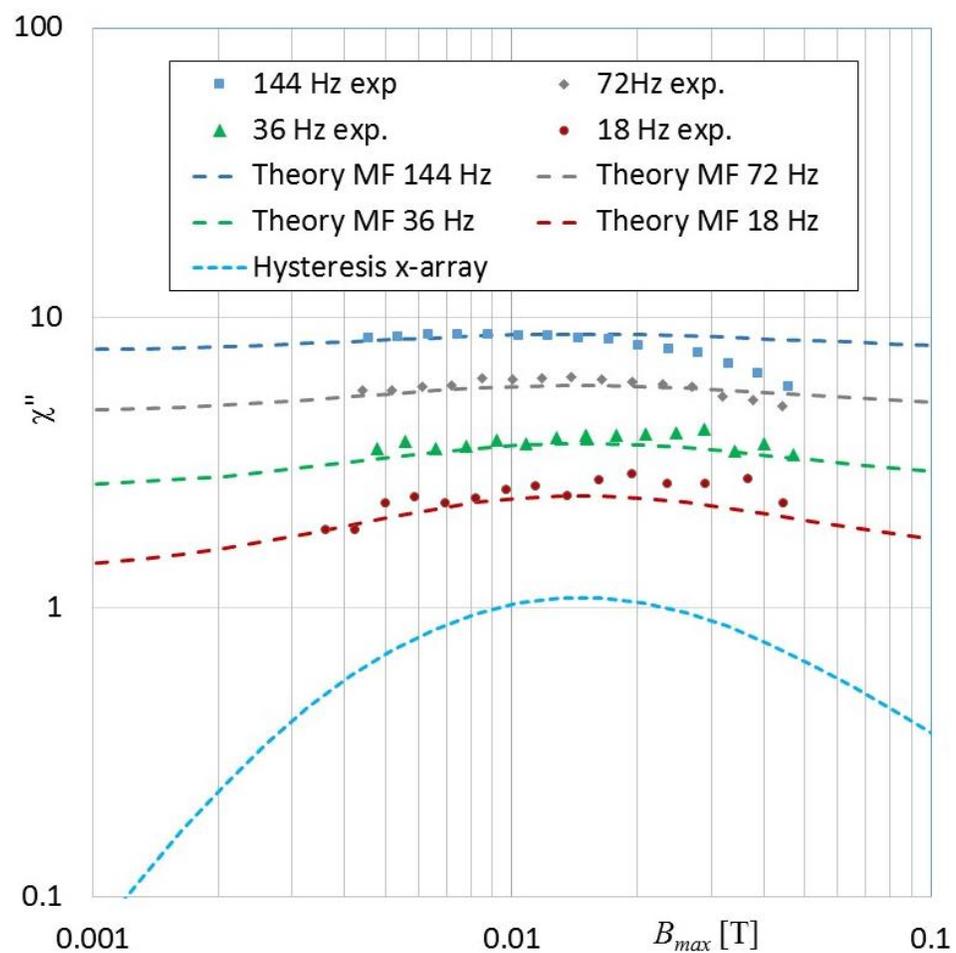
M D Sumption et al., Cryogenics 111 (2020) 103171

formula [\*]

# Model validation by AC magnetization experiments

Tape 4 mm wide,  $I_c = 90$  A, 7 filaments (500  $\mu\text{m}$ ), 3.5  $\mu\text{m}$  Ag + 14  $\mu\text{m}$  Cu

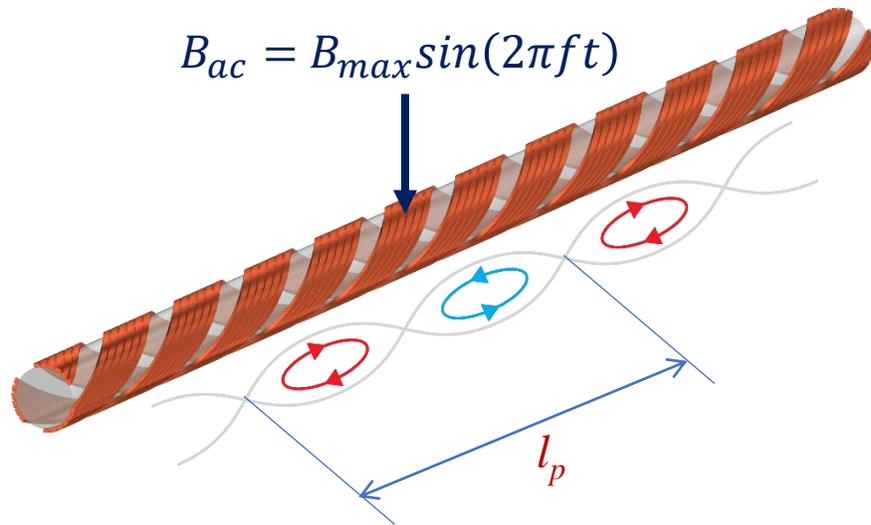
sample length: 3 cm



# Model extension to helical tapes and round cables

tape helicity (lay angle  $\alpha$ )

necessary for benefitting from the tape filamentization



length of transposition  $\rightarrow 2 \times$  equivalent sample length



tape length in coupling loss:

$$l_c \rightarrow L \quad l_c = \frac{l_p}{\pi \cos \alpha} + \frac{w_{tape}}{t g \alpha} \quad \tau = \frac{\mu_0 d l_c^2}{3\pi w \rho_{\perp}}$$

tape helicity:  $\rightarrow \times \frac{2}{\pi \cos \alpha}$

$$\frac{Q}{L_{cable}} = N_{tapes} \frac{2}{\pi \cos \alpha} \left[ \frac{Q_h + Q_c + Q_e}{L} \right]$$

# AC loss of round cables – low loss tapes

3 cable samples:

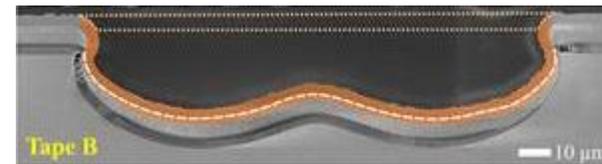
12 mm wide tapes, 1 mm filaments  
differing in Cu stabilisation

Tape	Cu [ $\mu\text{m}$ ]
A	2
B	3
C	6

from AC loss measurement on straight samples:

$$I_c = 250 \text{ A}$$

$$\rho_g / \rho_{Cu} = 2,6 \div 2,8$$



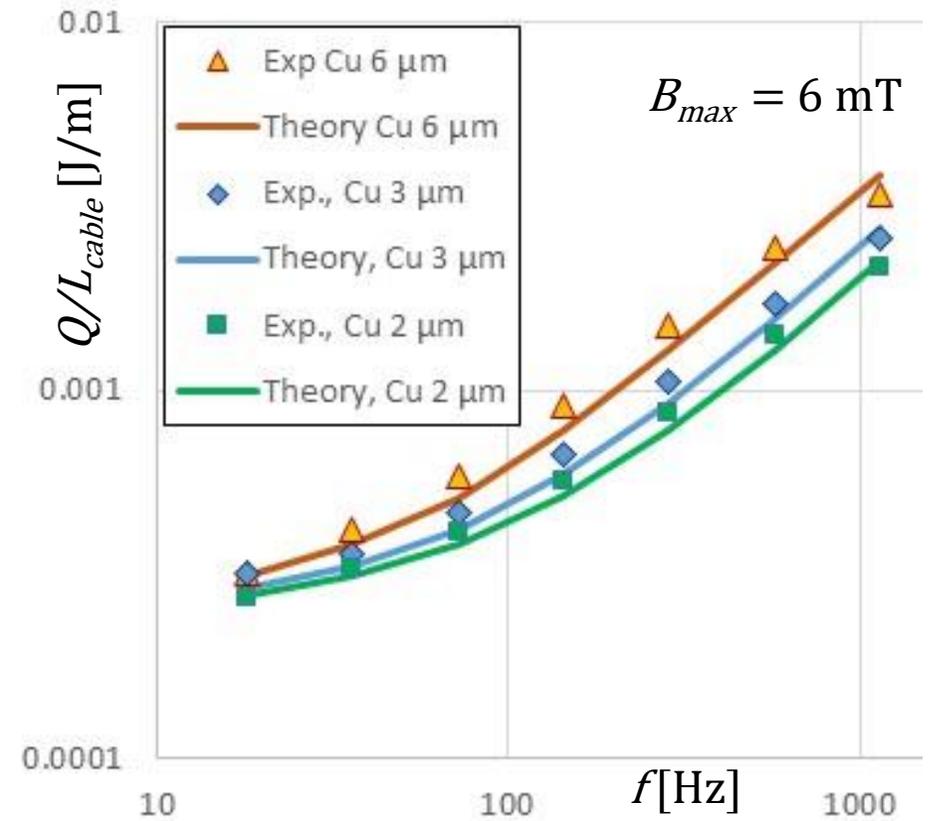
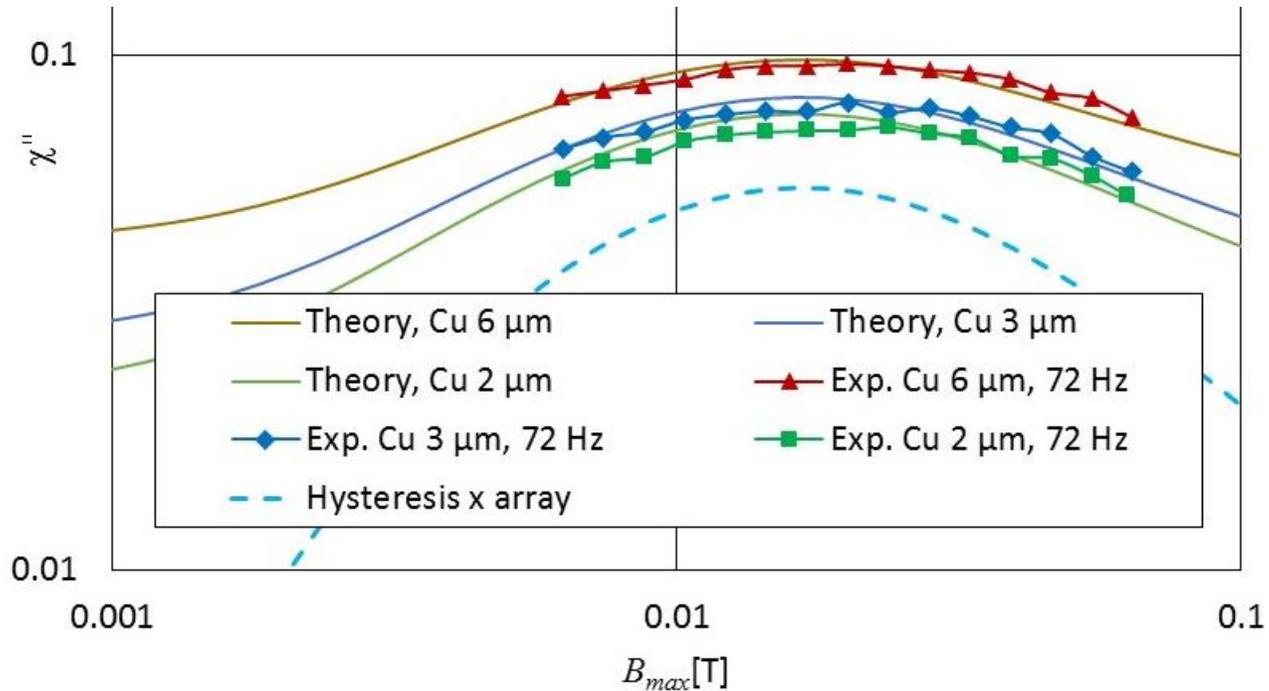
$$\rho_{Cu} = 2 \times 10^{-9} \Omega\text{m}$$

F Gömöry et al., IEEE Trans. Appl. Supercond.. 35 (2025) 5900205

# AC loss of round cables – low loss tapes

3 cable samples: single tape, 1 layer

$D = 10 \text{ mm}$ ,  $L_{cable} = 65 \text{ mm}$ ,  $l_p = 13 \text{ mm}$ ,  $\alpha = 67^\circ$



$I_c = 300 \text{ A}$

$\rho_g / \rho_{Cu} = 2.7$

# AC loss of round cables – low loss tapes

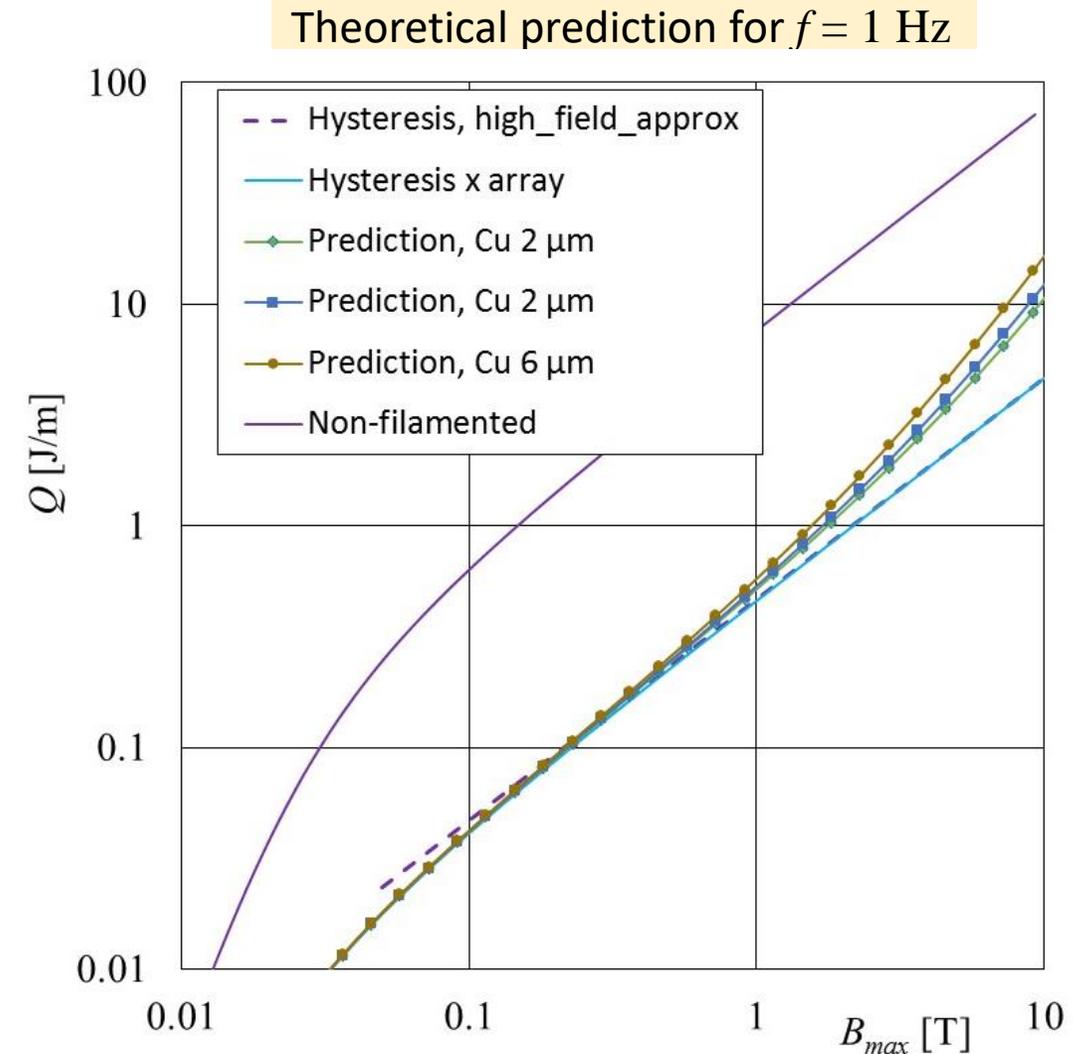
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Tape	Cu [ $\mu\text{m}$ ]
A	2
B	3
C	6

thin metallisation allows dramatic reduction of AC loss

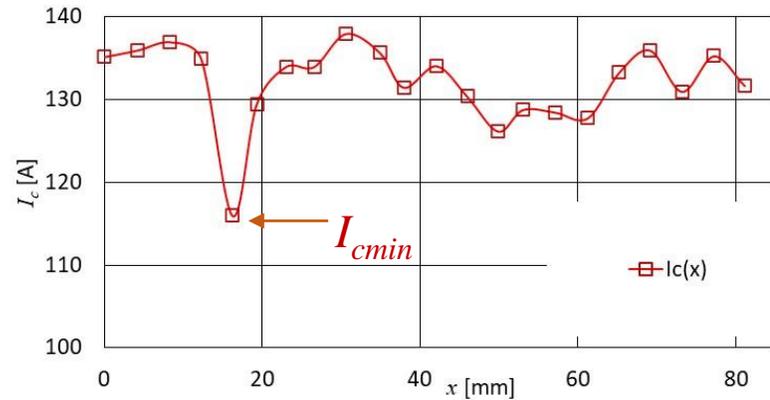
- is the stability sufficient?



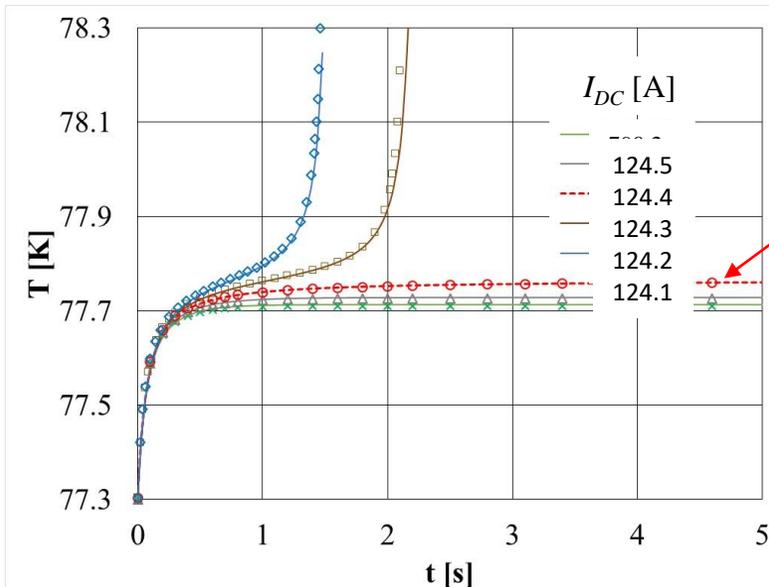
# Thermal runaway current – dependence on Cu thickness

computing the thermal runaway current,  $I_{tr}$

1 mm long defect  
“weak spot”

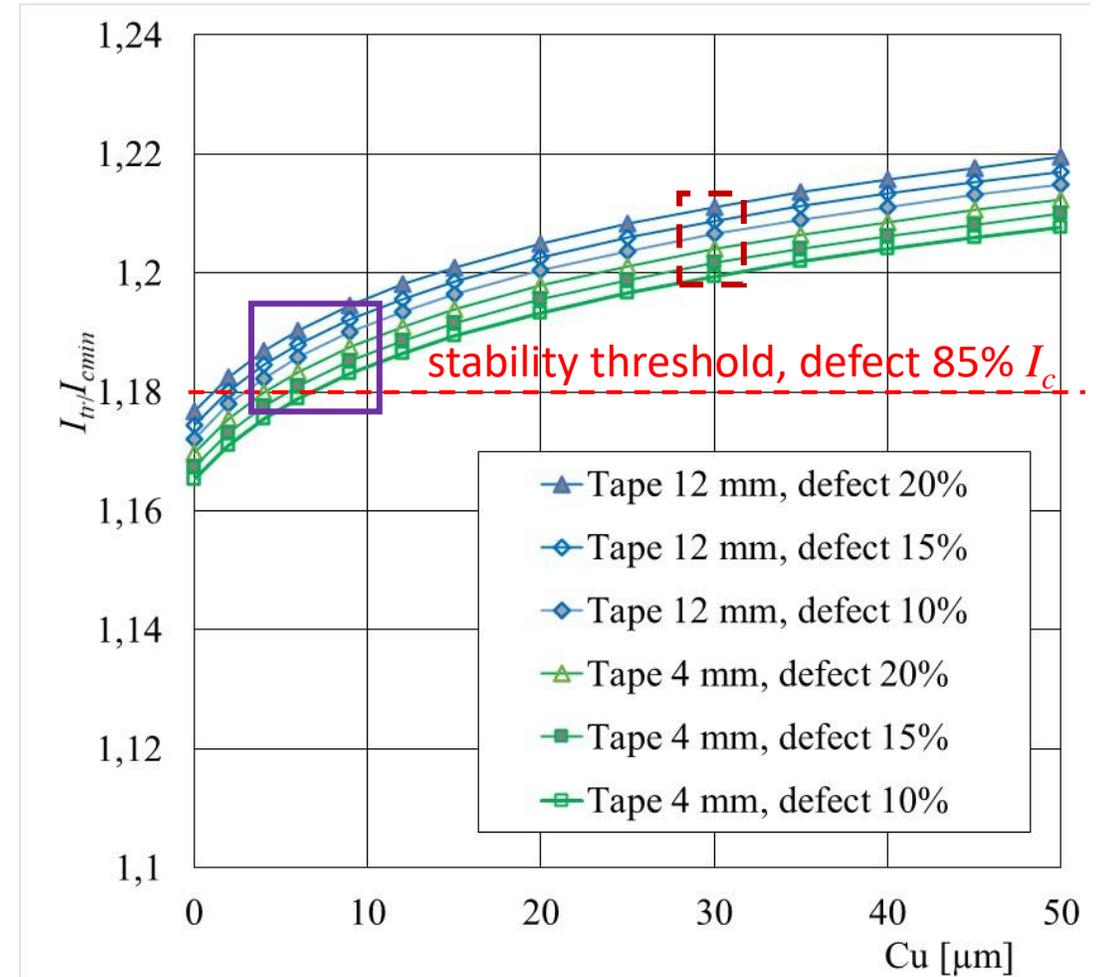


when surpassing **thermal runaway current**  
the weak spot converts into a **hot spot**:



thermal conductance between  
the weak spot and its surrounding

$$I_{tr} = I_{cmin} \left( \frac{K_0(T_c - T_0)}{I_{cmin} e \Delta x_{ws} E_c n} \right)^{\frac{1}{n+1}}$$

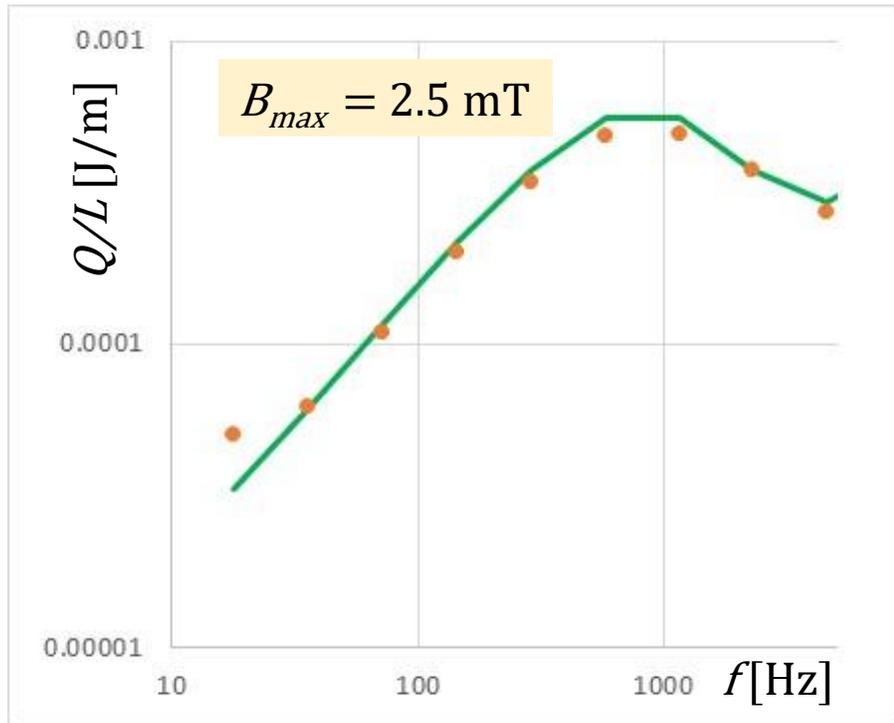


F Gömöry and J Šouc: Supercond. Sci. Technol. 34 (2021) 025005

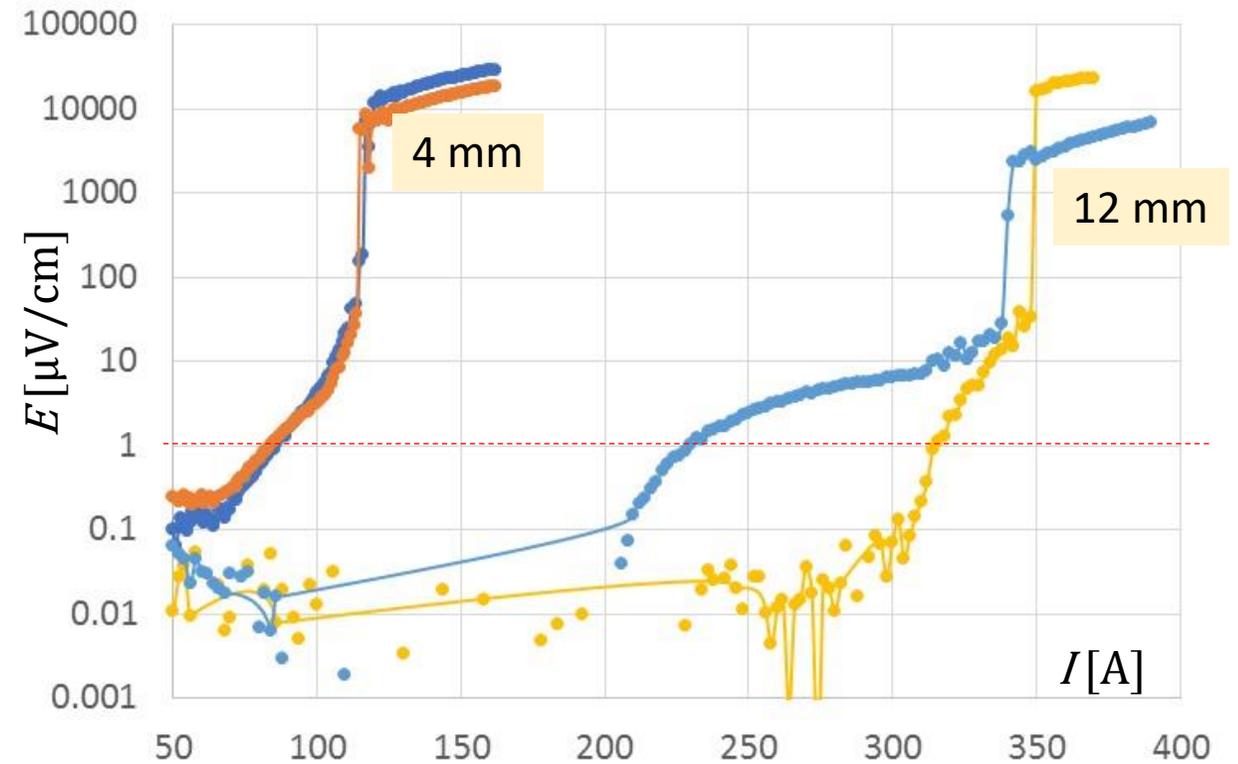
# AC loss of round cables – tape with thick metalisation

Tape 12 mm wide, 0.5 mm filaments, Cu stabilization 15  $\mu\text{m}$

straight sample:  $I_c = 264 \text{ A}$   $\rho_g/\rho_{Cu} = 3.2$



excellent stability, no degradation after quenching



# AC loss of round cables – tape with thick metalisation

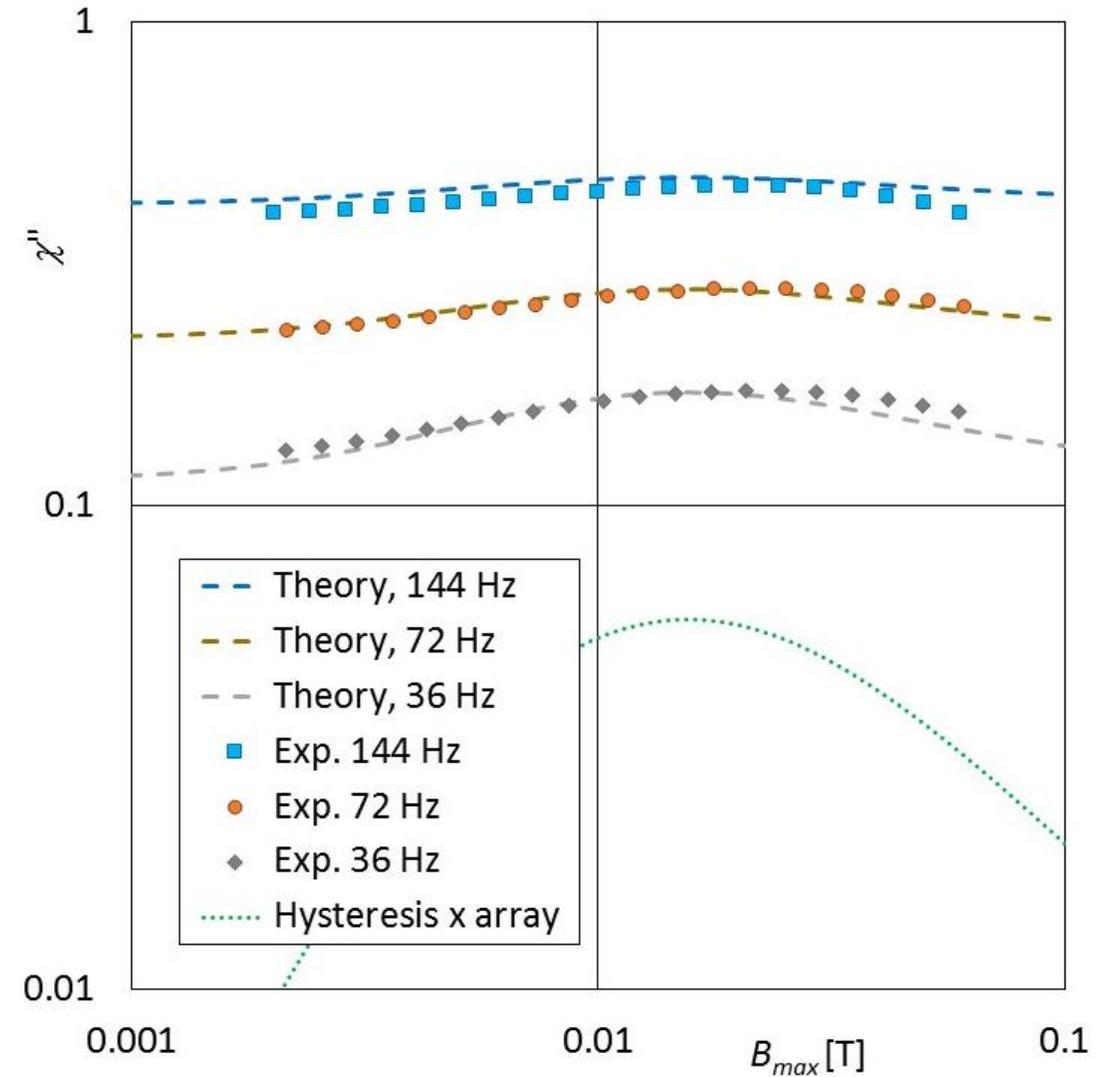
Tape 12 mm wide, 0.5 mm filaments, Cu stabilization 15  $\mu\text{m}$

cable: 2 layers  $\times$  2 tapes  $\alpha = 40^\circ$

$D = 10 \text{ mm}$ ,  $L_{\text{cable}} = 145 \text{ mm}$ ,  $l_p = 37 \text{ mm}$

$$I_c = 264 \text{ A}$$

$$\rho_g / \rho_{Cu} = 3.2$$



# AC loss of round cables – tape with thick metalisation

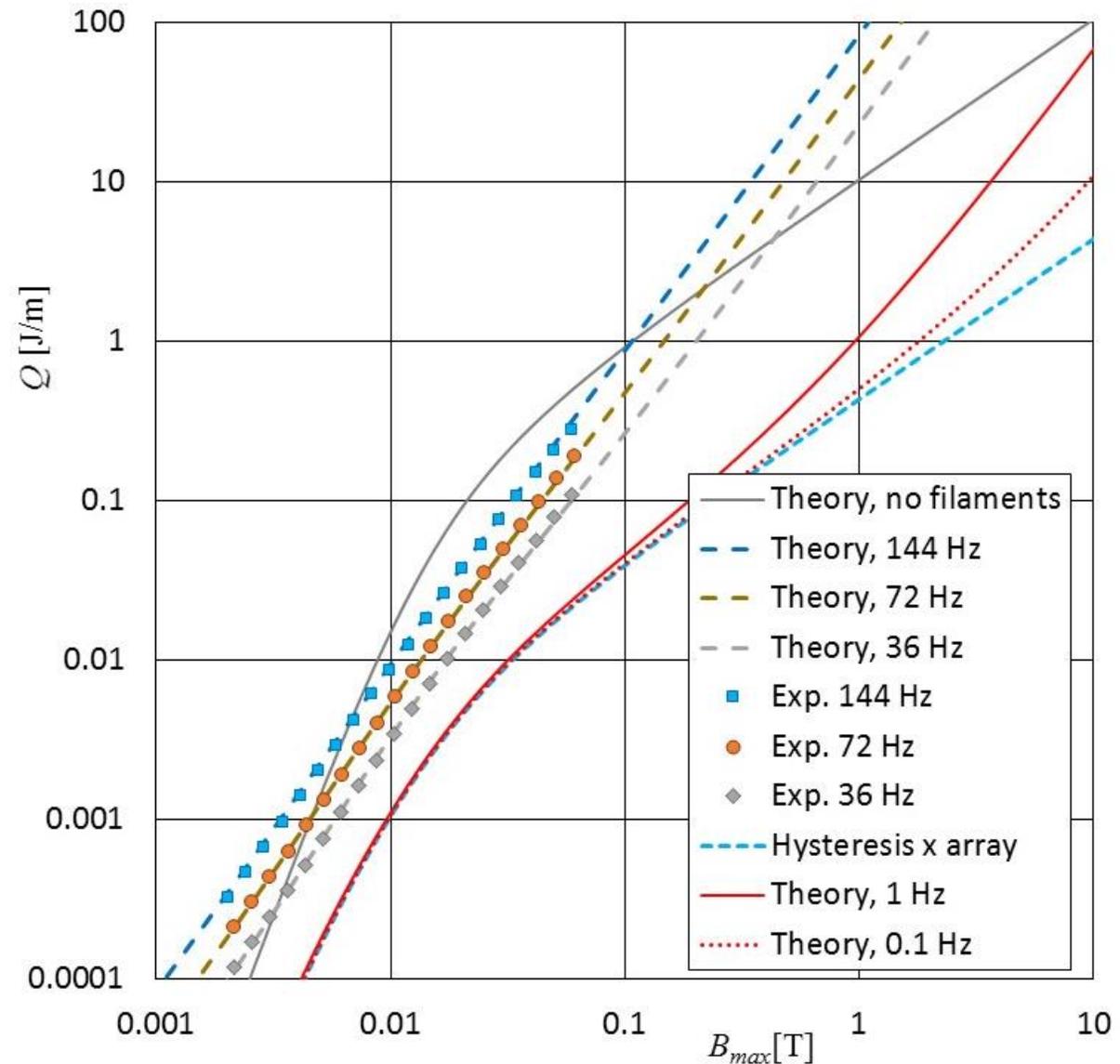
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# Conclusions

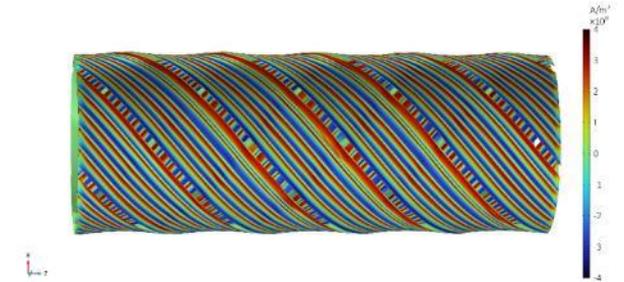
- Filamentization is a plausible solution for reducing AC loss in magnets for pulsed fields
- Theoretical models allow rapid estimate of AC loss in round cables (with helical tape arrangement)
- Optimal thickness of metallic stabilisation depends on application

[N Amemiya et al. IEEE Trans. Appl. Supercond. 33 \(2023\) 4701507](#)

# Important topics not covered in this presentation

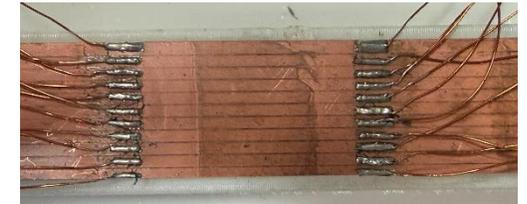
- Interplay between various loss mechanisms – **FEM**

CCA2025 poster Mykola Soloviov et al.



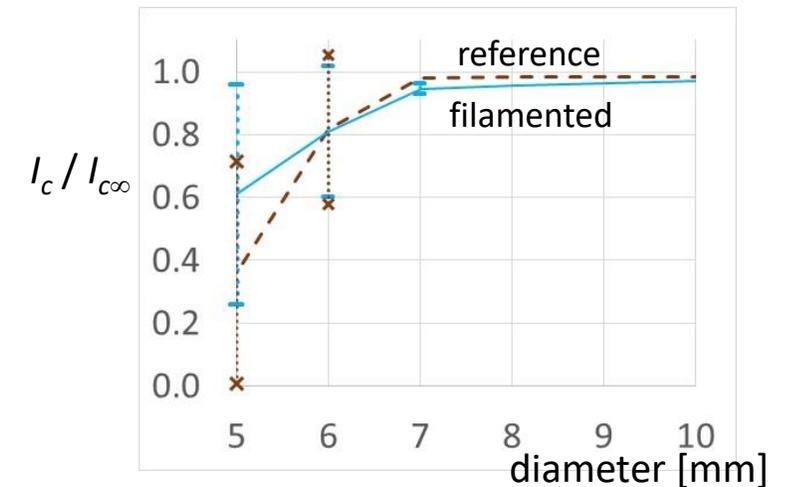
- Role of metallic stabilisation in **current sharing** among filaments

CCA2025 poster Martin Kucharovič et al.



- Mechanical endurance of filamentised tapes in **bending and cabling**

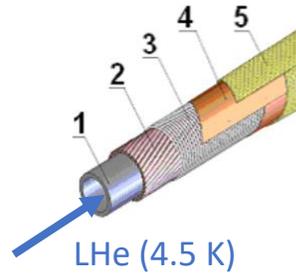
CCA2025 poster Tomáš Kujovič et al.



Thank you for your attention

# Potential relevance in magnet technology

- Particle accelerators

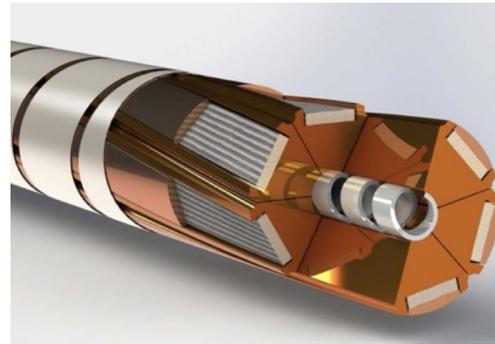


F Kaether et al., 12th Int. Particle Acc. Conf.  
doi:10.18429/JACoW-IPAC2021-TUPAB378

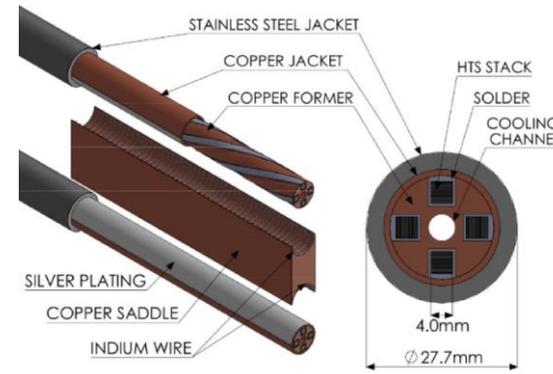
P Ferracin et al., IEEE Trans. Appl. Supercond. 32 (2022) 4000906



- Fusion (CS in particular)



L Muzzi et al., IEEE Trans. Appl. Supercond. 33 (2023) 4200106



Z Hartwig et al., Supercond. Sci. Technol. 33 (2020) 11LT01

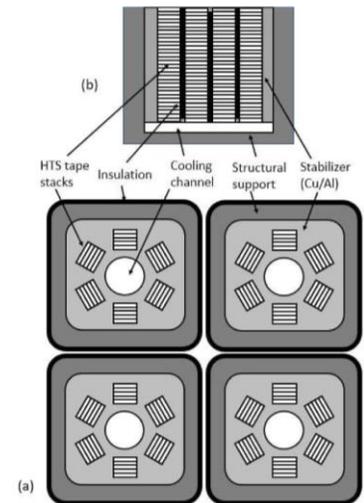


Y Ueno et al., Plasma Fus. Research 16 (2021) 2405071

- no effect in case of non-transposed tapes

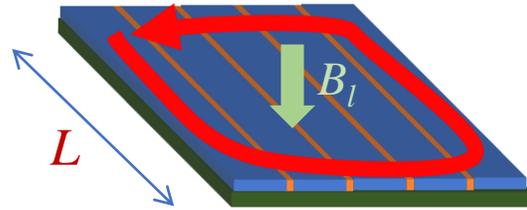
D Uglietti et al., Cryogenics 110 (2020) 103118

N Mitchell et al., Supercond. Sci. Technol. 34 (2021) 103001



# AC loss in (straight) filamentised tape: coupling loss

Coupling loss:



applied magnetic field:  $B_a = B_{max} \sin(\omega t)$

general treatment (**round wire**):

A M Campbell, Cryogenics 22 (1982) 3

assumption:  $B_l \approx B_a - \tau \frac{dB_l}{dt}$

time constant of magnetic flux diffusion

$$\frac{Q_c}{V} = \frac{B_{max}^2}{\mu_0} n\pi \frac{\omega\tau}{1 + \omega^2\tau^2}$$

shape factor (2 for round wires)

K Kwasnitza and St Clerc, Physica C 233 (1994) 423

round wire  $\tau = \frac{1}{2} \frac{\mu_0}{\rho_{\perp}} \left(\frac{L}{2\pi}\right)^2$

expectation for filamentized tapes:

$$\frac{Q_c}{L} \propto B_{max}^2 \frac{L^2}{\rho_m}$$

resistivity of the medium between filaments

N Amemiya et al., IEEE Trans Appl Supercond 32 (2022) 6602005  
M D Sumption et al., Cryogenics 111 (2020) 103171

**qualitative prediction only: unclear volume  $V$ , shape factor  $n$ , resistivity...**

# Coupling loss in filamentised tape, model extension to higher frequencies

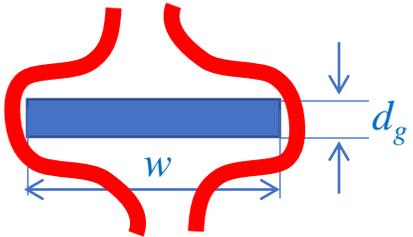
assumption: magnetic field decay from the tape ends is exponential

$$B_l = \frac{B_a}{\cosh(L/2\lambda)} \cosh(z/\lambda)$$

$$j_x(z) = \frac{-\dot{B}_a \lambda \sinh(z/\lambda)}{\rho_{\perp} \cosh(L/2\lambda)} \quad \rho_{\perp} = \rho_g \frac{(N_f - 1)w_g}{w}$$

$$M = \frac{\dot{B}_a \lambda^2}{\rho_{\perp}} \left[ 1 - \frac{2\lambda}{L} \tanh(L/2\lambda) \right] \quad (*)$$

penetration depth,  $\lambda$ , determined from the asymptote at perfect screening

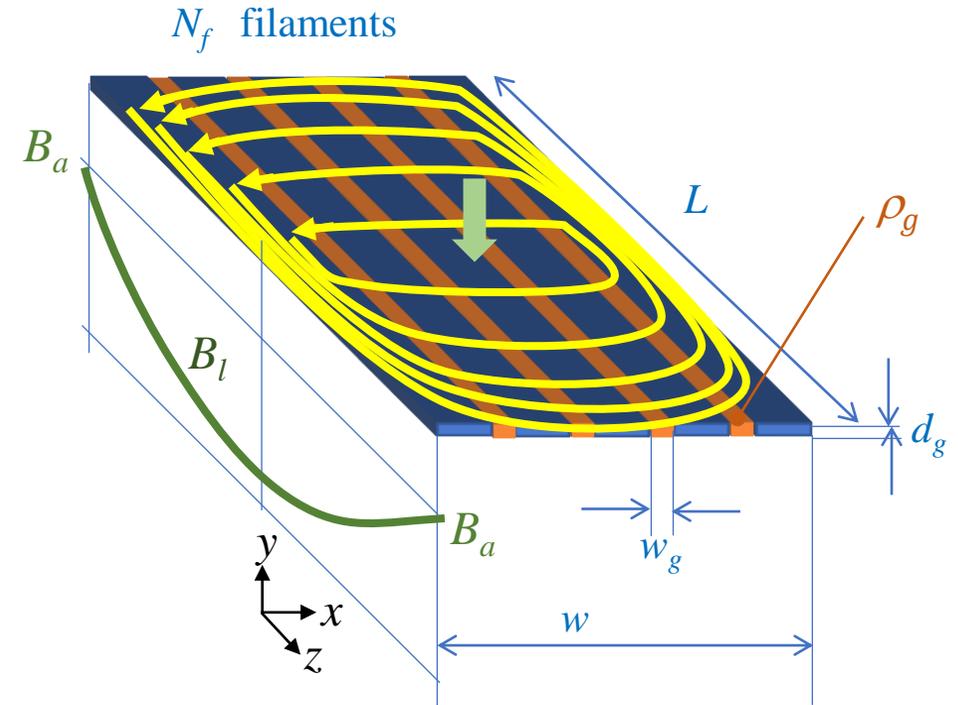


$$\lim_{\text{diamagnetic}} M = -\chi_0 B_a = -\frac{\pi w}{4 d_g} B_a$$

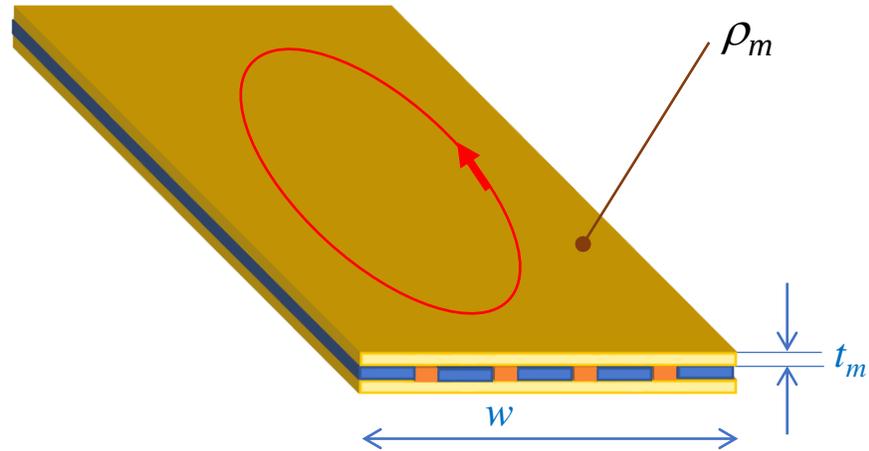
take  $\dot{B}_a \approx \frac{4B_a}{T}$  then

$$\lambda^2 = \frac{\pi^2 w}{8 d} \frac{\rho_{\perp}}{\mu_0 \omega}$$

on the other hand, from (\*):  $\lim_{\lambda \rightarrow 0} M = -\frac{\dot{B}_a \lambda^2}{\rho_{\perp}}$



# Eddy currents in metallic layer(s)



E. H. Brandt, Phys. Rev. B 50 (1994) 13833

$$\frac{Q_e}{L} = 2wt_m\pi\chi_0\chi''\frac{B_{max}^2}{\mu_0}$$

$$\chi'' = \left[ \frac{3}{4b} + \frac{\pi^2 b}{\ln(1 + b^2) + 5,57} \right]^{-1}$$

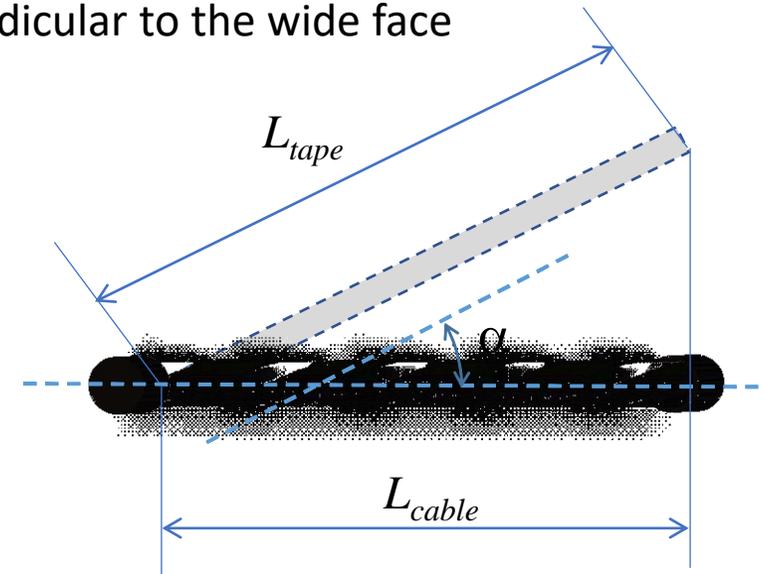
$$b = \omega\tau_m \quad \tau_m = \frac{t_m w \mu_0}{2 \rho_m}$$

# Model extension to round cables

All previous formulas are valid per unit length of tape [J/m], assuming  $B$  perpendicular to the wide face

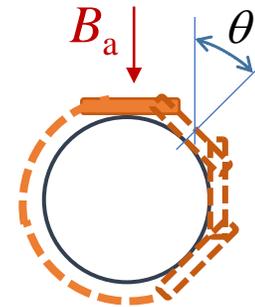
1) tape(s) longer than a cable

$$L_{tape} = \frac{L_{cable}}{\cos\alpha}$$



2) varying orientation with respect to the applied field

$$Q_{helical} = \frac{2}{\pi} Q_{\perp}$$

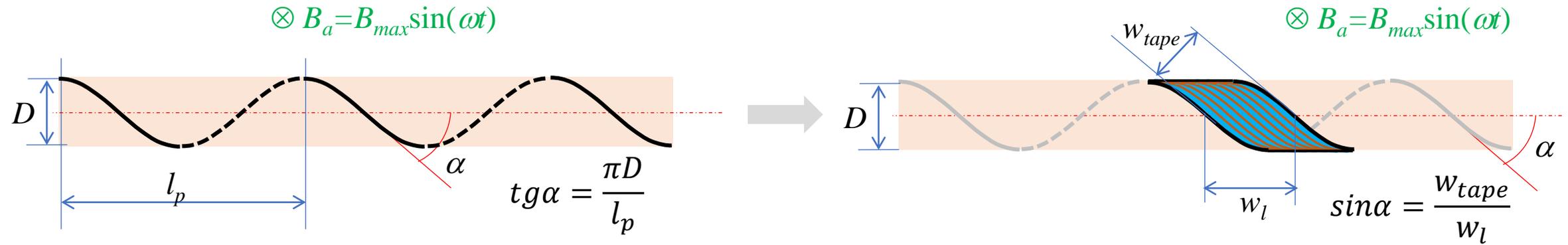


$$Q(\theta) = Q_{\perp} \cos(\theta)$$

$$\frac{1}{\pi} \int_0^{\pi} \cos(\theta) d\theta = \frac{2}{\pi}$$

3) coupling loss: dependence on the sample length

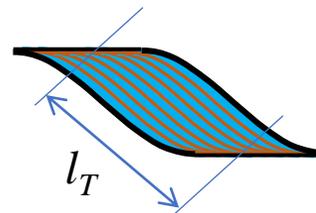
# Model extension to round cables – coupling loss



tape length in one transposition:

$$l_1 = \frac{l_p}{\cos\alpha} = \frac{\pi D}{\sin\alpha}$$

equivalent straight sample length at which the coupling currents close,  $l_c$ :



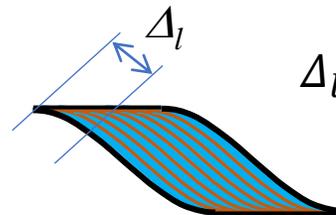
area:  $A = Dw_l = D \frac{w_{tape}}{\sin\alpha}$

as well:  $A \approx l_T w_{tape}$

then:

$$l_T \approx \frac{l_1}{\pi} = \frac{l_p}{\pi \cos\alpha}$$

correction for rounding of sharp corners:



$$\Delta_l = \frac{w_l}{2} \cos\alpha = \frac{w_{tape}}{2tg\alpha}$$

$$l_c = l_T + 2\Delta_l = \frac{l_p}{\pi \cos\alpha} + \frac{w_{tape}}{tg\alpha}$$