How to reduce hysteresis loss* in *Re*BCO based RCS super-ferric dipole magnets

***in theory**

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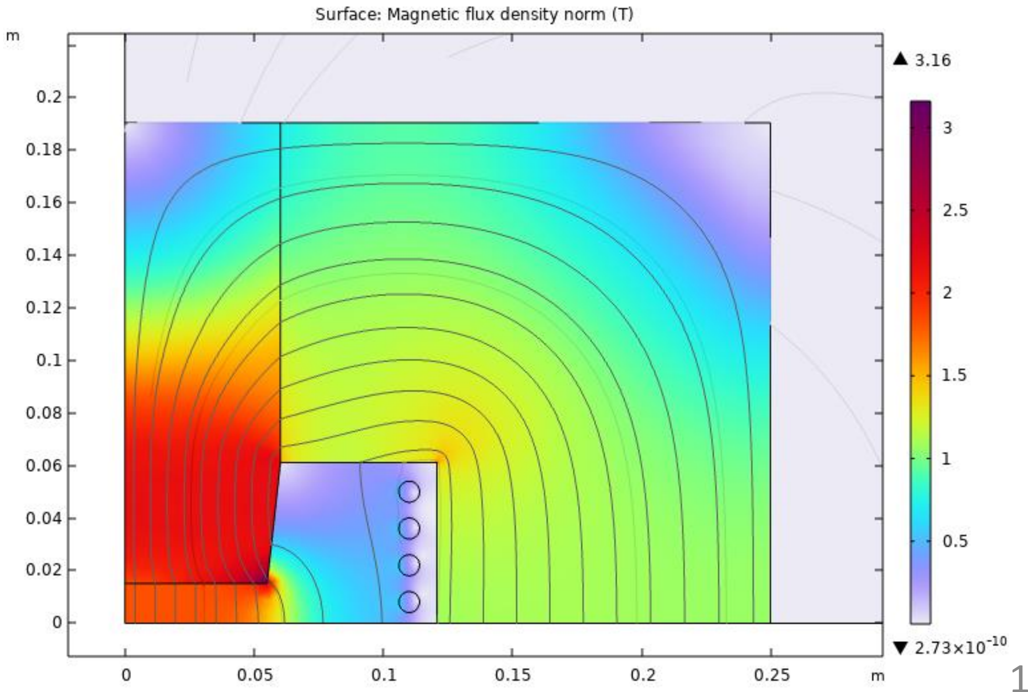
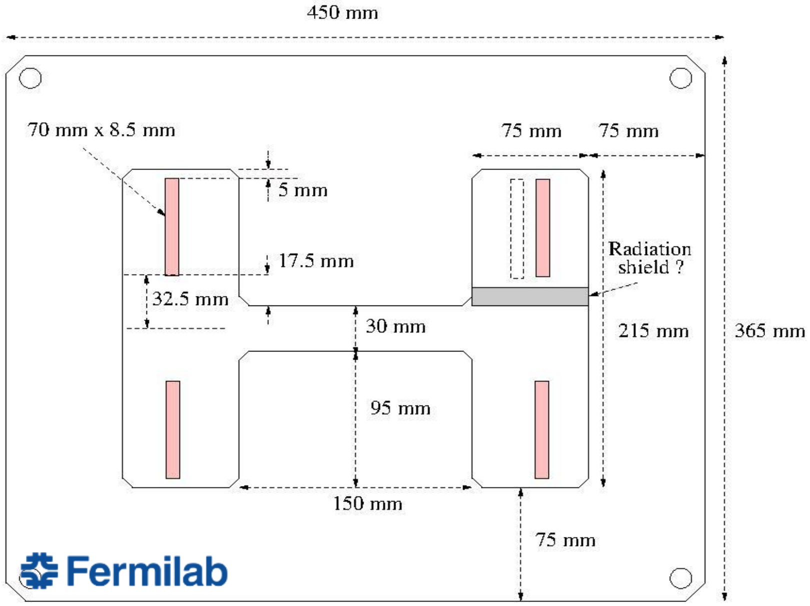


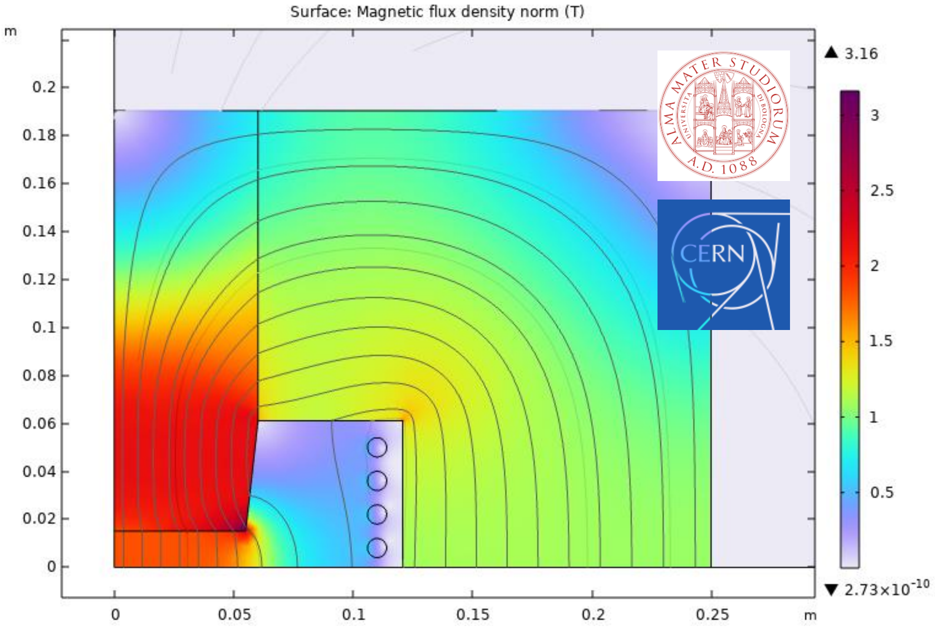
Presented at MuCOL annual meeting

- Hysteresis loss calculations for two *Re*BCO designs for RCS fast-ramping dipoles
- Values in the range 200-500 W/m-magnet at 15-40 K found, but heat is deposited at cold!
- Is it acceptable? How to reduce it?

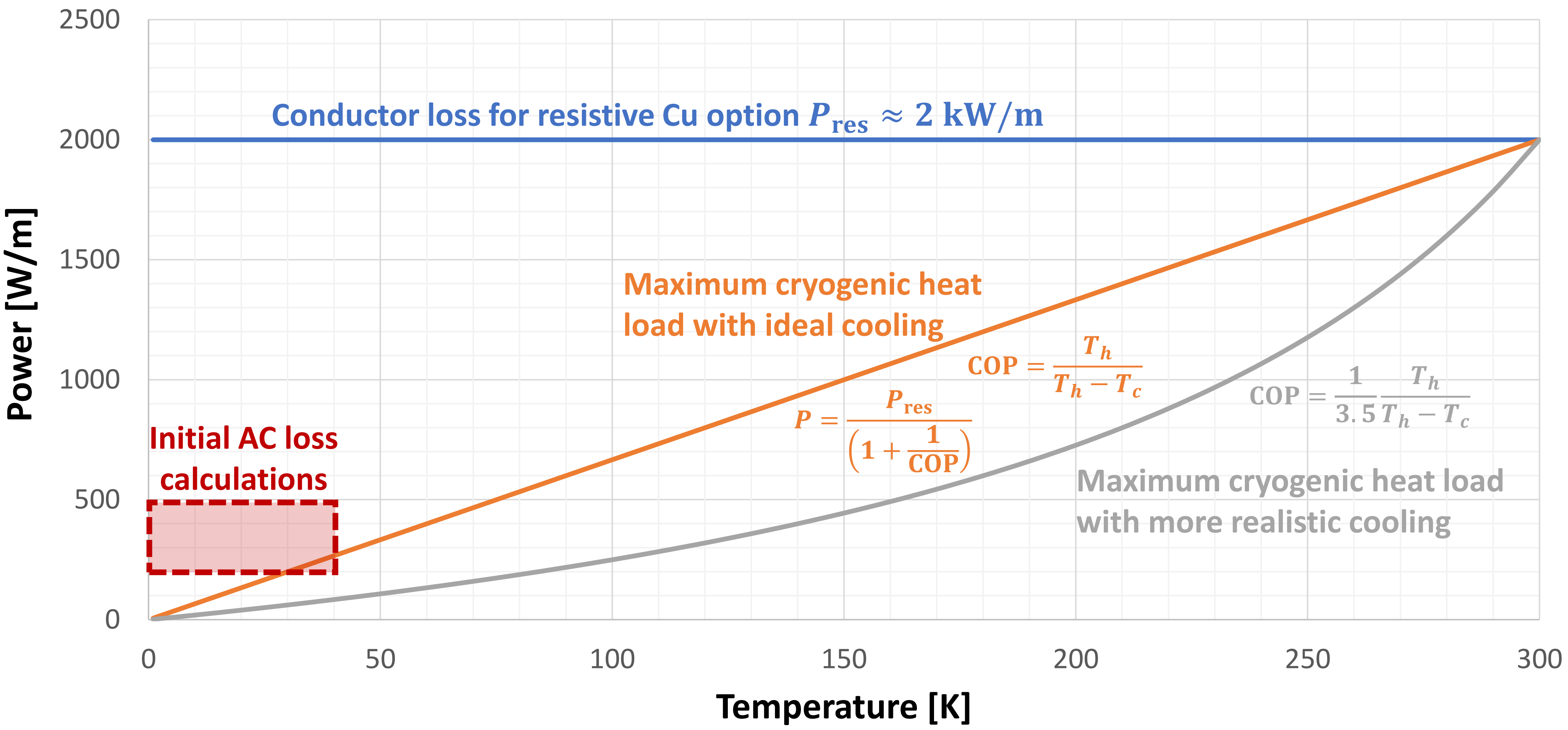
1. *Re*BCO magnet by FNAL
(H. Piekarz et al.)



2. *Re*BCO magnet using Unibo/CERN yoke design
(Breschi et al.)



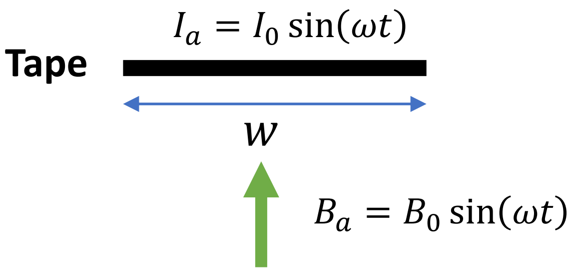
What level of AC loss acceptable for energy saving?



- Hysteresis AC loss has to be reduced by an order of magnitude at least.

Hysteresis loss in a single tape

Tape with width *w* exposed to applied current and magnetic field

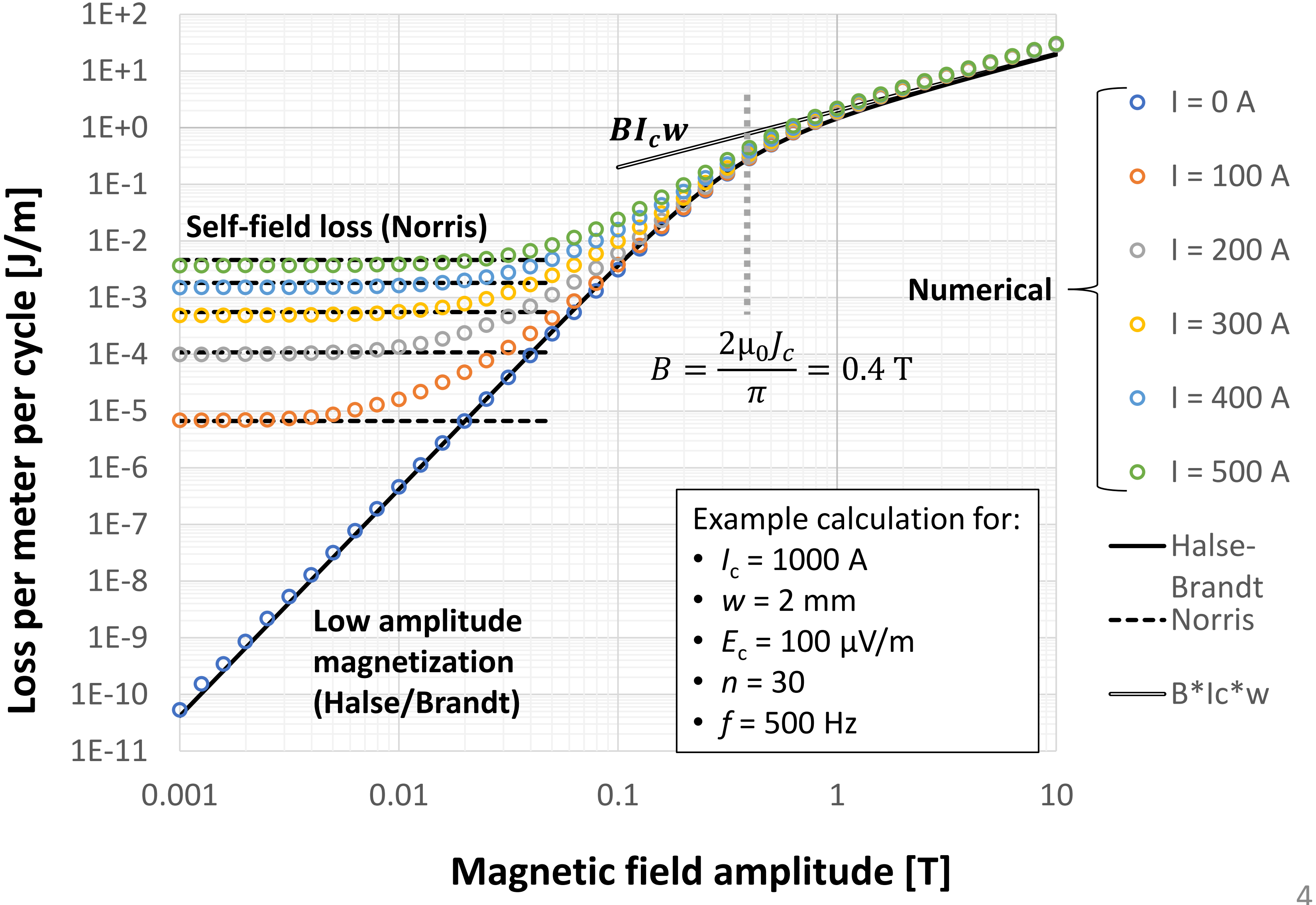


Halse-Brandt magnetization loss

$$Q = \frac{2\mu_0 J_c^2 w^2}{\pi}\left(\ln\left(\cosh\left(\frac{\pi B_0}{\mu_0 J_c}\right)\right) - \frac{\pi B_0}{2\mu_0 J_c}\tanh\left(\frac{\pi B_0}{\mu_0 J_c}\right)\right)$$

Norris self-field transport loss

$$Q = \frac{\mu_0 I_c^2}{\pi}\left(\left(1-\frac{I_0}{I_c}\right)\ln\left(1-\frac{I_0}{I_c}\right) + \left(1+\frac{I_0}{I_c}\right)\ln\left(1+\frac{I_0}{I_c}\right) - \left(\frac{I_0}{I_c}\right)^2\right)$$



Example calculation for:
- I_c = 1000 A
- w = 2 mm
- E_c = 100 µV/m
- n = 30
- f = 500 Hz

Halse: https://doi.org/10.1088/0022-3727/3/5/310
Brandt: https://doi.org/10.1103/PhysRevB.48.12893
Norris: https://doi.org/10.1088/0022-3727/3/4/308

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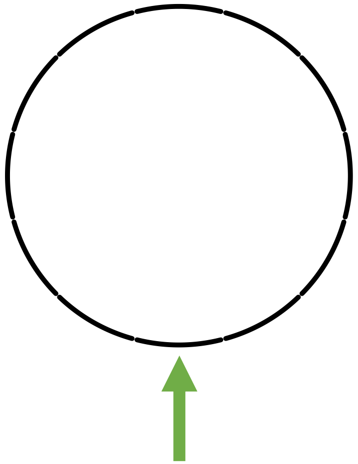
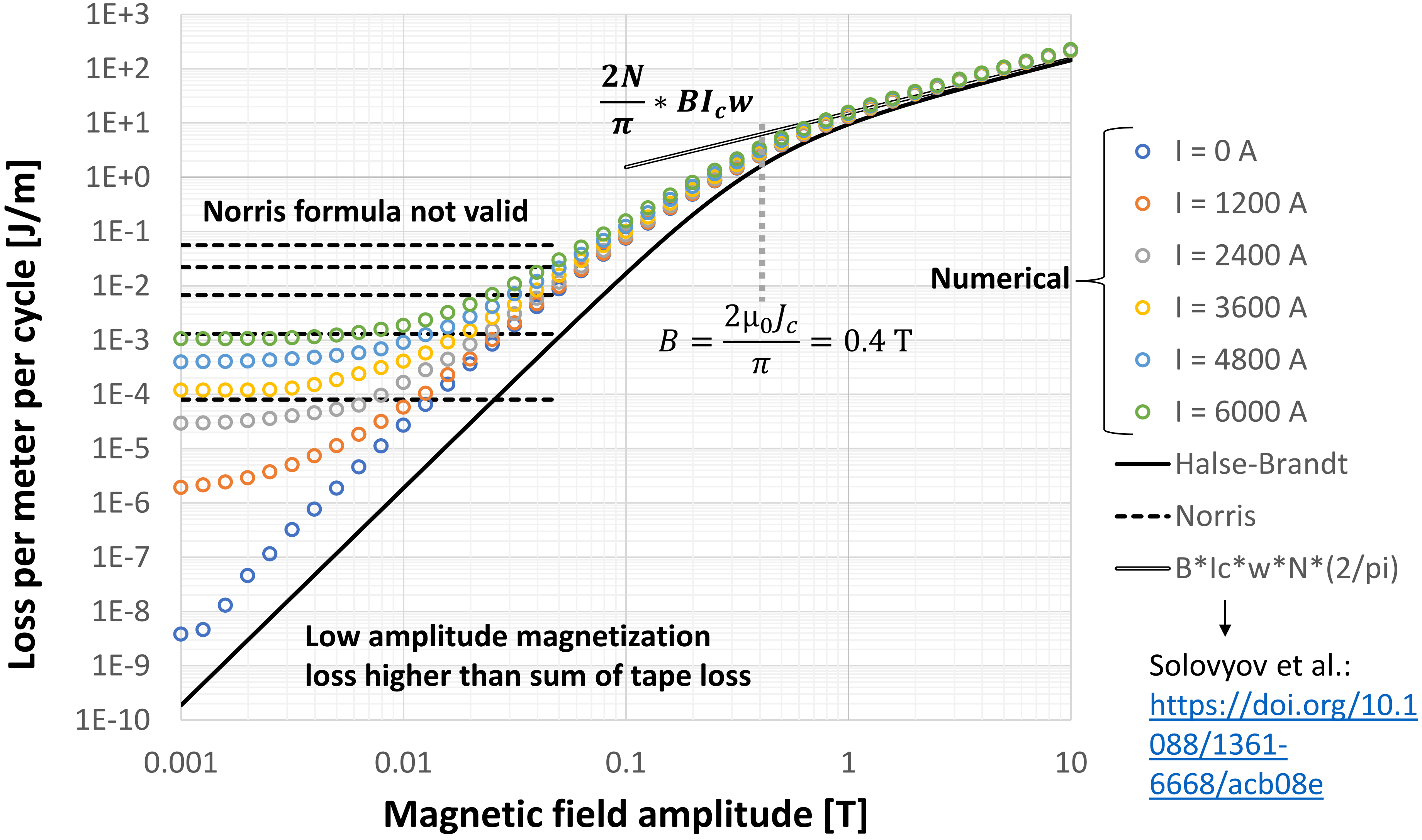
Hysteresis loss of a single round sub-cable

Circular cable of 12 2-mm-wide tapes on an 8 mm diameter core

$I_a = I_0 \sin(\omega t)$



$B_a = B_0 \sin(\omega t)$



Norris formula not valid

$$\frac{2N}{\pi} * BI_c w$$

$$B = \frac{2\mu_0 J_c}{\pi} = 0.4\ \mathrm{T}$$

Low amplitude magnetization loss higher than sum of tape loss

Solovyov et al.: https://doi.org/10.1088/1361-6668/acb08e

Effect of tape width/filamentization

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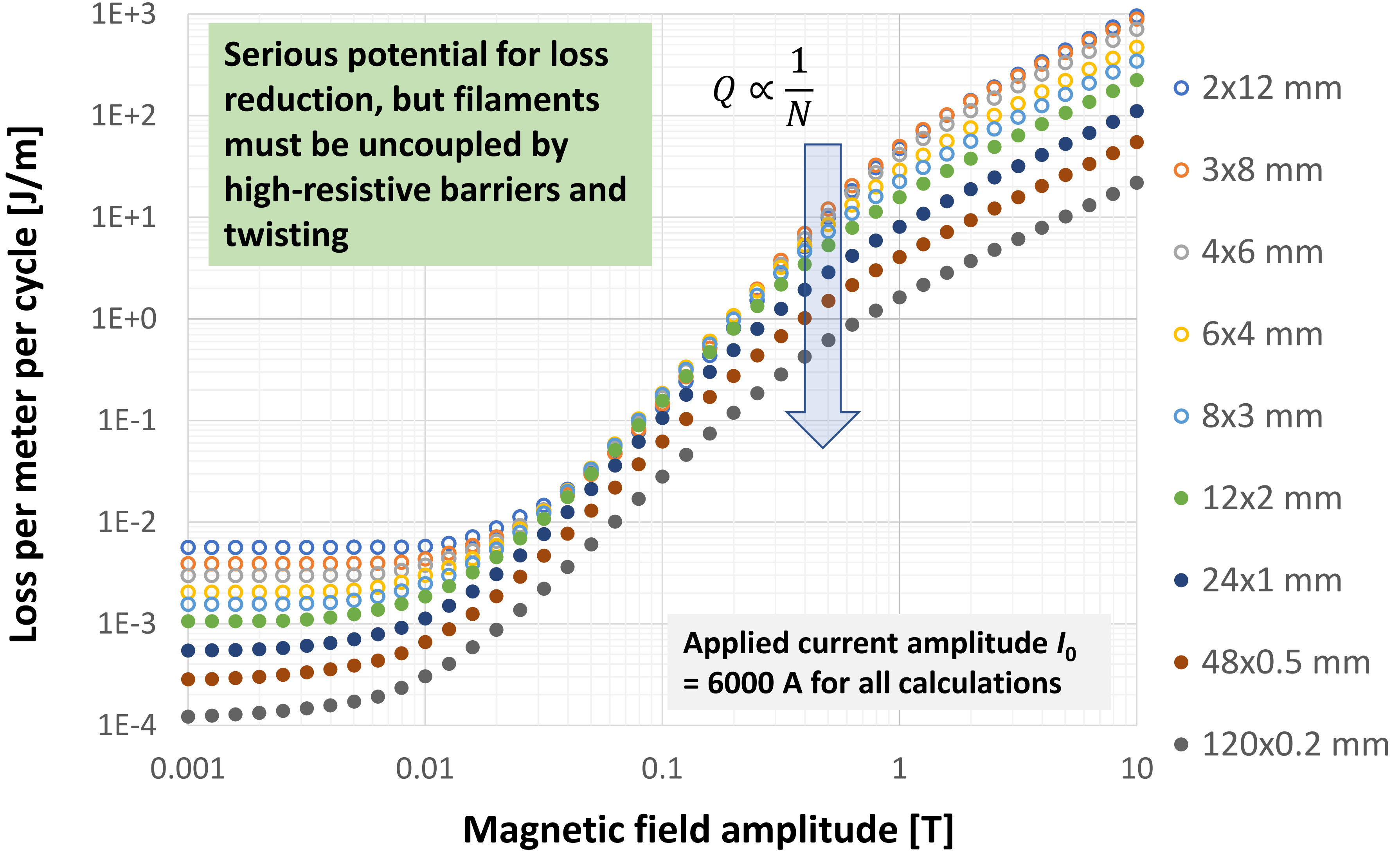
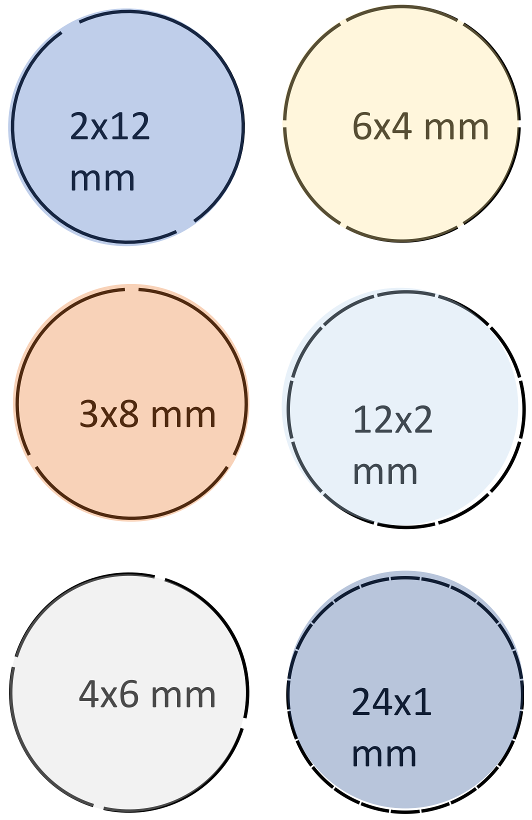


Serious potential for loss reduction, but filaments must be uncoupled by high-resistive barriers and twisting

$$Q \propto \frac{1}{N}$$

Applied current amplitude I_0 = 6000 A for all calculations



etc.

Effect of **critical current density** (12x 2 mm tapes)

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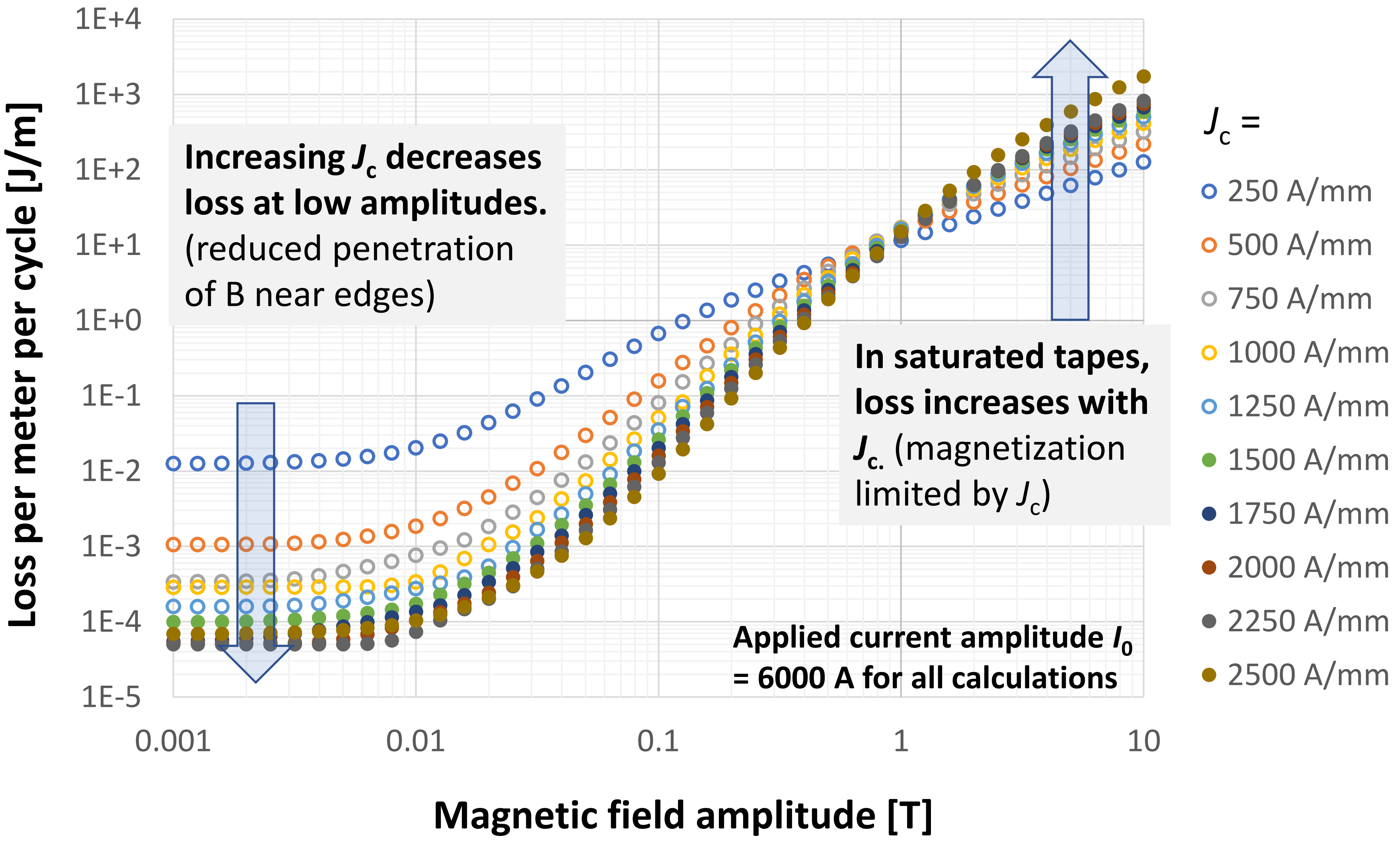
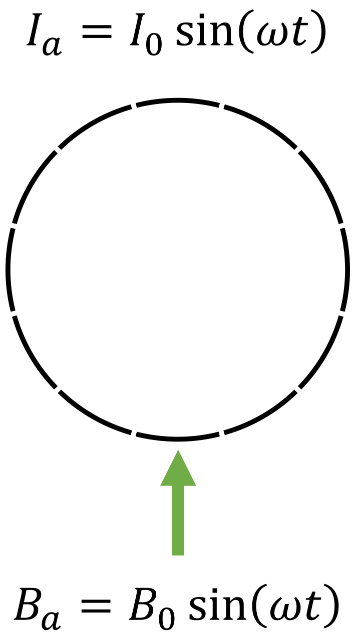


Increasing J_c decreases loss at low amplitudes. (reduced penetration of B near edges)

In saturated tapes, loss increases with J_c. (magnetization limited by J_c)

Applied current amplitude I_0 = 6000 A for all calculations

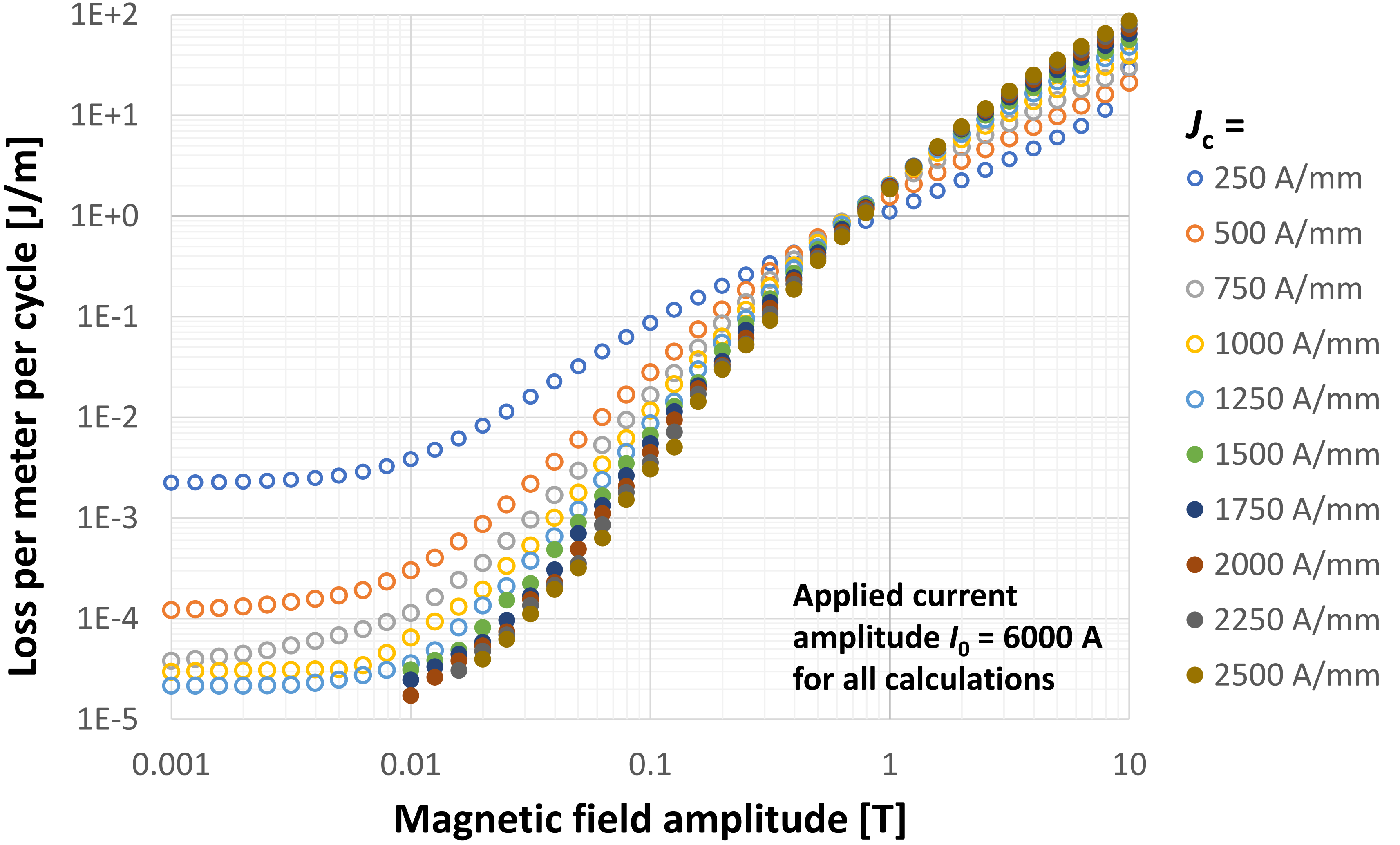
Circular cable of 12 tapes with 2 mm width, on 8 mm diameter core



$$I_a = I_0 \sin(\omega t)$$

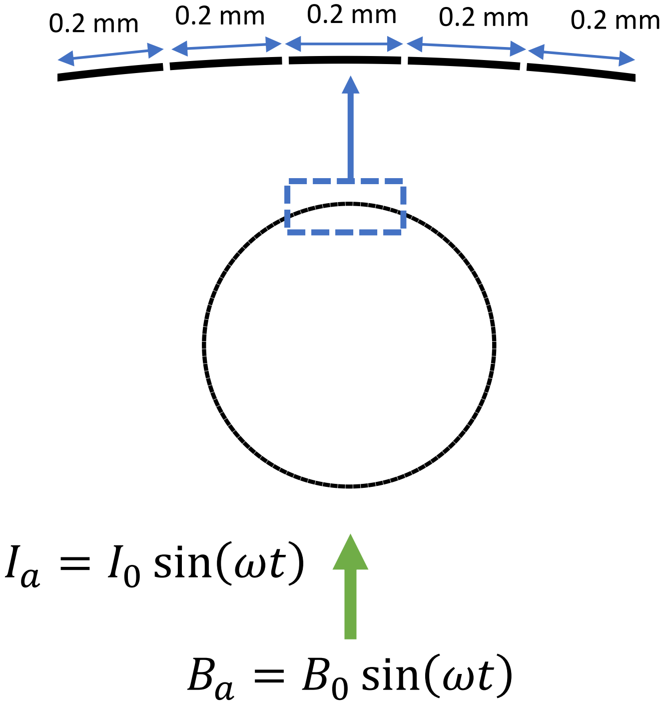
$$B_a = B_0 \sin(\omega t)$$

Effect of **critical current density** (120x0.2 mm)



Applied current amplitude I_0 = 6000 A for all calculations

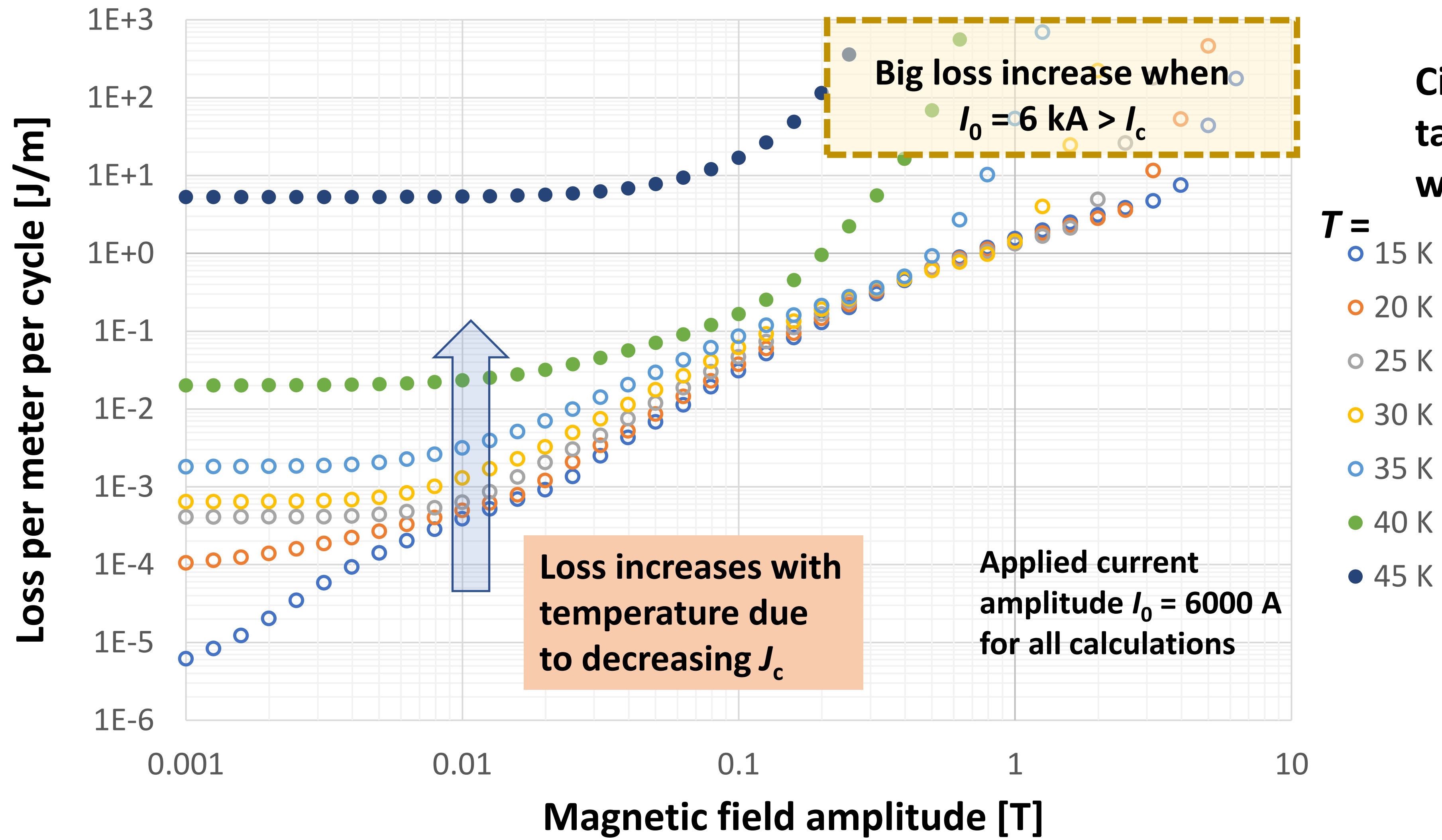
Circular cable of 120 tapes/filaments with 0.2 mm width on 8 mm diameter core



$$I_a = I_0 \sin(\omega t)$$

$$B_a = B_0 \sin(\omega t)$$

Effect of operating temperature

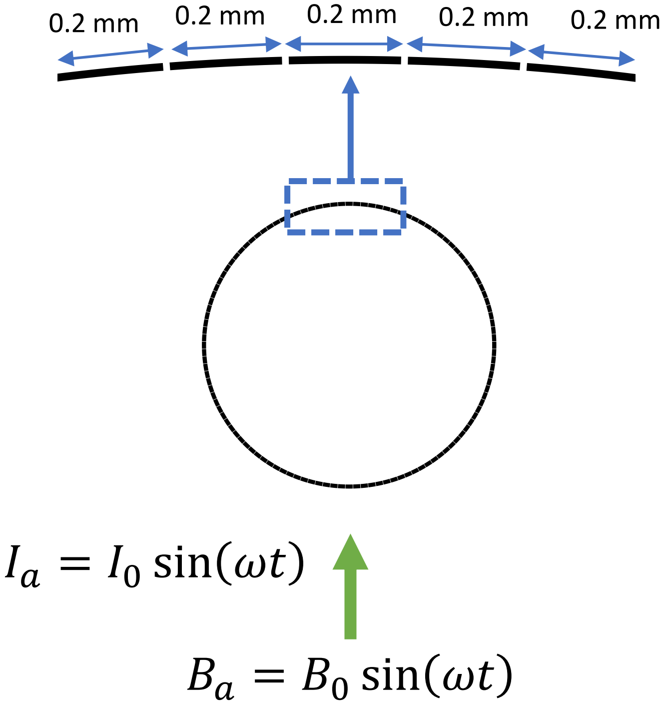


Big loss increase when I_0 = 6 kA > I_c

Loss increases with temperature due to decreasing J_c

Applied current amplitude I_0 = 6000 A for all calculations

Circular cable of 120 tapes/filaments with 0.2 mm width on 8 mm diameter core



$I_a = I_0 \sin(\omega t)$

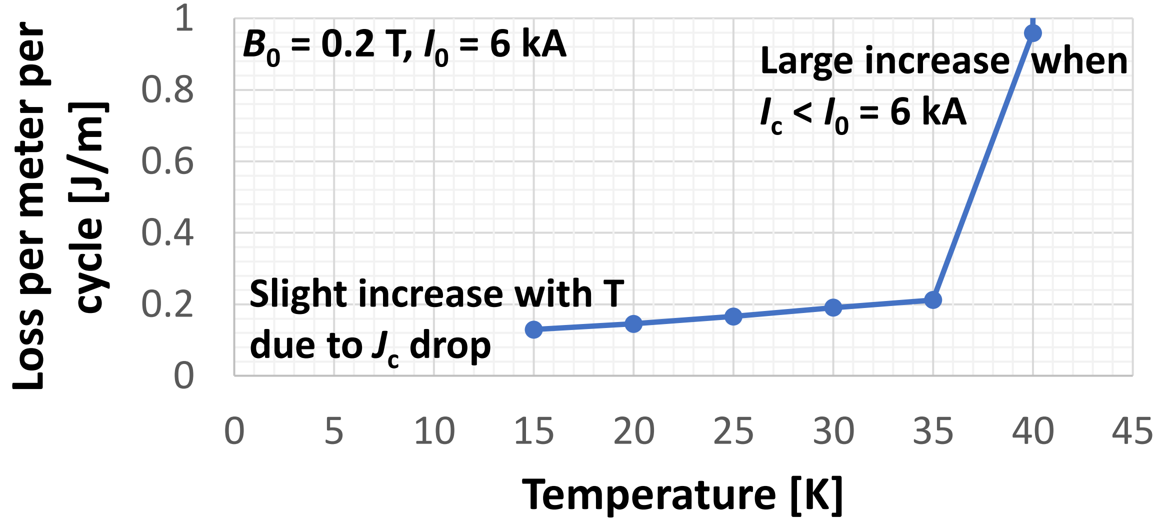
$B_a = B_0 \sin(\omega t)$

- Used measured J_c(**B**,*T*) data for SuperPower tape from Robinson Research Institute https://htsdb.wimbush.eu/dataset/4256624

Extrapolation to a full *Re*BCO based RCS fast-ramping dipole magnet

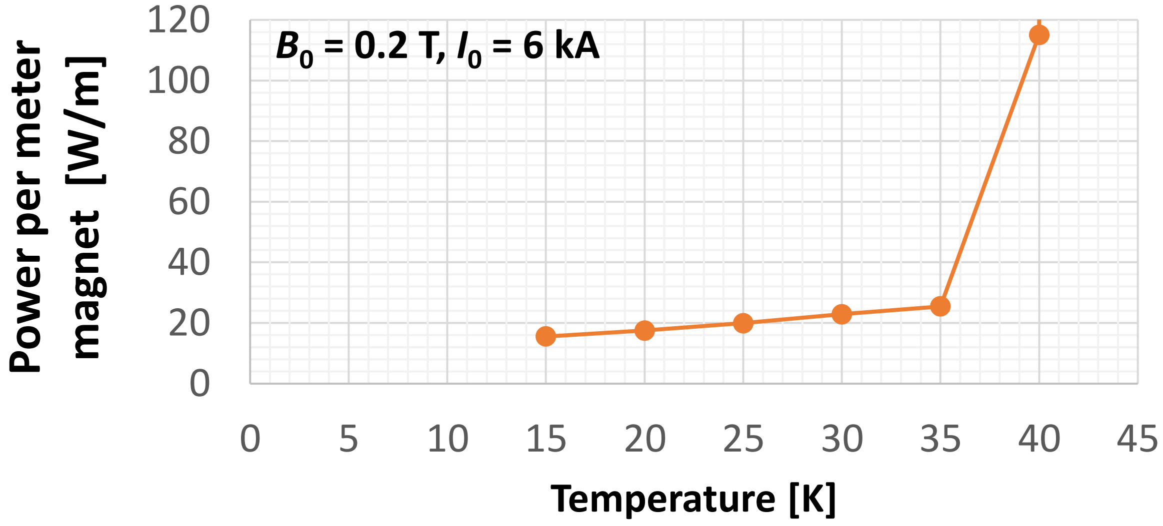
Case:

- $J_c(\mathbf{B},T)$ of SuperPower tape (RI data)
- Layout 120 tape/filaments, 0.2 mm wide
- Applied current 6 kA, applied field 0.2 T
- Loss/cycle per sub-cable 0.1-0.2 J for $T < 35$ K



Full magnet power:

- Multiply with number of sub-cables in the cross-section (24) and 5 Hz repetition rate
- This value is conservative as not all turns experience 0.2 T
- **Achieving 15 to 25 W in 15 to 30 K range**



What level of AC loss acceptable for energy saving?

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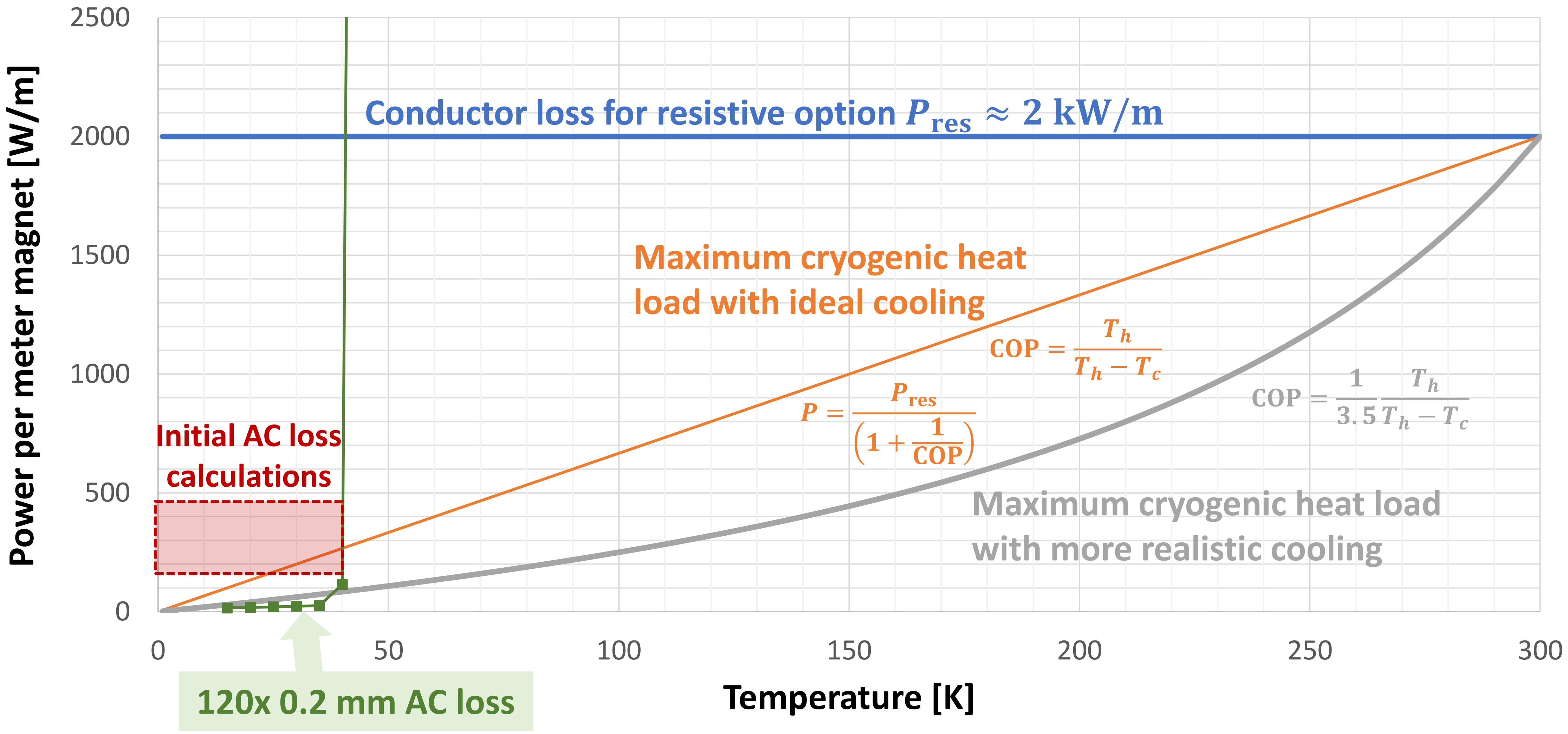
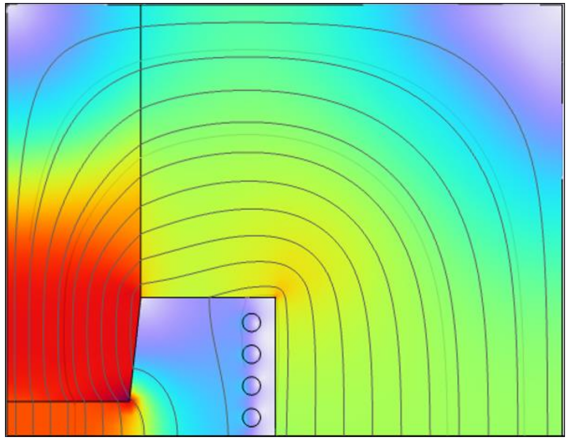


- **120x 0.2 mm layout yields AC loss below maximum cryogenic heat load for 15 K < *T* < 35 K !**

Conclusion & outlook



- We calculated hysteresis loss by analytical an numerical methods. There will be other contributions to the cryogenic heat load: coupling loss, eddy current loss, heat leaks, etc.
- Hysteresis loss strongly increases with perpendicular field, to be minimized through optimal conductor placement and yoke design
- Further reduction by reducing tape width and/or use filamented conductors as $Q \propto 1/N$
- Hysteresis loss *decreases* with increasing J_c for low field amplitudes and *increases* with increasing J_c for high amplitudes of magnetic field
- Case presented: round conductor with 120 filaments, 0.2 mm wide yields < 30 W hysteresis loss showing potential for saving energy compared to the resistive option