Mitigation of AC loss in a 15 MVA HTS transformer for wind energy system via numerical modeling

Asef Ghabeli, Francesco Grilli, Mathias Noe, Wescley de Sousa

Jürgen Gangel, Aime Mbuy, Stephan Rother, Christian Schacherer

Motivation & contents

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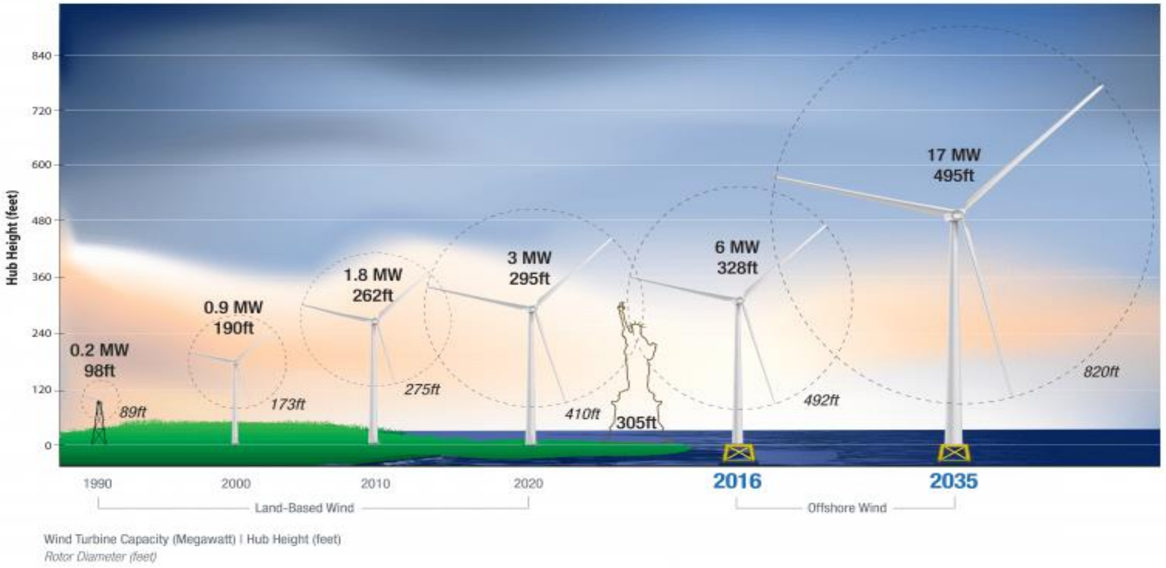
- Power of wind generators steadily increasing
- Ratings even beyond 15 MVA are envisaged
- Presented here: exemplary results on AC loss calculations in the windings



www.energy.gov/eere/articles/wind-turbines-bigger-better

Specification of the transformer

Parameter	Value
Rated power	15 MVA
Rated voltage	66 kV / 690 V
Rated current	131 A / 12.55 kA
Frequency	50 Hz
Core maximum field density	1.2 T

AC loss and efficiency at different temperatures

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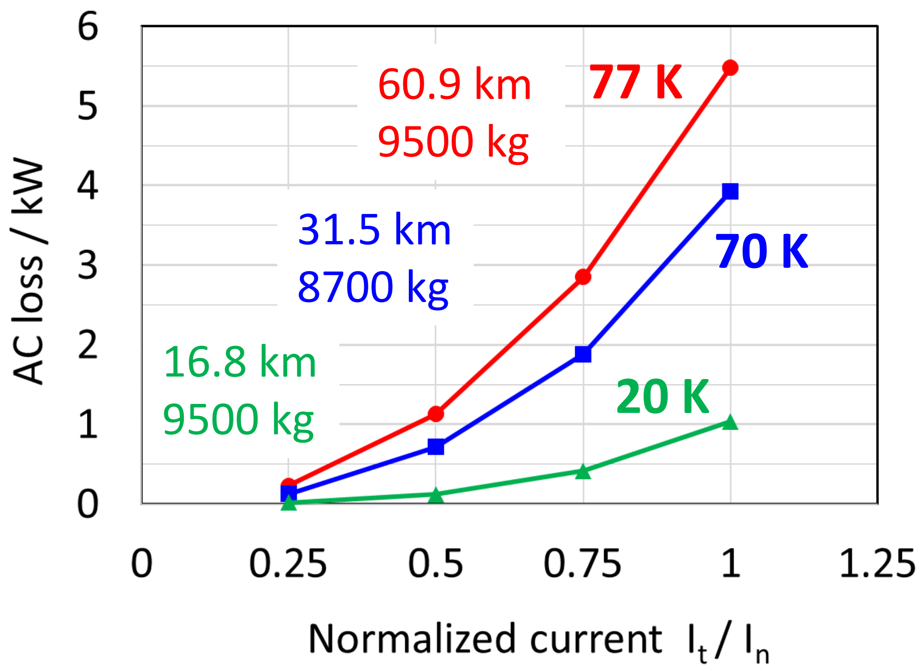
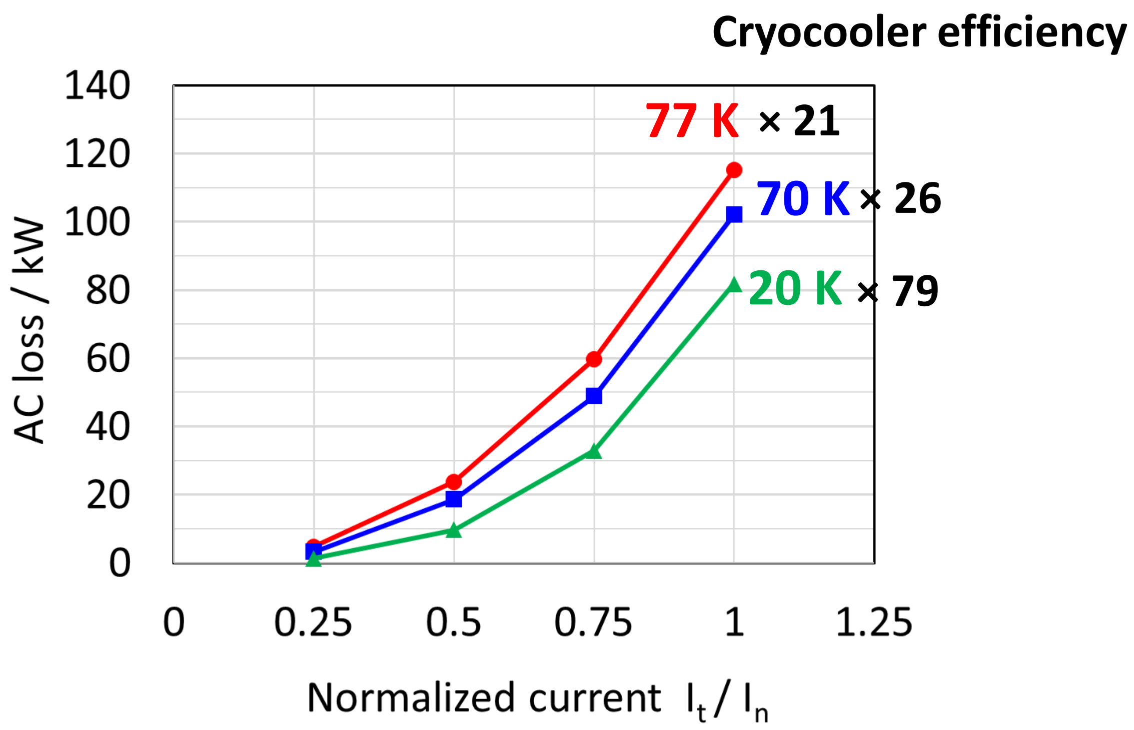
AC Loss at cryogenic temperature



AC Loss at room temperature

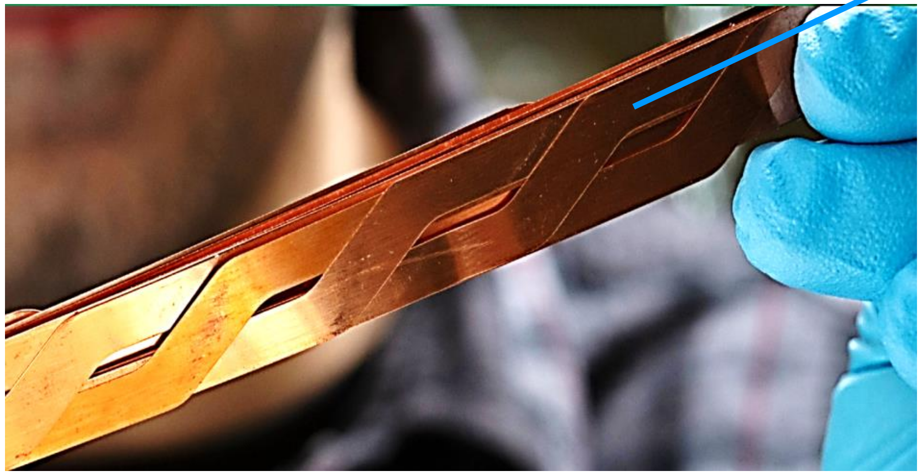


Transformer calculated efficiency
- **20 K = 98.9 %**
- **70 K = 99 %**
- **77 K = 99 %**

Note: Data here are for the whole transformer. In the rest of the presentation, data are for one phase only.

Low-voltage side (12.55 kA): Roebel cables

Cable made of fully transposed meander-shaped HTS tapes

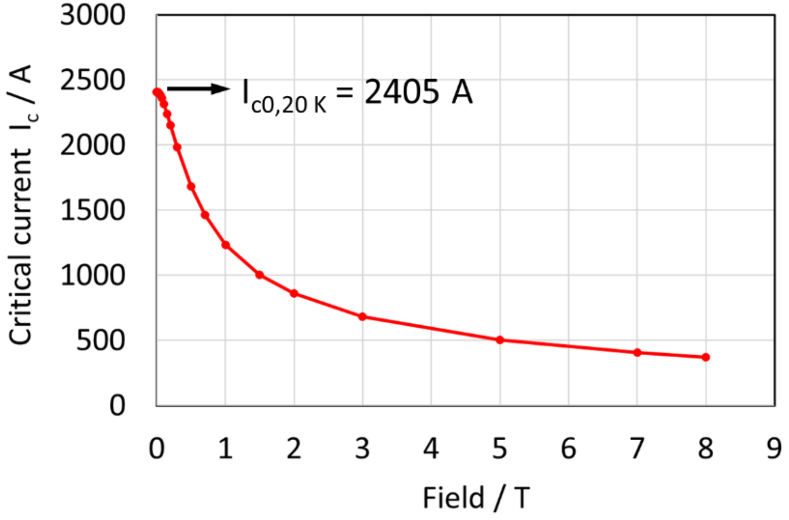


www.wgtn.ac.nz/robinson

Fujikura **RE-based tape (FESC 2021)**

Width = 4 mm
Thickness = 0.11 mm
Superconducting layer = 2 µm

Measured I_c of 4 mm tape at **20 K**



Provided by Fujikura

High-voltage side (131 A): 2 mm HTS tapes

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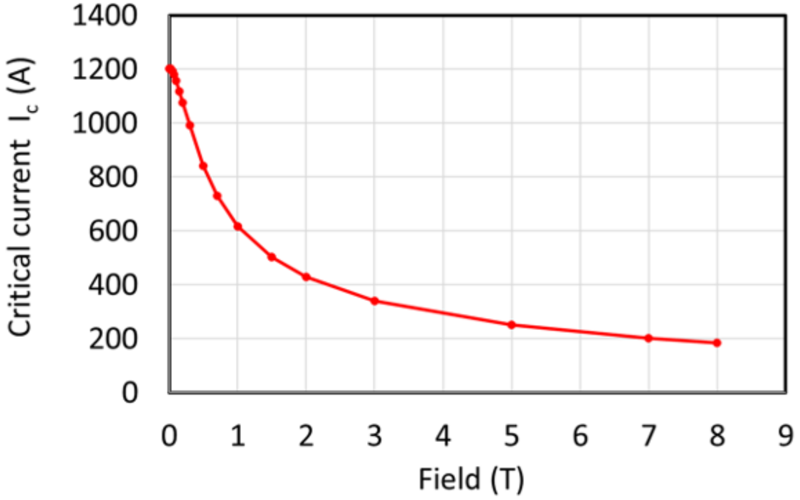
Fujikura **RE-based tape (FESC 2021)**

Width = 4 mm
Thickness = 0.11 mm
Superconducting layer = 2 µm

Measured I_c of 2 mm tape at **20 K**



Provided by Fujikura

Schematic of transformer at 20 K (45 V)

Similar variations were done for the 70 K and 77 K designs

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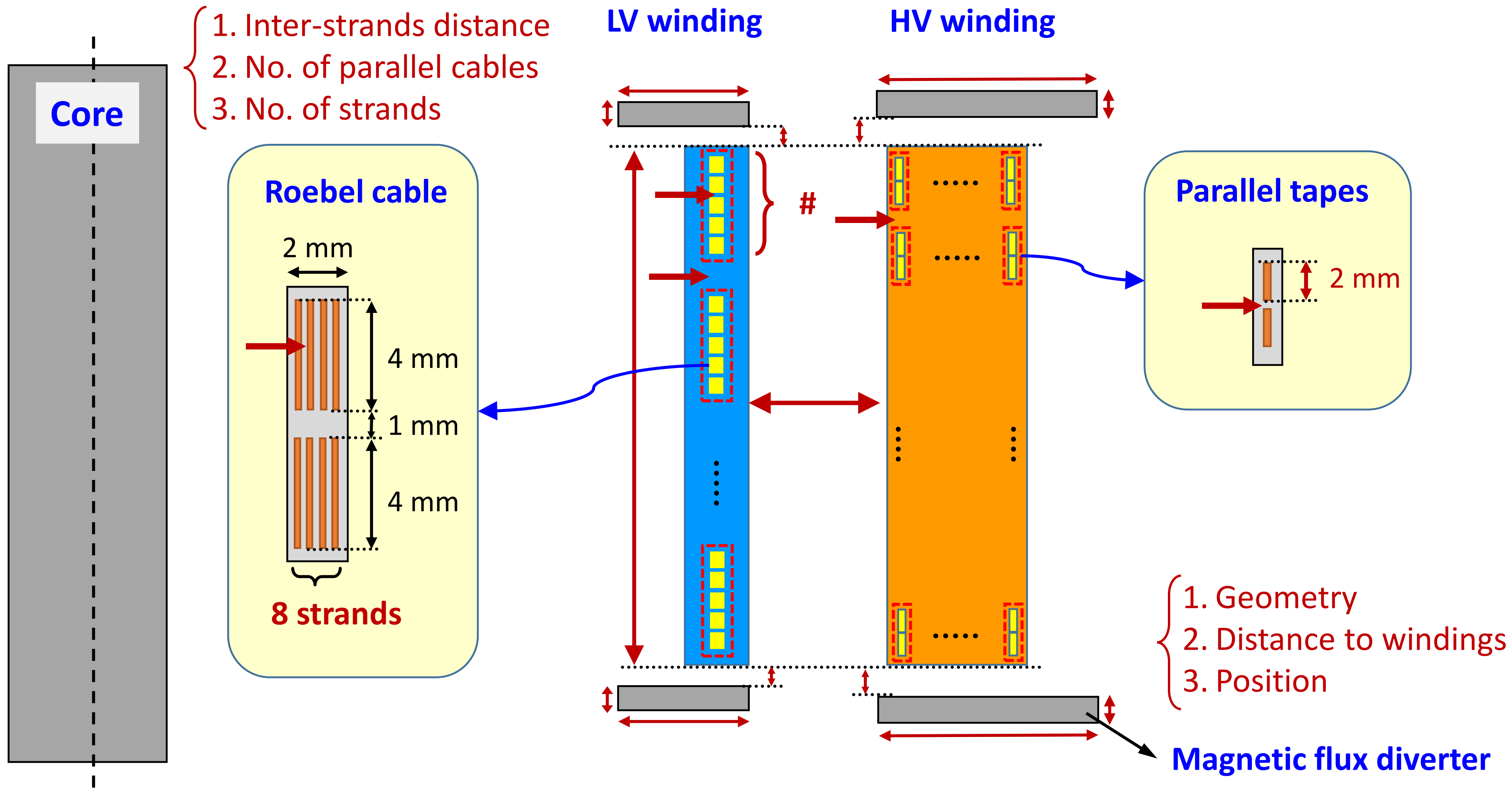
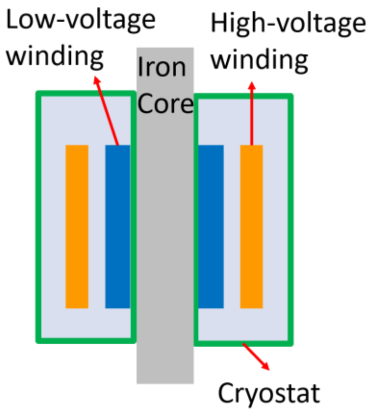


Not to scale!



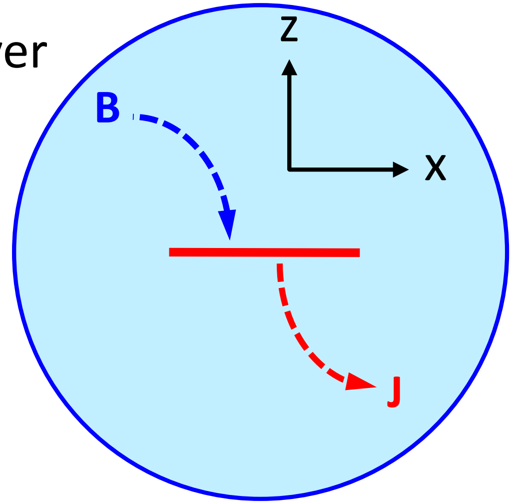
Numerical modeling strategy:
2D axisymmetric T-A formulation

T-formulation in superconducting layer

Current vector potential

$$\mathbf{J} = \nabla \times \mathbf{T}$$

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$ Faraday's law



A-formulation in whole domain

Magnetic vector potential

$$\mathbf{H} = \frac{\mathbf{B}}{\mu} \qquad \mathbf{B} = \nabla \times \mathbf{A}$$

$$\nabla \times \mathbf{H} = \mathbf{J}$$ Ampere's law

$$\boxed{\nabla \times (\rho \nabla \times \mathbf{T}) = -\frac{\partial \mathbf{B}}{\partial t}}$$ → Calculated from A-formulation

$$\boxed{\nabla \times (\frac{1}{\mu} \nabla \times \mathbf{A}) = \mathbf{J}}$$ → Calculated from T-formulation

Characterization of superconductor

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E-J power law

$$E = E_c \left(\frac{J}{J_c}\right)^n$$

Critical current density

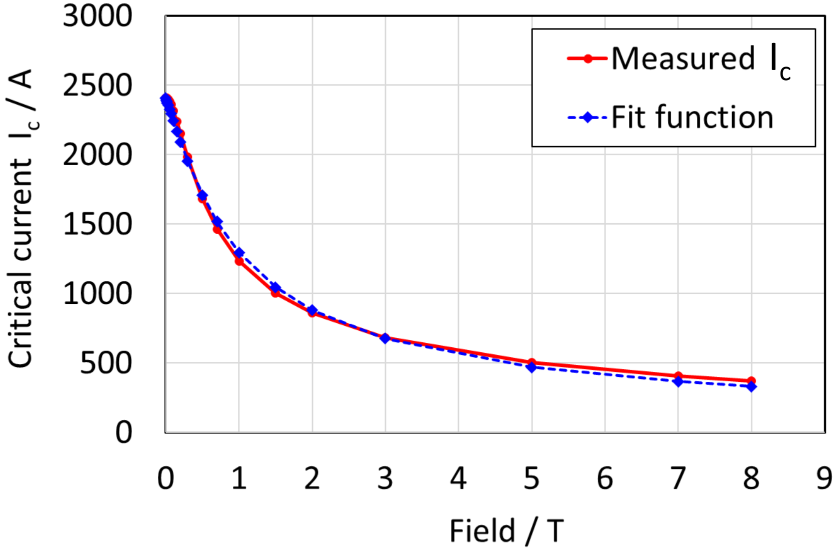
Critical electric field 10^{-4} (V/m)

Kim model

$$J_c(B) = \frac{J_{c0}}{(1 + |B|/B_0)^{\alpha}}$$

B_0 and α are obtained from fit function

Measured I_c of 4 mm Fujikura tape at 20 K



Provided by Fujikura

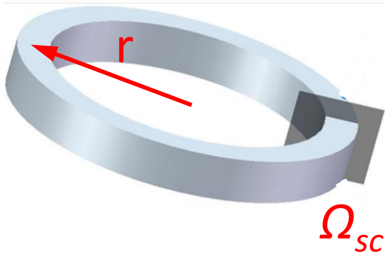
AC loss calculation

$$P = \frac{2}{T}\int_{T/4}^{3T/4} dt \iint_{\Omega_{sc}} \mathbf{E}\cdot\mathbf{J}\, ds$$

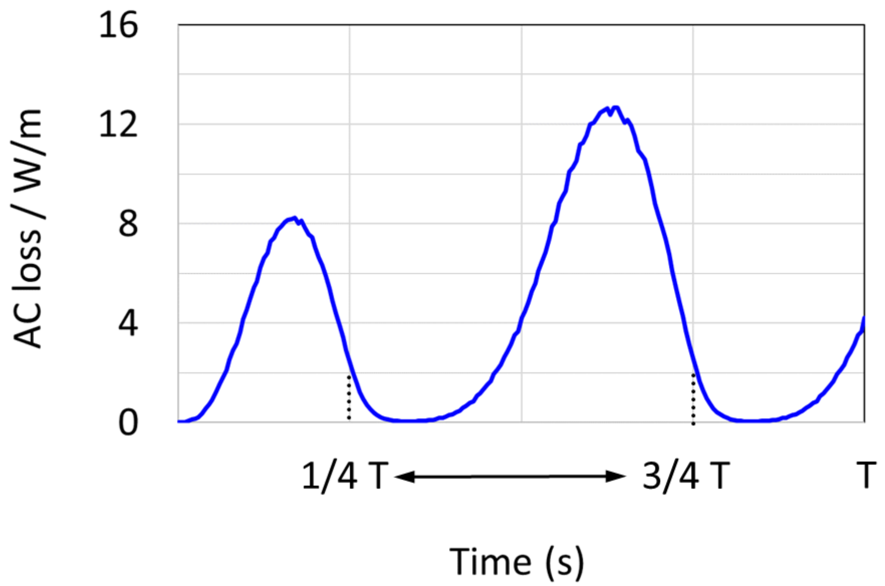
W/m

Time period

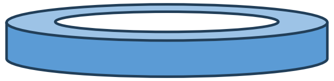
Superconducting domain



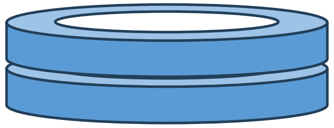
Calculation of AC loss in windings made of up to 4700 tapes (9400 tapes considering symmetry)



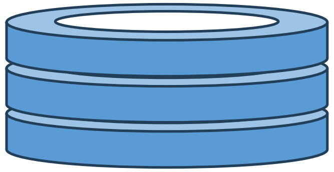
Model validation against experiments



Transport current of stacked HTS coils at 77 K

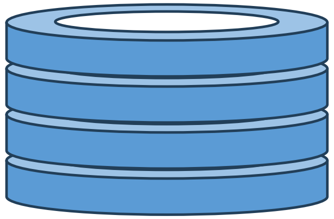


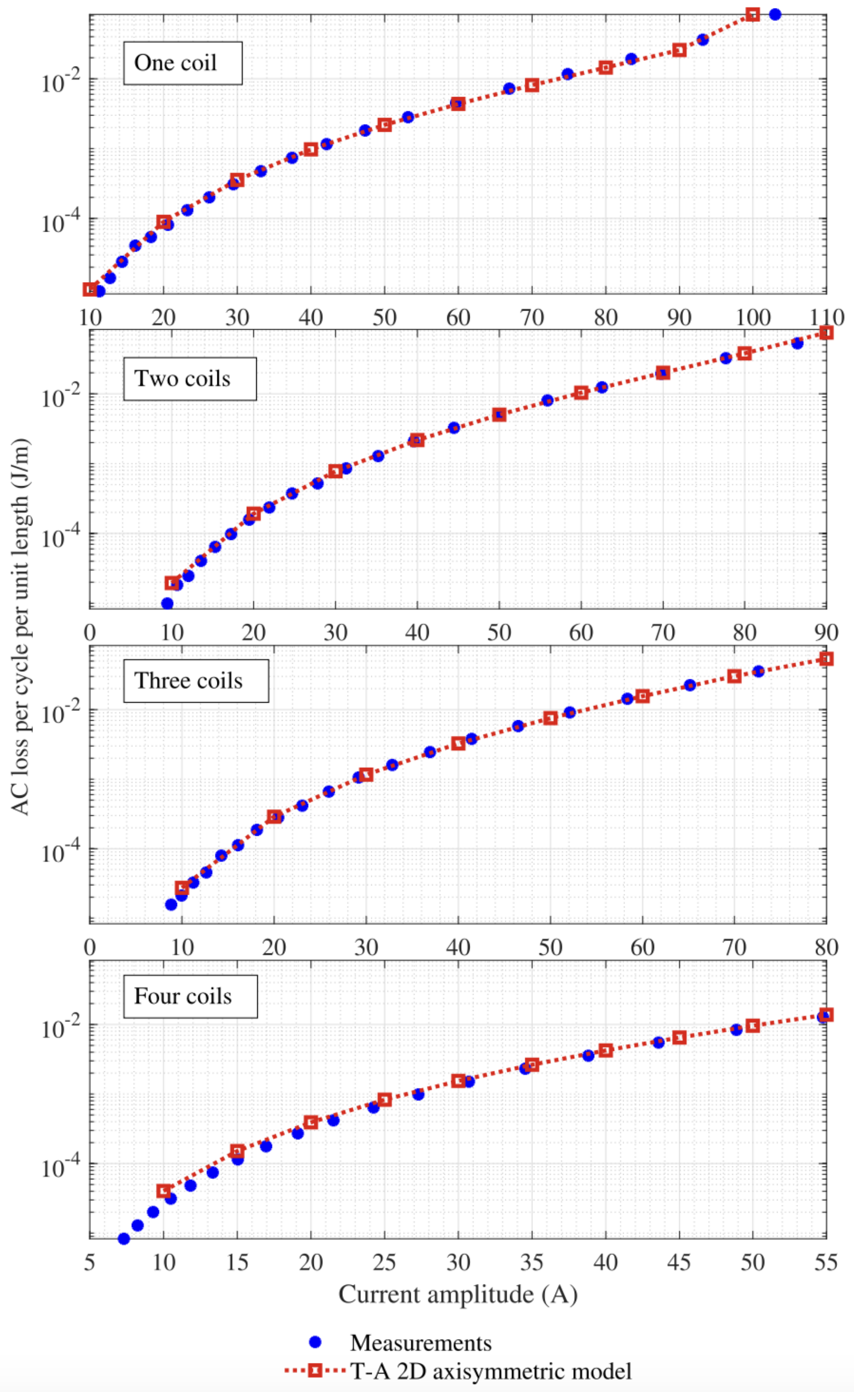
Up to 4 pancake coils, 24 turns each



Experiments
Pardo et al 2015 SuST **28** 044003

T-A model
Vargas Llanos et al 2021 IEEE TAS **31** 5206509

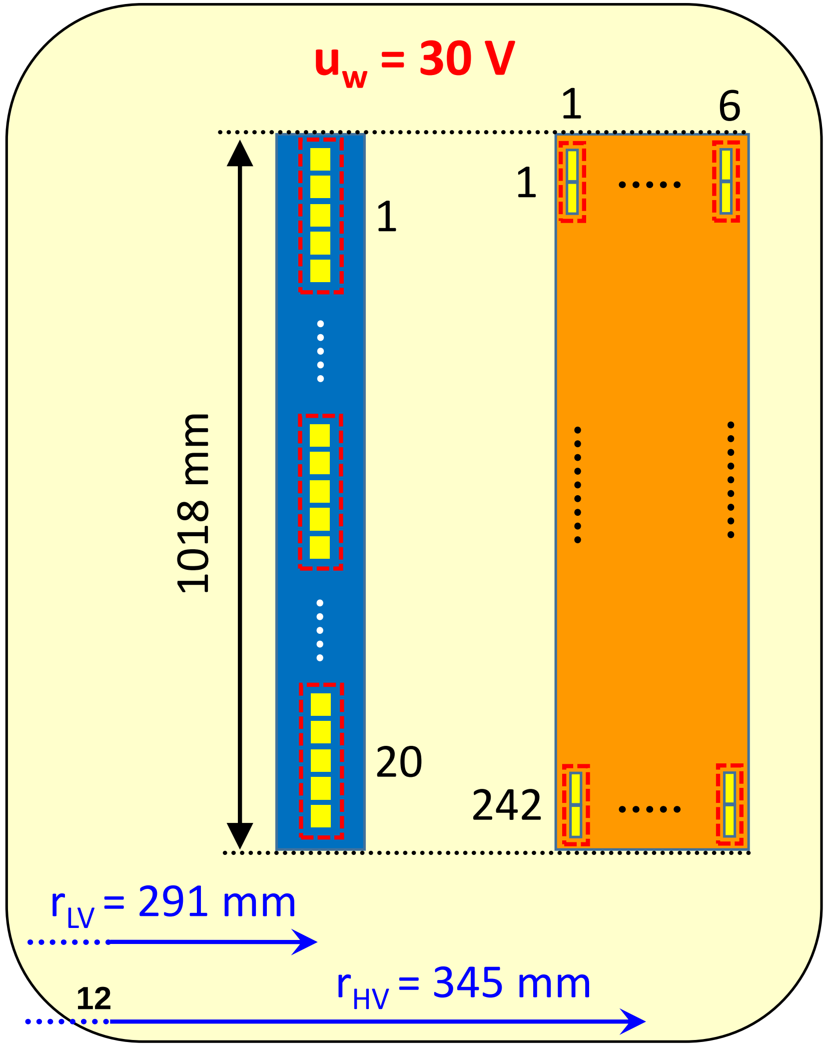


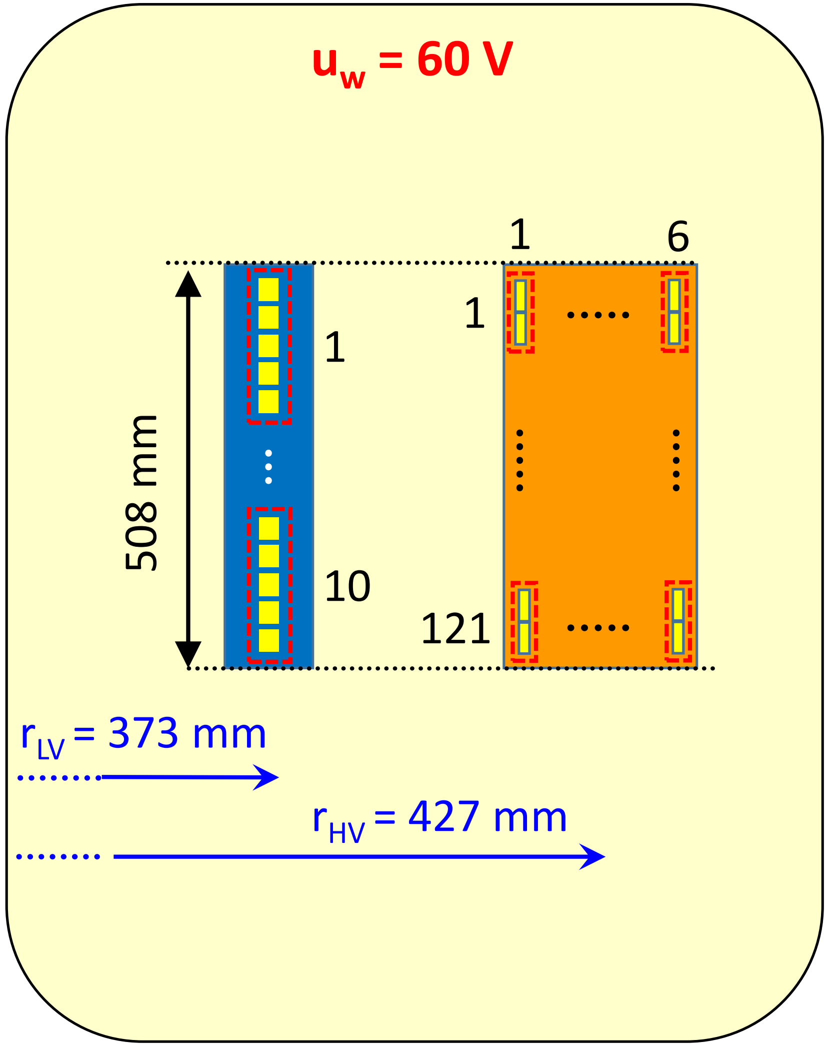


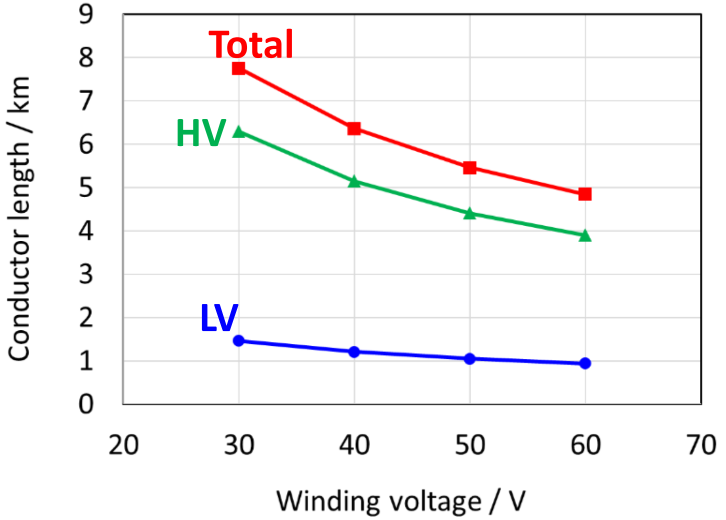
Influence of winding voltage on AC loss

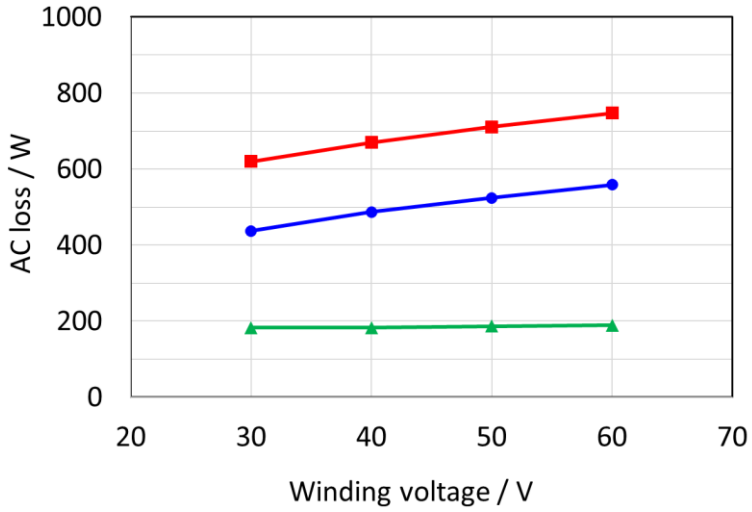
u_w = 30 V , 40 V , 50 V , 60 V

Vertical gaps are kept the same (LV = 1 mm, HV = 0.1 mm)









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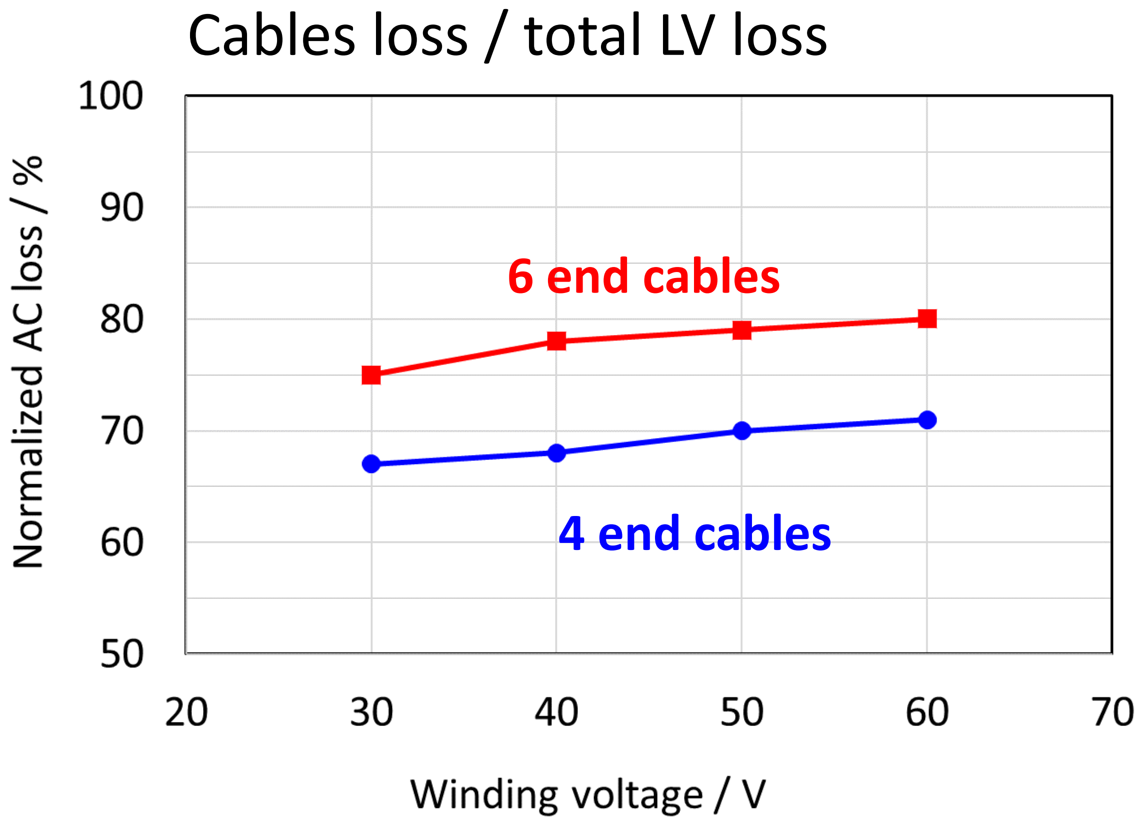
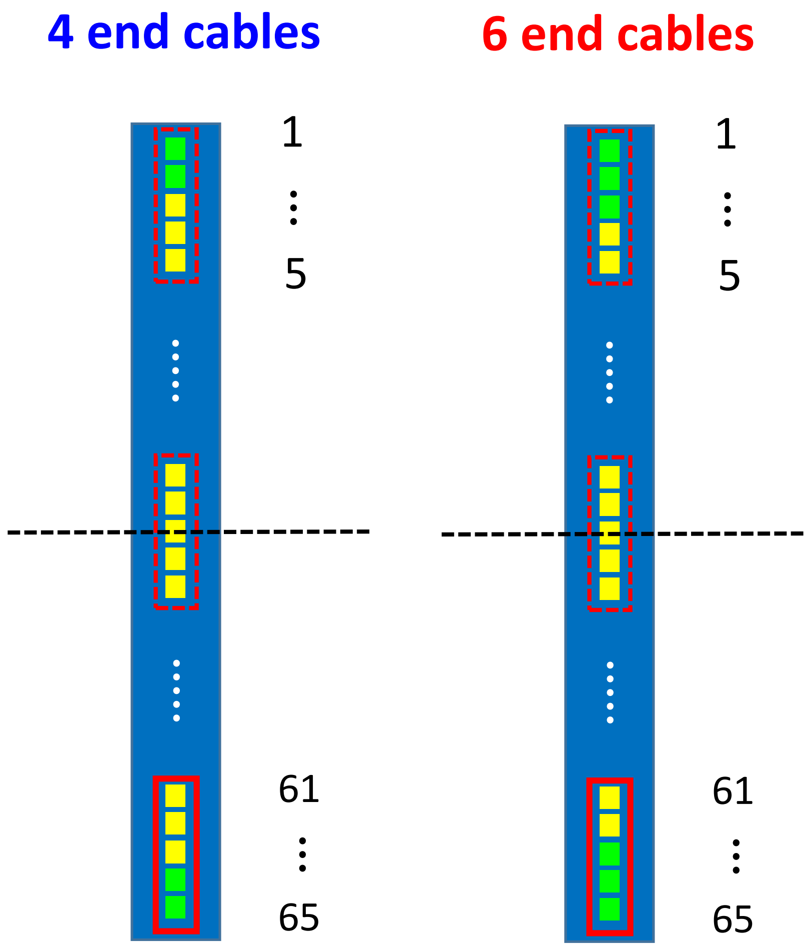
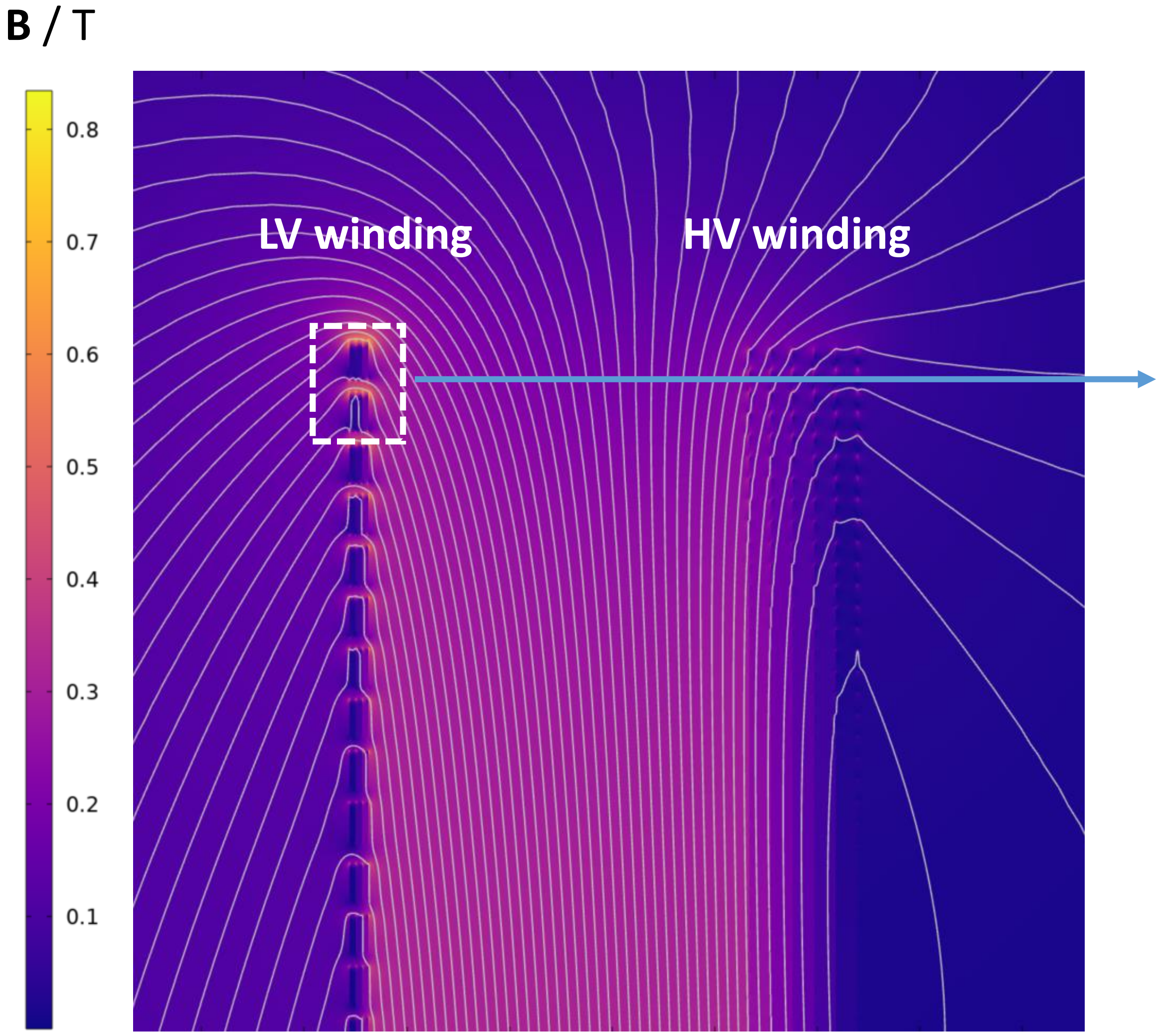
Influence of winding voltage on AC loss

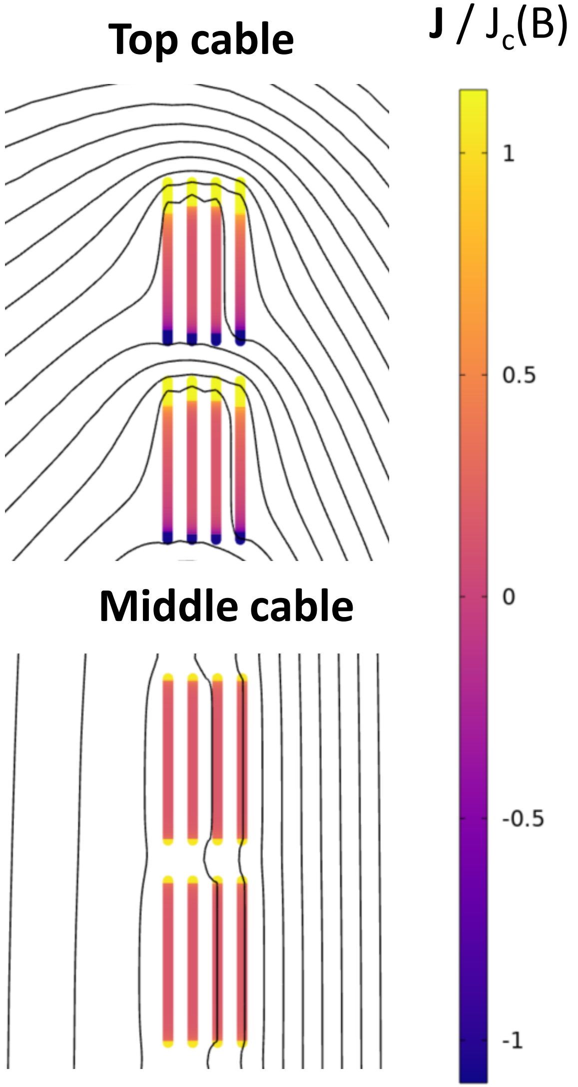


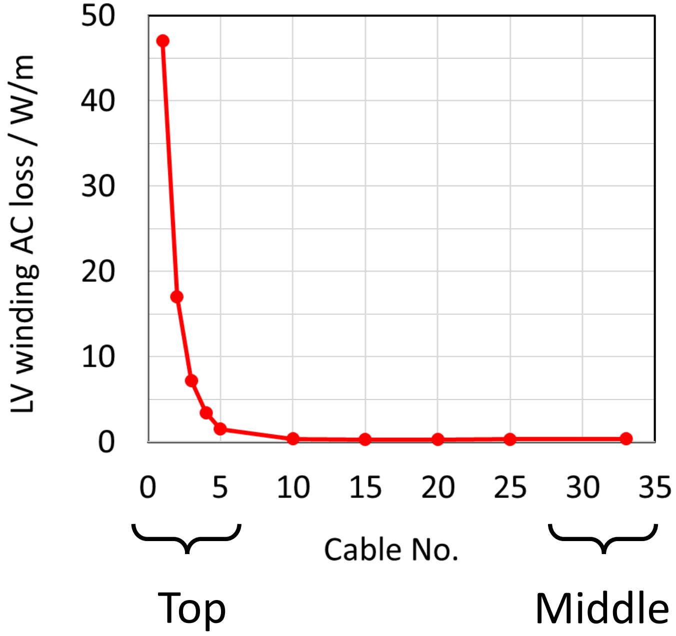


AC loss primarily depends on losses of end cables.
The last 6 cables represent:
- 6/100 = 6 % of the total number of cables at 30 V
- 6/50 = 12 % of the total number of cables at 60 V

Distribution of AC loss per cable







Summary

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- 3 transformer designs at temperatures of 20 K, 70 K and 77 K (99 % efficiency)
- Calculating AC loss using T-A formulation with up to 4700 HTS tapes
- Most AC loss occurs in end windings (→ flux diverters can help)
- At constant vertical gap, increasing winding voltage (less conductor) does not reduce AC loss
- Optimum AC loss is constrained by main optimization parameters (here costs and weight) and is obtained by compromising between parameters