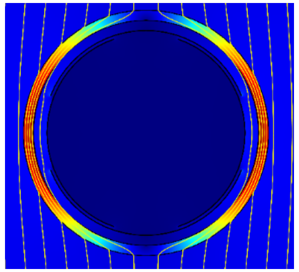
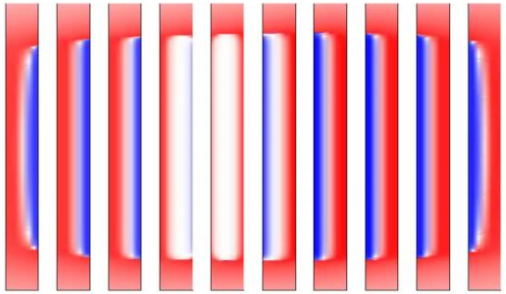
Voltage signals on the terminations of an HTS magnet modelled in A-T formulation

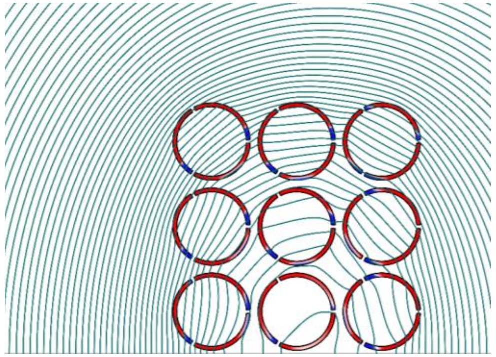
F. Gömöry, M. Solovyov
Institute of Electrical Engineering, Slovak Academy of Sciences, Bratislava, Slovakia

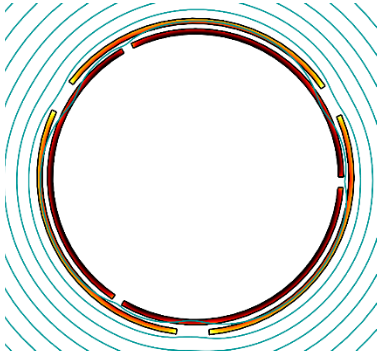
Introductory remarks

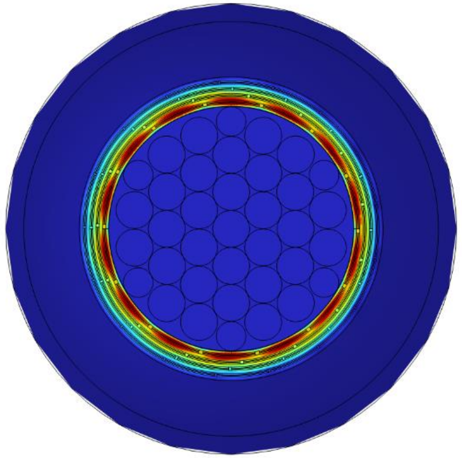
Research focus of our group:
Electromagnetic behaviour of devices from CC tapes
mainly AC loss











Methodology: Modelling and experimental verification
using electric masurements

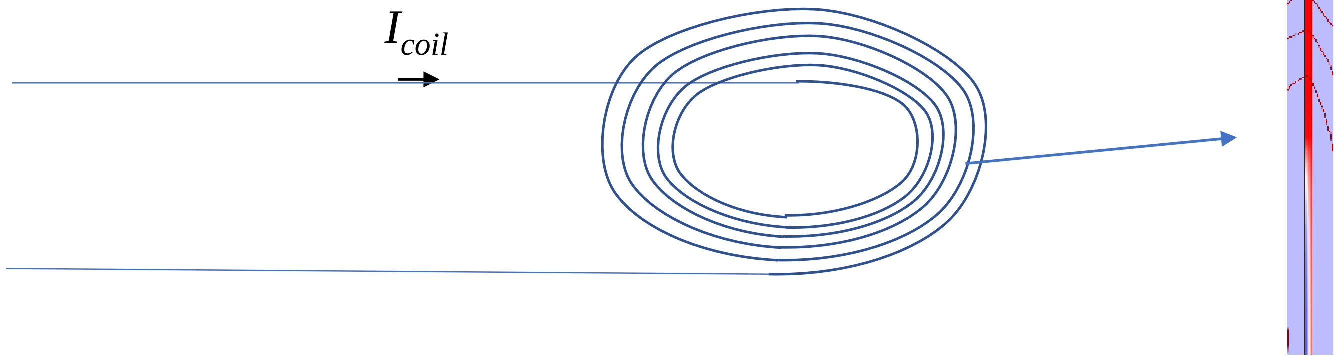
Outline

- Introduction
- Inspiration
- Novelty
- Application

Introduction

Device
(e.g. coil from CC tapes)

Modelling of AC loss



local values

$j(\vec{r})$
$E(\vec{r})$

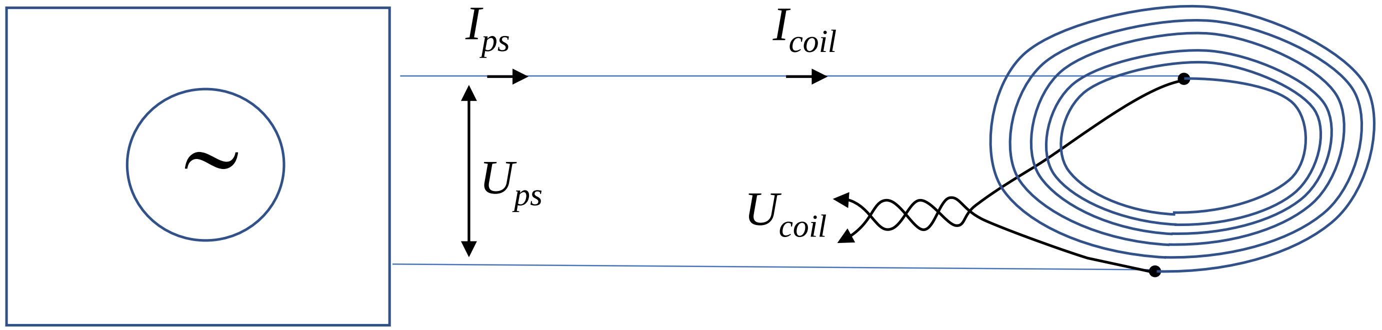
$$Q_{model} = \int_{T}^{2T} dt \int_{V} j(\vec{r})E(\vec{r})dV$$

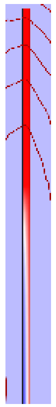
Introduction

Measurement of AC loss
(electric method)

Device
(e.g. coil from CC tapes)

Modelling of AC loss





local values

$j_{loc}(\vec{r})$
$E_{loc}(\vec{r})$

$$Q_{measurement} = \int_T^{2T} U_{coil}(t) I_{coil}(t) dt$$

$$Q_{model} = \int_T^{2T} dt \int_V j_{loc}(\vec{r}) E_{loc}(\vec{r}) dV$$

derivation of U_{coil} in modelling of AC loss → better comparison with experiment

Inspiration

Example of using macroscopic quantities derived from numerical model – transport AC loss in CC tape

A-φ formulation in 2D $\nabla^2 A = \mu_0 j_{loc}$

$$j_{loc} = j_{loc}(E_{loc})$$

superconductor:

$$j_{loc} = j_c \left(\frac{E_{loc}}{E_c}\right)^{\frac{1}{n}}$$

$$j_{loc} = j_c tanh\left(\frac{E_{loc}}{E_c}\right)$$

metals:

$$j_{loc} = \sigma_{metal} E_{loc}$$

Inspiration

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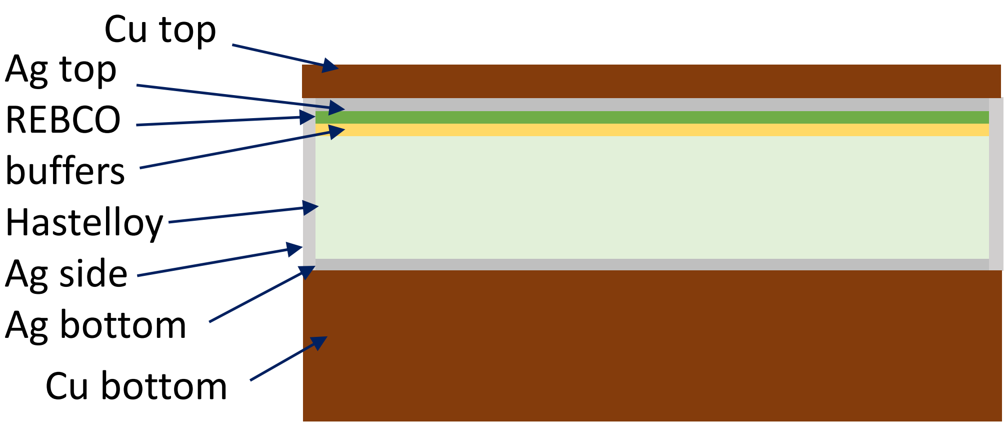


A-φ formulation in 2D

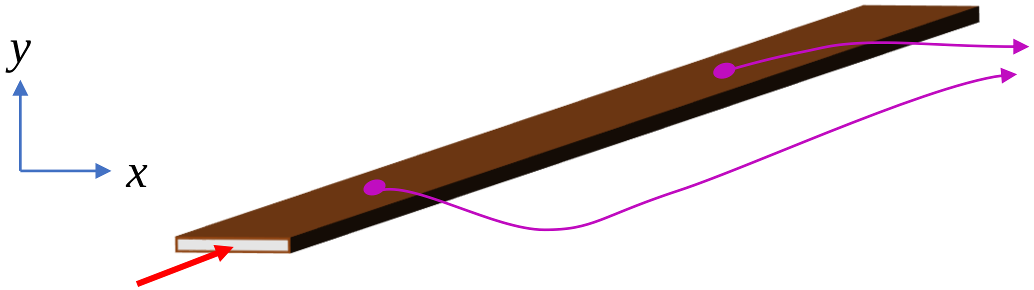
$$\nabla^2 A = \mu_0 j_{loc}$$

$$j_{loc} = j_{loc}(E_{loc})$$

$$\int_S j_{loc} dS = I_{ac}$$

$$E_{loc} = -\frac{\partial A}{\partial t} - \nabla\varphi$$

E. Pardo and F. Grilli, F.: Electromagnetic modeling of superconductors. In Numerical modeling of superconducting applications, World Sci Publ. Co. Pte. Ltd., 2023, Chapter 1.1.3



$I_{ac} = I_{max} sin(\omega t)$

macroscopic (measurable) quantity:

electric field intensity: $E_\varphi = -\nabla\varphi$

Inspiration

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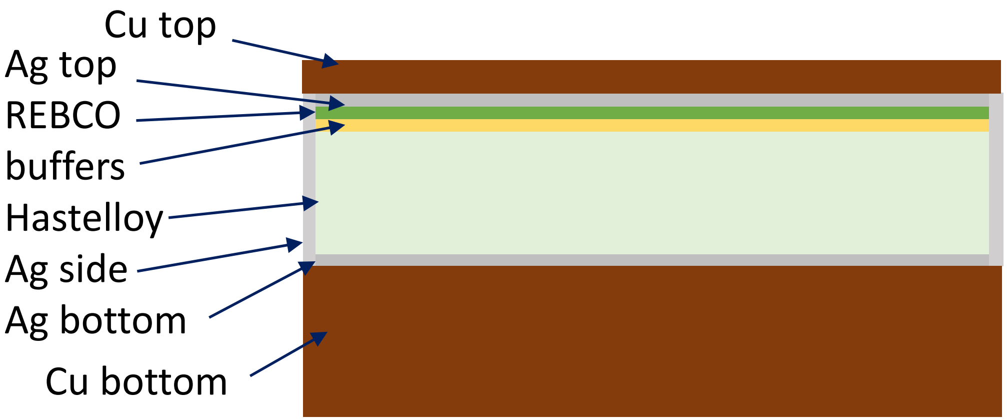

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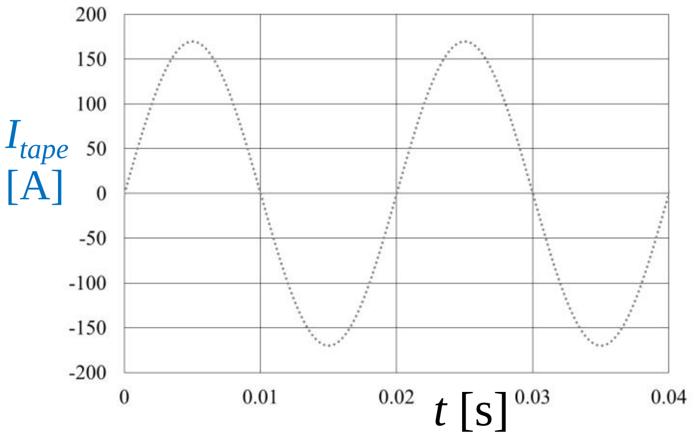

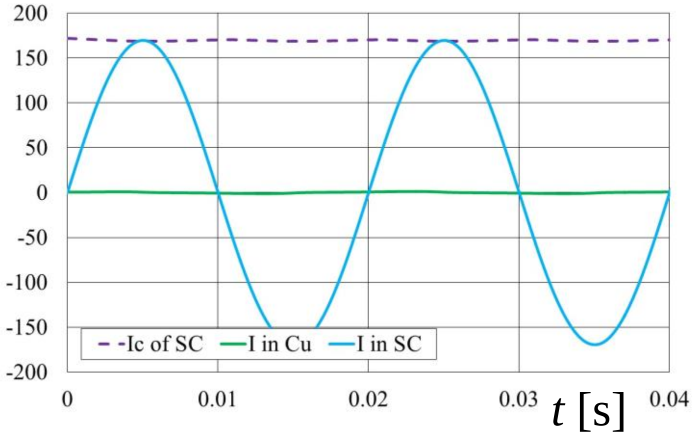

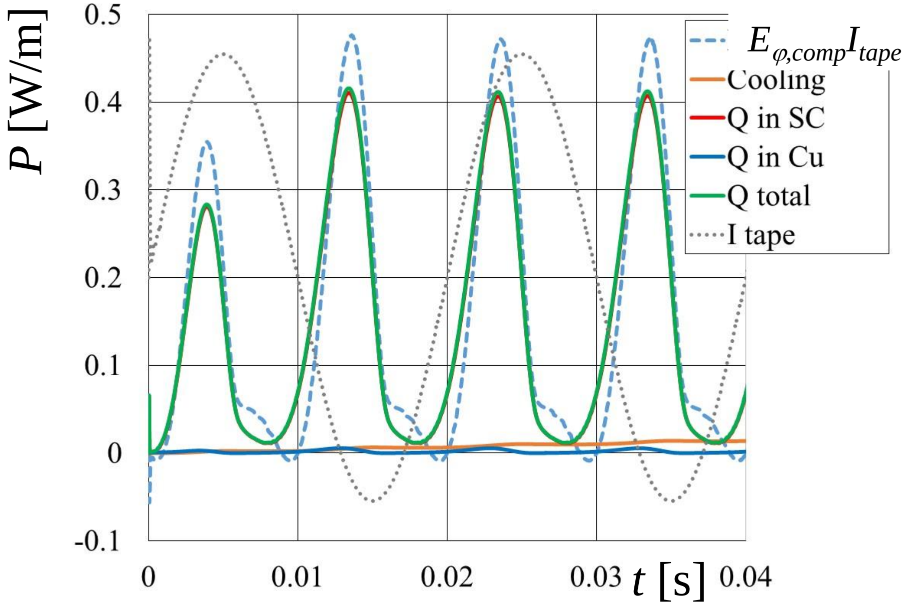

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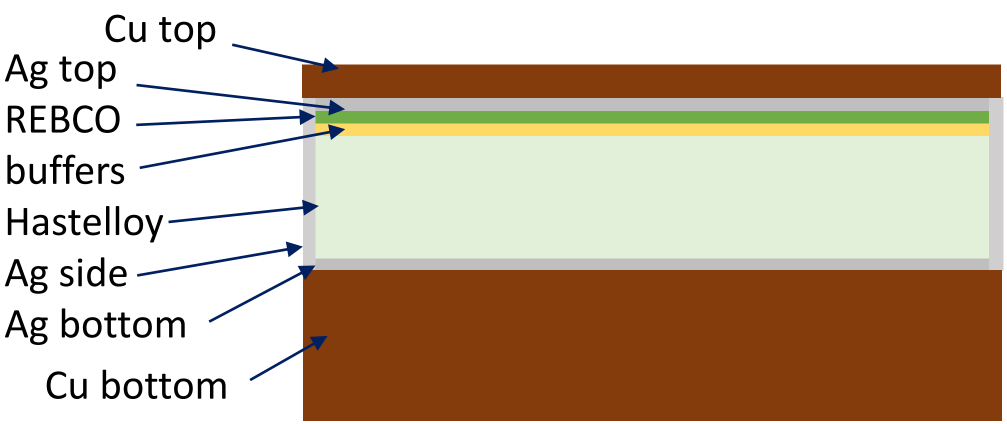

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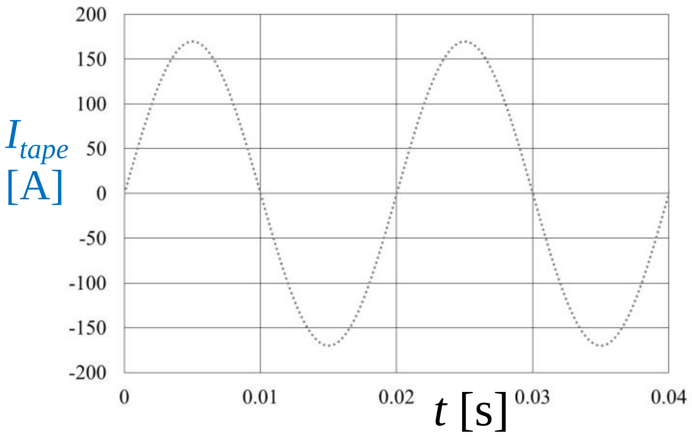
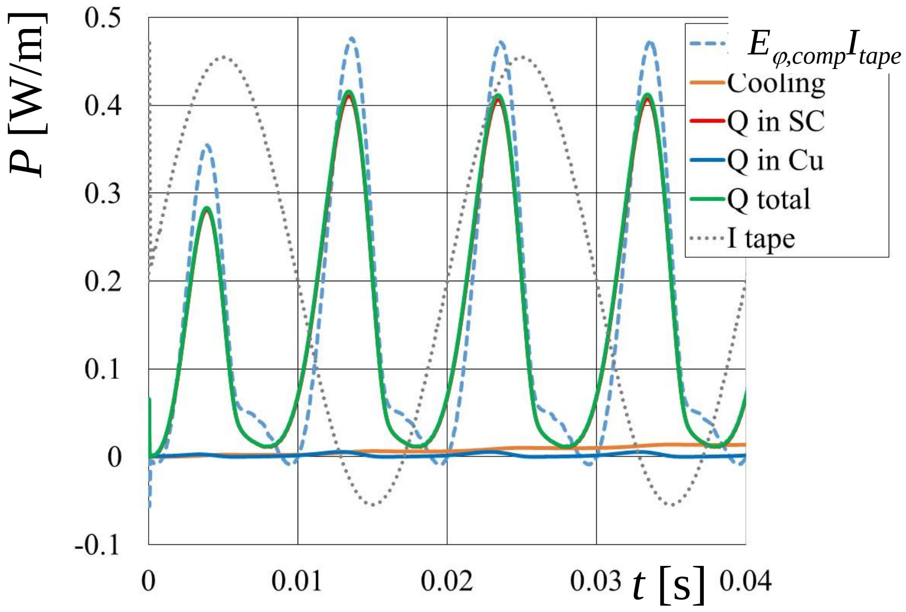


Removing of purely inductive signal

$$E_{\varphi,comp} = -\nabla\varphi - L_{aux}\frac{dI}{dt}$$

$$\frac{Q}{l} = \int_T^{2T} E_\varphi(t) I_{tape}(t)dt = \int_T^{2T} E_{\varphi,comp}(t) I_{tape}(t)dt$$



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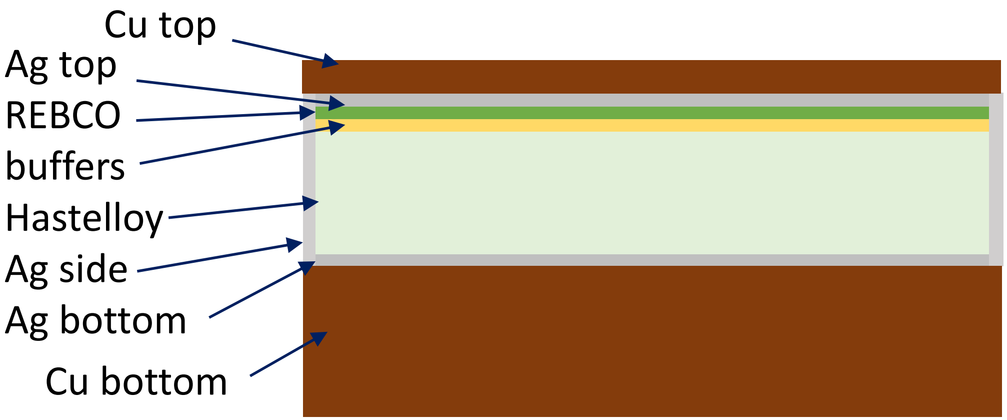

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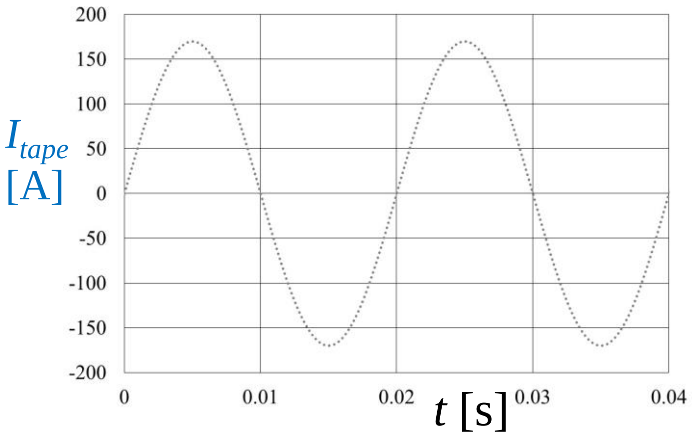
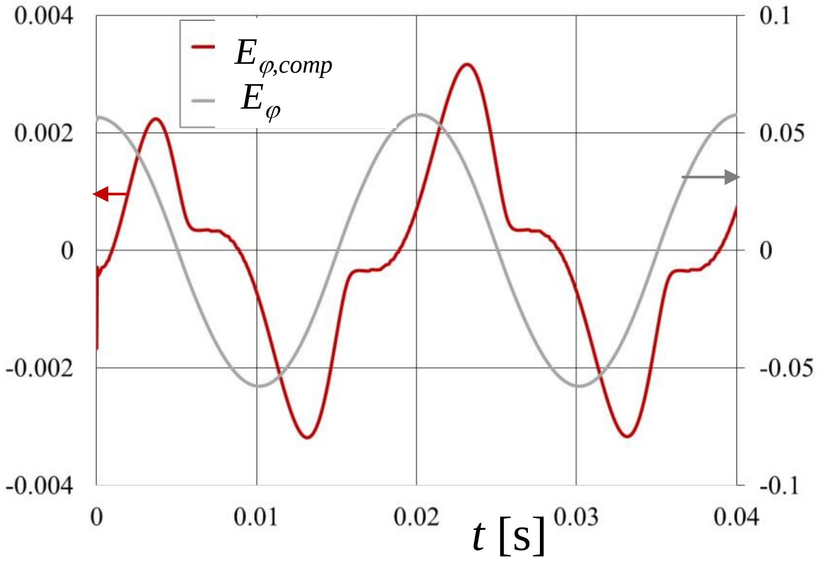
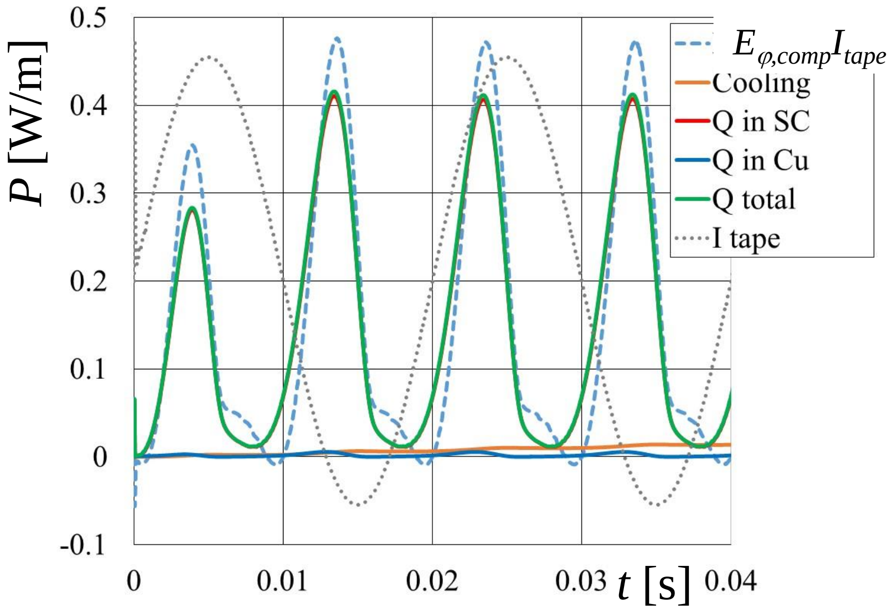


$$E_{\varphi,comp} = -\nabla\varphi - L_{aux}\frac{dI}{dt} \text{ [V/m]}$$





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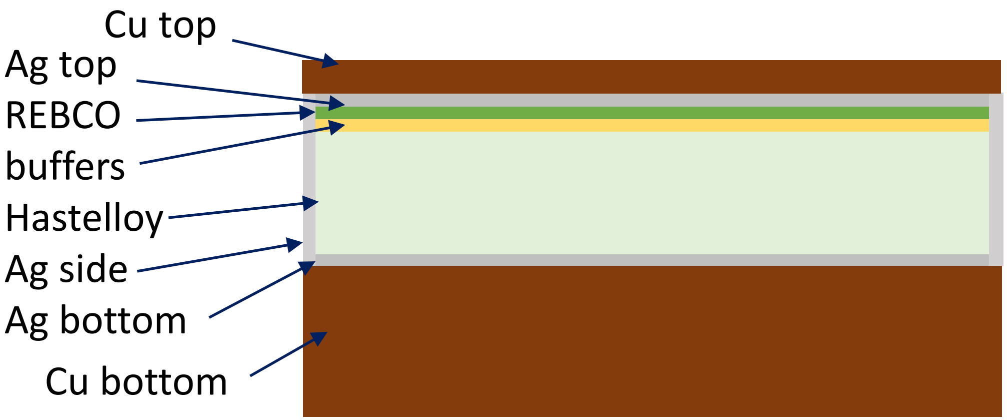

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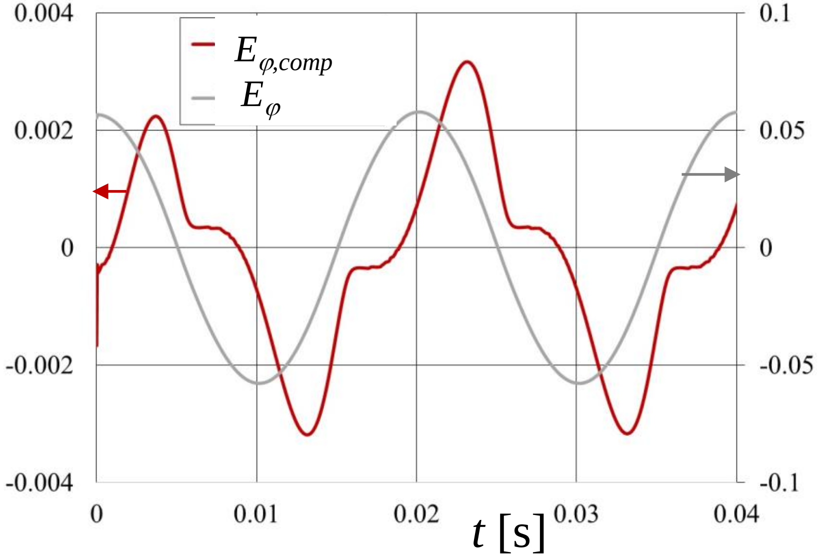
$$\int_S j_{loc} dS = I_{ac}$$

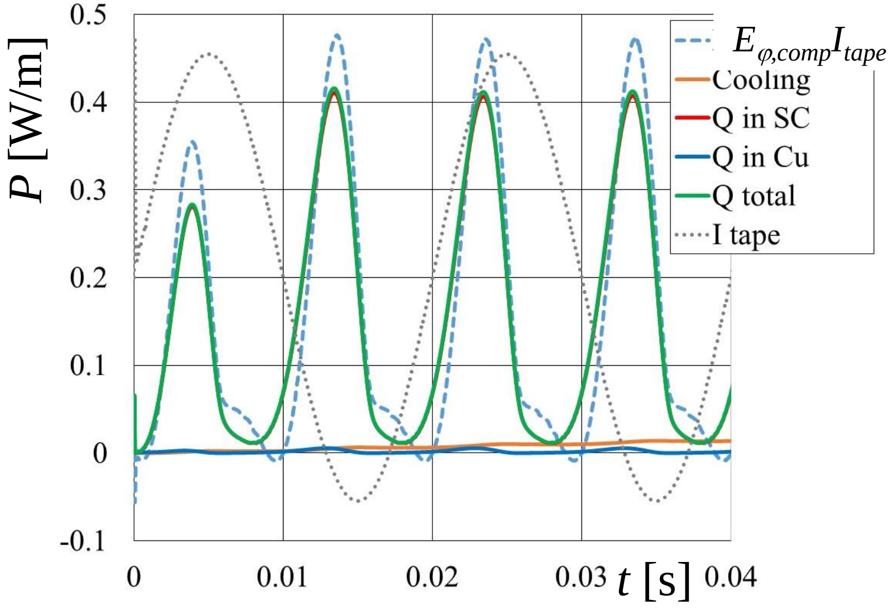
Check of correctness and precision:

$$\int_T^{2T} dt \int_S j_{loc}(\vec{r}) E_{loc}(\vec{r}) dS =$$

$$= \int_T^{2T} E_{\varphi,comp}(t) I_{tape}(t) dt$$

$$E_{\varphi,comp} = -\nabla\varphi - L_{aux}\frac{dI}{dt} \text{ [V/m]}$$

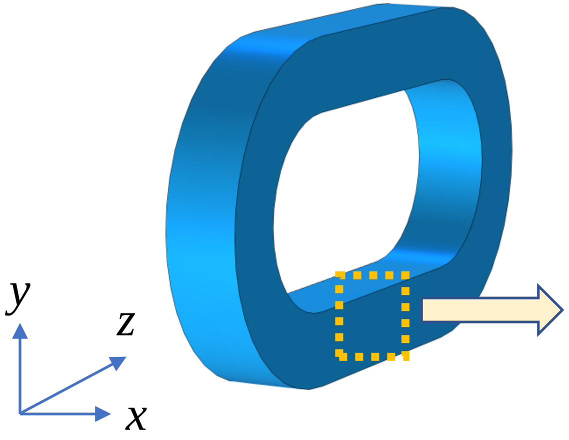




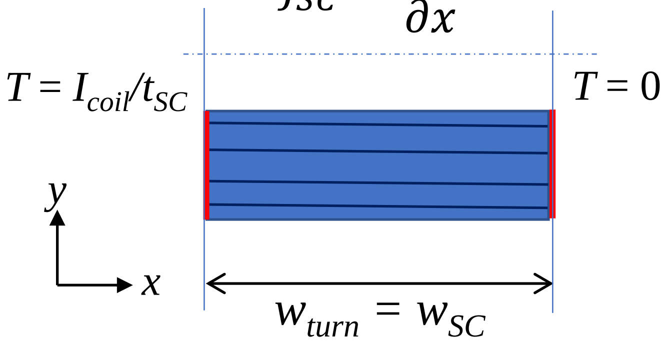
Inspiration – *T-A* formulation

N = 10 turns, superconductor w_{SC} = 12 mm × t_{SC} = 10 µm, Bean model with I_c = 800 A, $j_c = \frac{I_c}{w_{SC} t_{SC}}$

N, Amemiya, S. I. Murasawa, N. Banno N and K. Miyamoto,"Numerical modelings of superconducting wires for AC loss calculations," Physica C 310 (1998) 16–29



$$j_{SC} = \frac{\partial T}{\partial x}$$



$$\rho_{SC} = \frac{E_c}{j_c}\left(\frac{j_{SC}}{j_c}\right)^n \Rightarrow E_{SC} = \rho_{SC} j_{SC}$$

$$\frac{\partial E_{SC}}{\partial x} = -\frac{\partial B_y}{\partial t}$$

homogenization (not necessary for 10 turns): $j_{winding} = j_{SC}\frac{t_{SC}}{t_{turn}}$ t_{turn} = 1 mm

E. Berrospe-Juarez, V. M. R. Zermeno, F. Triallaud and F. Grilli, "Real-time simulation of large-scale HTS systems: multi-scale and homogeneous models using the T–A formulation," Supercond. Sci. Technol. 32 (2019) 065003

AC excitation [A]:

$$I_{coil} = I_{max} cos(2\pi f t)$$

Loss density [J/m³]:

$$q_{winding} = j_{winding} E_{SC}$$

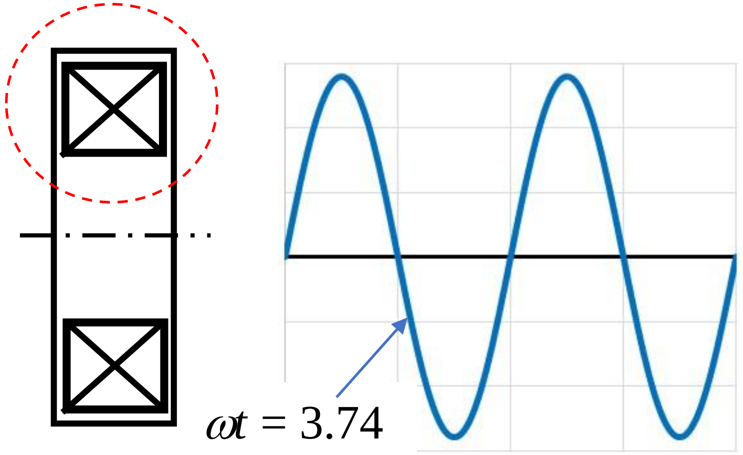
Loss per cycle [J/m]:

$$\frac{Q}{l} = \int_T^{2T} dt \int_S j_{winding}(x,y) E_{SC}(x,y) dS$$

Novelty

how to extract the E_φ ?

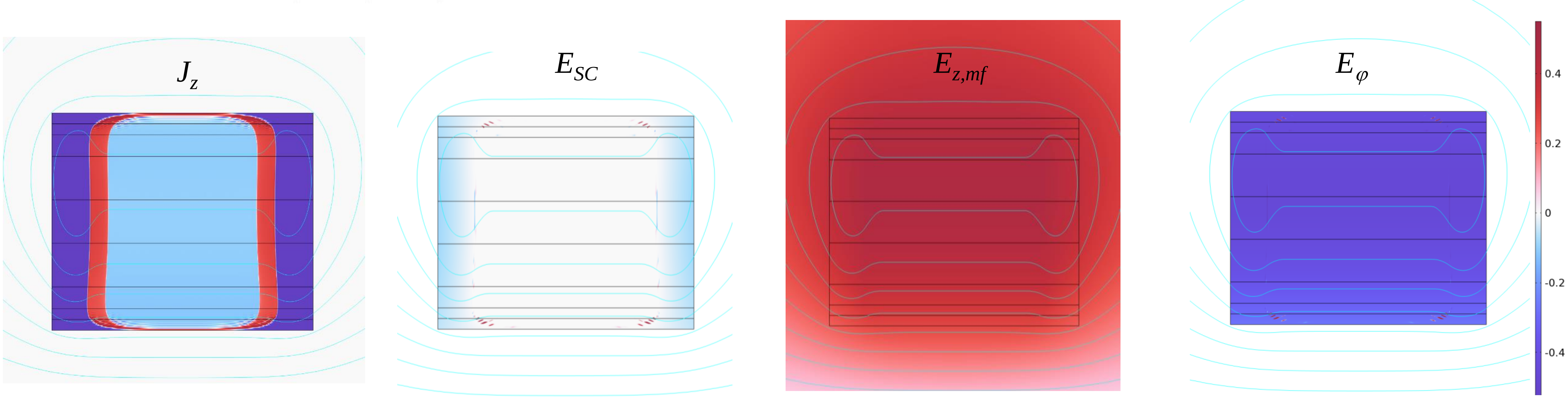
$$E_{SC} = -\frac{\partial A}{\partial t} - \nabla\varphi \qquad -\nabla\varphi = E_\varphi = E_{SC} + \frac{\partial A}{\partial t}$$



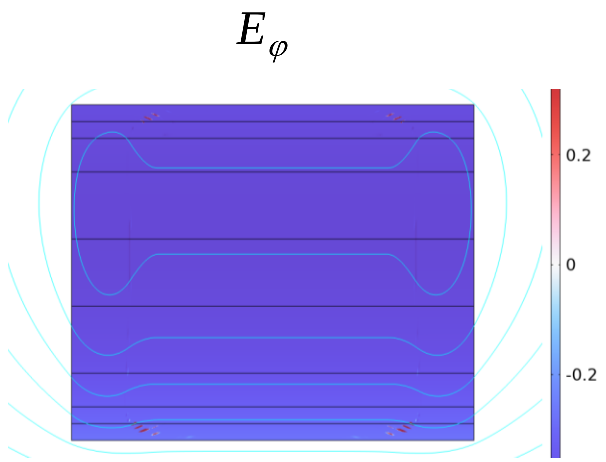
in ComsolMultiphysics, mf module:

$$j_{SC} = \frac{\partial T}{\partial x}$$ set as „external current density“, $$E_{SC} = \rho_{SC} j_{SC}$$

$$\frac{\partial A}{\partial t} = -E_{z,mf}$$ then: $$E_\varphi = E_{SC} - E_{z,mf}$$



Novelty



$E_\varphi = E_{SC} - E_{z,mf}$ is constant in each (fictive) turn

similar approach applicable to *H*- fomulation:

$$E_i = \tilde{E}_\varphi(t)|_{i\text{th turn}} = \frac{1}{S_i}\int_{S_i}\left[E_\theta(t, r, z) + \frac{\partial A_\theta(t, r, z)}{\partial t}\right]\mathrm{d}S \quad (18)$$

F. Gömöry and J. Sheng.: Two methods of AC loss calculation in numerical modelling of superconducting coils. Supercond. Sci Technol. 30 (2017) 064005

voltage on coil terminations: $U_{\varphi,coil} = \sum_1^N l_{turn}\, E_\varphi$

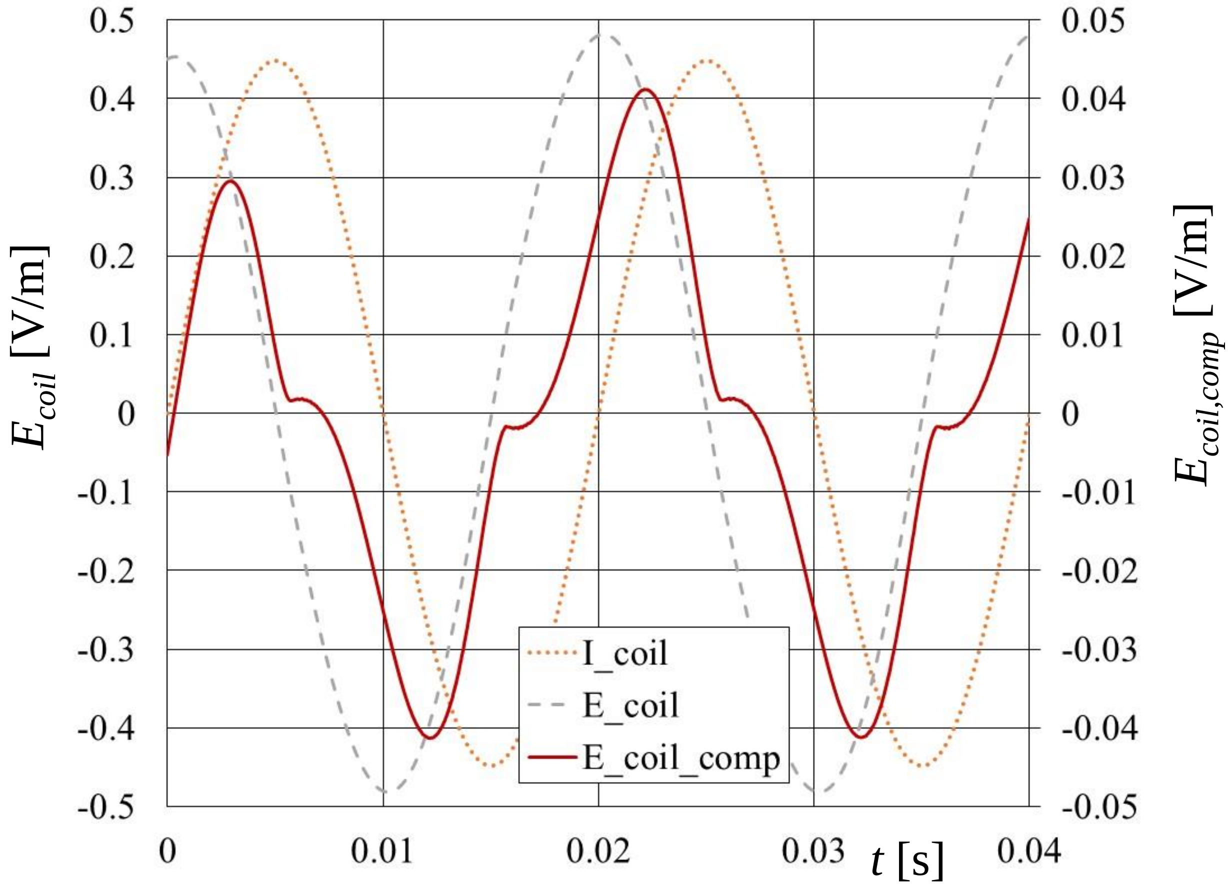
averaging over coil cross-section

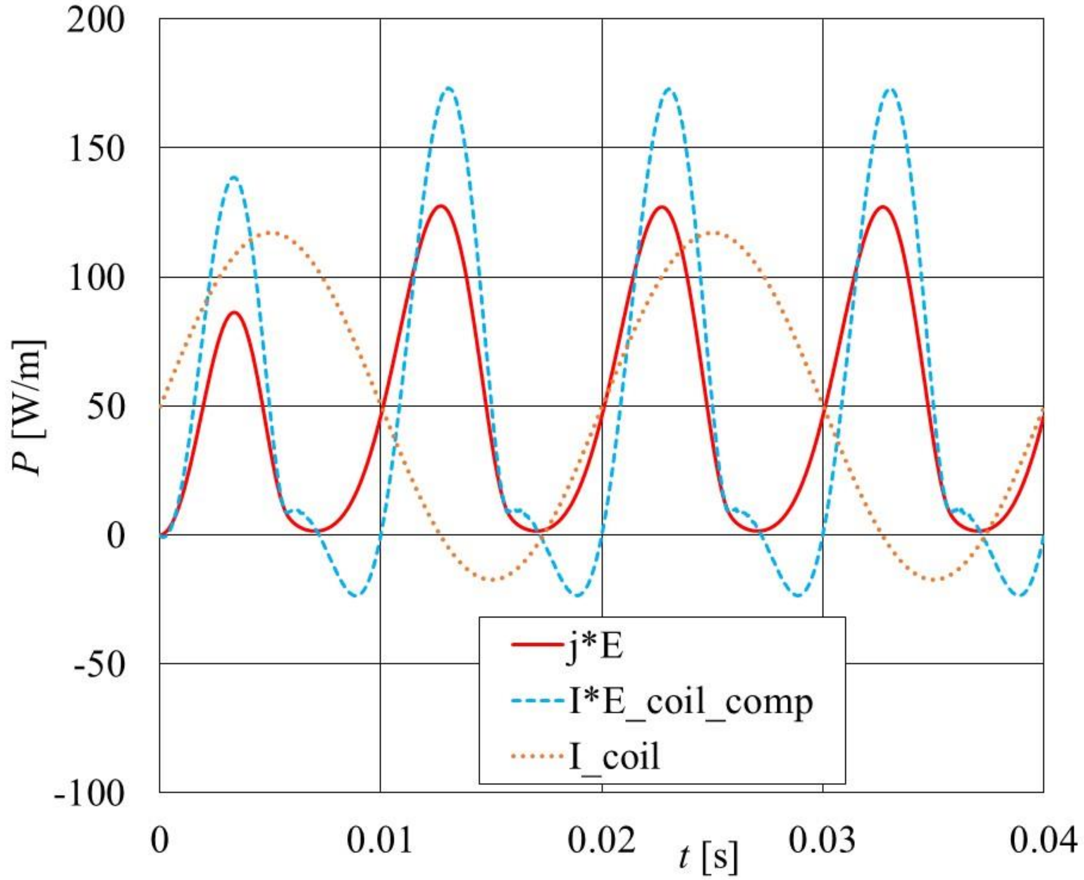
$$U_{\varphi,coil} = l_{turn} N \overline{E_\varphi} = l_{turn} N\left(\overline{E_{SC} - E_{z,mf}}\right)$$

representative: $E_{coil} = \overline{E_\varphi}$

Novelty

results for 50 Hz, I_{max} = 560 A

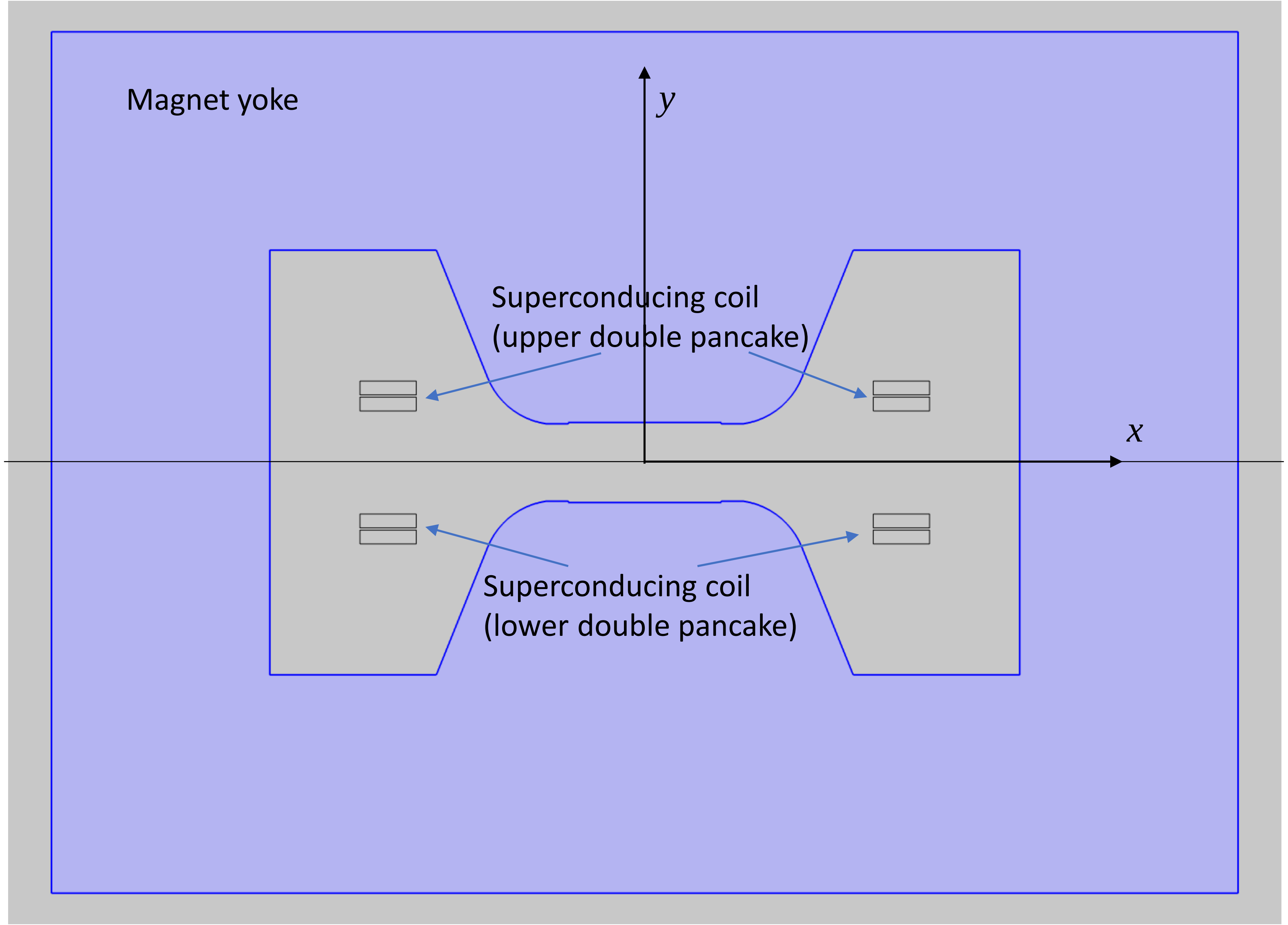




1st cycle: $Q_{loss,\ j*E} = 0.823$ J/m $Q_{loss,\ I*E} = 0.912$ [J/m]

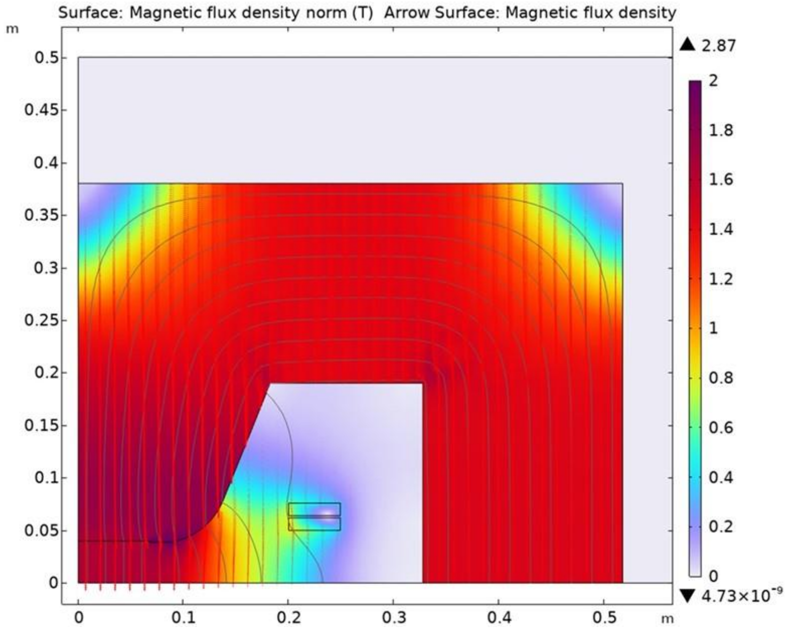
2nd cycle: $Q_{loss,\ j*E} = 1.06$ J/m $Q_{loss,\ I*E} = 1.07$ [J/m]

Example of use: superferric accelerator magnet



50 turns in each pancake
(200 turns in total)

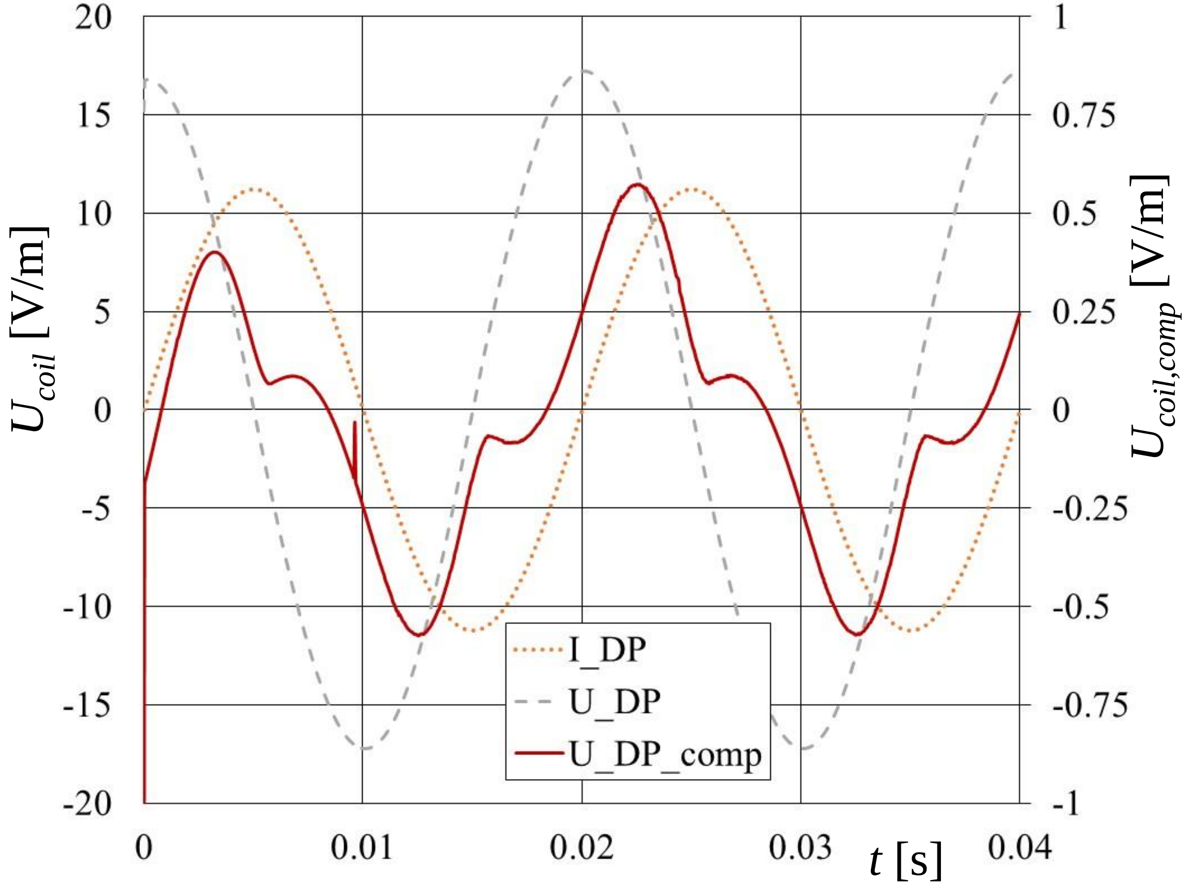
12 mm wide CC tape
generating 1.6 T at
I_{max} = 530 A



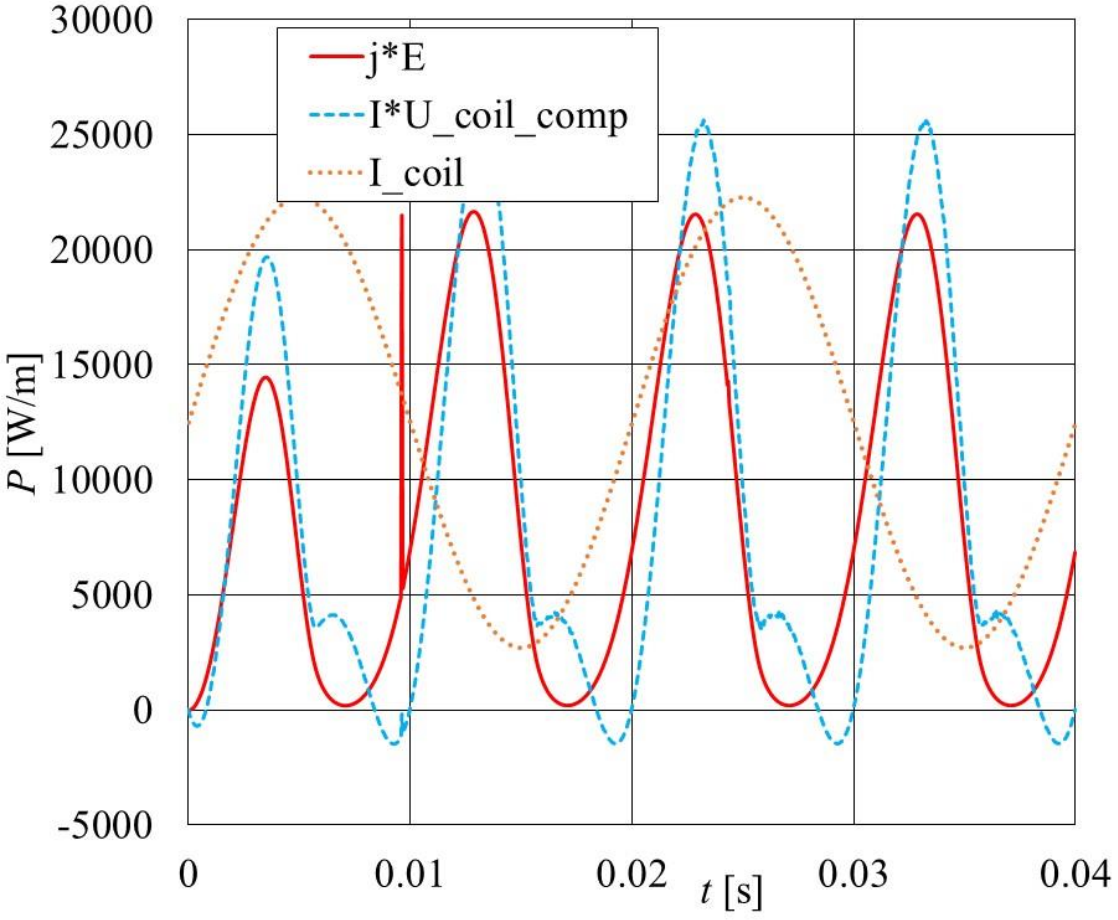
Example of use: superferric accelerator magnet

computations for I_{max} = 560 A, 50 Hz 1) I_c = const. = 1350 A, non-magnetic yoke

$$U_{coil} = NE_{coil}$$



Loss per 1 m of winding (100 turns)

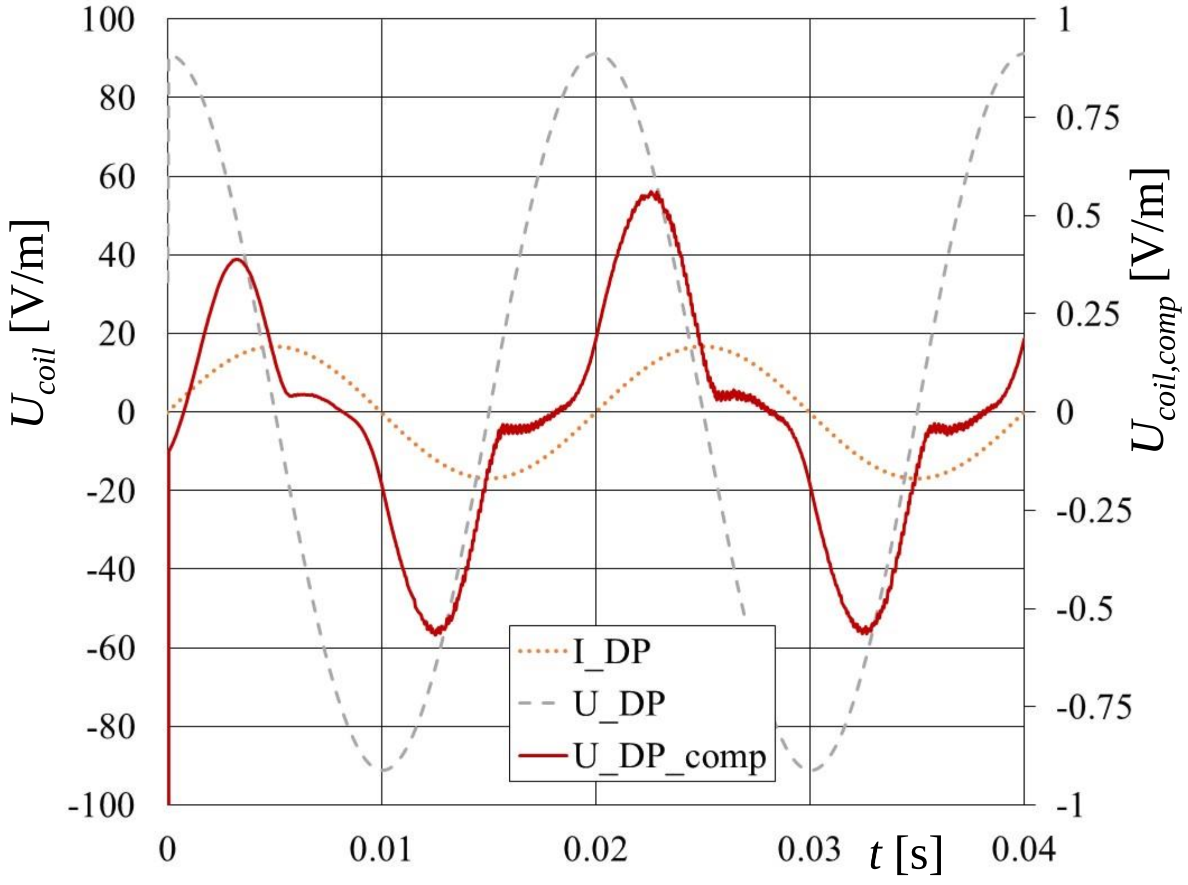


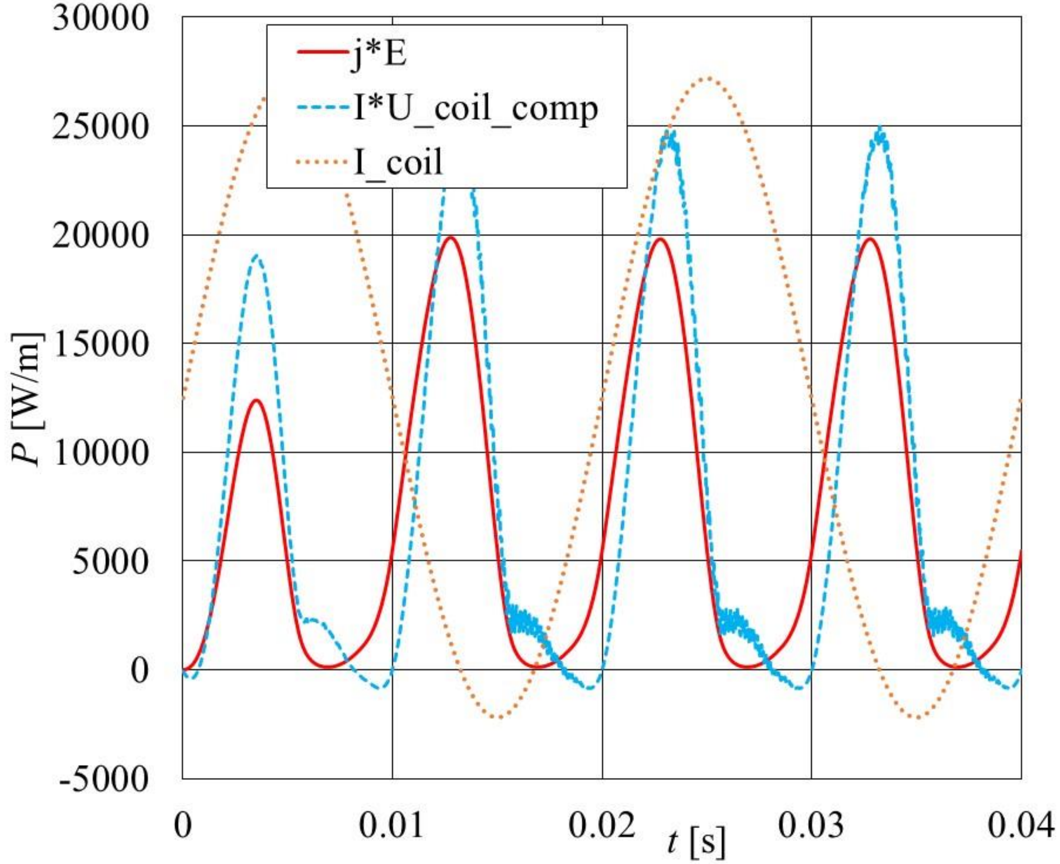
2[nd] cycle: $Q_{loss,\,j*E}$ = 178 J/m $Q_{loss,\,I*U}$ = 181 [J/m]

Example of use: superferric accelerator magnet

computations for I_{max} = 560 A, 50 Hz

2) $I_c(B) = \dfrac{I_{c0}}{\left(1 + \sqrt{kB_{\parallel}^2 + B_{\perp}^2}/B_0\right)^{\beta}}$; magnetic yoke μ_r = 600



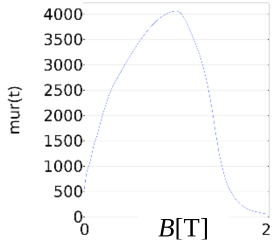


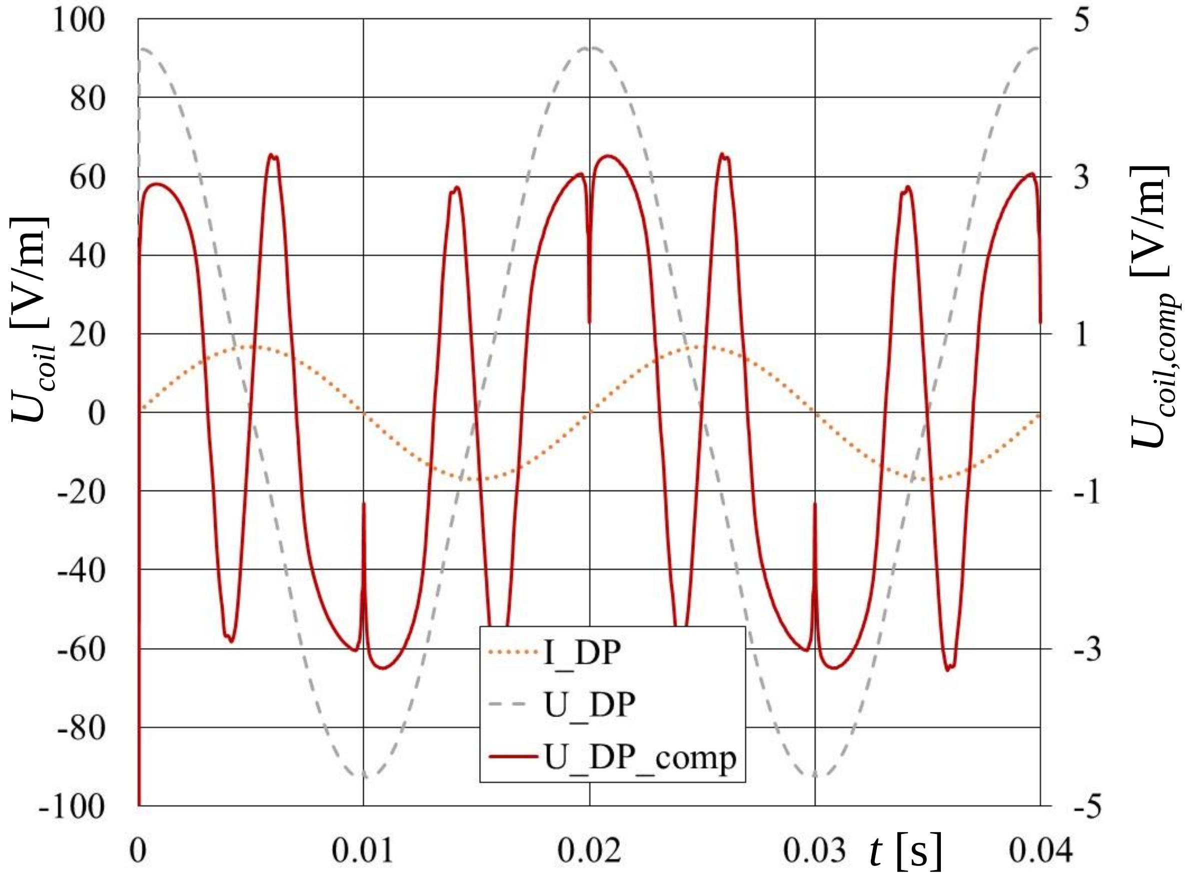
2nd cycle: $Q_{loss,\, j*E}$ = 156 J/m $Q_{loss,\, I*U}$ = 162 [J/m]

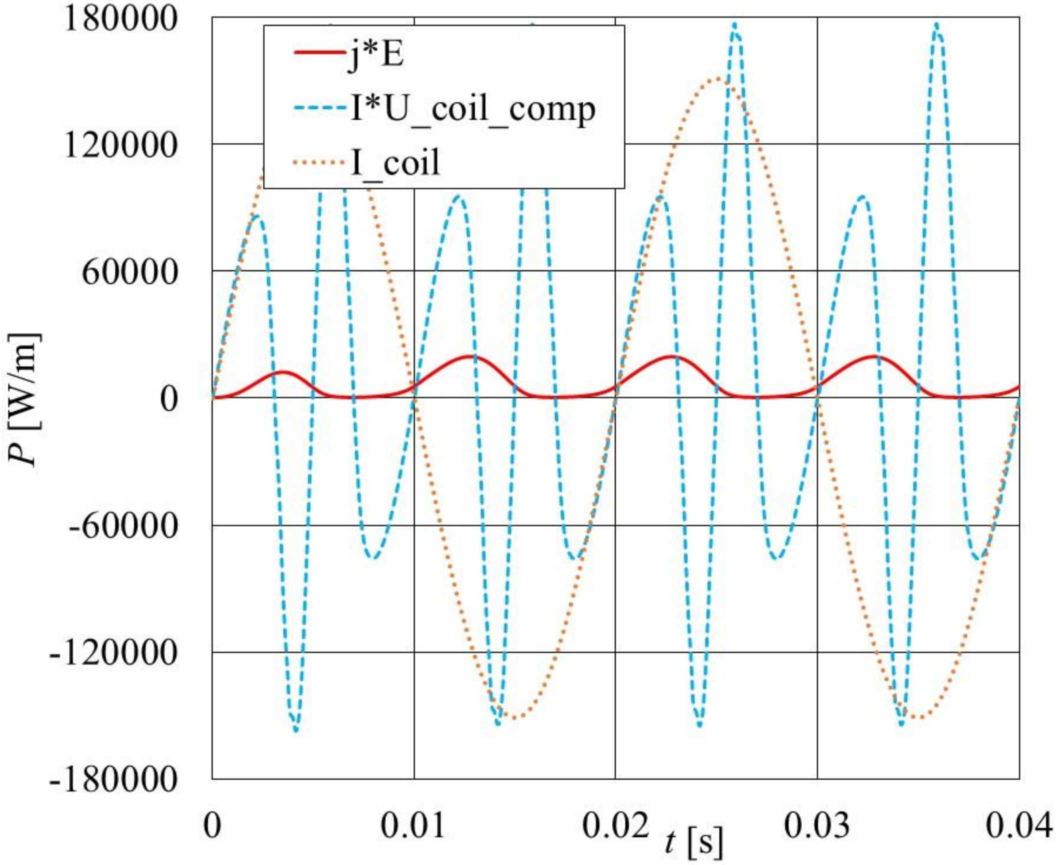
Example of use: superferric accelerator magnet

computations for I_{max} = 560 A, 50 Hz

3) $I_c(B) = \dfrac{I_{c0}}{\left(1 + \sqrt{kB_\parallel^2 + B_\perp^2}/B_0\right)^\beta}$; magnetic yoke $\mu_r = \mu_r(B)$







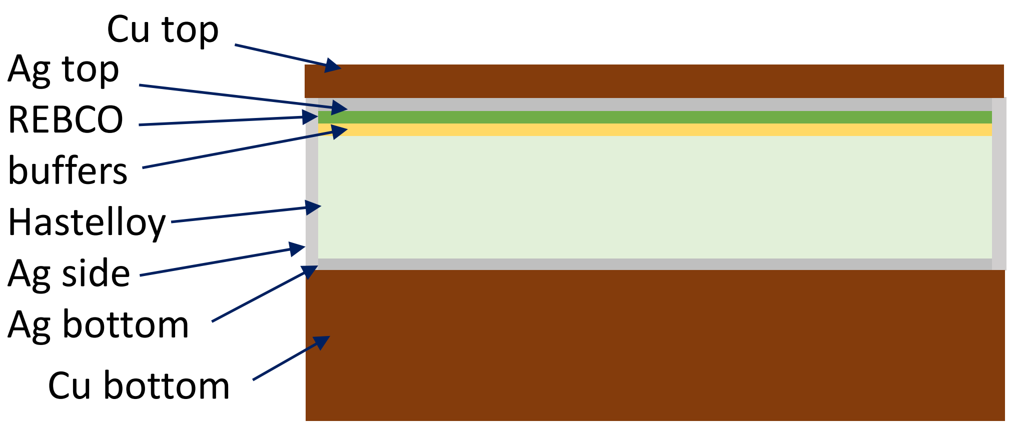
2nd cycle: $Q_{loss,\,j*E}$ = 157 J/m $Q_{loss,\,I*U}$ = 163 [J/m]

Conclusions

- It is possibe to extract the voltage on terminations of a superconducting CC pancake coil in electro-magnetic simulations utilising T-A formulation
- Interpretation of the „loss voltage signal“ could provide better insight into coil operation

Thank you

Example of using macroscopic quantities derived from numerical model – AC loss in CC tape



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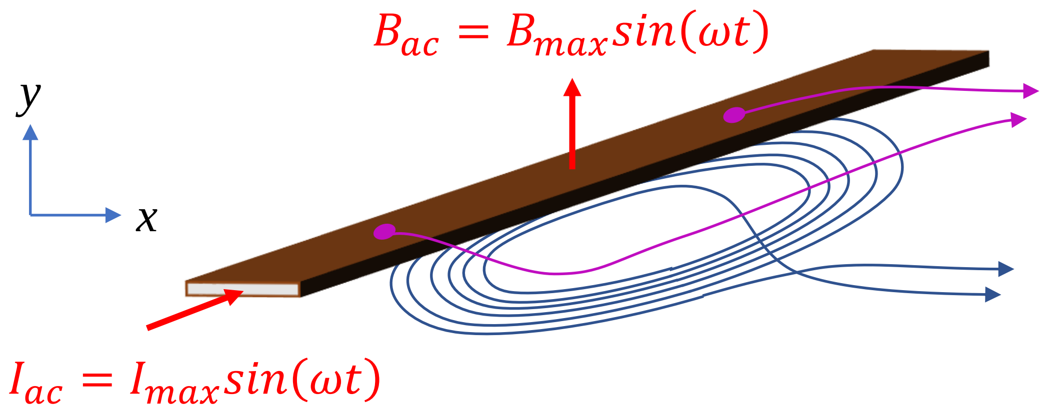
$$E_{loc} = -\frac{\partial A}{\partial t} - \nabla\varphi$$

$$\int_S j_{loc} dS = I_{ac}$$



macroscopic (measurable) quantities:

electric field intensity: $E_\varphi = -\nabla\varphi$

magnetic moment: $m = \int_S x j_{loc} dS$

AC-AC case

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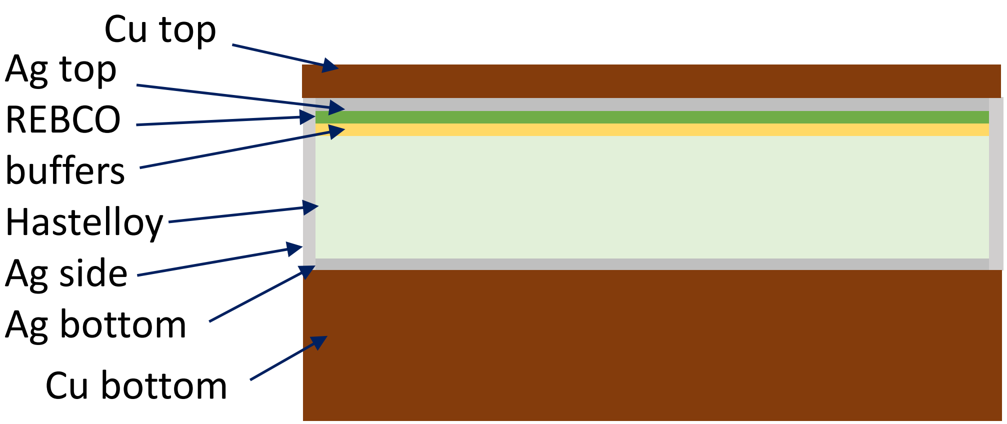

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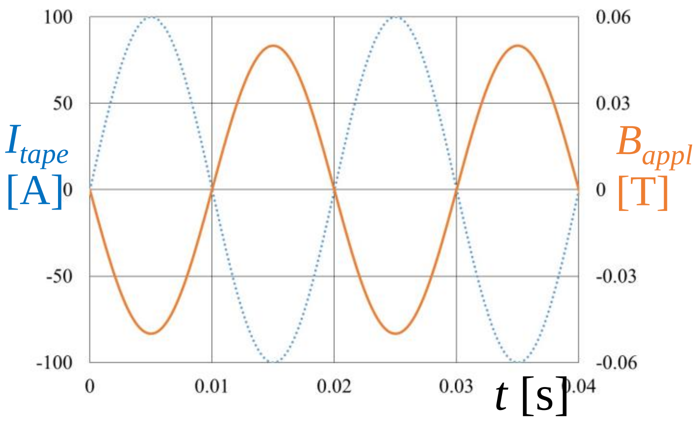

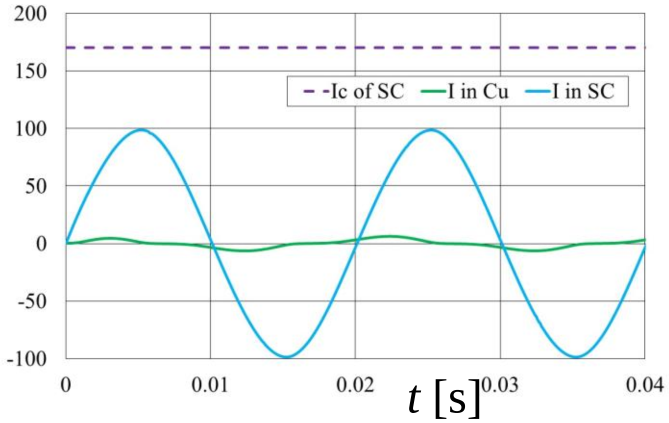

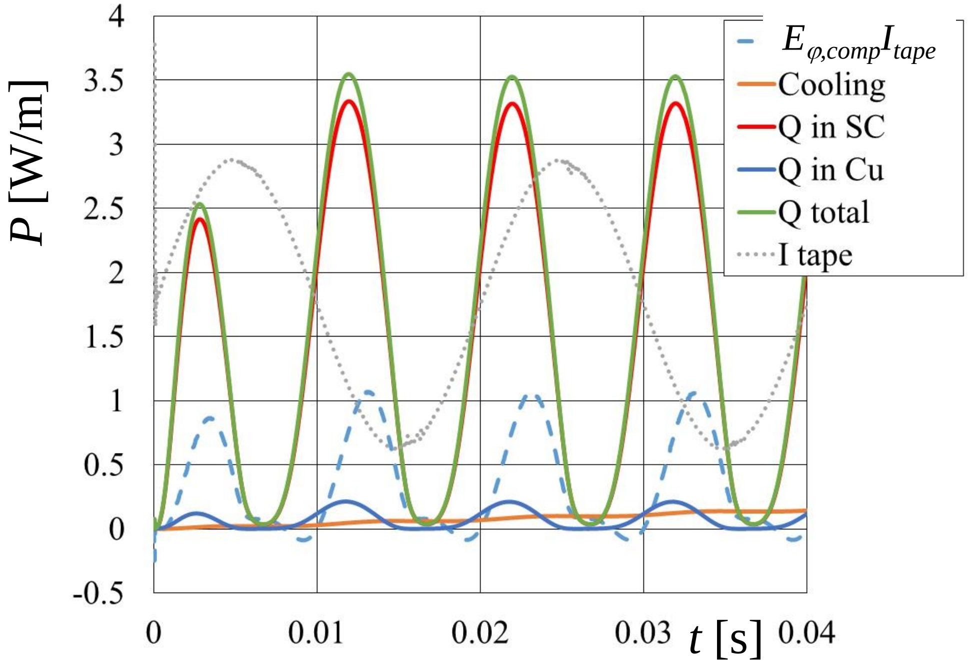

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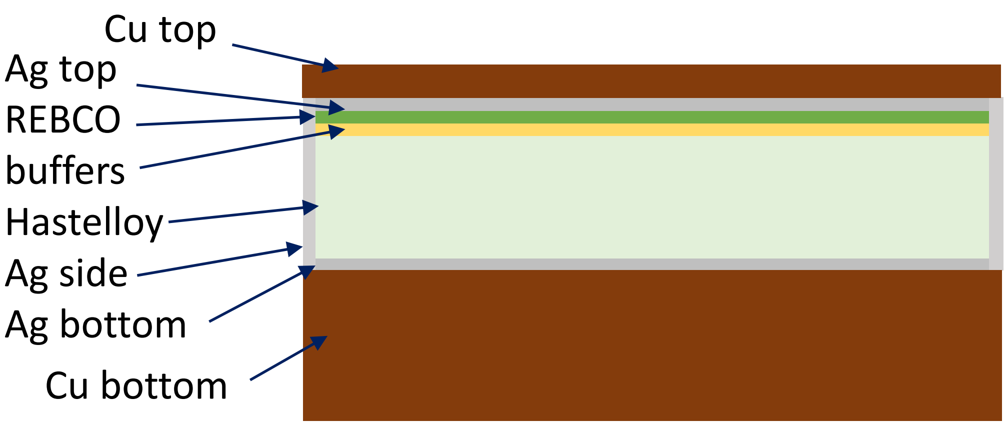

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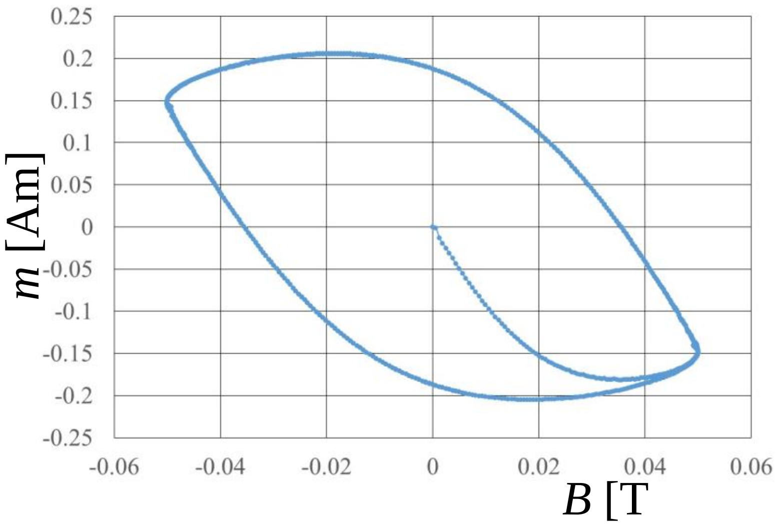
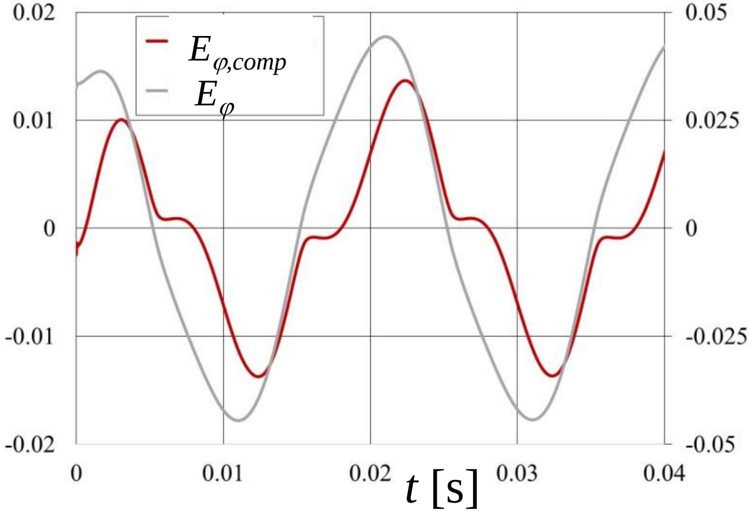
$$\int_S j_{loc} dS = I_{ac}$$

$$E_{\varphi,comp} = -\nabla\varphi - L_{aux}\frac{dI}{dt} \text{ [V/m]}$$





Check of correctness and precision:

$$\int_T^{2T} dt \int_S j_{loc}(\vec{r}) E_{loc}(\vec{r}) dS =$$

32.5 mJ/m

$$= \int_T^{2T} E_{\varphi,comp}(t) I_{tape}(t) dt - \oint m dB$$

7 mJ/m 22.5 mJ/m