

Validating a non-linear model of ferrite materials for power electronic applications using COMSOL®

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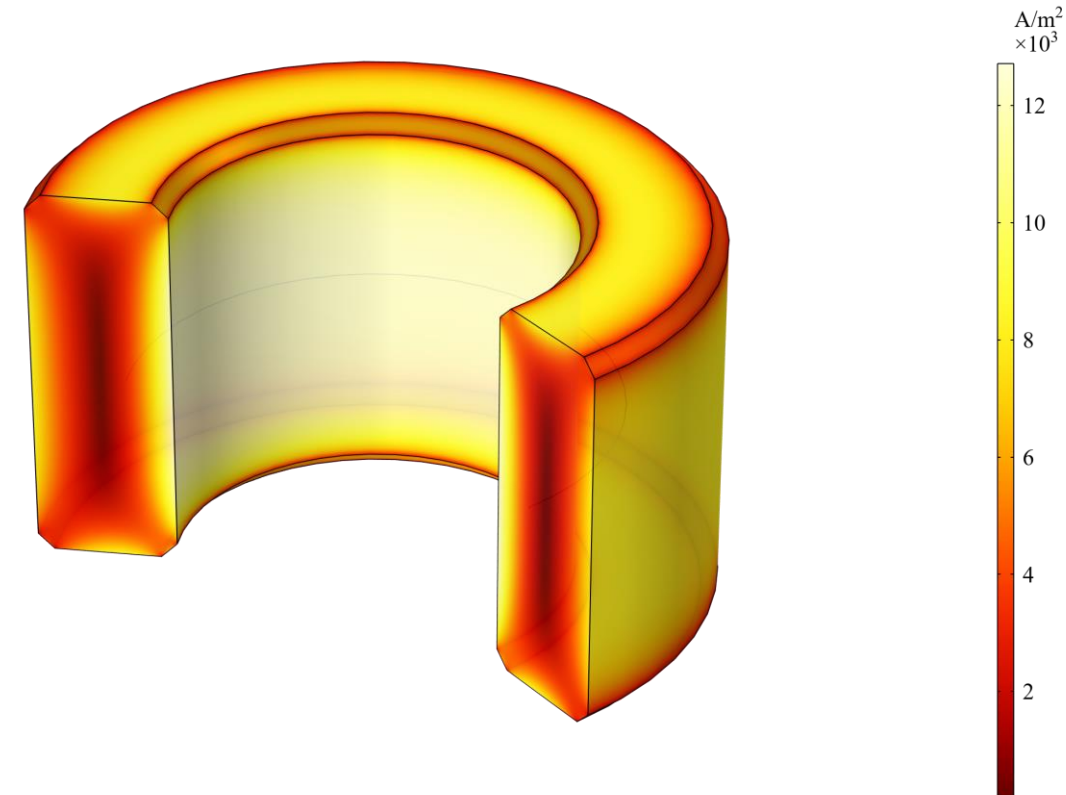
Validating a non-linear model of ferrite materials for power electronic applications using COMSOL®

In the framework of: T. Dimier & J. Biela, "Non-Linear Material Model of Ferrite to Calculate Core Losses with Full Frequency and Excitation Scaling," IEEE Tran. on Magnetics, vol. 59 (7), 2023

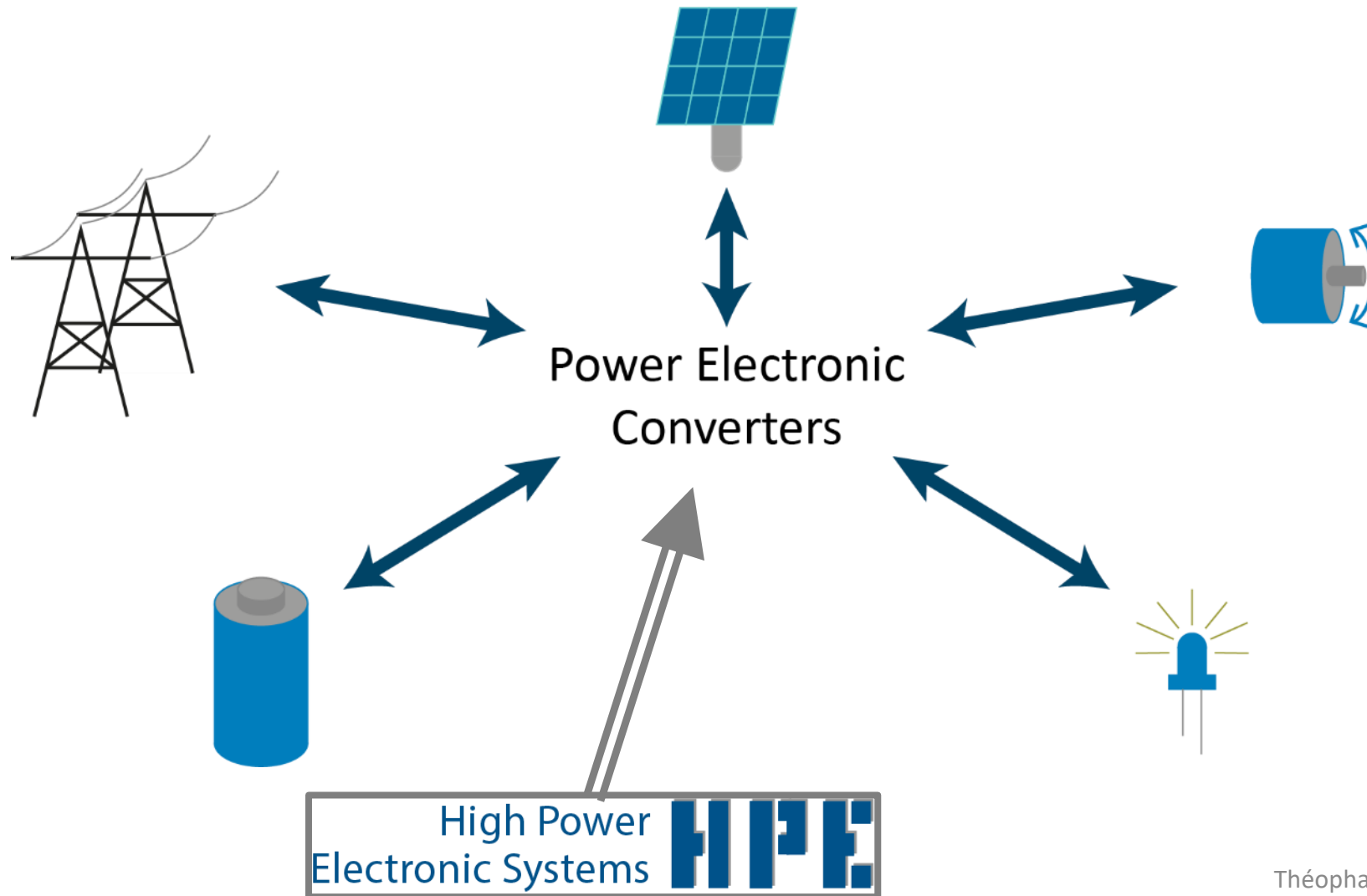
Théophane Dimier and Prof. Dr. Jürgen Biela

Laboratory for High Power Electronic Systems

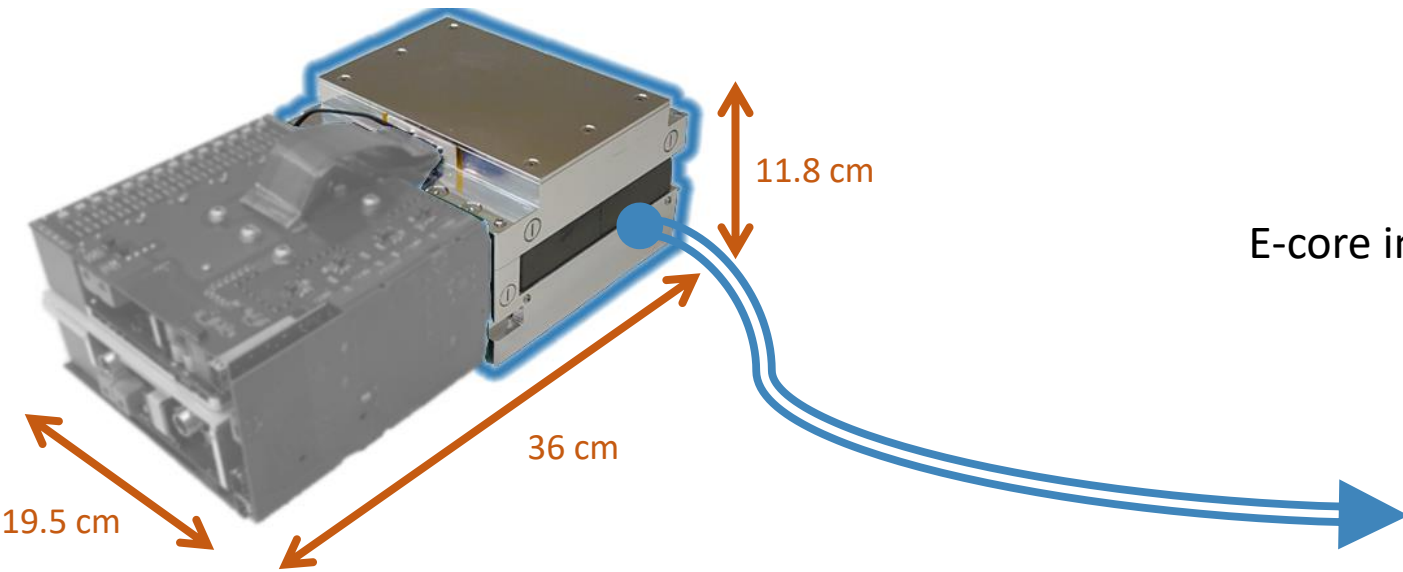
COMSOL Modelling Seminar at ETH Zurich, 2024.05.27



Power electronic converters adapt sources to loads

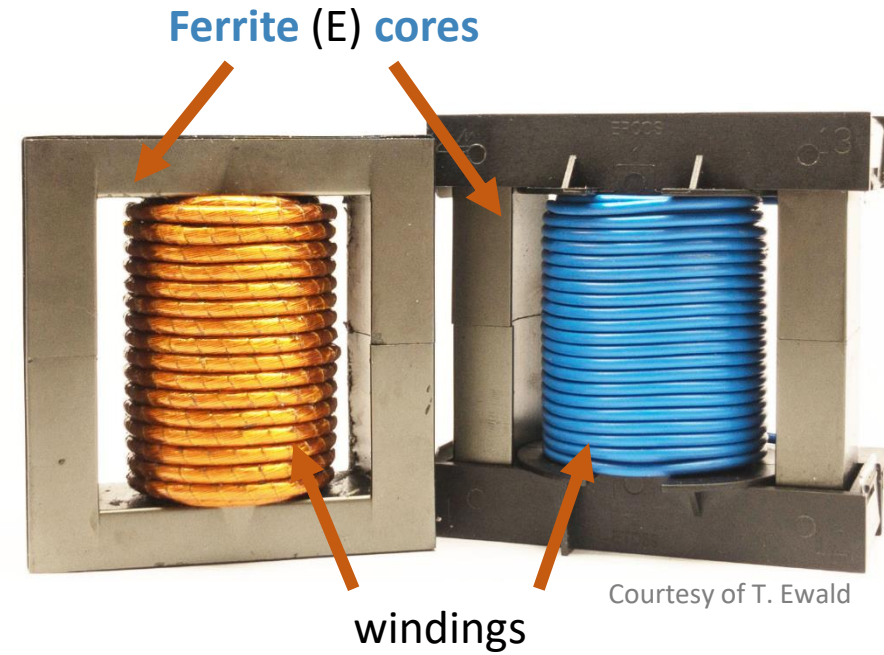


Ferrite cores can be found in transformers and inductors



Dual Active Bridge (DAB) converter from Stajadinovic and Biela, 2019

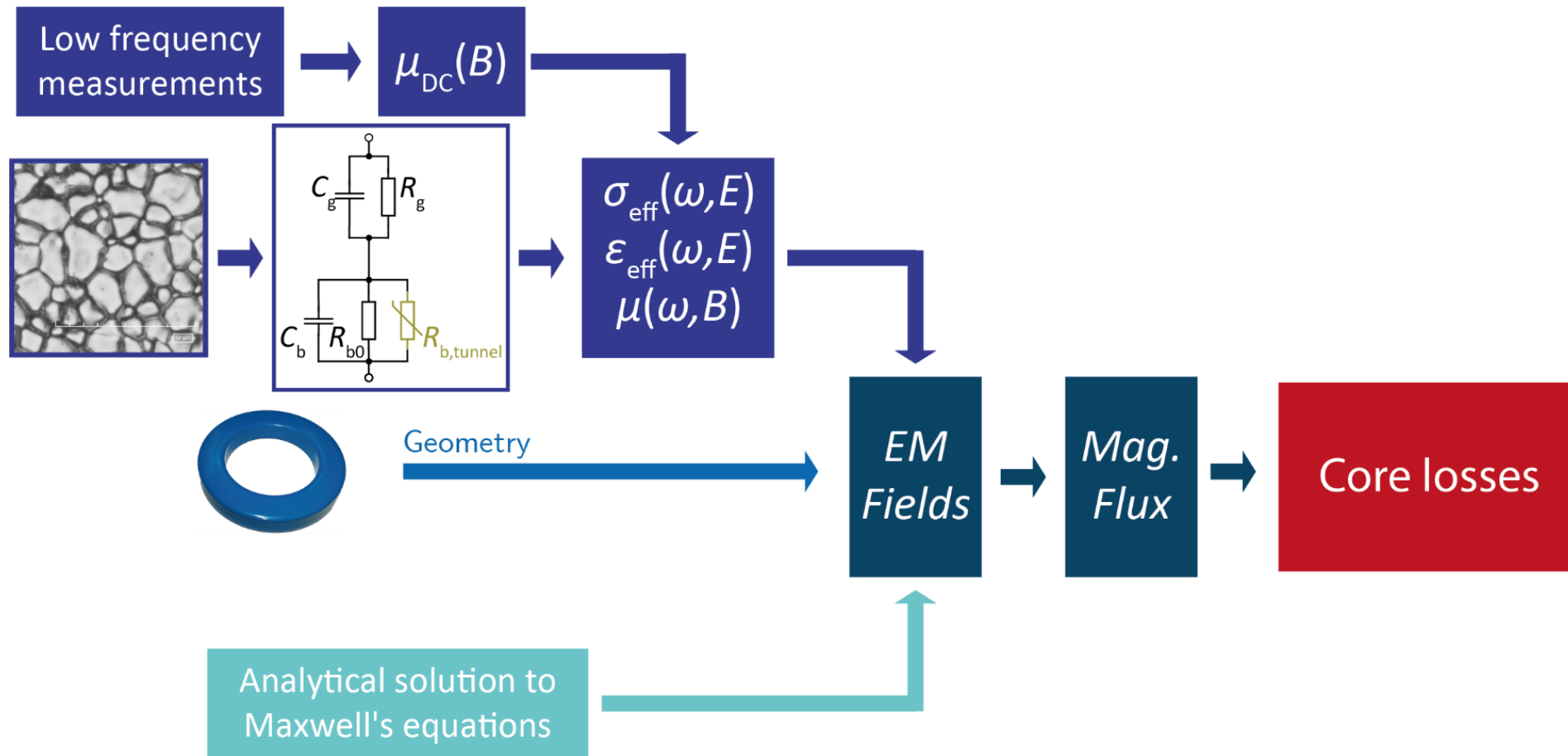
E-core inductors



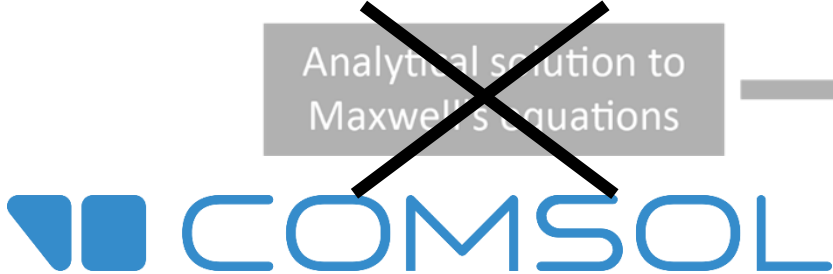
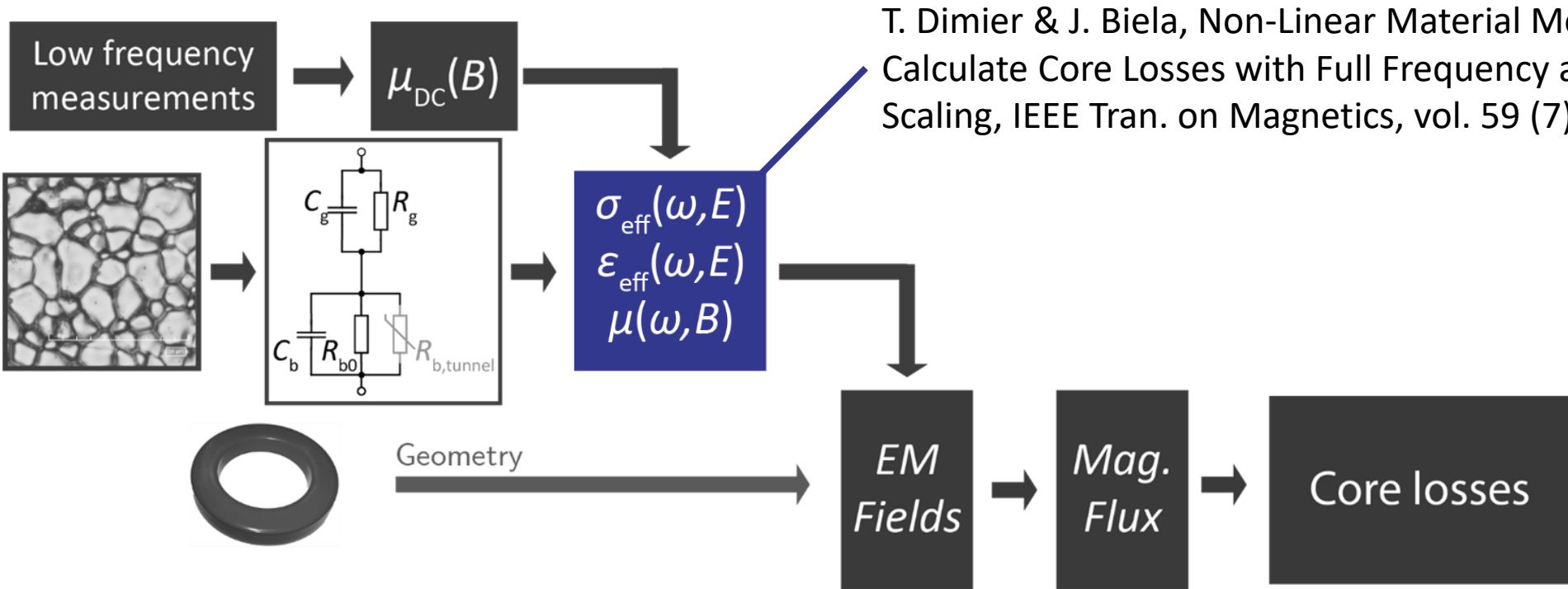
Ring-core inductor



Physical Modelling of Core Losses: Field and Material



How to test the material model?



Non-default settings enables to test the material model

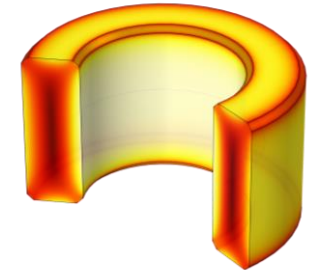
Material model and custom material node



Magnetic field interface settings



Results

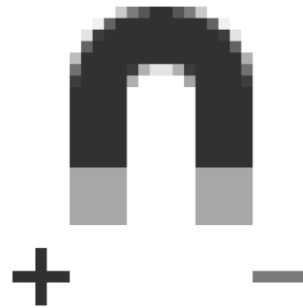


Non-default settings enables to test the material model

Material model and custom material node



Magnetic Field Interface Settings



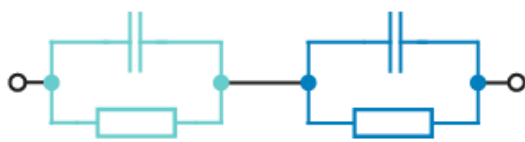
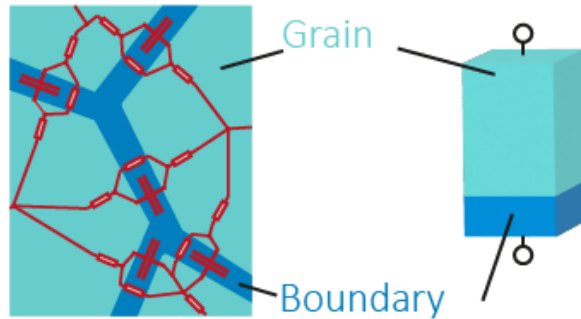
Results



Ferrites are complex materials : microstructure matters!

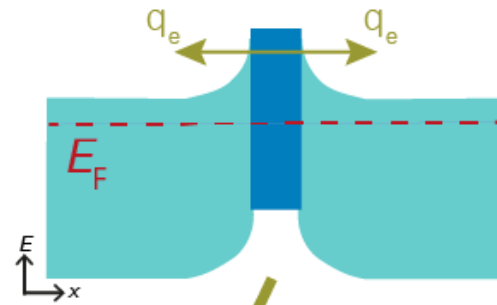
Permittivity and conductivity

Meta material effect and tunneling conduction



Grain

Boundary



Permeability

Magnetisation dynamics

$$\mu(f,B) = \mu_0(1 + \chi_{rot}(f) + \chi_{DW}(f,B))$$

Visuals from the companion presentation of: T. Dimier and J. Biela, "Semi-Analytical Non-Linear Physical Model of Core Losses in Ferrite Ring Cores," in *IEEE Tran. on Magnetics*, vol. 59, no. 11, pp. 1-5, Nov. 2023

Théophile Dimier – HPE Laboratory - ETHZ

COMSOL[®] material node allows custom models

- Parameters 1
- mesh param
- derived quantities
- rotational magnetization
- Default Model Inputs
- Materials
- Component 1 (comp 1)
 - Definitions
 - Geometry 1
 - Materials
 - ferrite (mat 1)
 - Basic (def)
 - boundary conductivity (sigma_b_)
 - permeability (perm)
 - sigma DC (sigma_DC)
 - conductivity (sigma)
 - DC permittivity (epsilon_DC)
 - permittivity (epsilon)
 - boundary conductivity to 0 V/m (sigma_b)
 - mu_dc (mu_dc)
 - mu_dc_i (mu_dc_i)
 - prob_dist (g)
 - chi_rot_loc_r (chi_rot_loc_r)
 - chi_rot_loc_i (chi_rot_loc_i)
- Magnetic Fields (mf)
- General Optimization (opt)
- Meshes
- Study 1
- Study 3
- Parameter Fit

Analytic Functions

Lookup tables

Output Properties

Property	Variable	Expression	Unit	Size	Info
Relative permeability	mur_iso ; murii =...	(mu_dc(mf.normB)-chi_rot_r 0+i*(mu_dc...	1	3x3	
Relative permittivity	epsilon_nr_iso ; epsi...	epsilon(2*pi*mf.freq,mf.normE)/epsilon0...	1	3x3	
Electrical conductivity	sigma_iso ; sigma...	sigma(2*pi*mf.freq,mf.normE)	S/m	3x3	

Expression:

Model Inputs

Physical quantity	Variable
Electric field	{E1, E2, E3}
Magnetic flux density	{B1, B2, B3}
Frequency	freq

Local Properties

Name	Expression	Unit	Description
chi_rot_r	2/3*integrate(g(H_k)*chi_rot_loc_...		real part of rotational susceptibility
chi_rot_i	-2/3*integrate(g(H_k)*chi_rot_loc_...		
chi_rot_r_0	2/3*integrate(g(H_k)*chi_rot_loc_...		
chi_rot_i_0	-2/3*integrate(g(H_k)*chi_rot_loc_...		

Local Properties

$$\chi_{rot,r}(f) = \frac{2}{3} \int_0^{\infty} g(H_k) \chi_{rot,loc,r}(H_k, 2\pi f) dH_k$$

Integration operator

Non-default settings enables to test the material model

Material model and custom material node



Magnetic Field Interface Settings

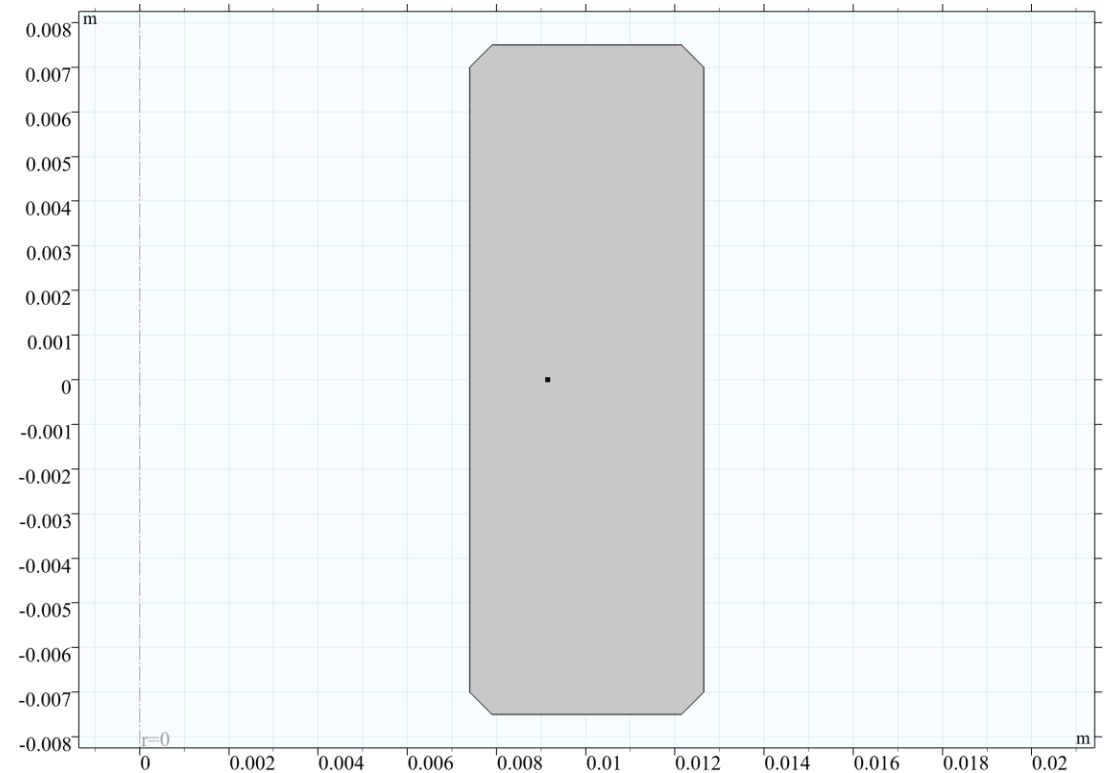


Results



2D axis symmetric geometry

- Ring core
 - $d_{out} = 25.3$ mm
 - $d_{in} = 14.8$ mm
 - $h = 15$ mm
- Current density **around** the cross section
- Frequency domain study



Non-default settings for the physics node

- Magnetic field (mf) physics
- Current density **around** the cross section => **Out-of-plane magnetic field**
- **Non-linear** conductivity and permittivity => **convergence** issues

Default settings

Equation

Components

Field components solved for:
Out-of-plane vector potential

Background Field

Port Sweep Settings

Use manual port sweep

Discretization

Magnetic vector potential:
Quadratic

Dependent Variables

In-Plane Exciting current

Convergence because of non-linear conductivity

This study

Equation

Components

Field components solved for:
In-plane vector potential

Background Field

Port Sweep Settings

Use manual port sweep

Discretization

Magnetic vector potential:
Cubic

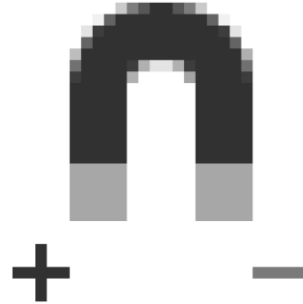
Dependent Variables

Non-default settings enables to test the material model

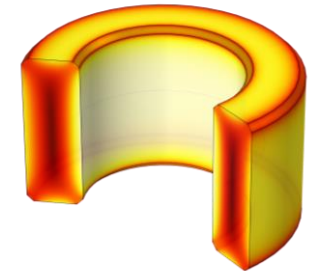
Material model and custom material node



Magnetic Field Interface Settings

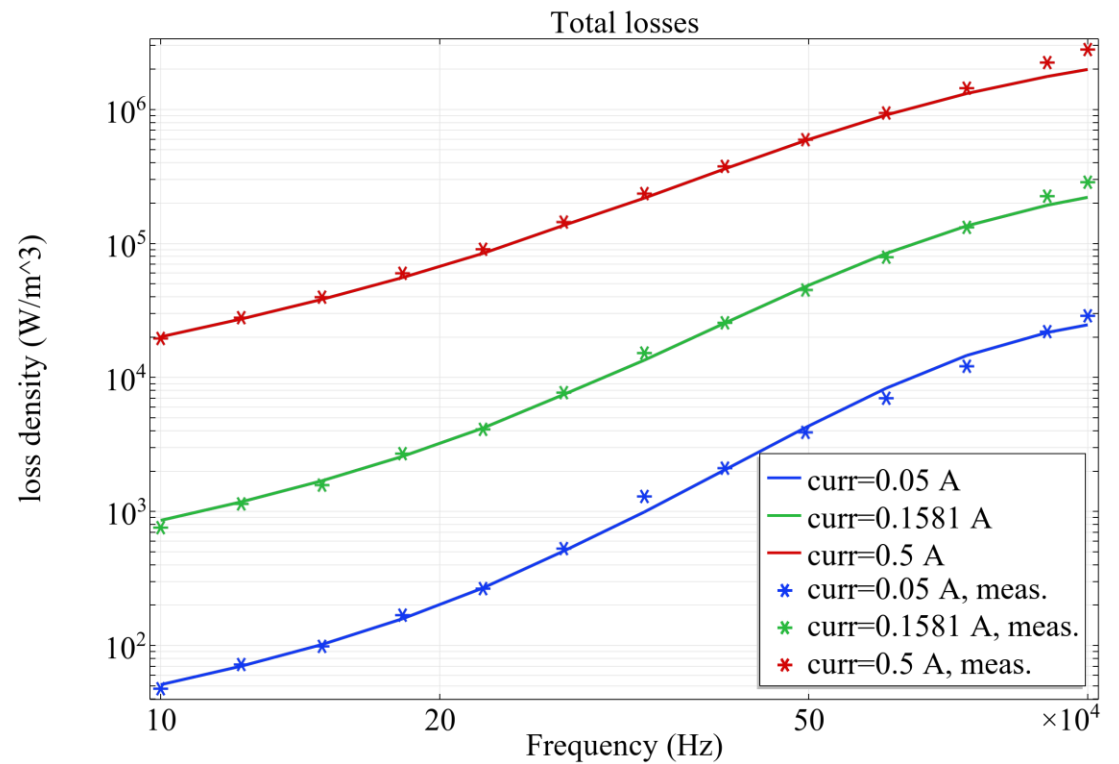
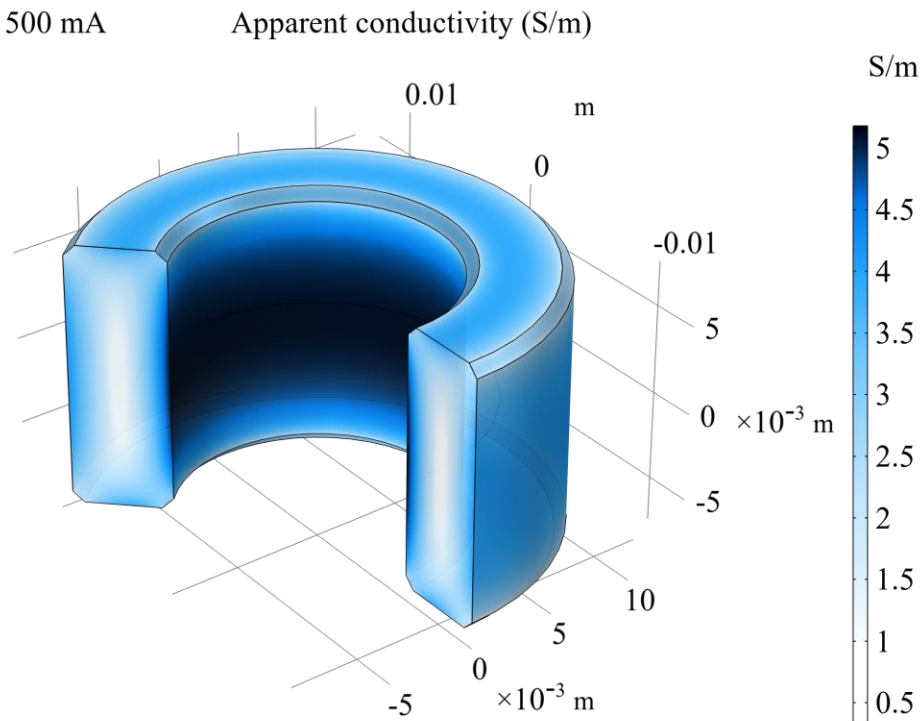


Results



Losses calculated using COMSOL[®] and the material model match with measurements

100 kHz, 500 mA



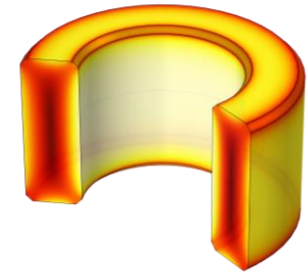
Conclusion: FEM using COMSOL[®] enables much more than field calculation



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Understanding
the material

+

Understanding the
electromagnetic field

=

Better magnetic cores
for power electronic
converters

References

- T. Dimier & J. Biela, “Non-Linear Material Model of Ferrite to Calculate Core Losses with Full Frequency and Excitation Scaling,” *IEEE Tran. on Magnetics*, vol. 59 (7), 2023, DOI: 10.1109/tmag.2023.3277492, accessible at: <https://www.research-collection.ethz.ch>
- Companion presentation (given at the INTERMAG 2023, Sendai, Japan) to: T. Dimier & J. Biela, "Semi-Analytical Non-Linear Physical Model of Core Losses in Ferrite Ring Cores," in *IEEE Tran. on Magnetics*, vol. 59, no. 11, pp. 1-5, Nov. 2023, DOI of the article: 10.1109/tmag.2023.3293713, article accessible at: www.research-collection.ethz.ch, presentation accessible at: www.research-collection.ethz.ch