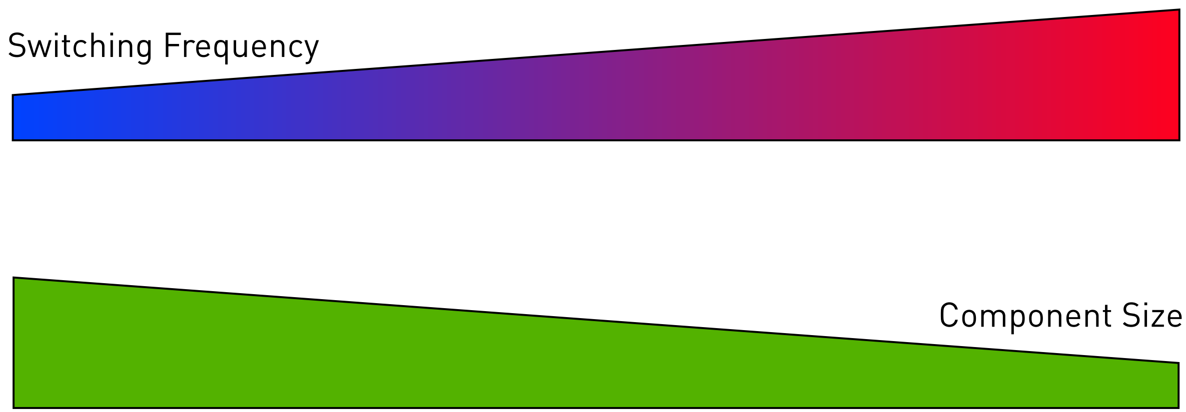
Magnetic Core Materials in HF Applications

Dr. Jonas Mühlethaler

Introduction

What We Expect from Higher Switching Frequencies



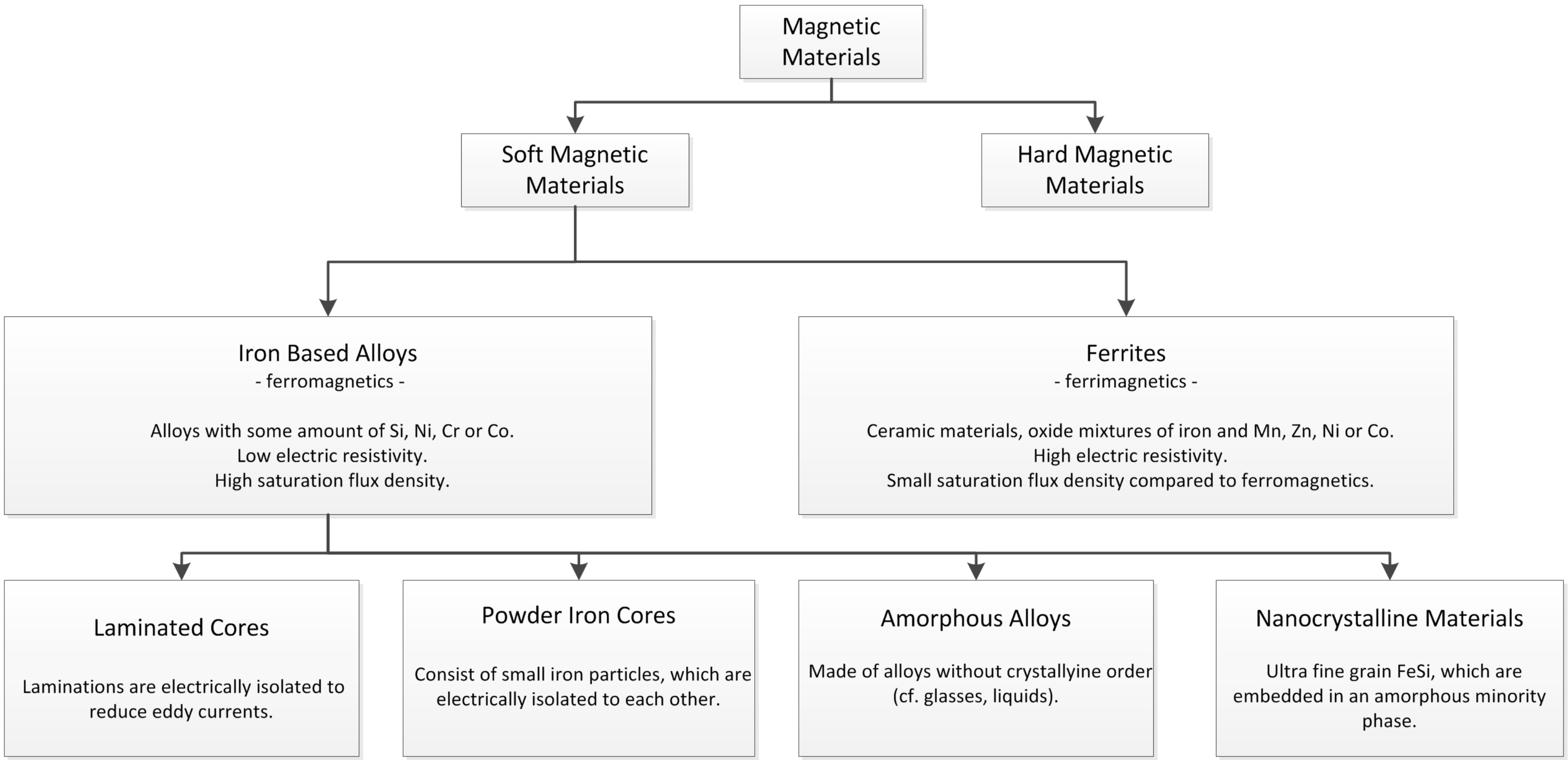
Two Main Issues

Selection of material

Modeling of material

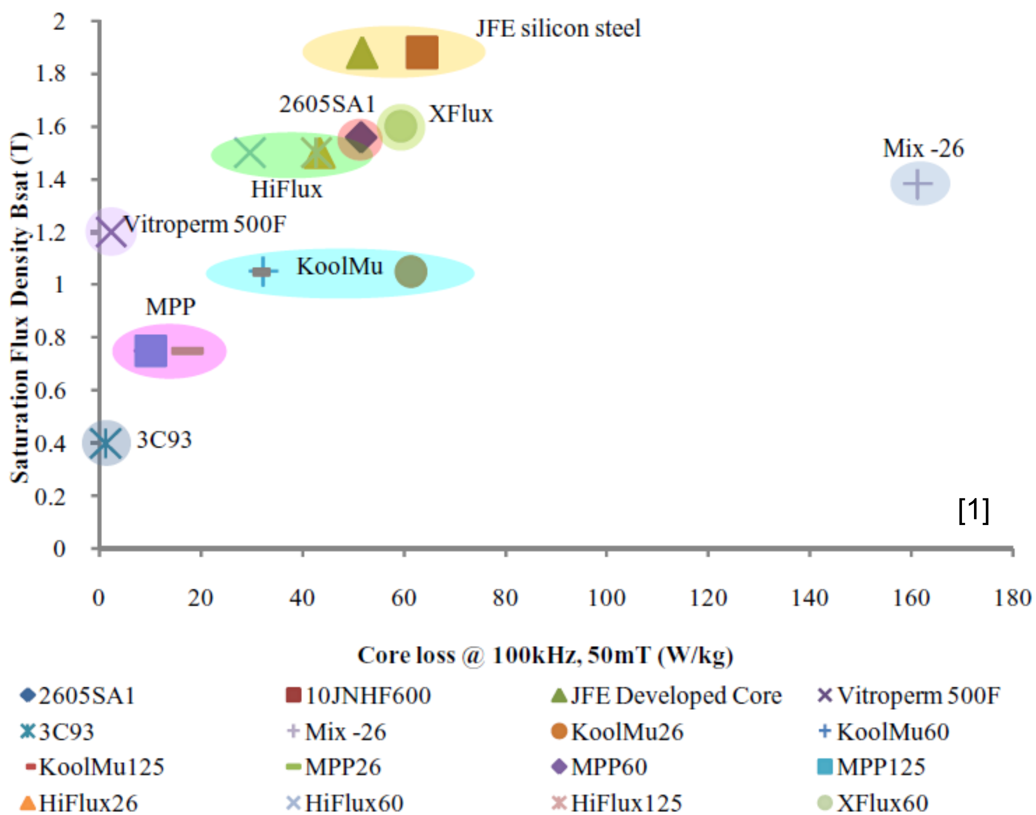
Core Materials

Overview of Different Core Materials (1)



Core Materials

Overview of Different Core Materials (2)

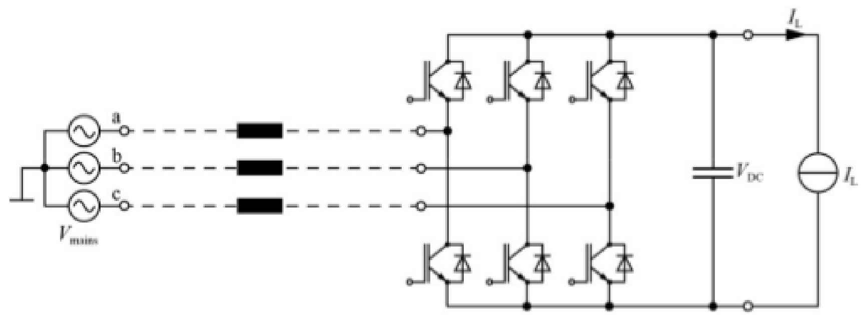


[1] M. S. Rylko, K. J. Hartnett, J. G. Hayes, M.G. Egan, "Magnetic Material Selection for High Power High Frequency Inductors in DC-DC Converters", in Proc. of the APEC 2009.

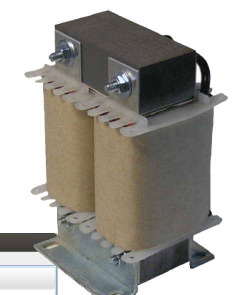
Core Materials

Example

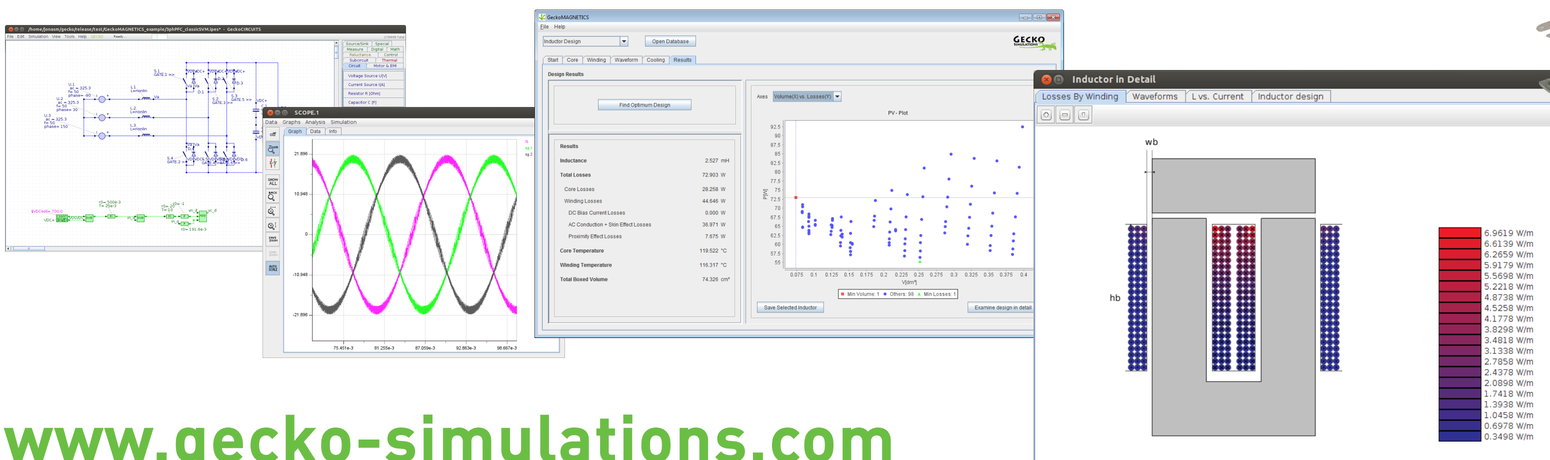
Parameter	Value
Input voltage AC V_{mains}	230 V
Mains frequency f_{mains}	50 Hz
DC Voltage V_{DC}	650 V
Load Current I_L	15.4 A



SiFe vs. Ferrite
2 kHz vs. 20 kHz



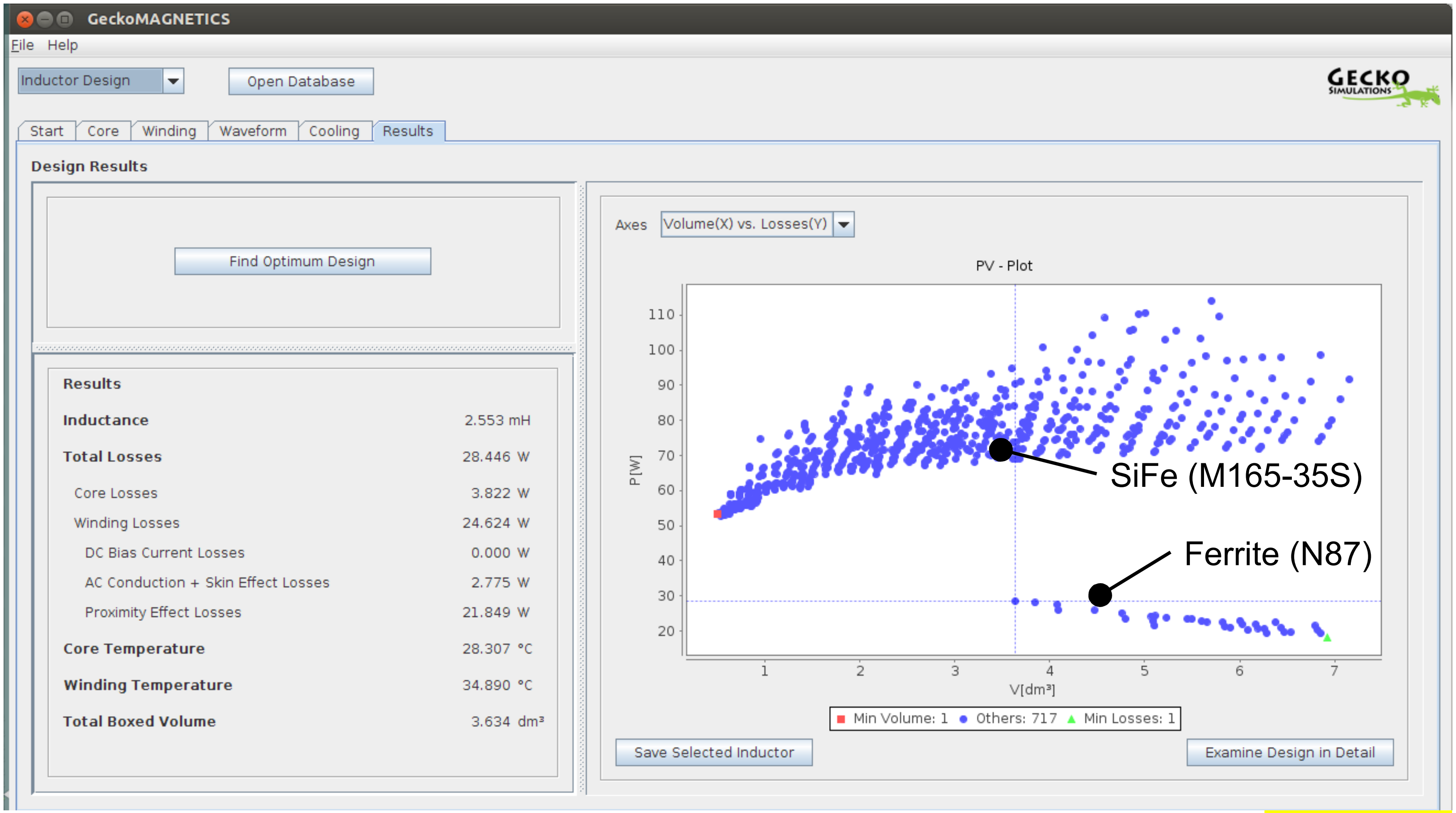
Modeling with GeckoMAGNETICS



Core Materials

GeckoMAGNETICS Example

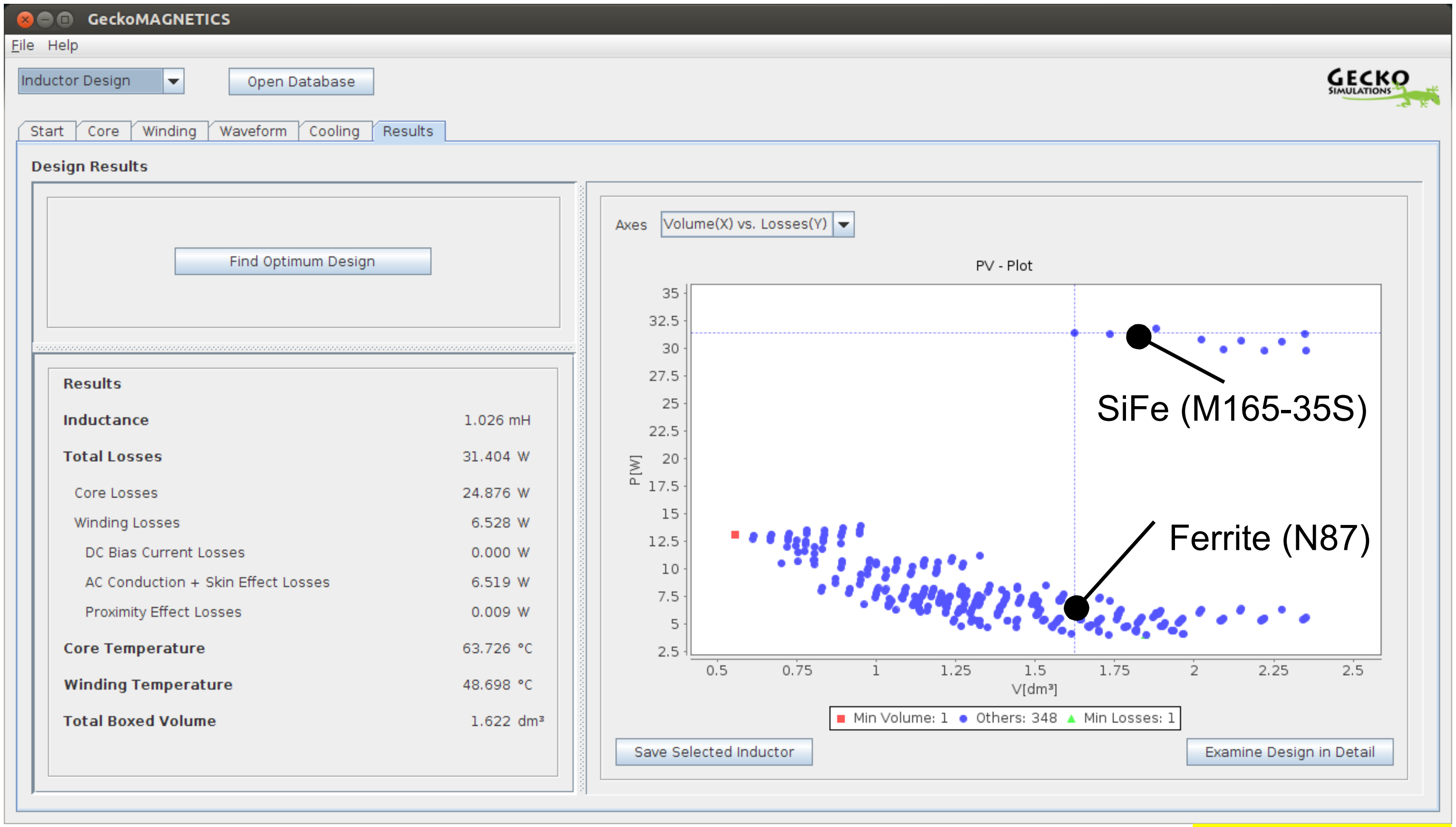
2 kHz / *Tmax* = 65 °C / *L* = 2.5 mH / Solid Round Wires



Sat. Limit

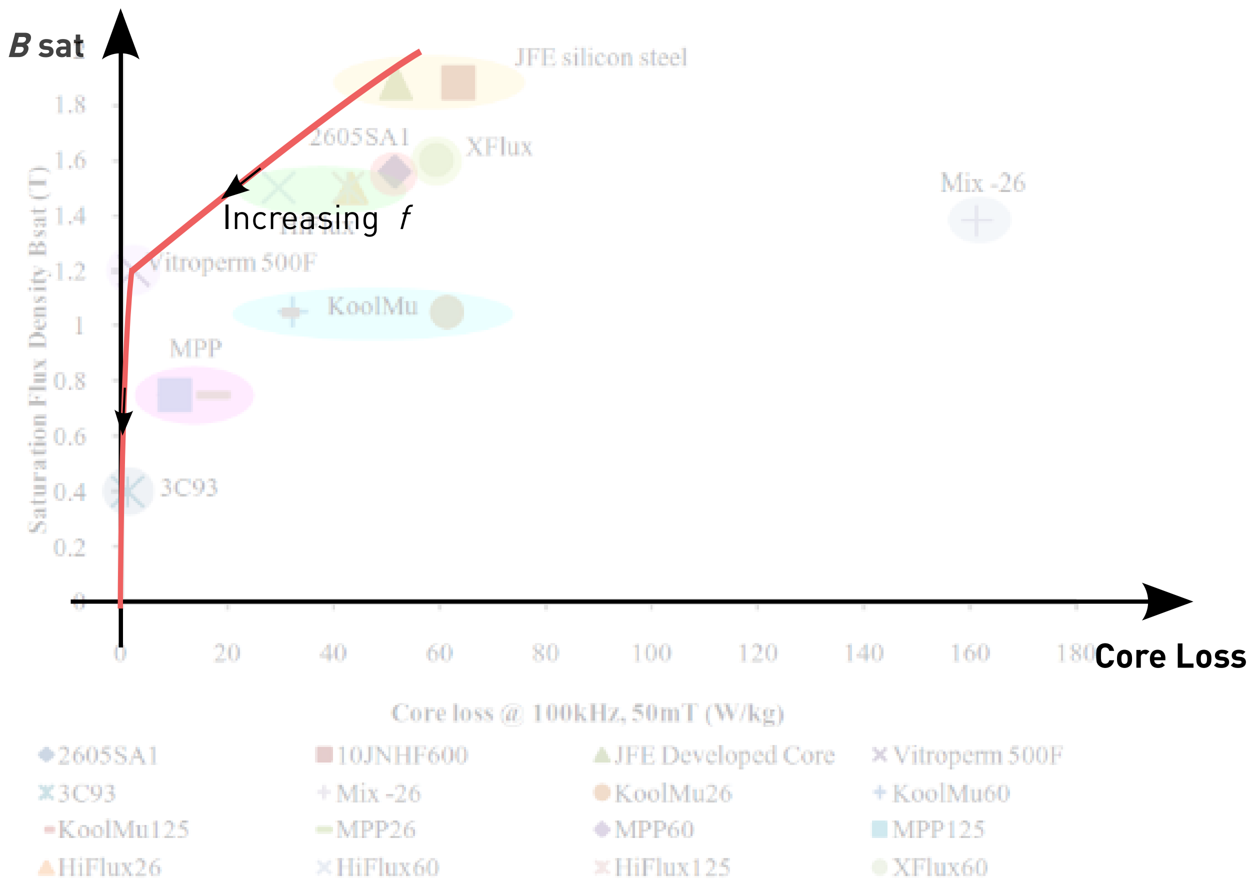
Core Materials
GeckoMAGNETICS Example

20 kHz / *T*max = 65°C / *L* = 1 mH / Litz Wires



Therm. Limit

Core Materials
Material Selection Criteria (2)



Introduction
Material Selection Criteria (1)

Saturation Flux Density vs. Core Losses

Selection Criteria
Sat. Flux Density — Losses

Frequency

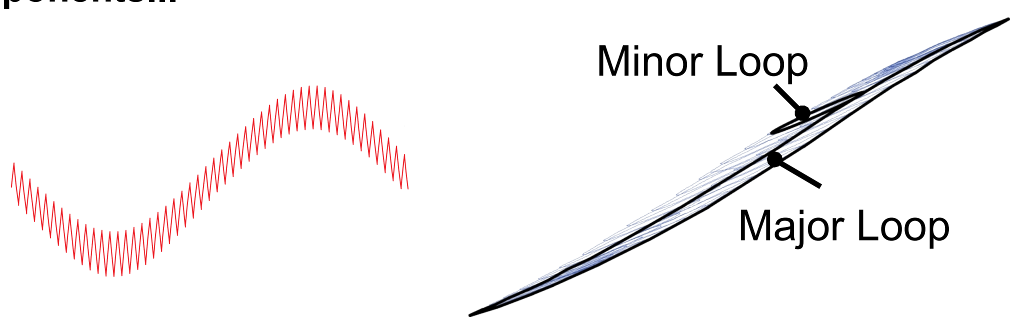
Materials
Laminated Steel Cores

Ferrites / Amorphous / Iron Powder

Ferrites / Nanocrystalline Materials

Sat. Limit — **Therm. Limit**

Often superposition of HF and LF components...



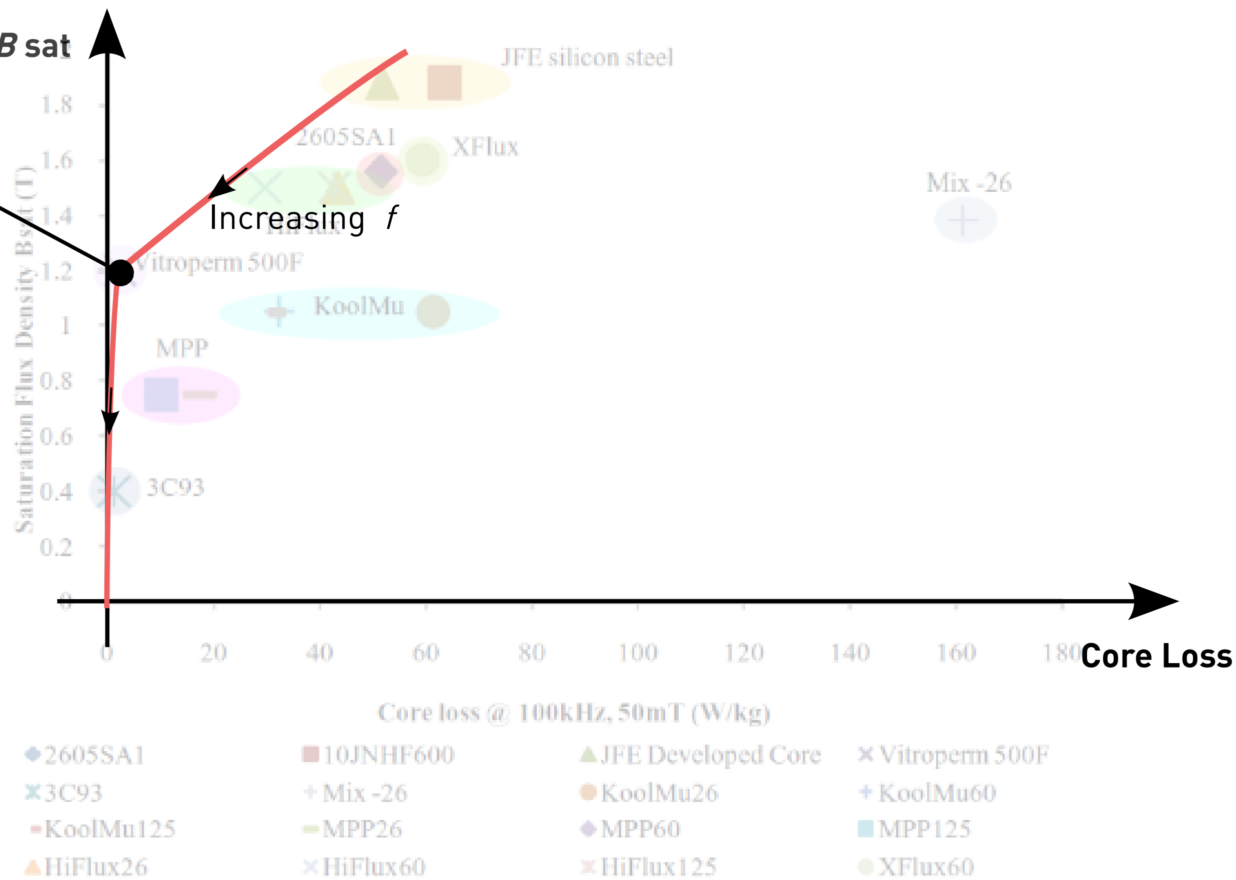
Ferrites

< 2 Mhz (approx.)
Manganese-zinc ferrite

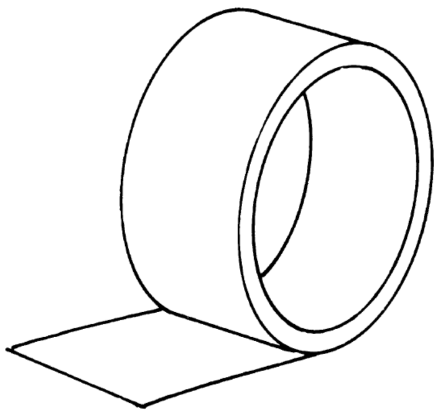
> 2 Mhz (approx.)
Nickel-zinc ferrite
Lower permeability,
Lower Bsat

Core Materials
Material Selection Criteria (2)

Best for components with LF and HF components?
(e.g. boost inductor?)



Core Materials
Effect in Tape Wound Cores



www.vacuumschmelze.de

Thin ribbons (approx. 20 μm)

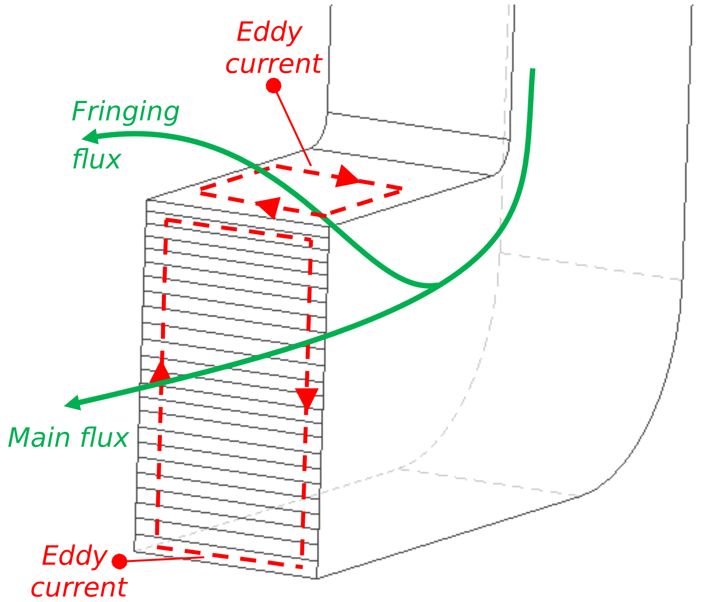
Wound as toroid or as double C core.

Amorphous or nanocrystalline materials.

Losses in gapped tape wound cores higher than expected!

Core Materials
Effect in Tape Wound Cores - Orthogonal Flux Lines

In [10] a core loss increase with increasing air gap length has been observed.



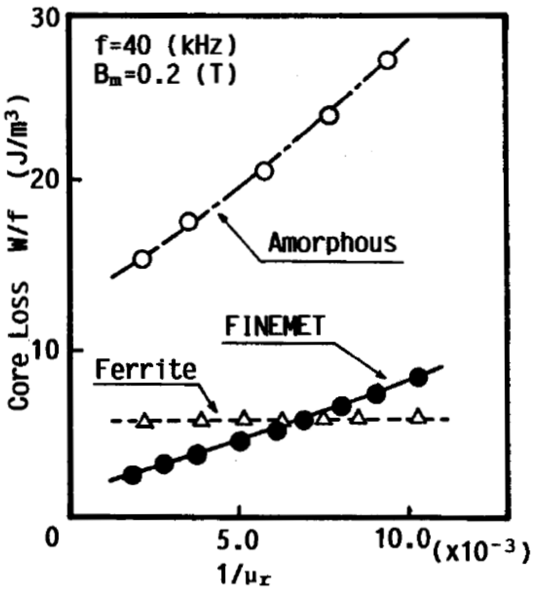


Fig.1 Core loss per cycle W/f in FINEMET, Fe-based amorphous, and ferrite cut cores as a function of inverse of the effective permeability μ_r.

Figure from [10]

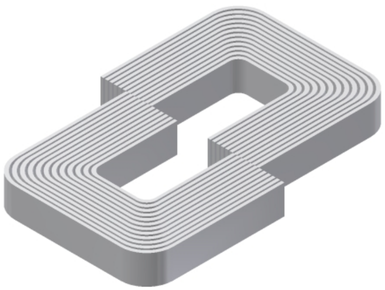
[10] H. Fukunaga, T. Eguchi, K. Koga, Y. Ohta, and H. Kakehashi, "High Performance Cut Cores Prepared From Crystallized Fe-Based Amorphous Ribbon", in IEEE Transactions on Magnetics, vol. 26, no. 5, 1990.

Core Materials

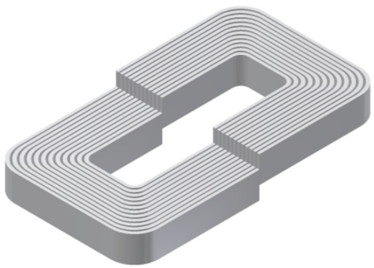
Effect in Tape Wound Cores - Orthogonal Flux Lines

An experiment that illustrates well the loss increase due to an orthogonal flux is given here.

Displacements

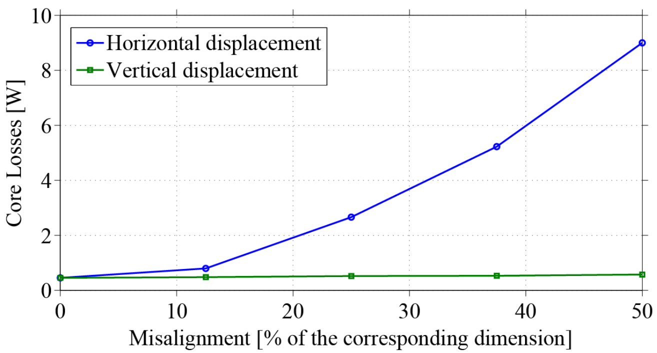


Horizontal Displacement



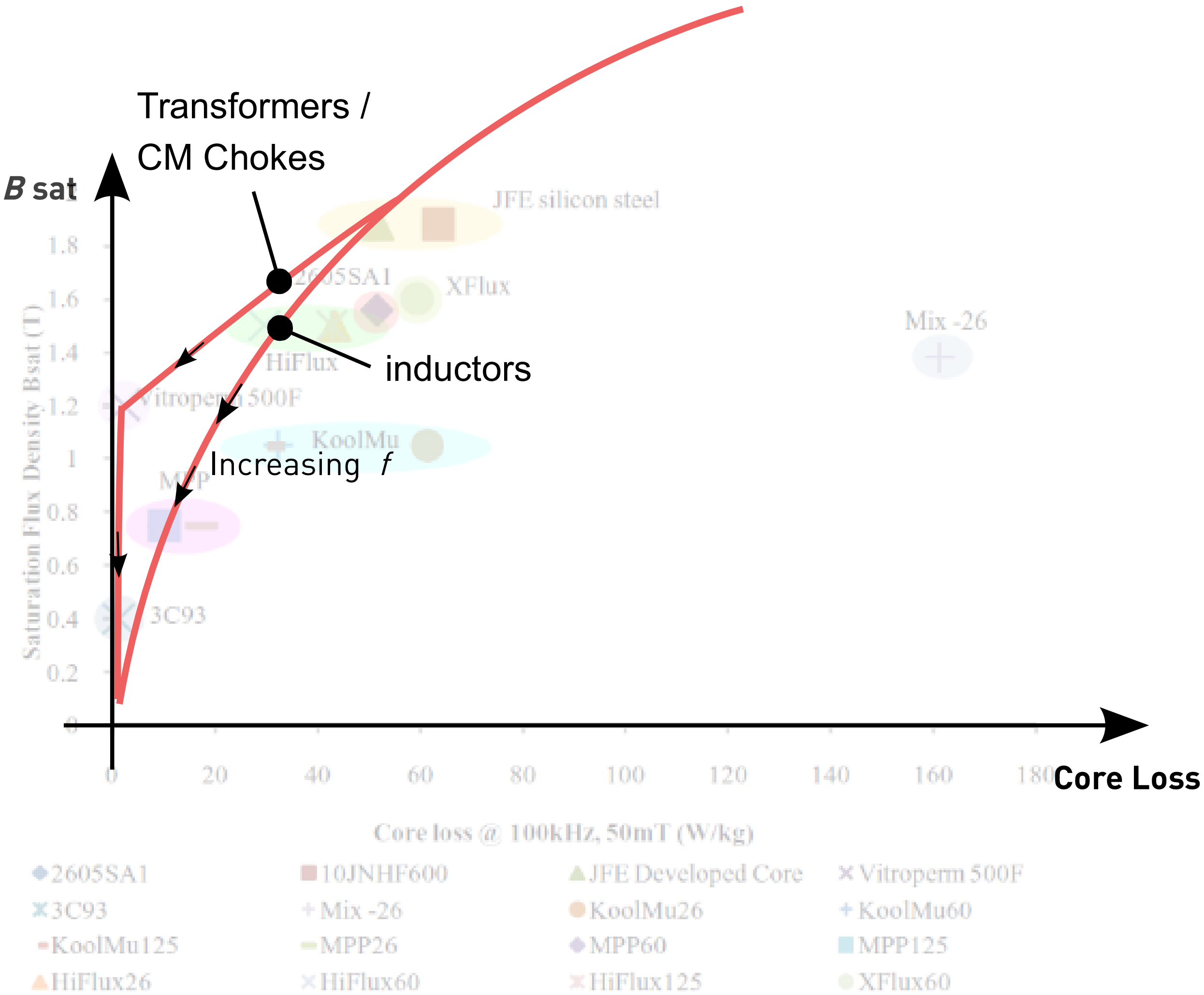
Vertical Displacement

Core Loss Results



Core Materials

Core Material Pareto Front



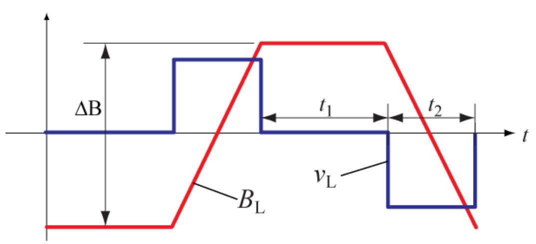
Core Materials
Conclusion

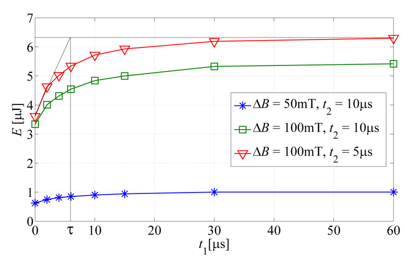
It is crucial to understand the core materials in detail.

Often material selection is not trivial (HF + LF).

Effects that become more important at HF:

Relaxation Effect





Orthogonal Flux

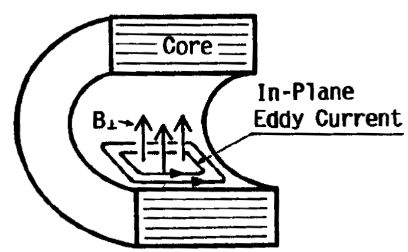


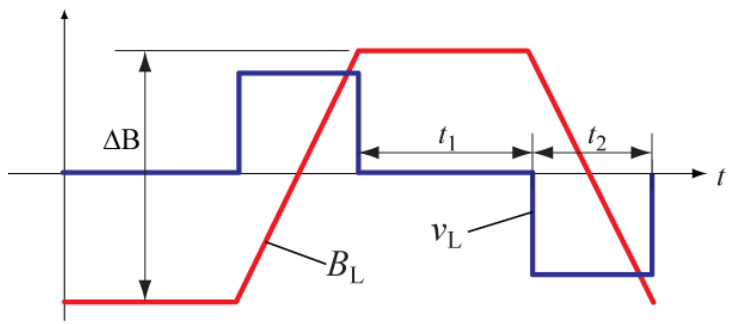
Fig.2 Schematic representation of in-plane eddy current generated by leakage flux normal to ribbon surfaces.

+ other effects, e.g. dimensional resonance

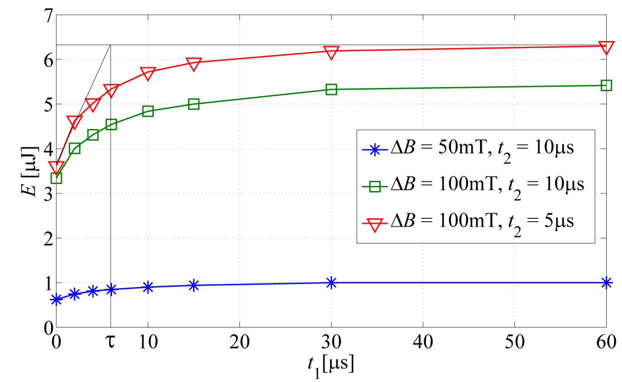
Understanding Core Losses

i²GSE – Motivation

Waveform



Results



iGSE

$$P_v = k f^{\alpha} \hat{B}^{\beta}$$

$$\Downarrow$$

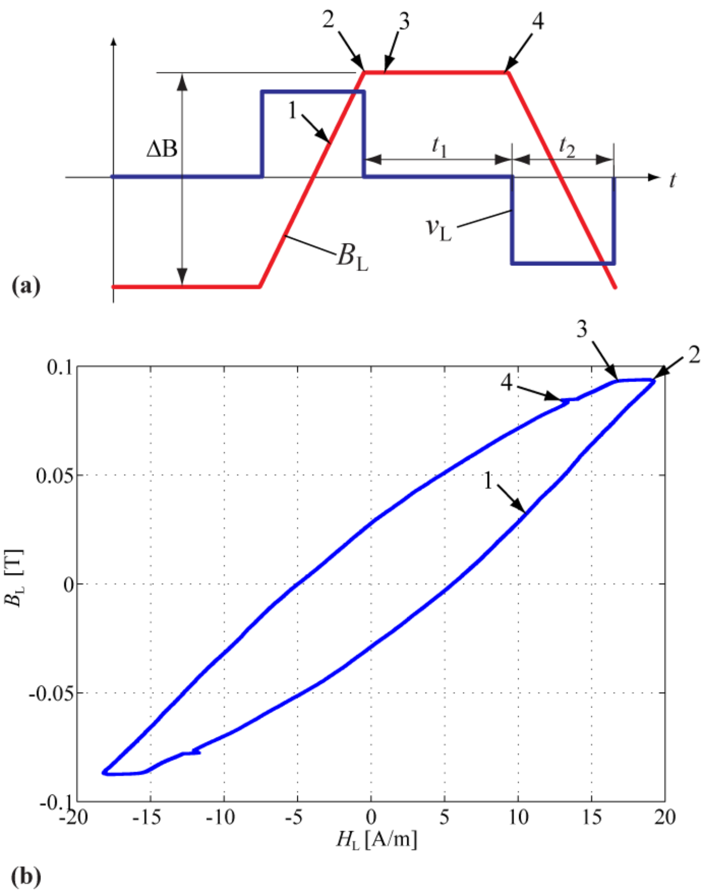
$$P_v = \frac{1}{T}\int_0^T k_i \left|\frac{dB}{dt}\right|^{\alpha} (\Delta B)^{\beta-\alpha}\, dt$$

Conclusion

Losses in the phase of constant flux!

Understanding Core Losses

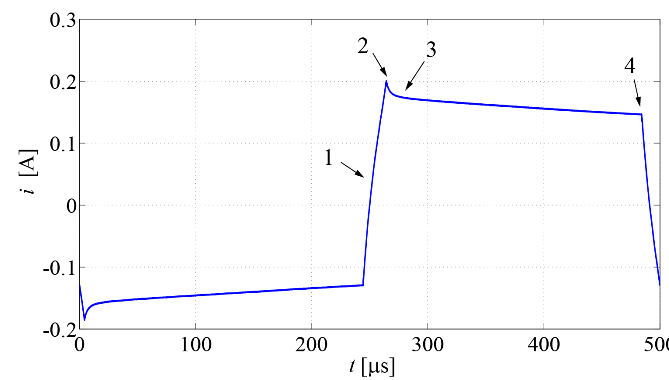
Derivation of the i^2GSE – *B-H*-Loop



Relaxation Losses

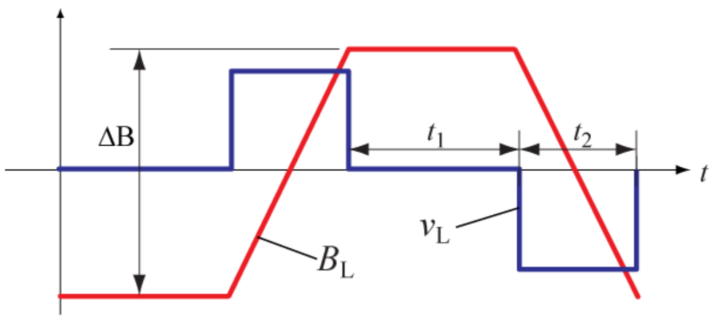
- Rate-dependent *BH* Loop.
- Reestablishment of a thermal equilibrium is governed by relaxation processes.
- Restricted domain wall motion.

Current Waveform



Understanding Core Losses

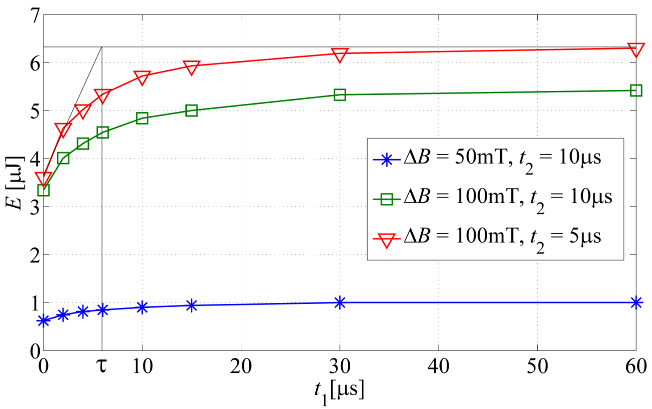
Derivation of the i²GSE – Model Part 1



Model Part 1

$$P_v = \frac{1}{T}\int_0^T k_i \left|\frac{\mathrm{d}B}{\mathrm{d}t}\right|^{\alpha} (\Delta B)^{\beta-\alpha}\,\mathrm{d}t + \sum_{l=1}^{n} P_{rl}$$

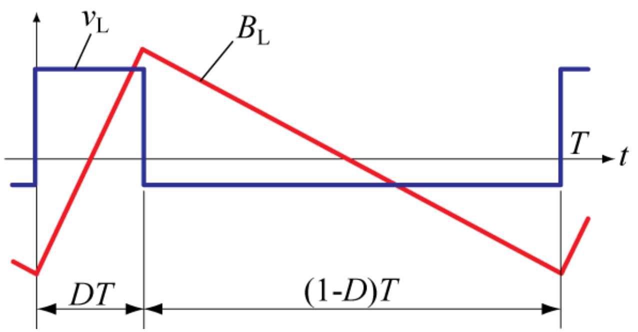
$$P_{rl} = \underbrace{\frac{1}{T} k_r \left|\frac{\mathrm{d}}{\mathrm{d}t}B(t)\right|^{\alpha_r} (\Delta B)^{\beta_r}}_{\Delta E} \left(1 - e^{-\frac{t_1}{\tau}}\right)$$



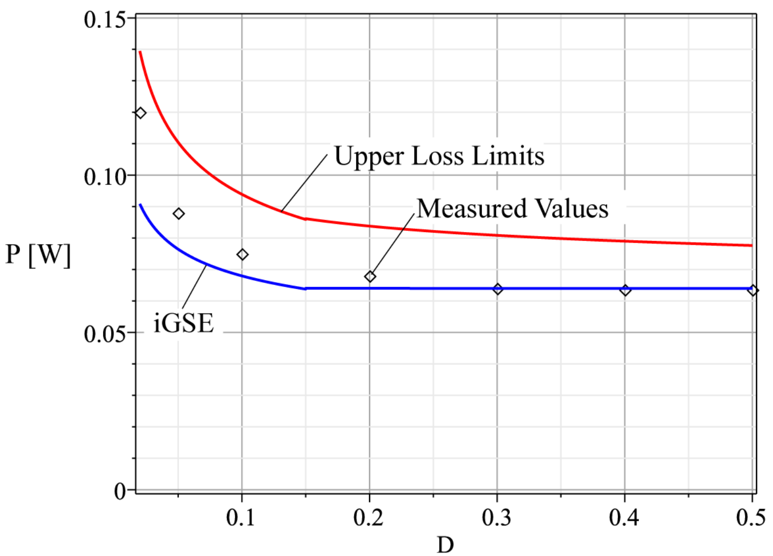
Understanding Core Losses

Derivation of the i²GSE – Model Part 2 (1)

Waveform



Power Loss



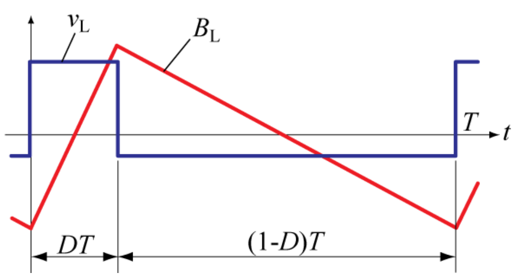
Explanation

1) For values of *D* close to 0 or close to 1 a loss underestimation is expected when calculating losses with iGSE (no relaxation losses included).
2) For values of *D* close to 0.5 the iGSE is expected to be accurate.
3) Adding the relaxation term leads to the upper loss limit, while the iGSE represents the lower loss limit.
4) Losses are expected to be in between the two limits, as has been confirmed with measurements.

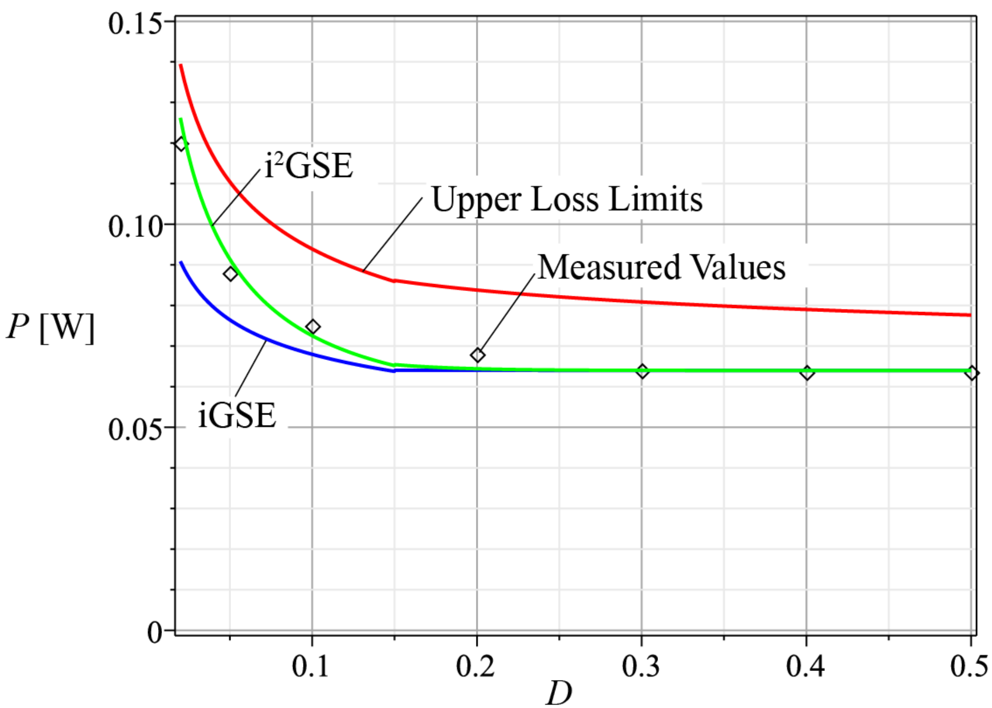
Understanding Core Losses

Derivation of the i²GSE – Model Results

Waveform



Power Loss



Understanding Core Losses

Derivation of the i^2GSE – Summary

The improved-improved Generalized Steinmetz Equation (i^2GSE) [9]

$$P_\mathrm{v} = \frac{1}{T}\int_0^T k_i \left|\frac{\mathrm{d}B}{\mathrm{d}t}\right|^{\alpha} (\Delta B)^{\beta-\alpha}\,\mathrm{d}t + \sum_{l=1}^{n} Q_{\mathrm{r}l} P_{\mathrm{r}l}$$

with

$$P_{\mathrm{r}l} = \frac{1}{T} k_\mathrm{r} \left|\frac{\mathrm{d}}{\mathrm{d}t} B(t)\right|^{\alpha_\mathrm{r}} (\Delta B)^{\beta_\mathrm{r}} \left(1 - \mathrm{e}^{-\frac{t_1}{\tau}}\right)$$

and

$$Q_{\mathrm{r}l} = \mathrm{e}^{-q_\mathrm{r}\left|\frac{\mathrm{d}B(t+)/\mathrm{d}t}{\mathrm{d}B(t-)/\mathrm{d}t}\right|}$$

[9] J. Mühlethaler, J. Biela, J.W. Kolar, and A. Ecklebe, “Improved Core Loss Calculation for Magnetic Components Employed in Power Electronic Systems”, in Proc. of the APEC, Ft. Worth, TX, USA, 2011.

Understanding Core Losses

Derivation of the i²GSE – Example

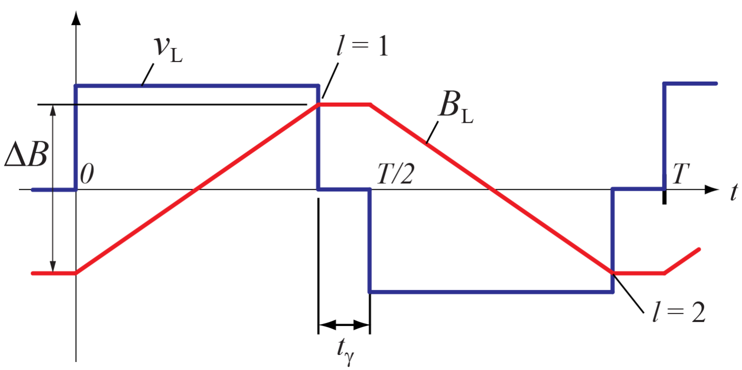
i2GSE

Evaluated for each piecewise-linear flux segment

Evaluated for each voltage step, i.e. for each corner point in a piecewise-linear flux waveform.

$$P_v = \underbrace{\frac{1}{T}\int_0^T k_i \left|\frac{dB}{dt}\right|^{\alpha} (\Delta B)^{\beta-\alpha} dt}_{} + \underbrace{\sum_{l=1}^{n} Q_{rl} P_{rl}}_{}$$

Example



$$\frac{dB}{dt} = \begin{cases} \dfrac{\Delta B}{T/2 - t_\gamma} & \text{for } t \geq 0 \text{ and } t < T/2 - t_\gamma \\ 0 & \text{for } t \geq T/2 - t_\gamma \text{ and } t < T/2 \\ -\dfrac{\Delta B}{T/2 - t_\gamma} & \text{for } t \geq T/2 \text{ and } t < T - t_\gamma \\ 0 & \text{for } t \geq T - t_\gamma \text{ and } t < T \end{cases}$$

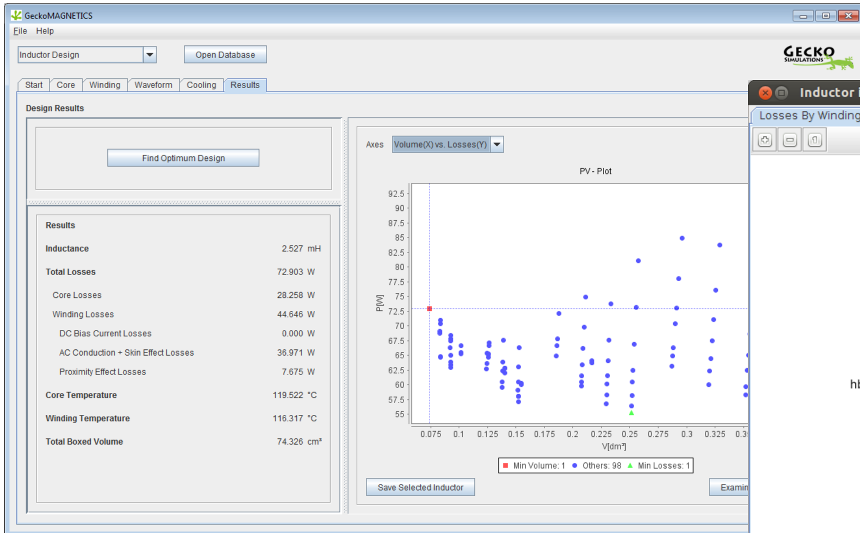
$$P_v = \frac{T - 2t_\gamma}{T} k_i \left|\frac{\Delta B}{T/2 - t_\gamma}\right|^{\alpha} (\Delta B)^{\beta-\alpha} + \sum_{l=1}^{2} Q_{rl} P_{rl}$$

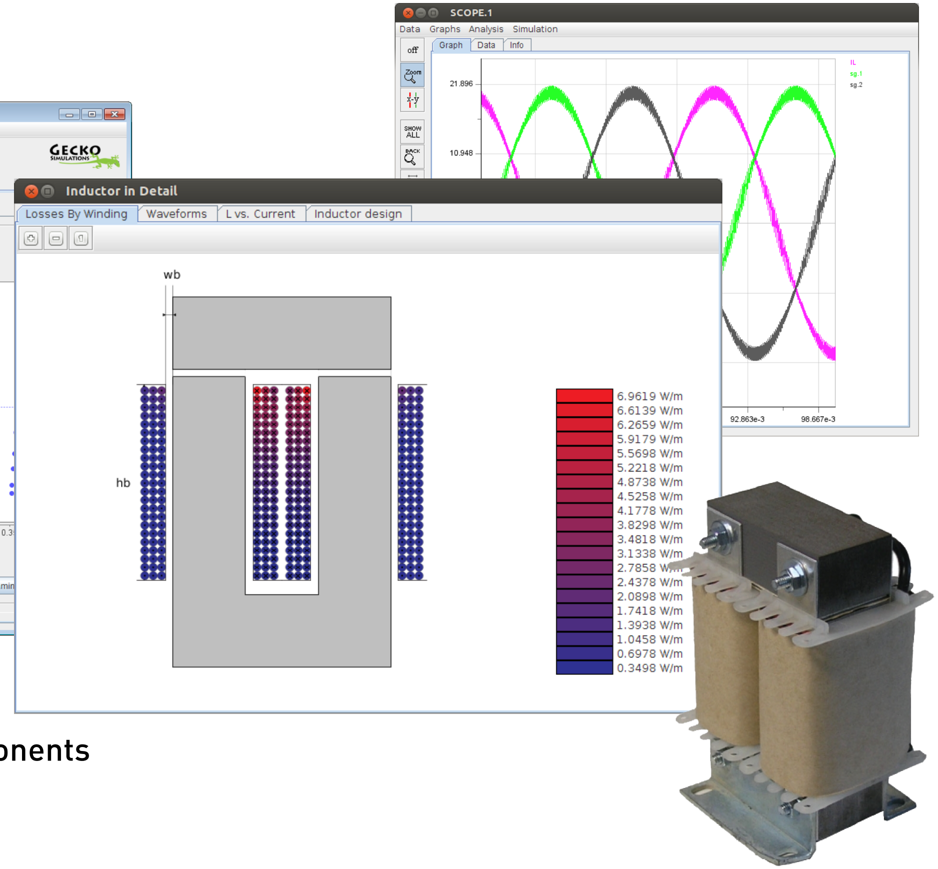
with Qr1 = Qr2 = 0

$$P_{r1} = P_{r2} = \frac{1}{T} k_r \left|\frac{\Delta B}{T/2 - t_\gamma}\right|^{\alpha_r} (\Delta B)^{\beta_r} \left(1 - e^{-\frac{t_\gamma}{\tau}}\right)$$

THANK YOU !!!

GeckoMAGNETICS





Save Time

Fast and accurate design of magnetic components

Easy-to-use for non-expert

Increase Flexibility

Tool shows more than one realization possibility

In-house design of magnetics crucial for optimal designs.

Most Loss Effects are Considered

Skin- and proximity losses in litz, round and foil windings, air gap stray field losses, DC bias core losses, thermal model, ...

GECKO SIMULATIONS