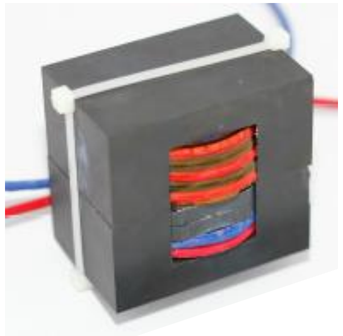
Power Electronics and Electrical Drives
Prof. Dr.-Ing. Joachim Böcker

PADERBORN UNIVERSITY



Overview: Core Loss in Ferrites

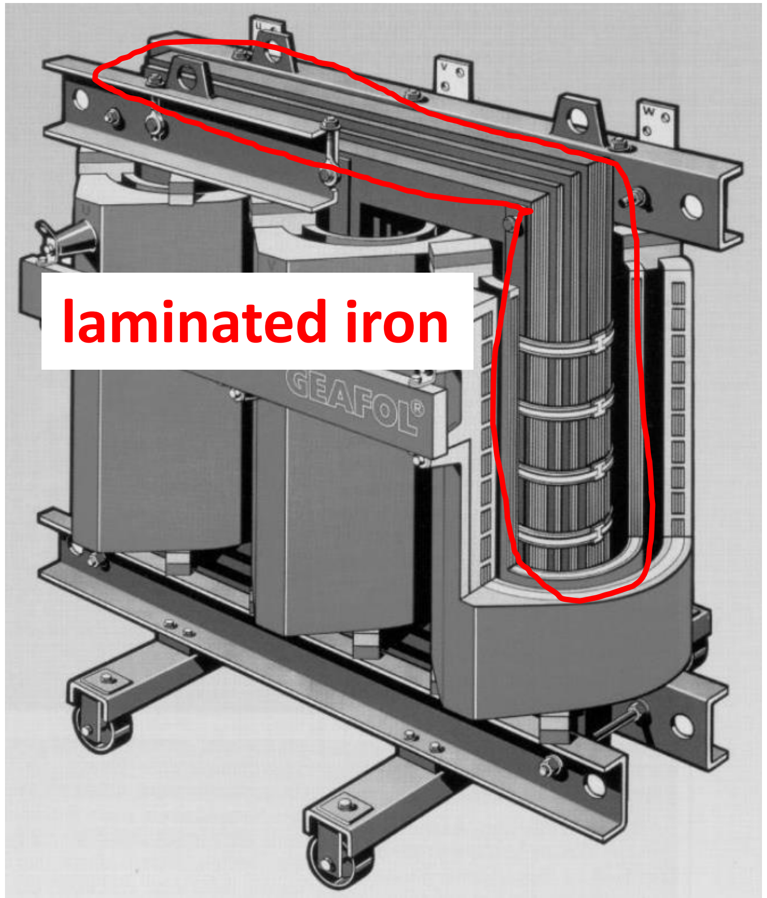
Till Piepenbrock

Agenda – Questions to be answered

- Where do we use ferrite cores?
- Temperature problem
- Some physics behind
- Loss modelling approaches
- BH curve modelling approaches
- Measurement methods

TRANSFORMERS…

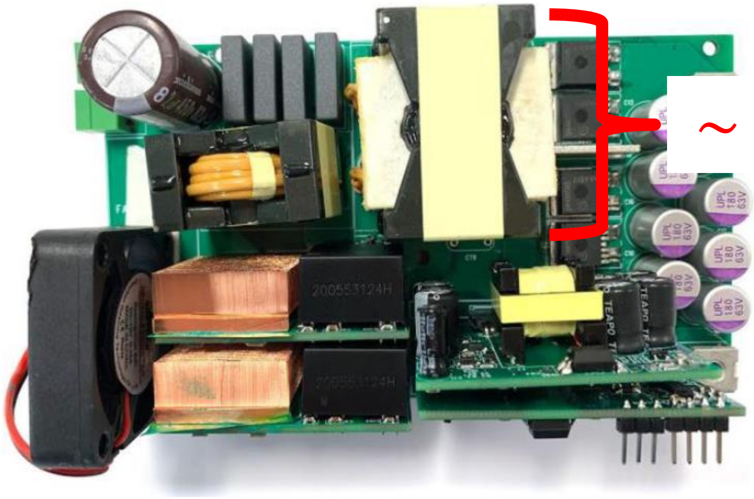
[1]



[2]

… and transformers

~ 100 kHz (frequency)
~ 1 kW (power)

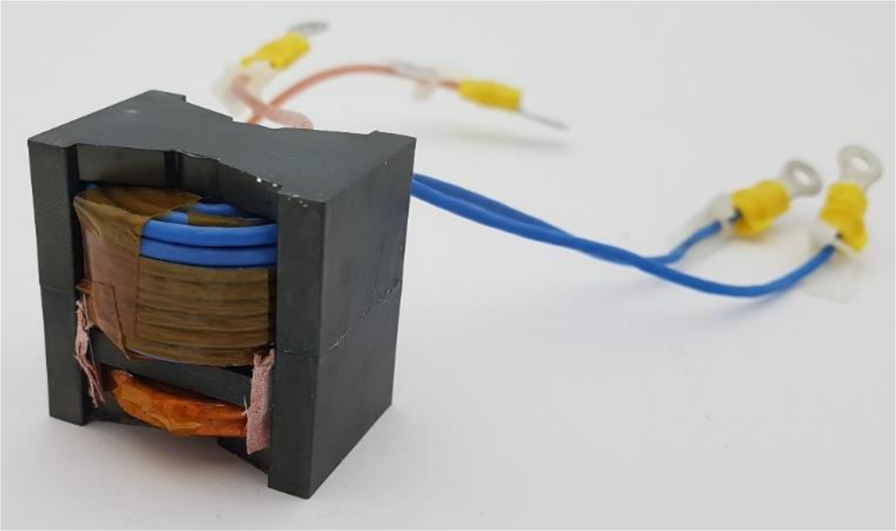


$\sim$ 3 cm

[3]

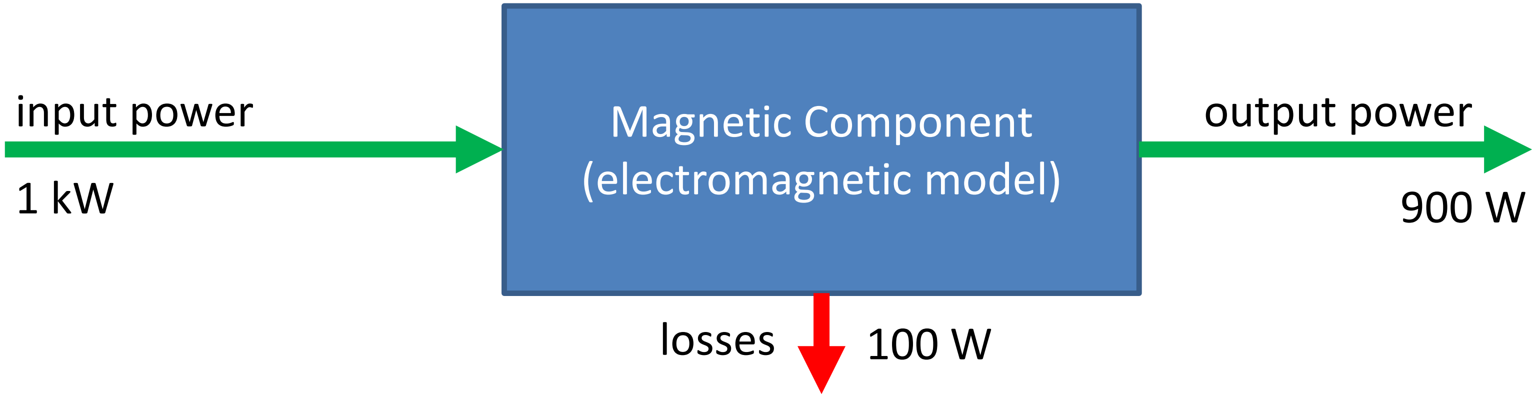
ferrite powder

Magnetics/Transformers at LEA



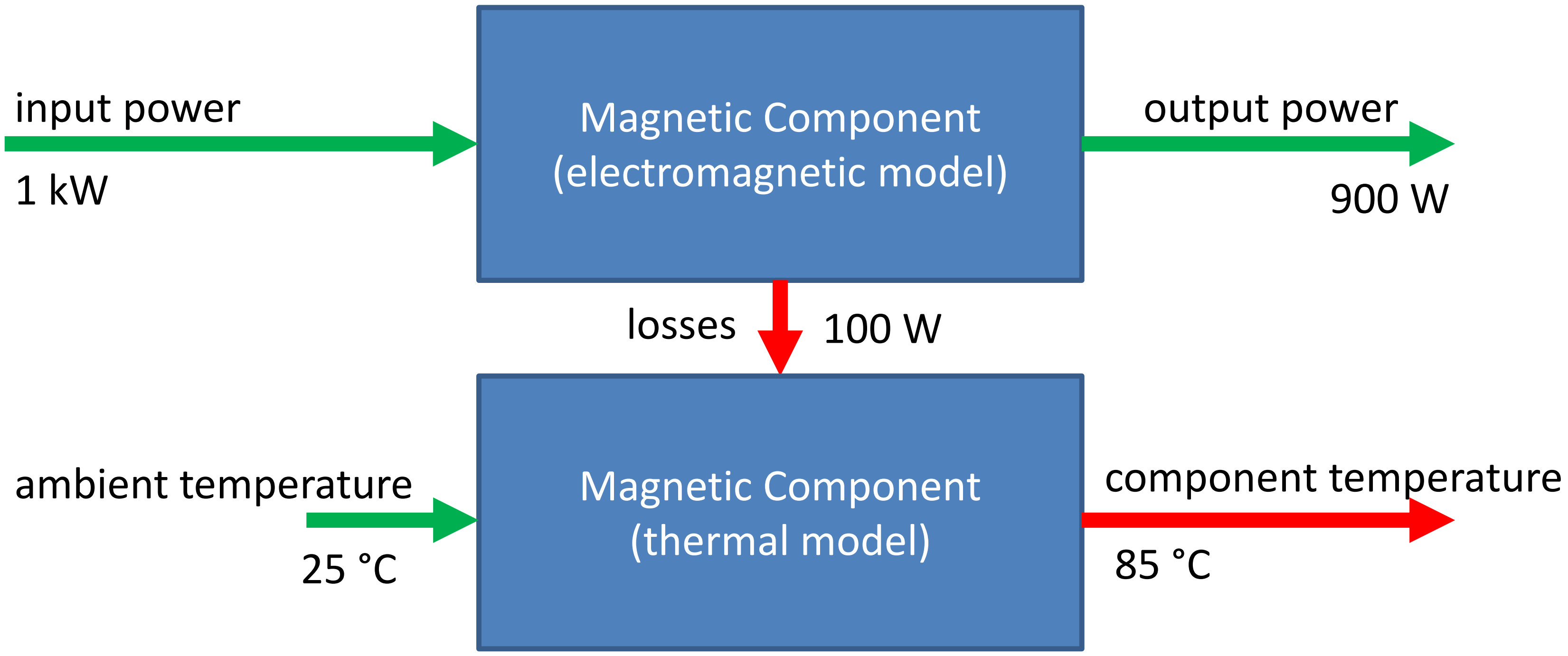
<u>**becomes hot in operation**</u>
<u>**-> damage at apprx. 150 °C**</u>

Why does the transformer become hot?



Efficiency: $\eta = \dfrac{\text{output power}}{\text{input power}} = \dfrac{\text{input power} - \text{losses}}{\text{input power}} = \dfrac{900\ \text{W}}{1000\ \text{W}} = 90\ \%$

Why does the transformer become hot?



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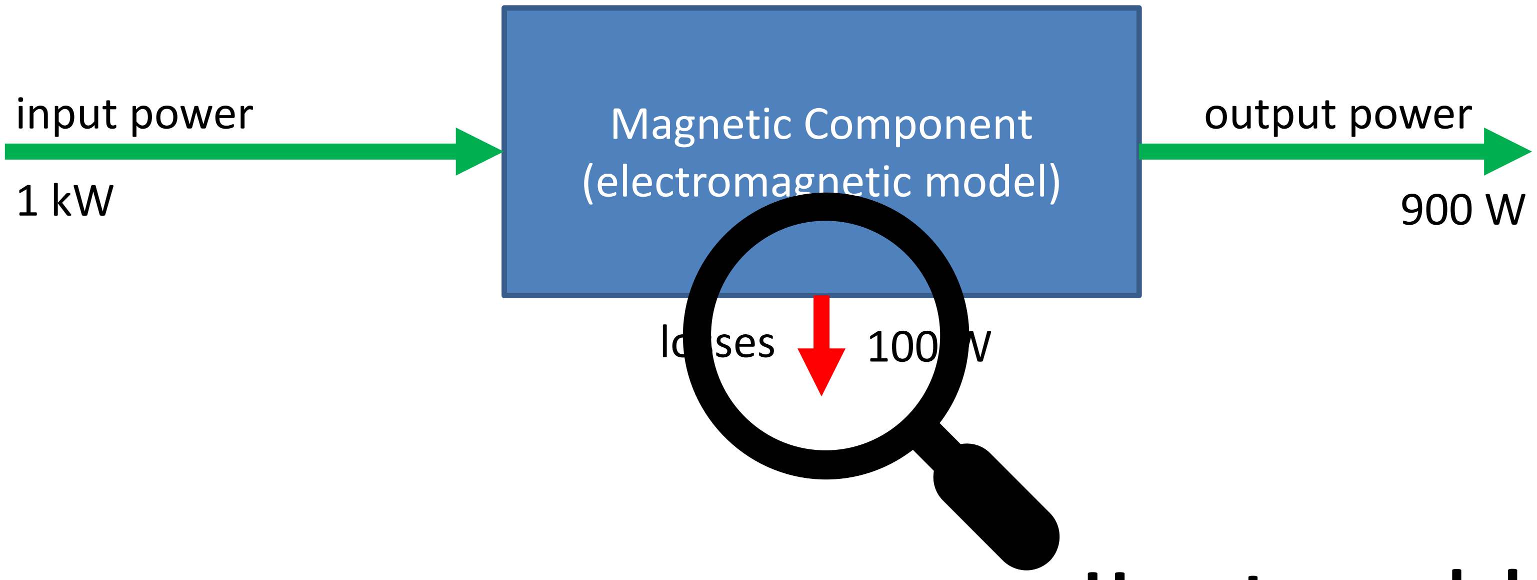
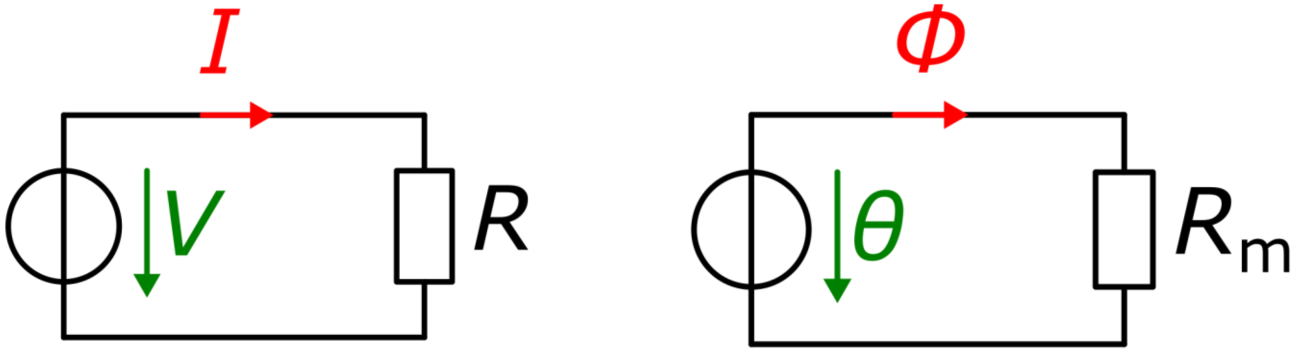
Why does the transformer become hot?



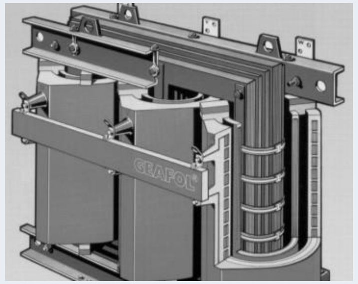
How to model the losses?

Electrical vs. magnetic circuits

Property	Electrical circuit	Magnetic circuit
Specific conductance	κ	μ
Resistance	$R = \frac{l}{\kappa\, A}$	$R_\mathrm{m} = \frac{l}{\mu\, A}$
Ohm’s law	$U = R\, I$	$\Theta = R_\mathrm{m}\, \phi$



Ferrite's properties

Property	Electrical circuit	Magnetic circuit
Specific conductance	κ	μ
Resistance	$R = \frac{l}{\kappa\, A}$	$R_\mathrm{m} = \frac{l}{\mu\, A}$
Ohm's law	$U = R\, I$	$\Theta = R_\mathrm{m}\, \phi$
Iron sheet 	**High** electric conductance $\boldsymbol{\kappa}$	**Very high** magnetic conductance $\boldsymbol{\mu}$
Ferrite powder 	**Low** electric conductance $\boldsymbol{\kappa}$	**High** magnetic conductance $\boldsymbol{\mu}$

Overview: Loss mechanisms

Mechanism 1: Eddy Currents

Property	Electrical circuit
Specific conductance	κ
Resistance	$R = \frac{l}{\kappa\, A}$
Ohm's law	$U = R\, I$
Iron sheet	**High** electric conductance $\boldsymbol{\kappa}$
Ferrite powder	**Low** electric conductance $\boldsymbol{\kappa}$

(recap)

crucial for eddy currents:
high electrical resistance → low eddy current losses

High eddy currents

Low eddy currents

Mechanism 2: Magnetic Hysteresis

Property	Magnetic circuit
Specific conductance	μ
Resistance	$R_\mathrm{m} = \dfrac{l}{\mu\, A}$
Ohm’s law	$\theta = R_\mathrm{m}\,\phi$
Ferrite powder	**High** magnetic conductance $\boldsymbol{\mu}$

“Imperfection of $\boldsymbol{\mu}$ causes losses“

...too complicated to explain in one slide...

Speaking:
„magnetic conductance“ **$\boldsymbol{\mu}$ is called permeability**

Overview: Loss mechanisms

Mechanism 1: Eddy Currents

- Almost linear material behaviour
- Precise modelling in FEM simulation
- In our case: **can probably be neglected** completely

Mechanism 2: Magnetic Hysteresis

- Highly nonlinear material behaviour
- Several approaches for modelling the losses
- In our case: is the **key point of investigation**

Mechanism 2: Magnetic Hysteresis

Property	Magnetic circuit
Specific conductance	μ
Resistance	$R_{\mathrm{m}} = \frac{l}{\mu\, A}$
Ohm's law	$\Theta = R_{\mathrm{m}}\, \phi$
Ferrite powder	**High** magnetic conductance $\boldsymbol{\mu}$

Switch from circuit to material

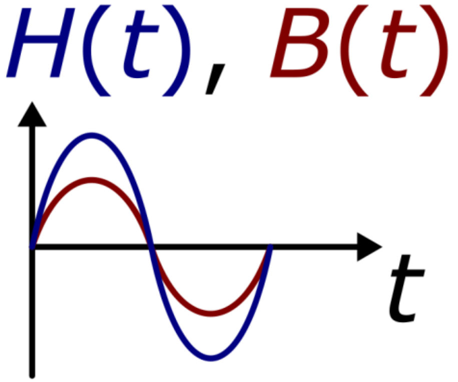
$$\boxed{b = \mu\, h}$$

Material equation

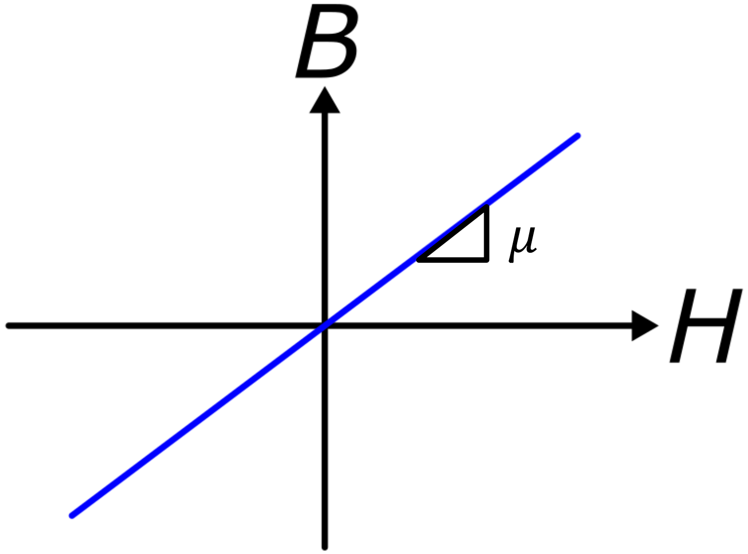
Speaking:
„magnetic conductance“ $\boldsymbol{\mu}$ **is called permeability**

$$\boxed{B(t) = \mu\, H(t)}$$

Material equation



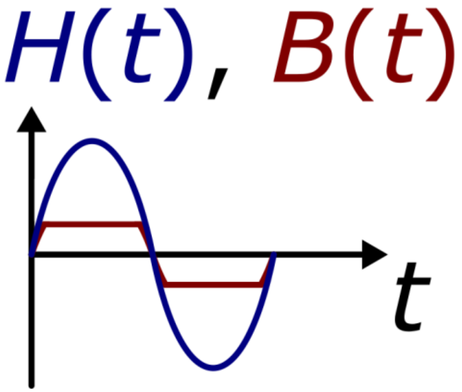
In a “perfect”/linear world:
Independent of the shape of B and H



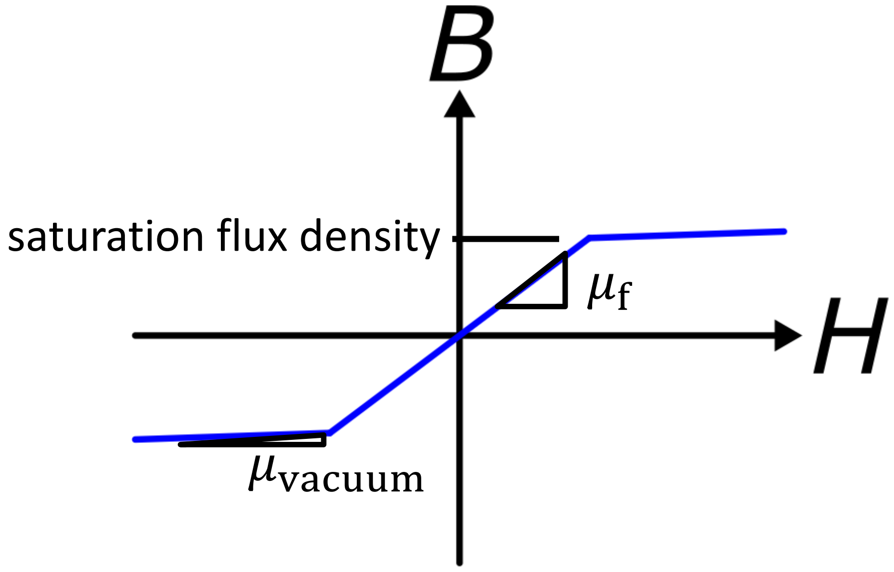
Linear BH Curve with saturation

$$\boxed{B(t) = \mu(H)\, H(t)}$$

Material equation



More realistic:

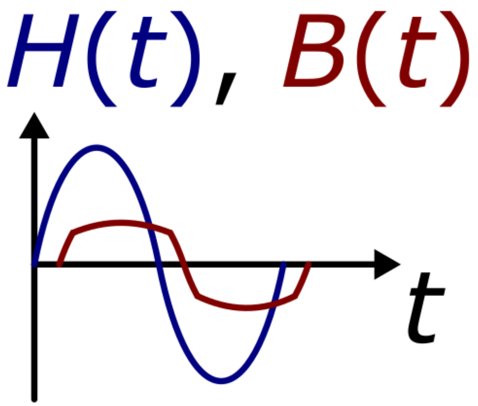


$\mu_{\mathrm{vacuum}} << \mu_{\mathrm{f}}$

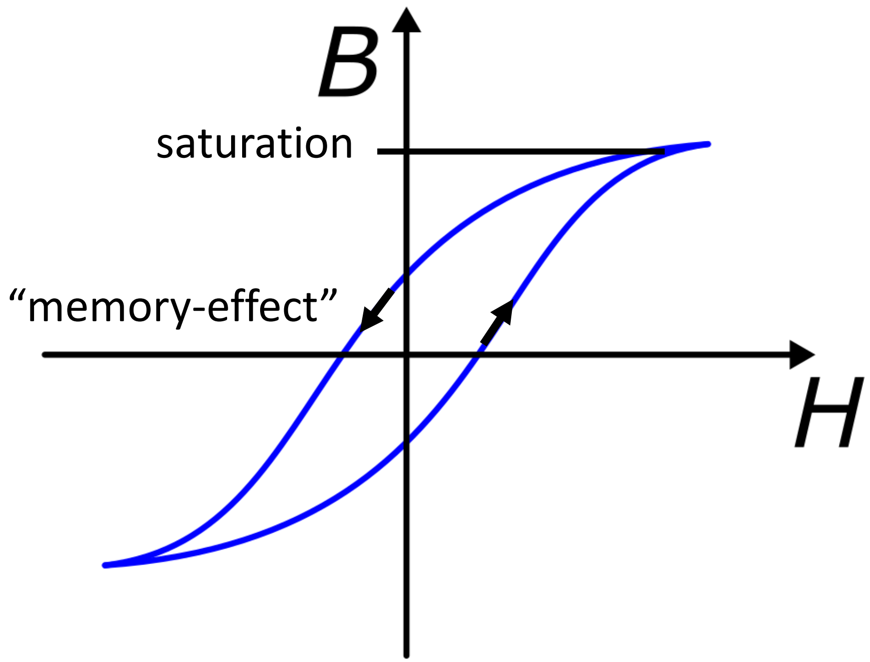
Nonlinear BH Curve with hysteresis and saturation

$$\boxed{B(t) = \mu(H, T, f, \dots)\, H(t)}$$

Material equation

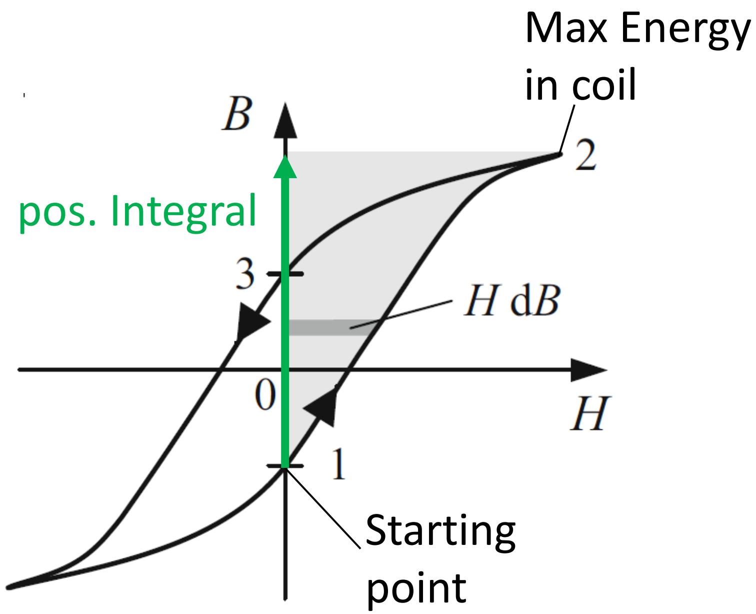


Reality:



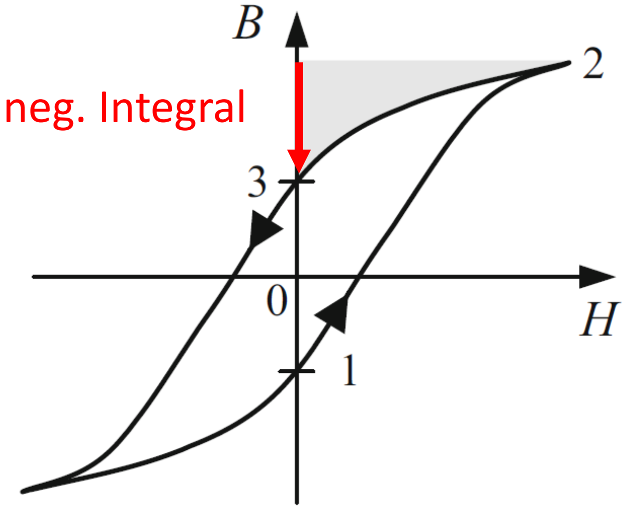
Losses due to Magnetic Hysteresis

Loading the coil

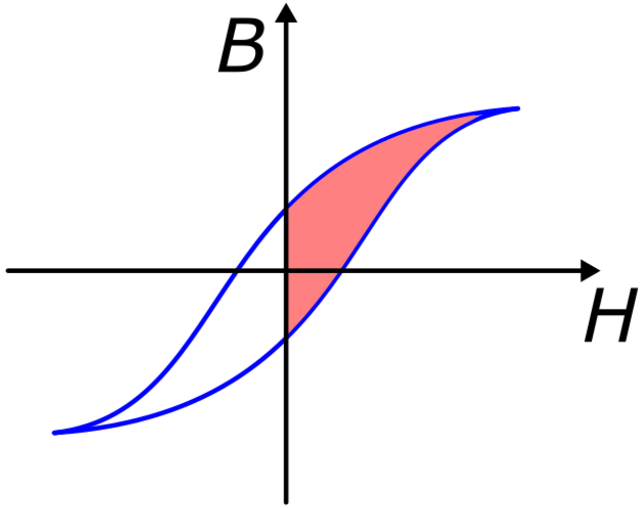


$[H{\cdot}B]=\frac{\mathrm{A}}{\mathrm{m}}\cdot\frac{\mathrm{Vs}}{\mathrm{m}^2}=\frac{\mathrm{J}}{\mathrm{m}^3}$

Unloading the coil



Dissipated energy w_v



$$\boxed{w_v = \int H(B)\,\mathrm{d}B}$$

Mechanism 2: Magnetic Hysteresis

This curve is run through repetitively with period $T = \frac{1}{f}$

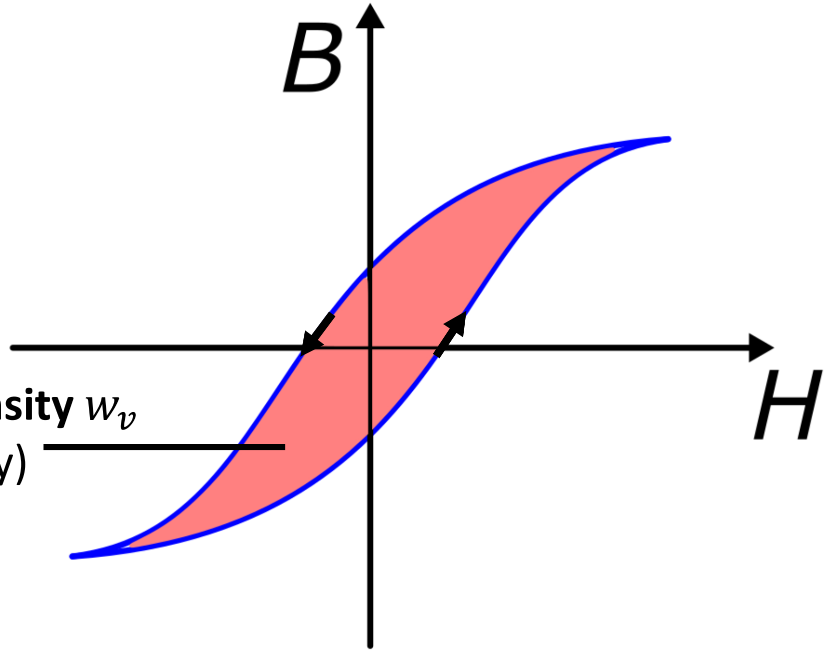
$$\boxed{B(t) = \mu(H, T, f, \ldots)\, H(t)}$$

Material equation

$$\boxed{p_v = \frac{w_v}{T} = f \int H(B)\, \mathrm{d}B}$$

power loss density

$[p_v] = \frac{\mathrm{W}}{\mathrm{m}^3}$



Dissipated energy density w_v
(Hysteresis loss density)

For a known curve: an exact calculation – Problem: impossible to measure each possible curve

Concept: Complex Numbers

Complex numbers:

$\underline{x} = a + \mathrm{j}b = \hat{x}\,(\cos(\varphi) + \mathrm{j}\sin(\varphi)) = \hat{x}e^{\mathrm{j}\varphi}$

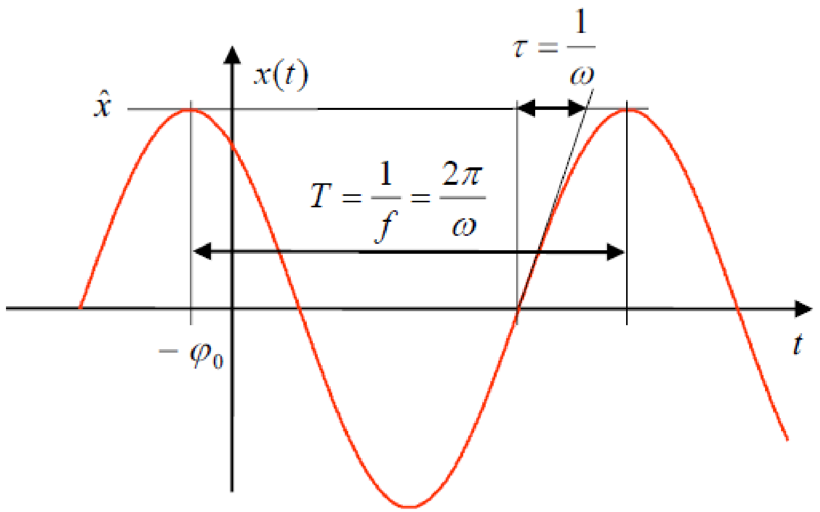
Real part:

$\mathrm{Re}\{\underline{x}\} = a = \hat{x}\cos(\varphi)$

Imaginary part:

$\mathrm{Im}\{\underline{x}\} = b = \hat{x}\sin(\varphi)$

-> used to model sinusoidal signals



Time domain:

$x(t) = \hat{x}\cos(\omega t + \varphi_0) = \mathrm{Re}\{\underline{x}(t)\}$

Use complex numbers:

$\underline{x}(t) = \hat{x}e^{\mathrm{j}(\omega t + \varphi_0)} = \underline{\hat{x}}e^{\mathrm{j}\varphi_0}e^{\mathrm{j}\omega t} = \underline{x}e^{\mathrm{j}\varphi_0}e^{\mathrm{j}\omega t}$

often

Usually only the complex amplitude $\underline{x}$ or $\underline{\hat{x}}$ is denoted!

Loss mechanisms: physical model, complex approach

(below saturation, sinusoidal excitation)

$$\underline{B} = \underline{\mu}\,(H,T,f)\,\underline{H}$$

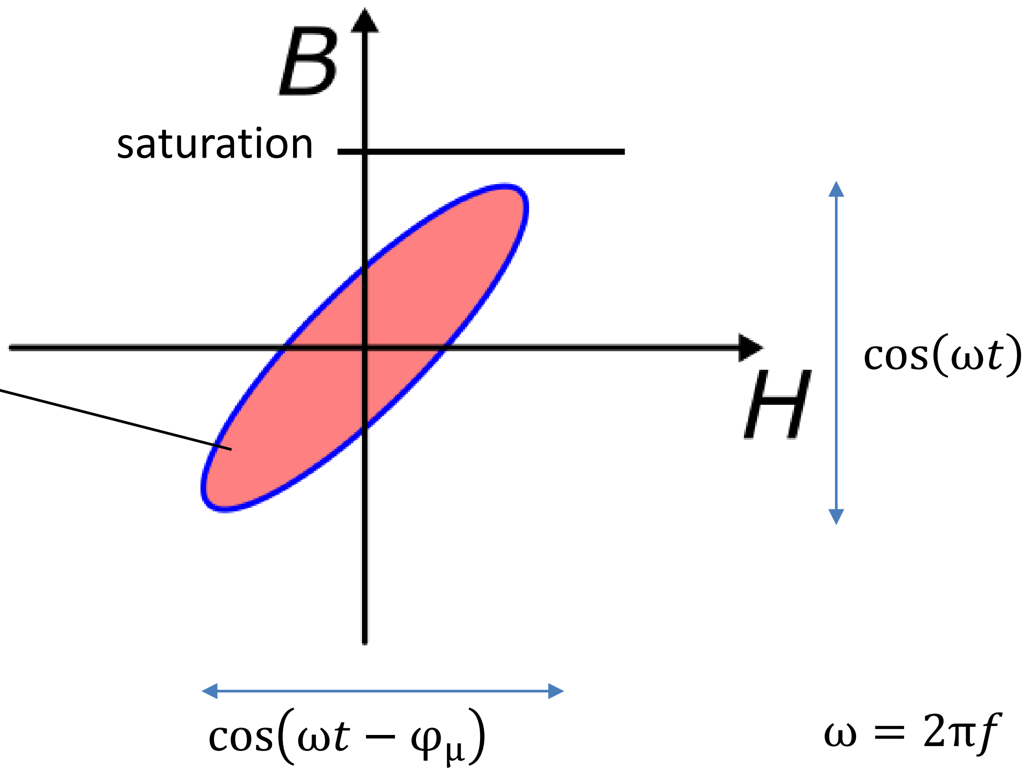
Material equation

$$p_v = \frac{1}{2} \cdot \omega \cdot \mathrm{Im}\left\{\underline{\mu}\right\} \cdot \underline{\hat{H}}^2$$

Loss density

$\cdot f$

elliptic approximation



$\omega = 2\pi f$

Benefits:	Drawbacks:
physical model	Only below saturation
simple	Only sinusoidal
fast	

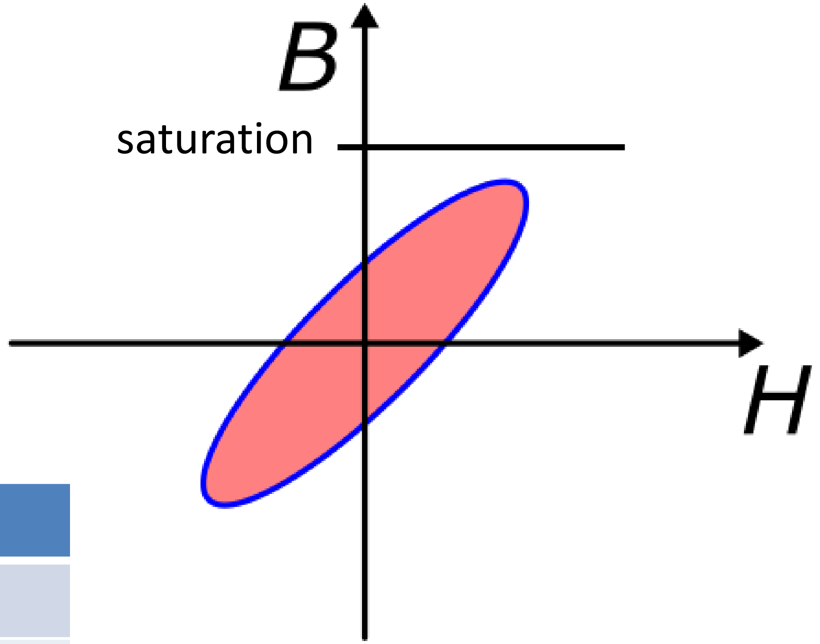
Loss mechanisms: Steinmetz equation

(below saturation, sinusoidal excitation)

$$\boxed{p_v = k\, f^{\alpha}\, B^{\beta}}$$

Steinmetz equation (SE) from 1892

$\alpha = 1 \ldots 1.5$
$\beta = 2 \ldots 2.5$



Benefits:	Drawbacks:
simple	Empirical / non physical
fast	Only below saturation
	Only sinusoidal

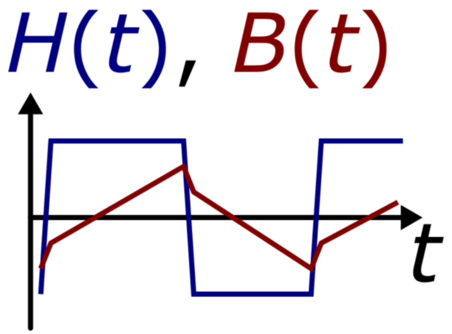
Loss mechanisms: improved Generalized Steinmetz Equation

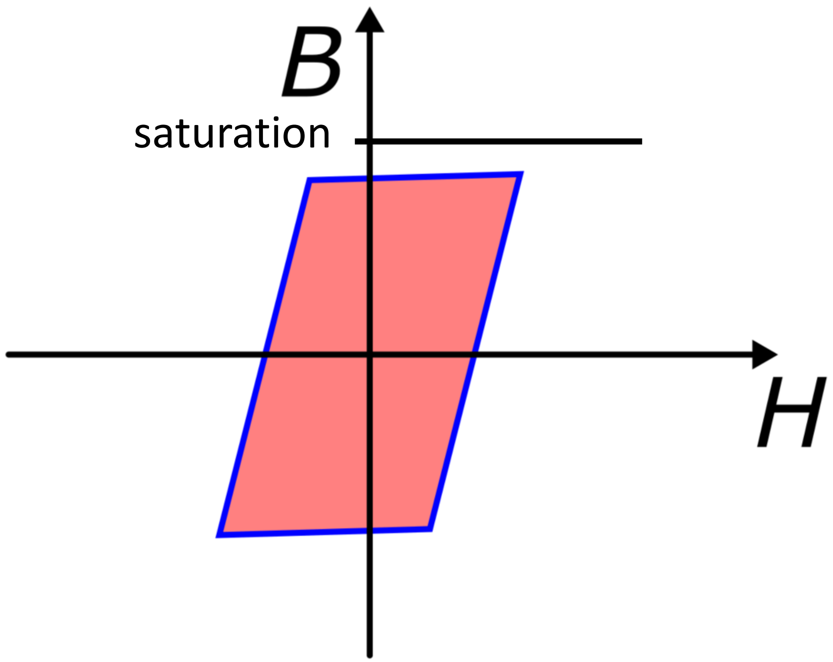
(below saturation)

$$p_v = \frac{1}{\mathrm{T}} \int_0^{\mathrm{T}} k_i \left|\frac{\mathrm{d}B}{\mathrm{d}t}\right|^{\alpha} \left(\Delta B^{\beta-\alpha}\right) \mathrm{d}t$$

improved Generalized Steinmetz Equation (iGSE)

with $k_i = \frac{k}{(2\pi)^{\alpha-1} \int_0^{2\pi} |\cos\theta|^{\alpha}\, 2^{\beta-\alpha}\, \mathrm{d}\theta}$





Benefits:	Drawbacks:
Allows arbitrary signals (AC)	Empirical / non physical
Simple (only sinusoidal loss measurements needed)	Becomes inaccurate (based on sinusoidal measurement data)
fast	Only valid below saturation

Loss mechanisms: improved Generalized Steinmetz Equation

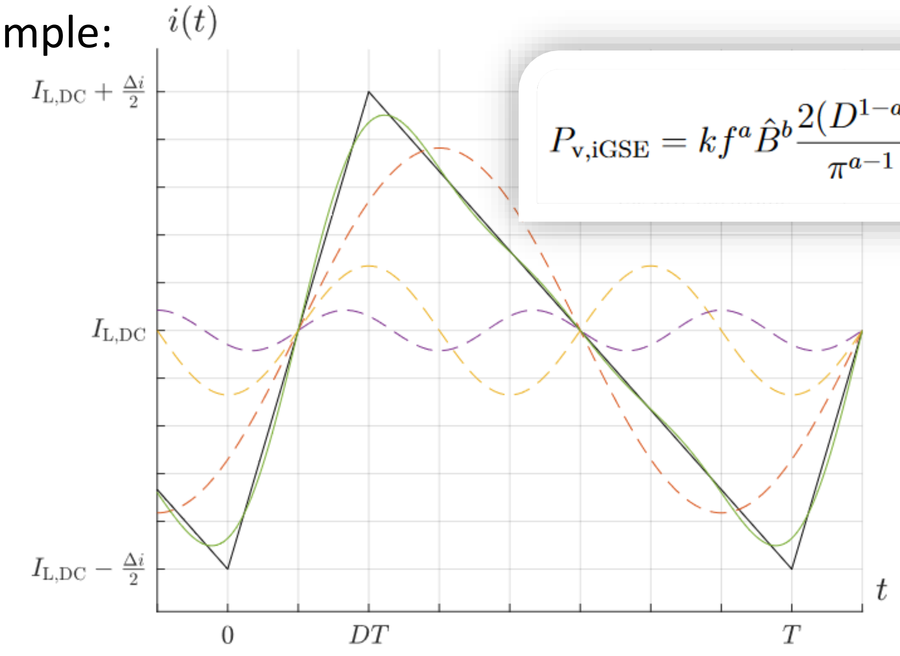
(below saturation)

$$\boxed{p_v = \frac{1}{\mathrm{T}}\int_0^{\mathrm{T}} k_i \left|\frac{\mathrm{d}B}{\mathrm{d}t}\right|^{\alpha} \left(\Delta B^{\beta-\alpha}\right) \mathrm{d}t}$$

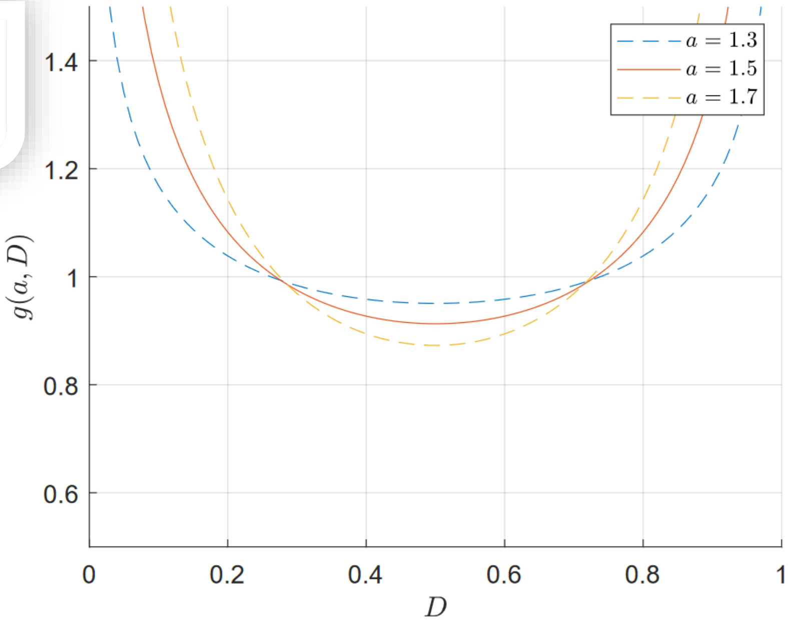
improved Generalized Steinmetz Equation (iGSE)

with $k_i = \frac{k}{(2\pi)^{\alpha-1}\int_0^{2\pi}|\cos\theta|^{\alpha}\, 2^{\beta-\alpha}\, \mathrm{d}\theta}$

Example:



$$P_{\mathrm{v,iGSE}} = k f^a \hat{B}^b \frac{2(D^{1-a} + (1-D)^{1-a})}{\pi^{a-1}\int_0^{2\pi}|\cos\theta|^a\, d\theta} = k f^a \hat{B}^b g(a, D)$$



Loss mechanisms: Overview Steinmetz Equations

Most approaches directly try to model the losses without exact modelling of the BH curve.

- **Steinmetz Equation (SE), 1890s**

  3 parameters

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

- **Improved Generalized Steinmetz Equation (iGSE), 2000s**

  $$P_V = \frac{1}{T}\int_0^T k_i \cdot \left|\frac{\mathrm{d}B}{\mathrm{d}t}\right|^{\alpha} \cdot (\Delta B)^{\beta}\,\mathrm{d}t$$

  3 parameters

- **Improved-improved GSE (i^2GSE), 2010s**

  8 parameters

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

(from MagNet webinar)

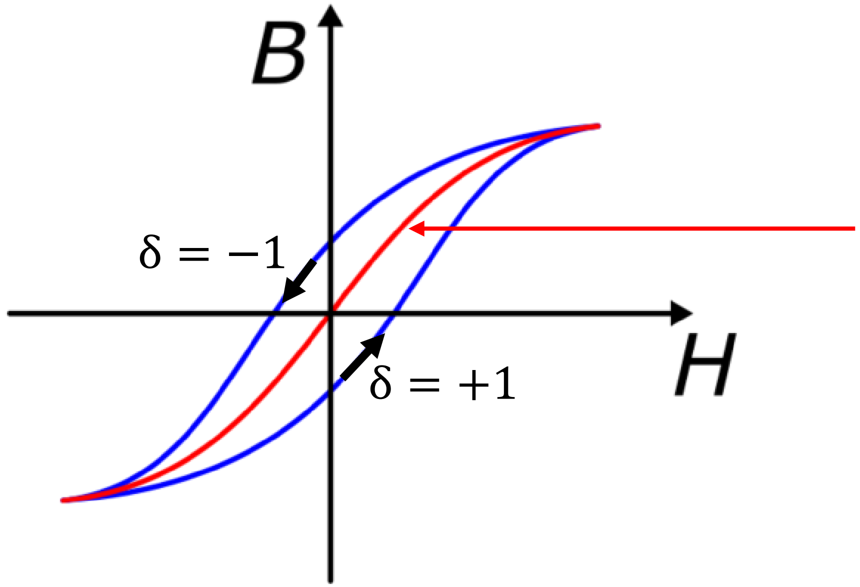
Loss mechanisms: Overview BH representations

Alternatively, it can be tried to model the full BH curve and calculate the losses by integrating the loop area.

Preisach model (1935)
Chua (1970)
Jiles-Atherton model (1980)
Coleman-Hogdon (1986)

Usually magnetization is used:

$$B = \mu_{\text{vacuum}} \, M$$



Anhysteretic magnetization curve:

$$M_{\mathrm{an}}^{\mathrm{iso}} = M_{\mathrm{s}} \left(\coth\left(\frac{H_{\mathrm{e}}}{a} \right) - \frac{a}{H_{\mathrm{e}}} \right)$$

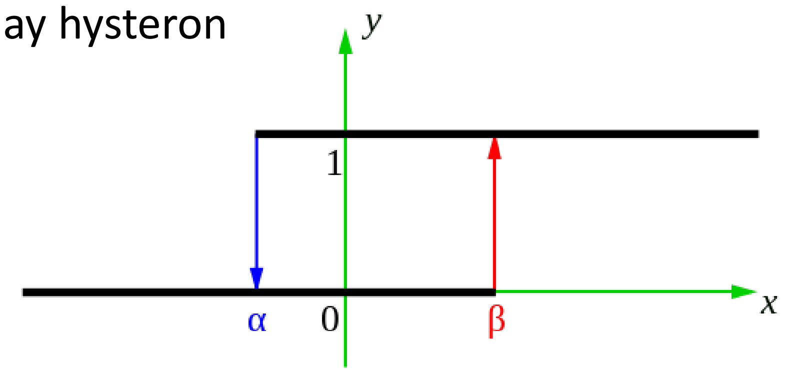
$$\frac{\partial M}{\partial H} = \frac{1}{1+c} \cdot \frac{M_{\mathrm{an}} - M}{\nu_0 \delta k - \alpha (M_{\mathrm{an}} - M)} + \frac{c}{(1+c)} \frac{\partial M_{\mathrm{an}}}{\partial H}$$

α, c, k must be estimated

Alternatively, it can be tried to model the full BH curve and calculate the losses by integrating the loop area.

Preisach model (1935)
Chua (1970)
Jiles-Atherton model (1980)
Coleman-Hogdon (1986)

relay hysteron



$$y(x) = \begin{cases} 1 & \text{if } x \geq \beta \\ 0 & \text{if } x \leq \alpha \\ k & \text{if } \alpha < x < \beta \end{cases}$$

Loss mechanisms: Overview BH representations

Alternatively, it can be tried to model the full BH curve and calculate the losses by integrating the loop area.

Preisach model (1935)
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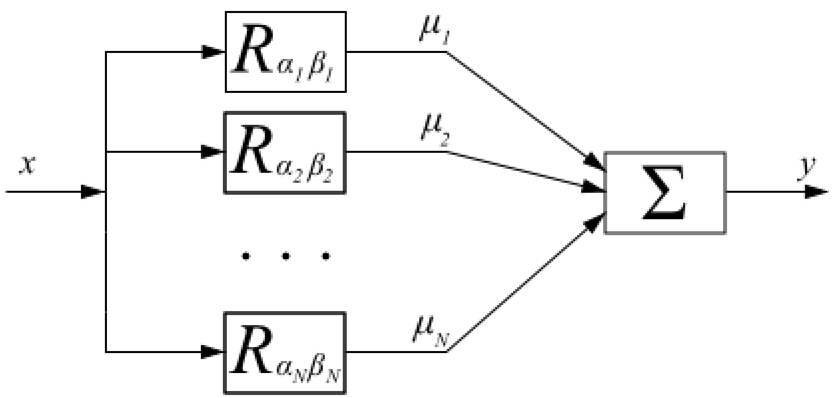
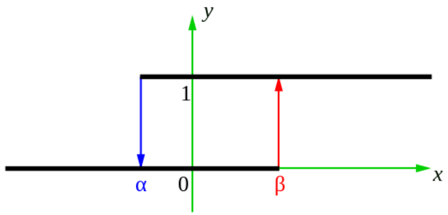
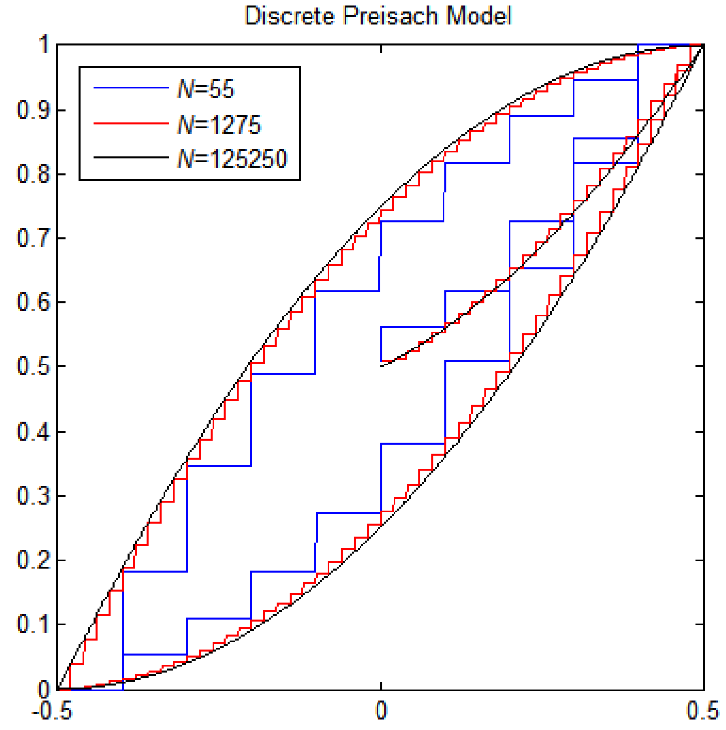




in parallel



$2N$ parameters have to be determined!

Loss mechanisms: Overview BH representations

Alternatively, it can be tried to model the full BH curve and calculate the losses by integrating the loop area.

Preisach model (1935)
Chua (1970)
Jiles-Atherton model (1980)
Coleman-Hogdon (1986)

	Error	Complexity of parameter estimation procedure	Complexity of required measurements
Jiles - Atherton	Medium	High	Low
Preisach	Low	Low	High
Chua	Medium	Medium	Low
Coleman - Hogdon	Medium	Medium	Low
Bouc - Wen	Medium	High	Low

Loss mechanisms: Overview BH representations

Alternatively, it can be tried to model the full BH curve and calculate the losses by integrating the loop area.

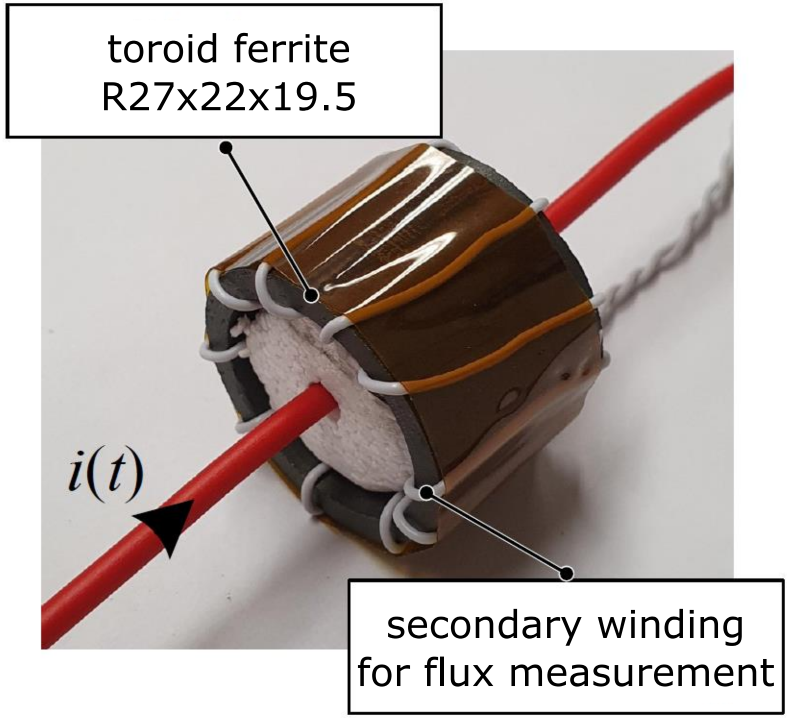
Preisach model (1935)
Chua (1970)
Jiles-Atherton model (1980)
Coleman-Hogdon (1986)

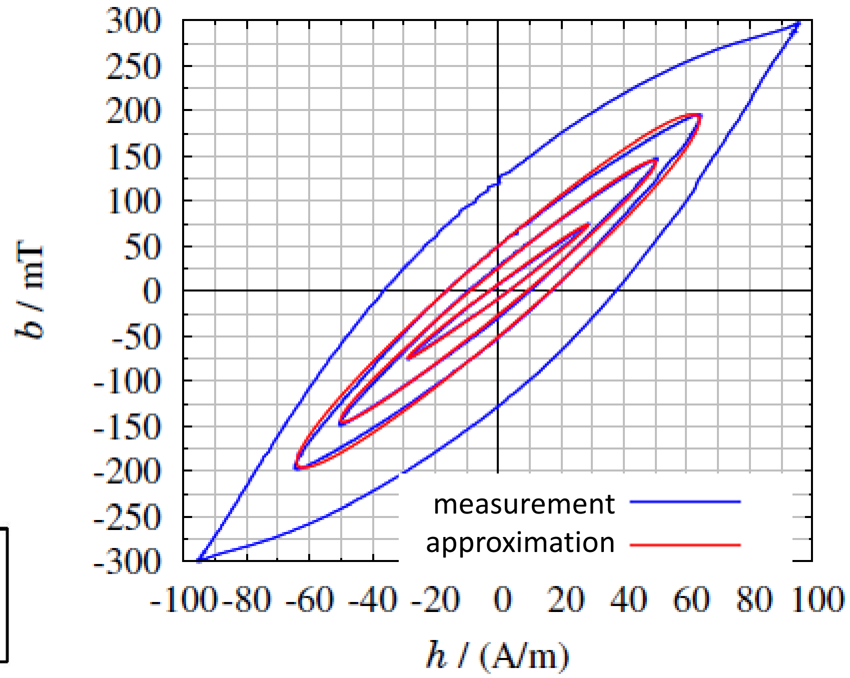
Why are they (almost) never used in Power Electronics?

“The modelling of

- Temperature
- Flux density shape
- Frequency
- (DC field premagnetisation) not covered in Challenge

requires extensive data sets for the various materials materials, but these are not made available by the manufacturers and have to be have to be collected through time-intensive measurements.”
(Albach, translated)

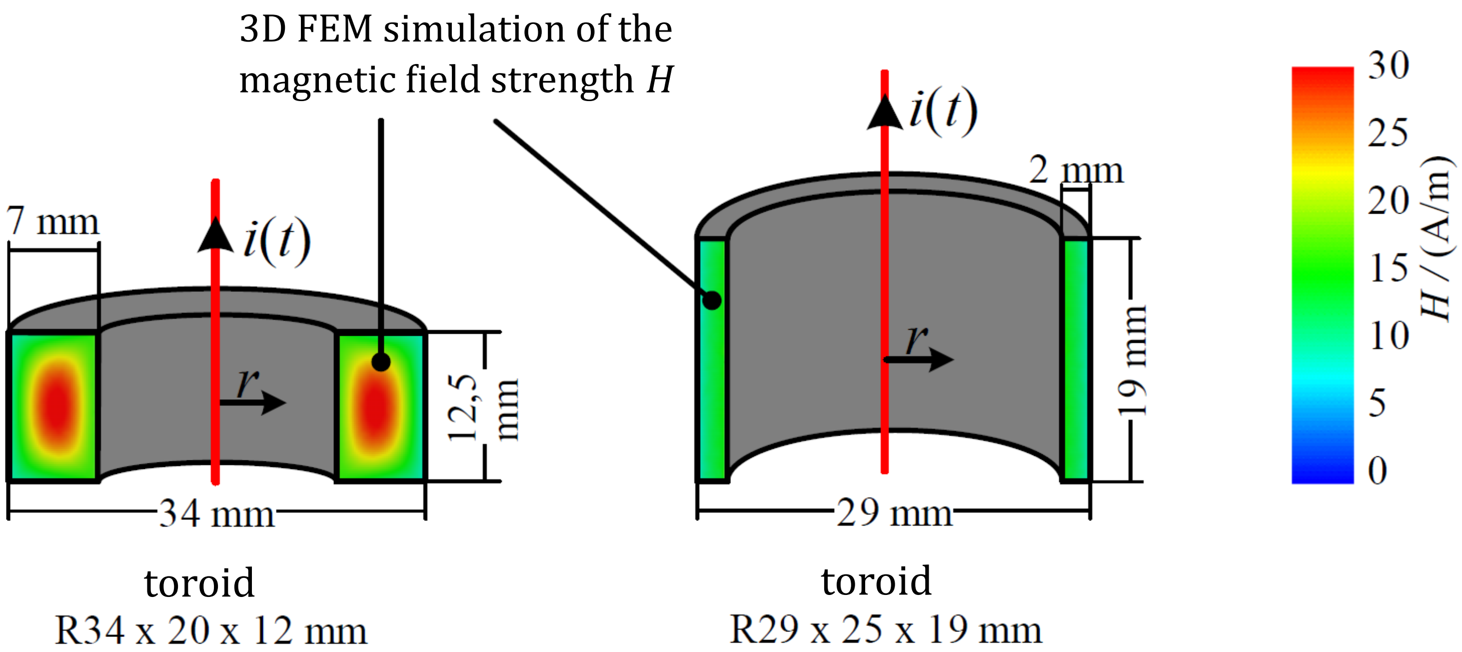




Assumption: homogeneous flux fields

BH Curve Measurement

- High frequency measurements require very thin toroid cores



$f = 2$ MHz
$\underline{\mu_r} = 1750e^{-j10°}$
$\underline{\varepsilon_r} = 60000e^{-j10°}$

Conlusion for MagNet Challenge

- Goal:

$$p_v = \text{function}(\text{waveform}, \text{frequency}, \text{temperature})$$

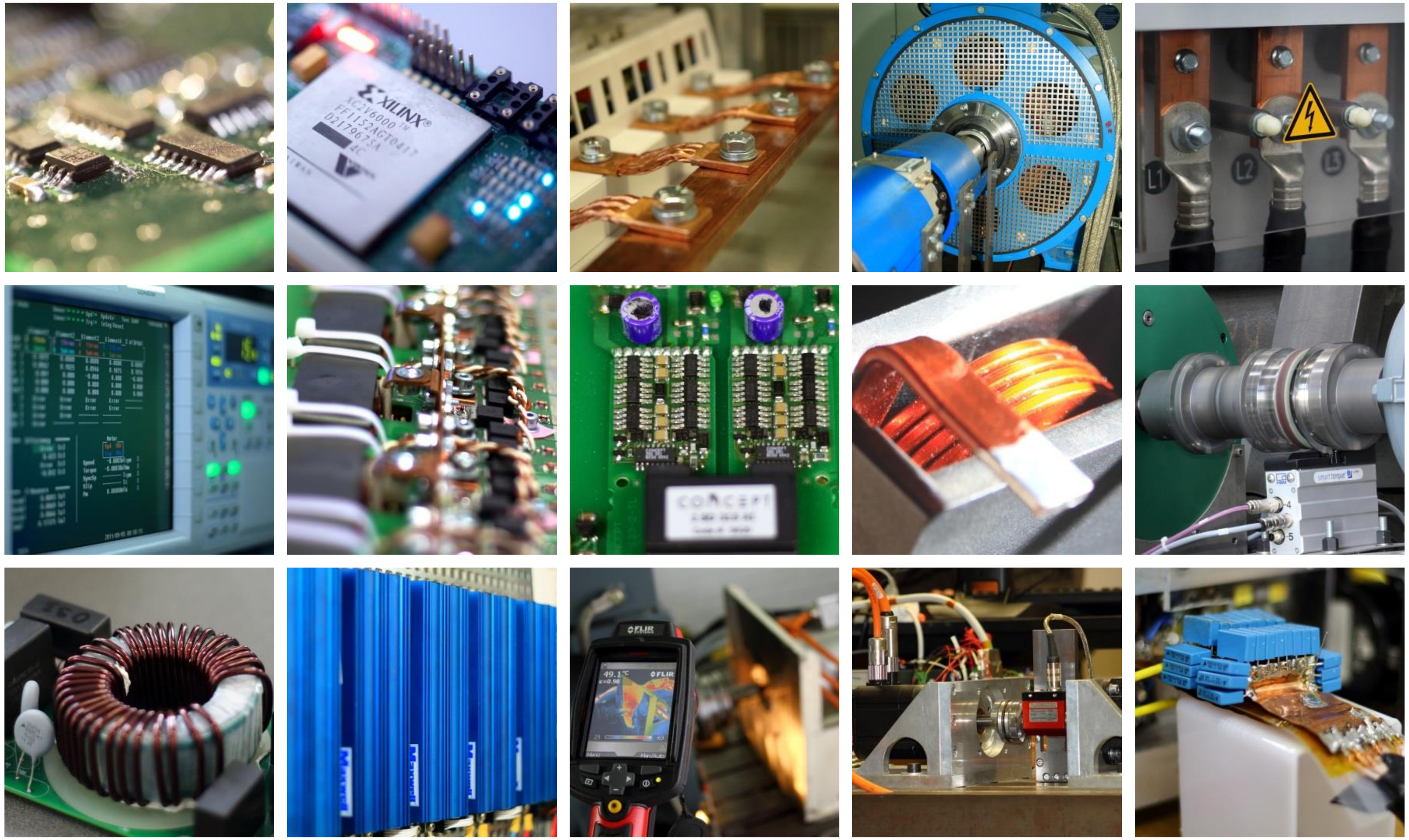
- Here: only hysteresis
- Usually calculated without exact modelling the BH curve (not enough data)
- Big dataset is given:
  - 1. model BH loop
  - 2. intergrate for losses p_v

feasible?

Thank you for your attention

Power Electronics and Electrical Drives

Paderborn University



Citations

- [1] https://www.reinhausen.com/de/service-details/transformatoren-serviceleistungen/modernisierung-und-austausch
- [2] https://www.ew.tu-darmstadt.de/media/ew/rd/ew_praktika/lv_praktika/anleitungen/M2_Drehstromtransformator_v2.18.pdf
- [3] GaN Systems - Reference Design *“GaN-Based 3KW Full Bridge LLC Resonant Converter”*