ETH zürich

Power Electronic Systems Laboratory

Opportunities for new Magnetics Designs to Address Market-Driven Technology Trends in Automotive Applications

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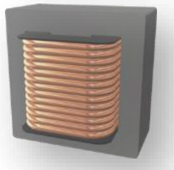

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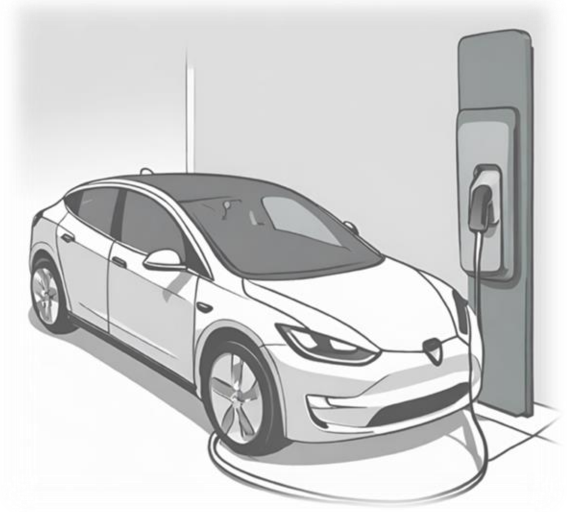
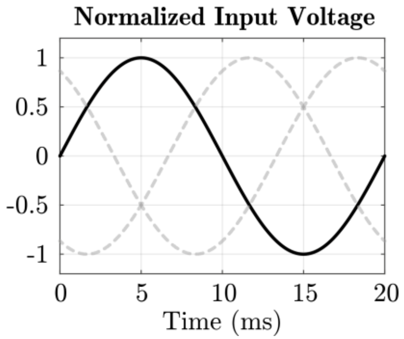


- **Suitable Converter Topologies for Electric Vehicle Applications**
  - *Conventional Two-Stage Approach*
  - *Single-Stage Approach using Bidirectional Switches*
- **Electromagnetic Requirements for the Transformer**

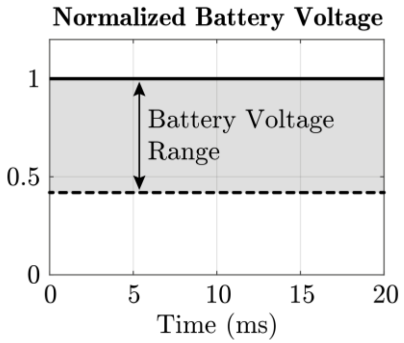
Application

▶ Suitable Converter Topologies for Electric Vehicle Applications

- The **primary function** of on-board **chargers** for **electric vehicles** is to **rectify** the input side **AC voltage** into a constant **output voltage** adapted to the battery voltage, all **without** the need for a **galvanic connection** between the supplying grid and the high-voltage battery



▶ ***Energy Source*** *in the form of a single-phase or three-phase AC voltage grid*



▶ ***Output DC Voltage*** *that needs to be adjusted to the momentary state-of-charge-dependent battery voltage*

Electric Vehicle Charger Requirements
- *Single-Phase (3.7 kW) / Three-Phase (11 kW) AC/DC Operation*
- ***Buck/Boost*** *Functionality*
- ***Galvanic Isolation*** *Mandatory*

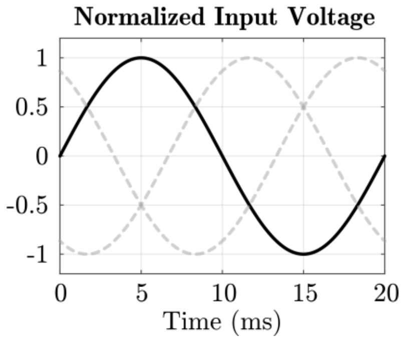
Application

▶ **Suitable Converter Topologies for Electric Vehicle Applications** – *Conventional Two - Stage Approach*

- The **two-stage approach** has proven to be the **most efficient**, particularly when using only **unipolar switches**

  - *Non-isolated PFC rectifier* ⇨ Sinusoidal input currents, boost operation

  - *Isolated DC/DC Converter* ⇨ Galvanic isolation, buck/boost operation



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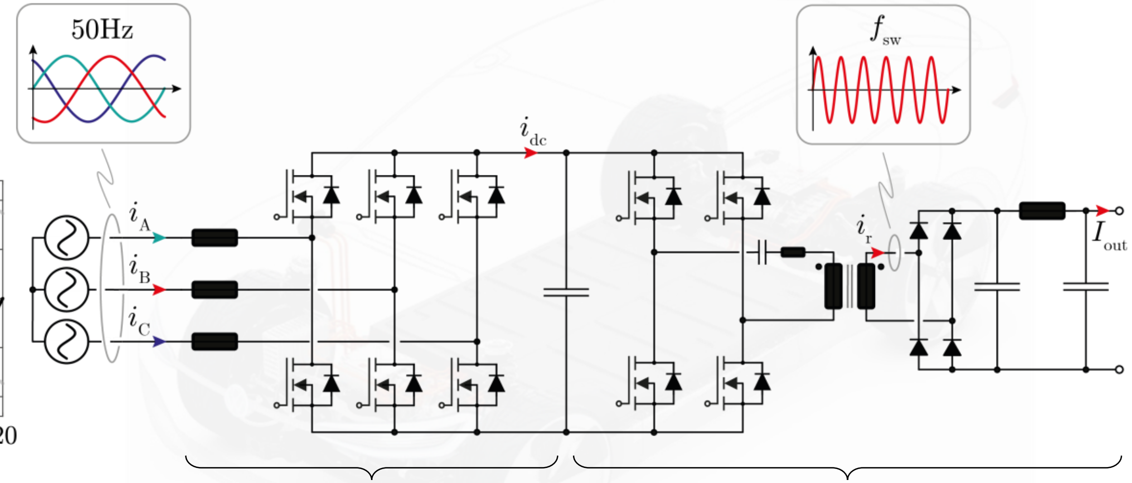
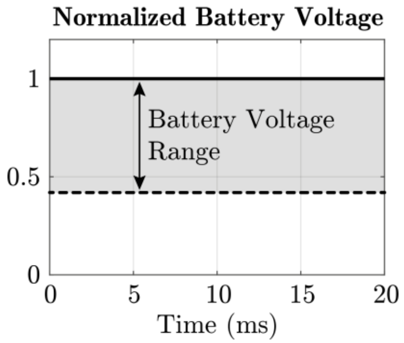


PFC Rectification *(boost)* ***Isolated DC/DC Conversion*** *(buck/boost)*



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- ***Galvanic Isolation*** *Mandatory*

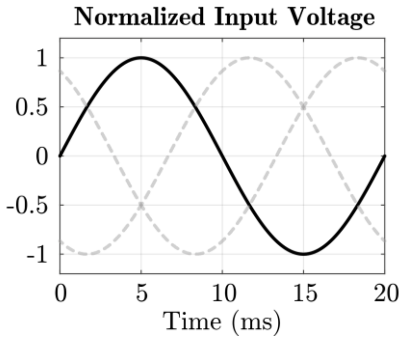
Application

▶ **Suitable Converter Topologies for Electric Vehicle Applications** – *Single - Stage Approach*

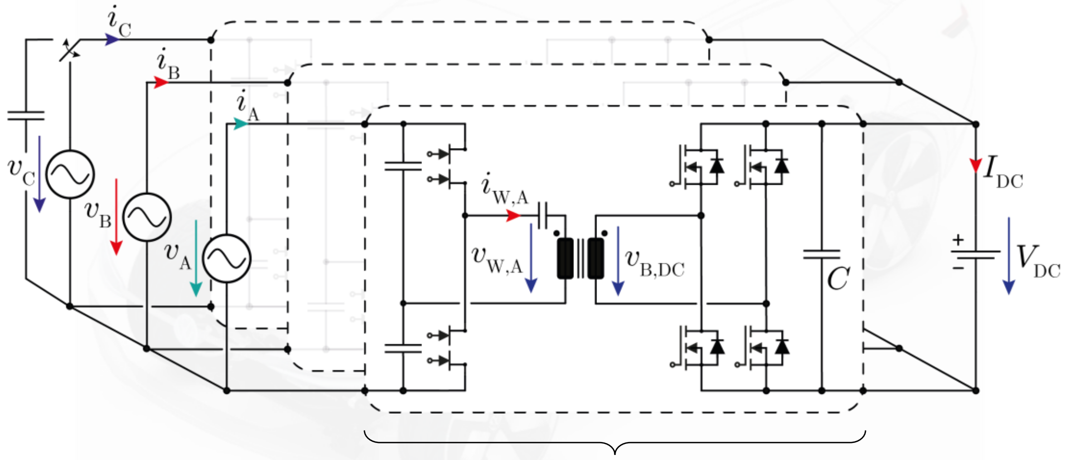
- If **bidirectionally controllable switches** are used, all functionalities can be implemented in a **single stage**

  - *Bidirectional Isolated AC/DC Converter* ⇨ Sinusoidal input currents, rectification, galvanic isolation, buck/boost operation

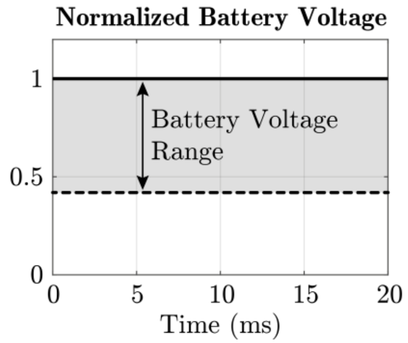
  - *Modular Approach* ⇨ Each phase is controlled independently, idle modules are operated as power pulsation buffers



▶ ***Energy Source*** *in the form of a single-phase or three-phase AC voltage grid*



Bidirectional Isolated AC/DC Conversion *(buck/boost)*



▶ ***Output DC Voltage*** *that needs to be adjusted to the momentary state-of-charge-dependent battery voltage*

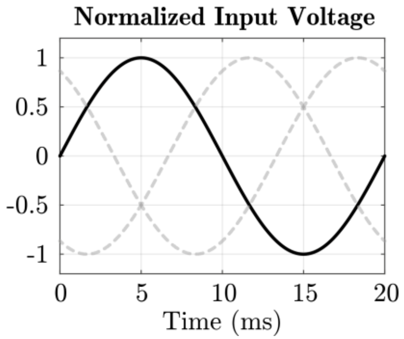
Electric Vehicle Charger Requirements

- *Single-Phase (3.7 kW) / Three-Phase (11 kW) AC/DC Operation*
- ***Buck/Boost*** *Functionality*
- ***Galvanic Isolation*** *Mandatory*

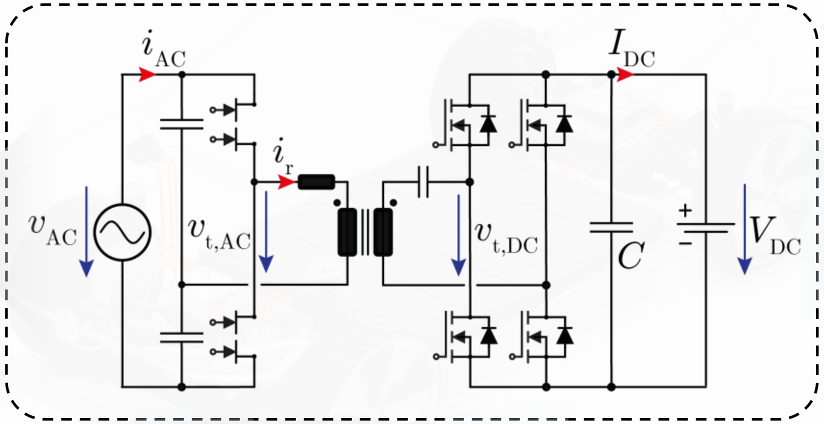
Application

Suitable Converter Topologies for Electric Vehicle Applications – *Single - Stage Approach*

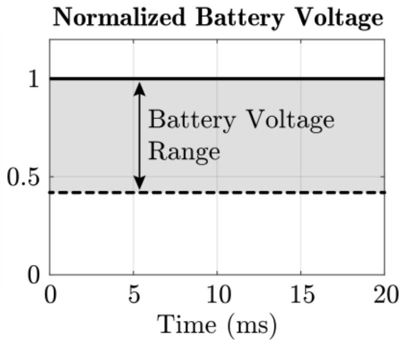
- The **bidirectionally controllable switches** generate a **high-frequency square wave voltage $v_{t,AC}$** of any frequency from the low-frequency input alternating voltage
- The **full-bridge** on the DC side generates a **high-frequency square wave voltage $v_{t,DC}$** of any **frequency** and with an **arbitrary duty cycle**



__Energy Source__ in the form of a single-phase or three-phase AC voltage grid



Generation of high-frequency __square wave__ voltages



__Output DC Voltage__ that needs to be adjusted to the momentary state-of-charge-dependent battery voltage

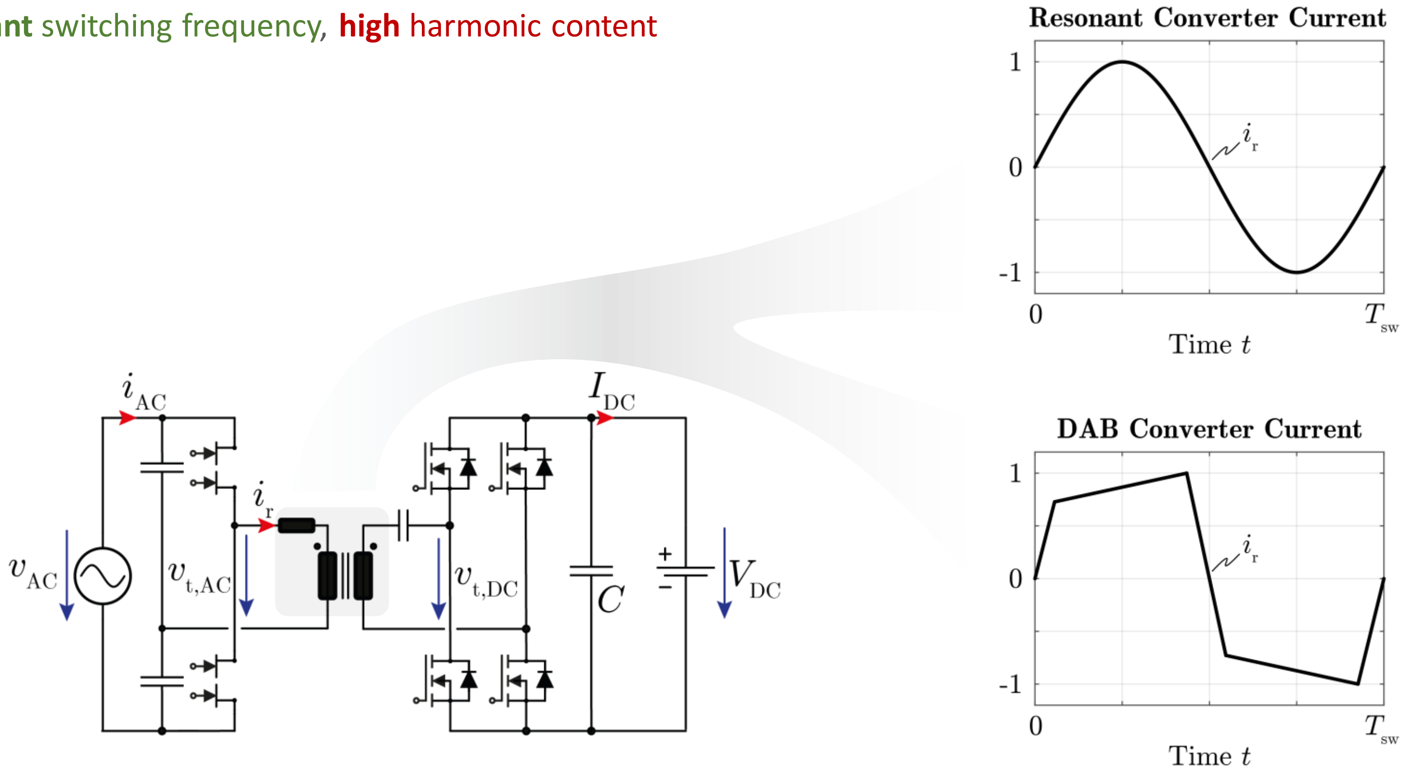
Application

▶ Electromagnetic Requirements for the Transformer

- Depending on the chosen **ratio** between **resonance capacitance** and **resonance inductance**, the **currents** in the **transformer** will either be **sinusoidal** or **trapezoidal** (i.e., piecewise linear), imposing distinct requirements on the transformer design

  - *Sinusoidal Currents* ⇨ Sinusoidal flux linkages, **widely varying** switching frequencies, **low** harmonic content

  - *Trapezoidal Currents* ⇨ Trapezoidal flux linkages, **constant** switching frequency, **high** harmonic content



▶ *Bidirectional Isolated* ***AC/DC Converter*** *(Buck/Boost)*

Application

Electromagnetic Requirements for the Transformer

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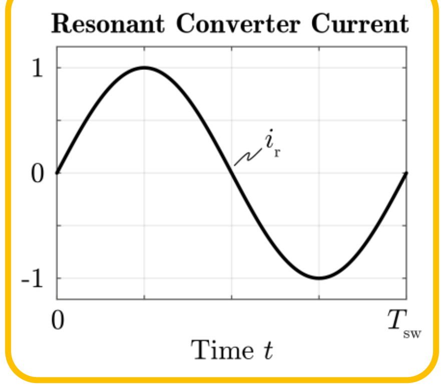
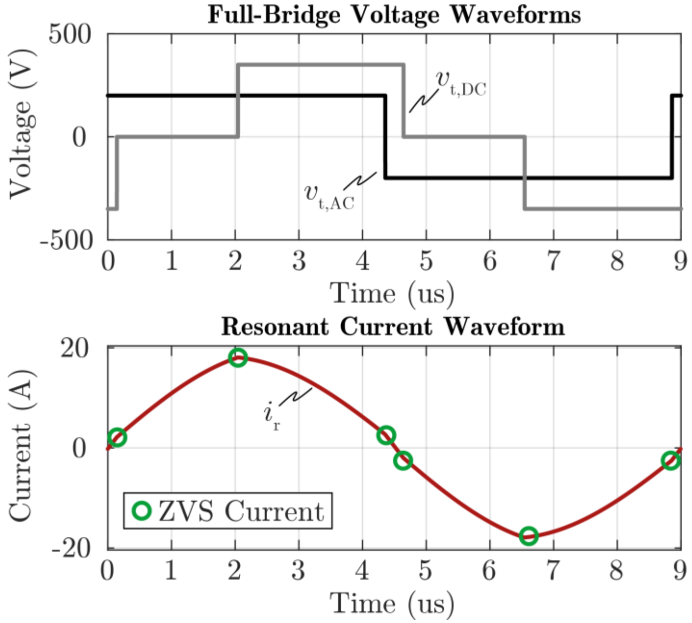
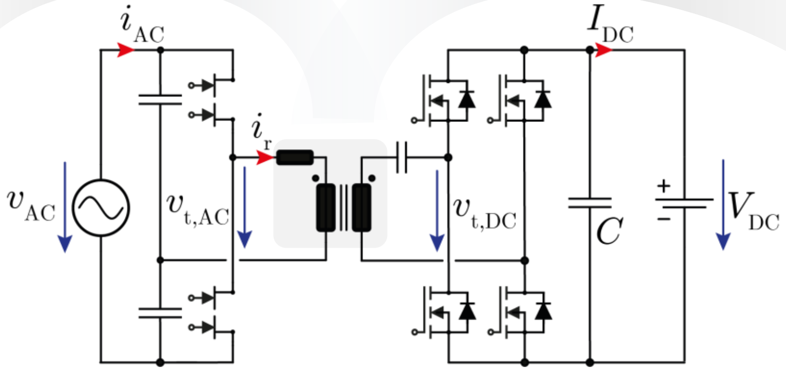






*Bidirectional Isolated **AC/DC Converter** (Buck/Boost)*

Characteristics
- Minimal HF Harmonic Content in Transformer Currents
- Minimal Reactive Power Flow
- Soft-Switching of all Semiconductors

Application

▶ Electromagnetic Requirements for the Transformer

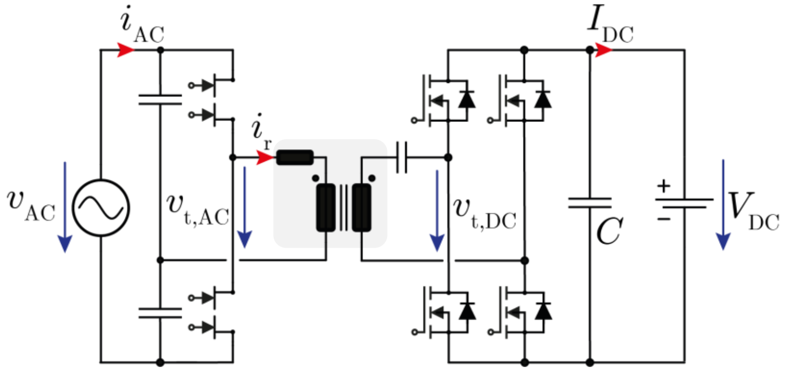
- To build the **converter** system as **compact** as possible and to **minimize** the **number of components**, the **resonance inductance** should be **integrated** into the transformer as **leakage inductance**

  ⇨ *The larger the chosen leakage inductance, the lower the required switching frequency range, as well as the harmonic content of the transformer currents*

- **Transformer Design Challenges**

  ⇨ *Large required leakage inductance*

  ⇨ *Efficient operation across a wide switching frequency range*



▶ *Bidirectional Isolated **AC/DC Converter** (Buck/Boost)*

Resonant Frequency (f_{res})
Defines $L_\sigma \cdot C_{res}$

▼

Quality Factor ($Q_{res} = L_\sigma / C_{res}$)
Given by max. Capacitor Voltage

▼

L_σ, C_{res}

▼

Maximum Switching Frequency ($f_{sw,max}$)
Given by min. Required ZVS Currents

▼

$f_{sw,min}$, $f_{sw,max}$

▼

Calculate Waveforms ($I_{rms,max}$, Ψ_{max}, f_{sw})
Including Current Harmonics

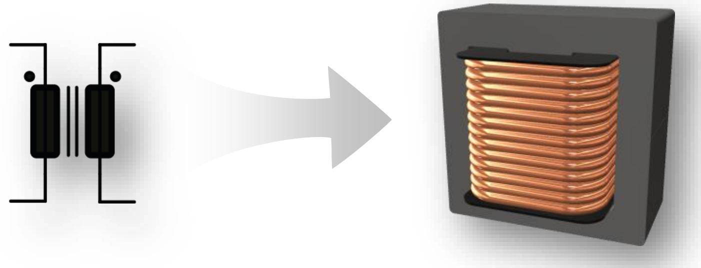
▼

Design Suitable Transformers

▼

Thermal Validation ($T_{hotspot}$)
Discard Non-Feasible Transformer Designs

Transformer Design Considerations



- **General Considerations**
  - *Core Geometries*
  - *Winding Technologies*
  - *Leakage Inductance Integration Method*
- **Transformer Optimization**

Transformer Design Considerations

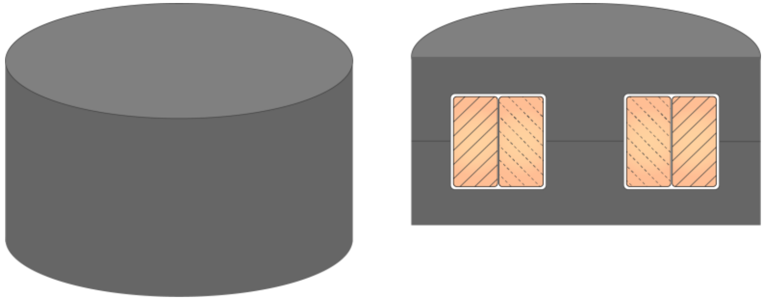
General Considerations – *Optimal Core Geometry*

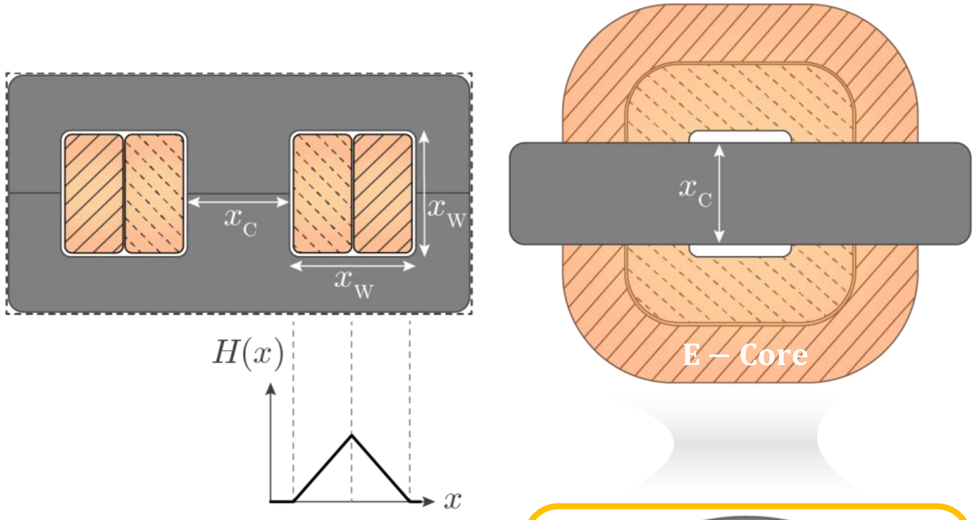
- If a significant leakage inductance is desired in a transformer, a large volume with a strong magnetic field must be generated

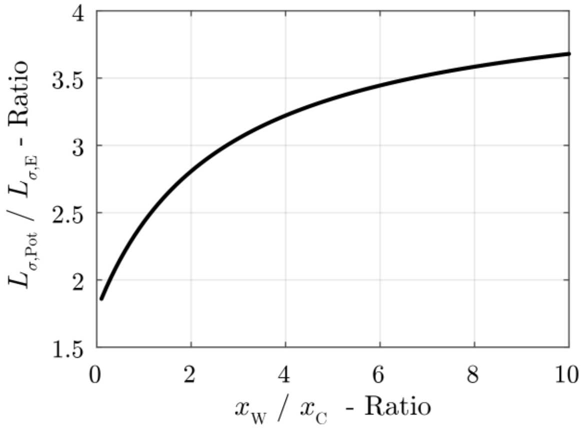
$$L_\sigma = \frac{\mu_0}{I^2} \cdot \int_V H^2 \, \mathrm{d}V$$

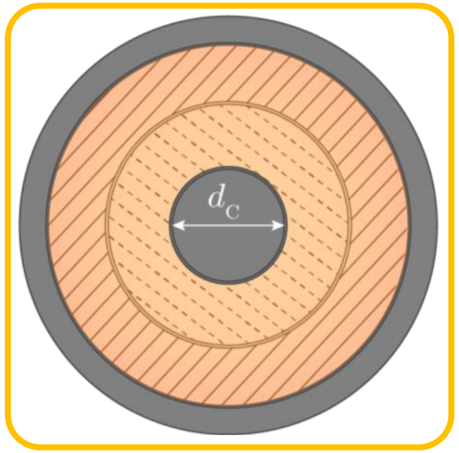
⇨ *However, since the **magnetic field strength** directly influences the **high-frequency conduction losses**, the **winding volume** should be used as **efficiently as possible** to minimize the required maximum magnetic field strength*

⇨ ***Pot cores** maximize the **stored magnetic energy** throughout the winding volume while **minimizing** the peak value of the **magnetic field***









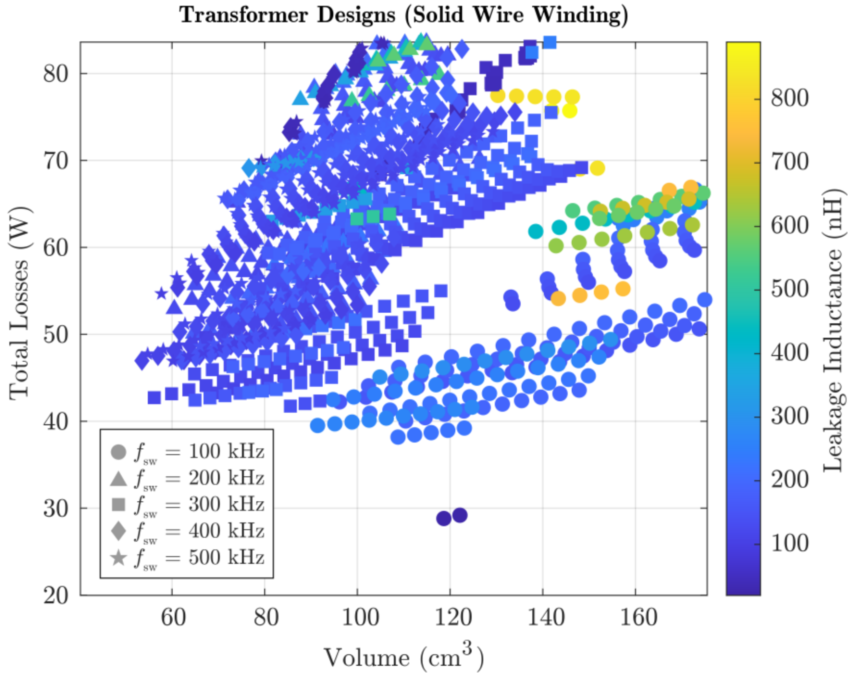
▶ ***Ratio of the Leakage Inductances** in a transformer with a pot core or an E-core for different winding window to core area ratios*

Transformer Design Considerations

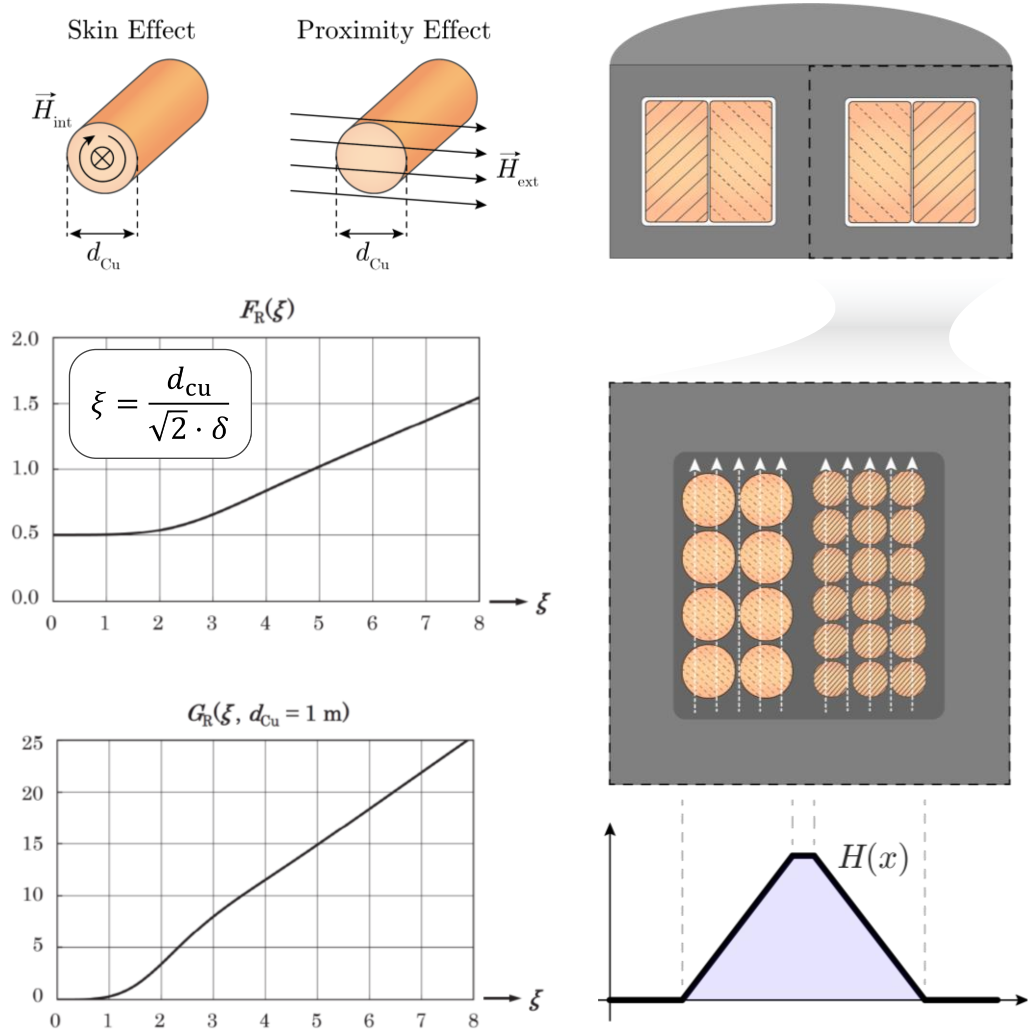
▶ **General Considerations** – *Optimal Winding Technology*

- The geometry of **solid wires** make them prone to **HF magnetic fields** from all directions which is why it is practically **impossible** to design an **efficient HF transformer** where **maximum leakage inductance** is desired

⇨ ***Small** leakage inductance but still **high** conduction losses*



▶ ***Maximum Leakage Inductance** in solid wire winding transformers for different switching frequencies*



▶ ***Parasitic High-Frequency Effects** in different wire types due to parasitic HF magnetic fields*

Transformer Design Considerations

▶ **General Considerations** – *Optimal Winding Technology*

- The **most efficient** approach would involve **completely filling** the **winding window** with **litz wire**, minimizing **HF conduction losses** and allowing for larger **leakage inductance** values

⇨ *Minimum required **winding window height** (thermal limit)*

$$h_{\mathrm{w,min}} = \frac{2 \cdot N_{\mathrm{p}} \cdot I_{\mathrm{rms}}}{k_{\mathrm{w}} \cdot b_{\mathrm{w}} \cdot J_{\mathrm{rms}}}, \qquad k_{\mathrm{w}} \approx 0.42 \dots 0.47$$

⇨ ***Average length** of a turn*

$$l_{\mathrm{w,avg}} = 2 \cdot \pi \cdot \left(\frac{r_{\mathrm{c}}(N_{\mathrm{p}} = 1)}{\sqrt{N_{\mathrm{p}}}} + \frac{b_{\mathrm{w}}}{2} \right)$$

⇨ *Achievable **leakage inductance***

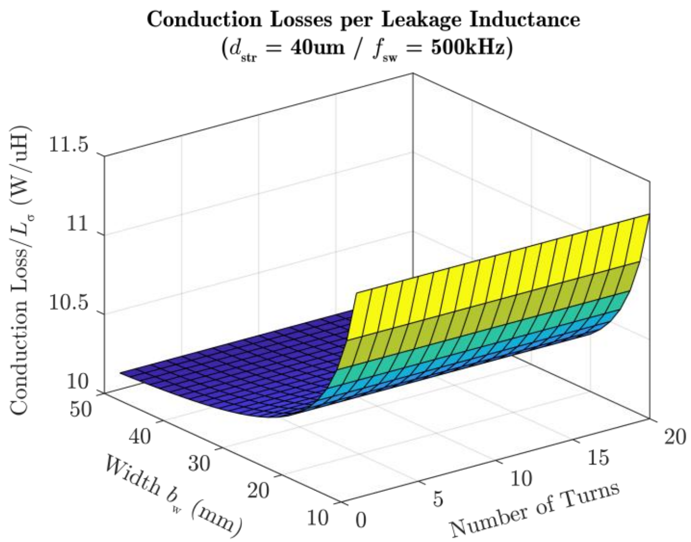
$$L_{\sigma} = \frac{\mu_0 \cdot l_{\mathrm{w,avg}} \cdot b_{\mathrm{w}} \cdot N_{\mathrm{p}}^2}{3 \cdot h_{\mathrm{w,min}}}$$

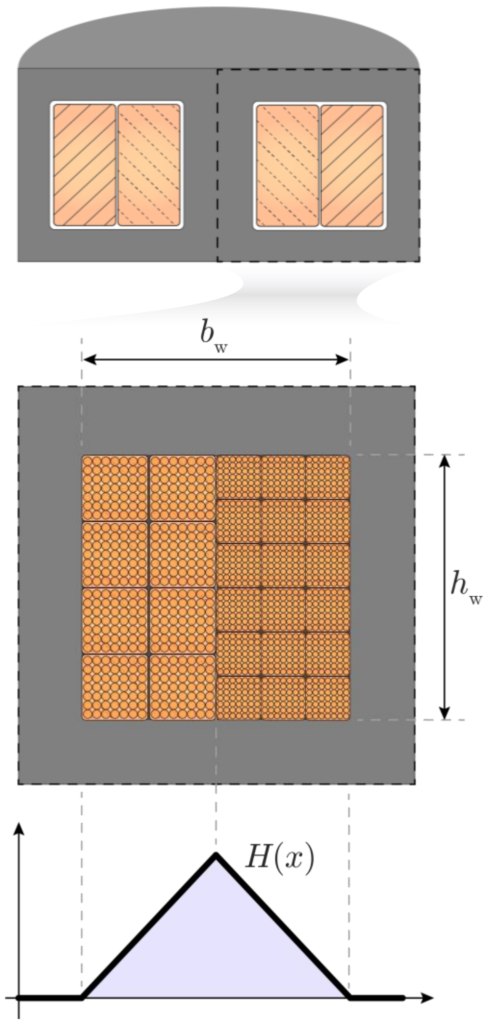
- The **conduction losses** can be estimated based on the **winding resistance**

$$R_{\mathrm{ac}} = \frac{4 \cdot N_{\mathrm{p}} \cdot l_{\mathrm{w,avg}}}{\sigma \cdot n_{\mathrm{str}} \cdot \pi \cdot d_{\mathrm{str}}^2} \left(1 + 2 \cdot G_{\mathrm{R,str}}(\delta, d_{\mathrm{str}}) \cdot n_{\mathrm{str}}^2 \cdot \left(\frac{H_{\mathrm{rms}}(x)}{I_{\mathrm{rms}}} \right)^2 \right)$$

- The **minimal conduction losses per leakage inductance** are given as

$$\rightarrow \frac{P_{\mathrm{w}}}{L_{\sigma}} = \frac{8 \cdot I_{\mathrm{rms}} \cdot n_{\mathrm{str}} \cdot k_{\mathrm{w}} \cdot J_{\mathrm{rms}} \cdot G_{\mathrm{R,str}}(\delta, d_{\mathrm{str}})}{\sigma \cdot d_{\mathrm{str}}^2 \cdot \mu_0 \cdot \pi}$$





▶ ***Conduction Losses per Leakage Inductance** in a pot core transformer with litz wire (40um) windings for different geometrical parameters*

Transformer Design Considerations

▶ General Considerations – *Optimal Winding Technology*

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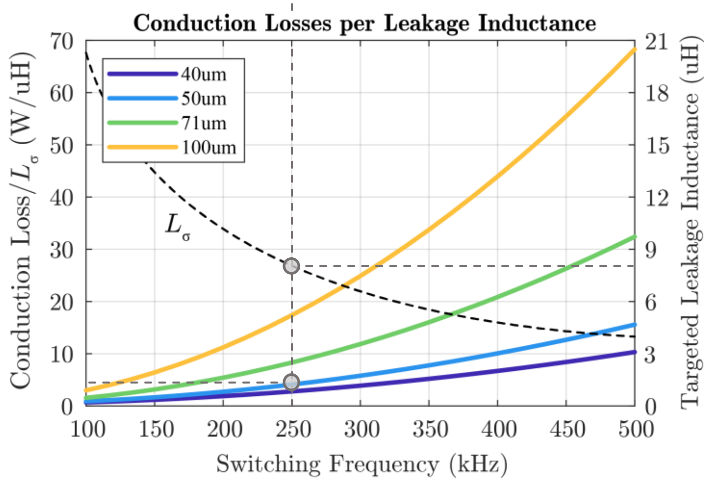
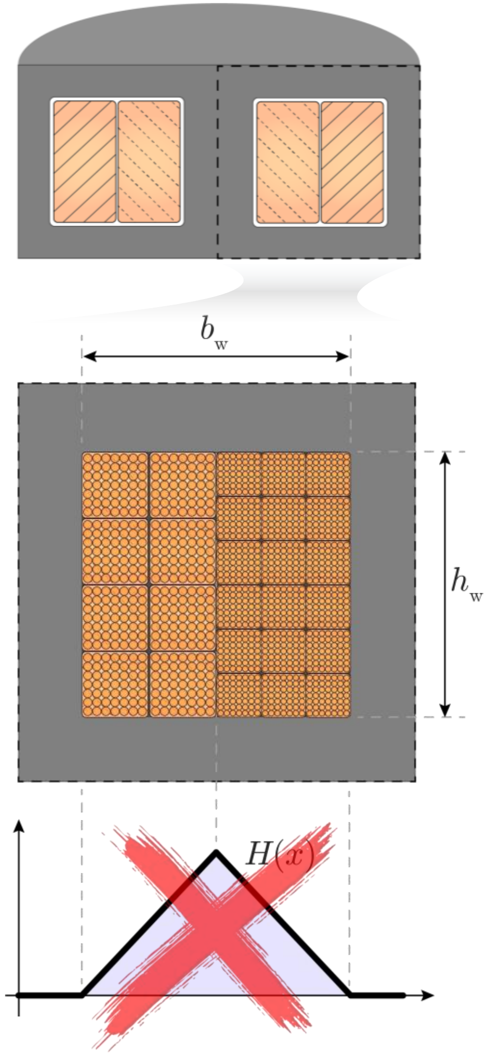
$$\rightarrow \frac{P_{\mathrm{w}}}{L_{\sigma}} = \frac{8 \cdot I_{\mathrm{rms}} \cdot n_{\mathrm{str}} \cdot k_{\mathrm{w}} \cdot J_{\mathrm{rms}} \cdot G_{\mathrm{R,str}}(\delta, d_{\mathrm{str}})}{\sigma \cdot d_{\mathrm{str}}^2 \cdot \mu_0 \cdot \pi}$$

$$P_{\mathrm{w,estimated}}(@50\ \mu\mathrm{m}) = 8\ \mu\mathrm{H} \cdot 4.5 \frac{\mathrm{W}}{\mu\mathrm{H}} = 36\ \mathrm{W}$$



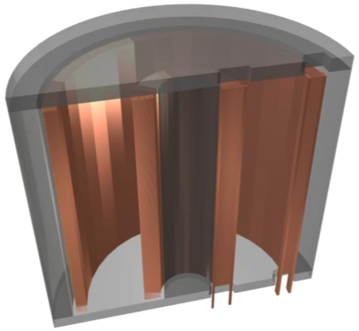


▶ ***Conduction Losses per Leakage Inductance** for different strand diameters, switching frequencies and an RMS current of 18 A*

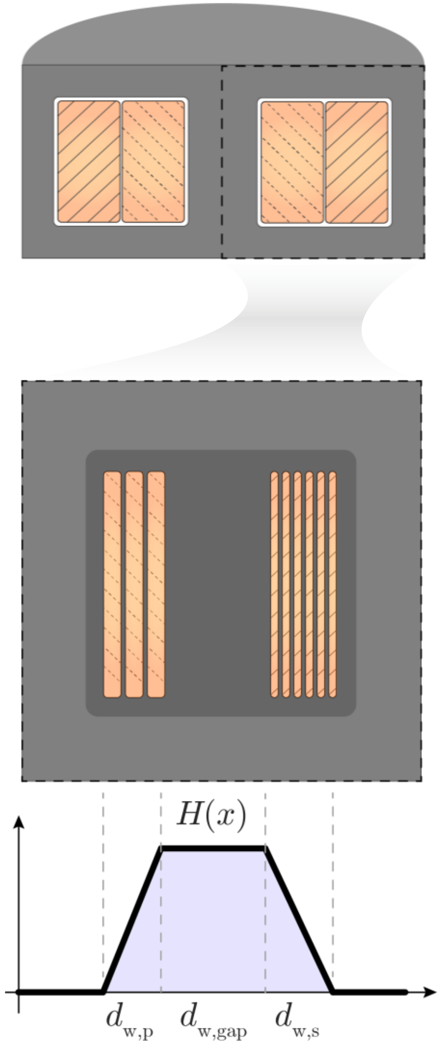
Transformer Design Considerations

General Considerations – *Leakage Inductance Integration Method*

- Instead of **uniformly distributing** the effectively utilized **copper cross-sectional area**, as with windings made of HF **litz wire**, the **unused area** of the winding window can be **concentrated between** the **two windings** using **foil windings**
- This allows for significantly **higher leakage inductances** with the **same** effective **copper cross-sectional area**



$$L_{\sigma,\text{foil}} = \frac{\mu_0 N_\text{p}^2}{3h_\text{w}} \cdot \left(l_{\text{w,p}} d_{\text{w,p}} + 3 l_{\text{w,gap}} d_{\text{w.gap}} + l_{\text{w,s}} d_{\text{w,s}}\right)$$



⇨ *The higher **copper fill factor** of **foil windings**, along with their higher **permissible current density**, results in significantly **higher leakage inductances** for the **same winding volume***

$$\frac{L_{\sigma,\text{foil}}}{L_{\sigma,\text{litz}}} = 3 - 2 \cdot \frac{J_\text{litz}}{J_\text{foil}} \cdot \frac{k_\text{w,litz}}{k_\text{w,foil}} = 3 - 2 \cdot \frac{10\,\frac{\text{A}}{\text{mm}^2}}{10\,\frac{\text{A}}{\text{mm}^2}} \cdot \frac{0.42}{0.8} = 1.95$$

Same DC - Resistance *($R_{\text{dc,foil}} = R_{\text{dc,litz}}$)*

$$\frac{L_{\sigma,\text{foil}}}{L_{\sigma,\text{litz}}} = 3 - 2 \cdot \frac{10\,\frac{\text{A}}{\text{mm}^2}}{50\,\frac{\text{A}}{\text{mm}^2}} \cdot \frac{0.42}{0.8} = 2.79$$

Maximum Power Density *(Thermal Limit)*

Transformer Design Considerations

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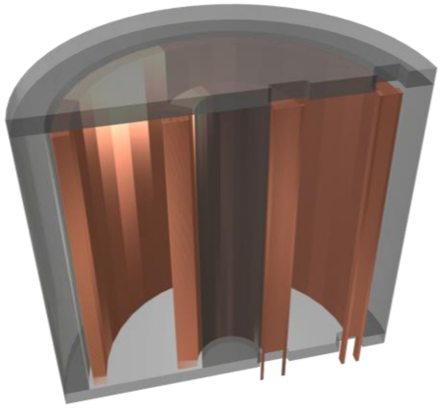
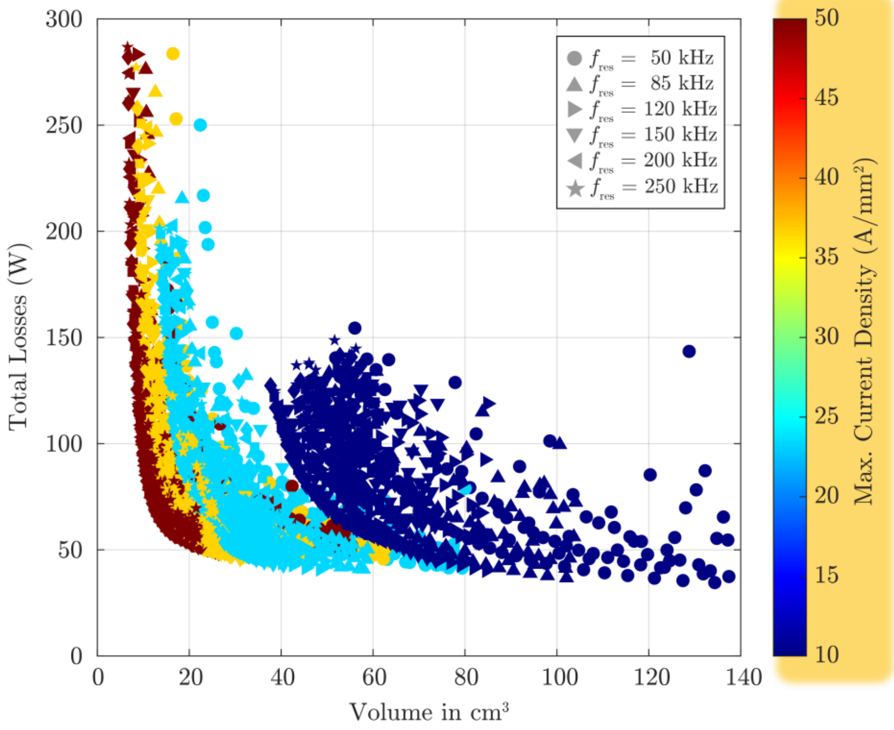




▶ ***Optimization Results** of foil winding transformers for the specifications of the application at hand*

Resonant Frequency (f_{res})
Defines $L_\sigma \cdot C_{res}$

Quality Factor ($Q_{res} = L_\sigma / C_{res}$)
Given by max. Capacitor Voltage

L_σ, C_{res}

Maximum Switching Frequency ($f_{sw,max}$)
Given by min. Required ZVS Currents

$f_{sw,min}$, $f_{sw,max}$

Calculate Waveforms ($I_{rms,max}$, Ψ_{max}, f_{sw})
Including Current Harmonics

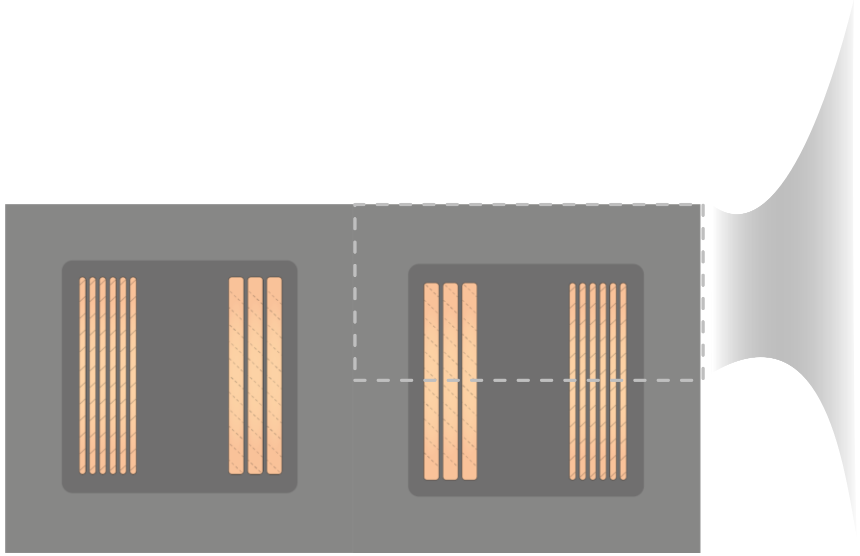
Design Set of Possible Transformers
Core Cross-Sectional Area
Winding Area (b_w, h_w)
Foil Thickness ($b_{cu,pri}$, $b_{cu,sec}$)
Number of Turns (N_{pri}, N_{sec})
Gap Width (d_{gap})
Core Material (N97, N49)

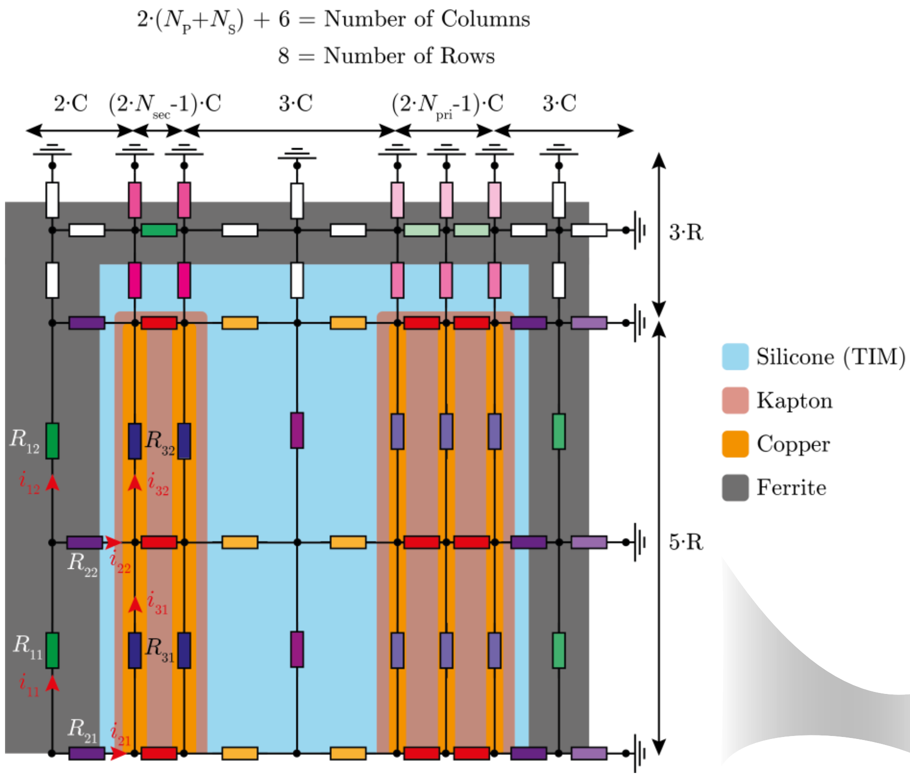
Thermal Validation ($T_{hotspot}$)
Discard Non-Feasible Transformer Designs

Transformer Design Considerations

▶ **Transformer Optimization** – *Foil Winding Transformer*

- To assess the **thermal viability** of the **foil winding transformer designs**, it is essential to develop a simple **thermal model**
- Due to **symmetry** reasons, it is sufficient to **model** only **half** of the **winding window**
- The **conduction** and the **core losses** are **distributed** among a discrete number of **nodes**





Resonant Frequency (f_{res})
Defines $L_\sigma \cdot C_{res}$

▼

Quality Factor ($Q_{res} = L_\sigma / C_{res}$)
Given by max. Capacitor Voltage

▼

L_σ, C_{res}

▼

Maximum Switching Frequency ($f_{sw,max}$)
Given by min. Required ZVS Currents

▼

$f_{sw,min}$, $f_{sw,max}$

▼

Calculate Waveforms ($I_{rms,max}$, Ψ_{max}, f_{sw})
Including Current Harmonics

▼

Design Set of Possible Transformers
Core Cross-Sectional Area
Winding Area (b_w, h_w)
Foil Thickness ($b_{cu,pri}$, $b_{cu,sec}$)
Number of Turns (N_{pri}, N_{sec})
Gap Width (d_{gap})
Core Material (N97, N49)

▼

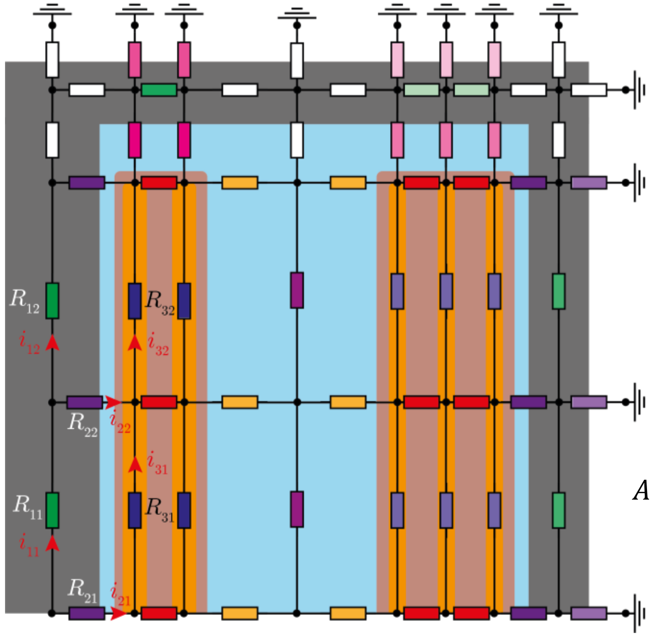
Thermal Validation ($T_{hotspot}$)
Discard Non-Feasible Transformer Designs

▶ ***Thermal Model*** *for estimating the temperatures in foil winding transformers for certain given conduction and core losses*

Transformer Design Considerations

Transformer Optimization – *Foil Winding Transformer*

- To assess the **thermal viability** of the **foil winding transformer designs**, it is essential to develop a simple **thermal model**
- The **conduction** and the **core losses** are **distributed** among a discrete number of **nodes**



Setup Grid of Heat Sources
Conduction/Core Losses

$$P = \begin{pmatrix} P_{14} & \cdots & P_{m4} \\ \vdots & \ddots & \vdots \\ P_{11} & \cdots & P_{m1} \end{pmatrix}$$

Setup Grid of Thermal Resistances
Considering Geometries and Thermal Properties of Materials

$$R_{\mathrm{th}} = \begin{pmatrix} R_{\mathrm{th},14} & \cdots & R_{\mathrm{th},m4} \\ \vdots & \ddots & \vdots \\ R_{\mathrm{th},11} & \cdots & R_{\mathrm{th},m1} \end{pmatrix} \rightarrow G_{\mathrm{th}} = \frac{1}{R_{\mathrm{th}}}$$

Calculate Admittance Matrix
Based on the Previous Two Grids

$$A \cdot x = b$$
$$x = [T_{11} \;\; T_{12} \;\; T_{13} \;\; T_{14} \;\; T_{\mathrm{amb}} \;\; T_{21} \cdots T_{\mathrm{amb}}]$$
$$b = [P_{11} \;\; P_{12} \;\; P_{13} \;\; P_{14} \;\; T_{\mathrm{amb}} \;\; P_{21} \cdots T_{\mathrm{amb}}]$$

Solve Linear Problem
With Fixed Boundary Temperatures

$$A = \begin{bmatrix} G_{\mathrm{th},11}+G_{\mathrm{th},21} & -G_{\mathrm{th},11} & 0 & 0 & 0 & -G_{\mathrm{th},21} & 0 & \cdots & 0 \\ -G_{\mathrm{th},11} & G_{\mathrm{th},11}+G_{\mathrm{th},21}+G_{\mathrm{th},22} & -G_{\mathrm{th},12} & 0 & 0 & 0 & -G_{\mathrm{th},22} & \cdots & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

$$\dim(A) = 5 \cdot (N_{\mathrm{pri}} + N_{\mathrm{sec}} + 4) \times 5 \cdot (N_{\mathrm{pri}} + N_{\mathrm{sec}} + 4)$$

Resonant Frequency (f_{res})
Defines $L_\sigma \cdot C_{\mathrm{res}}$

Quality Factor ($Q_{\mathrm{res}} = L_\sigma / C_{\mathrm{res}}$)
Given by max. Capacitor Voltage

L_σ, C_{res}

Maximum Switching Frequency ($f_{\mathrm{sw,max}}$)
Given by min. Required ZVS Currents

$f_{\mathrm{sw,min}}$, $f_{\mathrm{sw,max}}$

Calculate Waveforms ($I_{\mathrm{rms,max}}$, Ψ_{max}, f_{sw})
Including Current Harmonics

Design Set of Possible Transformers
Core Cross-Sectional Area
Winding Area (b_{w}, h_{w})
Foil Thickness ($b_{\mathrm{cu,pri}}$, $b_{\mathrm{cu,sec}}$)
Number of Turns (N_{pri}, N_{sec})
Gap Width (d_{gap})
Core Material (N97, N49)

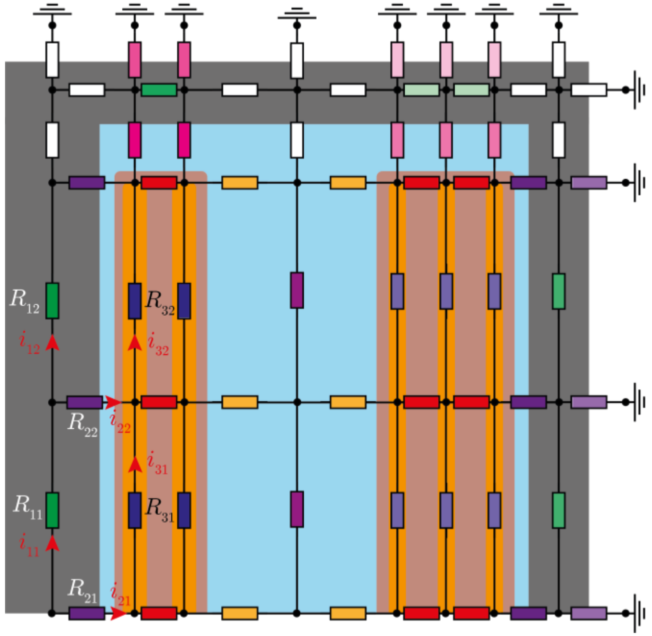
Thermal Validation (T_{hotspot})
Discard Non-Feasible Transformer Designs

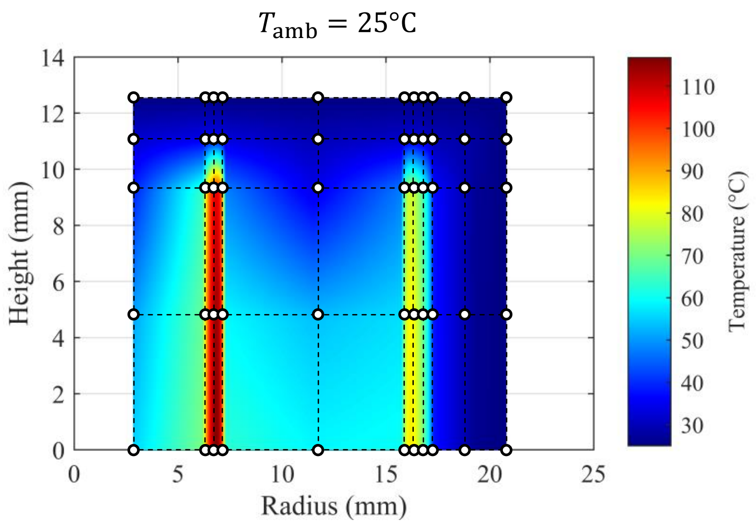
▶ ***Thermal Model*** *for estimating the temperatures in foil winding transformers for certain given conduction and core losses*

Transformer Design Considerations

▶ Transformer Optimization – *Foil Winding Transformer*

- The **temperature distribution** within the transformer are **calculated** within a couple of **milliseconds**
  - ⇨ *Ideal for a rough estimation of the hotspot temperature during a Pareto optimization*
  - ⇨ *Allows for identifying potential **thermal bottlenecks** (in this case Kapton tape between copper foils) → M3+ Kapton*





Resonant Frequency (f_{res})
Defines $L_\sigma \cdot C_{res}$

▼

Quality Factor ($Q_{res} = L_\sigma / C_{res}$)
Given by max. Capacitor Voltage

▼

L_σ, C_{res}

▼

Maximum Switching Frequency ($f_{sw,max}$)
Given by min. Required ZVS Currents

▼

$f_{sw,min}$, $f_{sw,max}$

▼

Calculate Waveforms ($I_{rms,max}$, Ψ_{max}, f_{sw})
Including Current Harmonics

▼

Design Set of Possible Transformers
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Number of Turns (N_{pri}, N_{sec})
Gap Width (d_{gap})
Core Material (N97, N49)

▼

Thermal Validation ($T_{hotspot}$)
Discard Non-Feasible Transformer Designs

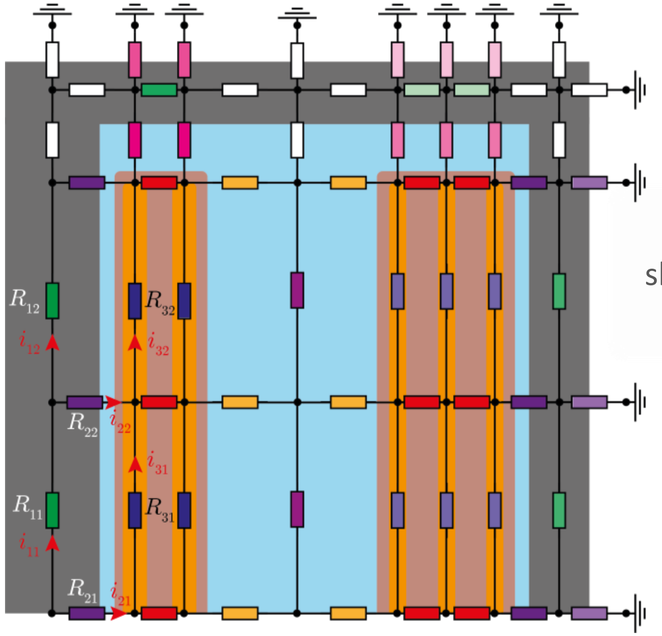
▶ ***Thermal Model*** *for estimating the temperatures in foil winding transformers for certain given conduction and core losses*

Transformer Design Considerations

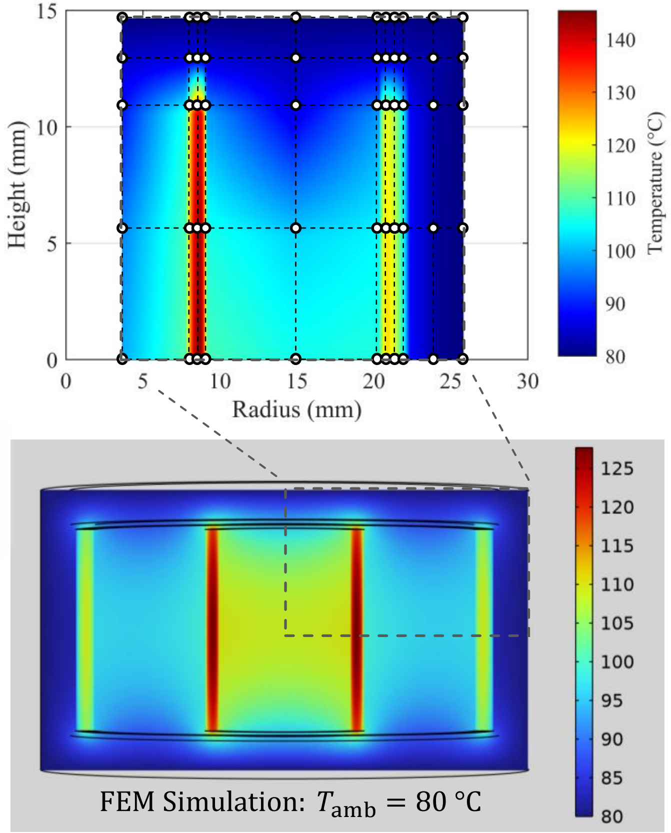
▶ Transformer Optimization – *Foil Winding Transformer*

- The **accumulation** and **distribution** of the **losses** across a discrete number of **nodes**, inherently leads to an **overestimation** of the maximum temperature

  ⇨ *Could easily be improved by using **more nodes***



Simple thermal model slightly **overestimates** the **hotspot temperature**



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Discard Non-Feasible Transformer Designs

▶ ***Thermal Model*** *for estimating the temperatures in foil winding transformers for certain given conduction and core losses*

Transformer Design Considerations

▶ Transformer Optimization – *Foil Winding Transformer*

- **Foil winding transformers** allow for integrating **large leakage inductances** relatively **efficient** while keeping **small** overall component volumes

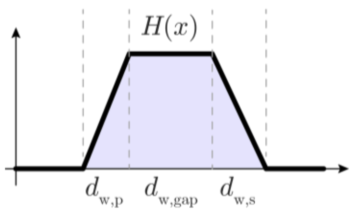
- **Transformer Losses:**

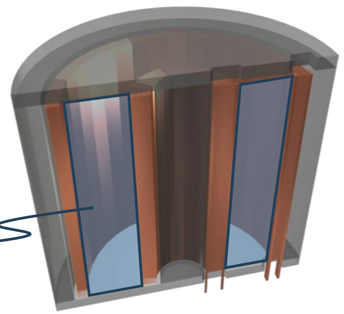
  ⇨ V_{out} = 200 V: P_W = 34.8 W P_C = 3.6 W

  ⇨ V_{out} = 470 V: P_W = 37.8 W P_C = 11.6 W

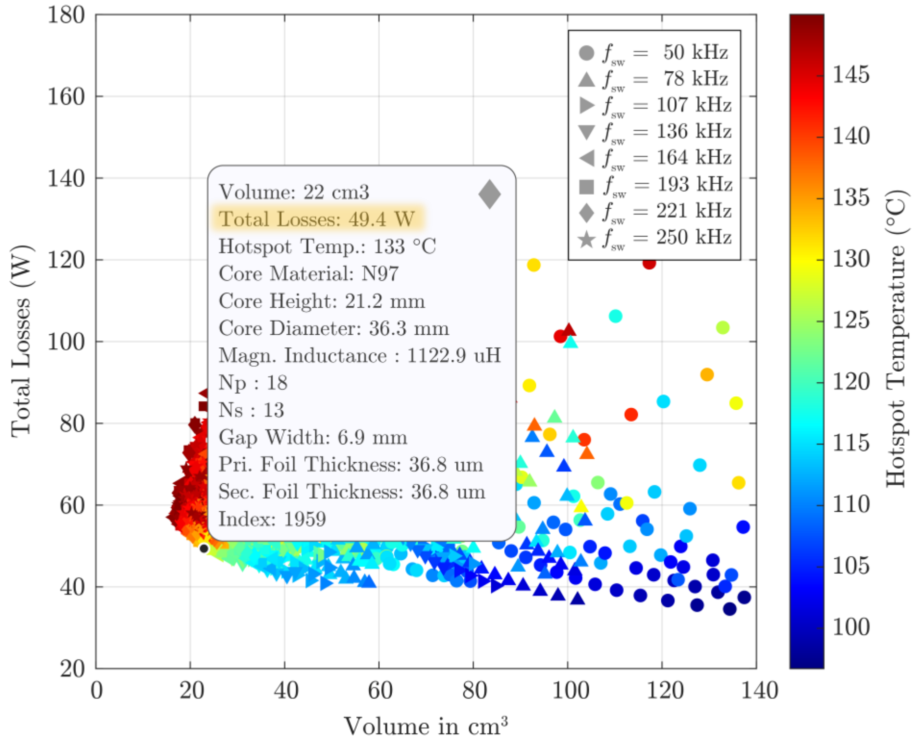
- Either **shorter windings** or **lower magnetic fields** within the winding volume are required to lower the conduction losses

  ⇨ *Increased **relative permeability** required*





TIM with a relative permeability μ_r > 1 desired



▶ ***Optimization Results** of the foil winding transformer with M3+ Kapton tape, where thermally unfeasible designs are discarded*

Resonant Frequency (f_{res})
Defines $L_\sigma \cdot C_{res}$

▼

Quality Factor ($Q_{res} = L_\sigma / C_{res}$)
Given by max. Capacitor Voltage

▼

L_σ, C_{res}

▼

Maximum Switching Frequency ($f_{sw,max}$)
Given by min. Required ZVS Currents

▼

$f_{sw,min}$, $f_{sw,max}$

▼

Calculate Waveforms ($I_{rms,max}$, Ψ_{max}, f_{sw})
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Design Set of Possible Transformers
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Number of Turns (N_{pri}, N_{sec})
Gap Width (d_{gap})
Core Material (N97, N49)

▼

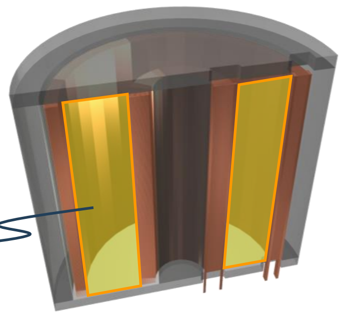
Thermal Validation ($T_{hotspot}$)
Discard Non-Feasible Transformer Designs

Transformer Design Considerations

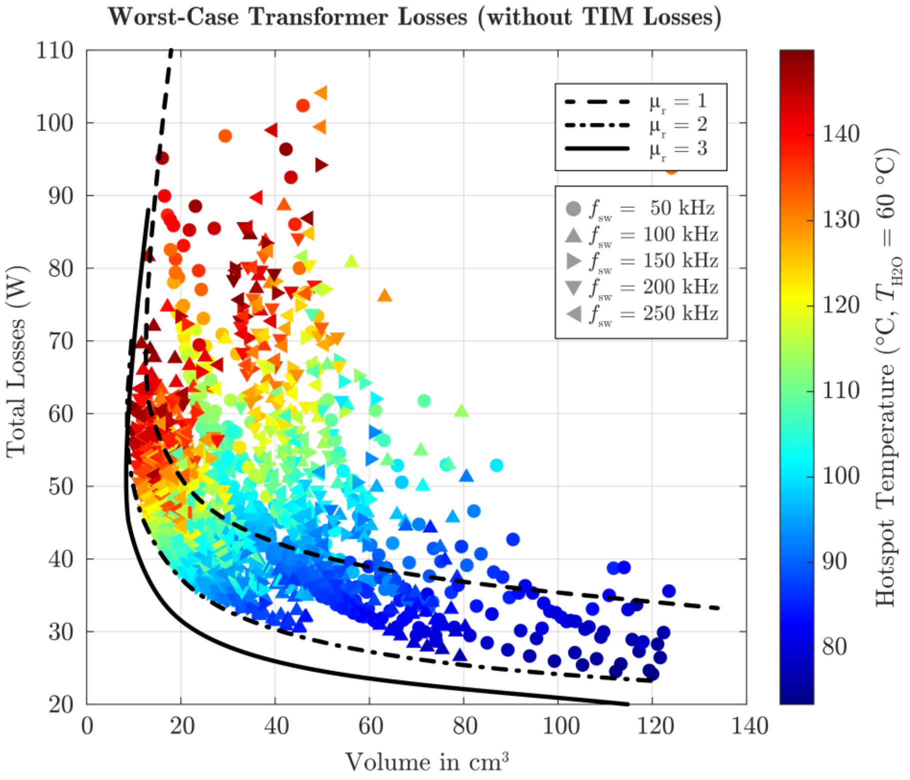
▶ Transformer Optimization – *Foil Winding Transformer*

- The **permeability** of the **thermal interface material** (TIM) between the primary and secondary side winding has a **significant impact** on the **power density** and particularly the **efficiency** of the **transformer**

- A **thermally conductive material** with a **permeability larger** than **1** is desired, which features the following properties
  - ⇨ **Minimal** additional **core losses** under high frequency (**> 100kHz**) low flux density (**30mT – 50mT**) operation
  - ⇨ Cost effective manufacturability
  - ⇨ Suitable **mechanical properties** for potting (low viscosity due to small gaps)



TIM with a relative permeability $\mu_r > 1$ desired



▶ ***Optimization Results** of the foil winding transformer with M3+ Kapton tape, where thermally unfeasible designs are discarded*

Resonant Frequency (f_{res})
Defines $L_\sigma \cdot C_{res}$

▼

Quality Factor ($Q_{res} = L_\sigma / C_{res}$)
Given by max. Capacitor Voltage

▼

L_σ, C_{res}

▼

Maximum Switching Frequency ($f_{sw,max}$)
Given by min. Required ZVS Currents

▼

$f_{sw,min}$, $f_{sw,max}$

▼

Calculate Waveforms ($I_{rms,max}$, Ψ_{max}, f_{sw})
Including Current Harmonics

▼

Design Set of Possible Transformers
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Number of Turns (N_{pri}, N_{sec})
Gap Width (d_{gap})
Core Material (N97, N49)

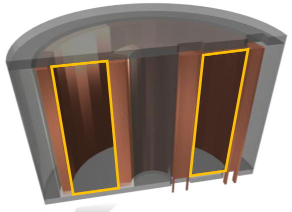
▼

Thermal Validation ($T_{hotspot}$)
Discard Non-Feasible Transformer Designs

Low Permeability Thermal Interface Material

- **Low Permeability Material Compound**
  - *Thermal Conductivity*
  - *Relative Permeability*
  - *Additional Losses*
- **Transformer Optimization**

Low Permeability Thermal Interface Material

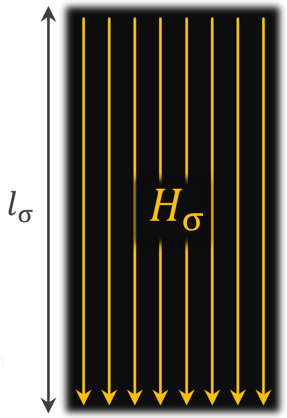


▶ Low Permeability Material Compound – *Mixing Material Properties*

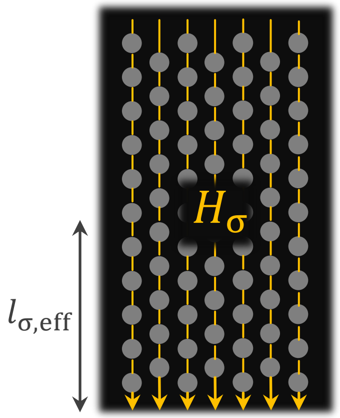
- There are different possibilities on how to **increase** the **relative permeability** of **thermally conductive epoxy resin** (potting material), as e.g. adding conventional **iron or ferrite powder** to the resin

  ⇨ The iron/ferrite particles **shorten** the **path lengths** in air of the **magnetic field** within the TIM and therefore, increase the effective **relative permeability** of the material

  ⇨ **Iron** has a comparably **high saturation flux density**, which might be beneficial regarding losses due to **saturation effects**

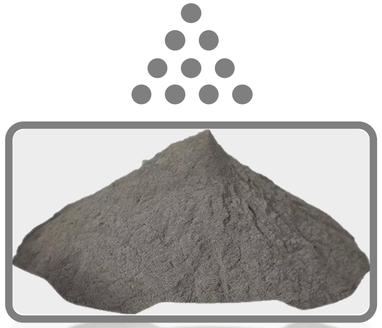


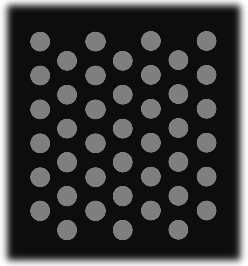
▶ *TIM only*



▶ *TIM + Fe*

[redacted]





⇨ *Thermal Conductivity?*

⇨ *Relative Permeability?*

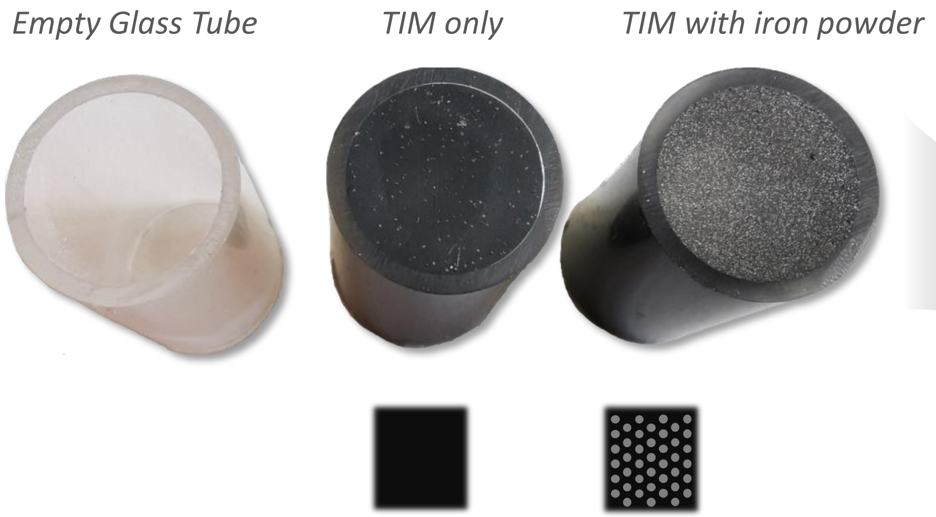
⇨ *Flux-Dependent Losses?*

▶ ***Thermally Conductive Epoxy Resin*** *to be mixed with magnetically conductive powder (iron or ferrite particles)*

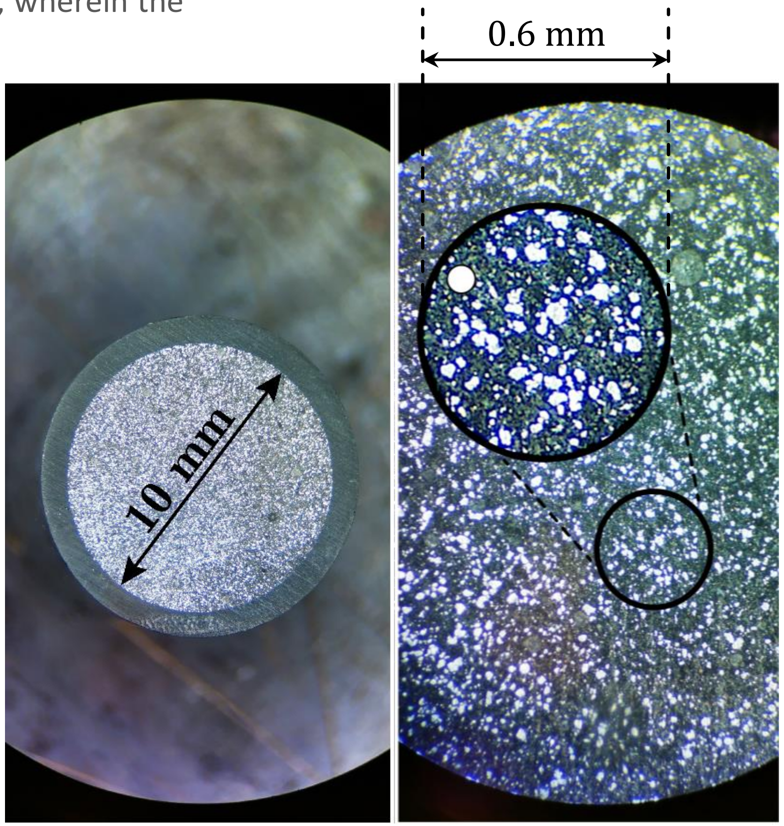
Low Permeability Thermal Interface Material

▶ Low Permeability Material Compound – *Thermal Conductivity*

- The **thermal conductivity** of the material can be determined through a **calorimetric measurement**, wherein the thermal resistance of material samples in **glass tubes** is measured



- Mutual **isolation** of **particles** is absolutely key for minimizing the occurring losses
  - ⇨ Intensive **mixing** prevents several particles from sticking together
  - ⇨ **Edgy iron particles** could potentially result in **additional losses** due to **saturation** phenomena

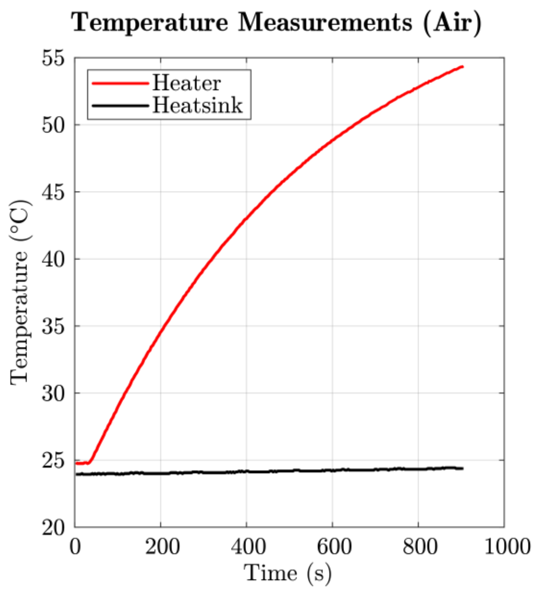


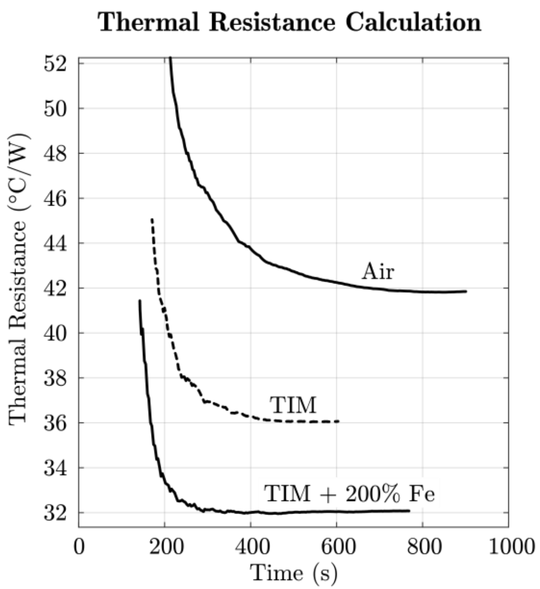
▶ ***Zoomed-in View*** *of the TIM with iron powder (70µm avg. particle size)*

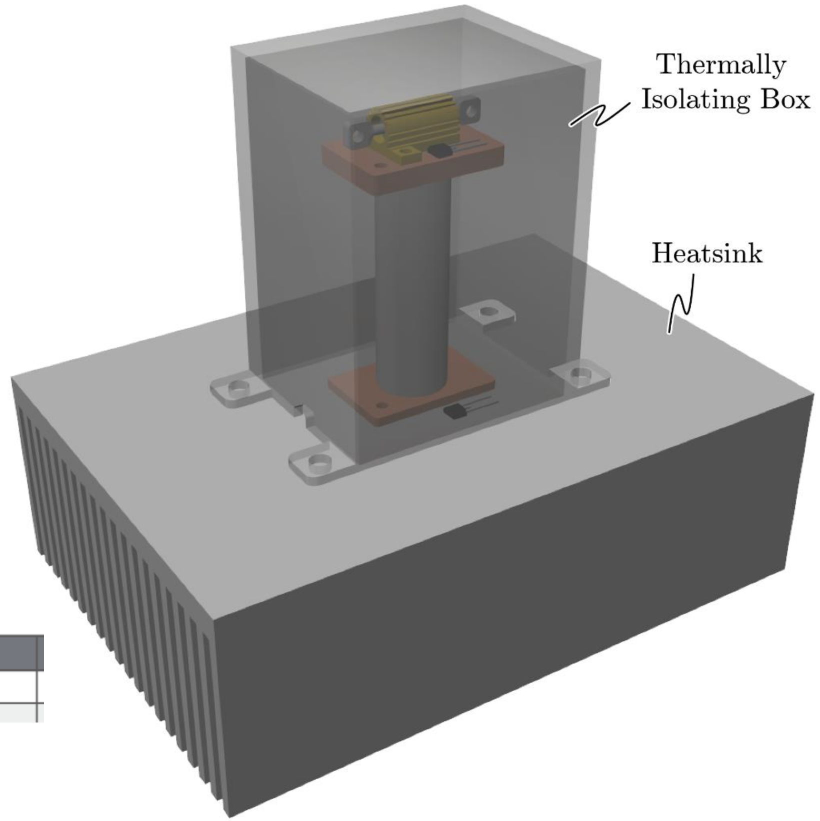
Low Permeability Thermal Interface Material

▶ Low Permeability Material Compound – *Thermal Conductivity*

- The **measurement setup** can be simplified by means of an **electrical equivalent circuit** comprising a thermal capacitance C_{th} of the heater setup and a thermal resistance R_{th} between the heater setup and the ambient temperature T_{amb}

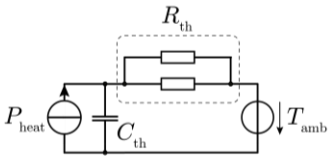


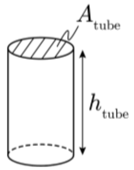




▶ ***Measurement results** of the different material samples by fitting the measured temperatures to a R_{th} / C_{th} fit-function*

ner	Mixed	Unit
	1.1	W/mK





$R_{th,tube,air} = 9705$ K/W
$R_{th,setup} = 42.1$ K/W

$R_{th,tube,TIM} = 248.5$ K/W
$R_{th,tube,TIM/Fe} = 133.4$ K/W

$\lambda_{TIM} = 1.03$ W/mK
$\lambda_{TIM/Fe} = 1.91$ W/mK

▶ ***Measurement Setup** for measuring the thermal conductivities of different potting materials*

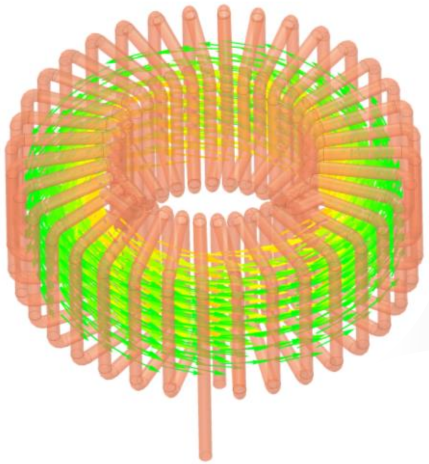
Low Permeability Thermal Interface Material

▶ Low Permeability Material Compound – *Relative Permeability*

- Measurements should ideally be performed on a DUT with a **similarly sized core volume** as in the final application
- **Relative permeability** indicates the **proportionality** between magnetic **field strength** and magnetic **flux density**, which is why a geometry is required, where the magnetic field strength is not affected by the relative permeability of the core material

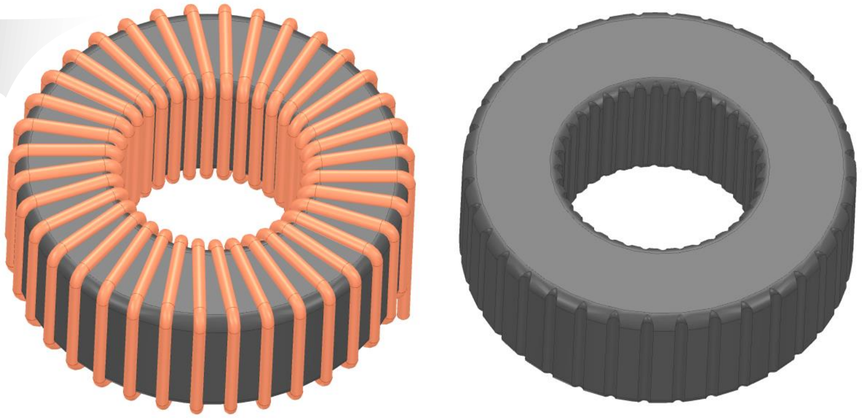
  ⇨ **Material along** the **whole path** of the **magnetic field** needs to be **replaced** with the new material

  ⇨ **Magnetic field** needs to be **confined** within a certain **volume**



$$L_{\mu_\mathrm{r}} = \frac{\mu_\mathrm{r}\mu_0}{I^2} \cdot \int_V H^2 \,\mathrm{d}V \rightarrow \frac{L_{\mu_\mathrm{r}}}{L_\mathrm{air}} \approx \mu_r$$

▶ ***FEM Simulation Result*** *of a toroidal inductor arrangement suitable for the measurement of the relative permeability and the core losses of a material*



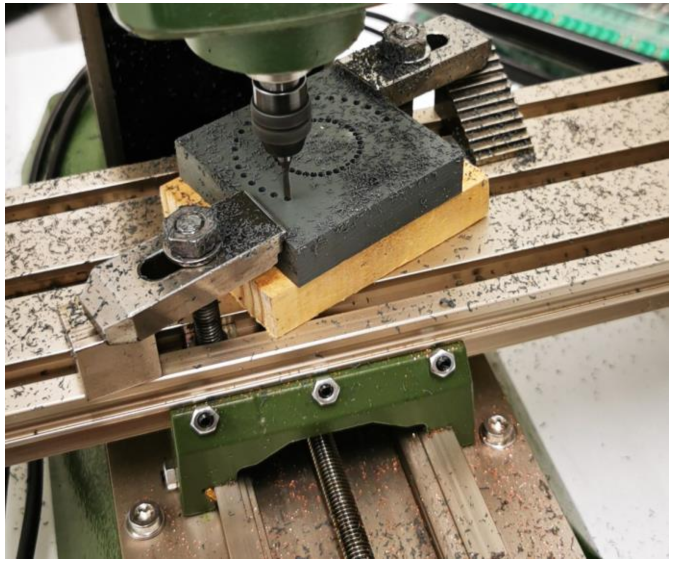
▶ ***Practical Implementation*** *of the inductors for testing the different material properties*

Low Permeability Thermal Interface Material

▶ **Low Permeability Material Compound** – *Relative Permeability*

- In order to compare the relative permeability of the materials, the inductor geometries must be absolutely identical, which means that the cores must be identical as well

  ⇨ **Silicone mold** for repeated use

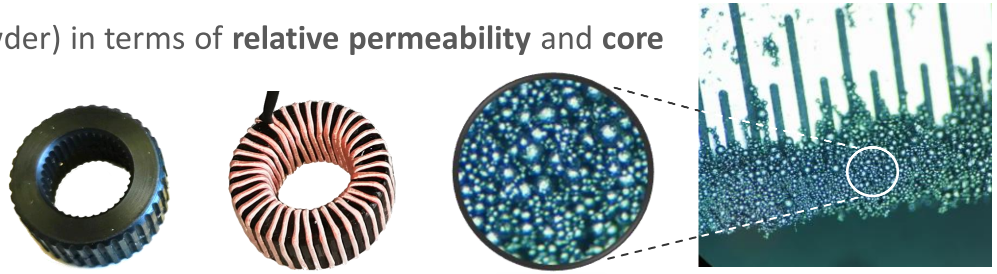


▶ ***Manufacturing Sequence*** *of the silicone molds used as the negative form of the final inductor cores*

Low Permeability Thermal Interface Material

▶ **Low Permeability Material Compound** – *Relative Permeability*

- In order to compare different **material additives** (iron powder, MZ97B ferrite powder) in terms of **relative permeability** and **core losses**, four identical inductors with different core materials have been built



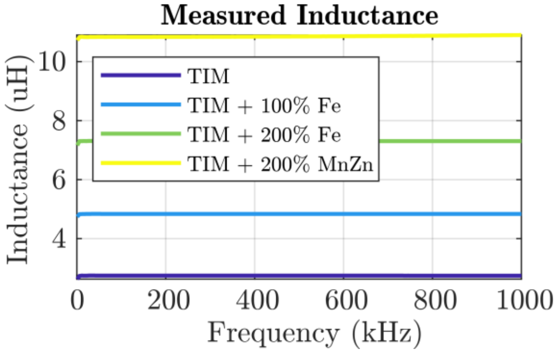
Air Coil Inductor	
Wire	70 µm Litz
N	36
Core Material	TIM[1]

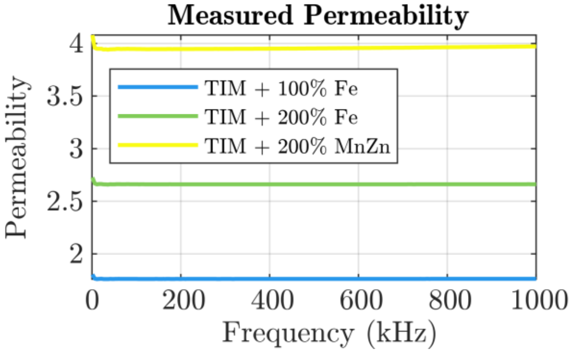
TIM + 100% Fe Inductor	
Wire	70 µm Litz
N	36
Core Material	TIM[1] + 100 % Fe[2]

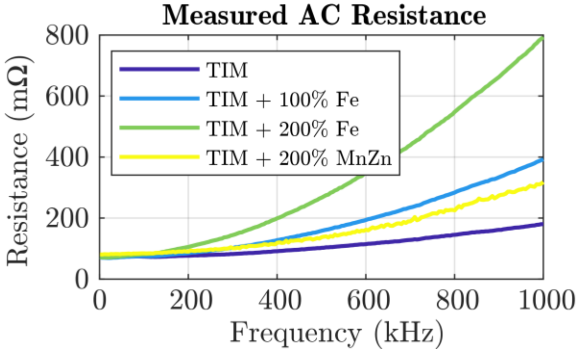
TIM + 200% Fe Inductor	
Wire	70 µm Litz
N	36
Core Material	TIM[1] + 200 % Fe[2]

TIM + 200% MnZn Inductor	
Wire	70 µm Litz
N	36
Core Material	TIM[1] + 200 % MnZn[3]

▶ ***DUTs** with different core materials / [1] TG-LH-FBPE-80 / [2] x % iron powder is added to the weight of the TIM / [3] x % ferrite powder is added to the weight of the TIM*







▶ ***Impedance Analyzer Measurement Results** of the different inductors/materials under test for frequencies up to 1MHz*

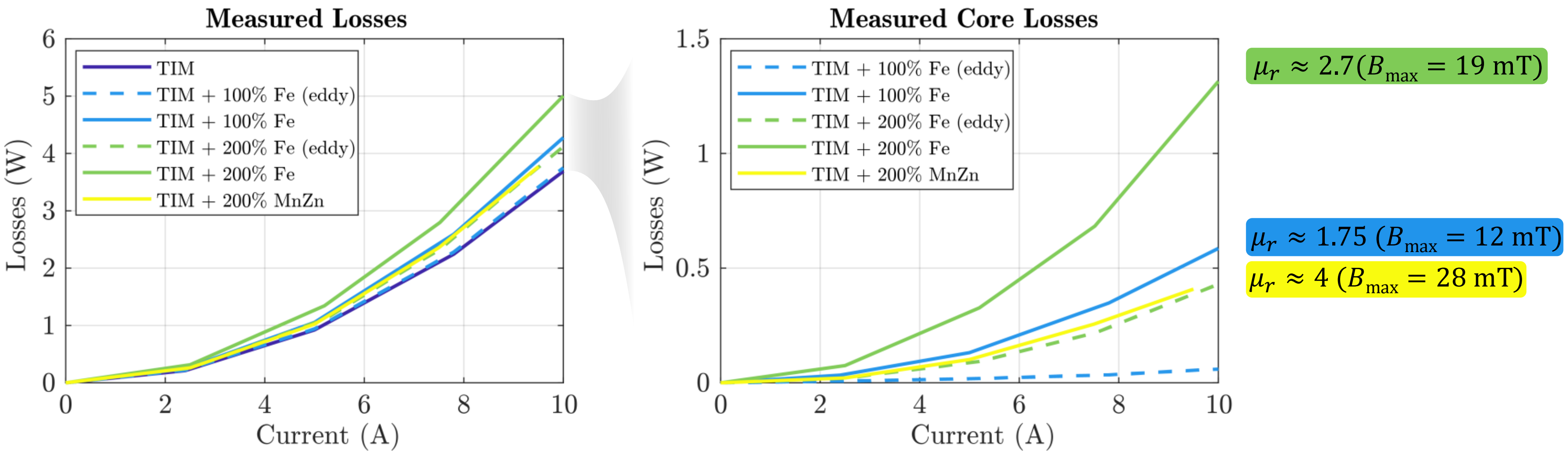
Low Permeability Thermal Interface Material

▶ **Low Permeability Material Compound** – *Additional Core Losses*

- In a **transformer** with "**TIM + 200% Fe**" material with a permeability of **2.7**, at **110 kHz**, **10 W** of **additional core losses** would arise (but the total worst-case transformer losses are still reduced by **7.7 W** and the transformer **volume** is at the same time **reduced** by **20%**)

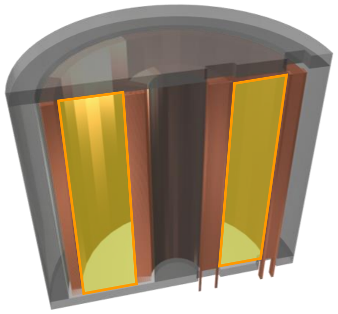
- Using MZ97B **ferrite powder** results in significantly **lower** additional **core losses** than for iron powder (below **3 W** under worst-case operating conditions)

  ⇨ **Optimal solution** for the target application



▶ ***Loss Comparison*** *of different core materials at 110 kHz for different inductor currents and flux densities – dashed lines = resistive losses (impedance analyzer) / solid lines = total losses (calorimetric measurement)*

Low Permeability Thermal Interface Material



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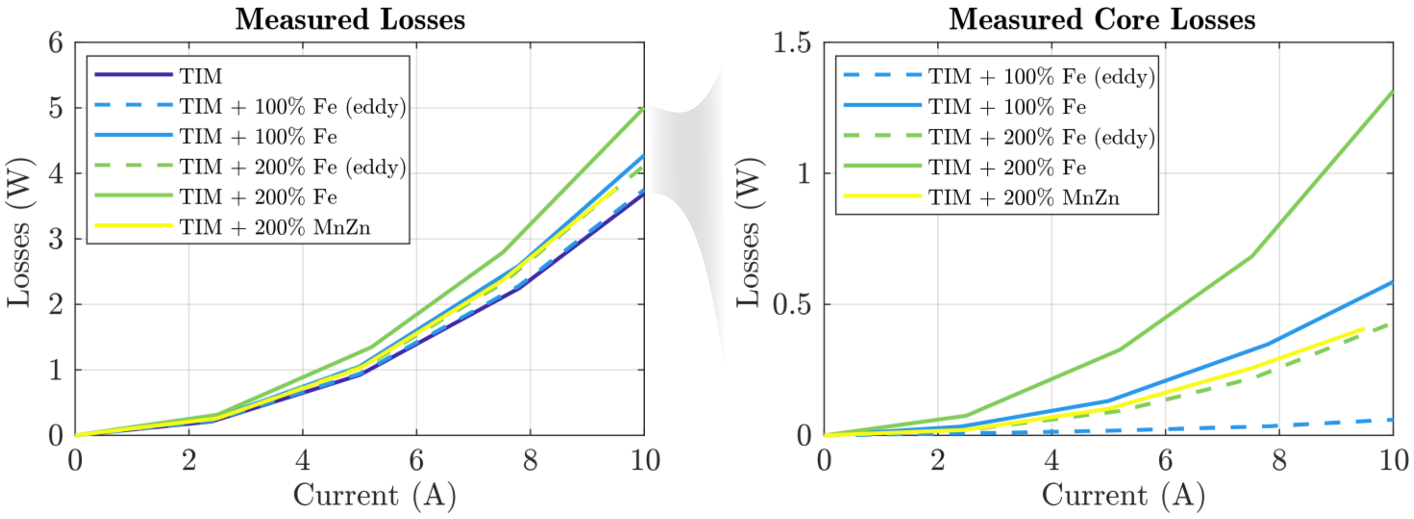
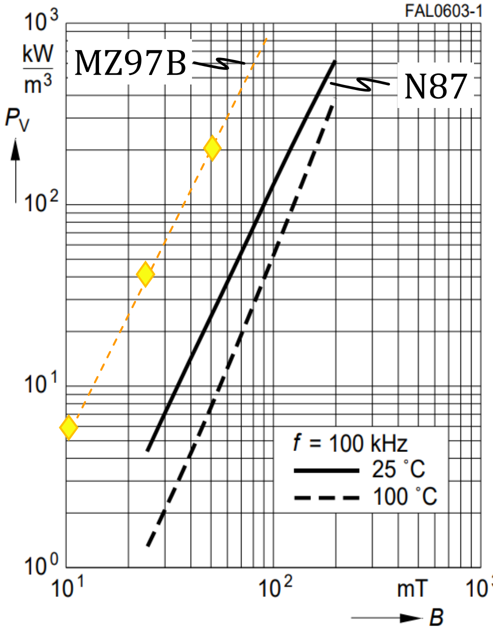
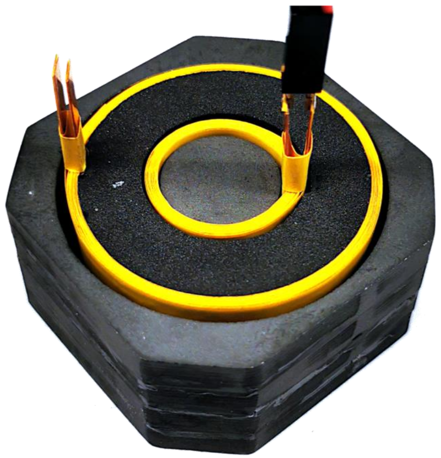




- ***Loss Comparison*** *of different core materials at 110 kHz for different inductor currents and flux densities – dashed lines = resistive losses (impedance analyzer) / solid lines = total losses (calorimetric measurement)*

Practical Implementation of the Transformer



- **Manufacturing the Transformer**
  - *Adaption of the Design due to Material Restrictions*
  - *Low Permeability Ring*
  - *Ferrite Core*
  - *Foil Winding*
  - *Foil Winding Termination*
  - *Leakage Inductance Integration Method*
- **Measurements**
  - *Impedance Analyzer Measurements*
  - *Thermal Validation*

Practical Implementation of the Transformer

- **Manufacturing the Transformer** – *Adaption of the Transformer Design*
  - Due to the **small quantities** to be ordered, not **all desired dimensions** of the base material are available

⇨ **Optimization parameters** need to be **restricted** accordingly

⇨ **MT+ Kapton** foil dimensions

- Foil Thickness	= 38 µm (no adhesive necessary)
- Foil Width (opt.)	= 10 mm + *n* · 1mm

⇨ **Ferrite** Plate Dimensions

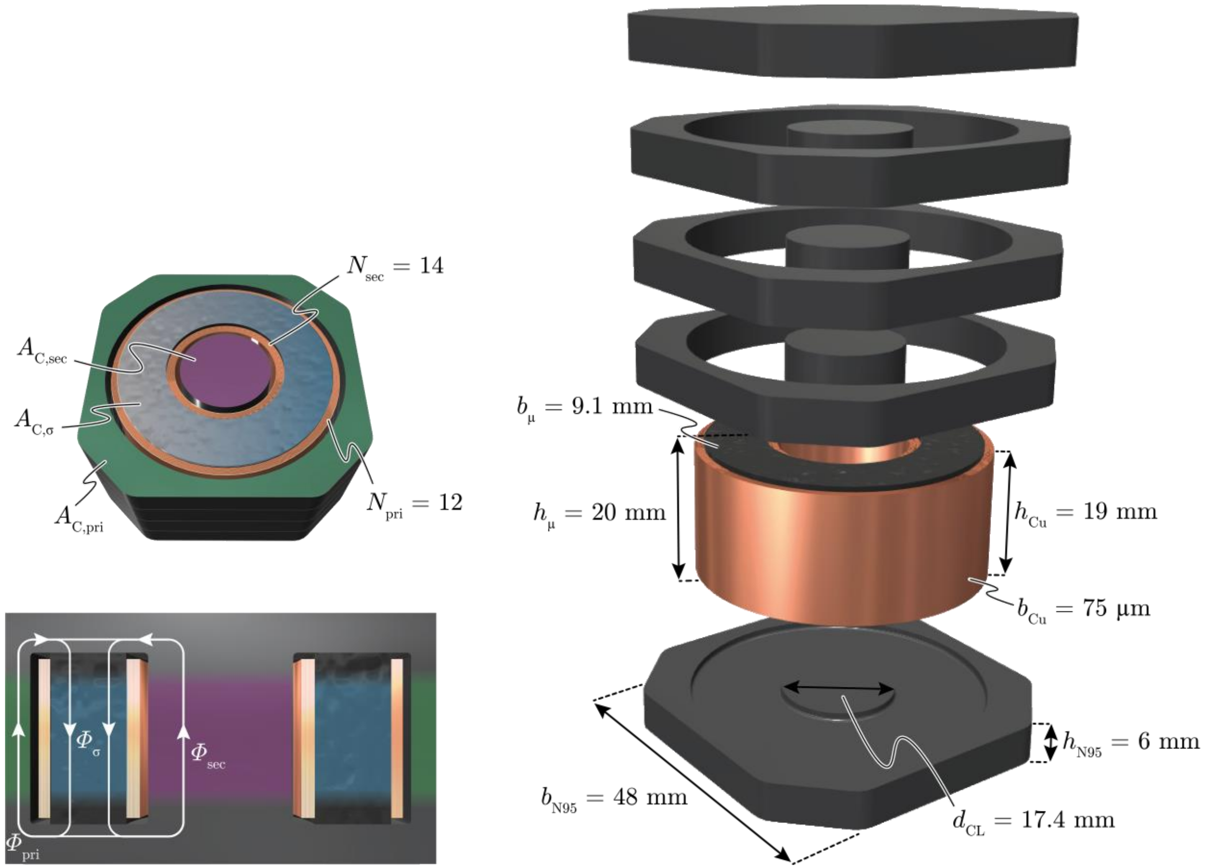
- Material	= N95
- Plate Width/Length	= 100 mm x 100 mm
- Plate Thickness	= 5 mm, 6 mm

⇨ **Copper** Foil Dimensions

- Foil Thickness	= 18 µm, 35 µm, 75 µm, 100 µm, …
- Foil Width (opt.)	= 10 mm, 15 mm, 20 mm, …

⇨ **Low Permeability Material** Ring Dimensions

- No dimensional restrictions



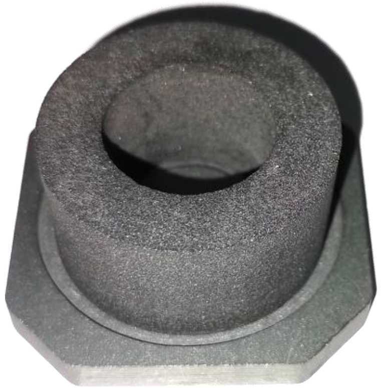
- ***Transformer Dimensions*** *and winding arrangement of the foil winding transformer*

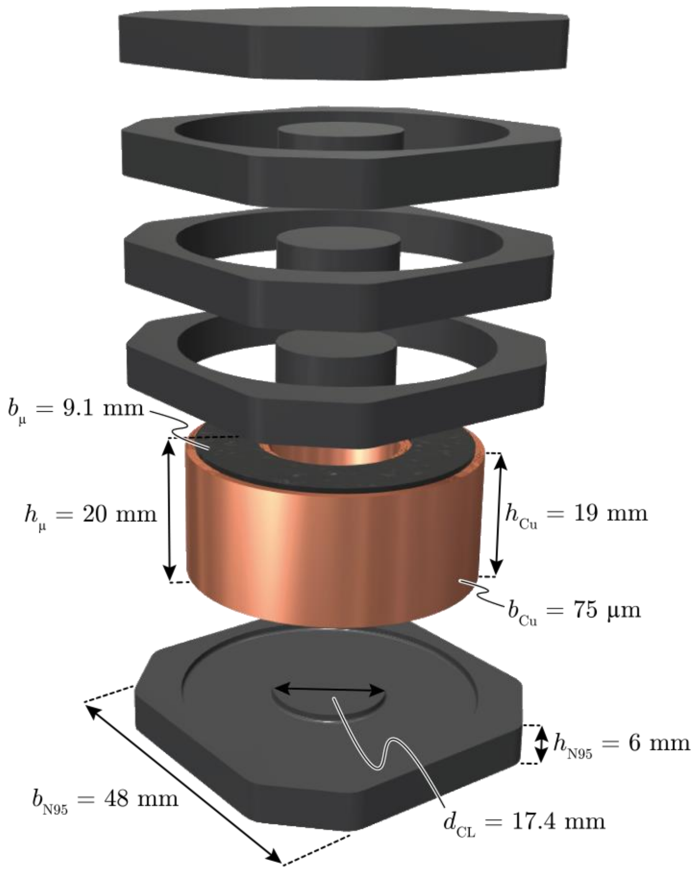
Practical Implementation of the Transformer

▶ **Manufacturing the Transformer** – *Low u_r - Ring*

- The manufacturing of the **ring** made from **low-permeability material**, which defines the **leakage inductance** of the transformer, is relatively simple, thanks to the series of **measurements** carried out on the **toroidal core samples**

  ⇨ Targeted max. **relative permeability** = 3





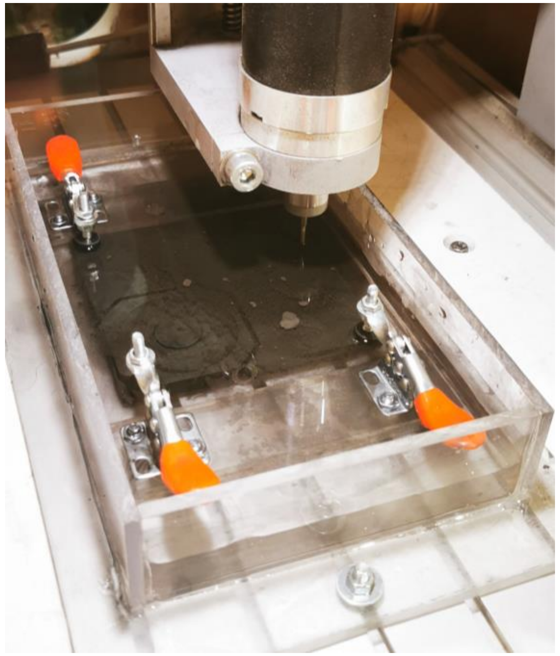
▶ ***Manufacturing** of the low permeability material ring, where the base material is mixed in a cup and cured in an oven, before the actual shape is milled*

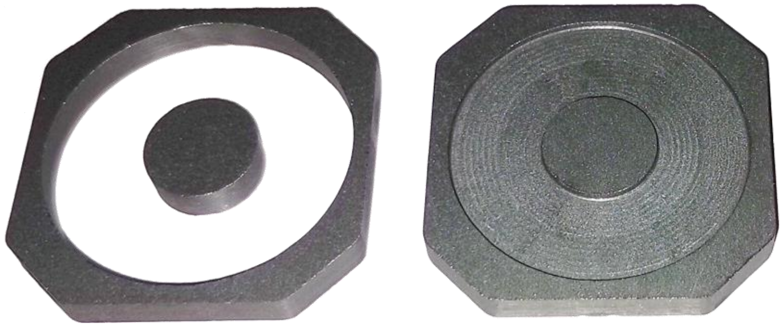
Practical Implementation of the Transformer

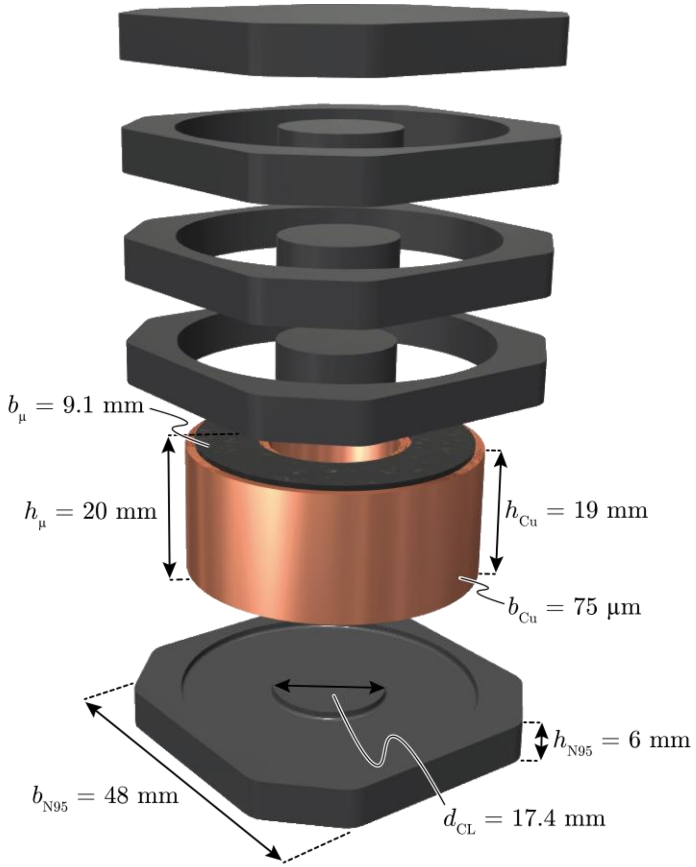
▶ Manufacturing the Transformer – *Ferrite Core*

- When designing and **manufacturing** the **ferrite core**, care must be taken to ensure that as little ferrite material (volume) as possible has to be removed during CNC milling (time consuming)

  ⇨ **Cutting** out **multiple pieces** is preferred







▶ ***Manufacturing*** *of the ferrite core parts by milling the eight individual core pieces out of N95 100 mm x 100 mm x 6 mm ferrite plates*

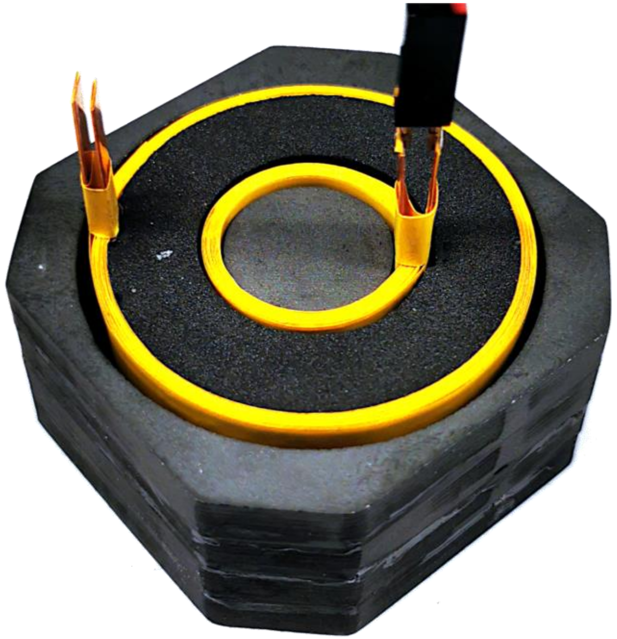
Practical Implementation of the Transformer

- **Manufacturing the Transformer** – *Foil Winding*
  - The **outer coil** is wound directly **onto** the low permeability **ring**, while the **inner coil** is first wound **onto** a **coil former** that is slightly larger in diameter than the center leg

    ⇨ Measured **Magnetizing Inductance** (secondary side): 660 µH

    ⇨ Measured **Leakage Inductance** (secondary side): 27.7 µH ($\mu_r \approx 2.6$)

*▶ **Winding Assembly** of the two foil windings with the low permeability ring in between*

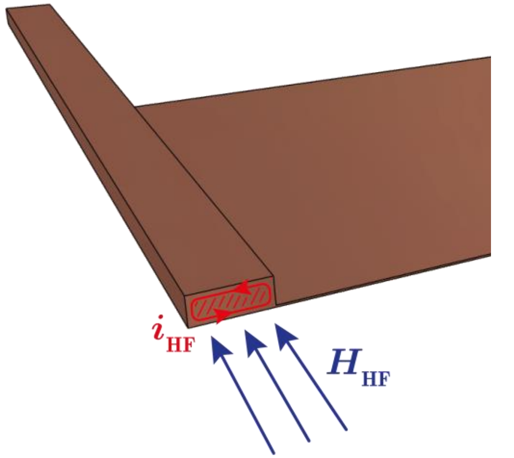


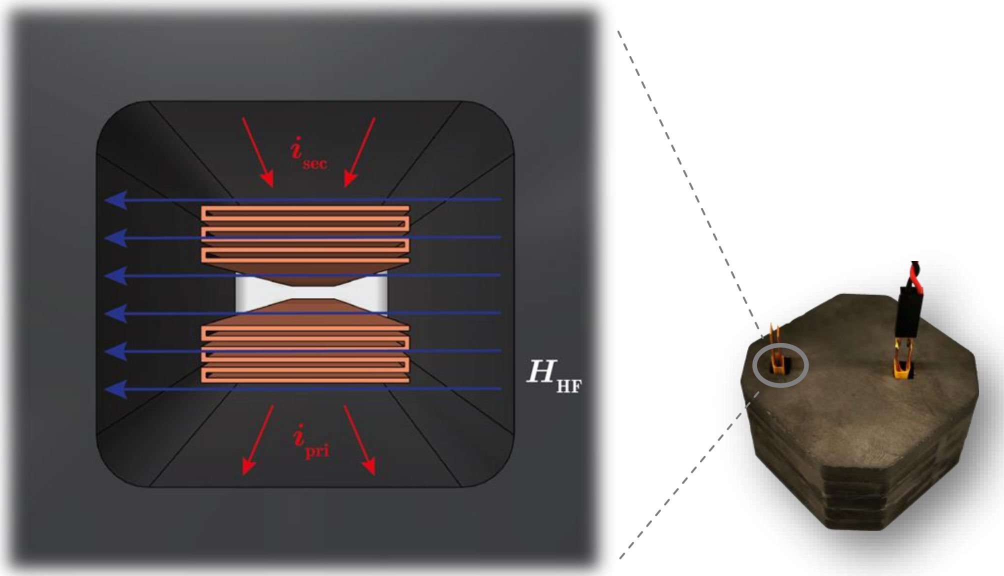
*▶ **Completely Assembled Transformer** without top plate and potting of the winding*

Practical Implementation of the Transformer

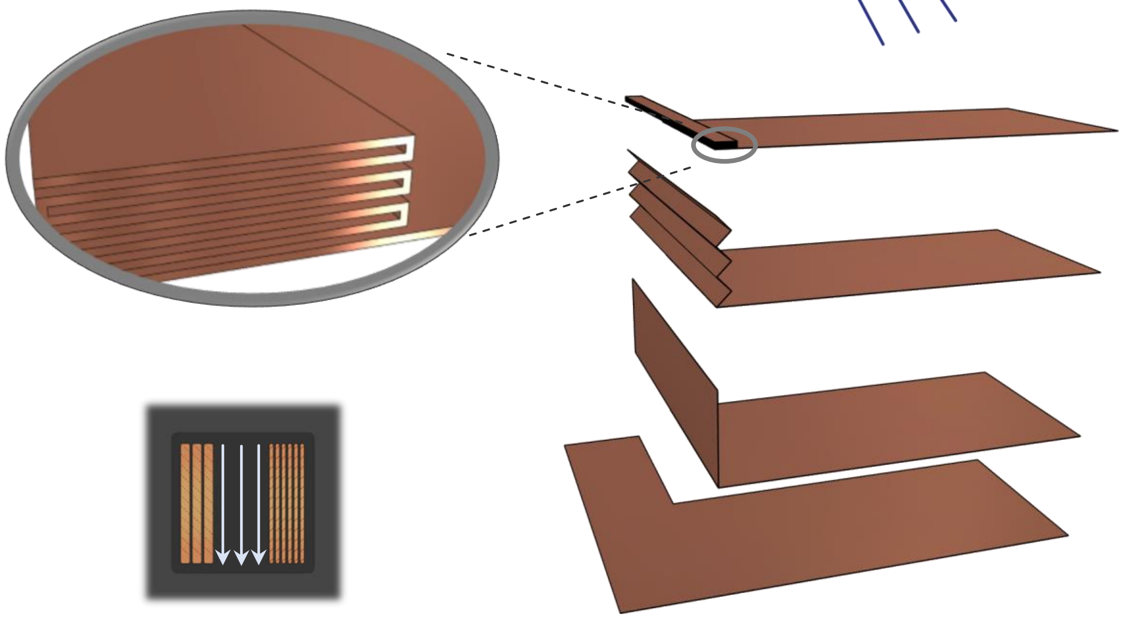
▶ **Manufacturing the Transformer** – *Foil Winding Termination*

- If the **foil winding** is wound **carefully**, the **HF conduction losses** occurring in the foil are relatively small
  - ⇨ Potential **HF conduction losses** in the **terminals** have a **significant impact** on the overall HF performance of the foil winding
  - ⇨ Theoretically, **folded terminals** have a **significantly lower** HF **resistance** than **solid terminals**
  - ⇨ In practice, the **differences** of the resistances are **much smaller**





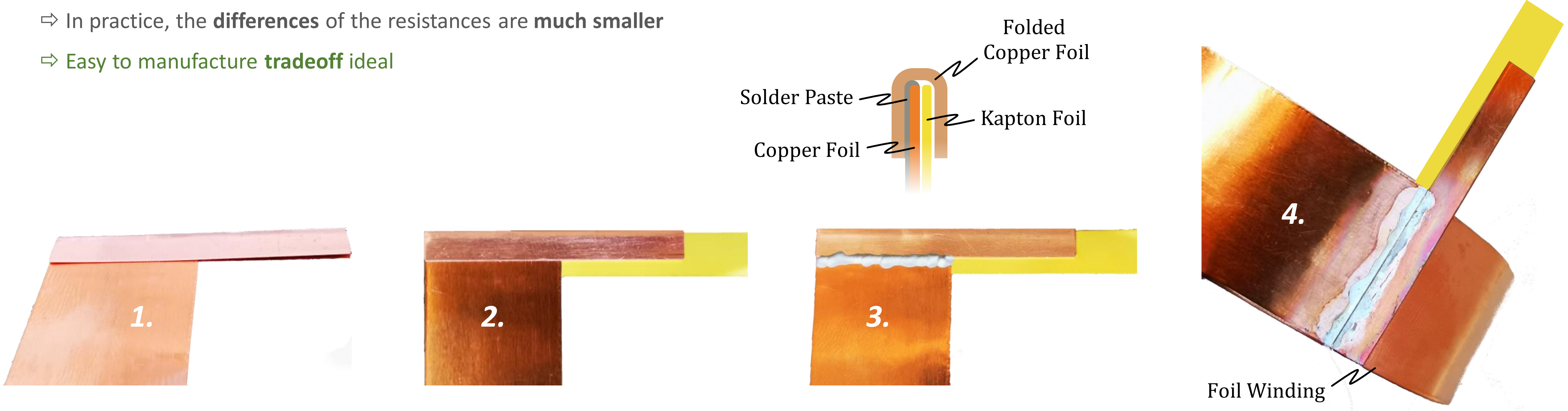
▶ ***Magnetic Field Distribution*** *in the cutouts in the transformer core for the winding terminals*



▶ ***Improved Foil Winding Termination*** *for reducing parasitic high-frequency effects within the winding window and the cutouts in the core for the terminals*

Practical Implementation of the Transformer

- **Manufacturing the Transformer** – *Foil Winding Termination*
  - If the **foil winding** is wound **carefully**, the **HF conduction losses** occurring in the foil are relatively small
    - ⇨ Potential **HF conduction losses** in the **terminals** have a **significant impact** on the overall HF performance of the foil winding
    - ⇨ Theoretically, **folded terminals** have a **significantly lower** HF **resistance** than **solid terminals**
    - ⇨ In practice, the **differences** of the resistances are **much smaller**
    - ⇨ Easy to manufacture **tradeoff** ideal



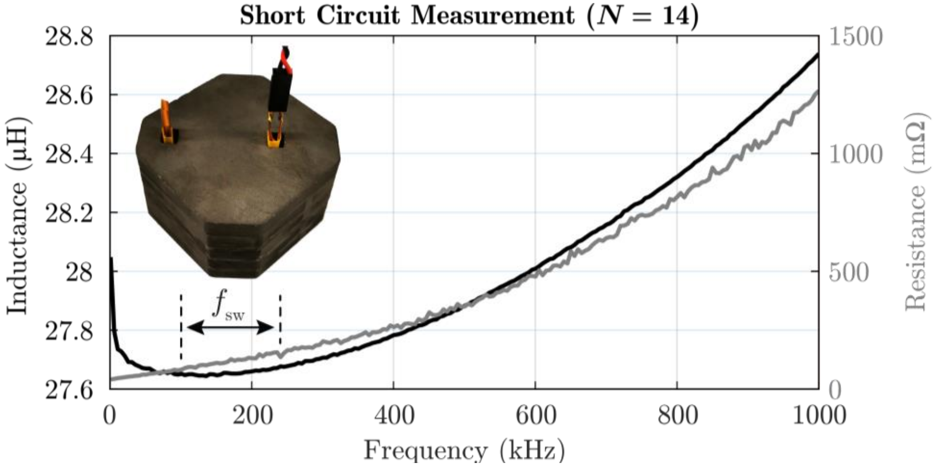
- ***Winding Terminal Manufacturing Sequence:*** *1. folding the copper foil around the end of the winding, 2. slide Kapton foil into folded copper foil, 3. add solder paste on the top side copper interface, 4. solder copper interface*

Practical Implementation of the Transformer

▶ **Measurements** – *Impedance Analyzer Measurement*

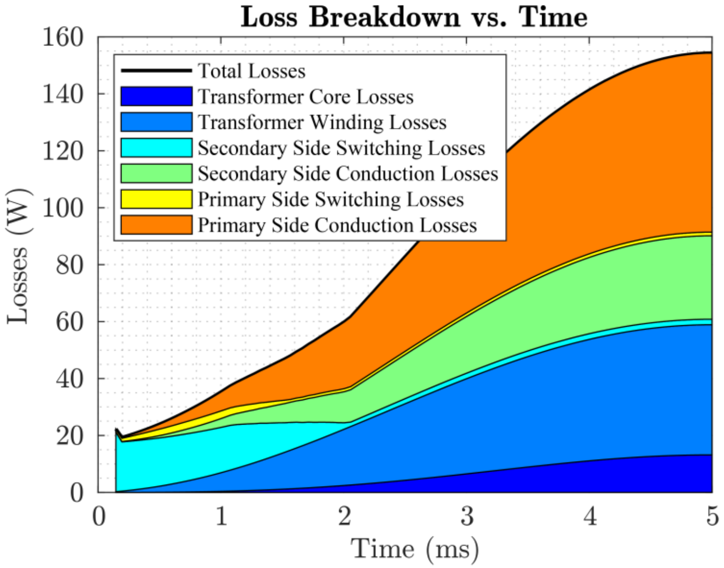
- The **short-circuit resistance** measured with the **impedance analyzer** allows for deriving both the **conduction losses** in the **windings** and the **core losses** in the **low-permeability ring**

⇨ The **measurements** align well with the **calculated values**, with the **additional losses** due to the **terminations** of the windings accounting for approximately **10 %**

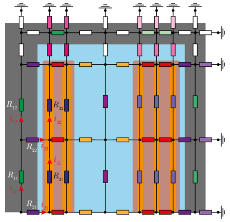


▶ ***Impedance Analyzer Measurements** of the transformer with a shorted secondary side winding*

Thermally feasible?



▶ ***Loss Breakdown** over a quarter mains period for an input voltage of **230V$_{rms}$**, output voltage of **470V** and output power of **3.7kW***



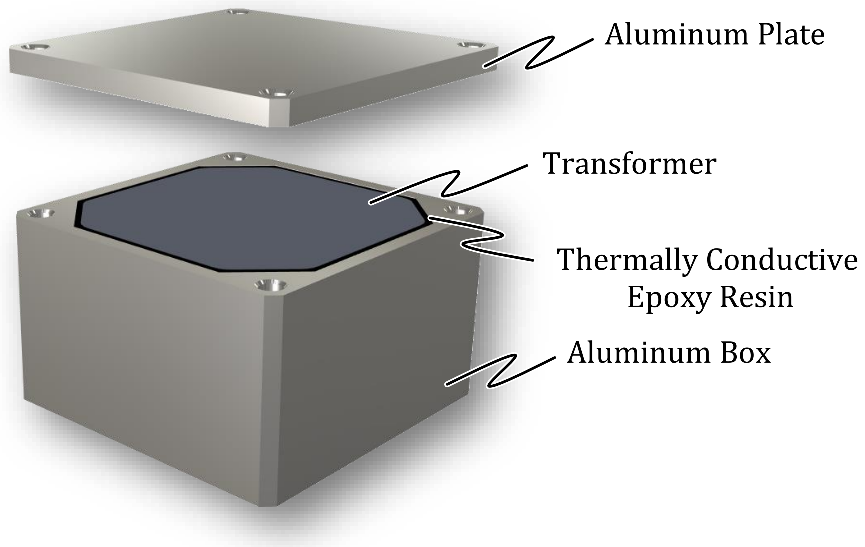
Practical Implementation of the Transformer

▶ **Measurements** – *Thermal Validation*

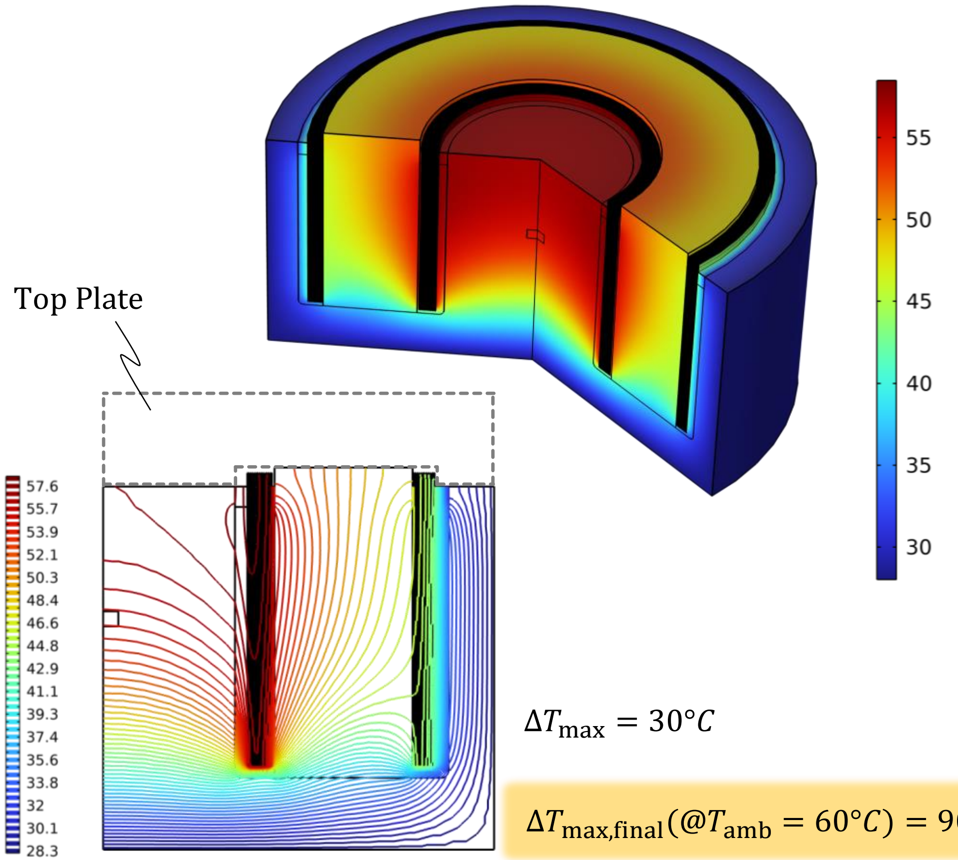
- The **thermal model** of the transformer assumes that the **entire surface** of the **transformer** is directly **connected** to the **heat sink**

⇨ **Complex** and **expensive** heat sink design

⇨ **Hot spot** temperature far **below material limits**



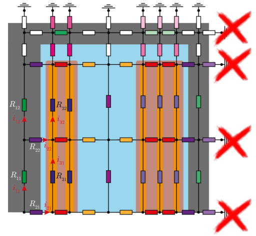
▶ ***Heat Sink Design*** *of achieving minimal hot spot temperatures*



$\Delta T_{\mathrm{max}} = 30°C$

$\Delta T_{\mathrm{max,final}}(@T_{\mathrm{amb}} = 60°C) = 90°C$

▶ ***Thermal Simulation*** *for 40 W conduction losses and a constant surface temperature of 28 °C on all outer surfaces of the transformer core*

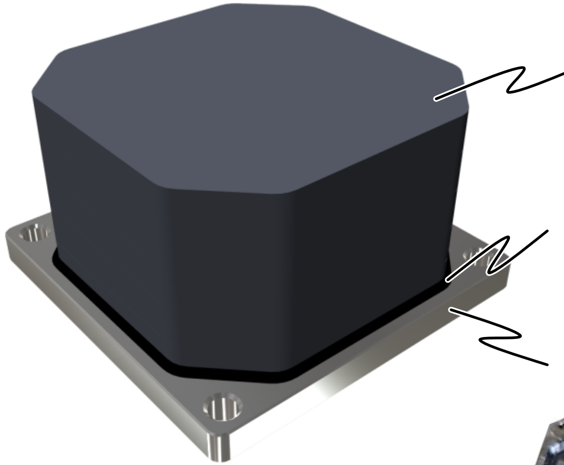


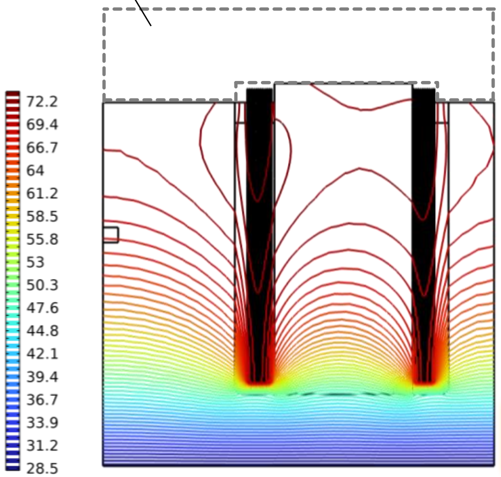
Practical Implementation of the Transformer

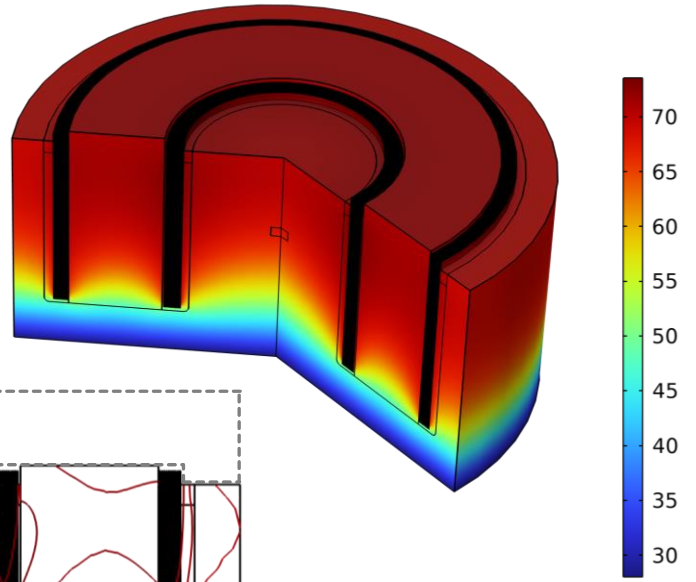
▶ **Measurements** – *Thermal Validation*

- The **thermal model** of the transformer assumes that the **entire surface** of the **transformer** is directly **connected** to the **heat sink**

⇨ Due to the model's **overestimation** of the **hotspot temperature**, it is sufficient to cool only **one side** of the transformer







$\Delta T_{\text{max}} = 44°C$

$\Delta T_{\text{max,final}}(@T_{\text{amb}} = 60°C) = 104°C$

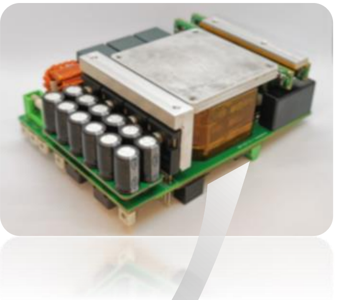
▶ ***Simplified Heat Sink Design*** *using an aluminum plate only*

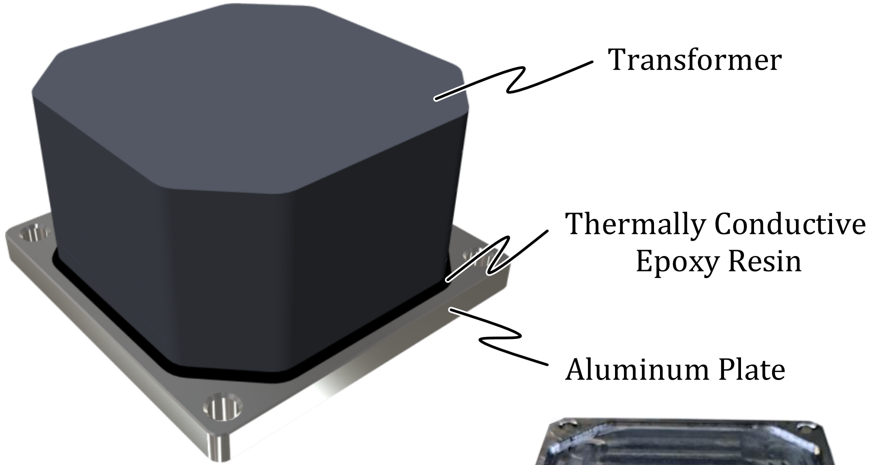
▶ ***Thermal Simulation*** *for 40 W conduction losses and a constant surface temperature of 28 °C on the bottom surface of the transformer core*

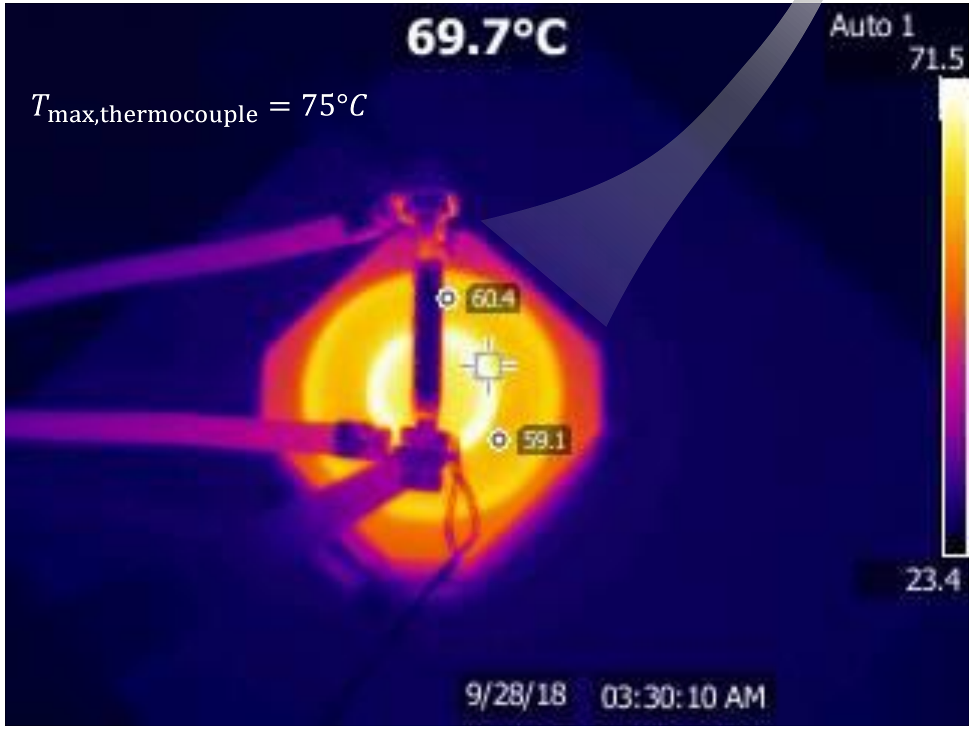
Practical Implementation of the Transformer

- **Measurements** – *Thermal Validation*
  - The **thermal model** of the transformer assumes that the **entire surface** of the **transformer** is directly **connected** to the **heat sink**

⇨ Due to the model's **overestimation** of the **hotspot temperature**, it is sufficient to cool only **one side** of the transformer

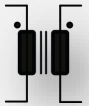




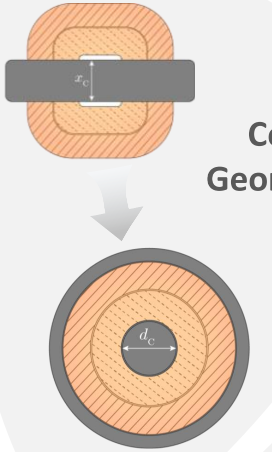


- ***Simplified Heat Sink Design*** *using an aluminum plate only*

- ***Measurement Results*** *for hot spot temperature measurements with 40 W impressed conduction losses and a heatsink temperature of 28 °C*

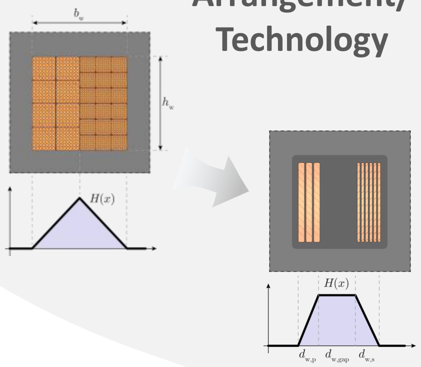


Specifications

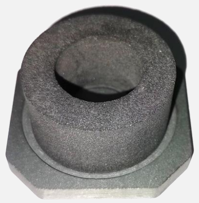


Core Geometry

Winding Arrangement/ Technology



Materials

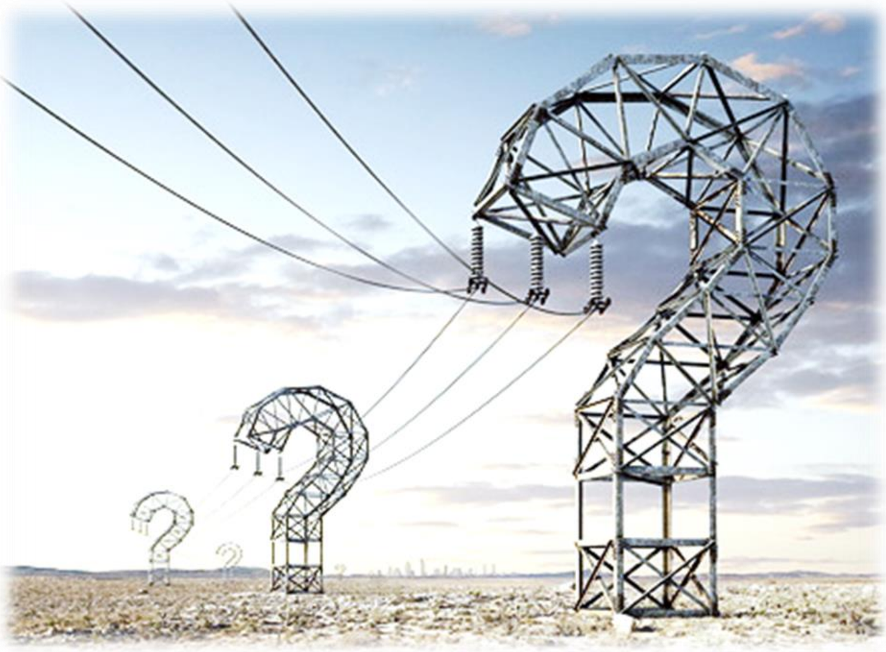


Transformer

Conclusions

Integration of Large Leakage Inductances in High-Frequency Transformers

- *The **complete winding** should be **enclosed** by the **ferrite core***
- ***Foil windings** generate a strong **trapezoidal magnetic field** distribution, **without** suffering from significant **HF conduction losses***
- *Using **low permeability material** in between the windings **increases** the **power density** and/or the **efficiency** of the transformer*
- *Mixing **thermally conductive epoxy resin** with **ferrite powder** results in a **low permeability material** with the **desired properties***



Acknowledgement

BOSCH