Introduction of the CFFC-Compensating Fringing Field Concept and its Application in PCB Winding Inductors

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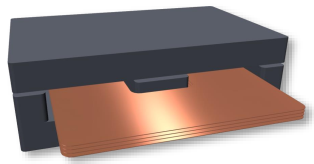
Brief Outline

- *Challenges in Conventional PCB Winding Inductor Designs*
- *Derivation of the CFFC*
- *Experimental Verification*
- *Thermally Improved Inductor Design*



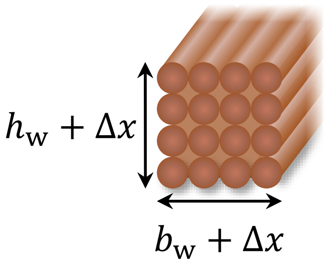
▶ Conventional PCB Winding Inductors

Challenges in the Design of PCB Winding Inductors

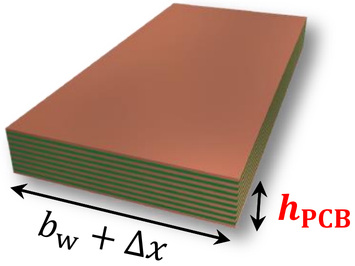
- **Limited available copper**

  Can only be increased by increasing the winding with b_w (2D $\longrightarrow$ poor power density)

▶ Wire Wound Winding



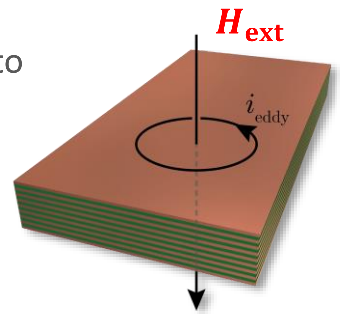
▶ PCB Winding



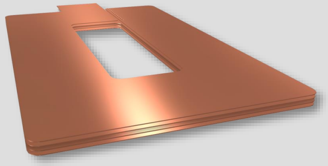
$\longrightarrow$ Efficient utilization of the available copper inevitable!

- **High frequency conduction losses**

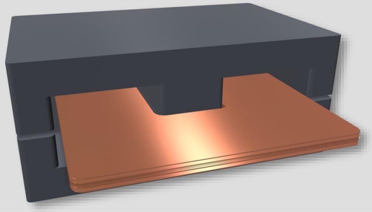
  $\longrightarrow$ Large copper planes are prone to eddy current induction



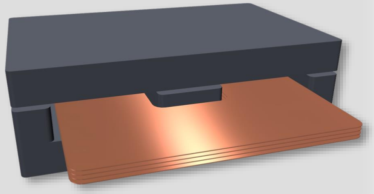
▶ Air Coil



▶ ELP Cores



▶ ELP+I Cores



▶ Conventional PCB Winding Inductors

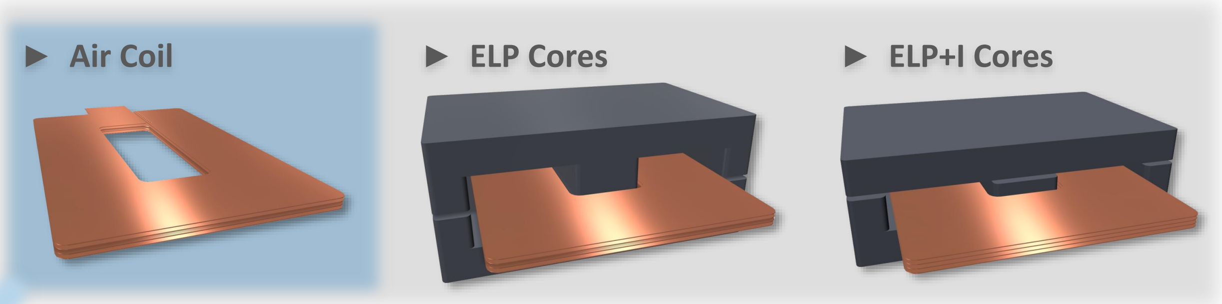
Air Coil – PCB Winding without Core

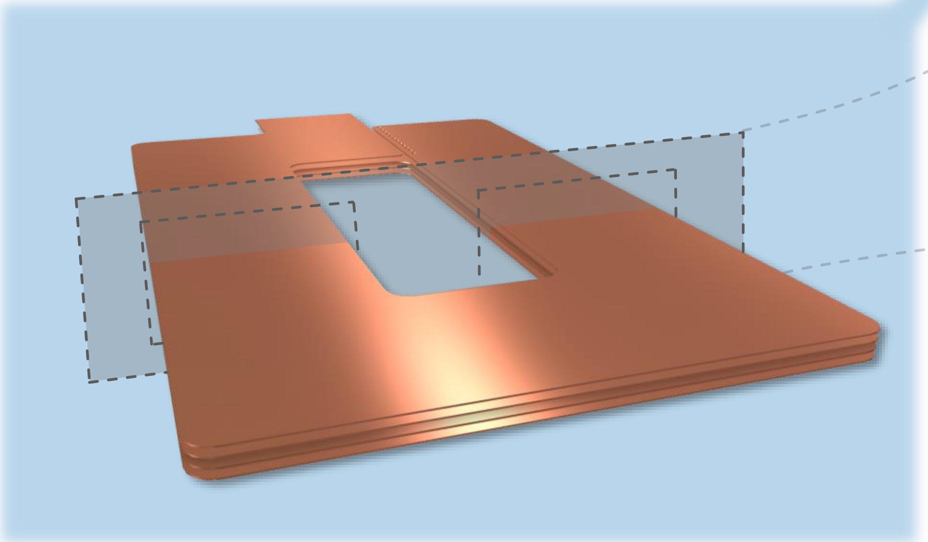
Assumption: One turn per layer

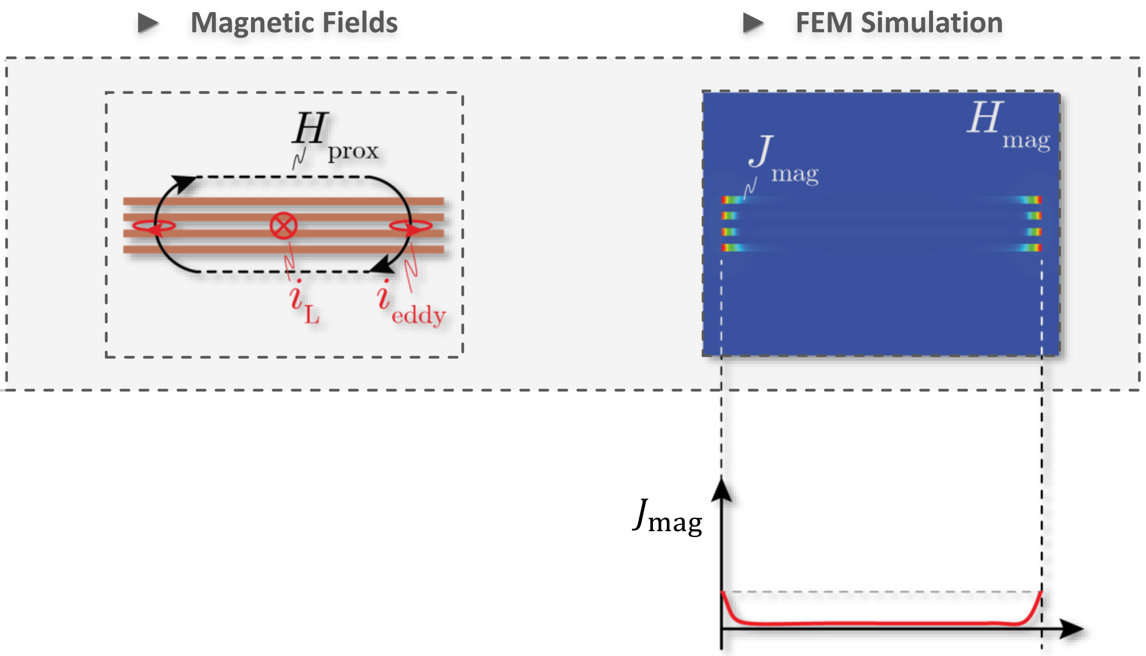
- **High frequency conduction losses**

→ Magnetic skin and proximity fields push the current towards the edges of the PCB winding

→ **AC** to **DC** resistance ratio of ≈ **2.1** @ 500kHz







▶ Conventional PCB Winding Inductors

Same PCB Winding with Two ELP Cores

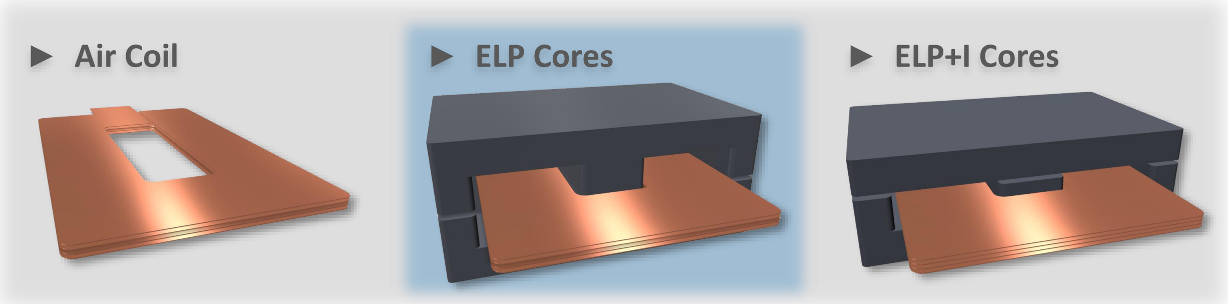
Assumption: One turn per layer

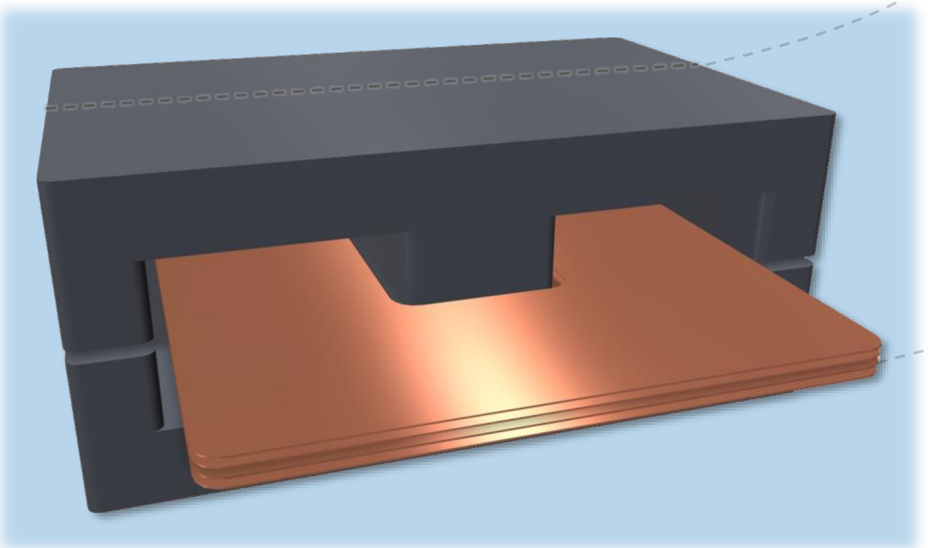
- **High frequency conduction losses**

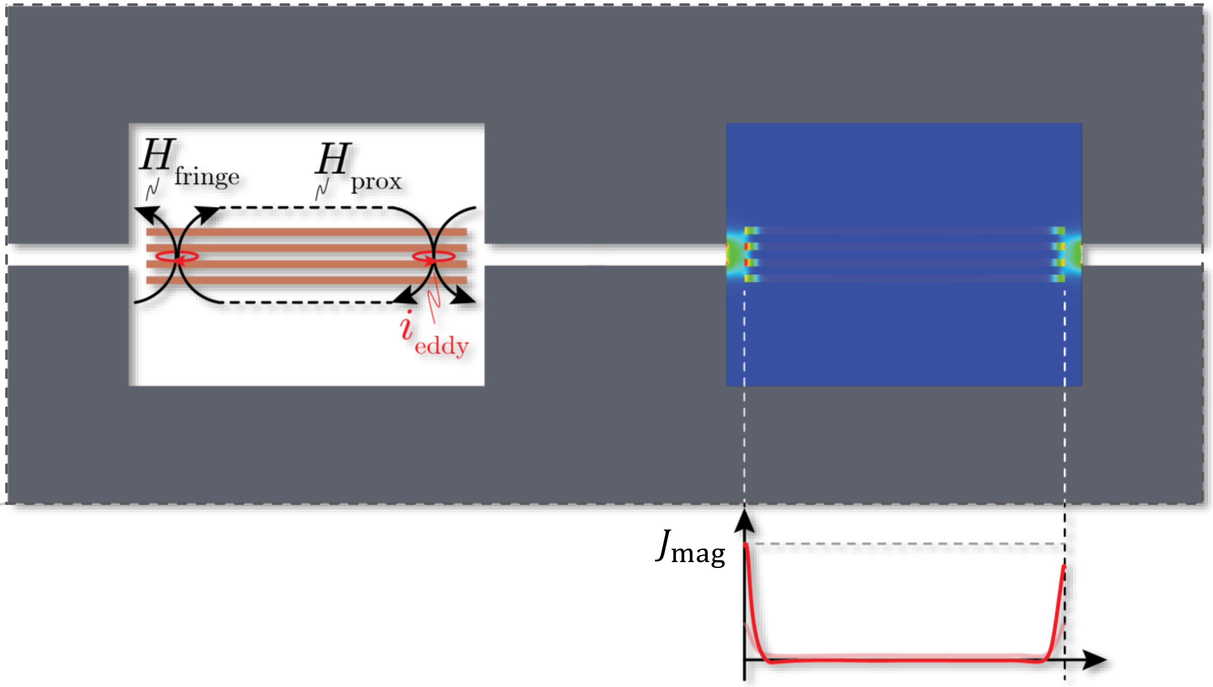
⟶ Magnetic skin and proximity fields push the current towards the edges of the PCB winding

⟶ Additionally, fringing field around the air gap exacerbates the current displacement

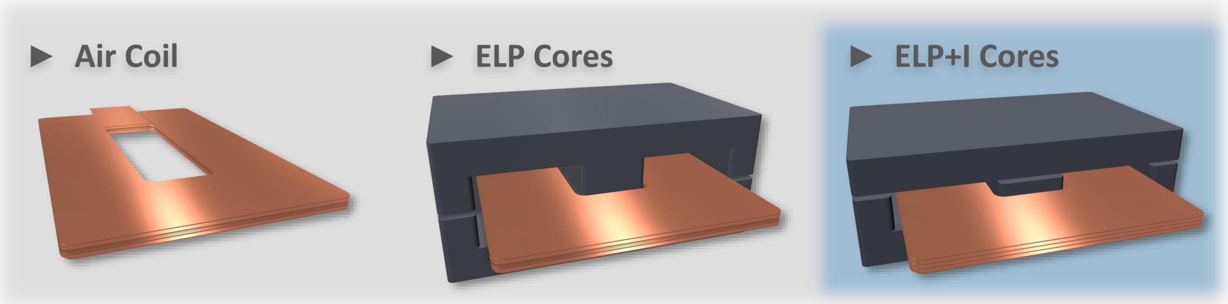
⟶ **AC** to **DC** resistance ratio of ≈ **8.2** @ 500kHz







▶ Conventional PCB Winding Inductors



Same PCB Winding with ELP+I Cores

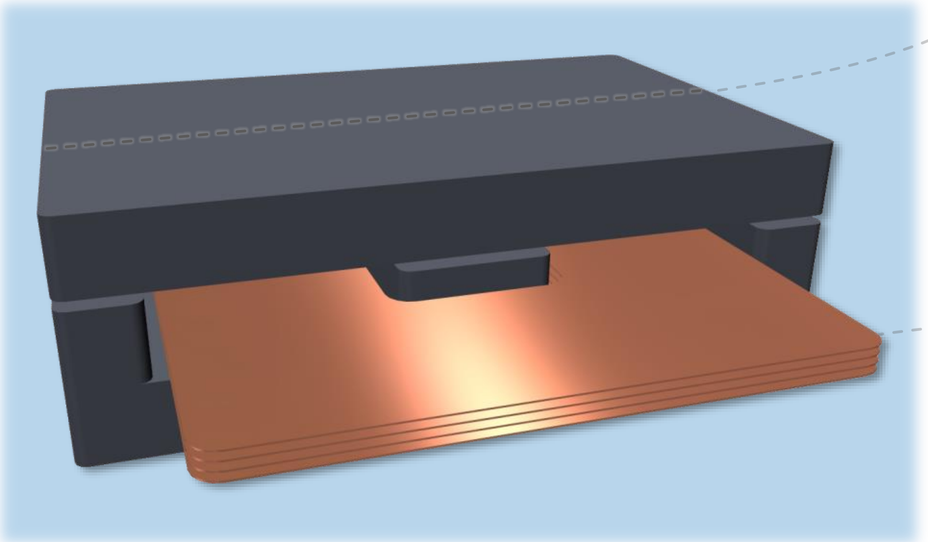
Assumption: One turn per layer

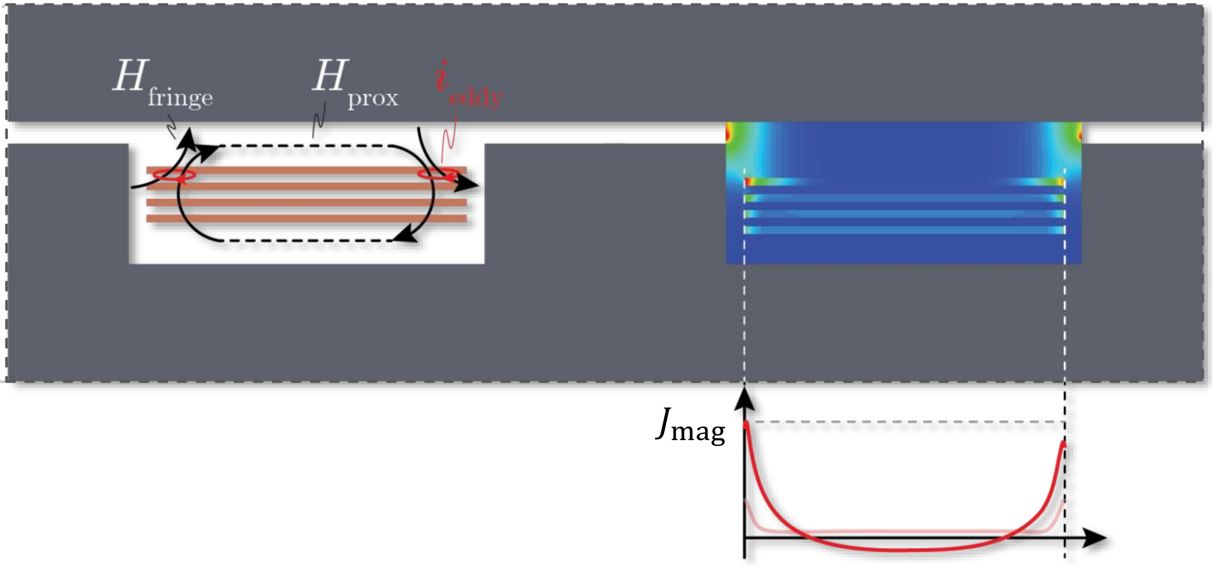
- **High frequency conduction losses**

⟶ Magnetic skin and proximity fields push the current towards the edges of the PCB winding

⟶ Fringing field around the air gap still exacerbates the current displacement

⟶ **AC** to **DC** resistance ratio of ≈ **5.1** @ 500kHz





▶ Conventional PCB Winding Inductors

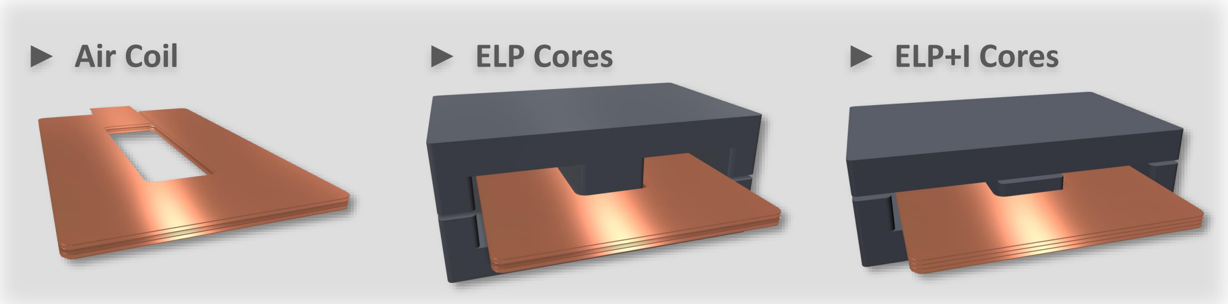
Special Challenges in the Design of PCB Winding Inductors

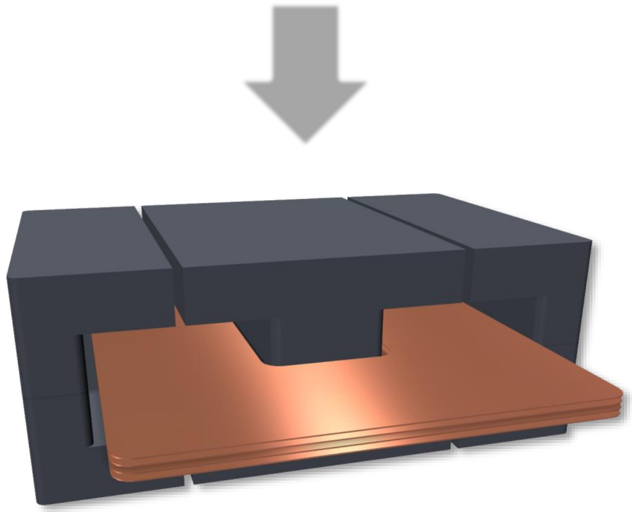
- **Conventional Inductor Designs**

  ⟶ Fringing field around the air gap is heading in the same direction as the skin and proximity fields

- **Possible Alternative ?**

  ⟶ Relocate the air gap, such that the fringing field counteracts the parasitic skin and proximity fields





▶ Customized Core with Perpendicular Air Gap

▶ Proposed PCB Winding Inductor Design

Same PCB Winding with a Customized Core

Assumption: One turn per layer

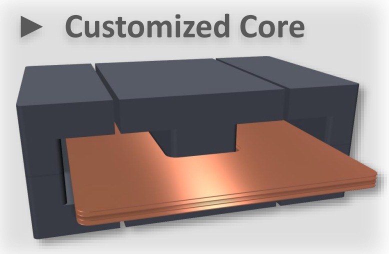
- **High frequency conduction losses**

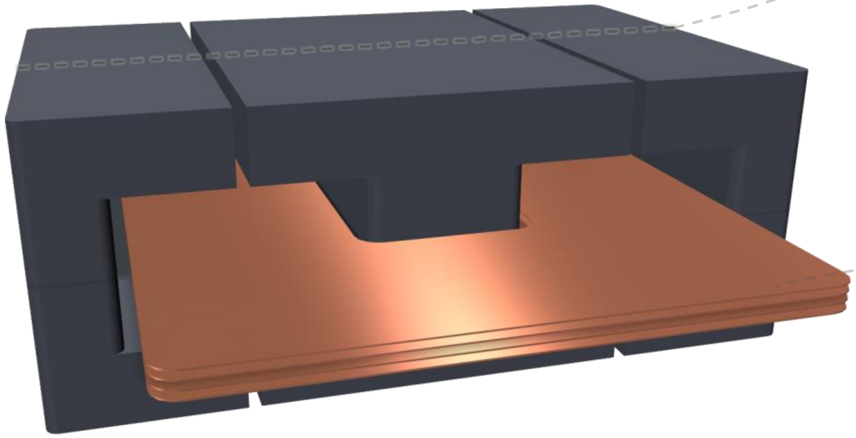
→ Magnetic skin/proximity fields and the fringing fields around the air gaps are heading in opposite direction

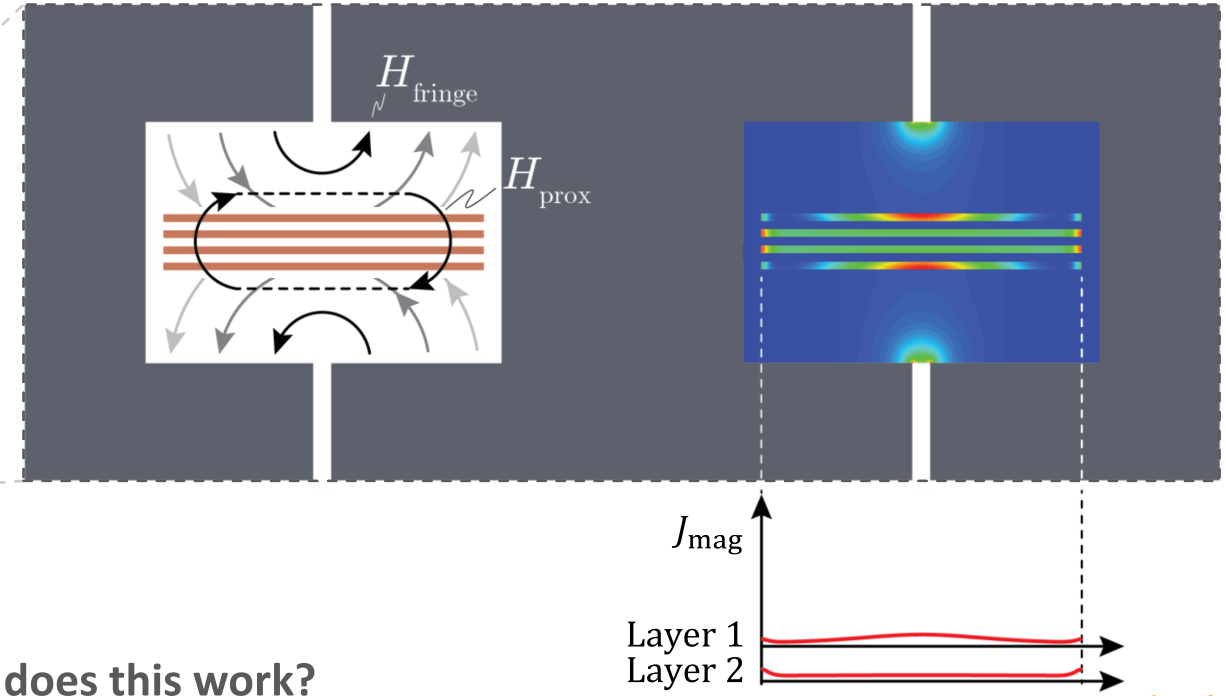
→ Mutual partial compensation of the fields

→ **AC** to **DC** resistance ratio < **1.1** @ 500kHz

▶ Customized Core







How does this work?

Compensating Fringing Field Concept (CFFC)

- *Simplified Analytical Derivation*
- *Power Density Improvement by Utilizing Multiple Air Gaps*
- *Effectivity of the CFFC for Multilayer PCB Windings*

▶ Compensating Fringing Field Concept

Analytical Derivation of the Magnetic Fields

- **Skin/Proximity Field**

  Skin/proximity field for a homogeneous current distribution within the conductor

$$H_{\mathrm{prox,y}}(x) = \frac{I_{\mathrm{L}}}{2\pi b_{\mathrm{w}}} \ln\left(\frac{b_{\mathrm{w}} - 2x}{-b_{\mathrm{w}} - 2x}\right)$$

- **Fringing Field Around the Air Gap**

  Fringing field for different distances between the air gap and the conductor [1]

$$H_{\mathrm{fringe,y}}(x, d_{\mathrm{ag}}) = \frac{H_{\mathrm{g}}}{2\pi} \ln\left(\frac{x^2 + (d_{\mathrm{ag}} - l_{\mathrm{ag}})^2}{x^2 + (d_{\mathrm{ag}} + l_{\mathrm{ag}})^2}\right)$$

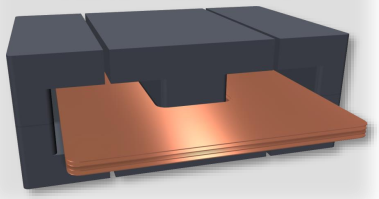
Effect of Vertical Magnetic Fields

- Increase of the conduction losses:

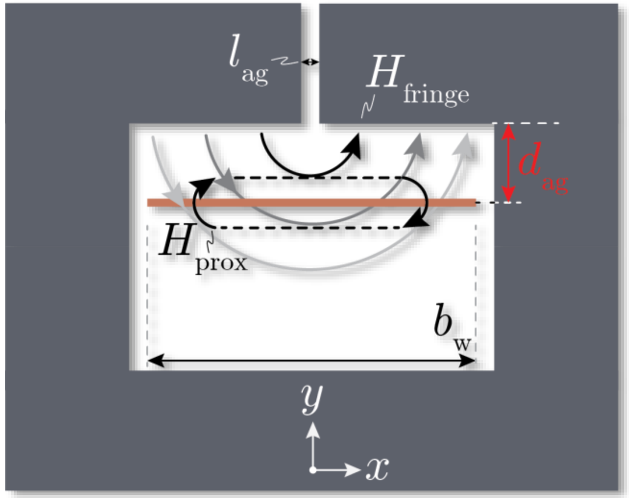
$$P_{\mathrm{AC}} = R_{\mathrm{DC}}\left(2F_{\mathrm{F}} I_{\mathrm{RMS}}^2 + 2G_{\mathrm{F}} H_{\mathrm{vert,RMS}}^2\right)$$

$$H_{\mathrm{vert,RMS}} = H_{\mathrm{prox,y}} + H_{\mathrm{fringe,y}}$$

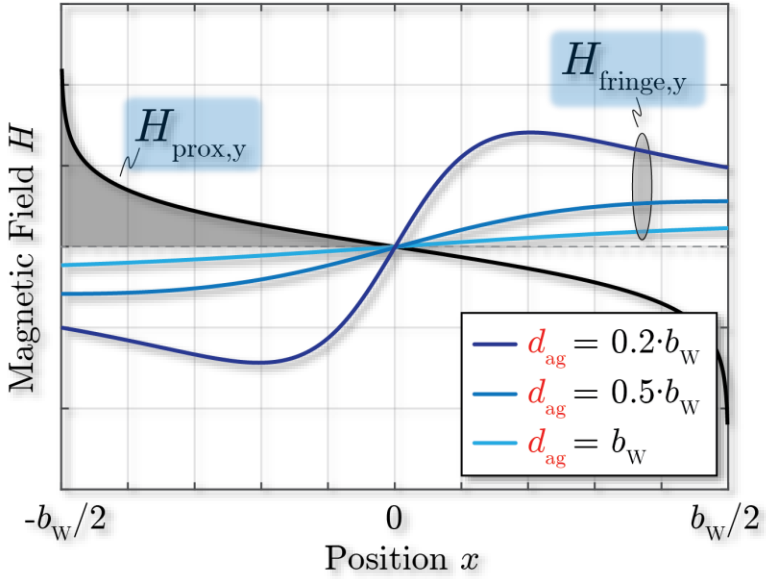
▶ Customized Core



▶ Magnetic Fields



▶ Calculated Magnetic Fields (y-Components)



[1] "Fringing Field Formulas and Winding Loss Due to an Air Gap", W. A. Roshen, IEEE Transactions on Magnetics, Vol. 43, No. 8

▶ Compensating Fringing Field Concept

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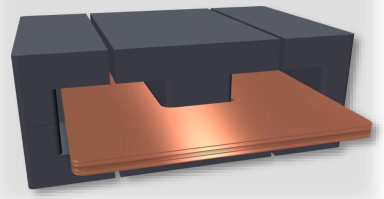
Partial Mutual Compensation of the Fields

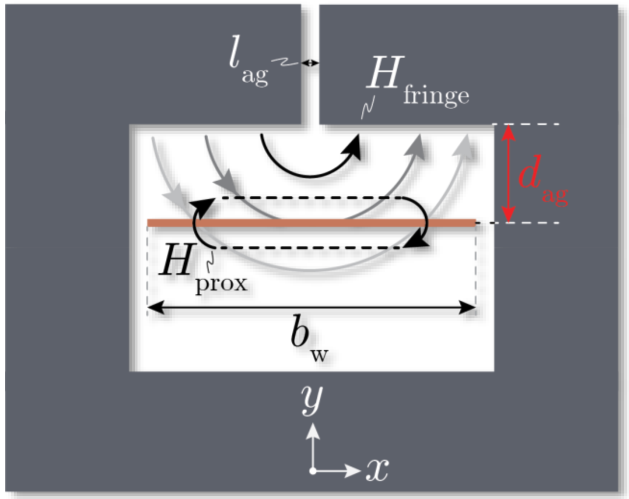
- Quality of the compensation depends on the distance d_{ag} between the air gap and the conductor

$$H_{\mathrm{tot,y}}(x) = H_{\mathrm{fringe,y}}(x, d_{\mathrm{ag}}) + H_{\mathrm{prox,y}}(x)$$

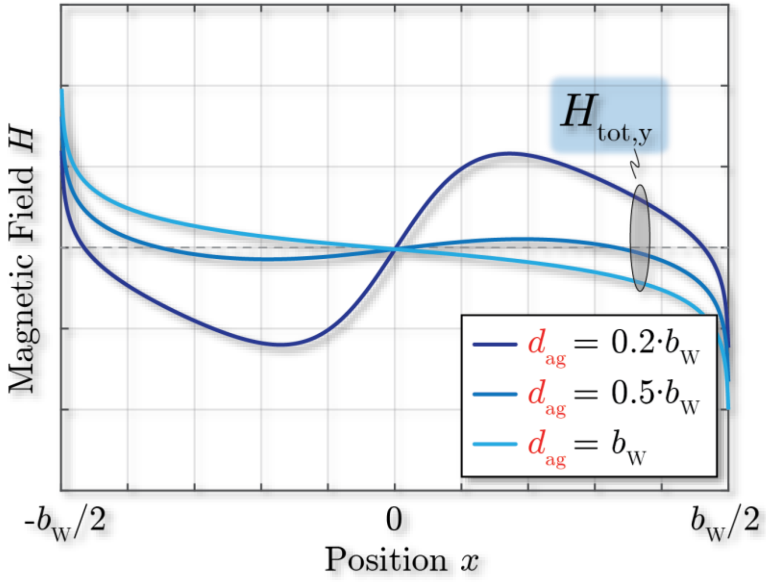
▶ Customized Core



▶ Magnetic Fields



▶ Calculated Total Magnetic Fields (y-Components)



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▶ Compensating Fringing Field Concept

Optimal Distance Between the Air Gap and the Conductor

- **Conduction Loss Estimation based on $H_{tot,y}$**

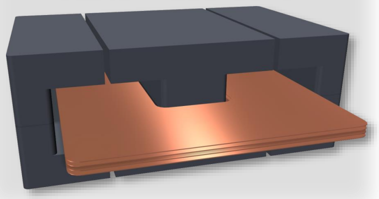
  In a first approximation, the local AC conduction losses are proportional to $H^2_{tot,y}$

$$P_{cond}(d_{ag}) \propto \int H^2_{tot,y} dx$$

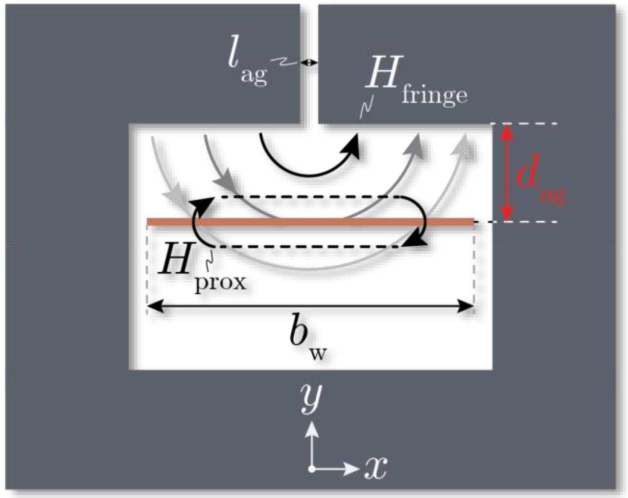
- **First Design Guideline**

$$d_{ag,opt} = \frac{b_w}{2}$$

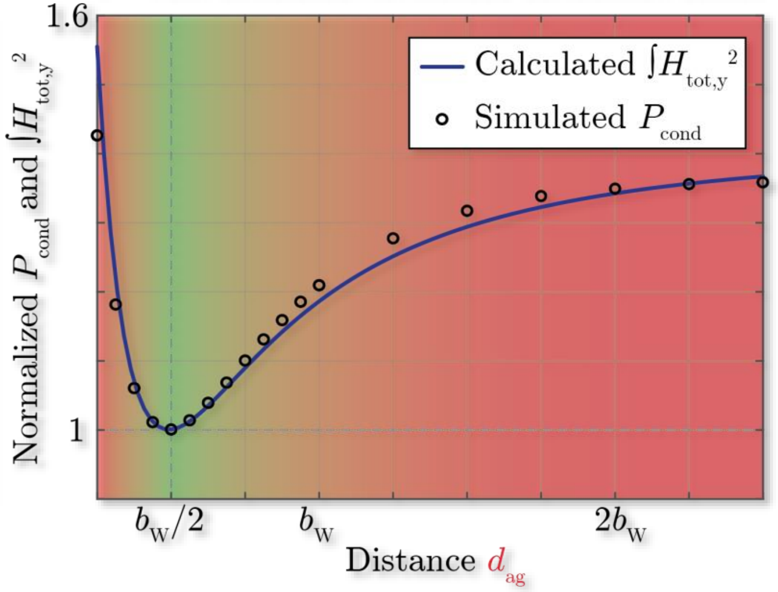
▶ Customized Core



▶ Magnetic Fields



▶ FEM-Simulated Normalized Conduction Losses



CFFC:

Use fringing field in a beneficial way!

Far away from the air gap is not always ideal!

▶ Compensating Fringing Field Concept

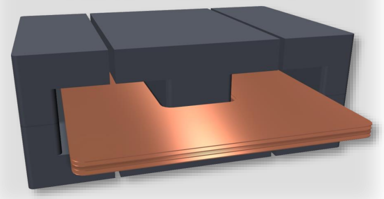
Utilization of Multiple Air Gaps to Reduce $d_{ag,opt}$

- **Magnetic Field Compensation of Multiple Air Gaps**

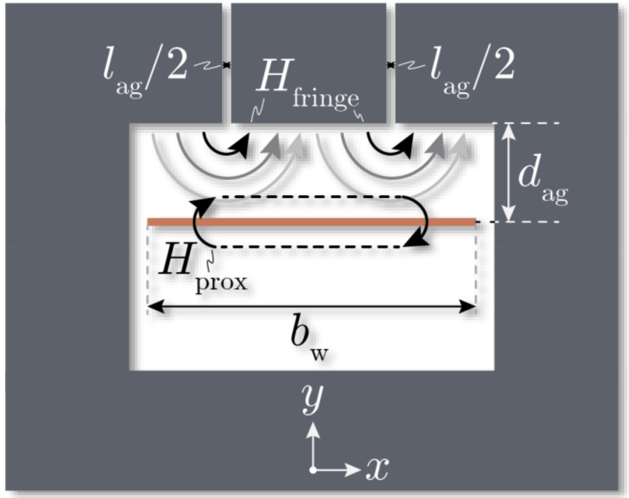
  The quality of the field compensation improves with the number of air gaps

$$P_{\mathrm{cond}}(d_{\mathrm{ag}}) \propto \int H_{\mathrm{tot,y}}^2 \mathrm{d}x$$

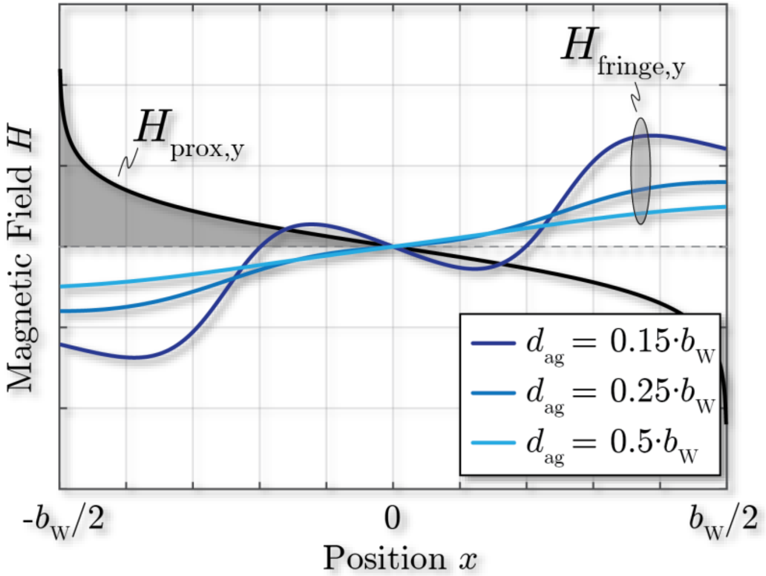
▶ Customized Core



▶ Magnetic Fields



▶ Calculated Magnetic Fields (y-Components)



▶ Compensating Fringing Field Concept

Utilization of Multiple Air Gaps to Reduce $d_{\mathrm{ag,opt}}$

Magnetic Field Compensation of Multiple Air Gaps

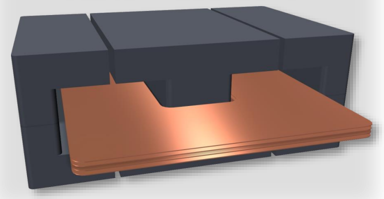
The quality of the field compensation improves with the number of air gaps

$$P_{\mathrm{cond}}(d_{\mathrm{ag}}) \propto \int H_{\mathrm{tot,y}}^2 \mathrm{d}x$$

Second Design Guideline

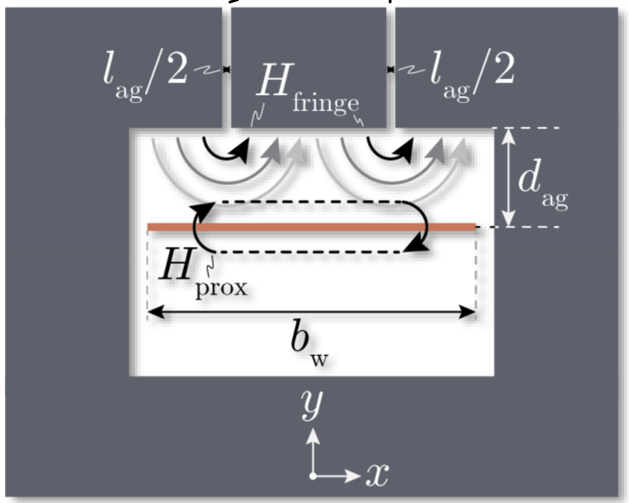
$$d_{\mathrm{ag,opt}} = \frac{b_{\mathrm{w}}}{2 \cdot N_{\mathrm{ag}}}$$

▶ Customized Core

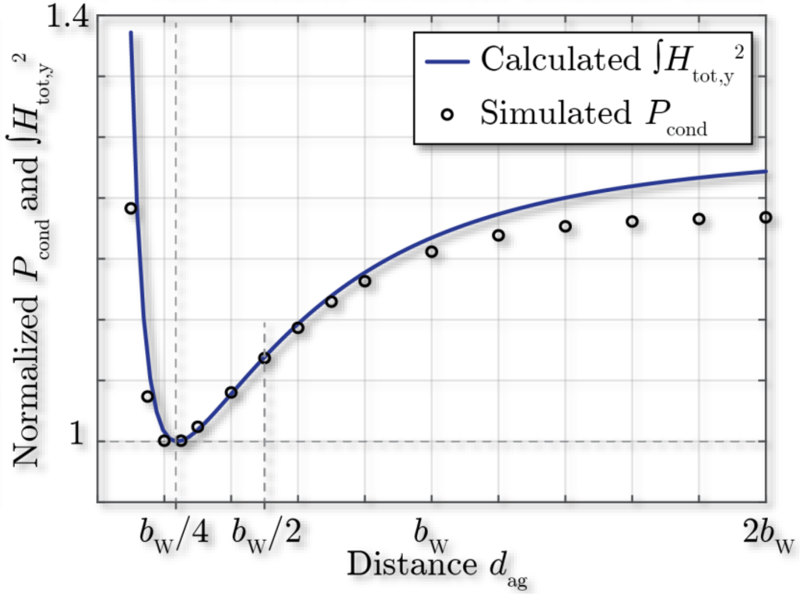


▶ Magnetic Fields

$N_{\mathrm{ag}} = 2$



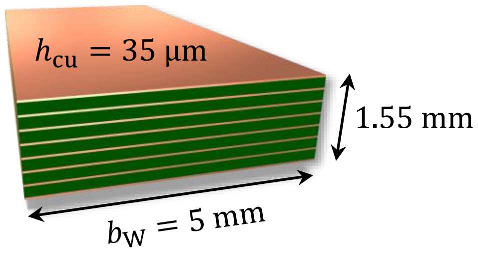
▶ FEM-Simulated Normalized Conduction Losses



▶ Compensating Fringing Field Concept

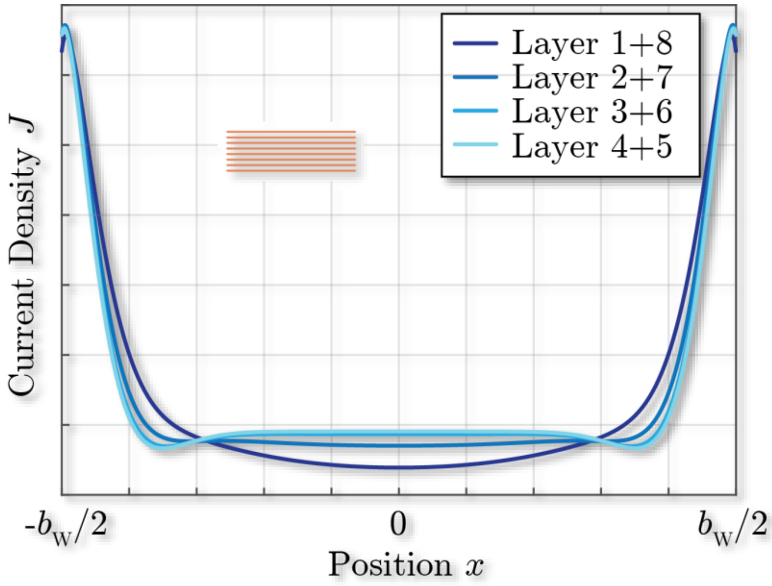
Multilayer PCB Winding

- How effective is the **CFFC** for multilayer PCB windings?
- Quality of compensation only slightly decreases with increasing the number of layers

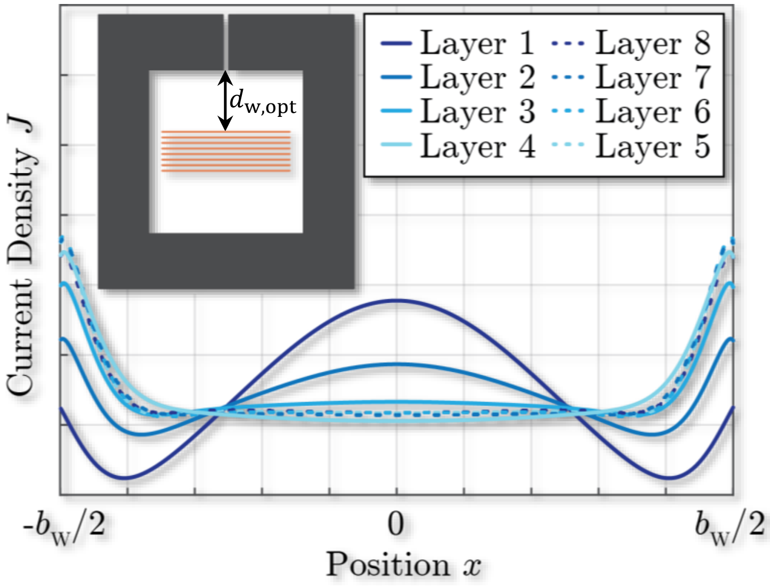


▶ Simulated Piece of PCB Winding

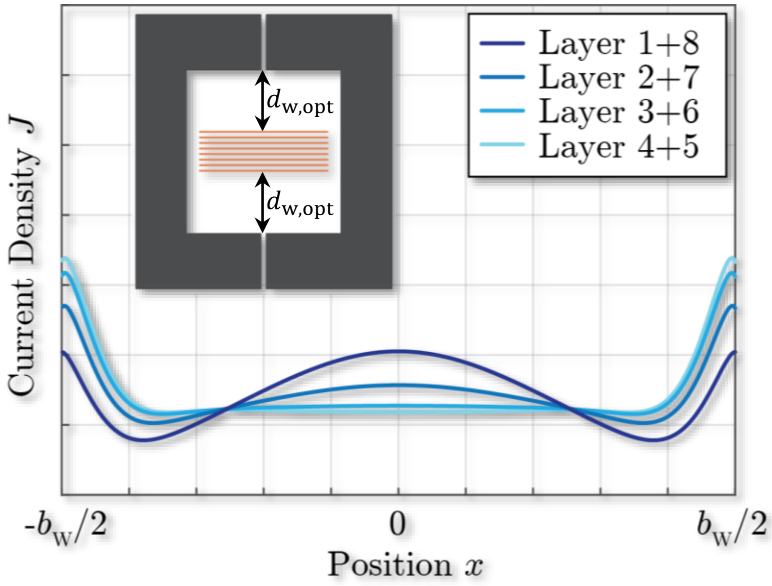
▶ FEM Simulated Current Densities



▶ Simulated Air Coil (**$R_{AC/DC}$ = 2.54**)



▶ Simulated with Single Air Gap (**$R_{AC/DC}$ = 1.34**)



▶ Simulated with Dual Air Gap (**$R_{AC/DC}$ = 1.18**)

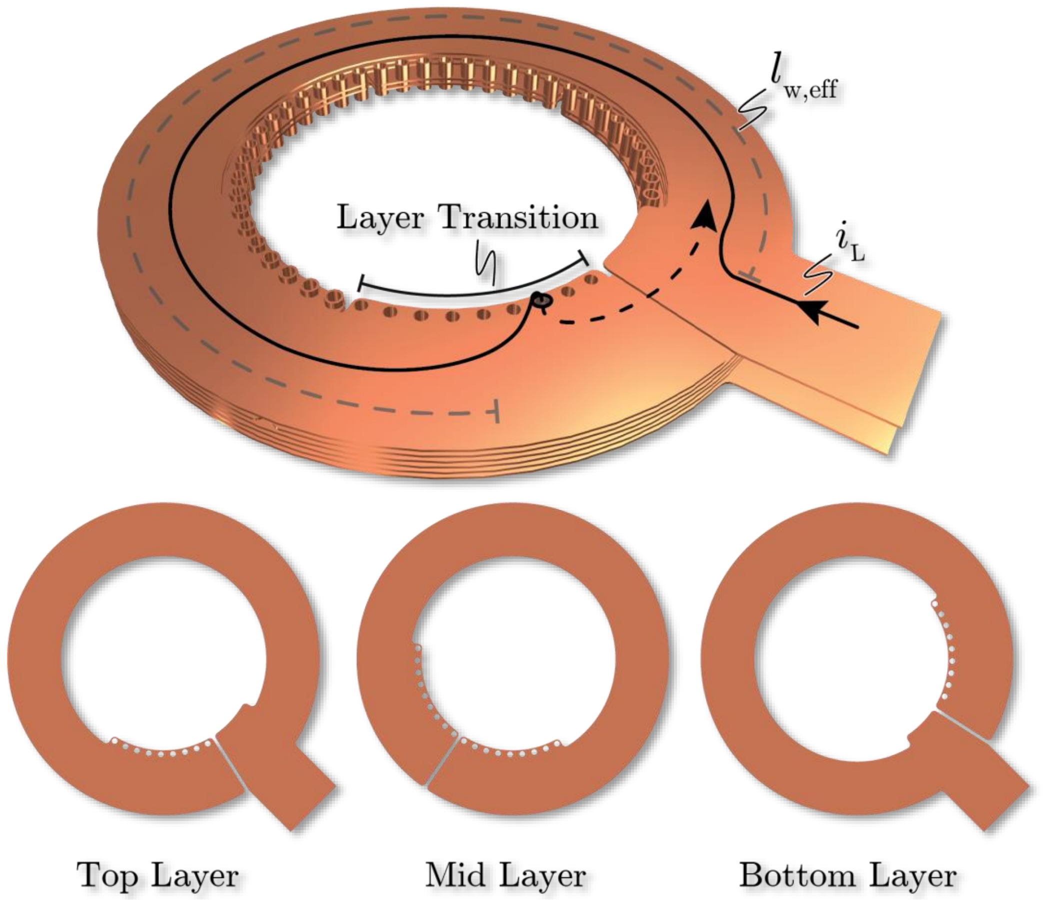
Experimental Verification

- *Design of the PCB Winding*
- *AC-Resistance Measurements*
- *Calorimetric Measurements*

▶ Practical Implementation of the CFFC

Design of the PCB Winding

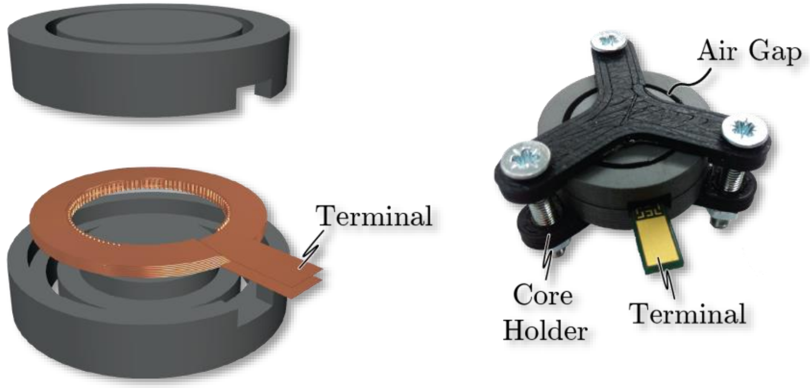
- Circular shape to minimize winding length
- Use through-hole vias to minimize costs
- Vertically aligned termination to minimize losses



▶ Design of a circular PCB inductor winding

Design of the Ferrite Core

- Circular air gap above and beneath the winding
- Customized CNC-milled core shape



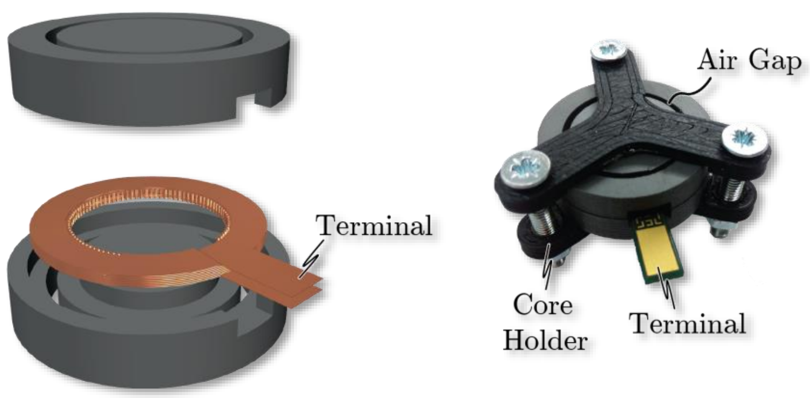
▶ Assembly of the PCB winding inductor (core diameter = 20mm)

▶ Experimental Verification

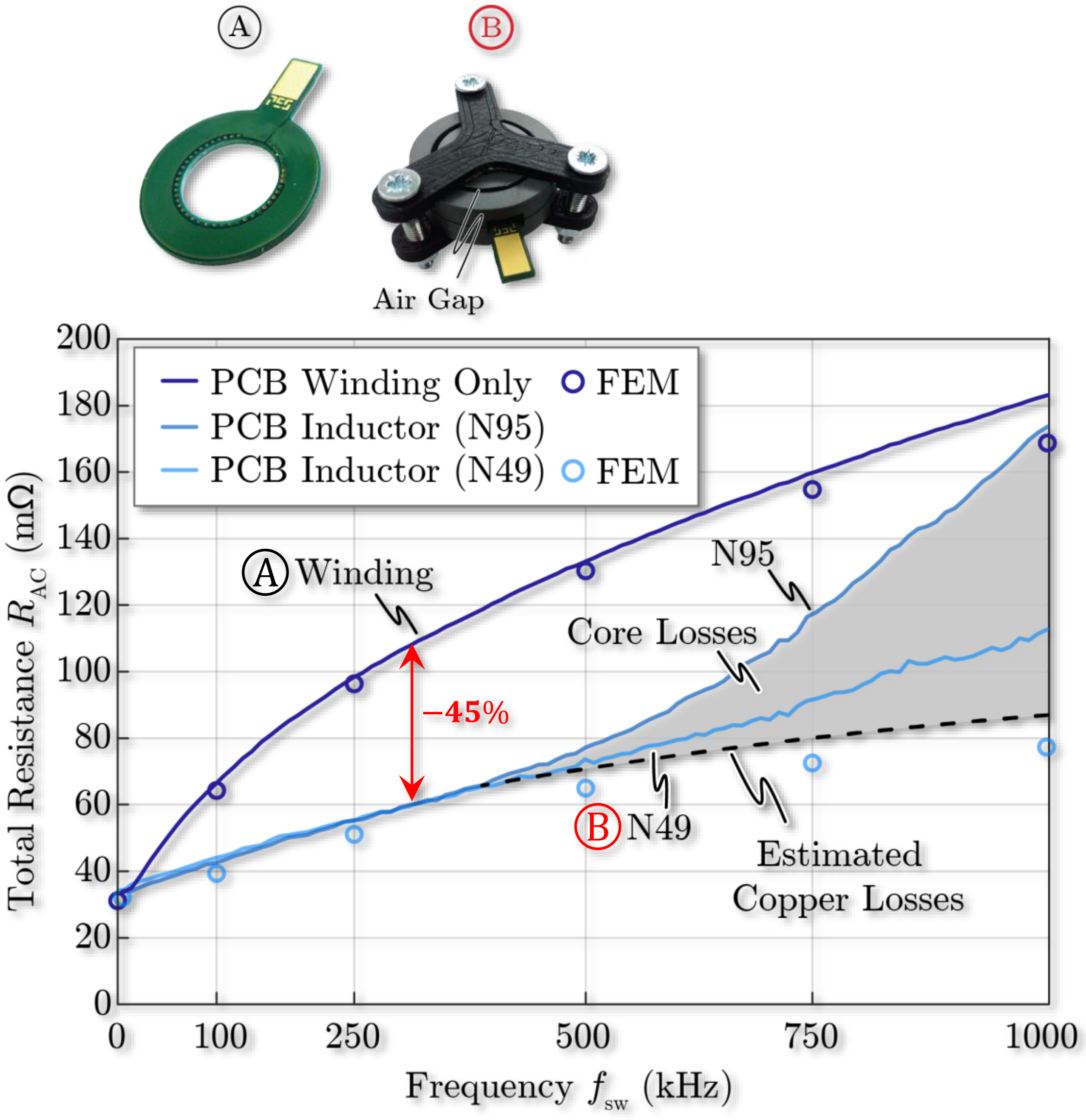
AC-Resistance Measurements

- Measurements have been performed using an impedance analyzer

  → **45%** less conduction losses at high frequencies



▶ Assembly of the PCB winding inductor (core diameter = 20mm)



▶ Experimentally measured AC-resistance of the PCB winding

▶ Experimental Verification

AC-Resistance Measurements

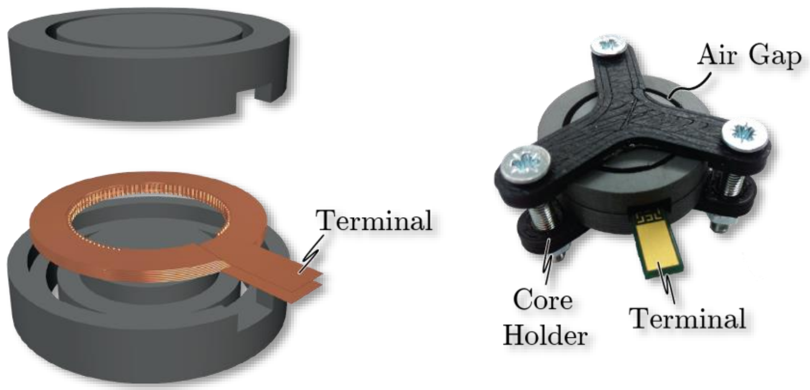
- Measurements have been performed using an impedance analyzer

→ **45%** less conduction losses at high frequencies

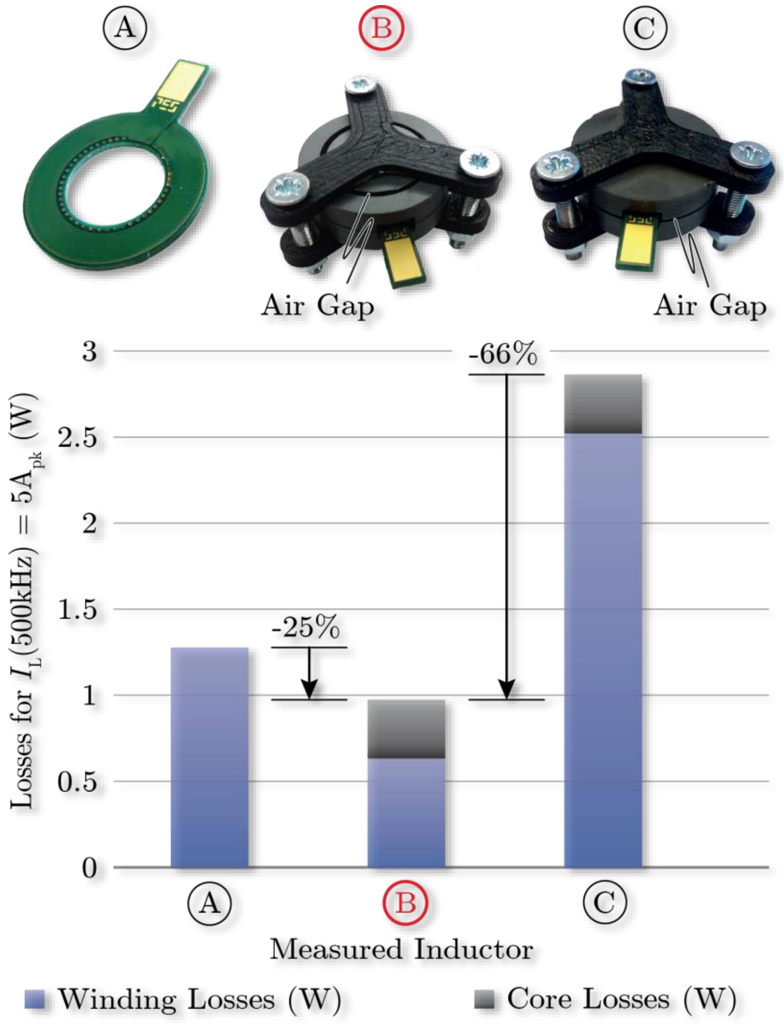
Calorimetric Measurements

- Even though the inductance of Ⓑ is 10x larger than the inductance of Ⓐ

→ **25%** less losses



▶ Assembly of the PCB winding inductor (core diameter = 20mm)

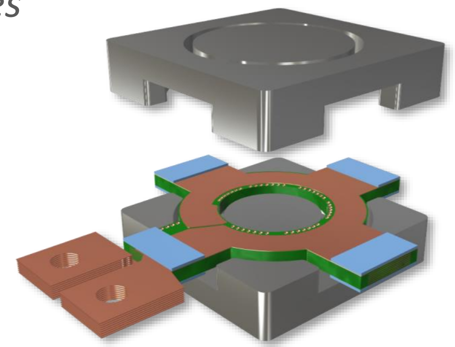


▶ Calorimetric measurements of the total inductor losses

Thermally limited to I_{rms} < 7A (T_{PCB} < 150°)

Thermally Improved PCB Winding Inductor

- *Derivation of the Thermal Model of a Circular PCB Winding*
- *Improving the Thermal Performance by Utilization of Additional Thermal Interfaces*
- *Experimental Verification*



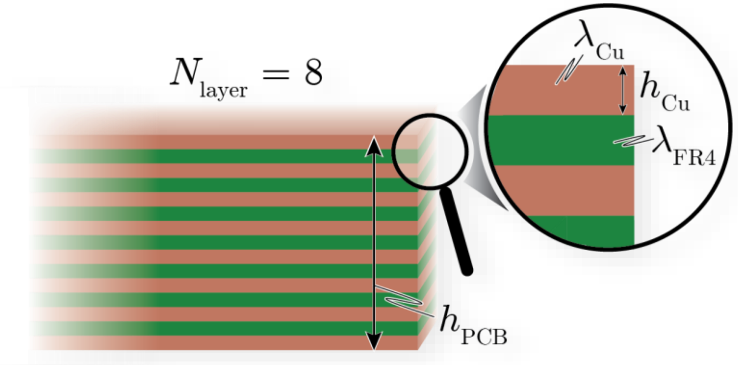
▶ Thermally Improved PCB Winding Inductor

Thermal Modelling of PCB Windings

- Equivalent thermal conductivity of a PCB

$$\lambda_{\mathrm{eff}} = r_{\mathrm{PCB}}\lambda_{\mathrm{Cu}} + (1 - r_{\mathrm{PCB}})\lambda_{\mathrm{FR4}}$$

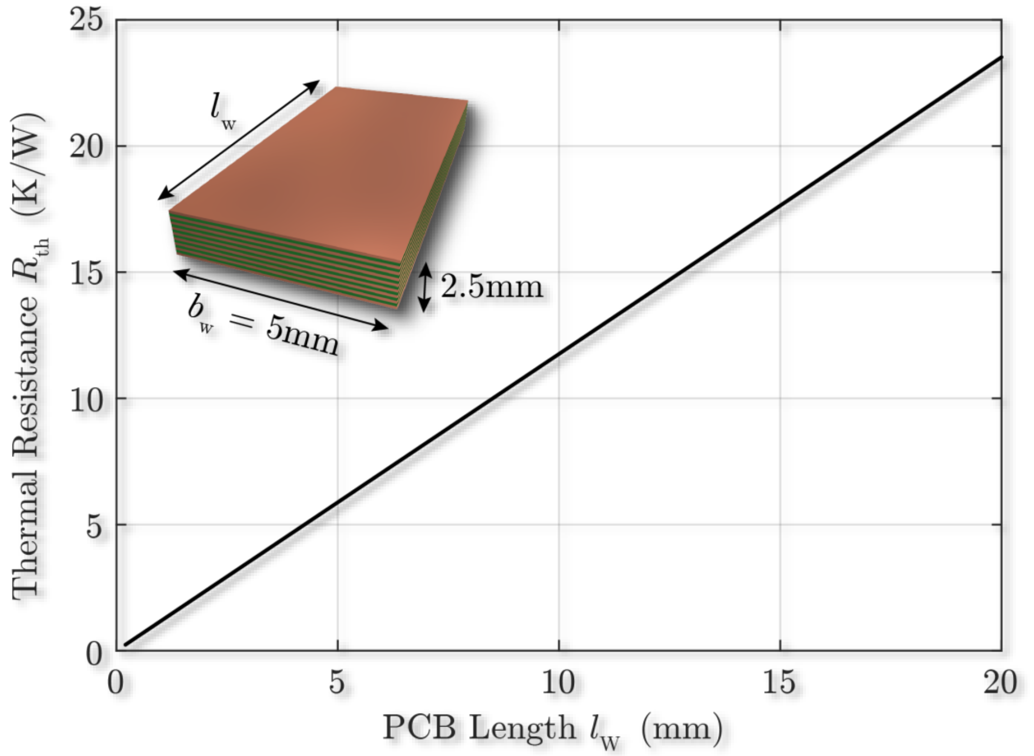
$$r_{\mathrm{PCB}} = \frac{N_{\mathrm{layer}} \cdot h_{\mathrm{Cu}}}{h_{\mathrm{PCB}}}$$



▶ **Simplified drawing of an 8 layer PCB**

- Thermal resistance of a rectangular piece of PCB

$$R_{\mathrm{th}} = \frac{l_{\mathrm{w}}}{\lambda_{\mathrm{eff}} \cdot b_{\mathrm{w}} \cdot h_{\mathrm{PCB}}}$$



▶ **Thermal resistance of a sample piece of an 8 layer 70um PCB**

▶ Thermally Improved PCB Winding Inductor

Thermal Model of a Circular PCB Winding

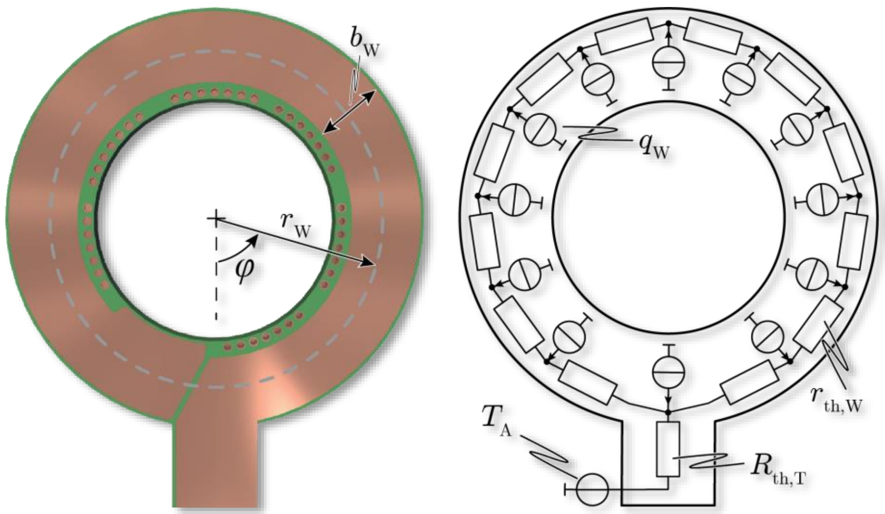
- Thermal "per-length" resistance

$$r_{\mathrm{th,W}} = \frac{1}{2\pi}\left(\frac{2 r_{\mathrm{W}} \pi}{\lambda_{\mathrm{eff}} \cdot b_{\mathrm{W}} \cdot h_{\mathrm{PCB}}}\right)$$

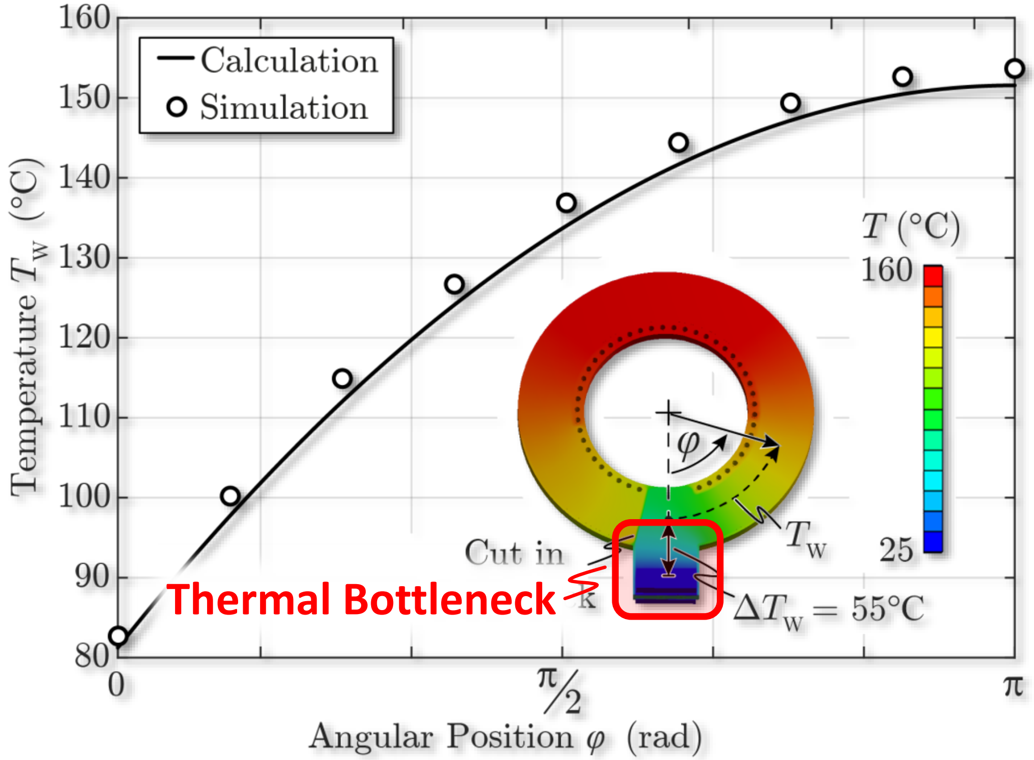
- "Per-length" conduction losses

$$q_{\mathrm{W}} = \frac{P_{\mathrm{W}}}{2\pi}$$

$$T_{\mathrm{W}}(\varphi) = T_{\mathrm{A}} + \boxed{R_{\mathrm{th,T}} \cdot P_{\mathrm{W}}} + q_{\mathrm{W}} \cdot r_{\mathrm{th,W}} \cdot \varphi \cdot \left(\pi - \frac{\varphi}{2}\right)$$



▶ Thermal model of a circular PCB winding (Assumption: homogeneous loss distribution within the winding)



▶ Simulated and calculated temperature distribution within the winding for P_W = 6W and a heat sink temperature of T_A = 25°C

▶ Thermally Improved PCB Winding Inductor

Thermally Improved PCB Winding

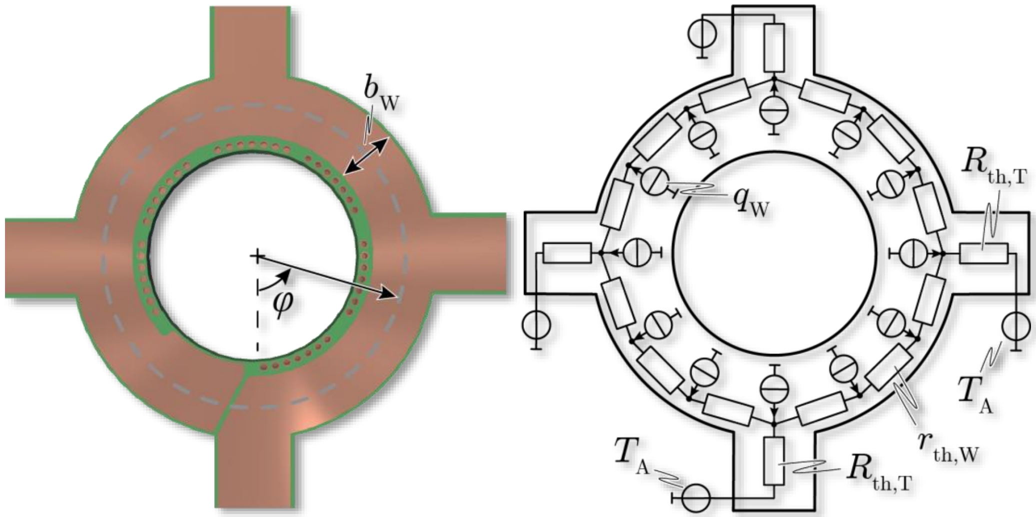
- Thermal "per-length" resistance

$$r_{\mathrm{th,W}} = \frac{1}{2\pi}\left(\frac{2 r_{\mathrm{W}} \pi}{\lambda_{\mathrm{eff}} \cdot b_{\mathrm{W}} \cdot h_{\mathrm{PCB}}}\right)$$

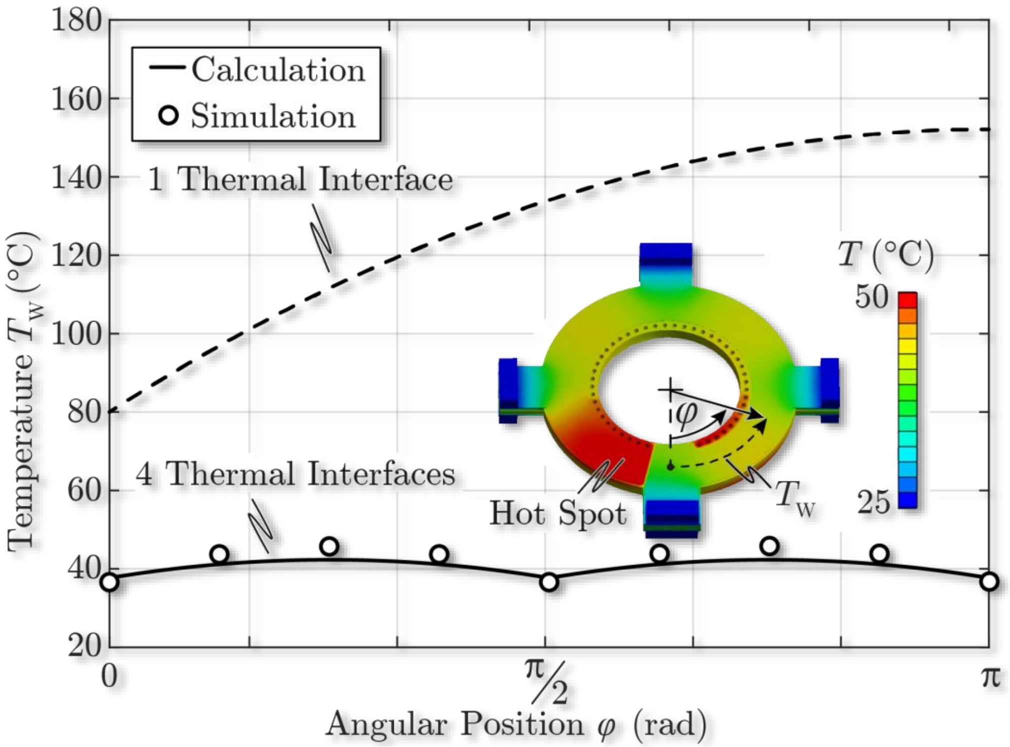
- "Per-length" conduction losses

$$q_{\mathrm{W}} = \frac{P_{\mathrm{W}}}{2\pi}$$

$$T_{\mathrm{W}}(\varphi) = T_{\mathrm{A}} + R_{\mathrm{th,T}} \cdot \frac{P_{\mathrm{W}}}{4} + q_{\mathrm{W}} \cdot \frac{r_{\mathrm{th,W}}}{4} \cdot \varphi \cdot (\pi - 2\varphi)$$



▶ Thermal model of a thermally improved PCB winding with four thermal interfaces

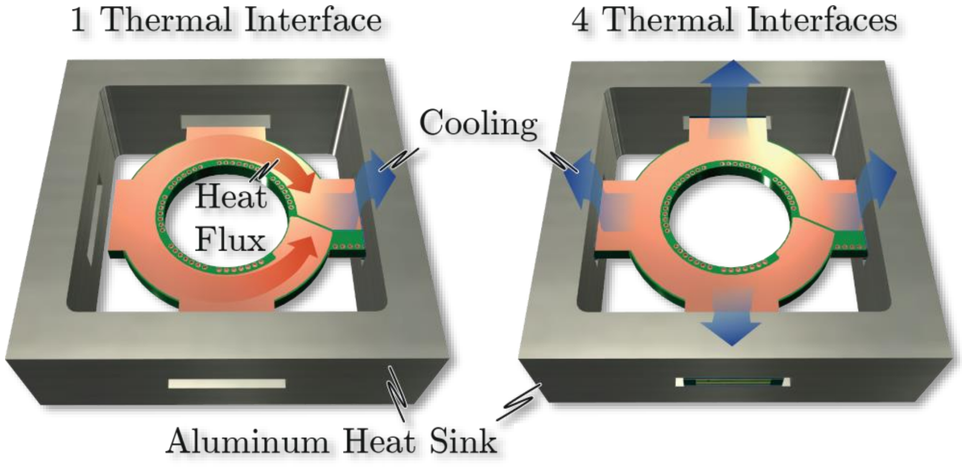


▶ Simulated and calculated temperature distribution within the winding for P_{W} = 6W and a heat sink temperature of T_{A} = 25°C

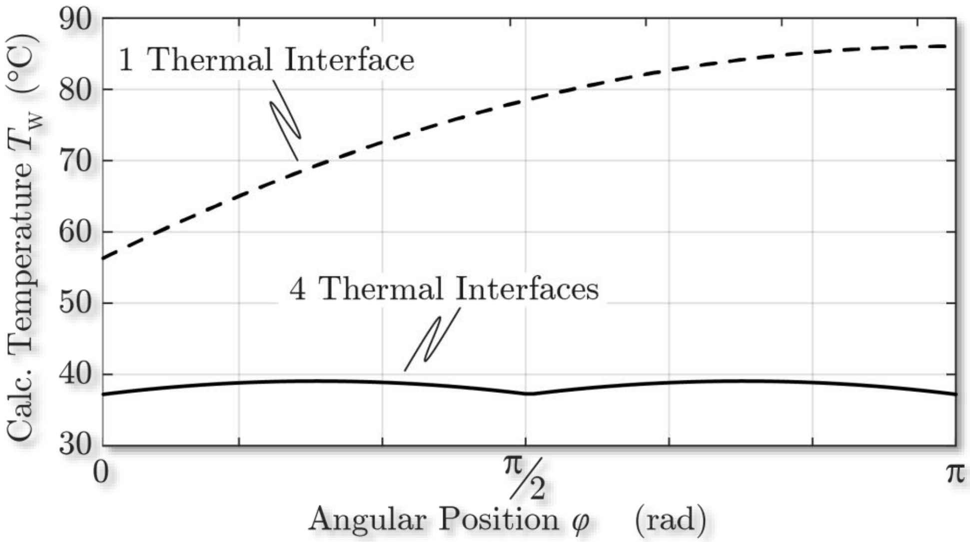
▶ Thermally Improved PCB Winding Inductor

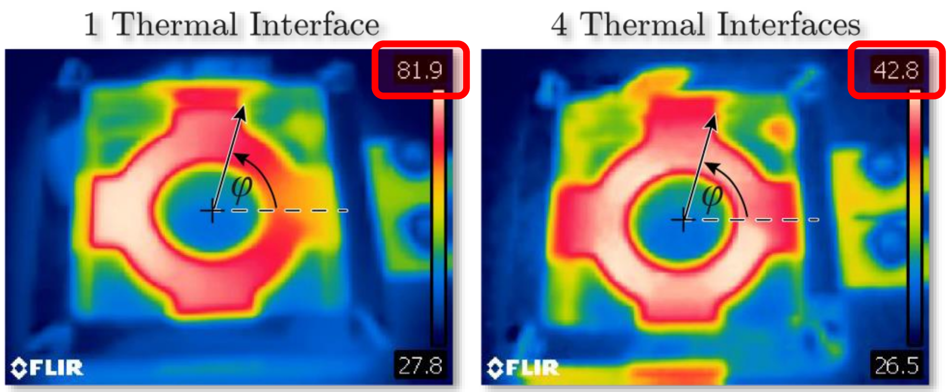
Experimental Verification of the Thermal Model

- Measurement of the temperature distribution within two identical PCB windings with either 1 or 4 thermal interfaces
- The rectangular aluminum heat sink was screwed on a water-cooled (T_A = 25°C) base plate



▶ Experimental setup for the temperature measurement of two sample inductor windings





▶ Calculated and measured temperature distribution within the winding for a constant loss of 3.5W and T_A = 25°C

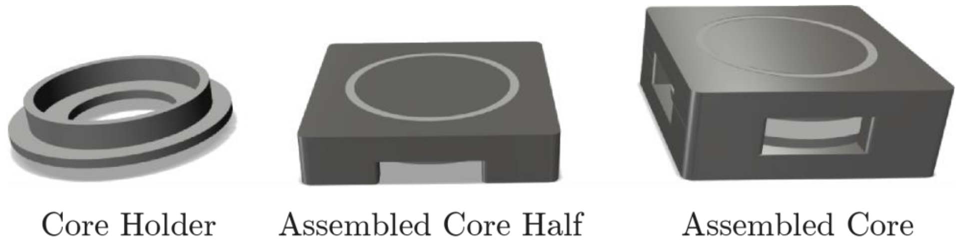
▶ Thermally Improved PCB Winding Inductor

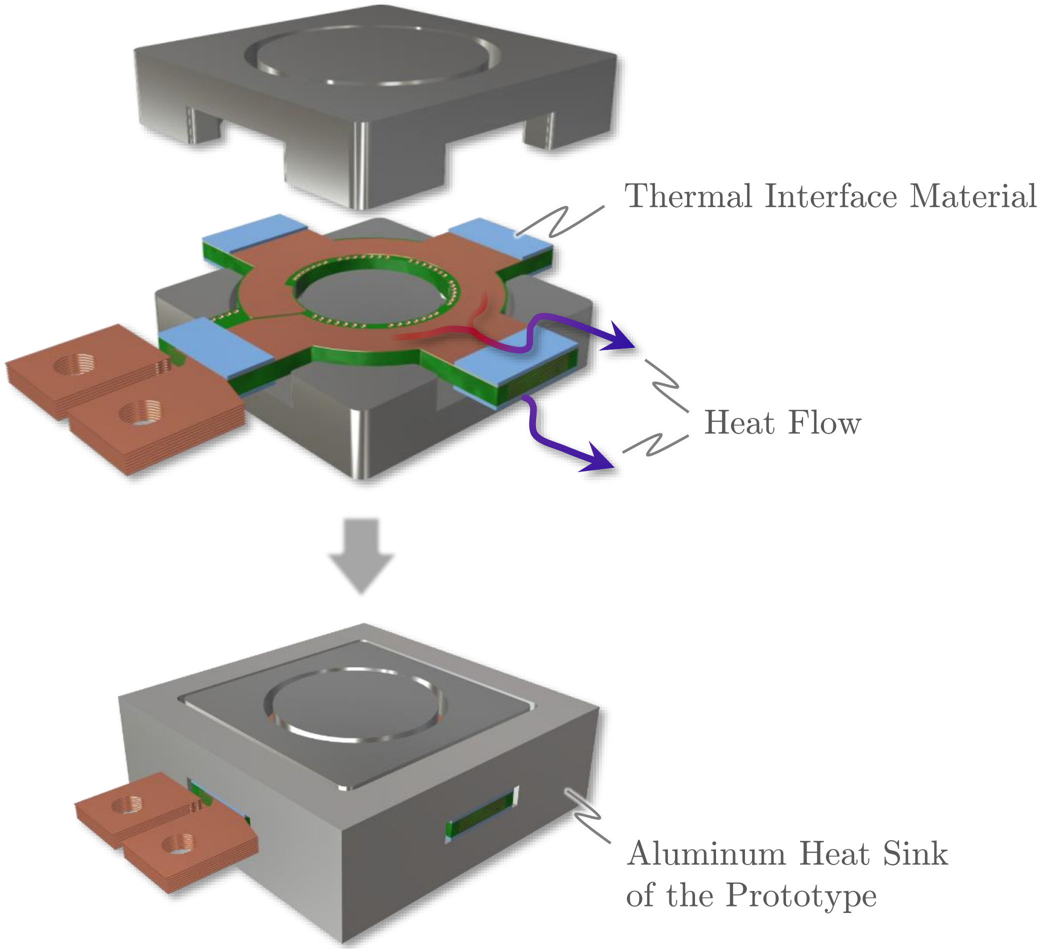
Adapted Inductor Core Design

- Circular core ⟶ Rectangular core
- Homogeneous flux density in the inner and outer core limbs required [2]

Core Holder for Improved Mechanical Stability

- 3D-printed core holder ensures homogeneous air gap and the ideal distance between air gap and winding
- Customized core can be used as conventional E cores



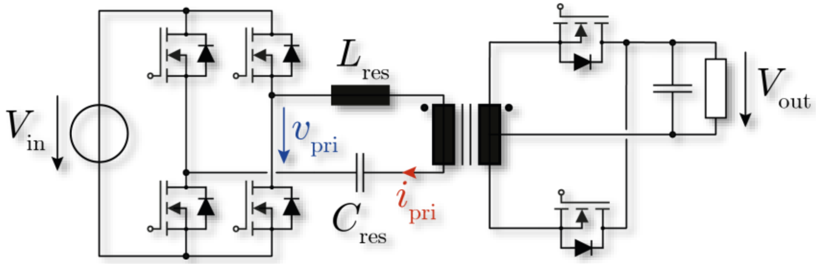


[2] "Highly Efficient/Compact Automotive PCB Winding Inductors Based on the Compensating Air-Gap Fringing Field Concept", J. Schäfer, D. Bortis, J. W. Kolar IEEE Transactions on Power Electronics

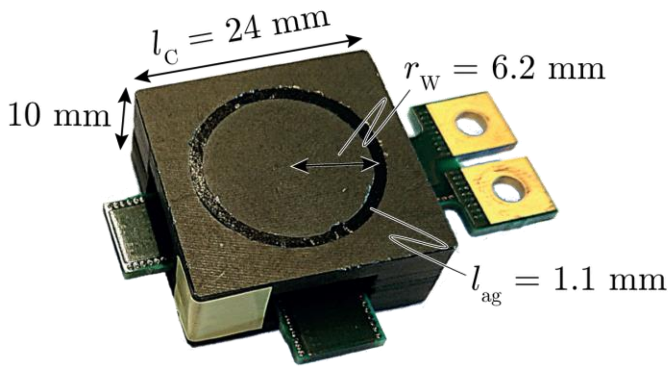
▶ Exemplary PCB-Winding Inductor

Series Resonant Inductor for 3kW DC/DC Converters

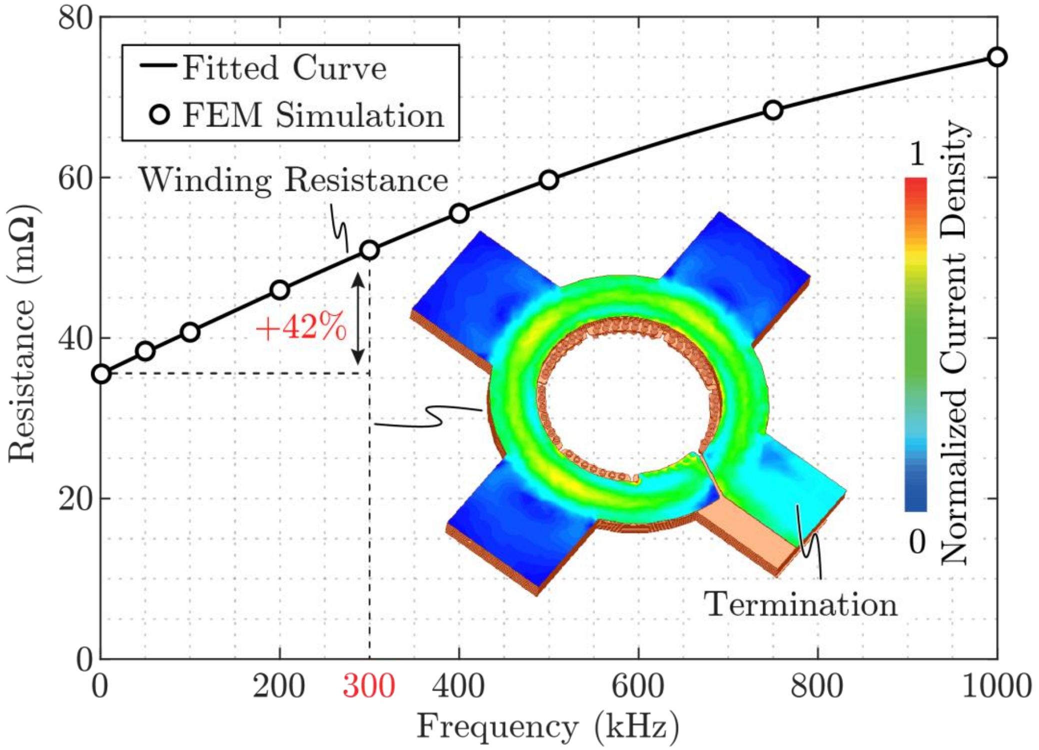
- **Specifications:**
- L_{res} = 6.8 µH
- I_{pk} = 25 A
- I_{rms} = 16.2 A



▶ **Simplified resonant converter topology for a 500V-12V DC/DC converter**



$N_L = 7$
$h_{Cu} = 70$ µm
$A_C = 95$ mm²
$b_W = 3.5$ mm
$d_W = 1.75$ mm
$P_{W,max} = 18$ W

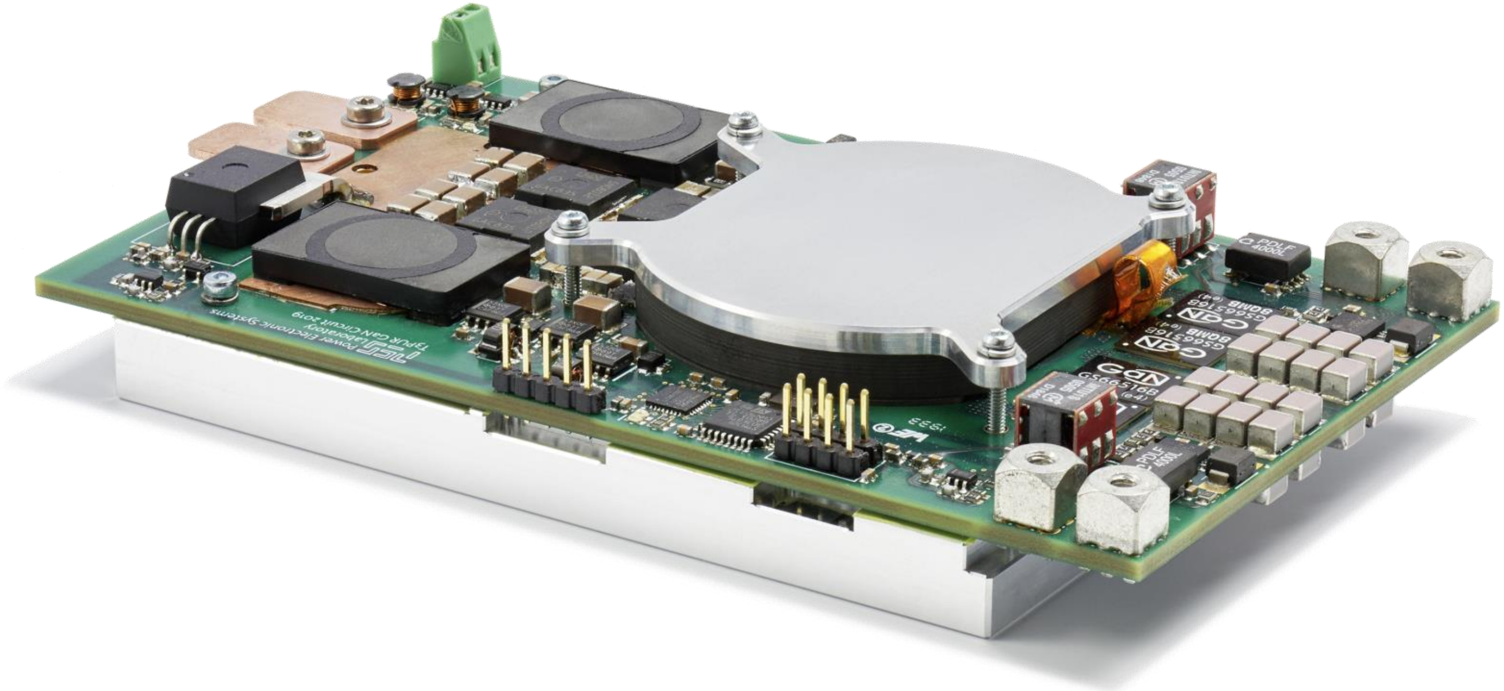


▶ **FEM-simulated resistance and current distribution of the 6.8µH inductor prototype (Measured AC to DC resistance ratio @ 300kHz: 1.49)**

▶ Exemplary PCB-Winding Inductor

Output Inductors of a Phase-Shifted Full-Bridge Converter

- **Specifications:**
- L_o = 250 nH
- I_{pk} = 210 A
- I_{rms} = 118 A



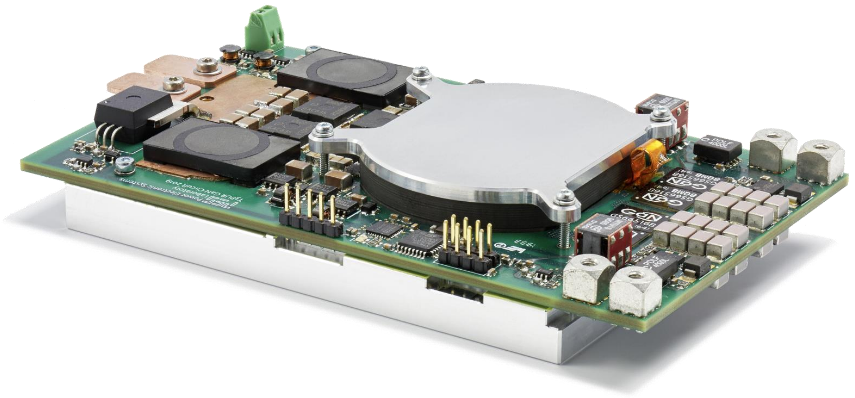
▶ **3.6kW 500V/12V three-port DC/DC converter for automotive applications**

▶ PCB-Winding Inductors Employing the CFFC

Conclusions

- Fringing field around air gaps can be used in a variety of applications for minimizing HF conduction losses
- CFFC can be used for shaping the current distribution in the conductor arbitrarily
- Good thermal design ⟶ Very high current densities can be allowed
- Customized cores are necessary to fully utilize the benefits of the CFFC

It is possible to design highly efficient and compact PCB winding inductors



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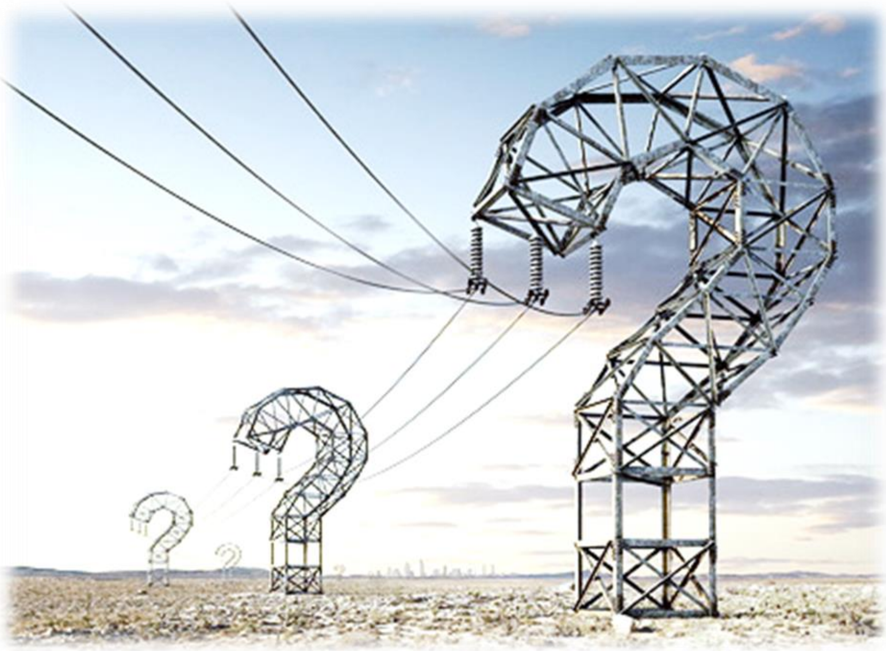

Thank You !