Power Electronic Systems Laboratory

ETH zürich

Minimum Loss Operation of High Frequency Inductors

Presentation
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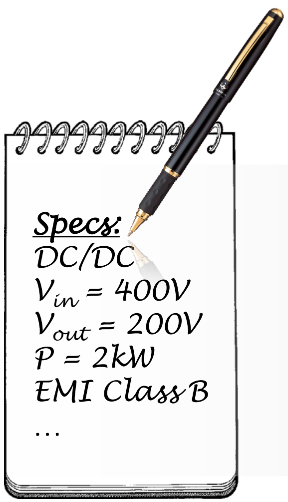
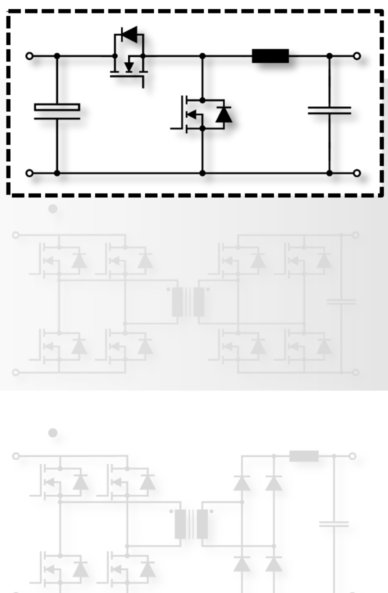
Motivation / Scientific contribution

System-level approach



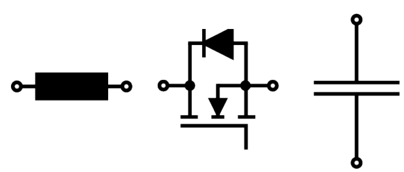
Topology



System DOF

- Switch. Freq f_{sw}
- Current ripple r
- In capacit. C_{in}
- Out capacit. C_{out}
- Filter Induct L

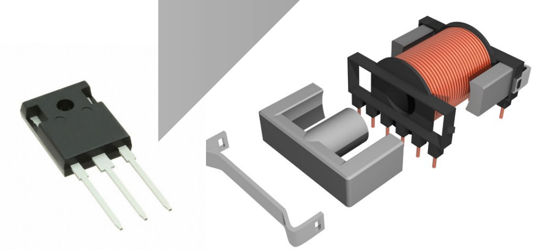
etc



Component DOF

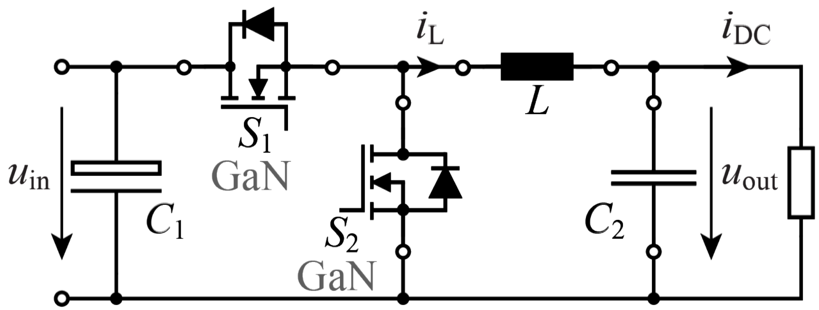
- IGBT, MOSFET ..
- Chip area
- E-core, ETD-core..
- Ferrite, Iron ..
- Round, Litz ..

etc



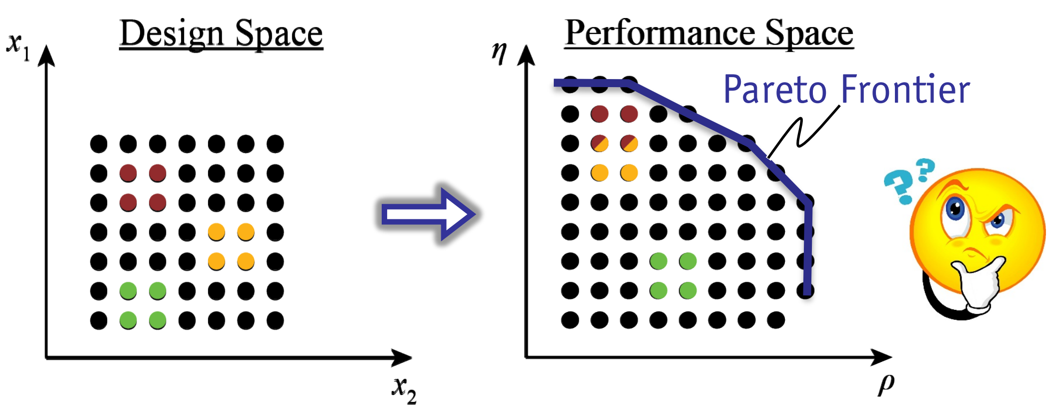
Motivation / Scientific contribution

System-level approach



▲ DC/DC Buck converter

- **Choosing the remaining DOF**
  - ▶ **System** DOF
  - ▶ **Component** DOF

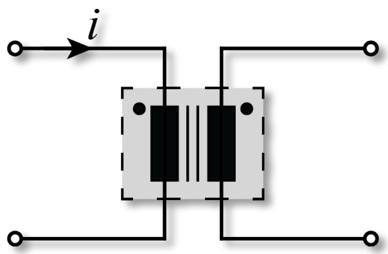


▲ Multi-objective Optimization

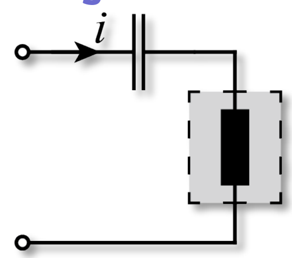
- **Component level difficulties**
  - ▶ Design/Performance **space diversity**
  - ▶ Complex **interactions** between **components**
  - ▶ Large number of **design variables**

Motivation / Scientific contribution

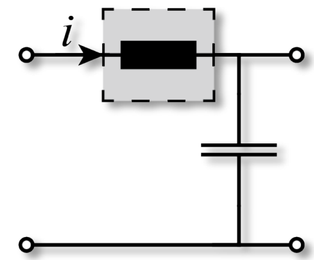
State-of-the-art characterization of magnetic components



▲ Transformer



▲ Resonance Inductor



▲ DC/AC Inductor

- **Performance factor:** $PF = B_{\mathrm{pk}} f$
- **Performance factor incl. winding losses:** $PF_{\mathrm{w}} = B_{\mathrm{pk}} f^{\mathrm{w}}$
- **Performance factor incl. dc bias:** $PF_{\mathrm{dc}} = \sqrt{f B_{\mathrm{ac}} B_{\mathrm{dc}}}$

@ Constant surface temperature

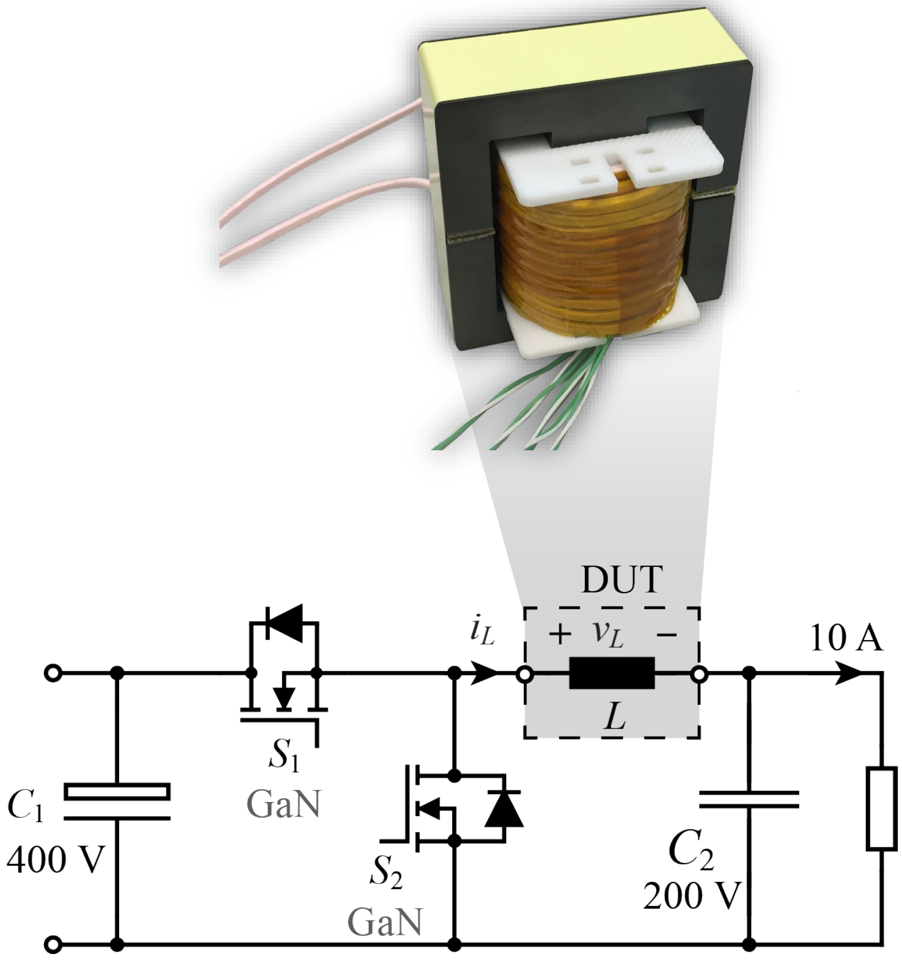
What is missing?

- ▶ Effect of **fringing field** on the copper losses (air-gap)
- ▶ **Temperature** sensitivities (core & coil)
- ▶ **DC-bias** effect on the core losses
- ▶ **Winding turns' packing**

- **Optimal operating condition of filter inductor?**

Motivation / Scientific contribution

Component-level approach



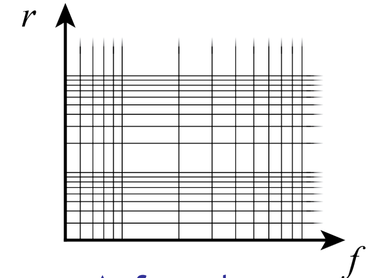
▲ DC/DC Buck converter

- **DC/DC Buck converter**
- **Specifications:**
  - V_{in} = 400 V
  - V_{out} = 200 V
  - d = 50 %
  - P = 2 kW
- **Power Inductor losses investigation**
- Concept can be **extended** to more **complex topologies**

Motivation / Scientific contribution

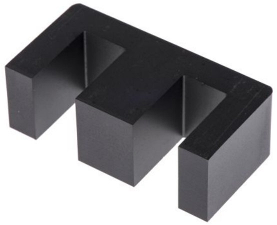
Component-level approach

- **Design space** (System DOF)
  - **Switching frequency (*f*)**
  - **Current ripple (*r*)**

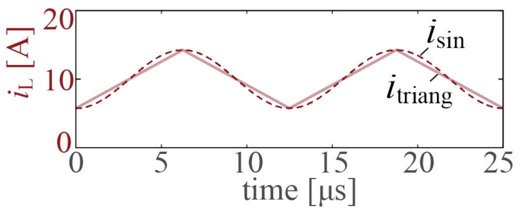


▲ ***f* − *r*** plane

- **Elimination of further influences by considering:**
  - Constant **magnetic core** : E55/28/21 – Ferrite N87
  - Constant **type of coil** : Litz wire – 100µm
  - **Sinusoidal HF** excitation + **DC bias**
  - Constant power, i.e., **constant power density**



▲ E55/28/21

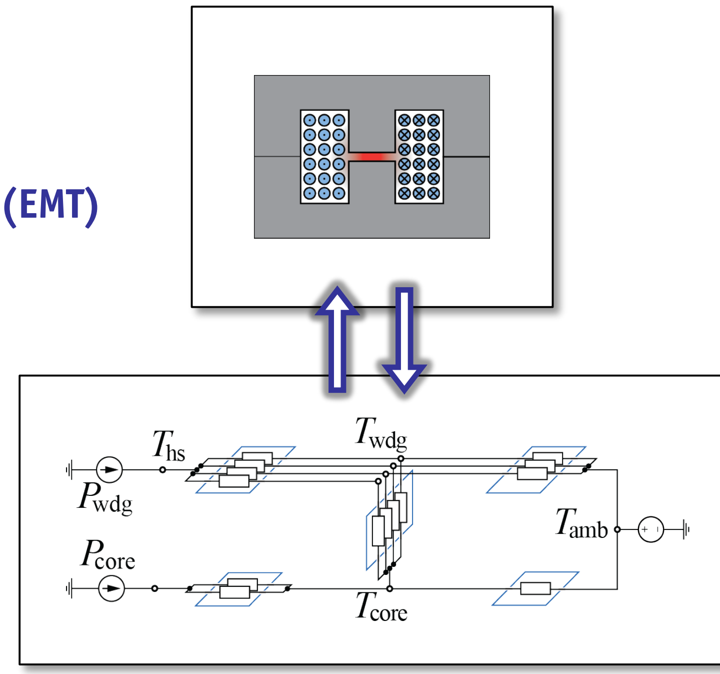


▲ AC excitation

Motivation / Scientific contribution

Component-level approach

- **Different models employed**
  - ▶ **Simplified analytic model**
  - ▶ **Employment of an Electromagnetic – Thermal (EMT) coupled model**



- **Investigation of the following matters:**
  - ▶ Optimal **switching frequency**
  - ▶ Reasonable **range of operation**
  - ▶ Important **influencing parameters**

In other words:

Provided a core, what are the best operating conditions of the component?

Brief Outline

- Scaling laws / simplified evaluation
- Electromagnetic-thermal coupled model (EMT)
- Analysis of identified losses
- Experimental verification
- Identified bottleneck & extension to advanced HF materials
- Practical design guidelines

Investigation based on analytic models

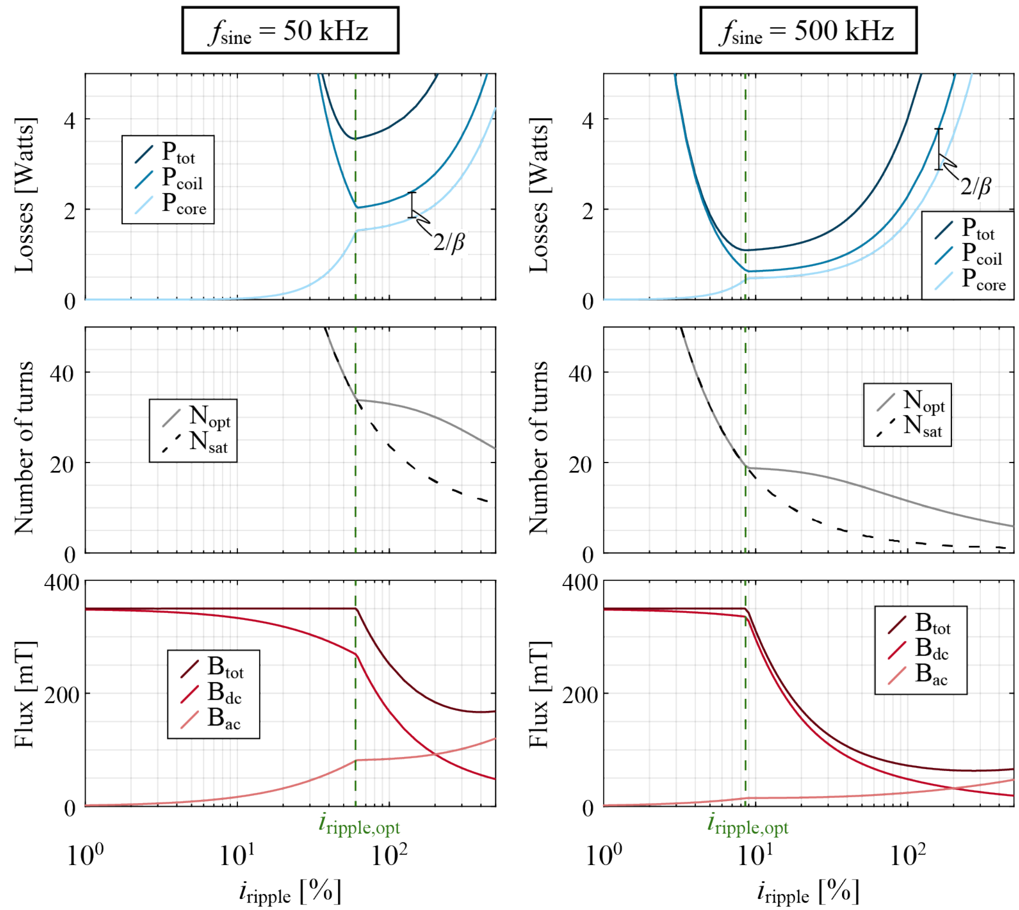
- **Core losses (General Steinmetz Equation)**

$$P_{core} = \mathrm{Vol}\ k\ f_{sine}^{\alpha}\ \mathrm{B}_{ac}^{\beta}$$

- **Coil losses (dc + skin/proximity effect ac losses)**

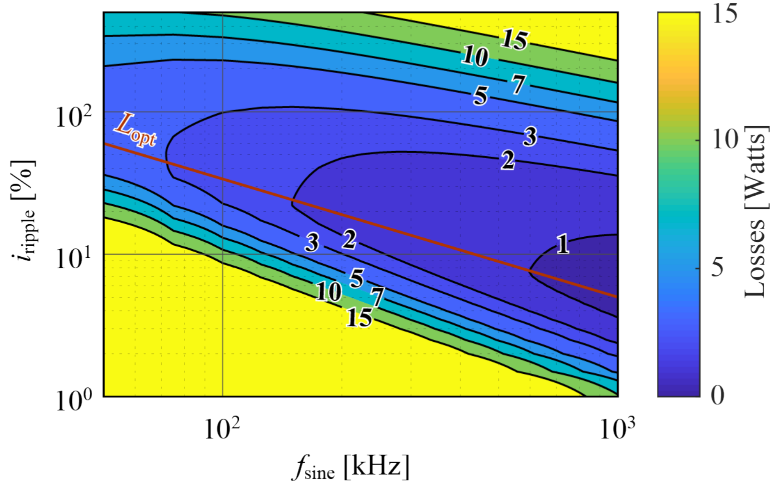
$$P_{coil} = R_{dc}\, i_{dc}^2 + R_{dc}(F_R i_{ac,pk}^2 + N_{strand}^2 G_R H_{s,rms,pk}^2)$$

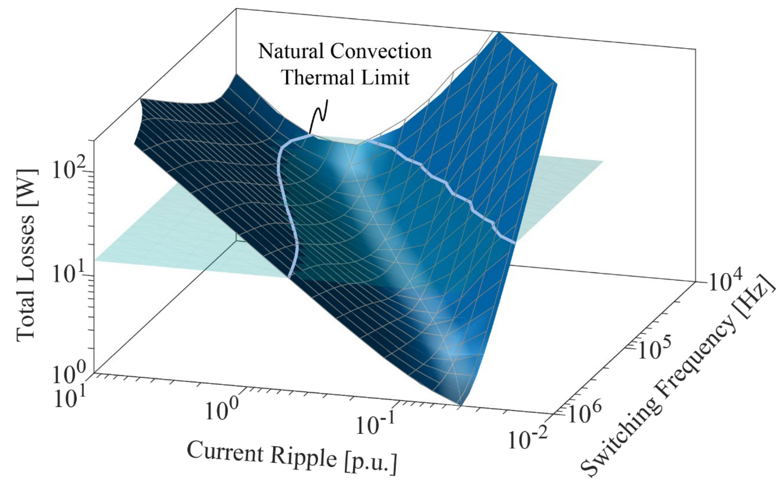
- **Simplified H-field calculation**
- **Constant Steinmetz parameters**
- **Temperature dependency disregarded**



Optimum ripple (i.e., Lopt) @Nopt ≈ Nsat

Investigation based on analytic models

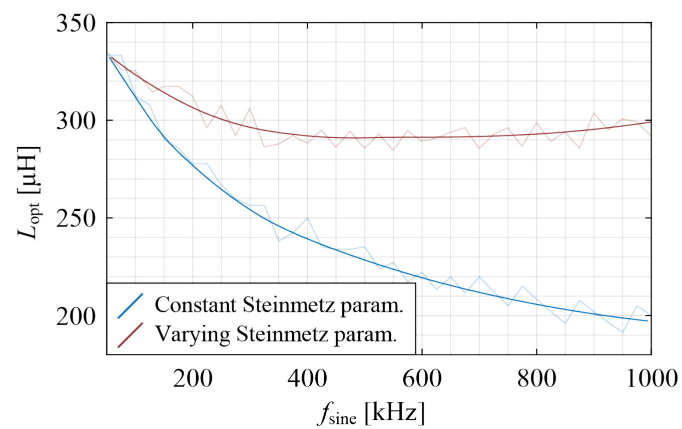




- **With increasing $f\uparrow \rightarrow i_{opt}\downarrow$**
- **With increasing $f\uparrow \rightarrow P_{tot}\downarrow$**
- **From analytical calculations:**

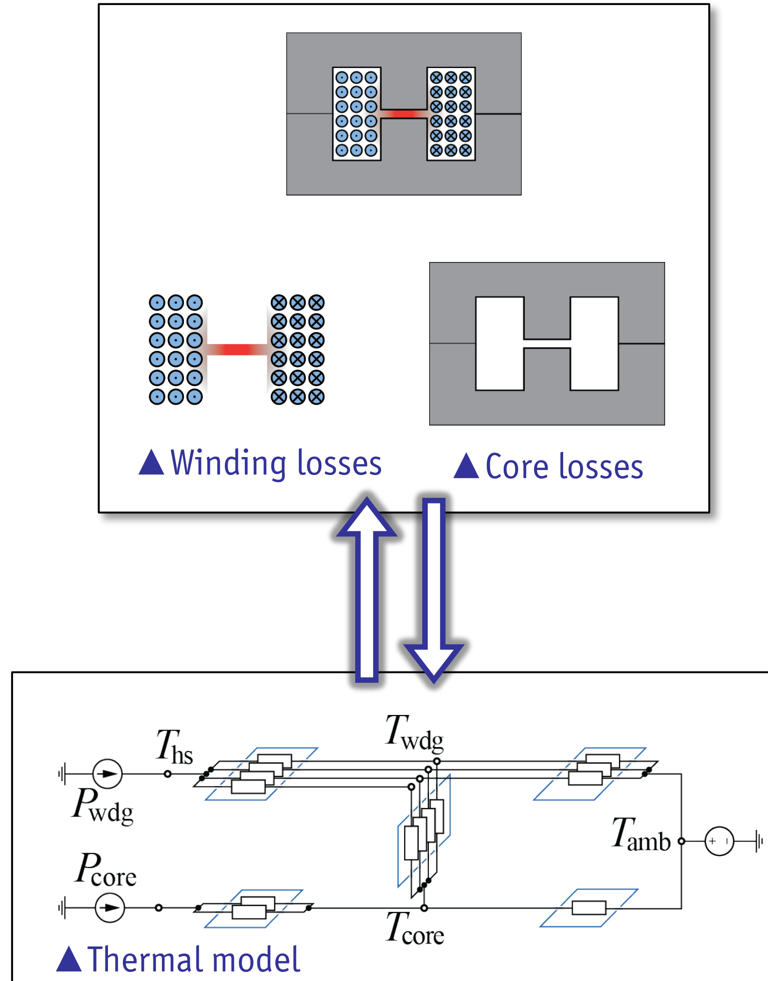
$$L_{opt} \propto f_{sine}^{\frac{\alpha-\beta}{2+\beta}}$$

With increasing $f\uparrow \rightarrow \alpha\uparrow$



ElectroMagnetic – Thermal (EMT) Model

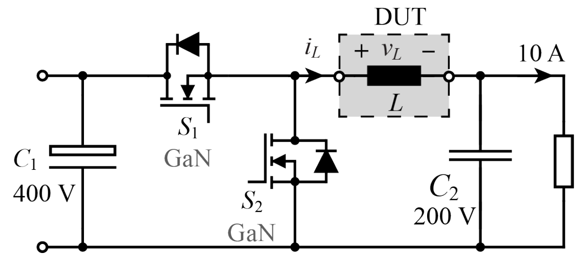
- **Implemented in MATLAB**
- **Core losses calculation:**
  - General Steinmetz Equation – **GSE**
  - Premeasured/Tabulated **Steinmetz coefficients** considering the effects of B_{ac}, B_{dc}, f, T
- **Winding losses calculation:**
  - **Ferreira – Bessel** functions
  - **H-field** estimation using the **mirroring method**
- **Reluctance model**
  - Accurate **airgap** and **flux DC-bias** definition
  - **3D airgap reluctance** calculation
- **Detailed thermal model**
- **EMT coupling iteratively until temperature convergence**



Analysis of identified losses

Analytic approach

- **Specifications**
  - V_{in} = 400 V
  - V_{out} = 200 V
  - d = 50 %
  - P = 2 kW



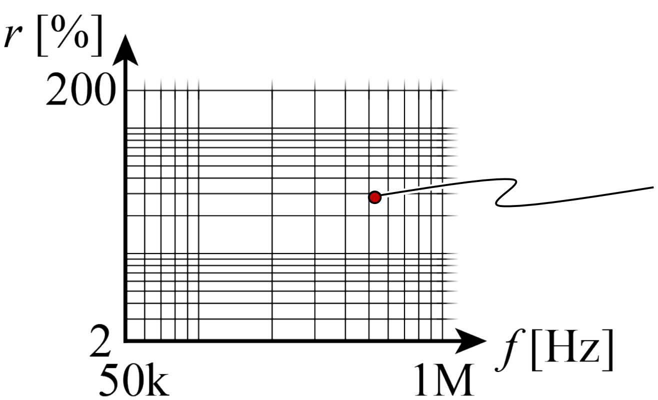
- **Semi-numeric approach using EMT model**
  - Considered ripple and frequency ranges:

    Switching frequency (*f*): **50kHz ... 1MHz**

    Current ripple pk-pk (*r*): **2% ... 200%**

$$r = \frac{I_{\mathrm{AC,pk-pk}}}{I_{\mathrm{dc}}}$$

▲Current ripple definition



- For each ***r* − *f*** pair ***L*** is defined from:

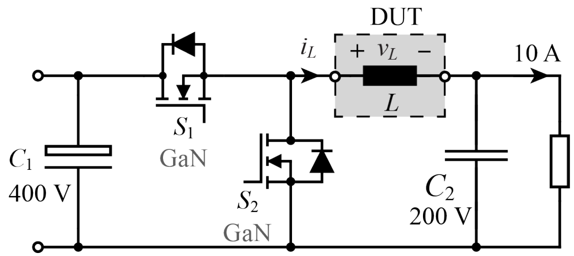
$$L(f,r) = \frac{1}{fr}\frac{(1-D)DU_{\mathrm{in}}}{I_{\mathrm{dc}}}$$

- Remaining **DOF** the **number of turns (N)**
- Local optimization wrt ***N***

Analysis of identified losses

Analytic approach

- Specifications
  - V_{in} = 400 V
  - V_{out} = 200 V
  - d = 50 %
  - P = 2 kW



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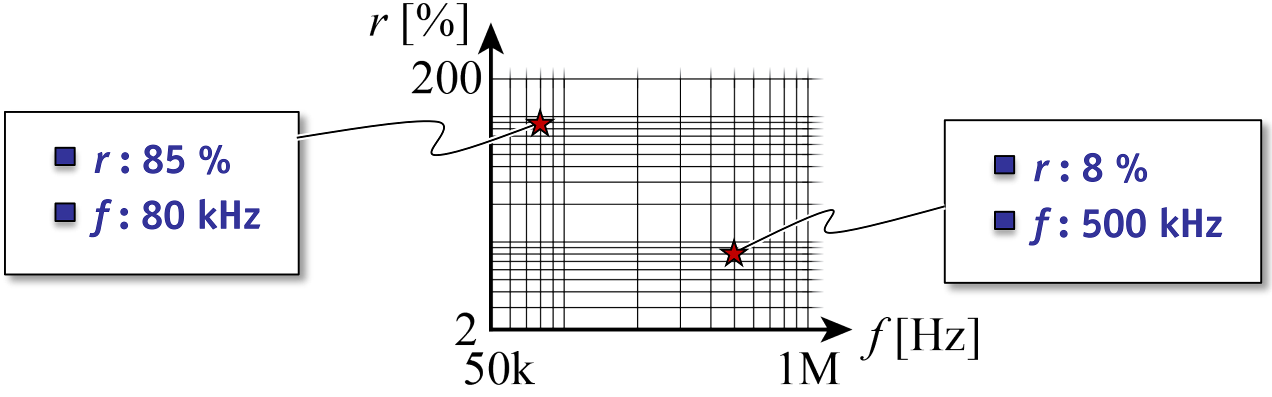
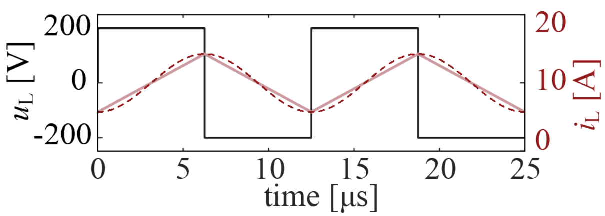


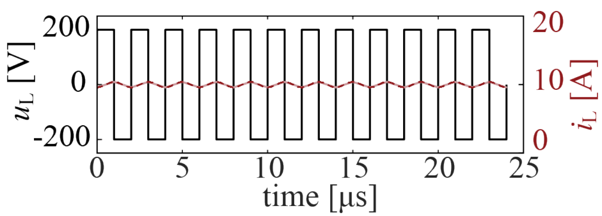
Analysis of identified losses

Local optimization of individual operating points (E55/28/21, N87 – d_{strand} = 100µm)

$\underbrace{r : 85\ \%,\ f : 80\ \mathrm{kHz}}_{L\,=\,147\,\mu\mathrm{H}}$



$\underbrace{r : 8\ \%,\ f : 500\ \mathrm{kHz}}_{L\,=\,250\,\mu\mathrm{H}}$



Analysis of identified losses

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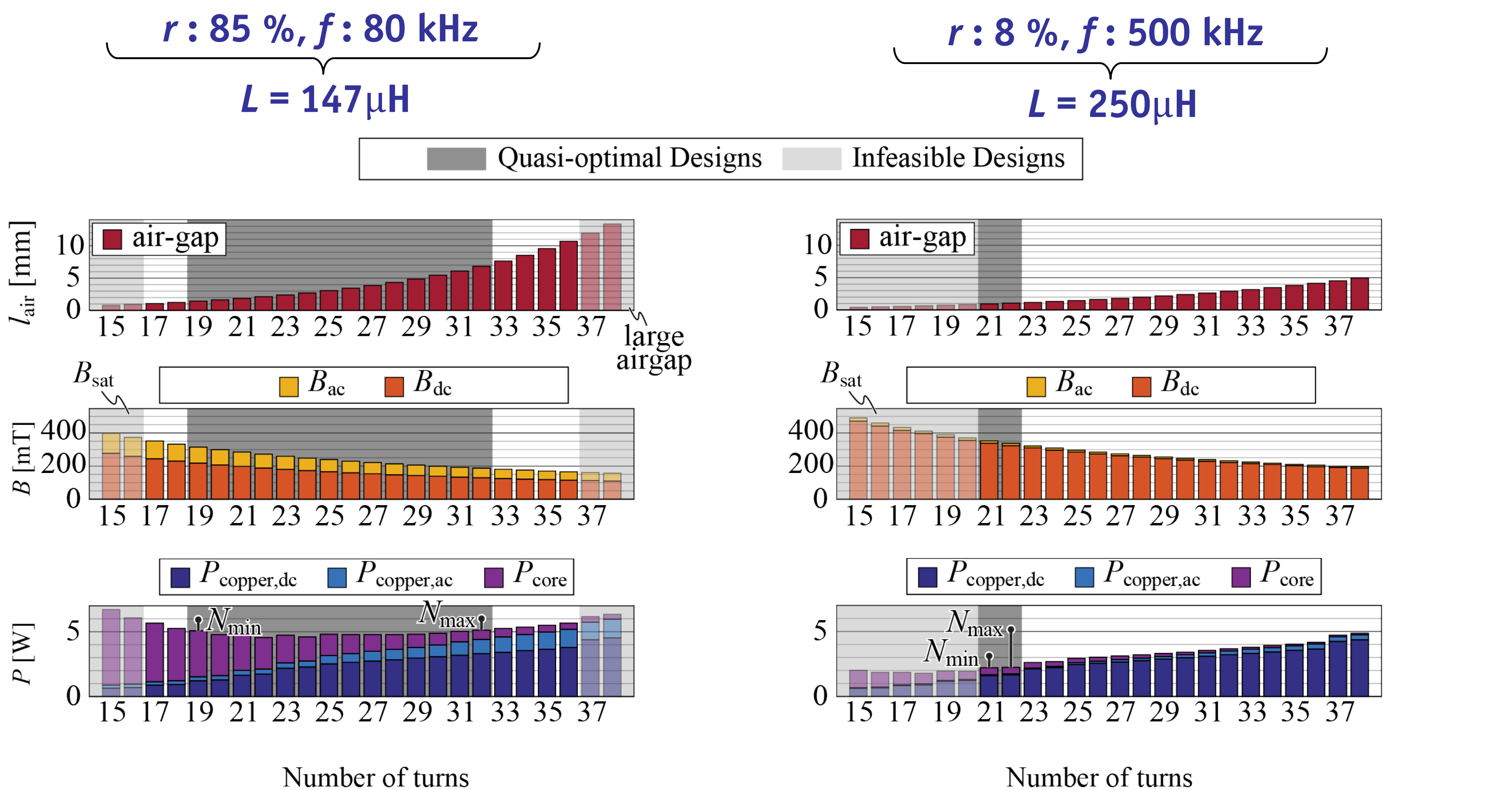
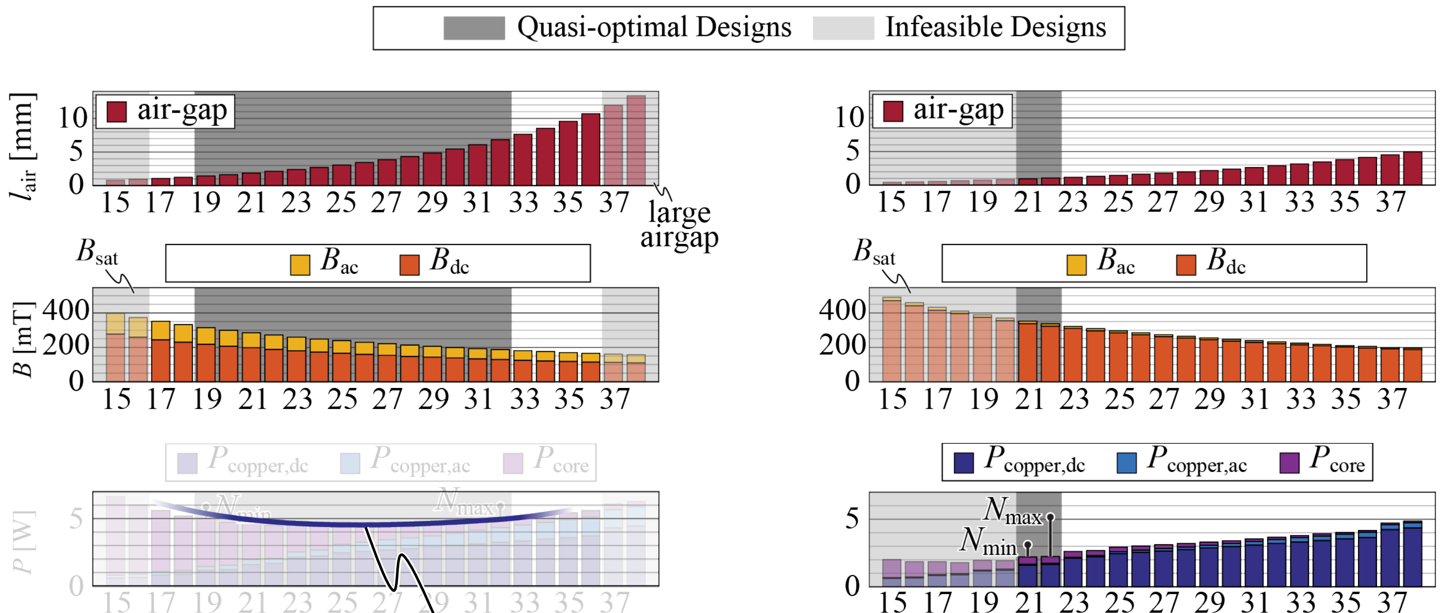


Analysis of identified losses

Local optimization of individual operating points (E55/28/21, N87 – d_{strand} = 100µm)

r : 85 %, f : 80 kHz — **L = 147µH**

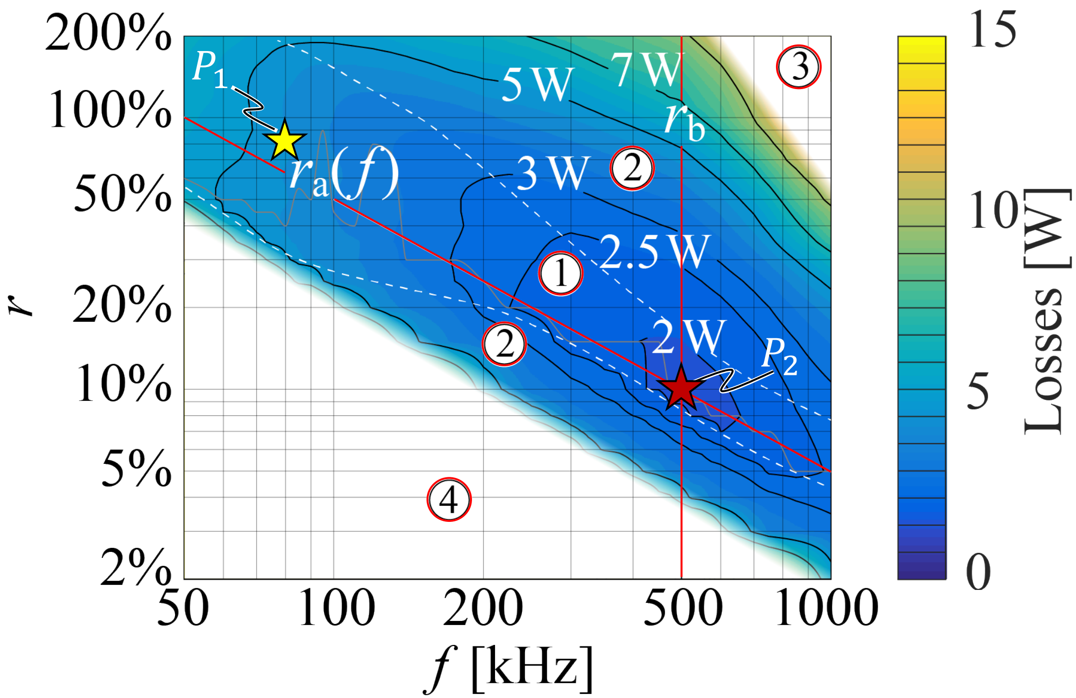
r : 8 %, f : 500 kHz — **L = 250µH**



$$P_{\text{tot}}(N) \approx P_{\text{coil},25}\left(\frac{N}{25}\right)^{2} + P_{\text{core},25}\left(\frac{N}{25}\right)^{-\beta}, \text{ where } P_{\text{coil},25} \approx P_{\text{core},25} \approx \frac{P_{\text{tot},25}}{2}$$

Analysis of identified losses

Complete f-r domain investigation (E55/28/21, N87 – d_{strand} = 100µm)



- **Regions identified:**
  1. Optimal design region
  2. Thermally valid – suboptimal designs
  3. Exceedingly high **HF losses**
  4. Exceedingly high **LF losses**
- $P_2 \approx 30\%\ P_1$
- **Trajectories of interest:**
  1. $\boldsymbol{r_a}$: optimal $\boldsymbol{r}$, $\boldsymbol{f}$ pairs

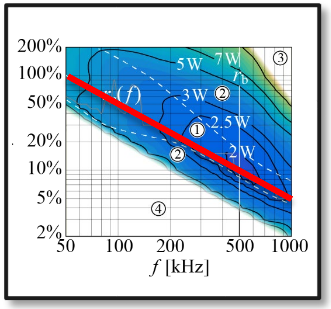
$$r_a(f) \approx \frac{1}{\left(\frac{f}{50\text{kHz}}\right)}$$

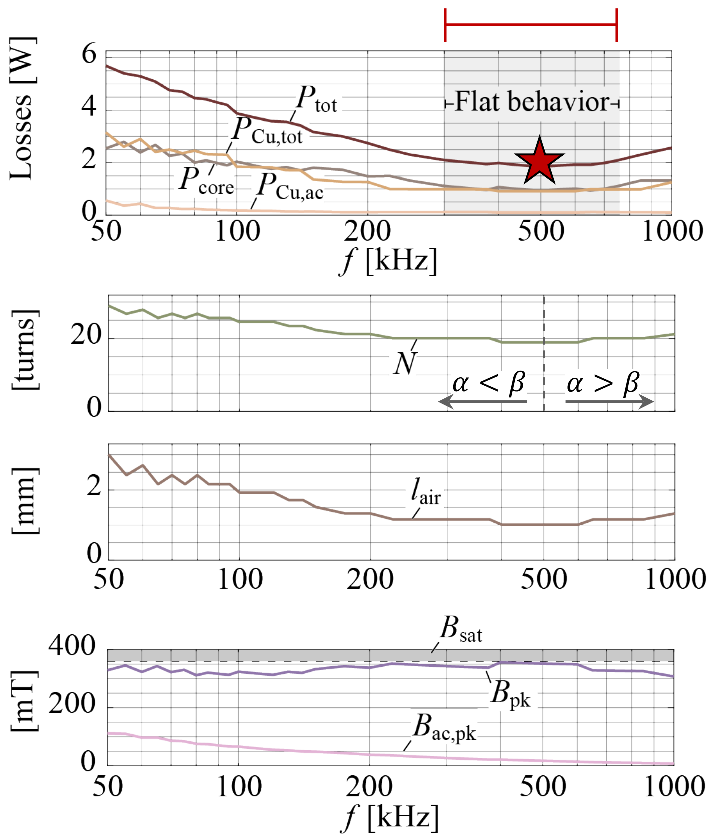
Constant Inductance !

  2. $\boldsymbol{r_b}$: constant frequency, ripple sensitivity

Analysis of identified losses

Optimal trajectory r_a





- **Constant L**
- **Flat behavior for** $f \in [300, 750]$ kHz
- **Basic scaling laws**

$$P_{\text{core}} \propto f^{\alpha-\beta}$$

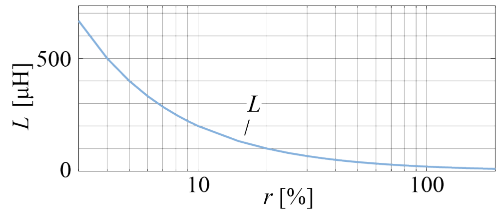
$$P_{\text{coil,HF}} \propto R_{dc} \underbrace{G_R}_{\propto f^2} \underbrace{H^2_{pk,HF}}_{\propto f^{-2}} \propto 1$$

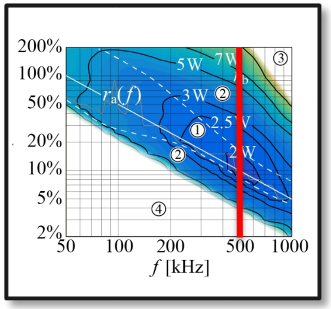
$$\text{With } f \uparrow \Rightarrow \begin{cases} N \downarrow, \text{if } \alpha < \beta \\ N \uparrow, \text{if } \alpha \geq \beta \end{cases} \quad \text{such that: } \boldsymbol{P}_{\textbf{core}} \approx \boldsymbol{P}_{\textbf{coil}}$$

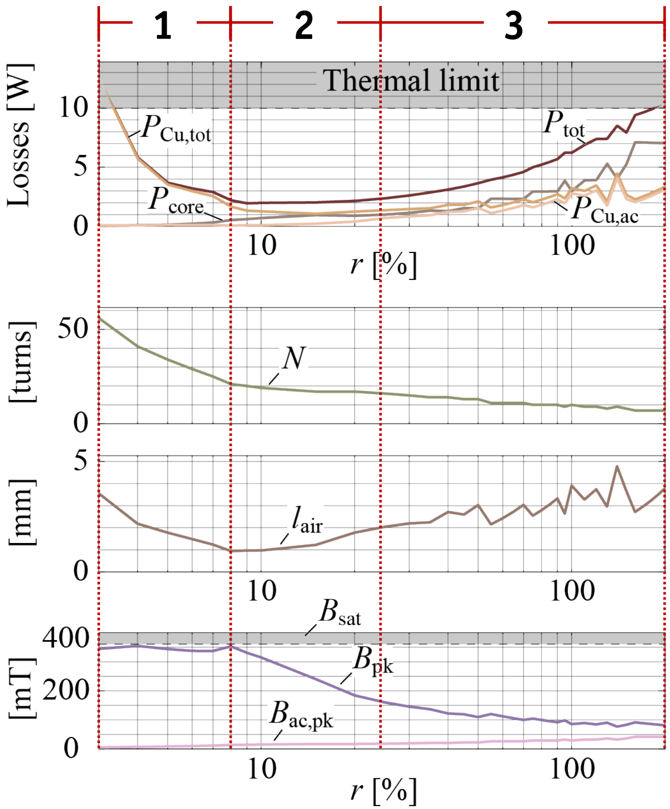
- **Global opt** $@f = 500$ kHz, where $\alpha \approx \beta$
- **Summary regarding opt. designs:**
  - **Balanced copper/core** losses
  - $\boldsymbol{B}_{\textbf{pk}}$ close to $\boldsymbol{B}_{\textbf{sat}}$

Analysis of identified losses

f = 500 kHz trajectory r_b







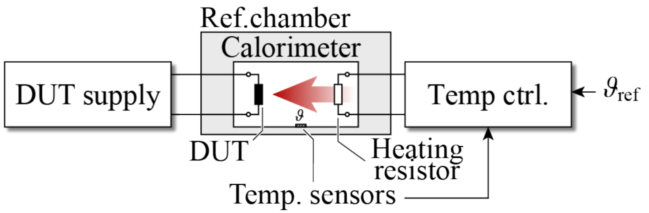
- **3 distinct Regions**
- **Region 1 ($r < 8\%$)**
  - High L → High N → High J
  - B_{pk} limited by B_{sat}
  - **High DC copper** losses
- **Region 3 ($20\% \geq r$)**
  - Increasing **AC losses**
- **Region 2 ($8\% \leq r < 20\%$)**
  - Flat behavior!
  - Further details → P. Papamanolis, APEC 2018

Experimental verification

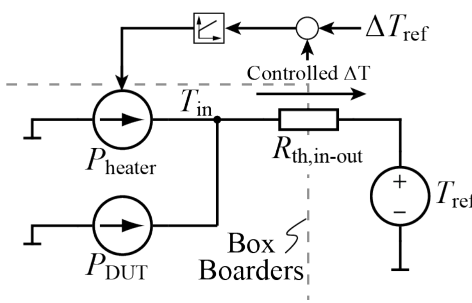
Measurement setup

- **Operating principle**
  - Step 1: **DUT disabled**
    @ steady state (i.e. $T_{in,amb} = T_{set}$). [$P_{heater} = P0$]
  - Step 2: **DUT enabled.** Controller adapts
    [$P_{heater} = P1$] to preserve constant T_{in}.
  - $P_{DUT} = P0 - P1$

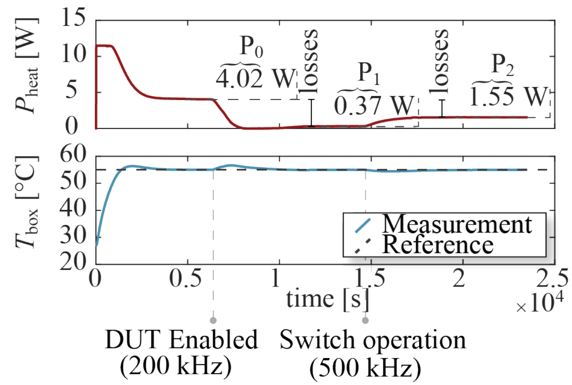
- **Properties of measurement method**
  + No calibration required
  + High accuracy at low loss measurements
  + Measurement at desired "ambient" temperature
  - Large time constants because of the DUT
  - Increased complexity



▲ Calorimetric meas. setup [Kleeb 2013]



▲ Simplified schematic

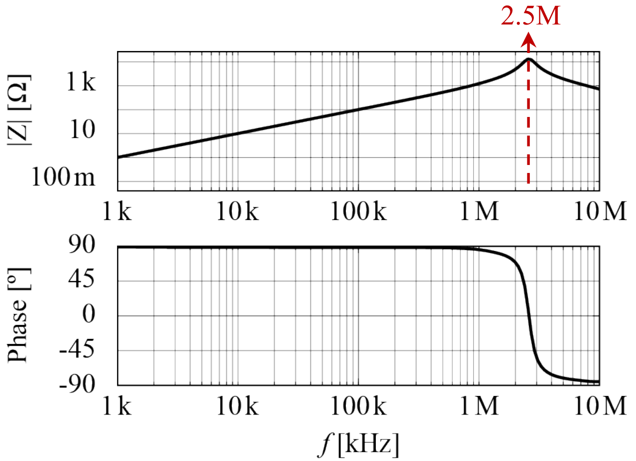


▲ Measurement example

Experimental verification

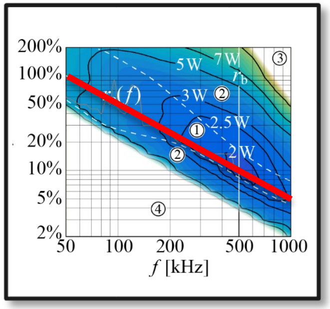
DUT considered

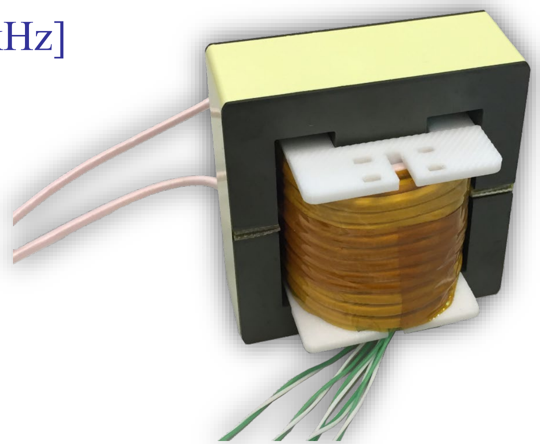
- **Single inductor design**
  - **Core:** E55/28/21
  - **Litz wire** – 900x100μm
  - **L** = 167 μH
  - **N** = 16 (2 layers x 8 turns)
  - **Total air-gap:** 800μm (400μm per leg)
  - **Resonance freq @ 2.5 MHz**



▲Impedance measurement of DUT

- **Compromise between optimal designs** for $f \in [200\text{kHz}, 750\text{kHz}]$





▲Picture of DUT

Experimental verification

Measurements

- **Same trend**
- **Underestimation** observed, up to **0.5** Watts (error below 25%), reasons:
  - ▶ **Core-loss data** interpolation for ***f* > 270 kHz**
  - ▶ Conductor close to air-gap → intense fringing field losses

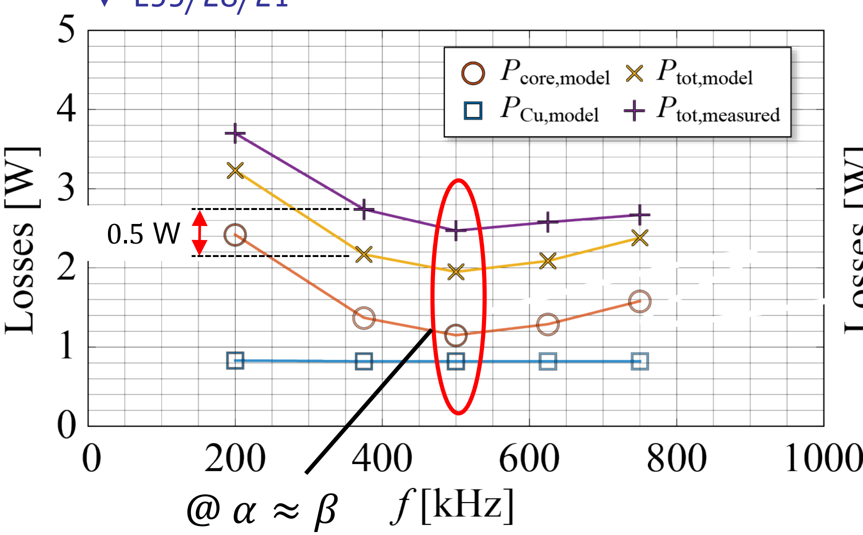
- According to prev. **scaling laws** for ***N* = const.**

$$P_{\text{core}} \propto f^{\alpha-\beta}$$

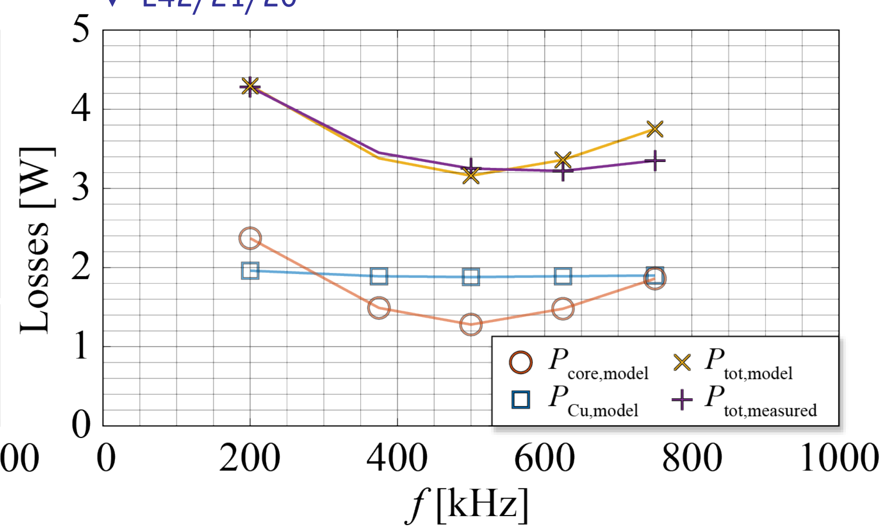
$$P_{\text{coil,HF}} \propto R_{dc}\underbrace{G_R}_{\propto f^2}\underbrace{H^2_{pk,HF}}_{\propto f^{-2}} \propto 1$$

- **Minimum @ α ≈ β**

▼ E55/28/21



▼ E42/21/20



▲ Model evaluation ***VS*** Measurement

Extension to further materials

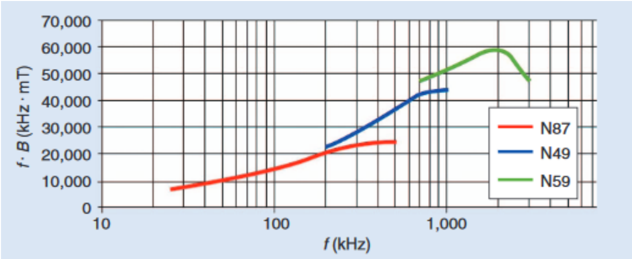
Measurements

- Main limitation is where $\alpha = \beta$ (This corresponds to the peak of the PF)

$$\text{GSE: } p = k\, f^{\alpha} B^{\beta} \Rightarrow B = \left(\frac{p}{k}\right)^{\frac{1}{\beta}} f^{-\frac{\alpha}{\beta}}, \qquad PF = Bf = \left(\frac{p}{k}\right)^{\frac{1}{\beta}} f^{\frac{\beta-\alpha}{\beta}} = \text{const.}\, f^{\frac{\beta-\alpha}{\beta}}$$

- Using existing **performance factor** data, together with the **proposed guideline**, allows for estimation of the **optimal operating points (r_{opt}, f_{opt})**.

  - Data from TDK-EPCOS
  - T = 100 °C
  - P_L = 300 kW/m^3



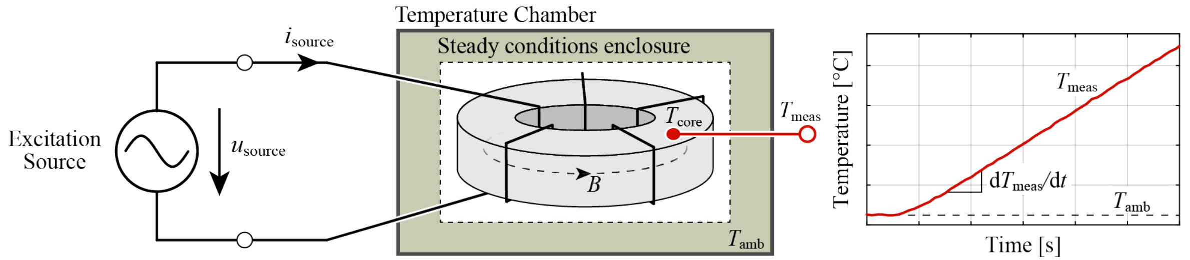
- Need of materials with **better PF** → Typically achieved at **higher frequencies** → At these frequencies **GaN semiconductors** achieve great performance

- Existing electrical methods limited, due to **parasitics**, intensive **calibration** and **post-process requirements** and need for **expensive equipment**

Extension to further materials

Measurements

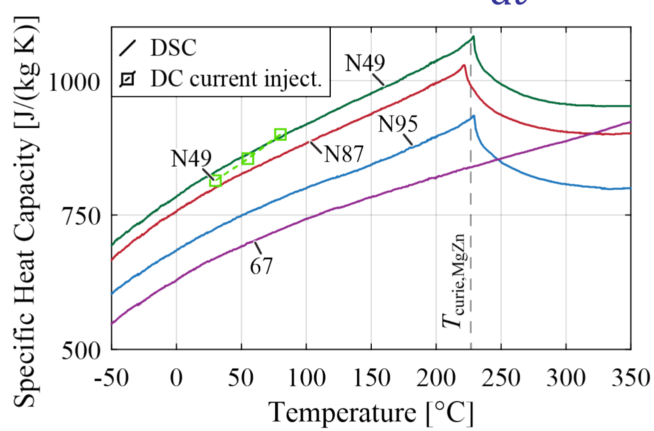
- Acquirement of new data using **newly proposed transient calorimetric method** from PES ETH-Zurich *(presented at APEC 20' – New Orleans)*



- Accurate measurement within some **tens of seconds**

- Knowledge of the **cores thermal capacitance** required, since: $P_{core} = C_{th,core}\dfrac{dT_{meas}}{dt}$

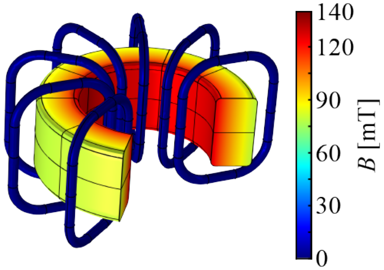
- Proposed methods:
  - **Differential Scanning Calorimetry (DSC)**
  - **DC current injection through core block**



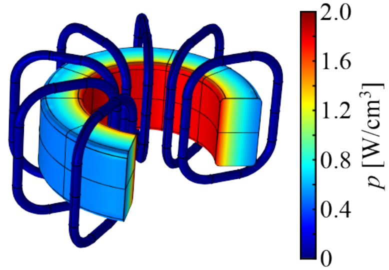
Extension to further materials

Measurements

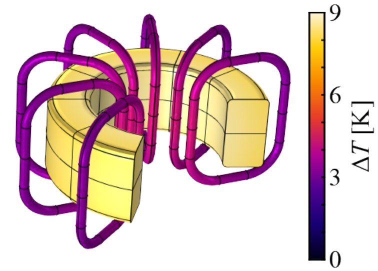
▶ Concept verification through coupled Magnetic and Heat transfer FEM simulations



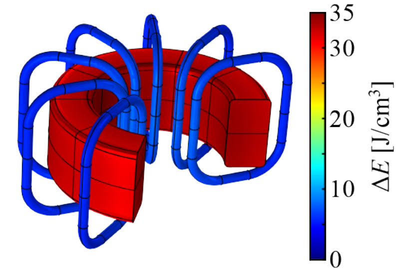
▲ Flux density



▲ Loss density



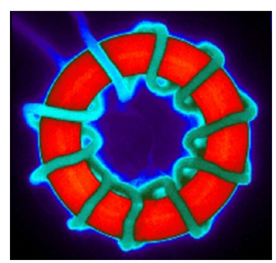
▲ Temperature distribution



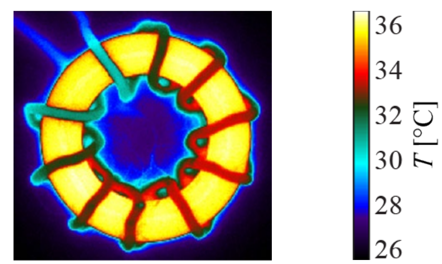
▲ Stored energy distribution

▶ Further verification using high accuracy IR thermal imaging

▲ T_{core} = 30°C



▲ T_{core} = 34°C

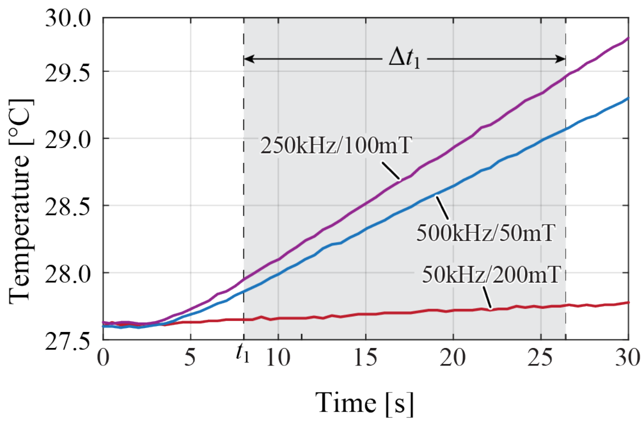


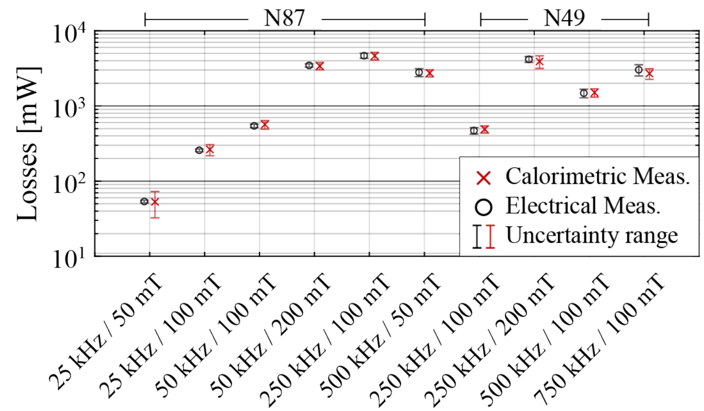
▲ T_{core} = 36°C

Extension to further materials

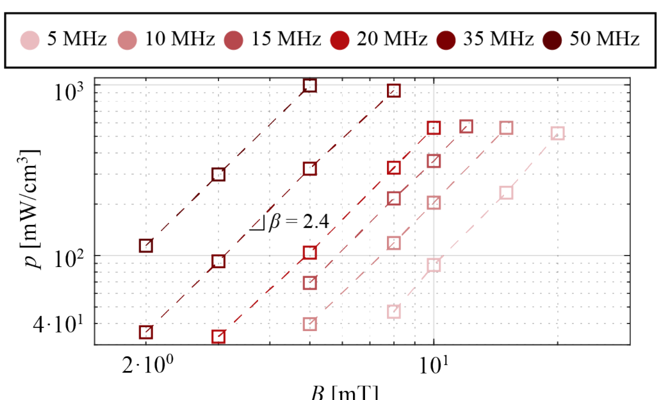
Measurements

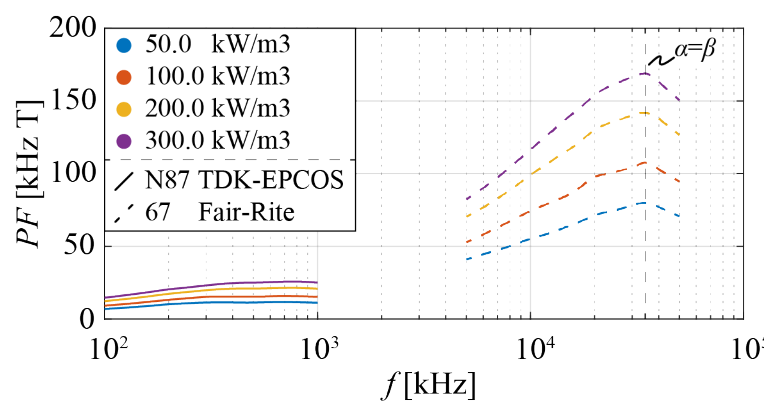
- Application on MnZn ferrite TDK-EPCOS N87/N49 – Comparison to electrical measurements





- Application on NiZn ferrite Fair-Rite 67 [5 – 50 MHz]





Conclusions

Conclusion (1) / Practical Guidelines

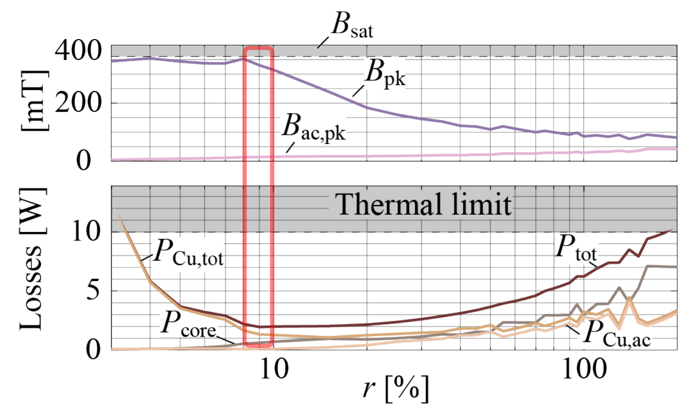
- Provided ***magnetic core*** → f_{opt} exists @ $\alpha \approx \beta$
  $f > f_{opt}$ → **Increases losses**
- Provided f_{opt}, choose N_{opt} and r_{opt} such that:
  - **Balanced copper/core** losses
  - B_{pk} close to B_{sat}
- **Minimum losses** correspond to approx. **constant** L_{opt}

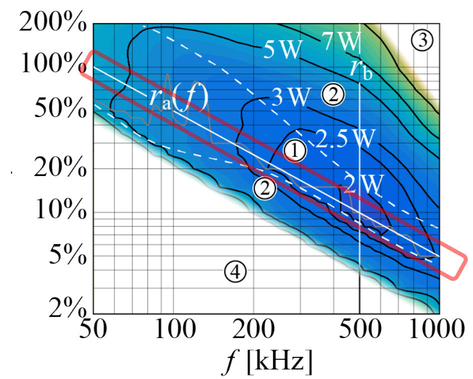
$$L_{opt} = \frac{1}{f_{opt} r_{opt}} \frac{(1-D)DU_{in}}{I_{dc}}$$

- For **any frequency** the **optimal current ripple** equals:

$$r_{subopt}(f) = \frac{1}{f L_{opt}} \frac{(1-D)DU_{in}}{I_{dc}}$$

@ $f = f_{opt}$





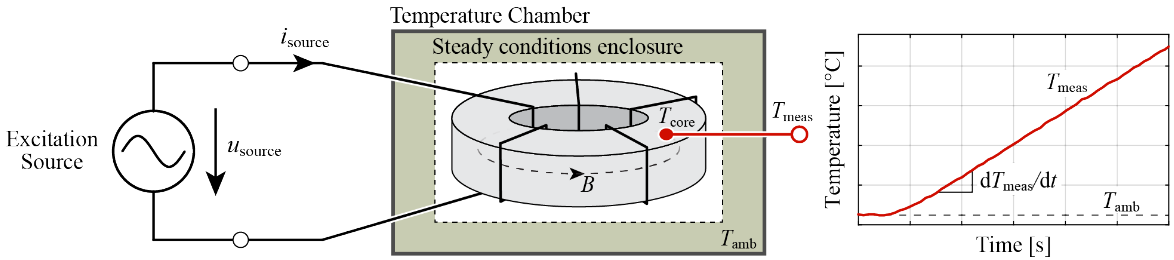
Conclusion (2) / Observations and Future steps

Useful Observations

- **3 different flat-optima regions of interest (N87 E55/28/21 – 100µm):**
  - ▶ Provided ***f* & *r*** with respect to ***N***. e.g. $N \in [\,19, 31\,]$ @ $f = 80$ kHz, $r = 85\%$
  - ▶ Provided ***L*** with respect to ***f***. e.g. $f \in [\,300\text{ kHz}, 750\text{ kHz}]$ @ $L = 167$ µH
  - ▶ Provided ***f*** with respect to ***r***. e.g. $r \in [\,8\%, 20\%\,]$ @ $f = 500$ kHz

Experimental Verification

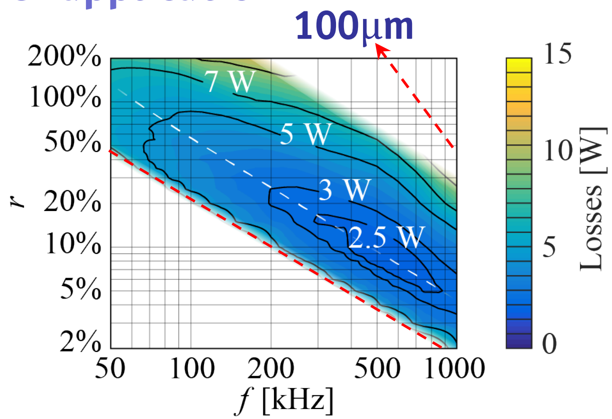
- ▶ **Total losses** measurement using **steady-state calorimeter**
- ▶ Measurement of **core-losses** and **PF** evaluation using **transient calorimetric measurement**
  (Further details at APEC 2020 – New Orleans)



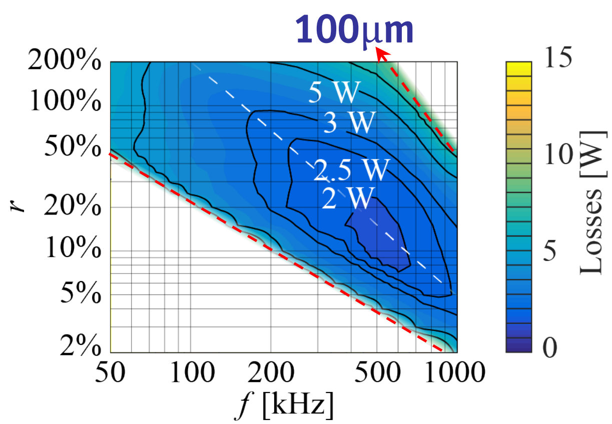
Discussion...

Analysis of identified losses

Further application

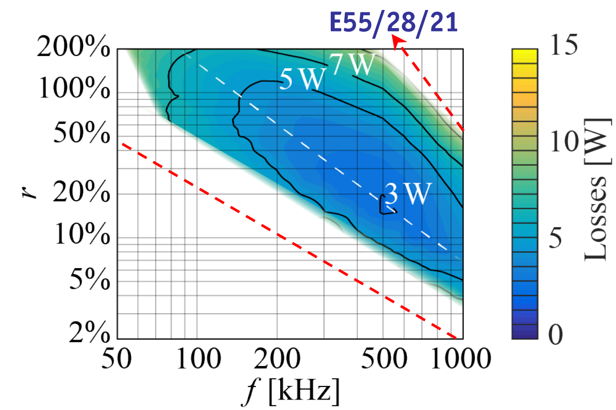


▲ Litz wire diameter: 200µm



▲ Litz wire diameter: 71µm

- **Different litz wire strand diameter**
  - 200µm: $d_{\text{strand}} \uparrow \rightarrow F_R, G_R \uparrow \rightarrow P_{\text{Cu,ac}} \uparrow$
  - 71µm : $d_{\text{strand}} \downarrow \rightarrow F_R, G_R \downarrow \rightarrow P_{\text{Cu,ac}} \downarrow$
  - $P_{\text{Cu,dc}} \rightarrow$ const. due to similar fill factor (k)



▲ E42/21/20 – 100µm

- **Different core: E42/21/20**
  - Area of **valid designs** narrower
  - Operation $@f_{\text{low}}$ **thermally** invalid

Experimental verification

Measurement setup

- Calorimeter consists of 2 boxes
  - ▶ Inner enclosure (temp. sensors, heater, DUT)
  - ▶ Outer enclosure (reference chamber)
- Heater control unit (preserve temperature)
- DUT excitation circuit
- Operating principle
  - ▶ Step 1: **DUT disabled**
    @ steady state (i.e. $T_{in,amb} = T_{set}$). [$P_{heater} = P0$]
  - ▶ Step 2: **DUT enabled.** Controller adapts
    [$P_{heater} = P1$] to preserve constant T_{in}.
  - ▶ $P_{DUT} = P0 - P1$
- Properties of measurement method

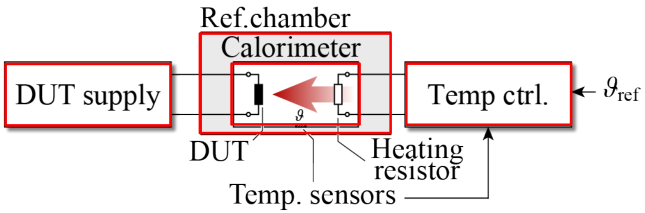
  \+ No calibration required

  \+ Measurement at desired "ambient" temperature

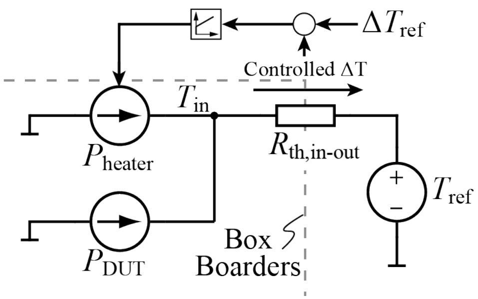
  \+ High accuracy at low loss measurements

  \- Large time constants because of the DUT

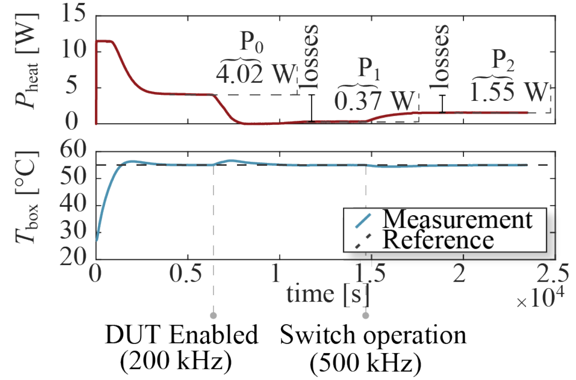
  \- Increased complexity



▲ Calorimetric meas. setup [Kleeb 2013]



▲ Simplified schematic



▲ Measurement example