Key Enablers for Ultra-Compact Server Power Supplies

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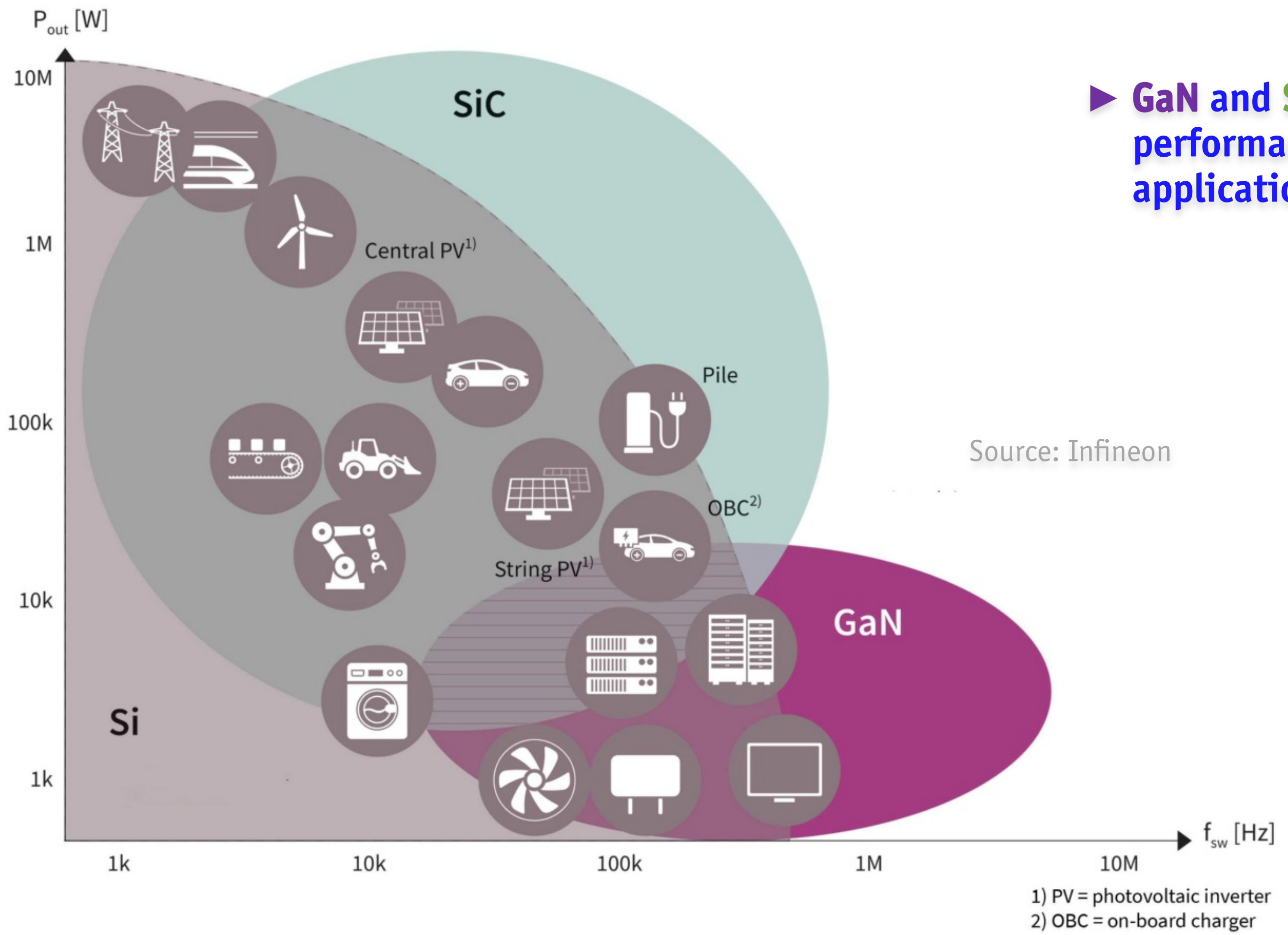
Wide-Bandgap Semiconductors



Source: Infineon

- **GaN and SiC devices allowing to improve performance in various power electronic applications**

State-of-the-Art PSU for Server Systems

- Si-based supplies
- 1+1 redundancy scheme
- 12-V output, kW-range
- High efficiency standards
  - 80 Plus Titanium
  - 96% peak efficiency @ 50% load
- Defined front frame, variable length
  - 40 mm X 72 mm X 265 mm @ 3.0 kW
    185 mm @ 2.4 kW
- High power densities
  - from 50 to 70 W/in^3

Source: Lenovo

Next-Generation PSU for Server Systems

- GaN-based supplies
- 1+1 redundancy scheme
- 12-V output, kW-range
- High efficiency standards
  - 80 Plus Titanium
  - 96% peak efficiency @ 50% load
- Defined front frame, shortest length
  - 40 mm X 72 mm X 170 mm @ 3 kW
- Ultra-high power densities
  - Above 100 W/in^3
- Is GaN a key enabler?
- Are there other players?

Source: Lenovo

Presentation Content

- ▶ System-Level Analysis
- ▶ DC/DC-Stage Analysis
- ▶ DC/DC-Stage Demonstrator
- ▶ AC/DC-Stage Analysis
- ▶ Conclusion

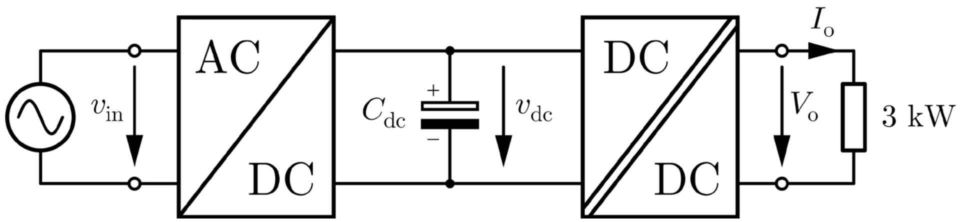
System-Level Analysis

- ► Reason for Two Conversion Stages
- ► PSU Volume Partitioning

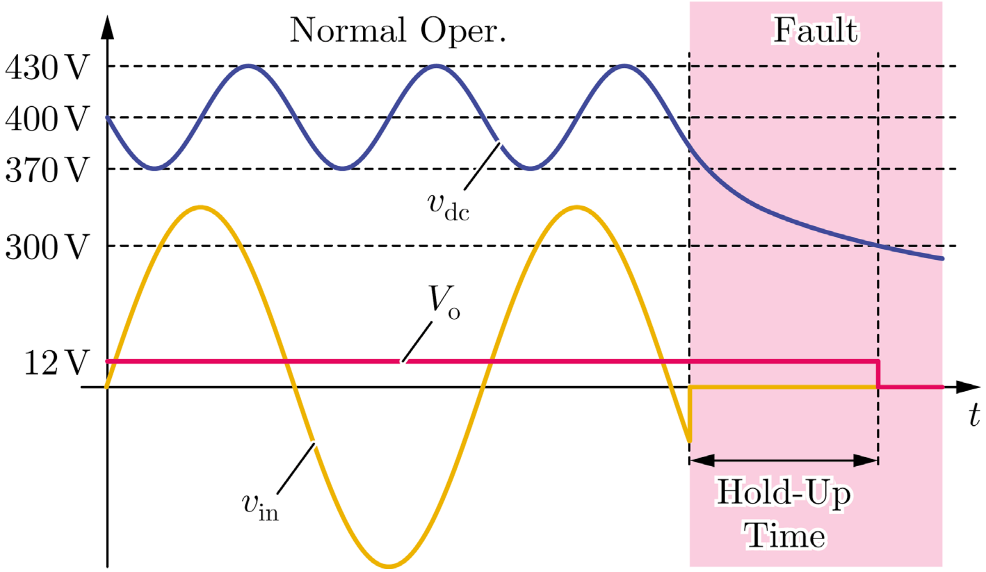
Reason for Two Conversion Stages

▶ Hold-Up Time criterion

- Requires a component that stores energy
- Defines the DC/DC-stage input voltage range



C_{dc} = 1000 µF → t_{hold} = 6 ms

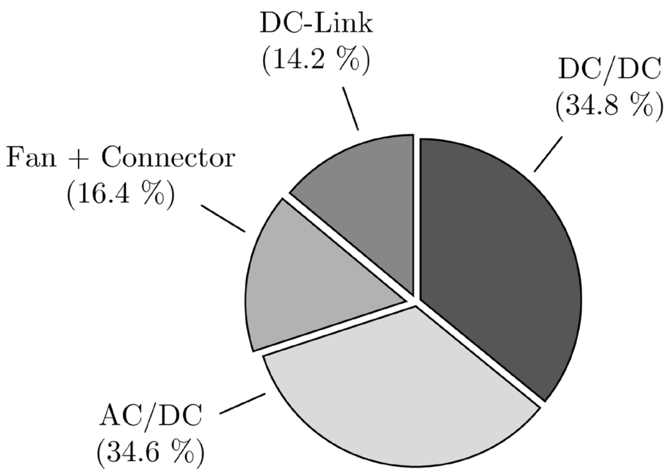


▶ 96% system efficiency

- AC/DC: 99%
- DC/DC: 97%

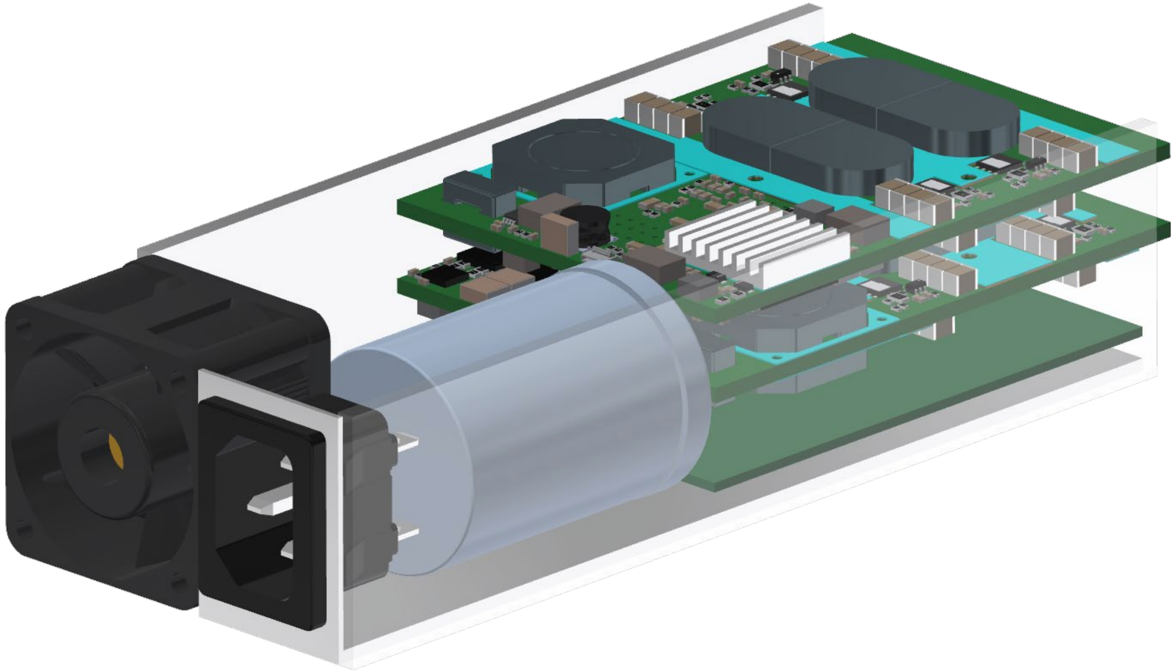
PSU Volume Partitioning

- Targeted form-factor
  - 40 mm x 72 mm x 170 mm (100 W/in³ @ 3kW)



- DC/DC module
  - P_o = 1.5 kW, $\eta_{50\%}$ = 97%, ρ = 350 W/in³

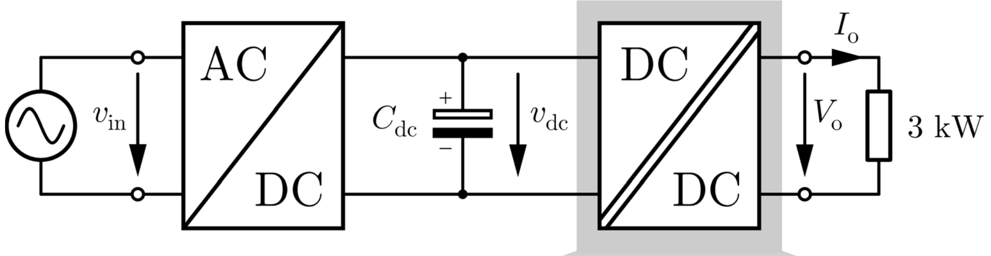
- Challenges on GaN-based DC/DC stages?

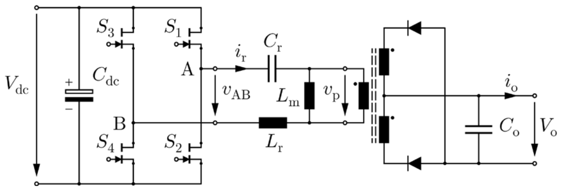


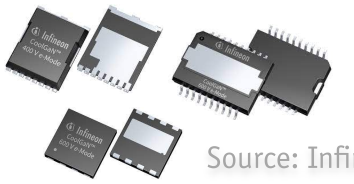
DC/DC-Stage Analysis

- ▶ Impacts of Choosing GaN Devices
- ▶ Topology as a Key Enabler
- ▶ Control as a Key Enabler
- ▶ Magnetics as Key Enablers
- ▶ Design & Efficiency

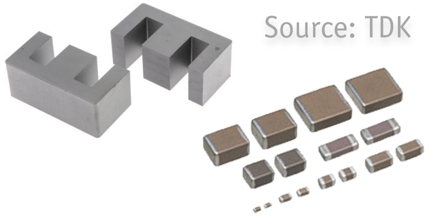
Impacts of Choosing GaN Devices







Source: Infineon



Source: TDK

▶ **Topology & Control**

- Low $I_{RMS}/|I|_{avg}$ ratios
- Soft switching
- Easy to control

▶ **CoolGaN™ Devices**

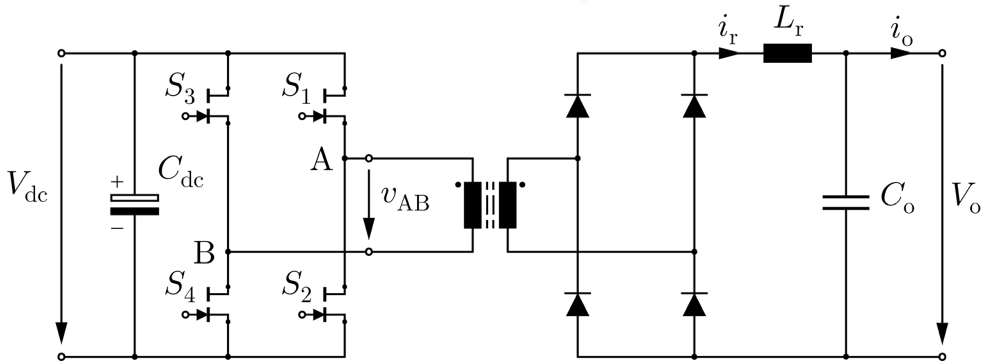
- Small on-state resistances
- Small capacitances
- No reverse recovering

▶ **HF Passives**

- Efficient
- Small
- Cost-effective

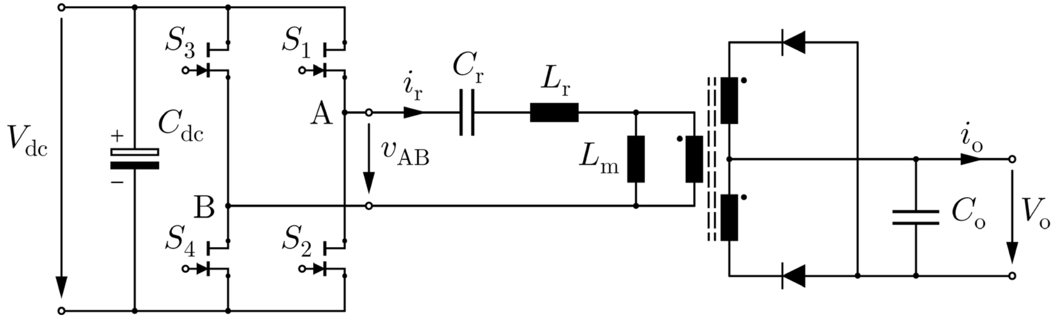
Topology as a Key Enabler

► Hard-switched, buck-based DC/DC converters



- Wide V_{dc} range
- Lower efficiency

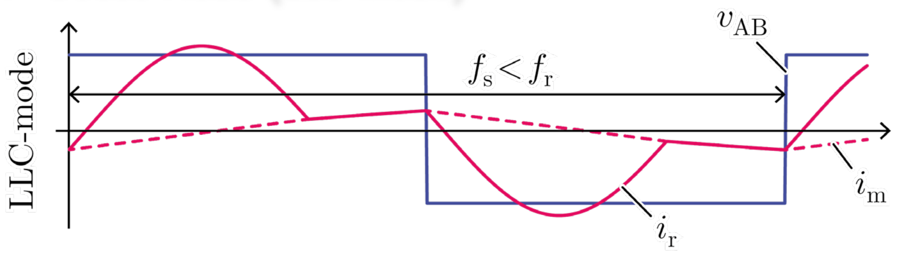
► Soft-switched, LLC-based DC/DC converters



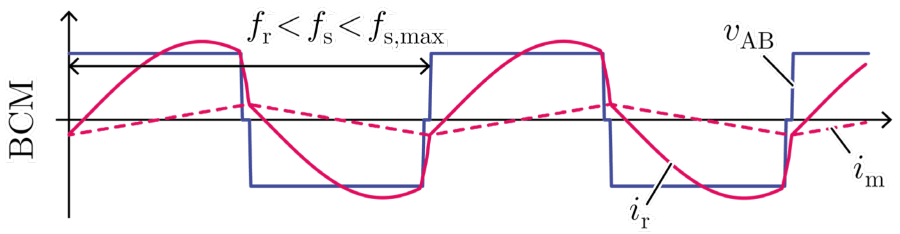
- Higher efficiency
- Narrow V_{dc} range

Control as a Key Enabler

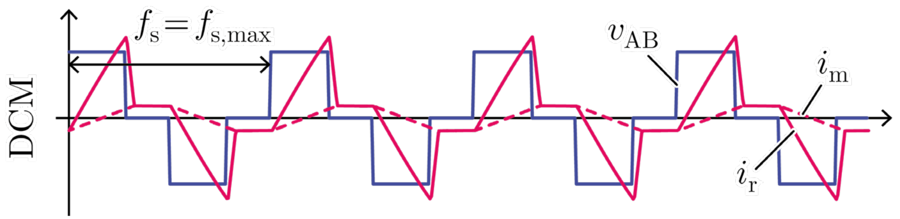
- **Boost-Mode (LLC-mode)**

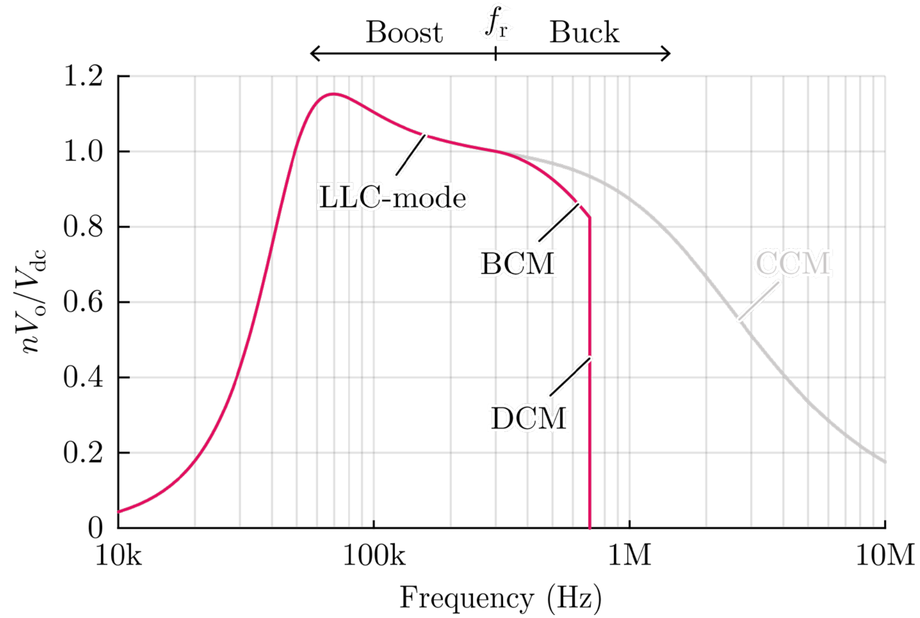


- **Boundary Conduction Mode (BCM)**

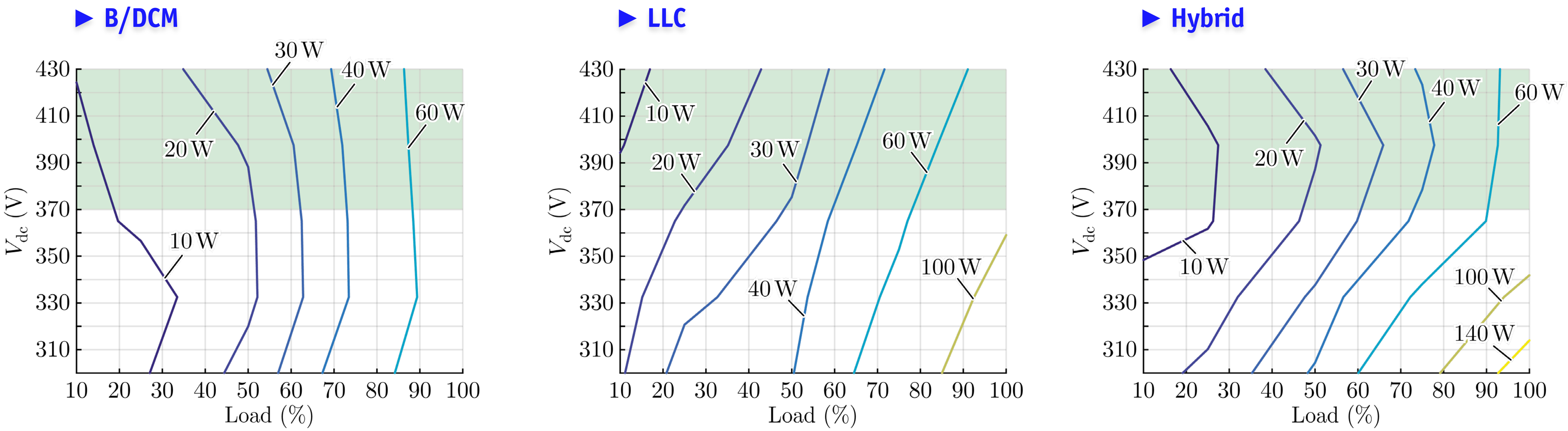


- **Discontinuous Conduction Mode (DCM)**





Control as a Key Enabler

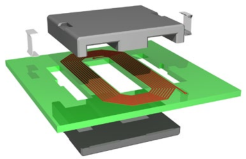


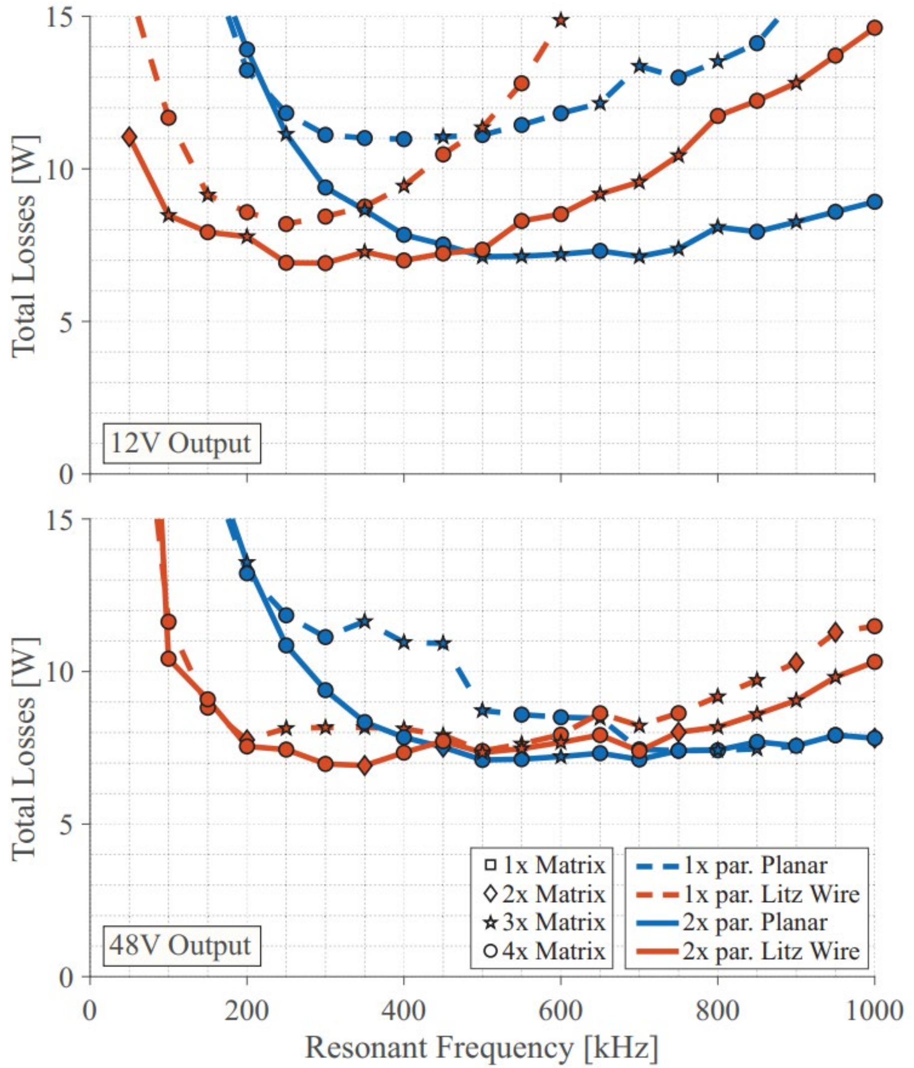
Source: G. Knabben et. al., "Wide-Input-Voltage-Range, 3 kW DC-DC Converter with Hybrid LLC & Boundary / Discontinuous Mode Control", Proc. APEC 2020

Magnetics as Key Enablers

► **Litz-wire or PCB-winding transformer?**

X





Litz

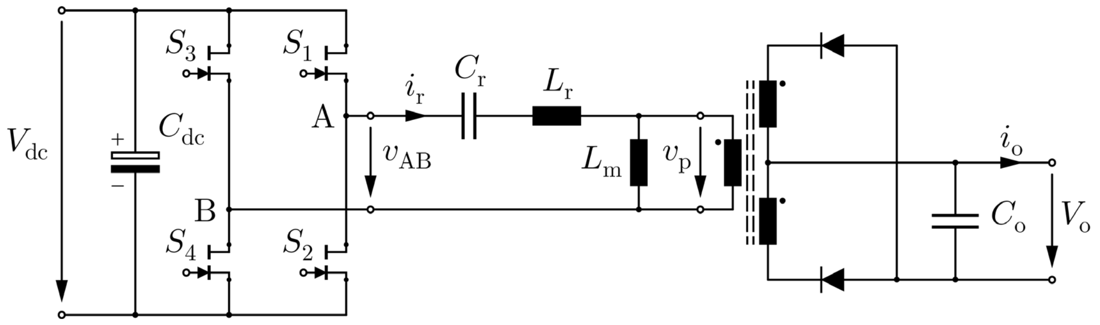
PCB

- 400V input, 3 kW DCX

Source: M. Kasper et. al., "Ultra-high Power Density Server Supplies Employing GaN Power Semiconductors and PCB-Integrated Magnetics", Proc. CIPS 2020

Magnetics as Key Enablers

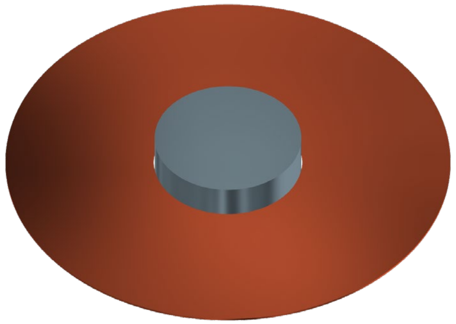
▶ **Number of turns?**



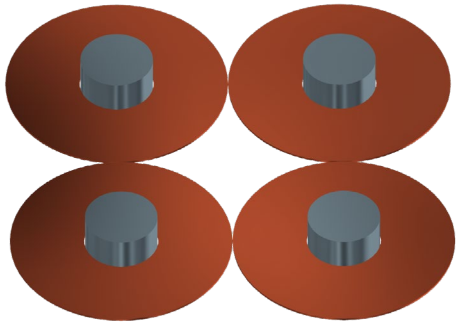
$$\hat{J} = \frac{\pi I_o N_s}{2A_w} \qquad \hat{B} = \frac{V_o}{4 f_s N_s A_c}$$

- **Single-turn secondary windings!**

▶ **Number of windings?**



Single winding



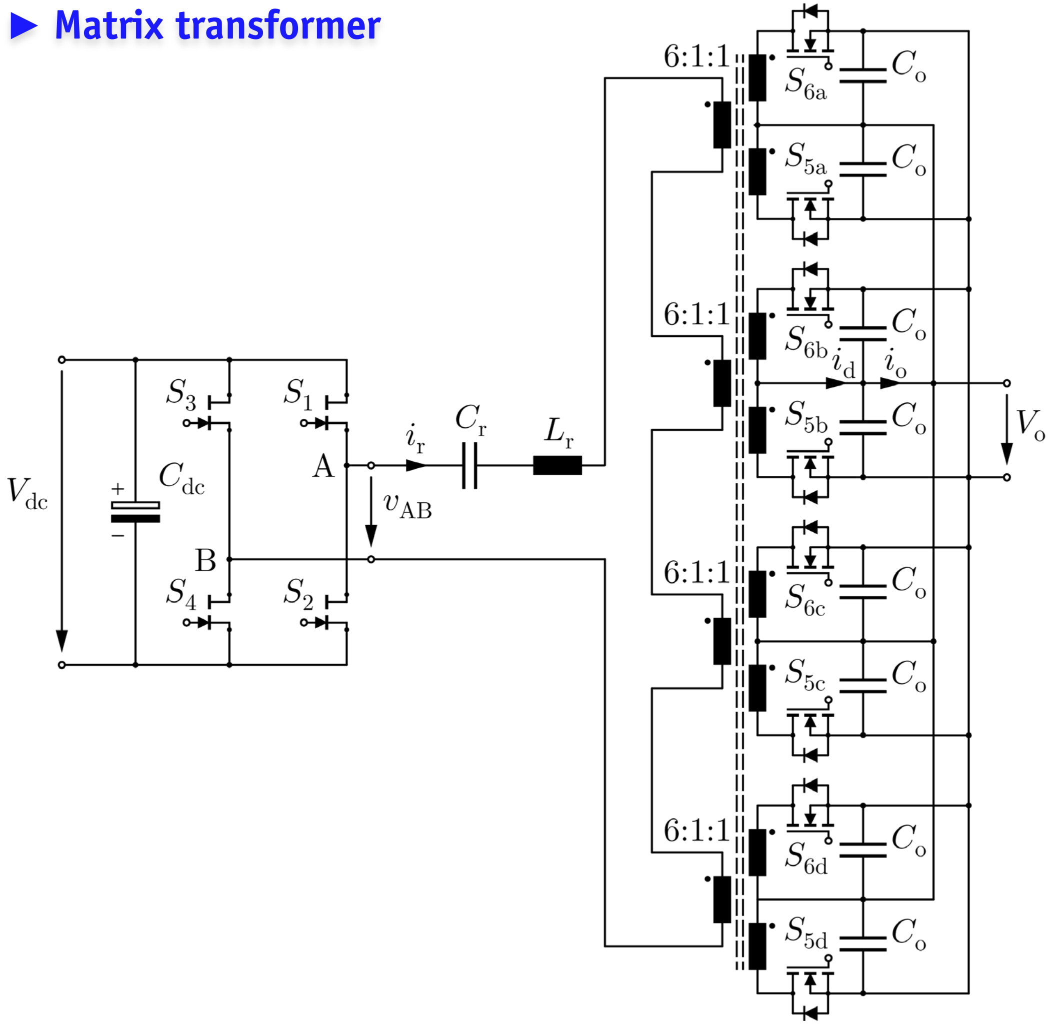
Multiple windings

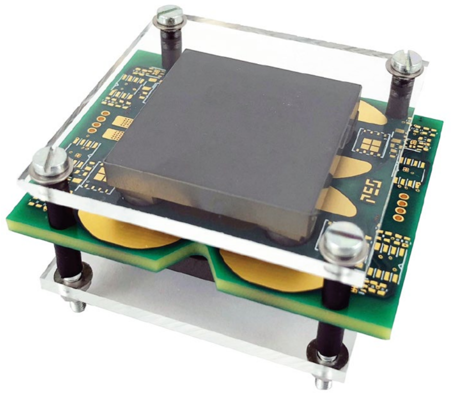
$$\hat{J}_{\text{4-mult}} = \frac{\hat{J}_{\text{single}}}{2} \qquad P = \frac{1}{2\sigma} \iiint \hat{J}^2 \, dV$$

- **Losses reduce proportionally to the number of windings!**

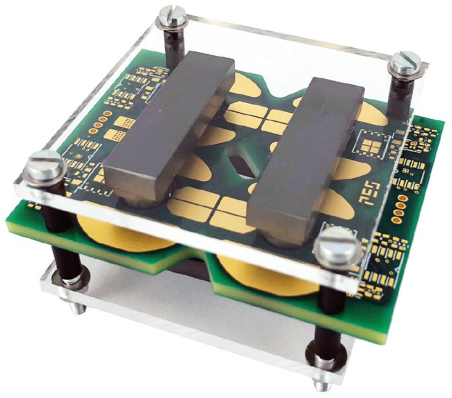
Magnetics as Key Enablers

▶ Matrix transformer





■ State-of-the-art core

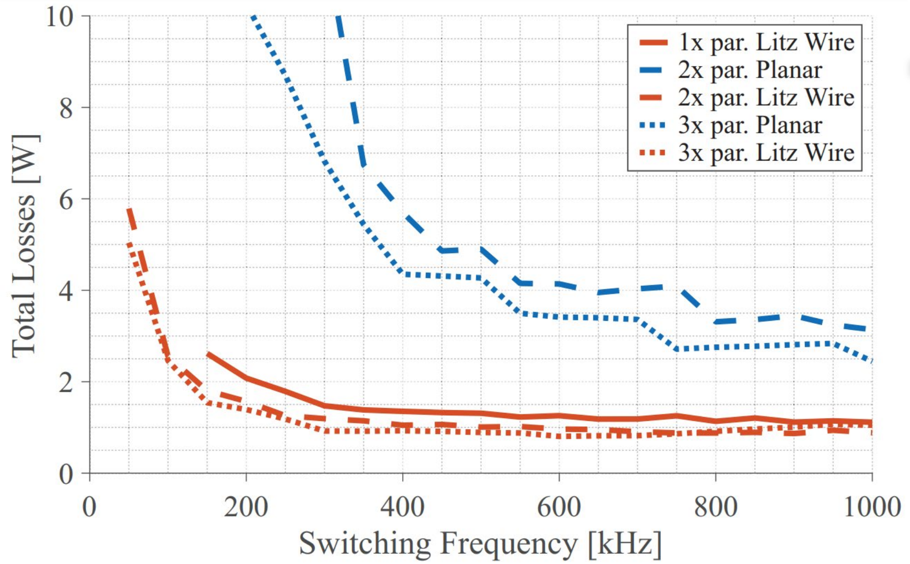


■ Snake Core

Source: G. Knabben et. al., "New PCB Winding 'Snake-Core' Matrix Transformer for Ultra-Compact Wide DC Input Voltage Range Hybrid B+DCM Resonant Server Power Supply," Proc. PEAC 2018

Magnetics as Key Enablers

▶ PCB-winding inductor?

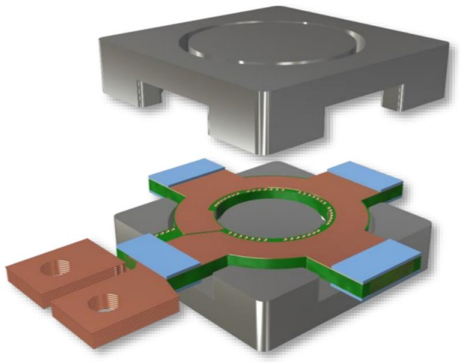


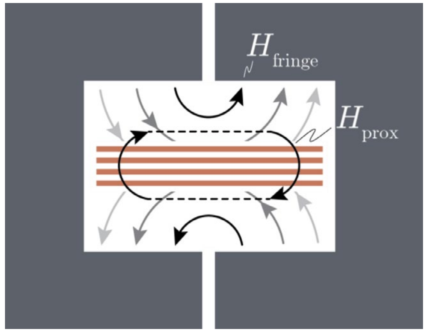
- 3 kW PFC inductor

PCB

Litz

Source: M. Kasper et. al., "Ultra-high Power Density Server Supplies Employing GaN Power Semiconductors and PCB-Integrated Magnetics", Proc. CIPS 2020



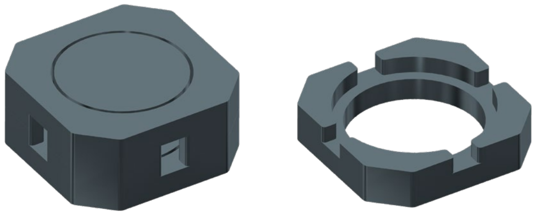


- CFFC PCB Inductor

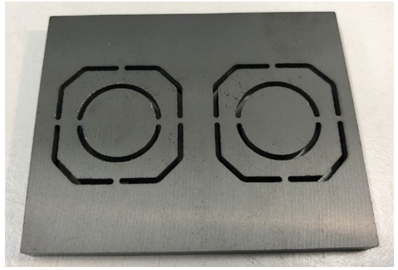
Source: J. Schäfer et. al., "Introduction of the CFFC - Compensating Fringing Field Concept and its Application in PCB Winding Inductors", ECPE Workshop 2020

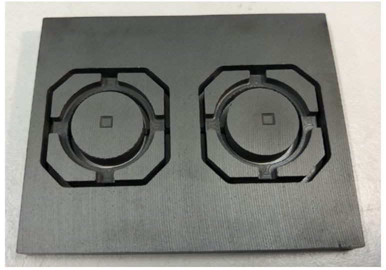
Magnetics as Key Enablers

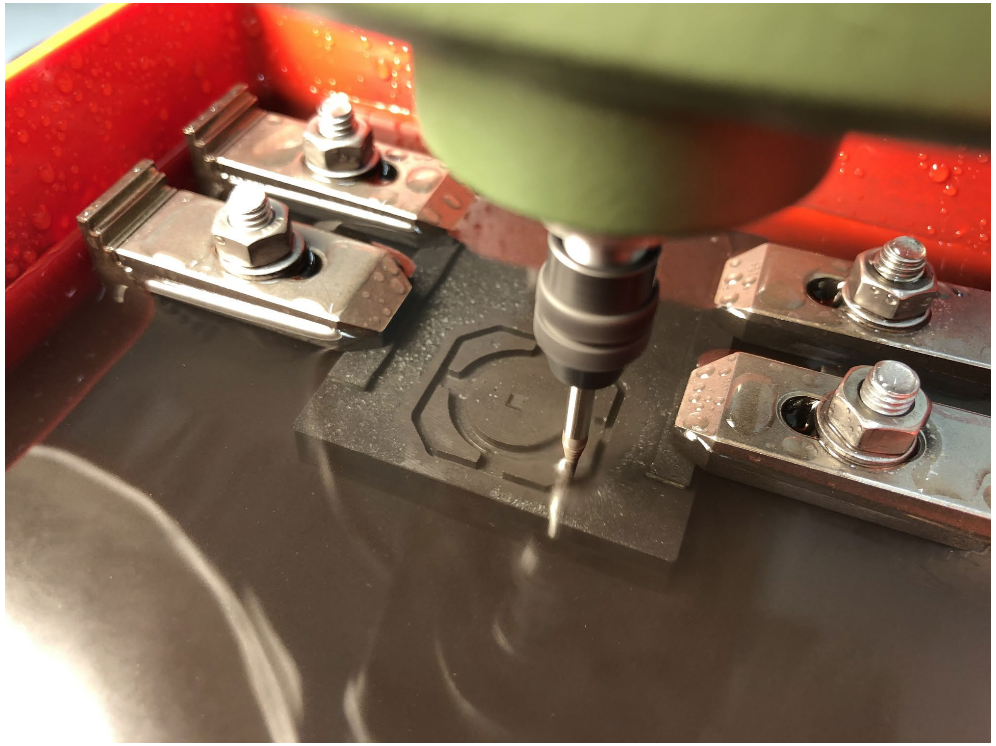
▶ Custom ferrite cores



▶ Ferrite machining



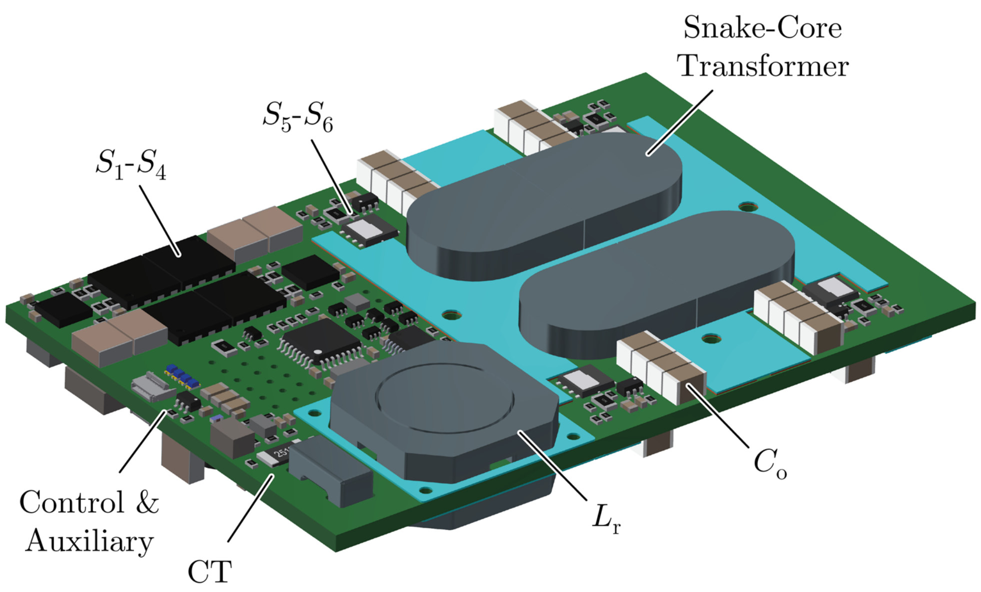


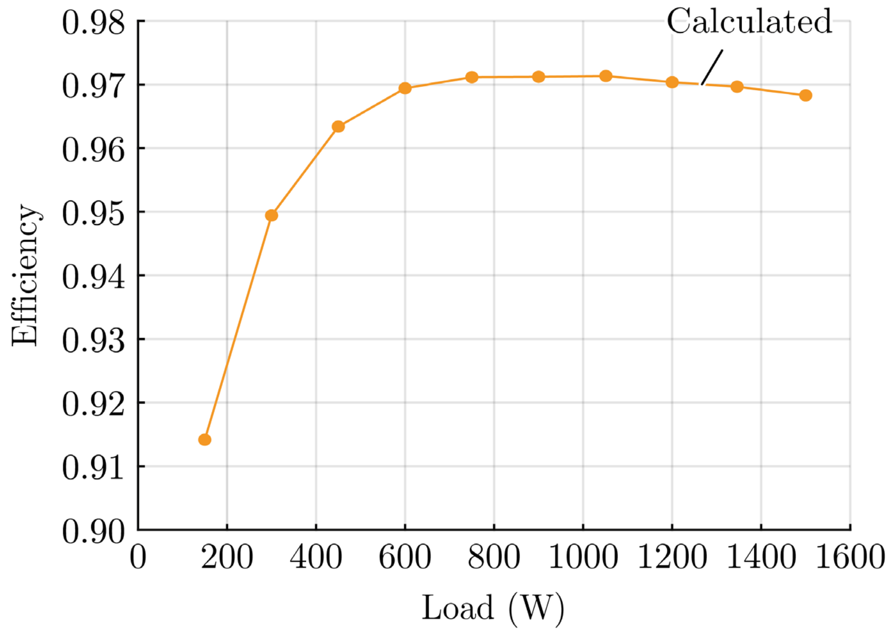


■ Water-cooled, 1 mm diamond drill bit

Design & Efficiency

- **DC/DC module**
  - V_{dc} = 400 V, V_o = 12 V, $P_{o,100\%}$ = 1.5 kW
  - 90.0 mm X 68.0 mm X 11.5 mm
  - $\eta_{50\%}$ = 97%, ρ = 350 W/in^3





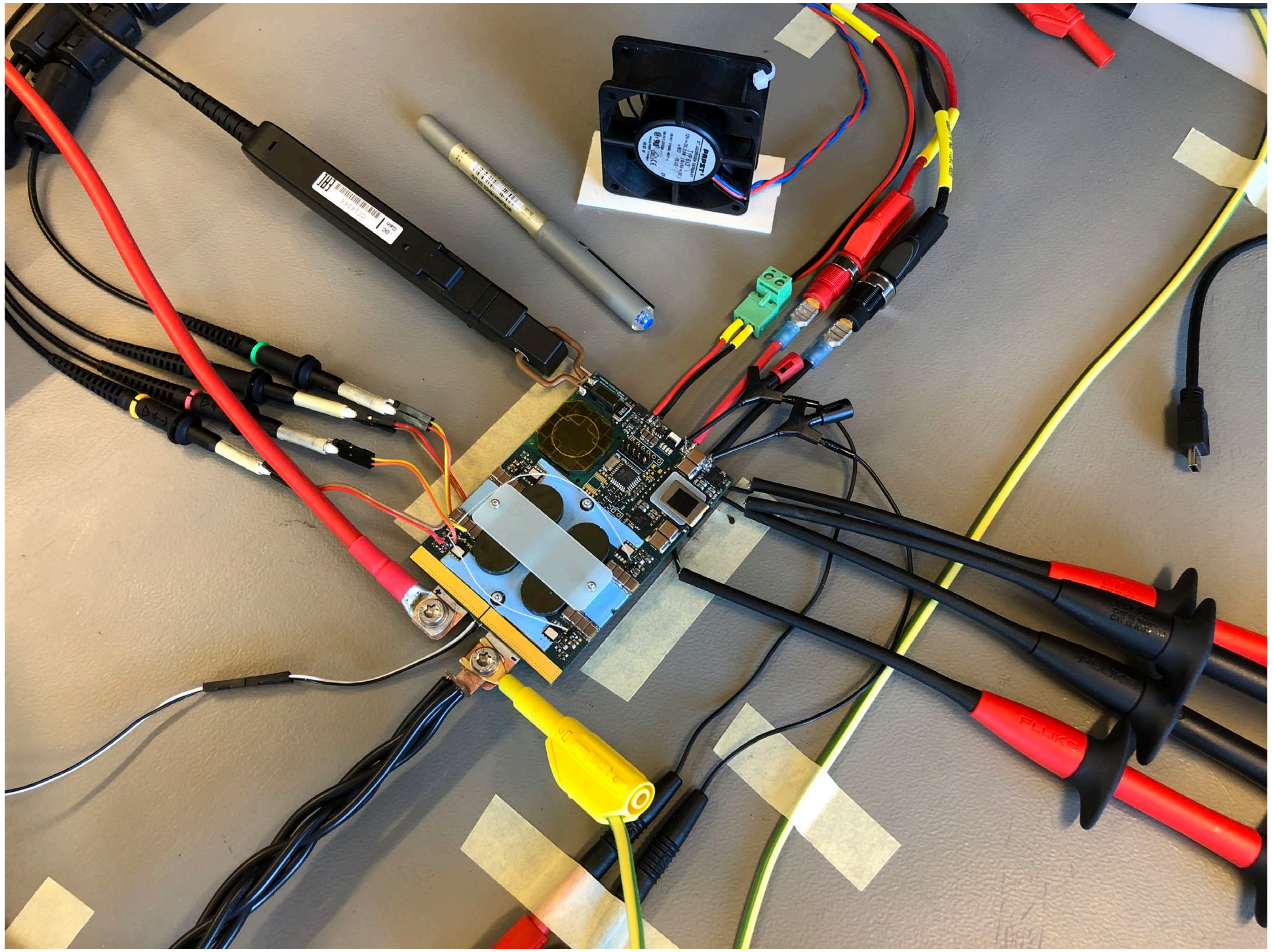
- **Measured efficiency?**

DC/DC-Stage Demonstrator

- ► Design Challenges
- ► Measurements
- ► Loss-Model Improvement

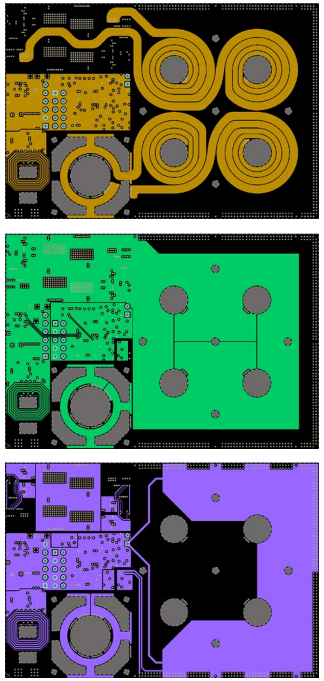
Design Challenges

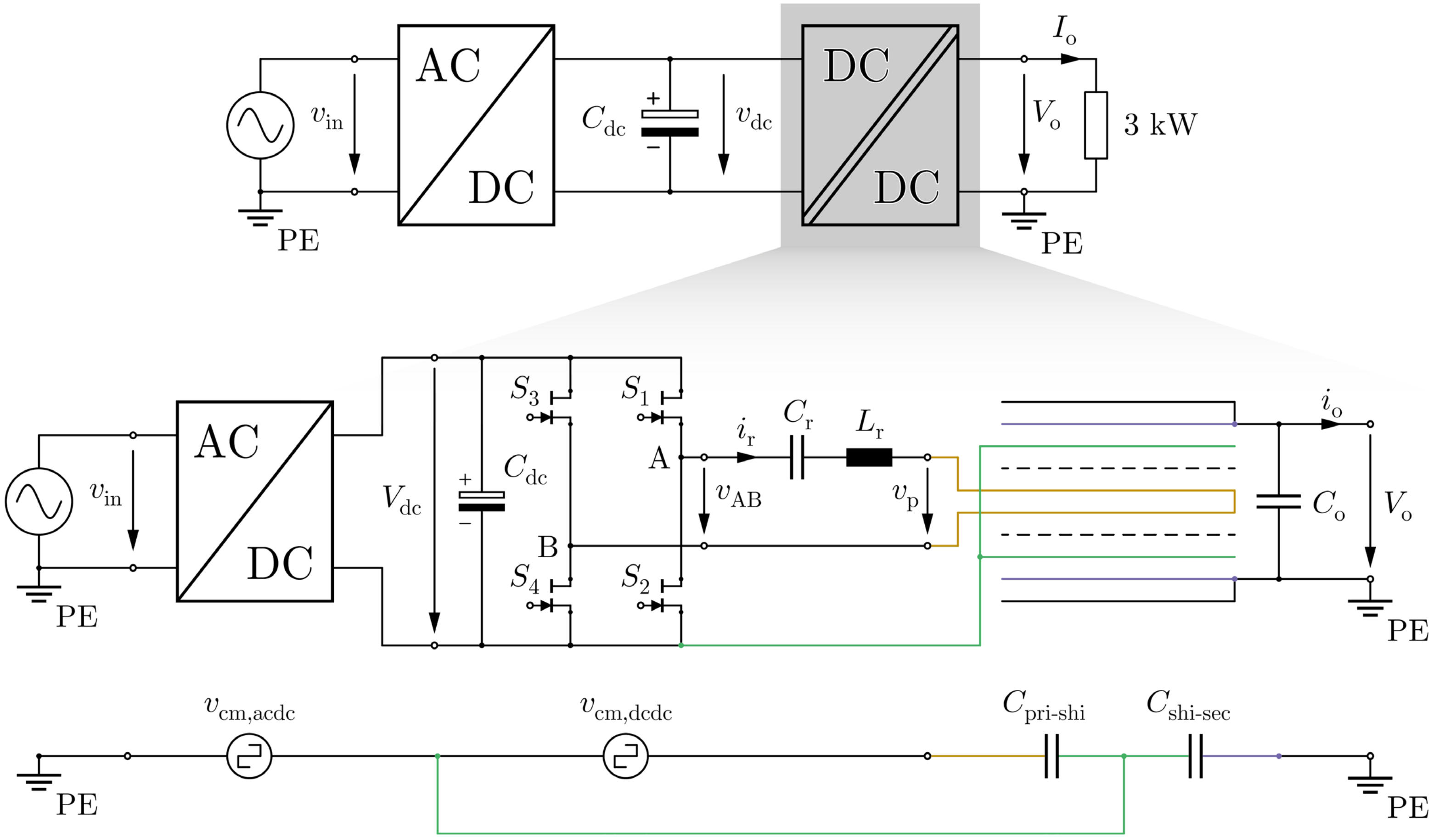
- ▶ Shielding layers
- ▶ Inter-winding capacitance
- ▶ Output layers
- ▶ Current transformer
- ▶ Thermal management
- ▶ Synchronous rectification



Design Challenges

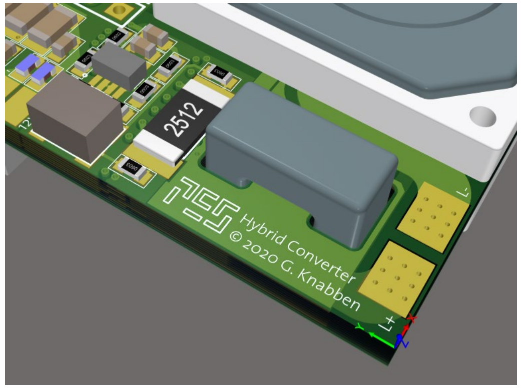
- Shielding layers
- Inter-winding capacitance
- Output layers

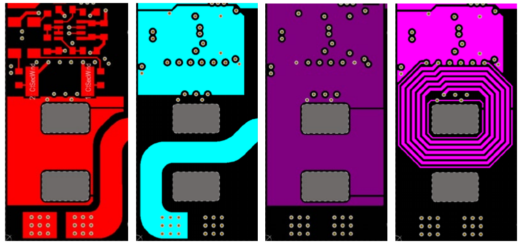




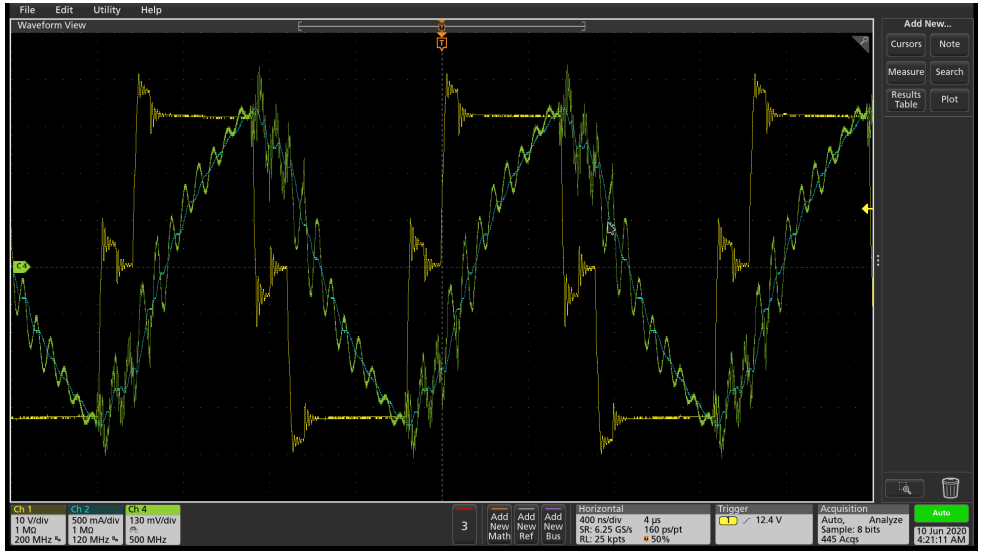
Design Challenges

- ▶ **Current transformer**
  - Detection of current zero-crossing in BCM

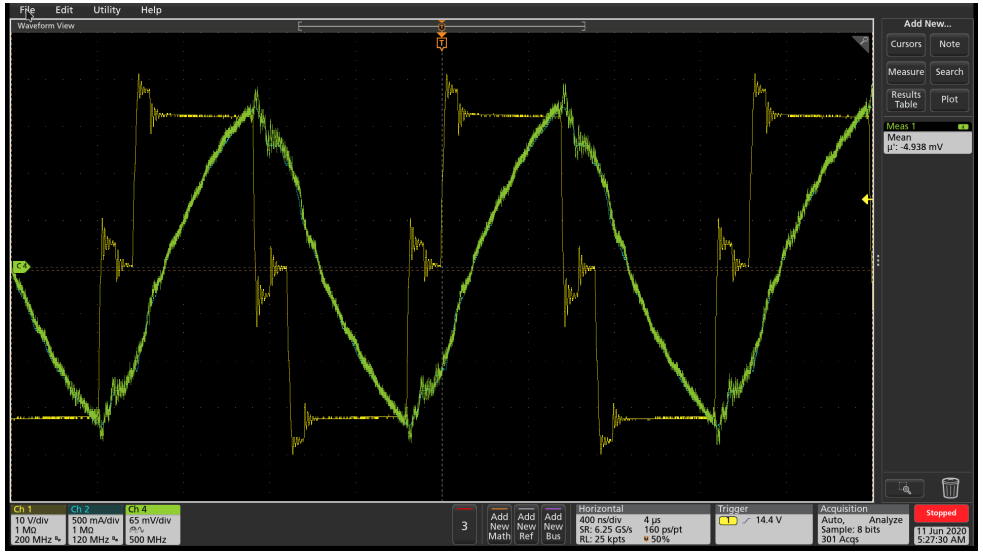




- Low CM Impedance

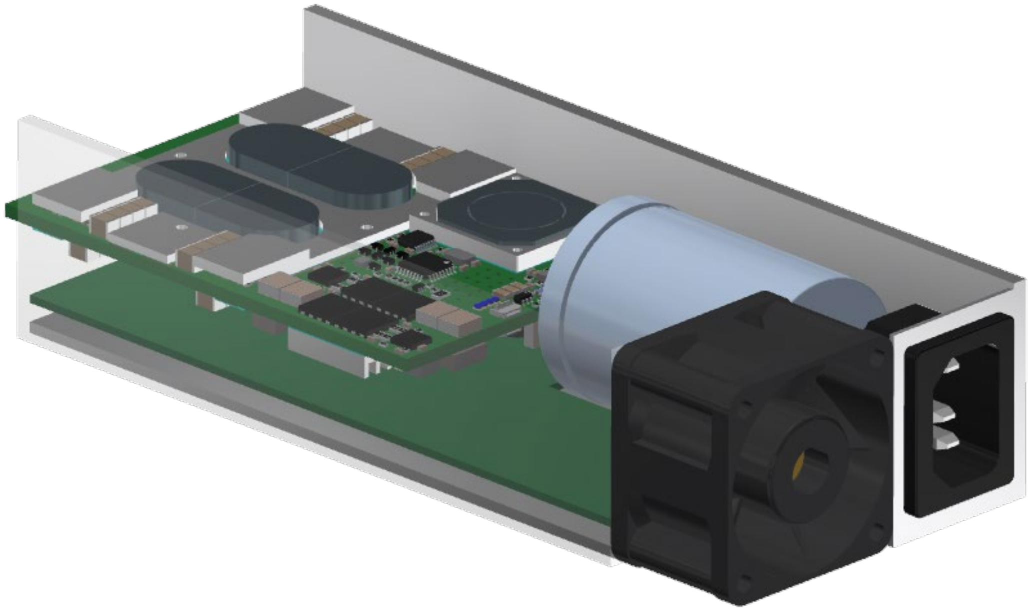


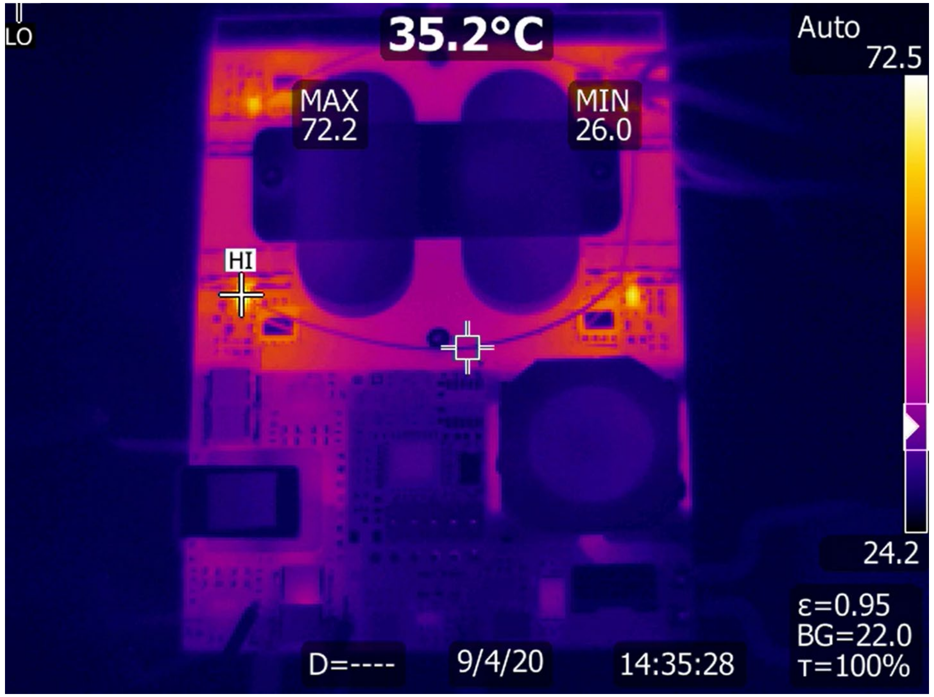
- Use of CM Chokes



Design Challenges

- **Thermal management**
  - Cooling by convection (fan)
  - Cooling by conduction (PSU walls)

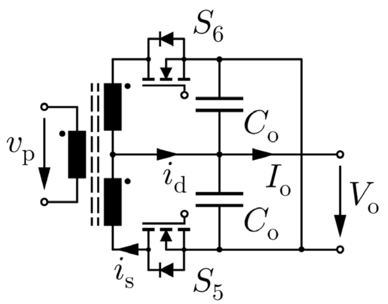


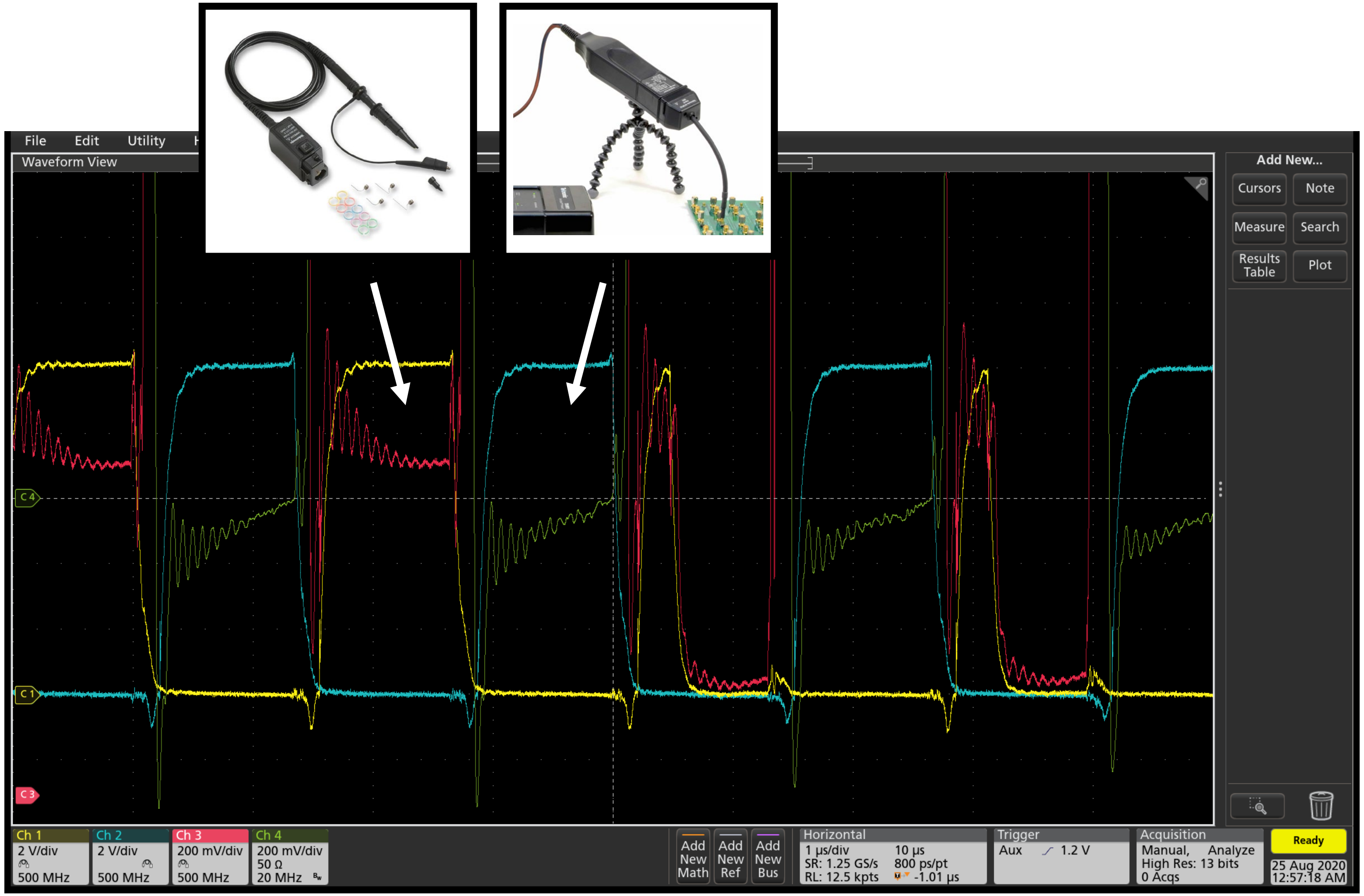


- V_{dc} = 400 V, V_o = 12 V, P_o = 1.5 kW

Design Challenges

▶ Synchronous rectification
- MAX17606, Maxim Int

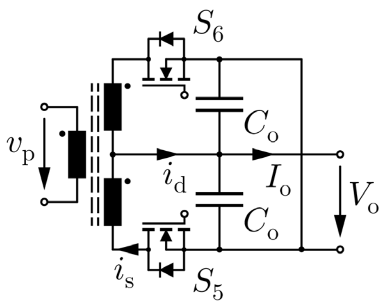


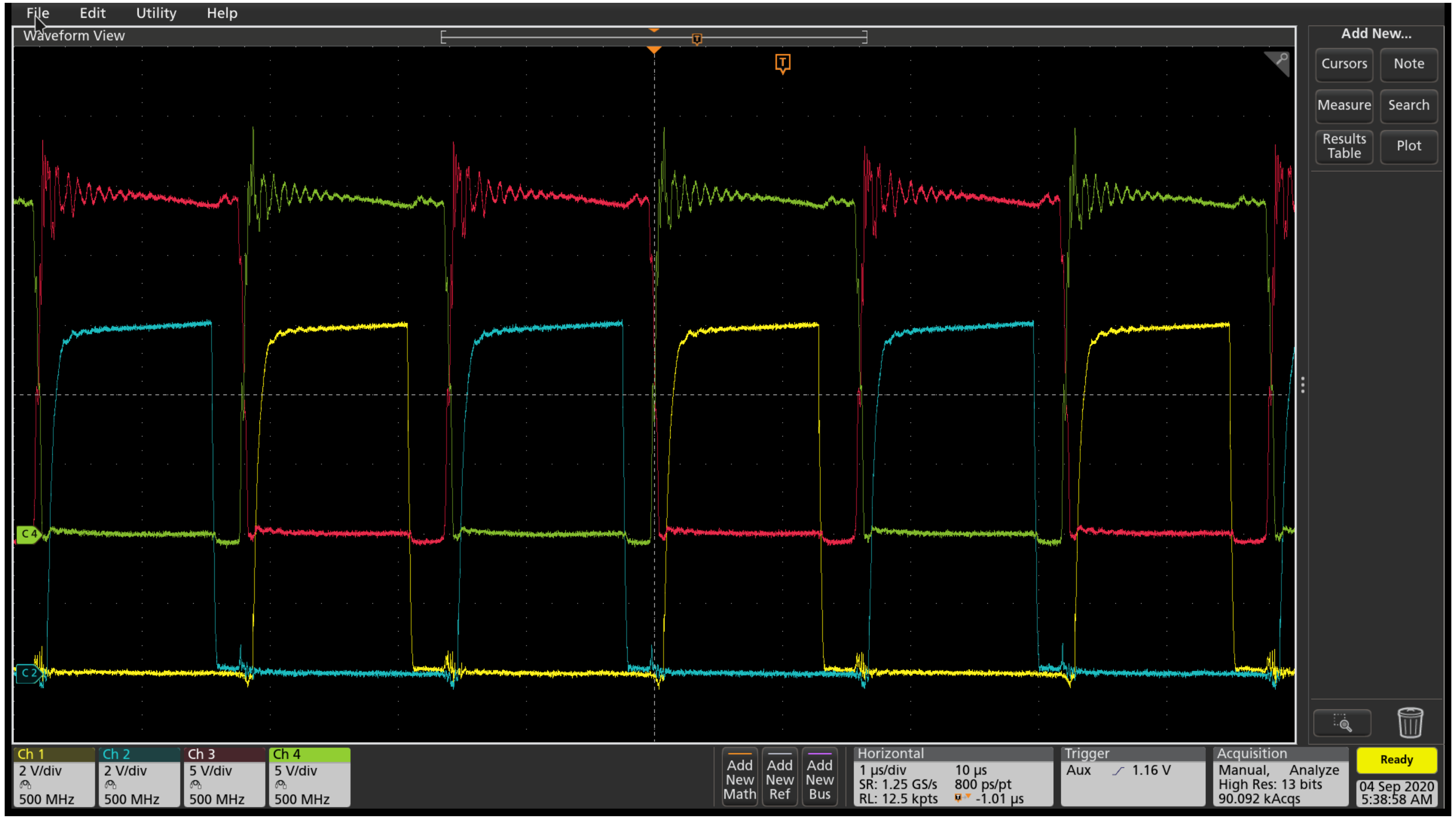


- Premature turn-off due to ringing

Design Challenges

- **Synchronous rectification**
  - NCP4306, On Semi





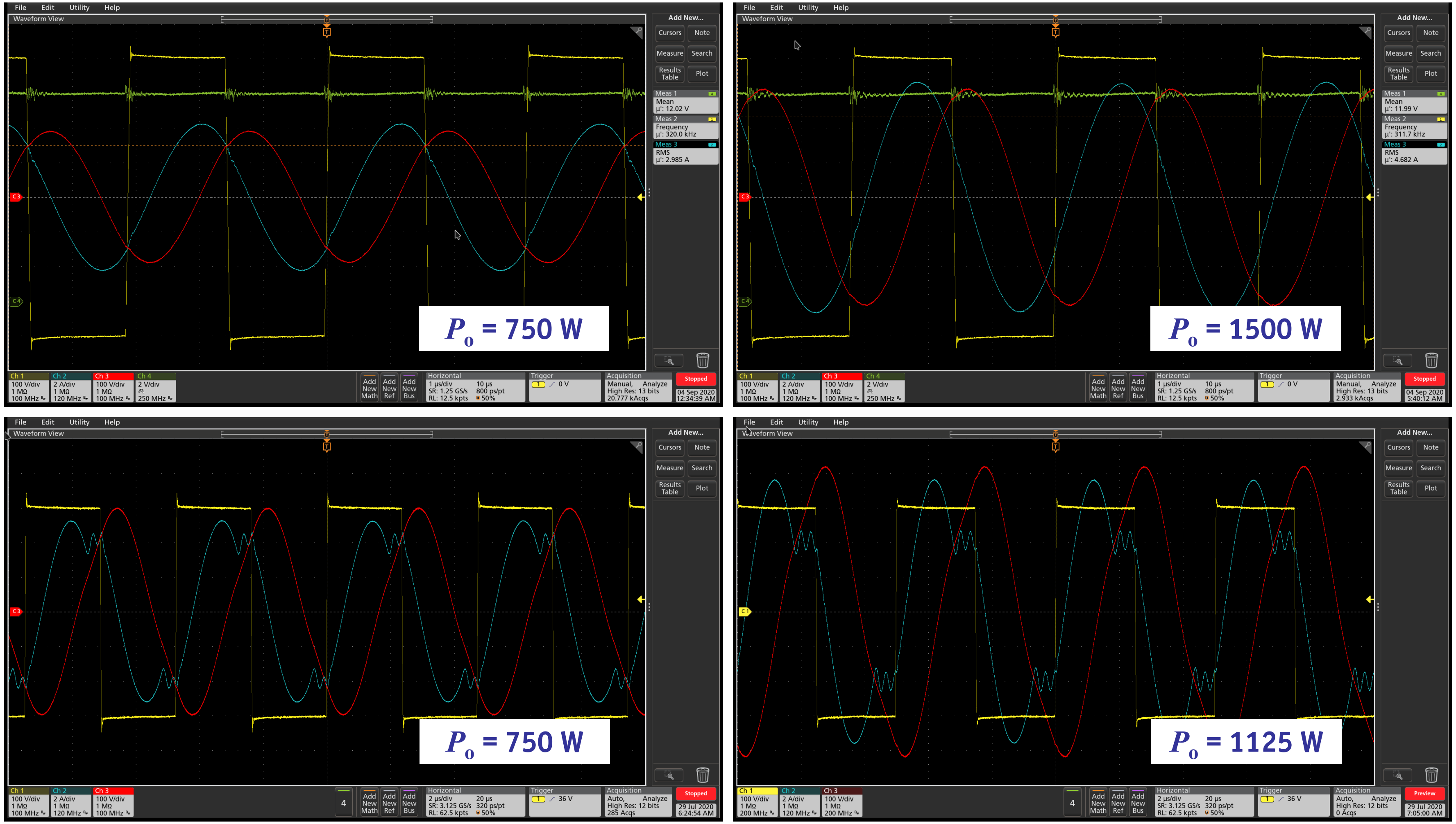
  - Body-diode conducts for a significant time

Measurements

CH1: v_{AB}
CH2: i_{Lr}
CH3: v_{Cr}
CH4: V_o

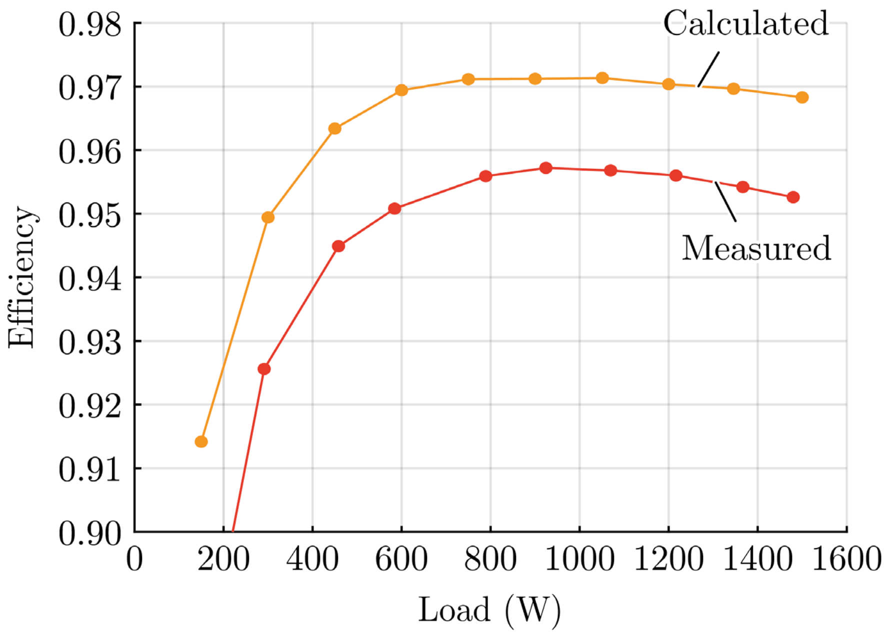
V_{dc} = 400 V

V_{dc} = 300 V



Measurements

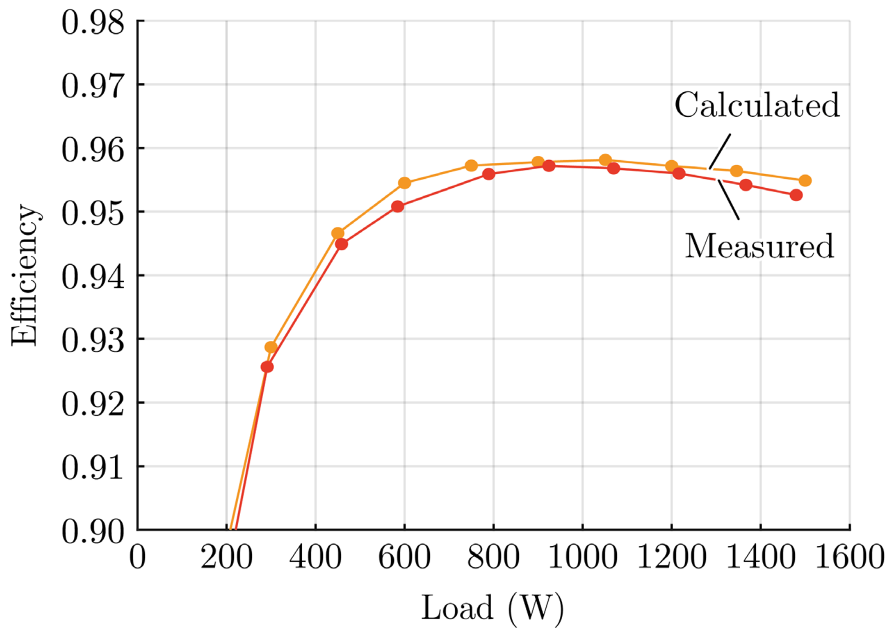
- **Efficiency**
  - V_{dc} = 400 V, V_o = 12 V



- Mismatching between simulated and measured waveforms
- Accuracy of ferrite machining – different resonant and magnetizing inductances
- SR body diodes conducting for a significant time
- Significant losses of PCB tracks that are not part of the model
- Difficulty in predicting transformer-core temperature

Loss-Model Improvement

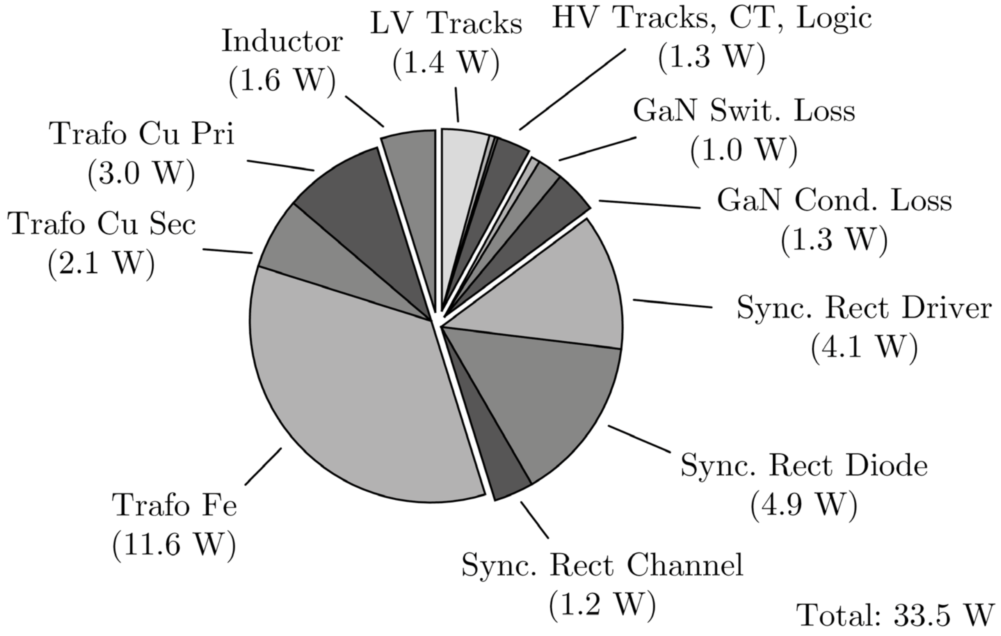
- **Efficiency**
  - V_{dc} = 400 V, V_o = 12 V



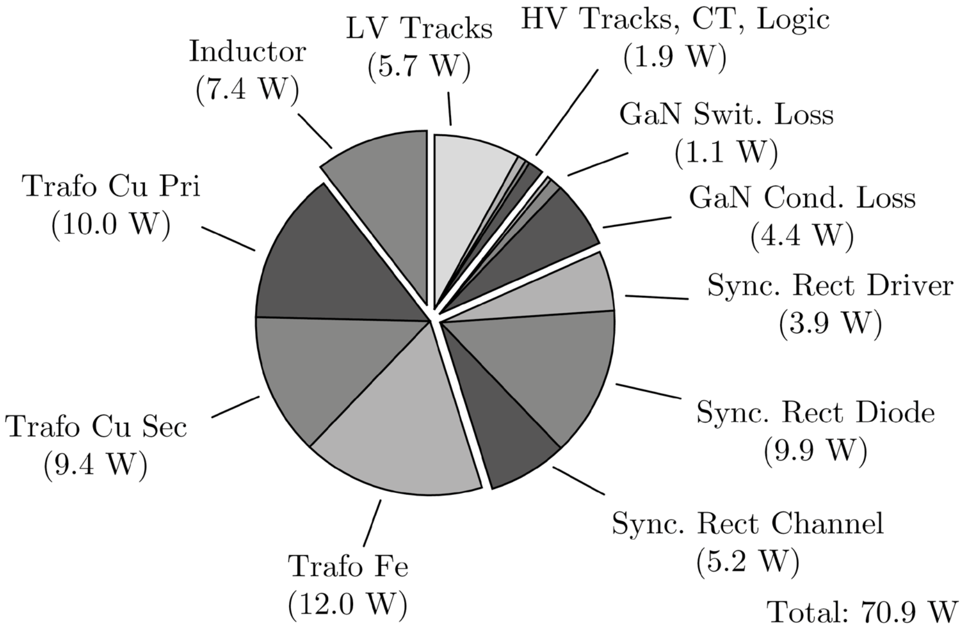
- Mismatching between simulated and measured waveforms
- Accuracy of ferrite machining – different resonant and magnetizing inductances
- SR body diodes conducting for a significant time
- Significant losses of PCB tracks that are not part of the model
- Difficulty in predicting transformer-core temperature

Loss-Model Improvement

- **Loss breakdown**
  - V_{dc} = 400 V, V_o = 12 V



P_o = 750 W



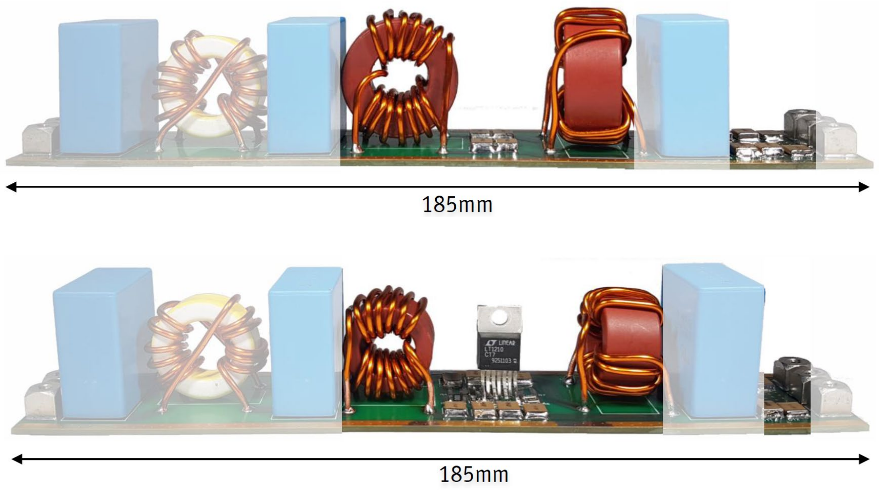
P_o = 1500 W

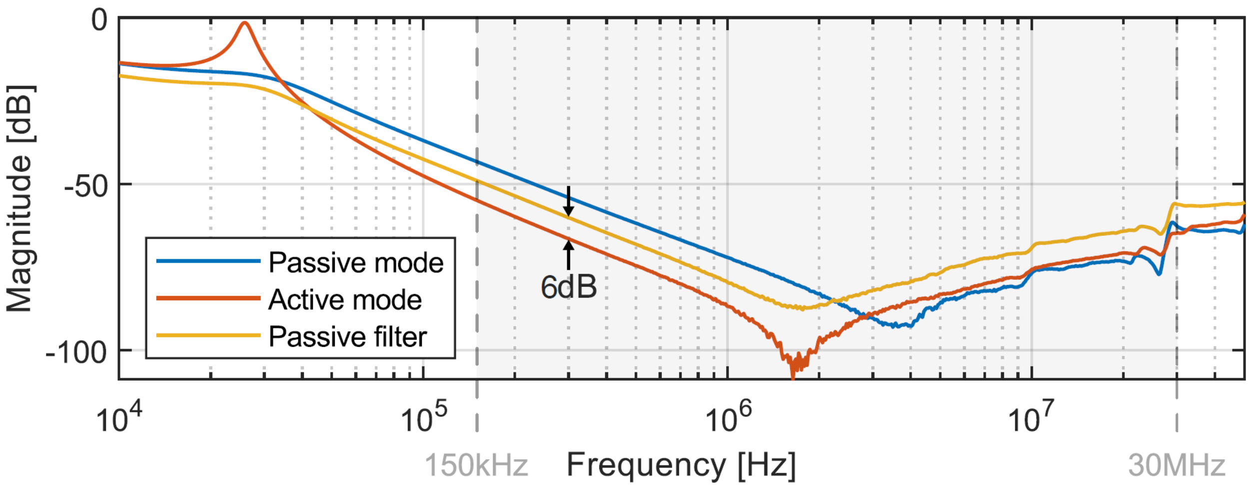
AC/DC-Stage Analysis

► Active EMI Filter

Active EMI Filter

- ▶ 6 dB gain in attenuation compared to passive CM filter
- ▶ CM chokes are 40% smaller
- ▶ Overall filter-volume reduction of 16%



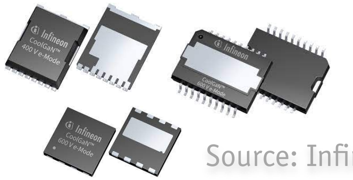


Conclusion

► Summary & Outlook

Summary & Outlook

▶ How to increase power density in server supplies?


Source: Infineon

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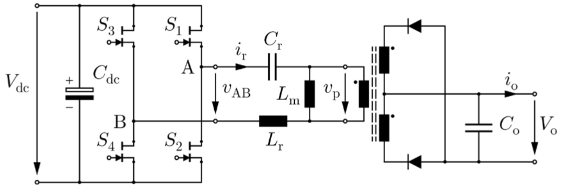

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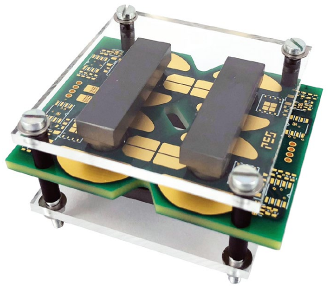

- ▶ GaN devices
- ▶ Proper topology & control
- ▶ Advanced planar magnetics

Thank You!

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