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SS - Sustainable Energy Systems & Opportunities for Power Electronics

Experimental Analysis of a 166 kW Medium-Voltage/Frequency Air-Core Transformer for 1:1-DCX Applications

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Outline

- *DCX Applications*
- *ACT Geometries*
- *ACT Pareto Optimization & Construction*
- *ACT Shielding*
- *ACT Loss & Stray Field Analysis*
- *ACT/MCT DCX Comparison*

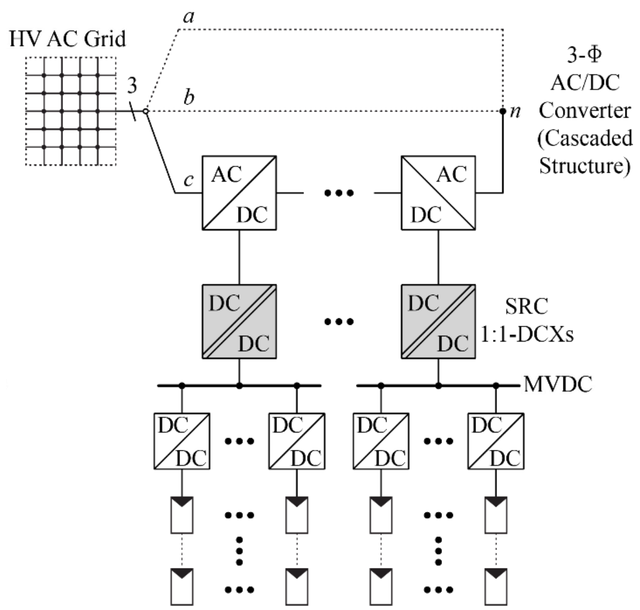
Acknowledgement
Energy
Swiss Competence Centers for Energy Research

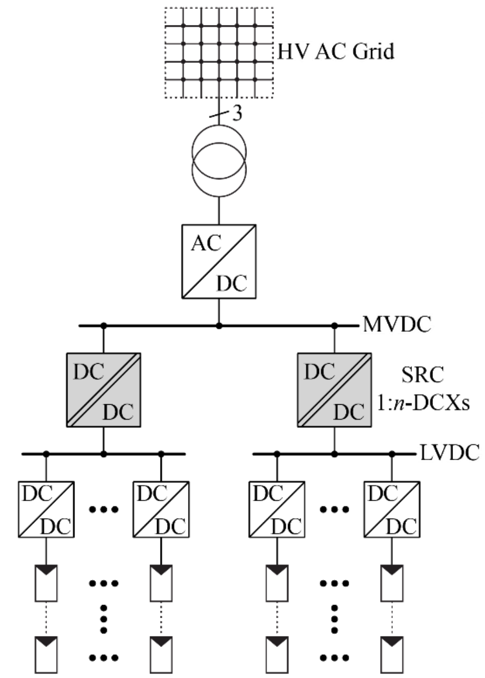
1:1-DCX Applications

Renewable Energy
Future Traction Vehicles
More Electric Ships
More Electric Aircraft

1:1-DCX Applications 1/2

— MVDC Collector Grids of Large PV Plants — Galv. Isol. of Sections / Local Grounding / Protection
— Isolation of Cascaded H-Bridge AC/DC Modules

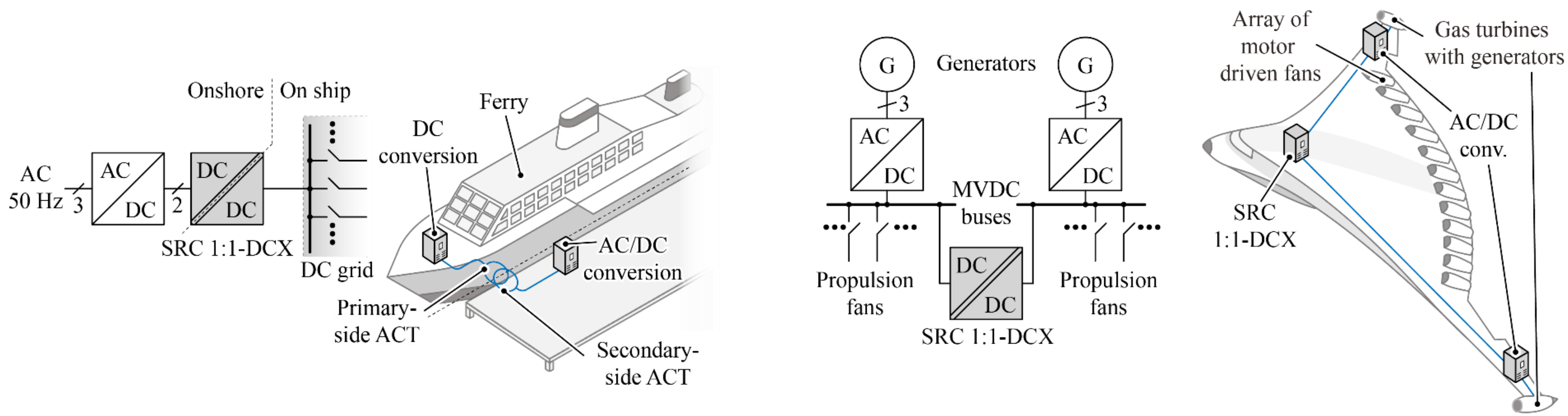




▶ 1:n-DCX or 1:1-DCX as Intelligent Isolated DC/DC Interface
▶ Demand for High-Efficiency / Low Weight / Ease of Manufacturing

1:1-DCX Applications 2/2

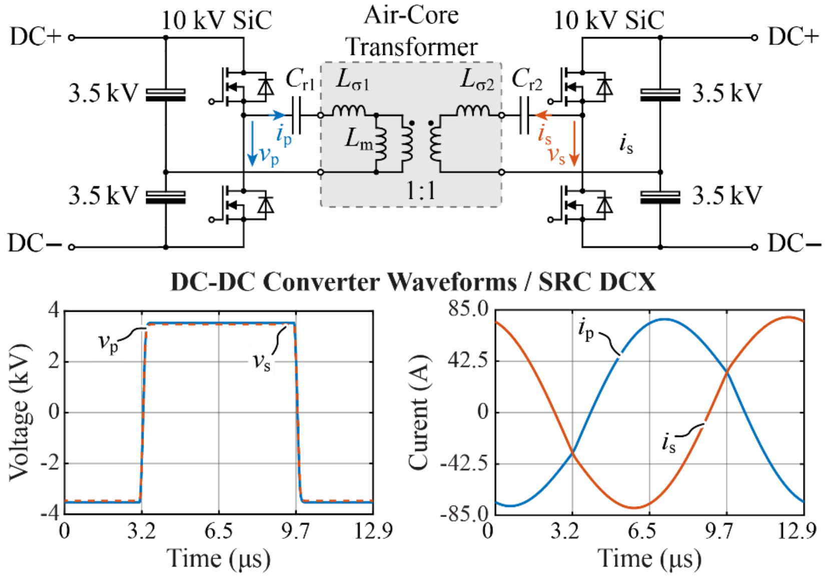
— Shore-to-Ship Power Transfer & On-Board MVDC Power Distribution of Future Ships
— Distributed Propulsion Aircraft



► DC Zonal Power Distribution System for Safety & Redundancy
► 1:1-DCX as "Intelligent Isolated Bus-Tie Switch" (i²-BTS)
► Demand for High-Efficiency / Low Weight / Ease of Manufacturing

1:1-DCX Series Resonant Converter

— Rated Power 166 kW
— DC Input / Output 7 kV

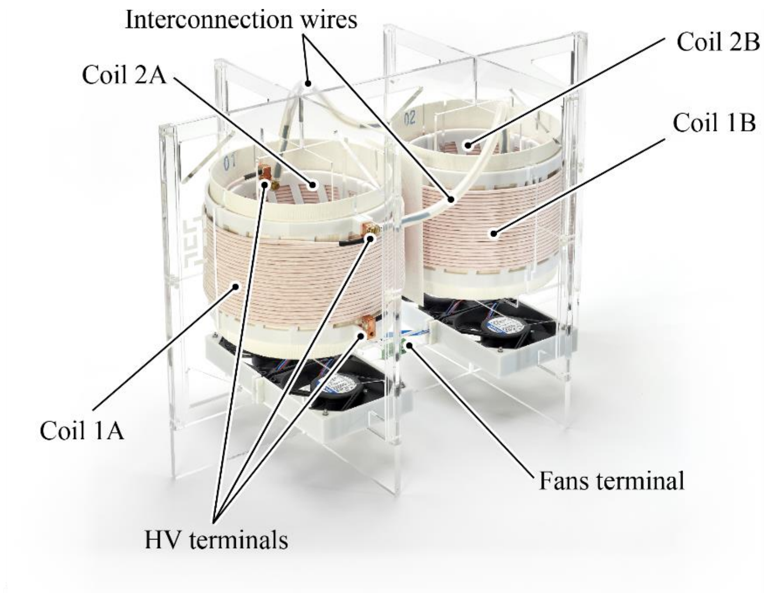


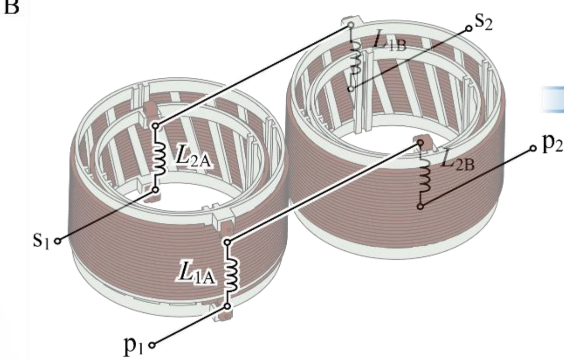
▶ 1:1 MF Transformer
▶ 10kV SiC MOSFETs
▶ Open Loop Control
▶ Magnetizing Current Splitting → ZVS of All Semiconductors

1:1 Medium Frequency
Air-Core Transformer

1:1 MF Air-Core Transformer (ACT) Concept - 1/2

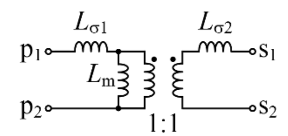
- Light-Weight Air-Core Transformer
- Air Insulation / Air Cooling





Equivalent circuit induc.:

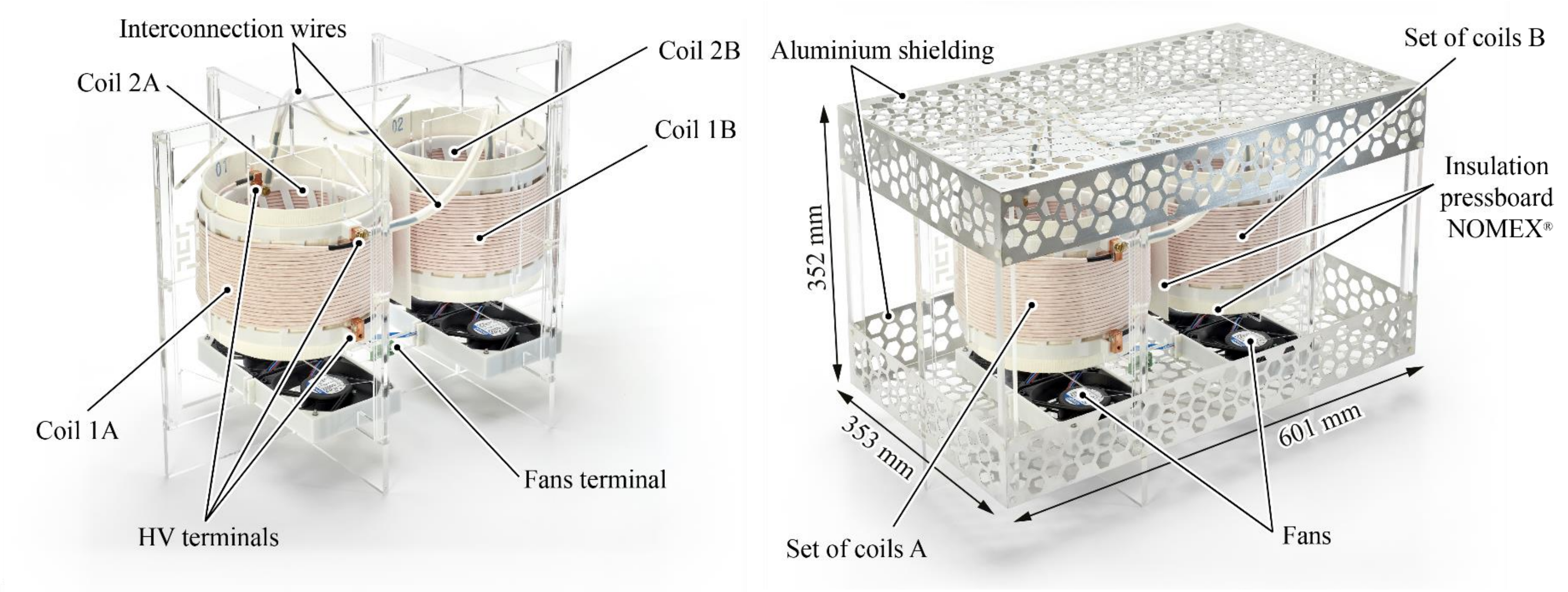
$$L_p = L_{1A} + L_{2B}$$
$$L_s = L_{2A} + L_{1B}$$
$$L_{\sigma 1} = L_p - L_m$$
$$L_{\sigma 2} = L_s - L_m$$



- ► Coaxial Primary- & Secondary-Side Windings
- ► Cylindrical Solenoids → HF Litz Wire Conductors
- ► Series Connections of Coil Sets A & B → Prim. & Sec. Wdgs Symmetrical

1:1 MF Air-Core Transformer (ACT) Concept - 2/2

— Pareto Optimization (Radius, Length, Winding, # of Turns, Oper. Freq., etc.)
— 7:7 kV/kV @ 15 kV Isolation
— 166 kW @ 77.4 kHz

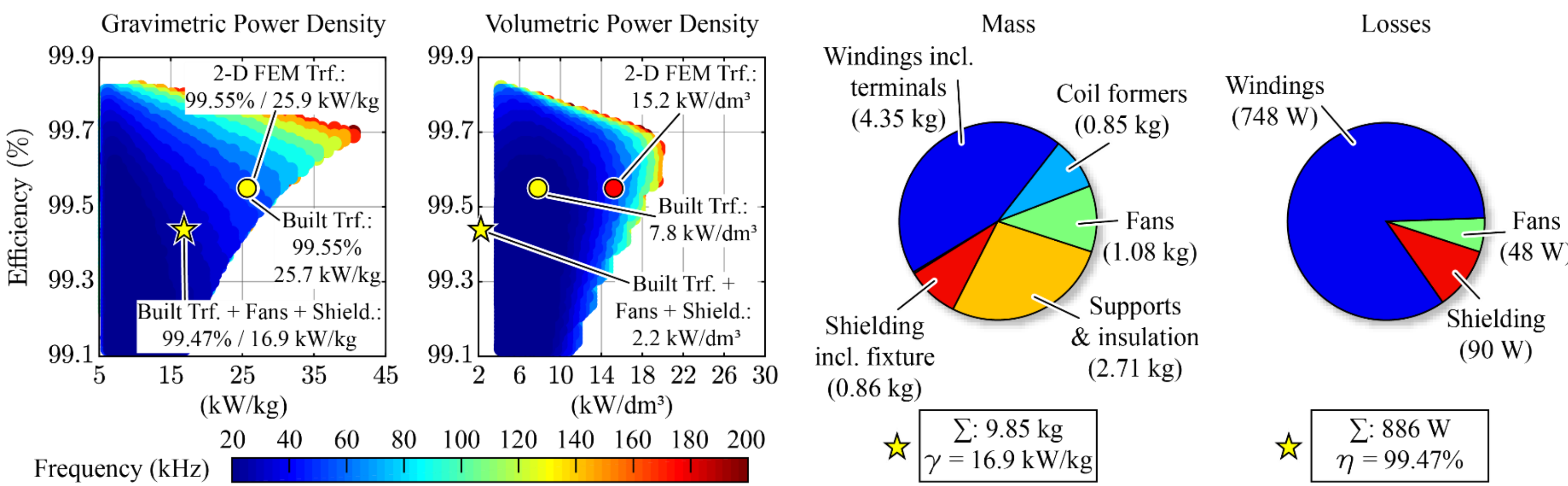


▶ Challenges: High Electric Fields & Magnetic Stray Fields

η-γ-ρ-Pareto Limits (2-D FEM)

— **Gravimetric Power Density**
- Sim./Calc.: 99.55%, 25.9 kW/kg
- Prototype: 99.55%, 25.7 kW/kg

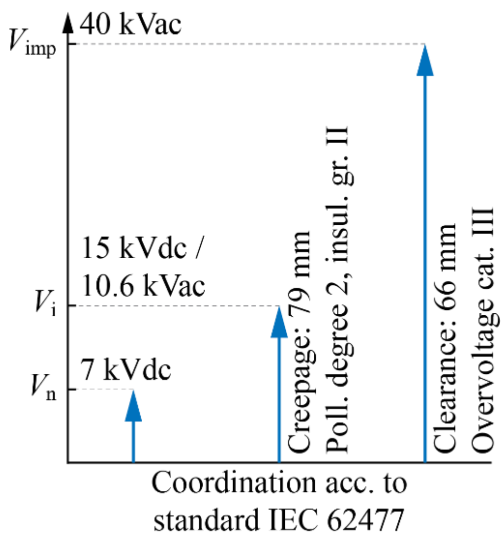
— **Volumetric Power Density**
- Sim./Calc.: 15.2 kW/l
- Prototype: 7.8 kW/l

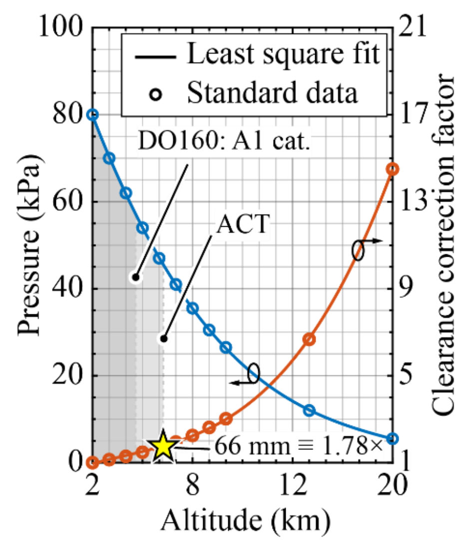


- ▶ **Complete Realized Prototype: 99.43% @ 16.9 kW/kg, 2.2 kW/l**
- ▶ **Significant Share of Mech. Parts (Supports, Fixtures, Fans) & Insulation**
- ▶ **Volume Box Dominated by Shielding Enclosure**

Isolation Requirements & Voltage Levels

- Rated Voltage — V_n = 7 kV DC
- Rated Insulation Volt. — V_i = 10 kV DC
- Poll. Deg. 2 / Insul. Gr. II — 50.2 mm Creepage Distance
- Impulse Withstand Volt. — $V_{imp} \geq 27.2$ kV AC_{peak}
- Overvoltage Cat. III — 37 mm Clearance Distance

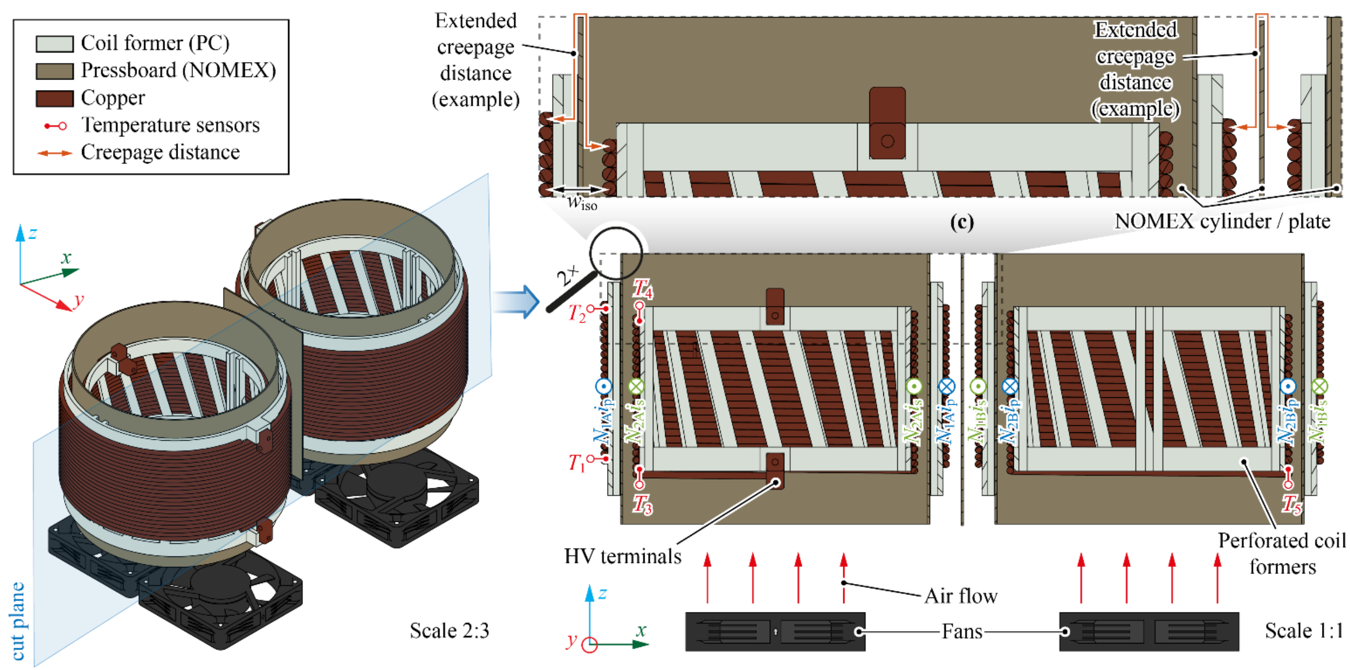




- ▶ Realized Creepage 79 mm → V_i = 15 kV DC
- ▶ Realized Clearance 66 mm → V_{imp} = 40 kV AC_{peak}
- ▶ A1 Airborne Cat. → Pressurized Zone up to 6.2 km (20,500 fts) and 45 kPa (0.45 bar)

166kW/7kV MF ACT — Construction

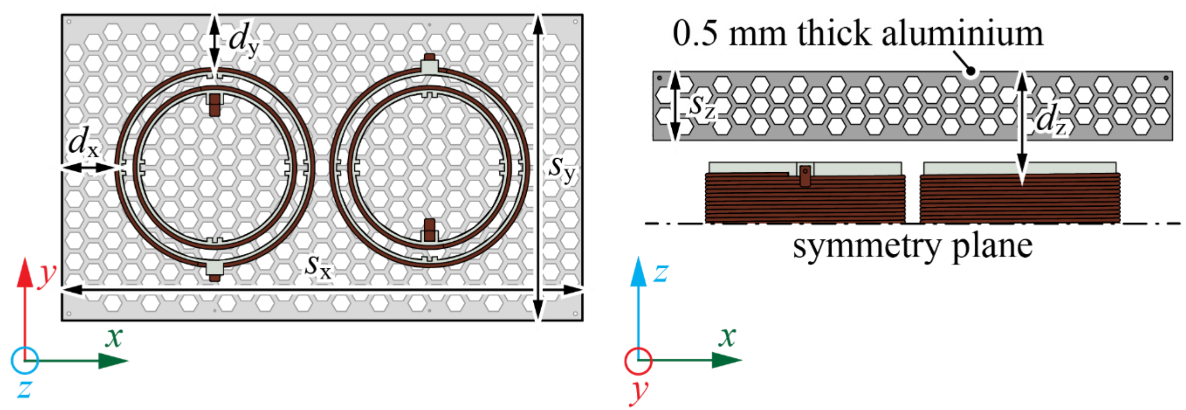
— Single Layer Wdg, 22 Turns / Coil, 2x Polyamide Insulation
— Isolation Distance wiso = 16.5 mm (0.95 kV/mm → ≥ 15.8 mm)
— 1.5 mm Nomex Pressboard Elements → Extended Creepage



▶ Perforated Walls of Coil Formers → Increased Cooling Surface
▶ NTC and Fiber Optic Temp. Sensors → Monitoring of Temp.

166kW/7kV MF ACT — Shielding

- Magnetic Shielding → Too Heavy (Ferrite)
- Conductive Shielding → 0.5 mm Aluminium - Incorporated into Enclosure



- ▶ Sufficient Shielding Efficacy for Distributed Honeycomb Holes
- ▶ 30% Weight Reduction but 29% Increase of Losses in the Shield

MV/MF ACT Testing

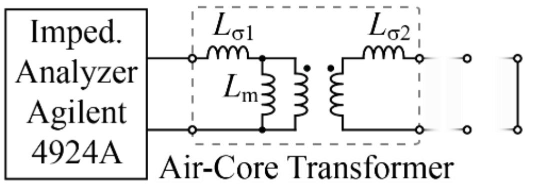
Source: Teledyne / LeCroy

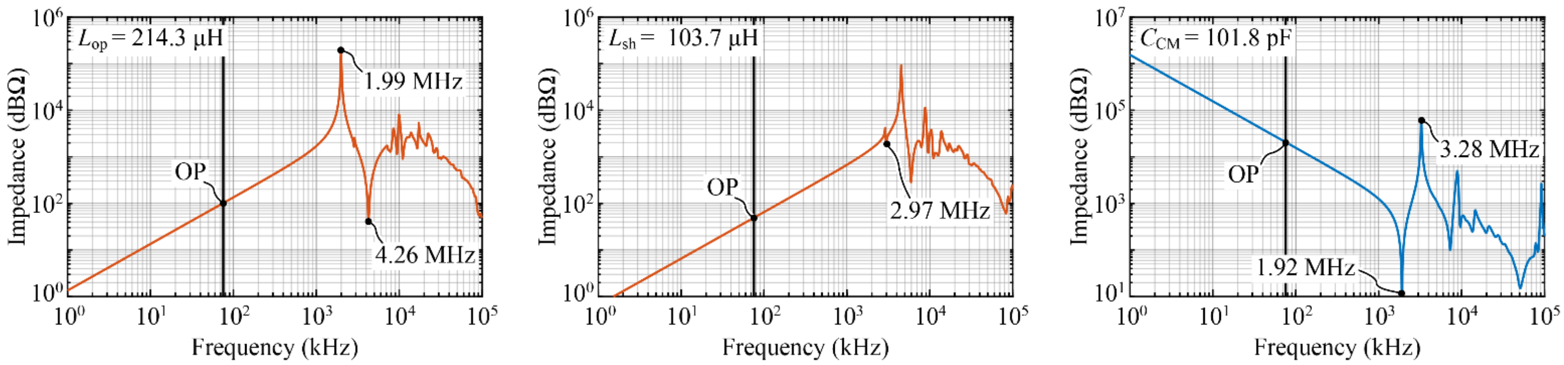
Impedances
Resonances
Losses
Thermal Responses
Magnetic Stray Field
Insulation Testing

MV/MF ACT — Impedance Measurements

- Impedance Analyzer
- Short- and Open-Circuit Imped. / CM Capacitance / Resonances

- $L_{s1,2}$ = 57.1 mH
- L_m = 155.64 mH
- Coupling 0.76

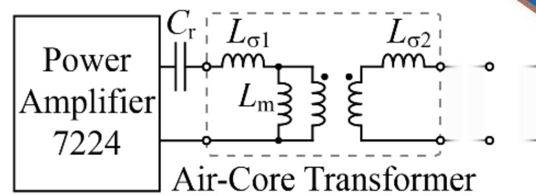


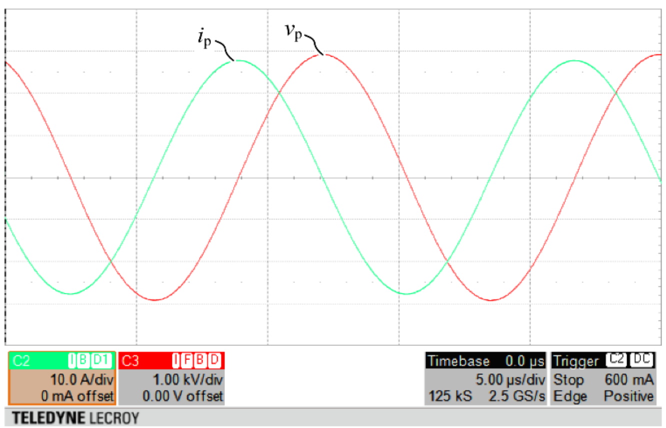


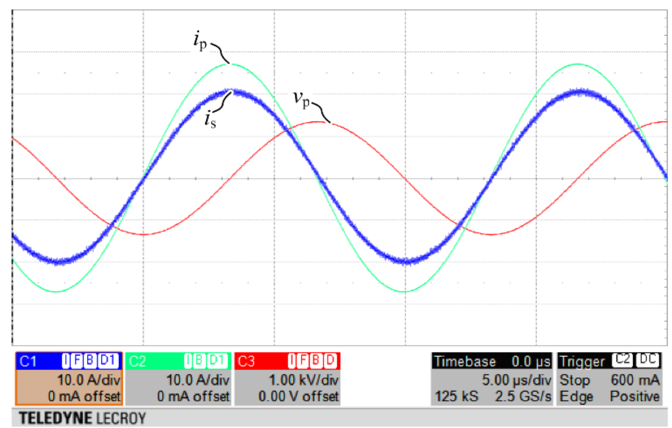
▶ Good Matching with 3D-Simulations (< 10% Deviation)
▶ Resonance Not Critical

MV/MF ACT — Series Resonance Circuit

- Power Amplifier + Series Capacitor
- CSP 120-200 Polypropylene Film Capacitor
- Transformer Short- and Open-Circuit Operation

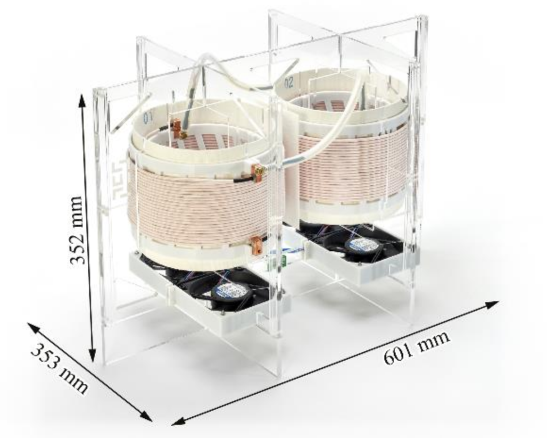






- ▶ **Open-Circuit:** $I_p = 19.9\ A_{rms}$, $V_p = 2.04\ kV_{rms}$
- ▶ **Short-Circuit:** $I_p = 19.6\ A_{rms}$, $V_p = 0.93\ kV_{rms}$, $I_s = 14.6\ A_{rms}$

MV/MF ACT — Winding Losses



— **Challenges**
- High Absol. Val. of Losses $P_{loss} \approx 800$ W
- Large Volume $V \approx 75$ dm^3
- High Coil Quality Factor $Q > 1000$

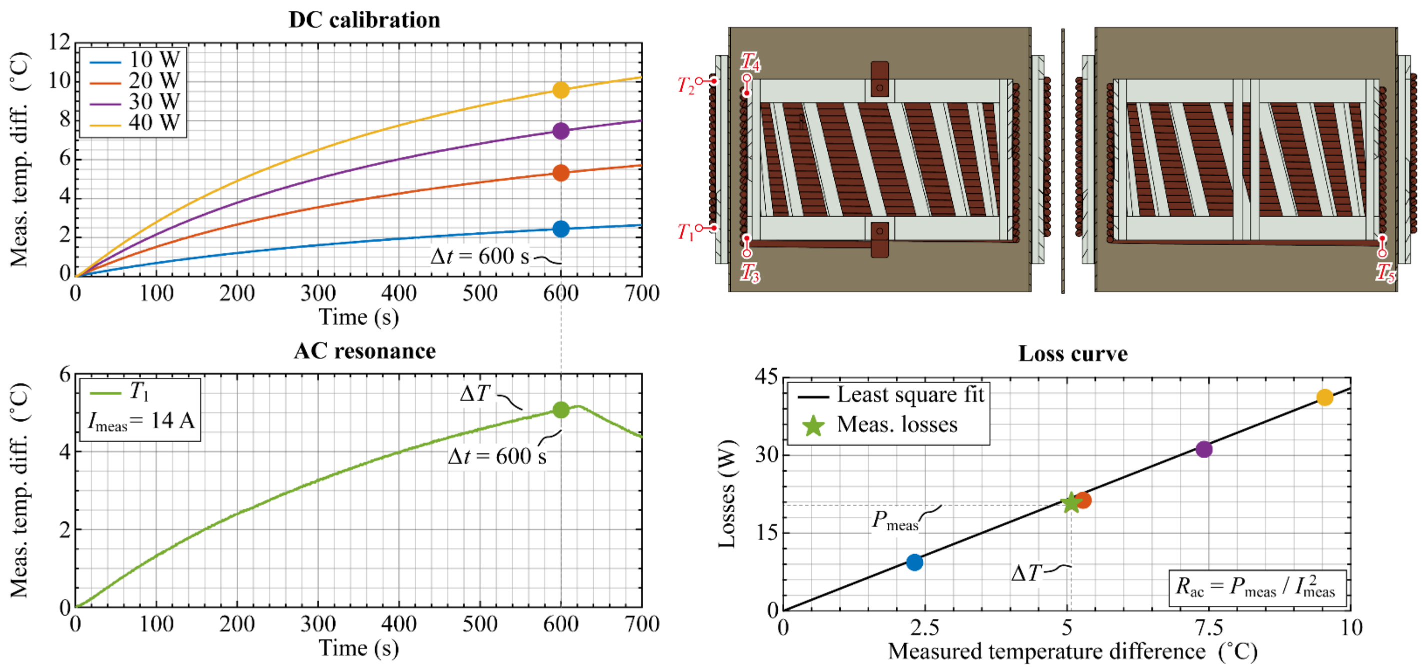
— **Methods**
- Direct Meas. (Electrical) → Poor Power Factor ✗
- Calorimeter → Large Volume & Losses ✗

— **Different Approach Required**
- AC Resistance Meas. w/ Series Cap. Compensation
- Small Signal → "Lossless" C0G Cap. Not Negligible ✗
- Large Signal → Transient Calorimetric Method ✓

- ▶ Linearity → Scaled Parameters Sufficient
- ▶ DC Thermal Calibration of Wdgs → Open- & Short-Circuit
- ▶ NTC and Fibre Optic Temp. Sensors

MV/MF ACT — Winding Losses (AC Resistance)

- Short- & Open-Circuit Operation
- DC Thermal Calibration
- Power Amplifier w/ Series Capacitive Compensation

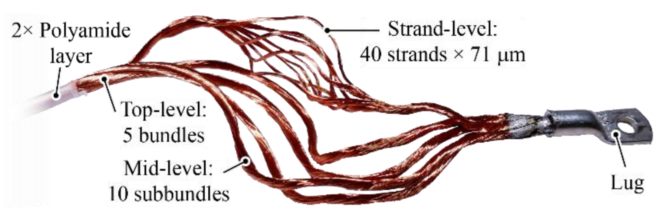


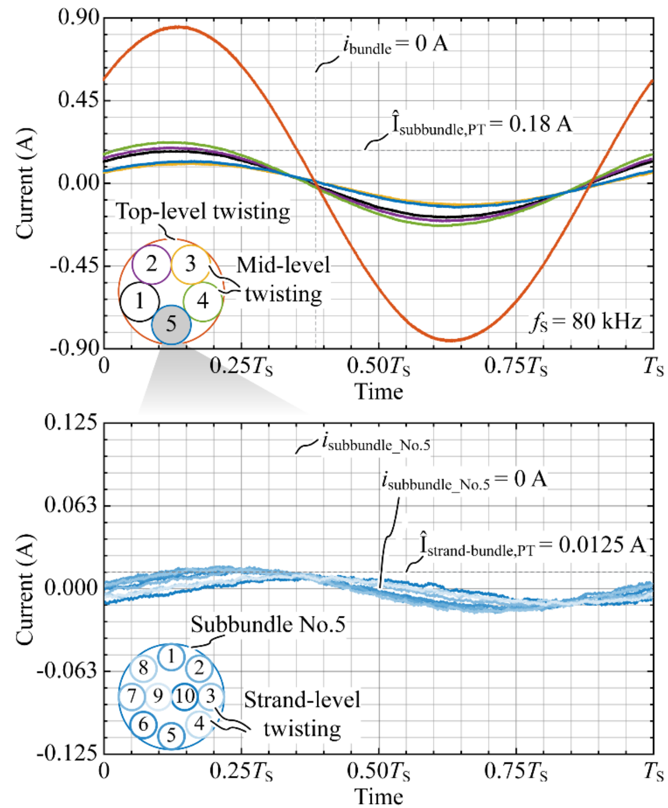
- ▶ Open-circuit: $R_{AC} = 102$ mΩ — 41% Deviation from 3D-FEM
- ▶ Short-circuit: $R_{AC} = 96$ mΩ — 31% Deviation from 3D-FEM
- → Increased R_{AC} due to Non-Ideal Twisting of Litz Wire?

MV/MF ACT — Litz Wire Non-Ideal Twisting

— **Litz Wire** 2000 x 71µm / 3 Twisting Levels

Top-Level - 5 Bundles
Mid-Level - 10 Sub-Bundles
Strand-Level - 40 Strands



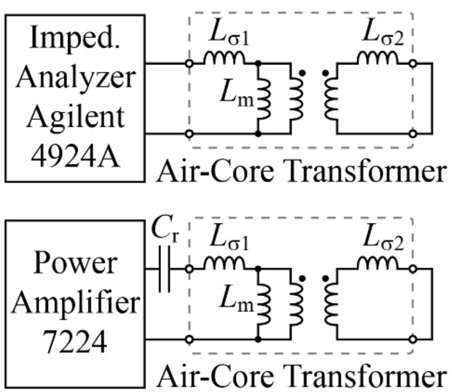


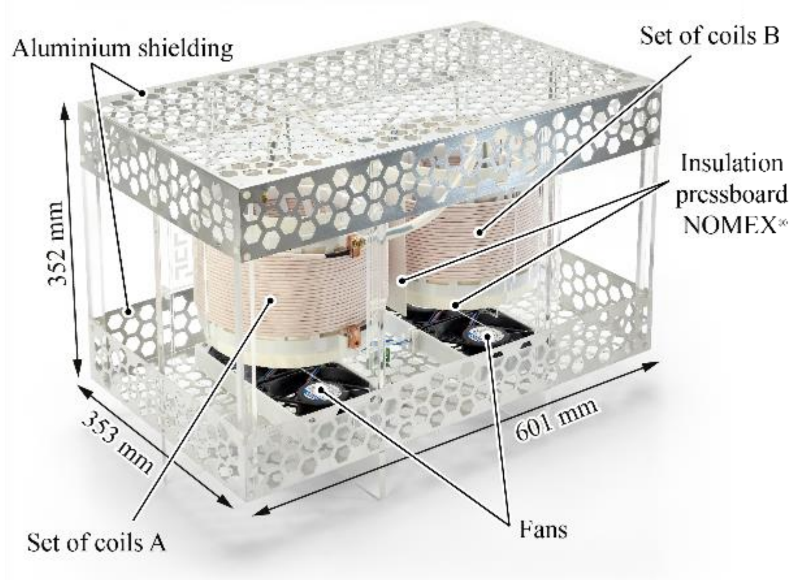
- ▶ **Estimated Add. Losses up to 25%!**
- ▶ **Bundle Level** → **Amplitudes Deviate 23.2%, Phase-Shifts -2°÷5°**
- ▶ **Sub-Bundle Level (No. 5)** → **Amplitudes Deviate 18.4%, Phase-Shifts -18°÷55°**

MV/MF ACT — Shielding Losses

— Relative Losses → AC Resistance Measured in Short-Circuit

- Small Signal → Winding + COG Capacitors + Shielding
- Small Signal → Winding + COG Capacitors
- Large Signal → Winding



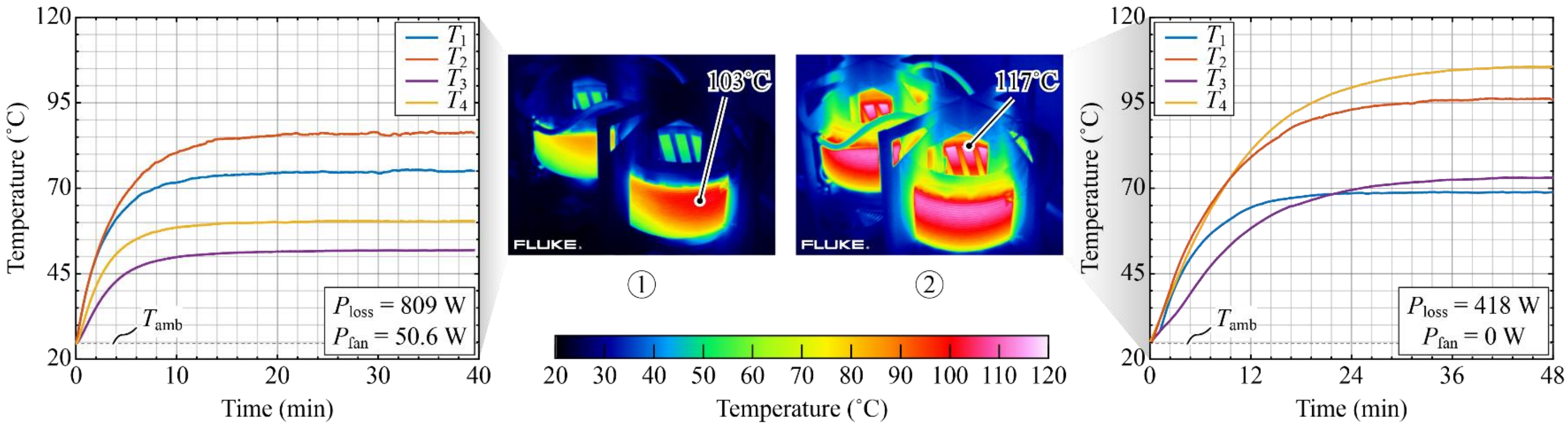


► Shielding Increases AC Resistance by 112%
► Shielding Losses: 90 W (10% Overall)

MV/MF ACT — Thermal Response

— Prim. & Sec. Windings in Series with DC Current Source
— DC Current to Inject the Required Losses

- Nominal Losses w/ Nominal Cooling
- Passive Cooling w/ Max. Allowable Load



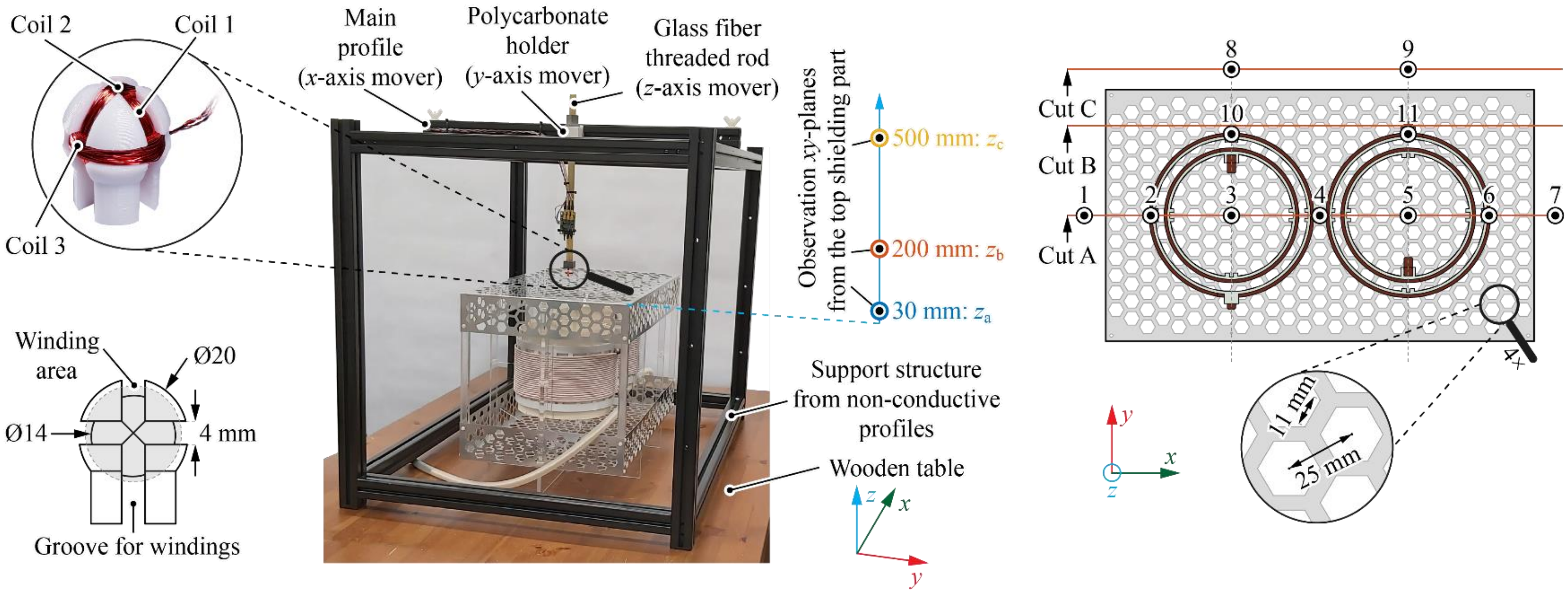
ΔT_{amb} = 25°C / T_{max} = 130°C (Polyamide)

▶ Hot-Spot of 103°C → ΔT = 27°C Increase Rel. to Ambient
▶ Passive Cooling → 117 kW (71% Rated Power)

MV/MF ACT — Magnetic Field Measurement

— **Custom-Built Field Probe**

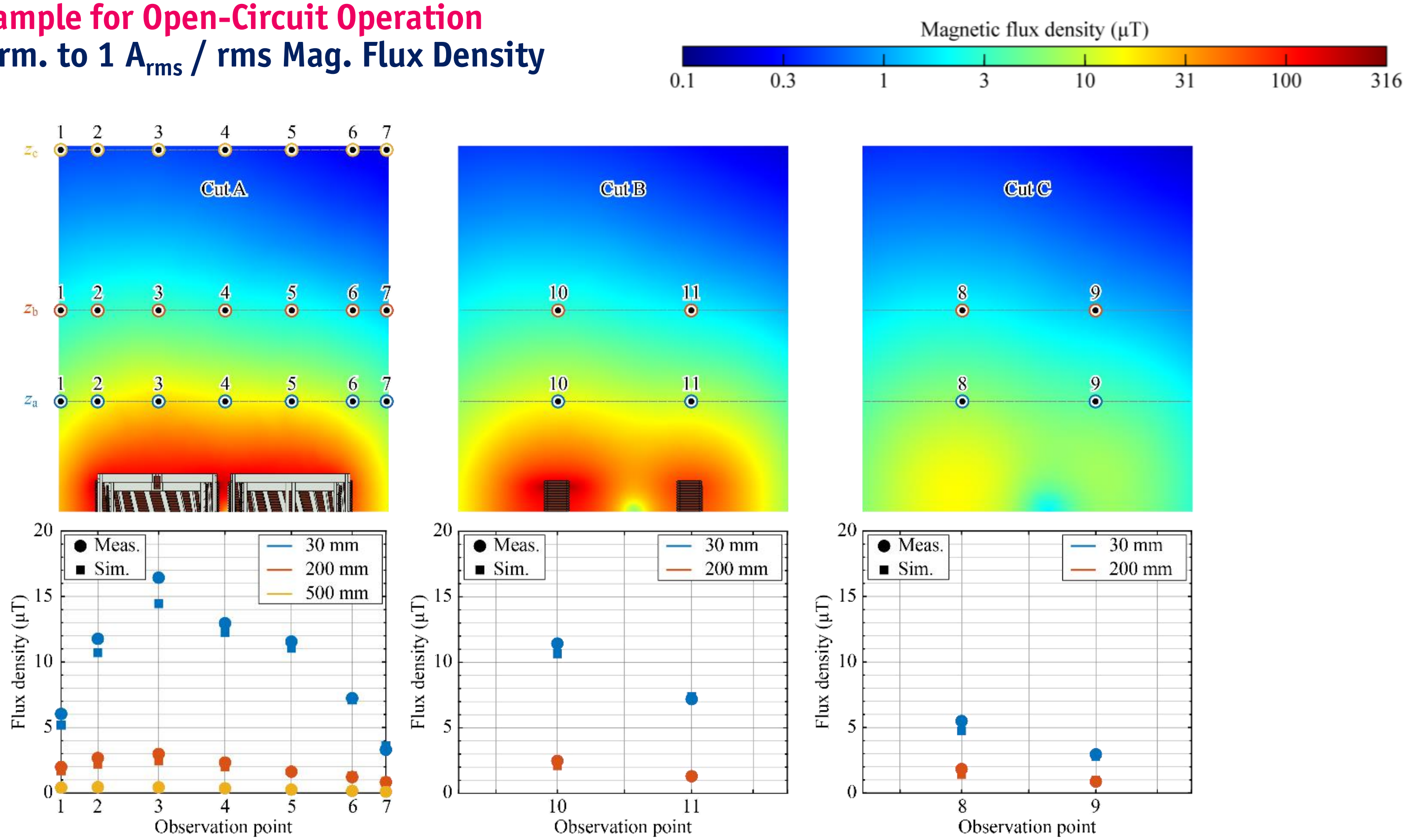
# of Turns	50
Design Freq.	80 kHz
Sensitivity	0.75 mV / µT
Wire Diam.	0.23 mm



▶ **Precise Positioning of the Probe — D = 20 mm**

MV/MF ACT — Verification of FEM Field Calculations

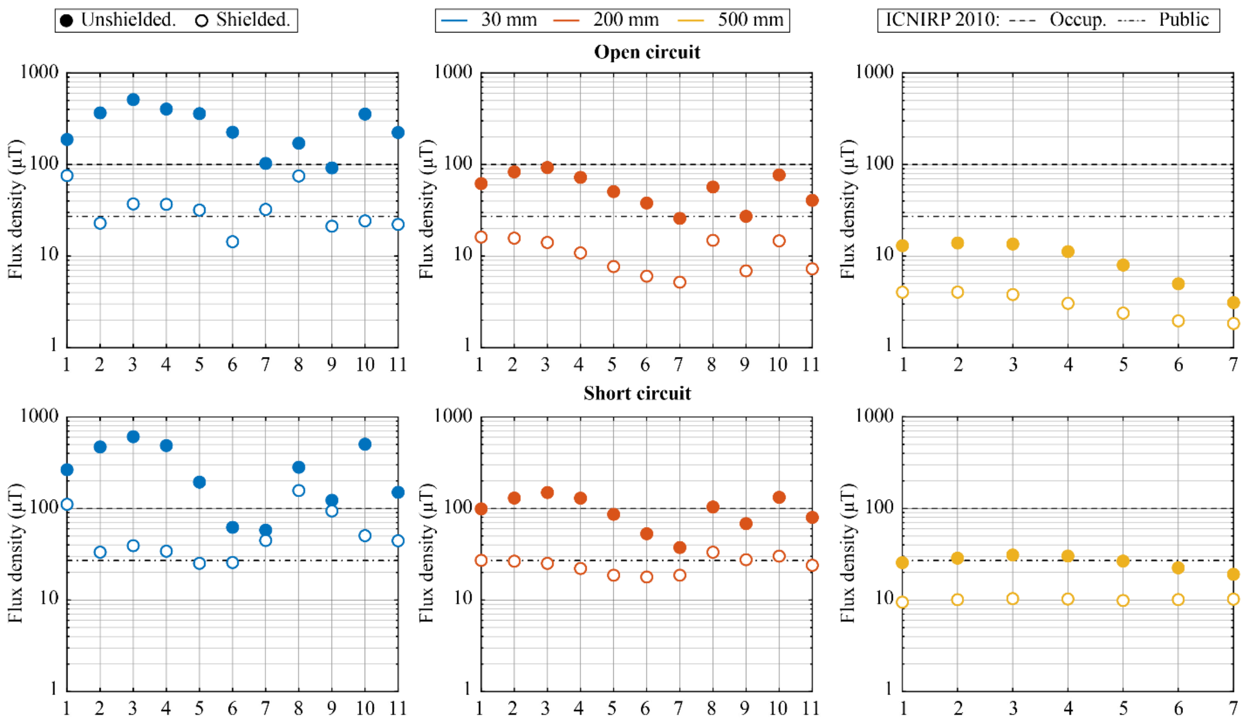
- Example for Open-Circuit Operation
- Norm. to 1 A_{rms} / rms Mag. Flux Density



► Avg. Absolute Rel. Error: 15.2% (Open-Circuit) / 26.8% (Short-Circuit)

MV/MF ACT — Stray Field (ICNIRP 2010)

— Stray Field for Open- & Short-Circuit Operation
— Results Scaled to Nom. Operation / rms Mag. Flux Density



- ▶ Occupational & Public Exposure* @ 200 mm
- ▶ Occupational Exposure* @ 30 mm

*based on Spatial Avg. Field

MV/MF ACT — Insulation Testing

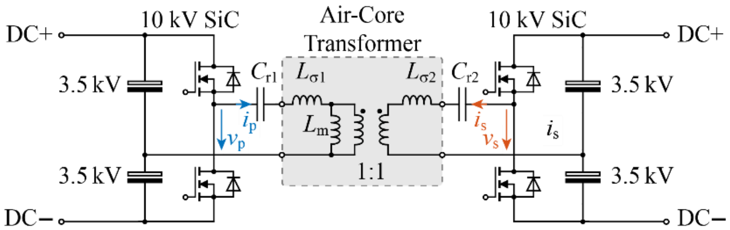
— DM Insulation (Prim.-Sec.) DC Resistance >100 GΩ
— DM Insulation Tests $+9.6\ kV_{DC}$, $-9.6\ kV_{DC}$
$6.36\ kV_{AC}$ @ 50Hz

— Summary of ACT Analysis

- Considered to Withstand the Rated Voltages
- Small and Large Signal Validation
- Evaluation of Losses
- Thermal Feasibility
- Stray Magnetic Field Compliance

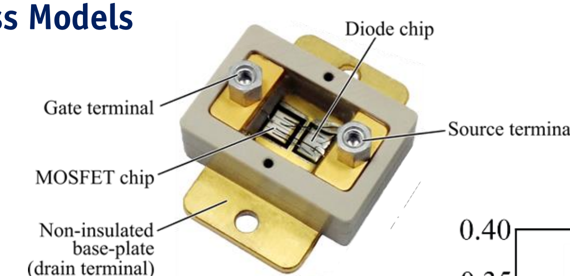
? Partial Load Efficiency of the ACT
? Performance of the Overall 1:1-DCX System

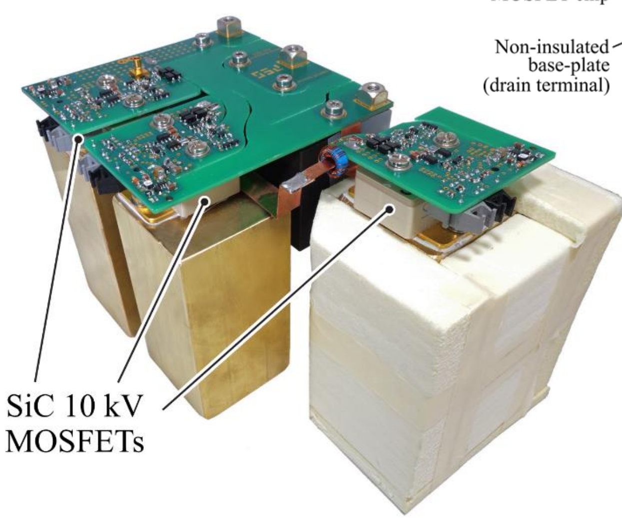
SRC 1:1-DCX Performance

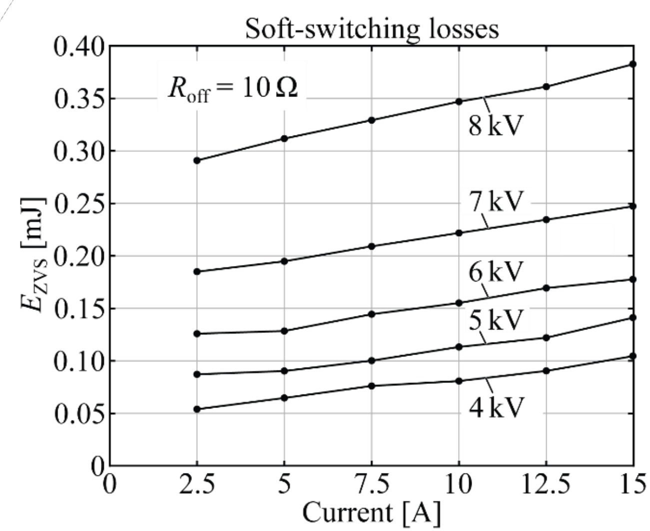


1:1-DCX Components

— 10 kV SiC MOSFETS $R_{ds,on}$ 550 mΩ @ T_j= 125°C
— Trans. Calorimetric Soft-Switching Loss Measurements
— Capacitors: Volume & Mass Models
— Cooling Syst.: Volume & Mass Models







► Converter Components Included in Pareto-Optimization

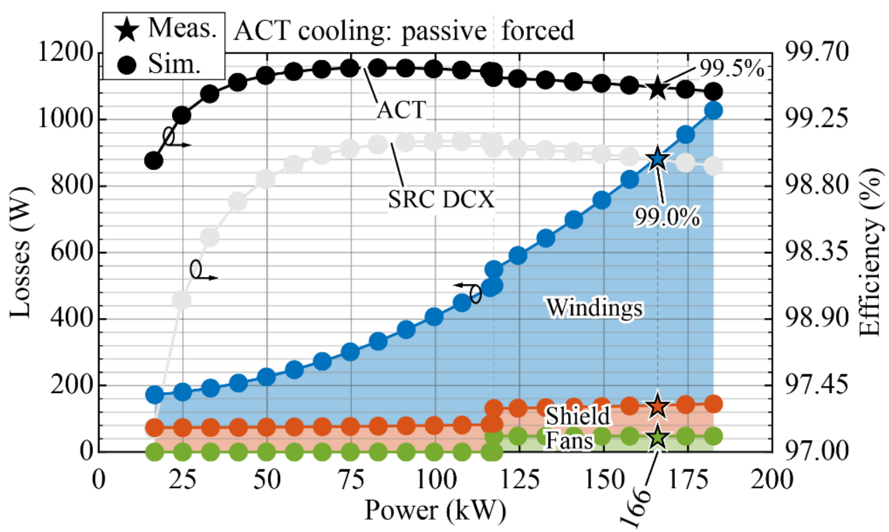
Meas. / Estimated ACT & SRC 1:1-DCX Performance

— **ACT Measured Performance**

- Output Power 166 kW
- Efficiency 99.5%
- Dimensions 35x35x60 cm
- Weight 9.9 kg
- Power Density 16.9 kW/kg
  2.2 kW/l

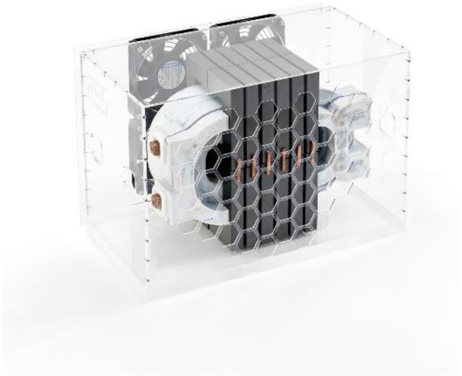
— **SRC 1:1-DCX Calc. Performance**

- Output Power 166 kW
- Efficiency 99.0%



▶ Passive ACT Cooling → up to 117 kW
▶ High ACT Partial Load Efficiency → >99.4% for P_o = [20%, 100%] P_n

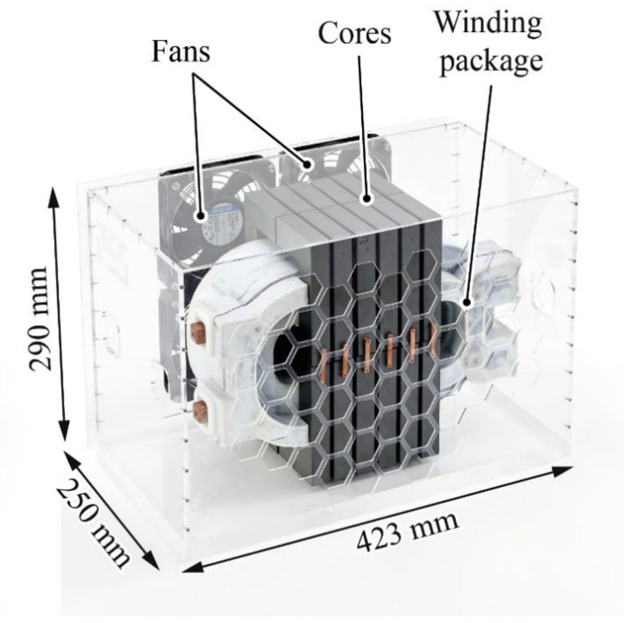
Comparison w/ Magnetic Core Transformer



1:1 MF Magnetic-Core Transformer (MCT)

- Output Power 166 kW
- Prim./Sec. Volt. 7kV

- Efficiency 99.64%
- Weight 23.4 kg
- Power Density 7.1 kW/kg (5.4 kW/l)

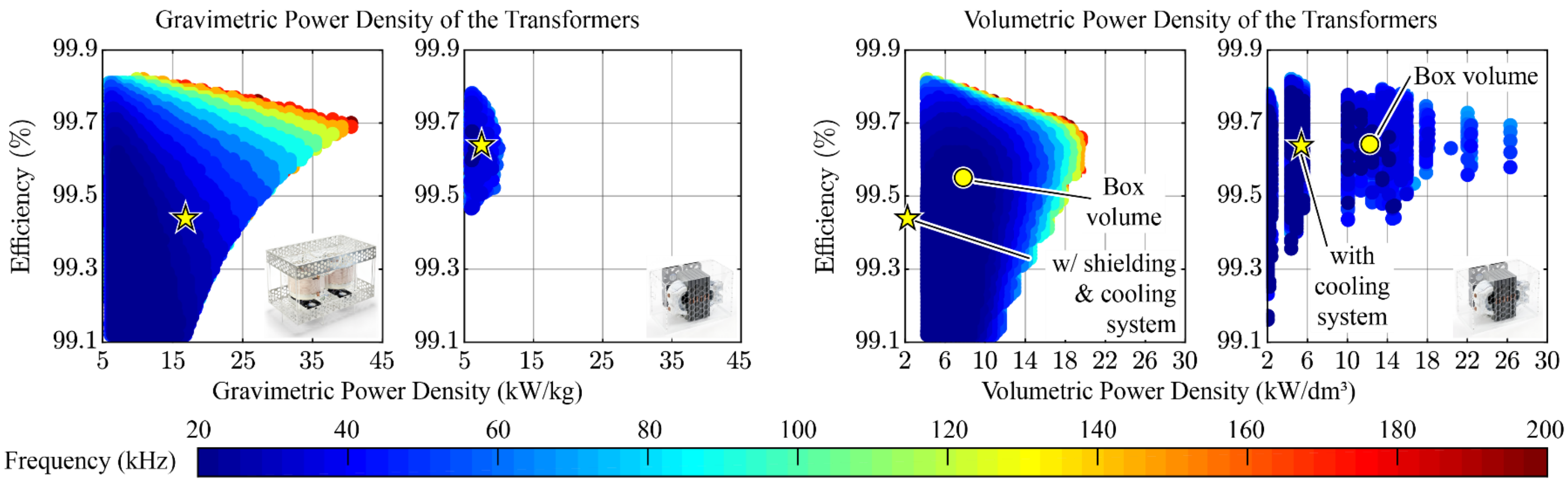


- Dry-Type Insulation
- 6 Parallel E-Cores (2x C-Cores) / Ferrite 3C94
- 17 Turns, 2 Layers, Litz Wire 5400 x 71µm

→ Comparison to ACT

ACT/MCT η-γ-ρ-Pareto Comparison

— **Volumetric & Gravimetric Power Density**
— **Efficiency**

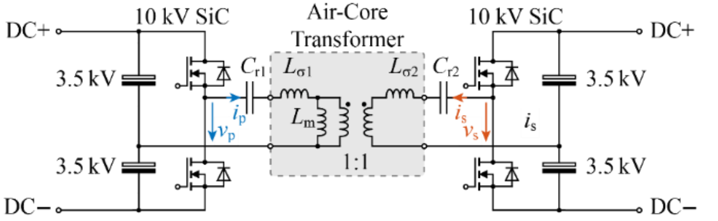


- ▶ **ACT** → **99.43%** @ **16.9 kW/kg** (2.2 kW/l / ● 7.8 kW/l)
- ▶ **MCT** → **99.63%** @ **7.1 kW/kg** (5.4 kW/l / ● 12.2 kW/l)

Conclusions

— **1:1-DCX Series Resonant Converter**

- Full Soft-Switching
- 99.0% Overall Efficiency @ 166 kW



— **1:1 MF Air-Core Transformer**

- 7:7 kV/kV @ 15 kV Isolation Soft-Switching
- 99.4% Overall Efficiency @ 166 kW (77 kHz)
- 16.9 kW/kg / 2.2 kW/l
- Fulfills Stray Field Limits (ICNIRP 2010)
- A1 Airborne Cat. / Press. Zone (DO160 G 2014)

vs.

— High Part-Load Efficiency
— Red. of Weight by Factor of >2 Comp. to MCT (!)
— Simpler Construction — Air Insul. & Air Cooling
— Volume Dominated by the Shielding
— Rel. High Coupling (0.76) for 15 kV Isolation

Questions ?