10kV SiC MOSFETs for Solid-State Transformers: Opportunities and Challenges

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Acknowledgement

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- *Piotr Czyz*

for their contributions.

Agenda

- Introduction
- 10kV SiC FETs
- Switching Frequency
- MV/MF Galvanic Insulation
- SST Prototypes
- Conclusion

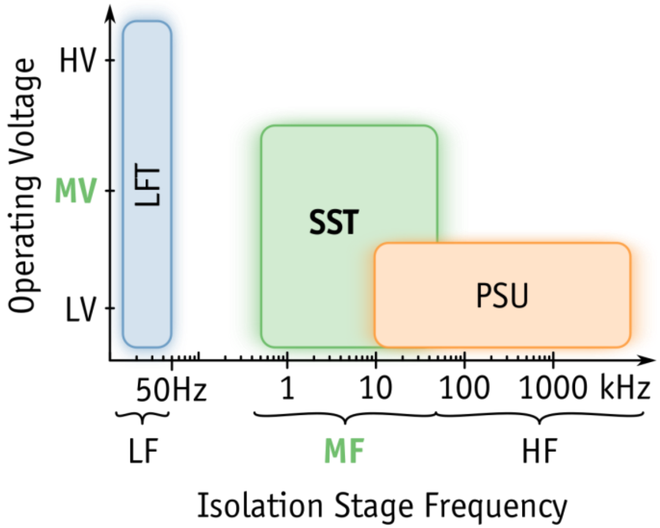
Introduction

SST Definition
Applications
25kW SwiSS-Transformer

▶ What is a Solid-State Transformer (SST)?

- **Power electronics interface**
- **Medium voltage connection**
- **Medium frequency isolation stage**
- **Communication link**

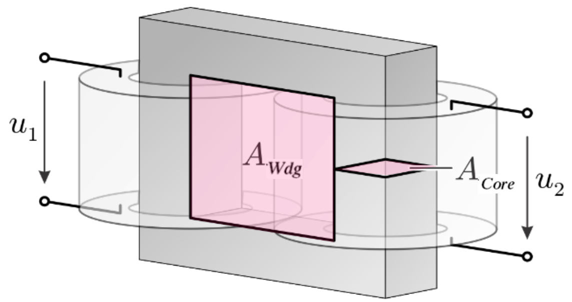
- **I/O quantities**
  - DC/DC
  - AC/DC
  - AC/DC
  - 1ph, 3ph, var. freq.
  - MV/LV, MV/MV



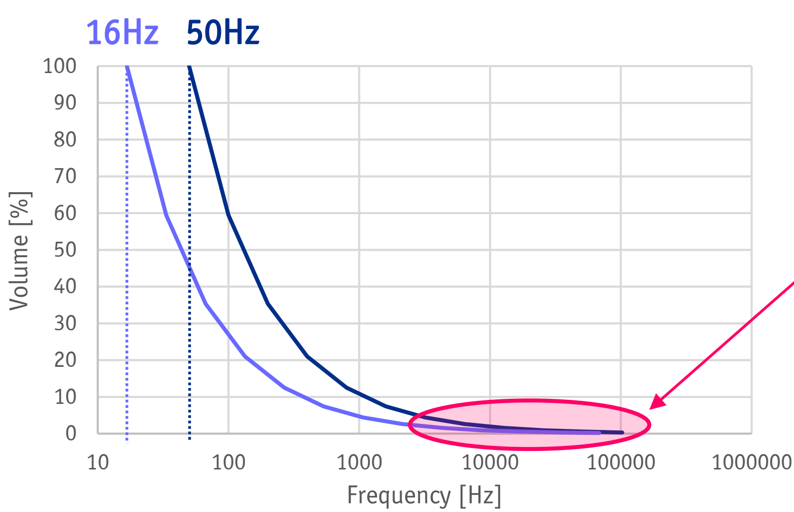
- **Terminology**

McMurray	Electronic Transformer (1968)
Brooks	**Solid-State Transformer (SST, 1980)**
EPRI	Intelligent Universal Transformer (IUT)
ABB	Power Electronics Transformer (PET)
Borojevic	Energy Control Center (ECC)
Wang	Energy Router

▶ Medium Frequency: Transformer Scaling Laws



- $A_{\text{Core}} = \frac{1}{\sqrt{2}\pi}\frac{U_1}{\hat{B}_{\max} f}\frac{1}{N_1}, \quad A_{\text{Wdg}} = \frac{2I_1}{k_{\text{W}} J_{\text{rms}}} N_1$
- Area Product: $A_{\text{Core}} A_{\text{Wdg}} = \frac{\sqrt{2}}{\pi}\frac{P_{\text{t}}}{k_{\text{W}} J_{\text{rms}} \hat{B}_{\max} f}$
- **Volume:** $V \propto \left(A_{\text{Core}} A_{\text{Wdg}}\right)^{\frac{3}{4}} \propto \frac{1}{f^{3/4}}$



- **Caution: too optimistic!**
  - No HF core losses
  - No HF winding losses

▶ DC Collecting Grids for PV

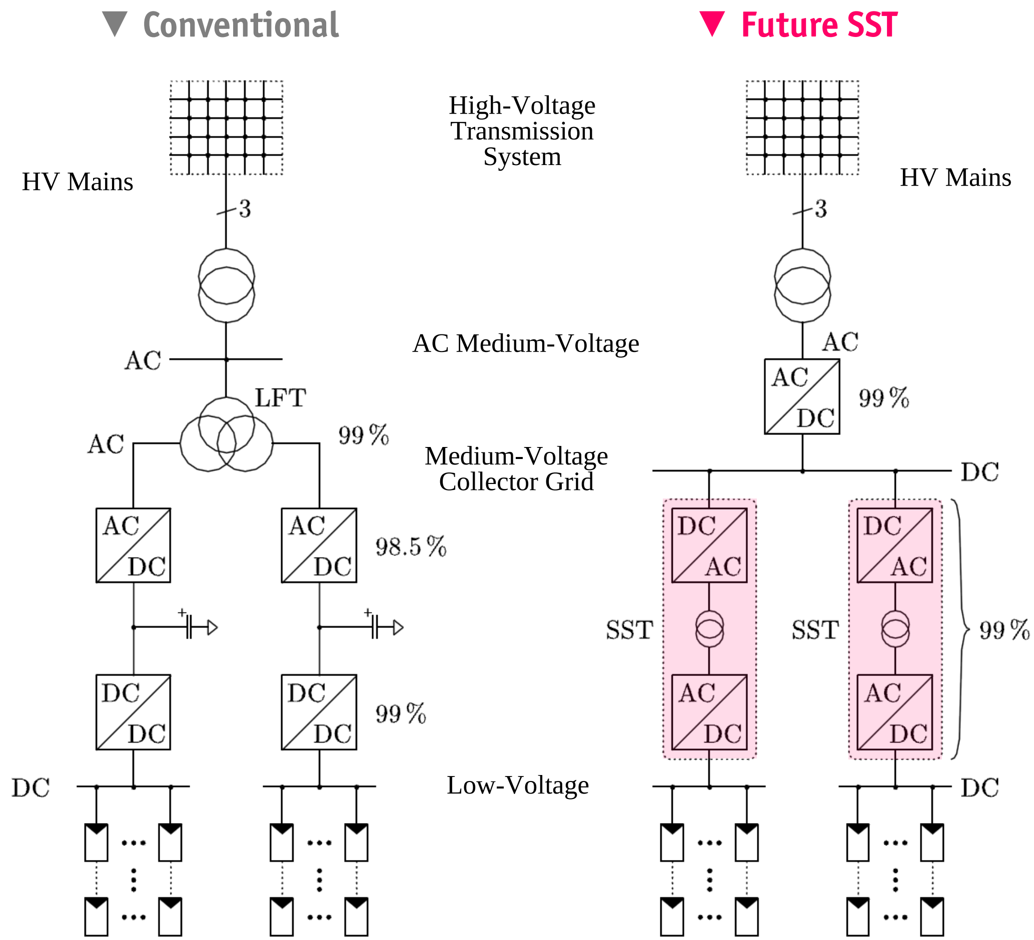
- **Globally installed PV: forecasted to 2.7 Terawatt by 2030** www.iea.org

Source: REUTERS/Stringer

- **Medium-Voltage power collection and transmission**

▶ DC Collecting Grids for PV

- **Conventional**
  - DC/DC for MPPT
  - LF transformer
- **Future SST**
  - Direct MV interface
  - DC/DC SST for MPPT
- **1.5% efficiency gain**



[Kolar/Schröder, Springer, 2018]

▶ Ultra-Fast / High-Power EV Charging

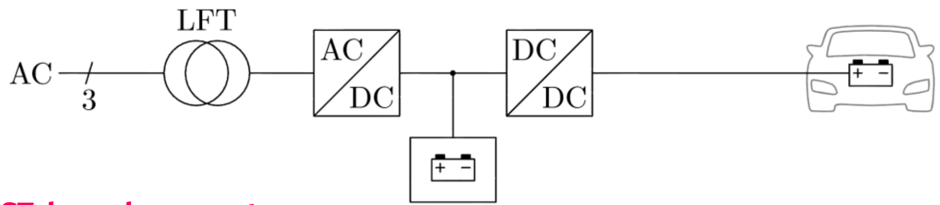
- **High power converter (100kW…2MW)**
- **Medium voltage connected charging systems**

E.g., Porsche FlexBox incl. cooling
Local battery buffer (140kWh)
320kW → 400km range in 20min

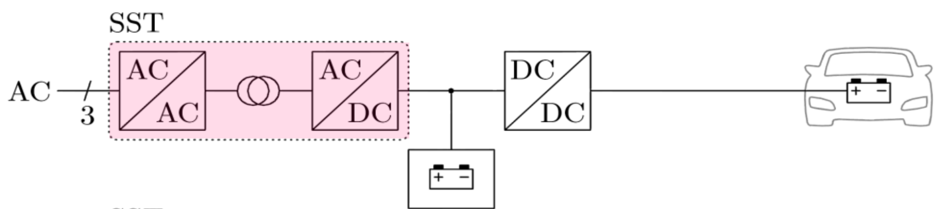
Source: Porsche / Mission-E Project

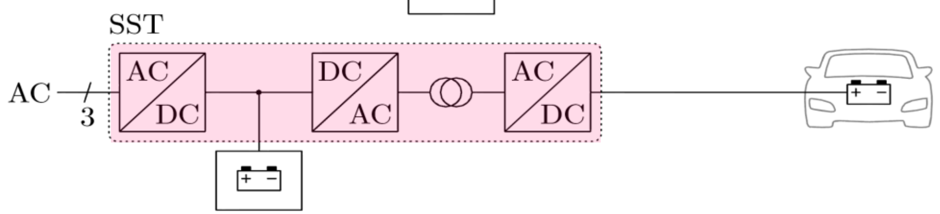
▶ Ultra-Fast / High-Power EV Charging

- **Conventional**



- **Future SST-based concepts**





- **Power / energy management → "energy-hub"**

[Kolar/Schröder, Springer, 2018]

▶ DC Systems for Datacenters

- **Ranging from medium voltage to power-supplies-on-chip**
- **Short power supply innovation cycles**

- **Advantages**
  - Modularity / scalability
  - Higher efficiency
  - Higher power density
  - Lower costs

Server-farms
up to 450 MW
99.9999% / 30s/a
$1.0 mio. / shutdown
Running costs > initial costs

Source: REUTERS/Sigtryggur Ari

33 Watts

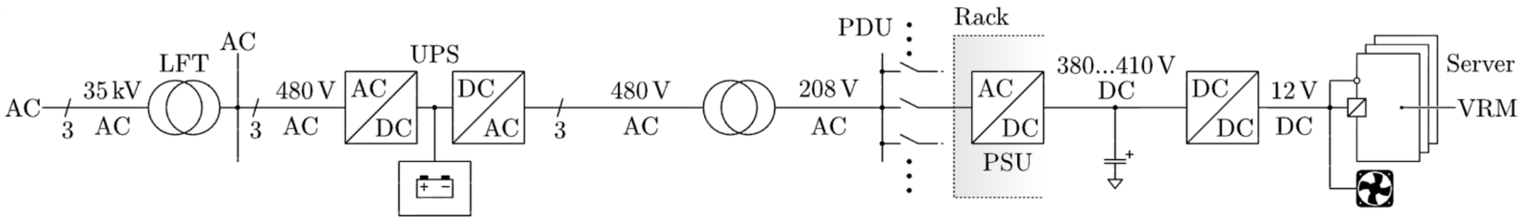
→

60 Watts

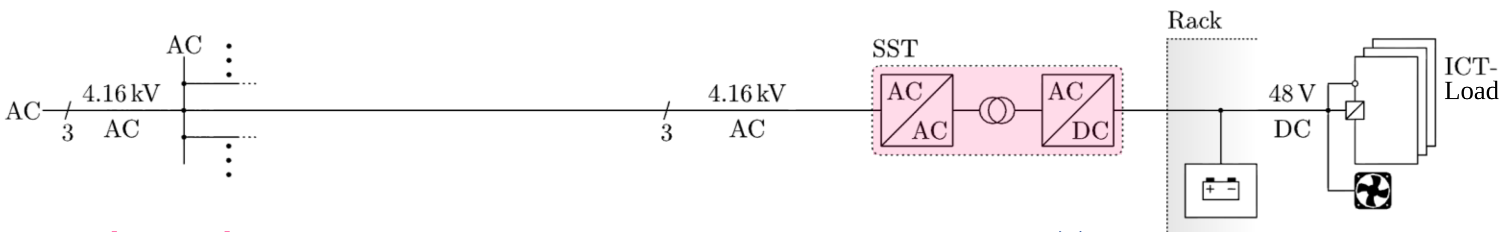
Source: www.vicorpower.com

▶ DC Systems for Datacenters

- **Conventional**



- **Direct 3-phase 6.6kV AC → 48V DC**

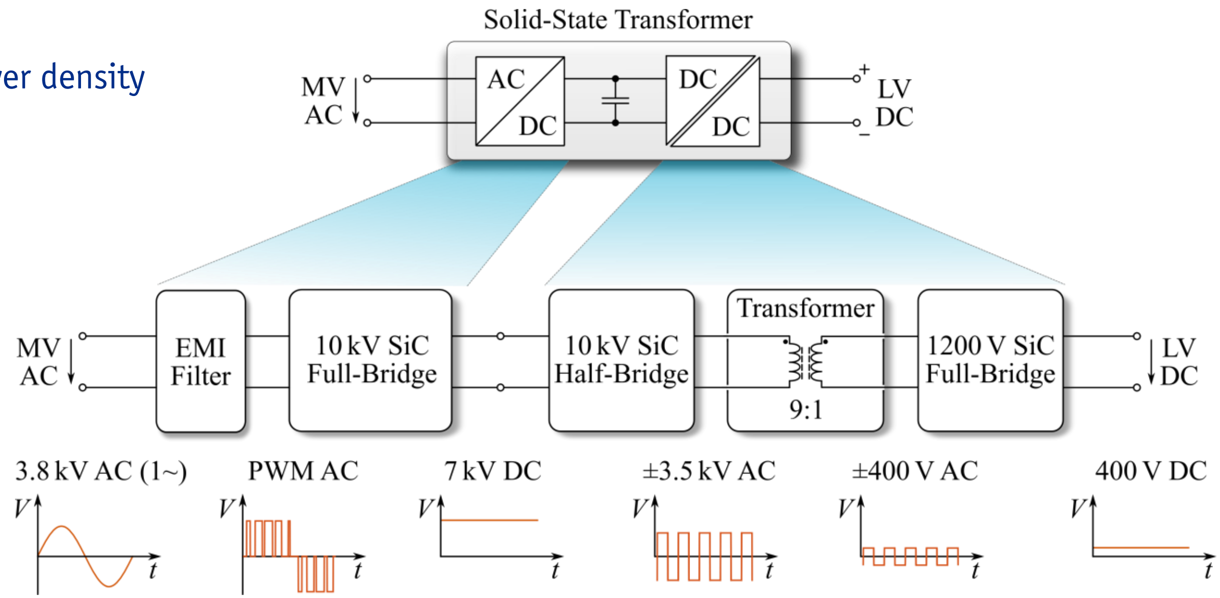


- **MV → 48V → 1.2V: only 2 conversion stages from MV to CPU-level (!)**
- **3...7% reduction in losses & smaller footprint**

[Kolar/Schröder, Springer, 2018]

►SwiSS-Transformer Concept for Datacenters @ ETH Zurich

- **Specifications**
  - Bidirectional 3.8kV AC (1-phase) to 400V DC SST
  - 25kW power rating
- **Target**
  - 98% efficiency
  - 1.5kW/dm^3 power density



- **Single-stage SST concept → 10kV SiC**

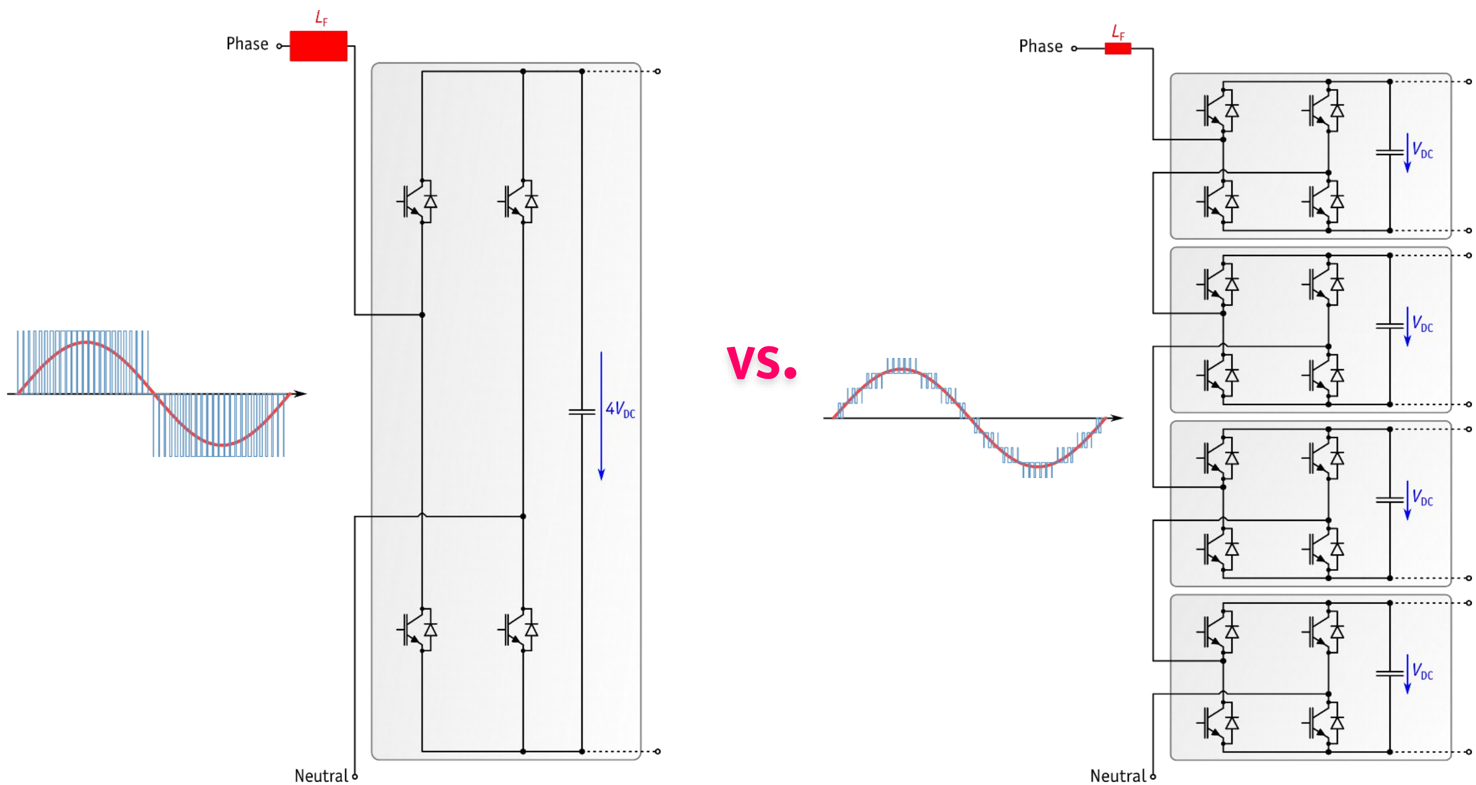
[Rothmund, IEEE JESTPE, 2018]

Handling MV with SiC

Single-stage
Multi-cell
Modular

▶ Single-Stage vs. Multi-Cell

- LV vs. MV semiconductors
- Si vs. SiC semiconductors



- Complexity / volume / losses / reliability / redundancy

[Kolar/Schröder, Springer, 2018]

▶ Complexity of Multi-Cell / Modular Converters

- **Actual realization of a modular MV converter systems → complex task**
  - Isolation coordination
  - Cooling
  - Control & communication
  - Hot-Swap
  - Auxiliary supply
  - Mechanical assembly
  - Fault protection
  - etc., etc.

PCIM Europe 2015, 19 – 21 May 2015, Nuremberg, Germany

Integration Technologies for a Fully Modular and Hot-Swappable MV Multi-Level Concept Converter

Didier Cottet, Wim van der Merwe, Francesco Agostini, Gernot Riedel, Nikolaos Oikonomou, Andrea Rüetschi, Tobias Geyer, Thomas Gradinger, Rudi Velthuis, Bernhard Wunsch, David Baumann, Willi Gerig, Franz Wildner, Vinoth Sundaramoorthy, Enea Bianda, Franz Zurfluh, Richard Bloch, Daniele Angelosante, Dacfey Dzung, ABB Switzerland Ltd., Corporate Research, 5405 Baden-Dättwil, Switzerland

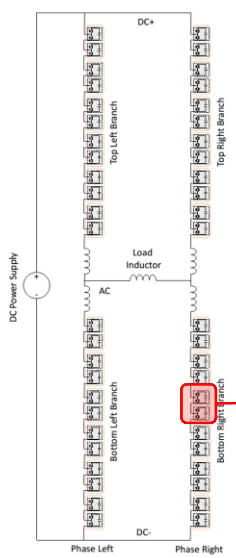
Tormod Wien, Anne Elisabeth Vallestad, Dalimir Orfanus, Reidar Indergaard, Harald Vefling, Arne Heggelund, ABB Norway Ltd., Corporate Research, 1375 Billingstad, Norway

Jonathan Bradshaw, DPS Ltd., Auckland 1010, New Zealand

Contact: didier.cottet@ch.abb.com

> 25 Authors (!)

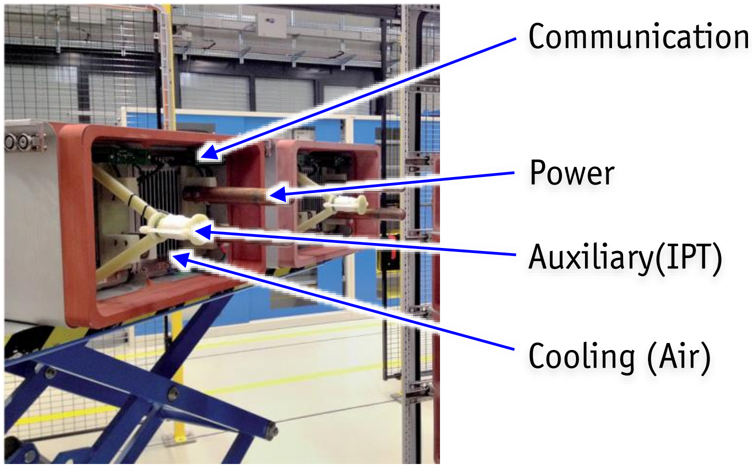
- **Example: MV MMC presented by ABB**



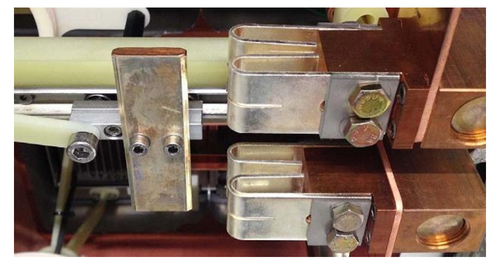
[Cottet, PCIM Europe, 2015] [Cottet, ECCE USA, 2015]

▶ Complexity of Multi-Cell / Modular Converters

- **All interfaces must support modularity – hot-swapping test @ 24kV (!)**

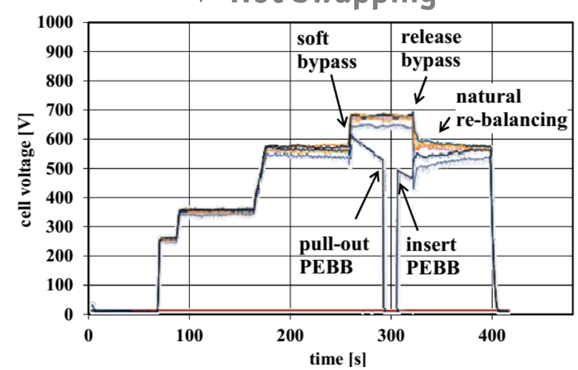


▼ Bypass Switch



▼ Bypass Test

▼ Hot Swapping

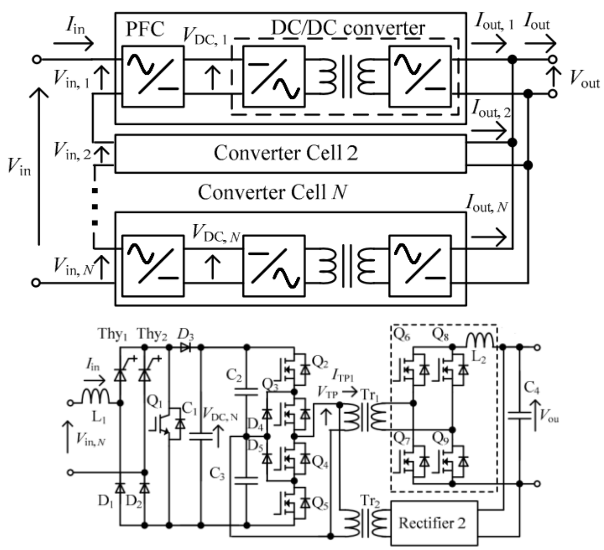


[Cottet, PCIM Europe, 2015] [Cottet, ECCE USA, 2015]

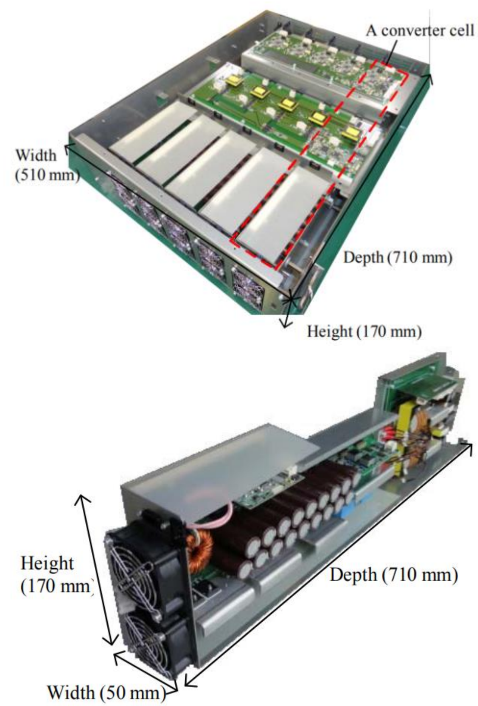
▶ SST for Datacenters: Multi-Cell

- **Multi-cell SST (ISOP) for datacenters presented by Fuji Electric**
  - 2.4kV AC input
  - 54V DC output
  - 25kW
  - Si technology
  - 5 cells
  - 65 switches / 35 diodes
  - 10 transformers / 12 inductors
  - No redundancy

▼ Topology



▼ Hardware

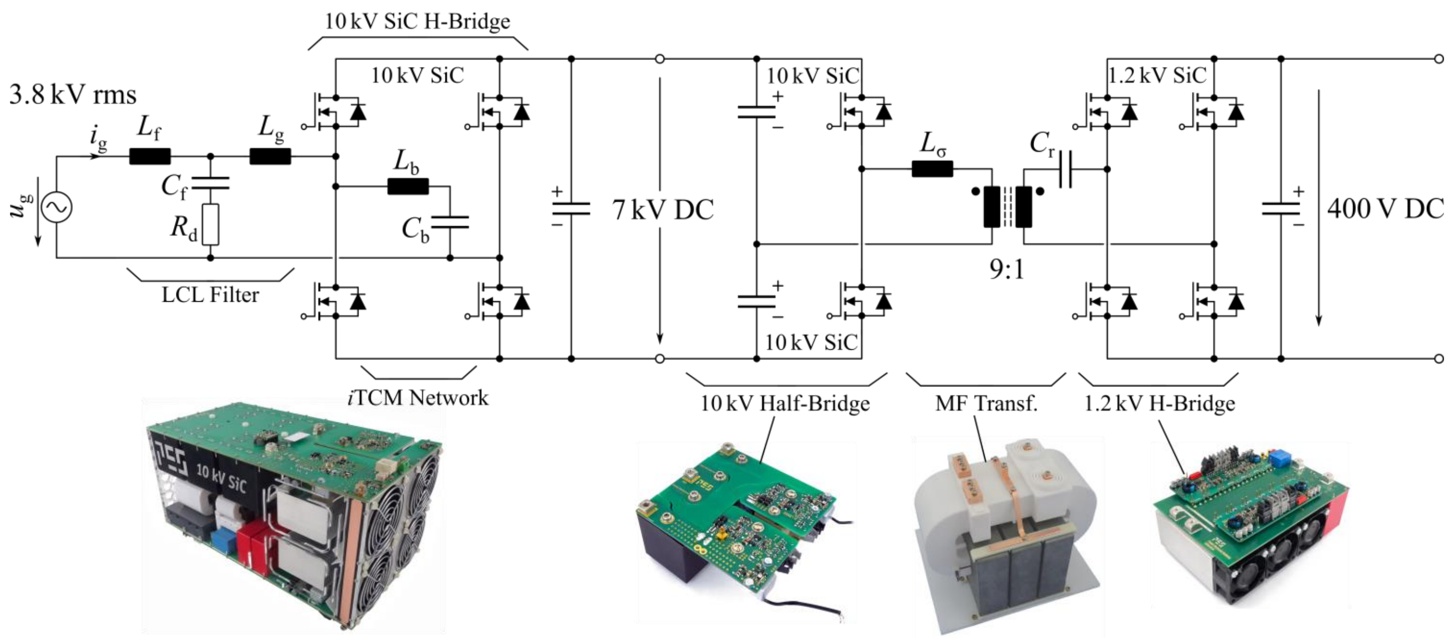


- **LV Si FETs → very complex structure**

[Kashihara, APEC, 2017]

▶ SST for Datacenters: Single-Stage

- **Single-stage SST for datacenters presented by ETH zürich**
  - 3.8kV AC input
  - 400V DC output
  - 25kW
  - SiC technology
  - 1 cells
  - 10 switches / 0 diodes
  - 1 transformers
  - 3 inductors



- **Much simpler structure → require HV SiC FETs**

[Rothmund, IEEE JESTPE, 2018]

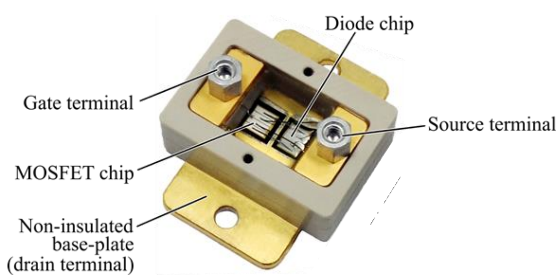
Driving HV SiC

Isolated Supply
Gate-Drive
Fault Protection

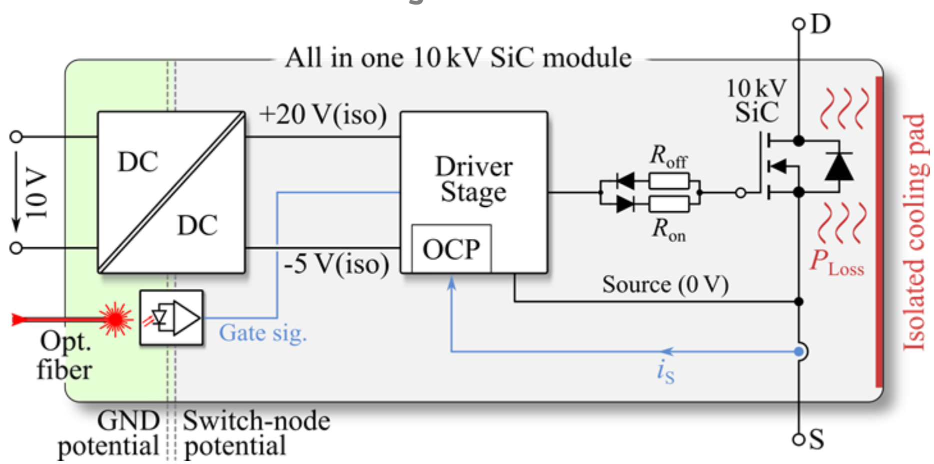
▶ HV SiC MOSFETs

- **6.5..15kV SiC FETs → new challenges for packaging, driving, etc.**
  - Isolated power supply
  - Isolated communication
  - Fault detection
  - Insulated cooling pad
  - Electric field shaping
  - Clearance / creepage

▼ 10kV SiC Prototype



▼ Integrated Module

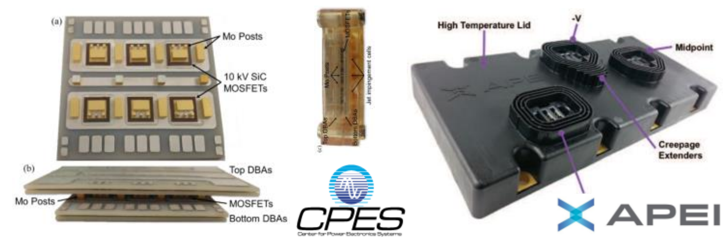


[Rothmund, IEEE CPSS, 2018]

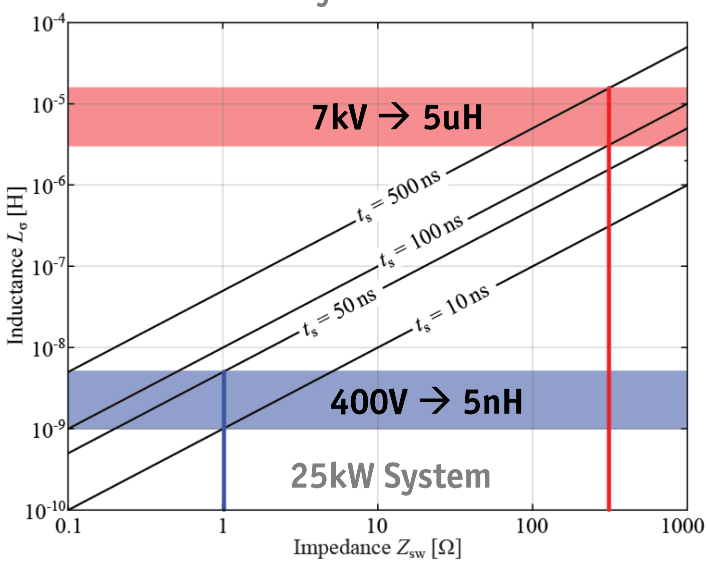
▶ Low Inductance or Low Capacitance?

- **HV system → high impedance**
  - Stray inductance are less critical
  - Stray capacitance are critical
- **Paradigm shift towards low capacitive designs**

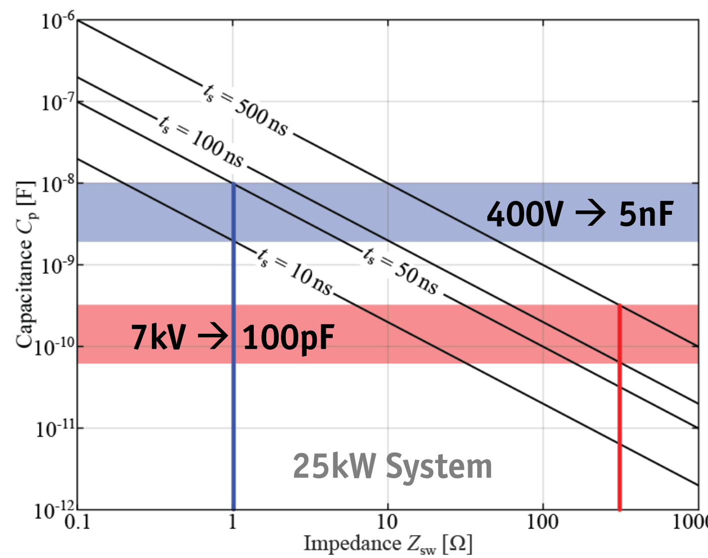
▼ HV SiC Module Prototypes



▼ Stray Inductance



▼ Stray Capacitance

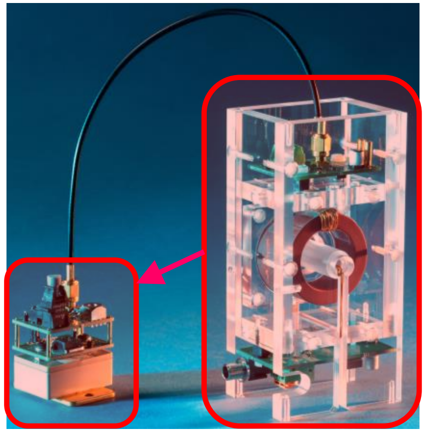


[DiMarino, CPES, 2019] [Kraig, NIST/DOE, 2014] [Rothmund, IEEE JESTPE, 2018]

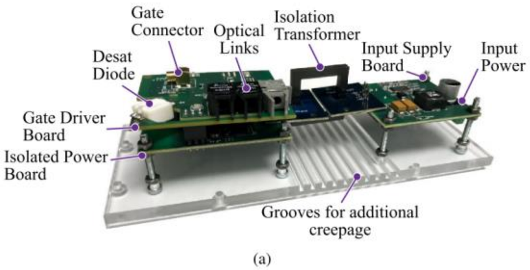
▶ Isolated Power Supply

- Low capacitance
- HV CM insulation
- EMI robustness
- Compact design

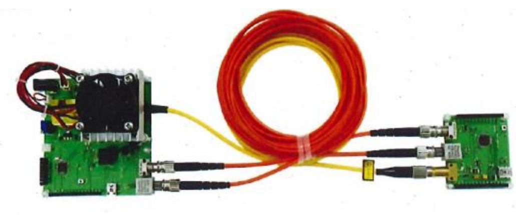
▼ Fraunhofer / Toroid



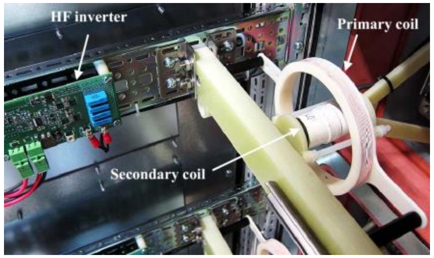
▼ FREEDM / PCB



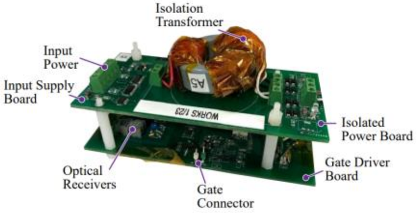
▼ TDK / Fiber



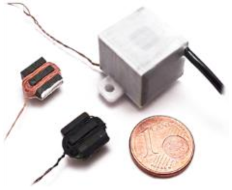
▼ ABB / IPT



▼ FREEDM / Toroid

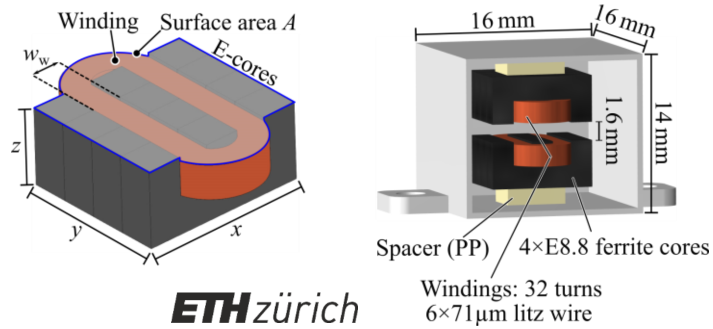


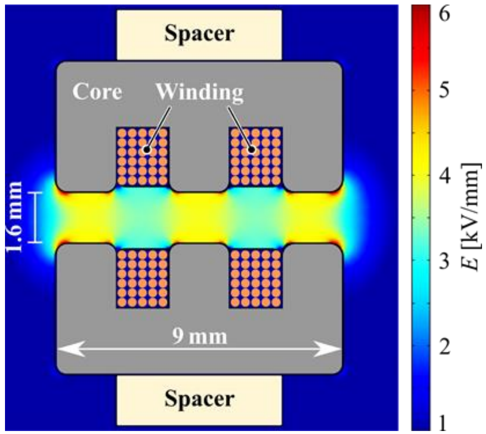
▼ ETHZ / Potted

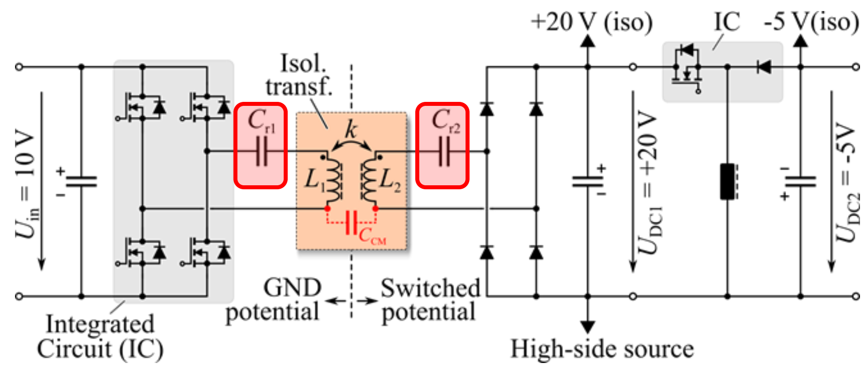


▶ Isolated Power Supply with Air Gap Insulation

- **Two core halves separated by insulation**
  - Vacuum potted in silicone
  - 2.6pF coupling capacitance
  - 3.1 cm^3 volume







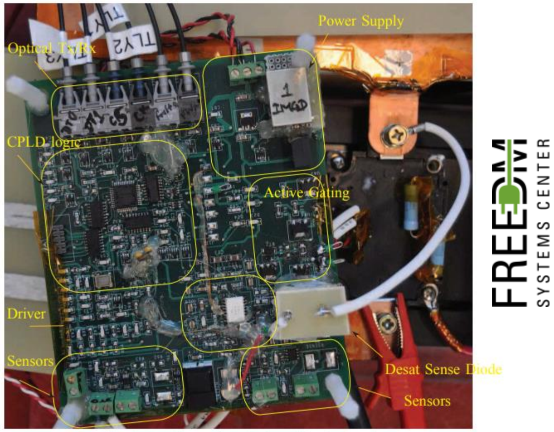
- **Isolation testing: 20kVDC for 1 hour & 7kV / 50...200kHz for > 50 hours**

[Rothmund, IEEE JESTPE, 2018]

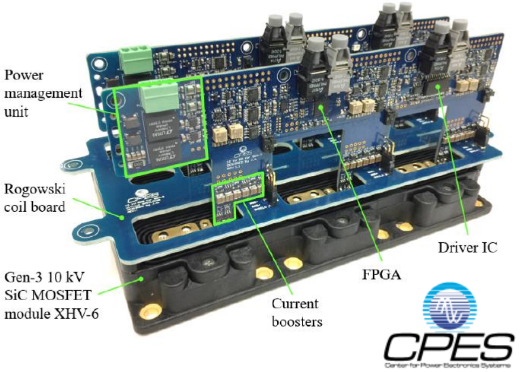
▶ Short-Circuit Detection

- **HV SiC devices**
  - Sensitive devices (compared to IGBTs)
  - Expensive devices
- **Fault detection**
  - EMI immunity
  - High bandwidth
  - Compact design
- **Different concepts are working**

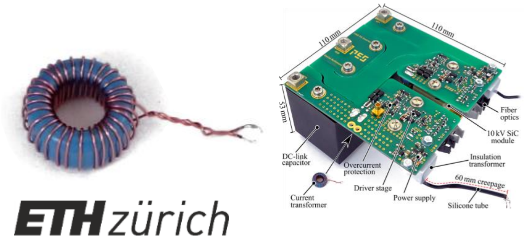
▼ FREEDM / Shunt / Desat.



▼ CPES / Rogowski Coil



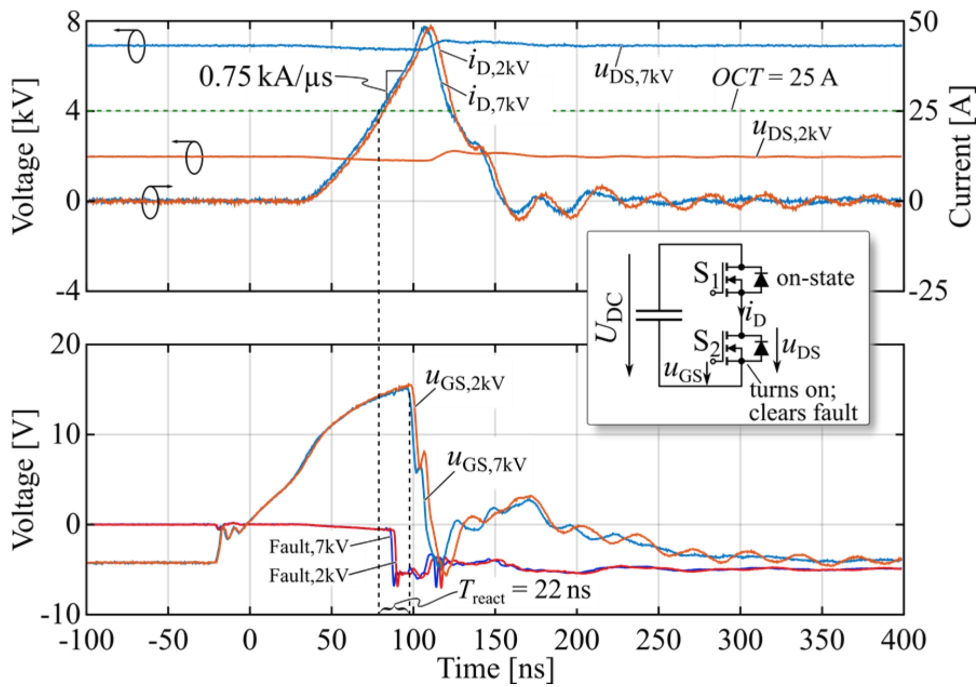
▼ ETHZ / Gapped Current Trf.



[Tripathi, APEC, 2016] [Wang, CPES, 2019] [Rothmund, IEEE JESTPE, 2018]

▶ Fault: Hard Switching

- **Testing for hard switching fault @ 7kVDC**
  - Current transformer for overcurrent detection
  - 25ns delay from overcurrent threshold to gate voltage reaction

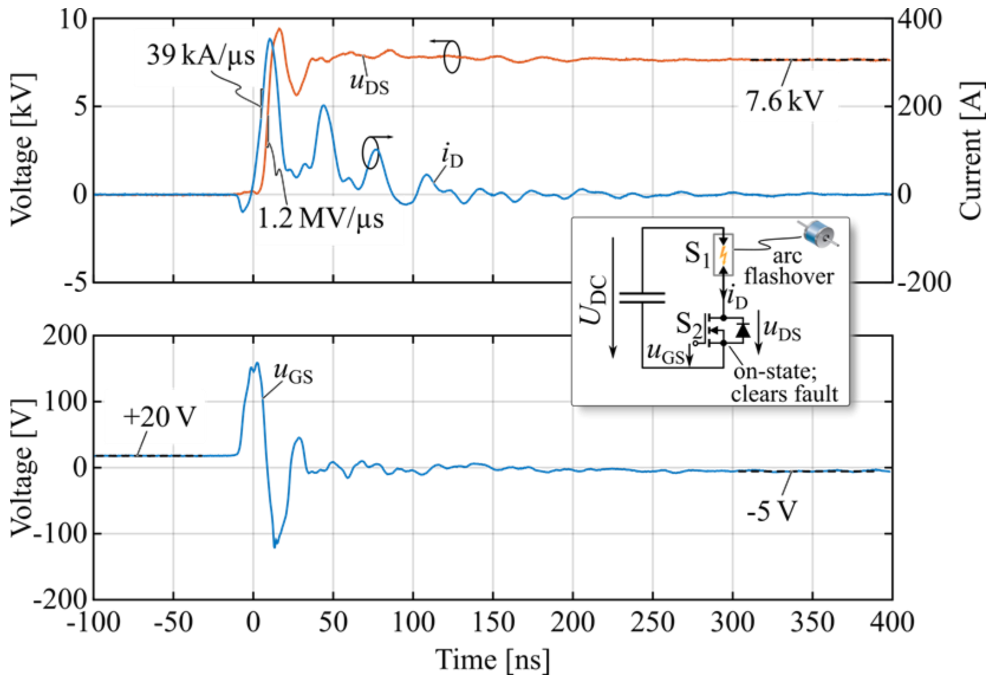


- **Hard switching → 50A max. curr. / 200ns for turn-on of low-side switch**

[Rothmund, IEEE JESTPE, 2018]

▶ Fault: Flashover

- **Testing for flashover fault @ 7kVDC**
  - Most critical case
  - Specific to MV systems

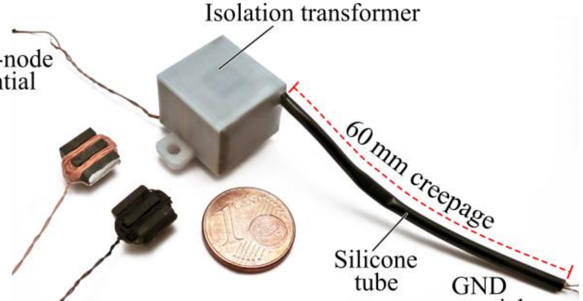


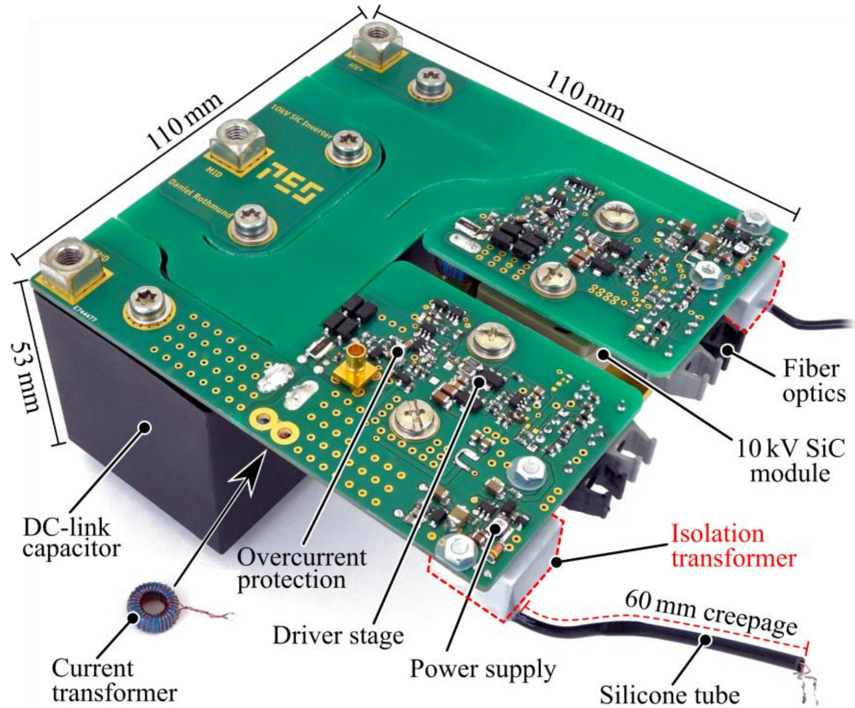
- **Flashover (gas discharge tube) → du/dt = 1.2MV/us / switching 7.2kV in 6.0ns (!)**

[Rothmund, IEEE JESTPE, 2018]

▶ Realized 10kV SiC Half-Bridge

- **Creepage: PCB slots / silicone tubes (IEC norm)**
- **Components**
  - Insulated supplies
  - Gate drivers
  - Fault protection
  - DC-link capacitor
- **Cooling of FETs**
  - Heatsink on potential
  - Reduced parasitic cap.





[Rothmund, IEEE JESTPE, 2018]

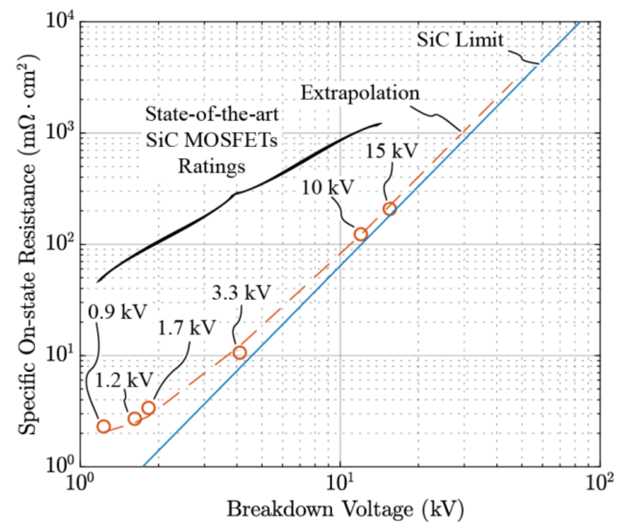
HV SiC Performance

Single-stage
Multi-cell
Modular

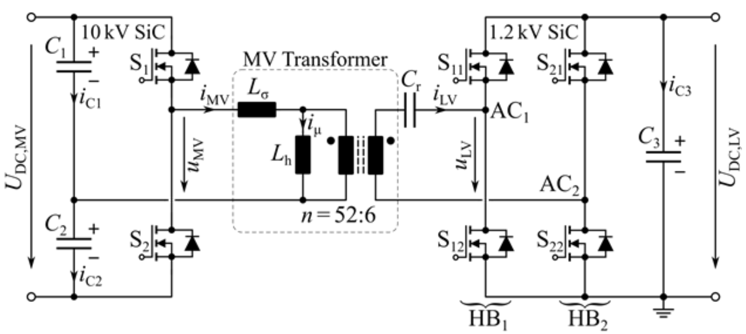
▶ Conduction Performances

- **HV SiC FETs approaches the SiC limit**
- **HV SiC FETs have low condution losses**
- **Beware: MV bipolar devices (SiC IGBTS) are even better**

▼ SiC FETs Scaling



▼ DC-DC Converter / 7kV / 400V



▼ DC-DC Converter / Conduction Losses

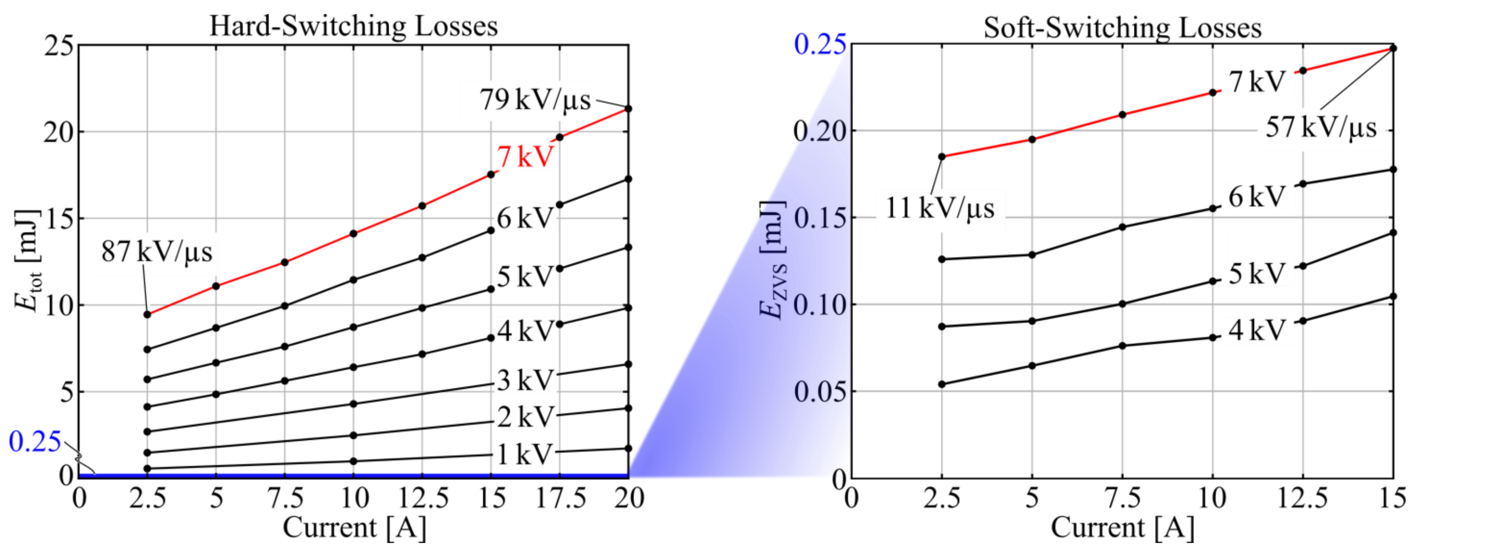
Side	Devices	Res. / Switch	Cond. Losses
7kV	1x parallel	400mΩ	28W
400V	3x parallel	11.3mΩ	113W

- **Equal MV and LV conduction losses → 2.6mΩ would be required (!)**

[Rothmund, IEEE JESTPE, 2018]

▶ Switching Losses

- **Hard-switching vs. soft-switching**
  - Significant hard sw. losses (still better than Si IGBT)
  - Hard switching limit the frequency to 5kHz
  - 30-times lower soft-sw. losses / lower d*u*/d*t*



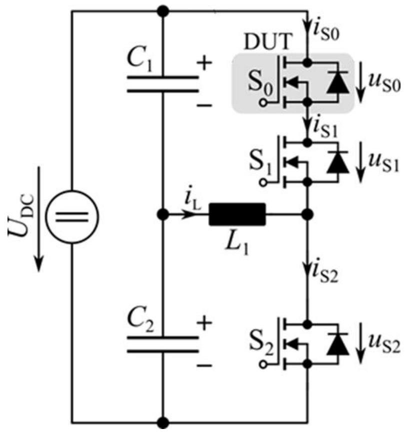
- **ZVS topologies should be favored**

[Rothmund, IEEE TPEL, 2018]

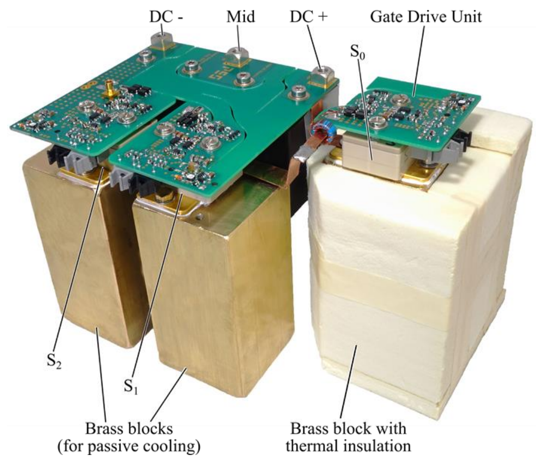
▶ Measuring ZVS Losses: Transient Calorimetric

- **Electric measurements are too inaccurate for MV ZVS losses**
- **Transient calorimetric measurements**
  - DUT on therm. isolated brass block
  - Temp. gradient indicates total power loss
  - Add. switch S_0 for separation of cond. & sw. losses

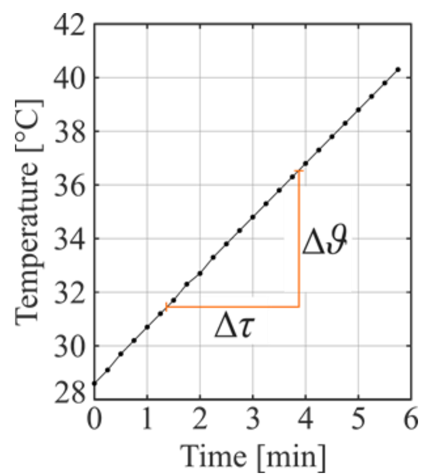
▼ Topology



▼ Setup



▼ Meas.



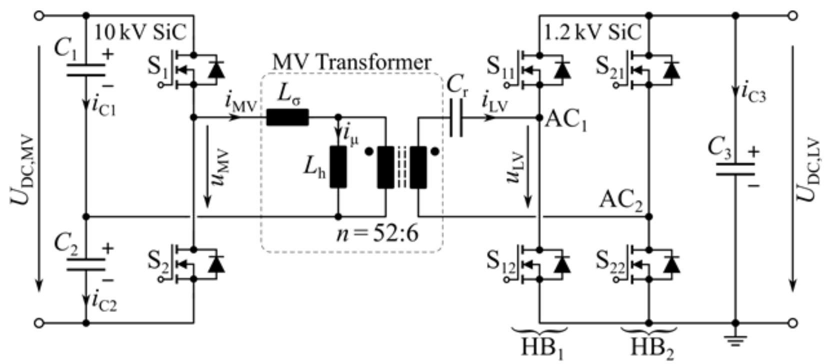
- **No subtraction between E_{on} and E_{off} → accurate measurements**

[Rothmund, IEEE TPEL, 2018]

▶ZVS Switching Performances

- HV SiC FETs have good ZVS performance
- ZVS losses still in range of cond. losses @ 48kHz

▼ DC-DC Converter / 7kV / 400V

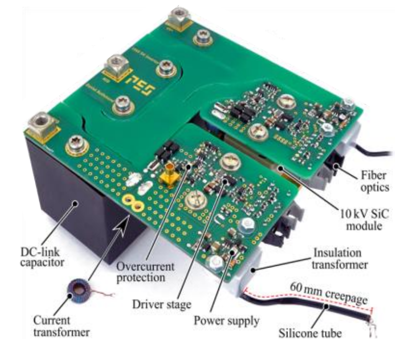


▼ DC-DC Converter / Switching Losses / 48kHz

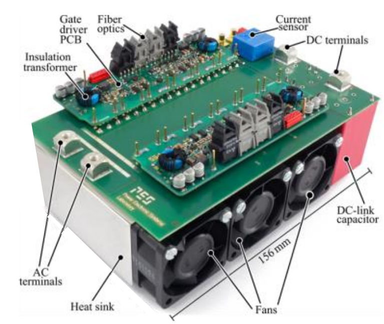
Side	Devices	Energy / switch	Sw. Losses
7kV	1x parallel	191µJ	18W
400V	3x parallel	8µJ	2W

- LV SiC FETs have better switching performances

▼ MV Bridge



▼ LV Bridge

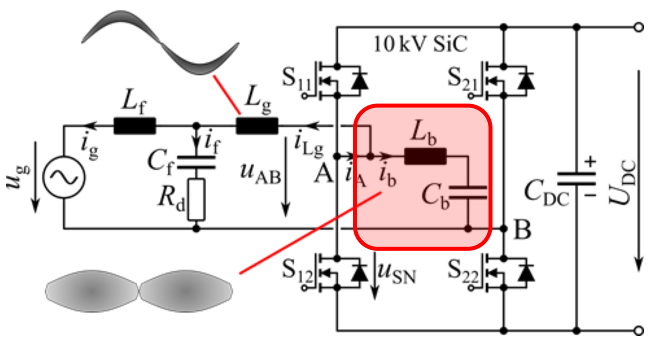


[Rothmund, IEEE JESTPE, 2018]

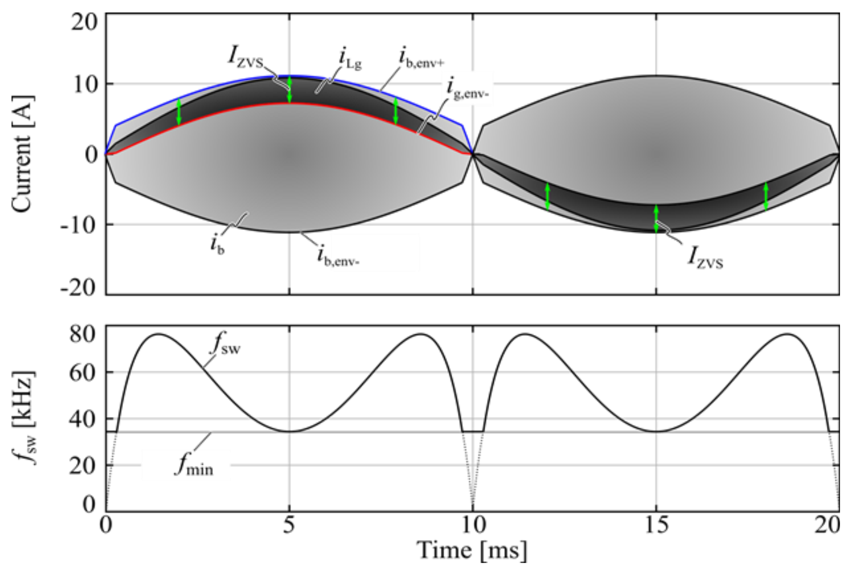
▶ SST for Datacenters: AC-DC ZVS

- **Integrated Triangular Current Mode (iTCM) topology**
  - Increase of current ripple by an additional LC-branch
  - Separation of the HF and the LF current

▼ Topology



▼ Waveforms



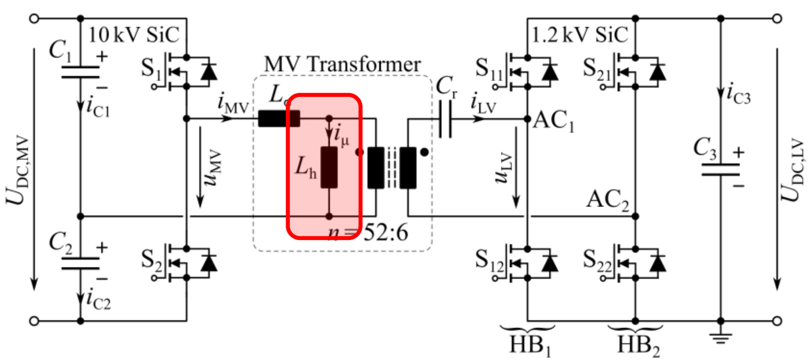
- **Open-loop variation of sw. frequency for const. ZVS current (35...75kHz)**
- **Well-known PWM modulation applicable**

[Rothmund, IEEE JESTPE, 2018]

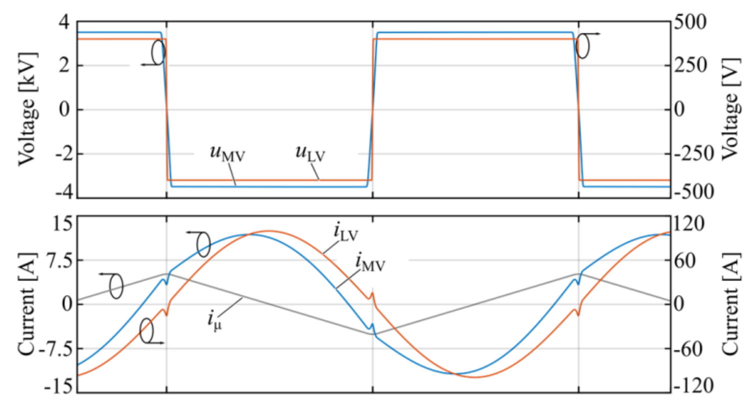
▶ SST for Datacenters: DC-DC ZVS

- **Series Resonant Converter (SRC) topology**
  - Operation at resonance frequency (48kHz)
  - Acts as “DC transformer”
  - ZVS with trf. mag. current

▼ Topology



▼ Waveforms



- **New phase-shift modulation scheme**
  - Active splitting of the mag. current between the LV and MV side
  - Better than synchronous rectification

[Guillod, IEEE TPEL, 2019]

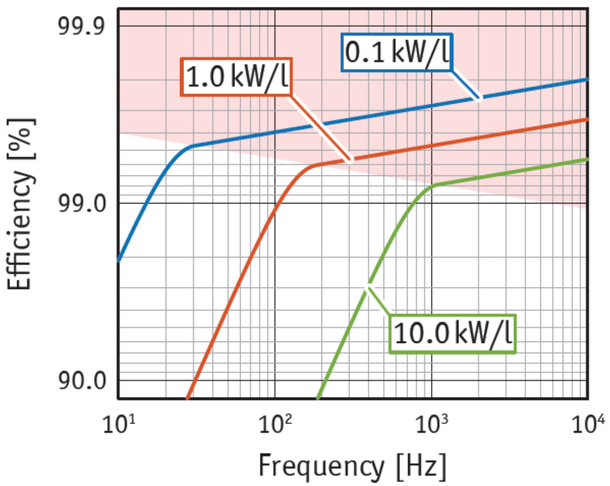
Switching Frequency

Frequency dependent losses
Optimal Frequency
Trade-offs

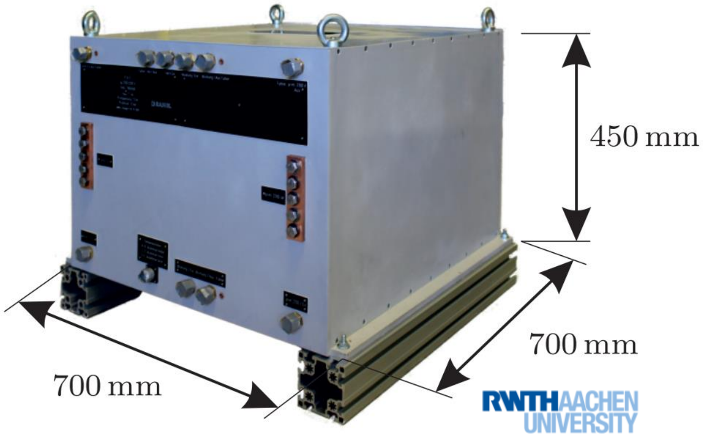
▶ Frequency Selection

- **Magnetics profit from high sw. frequencies**
  - Reduced losses
  - Reduced volume
- **Semiconductors profit from low sw. frequencies**
- **System optimum**

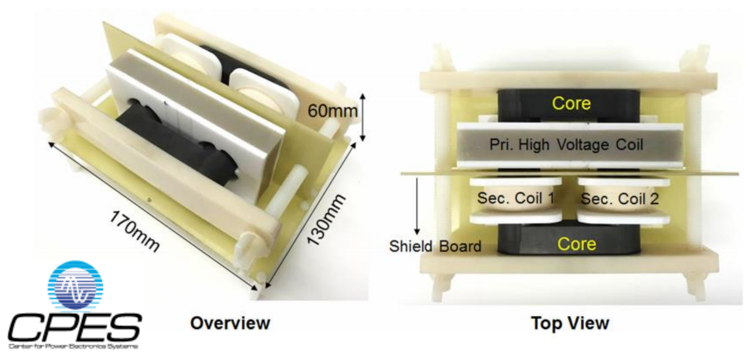
▼ Trf. Scaling



▼ RWTH / 1kHz / 2.2MVA



▼ CPES / 500kHz / 15kW

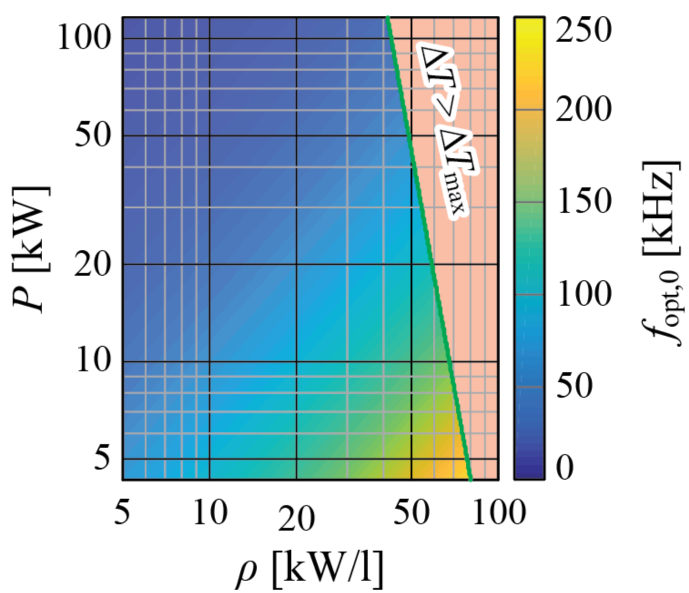


[Soltau, RWTH, 2017] [Zhao, IEEE TPEL, 2018]

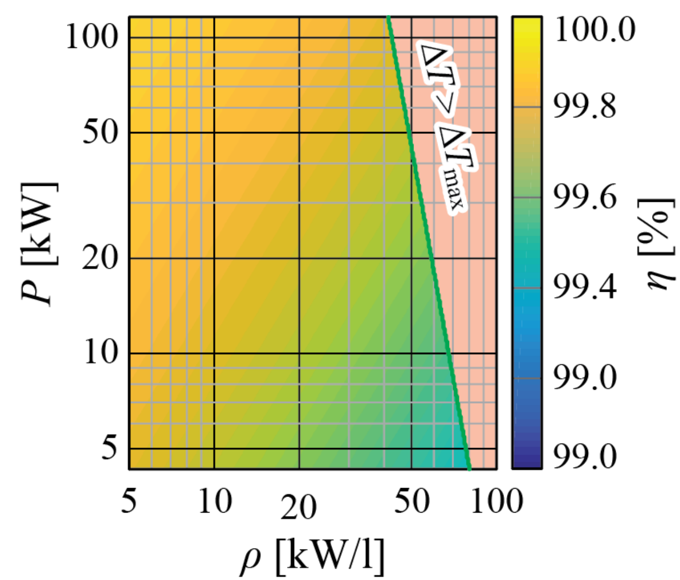
▶ Optimal Frequency of Transformers

- **Magnetics profit from high sw. frequencies**
  - Core losses → reducing (volt-second prod.)
  - Winding losses → increasing (skin / prox.)
- **Transformers have optimal op. frequencies**

▼ Opt. Frequency



▼ Max. Efficiency



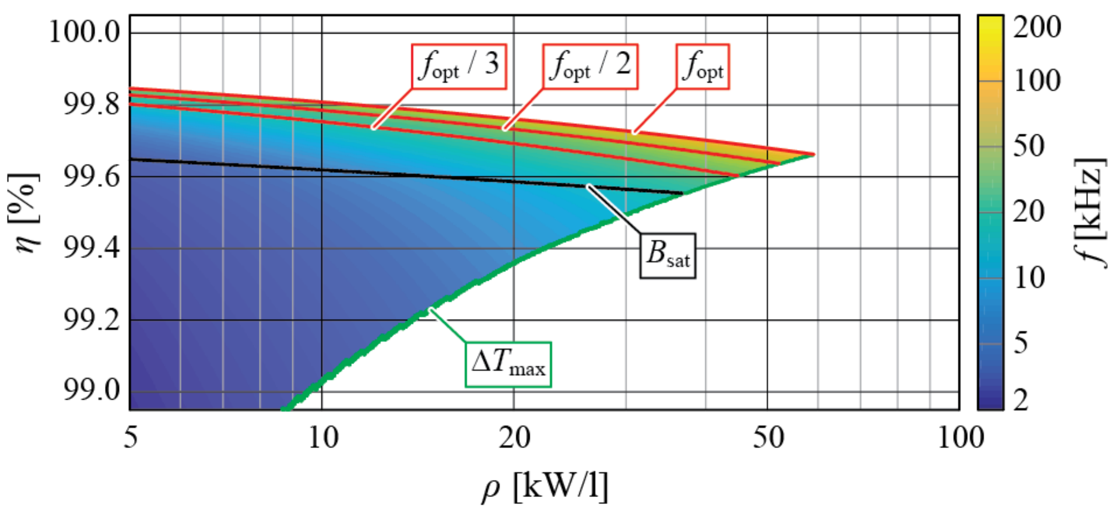
- **Increasing frequency is not always good (!)**

[Guillod, ETHZ, 2018]

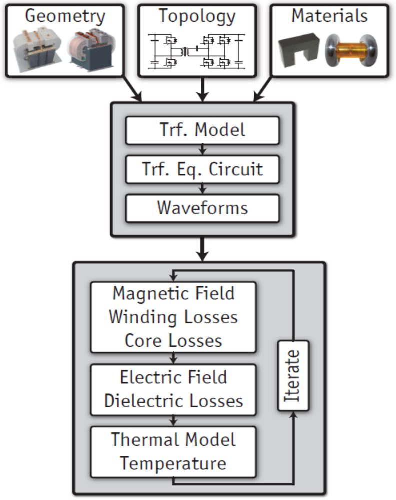
▶ Sensitivity: Optima are Flat

- **Transformer optima are flat**
- **$f_{opt}/2$ → max. 15% add. losses**
- **Additional effects**
  - Switching losses
  - Neglected losses, e.g. busbars

▼ Transformer: Pareto Front



▼ Optimization Method



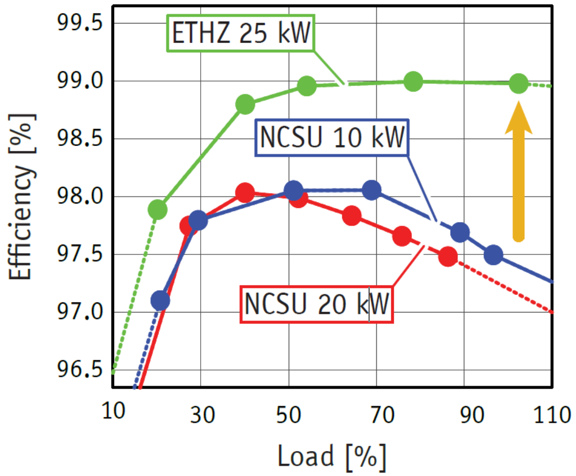
- **Opt. converter frequency << opt. trf. frequency**

[Guillod, ETHZ, 2018]

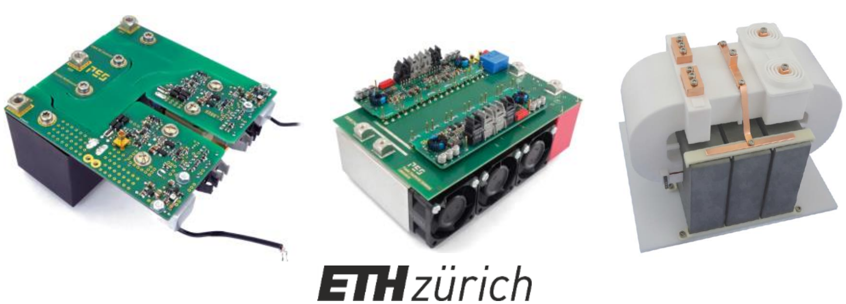
▶ Benchmark of DC-DC / Single-Cell

Side	ETHZ 25kW	NCSU 20kW	NCSU 10kW
Voltage	7kV / 400V	10kV / 340V	6kV / 400V
Frequency	48kHz	37kHz	40kHz
Switches	HV SiC	HV SiC	HV SiC
Density	3.8kW/dm³	1.5kW/dm³	n/a
Efficiency	99.0% ★	97.3%	97.4%

▼ Efficiency



▼ ETHZ 25kW



▼ NCSU 20kW

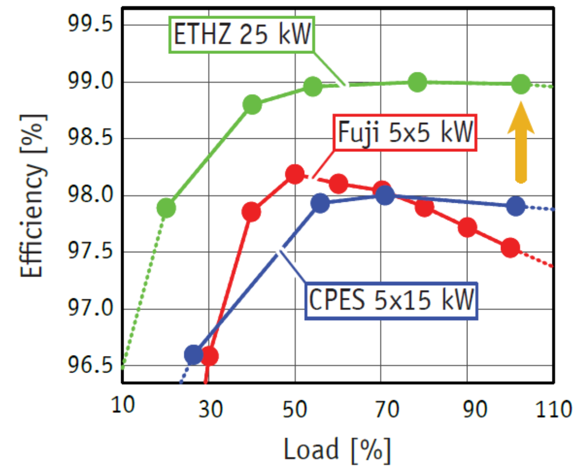
■ Similar sw. frequency ≠ similar performance

[Wang, IEEE JESTPE, 2017] [Zhu, APEC, 2018] [Rothmund, IEEE JESTPE, 2018]

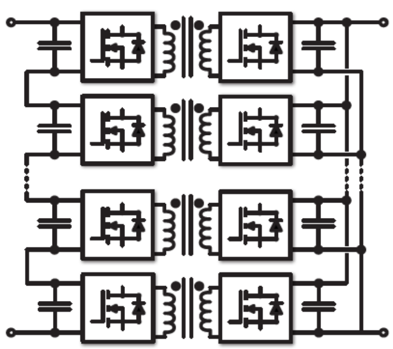
▶ Benchmark of DC-DC / Multi-Cell

Side	ETHZ 25kW	CPES 5x15kW	Fuji 5x5kW
Voltage	7kV / 400V	4kV / 400V	3.8kV / 54V
Frequency	**48kHz**	**500kHz**	**70kHz**
Switches	HV SiC	LV SiC/GaN	LV Si
Density	3.8kW/dm^3	2.9kW/dm^3	3.5kW/dm^3
Efficiency	**99.0%** ★	**97.9%**	**97.5%**

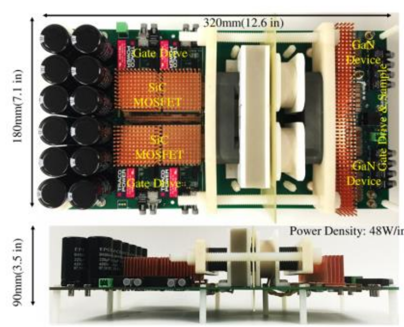
▼ Efficiency



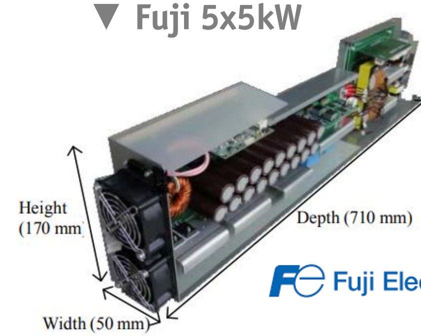
▼ Multi-Cell



▼ CPES 5x15kW



▼ Fuji 5x5kW



■ **High sw. frequency ≠ high performance**

[Zhao, IEEE TPEL, 2018] [Kashihara, APEC, 2017]

MV/MF El. Insulation

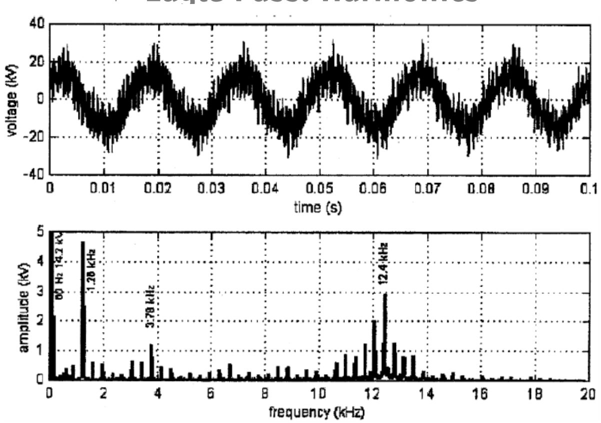
DC Voltages
LF AC Voltages
PWM Voltages

▶ Insulation with MV/MF Converters

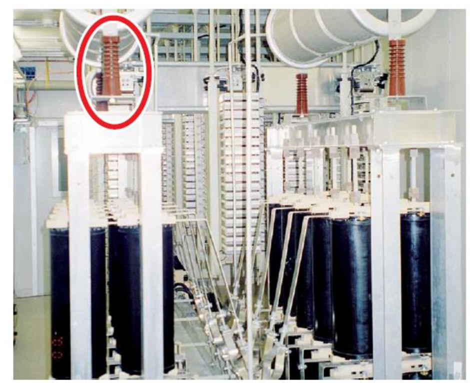
- **New HV SiC devices**
  - Voltages: 15kV
  - Frequencies: 200kHz
  - Switching speed: 150kV/µs

- **Example: Eagle Pass HVDC**
  - MF harmonics
  - Losses in cable terminations
  - Time to failure: one week

▼ Eagle Pass: Harmonics



▼ Eagle Pass: Terminations



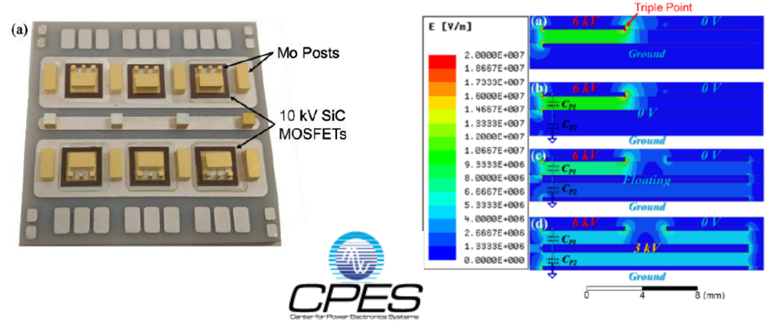
- **Design and aging of electrical insulation of MV/MF converters is critical**

[Paulsson, IEEE TPWRD, 2003]

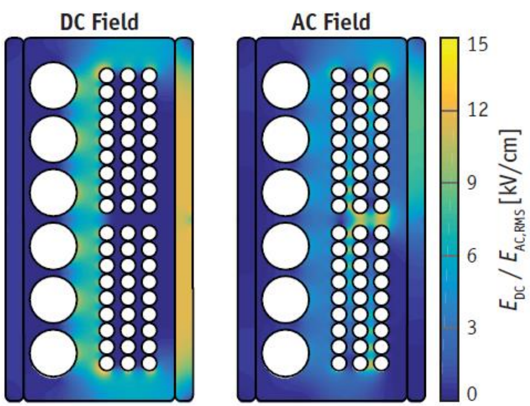
▶ Geometry & Field Shaping

- **Field shaping**
  - Wide spectrum: 0..10MHz
  - Grading without losses
  - Interfaces between media
- **Basic contradiction**
  - HV: large distances
  - MF: small distances

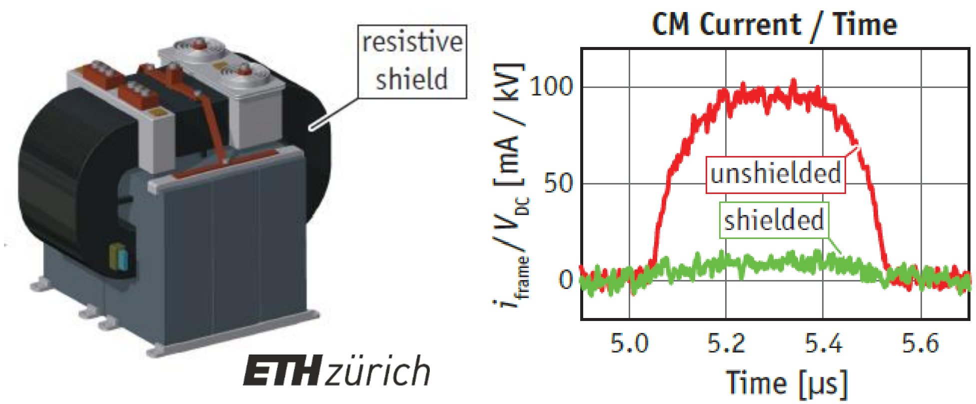
▼ 10kV Module: Field Shaping



▼ Transformer: DC vs. AC



▼ Transformer: Field Shaping & Shielding

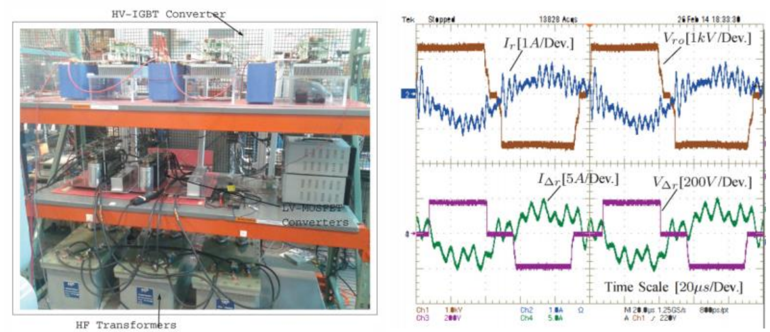


[DiMarino, CPES, 2019] [Guillod, APEC, 2017]

▶ Oscillations / Overvoltages

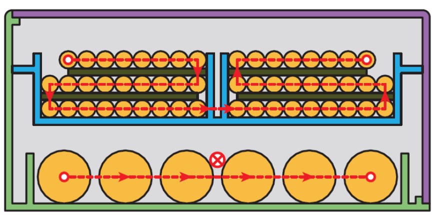
- **Component resonances**
  - Uneven voltage sharing
  - Additional stress
  - Additional losses
- **Careful design**
  - Geometry & materials
  - Low parasitics

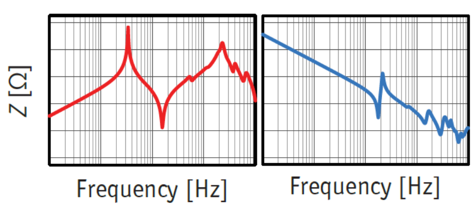
▼ MV/MF Transformer: Critical Resonances



FREEDM SYSTEMS CENTER

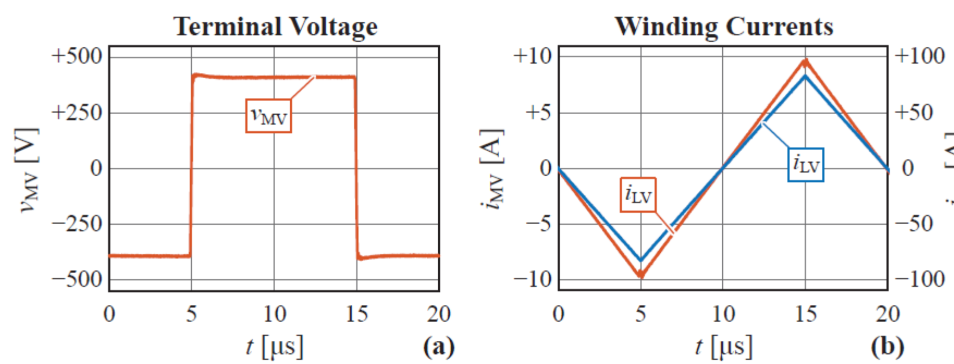
▼ Low Parasitic Design





ETH zürich

▼ MV/MF Transformer: No Resonance

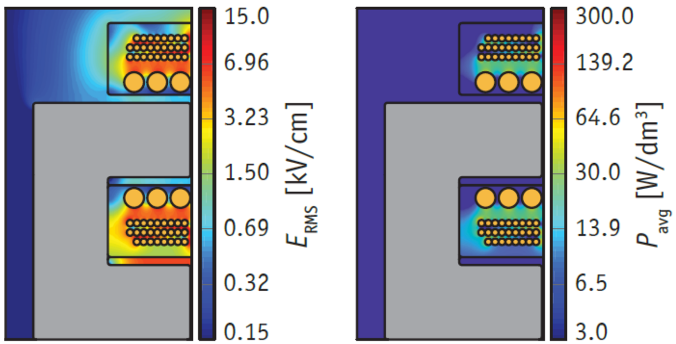


[Tripathi, ECCE Asia, 2014] [Rothmund, APEC, 2015]

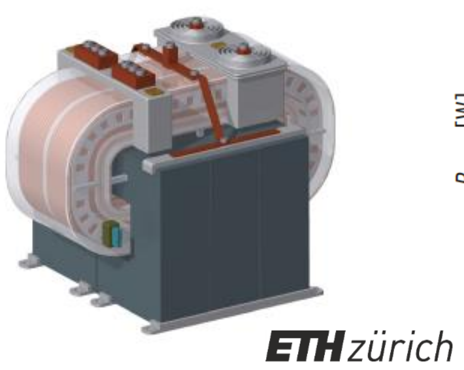
▶ Dielectric Losses

- **Dielectric losses**
  - Frequency dependent
  - Temperature dependent
- **Critical with MV/MF voltages**
- **MV/MF transformer @ 48kHz**
  - Epoxy resin
  - 17% of the full-load losses
  - Thermal runaway at 130°C
- **Better materials (e.g. silicone)**

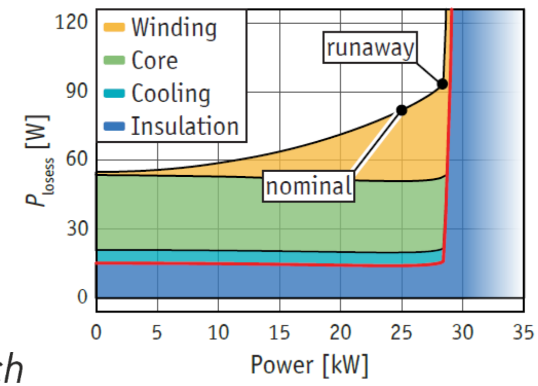
▼ Electric Field / Dielectric Losses



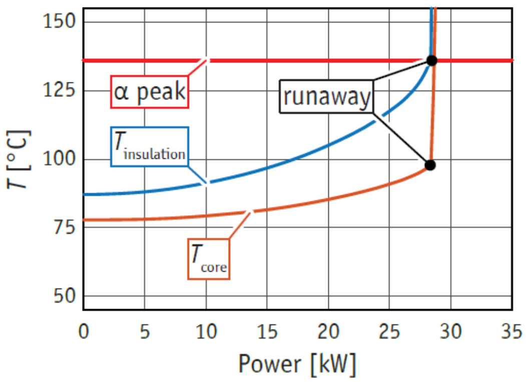
▼ 48kHz Prototype



▼ Losses



▼ Temperature

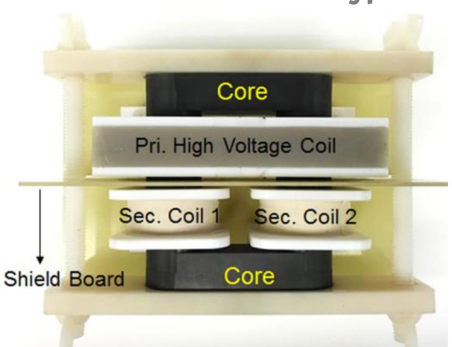


[Guillod, IEEE JESTPE, 2019]

▶ Partial Discharges

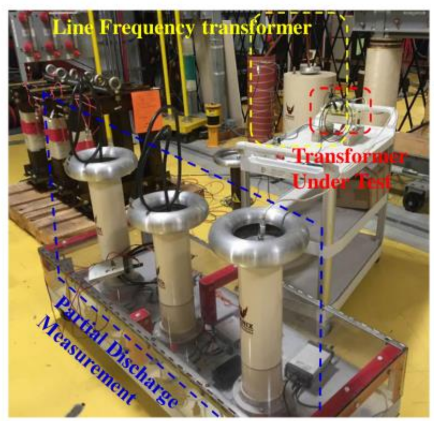
- **Partial discharges at MF**
  - Different that 50Hz
  - Sinus ≠ PWM
  - Extremely critical
- **Difficult task: meas. & interpretation**
- **Lack of knowledge for MV/MF systems**

▼ 500kHz Prototype

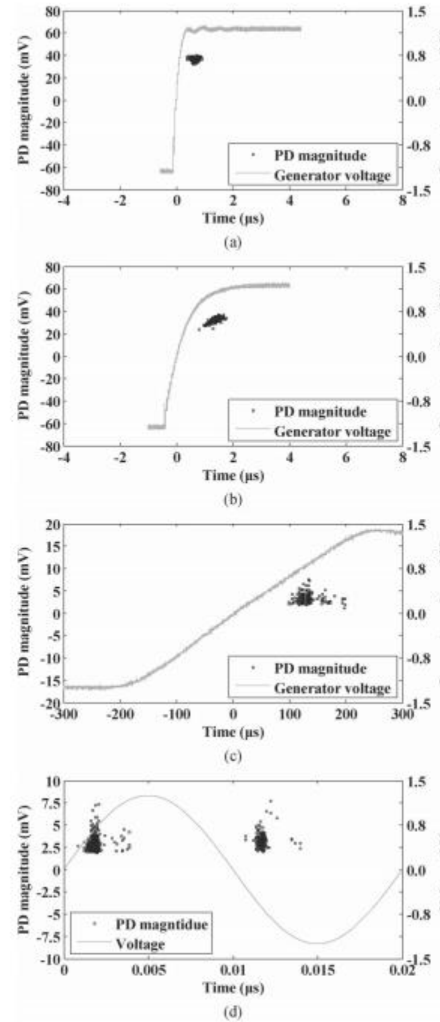


CPES

▼ 50Hz PD Test



▼ Sinus vs. PWM

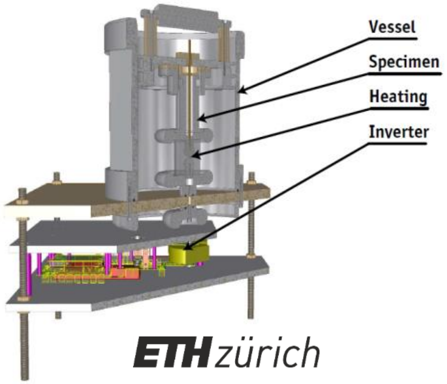


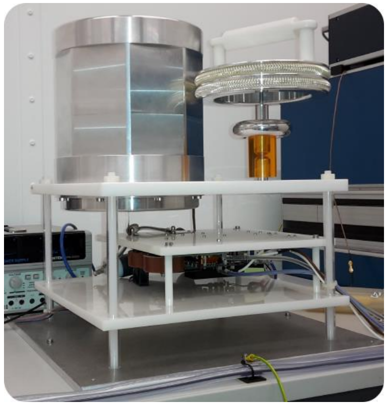
[Wang, IEEE TIE, 2014] [Zhao, IEEE TPEL, 2018]

▶ Insulation Test Bench

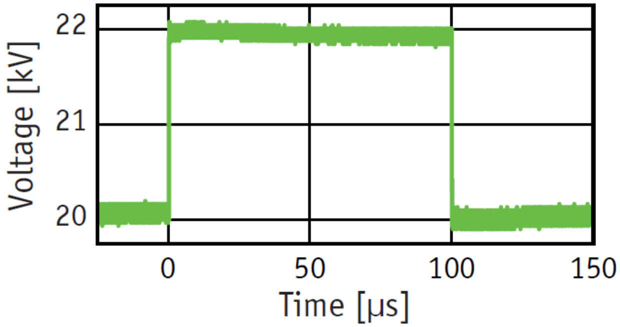
- **Reproduce converter stress: DC/AC+PWM**
  - 0..20kV DC or 50Hz
  - 0..2kV PWM Voltage
  - Variable rise time
  - Controlled temperature/humidity
- **Monitoring**
  - Dielectric spectroscopy
  - Optical monitoring
  - UV/IR monitoring
  - Automated testing

▼ Test Bench





▼ 20kV DC + 2kW PWM



▼ Remote Control

▼ Test Cell

[Collaboration ETHZ/PES and ETHZ/HVL]

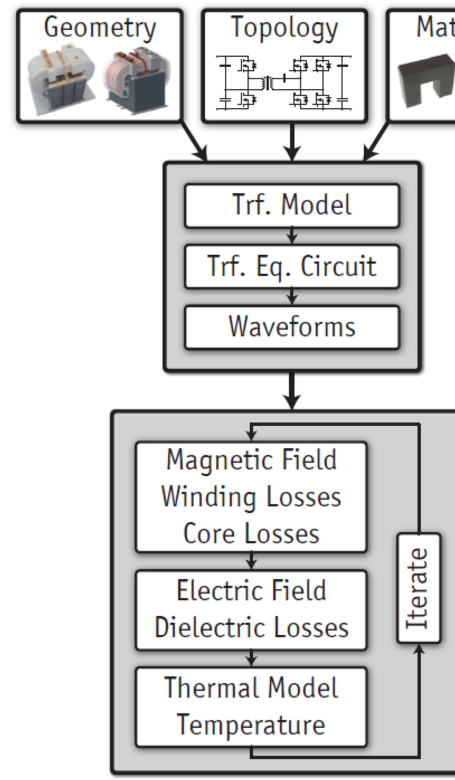
MV/MF Transformers

Fundamentals
Design Space Diversity
Electrical Insulation

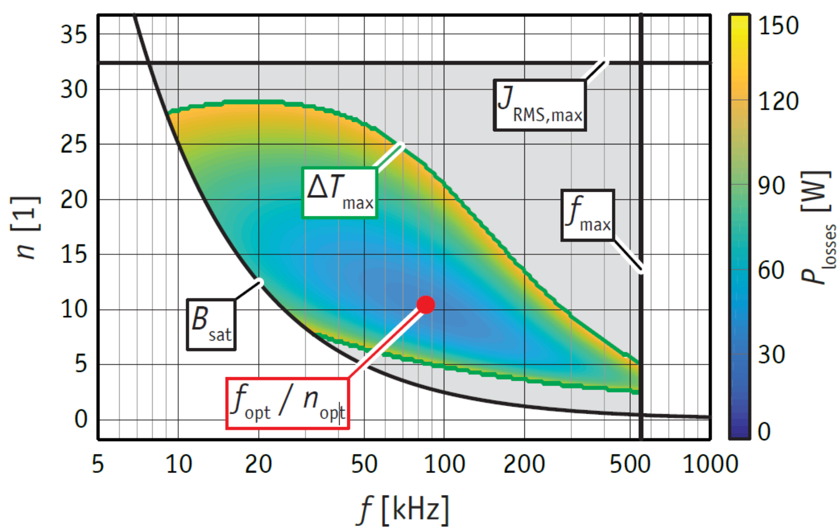
▶Transformer Optimum

- **Many degrees of freedom**
  - Geometry: coaxial, core, shell
  - Winding: litz wire, foil, PCB
  - Core: ferrite, amorphous, nanocrystaline
  - Cooling: oil, air, water, natural, forced
  - Insulation: air, dry-type, oil
- **Optimization procedure required**

▼ Optimization Method



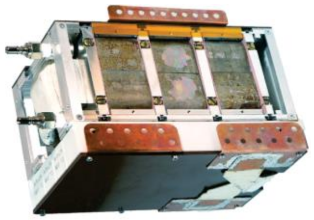
▼ Design Space: Optimum



[Guillod, ETHZ, 2018]

▶ Design Choices

▼ ETHZ



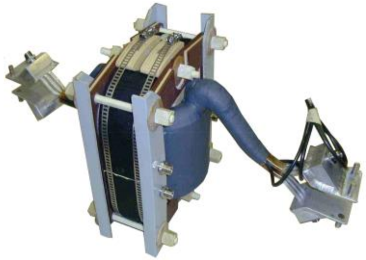
▼ STS

▼ ABB

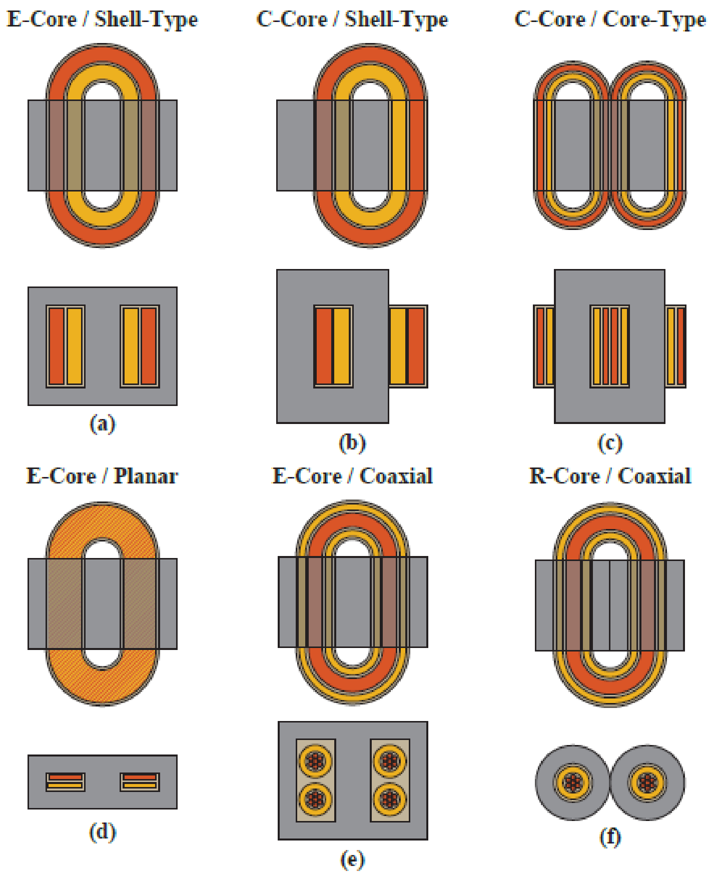
▼ STS

▼ EPFL

▼ Bombardier



▼ Transformer Types

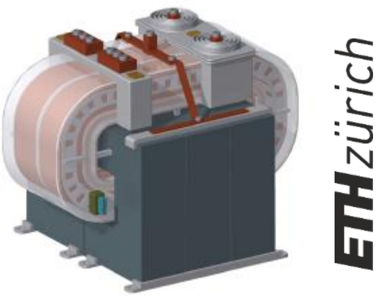


- Who is right / has the best concept?

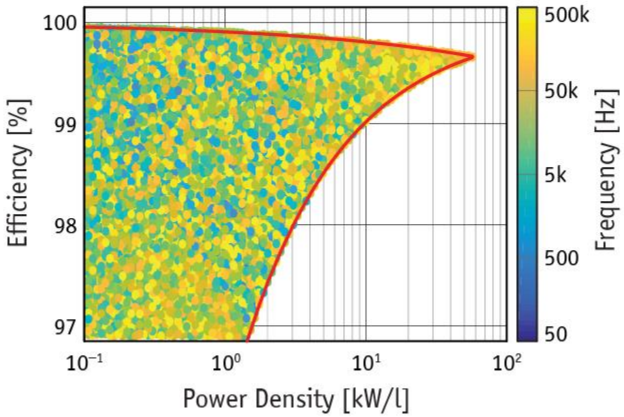
▶ Design Space Diversity

- **Design space diversity**
  - Many different designs have similar performances
  - Flat optima / local optima
- **Optimization**
  - Intrinsically difficult
  - Global optim. alg. required

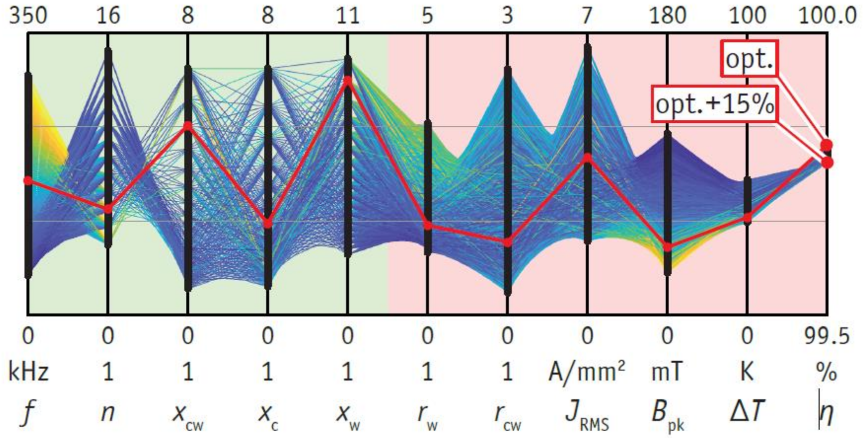
▼ 48kHz Prototype



▼ Pareto Front



▼ Diversity: Fixed Volume / Power



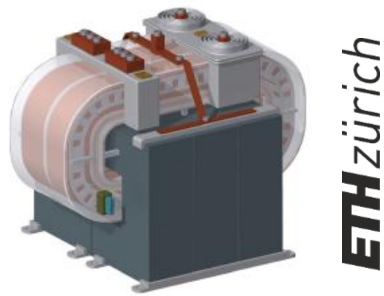
- **Design space diversity → numerical opt. required → add. freedom**

[Guillod, ETHZ, 2018]

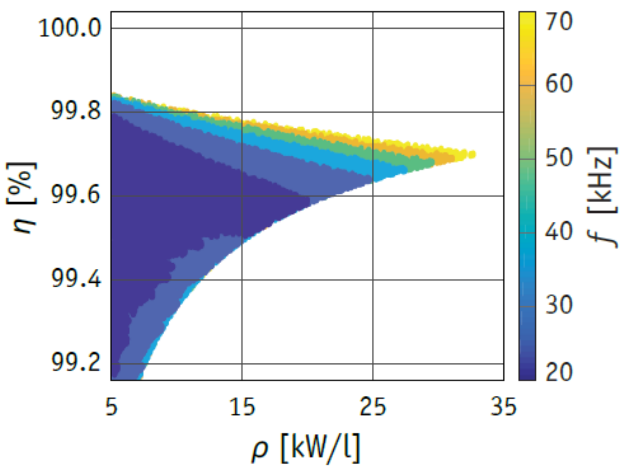
▶ Impact of Insulation

- **Electrical insulation**
  - >7kV DM insulation
  - >15kV CM insulation
  - Dry-type insulation
- **Critical impact on the power density**

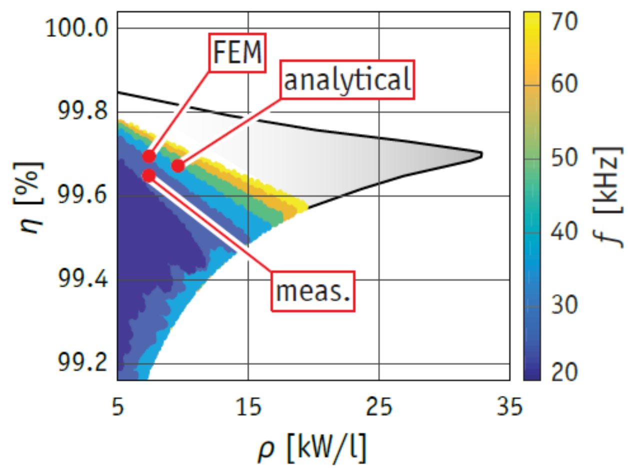
▼ 48kHz Prototype



▼ Without Insulation



▼ With Insulation



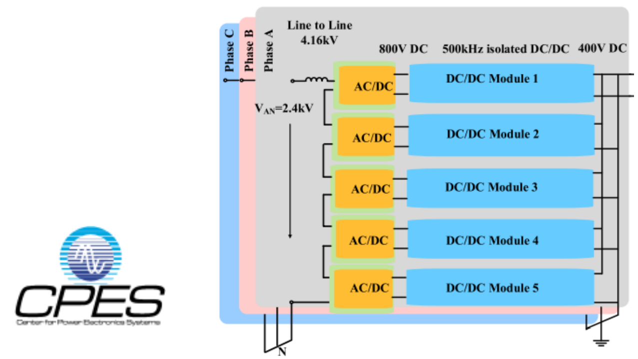
- **Electrical insulation should be considered during the optimization**

[Guillod, ETHZ, 2018]

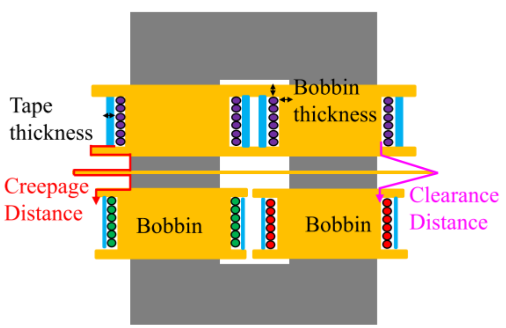
▶ Insulation Concept: Air Gap Insulation

- **Specifications**
  - 500kHz / 15kW
  - 800V to 400V
- **Multi-cell structure**
  - DM voltage is small
  - CM insulation (17kV$_{peak}$ / 30kV$_{surge}$)
- **Air gap insulation**
  - Epoxy / PTFE
  - CM insulation
  - Increased winding losses
- **Good for multi-cell SSTs**

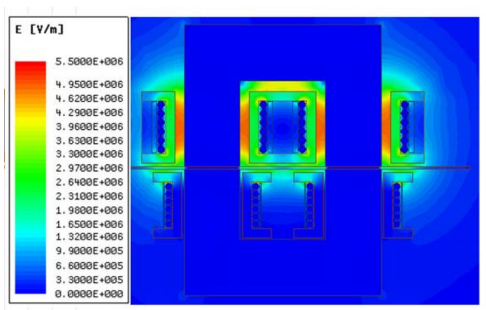
▼ Multi-Cell SST



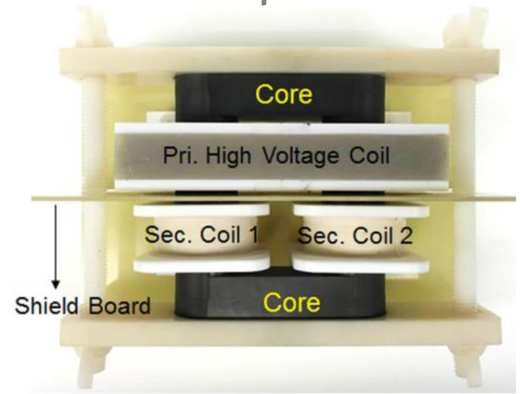
▼ Insulation Concept



▼ Electric Field



▼ Air Gap Insulation

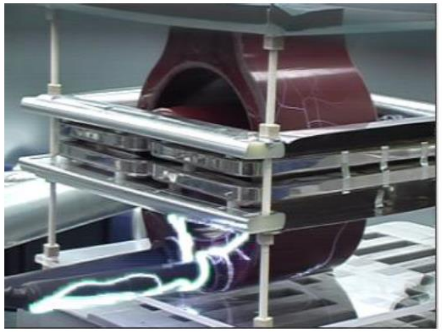


[Zhao, IEEE TPEL, 2018]

▶ Insulation Concept: Hybrid Insulation

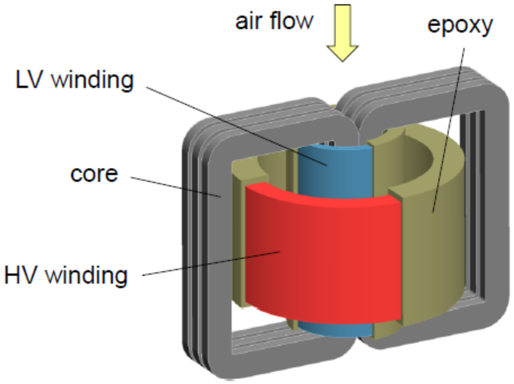
- **Specifications**
  - 10kHz / 240kVA
  - 800V to 600V
- **Voltage stress**
  - DM voltage is small
  - CM insulation (100kV$_{peak}$ / 150kV$_{surge}$)
- **Hybrid insulation**
  - Epoxy / air
  - Air cooling
  - Increased volume
- **Good for extreme CM voltages**

▼ Flashover

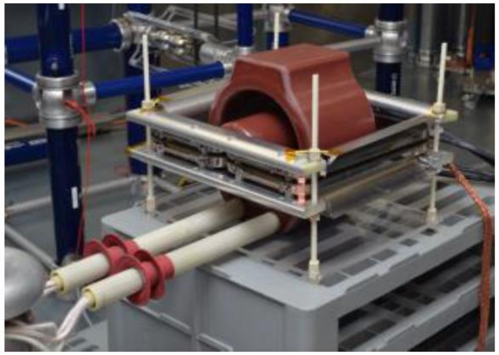


ABB

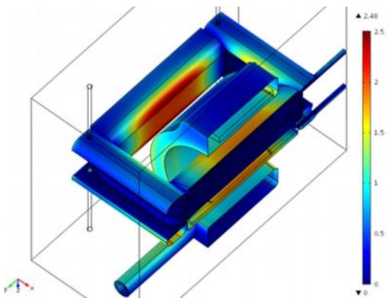
▼ Insulation Concept



▼ Prototype



▼ Electric Field

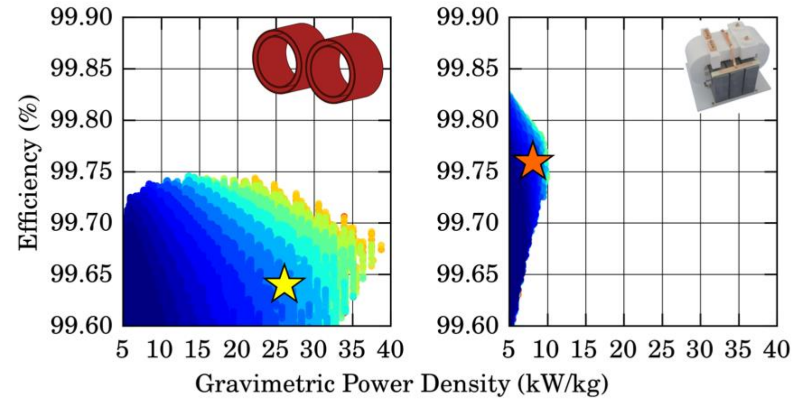


[Gradinger, PCIM Europe, 2017]

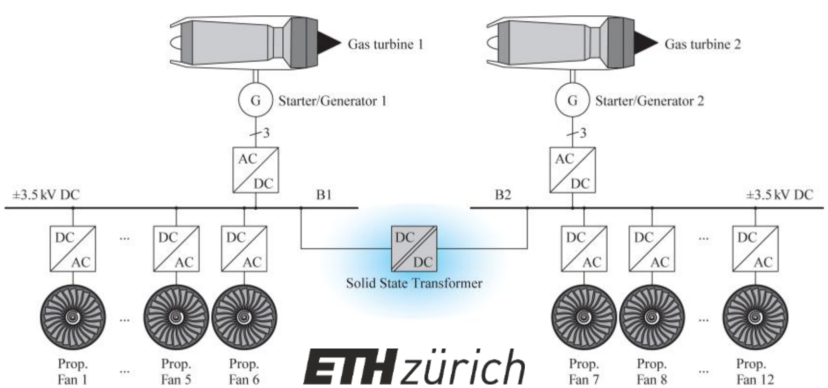
▶ Insulation Concept: Air-Core Transformer

- **Specifications**
  - 103kHz / 166kW
  - 7kV to 7kV
  - Aircraft applications
- **Air core transformer**
  - No magnetic core
  - Air insulation
  - High efficiency (>99.6%)
- **Reduced weight (>25kW/kg)**

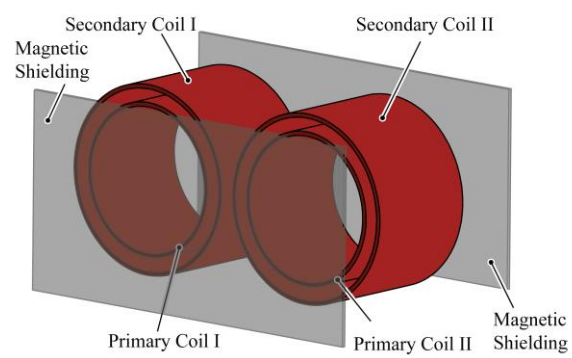
▼ Gravimetric Power Density



▼ Future Hybrid Aircraft



▼ Air-Core Transformer

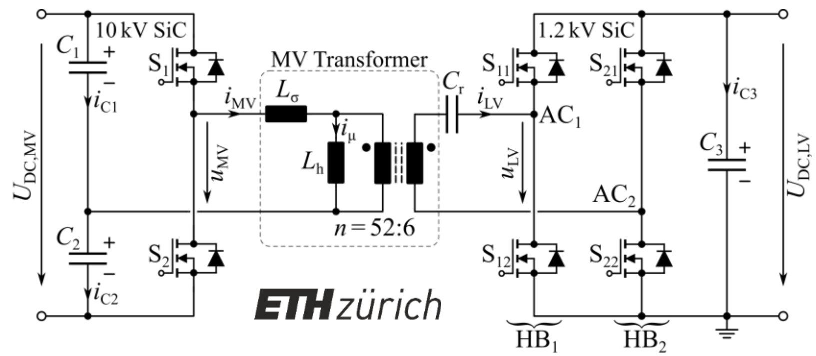


[Czyz, ECCE Asia, 2018]

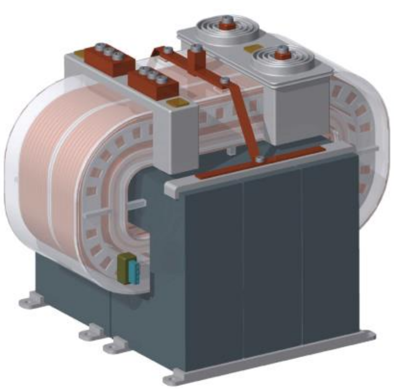
▶ Insulation Concept: Sillicone Insulation

- **Specifications**
  - 48kHz / 25kW
  - 7kV to 400V
- **Single-stage structure**
  - DM insulation (>7kV_{peak})
  - CM insulation (>15kV_{peak})
- **Potted winding**
  - Silicone insulation
  - Air ducts for cooling
  - Low winding losses
- **Good trade-off**

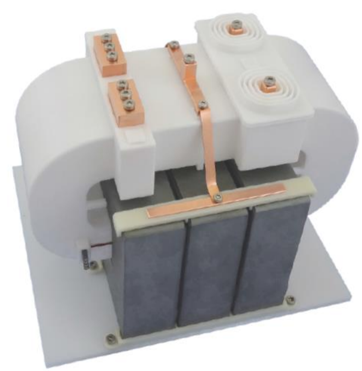
▼ Topology



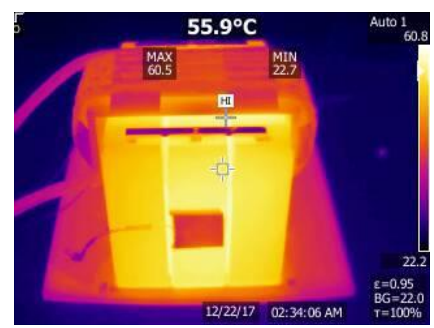
▼ CAD Design



▼ Prototype



▼ Measurements

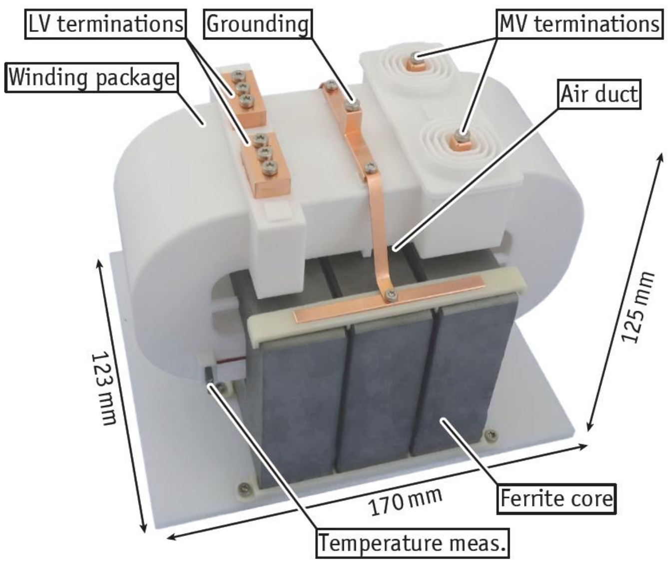


[Rothmund, IEEE JESTPE, 2018]

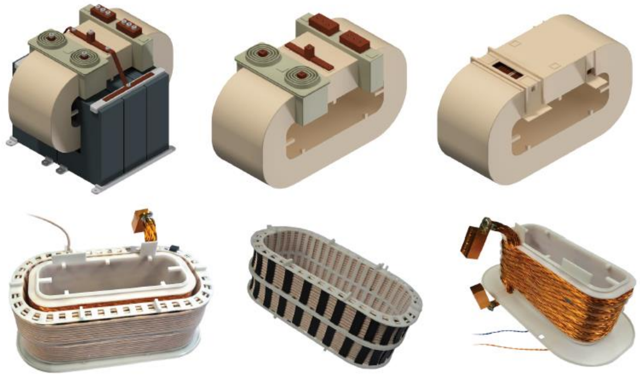
▶ Construction / Potting

- **Silicone insulation ("TC4605 HLV")**
  - Low losses at MF
  - High thermal conductivity
- **Vacuum silicone injection**

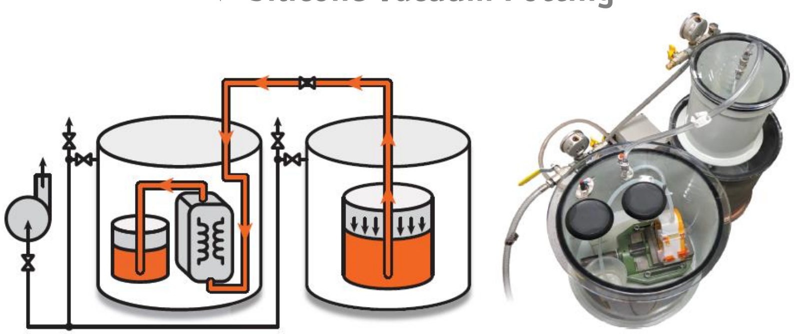
▼ MV/MF Transformer Prototype



▼ Construction Process



▼ Silicone Vacuum Potting

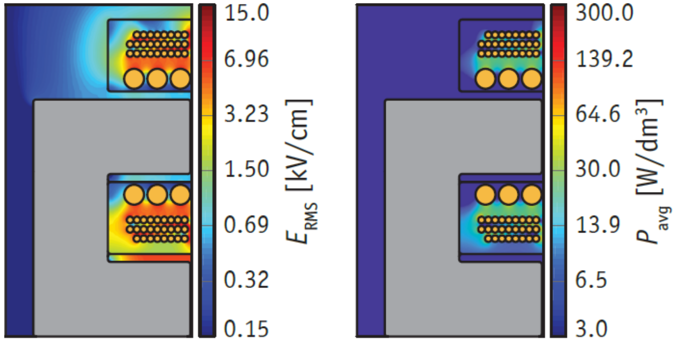


[Rothmund, IEEE JESTPE, 2018]

▶ Electric Field Shaping

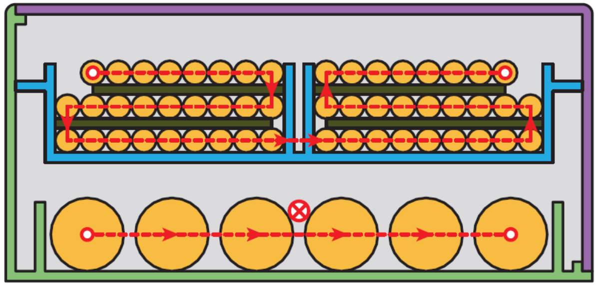
- **Field shaping**
  - 2 chambers with 3 layers
  - Reduced parasitics / resonances > 2MHz
- **Insulation stress**
  - 1.2 kVar cap. react. power
  - 8.4W dielectric losses
  - 2.3kV/mm in silicone
- **Controlled insulation stress**

▼ Electric Field / Dielectric Losses



▼ LV Winding / MV Winding

▼ Optimized Winding Scheme



[Rothmund, IEEE JESTPE, 2018]

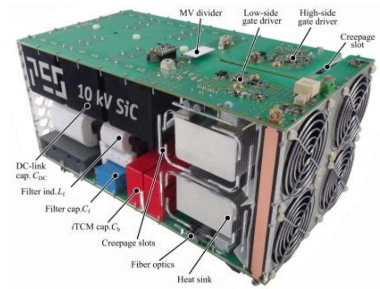
SST Prototypes

Commissioning
Efficiency
Calorimeter

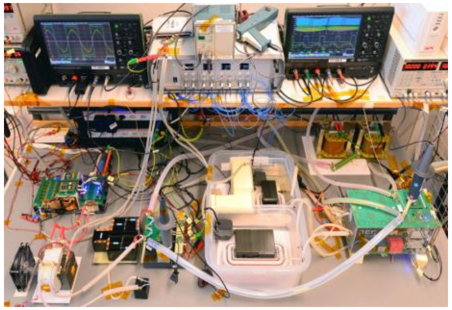
► AC-DC Stage: Design

- **Single-stage 25kW AC/DC**
  - 3.8kV AC input
  - 7kV DC output
- **Fully functional stand-alone system**

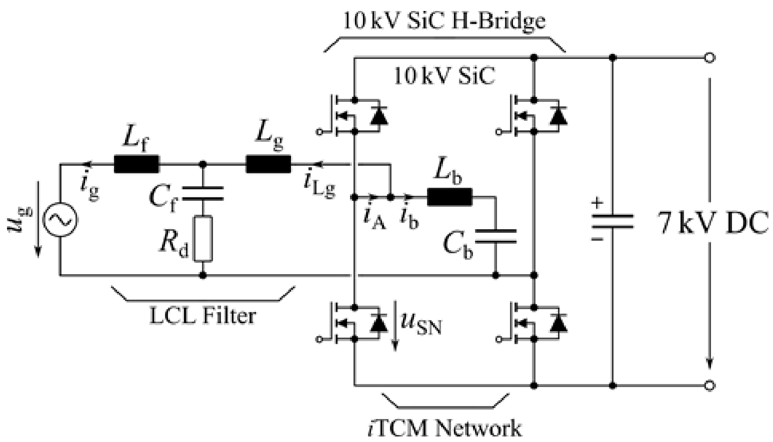
▼ Prototype

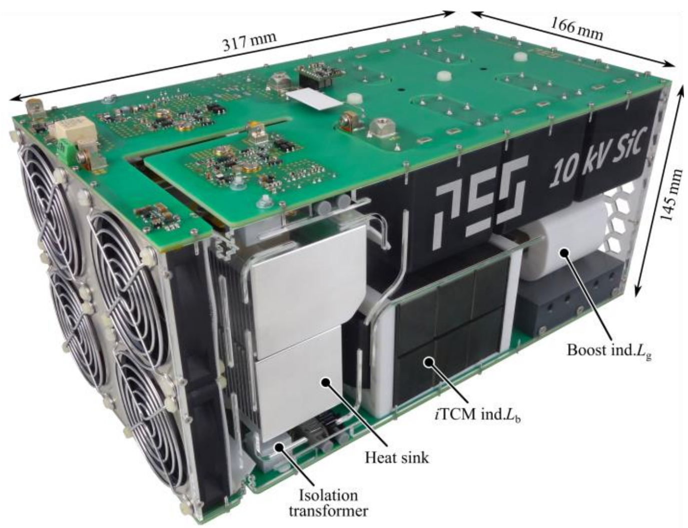


▼ Lab Setup



▼ Topology



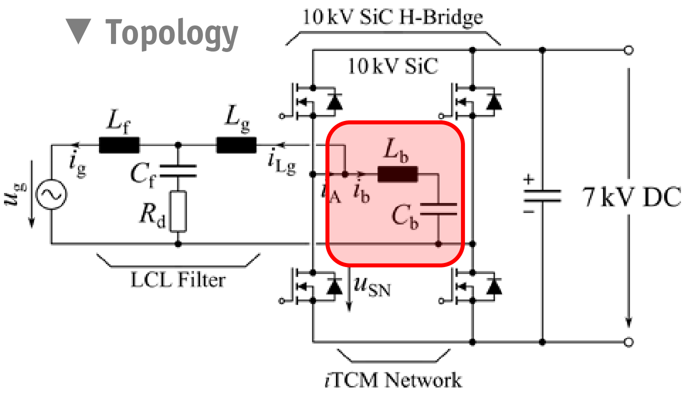


[Rothmund, IEEE JESTPE, 2018]

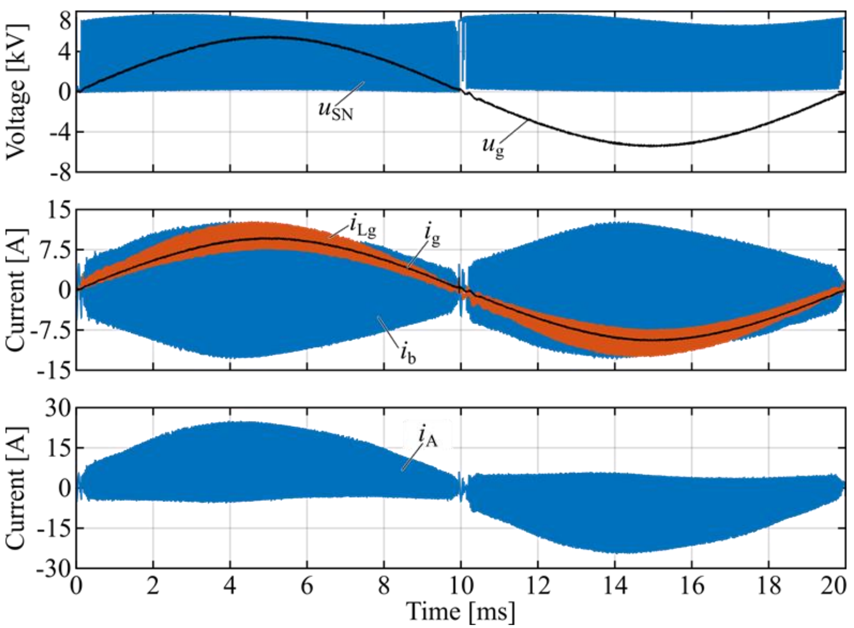
▶ AC-DC Stage: Waveforms

- **ZVS modulation scheme**
  - ZVS with iTCM modulation
  - 35..75kHz switching frequency
  - Constant ZVS current
- **IEEE 519 compliant**

▼ Topology



▼ Measurements



- **Full-load measurement (25kW @ 7kV DC) - ZVS over full AC cycle (!)**

[Rothmund, IEEE JESTPE, 2018]

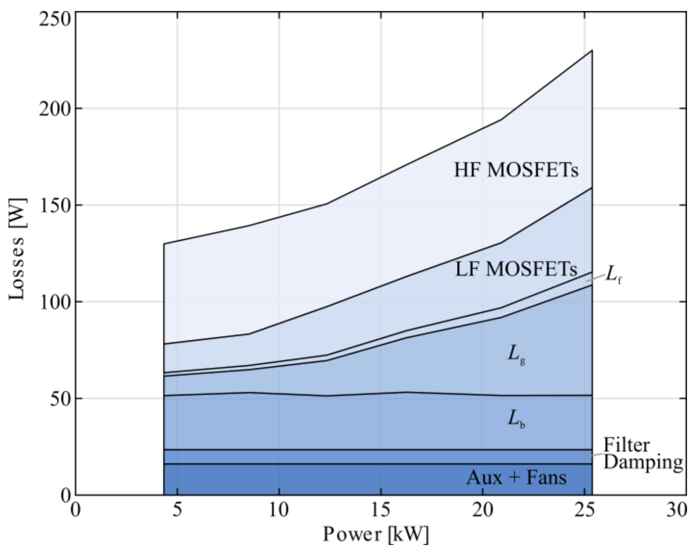
▶ AC-DC Stage: Efficiency

- **99.1% efficiency @ 100% load**
  - 98.7% efficiency @ 50% load
  - Low losses despite 35...75 kHz sw. frequency
- **3.3kW/dm³ (box volume)**

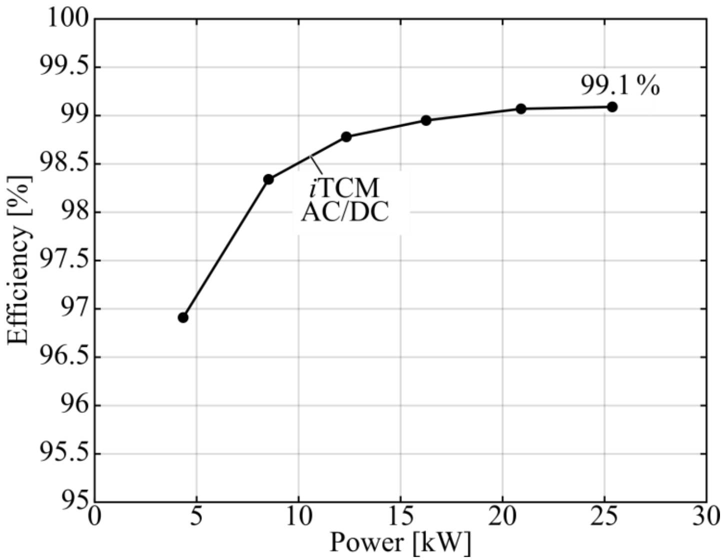
★ **99.1%**

★ **3.3kW/dm³**

▼ Loss Distribution



▼ Efficiency

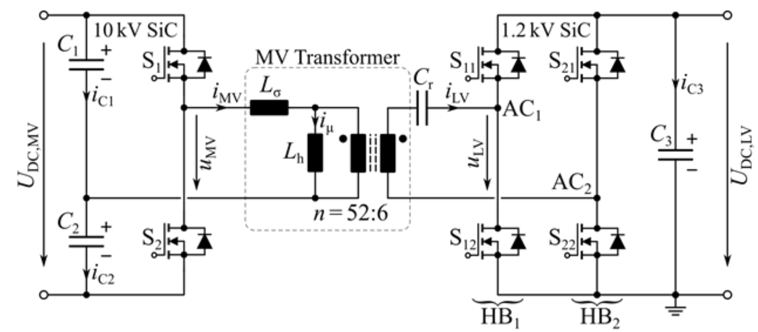


[Rothmund, IEEE JESTPE, 2018]

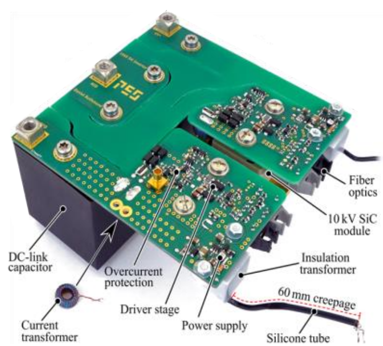
▶ DC-DC Stage: Design

- **Single-stage 25kW DC/DC**
  - 7kV DC input
  - 400V DC output
- **MV/MF transformer is the challenge**

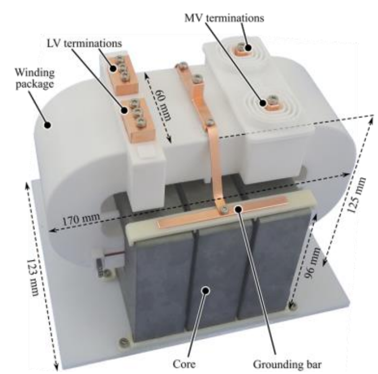
▼ Topology



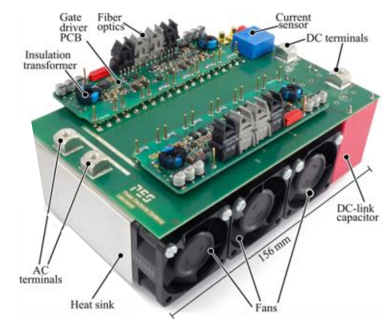
▼ MV Bridge



▼ MV/MF Trf.



▼ LV Bridge

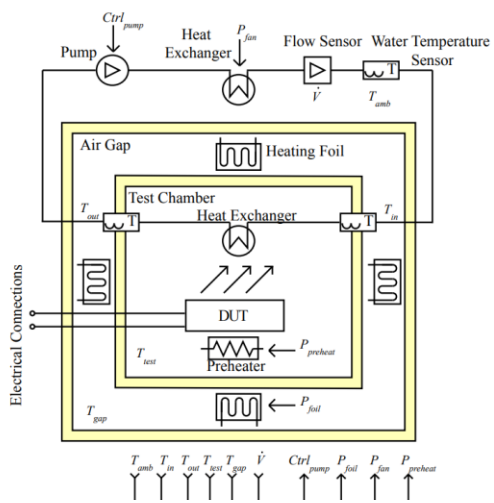


[Rothmund, IEEE JESTPE, 2018]

▶ Transformer Efficiency: Calorimeter

- **Electrical measurement**
  - Too inaccurate / >99.5% / 48kHz
  - MV probes are not accurate enough
- **Double-jacketed calorimeter**
  - Two insulated chambers
  - Water flow & heat exchanger

▼ Double-Jacketed Cal.

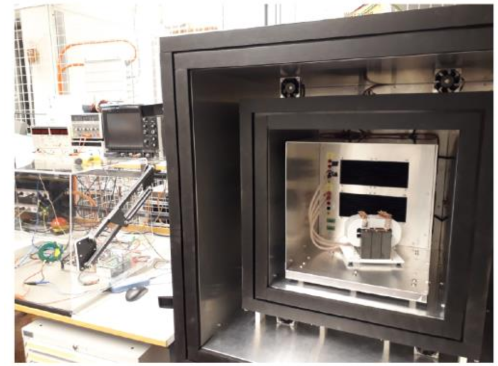


★ **99.69% sim.**

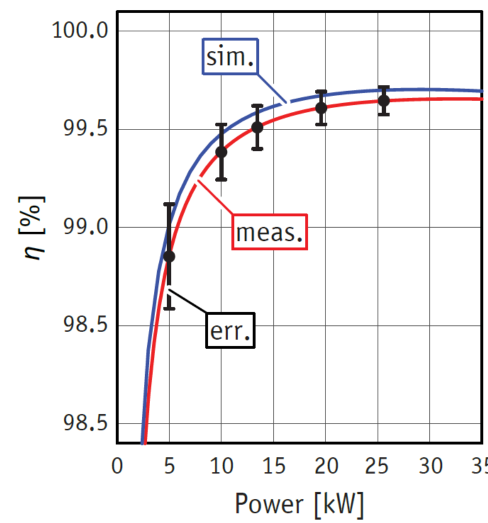
★ **99.65% meas.**

★ **7.4kW/dm³**

▼ Transformer / Calorimeter



▼ Trf. Efficiency



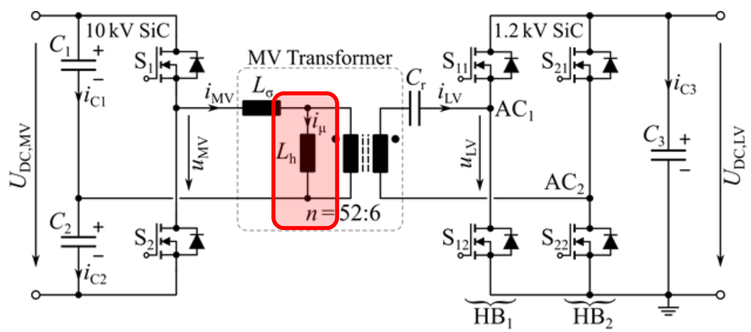
- **No out of the box meas. device exists for MV/MF systems**

[Christen, IPEC, 2010] [Rothmund, IEEE JESTPE, 2018]

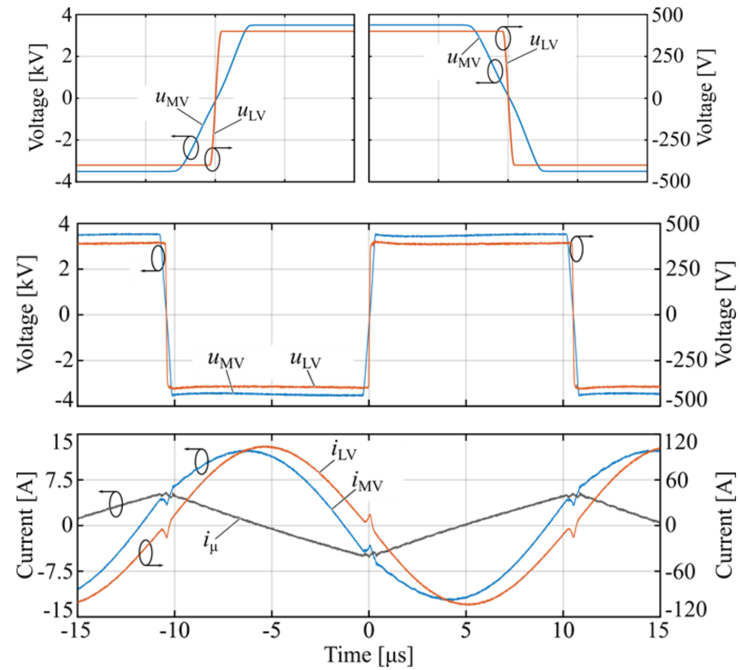
▶ DC-DC Stage: Waveforms

- **Phase-shift modulation scheme**
  - ZVS with mag. current
  - Active mag. current sharing (LV vs. MV)
  - 48kHz switching frequency
  - Constant ZVS current / quasi-ZCS

▼ Topology



▼ Measurements



- **Full-load measurement (25kW @ 7kV DC) – load-independent ZVS (!)**

[Rothmund, IEEE JESTPE, 2018]

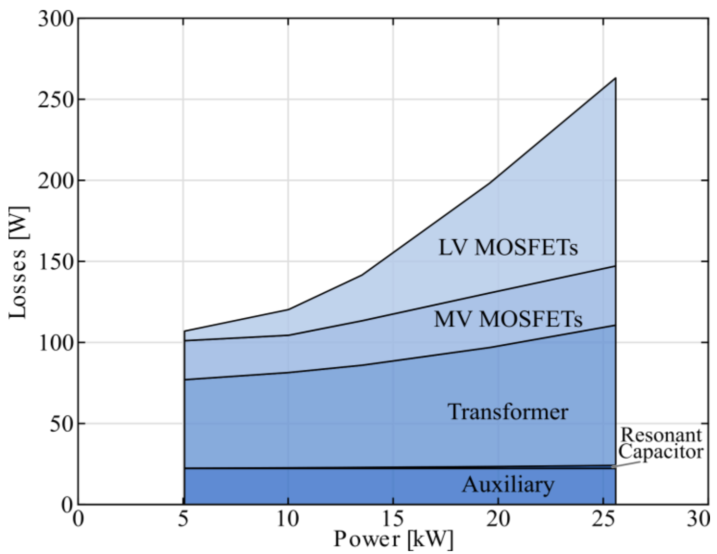
▶ DC-DC Stage: Efficiency

- **99.0% efficiency @ 100% load**
  - 99.0% efficiency @ 50% load
  - LV-MOSFETs (1200V) causing substantial losses
  - Efficiency improvement possible with 900V or 650V SiC
- **3.8kW/dm³ (box volume)**

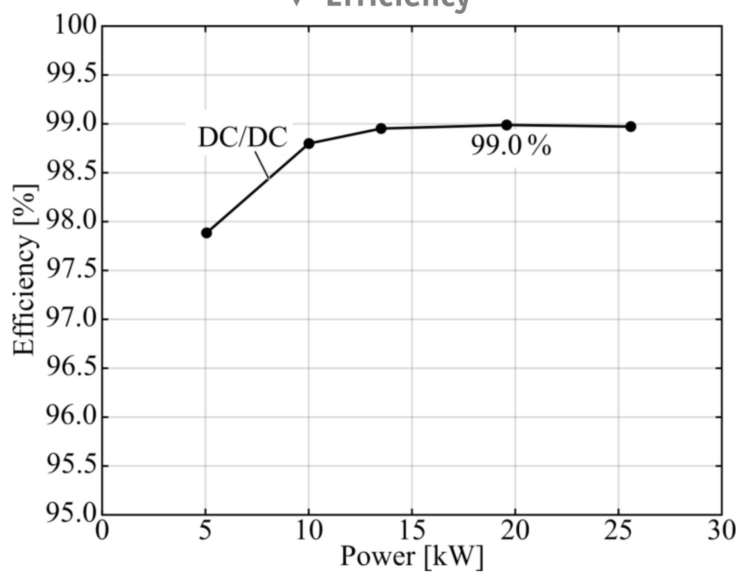
★ 99.0%

★ 3.8 kW/dm³

▼ Loss Distribution



▼ Efficiency



[Rothmund, IEEE JESTPE, 2018]

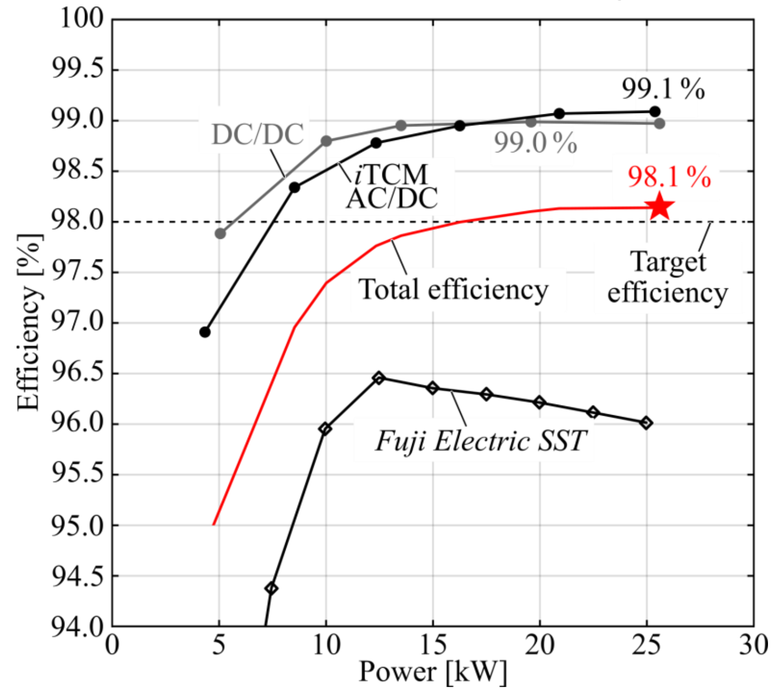
Conclusion & Outlook

10kV SiC for SSTs
Future Research Areas

▶ Si Multi-Cell vs. SiC Single Stage

	Fuji Electric	ETH zürich
Input	2.4kV AC	3.8kV AC
Output	54V DC	400V DC
Power	25kW	25kW
Cells	5x	1x
Technology	LV Si	HV SiC
Semiconductors	100x	10x
Transformer	10x	1x
Density	0.4-0.8 kW/dm^3	1.8 kW/dm^3
Efficiency	96.0%	98.1%

▼ Benchmark: Efficiency



- **LV Si / multi-cell:** state of the art & still competitive
- **HV SiC / single-cell:** simpler structure, compact, efficient

[Kashihara, APEC, 2017] [Rothmund, IEEE JESTPE, 2018]

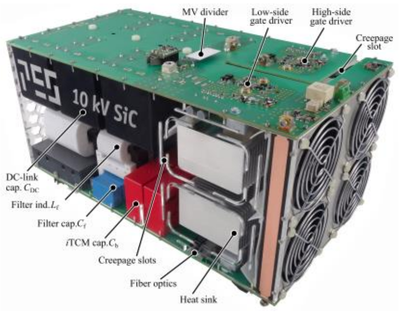
►Conclusion & Outlook

- **HV SiC FETs (6.5..15kV)**
  - Low conduction losses
  - Low ZVS switching losses
  - ZVS is not loss-free
- **MF transformer**
  - Optimal frequency is not infinity
  - Design space diversity
  - Electrical insulation at MF is critical

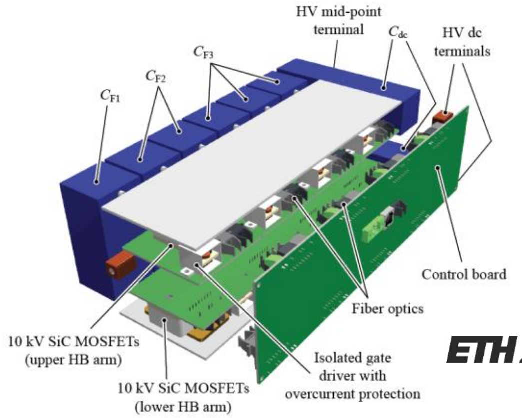
- **HV SiC allows simpler converter structure**
- **HV SiC allows extreme efficiency / volume**

- **Industrialization of HV SiC technology**
  - Reliability / availability
  - Protection (short-circuit, lightning)
- **Toward higher voltages (30..60kV)**
  - Modular structures
  - Series connection

▼ 10kV SiC-based SST



▼ 40kV FCC Half-Bridge



ETH zürich

★ ECCE ASIA 2019

Thank You!

Questions?