

# HIGH POWER MFT DESIGN OPTIMIZATION

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# INSTRUCTORS



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### Experience:

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- 2013 – 2014      ABB Medium Voltage Drives, Turgi, Switzerland
- 2009 – 2013      ABB Corporate Research, Baden-Dättwil, Switzerland
- 2006 – 2009      Liverpool John Moores University, Liverpool, United Kingdom
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### Education:

- 2008      PhD, Liverpool John Moores University, Liverpool, United Kingdom
- 2005      M.Sc., University of Novi Sad, Novi Sad, Serbia
- 2002      Dipl. Ing., University of Novi Sad, Novi Sad, Serbia



## Marko Mogorovic

### Education:

- Pending      PhD, École Polytechnique Fédérale de Lausanne (EPFL), Lausanne, Switzerland
- 2015      M.Sc., École Polytechnique Fédérale de Lausanne (EPFL), Lausanne, Switzerland
- 2013      Dipl. Ing., University of Belgrade, Belgrade, Serbia

# SCHEDULE

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## Before the Coffee Break

### 1) Introduction and Motivation

- ▶ Solid State Transformers
- ▶ Railway and Utility SST
- ▶ Medium Frequency Conversion

### 2) Medium Frequency Transformers

- ▶ Scaling laws
- ▶ Requirements
- ▶ Challenges

### 3) MFT Design Examples

- ▶ Railway related designs
- ▶ Utility related designs
- ▶ Other state-of-the-art designs



## After the Coffee Break

### 4) Materials

- ▶ Magnetic materials
- ▶ Winding materials
- ▶ Dielectric materials

### 5) MFT Modeling

- ▶ Core
- ▶ Winding
- ▶ Thermal

### 6) MFT Design Optimization

- ▶ Optimization based algorithms
- ▶ Brute force parametric optimization
- ▶ Design examples

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# INTRODUCTION and MOTIVATION

*Why high power medium frequency transformers are important technology?*

# LINE FREQUENCY TRANSFORMERS

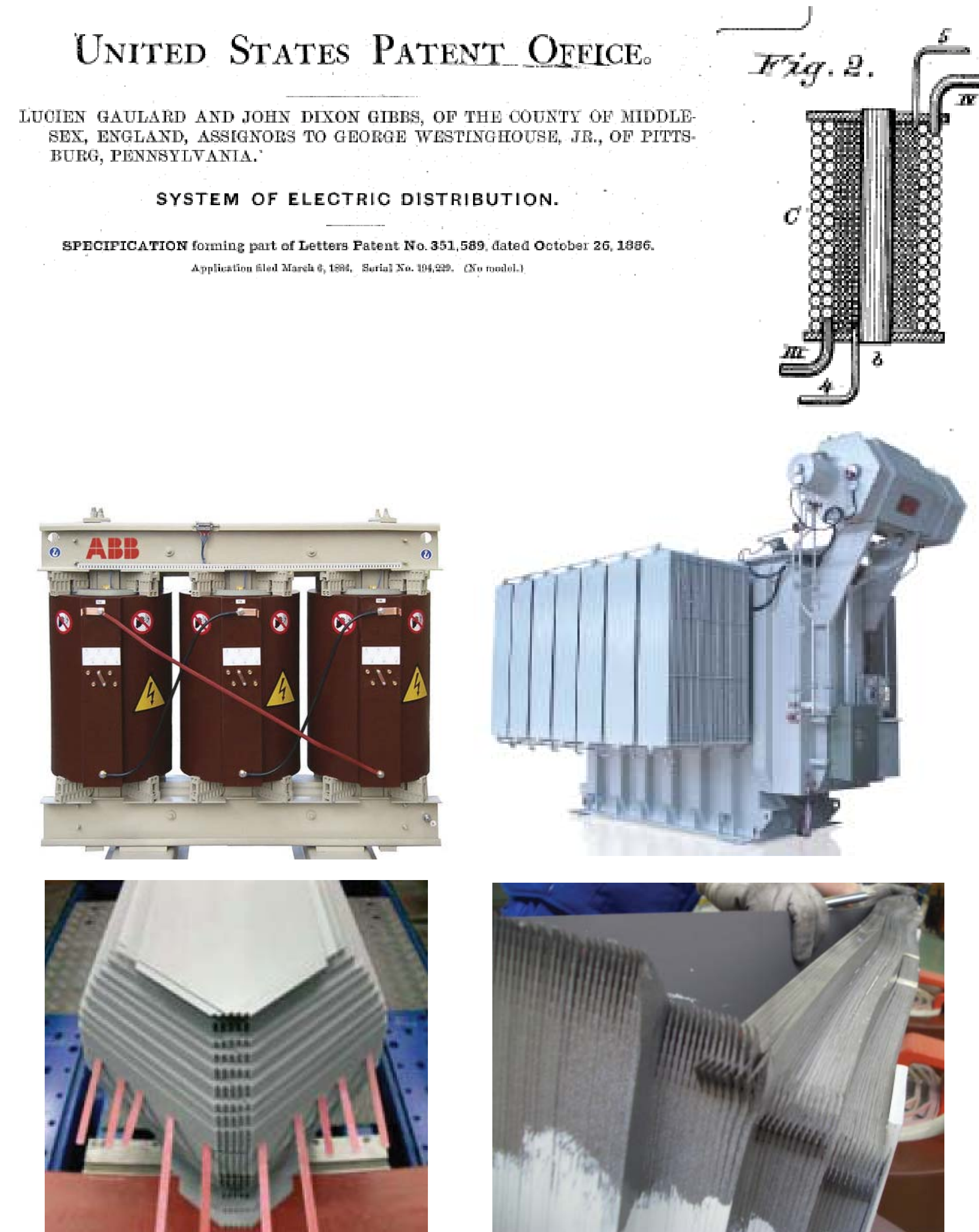
**IEC 60076-1 definition - Power Transformer:** *A static piece of apparatus with two or more windings which, by electromagnetic induction, transforms a system of alternating voltage and current into another system of voltage and current usually of different values and at the same frequency for the purpose of transmitting electrical power.*

## Line Frequency Transformers

- ▶ Around for more than 100 of years
- ▶ Operated at low (grid) frequencies: 16.7Hz, 25Hz, 50/60Hz
- ▶ Standardized shapes and materials
- ▶ Cheap:  $\approx 10\text{kUSD} / \text{MW}$
- ▶ Efficient: above 99 % for utility applications
- ▶ Simple and reliable device

## What are the problems?

- ▶ Bulky - for certain applications
- ▶ Inefficient - for certain applications
- ▶ Uncontrollable power flow
- ▶ Fixed transformation (power, voltage, current, frequency)



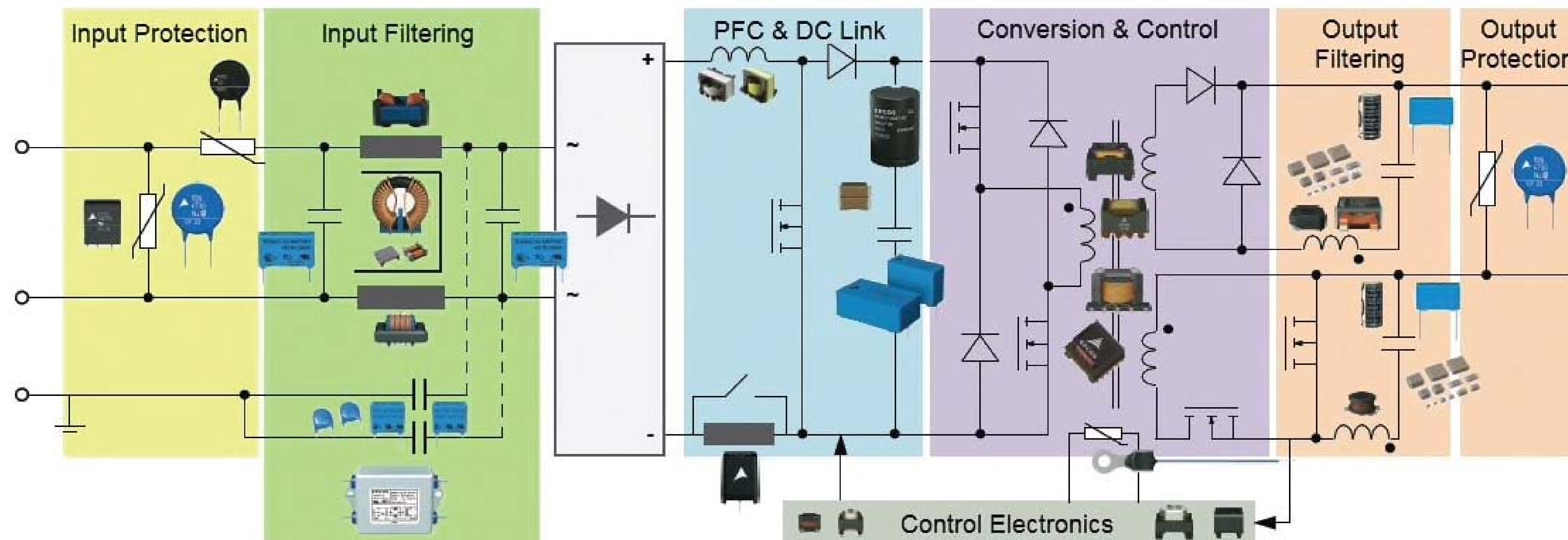
▲ Source: [www.abb.com](http://www.abb.com)

# MEDIUM-HIGH FREQUENCY CONVERSION

## Switched Mode Power Supply (SMPS) Technologies

- ▶ Medium or High frequency conversion is not a new thing!
- ▶ Widely deployed in low voltage/power applications
- ▶ High efficiency
- ▶ Galvanic isolation at high frequency (standardized core sizes and shapes)
- ▶ Compact size (e.g. laptop chargers)
- ▶ Increased power density
- ▶ Cost savings

## Could a Solid State Transformer provide that for a High Power Medium Voltage Applications?



▲ SMPS Technologies; Source: [www.mouser.ch/new/tdk/epcos-smps/](http://www.mouser.ch/new/tdk/epcos-smps/)

# SOLID STATE TRANSFORMERS

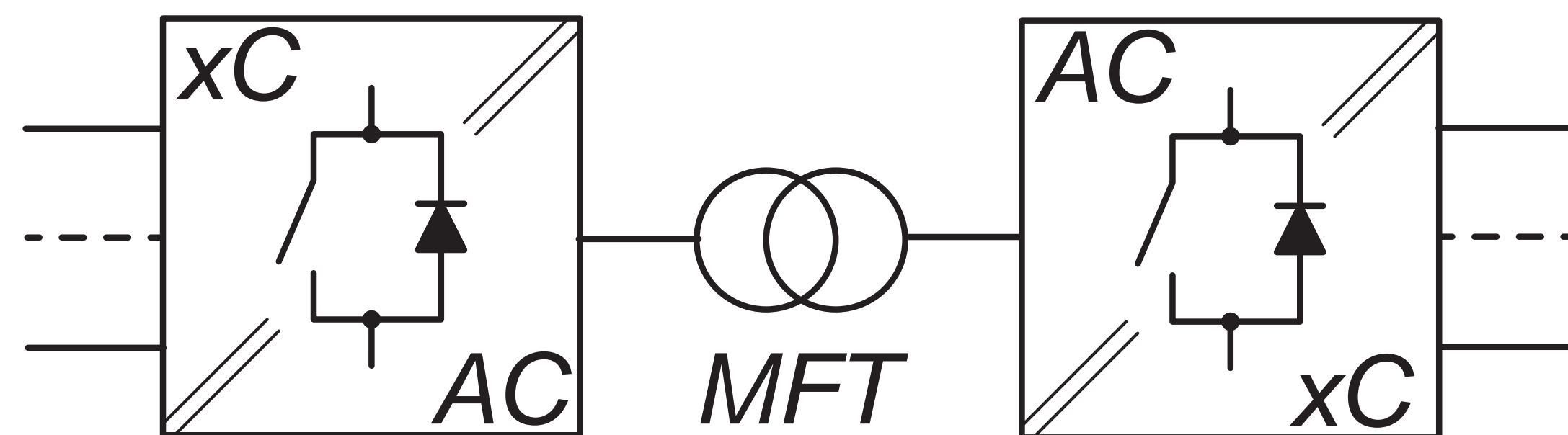
## What is a Solid State Transformers?

- ▶ Not a transformer replacement?
- ▶ Should not be compared against 50/60 Hz transformer!

## What is it?

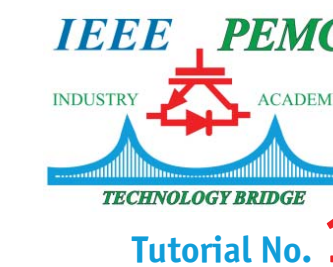
- ▶ A converter
- ▶ A converter with galvanic isolation
- ▶ Can be designed for DC and AC (1-ph, 3-ph) grid
- ▶ Can be used in LV, MV and HV applications
- ▶ Can be made for AC-AC, DC-DC, AC-DC, DC-AC conversion
- ▶ Has power electronics on each terminal
- ▶ Transformer frequency higher than 50/60 Hz

Excellent tutorials are available at: <https://www.pes.ee.ethz.ch>



▲ Simplified SST concept

ETH zürich



## Solid-State Transformers

Key Design Challenges, Applicability, and Future Concepts

Johann W. Kolar, Jonas E. Huber  
Power Electronic Systems Laboratory  
ETH Zurich, Switzerland



J. W. Kolar, J. Huber	Fundamentals and Application-Oriented Evaluation of Solid-State Transformer Concepts	Tutorial at the Southern Power Electronics Conference (SPEEC 2016), Auckland, New Zealand, December 5-8, 2016
J. W. Kolar, J. E. Huber	Solid-State Transformers - Key Design Challenges, Applicability, and Future Concepts	Tutorial at the Internal Conference on Power Electronics and Motion Control (PEMC 2016), Varna, Bulgaria, September 25-30, 2016
J. W. Kolar, J. Huber	Solid-State Transformers - Key Design Challenges, Applicability, and Future Concepts	Tutorial at the 8th International Power Electronics and Motion Control Conference (IPEMC 2016-ECCE Asia), Hefei, China, May 22-25, 2016
J. W. Kolar, J. Huber	Solid-State Transformers: Key Design Challenges, Applicability, and Future Concepts	Tutorial at the Applied Power Electronics Conference (APEC), Long Beach, CA, USA, Mar. 20-24, 2016
R. Burkart, J. W. Kolar	Advanced Modeling and Multi-Objective Optimization / Evaluation of SiC Converter Systems	Tutorial at the 3rd IEEE Workshop on Wide Bandgap Power Devices and Applications (WIPDA 2015), Blacksburg, USA, Nov. 2-5, 2015
R. Bosshard, J. W. Kolar	Fundamentals and Multi-Objective Design of Inductive Power Transfer Systems	Tutorial at the the 17th European Conference on Power Electronics and Applications (ECCE Europe 2015), Geneva, Switzerland, September 8-10, 2015
R. Bosshard, J. W. Kolar	Fundamentals and Multi-Objective Design of Inductive Power Transfer Systems	Tutorial at the 9th International Conference on Power Electronics (ICPE 2015-ECCE Asia), Seoul, Korea, June 1-5, 2015
R. Bosshard, J. W. Kolar	Fundamentals and Multi-Objective Design of Inductive Power Transfer Systems	Tutorial at the Conference for Power Conversion and Intelligent Motion (PCIM Europe 2015), Nuremberg, Germany, May 19-21, 2015
J. W. Kolar, J. Huber	Solid-State Transformers in Future Traction and Smart Grids	Tutorial at the Conference for Power Conversion and Intelligent Motion (PCIM Europe 2015), Nuremberg, Germany, May 19-21, 2015
G. Ortiz, J. W. Kolar	Solid State Transformer Concepts in Traction and Smart Grid Applications	Seminar at the Conference for Power Electronics, Intelligent Motion, Power Quality (PCIM South America 2014), São Paulo, Brazil, October 14-15, 2014.

# APPLICATIONS

## Railway

- ▶ 1-phase AC grids [1]
- ▶ Few voltage levels: 15kV (16.7Hz) or 25kV (50Hz)
- ▶ Low frequency (historically): (15kV) 16.7Hz or (25kV) 50Hz
- ▶ On-board installations - serious space constraints
- ▶ Volume and Weight reduction - system savings
- ▶ Reliability - high number of devices?
- ▶ Efficiency - easy to beat traction LFT
- ▶ Control - similar to existing solutions
- ▶ Cost?



▲ ABB's PETT (Source: [www.abb.com](http://www.abb.com))

## Utility

- ▶ 3-phase AC grids
- ▶ Many voltage levels: 3.3, 4.16, 6, 11, 15, 20kV, ...
- ▶ Grid frequency: 50Hz or 60Hz
- ▶ Sub-station installations - relatively low space constraints
- ▶ Volume and Weight reduction - not that relevant
- ▶ Reliability - even more complex due to 3-phases
- ▶ Efficiency - hard to beat distribution LFT
- ▶ Control - improved compared to existing solutions
- ▶ Cost?



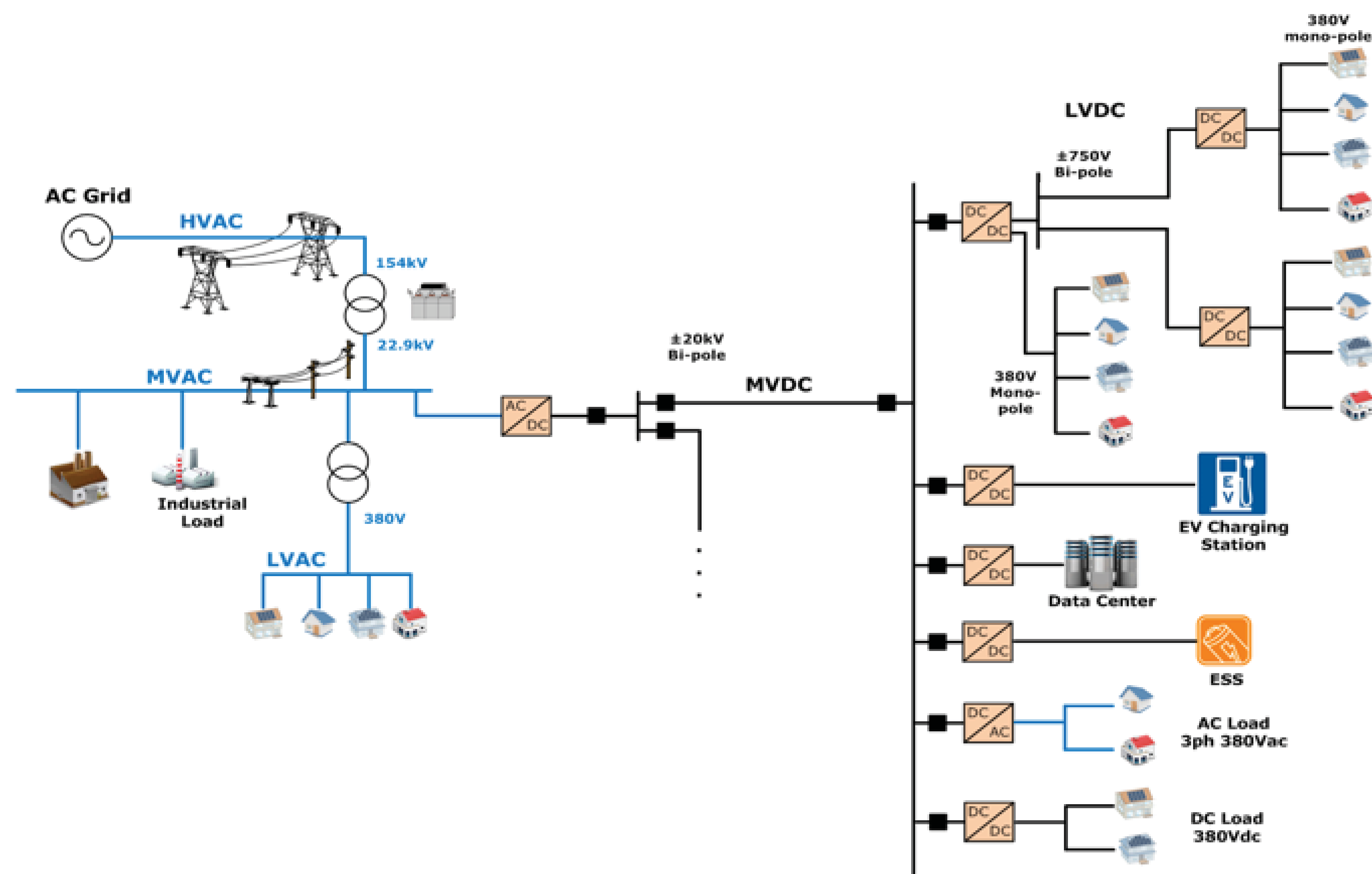
▲ GE's SST [2] (Source: [www.ge.com](http://www.ge.com))



# APPLICATIONS (CONT.)

## MVDC Grids

- ▶ Increased interest into DC grids
- ▶ Need for high power DC-DC converters
- ▶ Galvanic isolation seen as necessary
- ▶ Bidirectional power flow
- ▶ High efficiency



▲ MVDC grids (Source: [www.english.hhi.co.kr](http://www.english.hhi.co.kr))

## Marine LVDC / MVDC Distribution

- ▶ System level benefits
- ▶ Improved partial load efficiency
- ▶ No frequency synchronization of generators
- ▶ Integration of storage technologies
- ▶ Protection coordination



▲ MVDC marine distribution (Source: [www.abb.com](http://www.abb.com))

# RAILWAY ON-BOARD ELECTRICAL SYSTEM

## Railway on-board transformers:

- ▶ Step-down voltage to low levels
- ▶ Already optimized for low weight and volume
- ▶ Reduced efficiency as a price to pay
- ▶ Form factor depends on the mounting method
- ▶ Predominantly oil cooled / insulated
- ▶ Air cooled / solid insulation available as well

## Few things to consider:

- ▶ 50Hz transformer is already fairly small
- ▶ 16.7Hz transformer is relatively bulky and inefficient
- ▶ Single galvanic isolation - insulation coordination
- ▶ Often, new train design defines the available space
- ▶ Design customization is common
- ▶ Power levels are modest and below 15MW
- ▶ Different from the utility transformers



▲ Various realization of traction transformers, Source: [www.abb.com](http://www.abb.com)

# RAILWAY SST

## What traction SST offers in perspective:

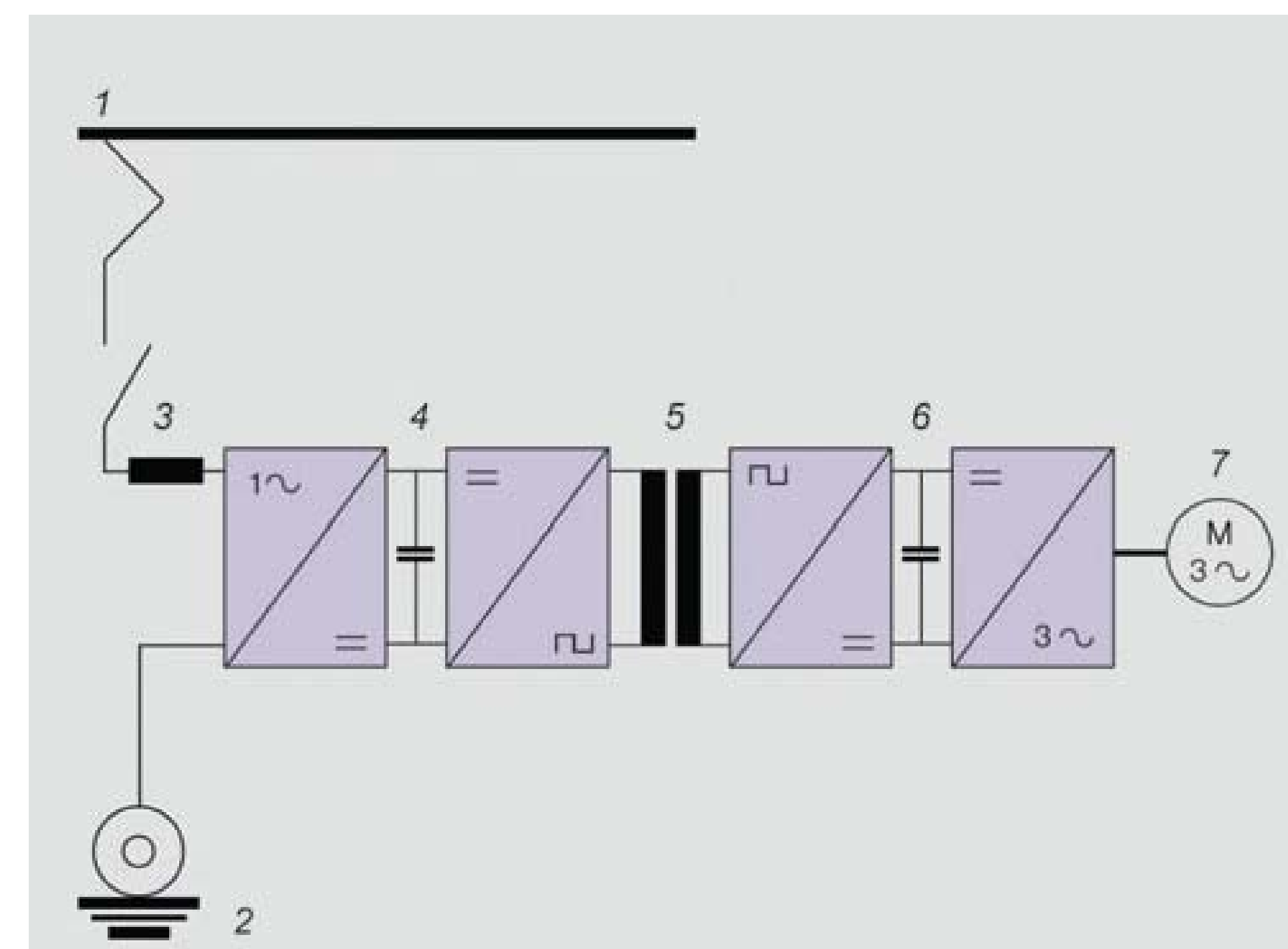
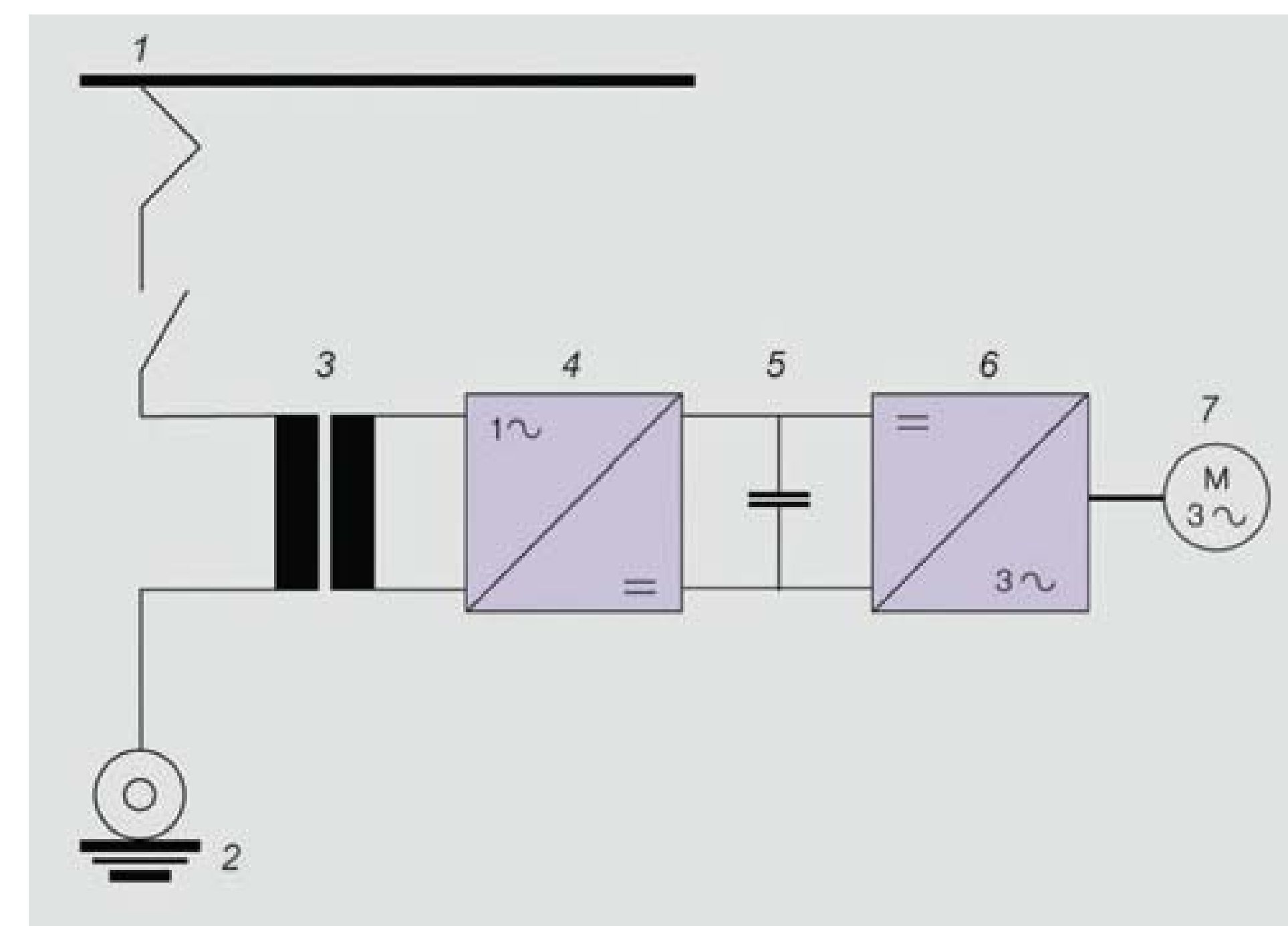
- ▶ Improved efficiency (specially for 16.7Hz systems)
- ▶ Weight reduction - less raw materials
- ▶ Volume reduction - questionable due to insulation coordination
- ▶ Control features

## Why traction SST is not out yet?

- ▶ Conservative traction market
- ▶ Lack of business case
- ▶ Reliability concerns
- ▶ Very hard to compete in 50Hz grids
- ▶ Not a major performance increase
- ▶ Increased cost compared to state-of-the-art solutions

## Prototypes

- ▶ ALSTOM
- ▶ ABB
- ▶ BOMBARDIER
- ▶ ...



▲ On-board traction system evolution with SST [1]

# ALSTOM - 1.5MW E-TRANSFORMER

## Ratings

- ▶ Power: 1.5MW
- ▶ Input AC voltage: 15kV, 16.7Hz
- ▶ Output DC voltage: 1650 V
- ▶ Weight: 3.1 t (vs 6.8 t 16.7Hz LFT)
- ▶ Volume: 3.22 m<sup>3</sup>
- ▶ Efficiency: 94%
- ▶ Cost: 50% increase

## Topology

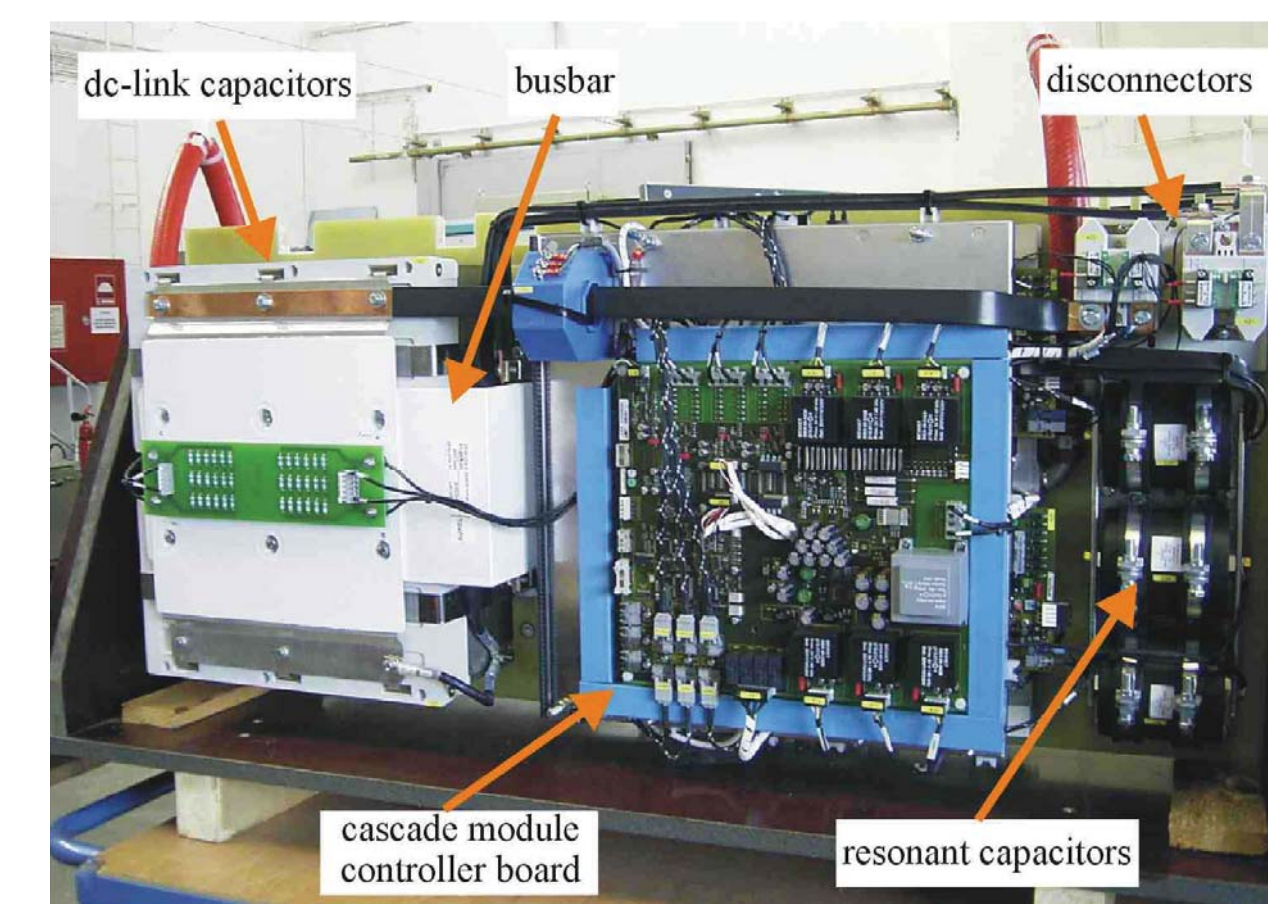
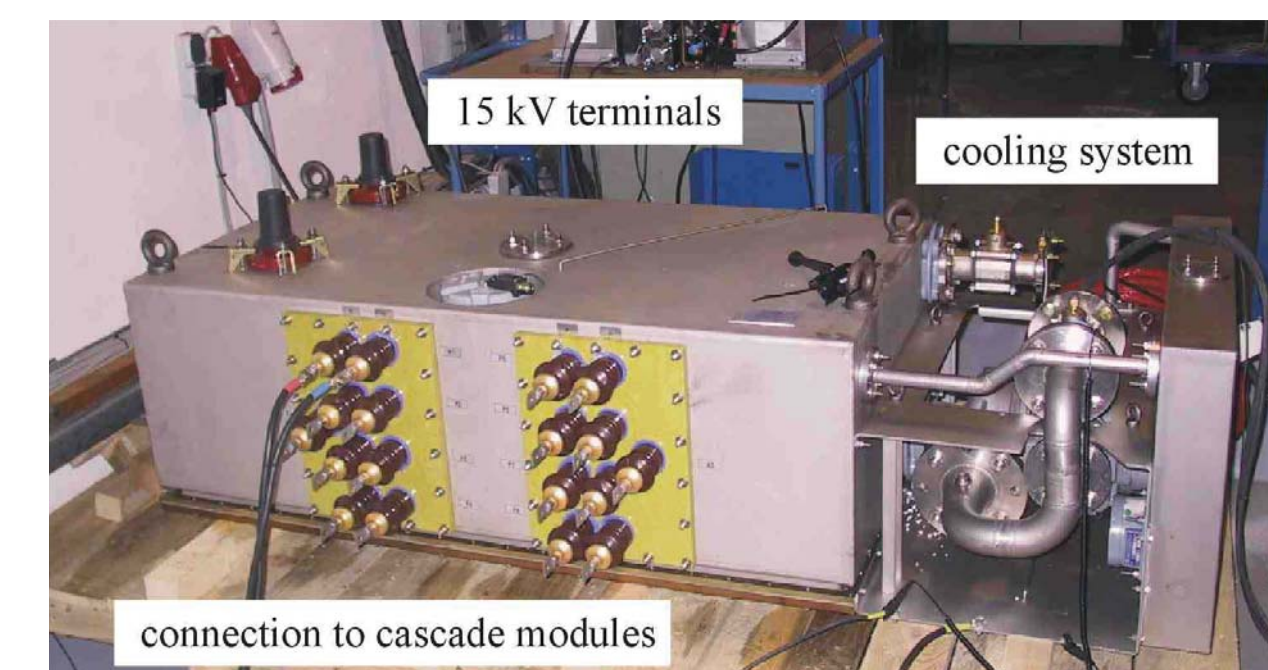
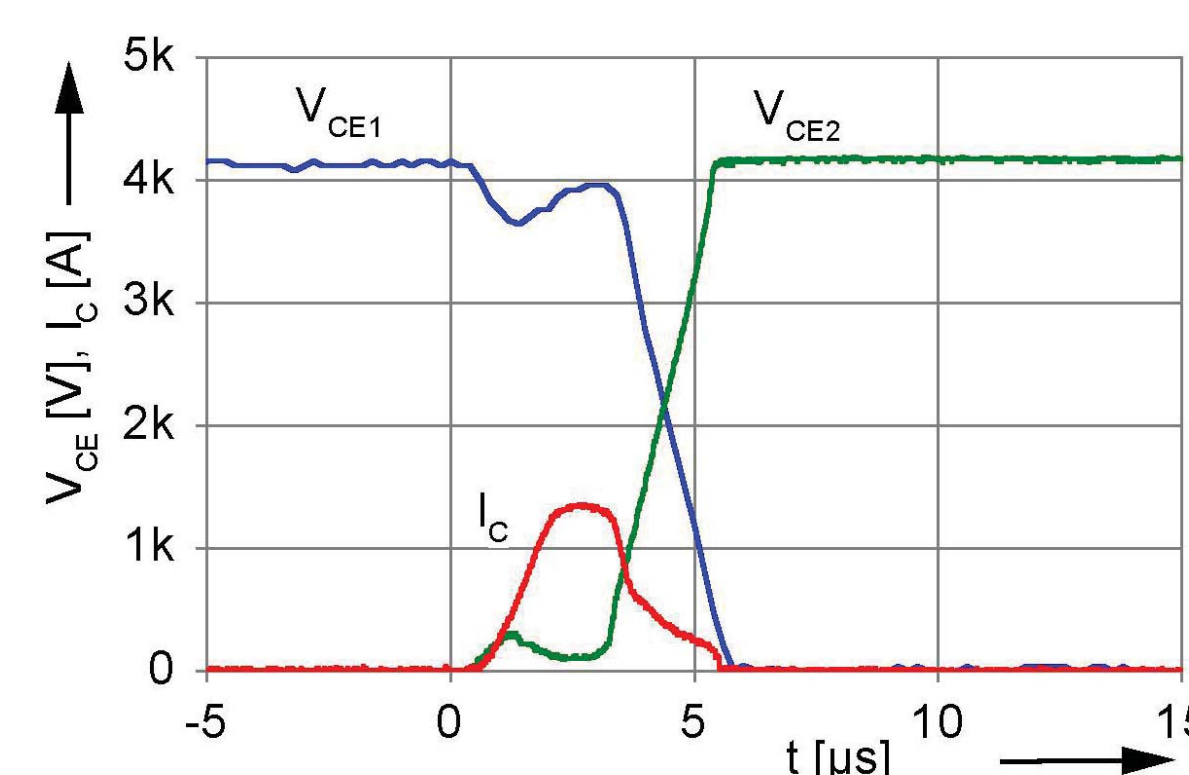
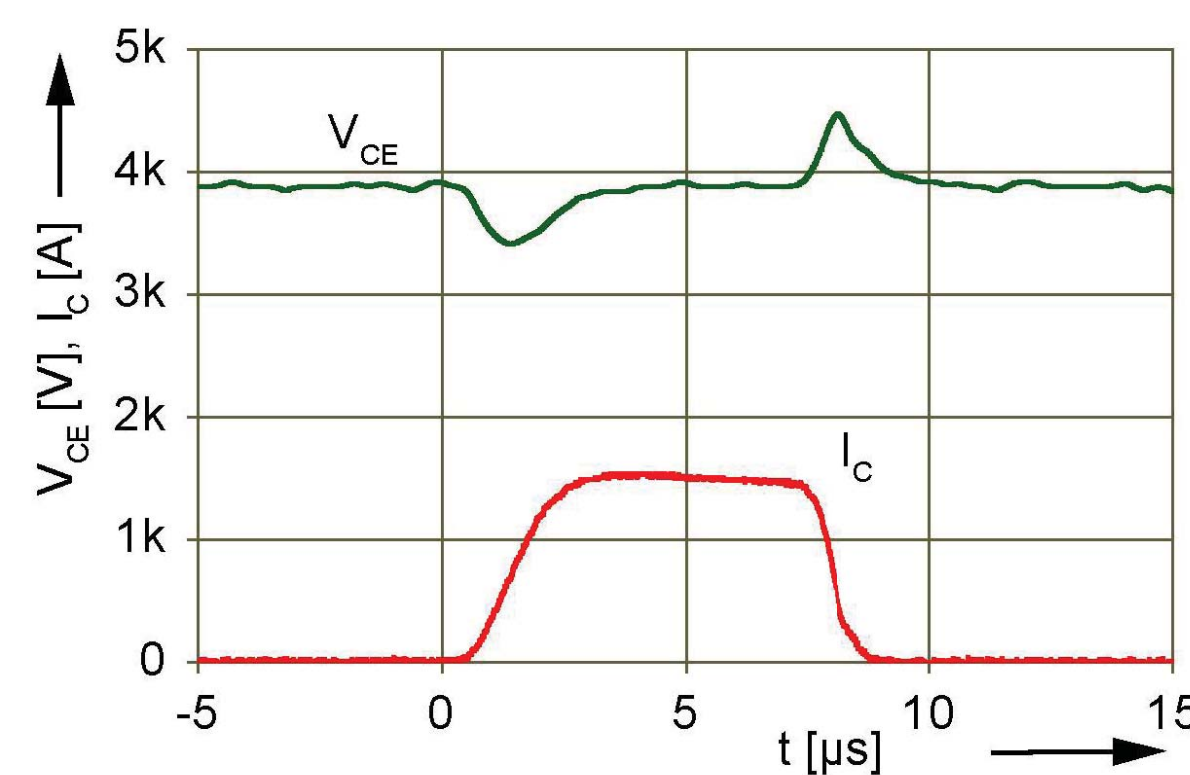
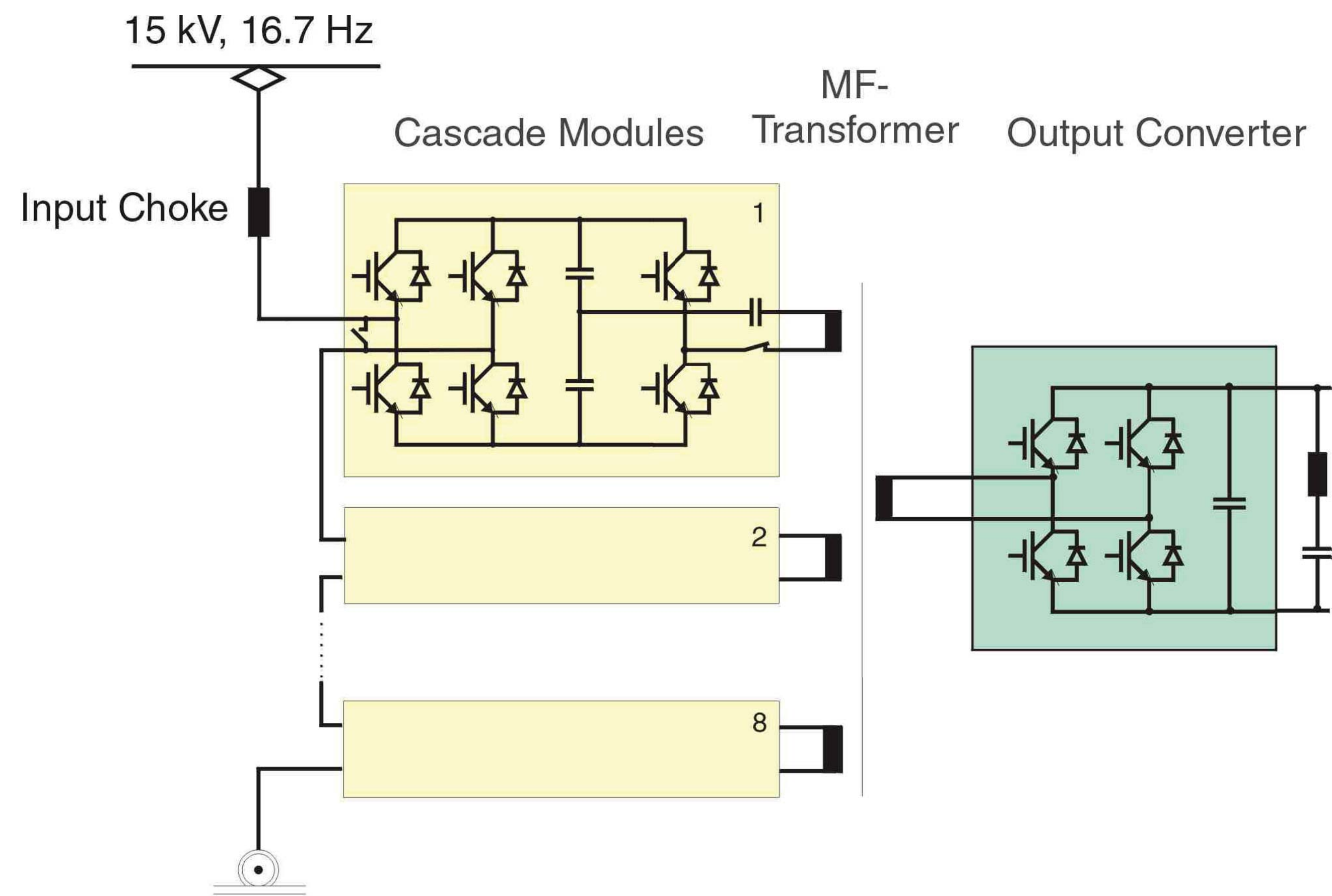
- ▶ 4Q AC-DC + resonant DC-DC
- ▶ 8 cascaded stages on primary

## Semiconductor Devices

- ▶ HV side: 6.5kV IGBTs (48x)
- ▶ LV side: 3.3kV IGBTs

## MFT

- ▶ Power: 1.5MW
- ▶ Frequency: 5kHz
- ▶ Core: Ferrite
- ▶ Insulation / Cooling: Oil



▲ ALSTOM reported Traction SST [3], [4]

# ABB - 1.2MW POWER ELECTRONIC TRACTION TRANSFORMER - PETT\_

## Ratings

- ▶ Power: 1.2MW
- ▶ Input AC voltage: 15kV, 16.7Hz
- ▶ Output DC voltage: 1800 V
- ▶ Efficiency: 95% (peak)

## Topology

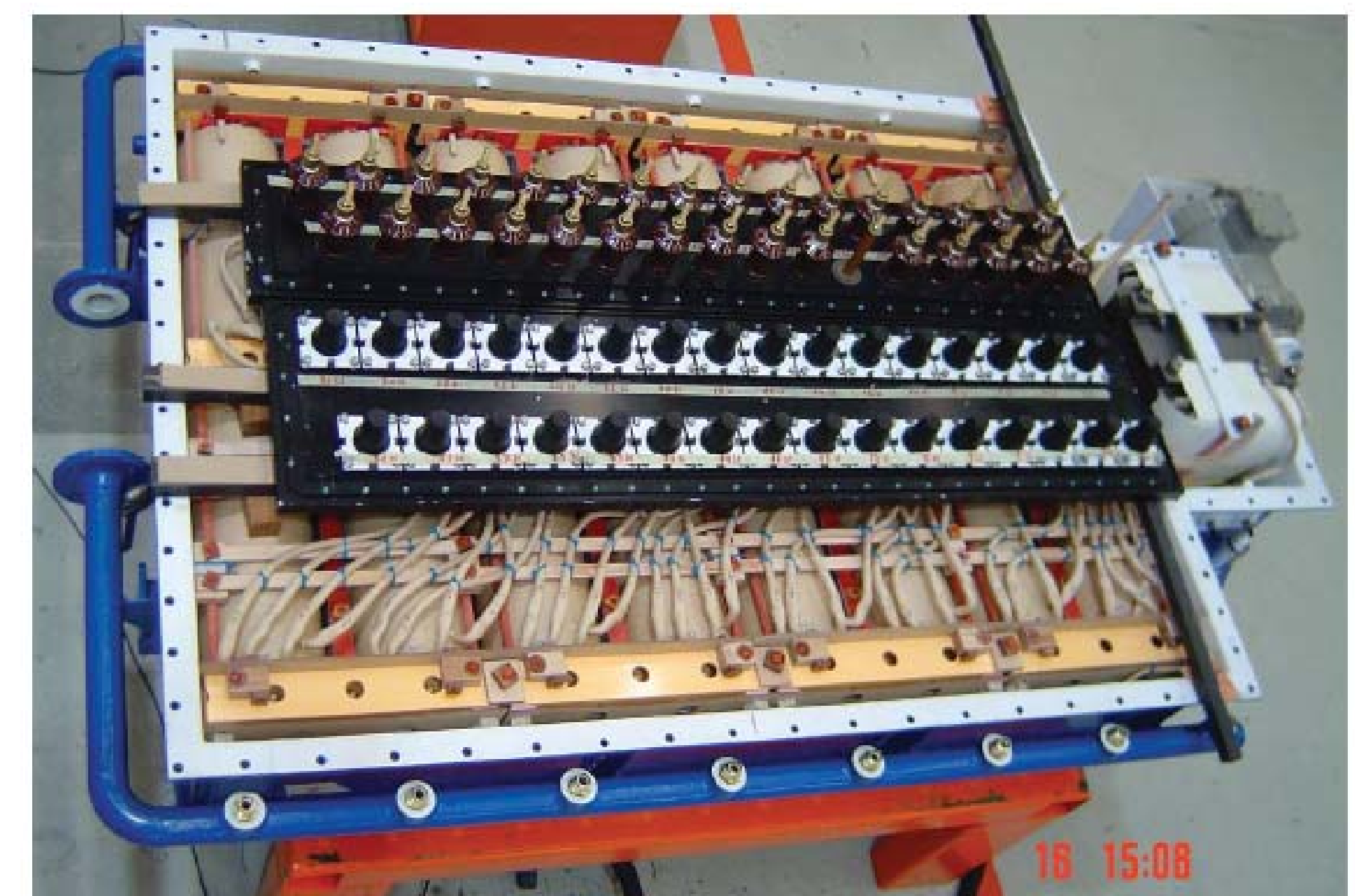
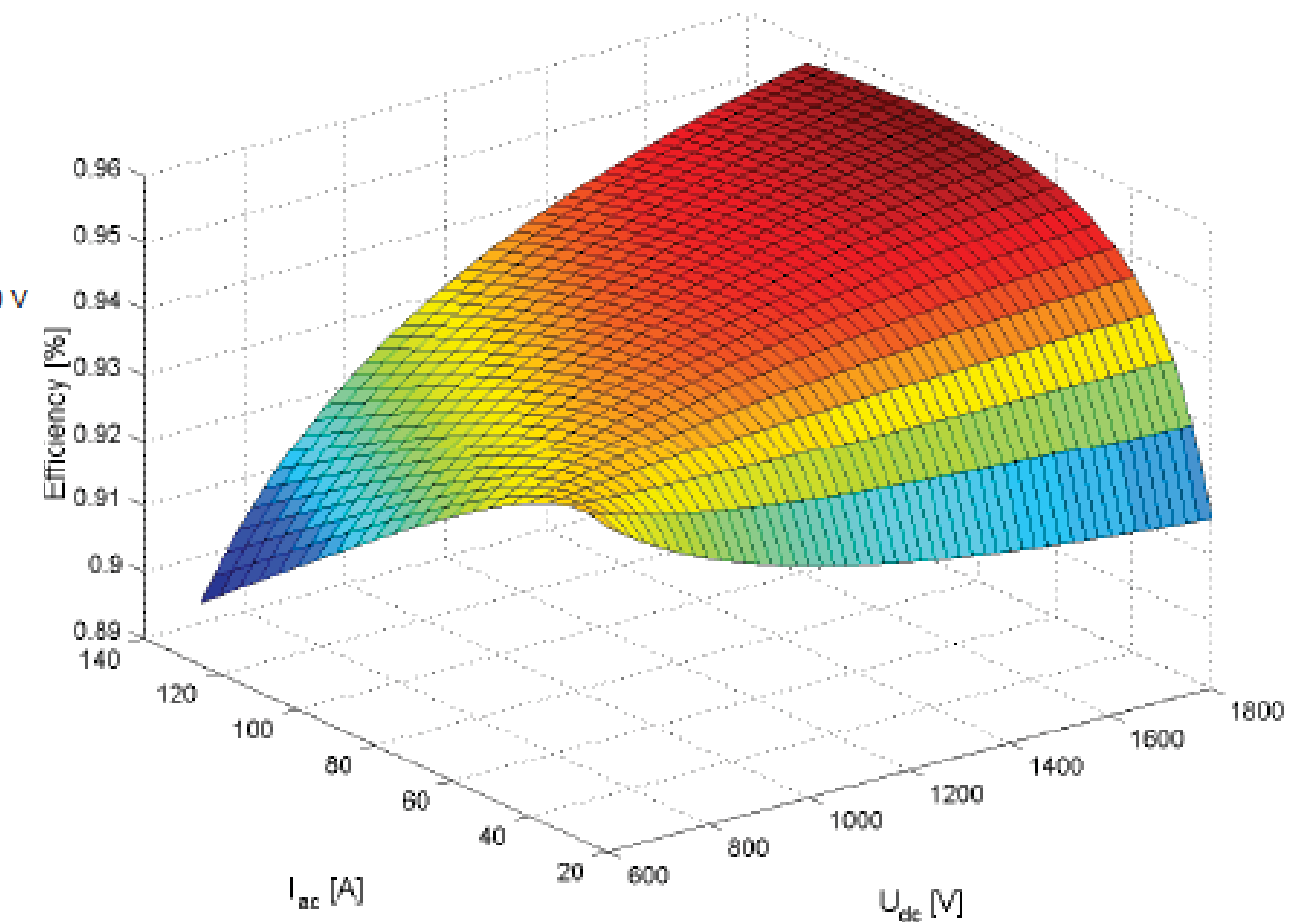
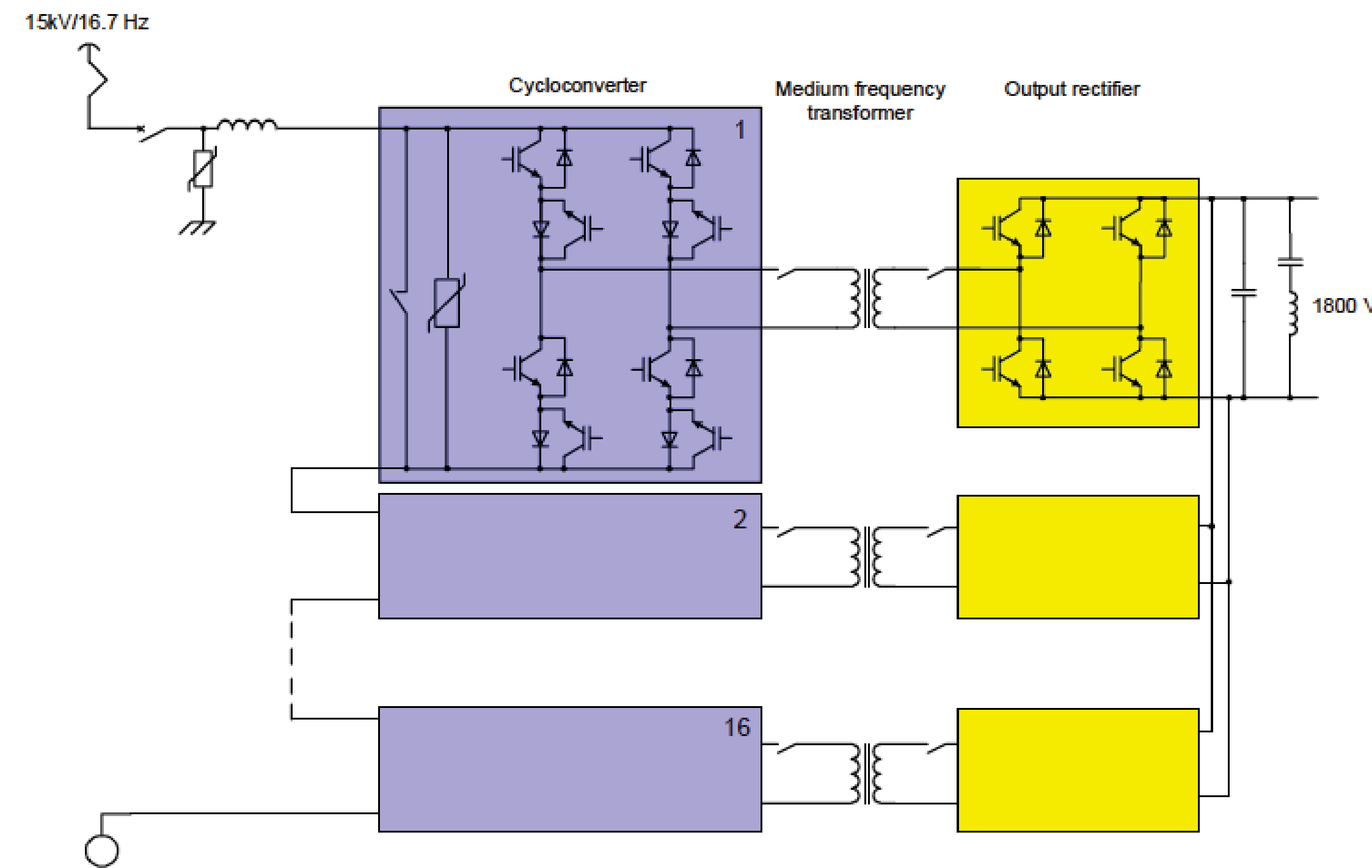
- ▶ 4Q AC-AC + AC-DC
- ▶ 16 cascaded stages

## Semiconductor Devices

- ▶ HV side: 3.3kV IGBTs
- ▶ LV side: 3.3kV IGBTs

## MFT

- ▶ Power: 75kW per MFT
- ▶ Frequency: 400Hz
- ▶ Core: SiFe
- ▶ Insulation / Cooling: oil



▲ ABB reported PETT [5]

# ABB - 1.2MW PETT

## Characteristics

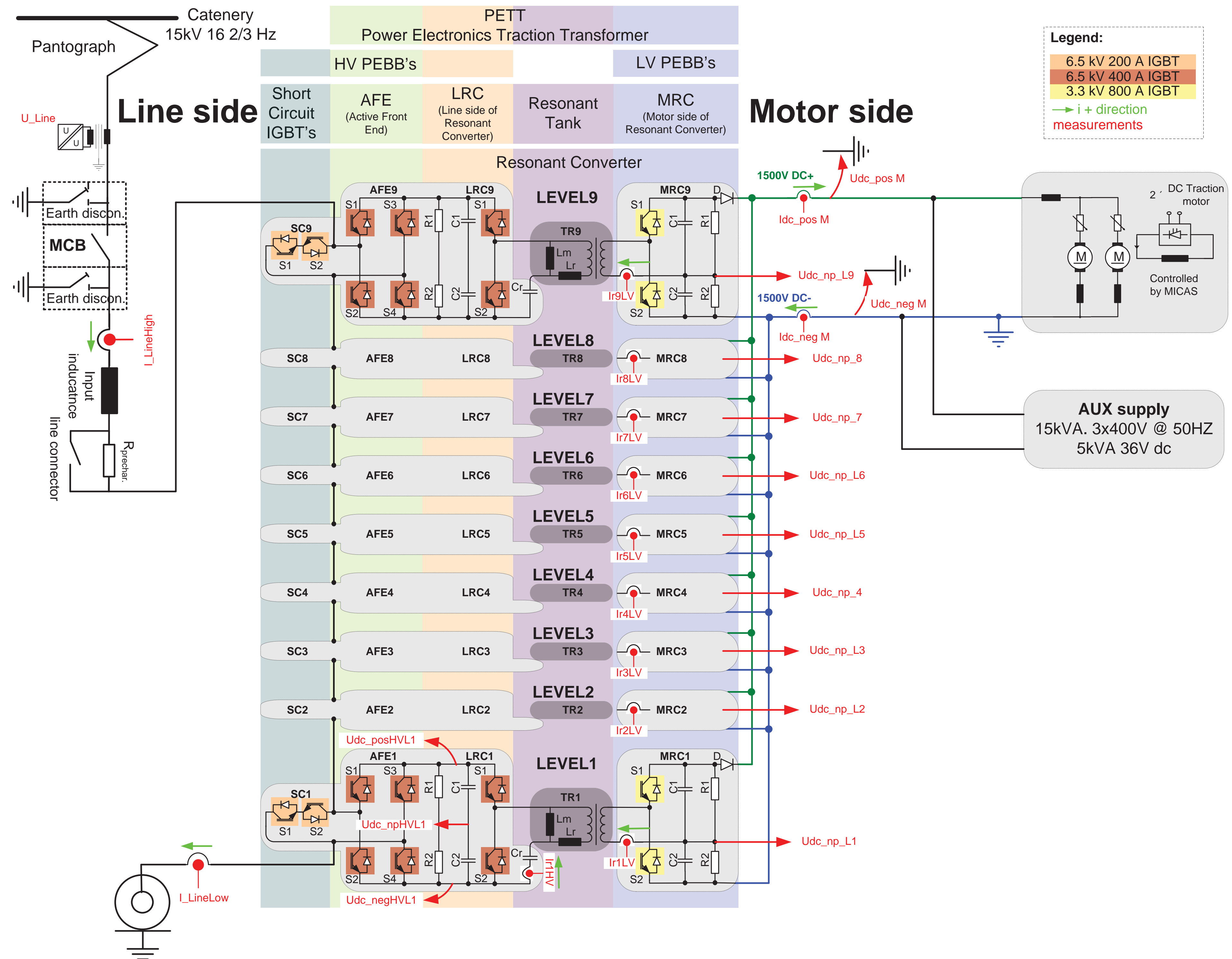
- ▶ 1-Phase MVAC to MVDC
- ▶ Power: 1.2MVA
- ▶ Input AC voltage: 15kV, 16.7Hz
- ▶ Output DC voltage: 1500 V
- ▶ 9 cascaded stages (n + 1)
- ▶ input-series output-parallel
- ▶ double stage conversion

## 99 Semiconductor Devices

- ▶ HV PEBB: 9 x (6 x 6.5kV IGBT)
- ▶ LV PEBB: 9 x (2 x 3.3kV IGBT)
- ▶ Bypass: 9 x (2 x 6.5kV IGBT)
- ▶ Decoupling: 9 x (1 x 3.3kV Diode)

## 9 MFTs

- ▶ Power: 150kW
- ▶ Frequency: 1.75kHz
- ▶ Core: Nanocrystalline
- ▶ Winding: Litz
- ▶ Insulation / Cooling: oil

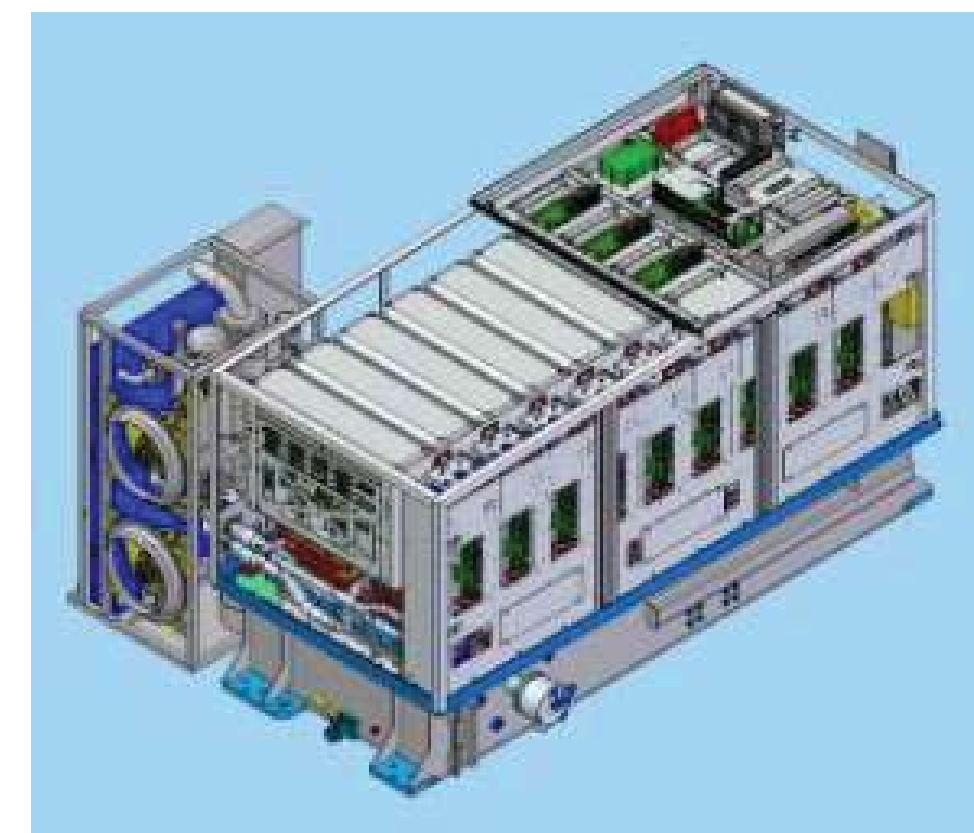


▲ ABB PETT scheme [6], [7]

# ABB - 1.2MW PETT DESIGN

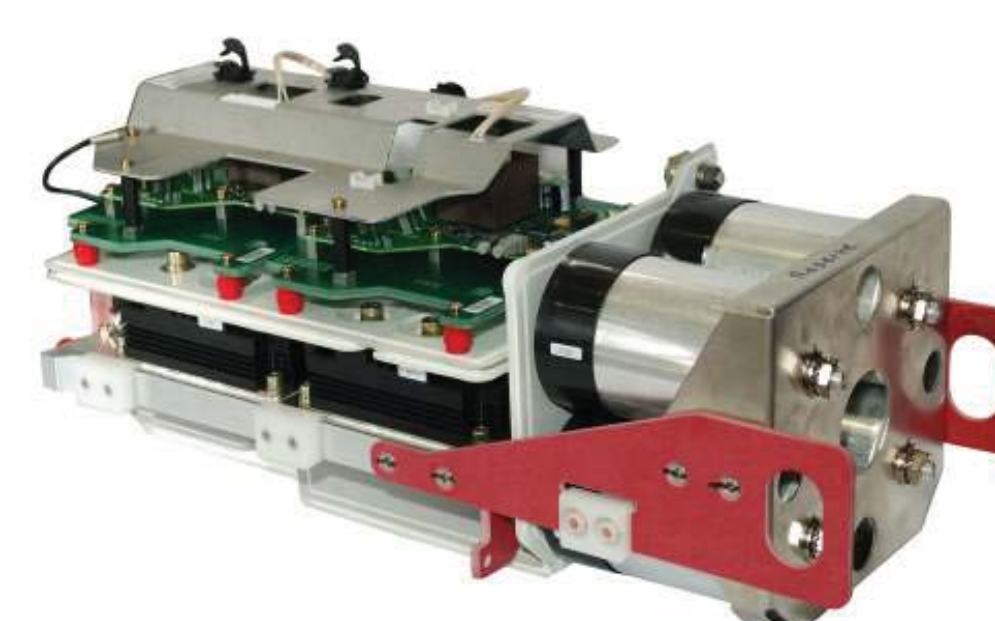
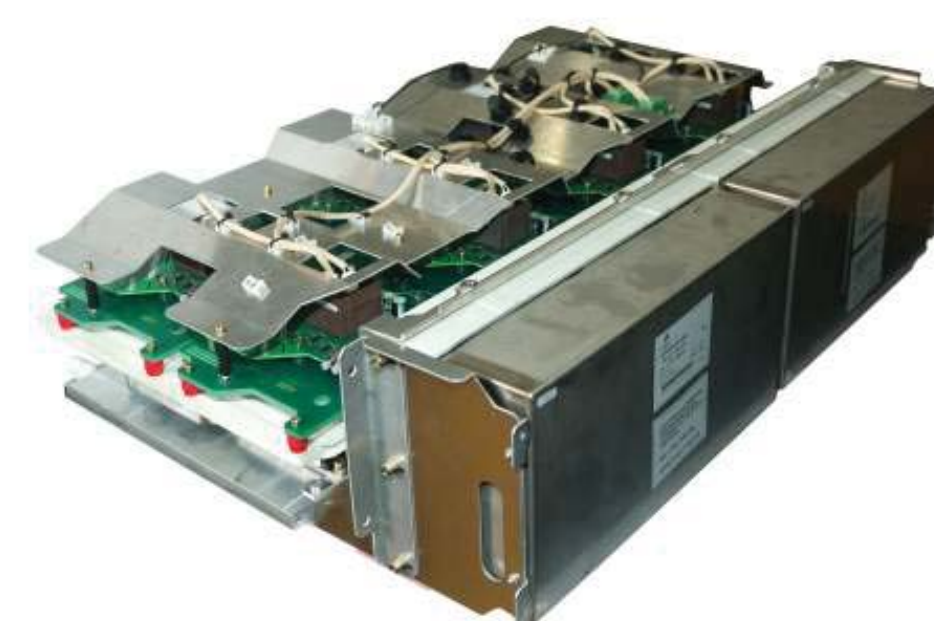
## Retrofitted to shunting locomotive

- ▶ Replaced LFT + SCR rectifier
- ▶ Propulsion motor - 450kW
- ▶ 12 months of field service
- ▶ No power electronic failures
- ▶ Efficiency around 96%
- ▶ Weight:  $\approx 4.5$  t



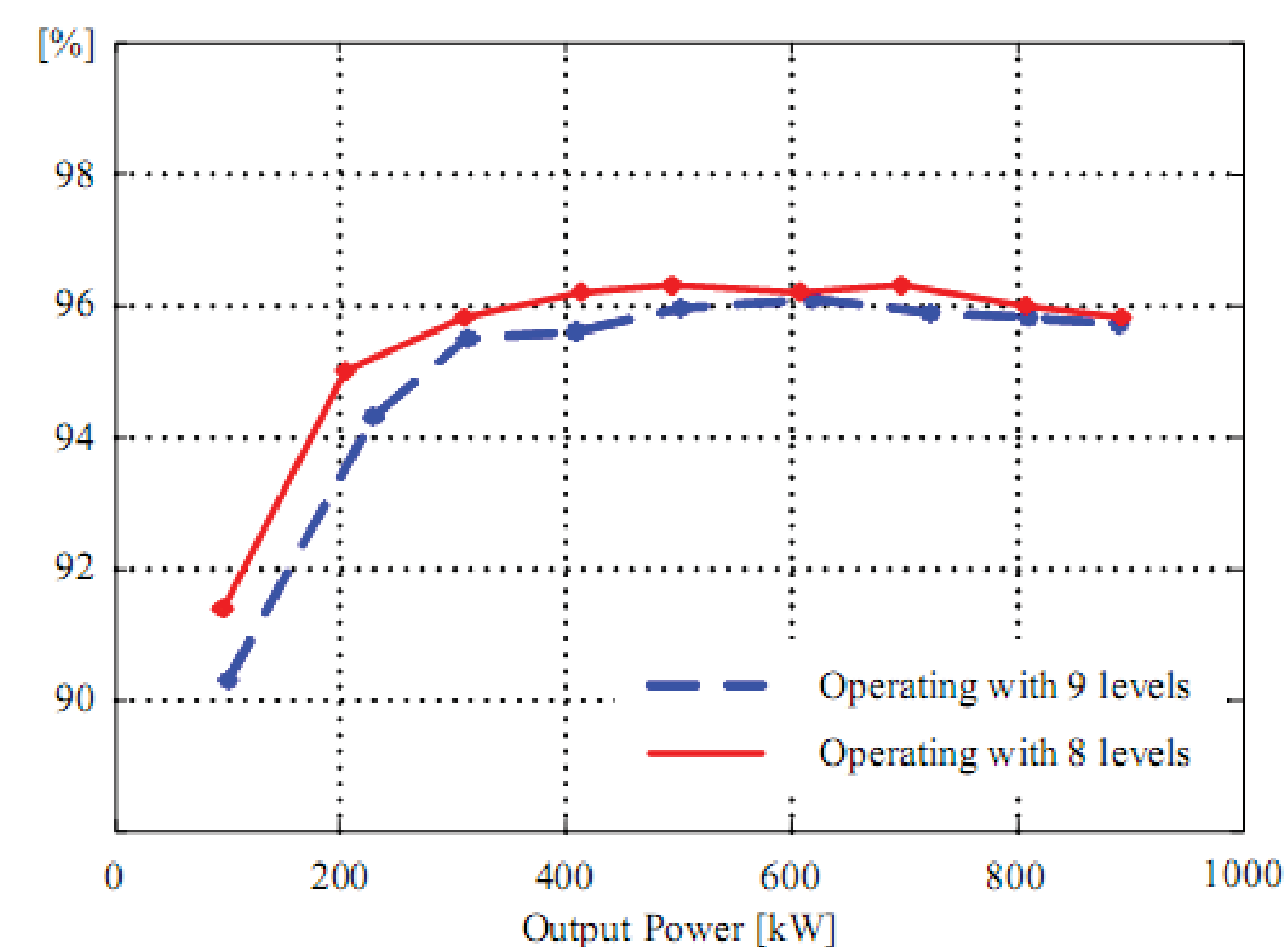
## Technologies

- ▶ Standard 3.3kV and 6.5kV IGBTs
- ▶ De-ionized water cooling
- ▶ Oil cooling/insulation for MFTs
- ▶ n + 1 redundancy
- ▶ IGBT used for bypass switch



## Displayed at:

- ▶ Swiss Museum of Transport
- ▶ <https://www.verkehrshaus.ch>



▲ ABB PETT prototype [6], [7]

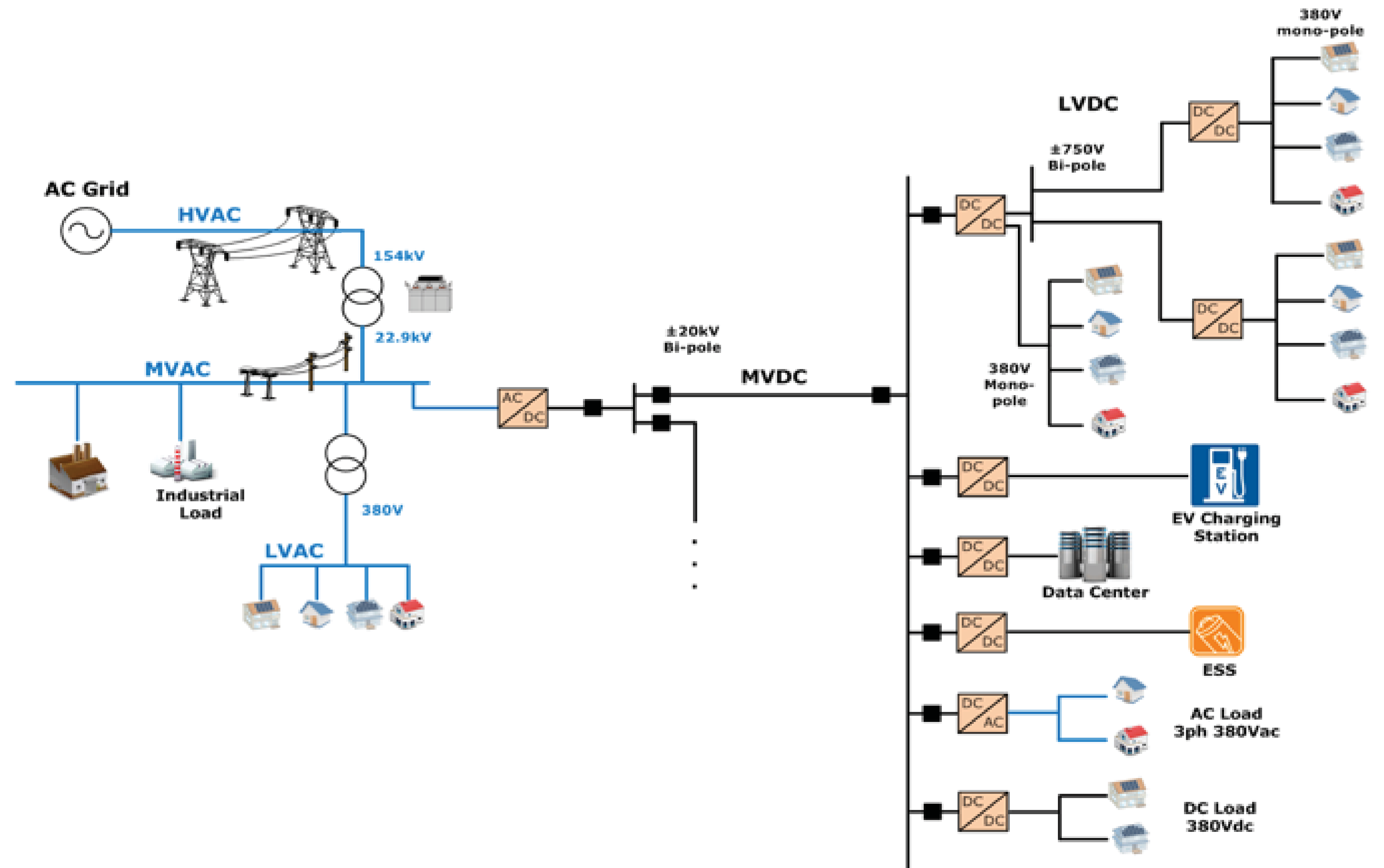
# UTILITY SST

## Quite different from railways

- ▶ 50 / 60 Hz grids
- ▶ Higher powers: MW, GW
- ▶ Much higher voltage: MV, HV
- ▶ High efficiency needed (> 99 %)
- ▶ High reliability needed
- ▶ High availability needed
- ▶ Weight may not be important
- ▶ Volume may not be important

## Challenges

- ▶ Business case
- ▶ Cost
- ▶ Efficiency
- ▶ Reliability
- ▶ Availability



Design of a converter is the least problem!

▲ Possible future grid connections ([www.english.hhi.co.kr](http://www.english.hhi.co.kr))



# UTILITY SST PROJECTS

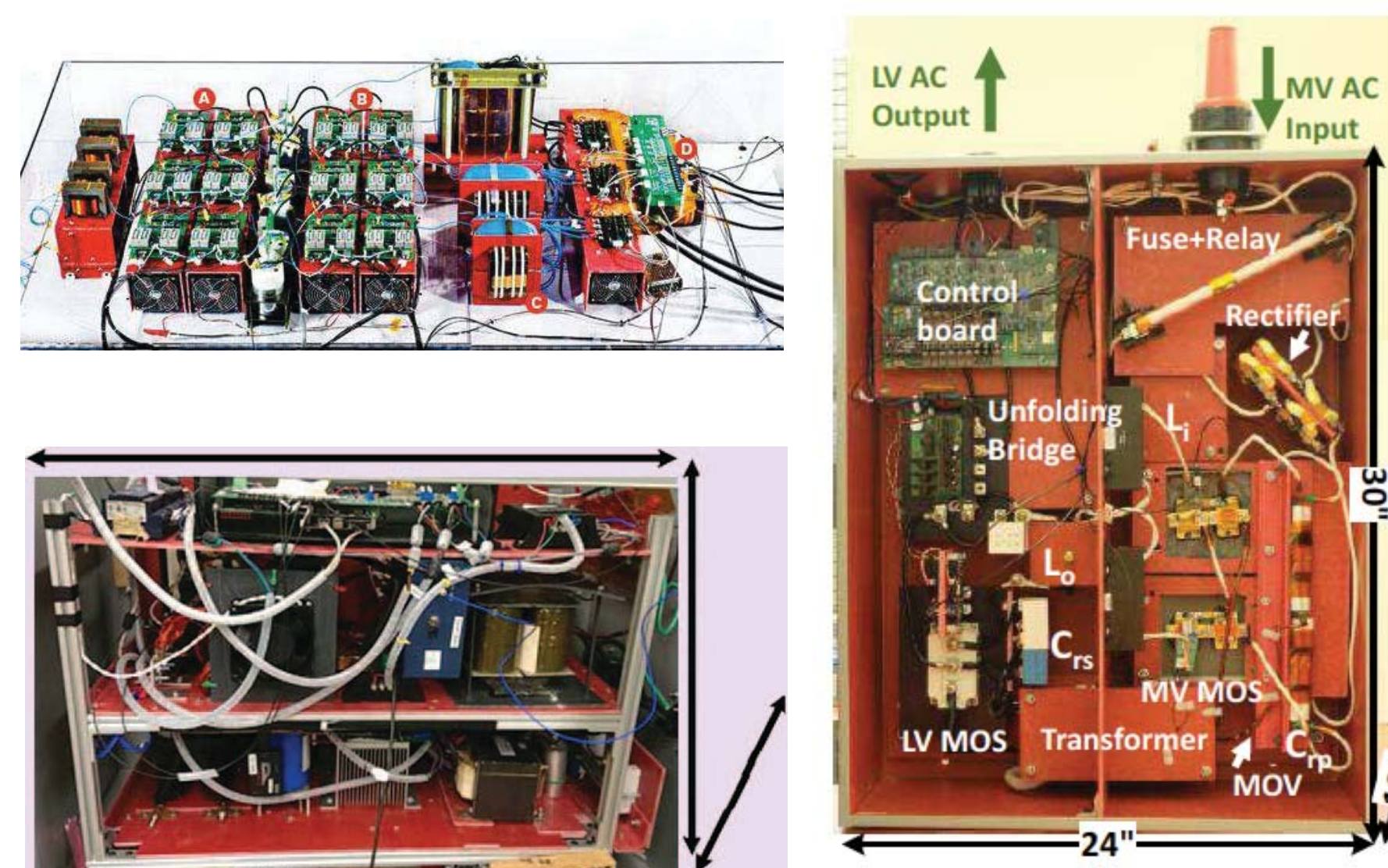
## UNIFLEX-PM

- ▶ [www.eee.nott.ac.uk/uniflex/index.html](http://www.eee.nott.ac.uk/uniflex/index.html)
- ▶ Academic initiative
- ▶ Multiport AC-AC-AC
- ▶ Power control
- ▶ Voltage control
- ▶ Reduced scale prototypes



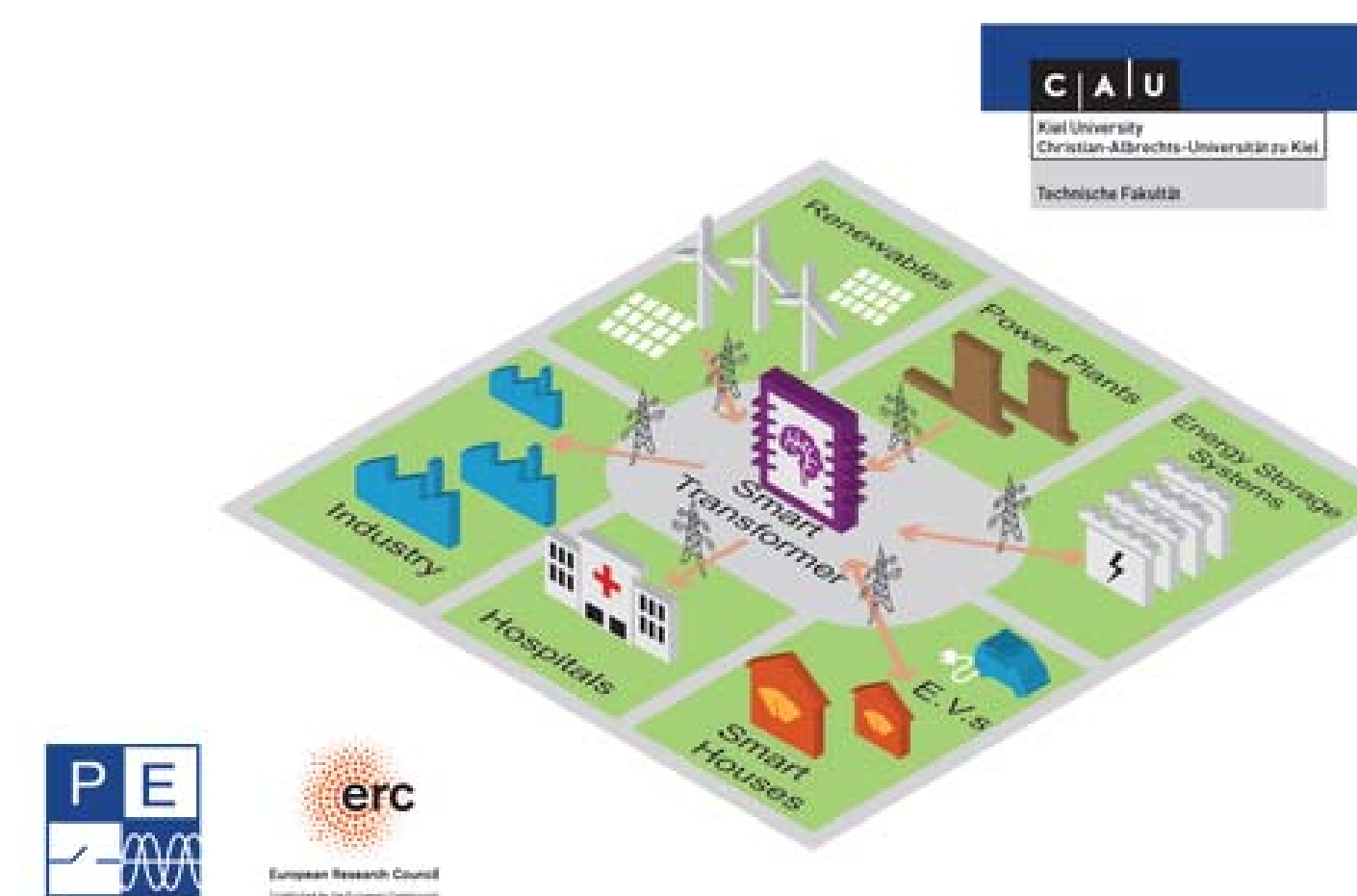
## FREEDM

- ▶ [www.freedm.ncsu.edu](http://www.freedm.ncsu.edu)
- ▶ Academic initiative
- ▶ Gen-1 SST: Si-based (6.5kV, 3kHz)
- ▶ Gen-2 SST: SiC-based (15kV, 10kHz)
- ▶ Gen-3 SST: SiC-based (15kV, 40kHz)
- ▶ Reduced scale prototypes



## HEART

- ▶ [www.heart.tf.uni-kiel.de/en/home](http://www.heart.tf.uni-kiel.de/en/home)
- ▶ Academic initiative
- ▶ AC grids
- ▶ Energy routing
- ▶ Control features
- ▶ Reduced scale prototypes



▲ UNIFLEX-PM prototype

▲ FREEDM SSTs [8]

▲ HEART project

# SUMMARY - SOLID STATE TRANSFORMER

## SST Pros

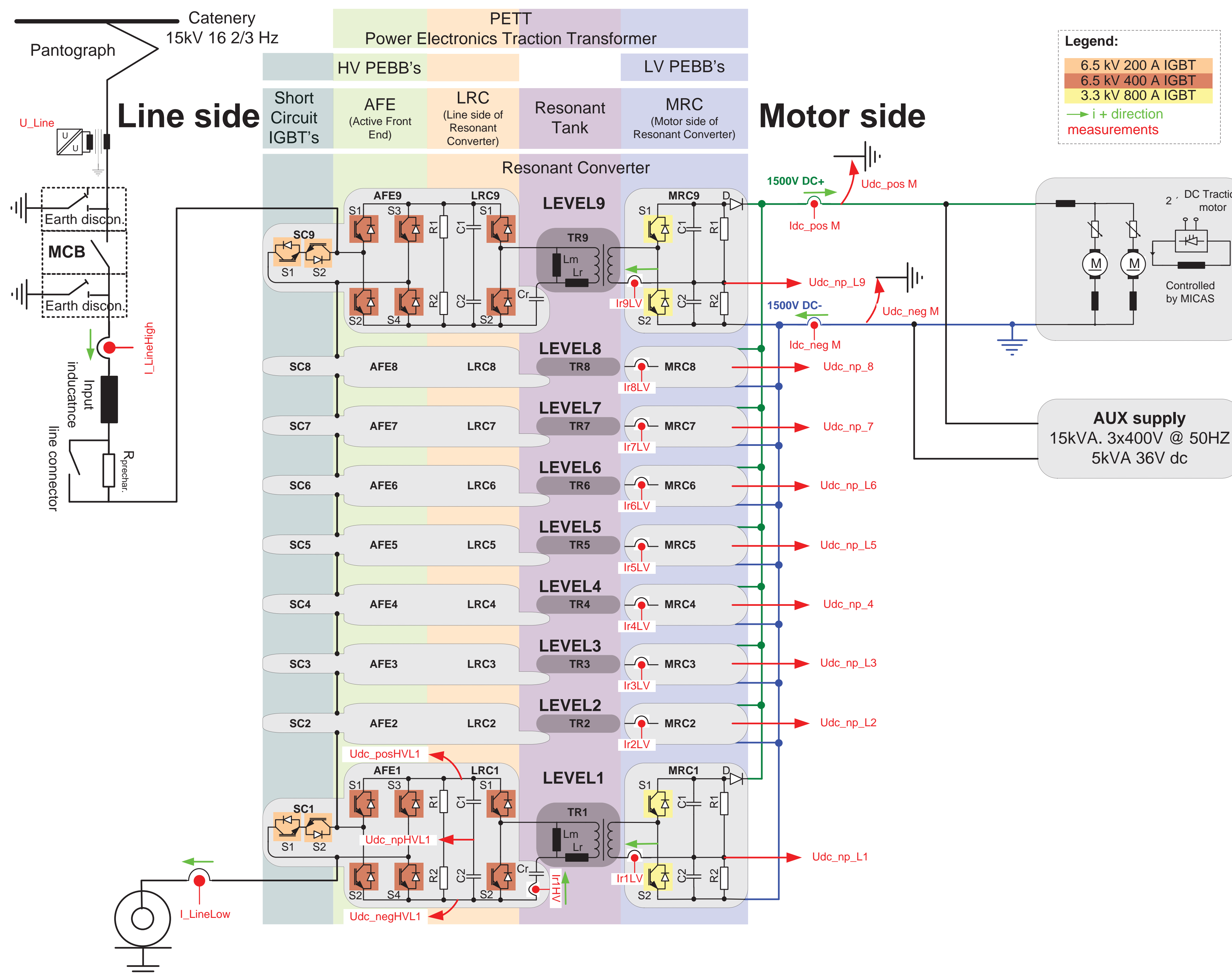
- ▶ Flexible grid interface
- ▶ AC-DC, AC-AC, DC-DC, DC-AC
- ▶ Galvanic isolation
- ▶ Advanced control features

## SST Cons

- ▶ Compromised efficiency
- ▶ Increased complexity
- ▶ Higher cost
- ▶ Reliability
- ▶ Scalability

## SST Future Research

- ▶ System level optimization
- ▶ Efficiency improvements
- ▶ Insulation coordination
- ▶ Protection
- ▶ MFT design optimization
- ▶ ...



▲ ABB PTT scheme: Not that simple...

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# MEDIUM FREQUENCY TRANSFORMERS

*What are the design challenges?*

# MOTIVATION

- ▶ **Lower Volume** – easier system integration
- ▶ **Lower Weight** – especially important for onboard traction applications
- ▶ **Less Material** – lower investment cost, lower environmental footprint
- ▶ **Improved Efficiency** – application specific case
- ▶ **Modularity** – fractional power processing

$$A_P = \frac{P_t}{K_f K_u B_m J f}$$

*size* ↓  
*power* ↓  
*waveform* ↑ *insulation* ↑ *material* ↑ *cooling* ↑ *frequency* ↑

▲ Approximate transformer scaling relation

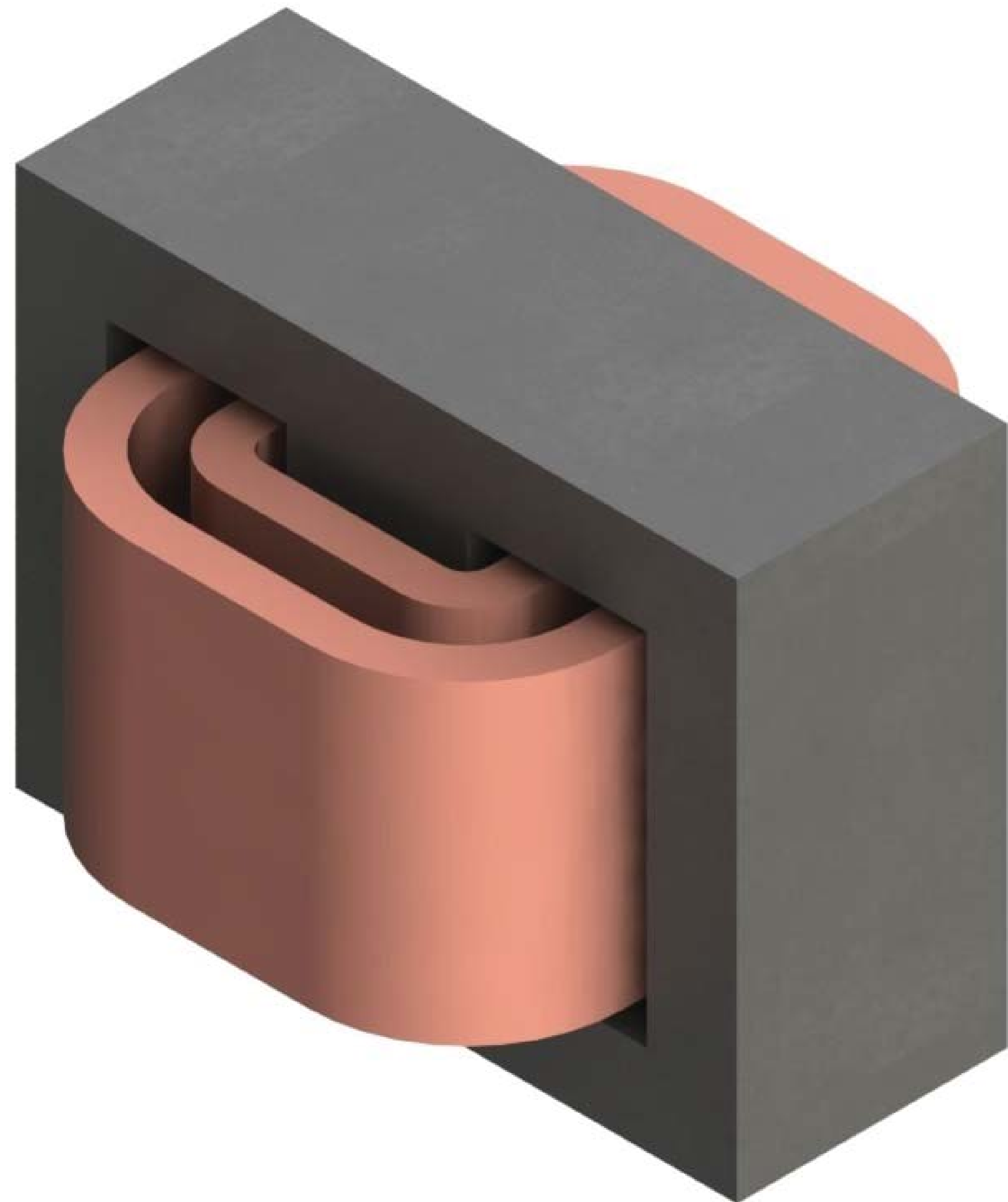


**Three-phase 200-V, 5-kVA,  
50-Hz Transformer**

**Single-phase, 250-V, 5-kVA,  
20-kHz Transformer**

▲ Example: frequency impact on the transformer size (Prof. Akagi)

# MFT SCALING LAWS



▲ Shell type MFT

## MFT dimension analysis for constant $B_m$ and $J$

Cooling Surface	$S_c = C_1 l^2$	$k^2$
Volume and Mass	$M = \gamma V = C_2 l^3$	$k^3$
Current	$I = JS_{Cu}$	$k^2$
Induced Voltage	$U = C_3 f B_m S_{Fe}$	$f k^2$
Apparent Power	$P = UI$	$f k^4$
DC Resistance	$R = N \rho l / S_{Cu}$	$1/k$
Copper Losses	$P_{Cu} = FRI^2$	$F(f)k^3$
Core Losses	$P_{Fe} = Kf^a B_m^b V$	$f^a k^3$
Temperature Rise	$\Delta\theta = (P_{Cu} + P_{Fe}) / (aS_c)$	$k(F(f) + f^a)$
Relative Losses	$P_r = (P_{Cu} + P_{Fe}) / P$	$(F(f) + f^a) / (kf)$
Relative Cost	$\varepsilon = M/P$	$1/(kf)$

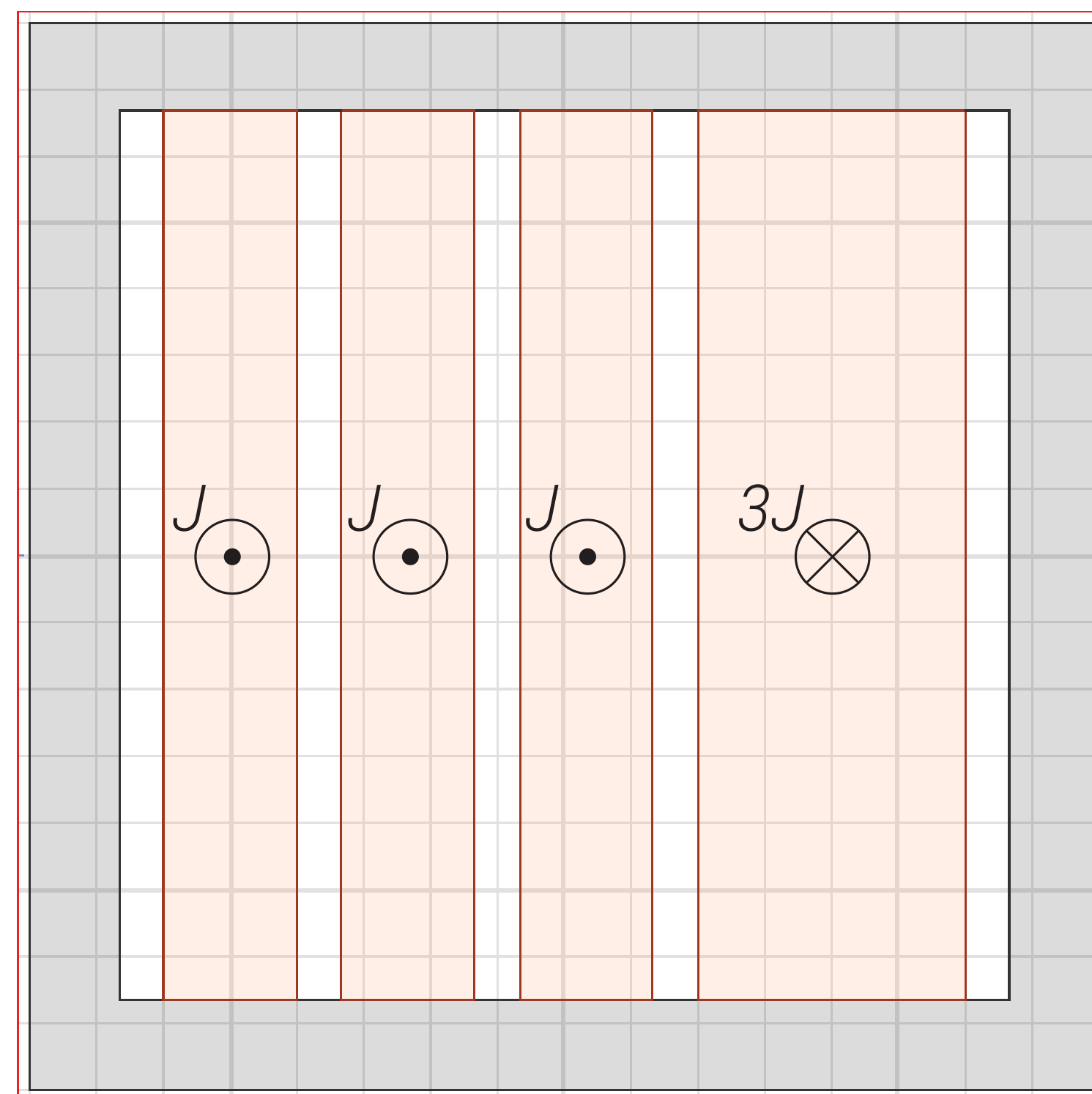
Where:  $F(f)$  - skin and proximity effect correction factor

# SKIN AND PROXIMITY EFFECT

## Effects

- ▶ Non-uniform current density
- ▶ Under-utilization of the conductor material
- ▶ Localized H-field distortion within the conductor volume
- ▶ Impact on conduction losses
- ▶ Impact on leakage inductance

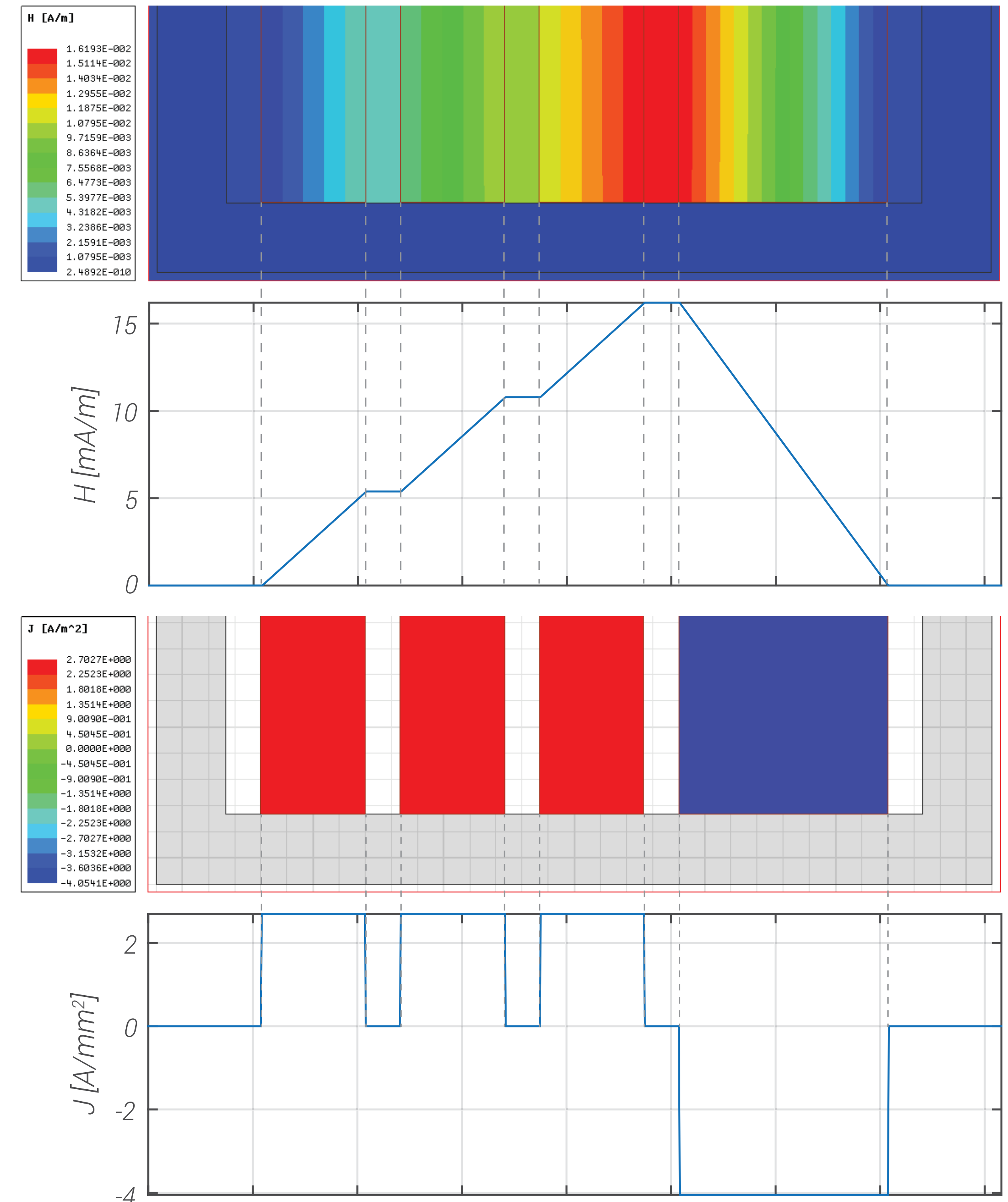
## Example of the Foil Winding MFT Geometry Cross-Section



— 0.1 [Hz] ( $\Delta = 0.01$ )

\*  $\Delta$  - the penetration ratio

▲ Generic foil winding geometry



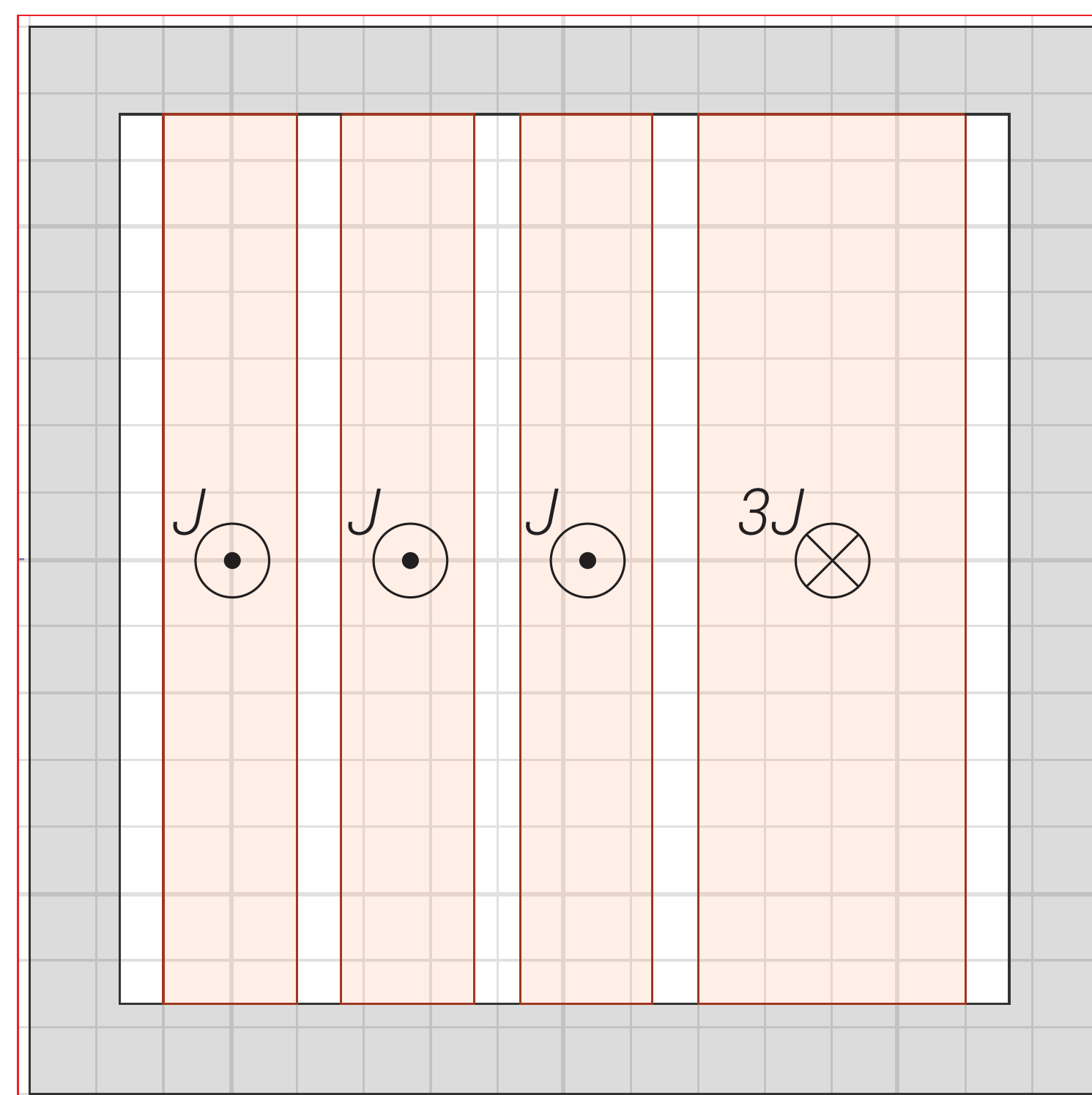
▲ H and J distribution within the core window area

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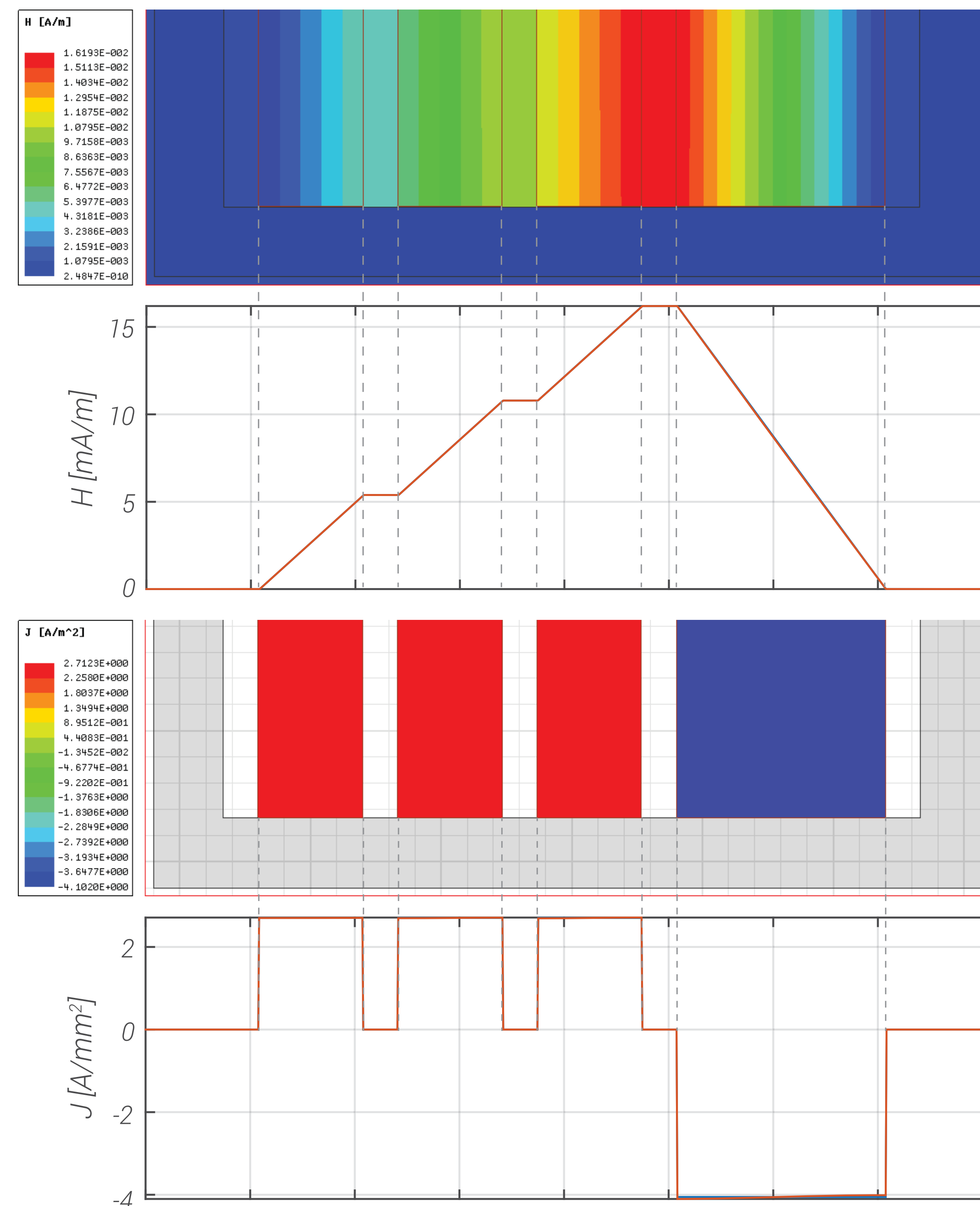
## Example of the Foil Winding MFT Geometry Cross-Section



— 0.1 [Hz] ( $\Delta = 0.01$ )  
 — 100 [Hz] ( $\Delta = 0.3$ )

\*  $\Delta$  - the penetration ratio

▲ Generic foil winding geometry



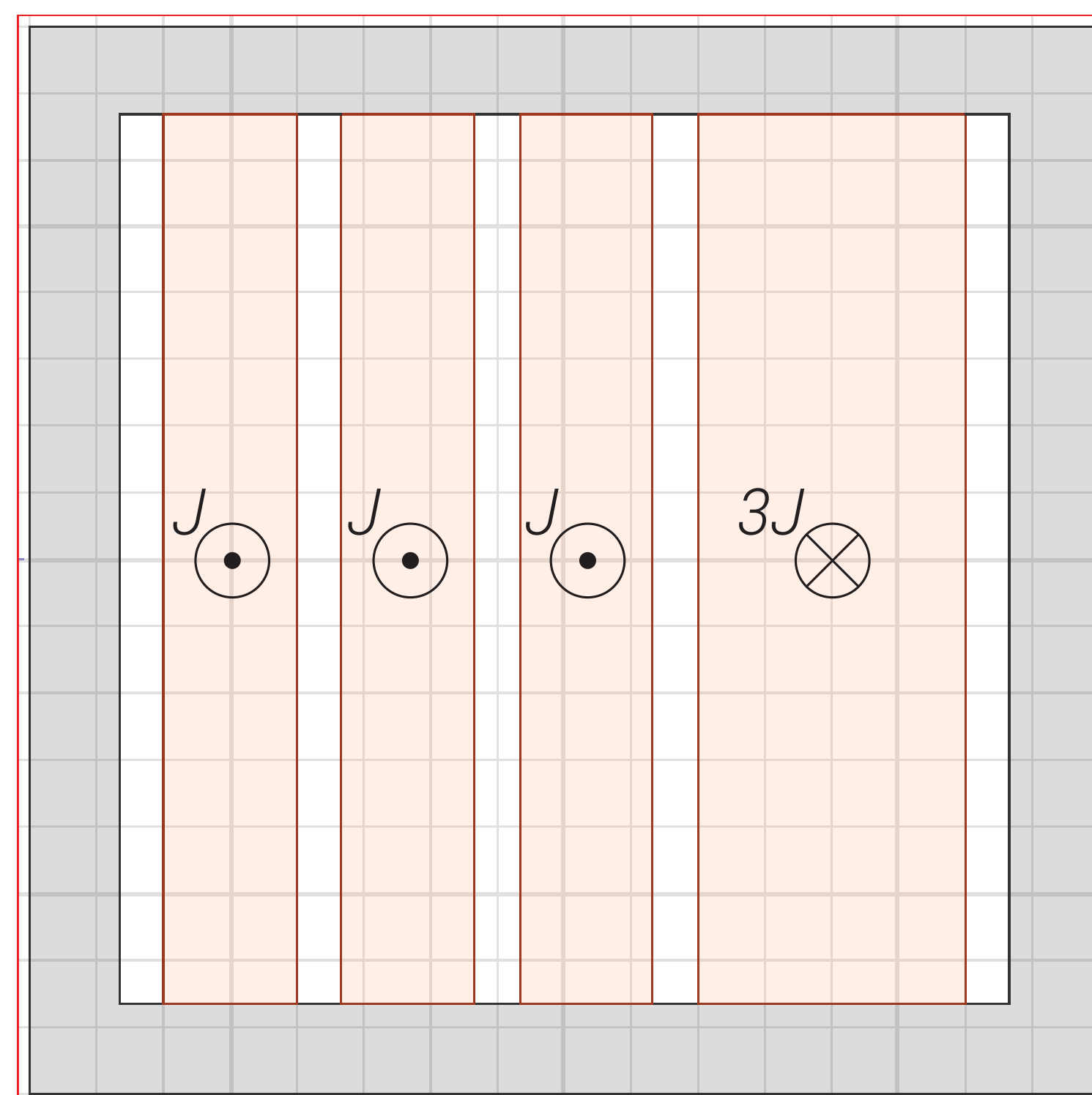
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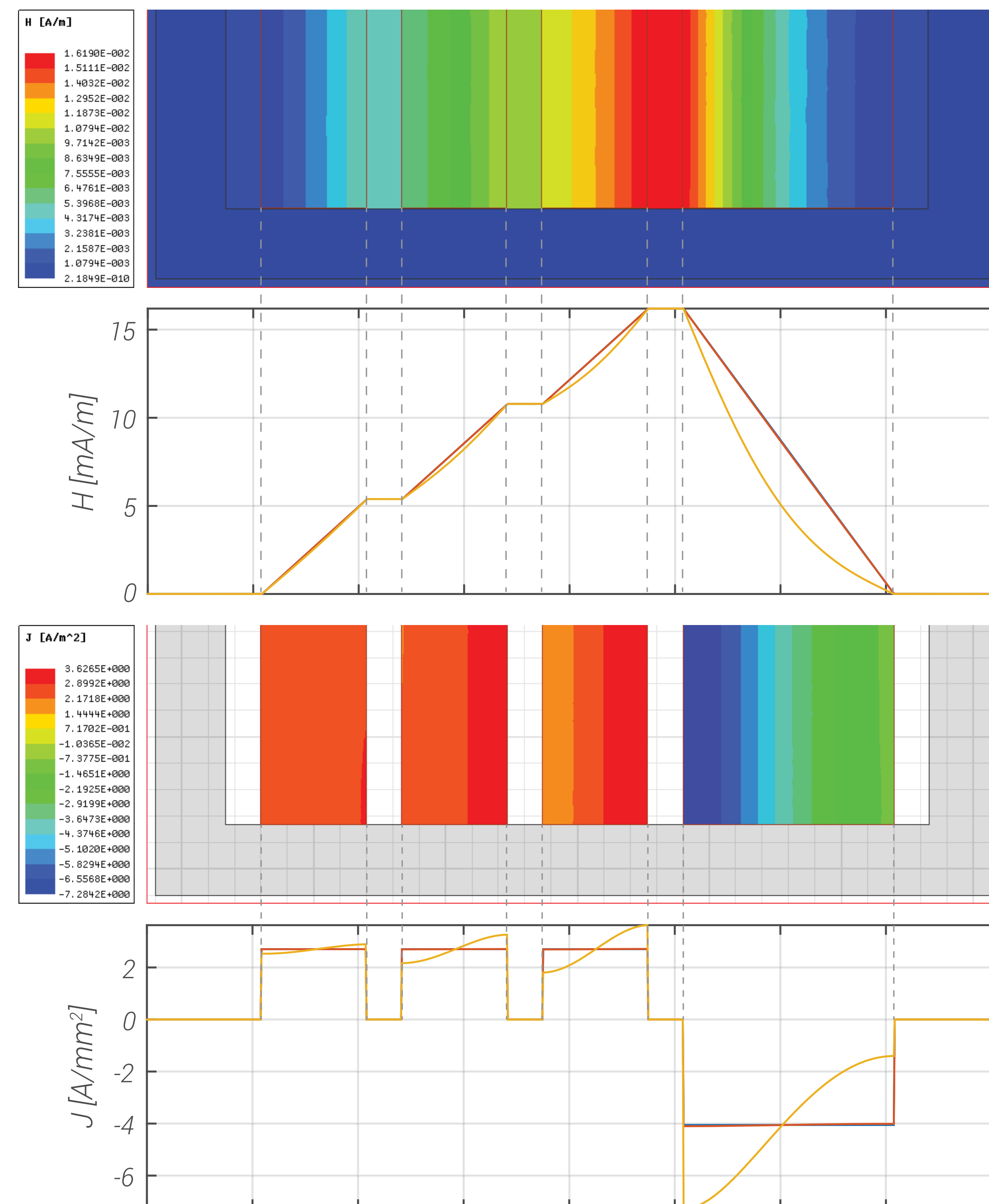
## Example of the Foil Winding MFT Geometry Cross-Section



- 0.1 [Hz] ( $\Delta = 0.01$ )
- 100 [Hz] ( $\Delta = 0.3$ )
- 1000 [Hz] ( $\Delta = 1$ )

\*  $\Delta$  - the penetration ratio

▲ Generic foil winding geometry



▲ H and J distribution within the core window area

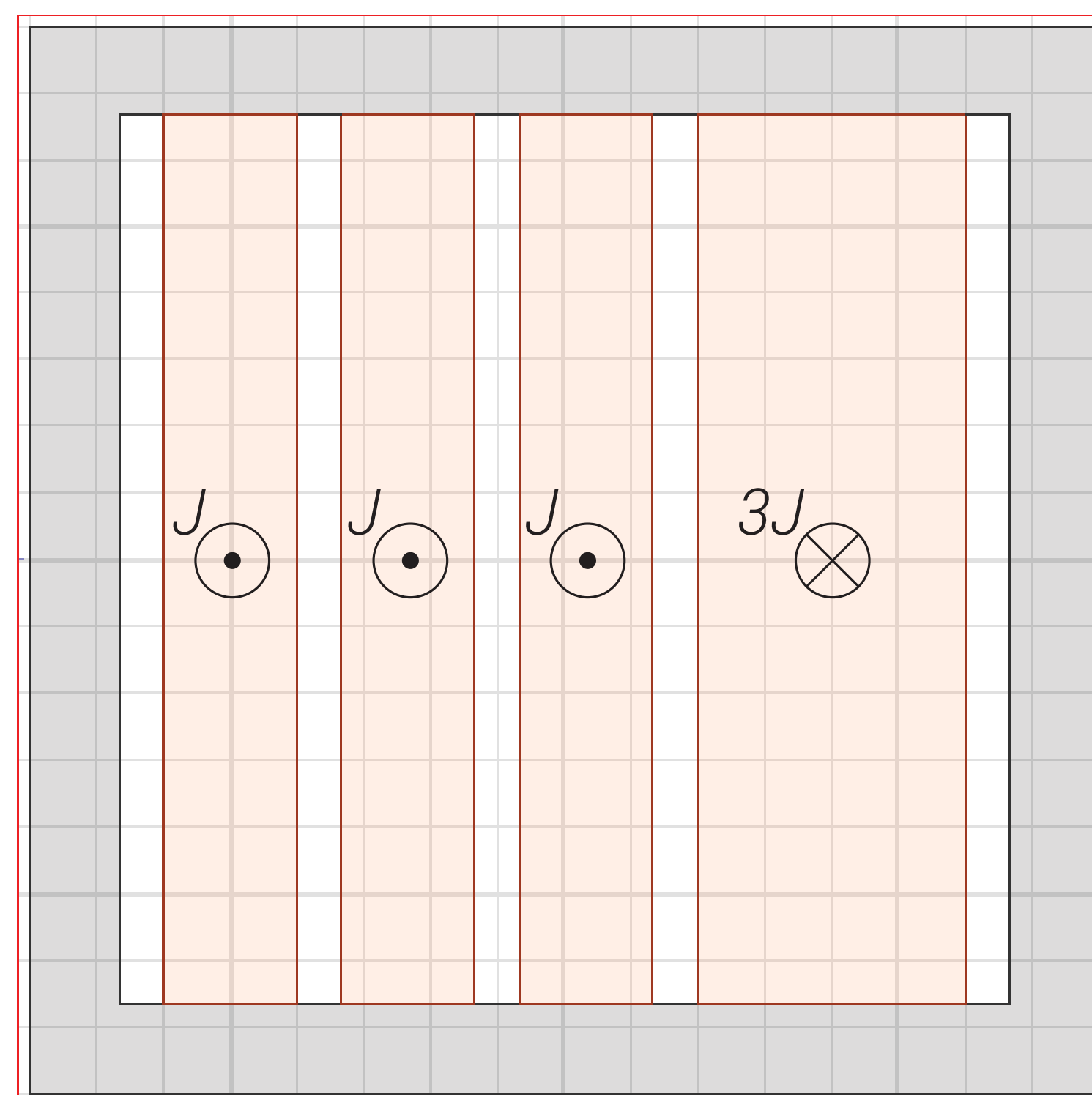


# SKIN AND PROXIMITY EFFECT

## Effects

- ▶ Non-uniform current density
- ▶ Under-utilization of the conductor material
- ▶ Localized H-field distortion within the conductor volume
- ▶ Impact on conduction losses
- ▶ Impact on leakage inductance

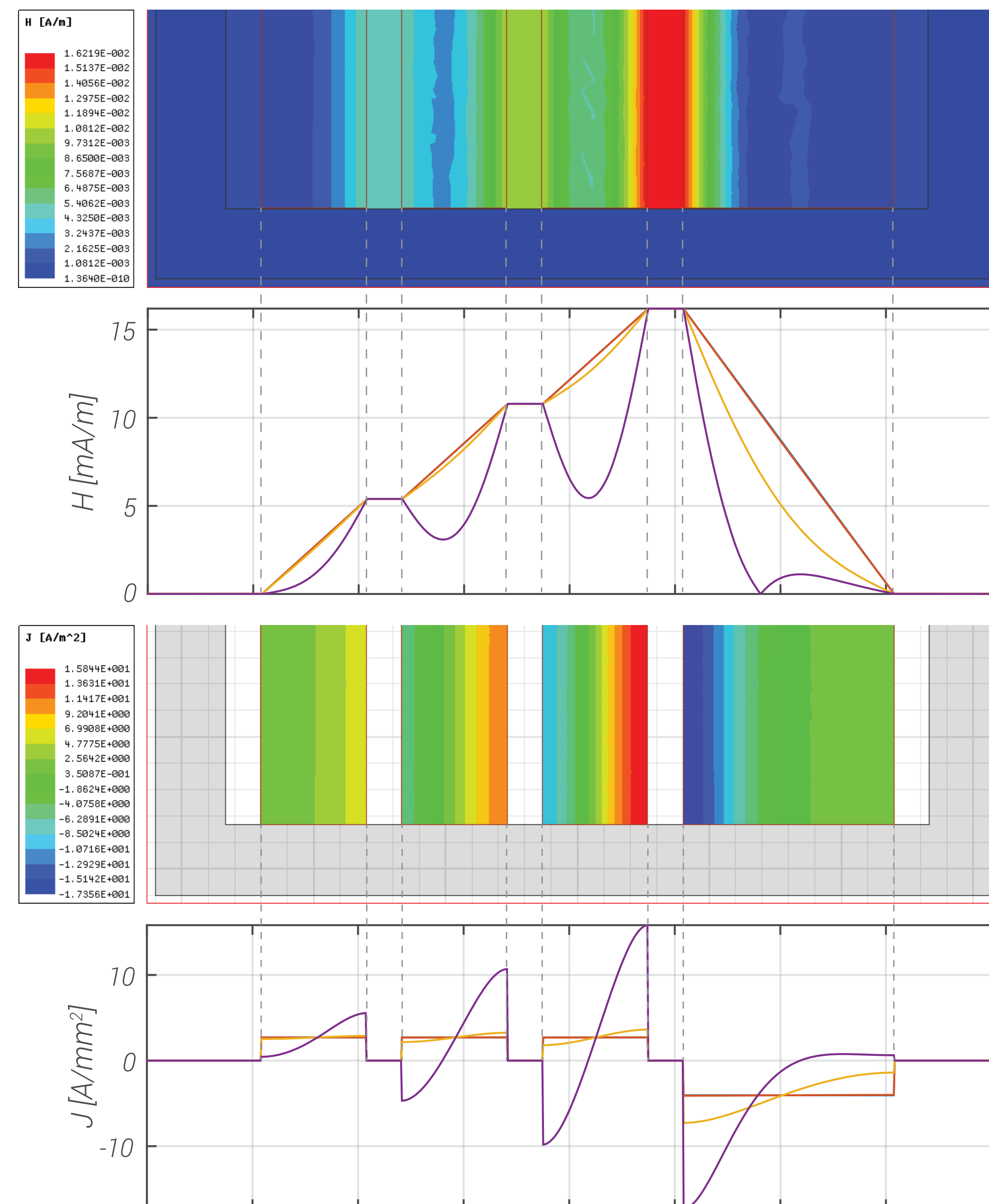
## Example of the Foil Winding MFT Geometry Cross-Section



- 0.1 [Hz] ( $\Delta = 0.01$ )
- 100 [Hz] ( $\Delta = 0.3$ )
- 1000 [Hz] ( $\Delta = 1$ )
- 5000 [Hz] ( $\Delta = 2.15$ )

\*  $\Delta$  - the penetration ratio

▲ Generic foil winding geometry



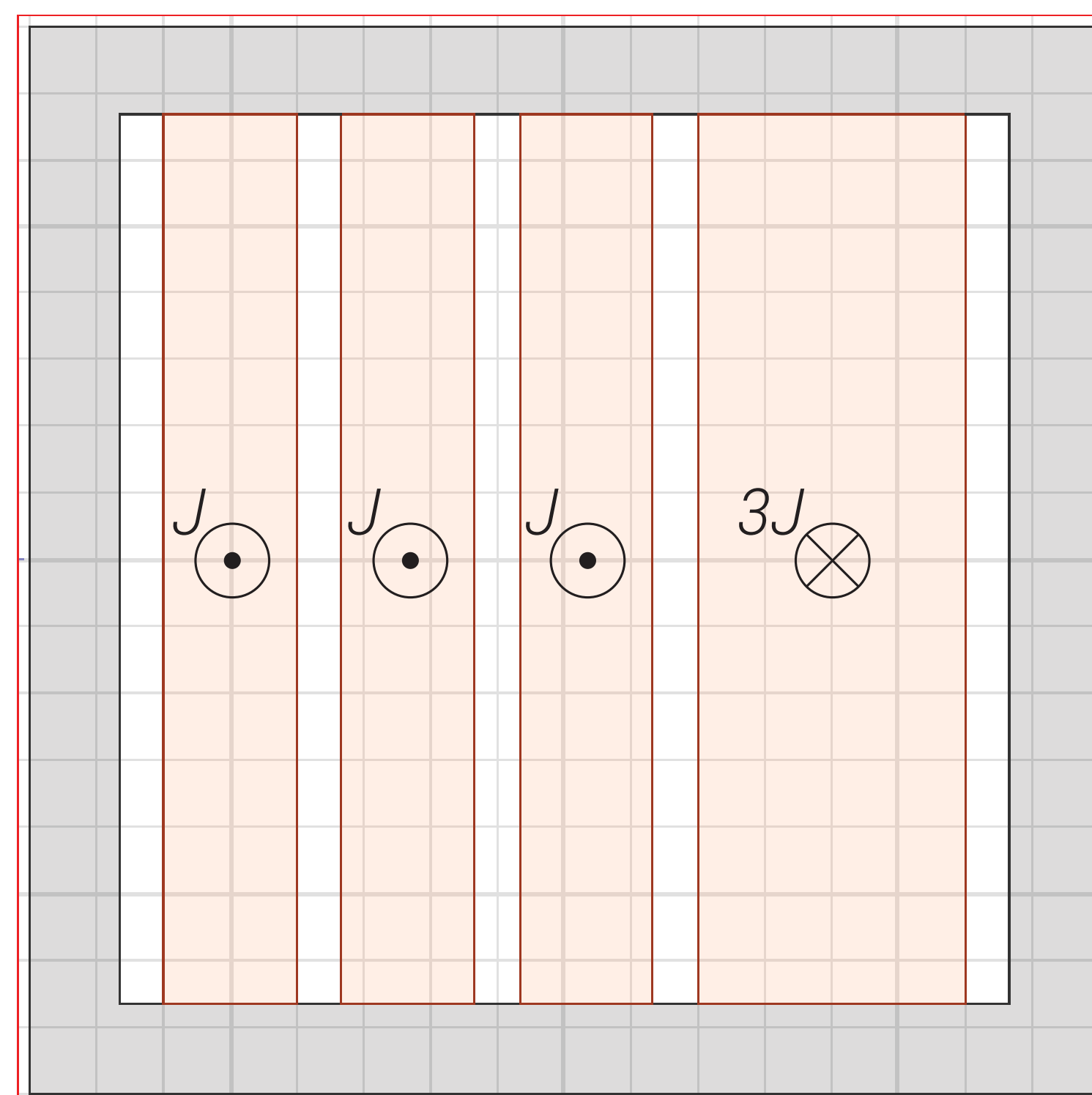
▲ H and J distribution within the core window area

# SKIN AND PROXIMITY EFFECT

## Effects

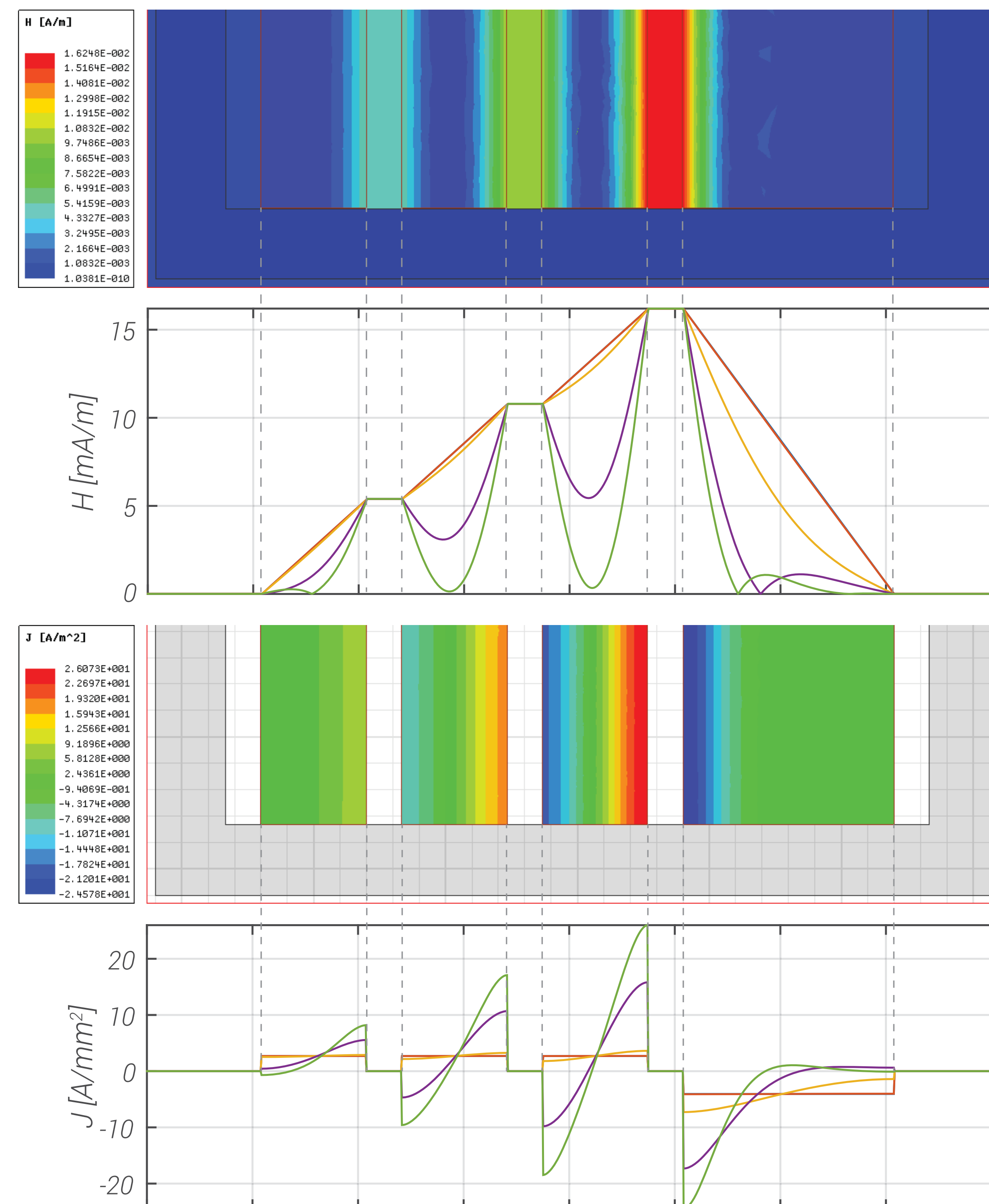
- ▶ Non-uniform current density
- ▶ Under-utilization of the conductor material
- ▶ Localized H-field distortion within the conductor volume
- ▶ Impact on conduction losses
- ▶ Impact on leakage inductance

## Example of the Foil Winding MFT Geometry Cross-Section



- 0.1 [Hz] ( $\Delta = 0.01$ )
  - 100 [Hz] ( $\Delta = 0.3$ )
  - 1000 [Hz] ( $\Delta = 1$ )
  - 5000 [Hz] ( $\Delta = 2.15$ )
  - 10000 [Hz] ( $\Delta = 3$ )
- \*  $\Delta$  - the penetration ratio

▲ Generic foil winding geometry



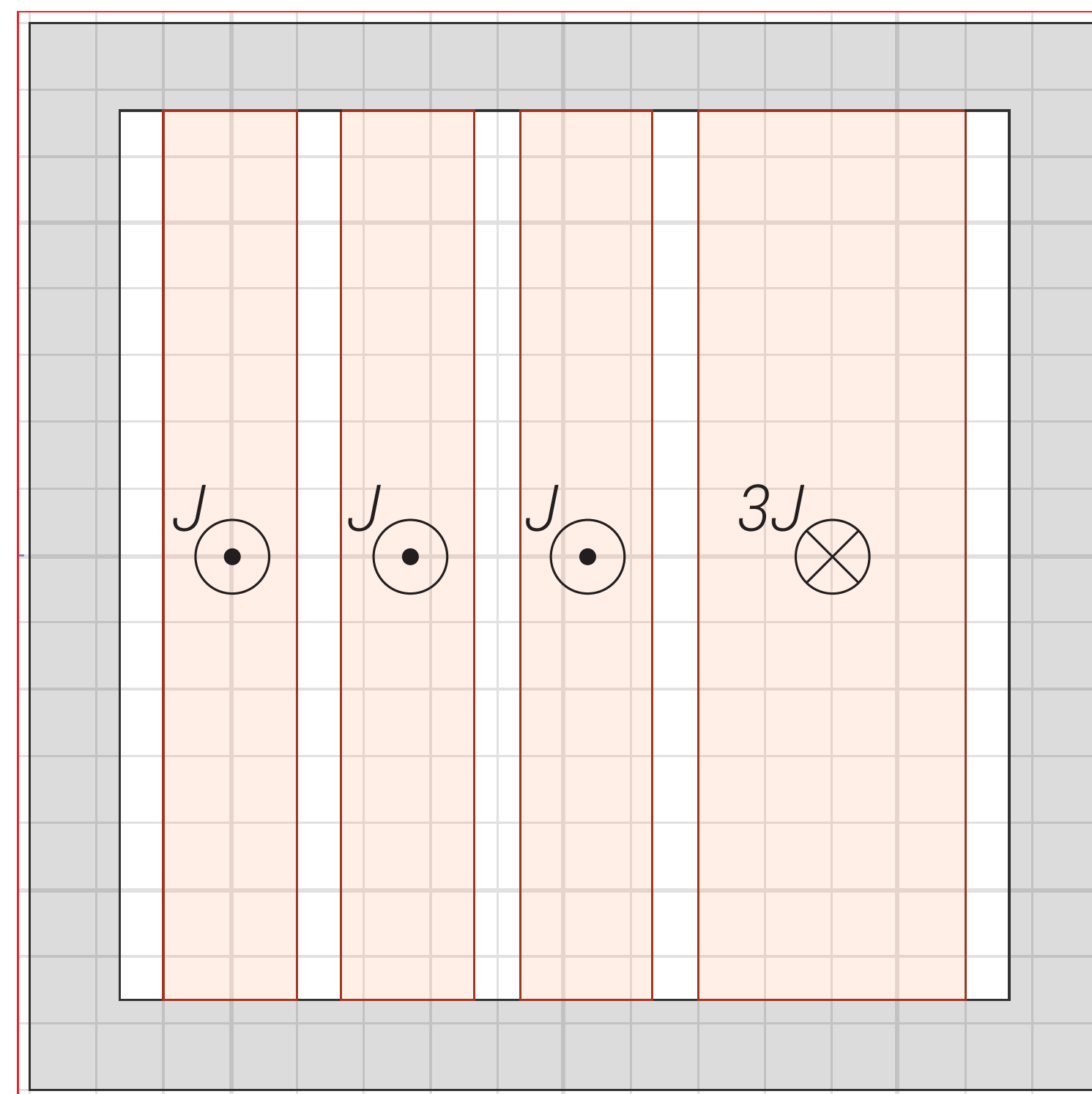
▲ H and J distribution within the core window area

# SKIN AND PROXIMITY EFFECT

## Effects

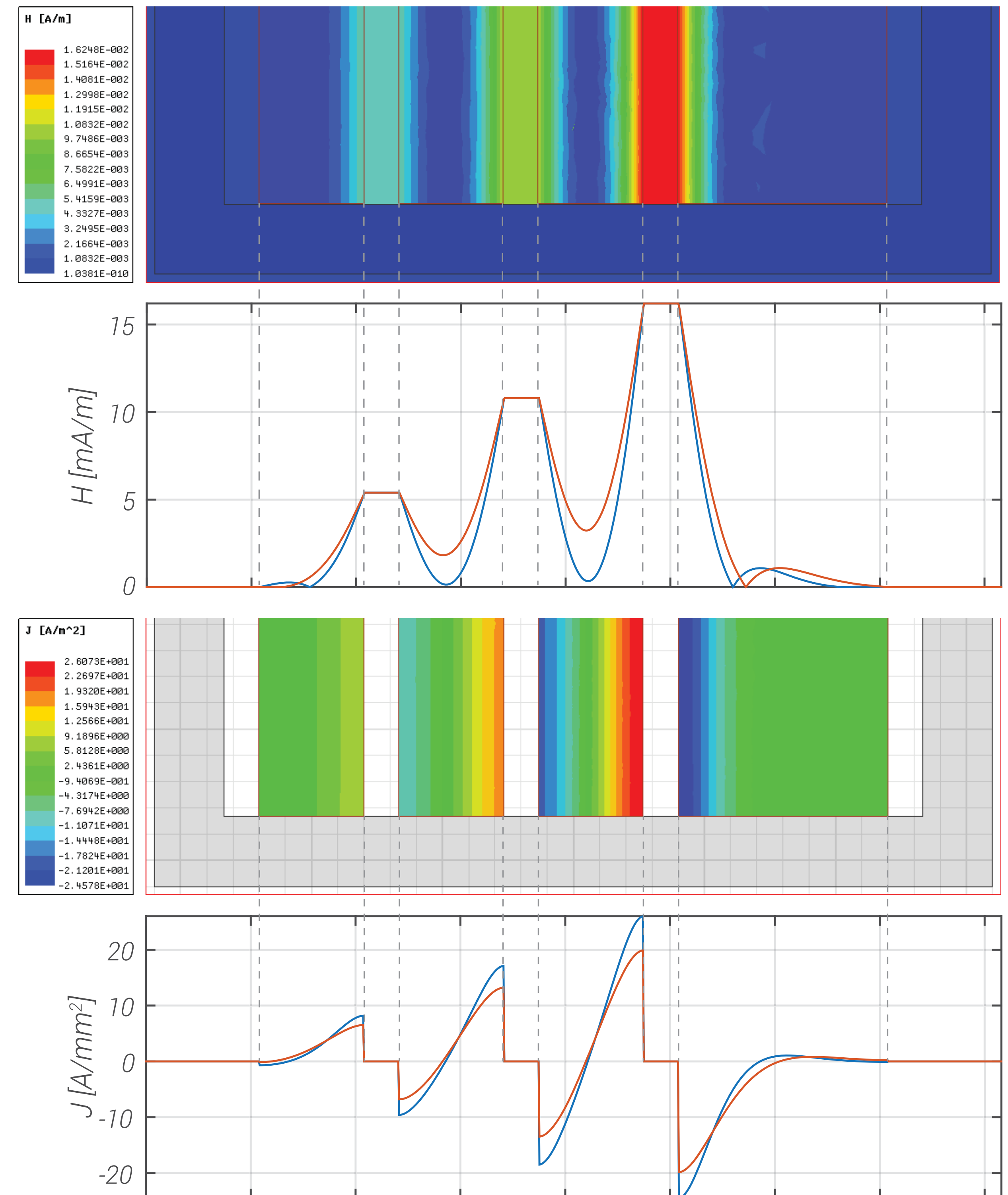
- ▶ Non-uniform current density
- ▶ Under-utilization of the conductor material
- ▶ Localized H-field distortion within the conductor volume
- ▶ Impact on conduction losses
- ▶ Impact on leakage inductance

## Example of the Foil Winding MFT Geometry Cross-Section



— 10000 [Hz] (Cu)  
 — 10000 [Hz] (Al)

▲ Generic foil winding geometry

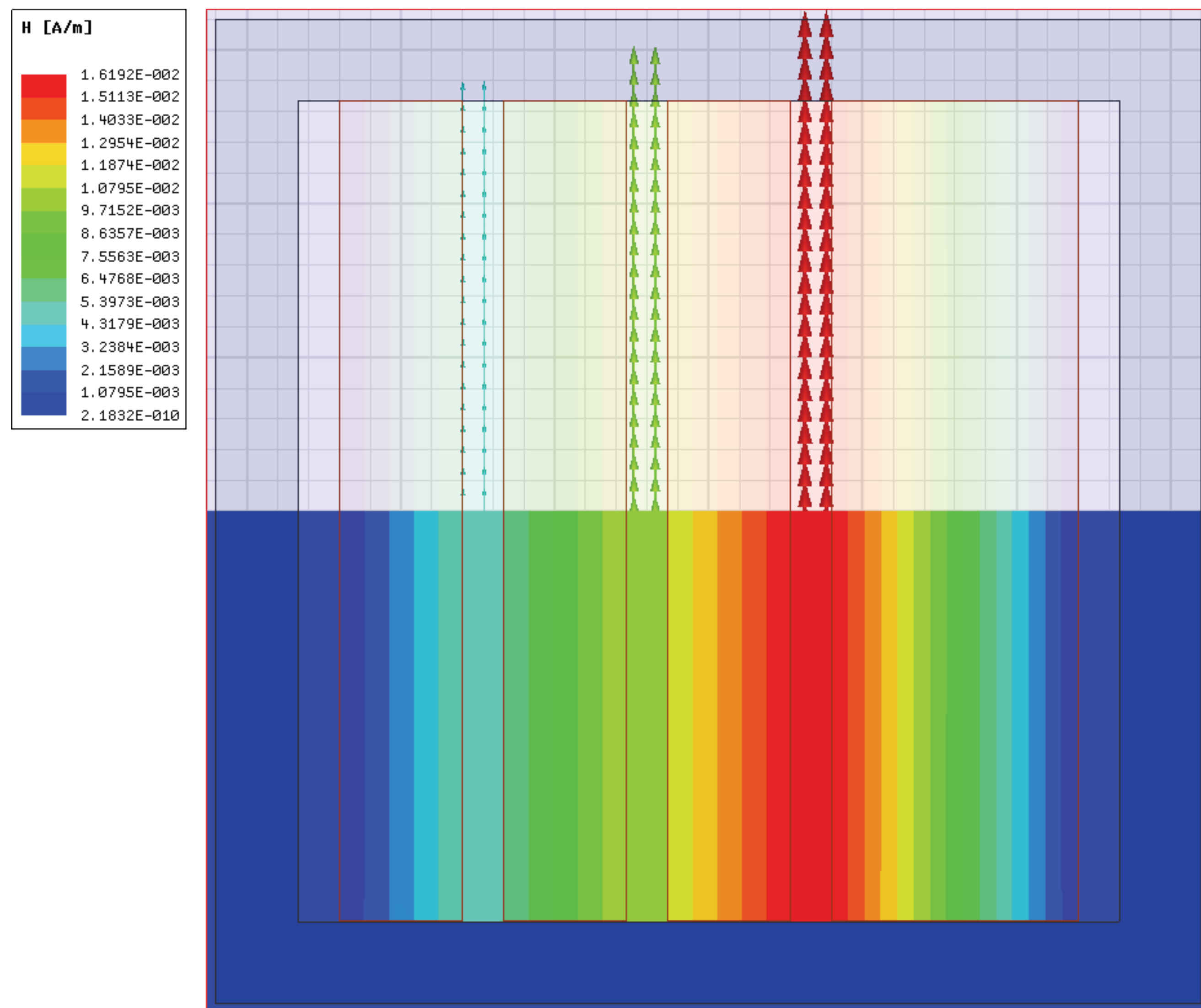


▲ H and J distribution within the core window area

# EDGE EFFECT

## MFT with fully filled core window height

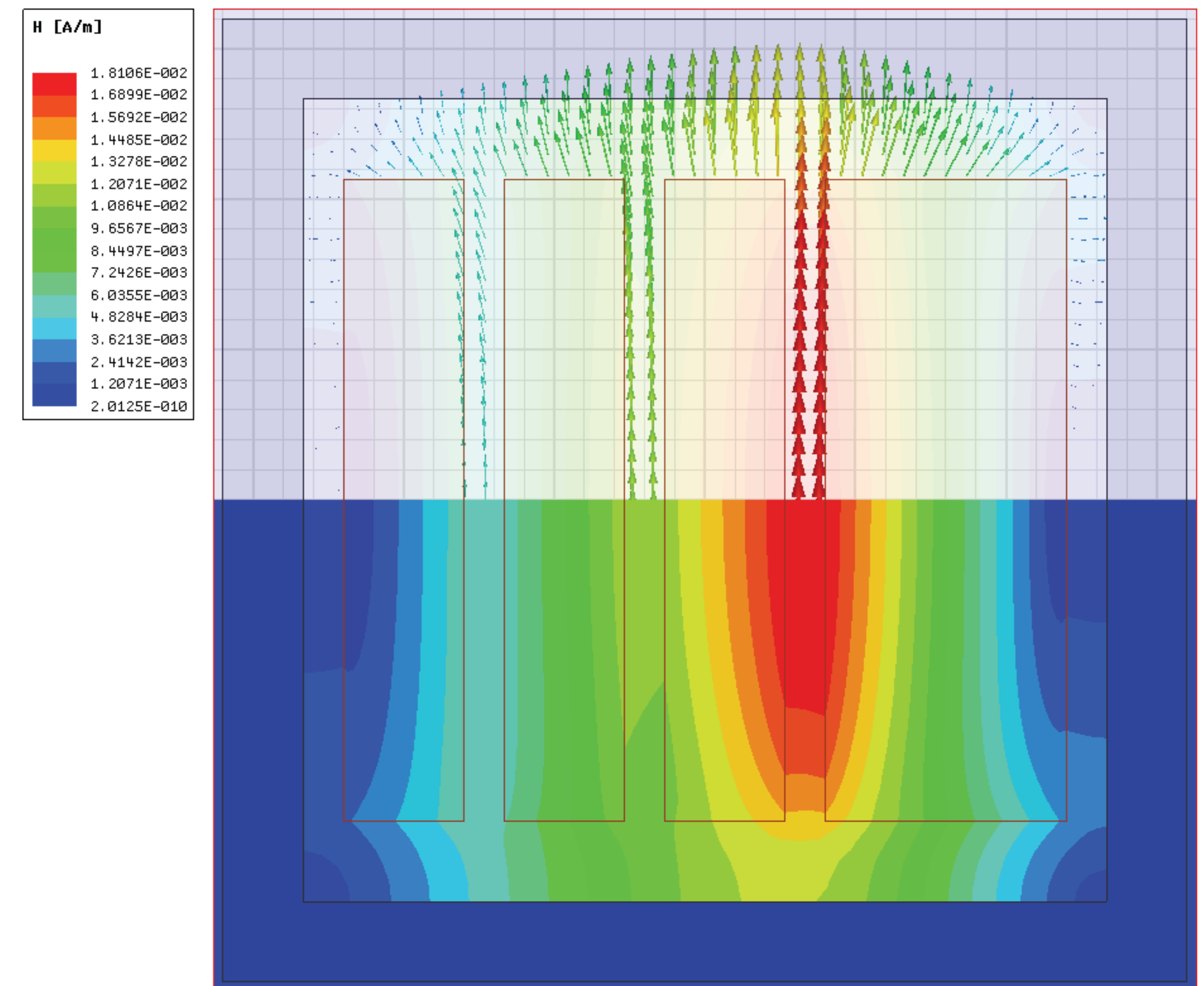
- ▶ Only  $H_y$  component exists
- ▶  $H$  field is tangential to the foil surface



▲ Fully utilized core window height

## MFT with 80% filled core window height

- ▶ Both  $H_x$  and  $H_y$  components exist
- ▶  $H$  field is not tangential to the foil surface



▲ Partially utilized core window height

# THERMAL COORDINATION

## MFT Losses:

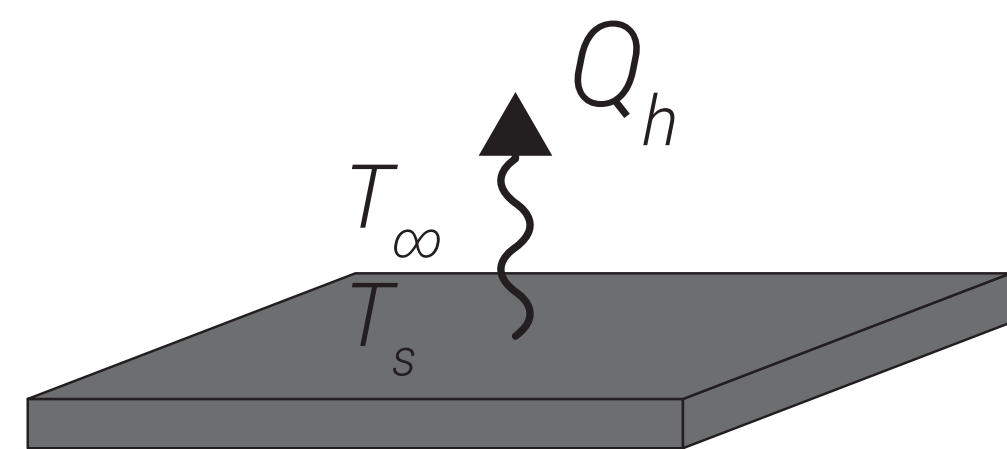
- ▶ Winding Losses
- ▶ Core Losses

## Heat Transfer Mechanisms:

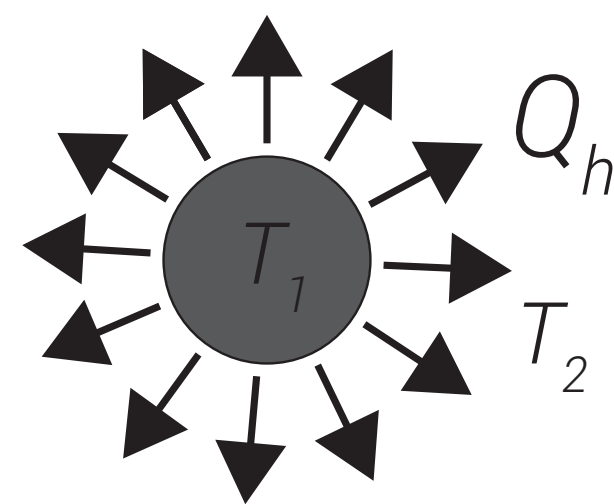
- ▶ Conduction



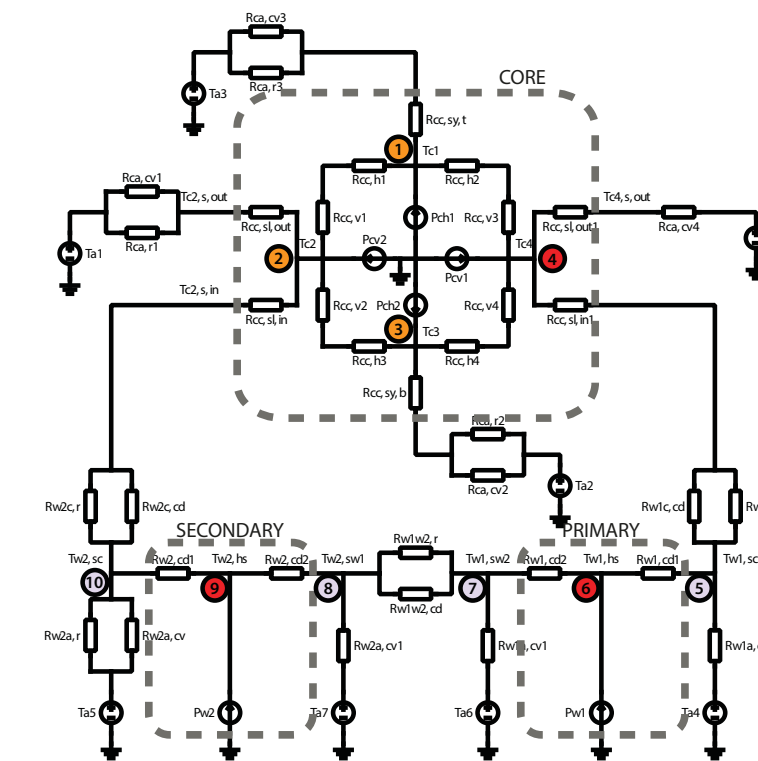
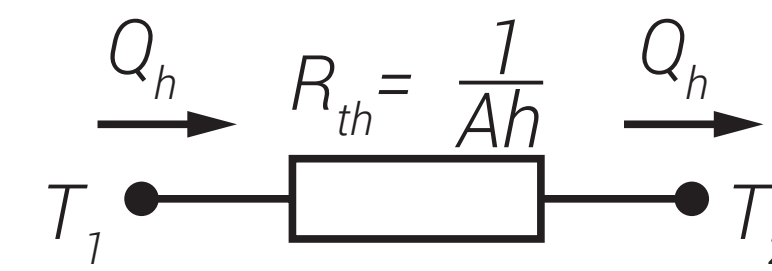
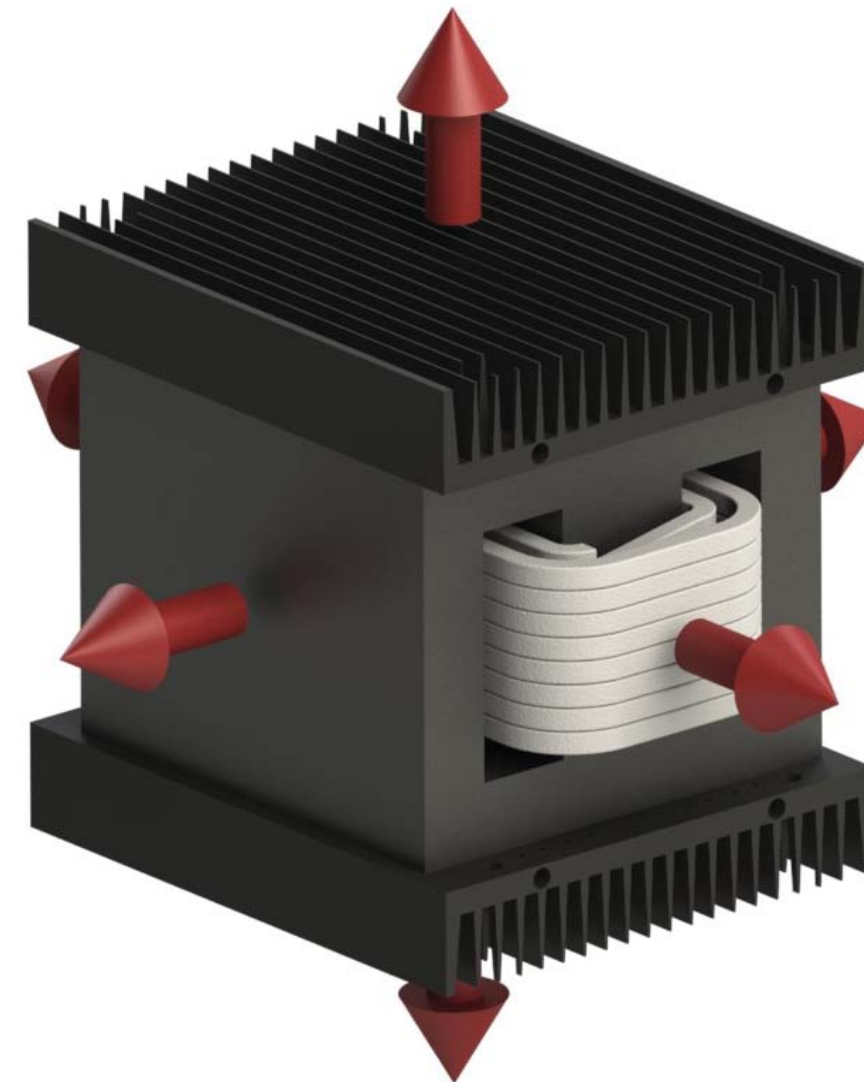
- ▶ Convection



- ▶ Radiation



## Qualitative Analysis:



- ▶ Heat transfer

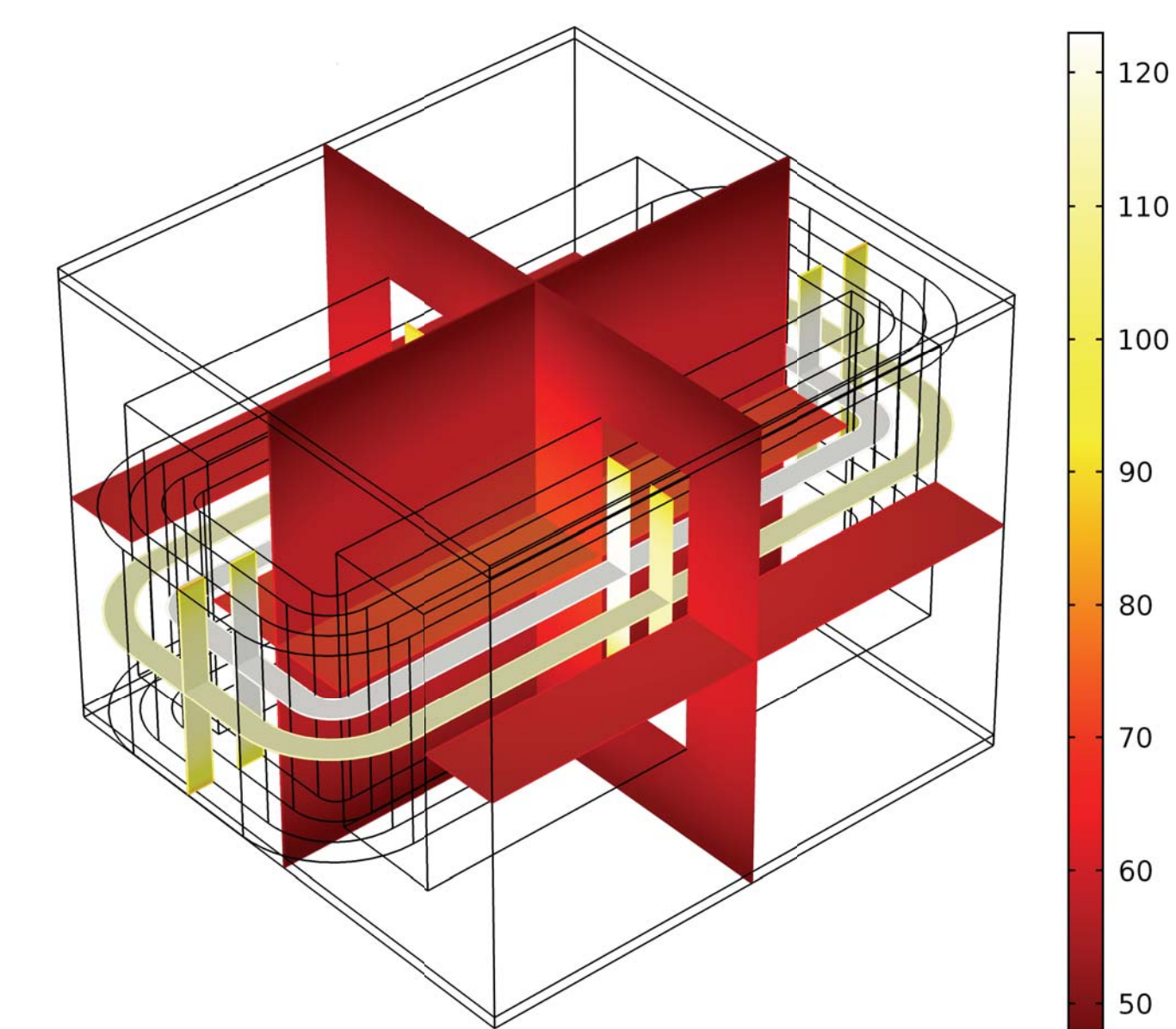
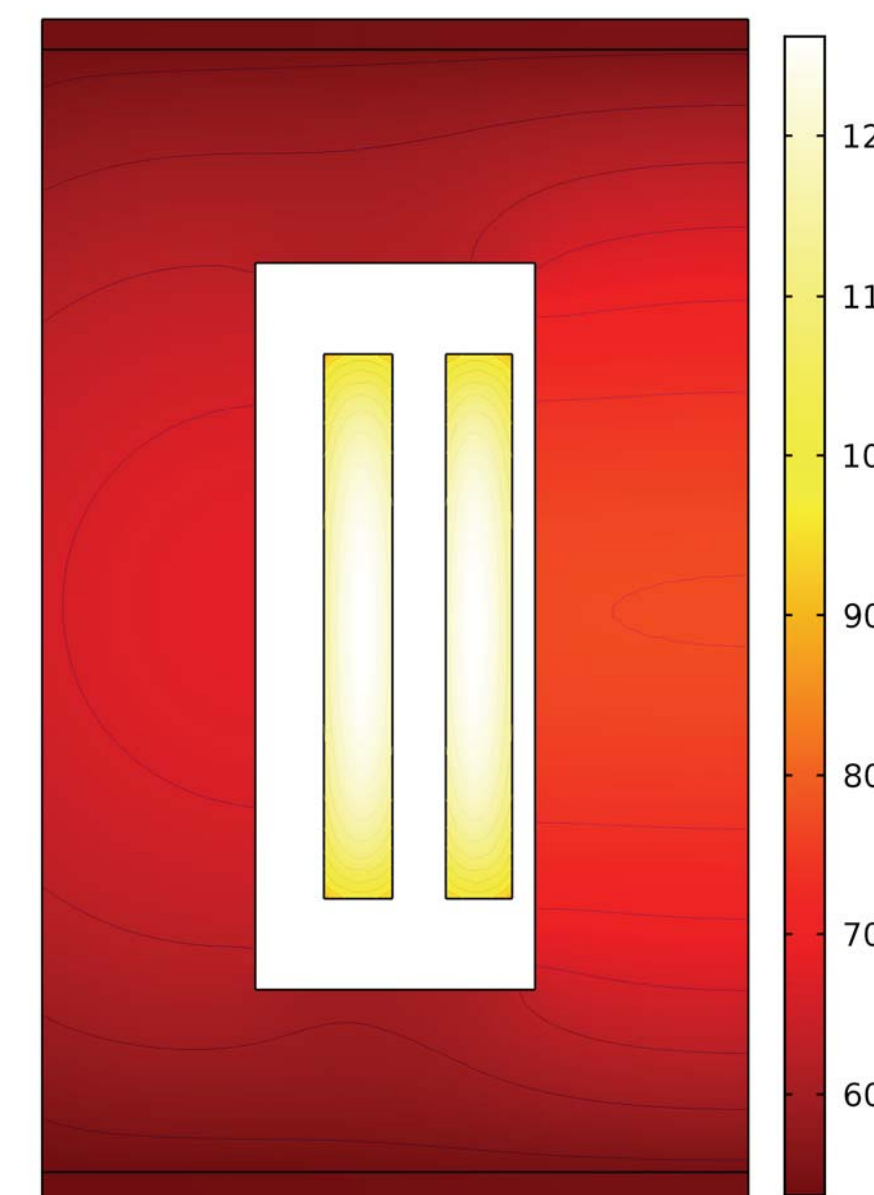
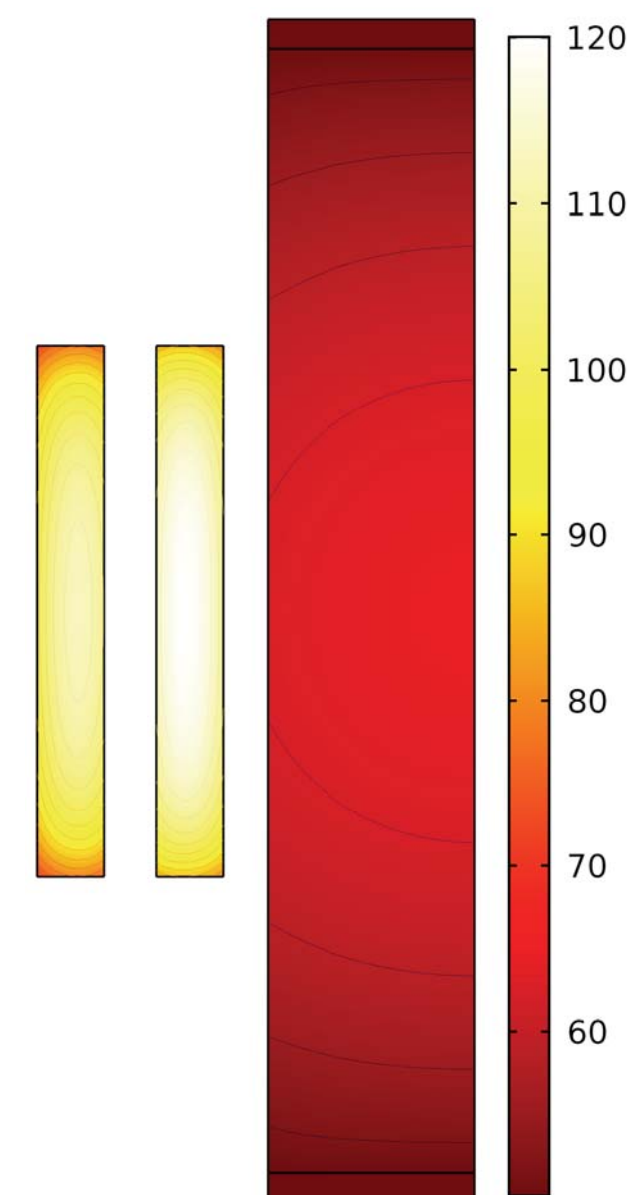
$$Q_h = hA\Delta T$$

- ▶ Temperature gradient

$$\Delta T = \frac{Q_h}{hA}$$

- ▶ Size decrease ( $A \searrow$ ) implies  $\Delta T \nearrow$

## Temperature Distribution Example:



# THERMAL COORDINATION (CONT.)

## Core Materials:

- ▶ Thermal conductivity varies from  $4Wm/K$  (ferrites) to  $8.35Wm/K$  (Nanocrystalline)
- ▶ Isotropic thermal conductivity (e.g. ferrites)
- ▶ Anisotropic thermal conductivity (laminated cores e.g. Nanocrystalline)



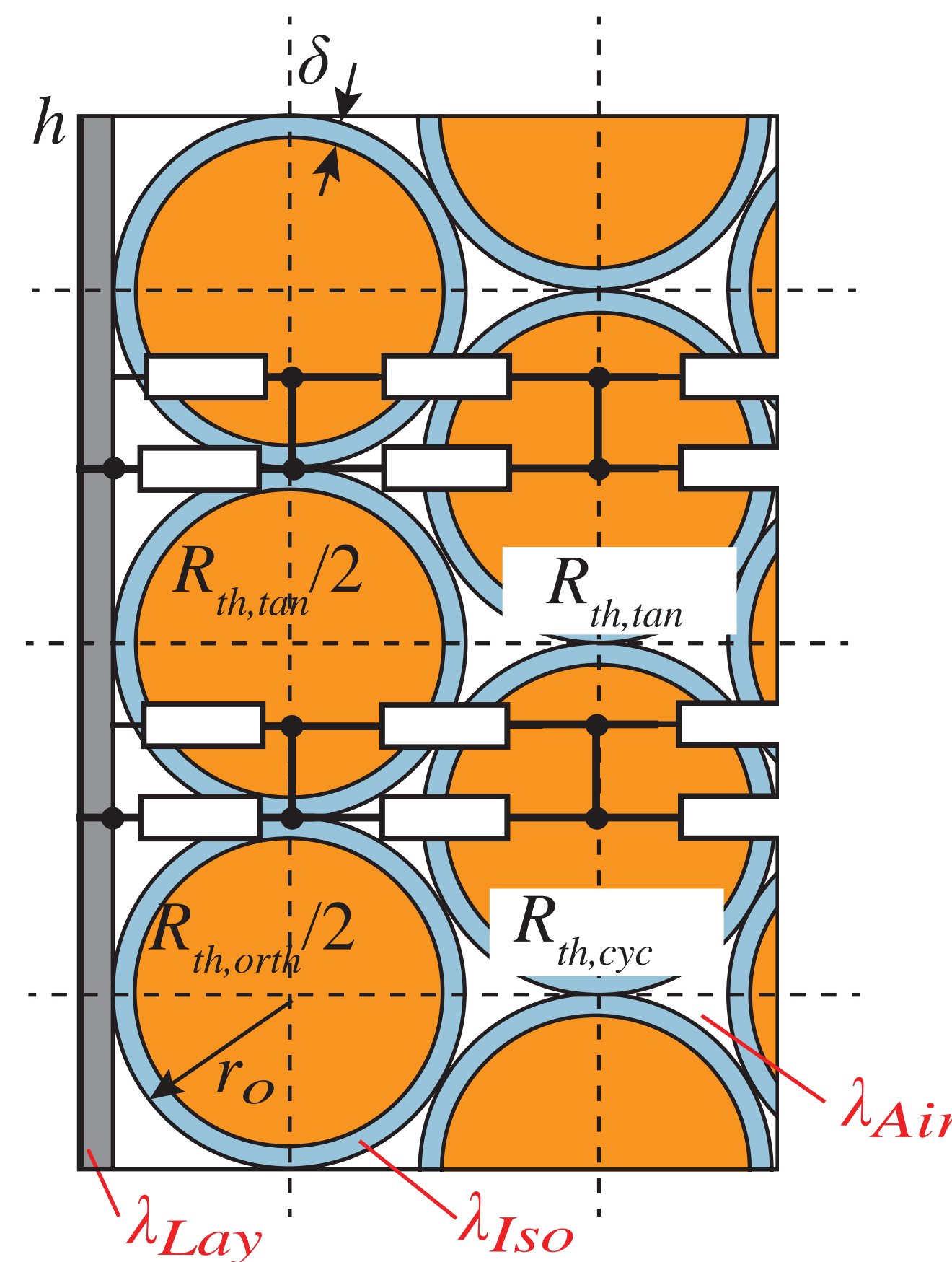
▲ Ferrite core - Isotropic



▲ Metglas core - Anisotropic

## Windings:

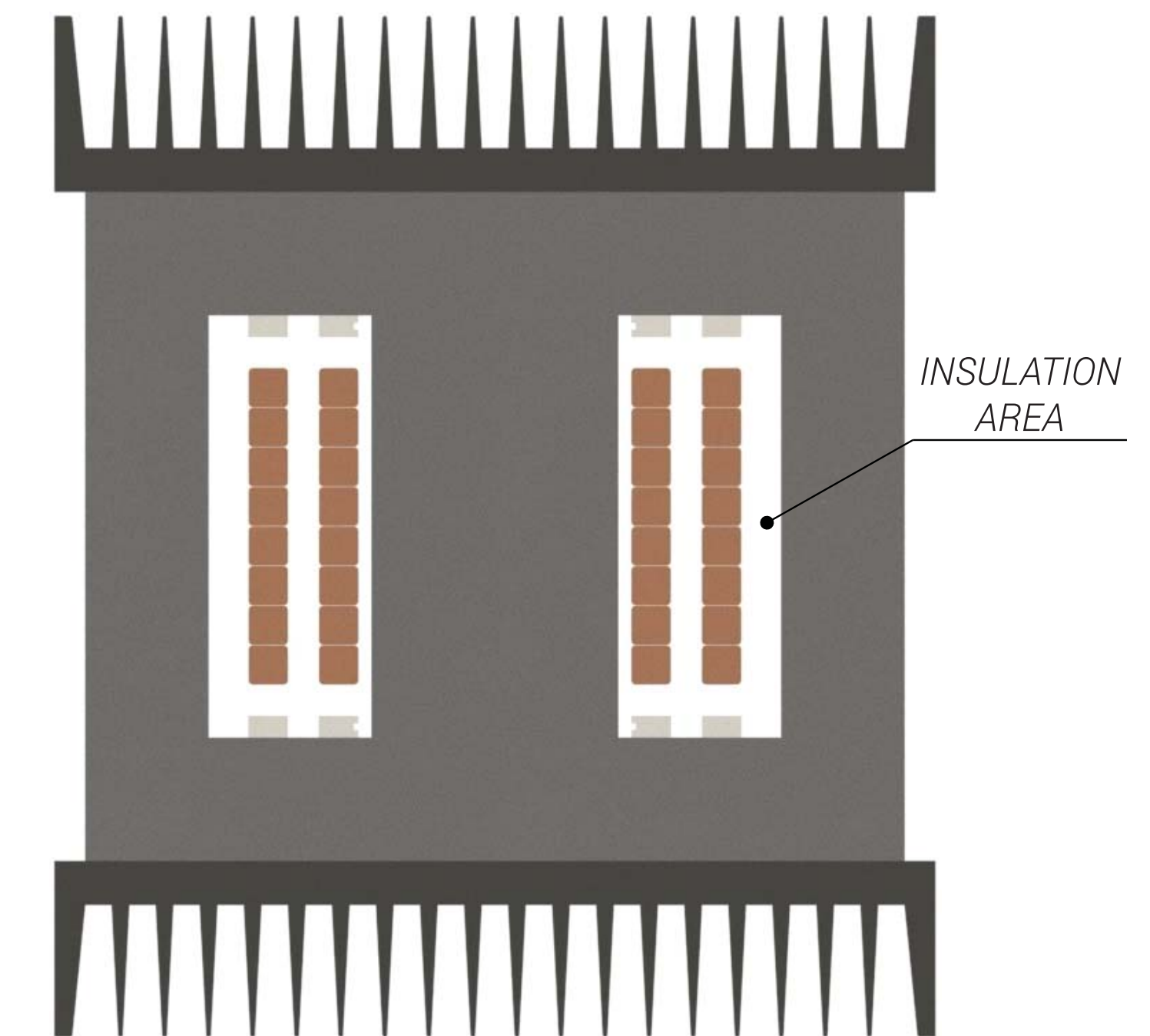
- ▶ Copper and Aluminum conductors combined with insulation
- ▶ Low  $R_{th}$  along the conductor path due to low  $R_{th}$  of Cu and Al
- ▶ High  $R_{th}$  in radial direction due to layers of insulation with high  $R_{th}$



▲ Cross section of a round wire winding [9]

## Winding insulation and cooling:

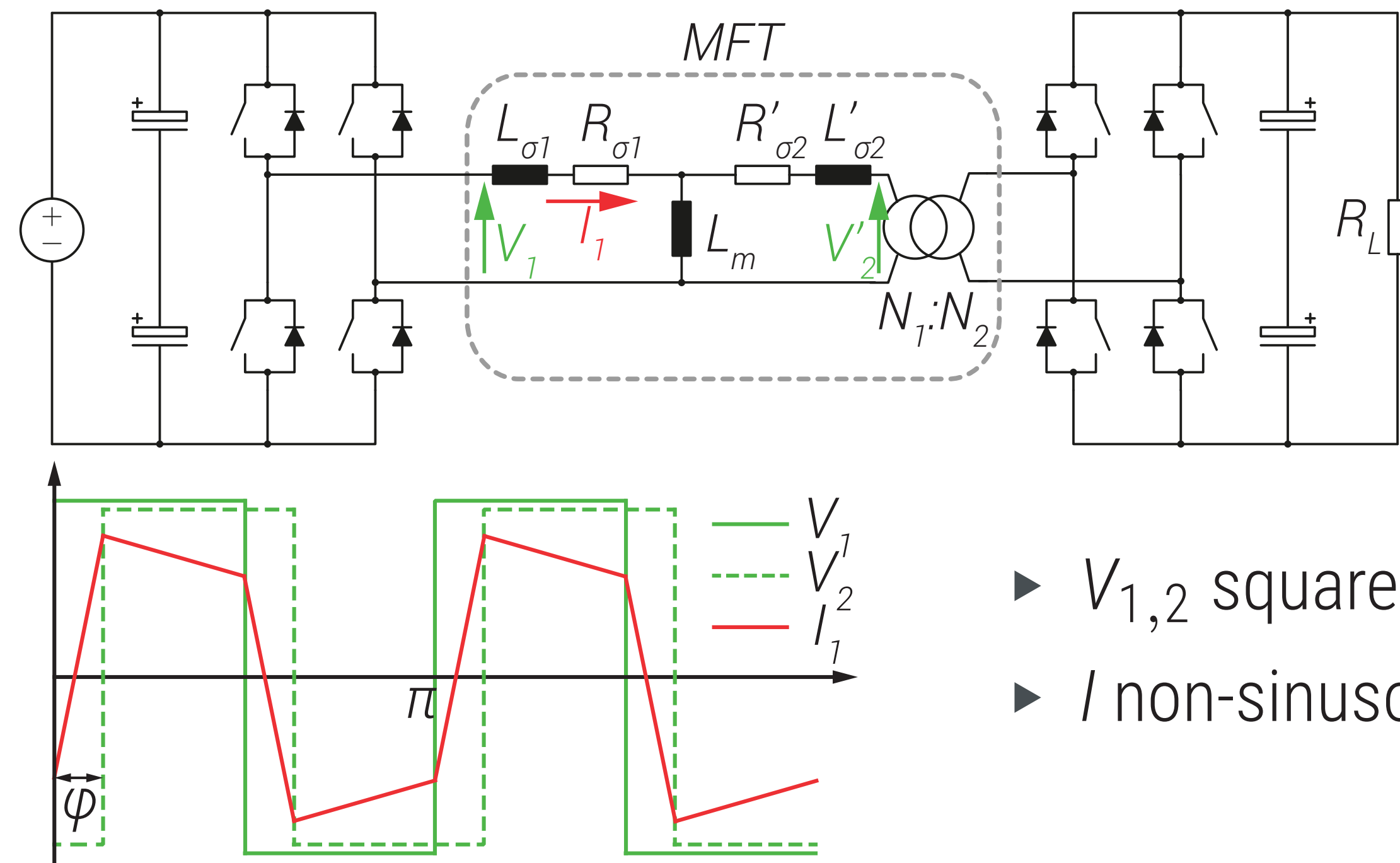
- ▶ Much higher insulation level requirement than within the winding insulation
- ▶ Good insulators have very low thermal conductivity (solid or fluid)
- ▶ Fluid based insulation provides much better cooling due to convection



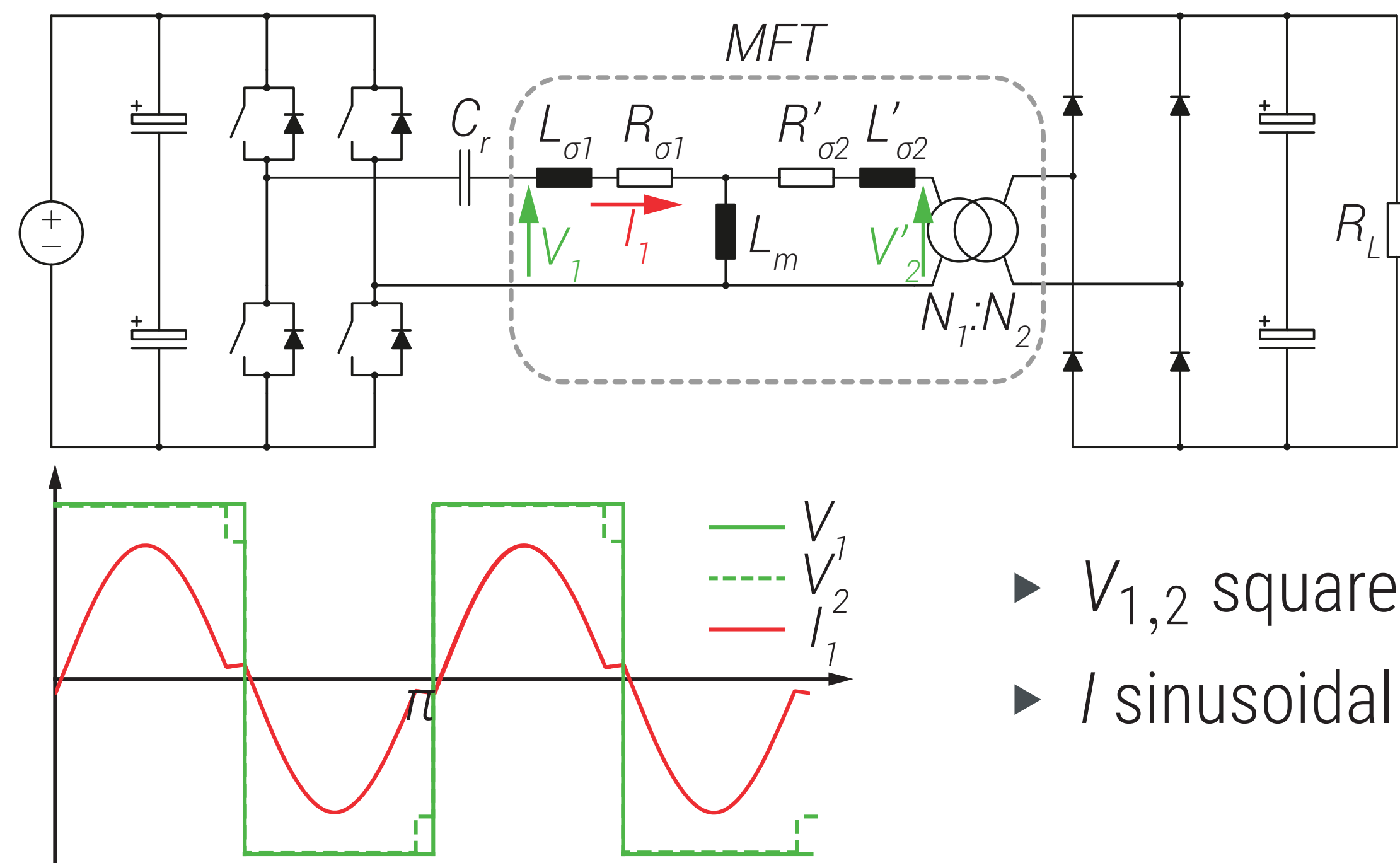
▲ MFT cross section area

# NONSINUSOIDAL WAVEFORMS

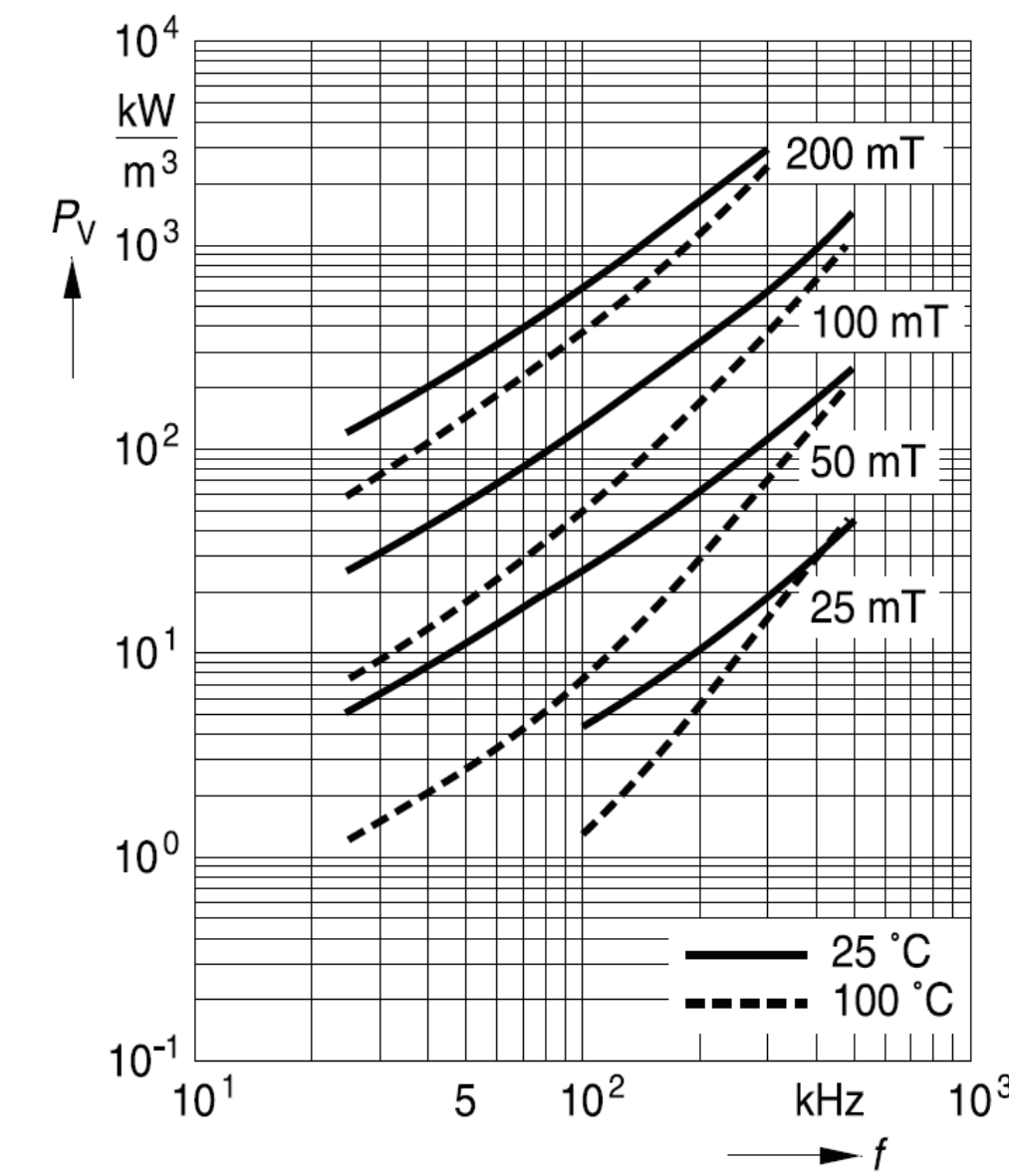
## DAB Converter:



## Series Resonant Converter:



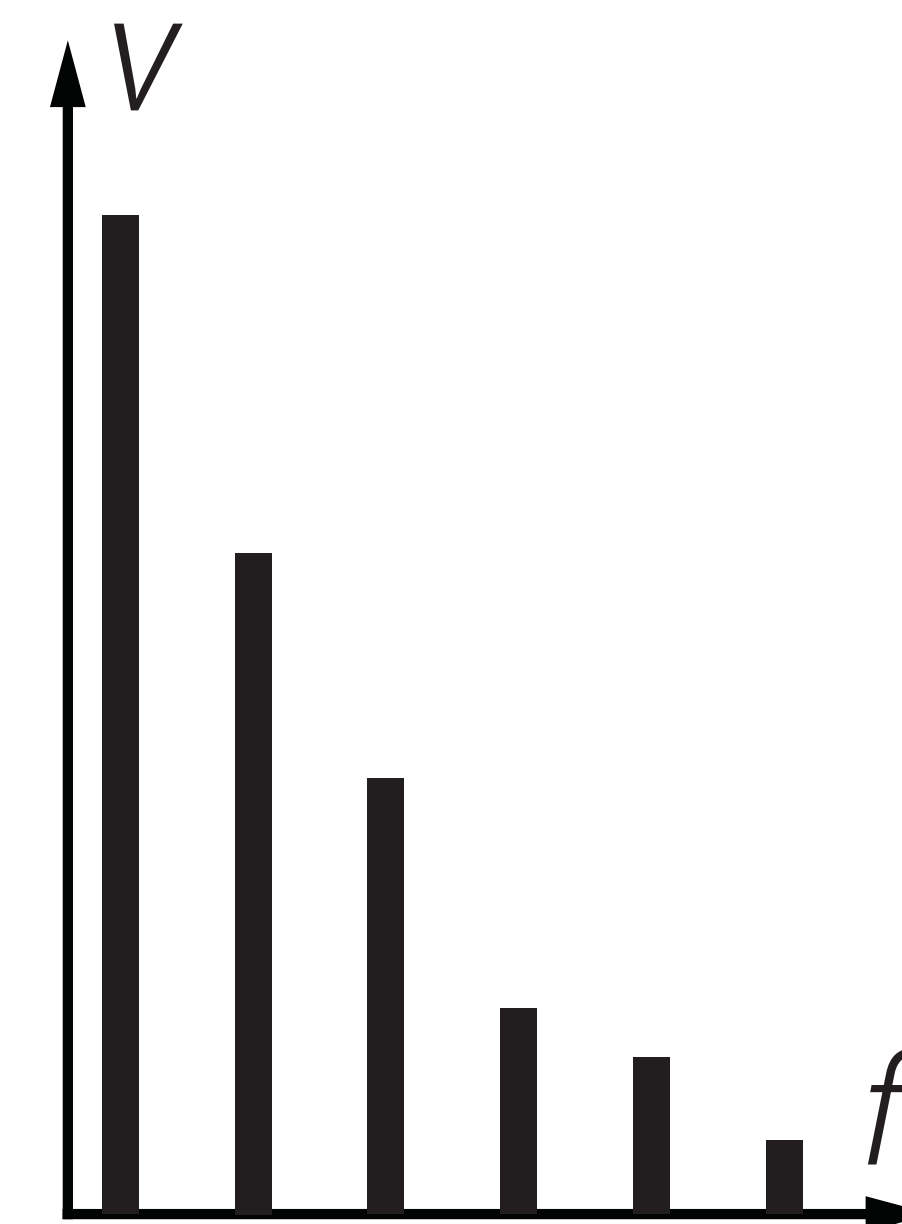
## Core Losses:



▲ AC core losses

- ▶ Data-sheet data is for sinusoidal excitation
- ▶ Derived Steinmetz coefficients describe sinusoidal excitation losses
- ▶ Core is excited with square pulses
- ▶ Losses are effected
- ▶ Generalization of Steinmetz model

## Winding Losses:

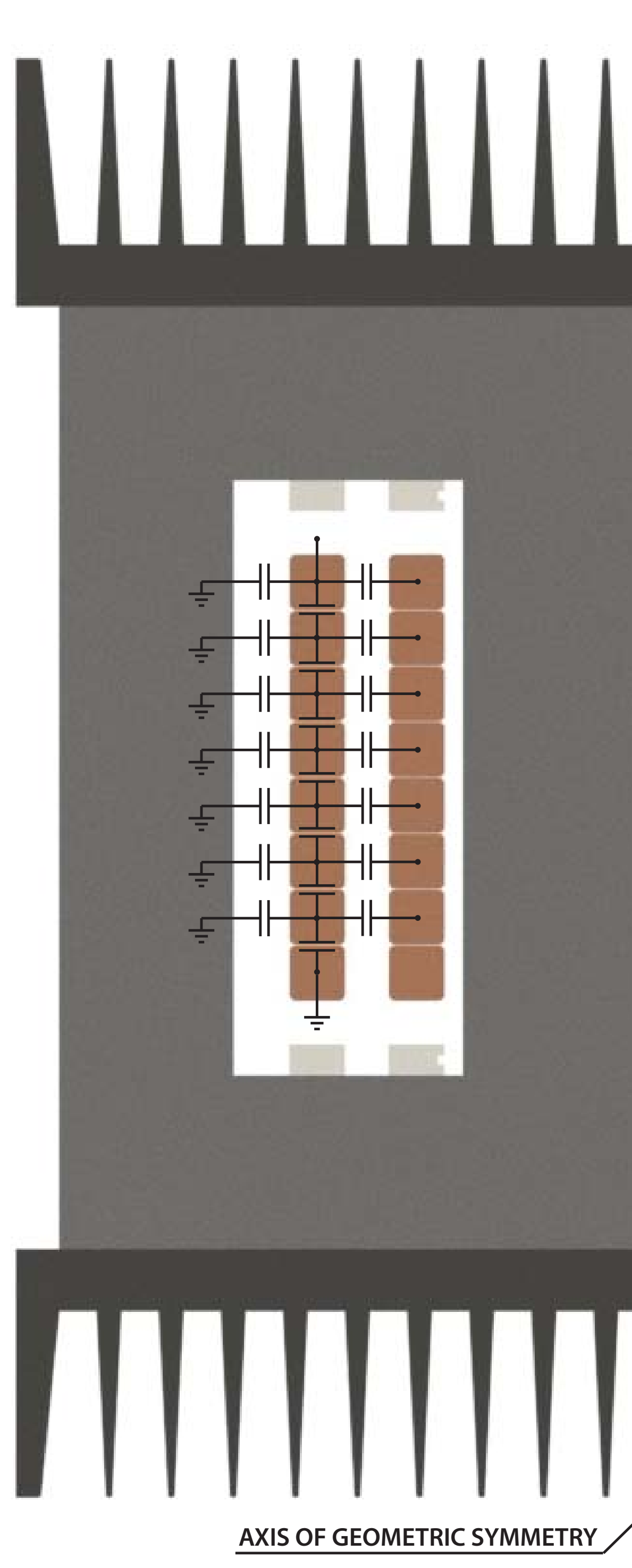


▲ Harmonics

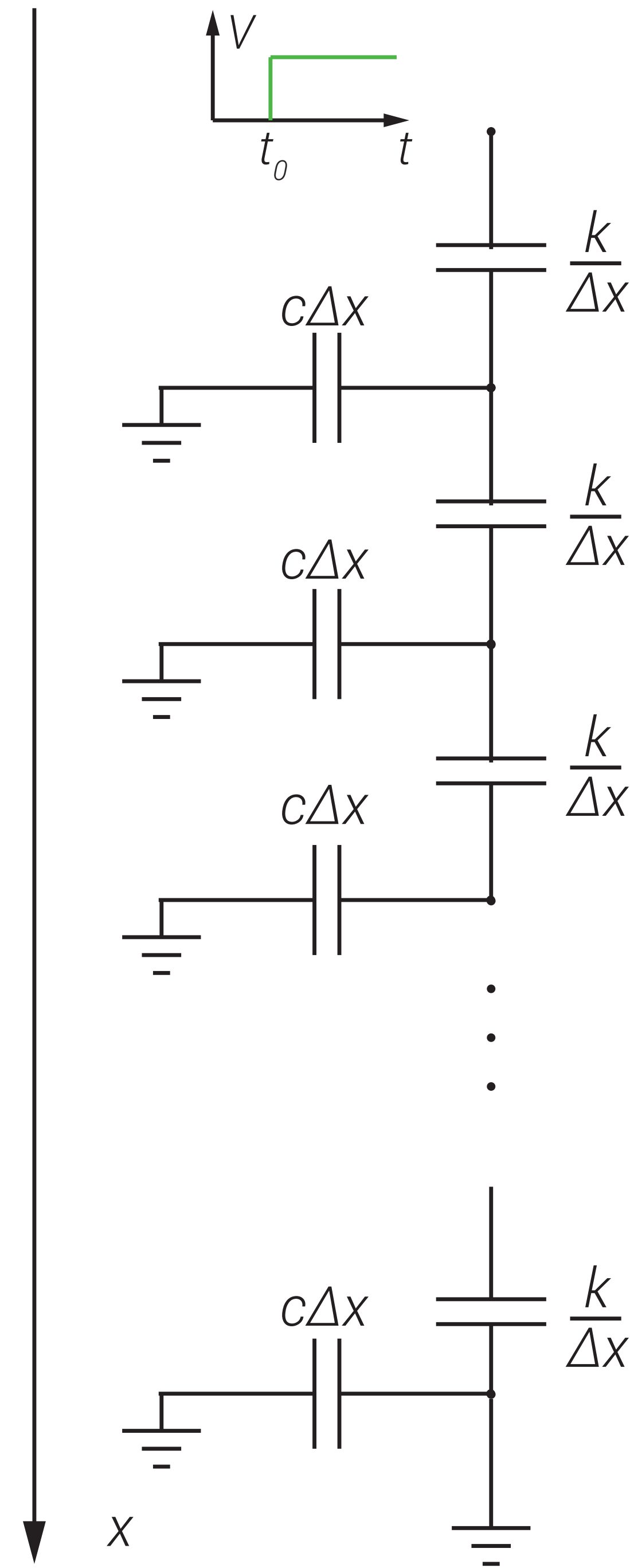
- ▶ Current waveform impacts the winding losses
- ▶ Copper is a linear material
- ▶ Losses can be evaluated in harmonic basis
- ▶ Current harmonic content must be evaluated
- ▶ Total losses are the sum of the individual harmonic losses

# INSULATION COORDINATION

## MFT Geometry Crosssection:

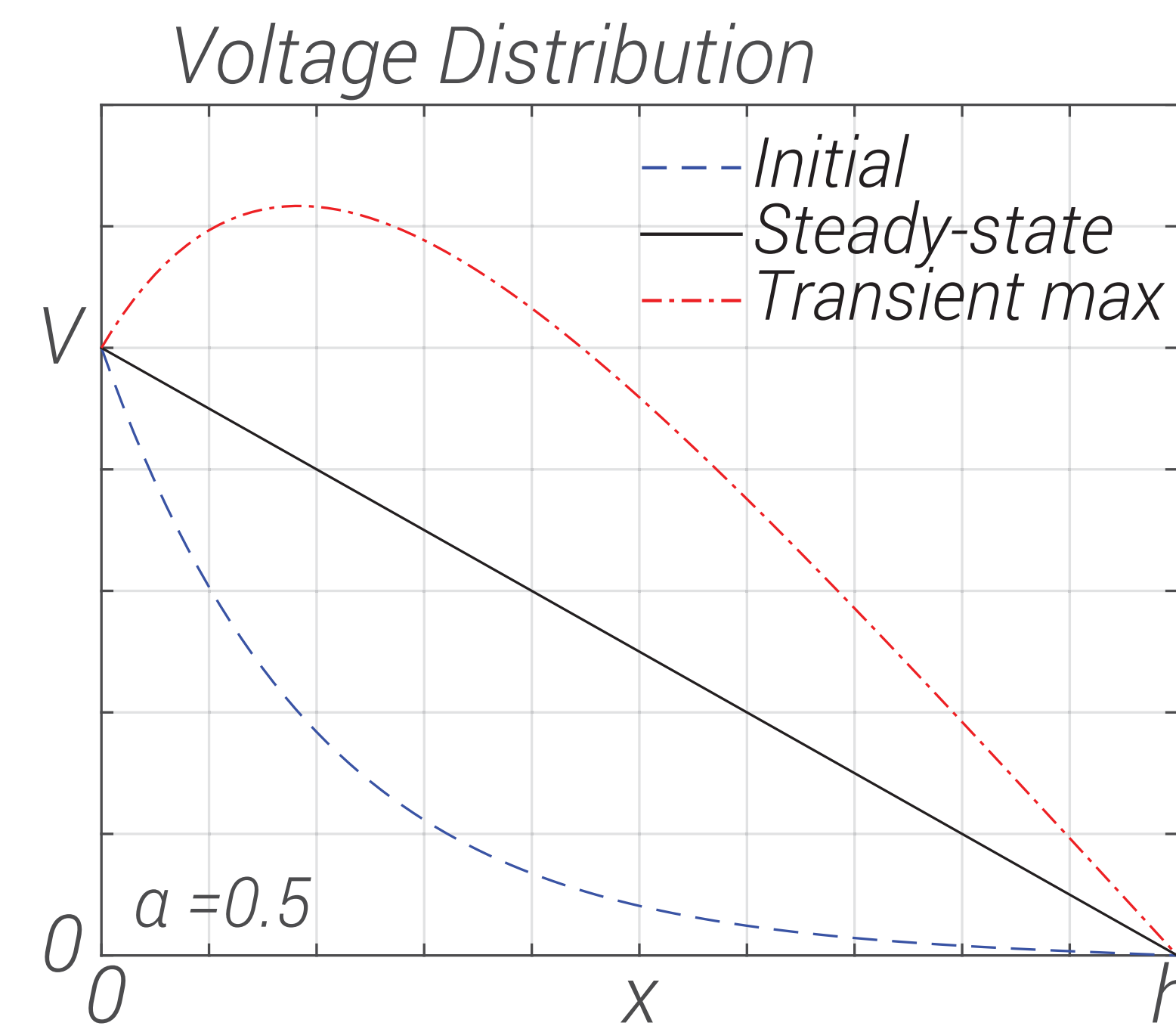


## HF Winding Model:



## MFT Electric Parameters:

- ▶ Parasitic capacitance cannot be neglected for HF
- ▶ Capacitances exist between turns, windings and core
- ▶ For pulse excitation voltage distribution is nonlinear
- ▶ Higher voltage gradient at the winding input than expected
- ▶ Damped oscillatory transient due to turn inductance
- ▶ Higher max voltage than expected during transient
- ▶ Need for overall insulation reinforcement
- ▶ Turn to turn insulation must especially be increased



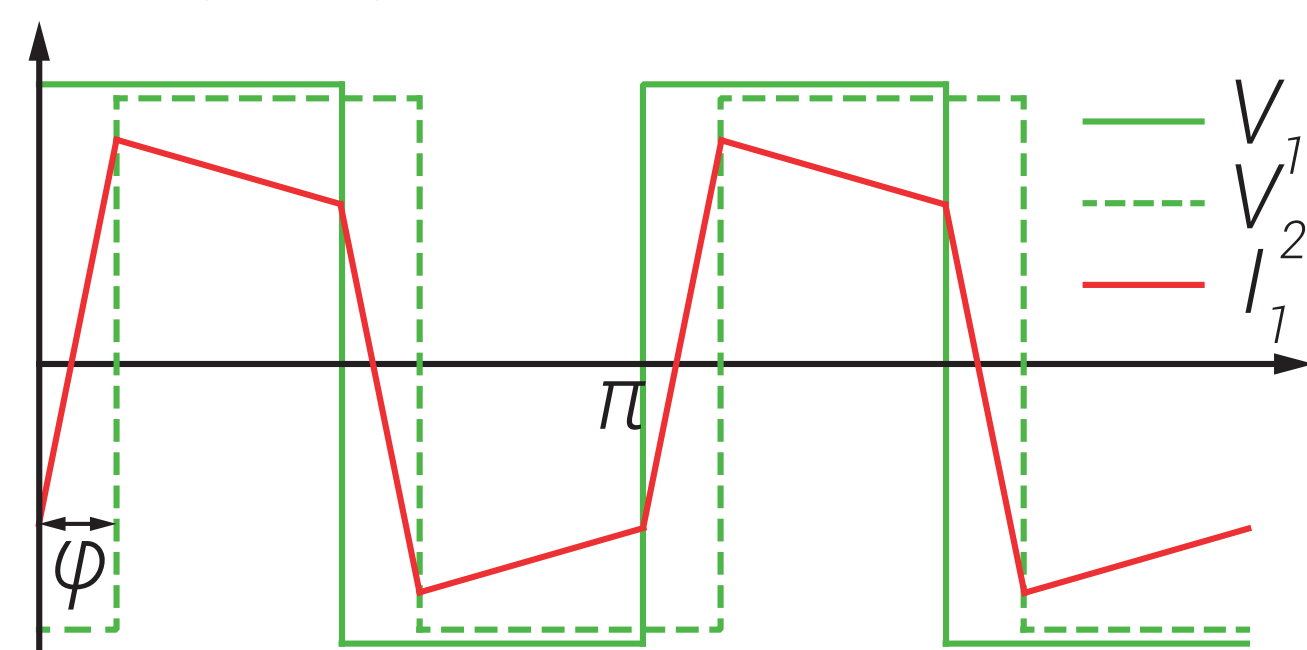
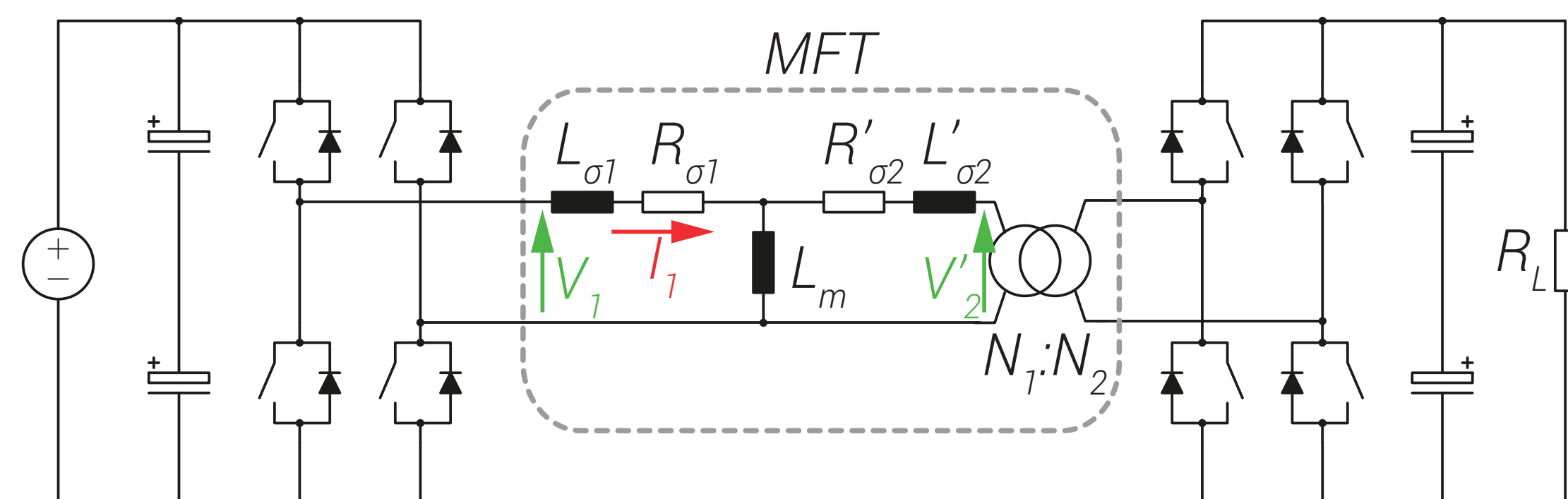
$$V(x) = V \frac{\sinh(ax)}{ah}$$

$$a = \sqrt{\frac{c}{k}}$$



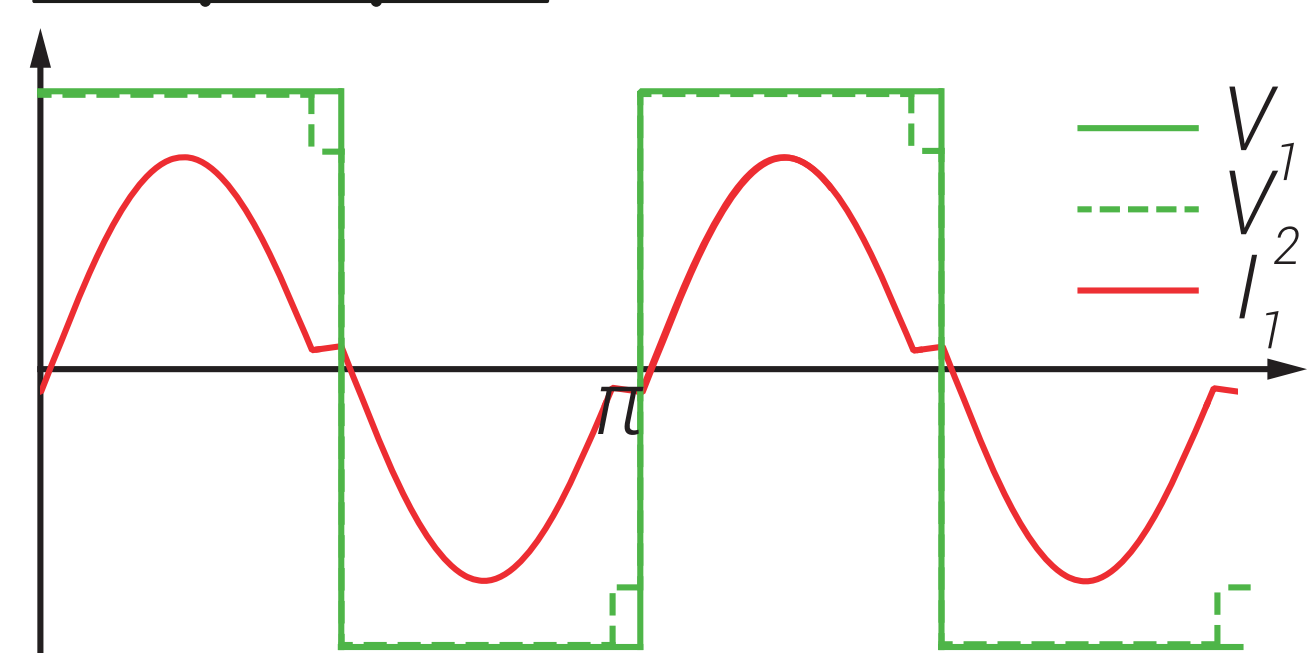
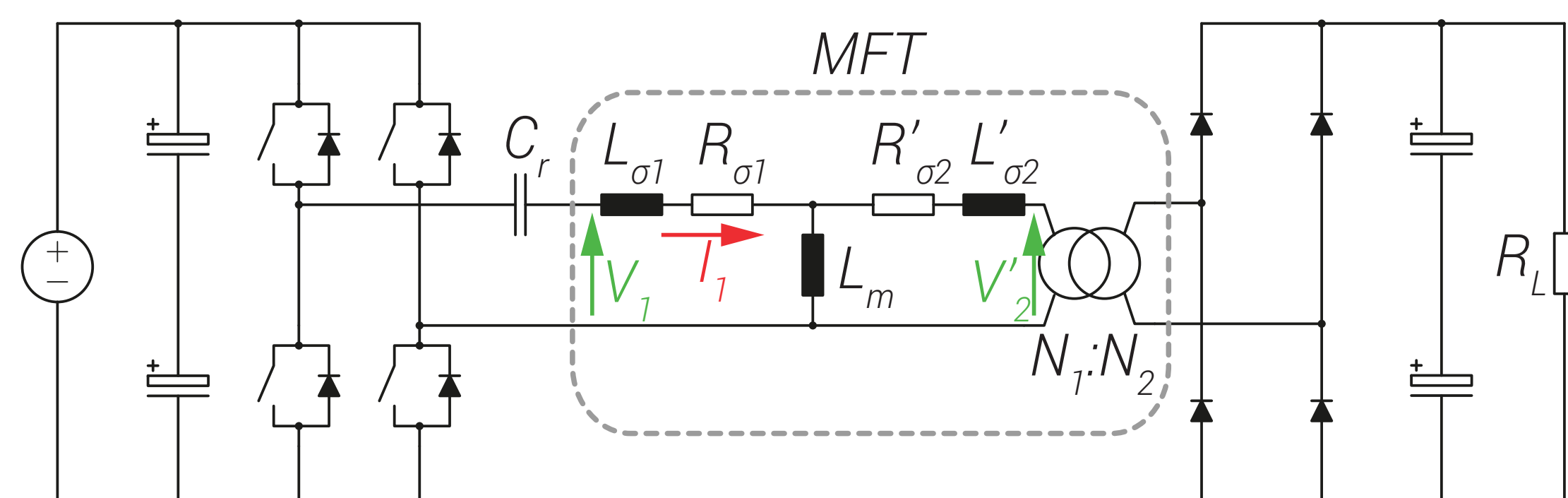
# ACCURATE MFT ELECTRIC PARAMETER CONTROL

## DAB Converter:



- ▶  $V_{1,2}$  square
- ▶  $I$  non-sinusoidal

## Series Resonant Converter:



- ▶  $V_{1,2}$  square
- ▶  $I$  sinusoidal

## DAB

- ▶ Leakage Inductance
- ▶ Controllability of the power flow
- ▶ Higher than  $L_{\sigma.min}$  :

$$L_{\sigma.min} = \frac{V_{DC1} V_{DC2} \varphi_{min} (\pi - \varphi_{min})}{2P_{out} \pi^2 f_s n}$$

- ▶ Magnetizing Inductance is normally high

## SRC

- ▶ Leakage inductance is part of resonant circuit
- ▶ Must match the reference:

$$L_{\sigma.ref} = \frac{1}{\omega_0^2 C_r}$$

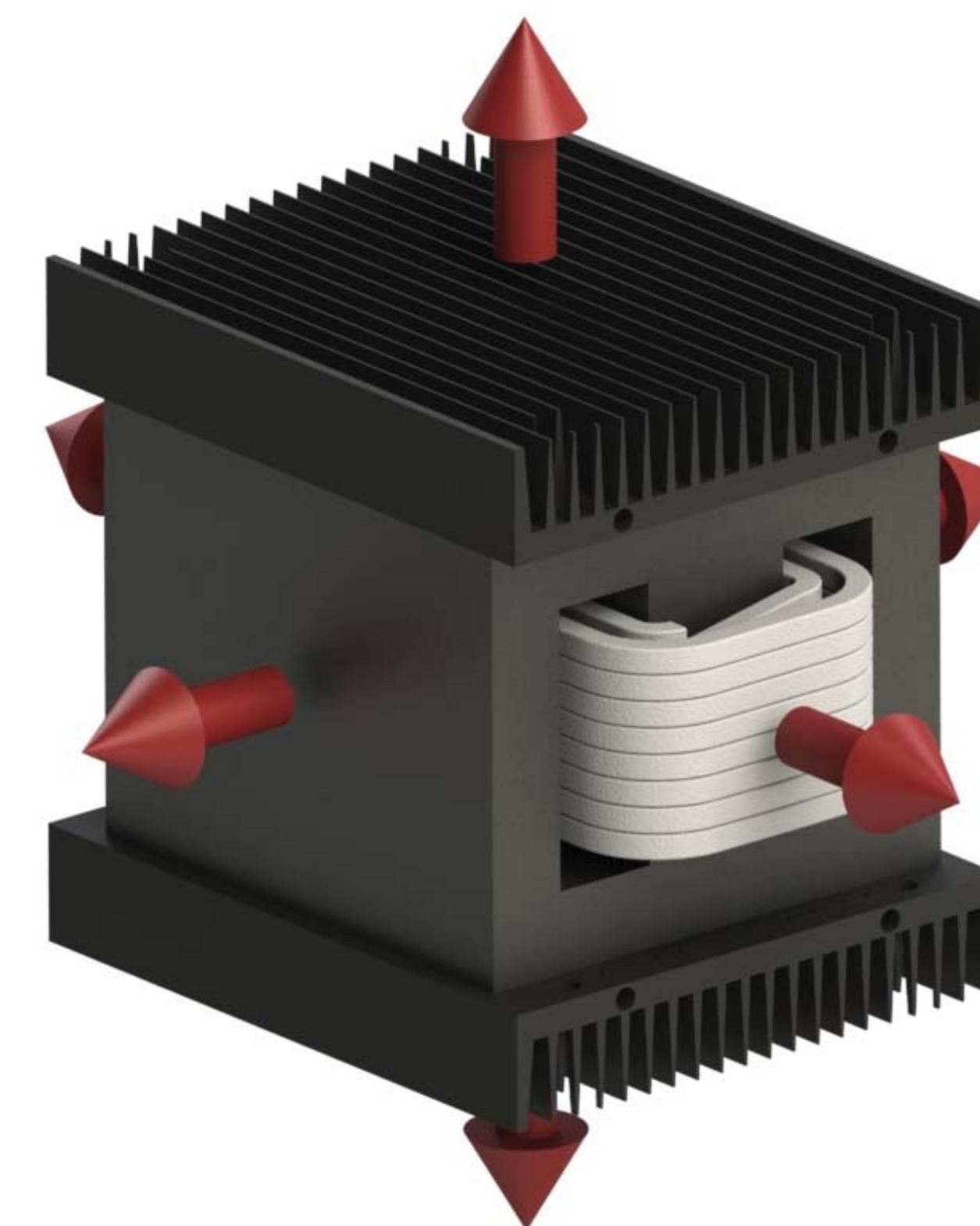
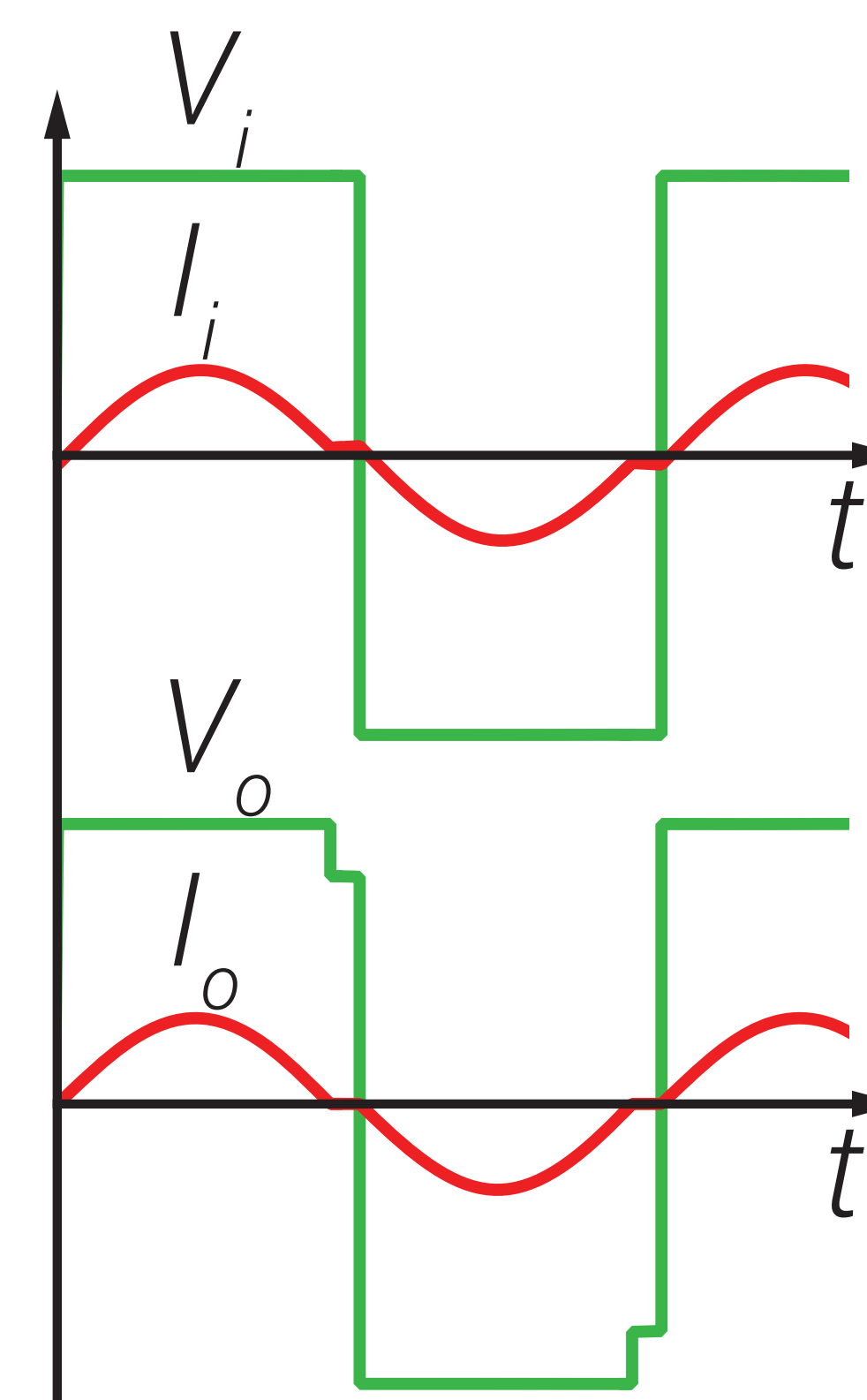
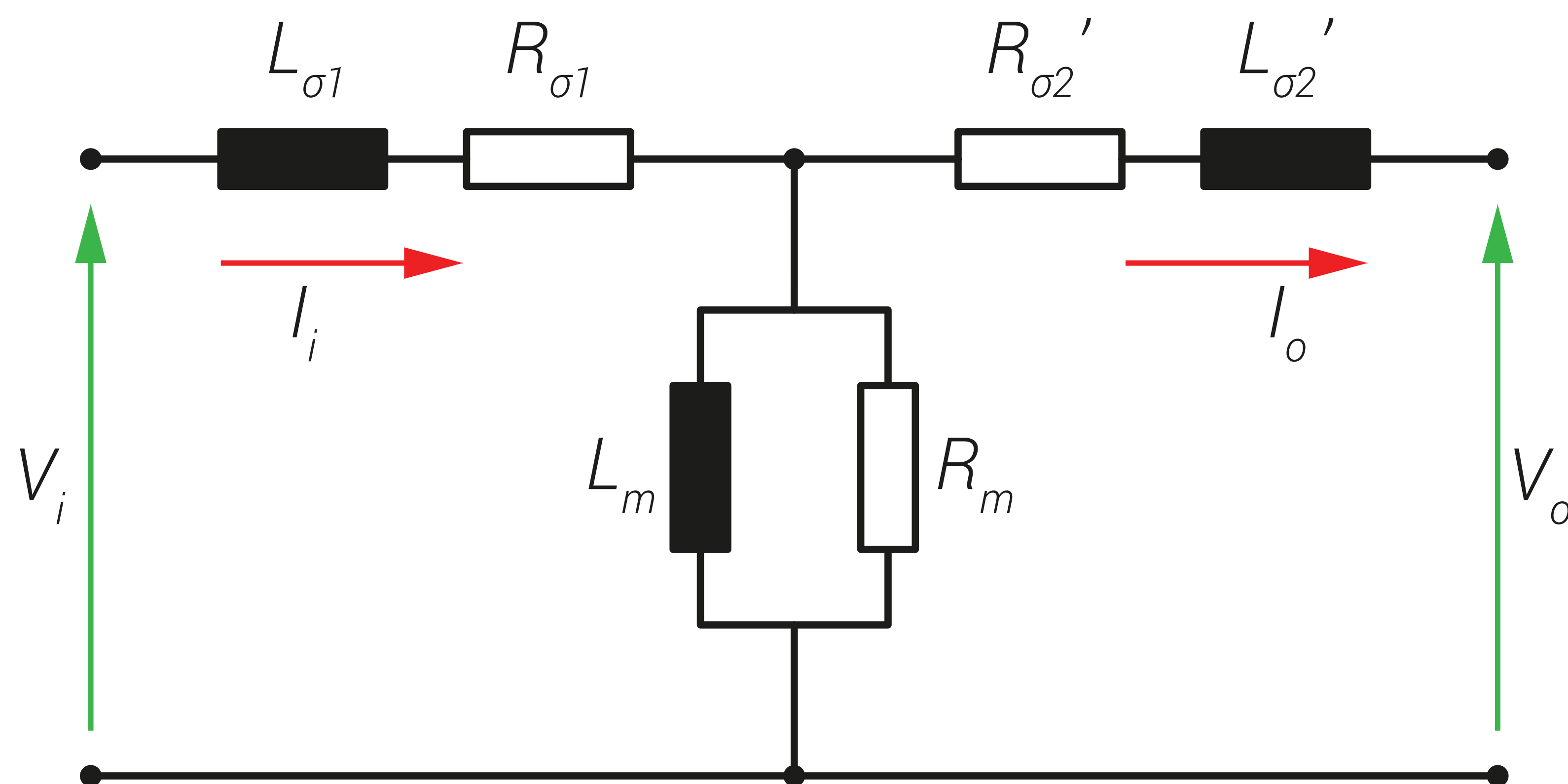
- ▶ Magnetizing inductance is normally high
- ▶ Reduced in case of LLC
- ▶ Limits the magnetization current to the reference  $I_{m.ref}$
- ▶ Limits the switch-off current and losses

$$L_m = \frac{n V_{DC2}}{4 f_s I_{m.ref}}$$

- ▶  $I_{m.ref}$  has to be sufficiently high to maintain ZVS

# MFT CHALLENGES - SUMMARY

- ▶ **Skin and proximity effect losses:** impact on efficiency and heating
- ▶ **Cooling:** increase of power density  $\Rightarrow$  decrease in size  $\Rightarrow$  less cooling surface  $\Rightarrow$  higher  $R_{th}$   $\Rightarrow$  higher temperature gradients
- ▶ **Non-sinusoidal excitation:** impact on core and winding losses and insulation
- ▶ **Insulation:** coordination and testing taking into account high  $\frac{dV}{dt}$  characteristic for power electronic converters
- ▶ **Accurate electric parameter control:** especially in case of resonant converter applications





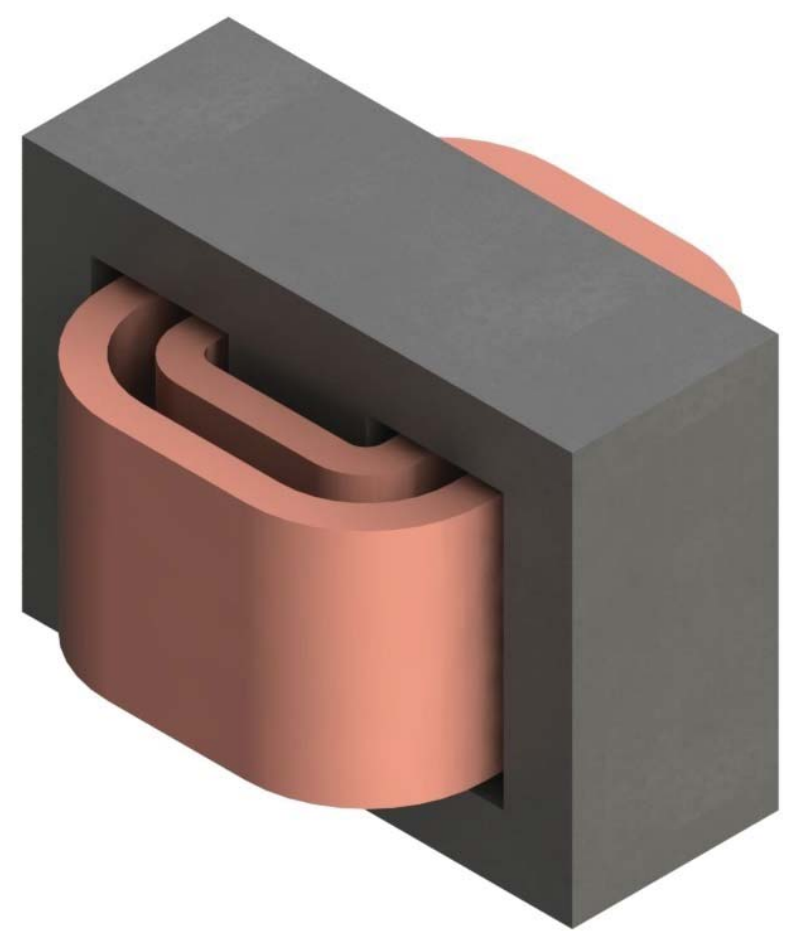
# MFT Clinics

*Optimize at will!*

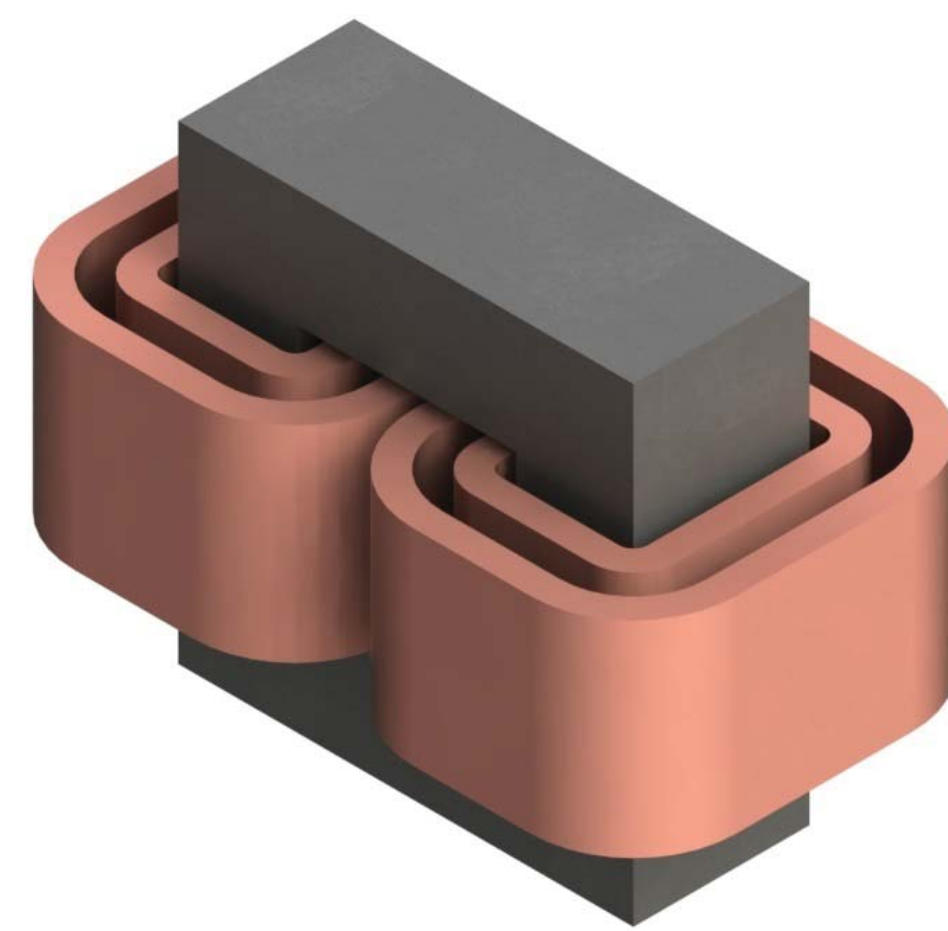
# TECHNOLOGIES, MATERIALS, DESIGNS

## Construction Choices:

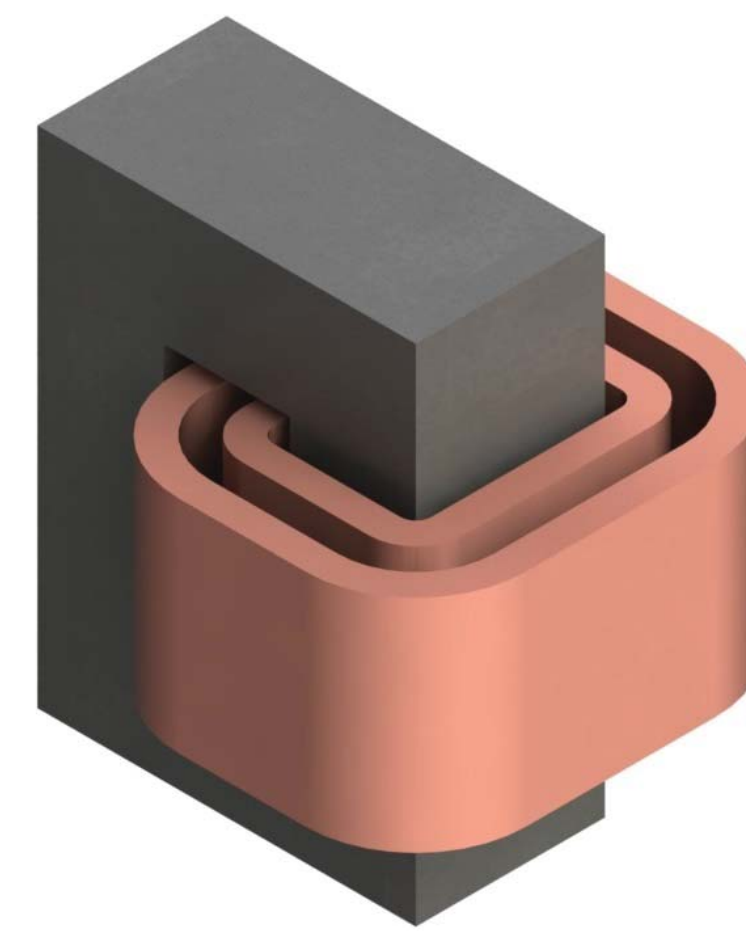
### ▶ MFT Types



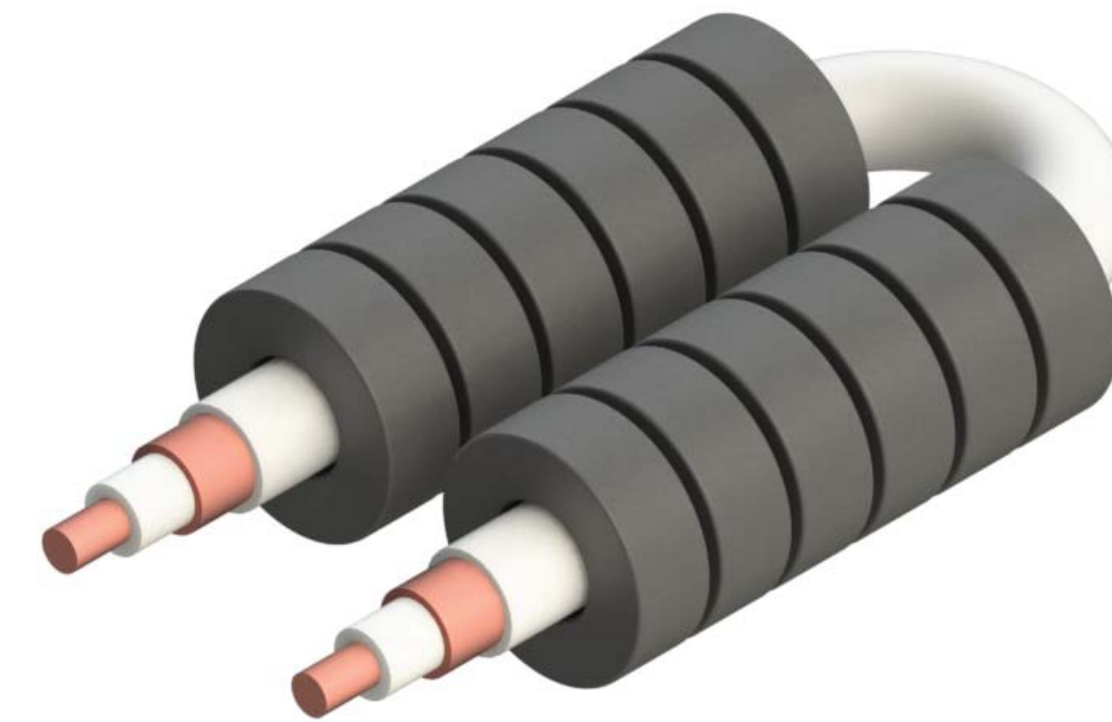
Shell Type



Core Type



C-Type



Coaxial Type

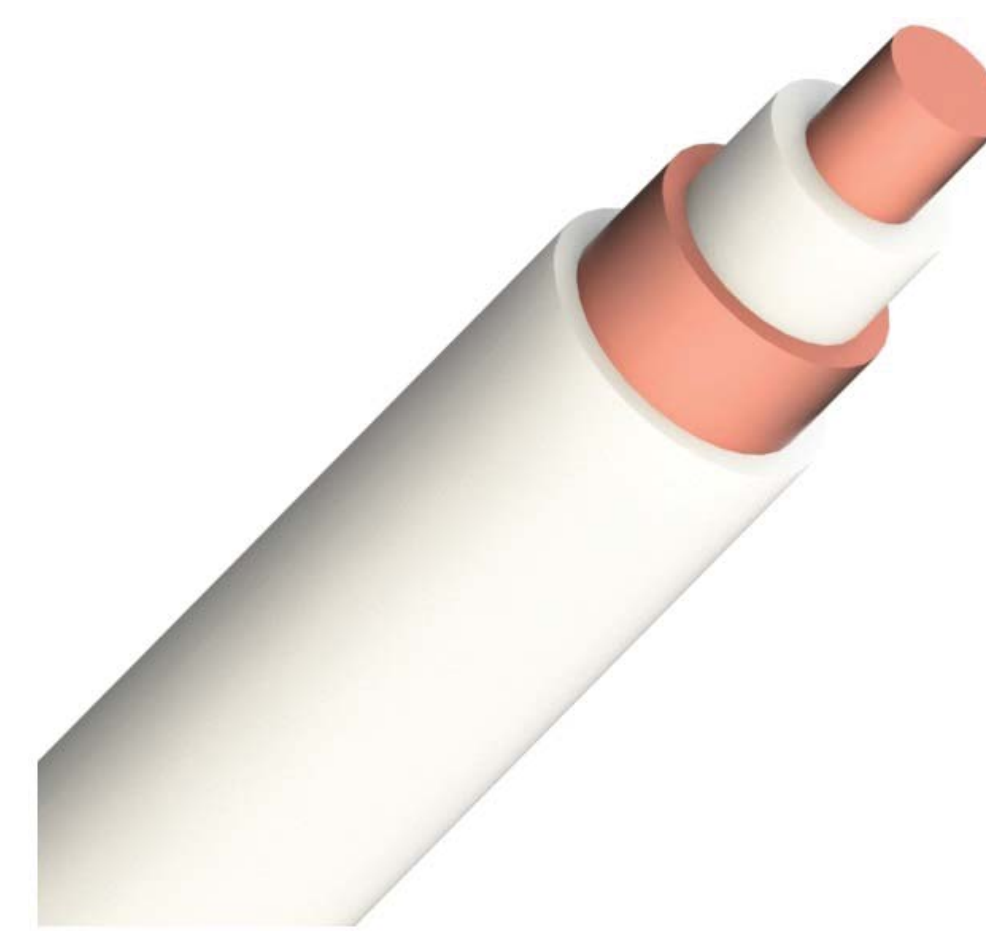
### ▶ Winding Types



Litz Wire



Foil



Coaxial



Hollow

## Materials:

### ▶ Magnetic Materials

- ▶ Silicon Steel
- ▶ Amorphous
- ▶ Nanocrystalline
- ▶ Ferrites

### ▶ Windings

- ▶ Copper
- ▶ Aluminum

### ▶ Insulation

- ▶ Air
- ▶ Solid
- ▶ Oil

### ▶ Cooling

- ▶ Air natural/forced
- ▶ Oil natural/forced
- ▶ Water

# STATE OF THE ART: SOME OF REPORTED PROTOTYPES

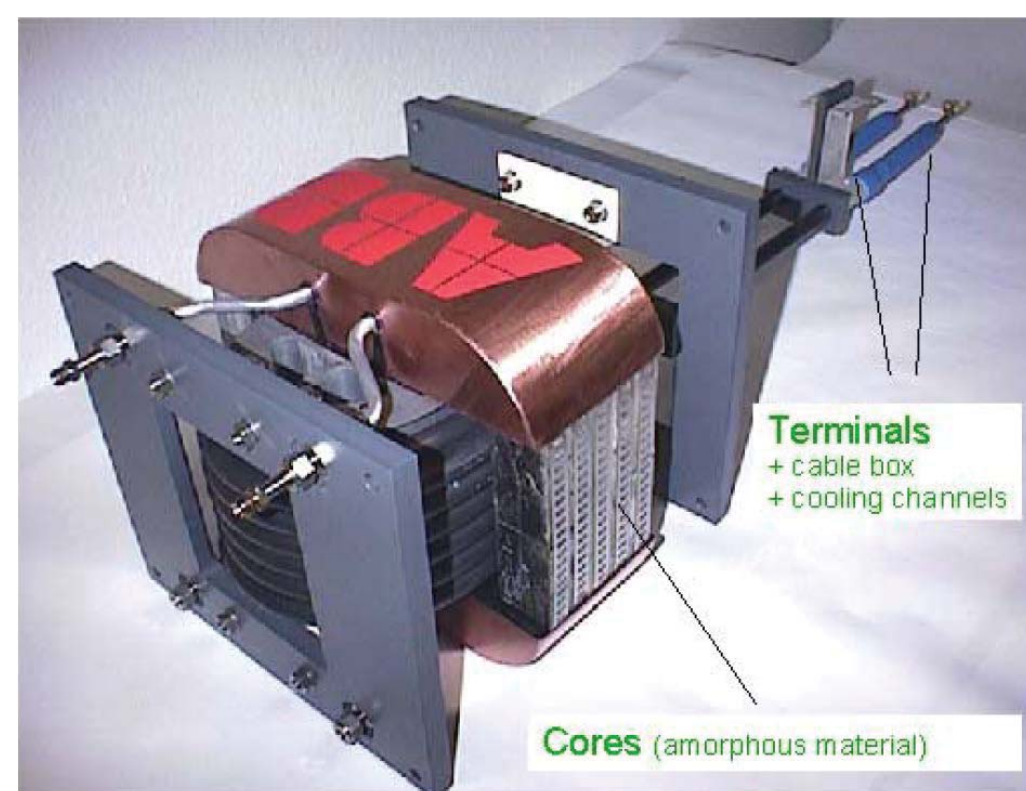
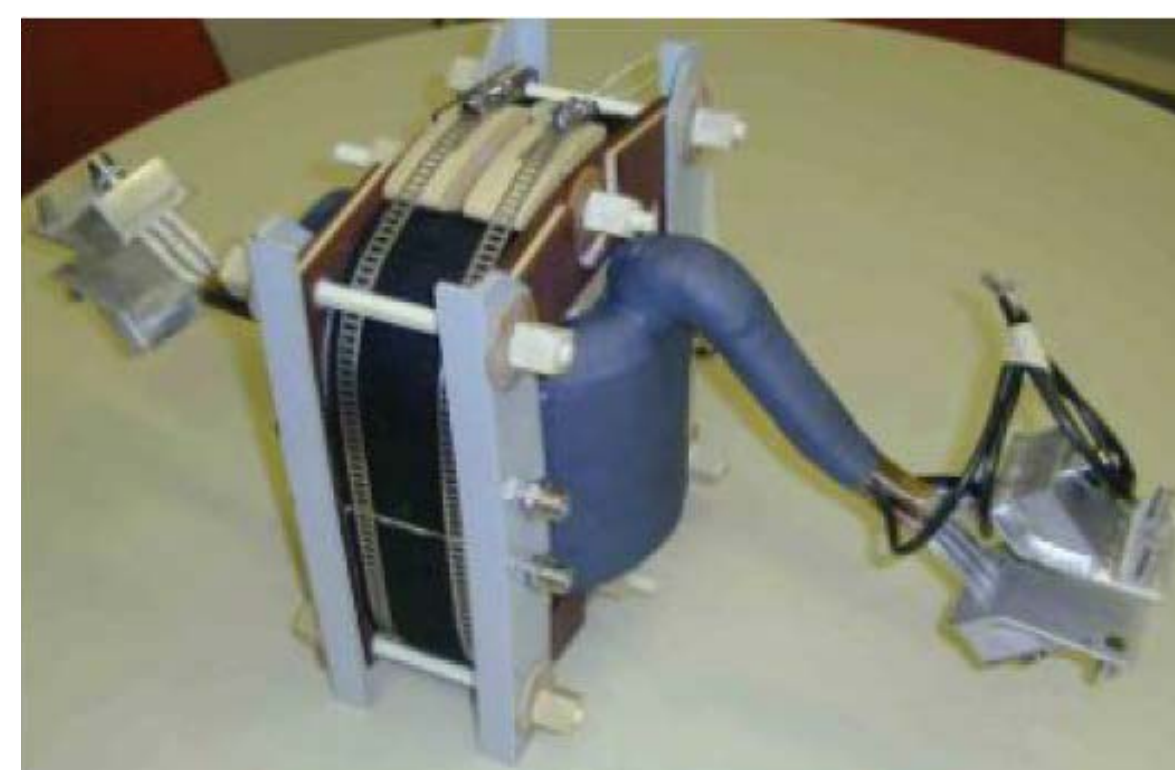


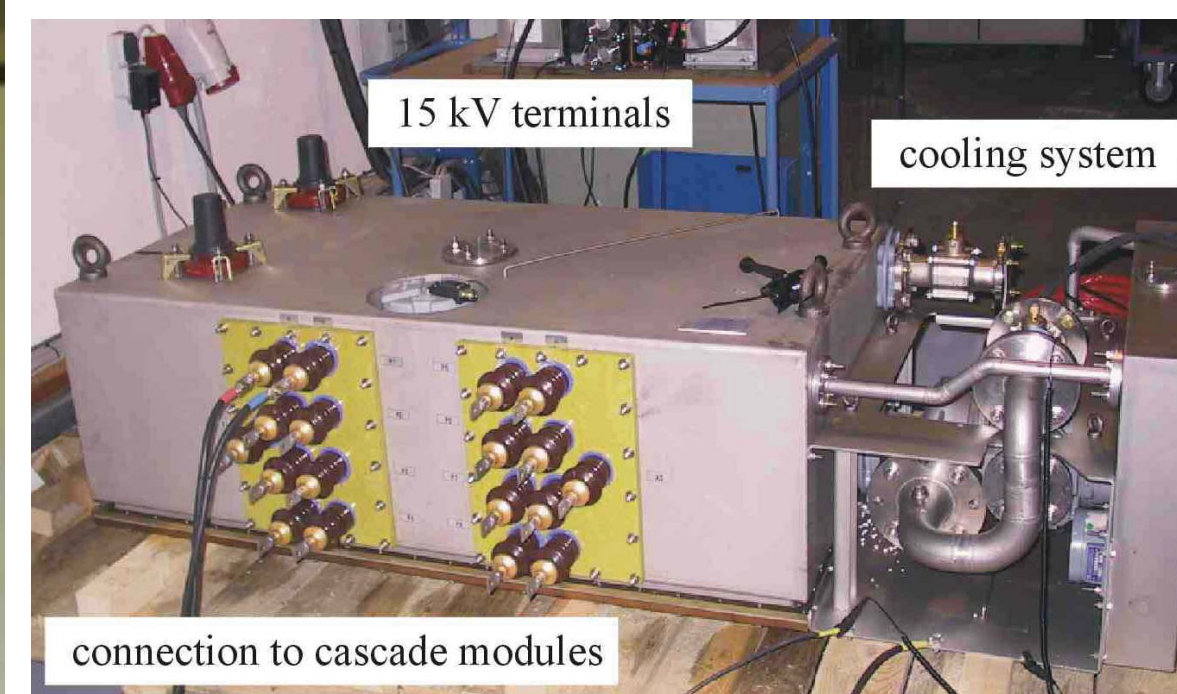
ABB: 350kW, 10kHz



ABB: 3x150kW, 1.8kHz



BOMBARDIER: 350kW, 8kHz



ALSTOM: 1500kW, 5kHz



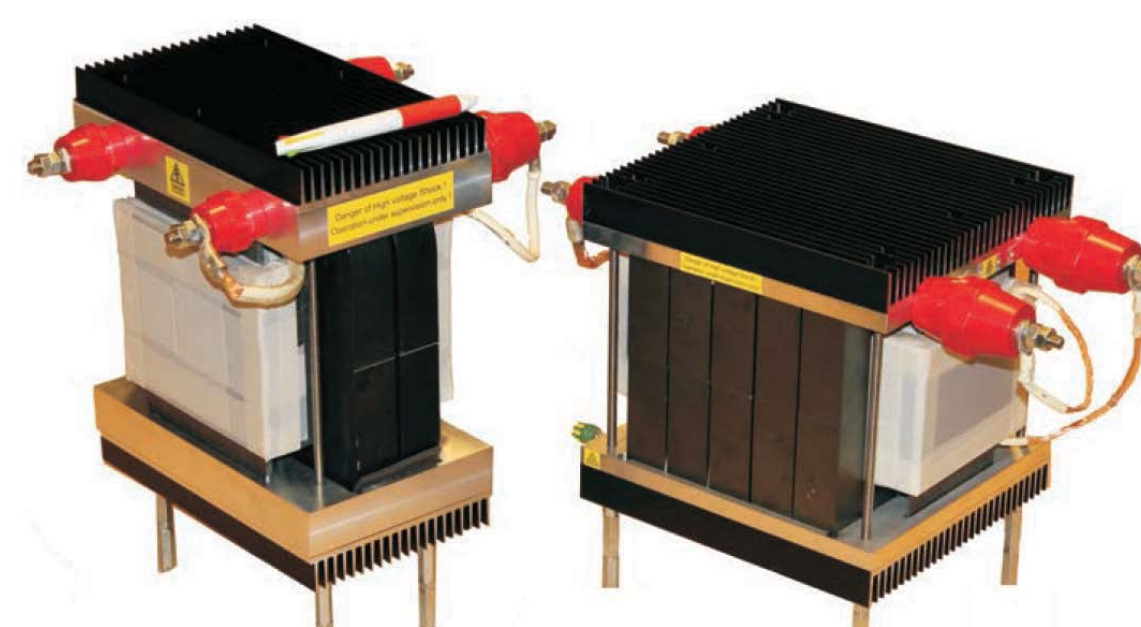
IKERLAN: 400kW, 5kHz



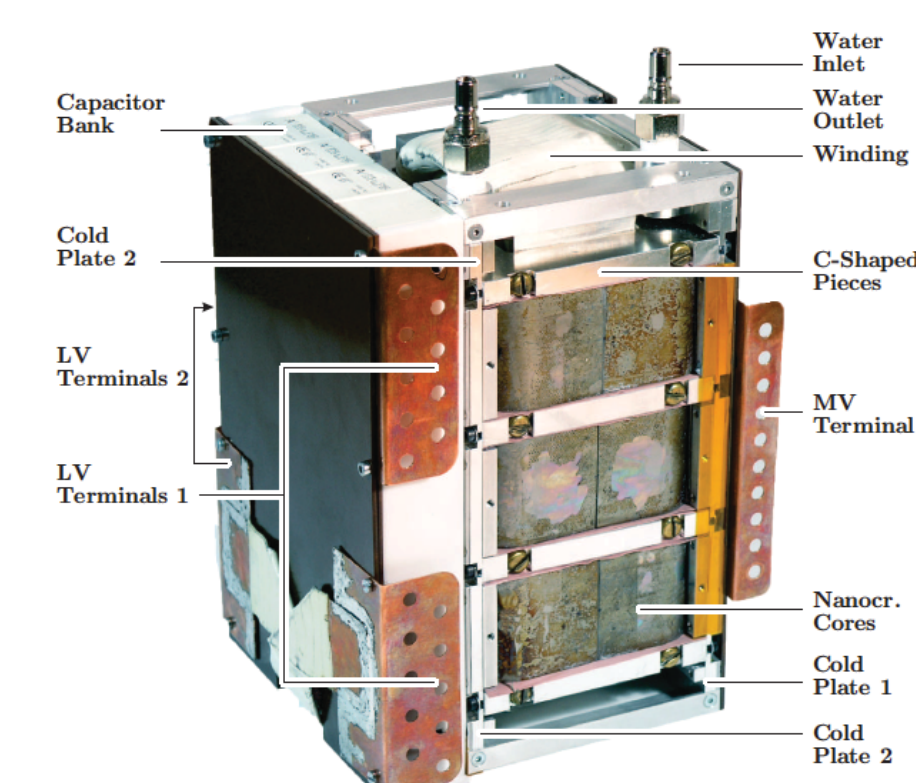
IKERLAN: 400kW, 1kHz



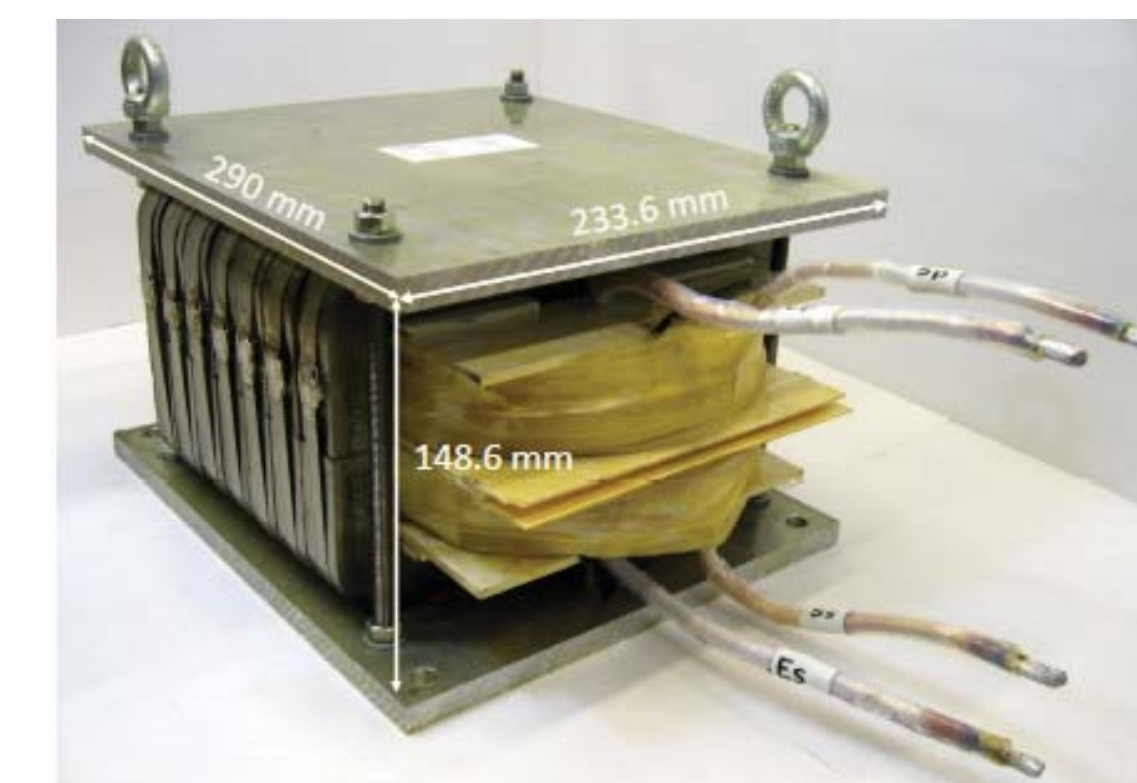
FAU-EN: 450kW, 5.6kHz



CHALMERS: 50kW, 5kHz



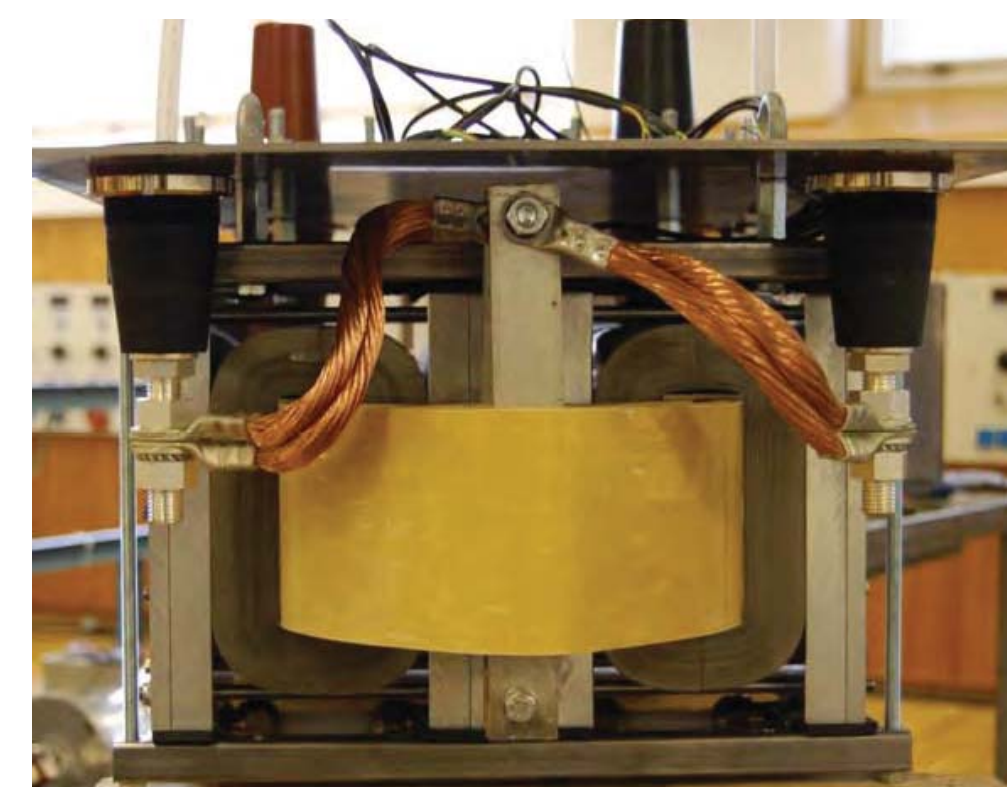
ETHZ: 166kW, 20kHz



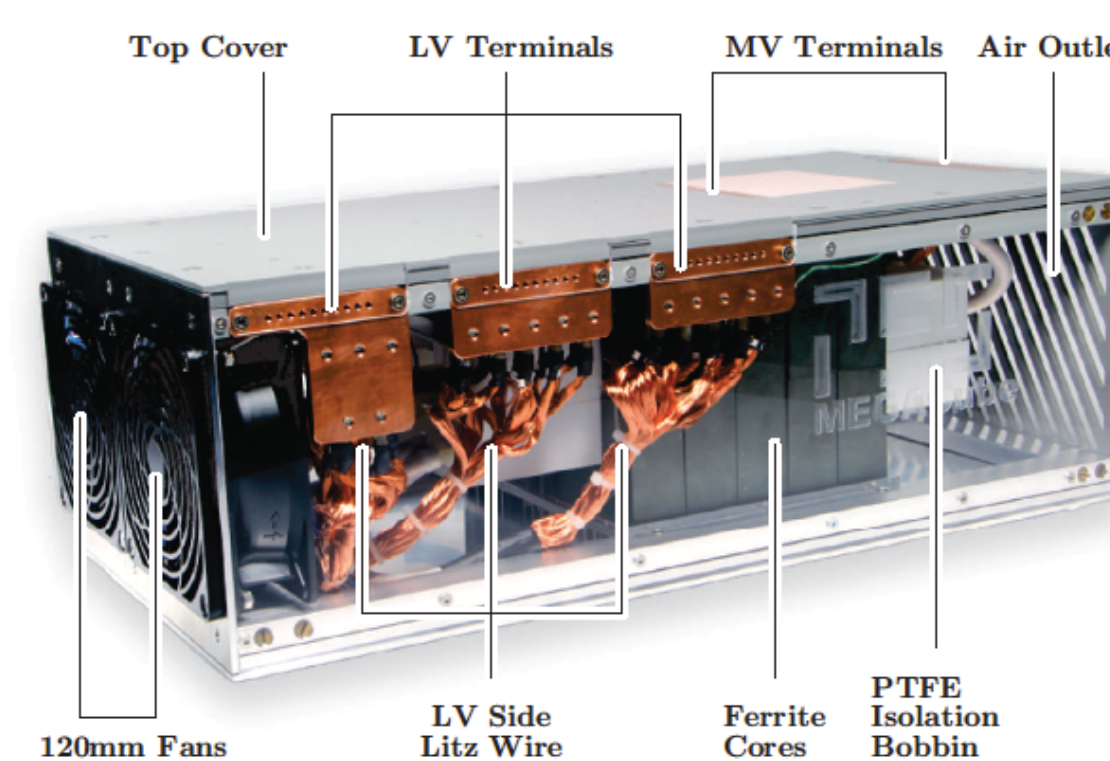
EPFL: 300kW, 2kHz



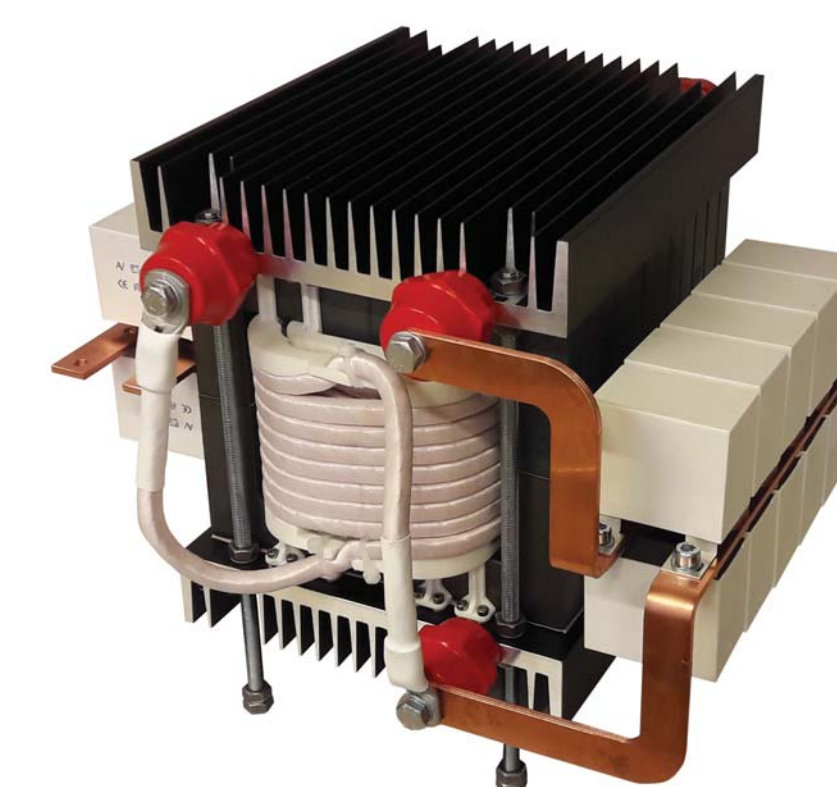
STS: 450kW, 8kHz



KTH: 170kW, 4kHz



ETHZ: 166kW, 20kHz



EPFL: 100kW, 10kHz

?

ACME: ???kW, ???kHz

# ABB MFT - 2002

## Construction

- ▶ Shell Type
- ▶ Coaxial winding

## Electrical Ratings

- ▶ Power: 350kW
- ▶ Frequency: 10kHz
- ▶ Input Voltage:  $\pm 3000V$
- ▶ Output Voltage:  $\pm 3000V$

## Core Material

- ▶ VAC Vitroperm 500F
- ▶ U cores

## Windings

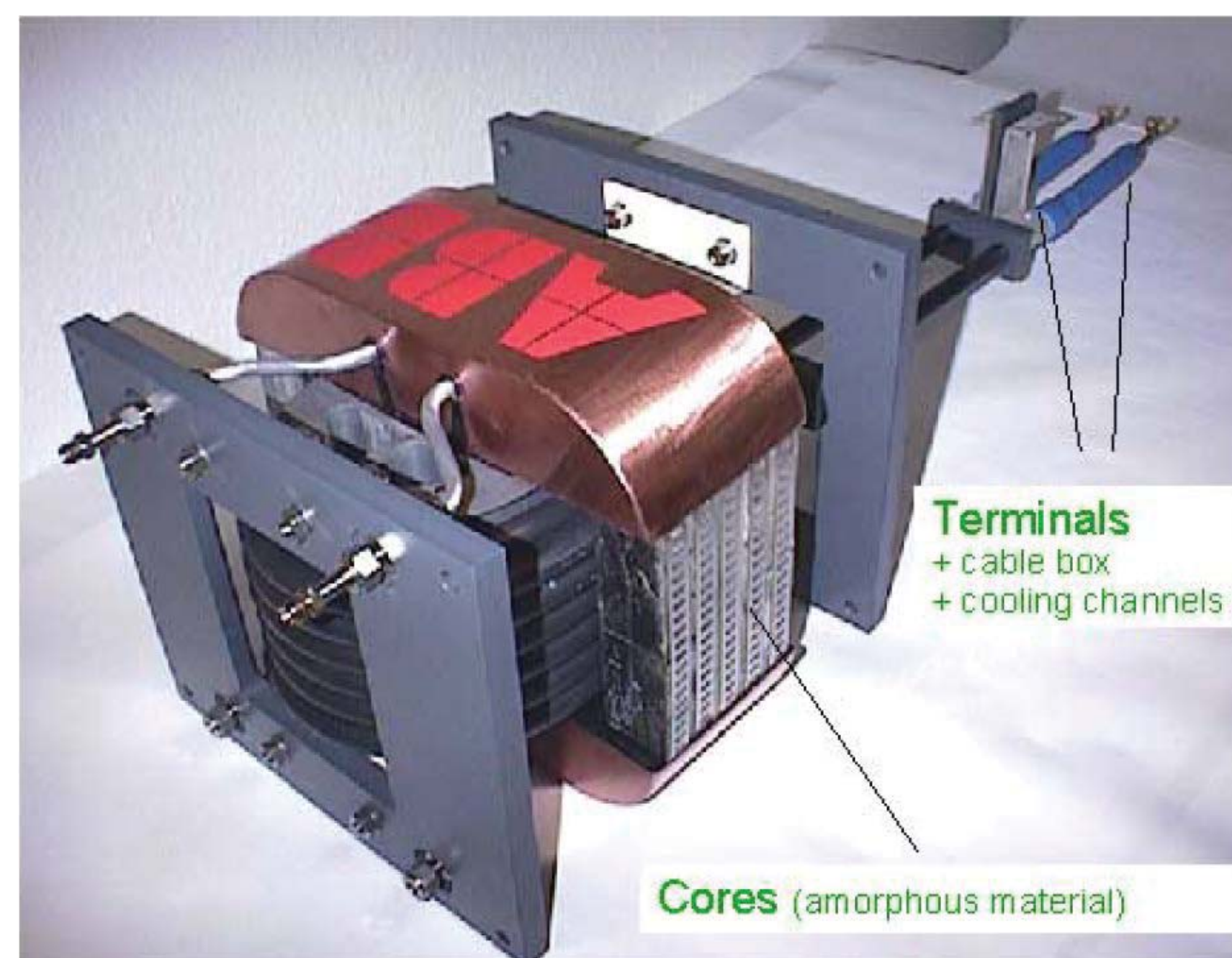
- ▶ Coaxial (Al inside, Cu outside)

## Cooling

- ▶ Winding - De-ionized water
- ▶ Core - Air

## Insulation

- ▶ Solid



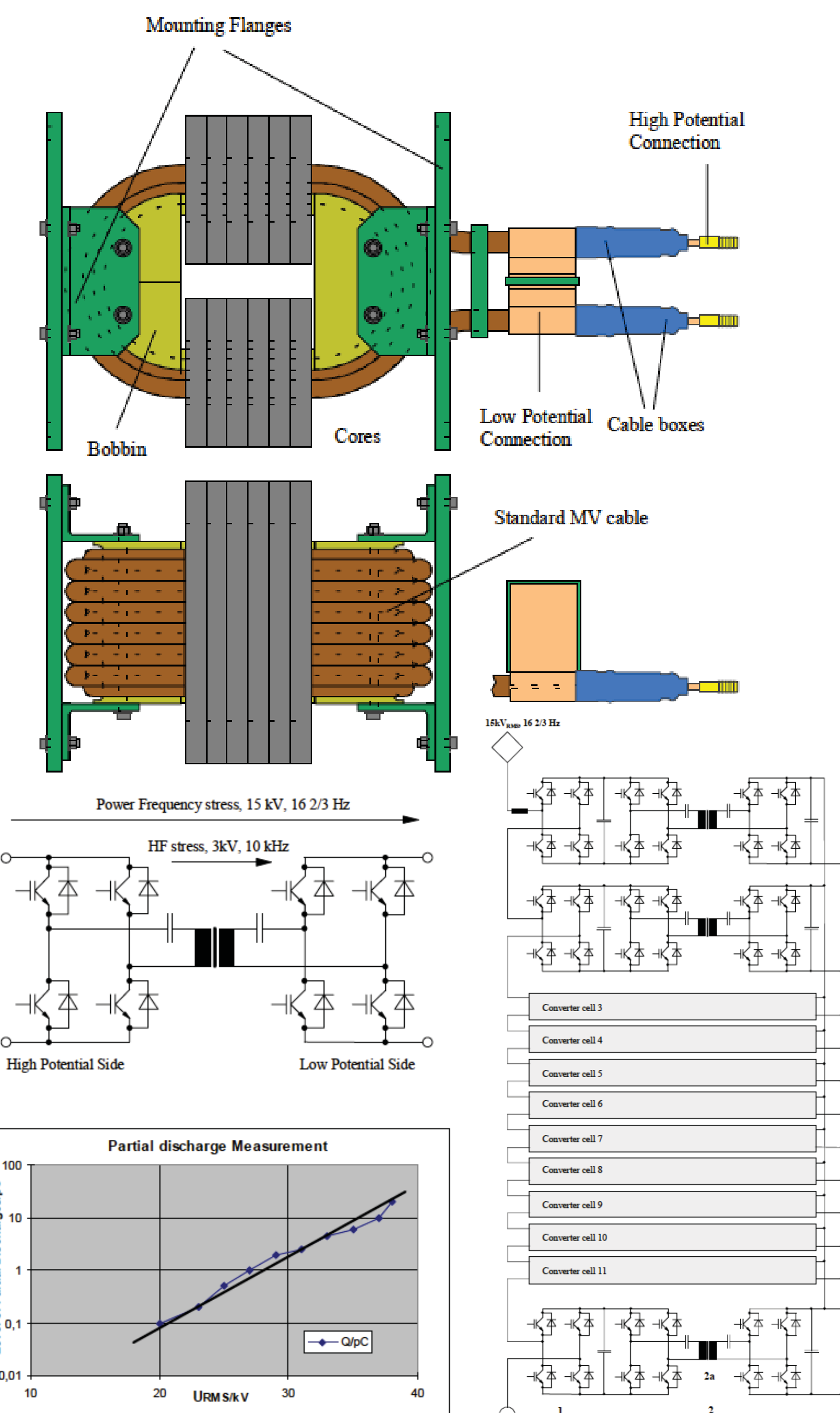
▲ 350kW MFT by ABB [10]

## MFT dimensions

- ▶ Volume: not reported
- ▶ V-Density: not reported
- ▶ Weight: < 50 kg
- ▶ W-Density:  $\approx 7 \text{ kW/kg}$

## Insulation Tests

- ▶ PD: 38kV, 50Hz, 1 min
- ▶ BIL: 95 kV (peak), 10 shots



▲ Multilevel line side converter by ABB (2002)

# ALSTOM MFT - 2003

## Construction

- ▶ Single core with multiple windings

## Electrical Ratings

- ▶ Power: 1.5MW
- ▶ Frequency: 5kHz
- ▶ Input Voltage:  $\pm 1800V$
- ▶ Output Voltage:  $\pm 1650V$

## Core Material

- ▶ Ferrite
- ▶ Size and shape unclear

## Windings

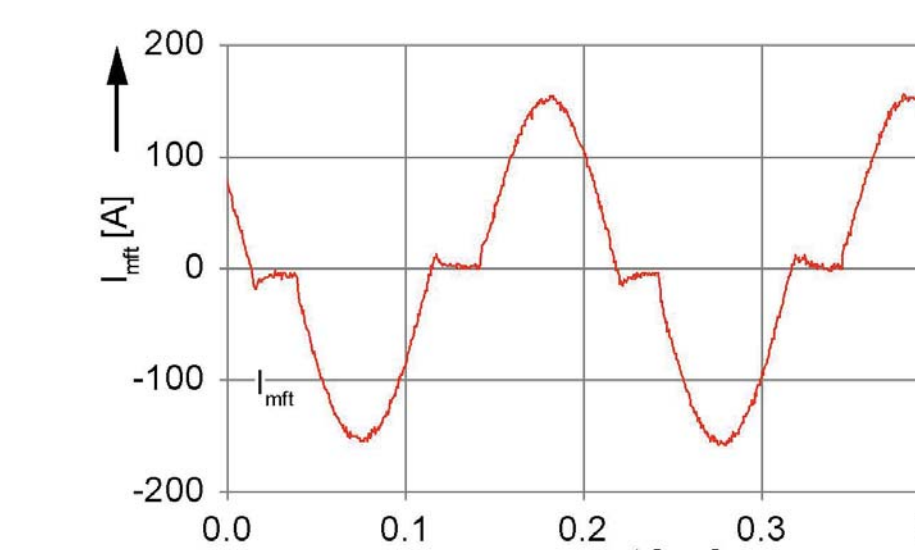
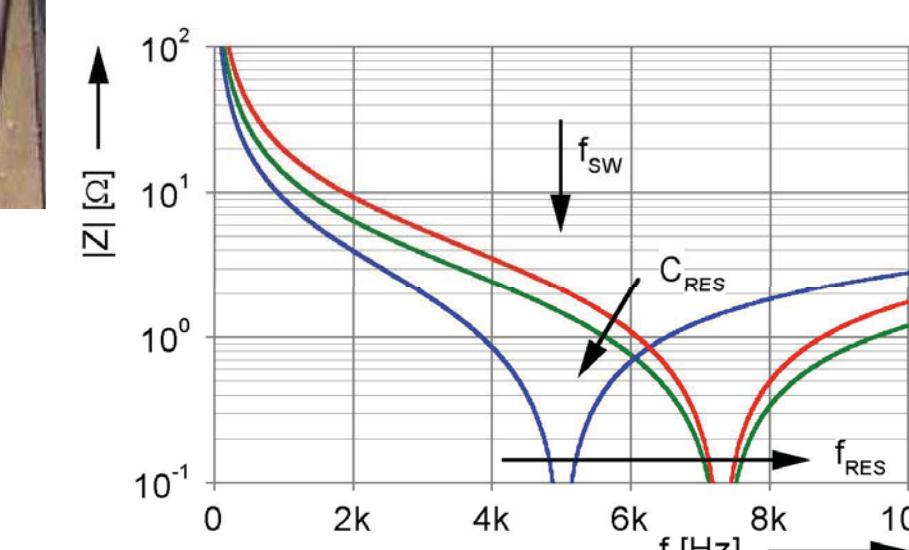
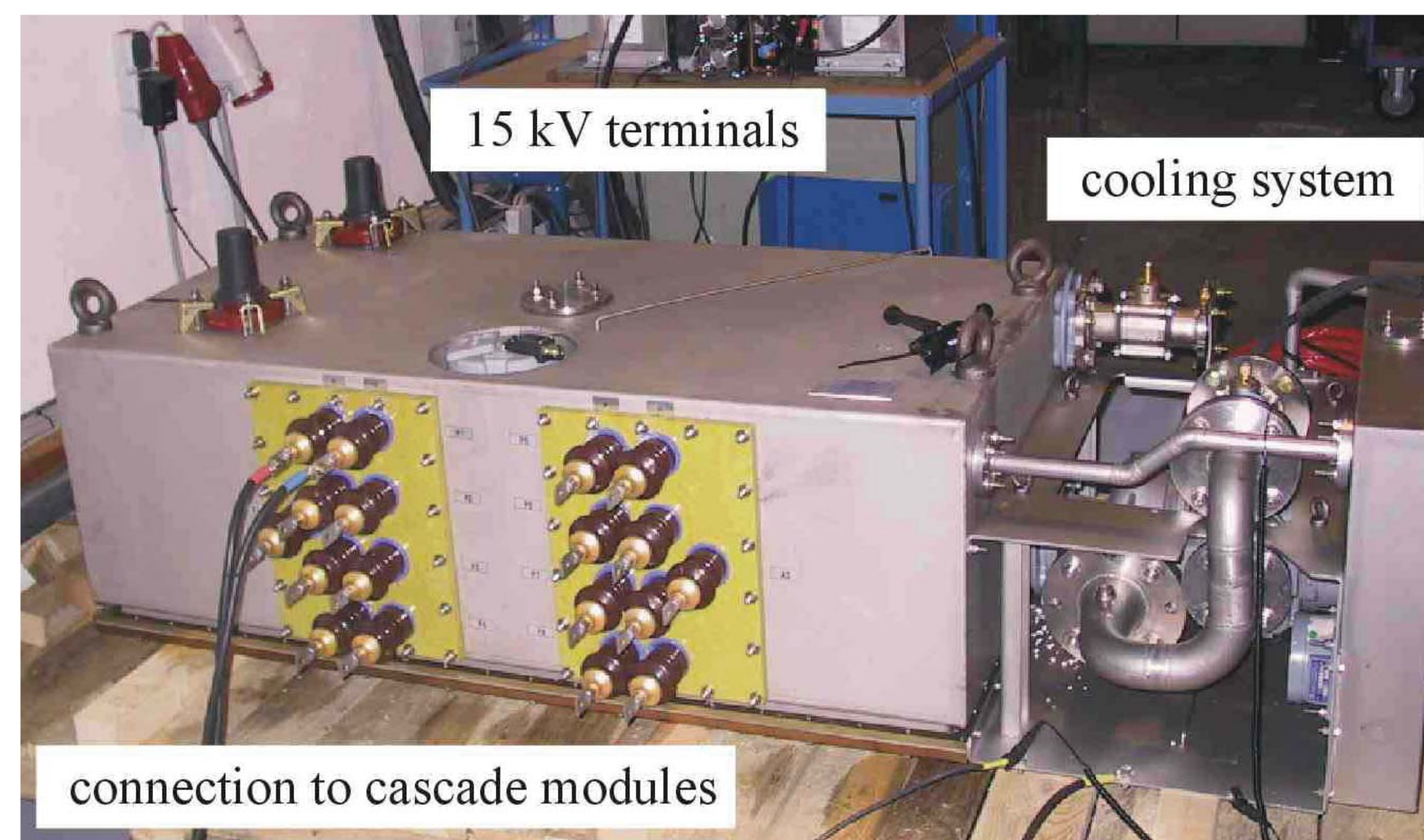
- ▶ Litz wire

## Cooling

- ▶ Oil (MIDEL)
- ▶ Common with power electronics

## Insulation

- ▶ Oil (MIDEL)
- ▶ Immersed



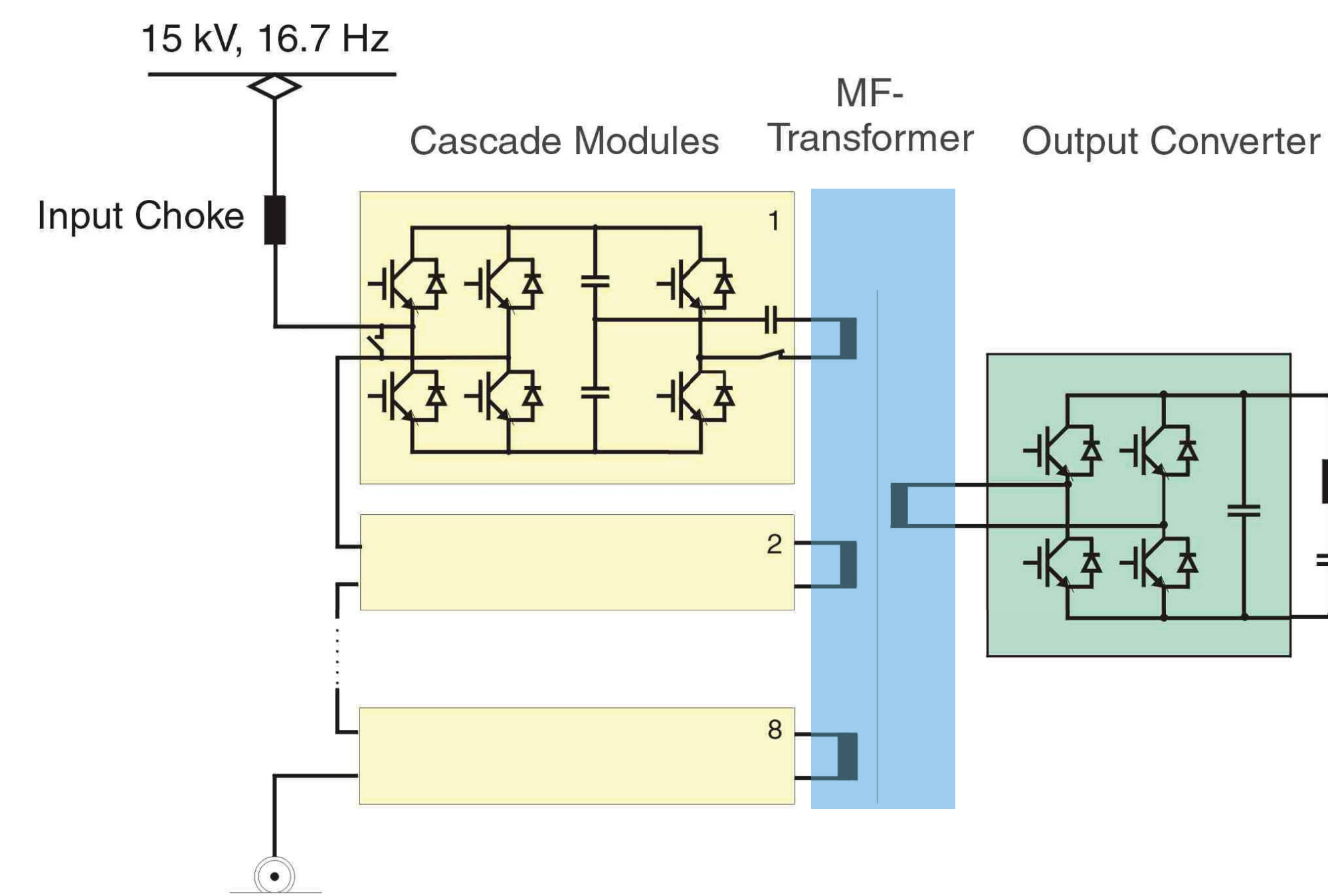
- ▲ 1.5MW MFT by ALSTOM

## MFT dimensions

- ▶ Volume:  $0.72 m^3$  (2.0 x 0.73 x 0.49) m
- ▶ V-Density: 2.1 kW/l
- ▶ Weight: < 1 t (estimation)
- ▶ W-Density: < 1.5 kW / kg (estimation)

## e-Transformer dimensions

- ▶ (2.1 x 2.62 x 0.58) m
- ▶ Volume:  $3.22 m^3$
- ▶ Weight: 3.1 t (50% less)



- ▲ e-Transformer by ALSTOM [3], [4]

# ABB MFT - 2007

## Construction

- ▶ C-type

## Electrical Ratings

- ▶ Power: 75kW (x16)
- ▶ Frequency: 400Hz
- ▶ Input Voltage:  $\pm 1800V$
- ▶ Output Voltage:  $\pm 1800V$

## Core Material

- ▶ SiFe
- ▶ Custom made sheets

## Windings

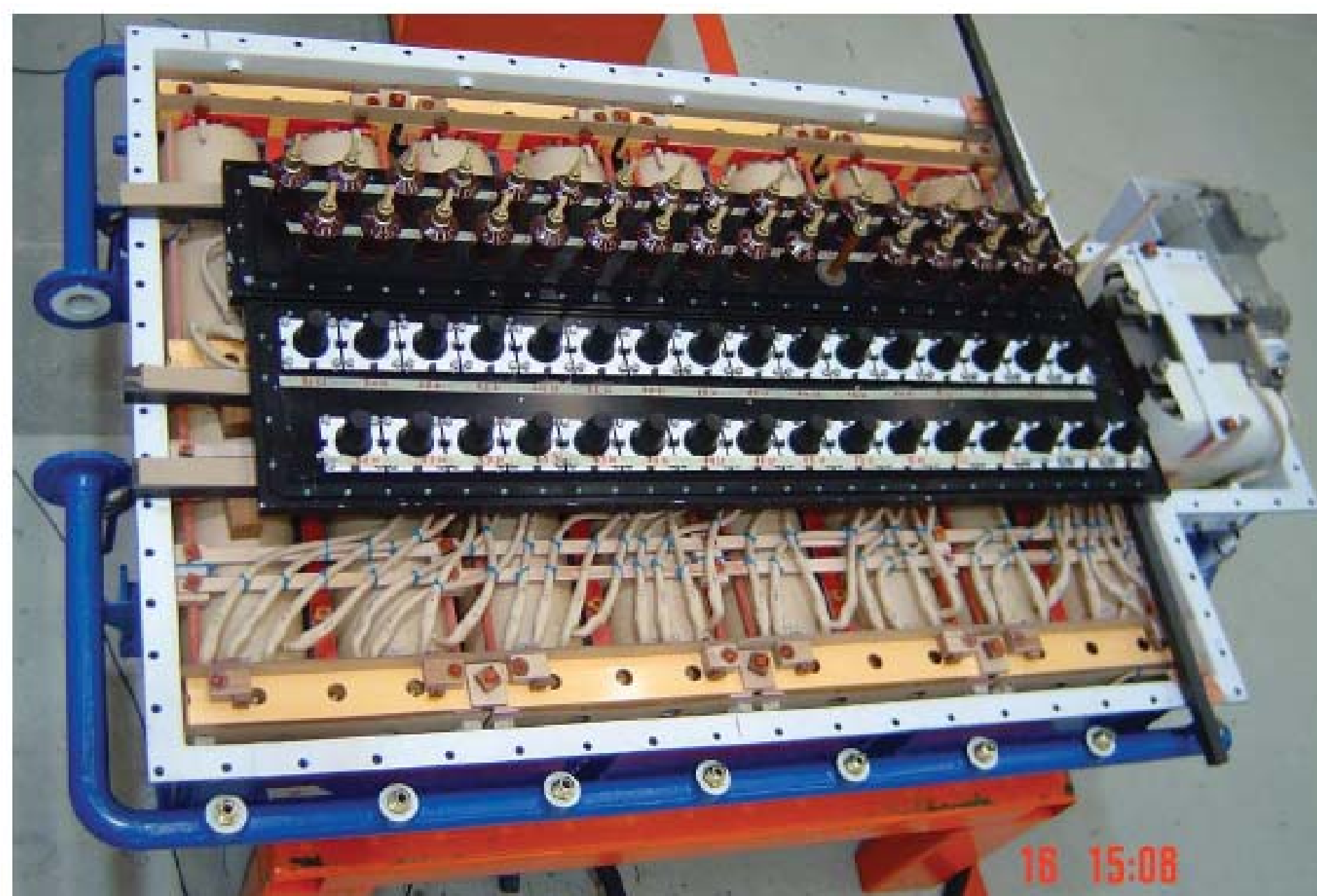
- ▶ Bar wire

## Cooling

- ▶ Oil
- ▶ Common with power electronics

## Insulation

- ▶ Oil
- ▶ Immersed



▲ Enclosure with 16 MFTs by ABB

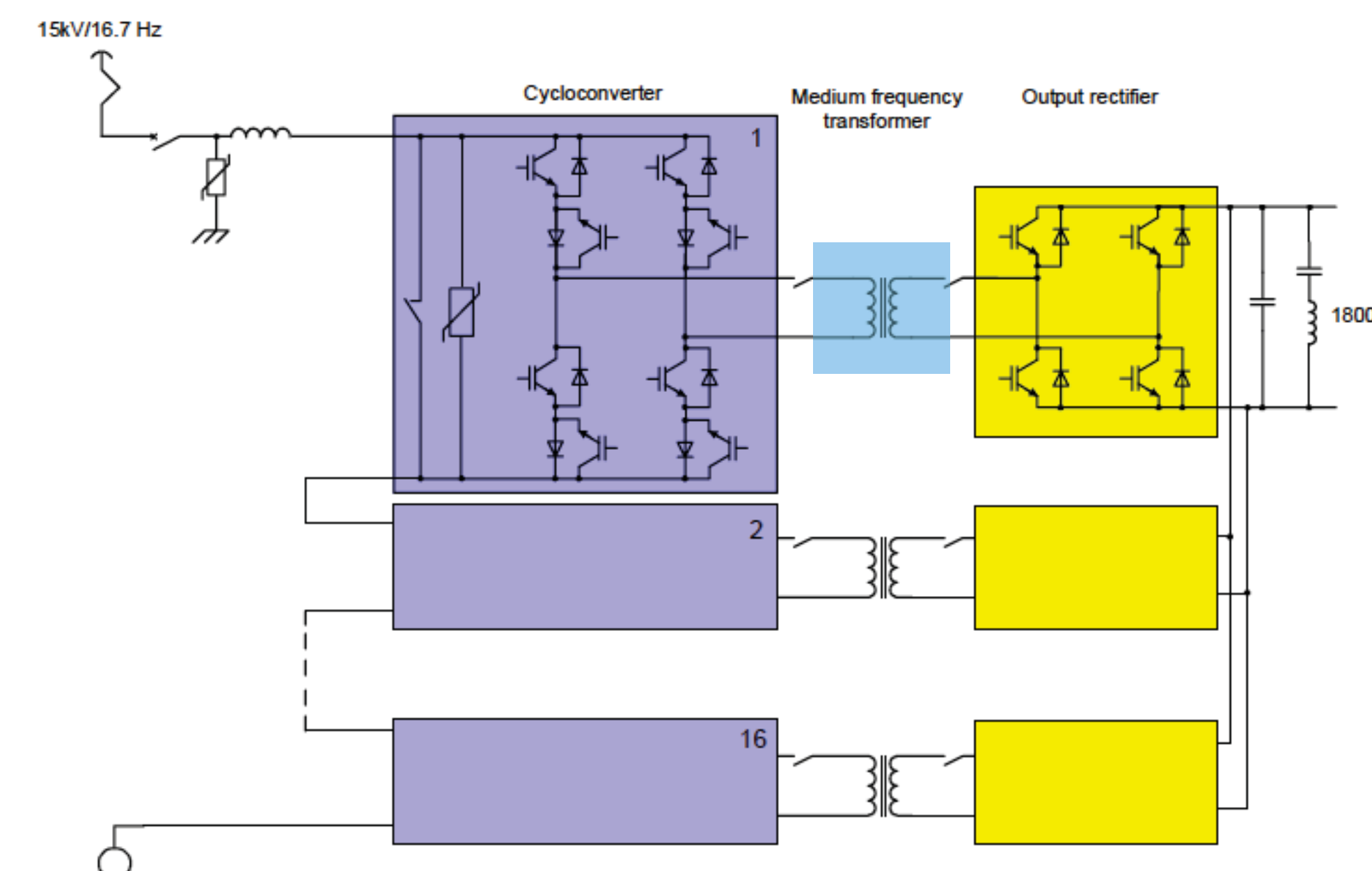


## MFT dimensions

- ▶ Volume: not reported
- ▶ V-Density: ? kW/l
- ▶ Weight: not reported
- ▶ W-Density: ? kW/kg

## PETT dimensions

- ▶ Volume: 20% less
- ▶ Weight: 50% less
- ▶ Efficiency: 3% increase



▲ PETT by ABB [5]



# BOMBARDIER MFT - 2007

## Construction

- ▶ Core Type
- ▶ Hollow conductors

## Electrical Ratings

- ▶ Power: 350kW (500kW peak)
- ▶ Frequency: 8kHz
- ▶ Input Voltage:  $\pm 1000V$
- ▶ Output Voltage:  $\pm 1000V$

## Core Material

- ▶ Nanocrystalline
- ▶ U cores

## Windings

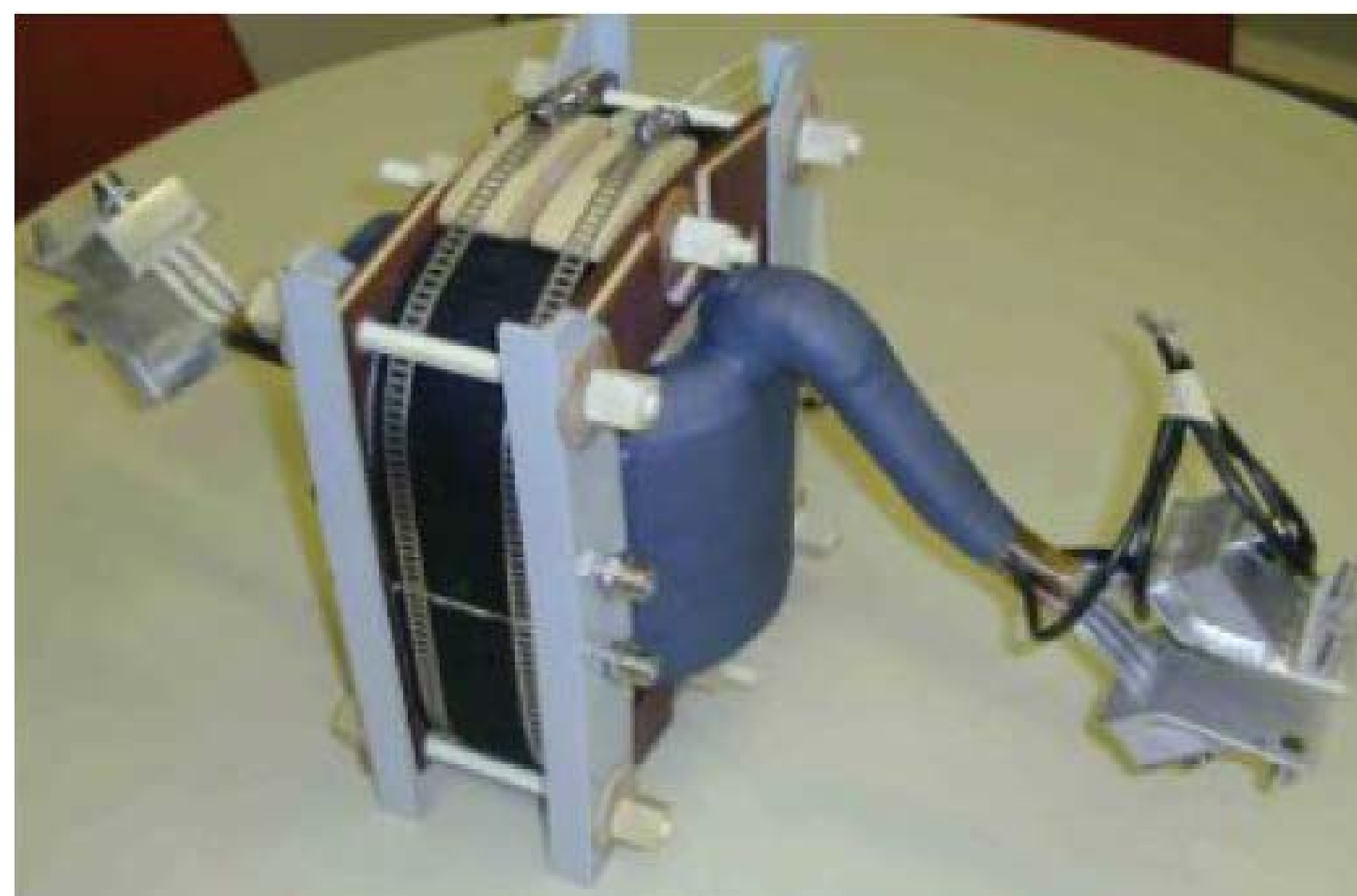
- ▶ Hollow tubes

## Cooling

- ▶ Winding - De-ionized water
- ▶ Core - Water cooled heatsink

## Insulation

- ▶ Solid



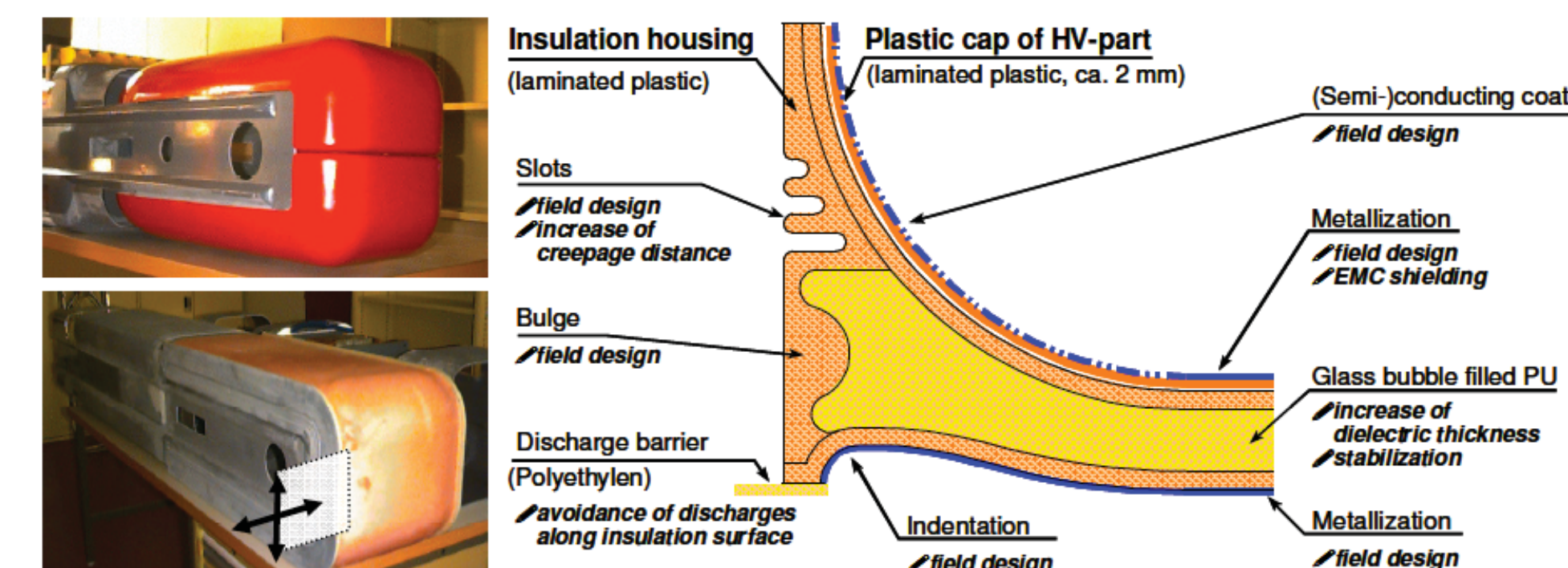
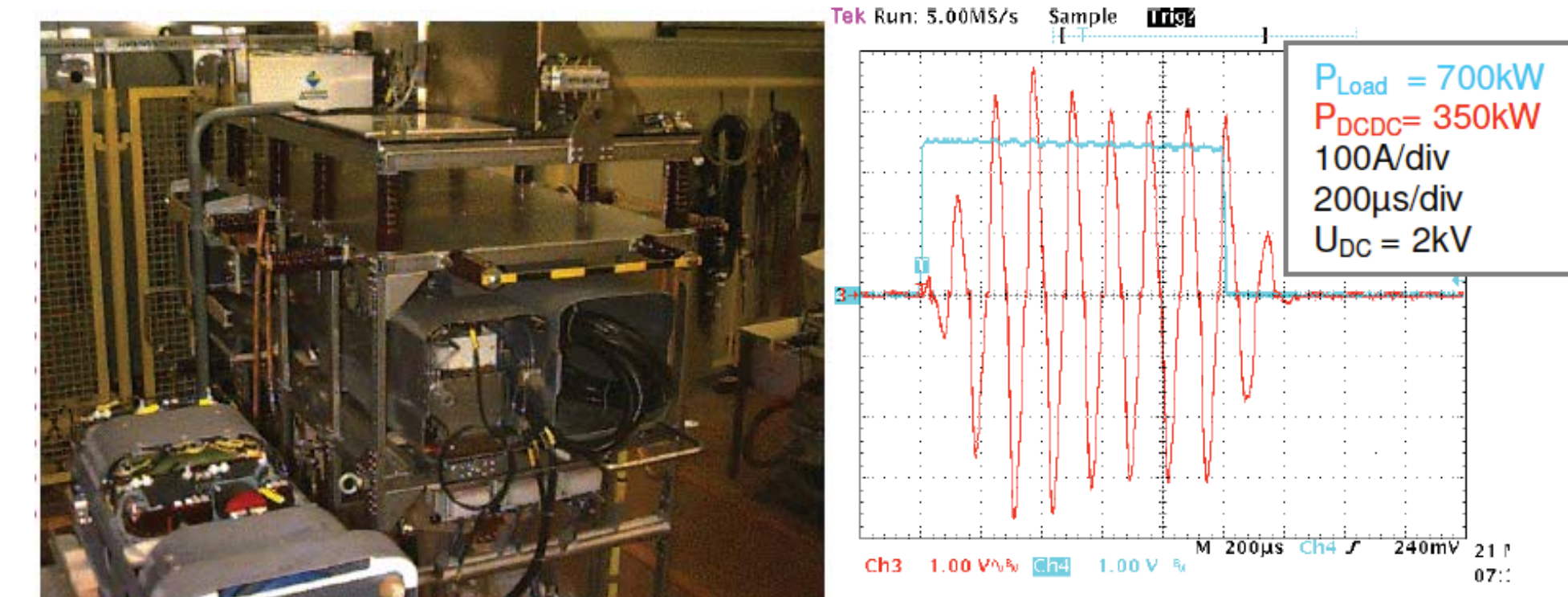
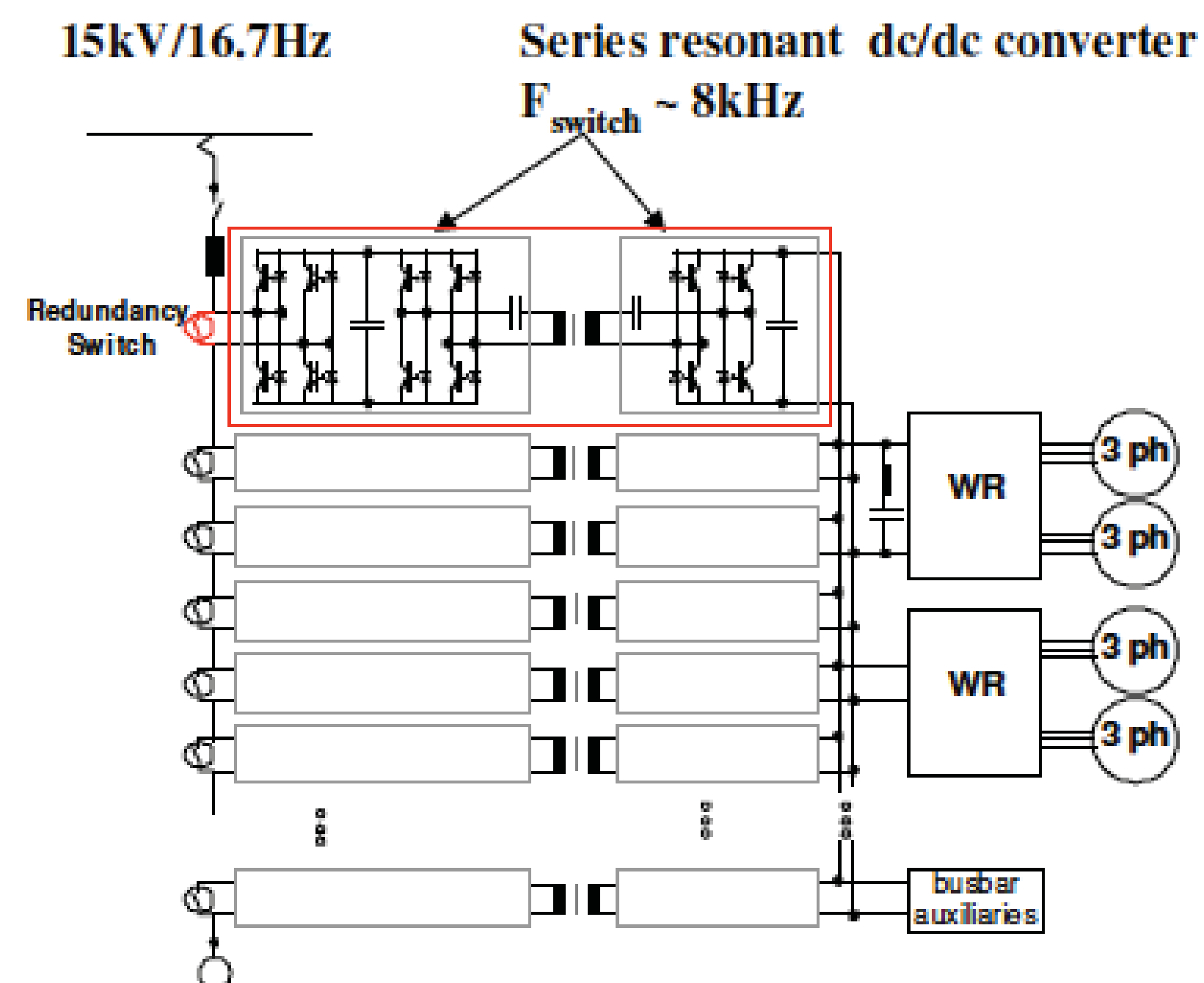
▲ 350kW MFT by Bombardier [11]

## MFT dimensions

- ▶ Volume: not reported
- ▶ V-Density: ? kW/l
- ▶ Weight: 18 kg
- ▶ Density:  $\approx 7$  kW/kg

## Insulation Tests

- ▶ PD: 33kV, 50Hz
- ▶ BIL: 100 kV (1.2/50)



▲ Medium frequency topology by Bombardier

# ABB MFT - 2011

## Construction

- ▶ C-core
- ▶ Assembly with 3 MFTs

## Electrical Ratings

- ▶ Power: 150kW
- ▶ Frequency: 1.75kHz
- ▶ Input Voltage:  $\pm 1800V$
- ▶ Output Voltage:  $\pm 750V$

## Core Material

- ▶ Nanocrystalline
- ▶ C-cut cores

## Windings

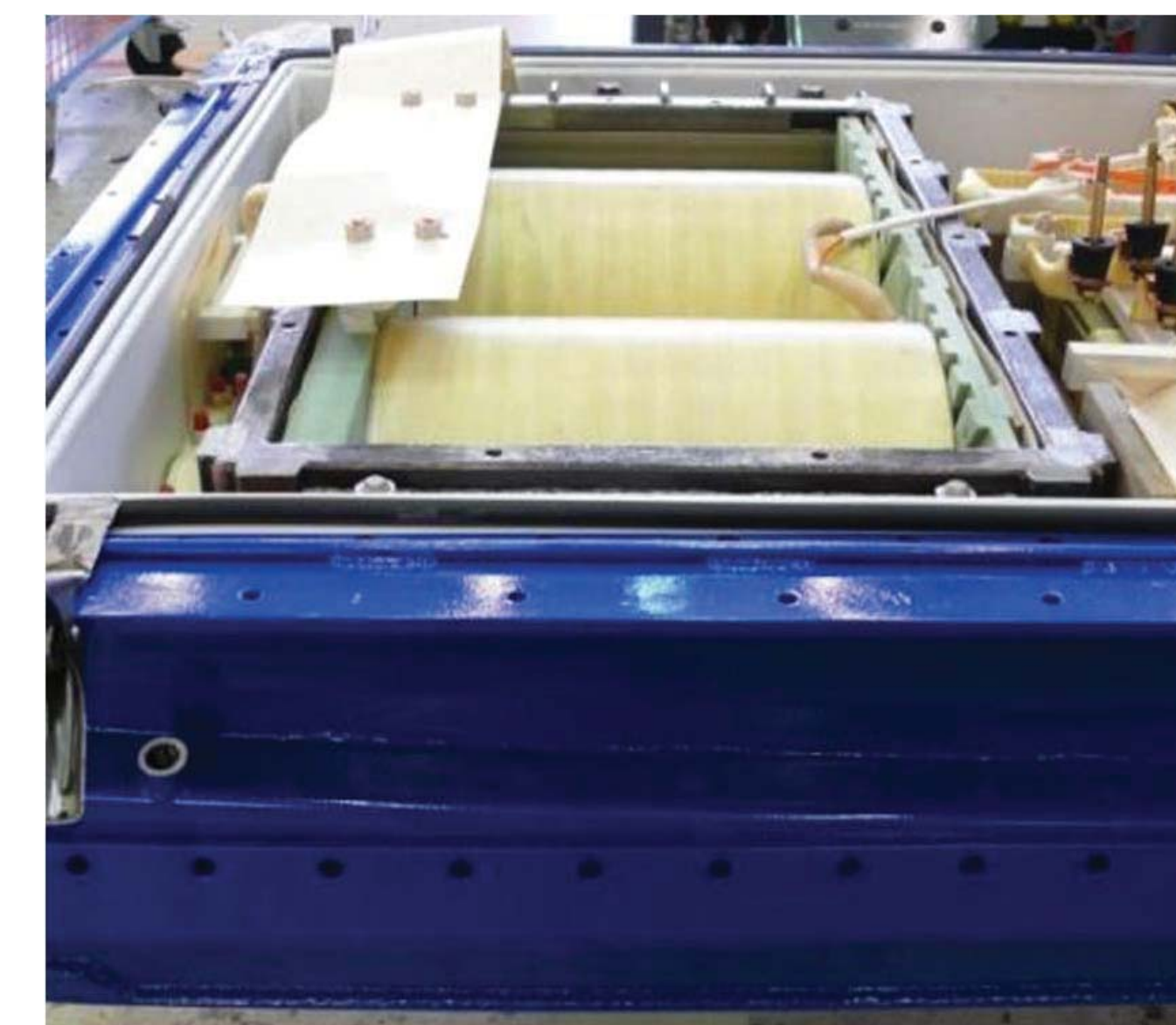
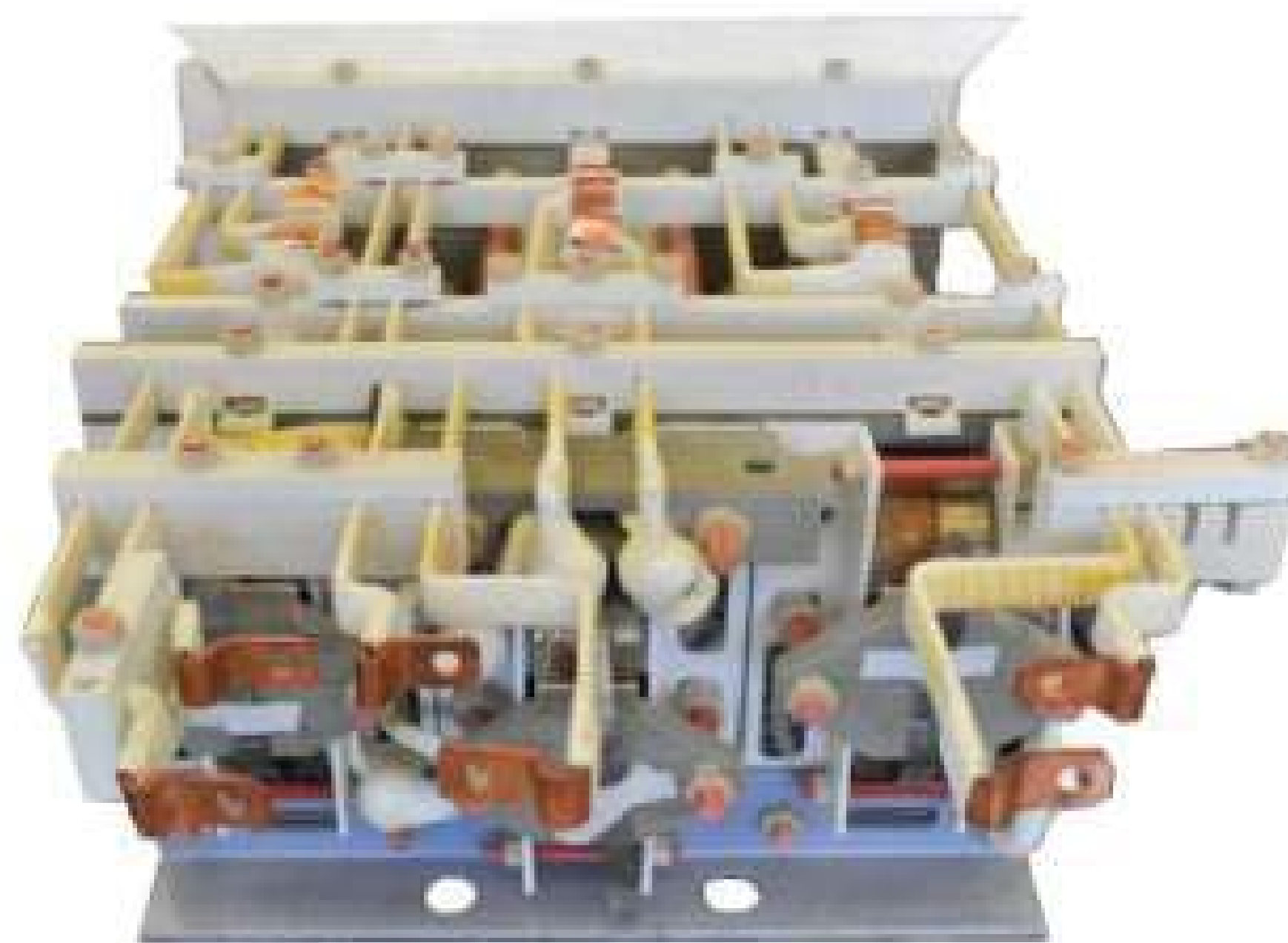
- ▶ Bar wire

## Cooling

- ▶ Oil

## Insulation

- ▶ Oil
- ▶ Immersed



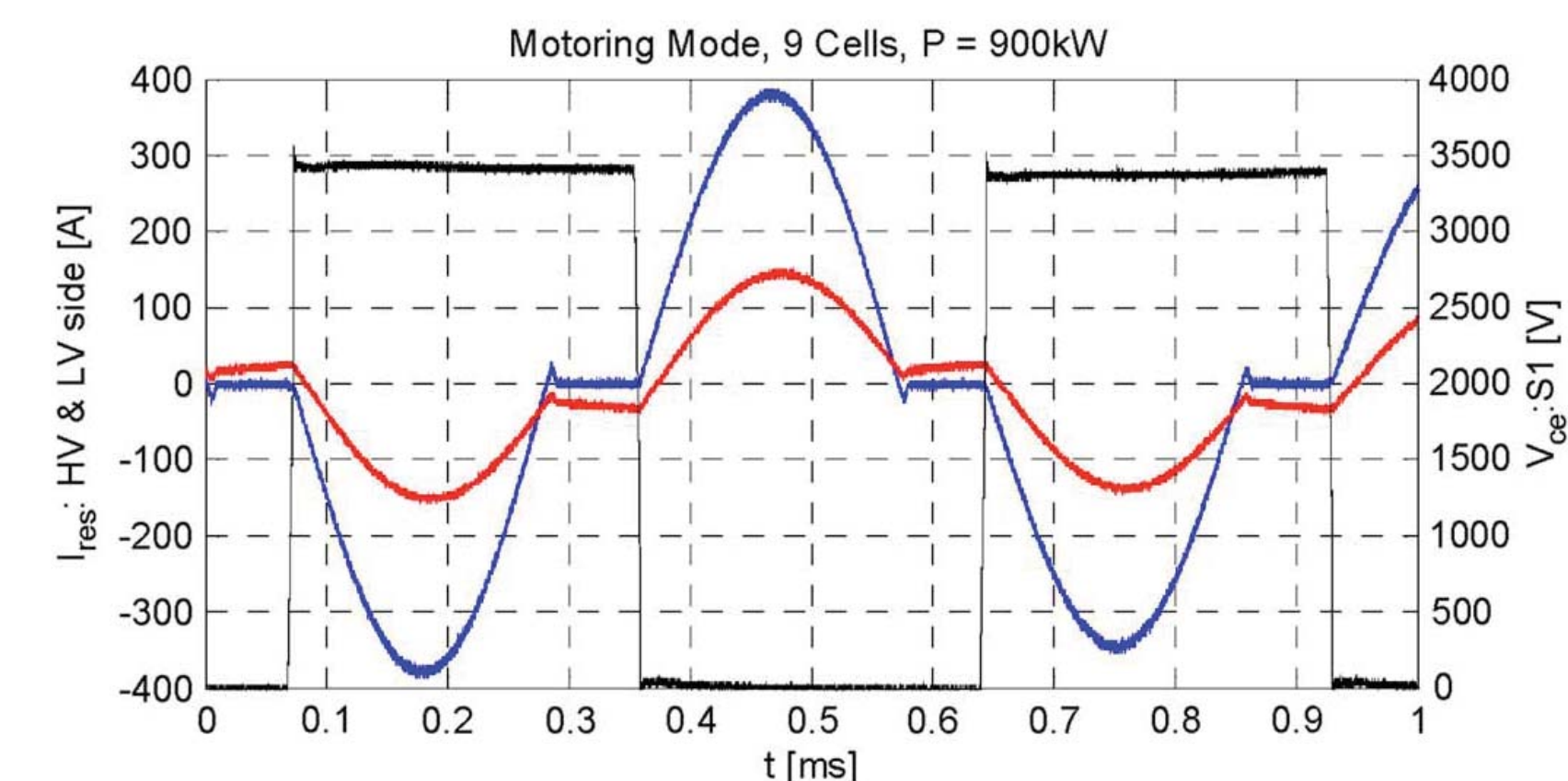
- ▲ 3 x 150kW MFT by ABB

## MFT dimensions

- ▶ Volume:  $\approx 80$  l
- ▶ V-Density:  $\approx 2.4$  kW/l
- ▶ Weight:  $\approx 170$  kg
- ▶ W-Density:  $\approx 1.1$  kW/kg

## PETT dimensions

- ▶ Weight: 4.5 t



- ▲ PETT tank with magnetics by ABB [6], [7]

## Construction

- ▶ Core Type

## Electrical Ratings

- ▶ Power: 450kW
- ▶ Frequency: 5.6kHz
- ▶ Input Voltage:  $\pm 3600V$
- ▶ Output Voltage:  $\pm 3600V$

## Core Material

- ▶ Nanocrystalline VITROPERM 500F
- ▶ U cores

## Windings

- ▶ Aluminum
- ▶ Hollow profiles

## Cooling

- ▶ Winding - de-ionized water
- ▶ Core - Oil

## Insulation

- ▶ Oil - Immersed (primary to secondary)
- ▶ NOMEX - between turns



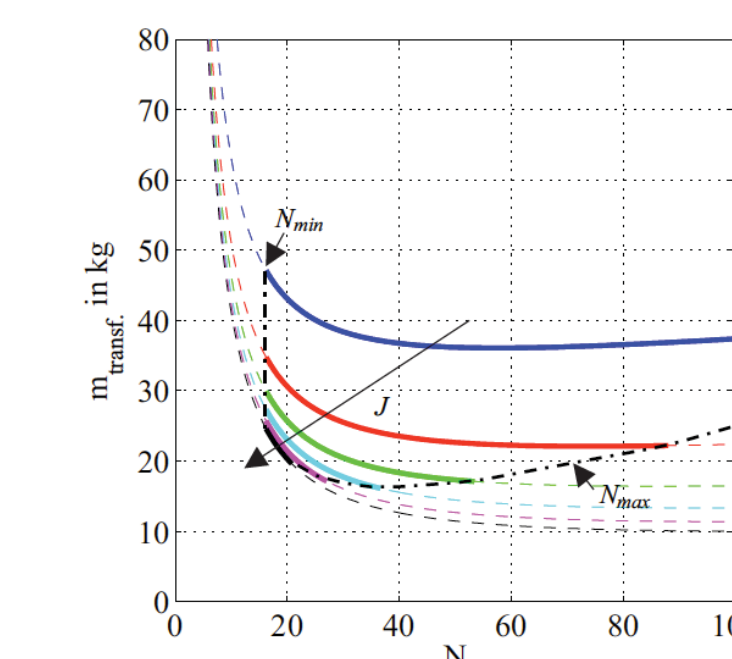
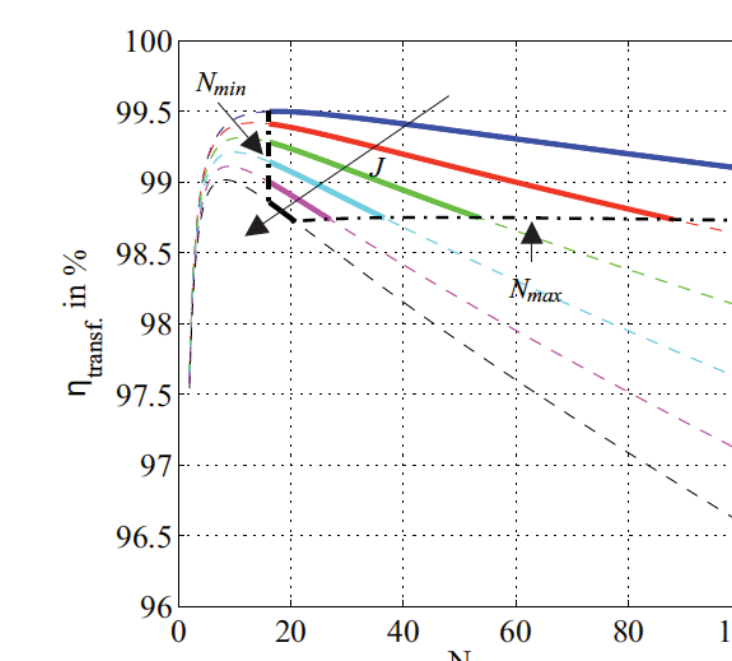
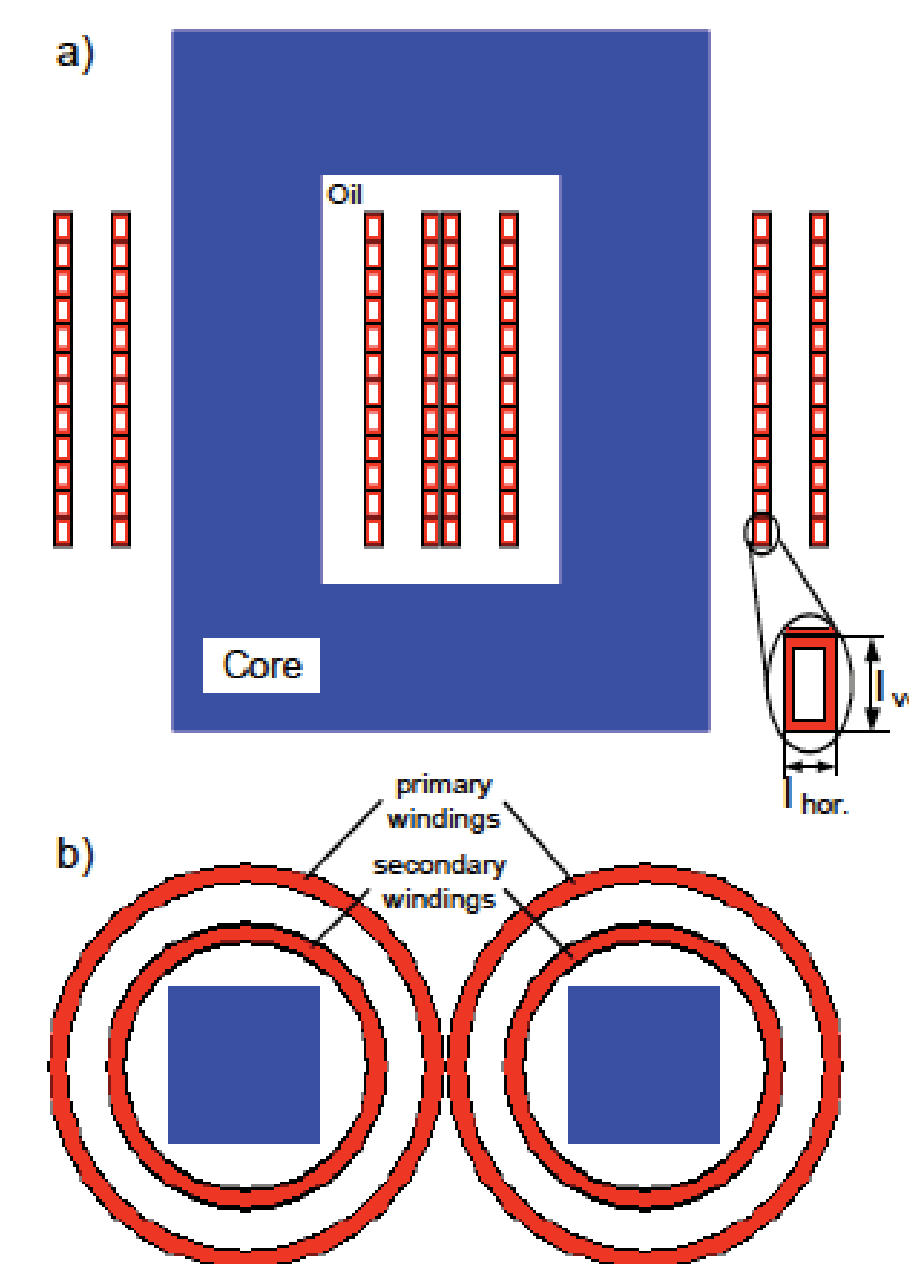
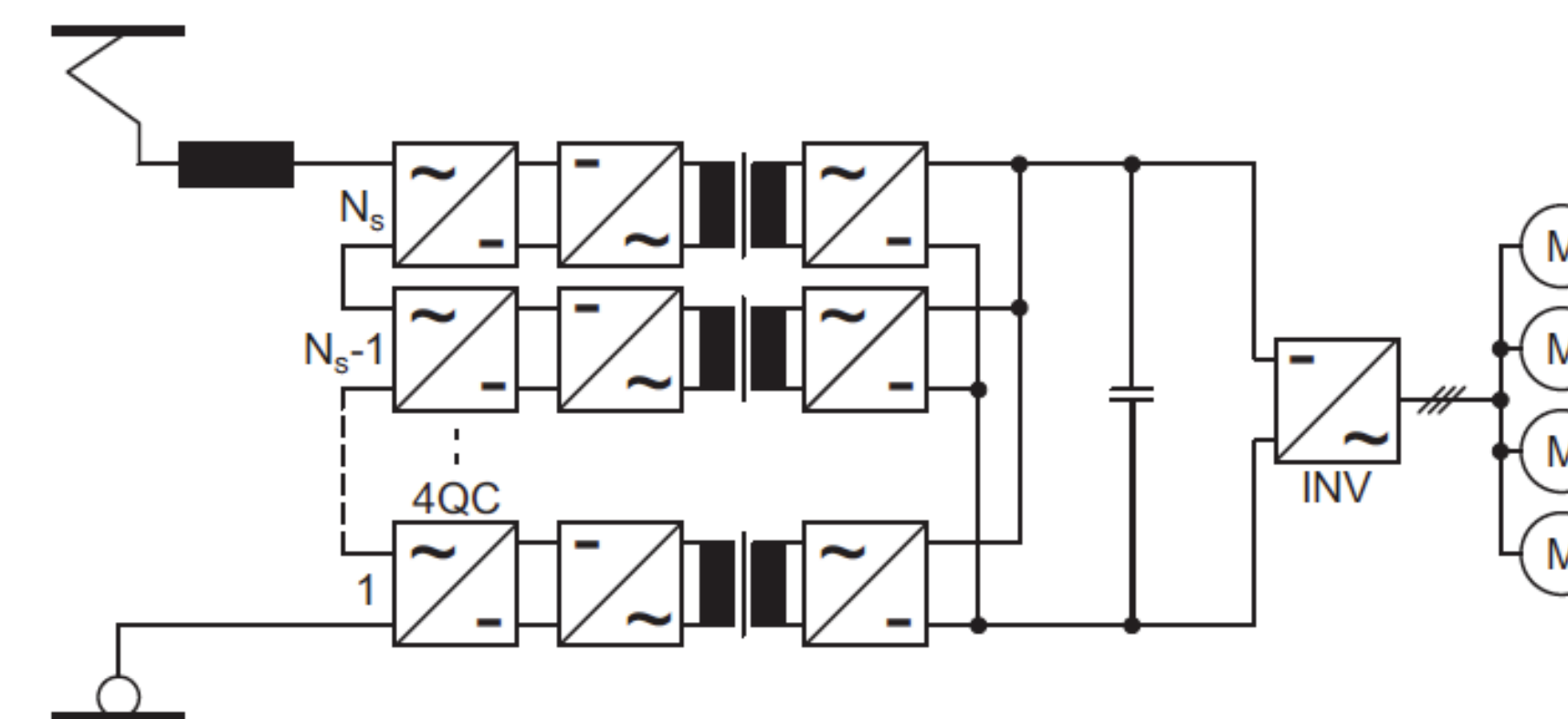
▲ 450kW MFT by UEN [12], [13], [14]

## MFT dimensions

- ▶ Volume: not reported
- ▶ V-Density: ? kW/l
- ▶ Weight: 24 - 38.2 kg
- ▶ W-Density:  $\approx 18.8 - 11.8$  kW/kg

## Insulation Tests

- ▶ Designed for 25kV railway lines
- ▶ PD, BIL: not reported



▲ MFT by UEN

# ETHZ PES MFT - 2014

## Construction

- ▶ Shell Type
- ▶ for the use with HC-DCM-SRC

## Electrical Ratings

- ▶ Power: 166kW
- ▶ Frequency: 20kHz
- ▶ Input Voltage:  $\pm 1000V$
- ▶ Output Voltage:  $\pm 400V$

## Core Material

- ▶ Nanocrystalline Vitroperm 500F
- ▶ C-cores

## Windings

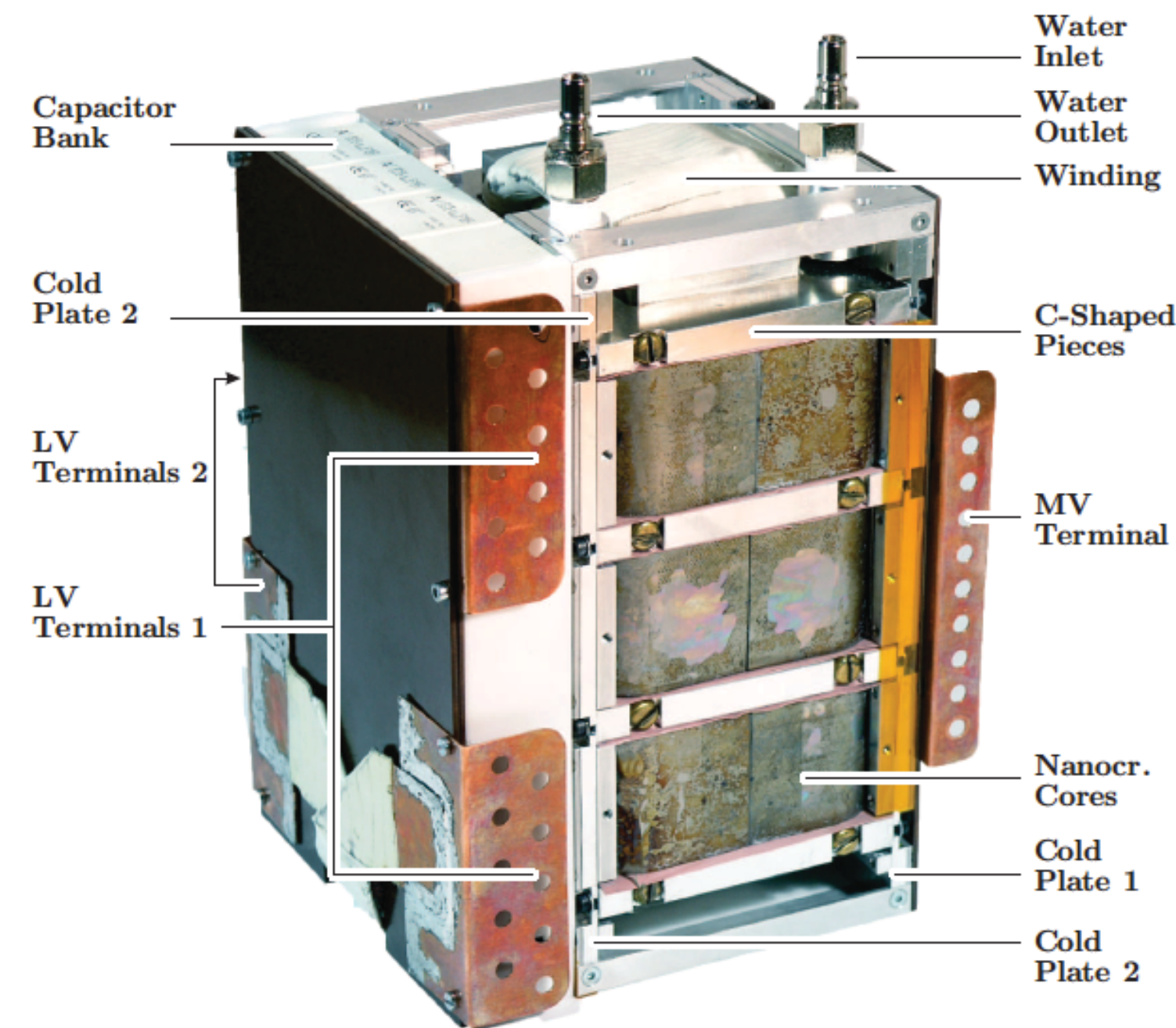
- ▶ Square Litz Wire

## Cooling

- ▶ Water-cooled heat sinks

## Insulation

- ▶ Solid
- ▶ Mica tape



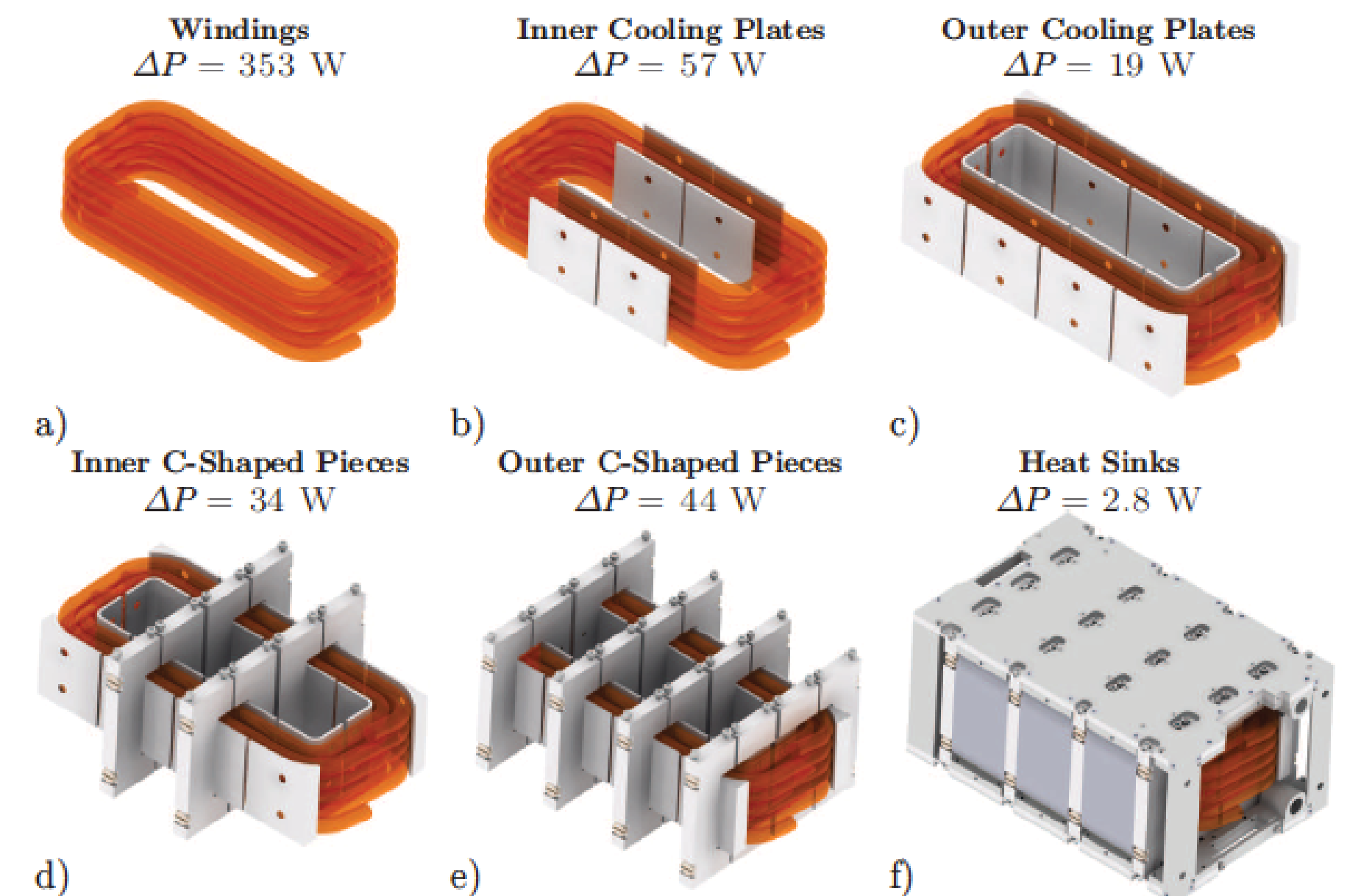
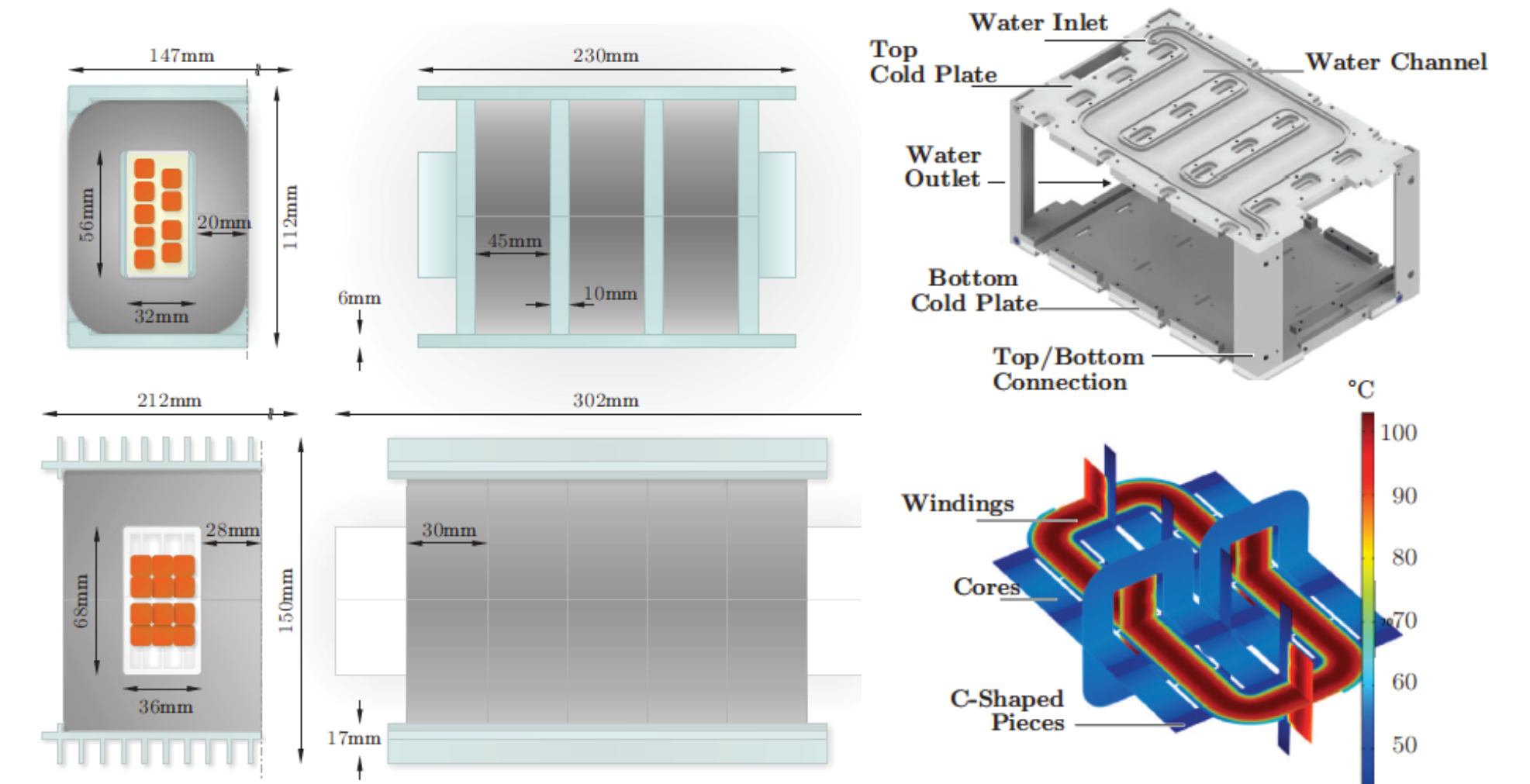
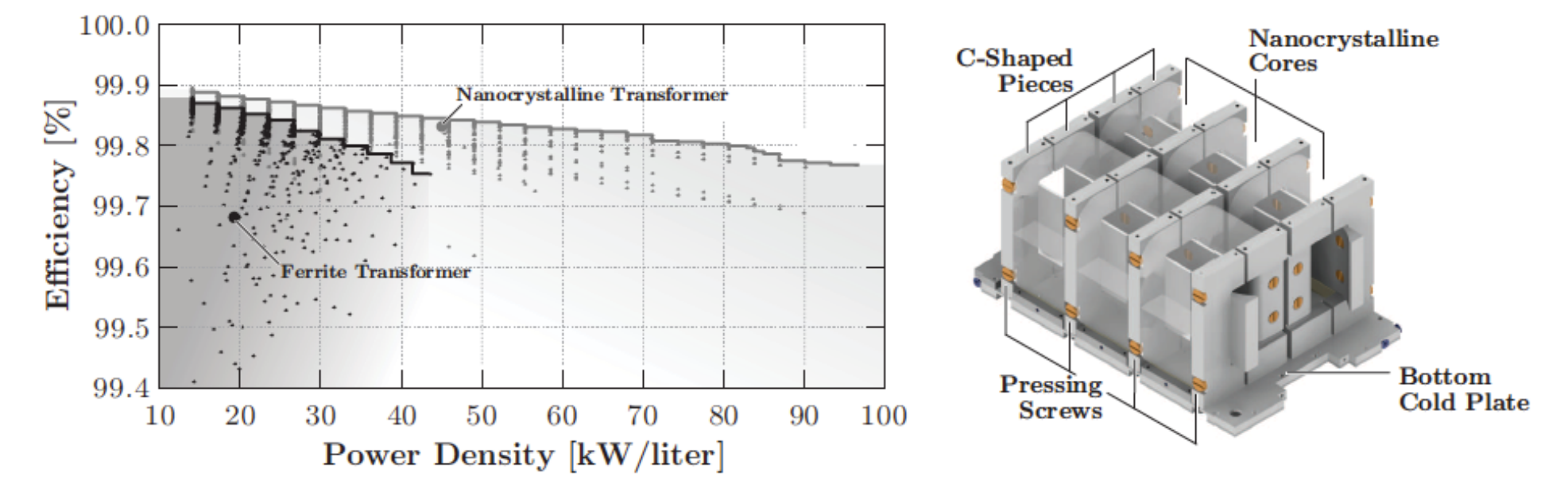
- ▲ 166kW MFT by ETH [15], [16], [17]

## MFT dimensions

- ▶ Volume:  $\approx 5$  l
- ▶ V-Density:  $\approx 32.7$  kW/l
- ▶ Weight:  $\approx 10$  kg
- ▶ W-Density:  $\approx 16.6$  kW/kg

## Insulation Tests

- ▶ No details provided



- ▲ Nanocrystalline MFT by ETHZ

# ETHZ PES MFT - 2014 (CONT.)

## Construction

- ▶ Shell Type
- ▶ for the use with TCM-DAB

## Electrical Ratings

- ▶ Power: 166kW
- ▶ Frequency: 20kHz
- ▶ Input Voltage:  $\pm 750V$
- ▶ Output Voltage:  $\pm 750V$

## Core Material

- ▶ Ferrite N87
- ▶ U-cores U96/76/30

## Windings

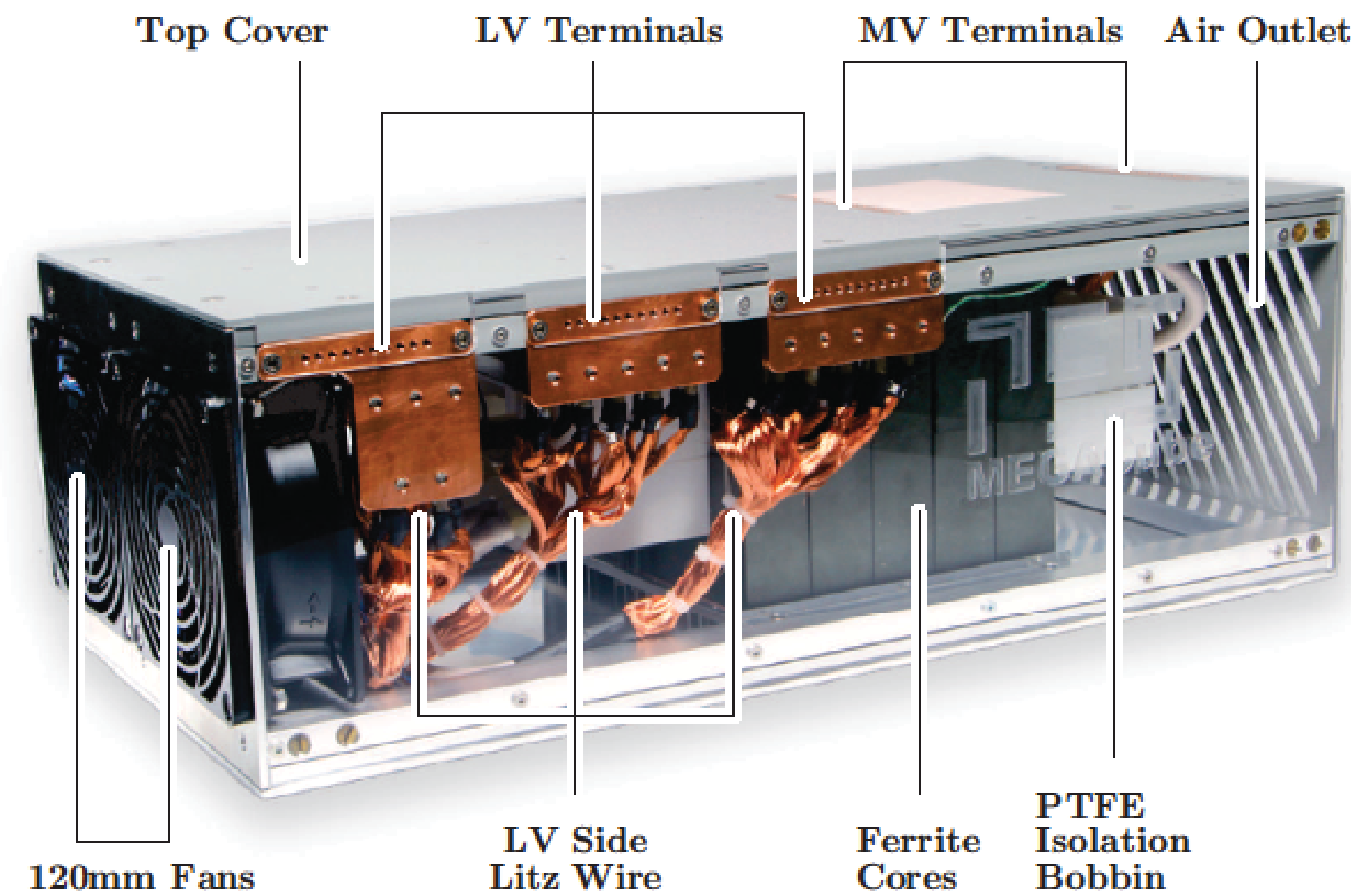
- ▶ Square Litz Wire

## Cooling

- ▶ Winding - Forced air
- ▶ Core - Heatsinks (Forced air)

## Insulation

- ▶ PTFE (teflon)



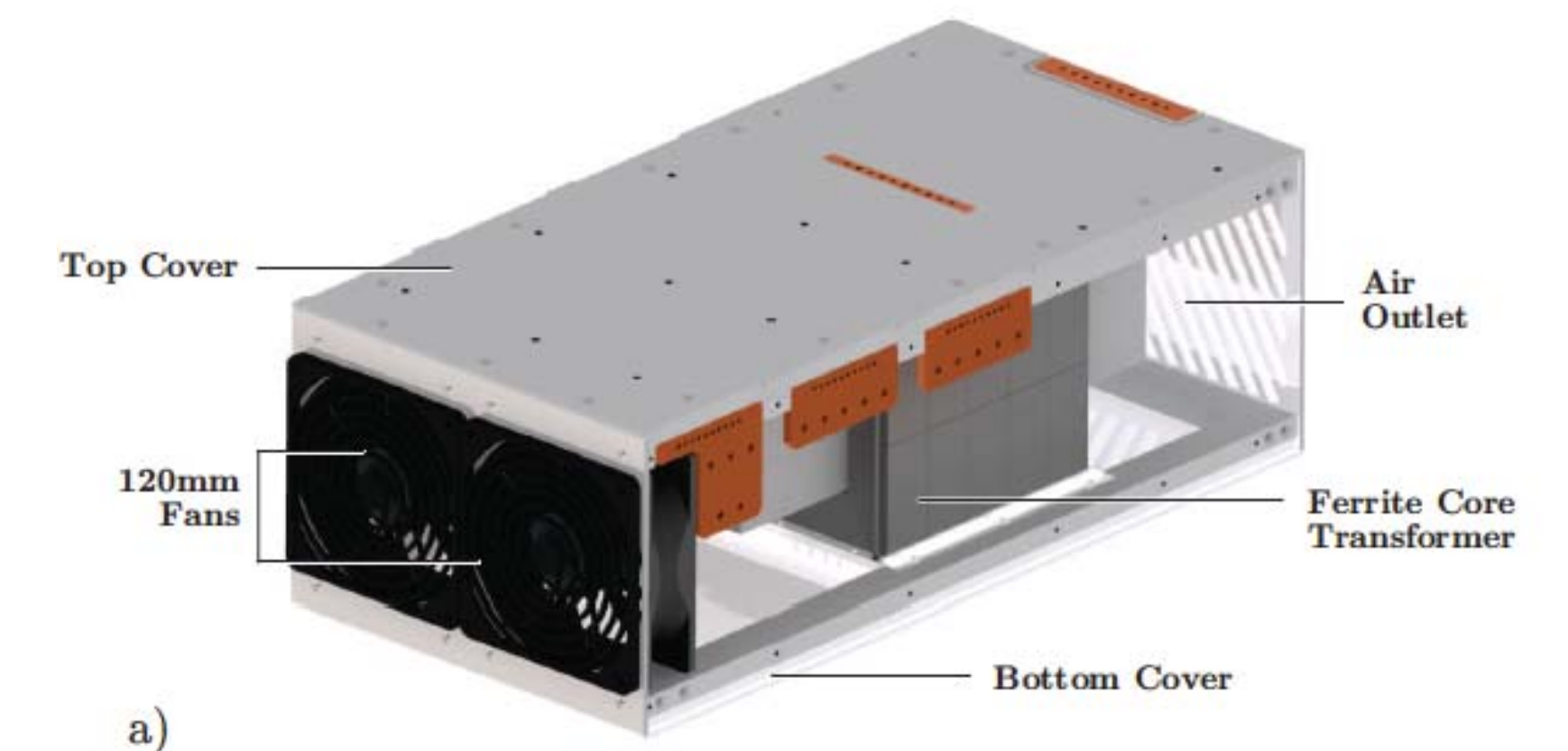
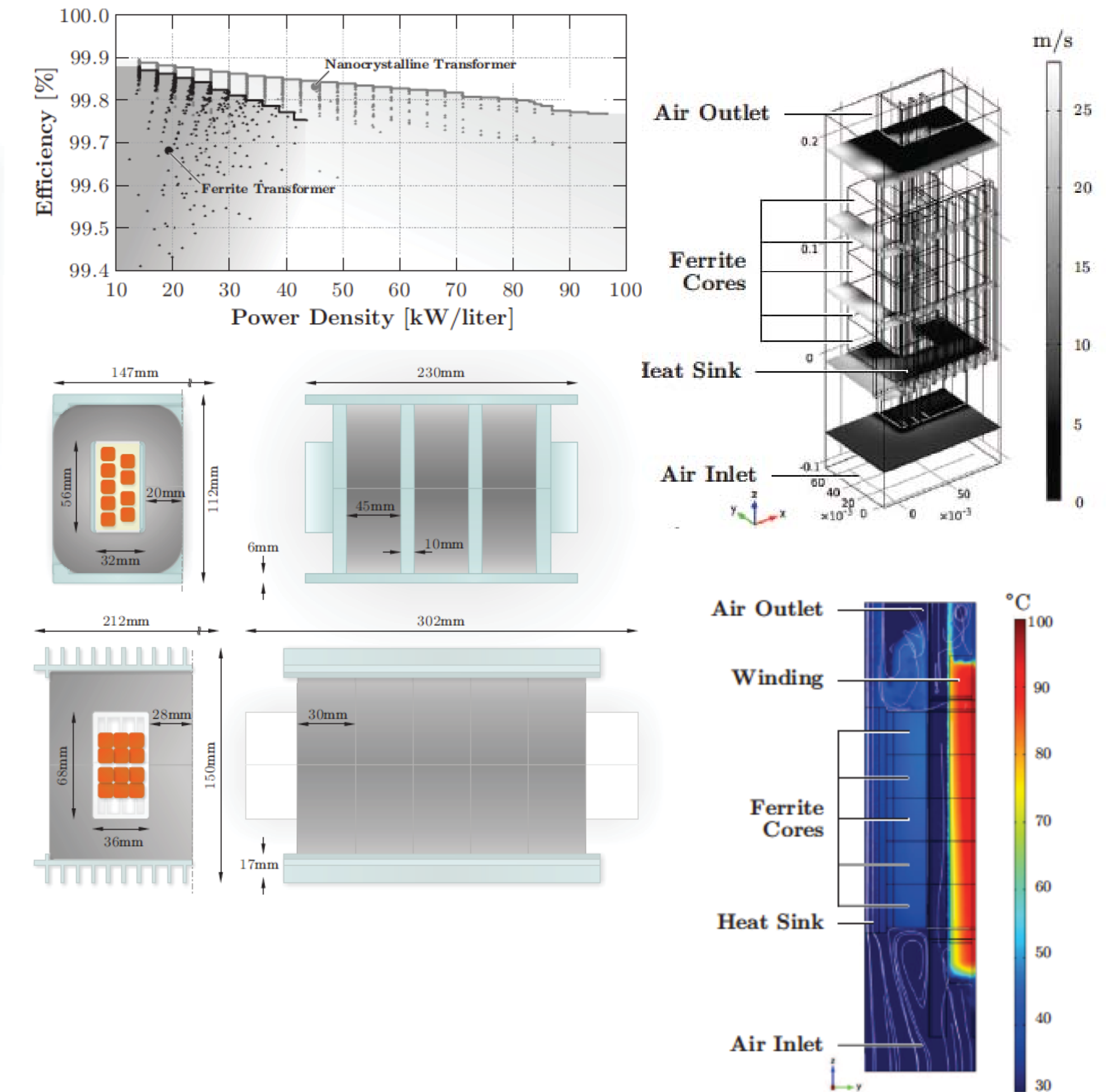
- ▲ 166kW MFT by ETH [15]

## MFT dimensions

- ▶ Volume:  $\approx 20$  l
- ▶ V-Density:  $\approx 8.21$  kW/l
- ▶ Weight: not reported
- ▶ W-Density: not reported

## Insulation Tests

- ▶ No details provided



- ▲ Ferrite MFT by ETHZ

# EPFL PEL MFT - 2017

## Construction

- ▶ Core Type

## Electrical Ratings

- ▶ Power: 100kW
- ▶ Frequency: 10kHz
- ▶ Input Voltage:  $\pm 750V$
- ▶ Output Voltage:  $\pm 750V$

## Core Material

- ▶ SiFerrite (UU9316 - CF139)
- ▶ U cores

## Windings

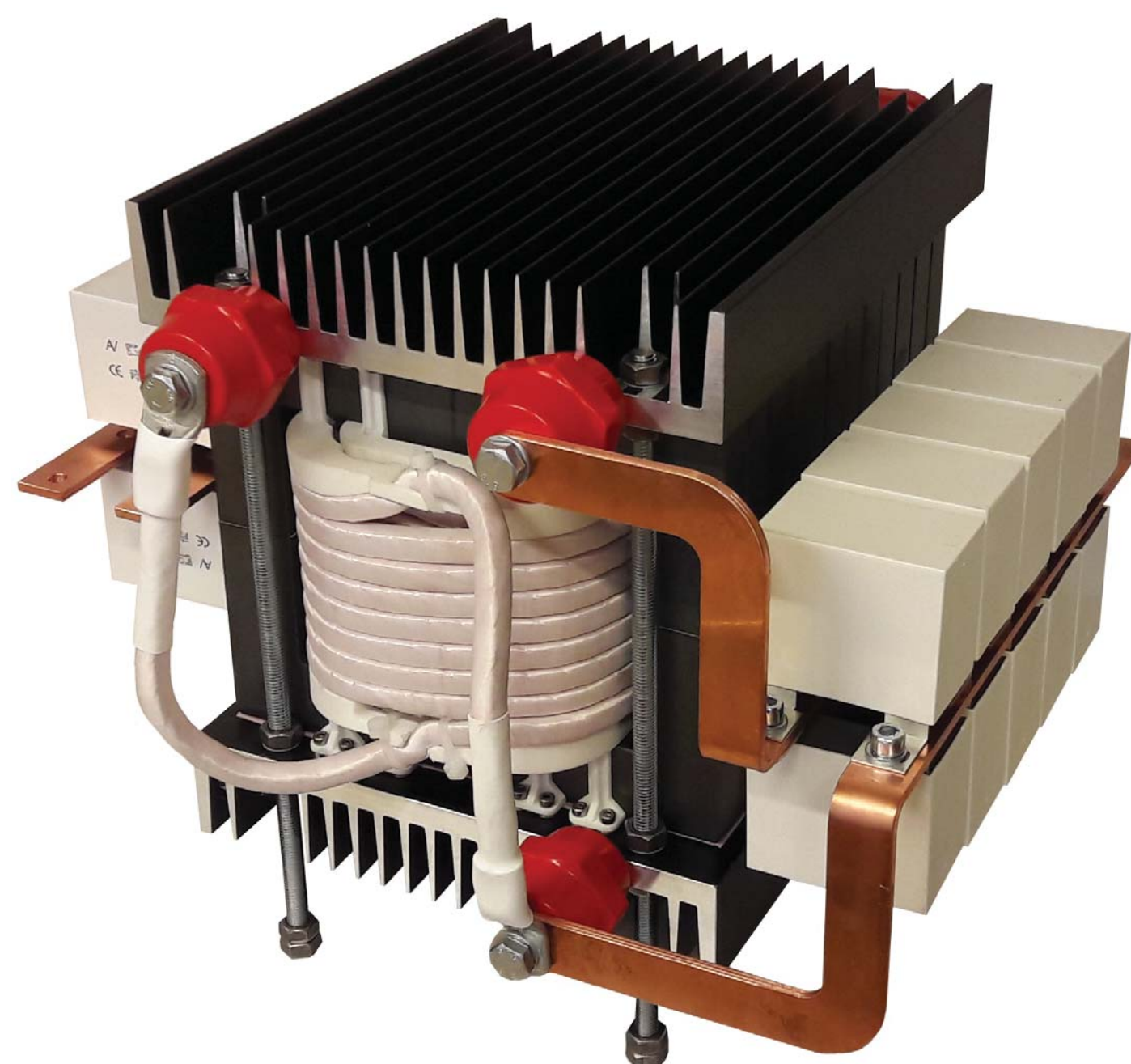
- ▶ Square Litz Wire

## Cooling

- ▶ Winding - Air
- ▶ Core - Air cooled heatsink

## Insulation

- ▶ Air



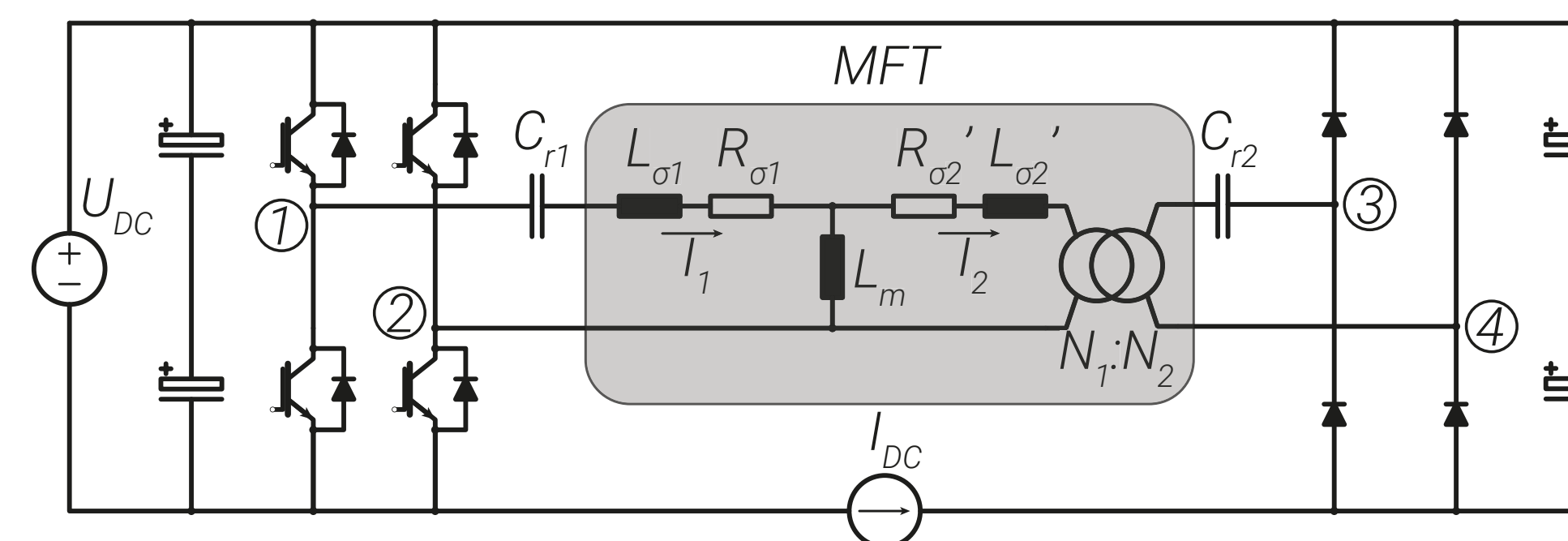
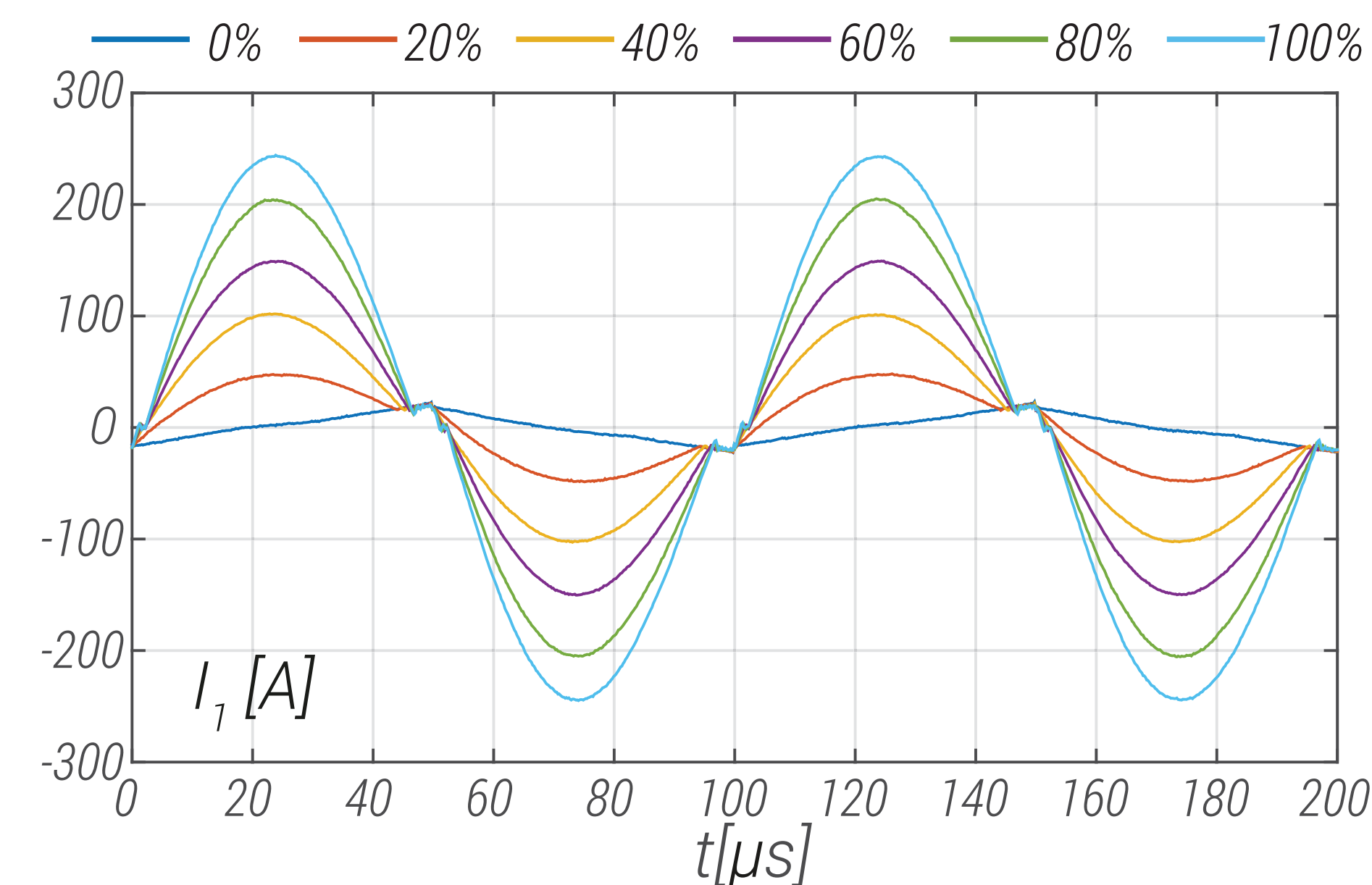
- ▲ 100kW MFT by EPFL [18]

## MFT dimensions

- ▶ Volume: 12.2 l
- ▶ V-Density:  $\approx 8.2 \text{ kW/l}$
- ▶ Weight: 28 kg
- ▶ W-Density:  $\approx 3.6 \text{ kW/kg}$

## Insulation Tests

- ▶ PD: 6kV, 50Hz
- ▶ BIL: not performed



- ▲ MFT by EPFL

# SUMMARY - MFT DESIGNS

## Variety of MFT designs

- ▶ Shell Type, Core Type, C-Type
- ▶ Copper, Aluminum
- ▶ Solid wire, Hollow conductors, Litz wire, Foil
- ▶ SiFe, Nanocrystalline, Amorphous, Ferrite


## Integration with Power Electronics

- ▶ Insulation coordination
- ▶ Cooling
- ▶ Electrical parameters
- ▶ Choice of core materials
- ▶ Form factor constraints
- ▶ Optimization at the system level

## Custom designs prevail

## There is no best design...

Limited commercial options. Example: STS ⇒




**Railway**

**MF Transformer for Traction**

Applications	Your benefits
<ul style="list-style-type: none"> <li>• MF transformer directly linked to catenary (15 kV @ 16 2/3 Hz, 25 kV @ 50 Hz)</li> <li>• Cascadable – e.g. 9 x 450 kW = 4 MW</li> <li>• High Voltage P.D. stable insulation system up to 37 kVrms (P. D. &lt; 5 pC)</li> <li>• Switching frequency: 8 kHz</li> <li>• Power: 450 kW / 600 kVA (single transformer)</li> <li>• Weight: 50 kg</li> <li>• Efficiency: 99,7 %</li> </ul>	<ul style="list-style-type: none"> <li>• Distributed traction power supply possible</li> <li>• Reducing system weight by 40 %</li> <li>• Long life time due to P. D. free solid-fluid insulation system</li> <li>• Low noise</li> <li>• Environmental insulation and cooling system of transformer</li> </ul>

www.sts-trafo.de



Source/ Type	$P_n$ kVA	Freq. kHz	$U_{iso}$ kV	Core mat.*	Cooling method	Tran. Power density <sup>†</sup>	Eff.* %	Struct./ Wind. <sup>‡</sup>
GE:1992[65] Dry	50	50	N/A	Ferr.	Air	12(wt)	99.4 <sup>a,c</sup>	Coaxial/ Cable
GE:2008[66] Dry	150	10	N/A	Amor.	Air	N/A	N/A	Core/ Ro. Litz
UWM:1995[67] Dry	120	20.4	N/A	Ferr.	Water	59.5(vol)	99.6 <sup>a,c</sup>	Coaxial/ Cable
ABB:2002[43] Dry	350	10	15	Nano.	Water	>7(wt) <sup>‡</sup>	N/A	Coaxial/ Cable
ABB:2007[47] Oil	75	0.4	15	Si-Fe	Oil	N/A	>95 <sup>b,c</sup>	So. Cu
ABB:2011[50, 52] Oil	150	1.75	15	Nano.	Oil	N/A	≈96 <sup>b,c</sup>	Ro. Litz
KTH:2009[68] Oil	170	4	30	Amor.	Water Oil	3.45(wt)	99 <sup>a,c</sup>	Shell/ Ro. Litz Foil
TUD:2005[69, 70] Dry	50	25	N/A	Nano.	Water	≈50(vol)	>97 <sup>b,c</sup>	Shell/ Foil
Bomb:2007[30] Dry	500	8	15	Nano.	Water	27.8(wt)	N/A	Shell/ Hol. Al
FAU:2011[71] Oil	450	5.6	25	Nano.	Water Oil	N/A	N/A	Core/ Hol. Al
NCSU:2010[72] <sup>◊</sup> Dry	10	3	15	Amor.	Air	N/A	96.76 <sup>a,c</sup> 97.3 <sup>a,c</sup> 97.16 <sup>a,c</sup>	Core/ Ro. Litz
NCSU:2012[73] Dry	30	20	9.5	Nano.	Air	N/A	99.5 <sup>a,d</sup>	Coaxial/ Ro. Litz So. Cu
EPFL:2010[8] Dry	25	2	8	Amor.	Air	2.5(vol)	99.13 <sup>a,d</sup>	Shell/ Rec. Litz
IK4:2012[74] <sup>◊</sup> Dry	400	<1 >5	18	Si-Fe Nano.	Air Fan	3.41(vol) 14.88(vol)	99.36 <sup>a,d</sup> 99.76 <sup>a,d</sup>	Shell Core
ETH:2013[14, 23] <sup>◊</sup> Dry	166	20	N/A	Nano. Ferr.	Water Fan	32.7(vol) 8.21(vol)	99.5 <sup>a,c</sup> 99.4 <sup>a,c</sup>	Shell/ Rec. Litz
ETH:2015[75] <sup>◊</sup> Dry	25	25 50 83	N/A	Ferr.	Air	8.2(vol) 13.3(vol) 15.9(vol)	N/A	Matrix/ Litz
Chalm:2016[76] <sup>◊</sup> Dry	50	5	6	Nano. Ferr.	Air Air	15.1(vol) 11.5(vol)	99.66 <sup>a,c</sup> 99.58 <sup>a,c</sup>	Shell/ Rec. Litz
STS:2014[77] Oil/Dry <sup>∇</sup>	450	8	>30	N/A	Oil Air	9(wt)	99.7 <sup>a,c</sup>	Shell/ Litz

▲ Another overview of MFTs reported in literature [19]

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# COFFEE BREAK







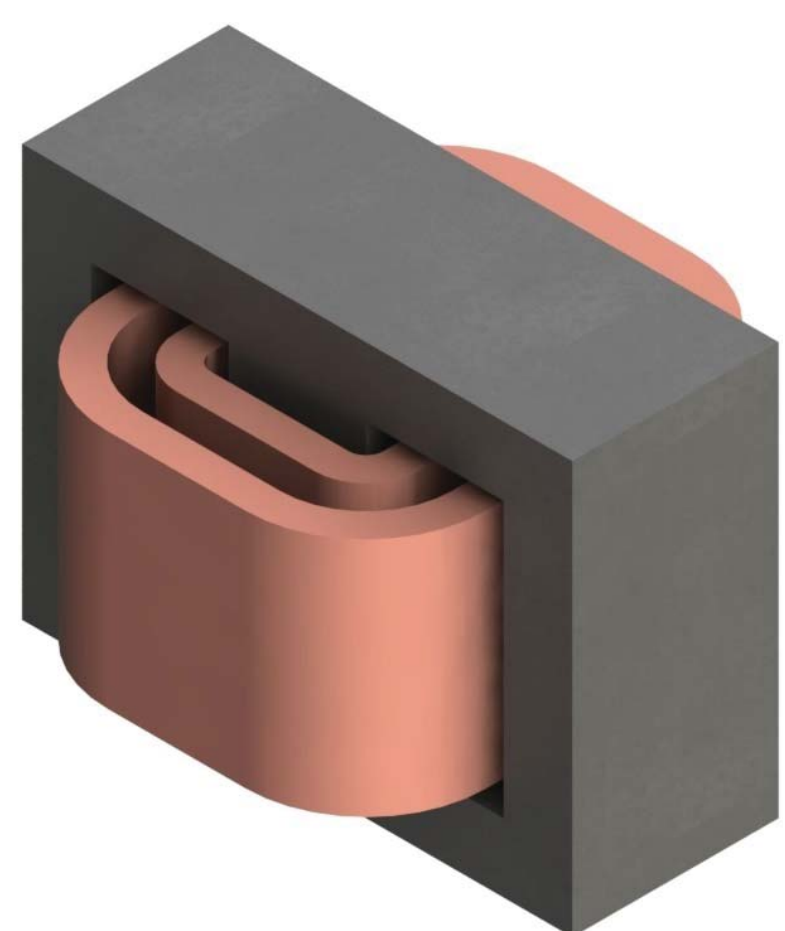
# MATERIALS

*What design choices are available?*

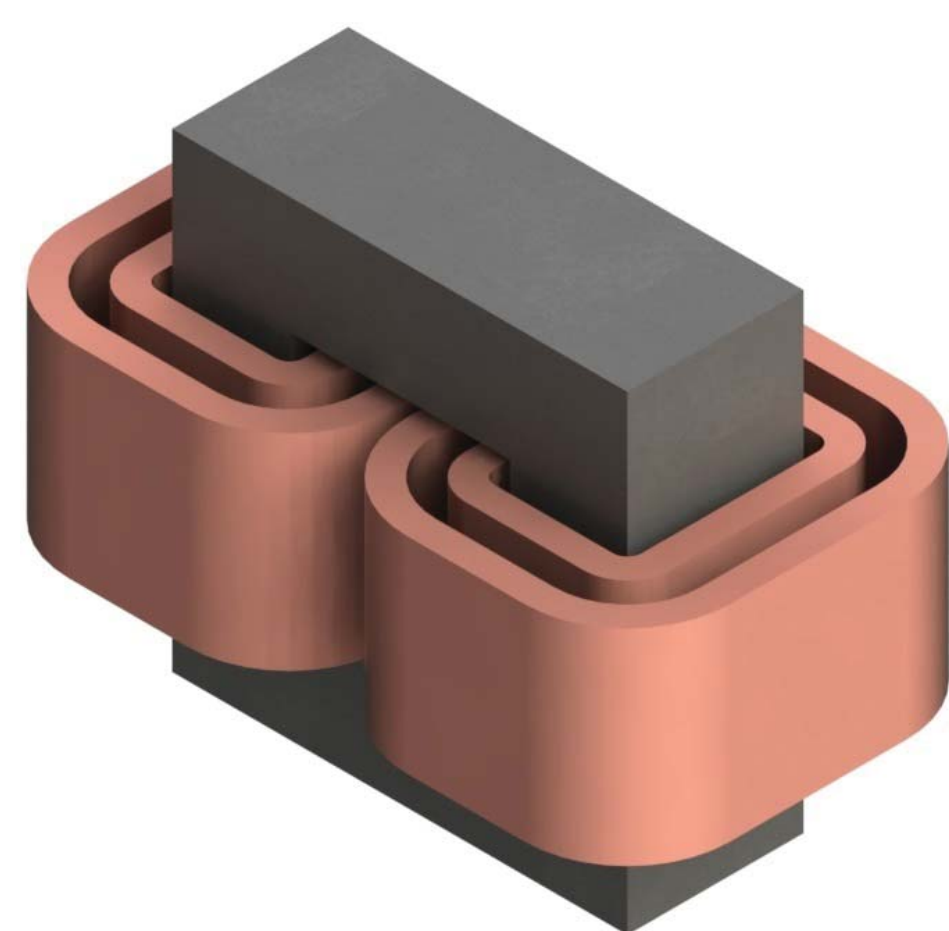
# TECHNOLOGIES AND MATERIALS

## Construction Choices:

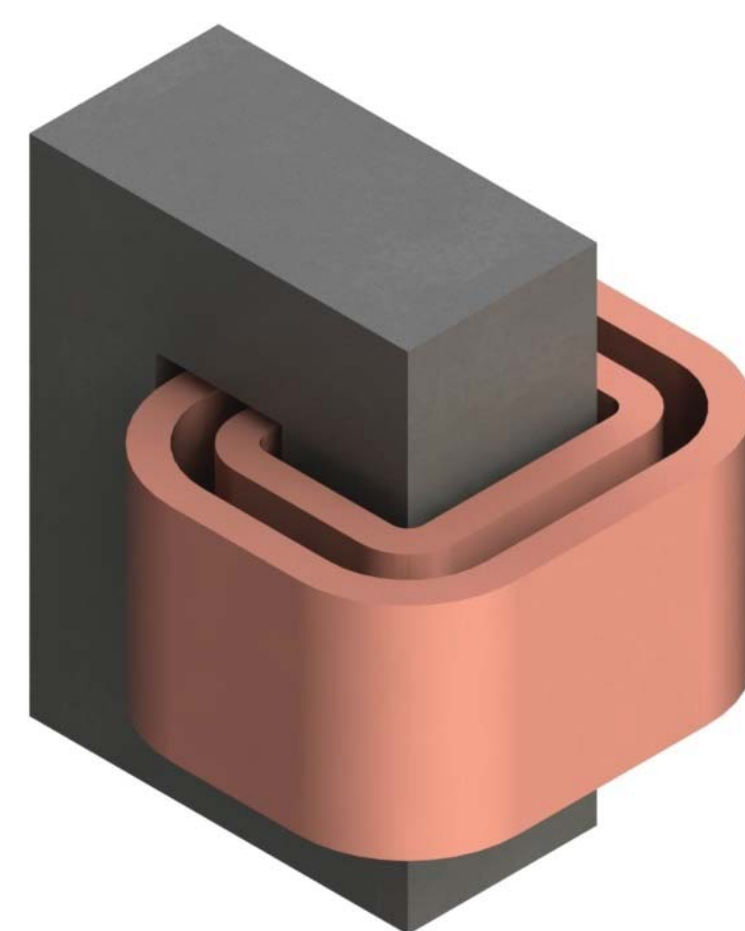
### ▶ MFT Types



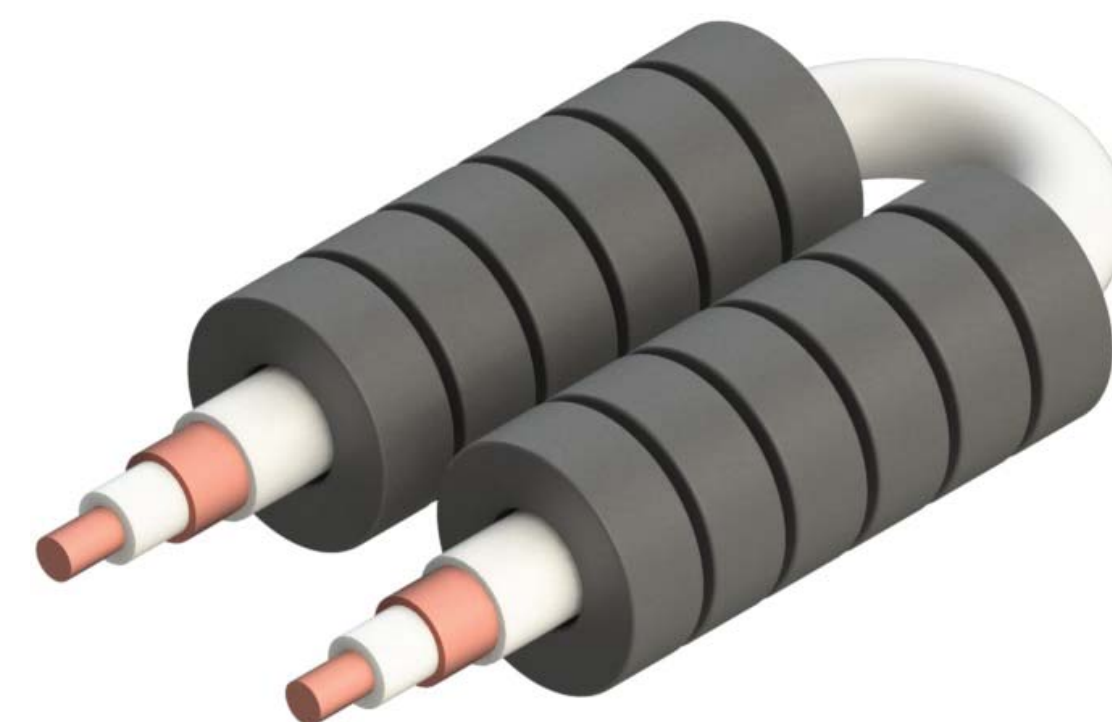
Shell Type



Core Type



C-Type



Coaxial Type

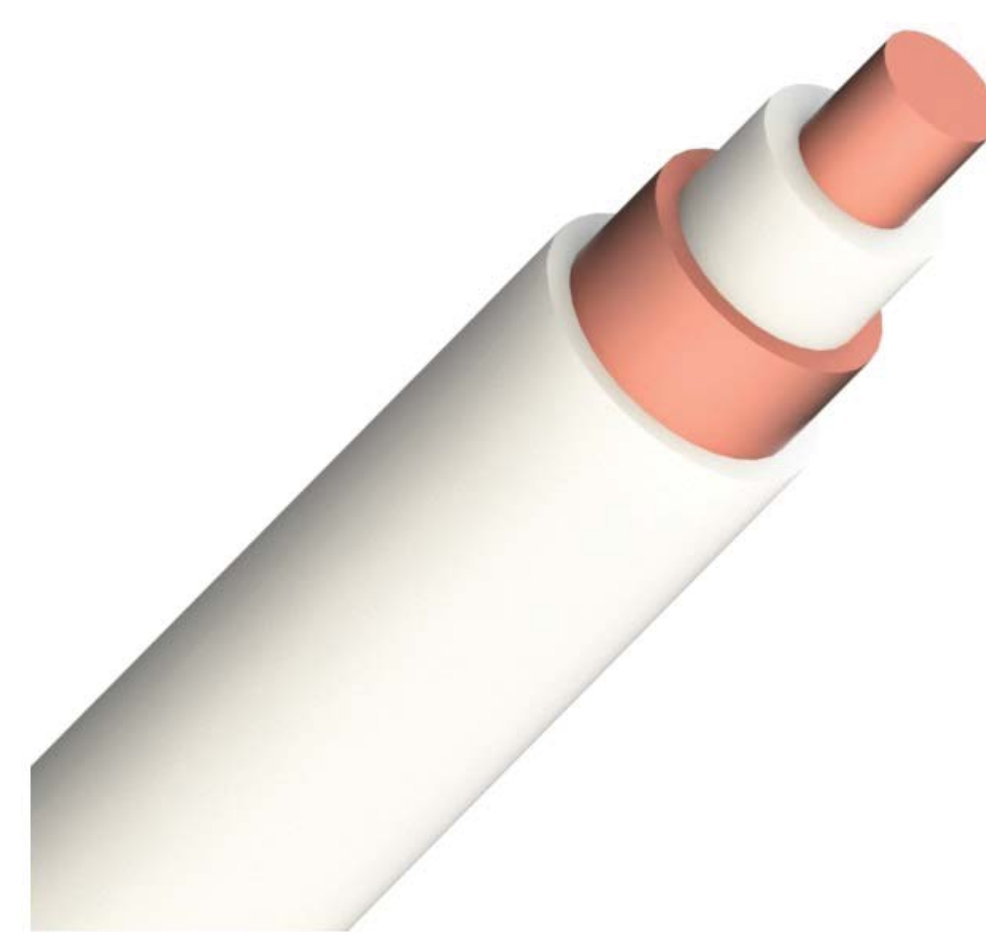
### ▶ Winding Types



Litz Wire



Foil



Coaxial



Hollow

## Materials:

### ▶ Magnetic Materials

- ▶ Silicon Steel
- ▶ Amorphous
- ▶ Nanocrystalline
- ▶ Ferrites

### ▶ Windings

- ▶ Copper
- ▶ Aluminum

### ▶ Insulation

- ▶ Air
- ▶ Solid
- ▶ Oil

### ▶ Cooling

- ▶ Air natural/forced
- ▶ Oil natural/forced
- ▶ Water

# MAGNETIC MATERIALS - SILICON STEEL

## Ferromagnetic - Silicon Steel

- ▶ Iron based alloy of Silicon provided as isolated laminations
- ▶ Mostly used for line frequency transformers

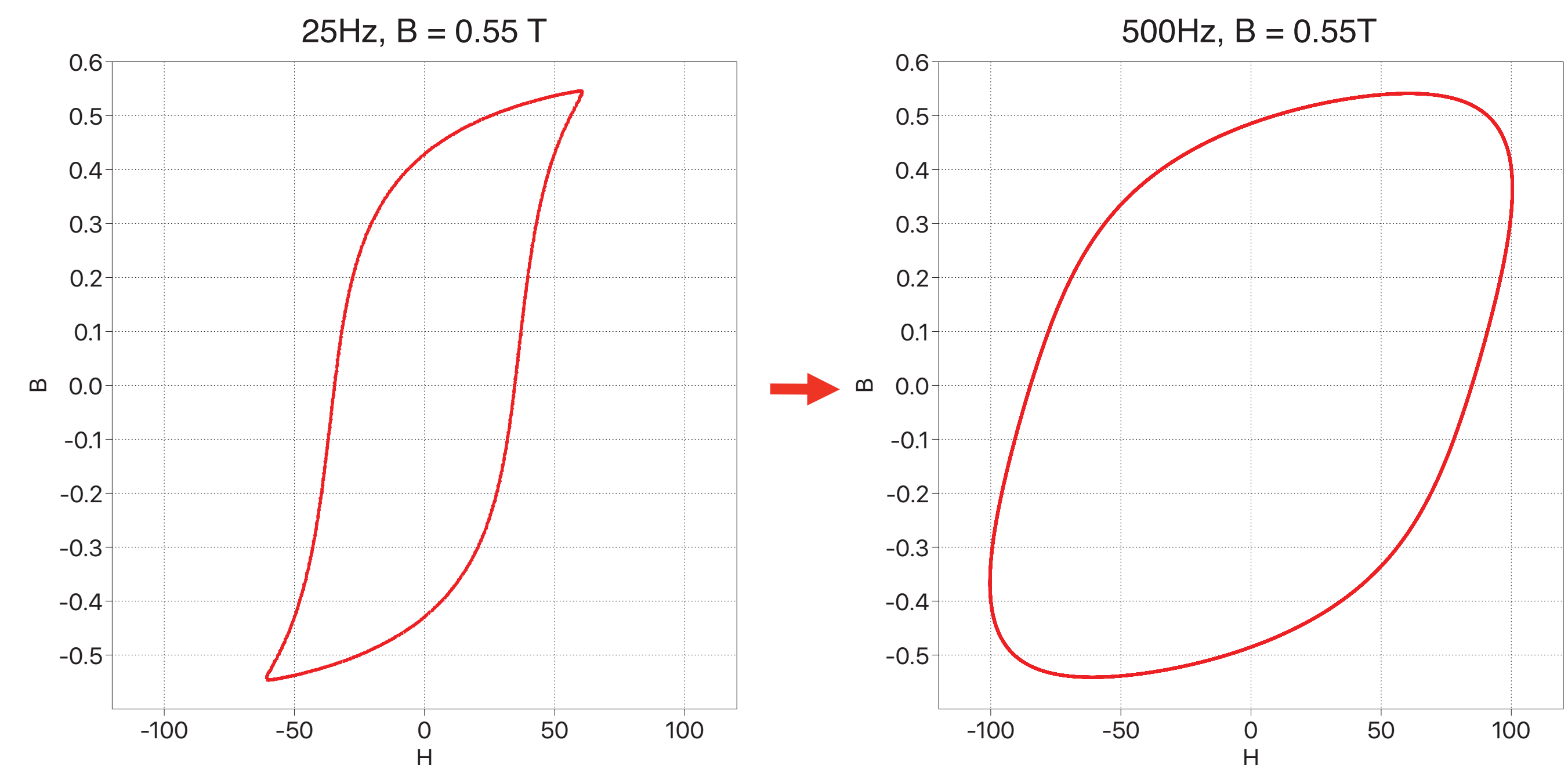
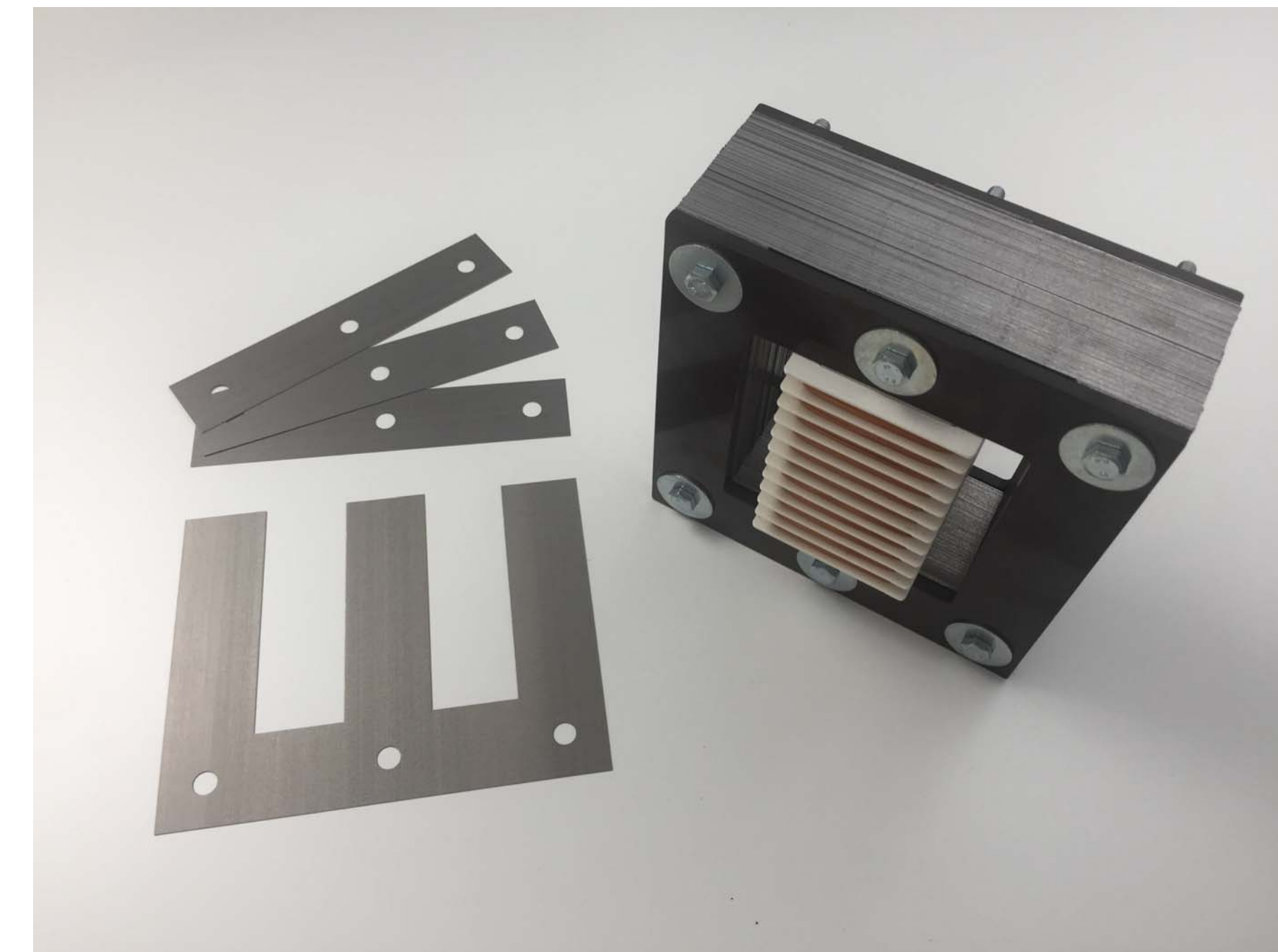
## Advantages

- ▶ Wide initial permeability range
- ▶ High saturation flux density
- ▶ High Curie-temperature
- ▶ Relatively low cost
- ▶ Mechanically robust
- ▶ Various core shapes available (easy to form)

## Disadvantages

- ▶ High hysteresis loss (irreversible magnetisation)
- ▶ High eddy current loss (high electric conductivity)
- ▶ Acoustic noise (magnetostriction)

Saturation B	Init. permeability	Core loss (10 kHz, 0.5T)	Conductivity
0.8 ~ 2.2 T	$0.6 \sim 100 \cdot 10^3$	50 ~ 250 W/kg	$2 \cdot 10^7 \sim 5 \cdot 10^7$ S/m



▲ Example: Measured B-H curve of M330-35 laminate

# MAGNETIC MATERIALS - AMORPHOUS ALLOY

## Ferromagnetic - Amorphous Alloy

- ▶ Iron based alloy of Silicon as thin tape without crystal structure
- ▶ For both line frequency and switching frequency applications

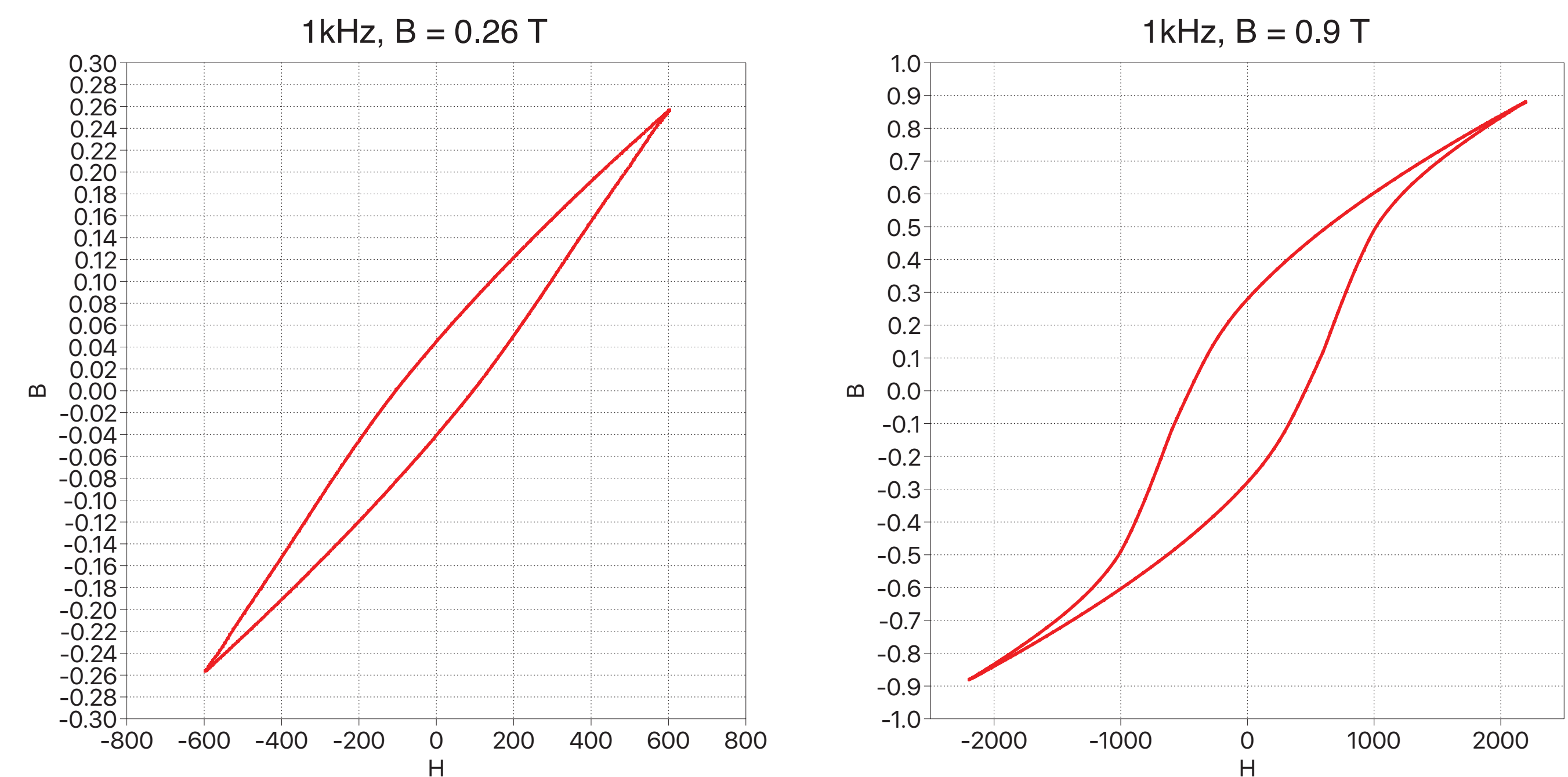
## Advantages

- ▶ High saturation flux density
- ▶ Low hysteresis loss
- ▶ Low eddy current loss (low electric conductivity)
- ▶ High Curie-temperature
- ▶ Mechanically robust

## Disadvantages

- ▶ Relatively narrow initial permeability range
- ▶ Very high acoustic noise (magnetostriction)
- ▶ Limited core shapes available (difficult to form)
- ▶ Relatively expensive

Saturation B	Init. permeability	Core loss (10kHz, 0.5T)	Conductivity
0.5 ~ 1.6 T	$0.8 \cdot 10^3 \sim 50 \cdot 10^3$	2 ~ 20 W/kg	$< 5 \cdot 10^3$ S/m



▲ Example: Measured B-H curve of Metglas 2605SA

# MAGNETIC MATERIALS - NANOCRYSTALLINE ALLOY

## Ferromagnetic - Nanocrystalline Alloy

- ▶ Iron based alloy of silicon as thin tape with minor portion of crystal structure
- ▶ For both line frequency and switching frequency applications

## Advantages

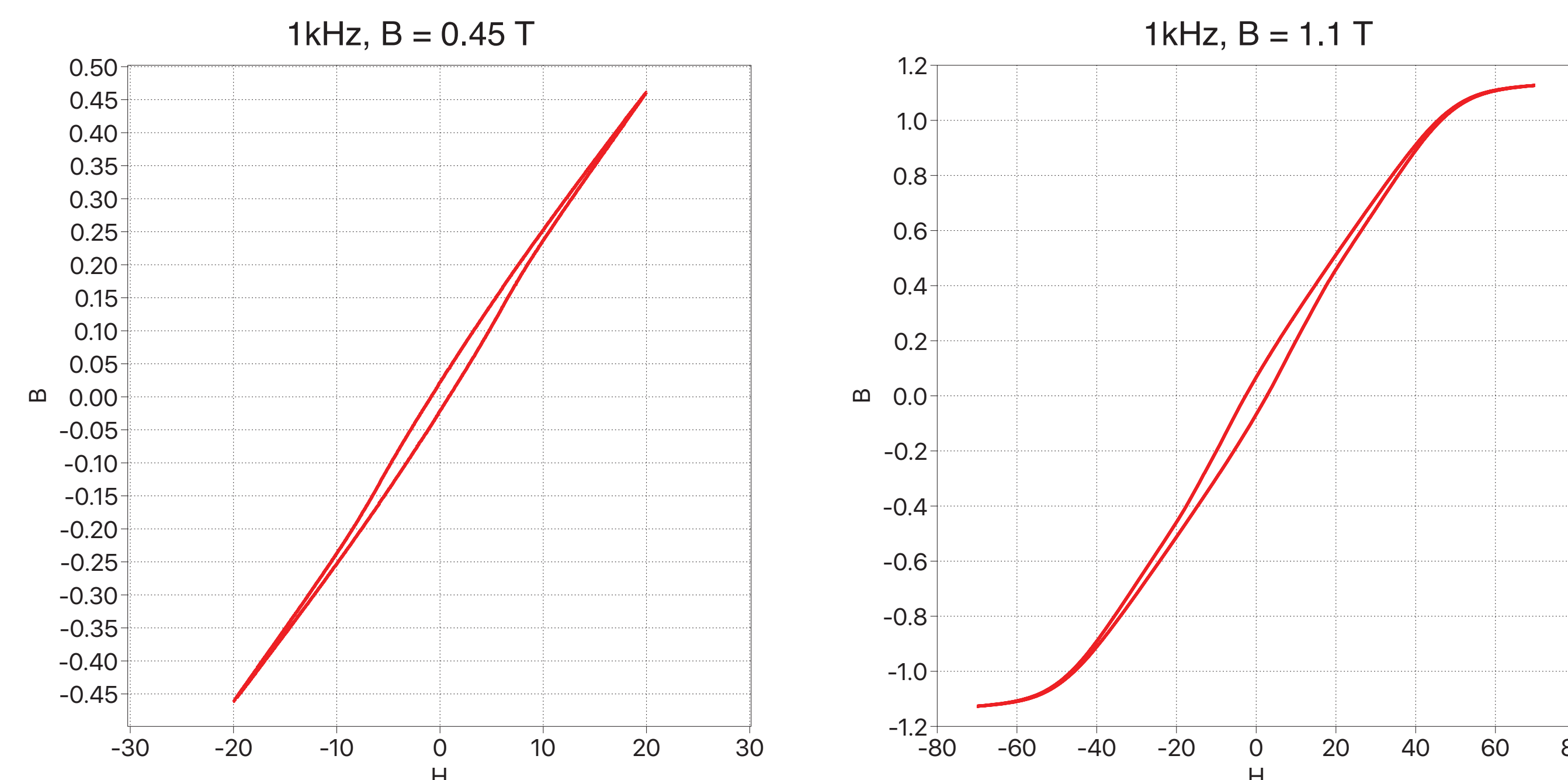
- ▶ Relatively narrow initial permeability range
- ▶ High saturation flux density
- ▶ Low hysteresis loss
- ▶ High Curie-temperature
- ▶ Low acoustic noise

## Disadvantages

- ▶ Eddy current loss (compensated thanks to the thin tape)
- ▶ Mechanically fragile
- ▶ Limited core shapes available (difficult to form)
- ▶ Relatively expensive



Saturation B	Init. permeability	Core loss (10kHz, 0.5T)	Conductivity
1 ~ 1.2 T	$0.5 \cdot 10^3 \sim 100 \cdot 10^3$	< 50 W/kg	$3 \cdot 10^3 \sim 5 \cdot 10^4$ S/m



▲ Example: Measured B-H curve of VITROPERM 500F

# MAGNETIC MATERIALS - FERRITES

## Ferrimagnetic - Ferrites

- ▶ Ceramic material made from powder of different oxides and carbons
- ▶ For both line frequency and switching frequency applications

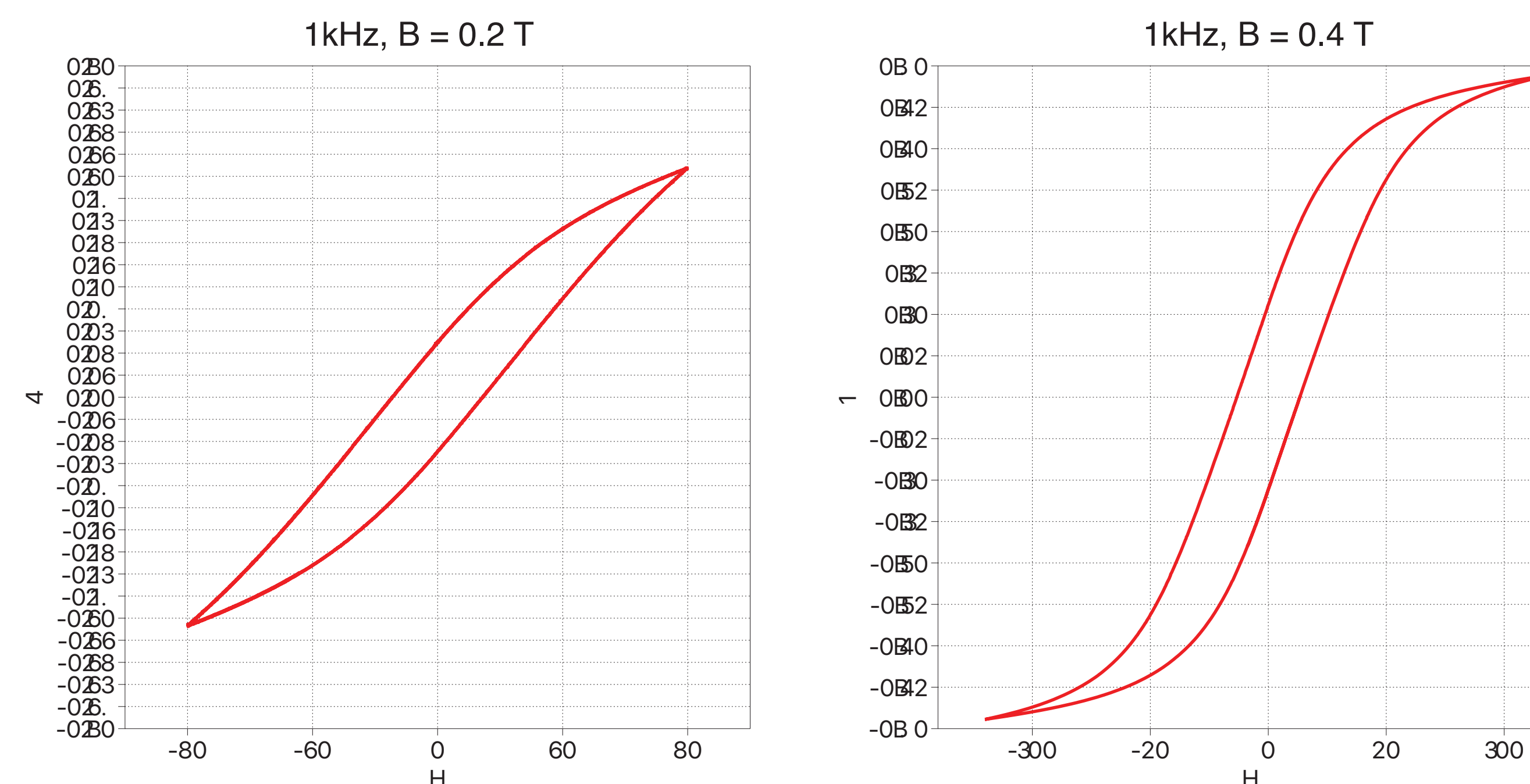
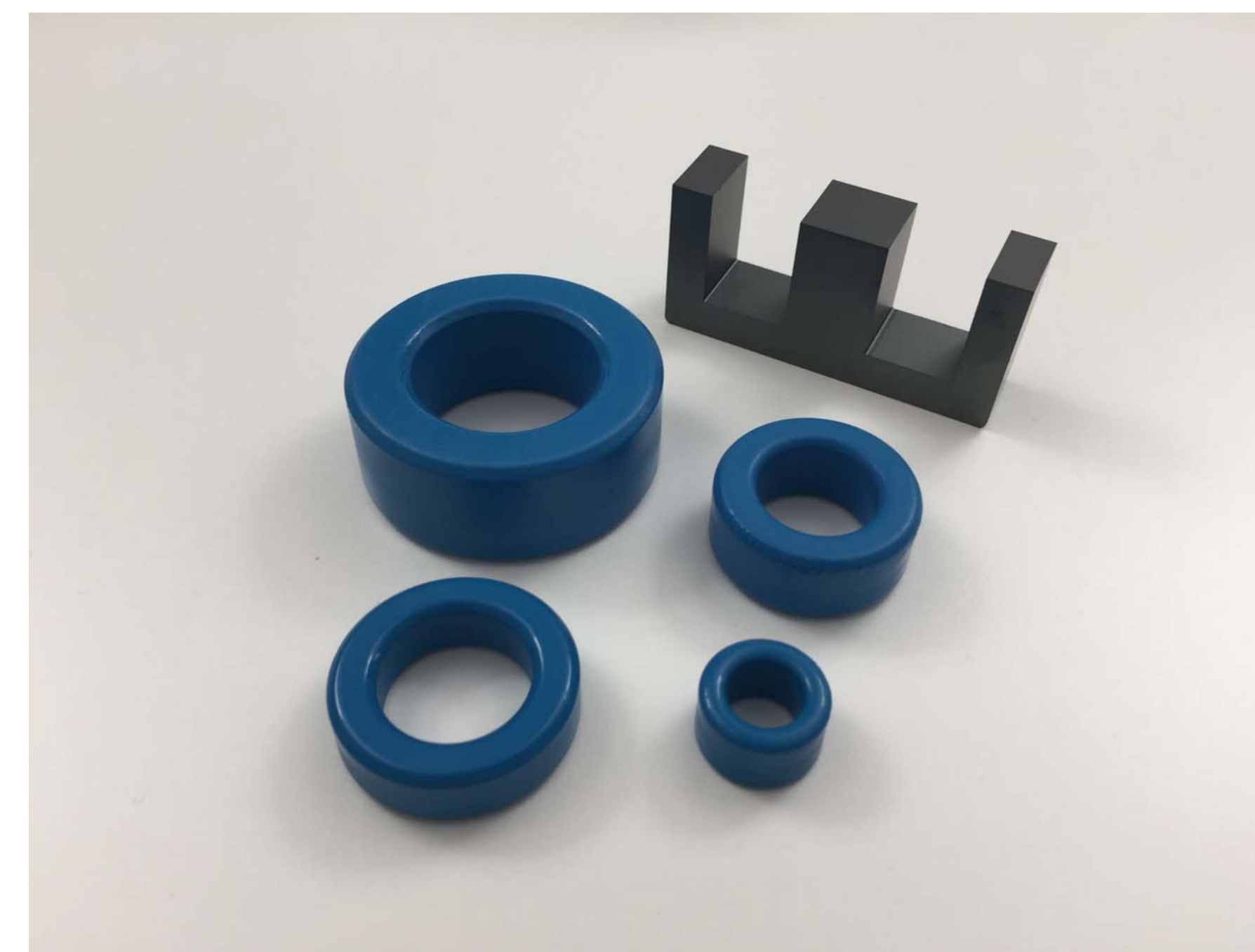
## Advantages

- ▶ Relatively narrow initial permeability range
- ▶ Low hysteresis loss
- ▶ Very low eddy current loss
- ▶ Low acoustic noise
- ▶ Relatively low cost
- ▶ Various core shapes available

## Disadvantages

- ▶ Low saturation flux density
- ▶ Narrow range of initial permeability
- ▶ Magnetic properties deteriorate with temperature increase
- ▶ Mechanically fragile

Saturation B	Init. permeability	Core loss (10kHz, 0.5T)	Conductivity
0.3 ~ 0.5 T	$0.1 \cdot 10^3 \sim 20 \cdot 10^3$	5 ~ 100 W/kg	$< 1 \cdot 10^{-5}$ S/m



▲ Example: Measured B-H curve of Ferrite N87

# MAGNETIC MATERIALS - CHARACTERIZATION

## Material characterisation

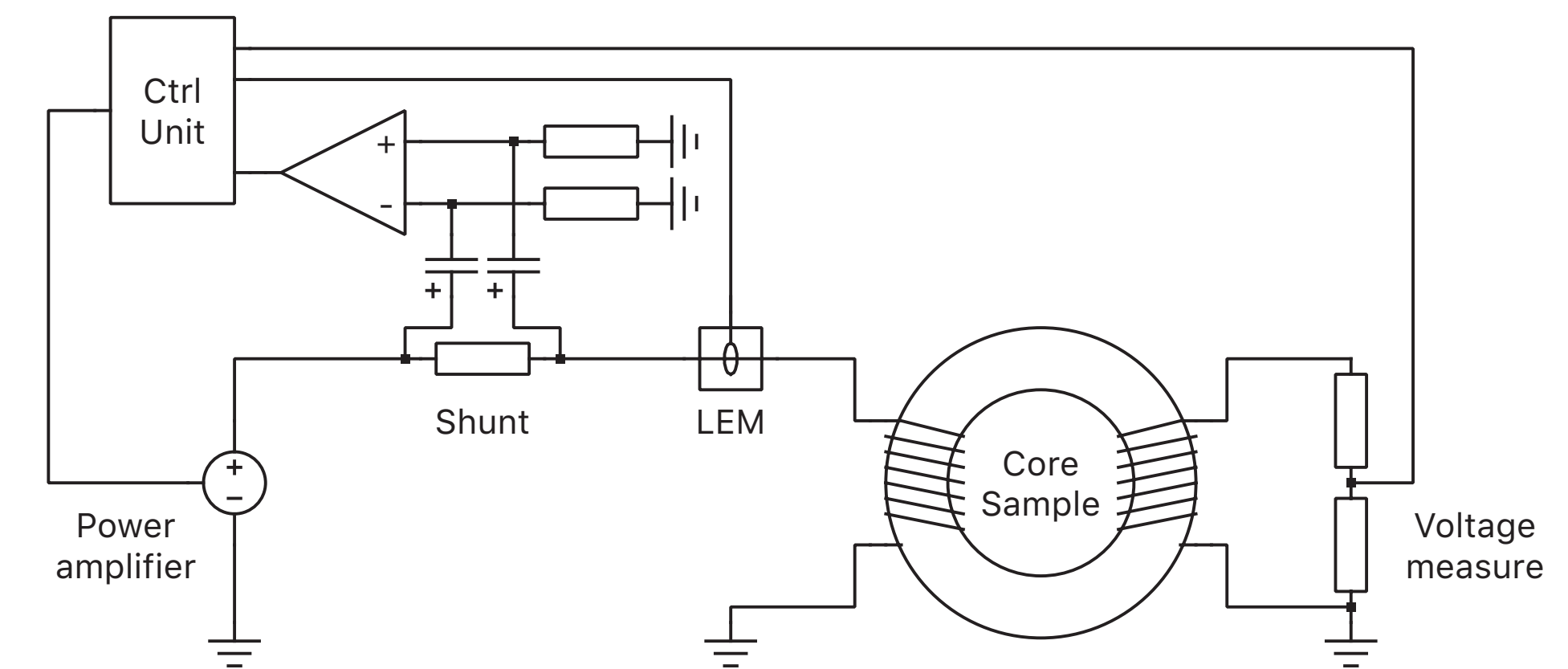
- ▶ Data sheet are often not sufficient
- ▶ Power Electronics non-sinusoidal waveforms

## Calorimetric approach

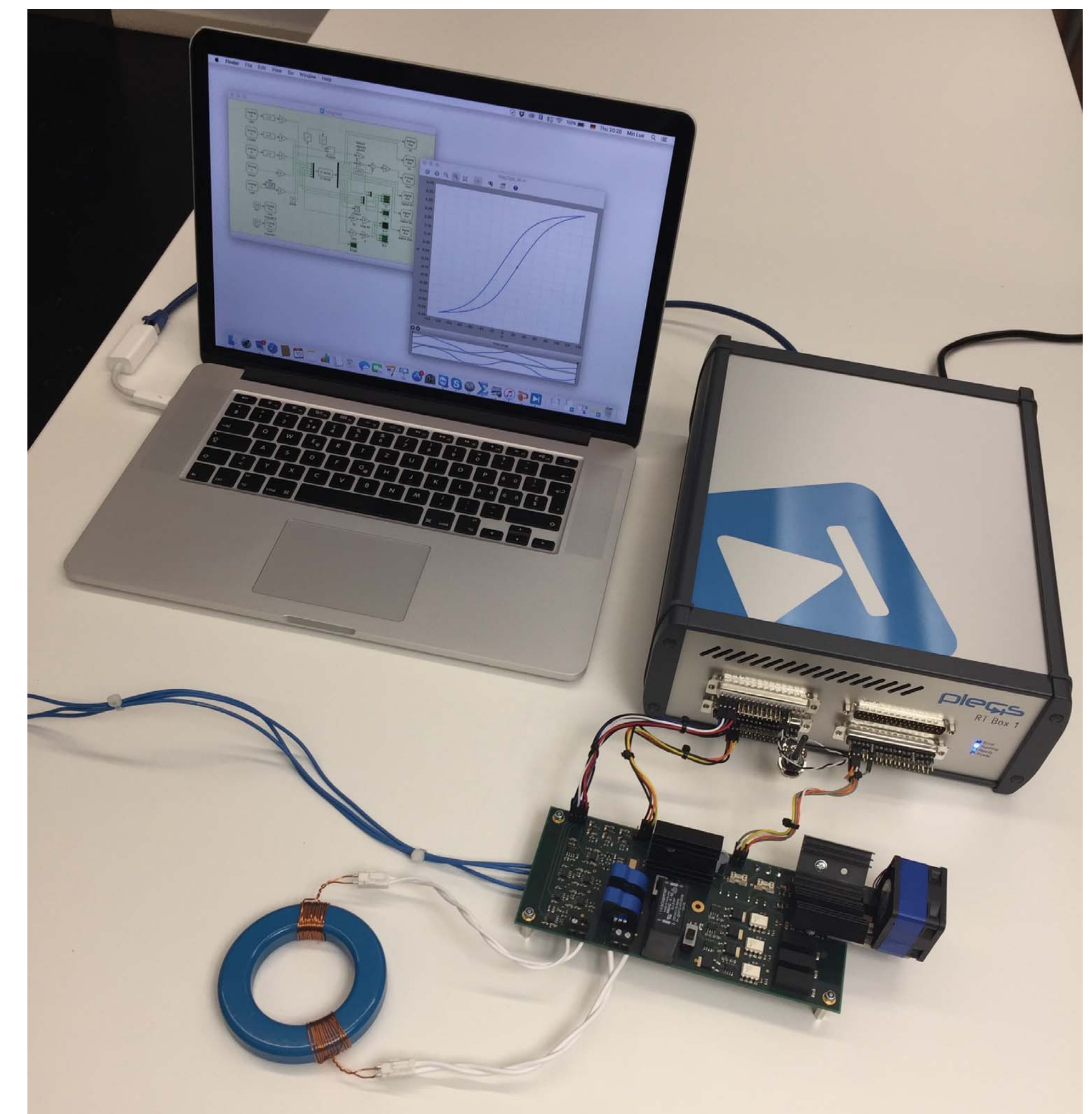
- ▶ Core sample placed in thermally isolated chamber
- ▶ Measure temperature difference between the inlet- and outlet coolant
- ▶ Time consuming and difficult to exclude winding loss

## Electrical approach

- ▶ Two windings installed on the sample core
- ▶ RF Power amplifier provides sinusoidal on the primary winding
- ▶ Primary winding current sensing using shunt resistor, to obtain  $H$
- ▶ Secondary winding voltage sensing using resistor divider, integrated to get  $B$
- ▶ Control unit for reference signal generation and data acquisition



▲ Commercial B-H Analyser; Source: [www.iti.iwatsu.co.jp/en](http://www.iti.iwatsu.co.jp/en)



▲ EPFL characterisation setup for magnetic materials

# WINDING MATERIALS

## Copper winding

- ▶ Flat wire - low frequency, easy to use
- ▶ Litz wire - high frequency, limited bending
- ▶ Foil - provide flat windings
- ▶ Hollow tubes - provide cooling efficiency
- ▶ Better conductor
- ▶ More expensive
- ▶ Better mechanical properties

## Copper Parameters

<b>Electrical conductivity</b>	$58.5 \cdot 10^6 \text{ S/m}$
<b>Electrical resistivity</b>	$1.7 \cdot 10^{-8} \Omega\text{m}$
<b>Thermal conductivity</b>	$401 \text{ W/mK}$
<b>TEC (from 0° to 100° C)</b>	$17 \cdot 10^{-6} \text{ K}^{-1}$
<b>Density</b>	$8.9 \text{ g/cm}^3$
<b>Melting point</b>	$1083 \text{ }^\circ\text{C}$

## Aluminium winding

- ▶ Flat wire
- ▶ Foil - skin effect differences compared to Copper
- ▶ Hollow tubes
- ▶ Difficult to interface with copper
- ▶ Offer some weight savings
- ▶ Cheaper
- ▶ Somewhat difficult mechanical manipulations

## Aluminum Parameters

<b>Electrical conductivity</b>	$36.9 \cdot 10^6 \text{ S/m}$
<b>Electrical resistivity</b>	$2.7 \cdot 10^{-8} \Omega\text{m}$
<b>Thermal conductivity</b>	$237 \text{ W/mK}$
<b>TEC (from 0° to 100° C)</b>	$23.5 \cdot 10^{-6} \text{ K}^{-1}$
<b>Density</b>	$2.7 \text{ g/cm}^3$
<b>Melting point</b>	$660 \text{ }^\circ\text{C}$



# INSULATING MATERIALS

## Multiple influencing factors

- ▶ Operating voltage levels
- ▶ Over-voltage category
- ▶ Environment - IP class
- ▶ Temperature
- ▶ Moisture
- ▶ Cooling implications
- ▶ Ageing (self-healing?)
- ▶ Manufacturing complexity
- ▶ Partial Discharge
- ▶ BIL
- ▶ Cost

## Dielectric properties

- ▶ Breakdown voltage (dielectric strength)
- ▶ Permittivity
- ▶ Conductivity
- ▶ Loss angle

Dielectric material	Dielectric strength (kV/mm)	Dielectric constant
Air	3	1
Oil	5 - 20	2 - 5
Mica tape	60 - 230	5 - 9
NOMEX 410	18 - 27	1.6 - 3.7
PTFE	60 - 170	2.1
Mylar	80 - 600	3.1
Paper	16	3.85
PE	35 - 50	2.3
XLPE	35 - 50	2.3
KAPTON	118 - 236	3.9



▲ Variety of choices available...  
September 11, 2017

# INSULATING MATERIALS - AIR

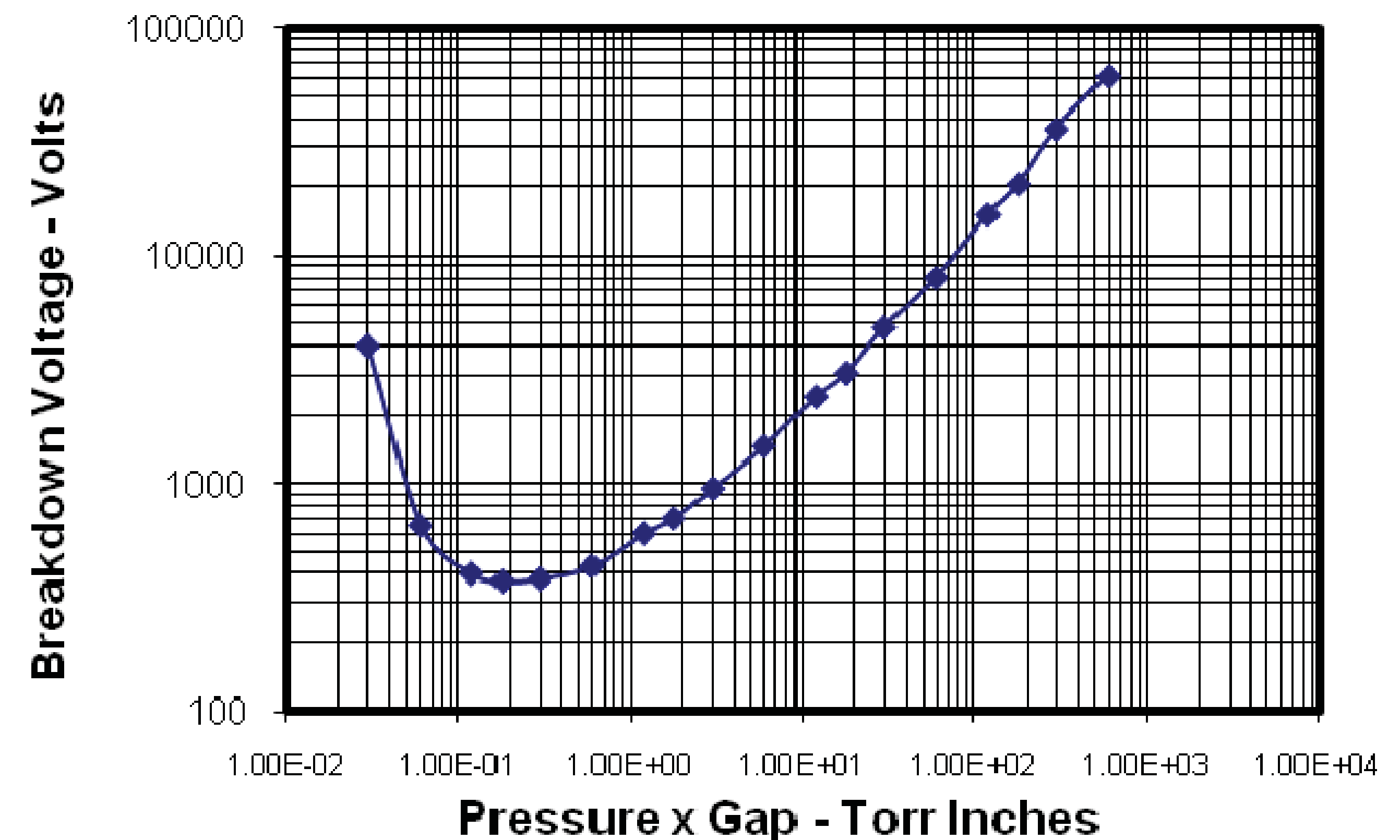
## Air

- ▶ Generally good electric insulator
- ▶ Available
- ▶ Add no mass to design
- ▶ Free
- ▶ Provides cooling
- ▶ Not sufficient alone
- ▶ Additional insulation (e.g. turn-to-turn)
- ▶ Generally, not the smallest design
- ▶ Dielectric strength variation - **Pachen Law**

$$V_{BD} = \frac{Bpd}{\ln(Apd) - \ln\left(\ln\left(1 + \frac{1}{\gamma_{se}}\right)\right)}$$

- ▶  $V_{BD}$  breakdown voltage in volts
- ▶  $p$  - pressure in pascals
- ▶  $d$  - gap distance in meters
- ▶  $\gamma_{se}$  - secondary electron emission coef.
- ▶  $A, B$  - parameters experimentally determined

Breakdown Voltage vs. Pressure x Gap  
(Air)



▲ Paschen curve for air

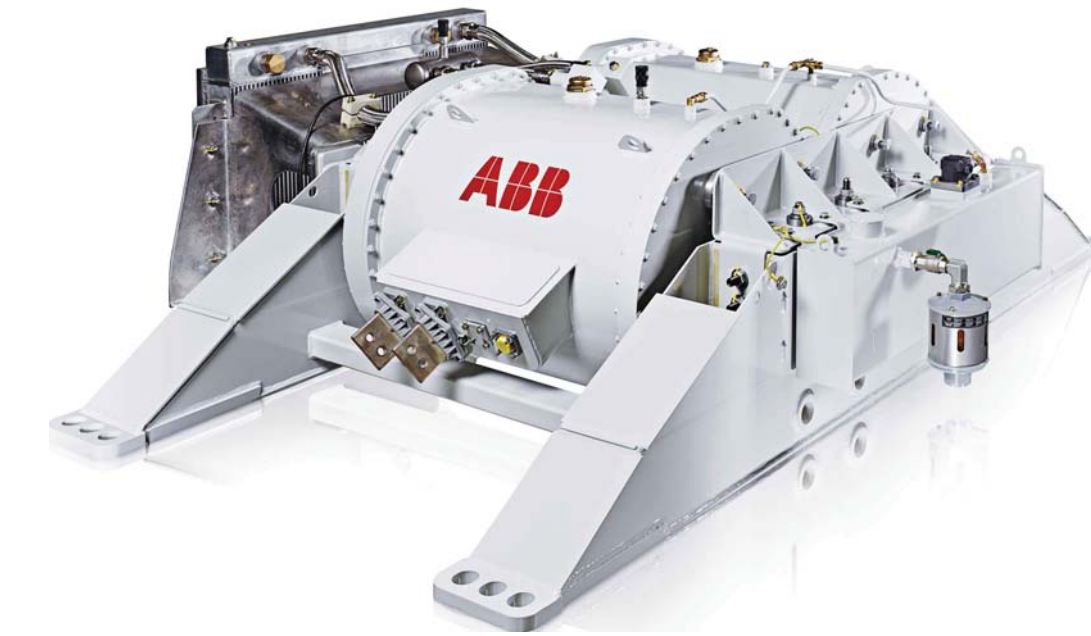
# INSULATING MATERIALS - OIL

## Oil

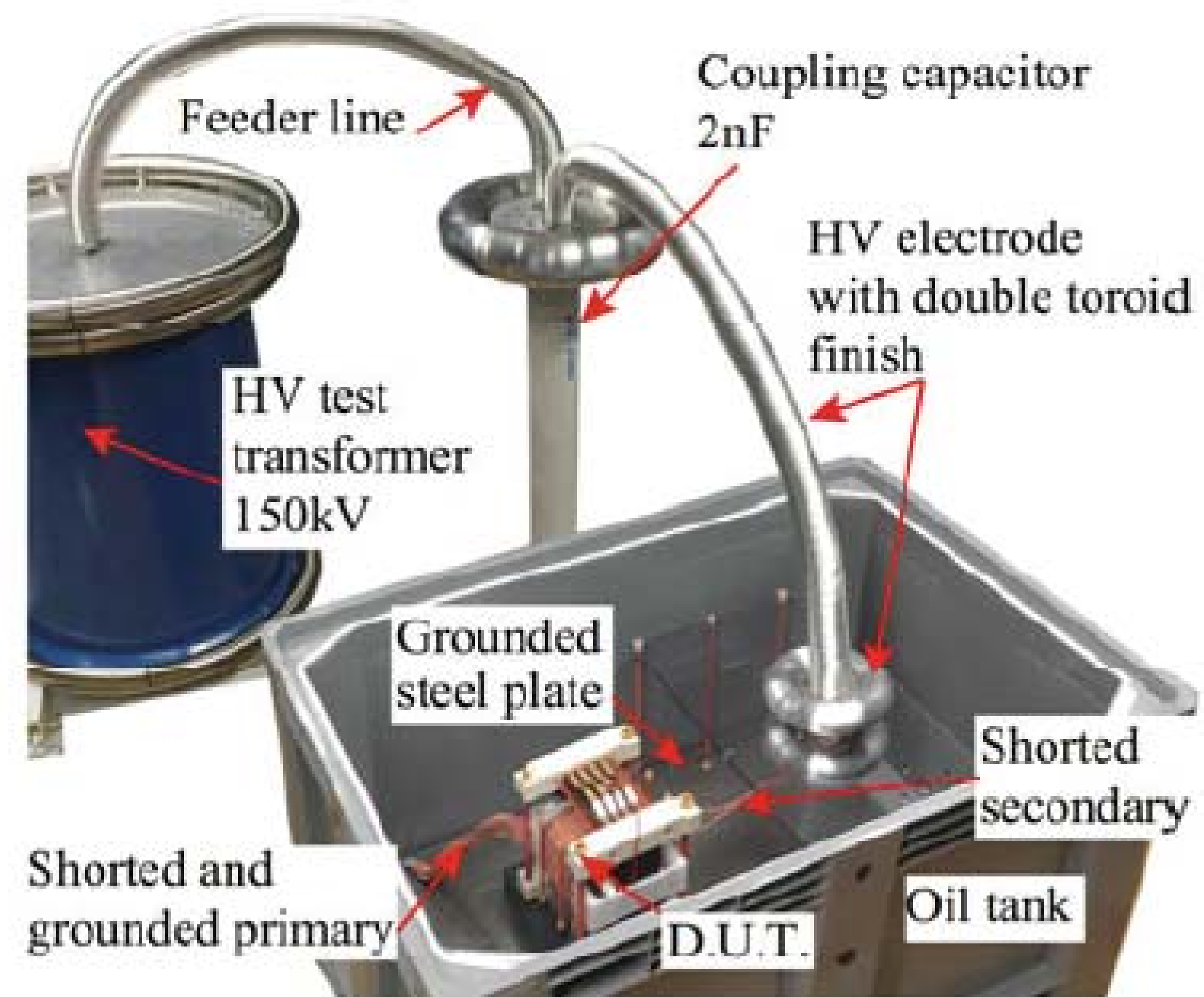
- ▶ In use for a very long time
- ▶ Excellent insulating properties
- ▶ Good thermal conductivity
- ▶ High voltage transformers
- ▶ Insulate and cool at the same time
- ▶ Natural or forced convection
- ▶ Self-healing (PD)
- ▶ Environmental concerns

## Challenges

- ▶ Not a power electronics technology
- ▶ Integration issues
- ▶ Thermal expansion
- ▶ Forced convection - need for pump
- ▶ Flammability (mineral oils)
- ▶ Adds weight to the design
- ▶ Oil degradation



▲ left: Distribution oil transformer; right: New traction oil transformer; [www.abb.com](http://www.abb.com)



▲ Oil insulated HFT PD testing [20]

# INSULATING MATERIALS - SOLID

## Solid Insulation

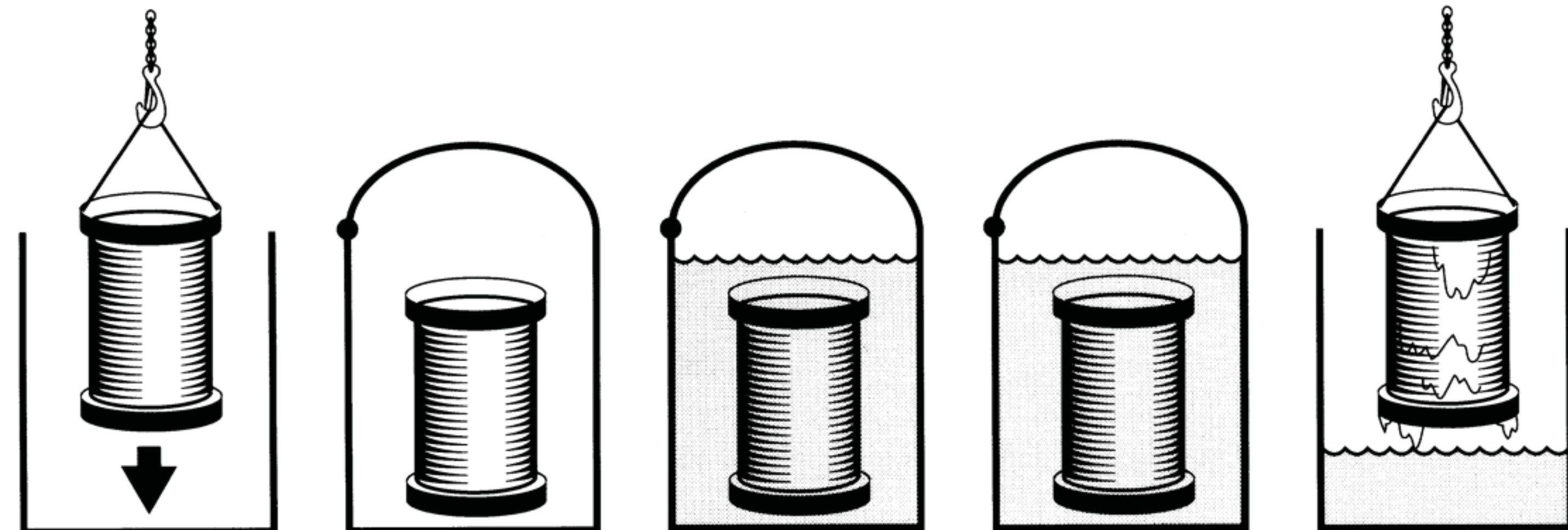
- ▶ Dry Type designs
- ▶ Vacuum-Pressure Impregnation (VPI)
- ▶ Vacuum-immersion (resin-encapsulated)
- ▶ Vacuum-fill (solid-cast)
- ▶ Variety of resin mixtures available
- ▶ Need for specialized equipment

## Challenges

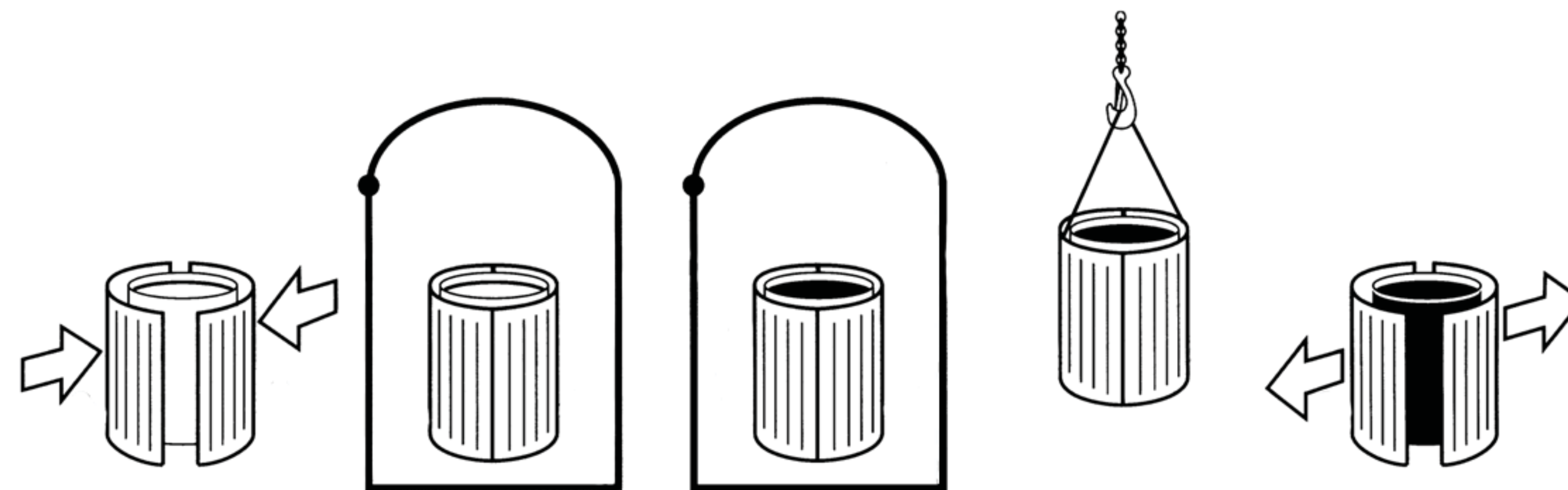
- ▶ Direct impact on thermal design
- ▶ Adds weight to the design
- ▶ Ageing uncertainty
- ▶ Mixed frequency stress
- ▶ Partial Discharge
- ▶ Mechanical strength - cracks
- ▶ CTI - Creepage distances



▲ left: [www.sts-trafo.com](http://www.sts-trafo.com); right: [www.siemens.com](http://www.siemens.com)



▲ Resin-Encapsulated transformer winding ([www.schneider-electric.com](http://www.schneider-electric.com))



▲ Solid-Cast transformer winding ([www.schneider-electric.com](http://www.schneider-electric.com))

September 11, 2017

# SUMMARY - TECHNOLOGIES AND MATERIALS

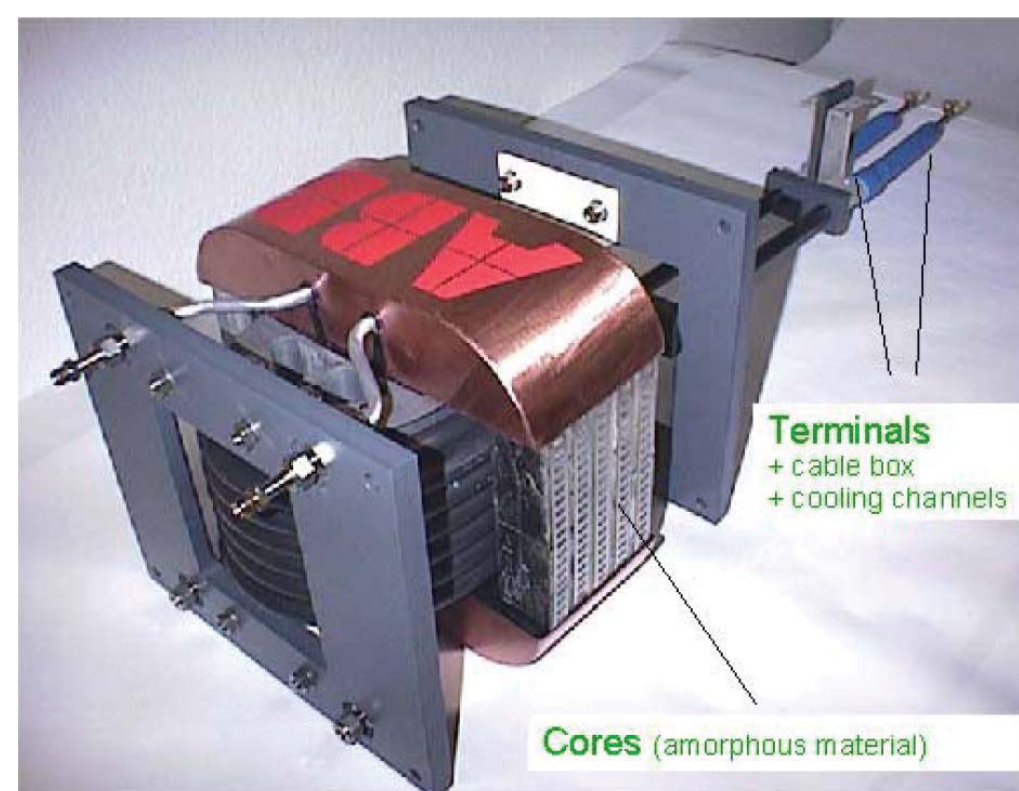
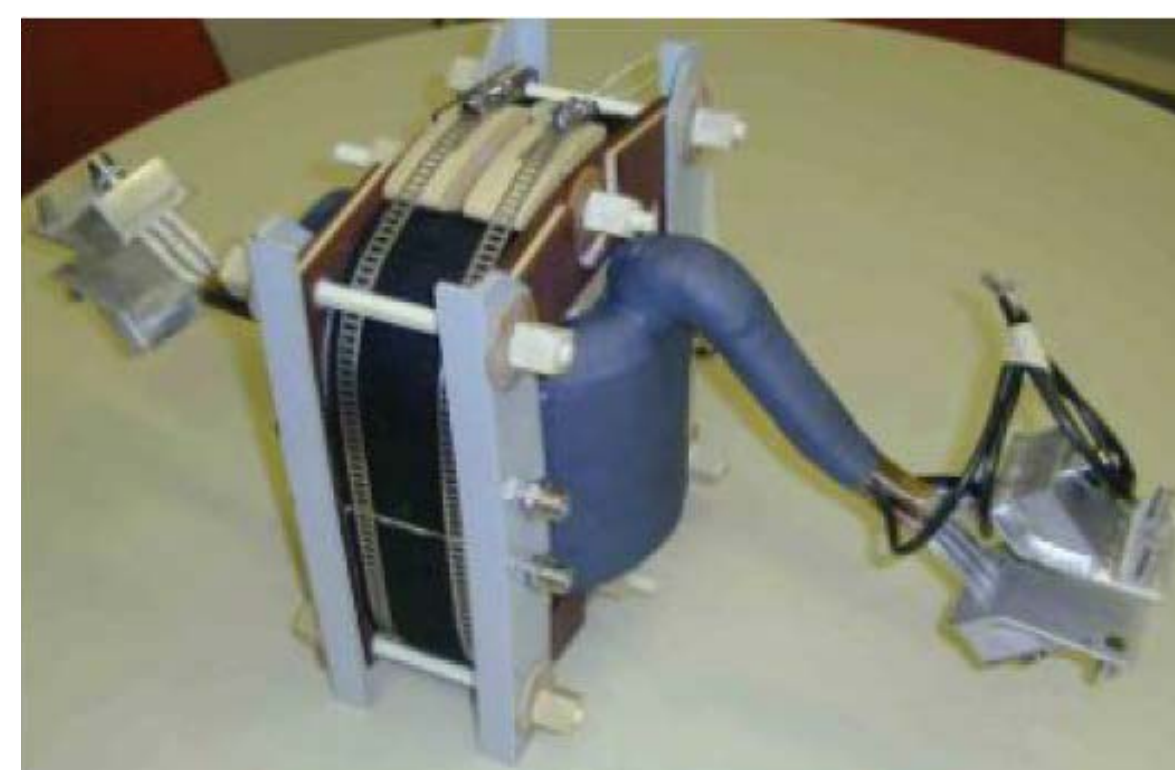


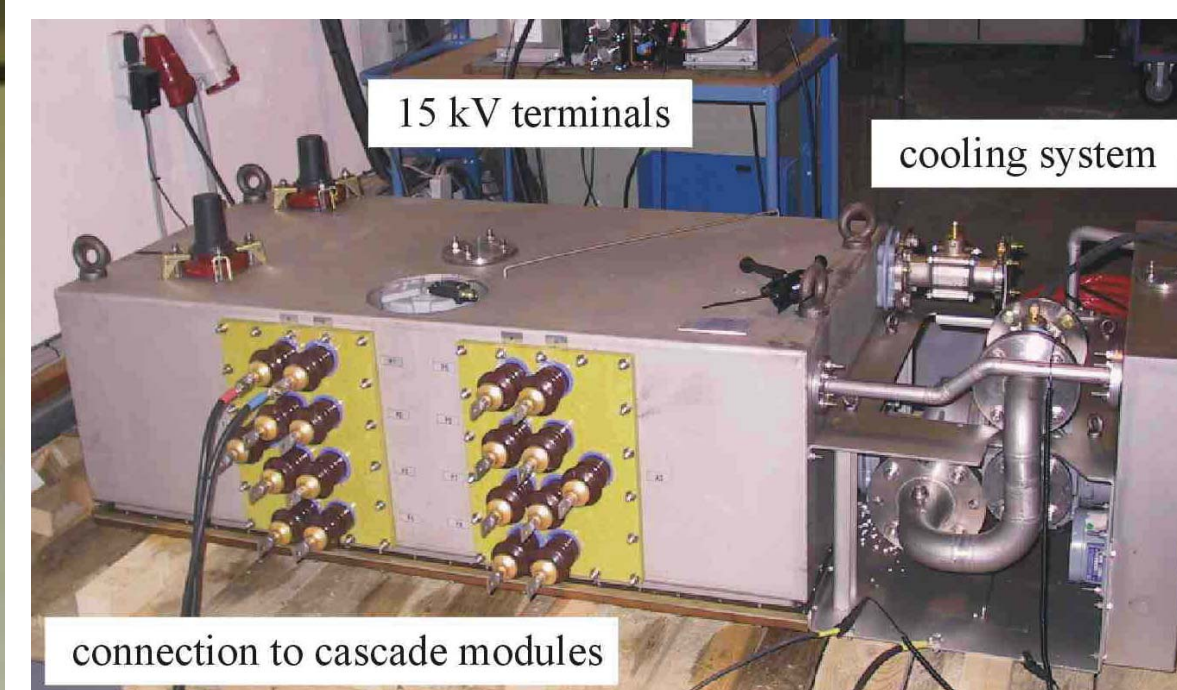
ABB: 350kW, 10kHz



ABB: 3x150kW, 1.8kHz



BOMBARDIER: 350kW, 8kHz



ALSTOM: 1500kW, 5kHz



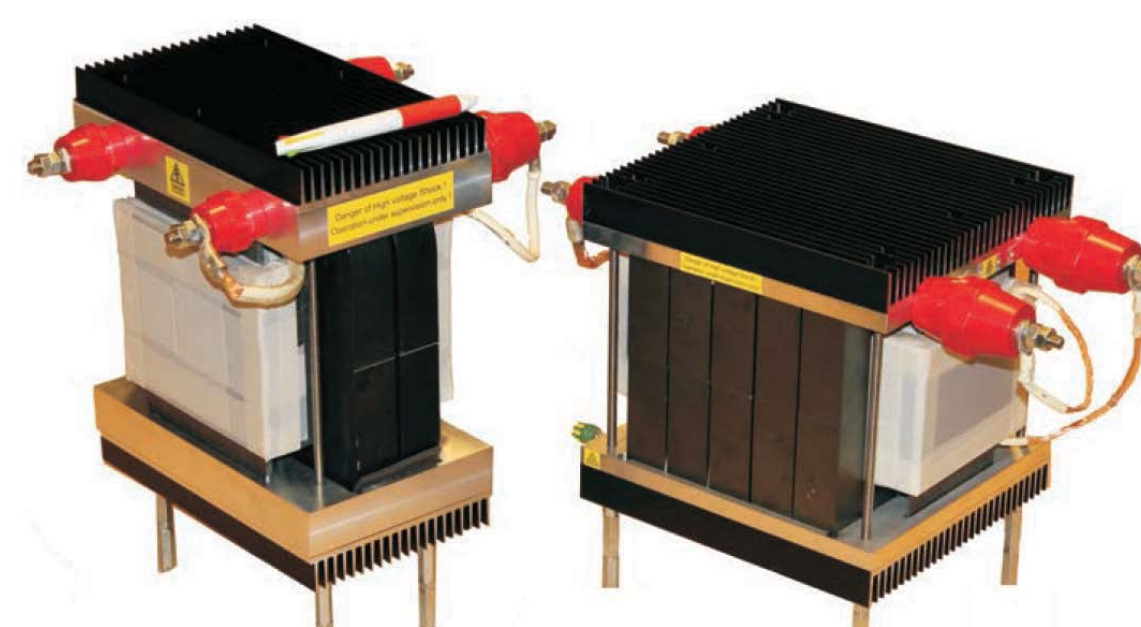
IKERLAN: 400kW, 5kHz



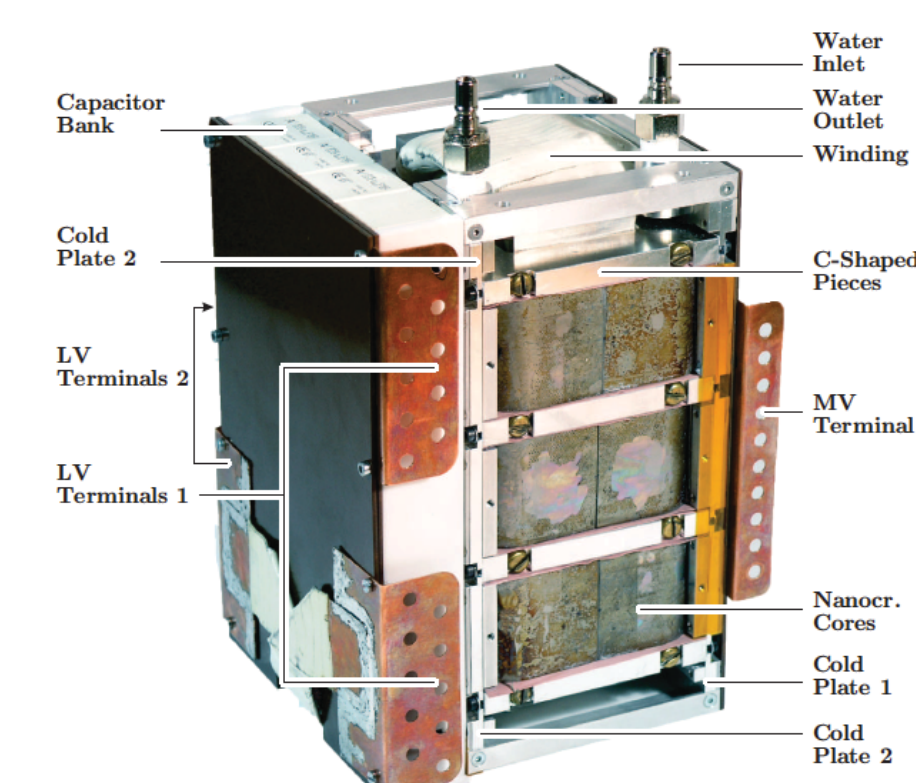
IKERLAN: 400kW, 1kHz



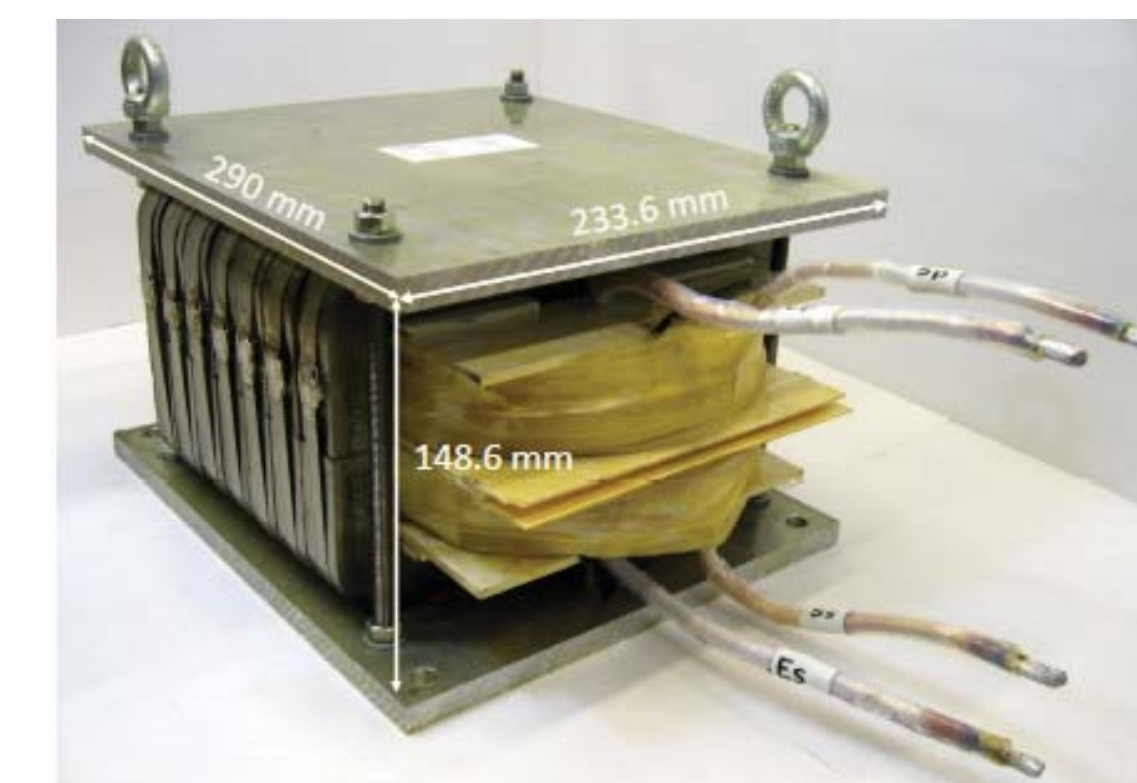
FAU-EN: 450kW, 5.6kHz



CHALMERS: 50kW, 5kHz



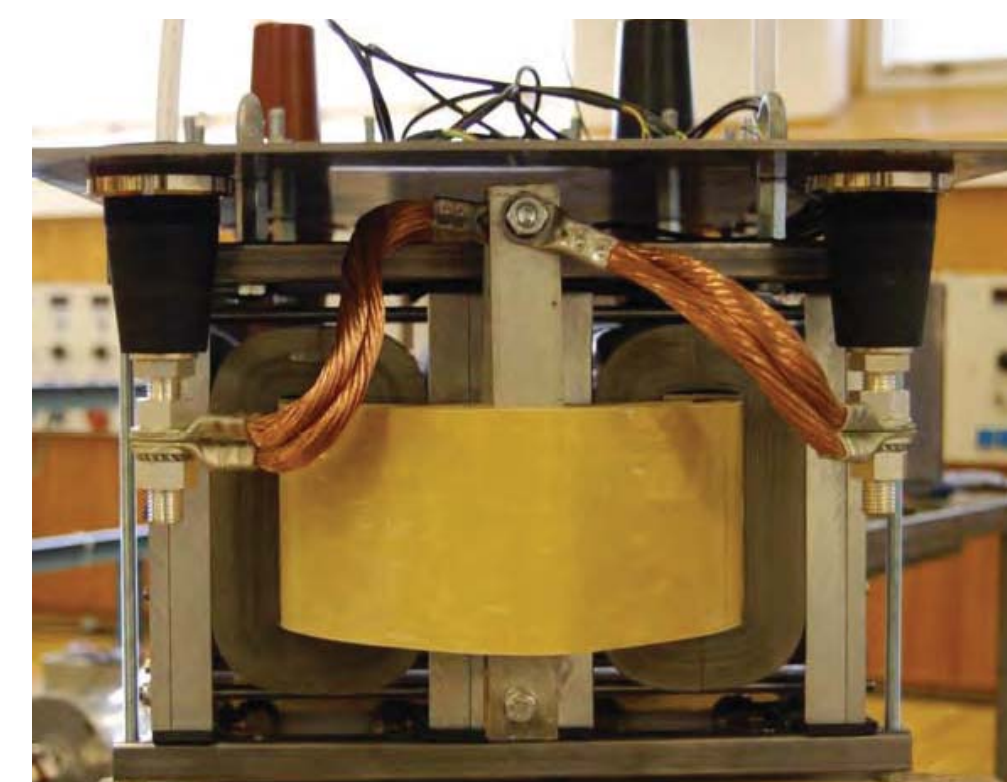
ETHZ: 166kW, 20kHz



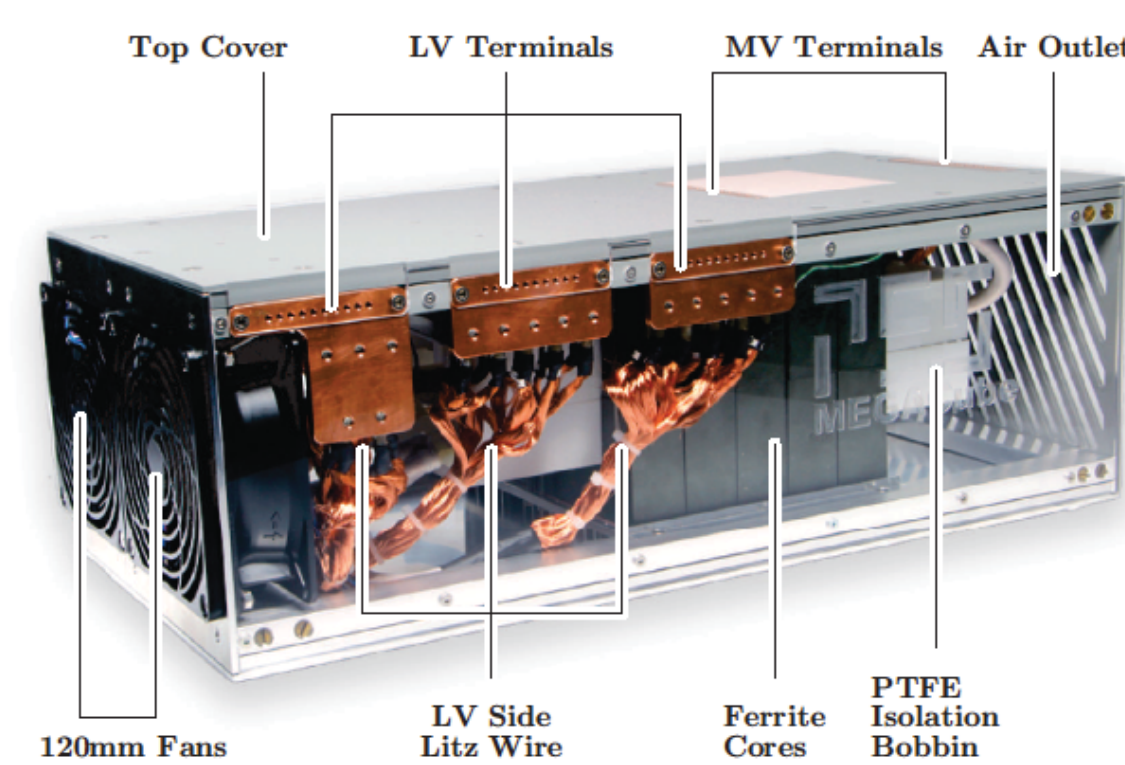
EPFL: 300kW, 2kHz



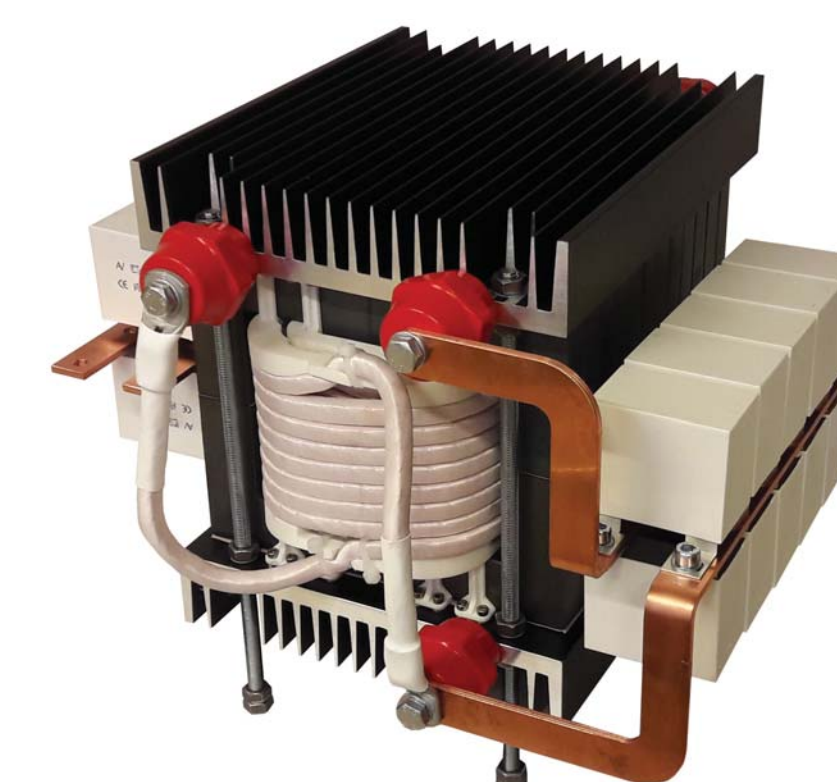
STS: 450kW, 8kHz



KTH: 170kW, 4kHz



ETHZ: 166kW, 20kHz



EPFL: 100kW, 10kHz



ACME: ???kW, ???kHz



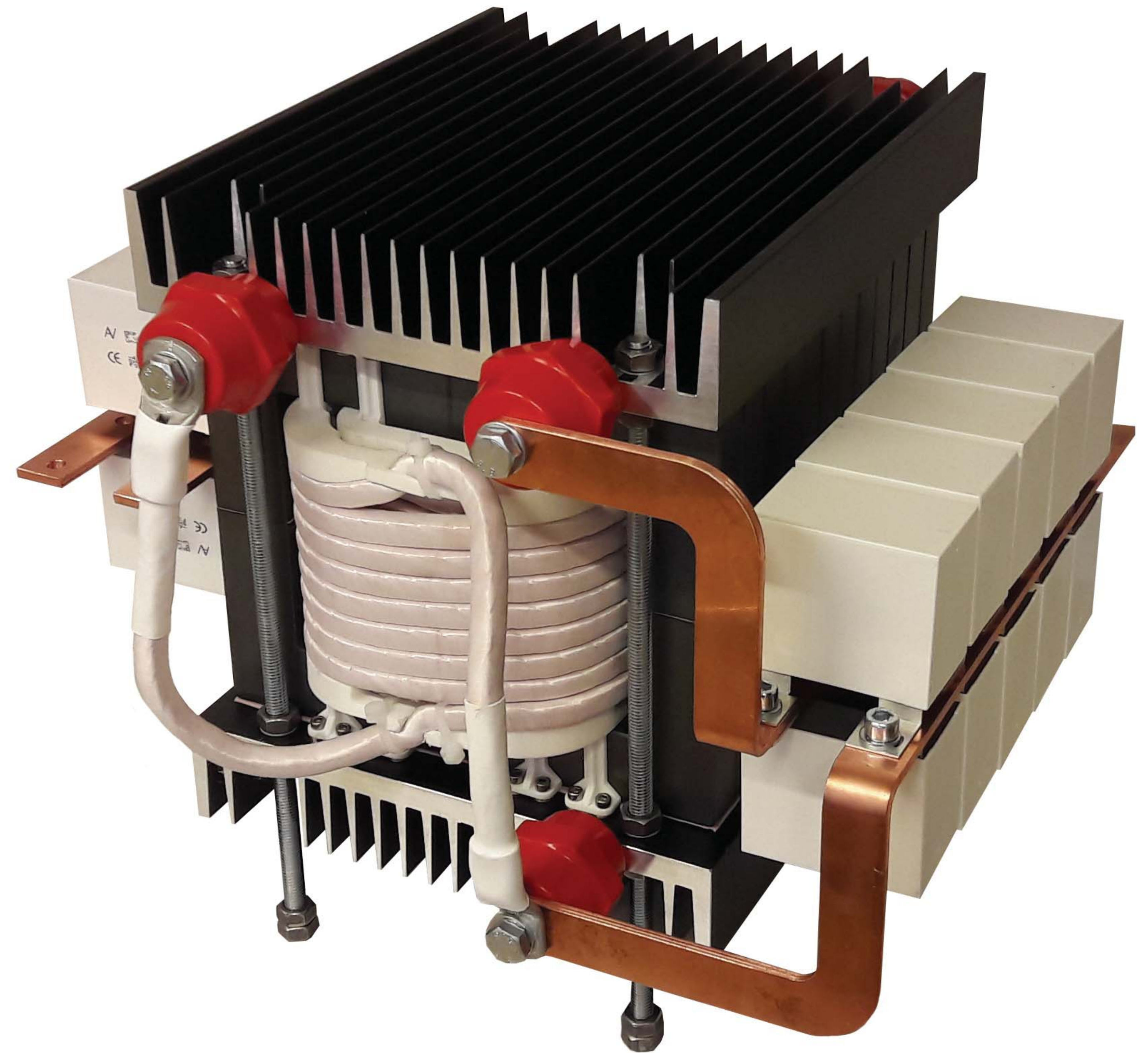
# MFT MODELING

*The underlying analytical descriptions?*

# MODELING: RELEVANT EFFECTS

---

- ▶ Core Losses
- ▶ Winding Losses
- ▶ Leakage Inductance
- ▶ Magnetizing Inductance
- ▶ Thermal Model



# MODELING: CORE LOSSES

## Different core loss models:

- ▶ Based on characterization of magnetic hysteresis [21], [22], [23]
- ▶ Based on loss separation [24]
- ▶ Time domain core loss model [25]
- ▶ Based on Steinmetz Equation (MSE [26], IGSE [27], iIGSE [28])

## Original Steinmetz Equation:

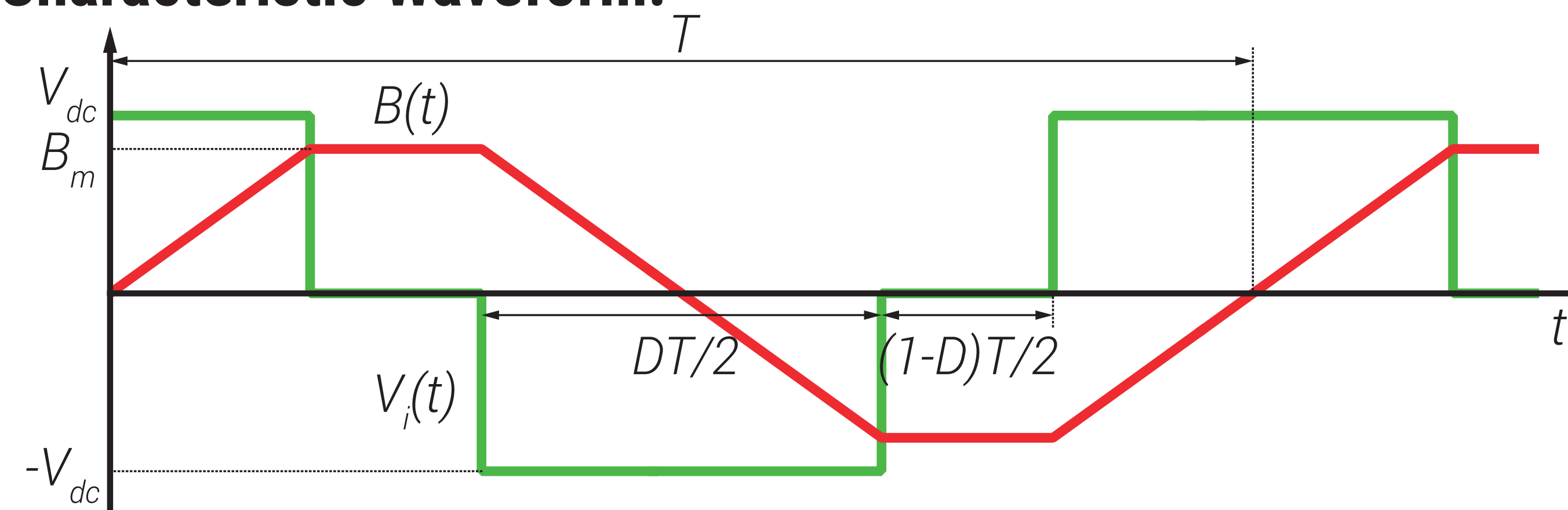
$$P_c = K f^a B_m^\beta$$

## Improved Generalized Steinmetz Equation (IGSE):

$$P_c = \frac{1}{T} \int_0^T k_i \left| \frac{dB(t)}{dt} \right|^a (\Delta B)^{\beta-a} dt$$

$$k_i = \frac{K}{(2\pi)^{a-1} \int_0^{2\pi} |\cos(\theta)|^a 2^{\beta-a} d\theta}$$

## Characteristic Waveform:



$$\left| \frac{dB(t)}{dt} \right| = \begin{cases} 0 & \text{for } (1-D)T \\ \frac{2\Delta B}{DT} & \text{for } DT \end{cases}$$

## Application of IGSE on the Characteristic Waveform:

$$P_s = 2^{a+\beta} k_i f^a B_m^\beta D^{1-a}$$

$$k_i = \frac{K}{2^{\beta-1} \pi^{a-1} \left( 0.2761 + \frac{1.7061}{\alpha+1.354} \right)}$$

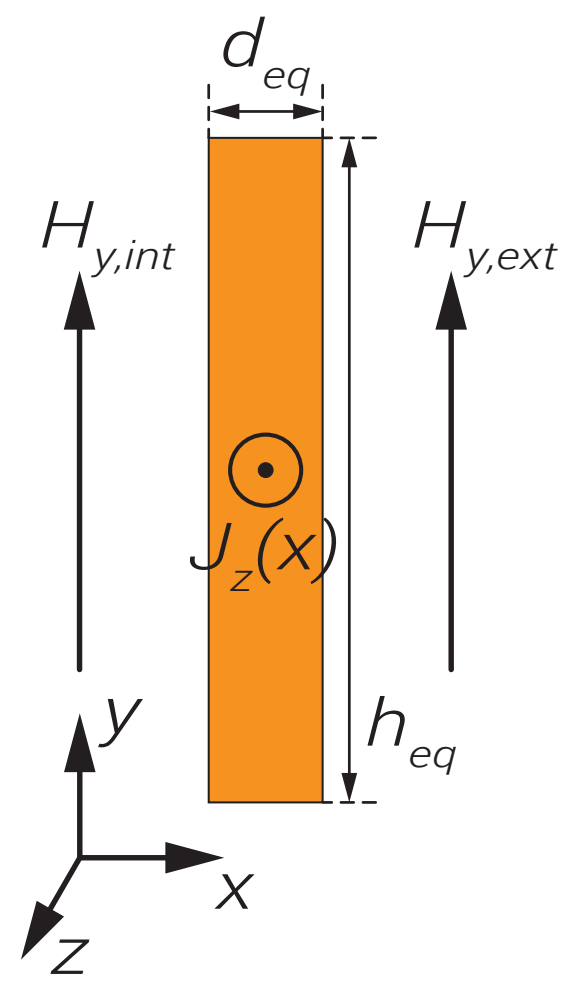


# MODELING: WINDING LOSSES

## Foil Winding Electromagnetic Field Analysis:

- ▶ Dowell foil winding loss model [29]
- ▶ Porosity factor validity analysis [30], [31]
- ▶ Round wire winding loss model [32]
- ▶ ...

## Foil Winding Electromagnetic Field Analysis:



$$H_y = H_{ext} \frac{\sinh(ax)}{\sinh(ad_{eq})} - H_{int} \frac{\sinh(a(x - d_{eq}))}{\sinh(ad_{eq})}$$

$$J_z = aH_{ext} \frac{\cosh(ax)}{\sinh(ad_{eq})} - aH_{int} \frac{\cosh(a(x - d_{eq}))}{\sinh(ad_{eq})}$$

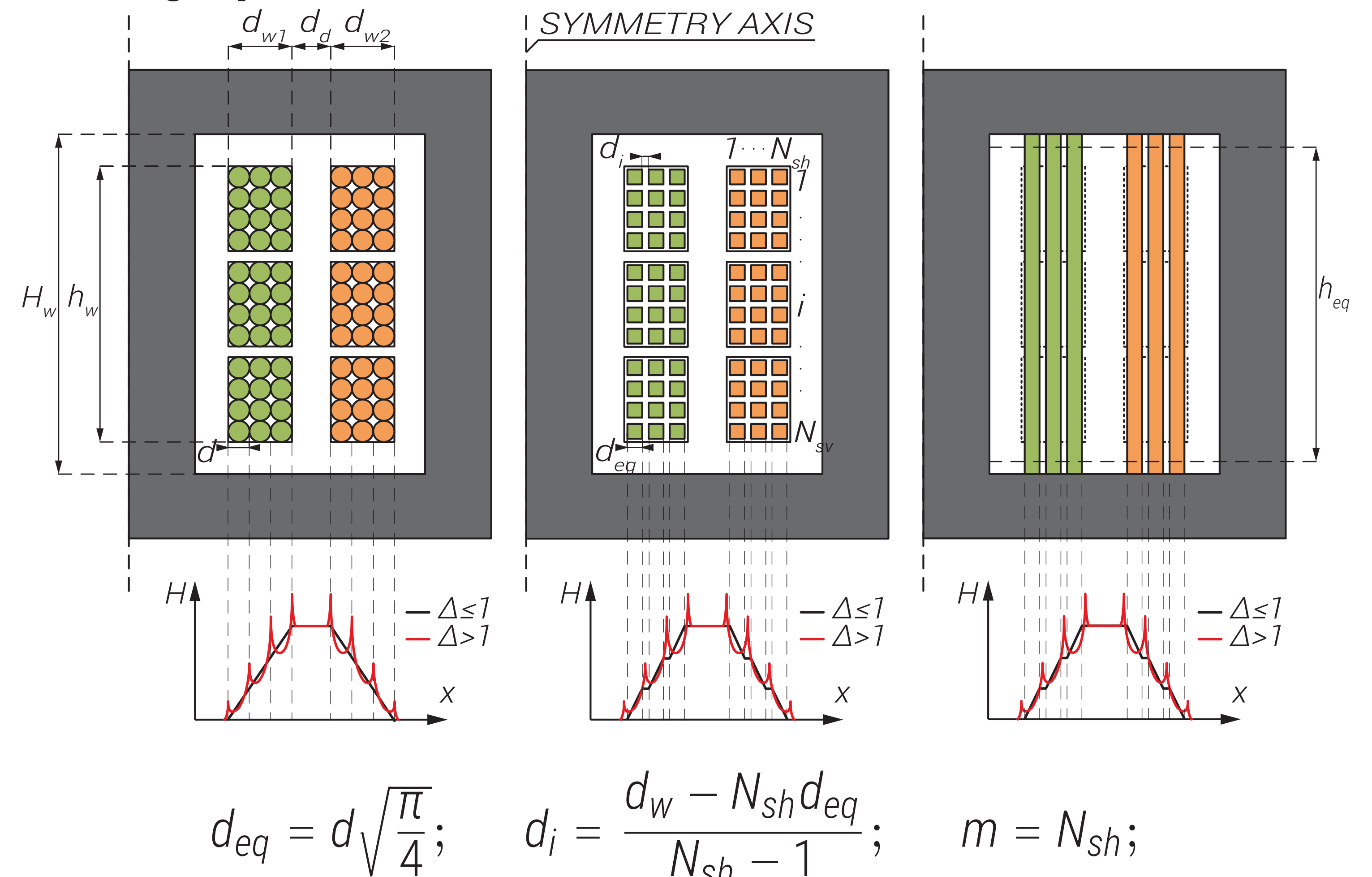
$$a = \frac{1+j}{\delta}; \quad \delta = \sqrt{\frac{\rho}{\pi\mu f}}$$

## Foil Winding Loss Calculation:

$$P_\sigma = \frac{1}{\sigma} \int JJ^* dv; \quad P_\sigma = I^2 \frac{L_w}{\delta\sigma h_w} m \left[ \zeta_1 + \frac{2}{3}(m^2 - 1)\zeta_2 \right];$$

$$\zeta_1 = \frac{\sinh(2\Delta) + \sin(2\Delta)}{\cosh(2\Delta) - \cos(2\Delta)}; \quad \zeta_2 = \frac{\sinh(\Delta) - \sin(\Delta)}{\cosh(\Delta) + \cos(\Delta)}; \quad \Delta = \frac{d_{eq}}{\delta}$$

## Winding Equivalence:



$$N_{sh} = \sqrt{\frac{N_s}{K_w}}; \quad N_{sv} = \sqrt{K_w N_s};$$

$$K_w = \frac{h_w}{d_w}$$

$$\Delta' = \sqrt{\eta}\Delta; \quad \eta = d_{eq} \frac{N_{sv}}{H_w};$$

# MODELING: F-DEPENDENT LEAKAGE INDUCTANCE

## Application of Dowell's Model on the Equivalent Foil Winding:

$$L_{\sigma} = N_1^2 \mu_0 \frac{I_w}{H_w} \left[ \underbrace{\frac{d_{w1eq} m_{w1}}{3} F_{w1} + \frac{d_{w2eq} m_{w2}}{3} F_{w2}}_{\text{Frequency dependent portion due to the magnetic energy within the copper volume of the windings}} \right]$$

$$+ \underbrace{d_d}_{\text{Portion due to magnetic energy within the inter-winding dielectric volume}}$$

$$+ \underbrace{d_{w1i} \frac{(m_{w1} - 1)(2m_{w1} - 1)}{6m_{w1}}}_{\text{Portion due to magnetic energy within the inter-layer dielectric of the primary winding}}$$

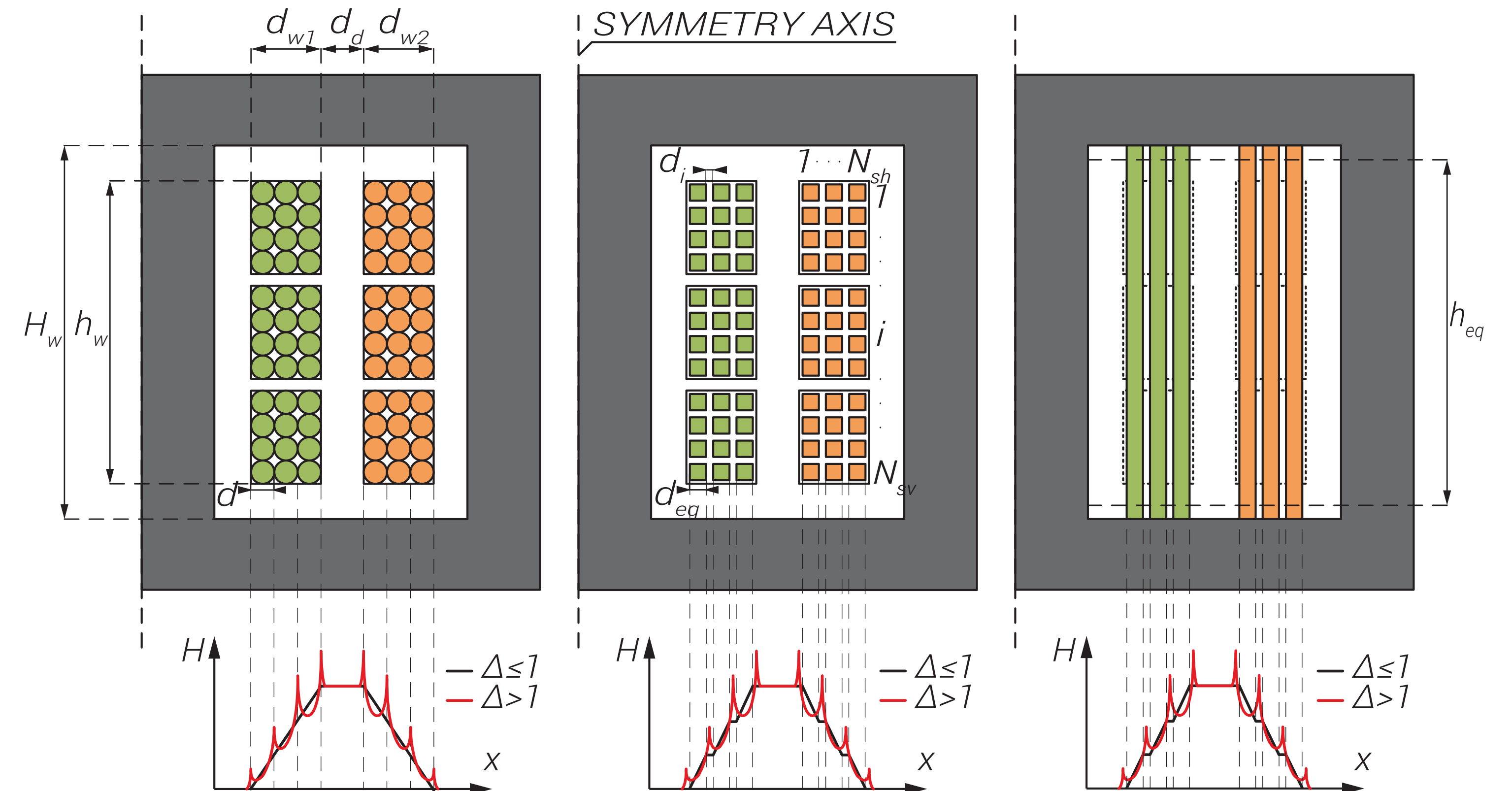
$$+ \underbrace{d_{w2i} \frac{(m_{w2} - 1)(2m_{w2} - 1)}{6m_{w2}}}_{\text{Portion due to magnetic energy within the inter-layer dielectric of the secondary winding}}$$

where:

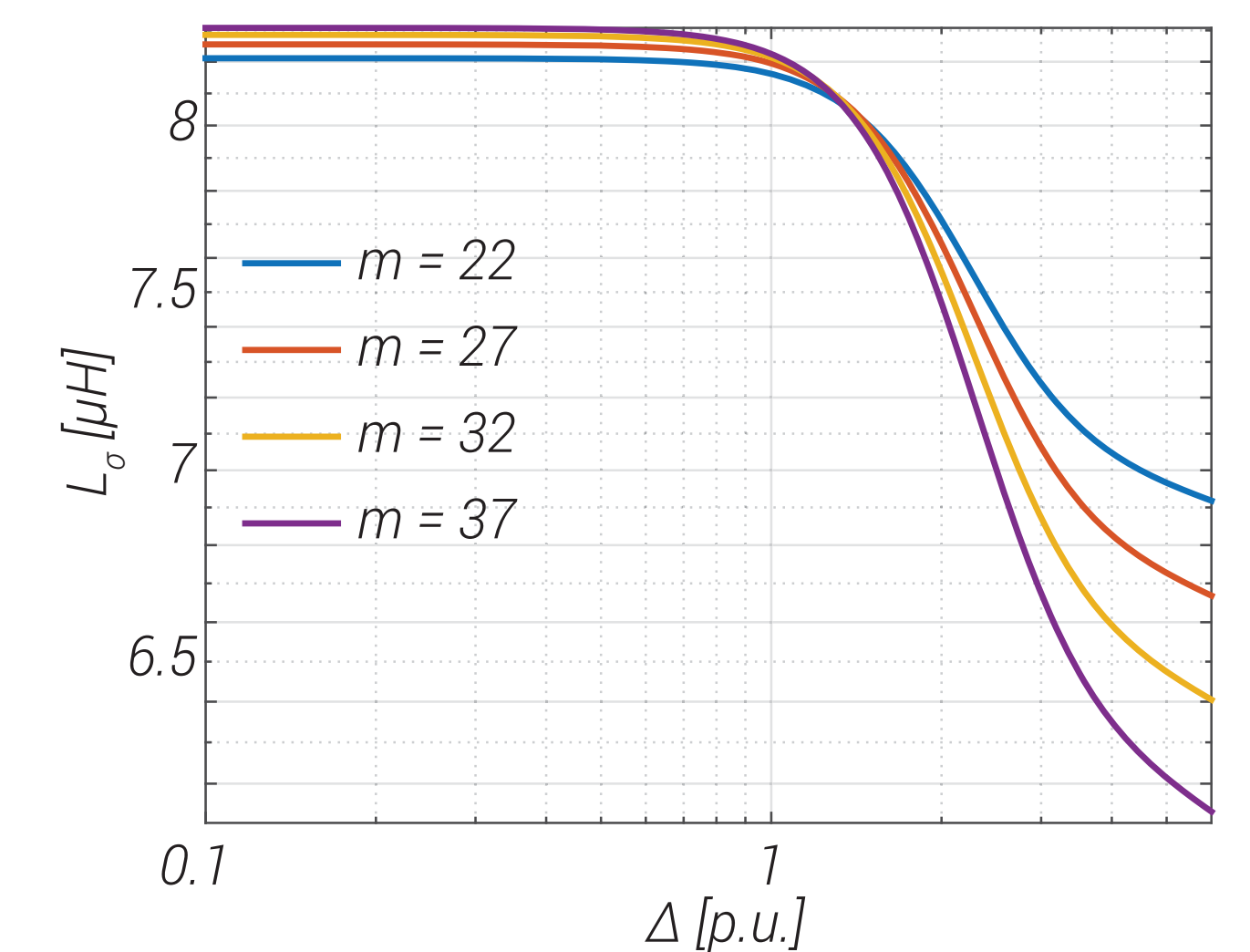
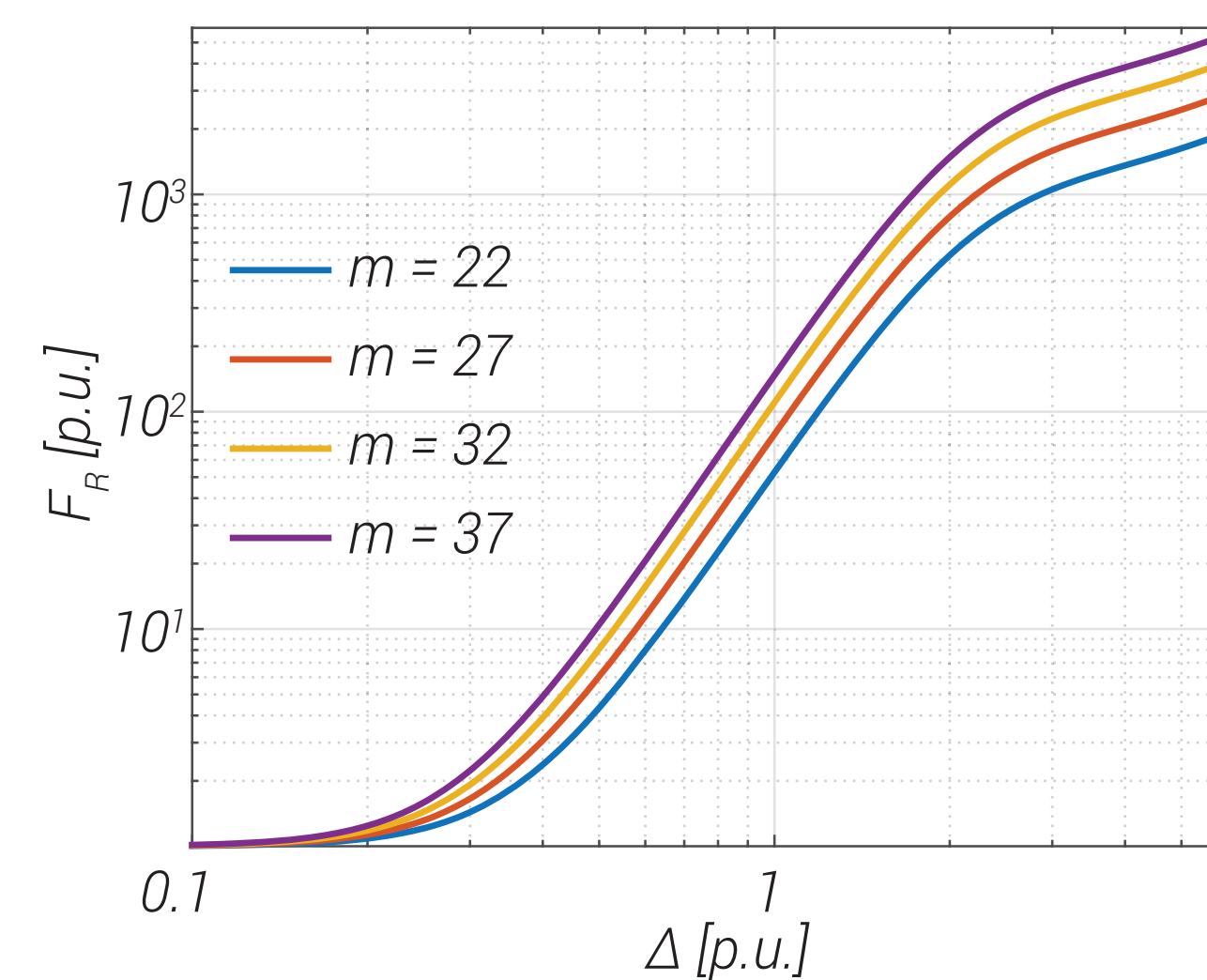
$$F_w = \frac{1}{2m^2 \Delta} \left[ (4m^2 - 1)\varphi_1 - 2(m^2 - 1)\varphi_2 \right]$$

$$\varphi_1 = \frac{\sinh(2\Delta) - \sin(2\Delta)}{\cosh(2\Delta) - \cos(2\Delta)}; \quad \varphi_2 = \frac{\sinh(\Delta) - \sin(\Delta)}{\cosh(\Delta) - \cos(\Delta)}$$

## Winding Equivalence:

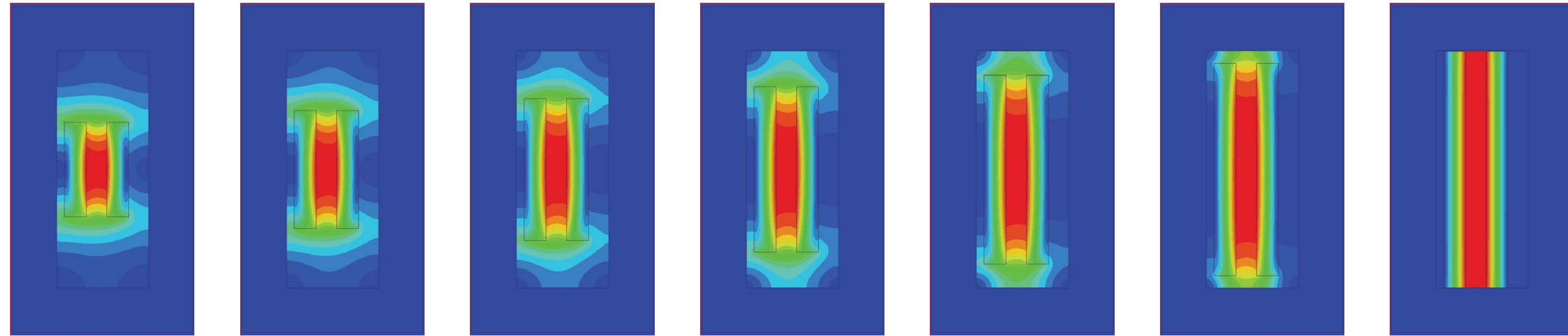


$$\Delta' = \sqrt{\eta} \Delta; \quad \eta = d_{eq} \frac{N_{sv}}{H_w}; \quad m = N_{sh}; \quad d_i = \frac{d_w - N_{sh} d_{eq}}{N_{sh} - 1};$$



# MODELING: LEAKAGE INDUCTANCE (HYBRID MODEL)

## Influence of Winding Geometry on Leakage inductance:



## Hybrid Leakage Inductance Model:

- ▶ Rogowski correction factor:

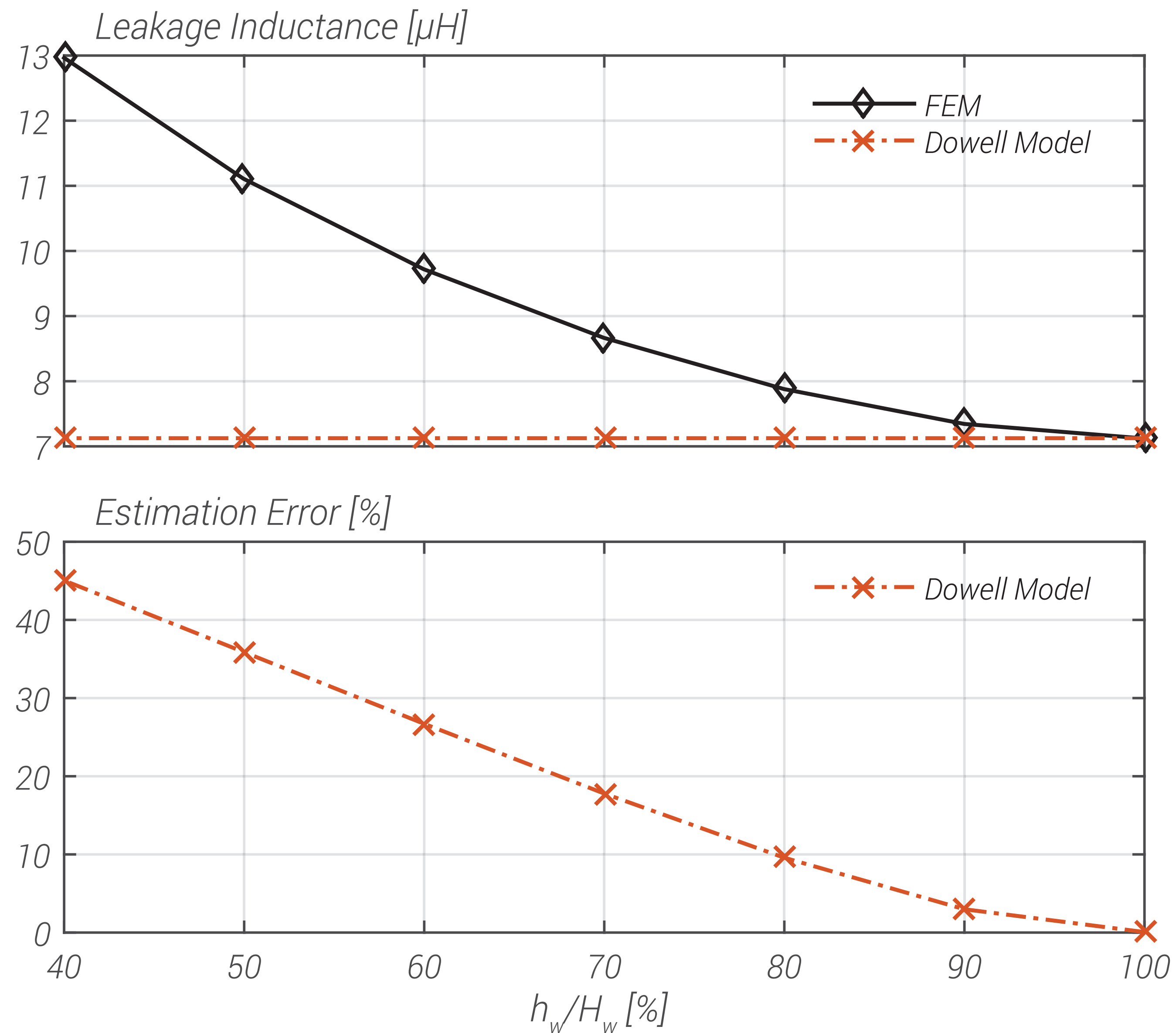
$$h_{eq} = \frac{h_w}{K_R}$$

$$K_R = 1 - \frac{1 - e^{-\pi h_w / (d_{w1} + d_d + d_{w2})}}{\pi h_w / (d_{w1} + d_d + d_{w2})}$$

- ▶ Correction of Dowell's model ( $H_w \rightarrow h_{eq}$ ):

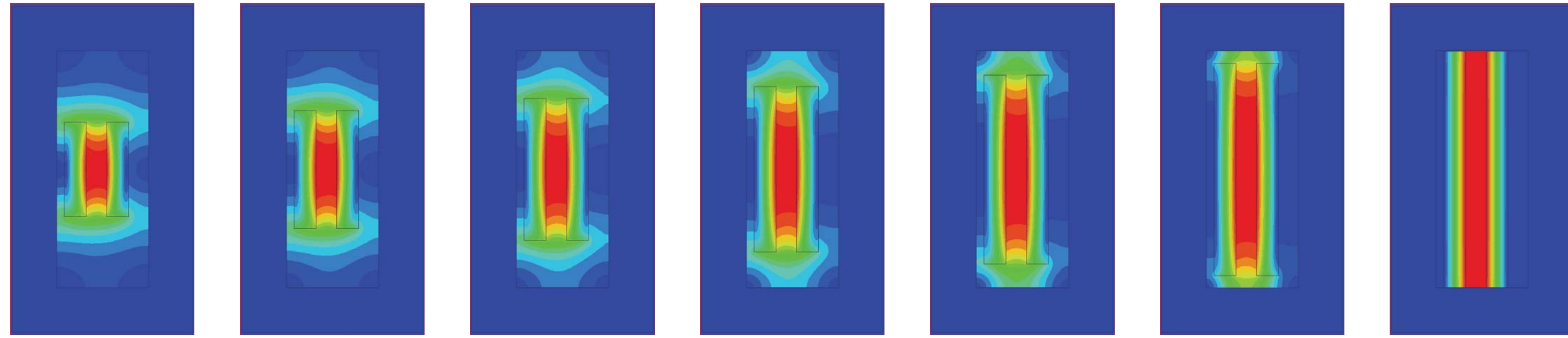
$$L_\sigma = N_1^2 \mu_0 \frac{I_w}{H_w} \left[ \frac{d_{w1eq} m_{w1}}{3} F_{w1} + \frac{d_{w2eq} m_{w2}}{3} F_{w2} + d_d + d_{w1i} \frac{(m_{w1} - 1)(2m_{w1} - 1)}{6m_{w1}} + d_{w2i} \frac{(m_{w2} - 1)(2m_{w2} - 1)}{6m_{w2}} \right]$$

$$\Delta' = \sqrt{\eta} \Delta; \quad \eta = d_{eq} \frac{N_{sv}}{H_w};$$



# MODELING: LEAKAGE INDUCTANCE (HYBRID MODEL)

## Influence of Winding Geometry on Leakage inductance:



## Hybrid Leakage Inductance Model:

- ▶ Rogowski correction factor:

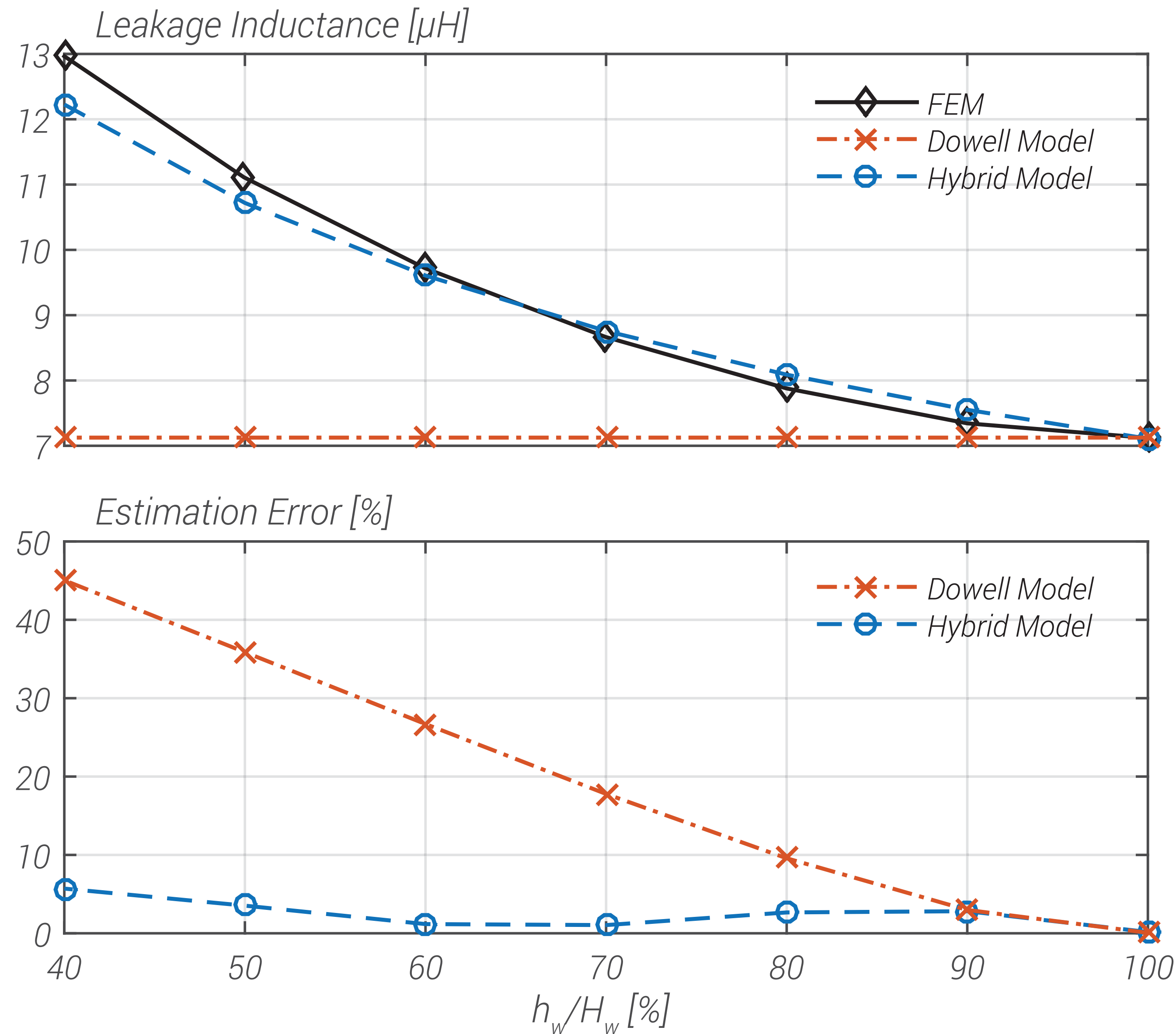
$$h_{eq} = \frac{h_w}{K_R}$$

$$K_R = 1 - \frac{1 - e^{-\pi h_w / (d_{w1} + d_d + d_{w2})}}{\pi h_w / (d_{w1} + d_d + d_{w2})}$$

- ▶ Correction of Dowell's model ( $H_w \rightarrow h_{eq}$ ):

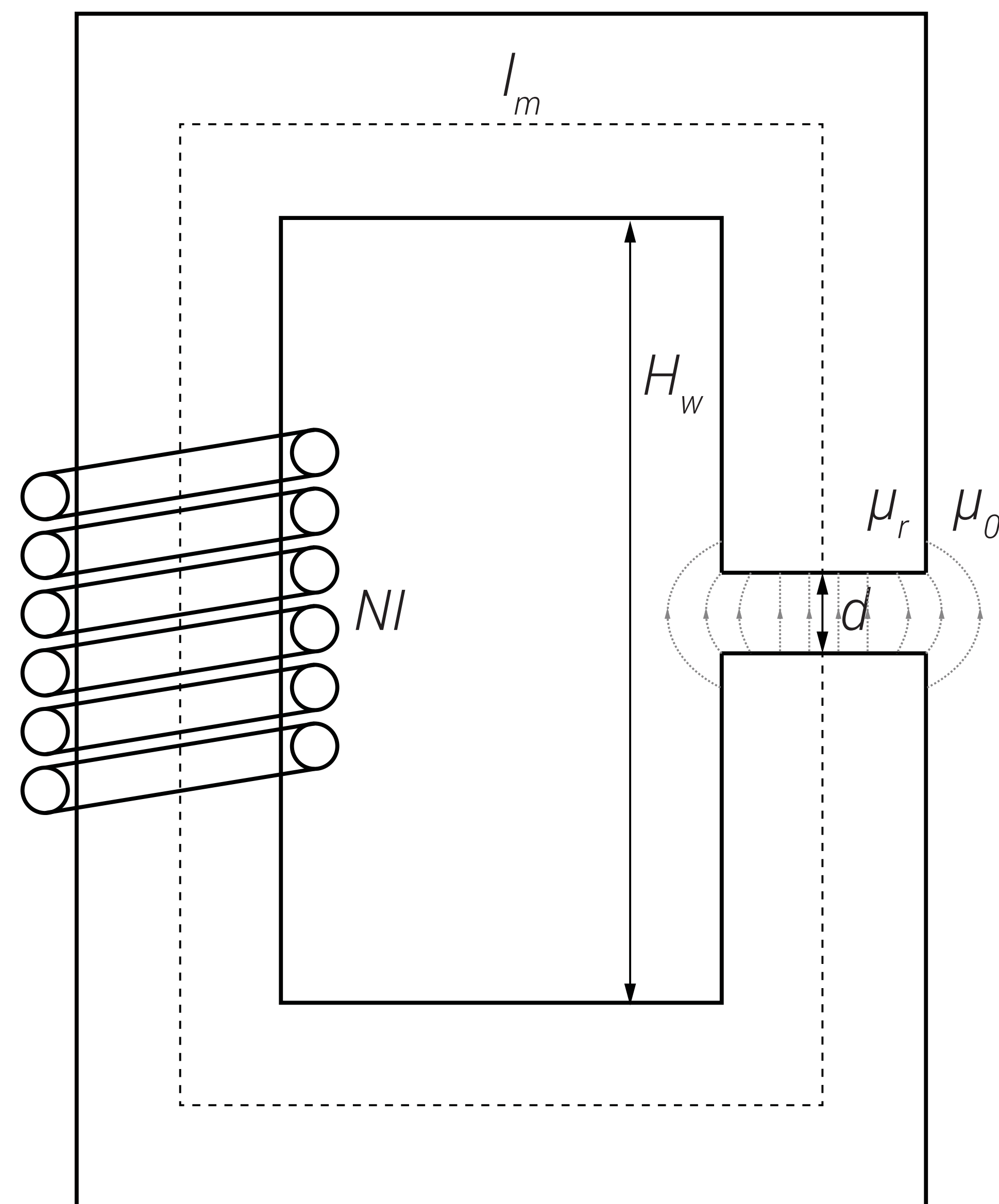
$$L_\sigma = N_1^2 \mu_0 \frac{l_w}{h_{eq}} \left[ \frac{d_{w1eq} m_{w1}}{3} F_{w1} + \frac{d_{w2eq} m_{w2}}{3} F_{w2} + d_d + d_{w1i} \frac{(m_{w1} - 1)(2m_{w1} - 1)}{6m_{w1}} + d_{w2i} \frac{(m_{w2} - 1)(2m_{w2} - 1)}{6m_{w2}} \right]$$

$$\Delta' = \sqrt{\eta} \Delta; \quad \eta = d_{eq} \frac{N_{sv}}{h_{eq}}$$



# MODELING: MAGNETIZING INDUCTANCE

## Magnetic Circuit with an Air-Gap:



## Magnetizing Inductance Calculation:

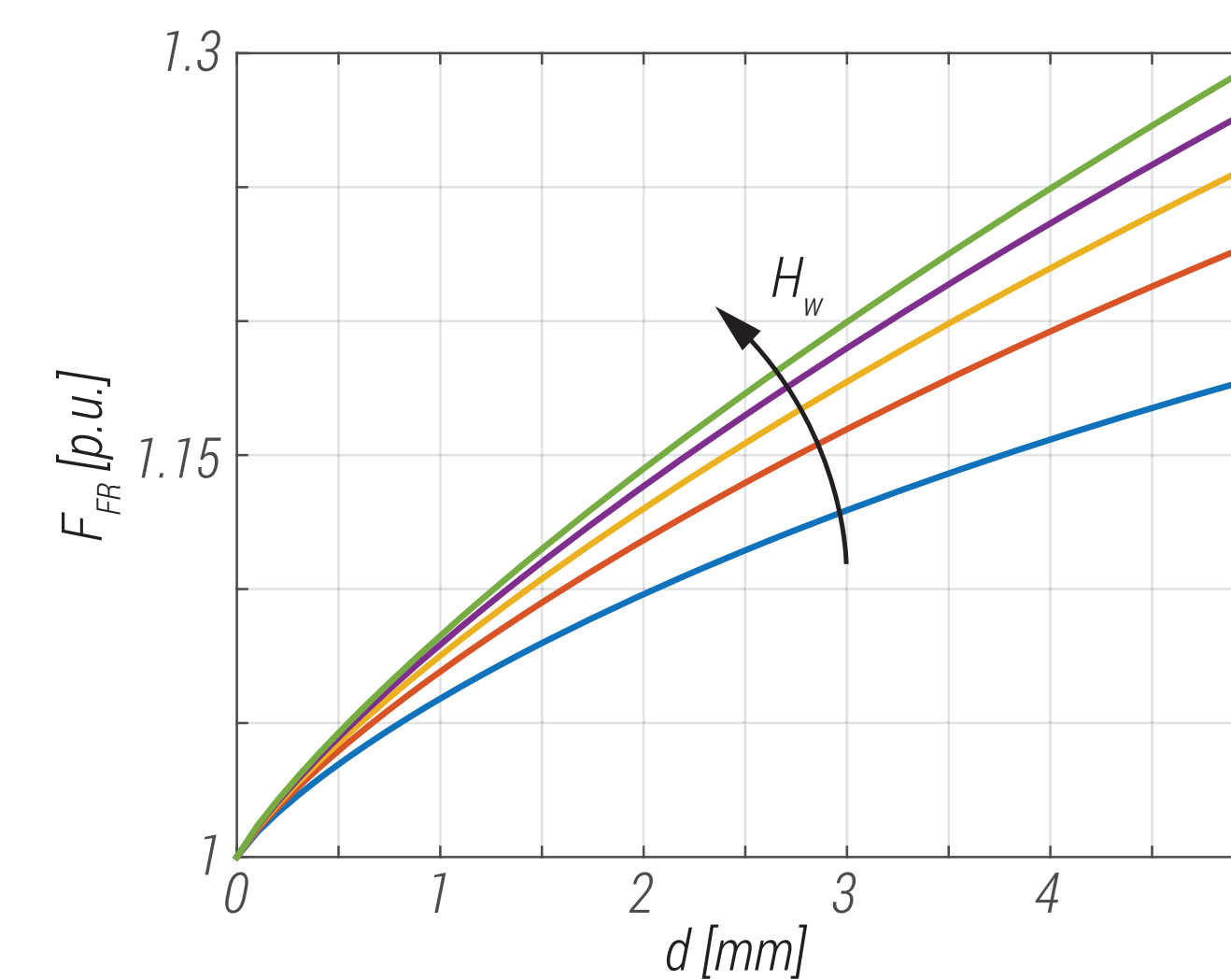
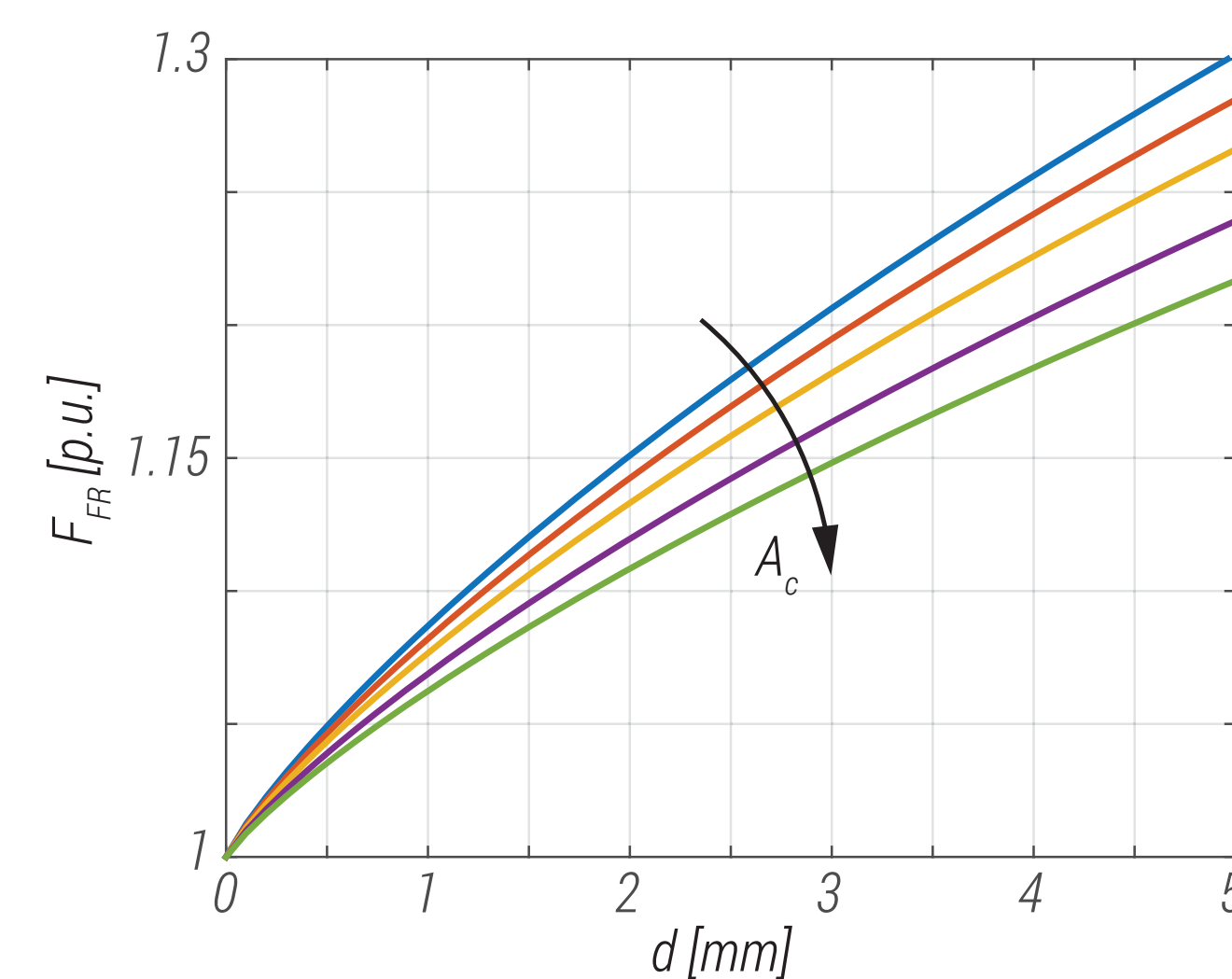
$$L_m = \frac{\mu_0 N^2 A_c}{\frac{l_m}{\mu_r} + d}$$

## Air-Gap Calculation:

$$d = \mu_0 \frac{N^2 A_c}{L_m} - \frac{l_m}{\mu_r}$$

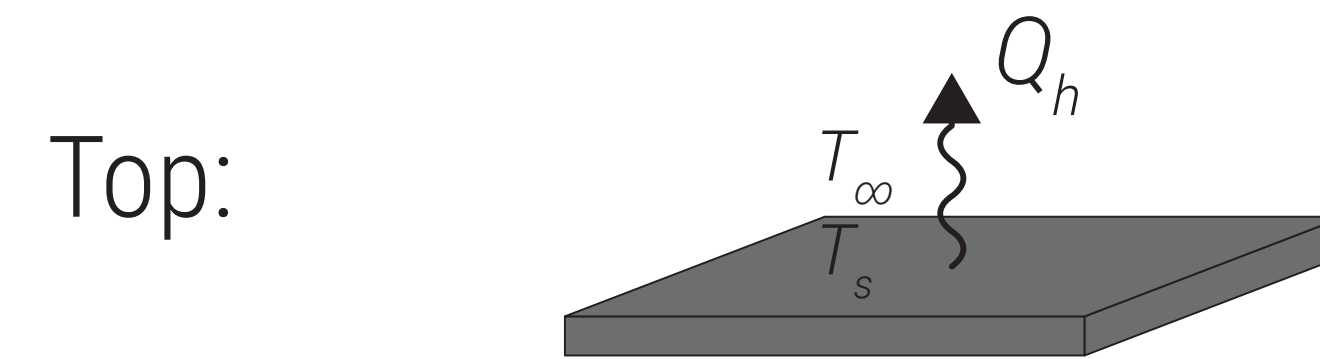
## Fringing Effect:

$$L'_m = L_m F_{FR}; \quad F_{FR} = 1 + \frac{d}{\sqrt{A_c}} \ln \left( \frac{2H_w}{d} \right);$$



# MODELING: HEAT-TRANSFER MECHANISMS

Conduction  $Q_h = kA \frac{\Delta T}{L}$

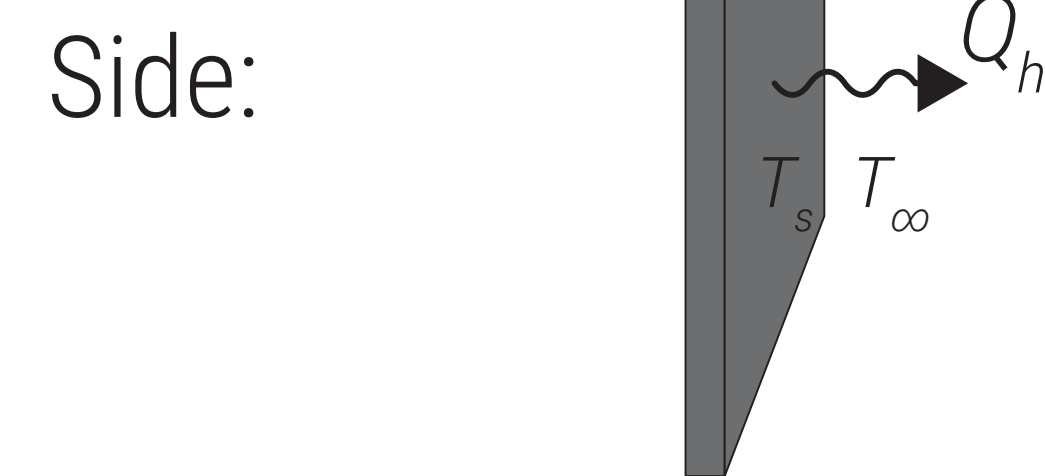


$$h = \frac{k(0.65 + 0.36Ra_L^{1/6})^2}{L}$$

$$L = \frac{\text{Area}}{\text{Perimeter}}$$

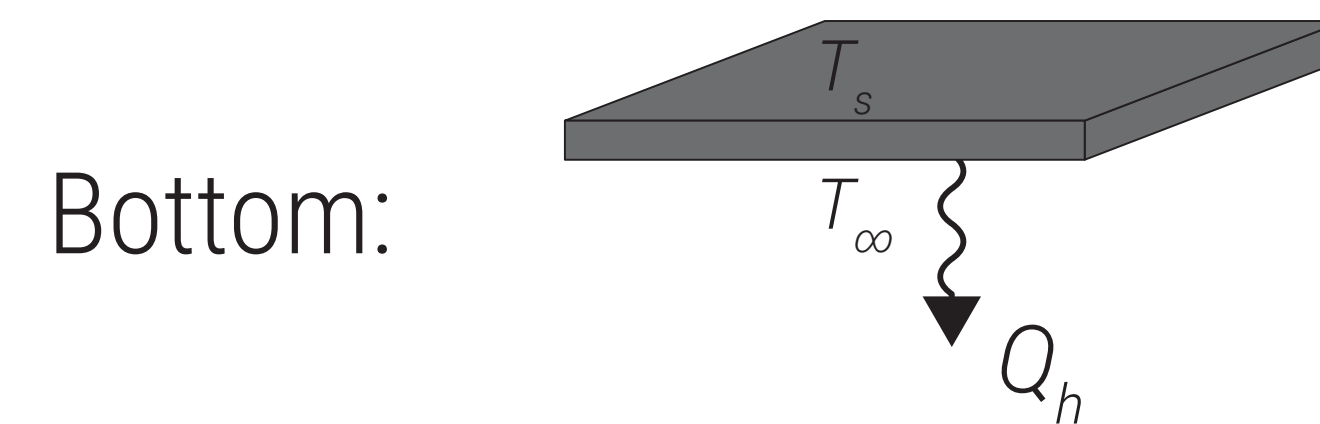
Convection  
over  
Hot-Plate

$$Q_h = hA(T_s - T_\infty)$$



$$h = \frac{k}{L} \left( 0.825 + \frac{0.387Ra_L^{1/6}}{(1 + (0.492/Pr)^{9/16})^{8/27}} \right)^2$$

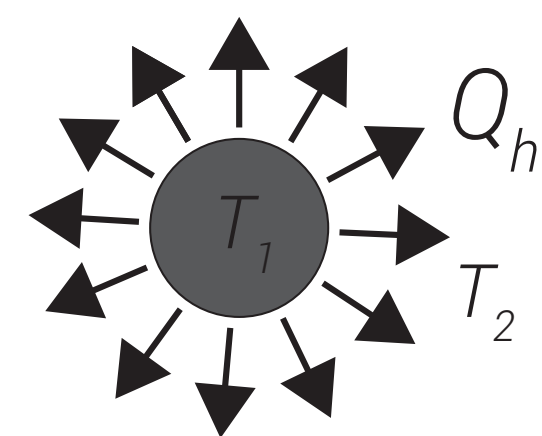
$$L = \text{Height}$$



$$h = \frac{k0.27Ra_L^{1/4}}{L}$$

$$L = \frac{\text{Area}}{\text{Perimeter}}$$

Radiation  $Q_h = hA(T_1 - T_2)$



$$h = \varepsilon\sigma \frac{(T_1 + 273.15)^4 - (T_2 + 273.15)^4}{(T_1 - T_2)}$$

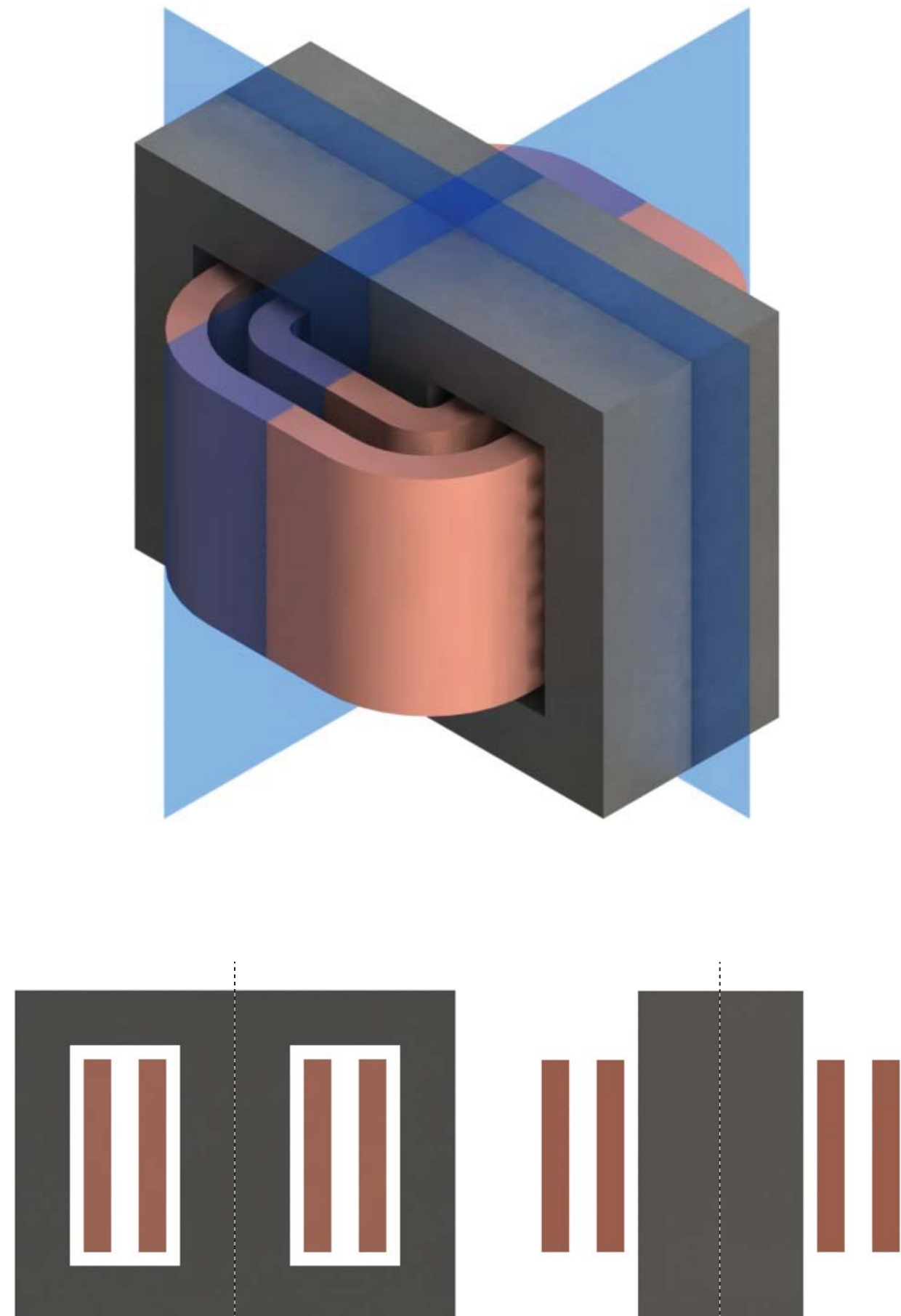
where:  $Ra_L$  - Rayleigh number,  $Pr$  - Prandtl number,  $\varepsilon$  - Emissivity,  $\sigma$  - Stefan-Boltzmann constant [33], [34], [35]

# MODELING: THERMAL MODEL

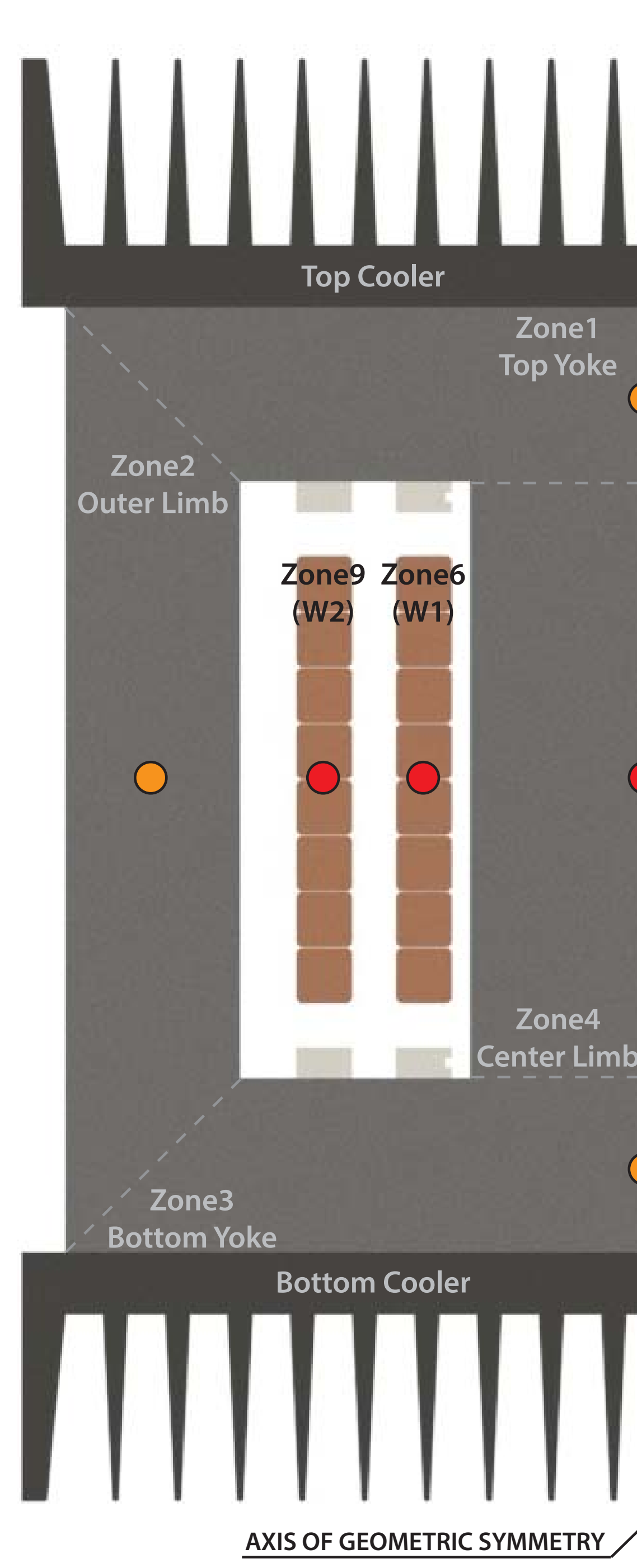
## Modes Of Heat Transfer:

- ▶ Conduction
- ▶ Convection
- ▶ Radiation

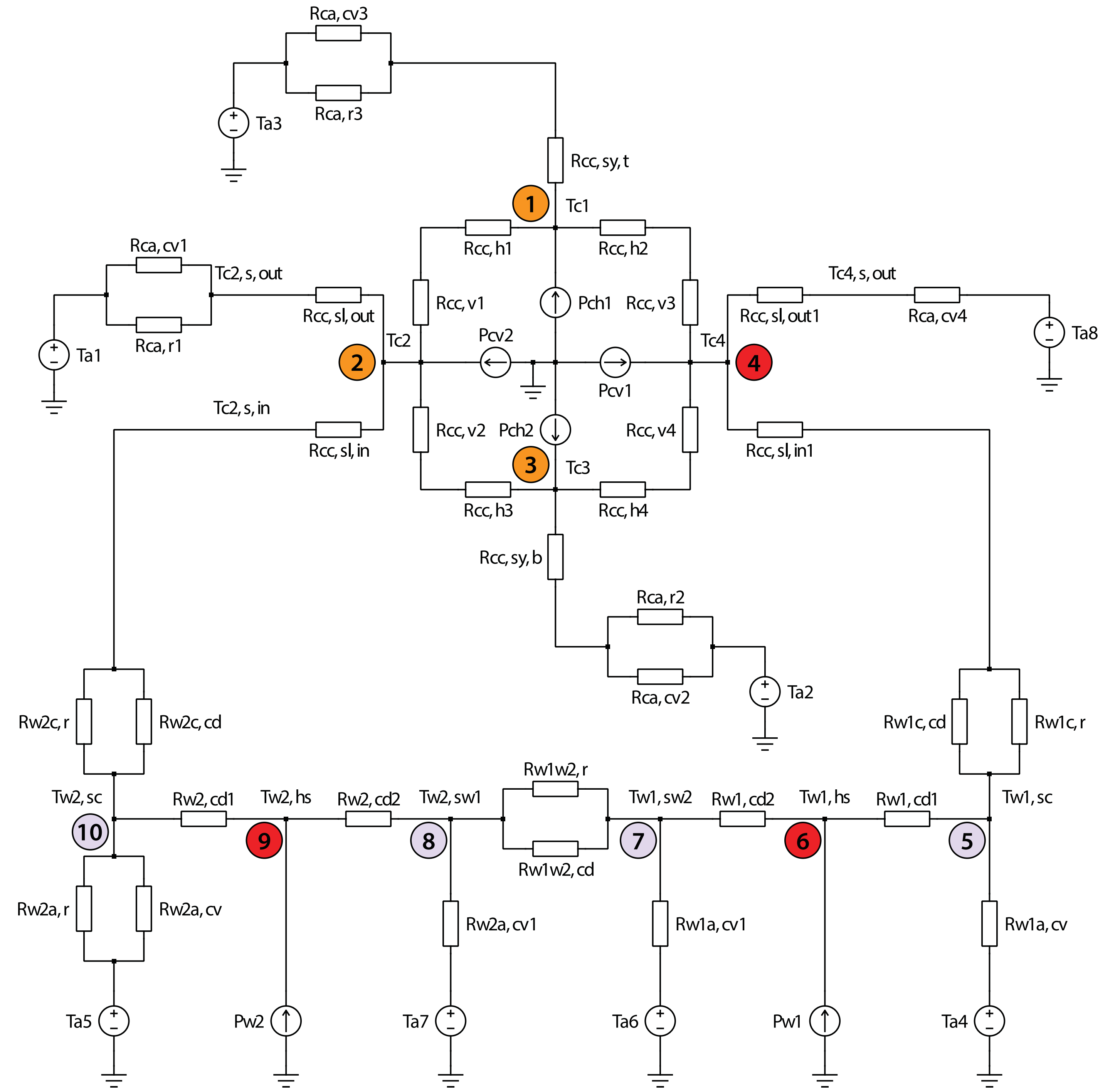
## Planes of Symmetry:



## Partitioning Into Zones:



## Detailed Thermal Network Model:

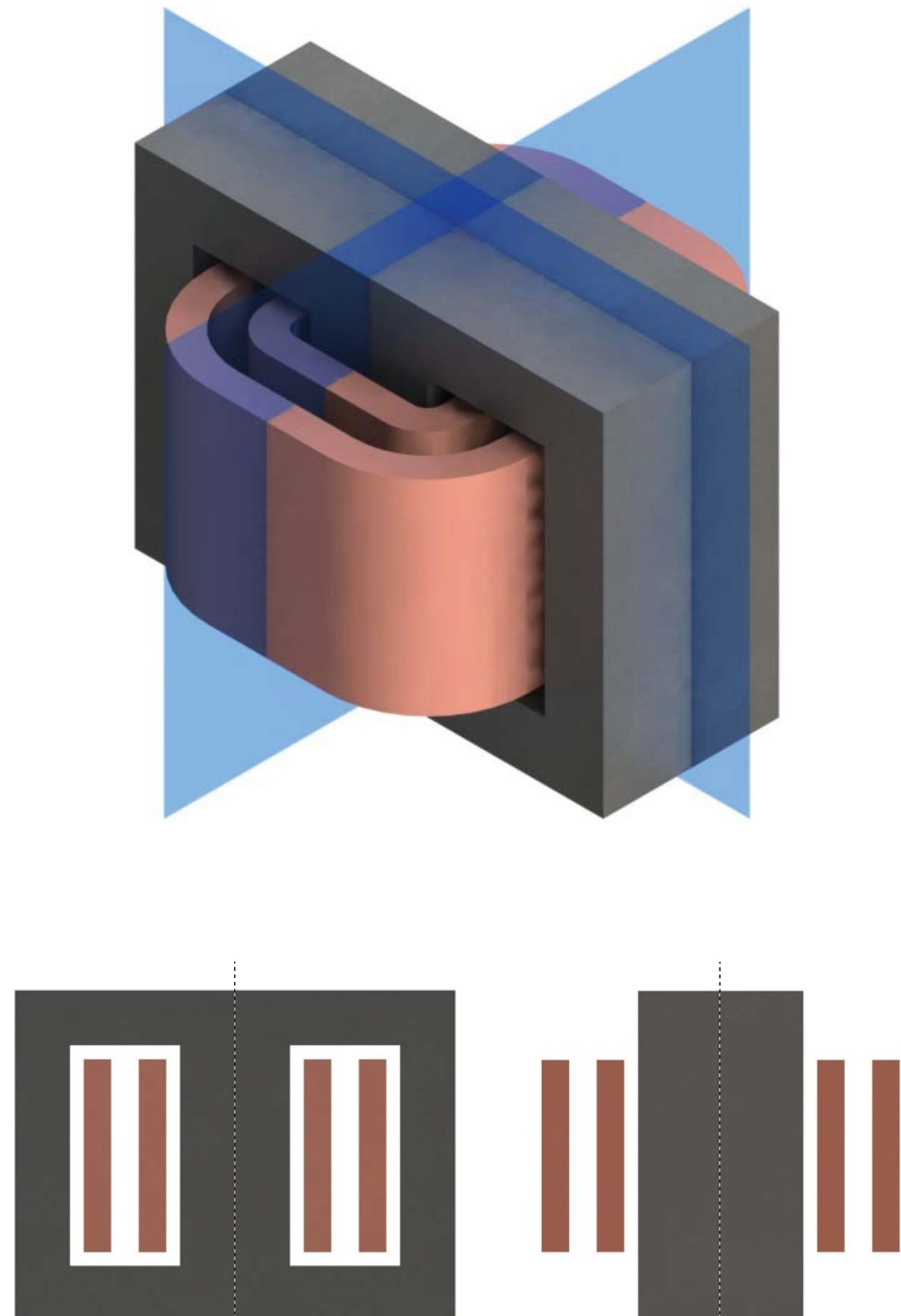


# MODELING: THERMAL MODEL

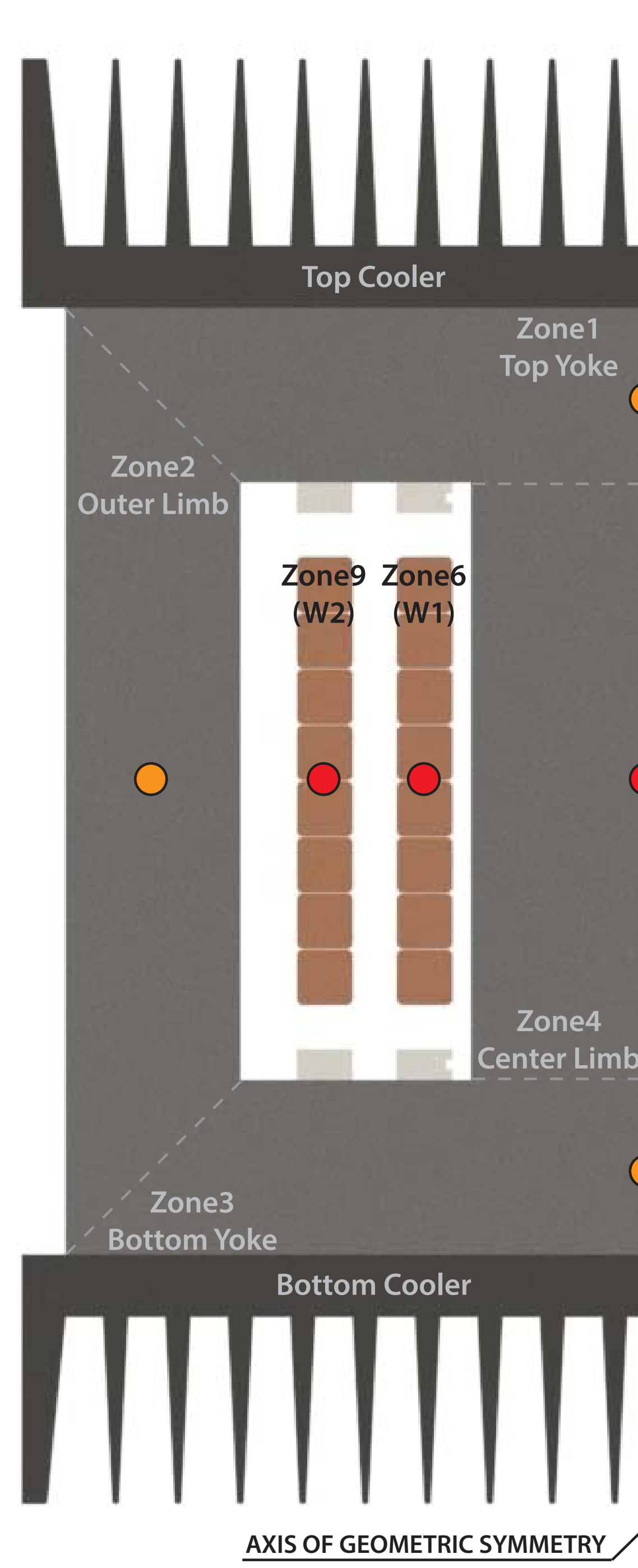
## Modes Of Heat Transfer:

- ▶ Conduction
- ▶ Convection
- ▶ Radiation

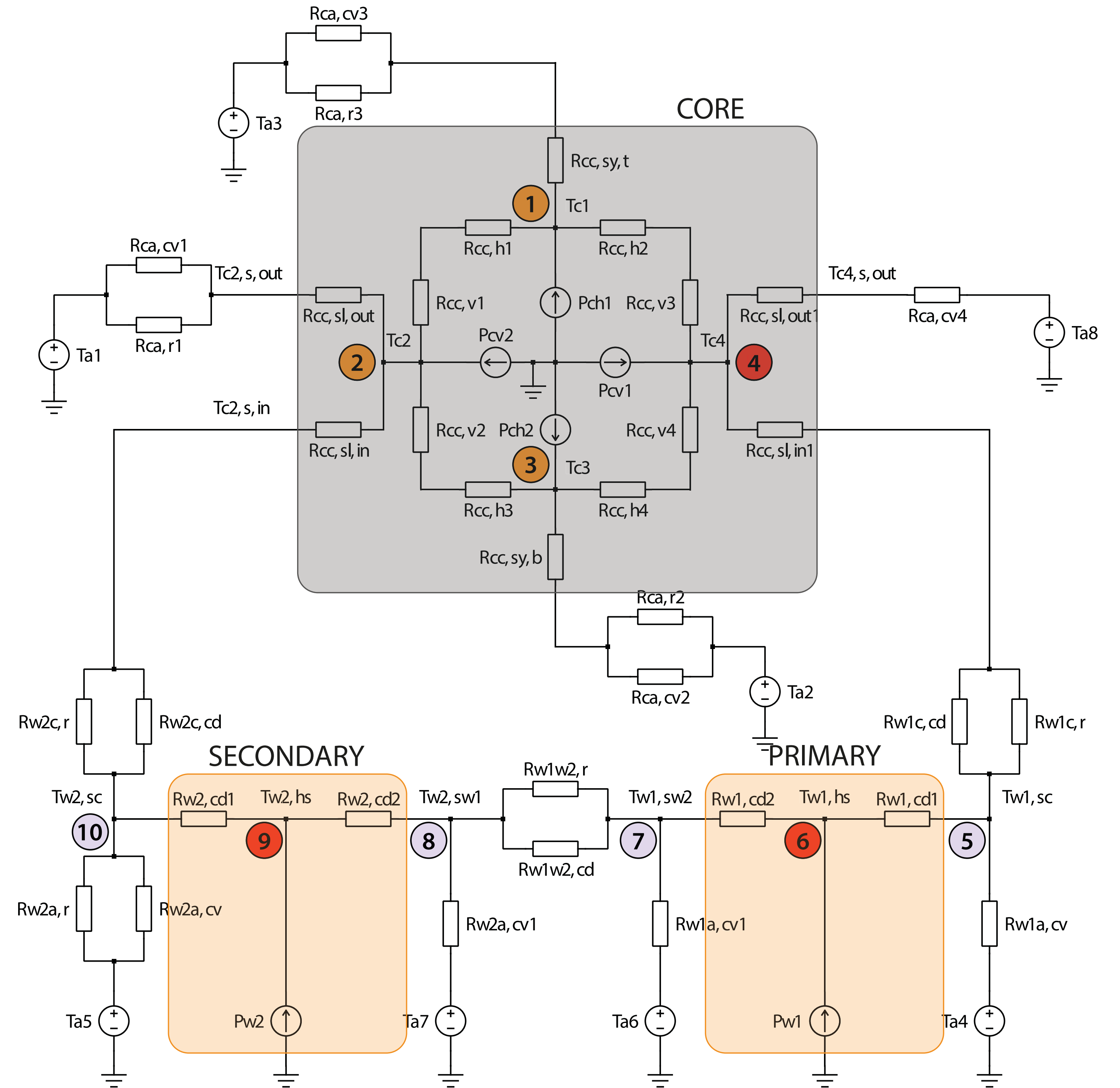
## Planes of Symmetry:



## Partitioning Into Zones:



## Detailed Thermal Network Model:



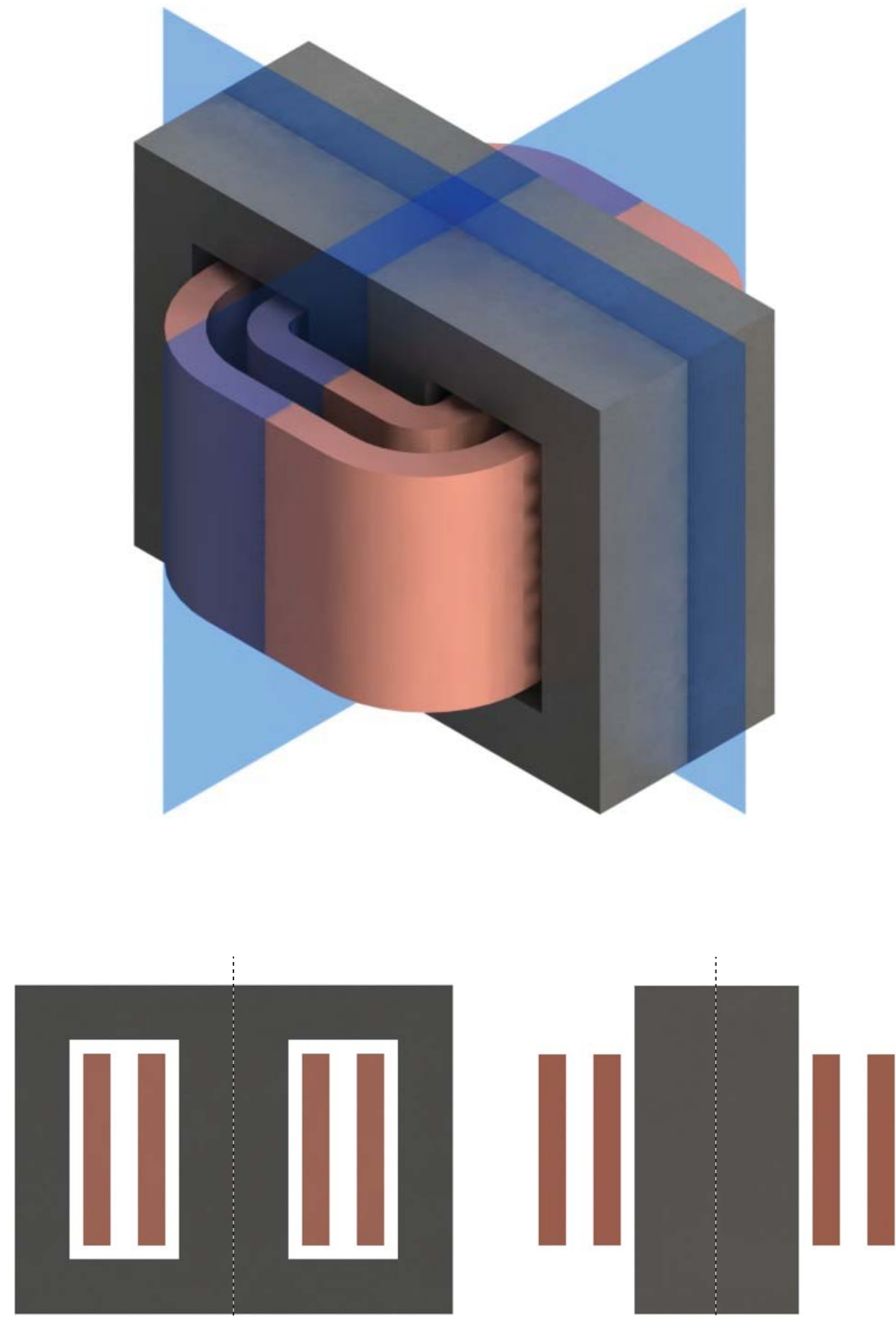


# MODELING: THERMAL MODEL

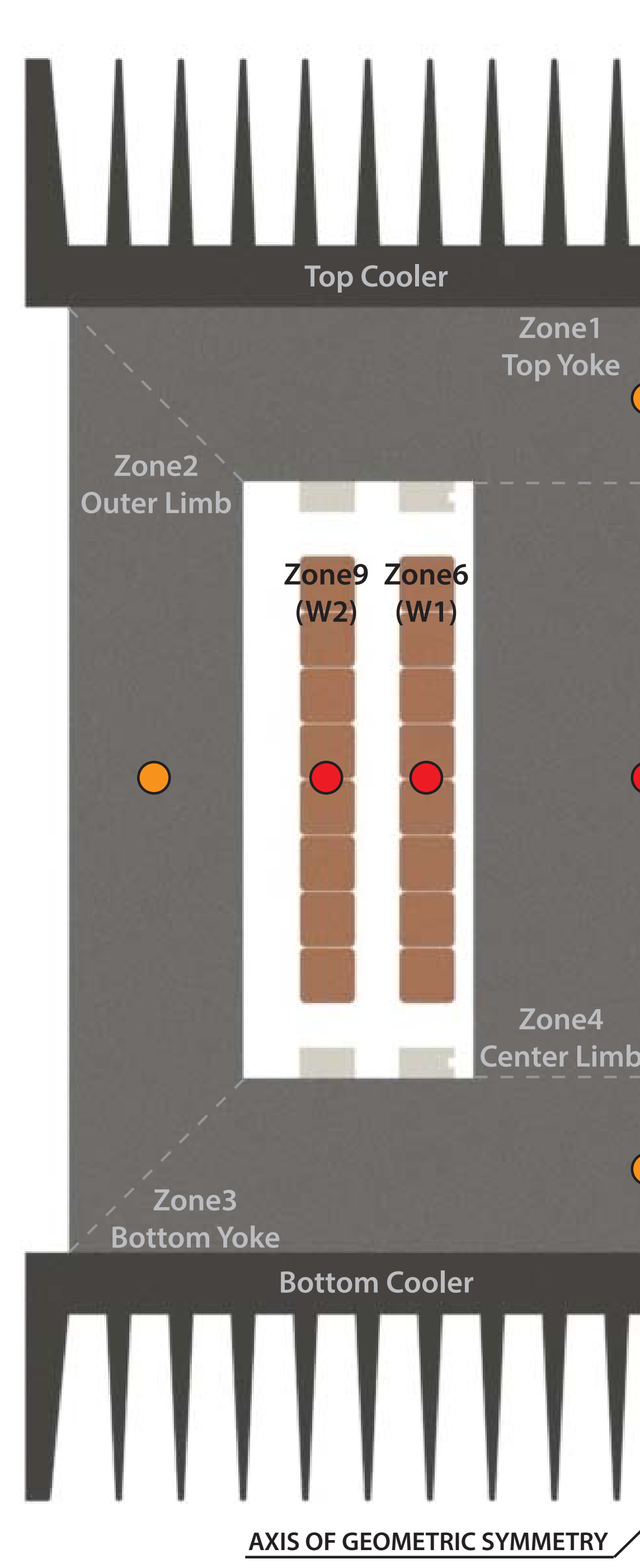
## Modes Of Heat Transfer:

- ▶ Conduction
- ▶ Convection
- ▶ Radiation

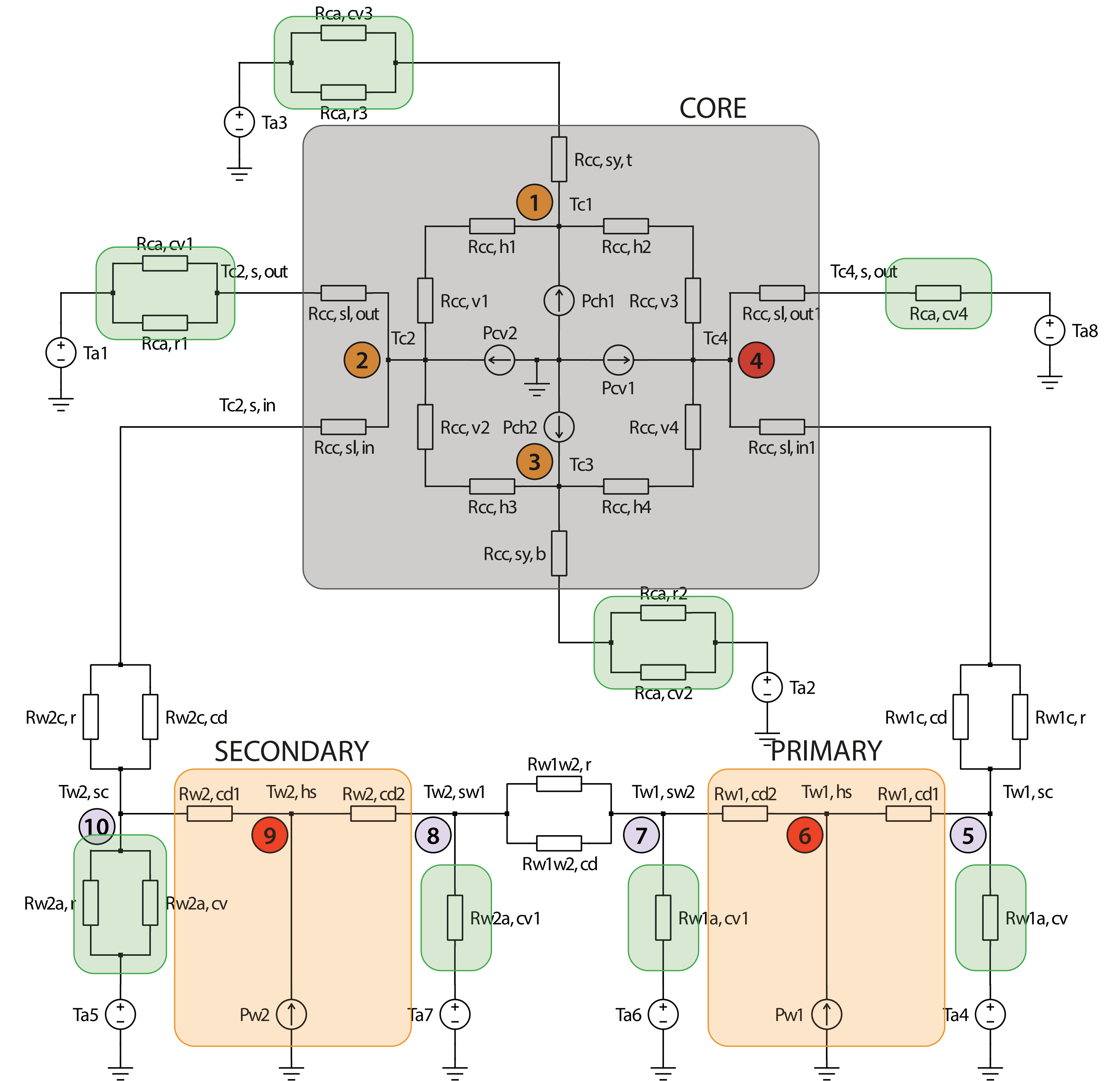
## Planes of Symmetry:



## Partitioning Into Zones:



## Detailed Thermal Network Model:

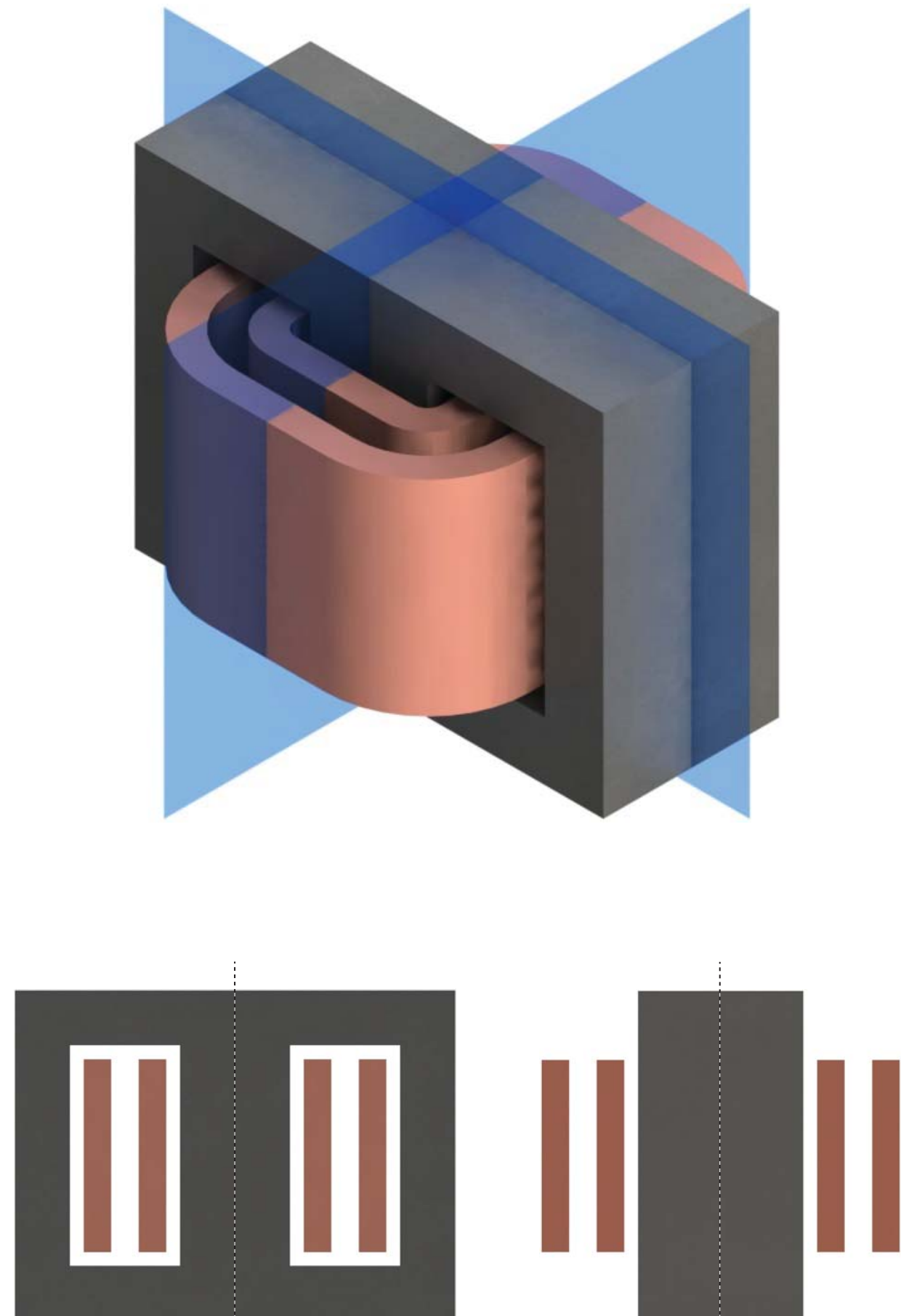


# MODELING: THERMAL MODEL

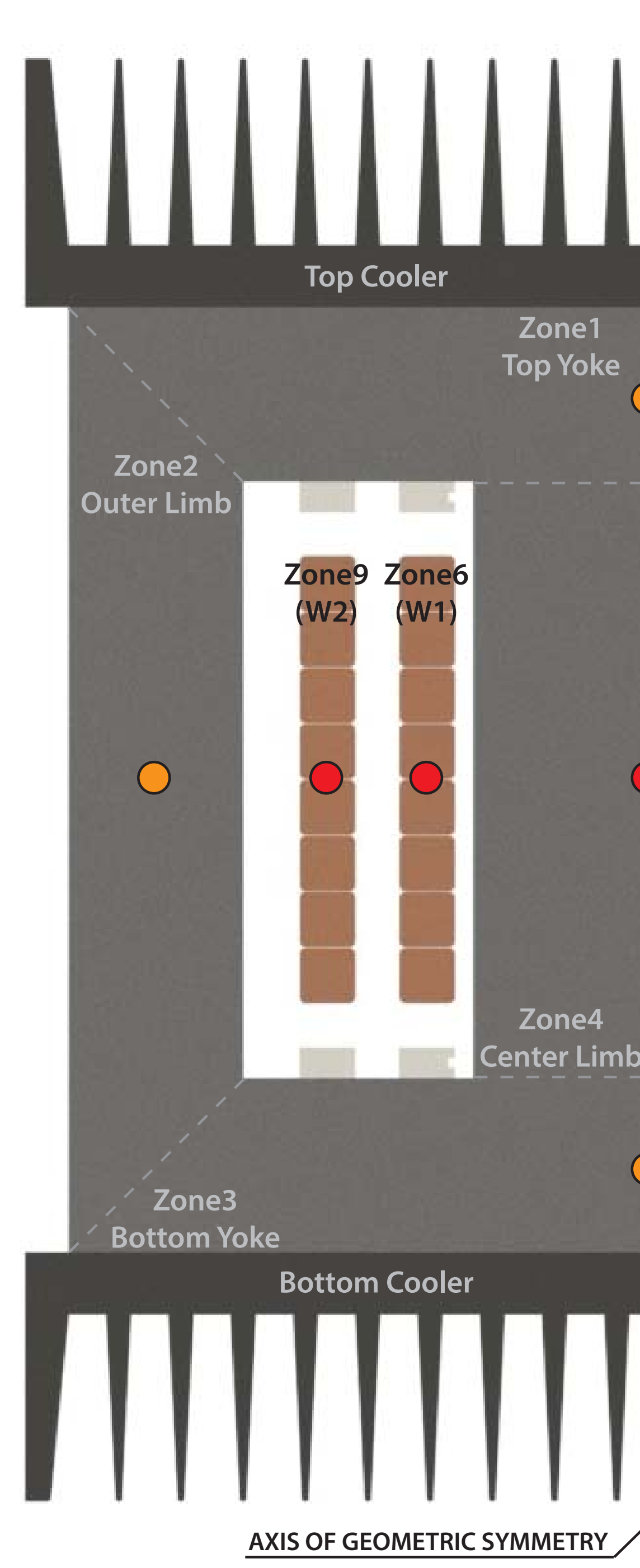
## Modes Of Heat Transfer:

- ▶ Conduction
- ▶ Convection
- ▶ Radiation

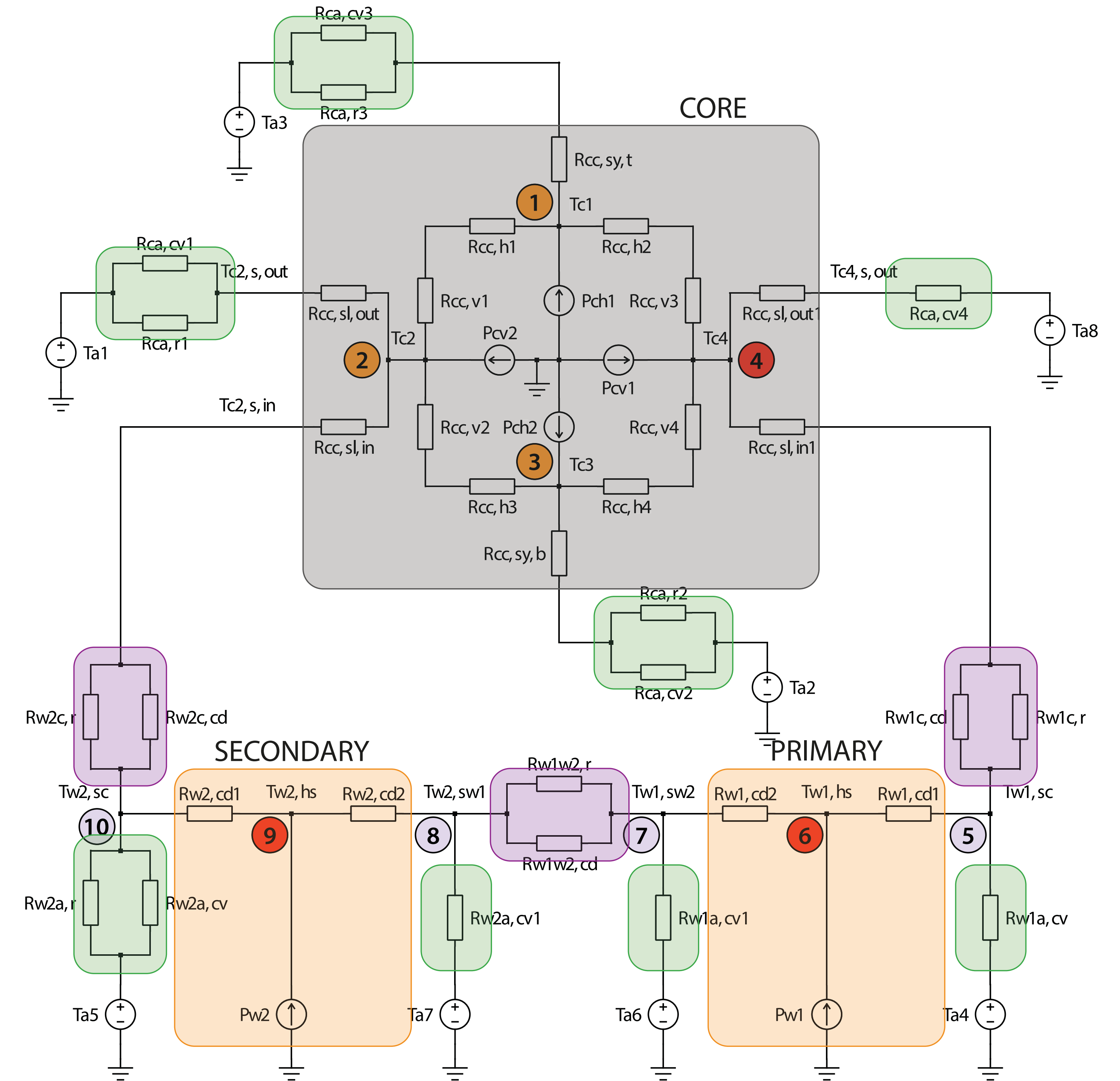
## Planes of Symmetry:



## Partitioning Into Zones:



## Detailed Thermal Network Model:





# MODELING: THERMAL FEM ANALYSIS

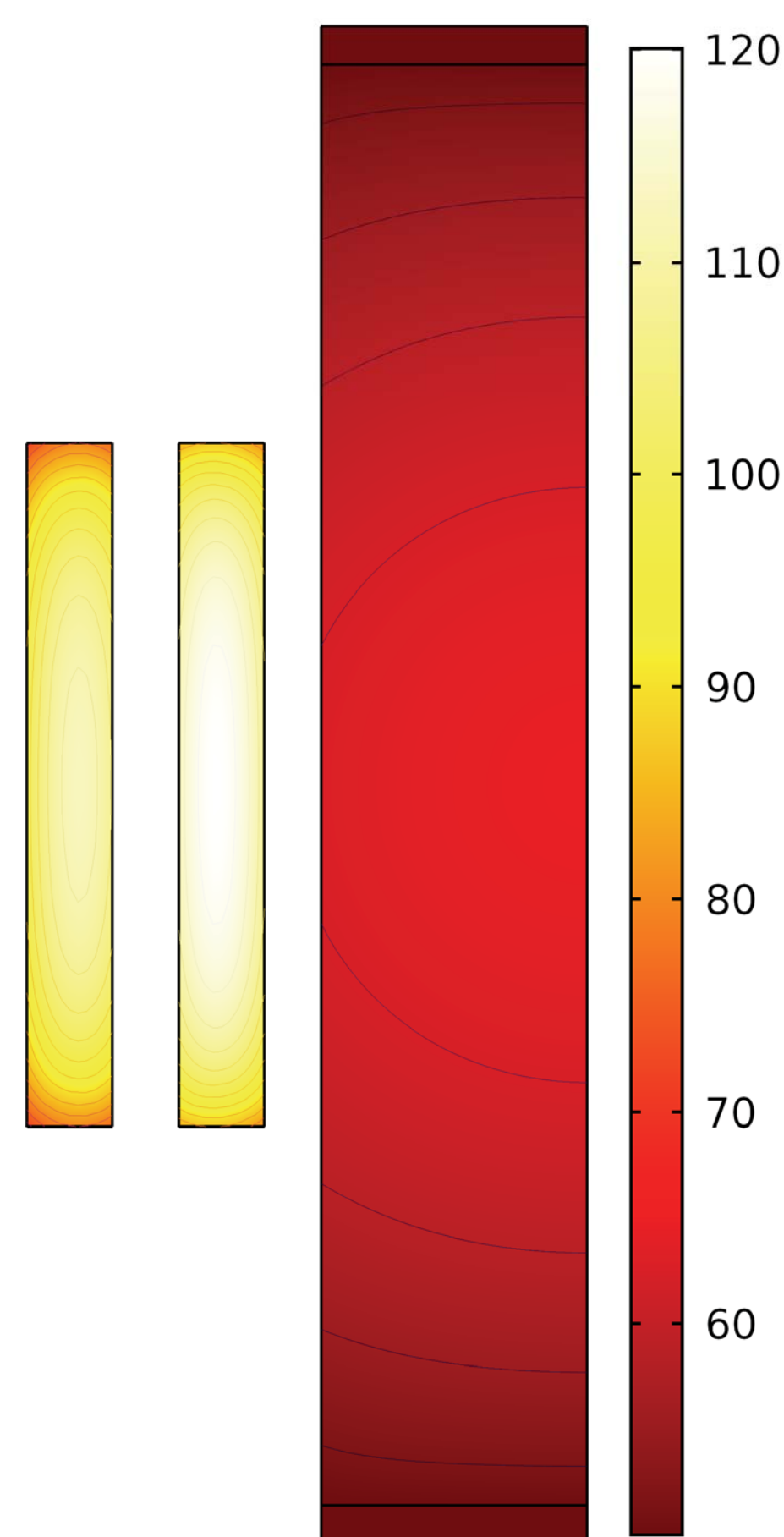
## Results:

- ▶ Different cooling conditions inside and outside of core window
- ▶ High thermal conduction equalizes the temp along the conductors
- ▶ Full 3D model estimations correlate well with analytical ones

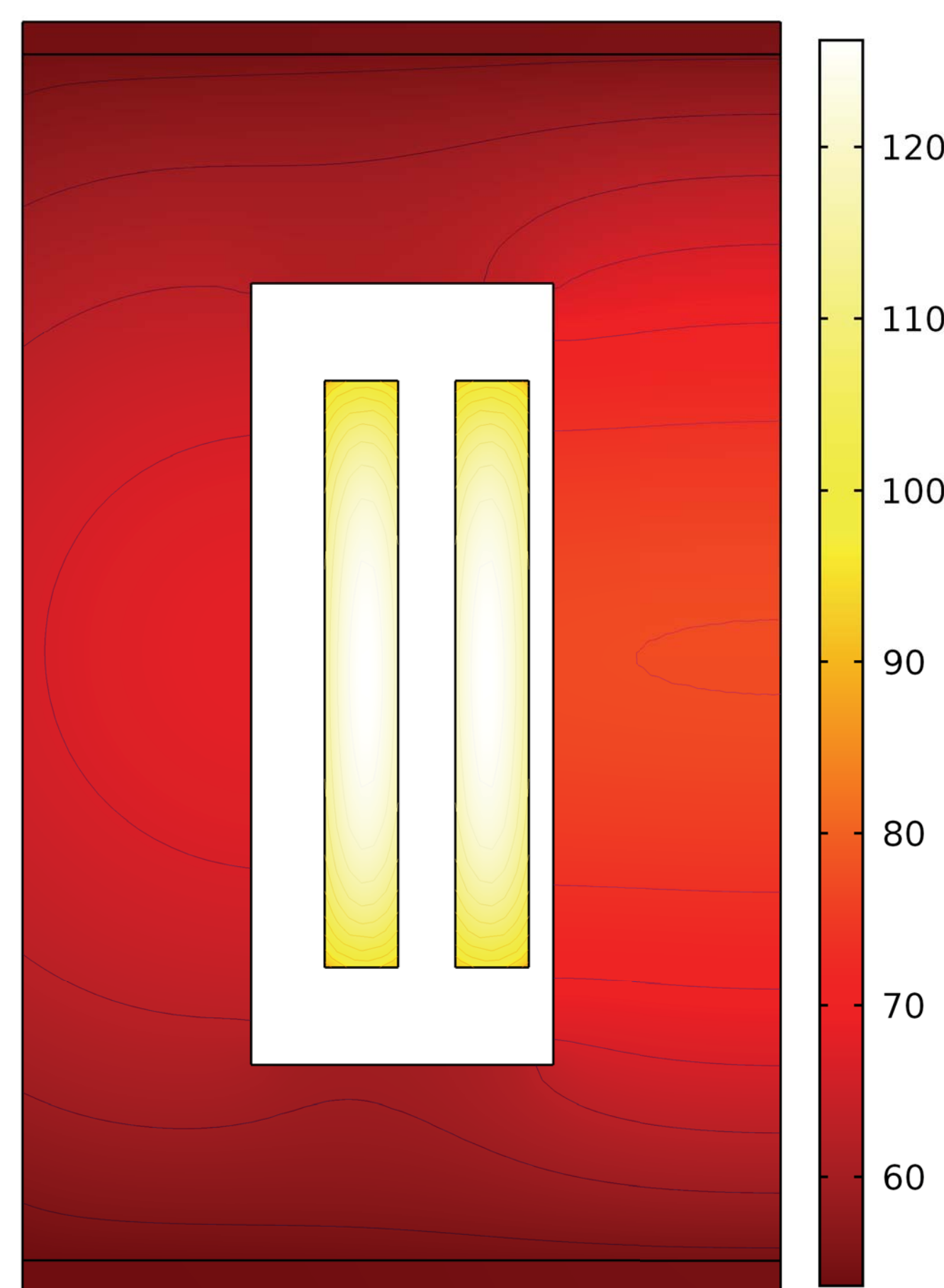
## Hot-Spot Temperature Estimation Comparison:

Hot-spot nodes	$T_1 [^{\circ}C]$	$T_2 [^{\circ}C]$	$T_3 [^{\circ}C]$	$T_4 [^{\circ}C]$	$T_6 [^{\circ}C]$	$T_9 [^{\circ}C]$
FEM 2D detail 1	/	/	/	70	120	106
FEM 2D detail 2	/	/	/	76	127	125
FEM 3D full	/	/	/	75	122	113
Analytical	51.3	59.9	58.4	73.75	124.6	116.3

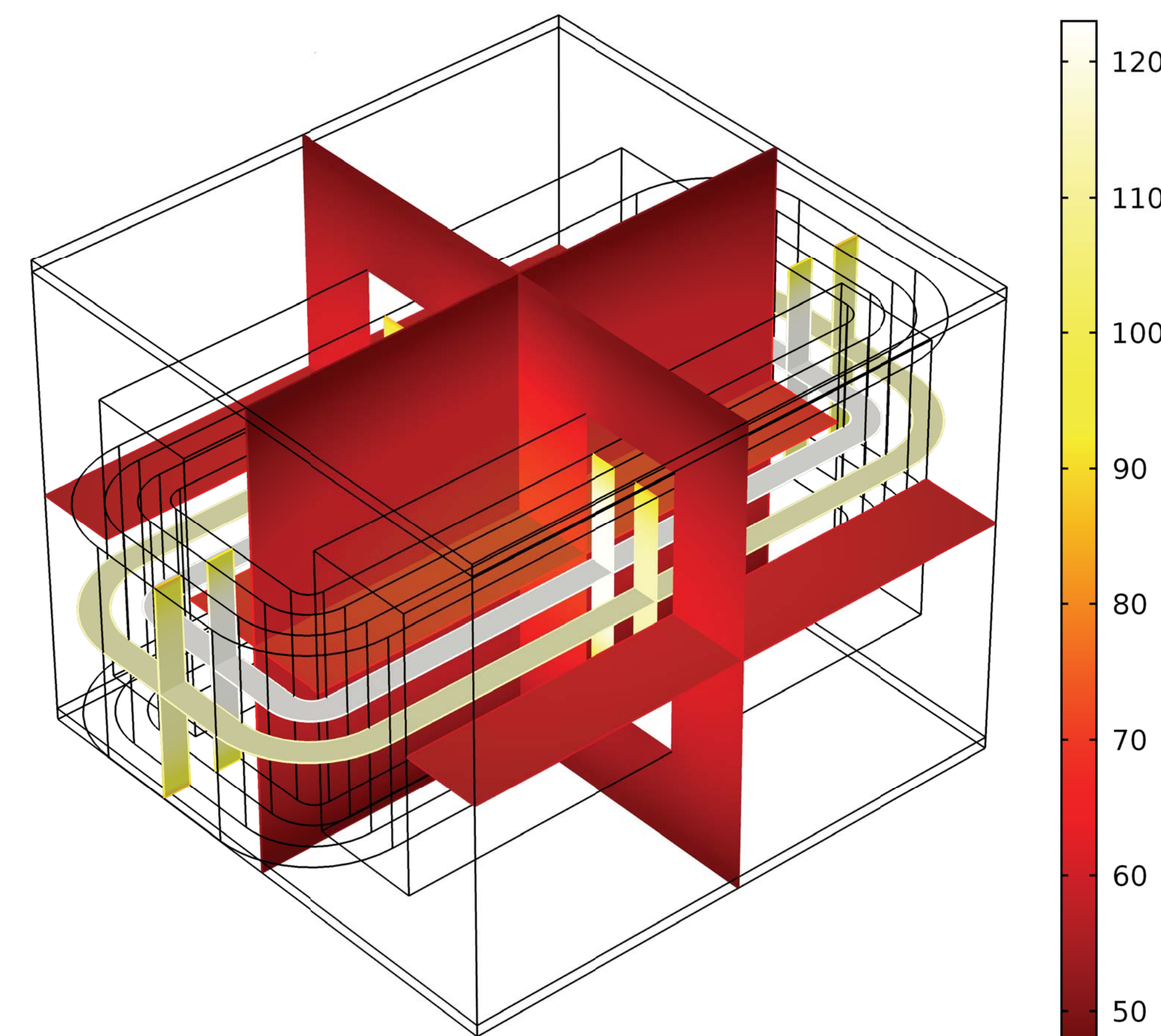
### 2D symmetry detail 1:



### 2D symmetry detail 2:



### Full 3D model:



---

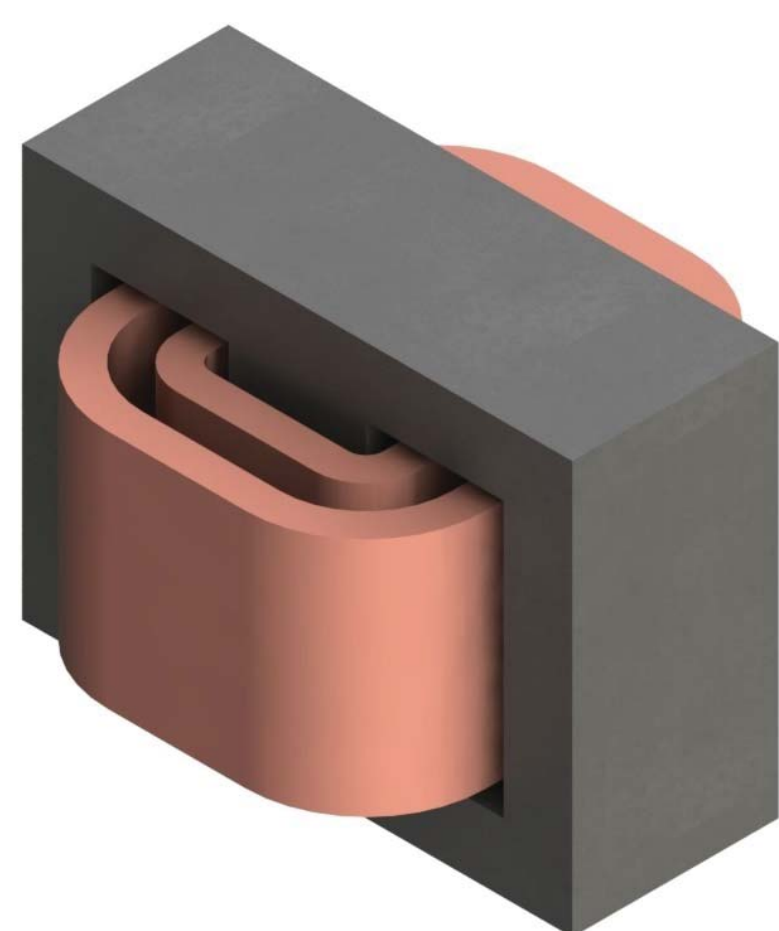
# MFT DESIGN OPTIMIZATION

*Brute force academic example?*

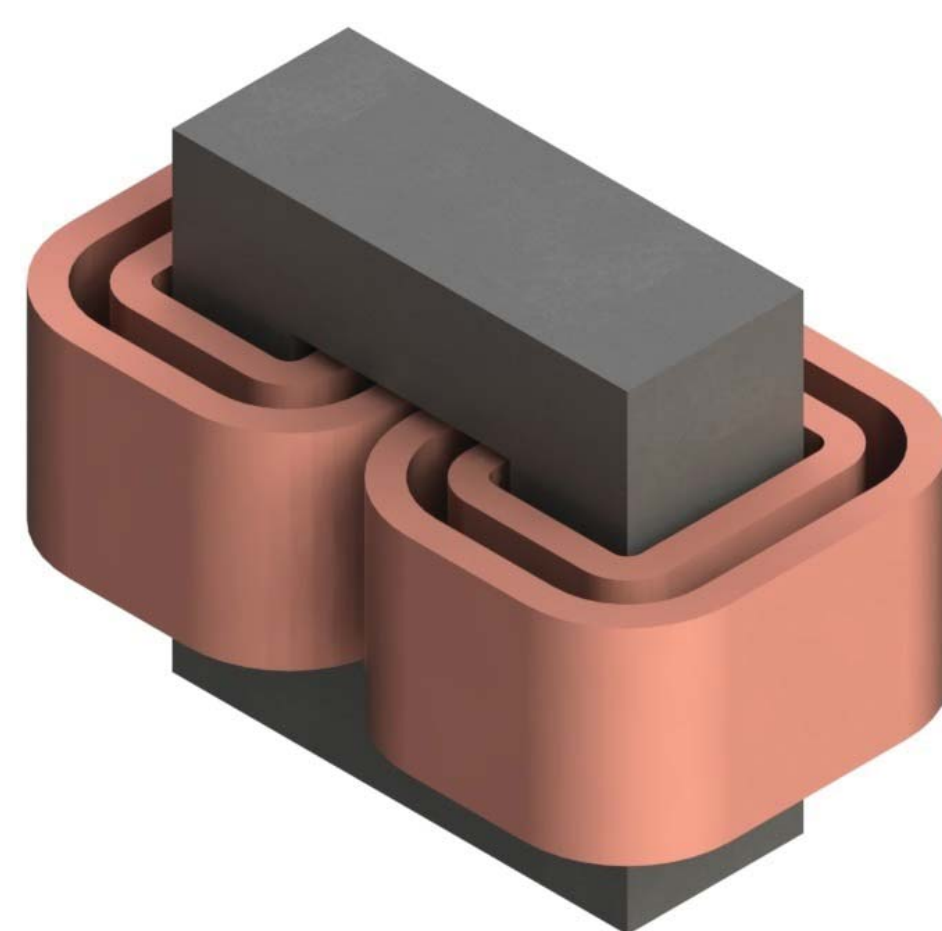
# TECHNOLOGIES AND MATERIALS

## Construction Choices:

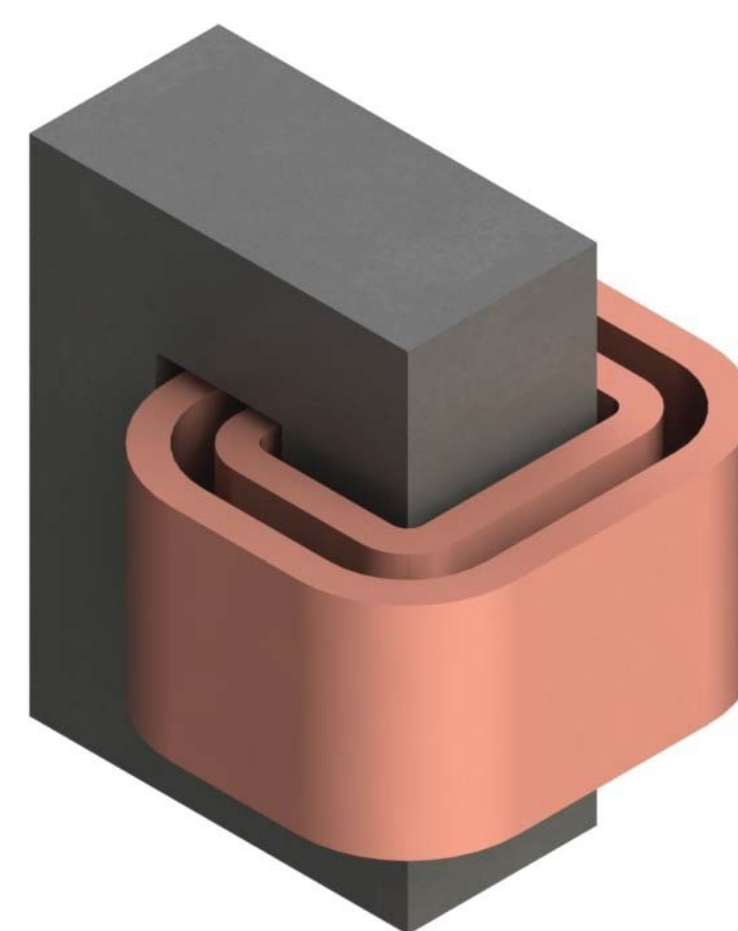
### ▶ MFT Types



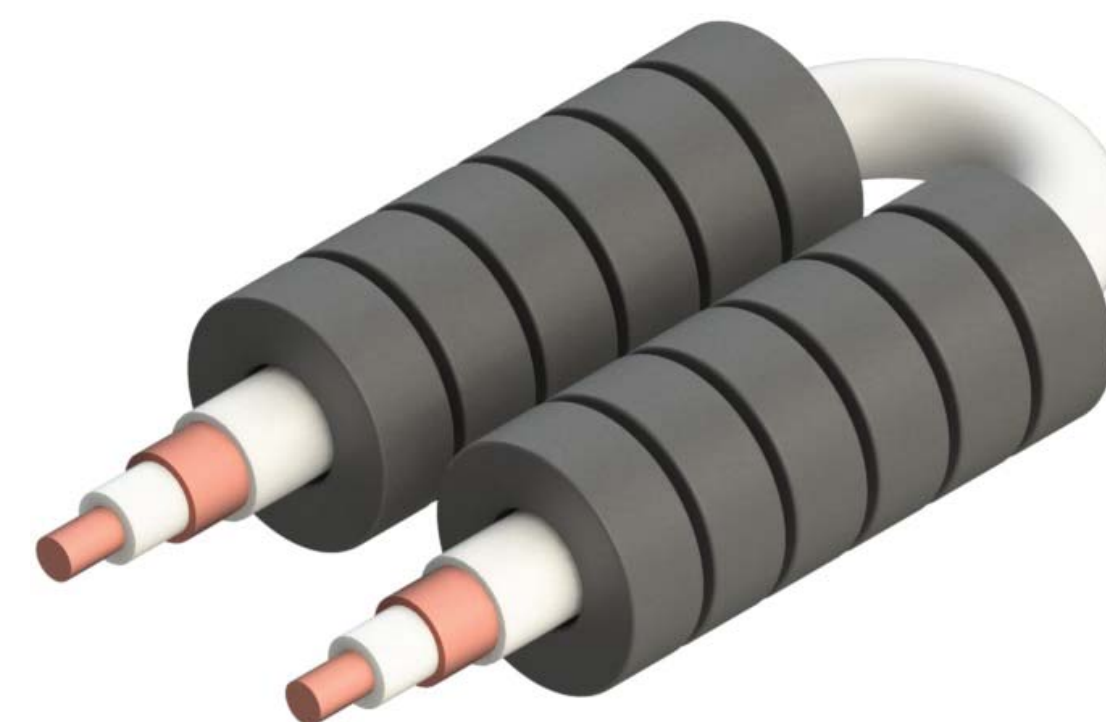
Shell Type



Core Type



C-Type



Coaxial Type

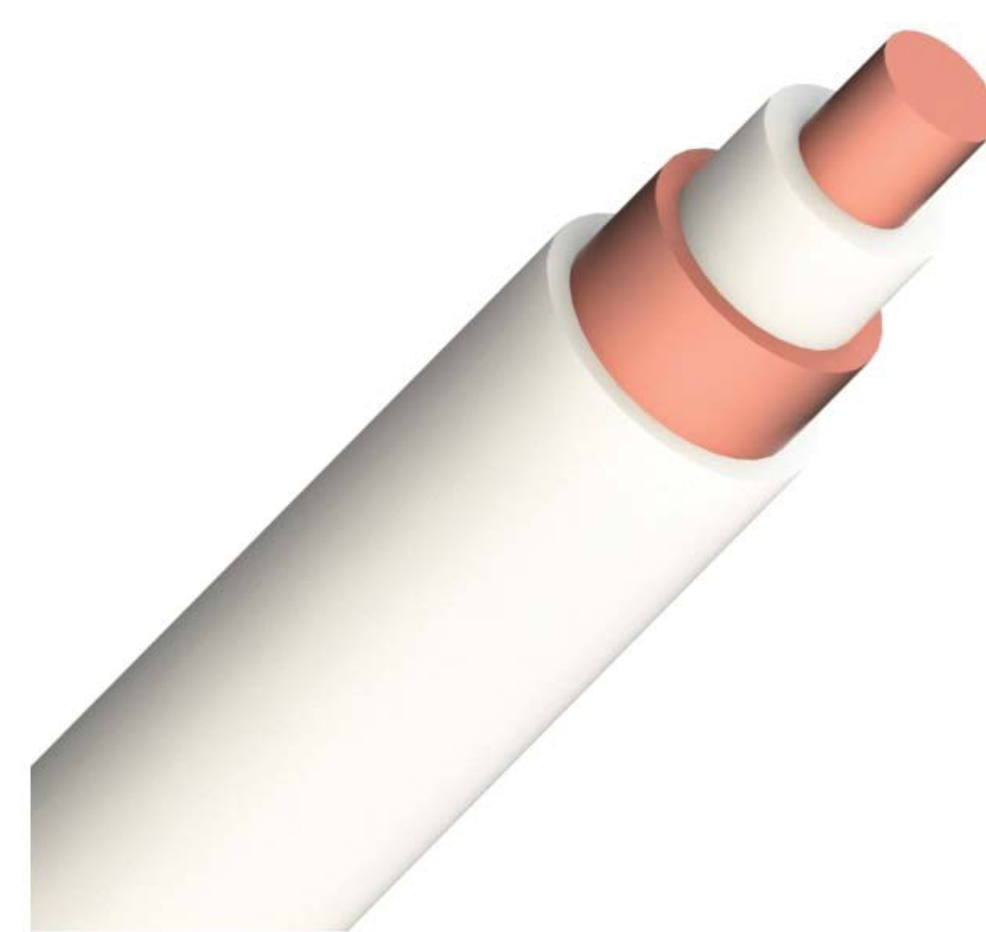
### ▶ Winding Types



Litz Wire



Foil



Coaxial



Hollow

## Materials:

### ▶ Magnetic Materials

- ▶ Silicon Steel
- ▶ Amorphous
- ▶ Nanocrystalline
- ▶ **Ferrites**

### ▶ Windings

- ▶ **Copper**
- ▶ Aluminum

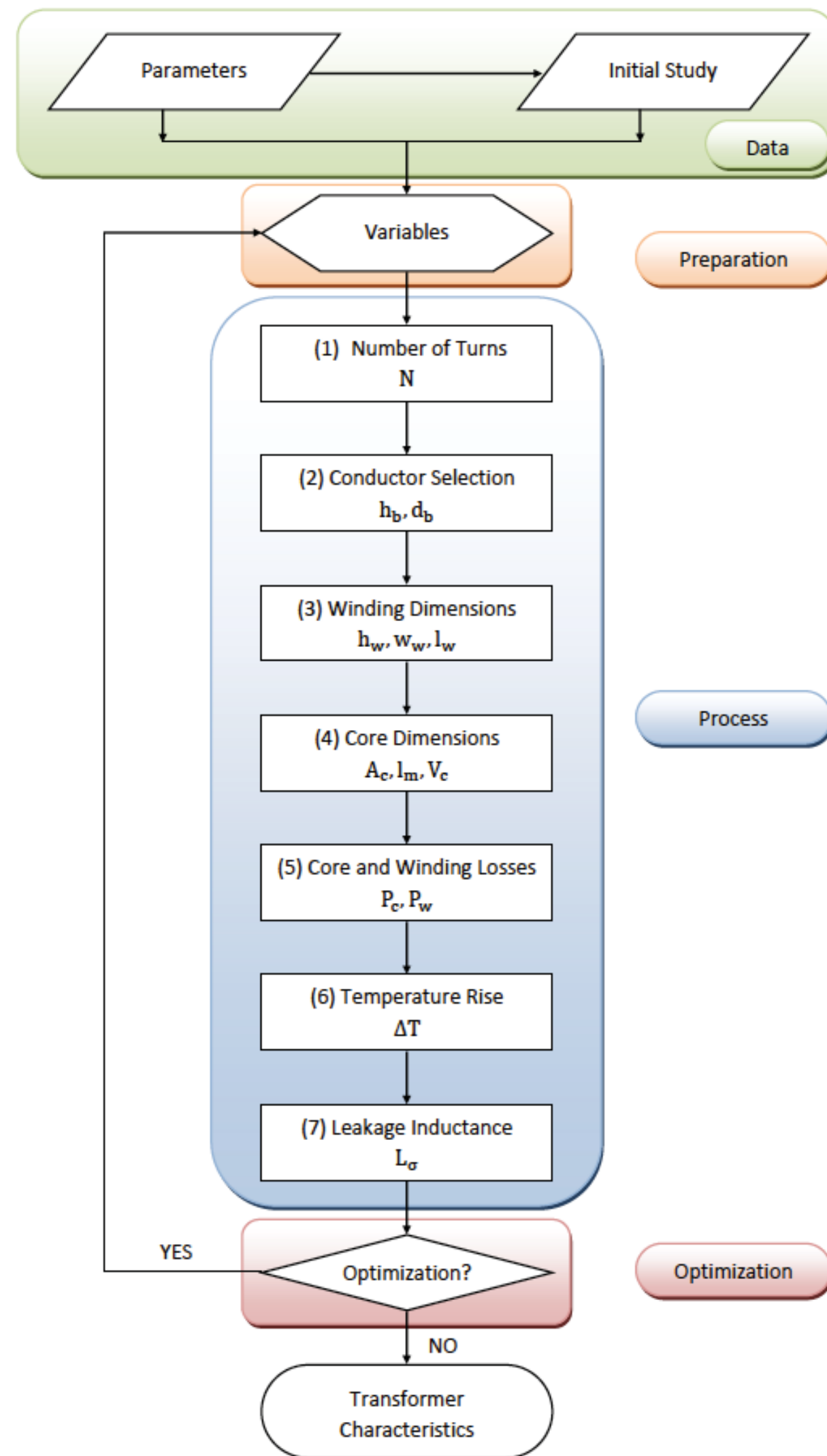
### ▶ Insulation

- ▶ **Air**
- ▶ Solid
- ▶ Oil

### ▶ Cooling

- ▶ **Air natural/forced**
- ▶ Oil natural/forced
- ▶ Water

# MFT DESIGN OPTIMIZATION

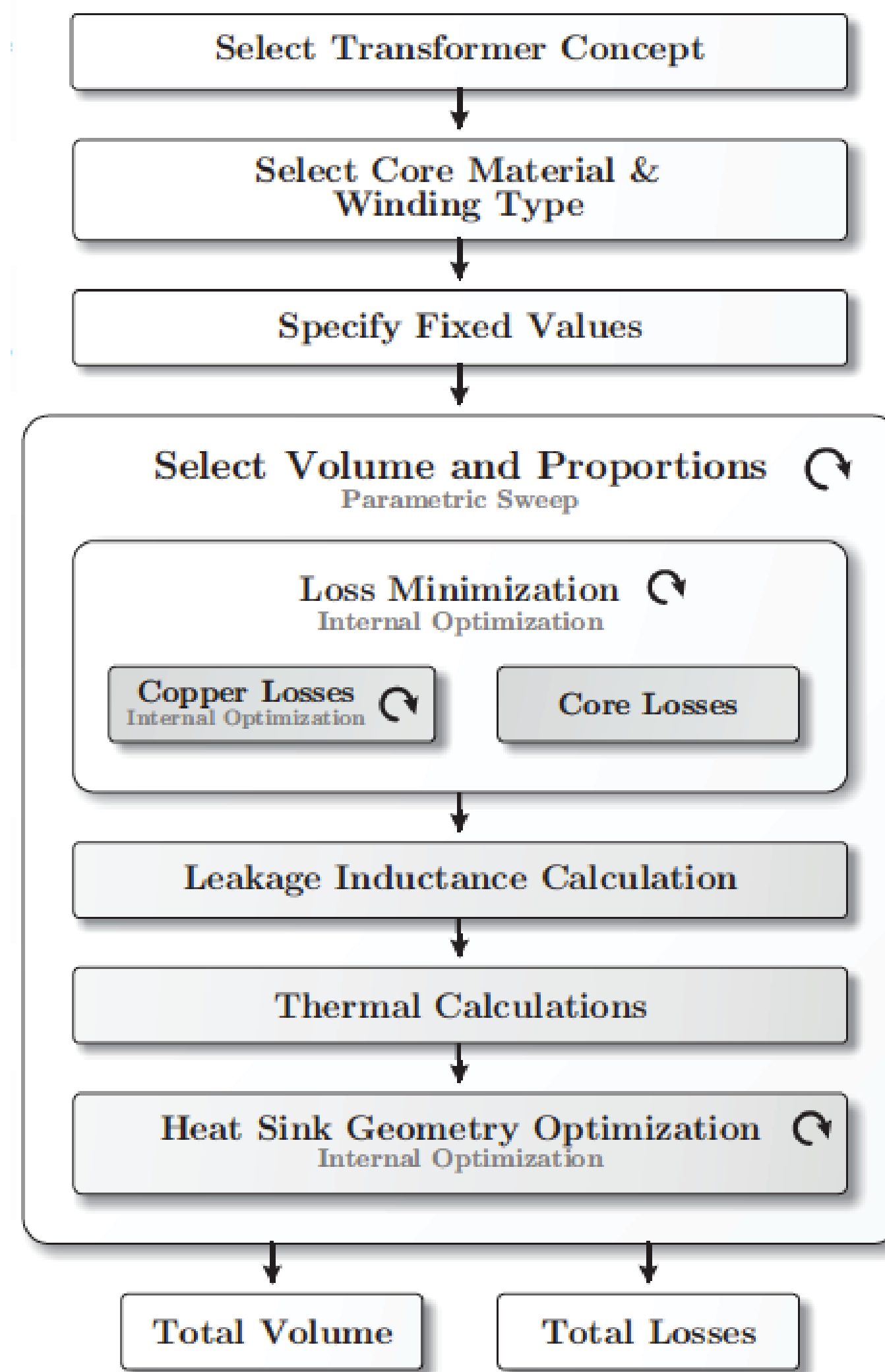


EPFL PhD: Villar [36]

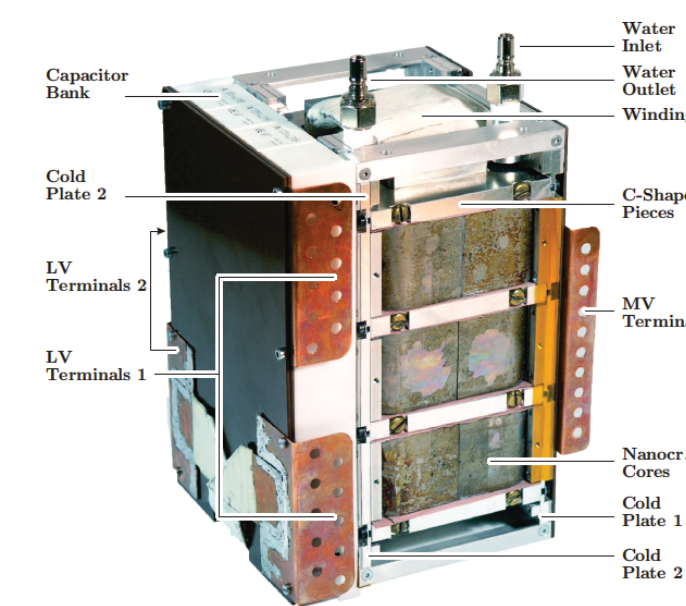


EPFL: 300kW, 2kHz

EPE'17 - ECCE Europe, Warsaw, Poland

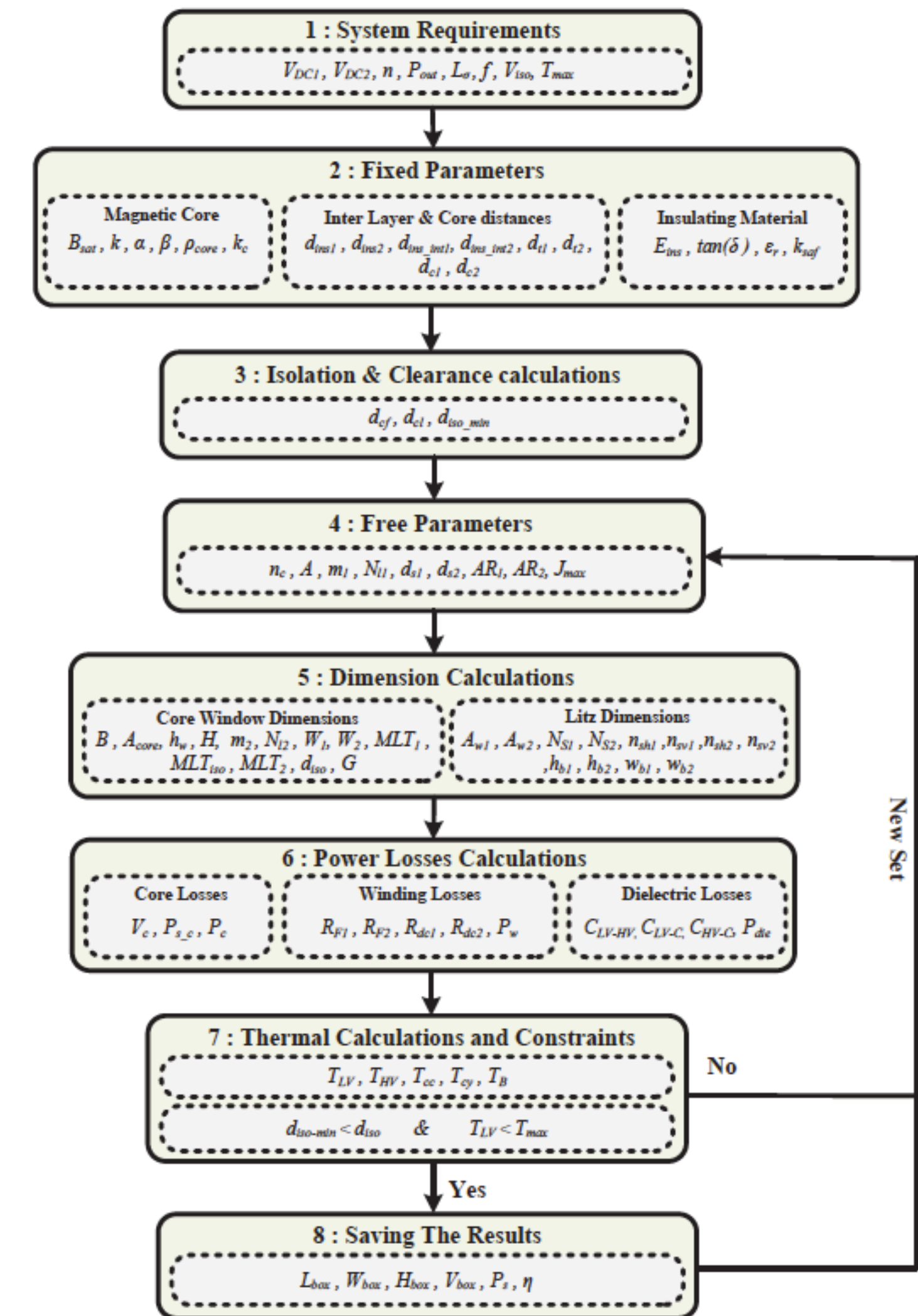


ETHZ PhD: Ortiz [15]

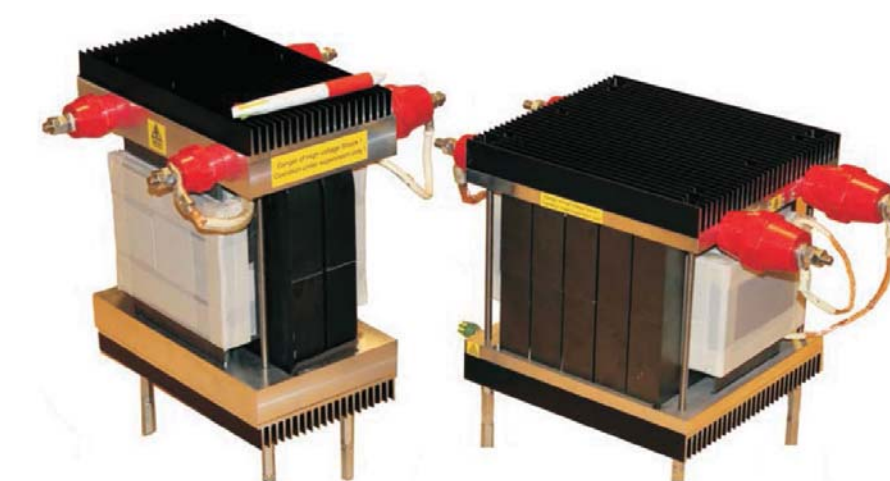


ETHZ: 166kW, 20kHz

September 11, 2017



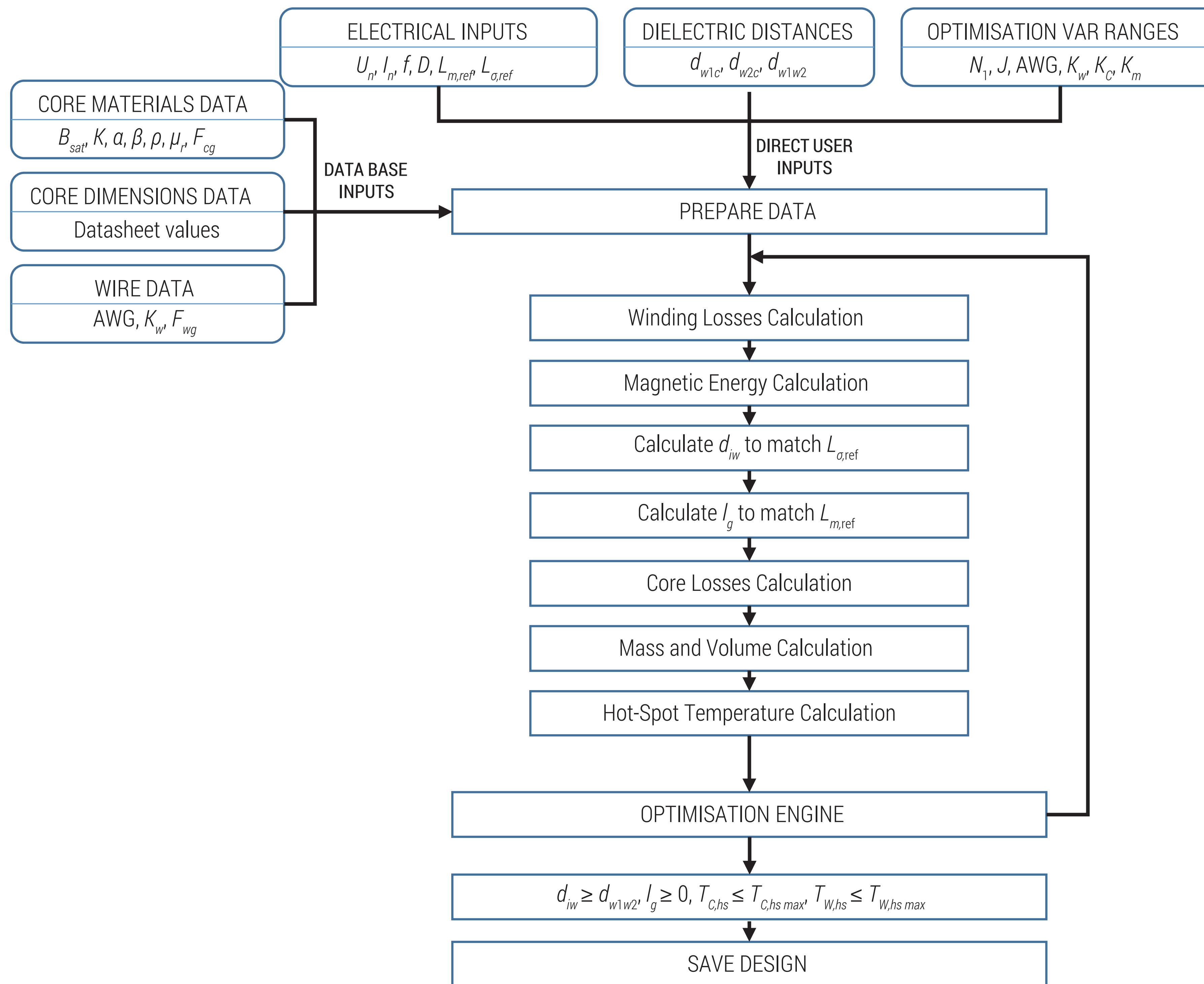
CHALMERS PhD: Bahmani [37]



CHALMERS: 50kW, 5kHz

Power Electronics Laboratory | 70 of 88

# DESIGN OPTIMIZATION: ALGORITHM



▲ MFT design optimization algorithm

## Algorithm Specifications:

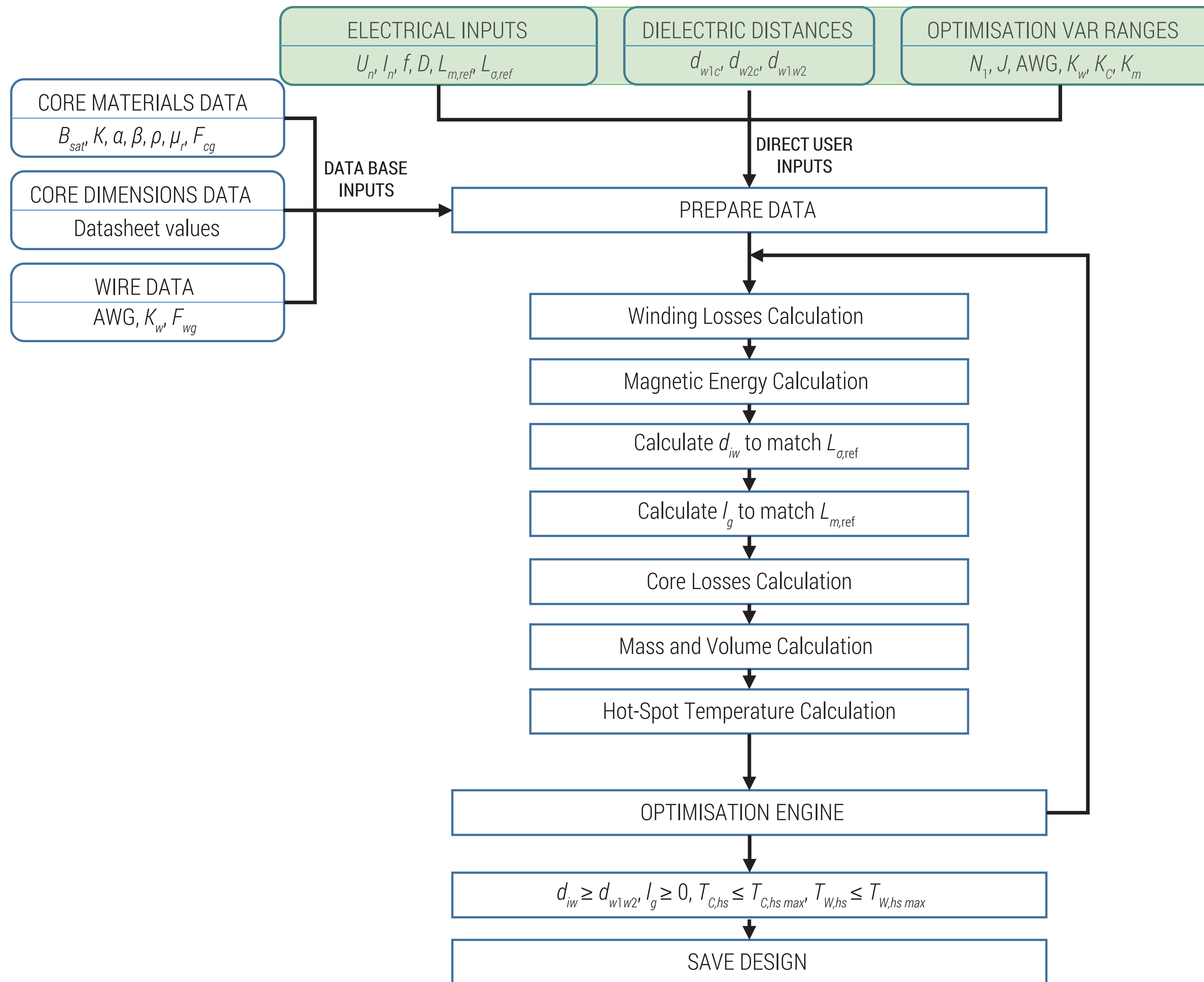
- ▶ Used Software Platform:
  - ▶ MathWorks MATLAB
- ▶ Used Hardware Platform:
  - ▶ Laptop PC (i7-2.1GHz, 8GB RAM)
- ▶ Performance Measure:
  - ▶ 59000 designs are generated in less than 190 seconds

### Electrical Specifications:

$P_n$	100kW	$f_{sw}$	10kHz
$V_1$	750V	$V_2$	750V
$L_{\sigma 1,2}$	3.27μH	$L_m$	1.8mH



# DESIGN OPTIMIZATION: ALGORITHM



▲ MFT design optimization algorithm

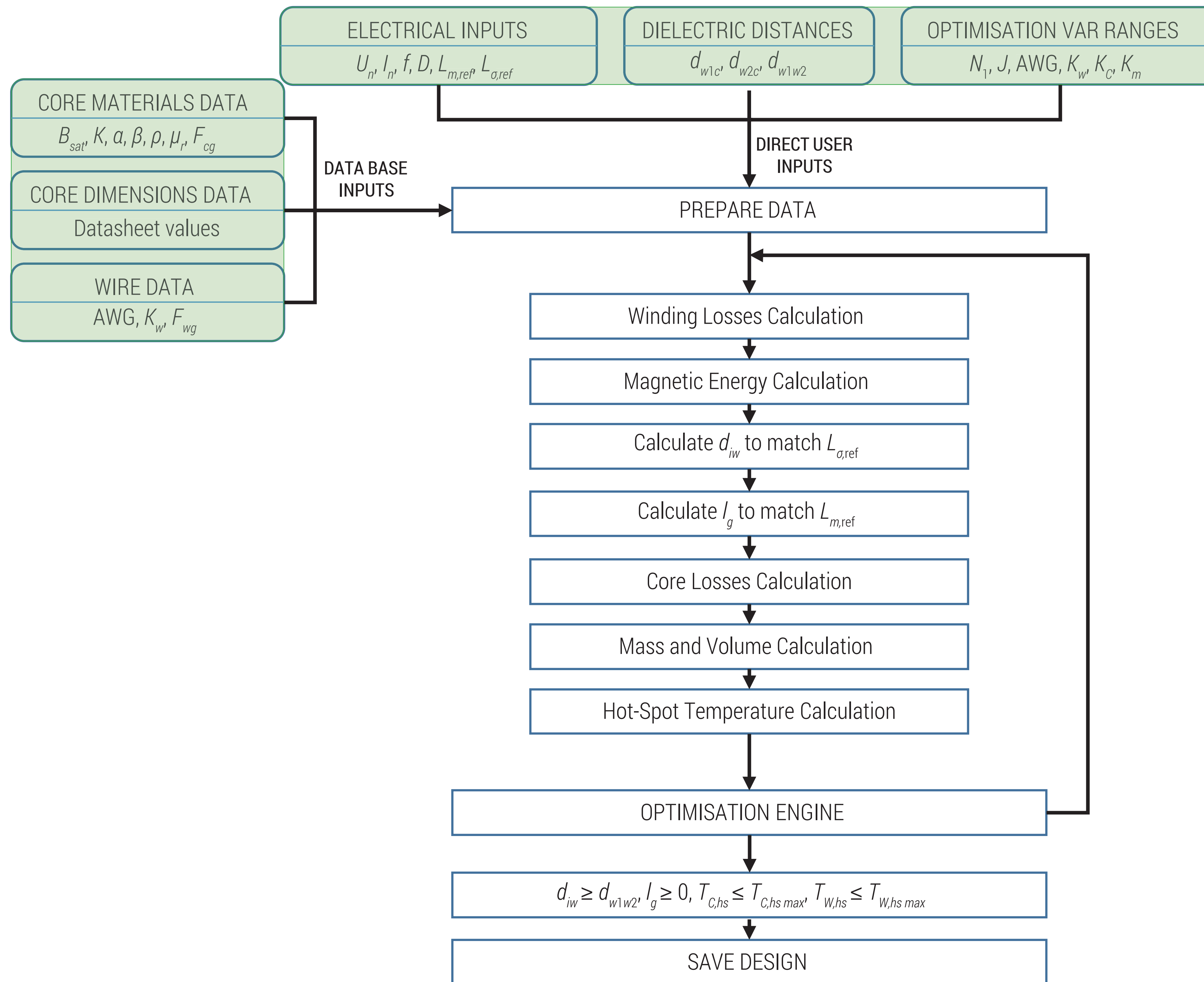
## Algorithm Specifications:

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# DESIGN OPTIMIZATION: ALGORITHM



▲ MFT design optimization algorithm

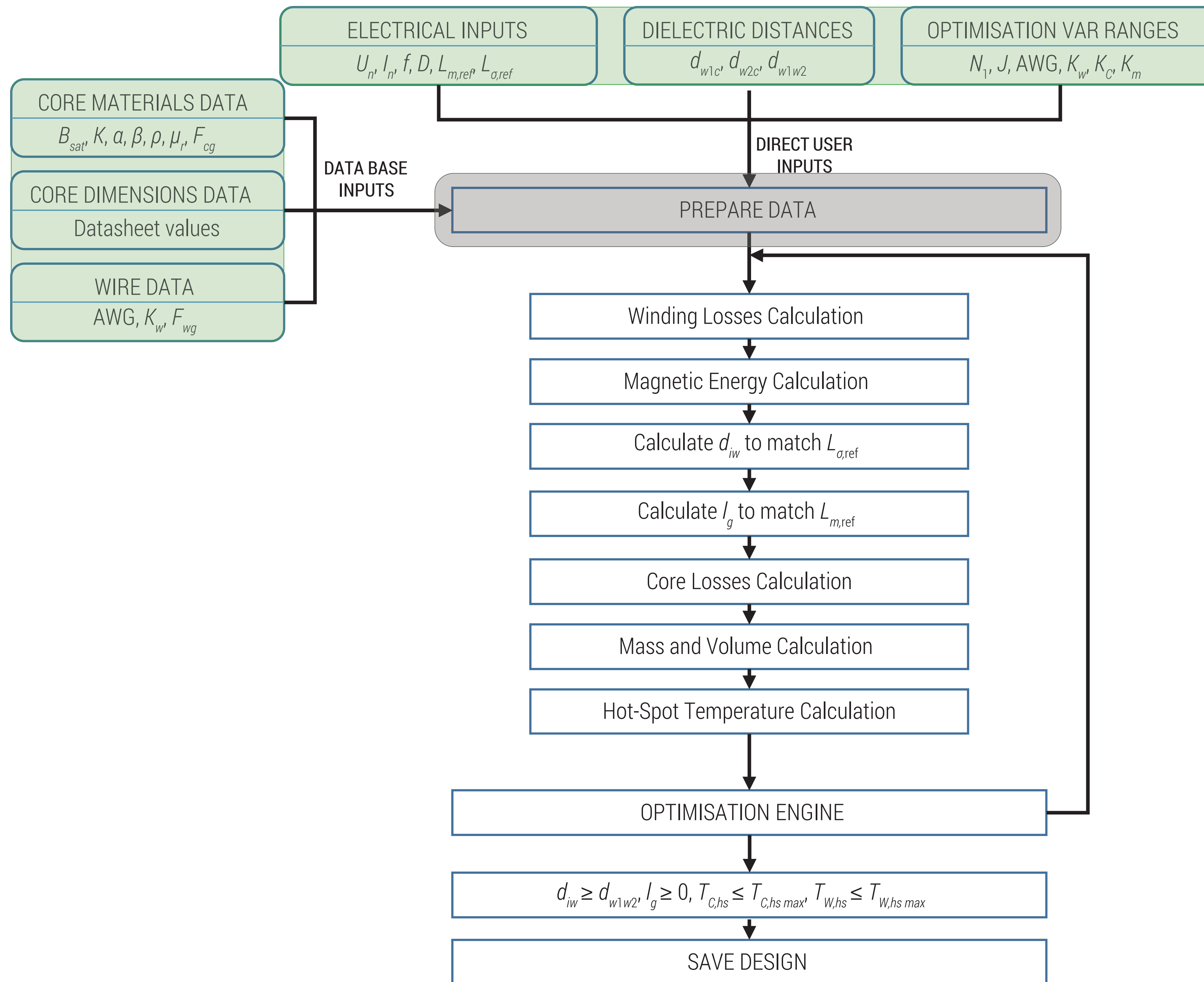
## Algorithm Specifications:

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# DESIGN OPTIMIZATION: ALGORITHM



▲ MFT design optimization algorithm

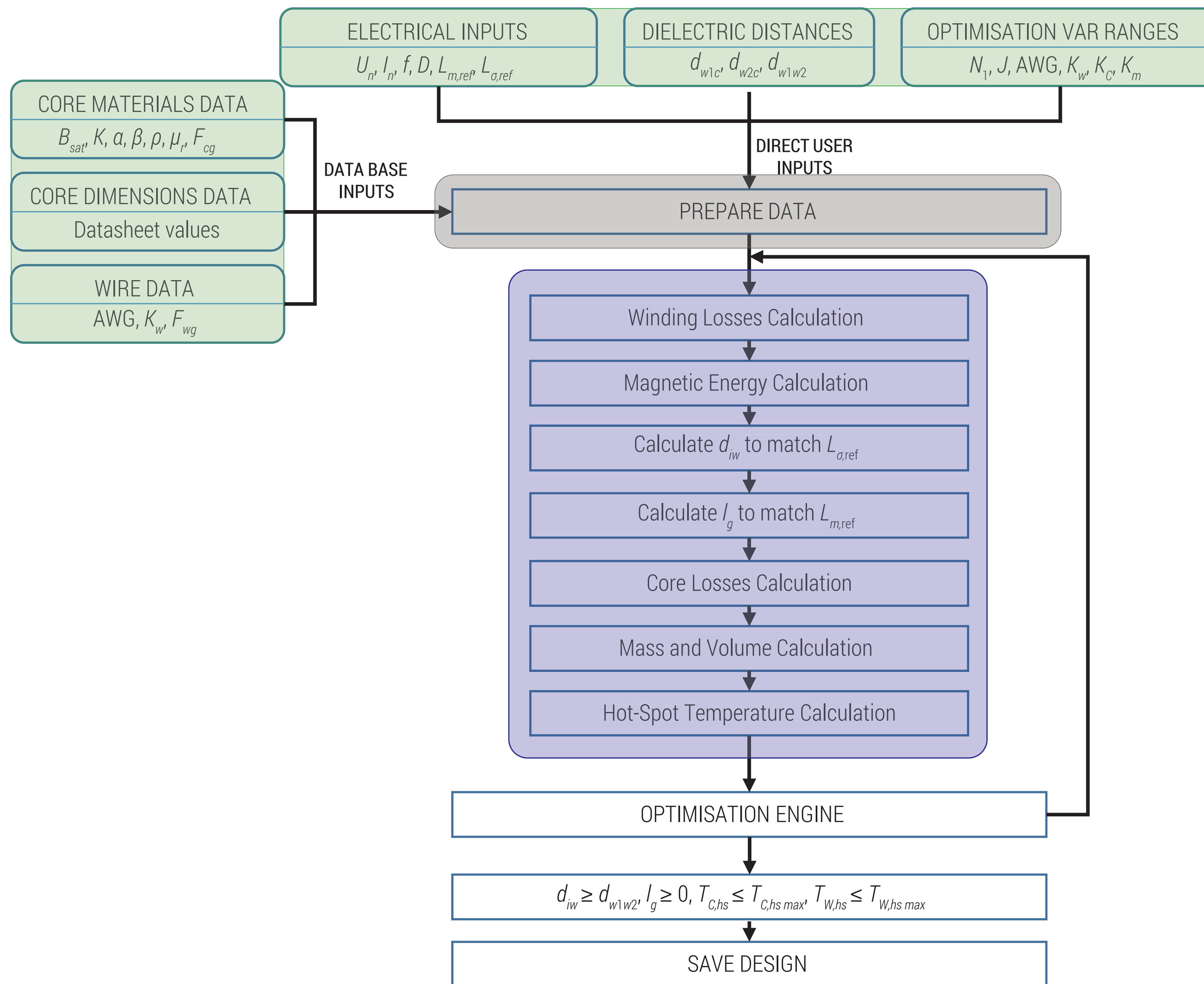
## Algorithm Specifications:

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- ▶ Used Hardware Platform:
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# DESIGN OPTIMIZATION: ALGORITHM



▲ MFT design optimization algorithm

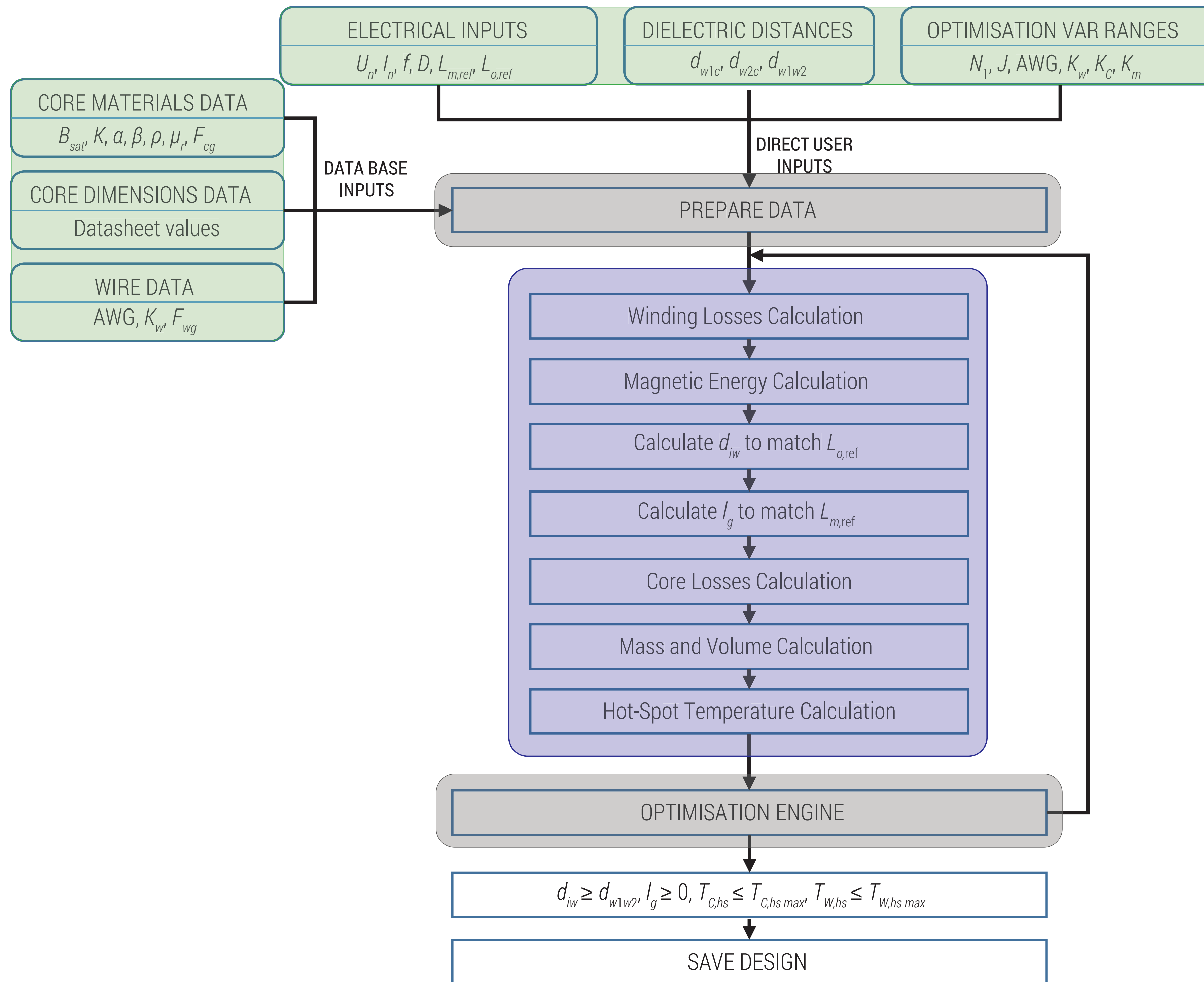
## Algorithm Specifications:

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# DESIGN OPTIMIZATION: ALGORITHM



▲ MFT design optimization algorithm

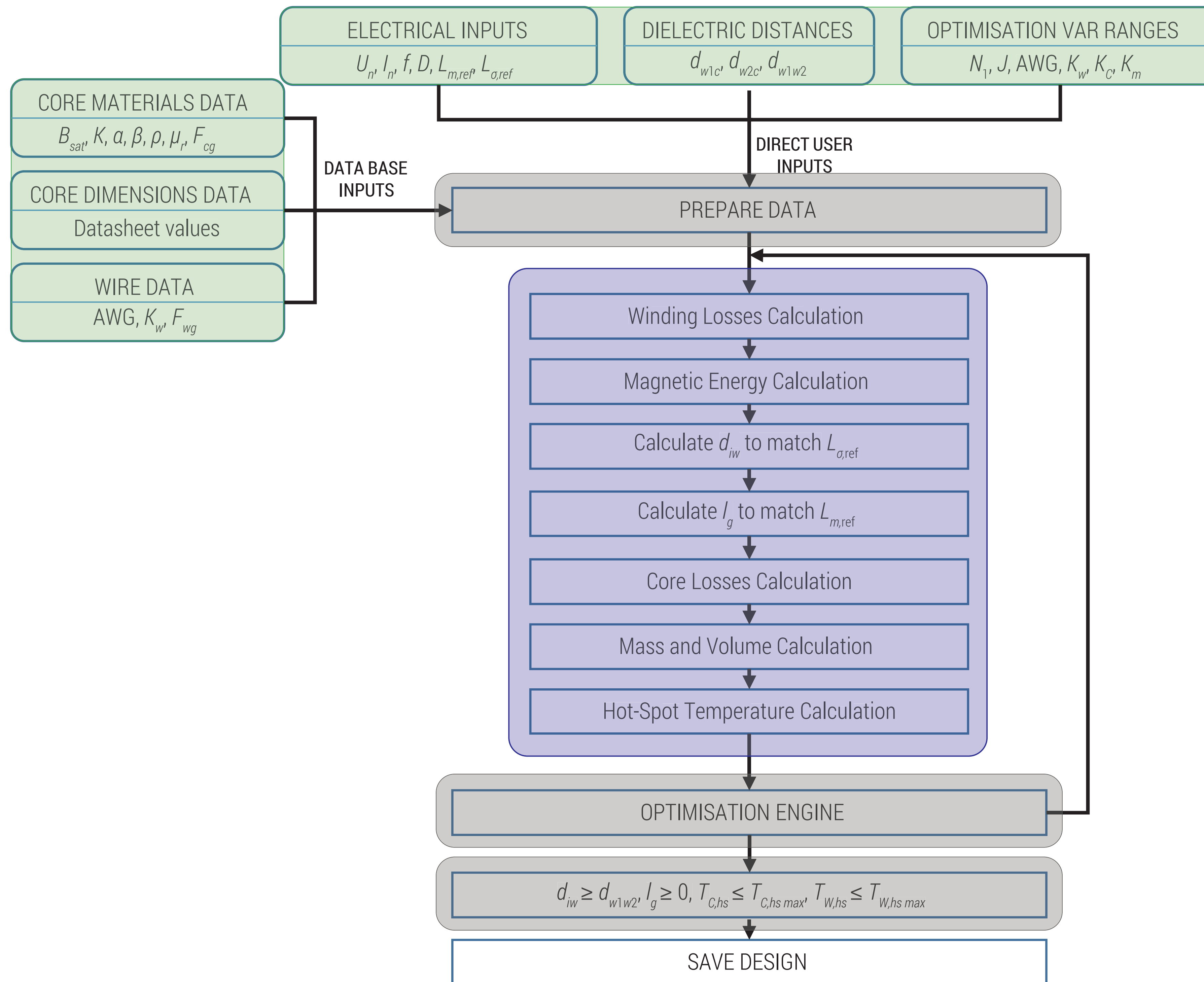
## Algorithm Specifications:

- ▶ Used Software Platform:
  - ▶ MathWorks MATLAB
- ▶ Used Hardware Platform:
  - ▶ Laptop PC (i7-2.1GHz, 8GB RAM)
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$V_1$	750V	$V_2$	750V
$L_{\sigma 1,2}$	3.27μH	$L_m$	1.8mH

# DESIGN OPTIMIZATION: ALGORITHM



## Algorithm Specifications:

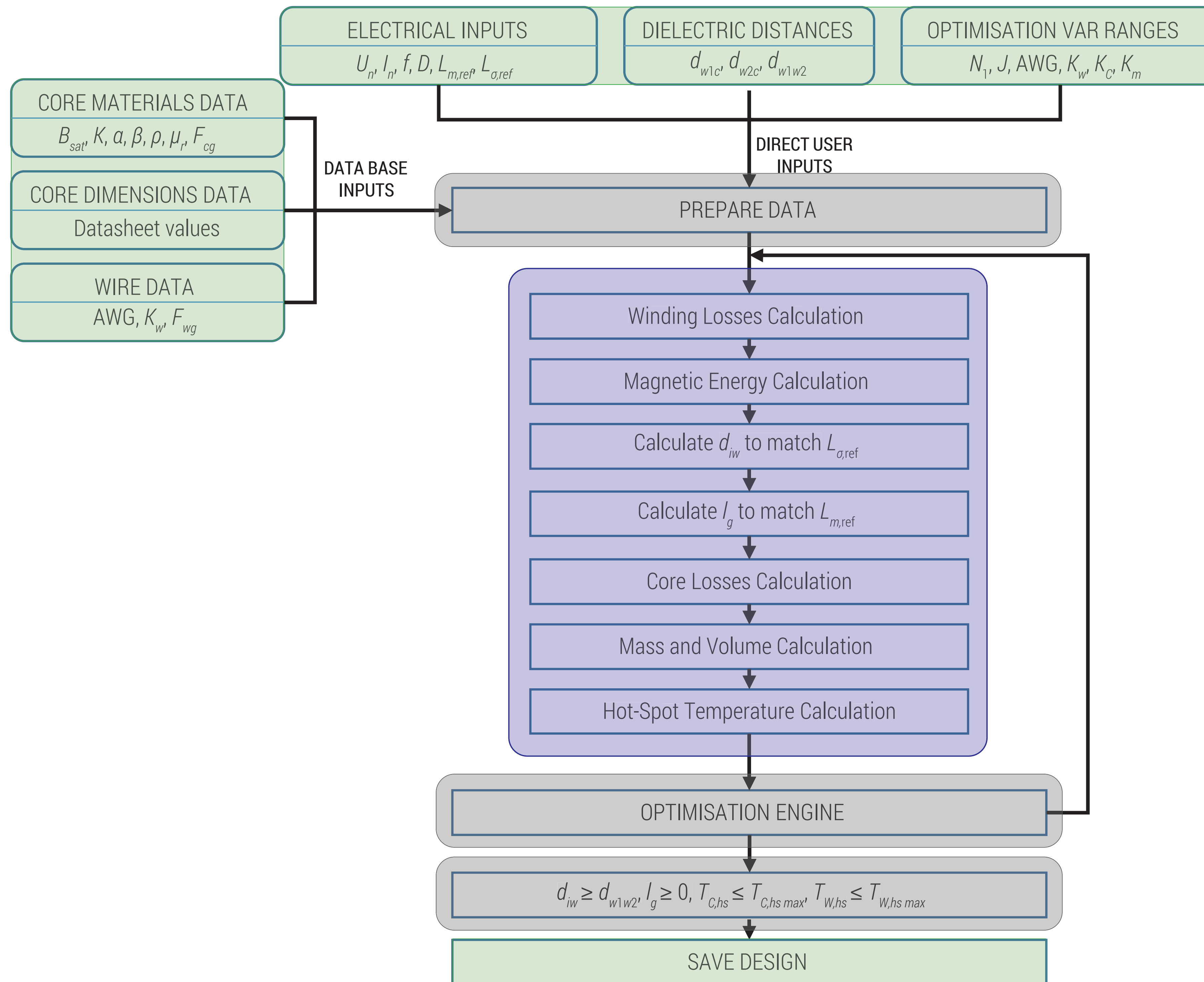
- ▶ Used Software Platform:
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▲ MFT design optimization algorithm

# DESIGN OPTIMIZATION: ALGORITHM



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▲ MFT design optimization algorithm

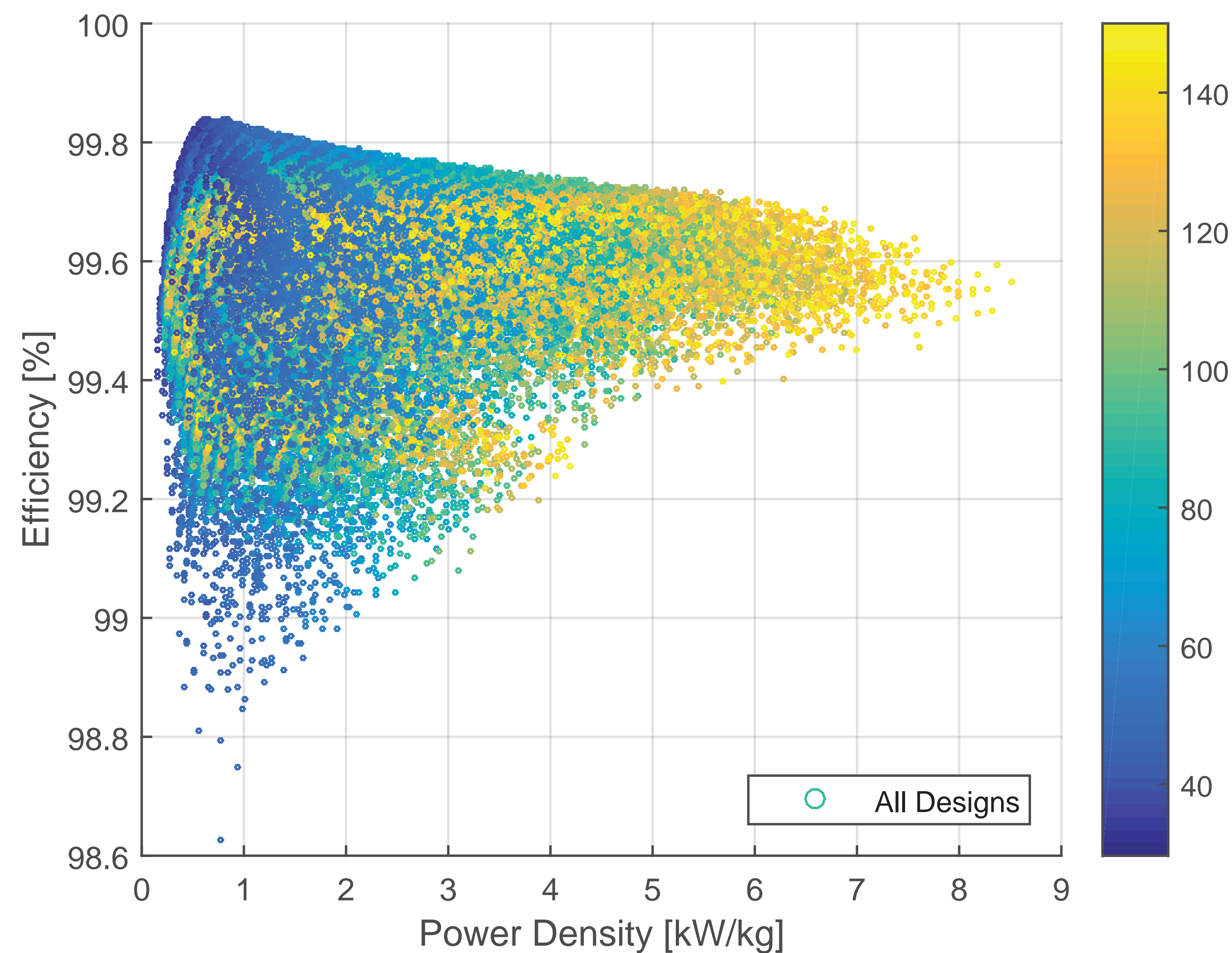
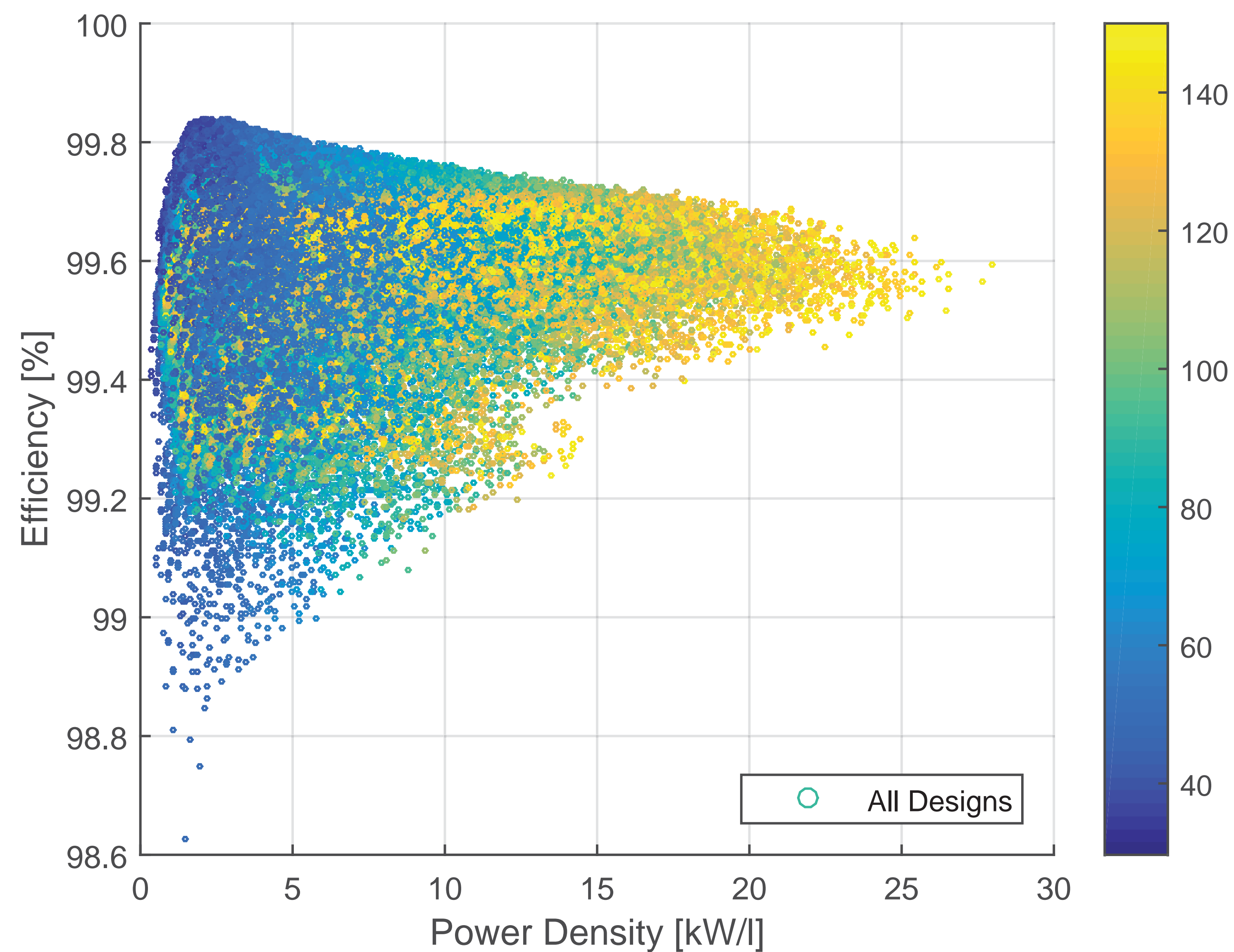
# DESIGN OPTIMIZATION: RESULTS

## Applied Filters:

$T_{Wmax}$ [ $^{\circ}C$ ]	$T_{Cmax}$ [ $^{\circ}C$ ]	$V_{max}$ [l]	$M_{max}$ [kg]	$\eta_{min}$ [%]
150	100	/	/	/

## Number of Designs:

► More than 1.8 Million



▲ Generated designs: left: Efficiency vs V-density; right: Efficiency vs W-density. Color code indicates hot-spot temperature



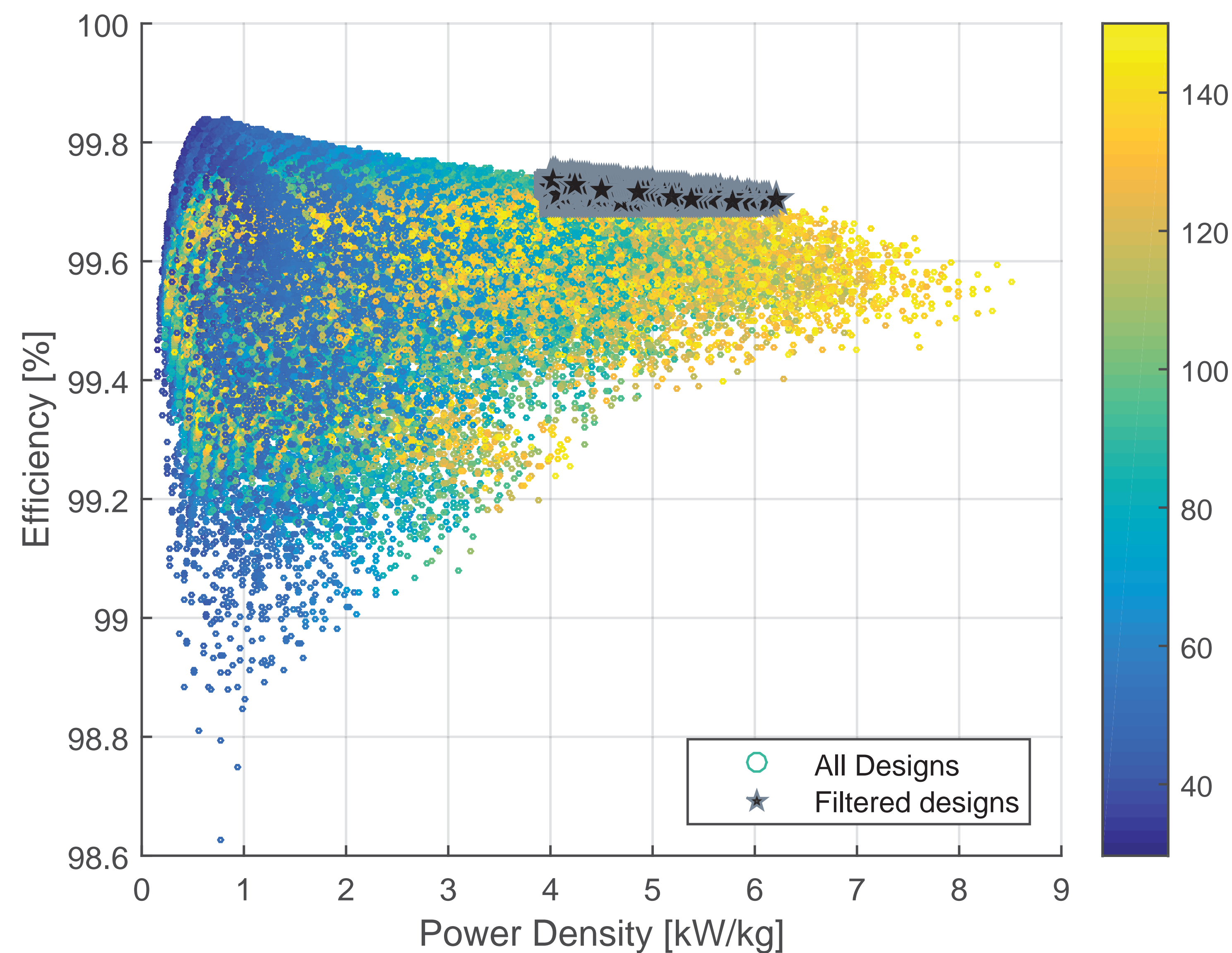
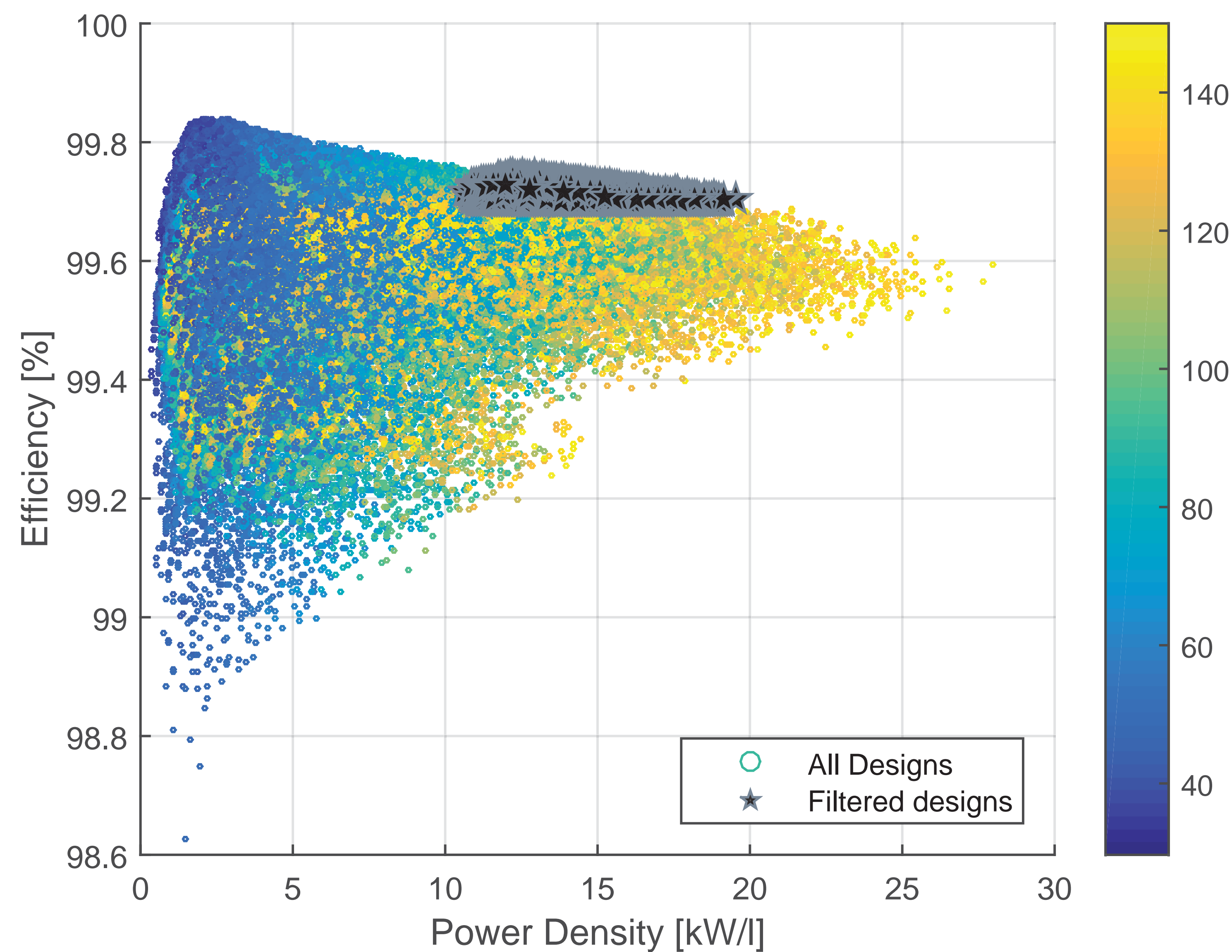
# DESIGN OPTIMIZATION: RESULTS

## Applied Filters:

$T_{Wmax}$ [ $^{\circ}C$ ]	$T_{Cmax}$ [ $^{\circ}C$ ]	$V_{max}$ [l]	$M_{max}$ [kg]	$\eta_{min}$ [%]
150	100	12	25	99.7

## Number of Designs:

► More than 1.8 Million



▲ Generated designs: left: Efficiency vs V-density; right: Efficiency vs W-density. Color code indicates hot-spot temperature

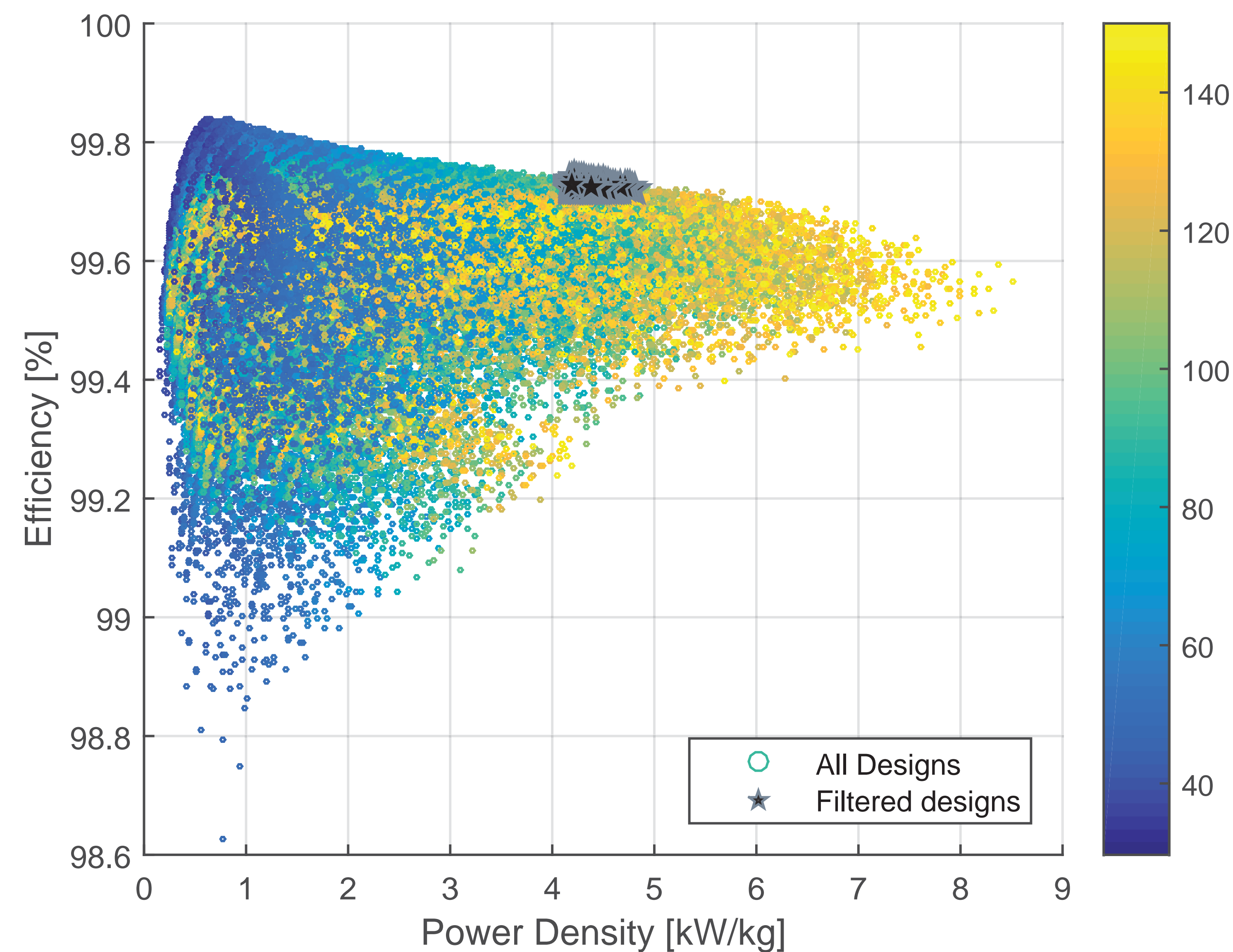
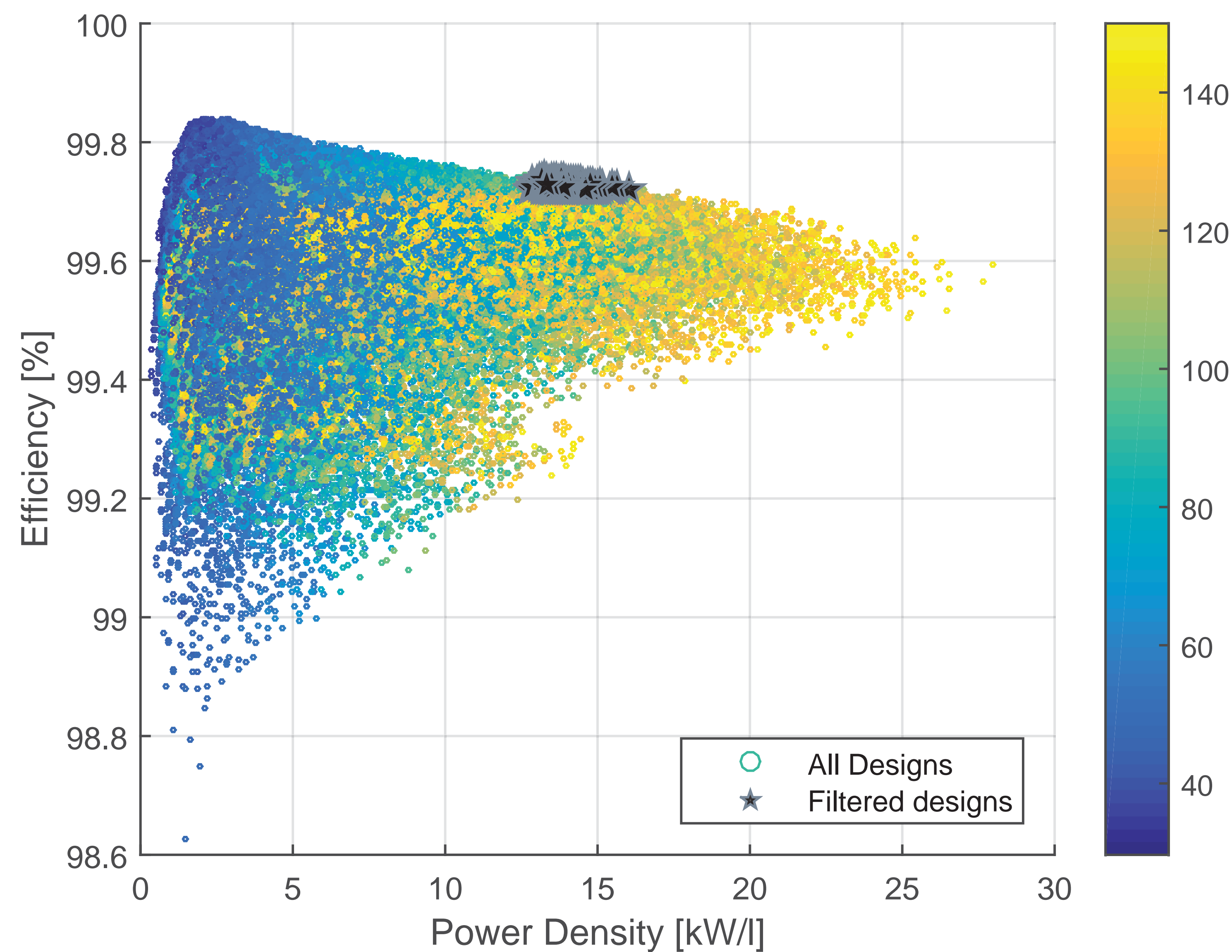
# DESIGN OPTIMIZATION: RESULTS

## Applied Filters:

$T_{Wmax}$ [ $^{\circ}C$ ]	$T_{Cmax}$ [ $^{\circ}C$ ]	$V_{max}$ [l]	$M_{max}$ [kg]	$\eta_{min}$ [%]
130	80	9	24	99.72

## Number of Designs:

► More than 1.8 Million



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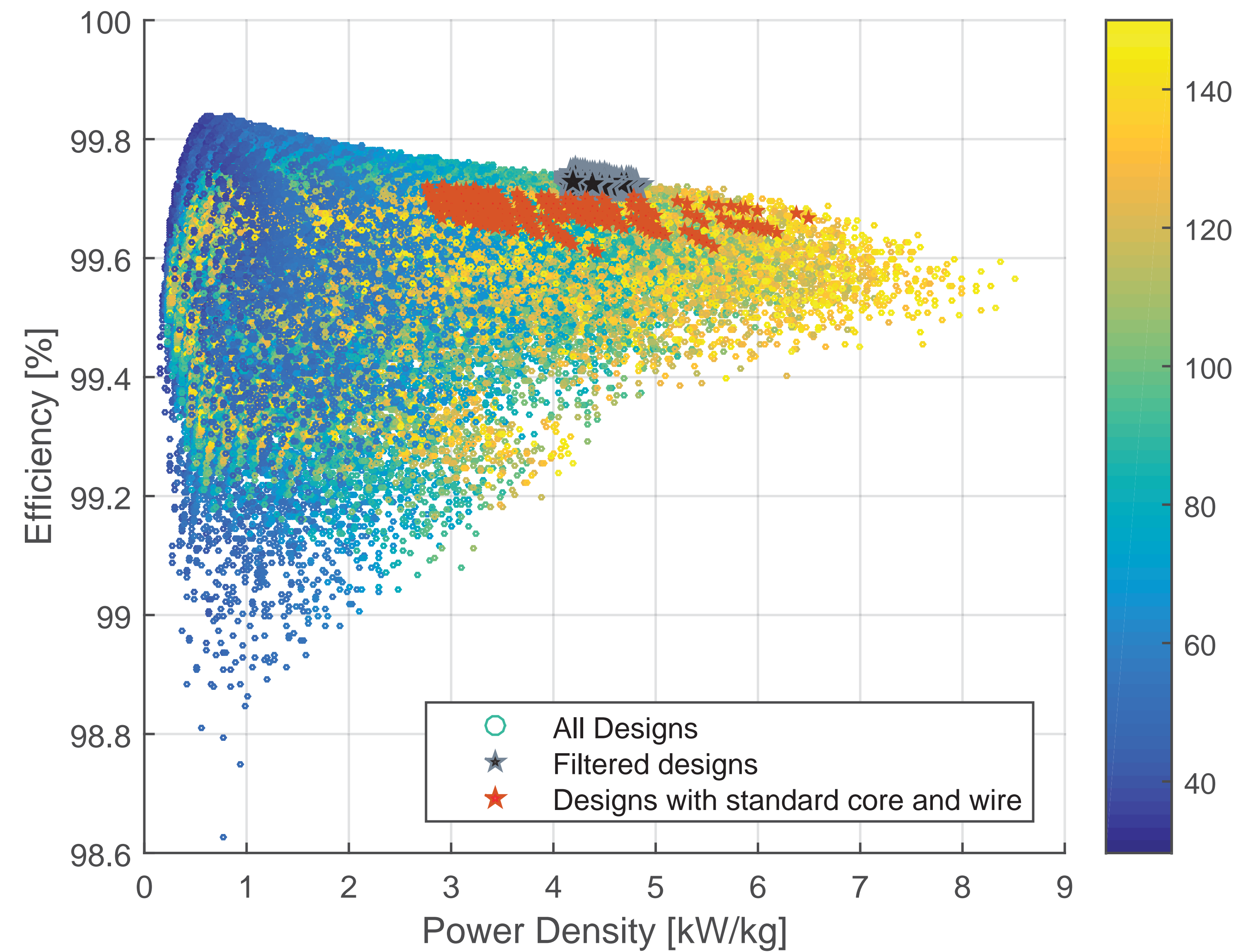
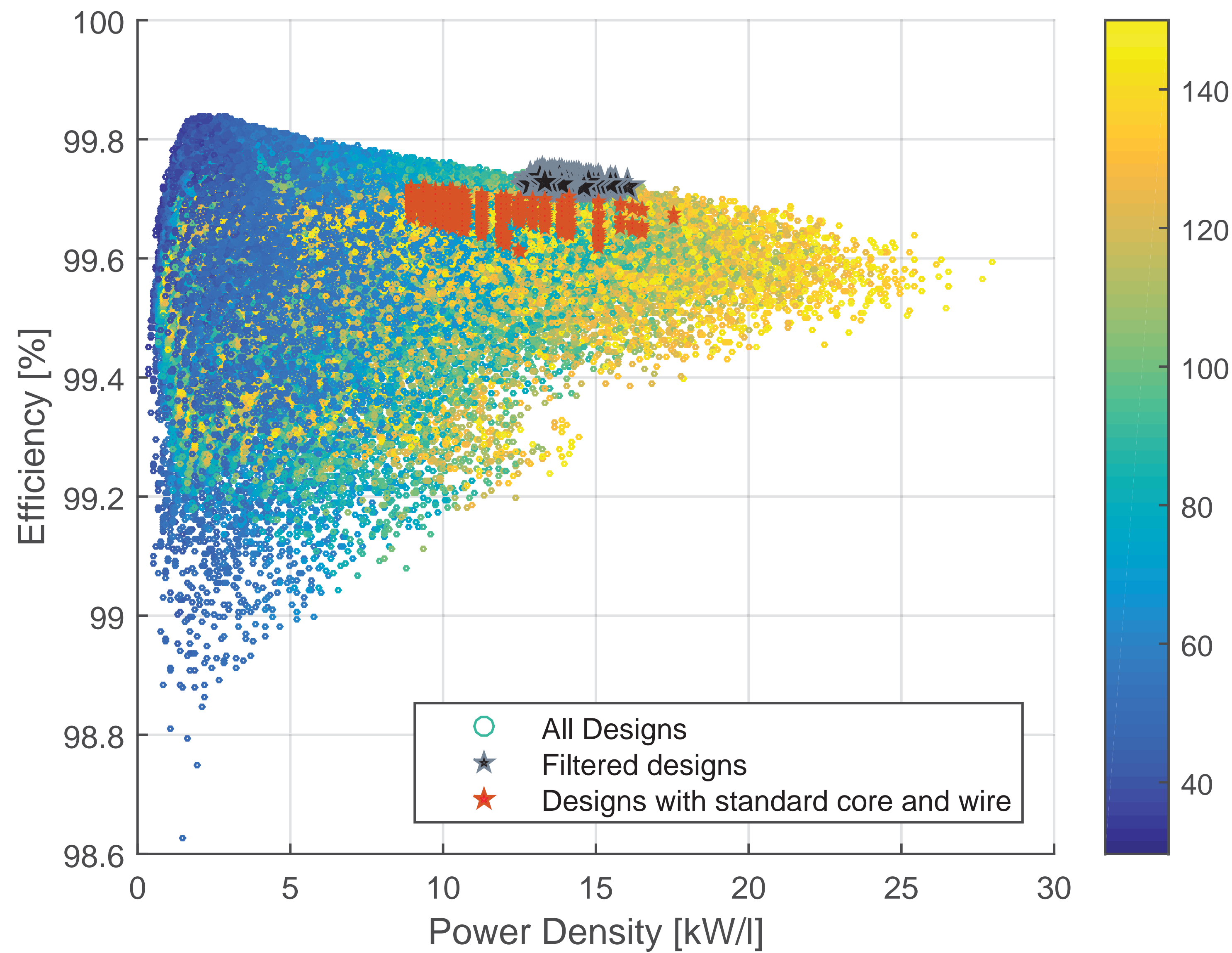
# DESIGN OPTIMIZATION: RESULTS

## Applied Filters:

$T_{Wmax}$ [ $^{\circ}C$ ]	$T_{Cmax}$ [ $^{\circ}C$ ]	$V_{max}$ [l]	$M_{max}$ [kg]	$\eta_{min}$ [%]
130	80	9	24	99.72

## Number of Designs:

► More than 1.8 Million



▲ Generated designs: left: Efficiency vs V-density; right: Efficiency vs W-density. Color code indicates hot-spot temperature

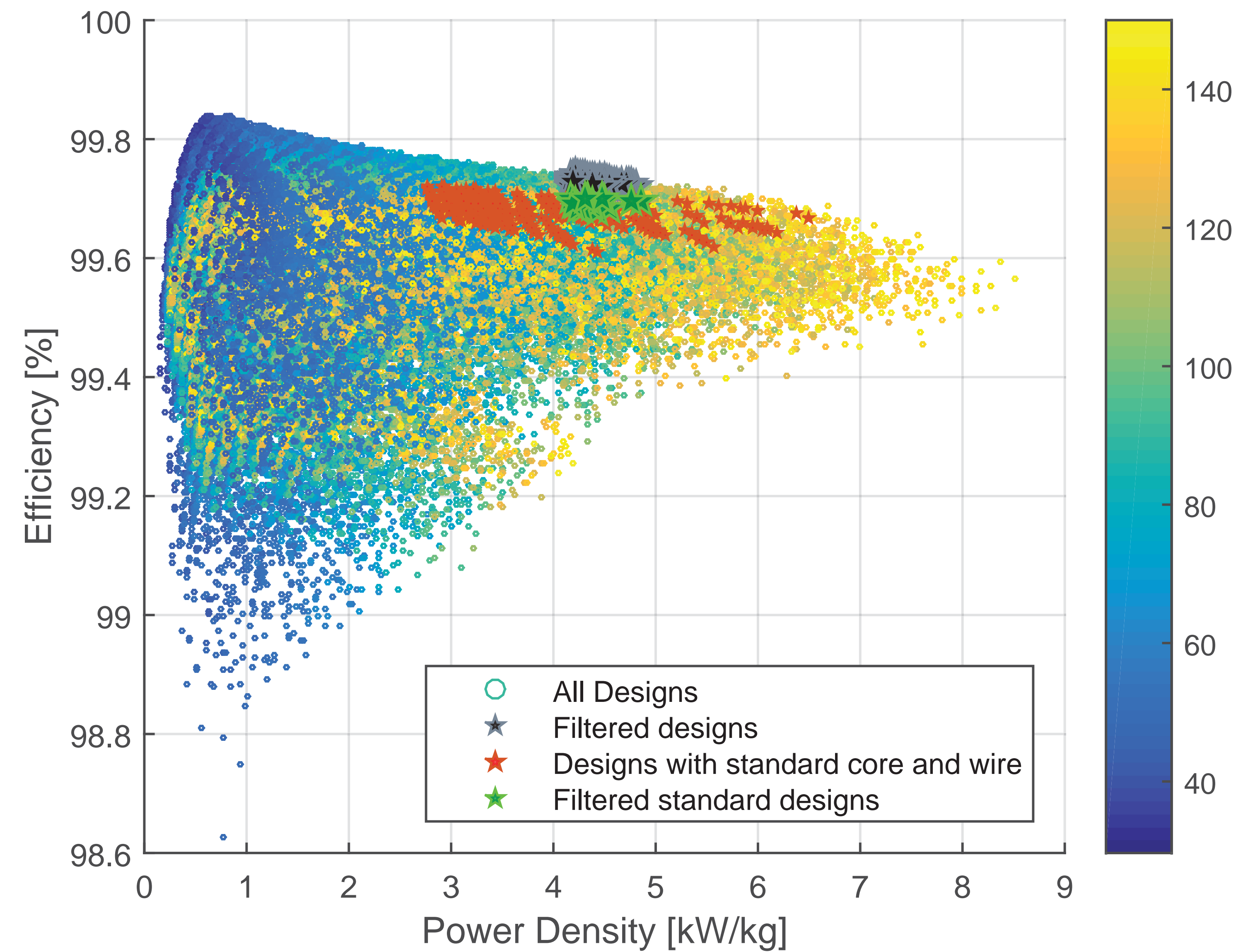
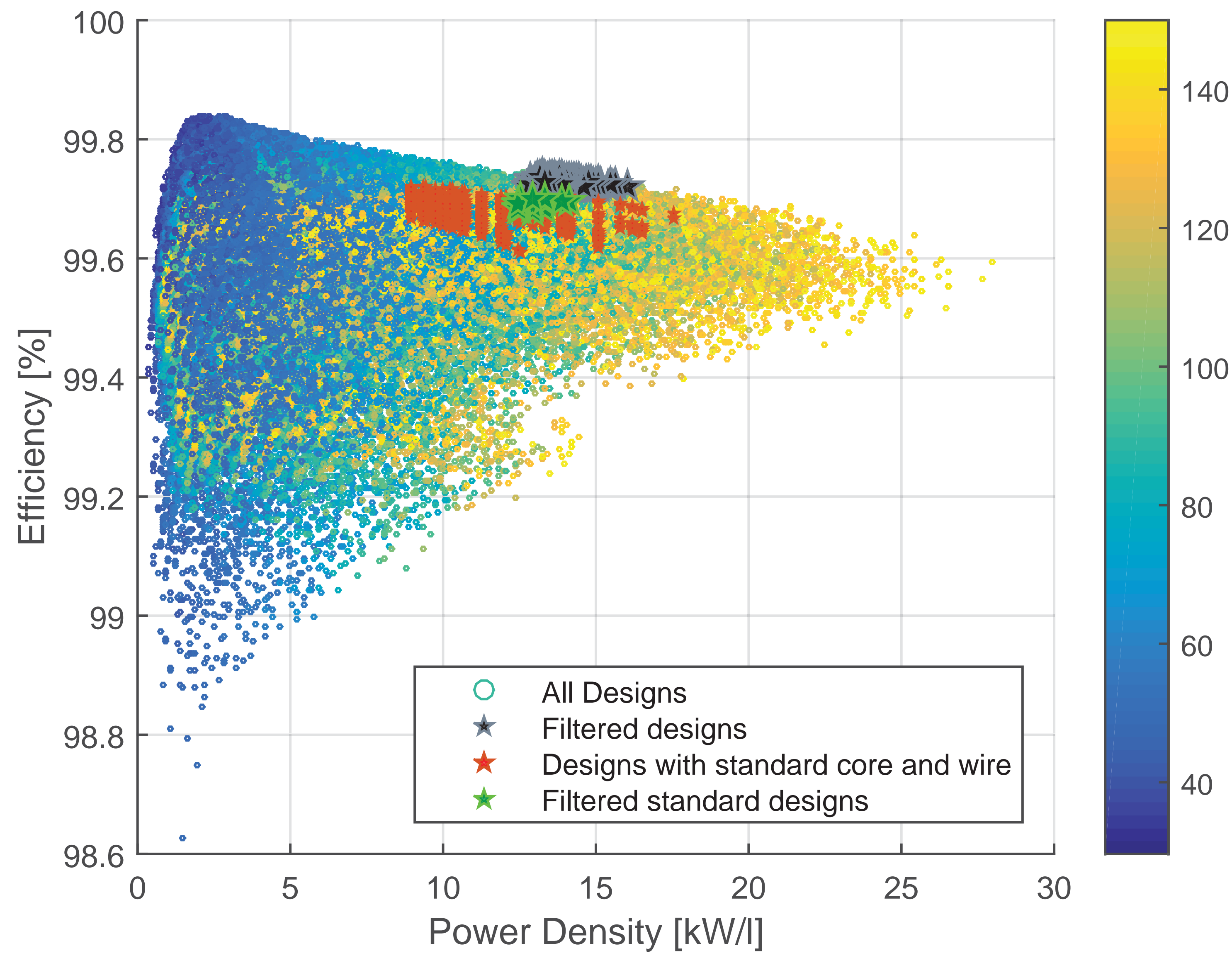
# DESIGN OPTIMIZATION: RESULTS

## Applied Filters:

$T_{Wmax}$ [ $^{\circ}C$ ]	$T_{Cmax}$ [ $^{\circ}C$ ]	$V_{max}$ [l]	$M_{max}$ [kg]	$\eta_{min}$ [%]
135	80	10	24	99.6

## Number of Designs:

► More than 1.8 Million



▲ Generated designs: left: Efficiency vs V-density; right: Efficiency vs W-density. Color code indicates hot-spot temperature

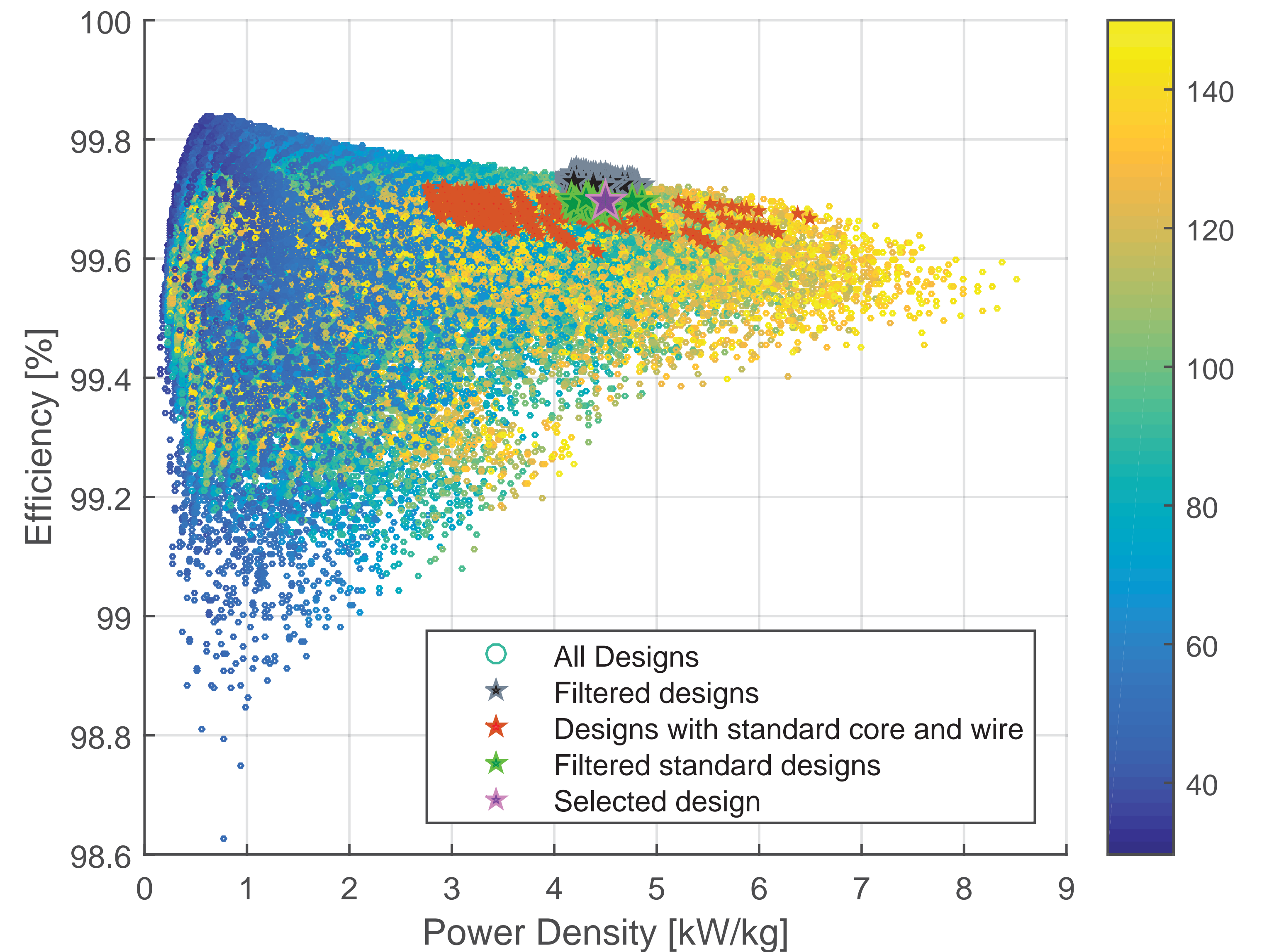
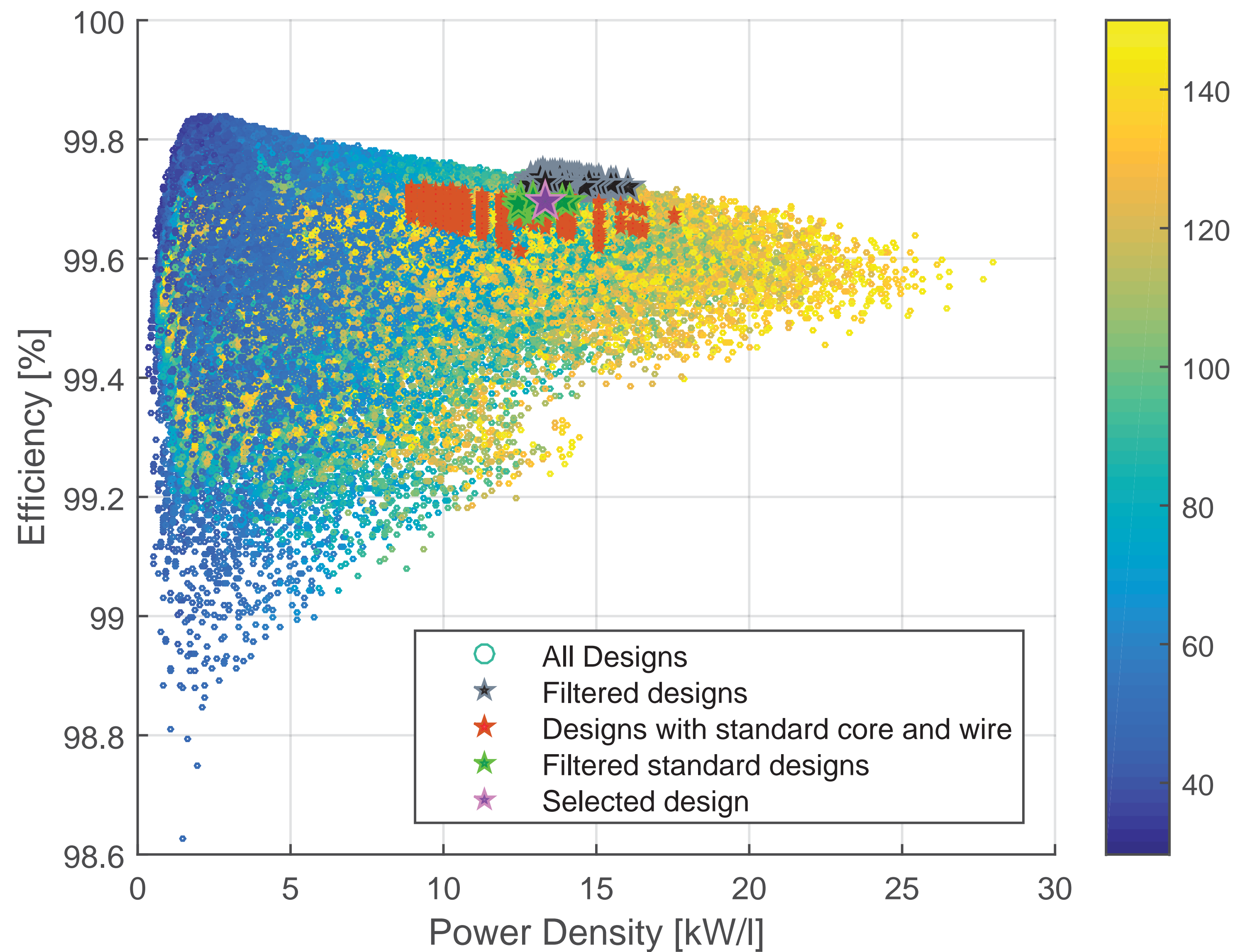
# DESIGN OPTIMIZATION: RESULTS

## Applied Filters:

$T_{Wmax}$ [ $^{\circ}C$ ]	$T_{Cmax}$ [ $^{\circ}C$ ]	$V_{max}$ [l]	$M_{max}$ [kg]	$\eta_{min}$ [%]
135	80	10	24	99.6

## Number of Designs:

► More than 1.8 Million



▲ Generated designs: left: Efficiency vs V-density; right: Efficiency vs W-density. Color code indicates hot-spot temperature

# PROTOTYPE: OPTIMAL MFT DESIGN ASSEMBLY



Optimal MFT Design 3D-CAD



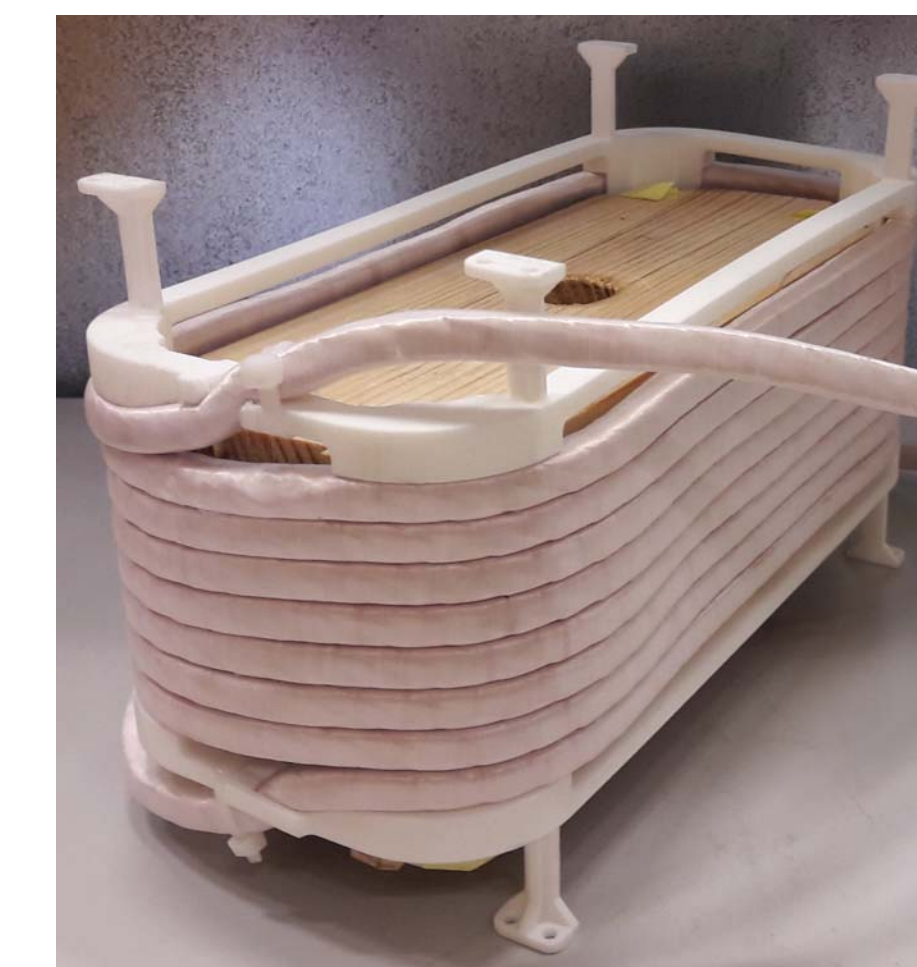
Coil-Formers 3D-CAD



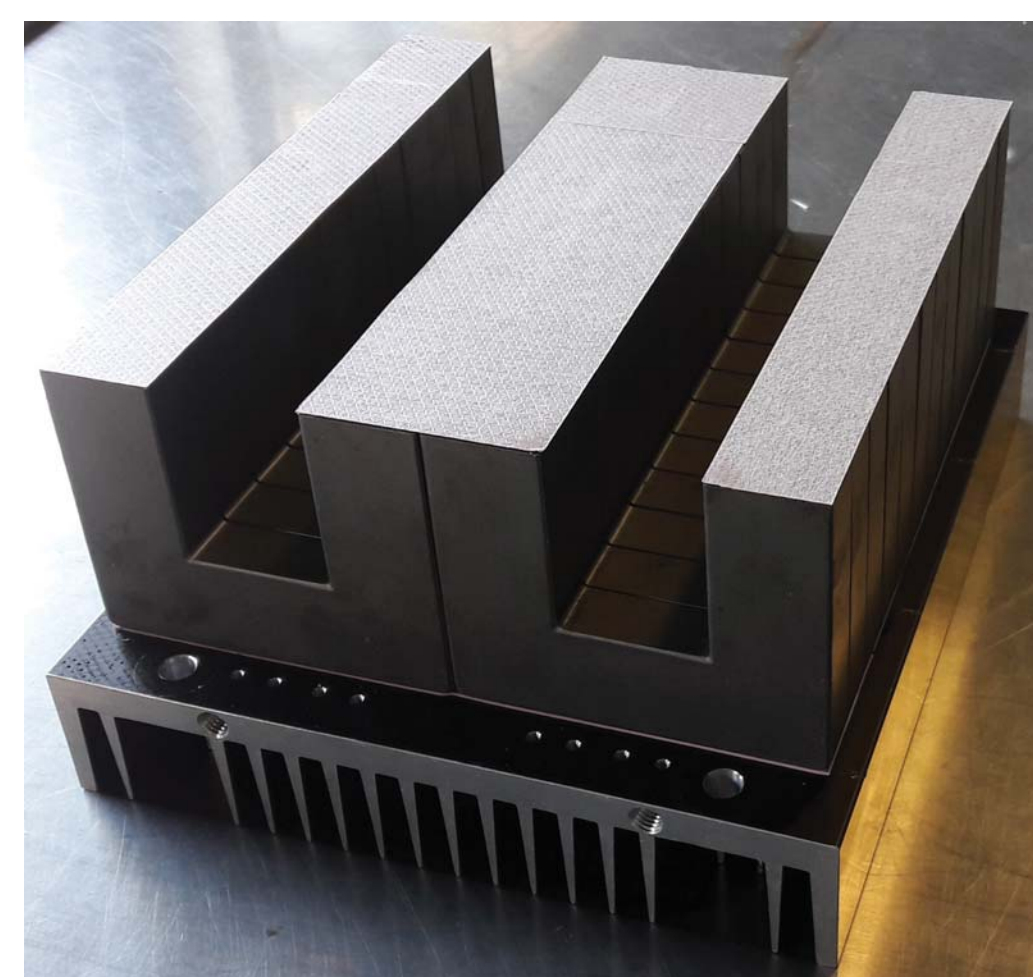
Coil-Formers 3D-Print



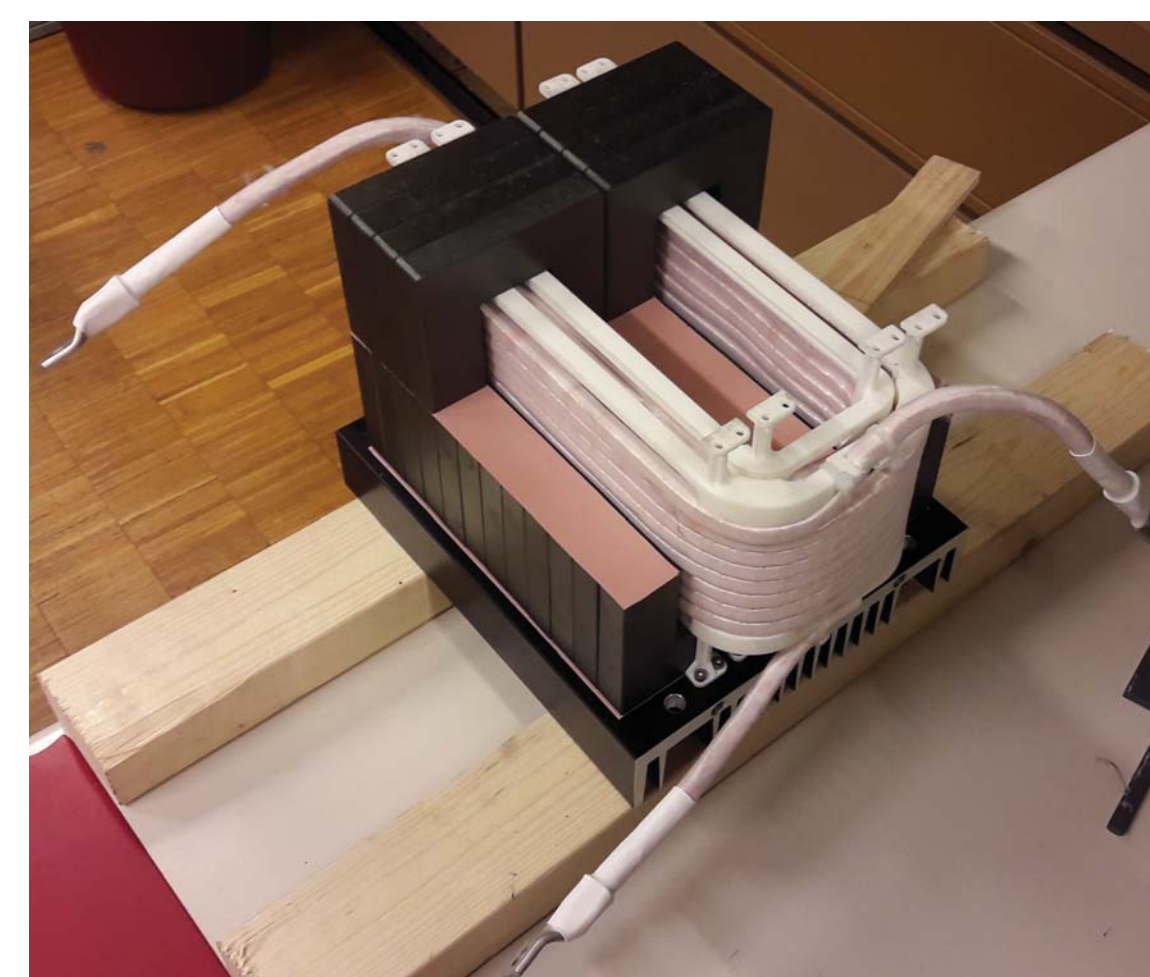
Primary Winding



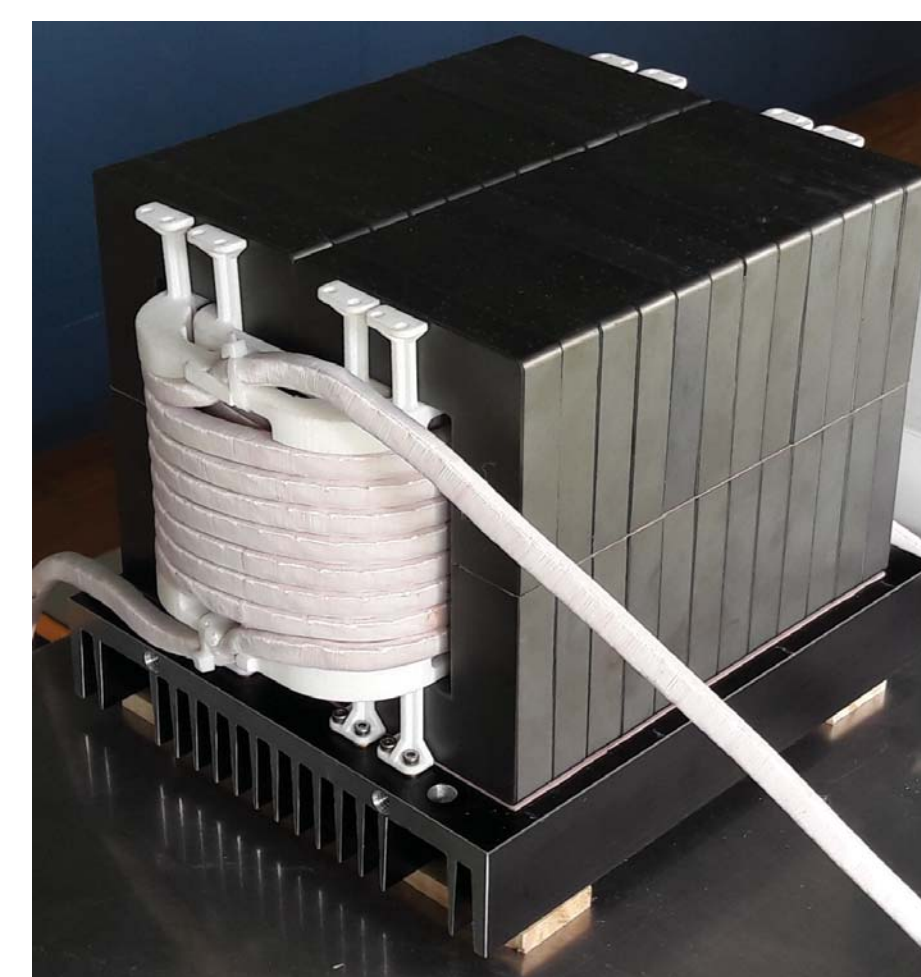
Secondary Winding



Core Assembly



MFT Assembly1



MFT Assembly2



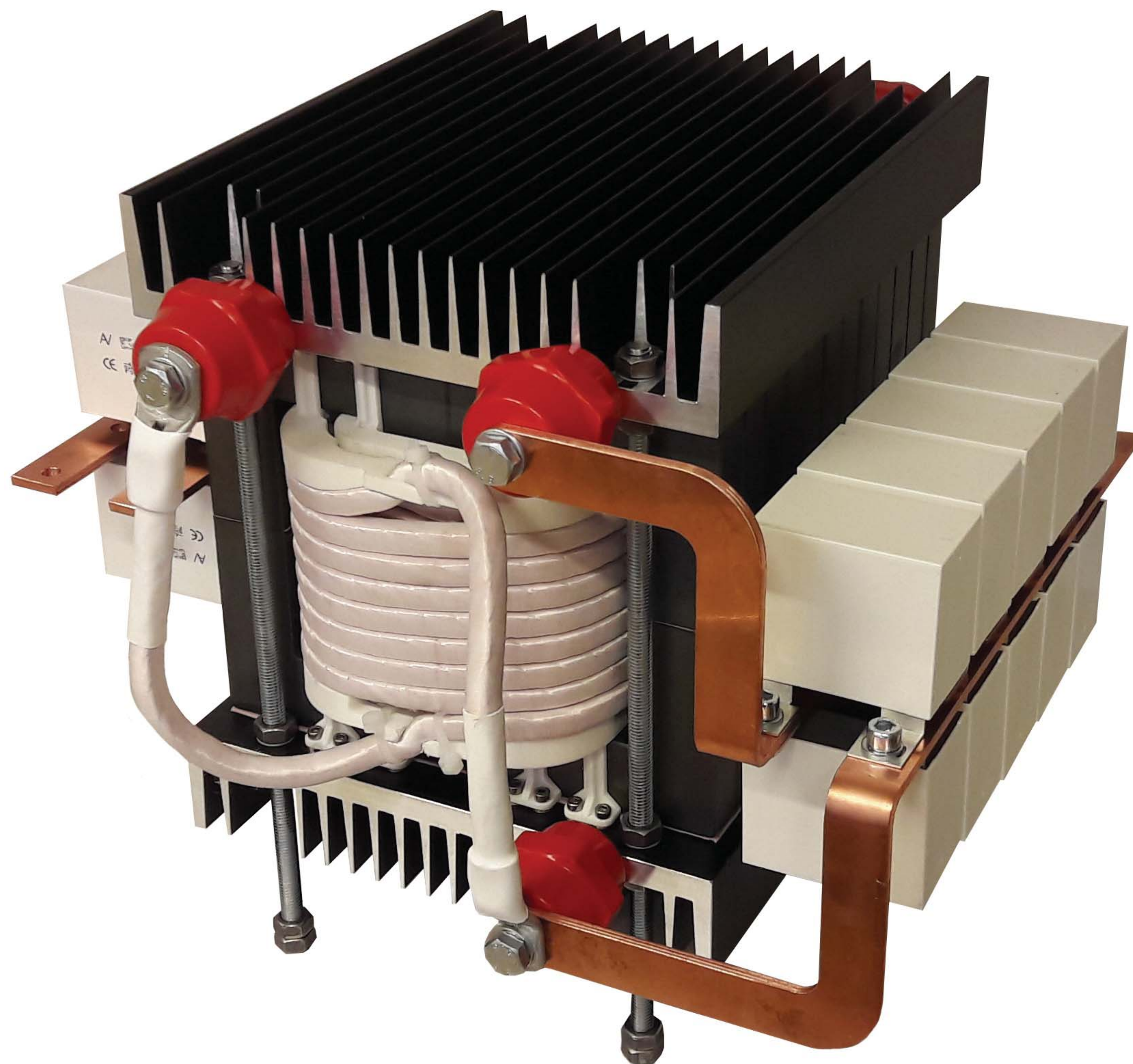
Litz-Wire Termination



MFT Prototype

# PROTOTYPE: FINAL ASSEMBLY

## MFT Prototype



▲ 100kW, 10kHz MFT including resonant capacitors

## Prototype Specifications:

- ▶ Core:
  - ▶ 12 stacks of 4 x SiFERRITE U-Cores (UU9316 - CF139)
- ▶ Windings:
  - ▶ 8-Turns
  - ▶ Square Litz Wire (8.7x8.7mm, 1400 strands, AWG 32, 43.69mm<sup>2</sup>)
- ▶ Coil-Formers:
  - ▶ Additive manufacturing process (3-D printing)
  - ▶ High strength thermally resistant plastic (PA2200)
- ▶ Resonant Capacitor Banks:
  - ▶ (7x5μF + 1x2.5μF) AC film capacitors in parallel
  - ▶ Custom designed copper bus-bars

### Electrical Ratings:

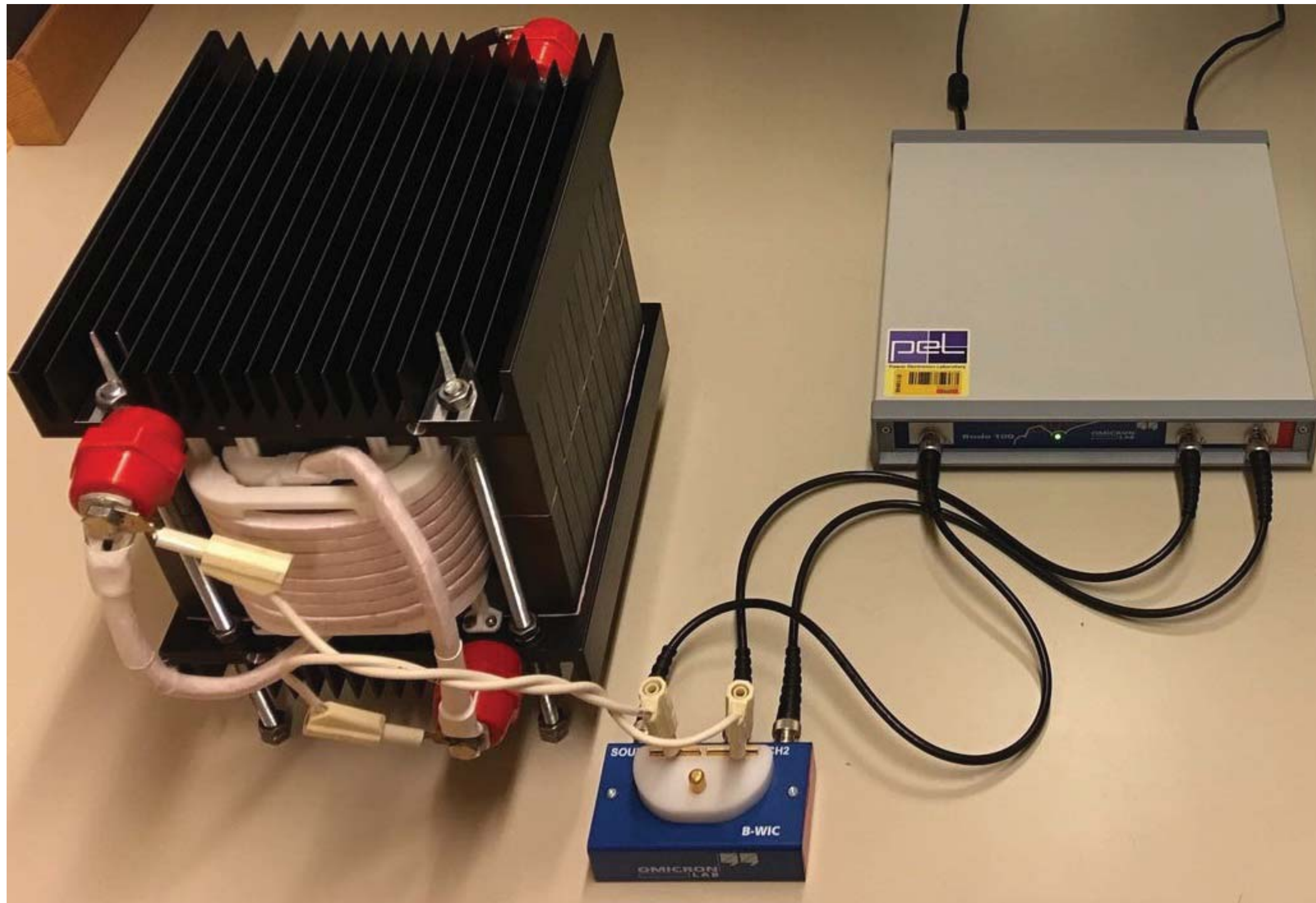
$P_n$	100kW	$V_1$	750V	$L_{\sigma 1,2}$	4.2μH
$f_{sw}$	10kHz	$V_2$	750V	$L_m$	750μH

# MEASUREMENTS: ELECTRIC PARAMETERS

## Measurement of Electric Parameters:

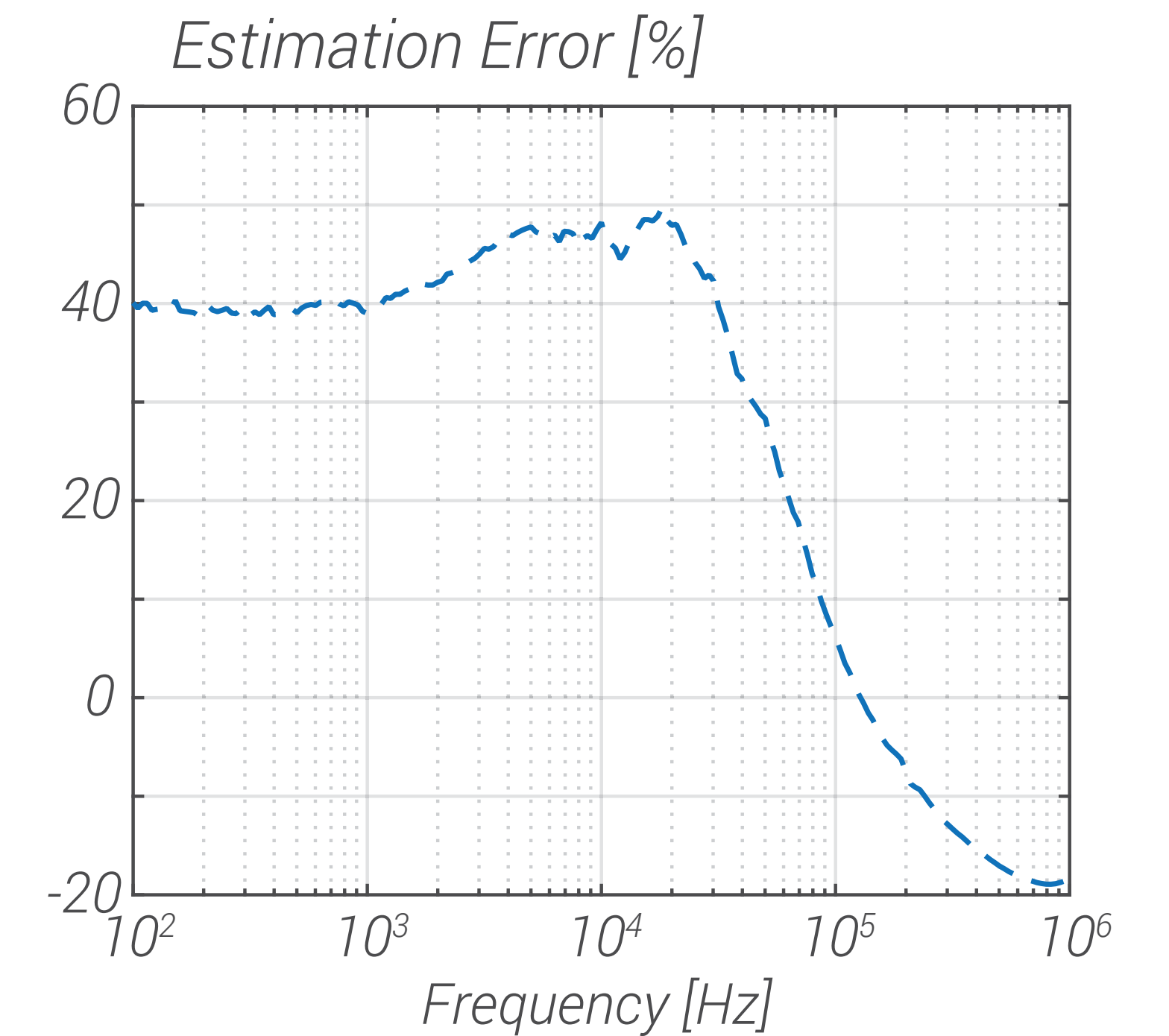
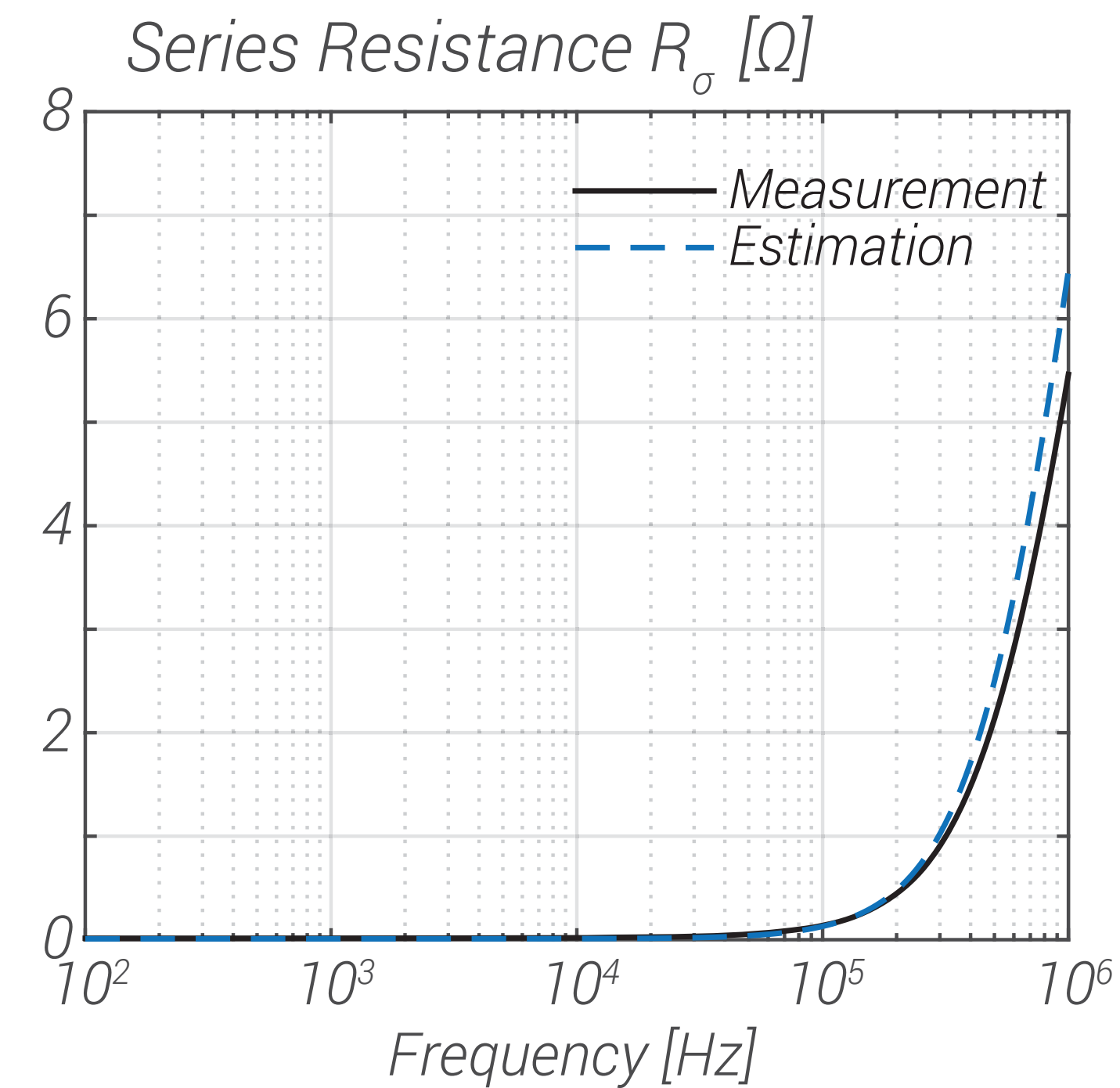
- ▶ Network Analyzer Bode100
- ▶ Impedance Measurement
- ▶ Results at 10kHz:  $L_\sigma = 8.4\mu\text{H}$ ,  $L_m = 750\mu\text{H}$ ,  $R_\sigma = 0.2\mu\Omega$

## LV Measurement Setup:

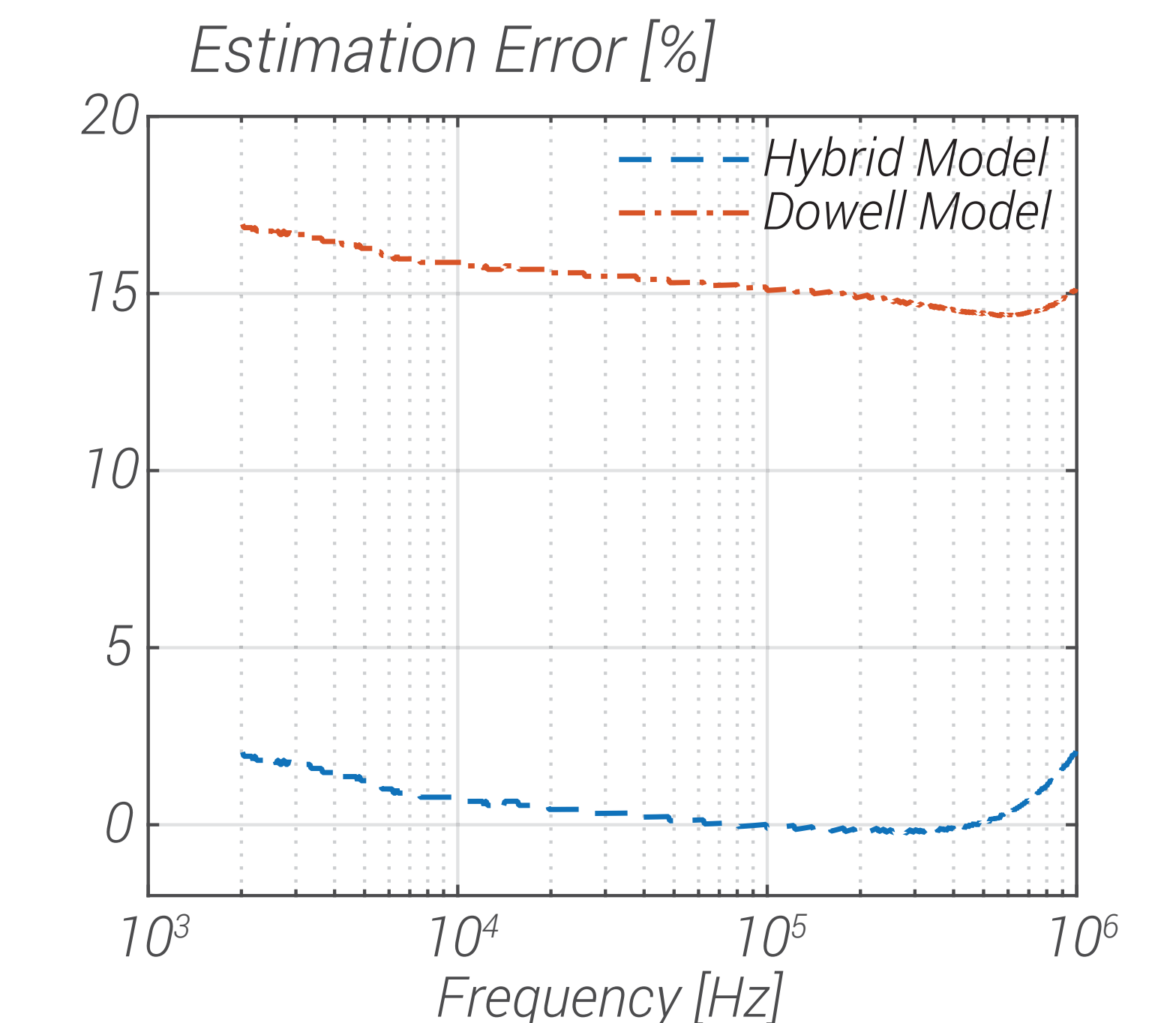
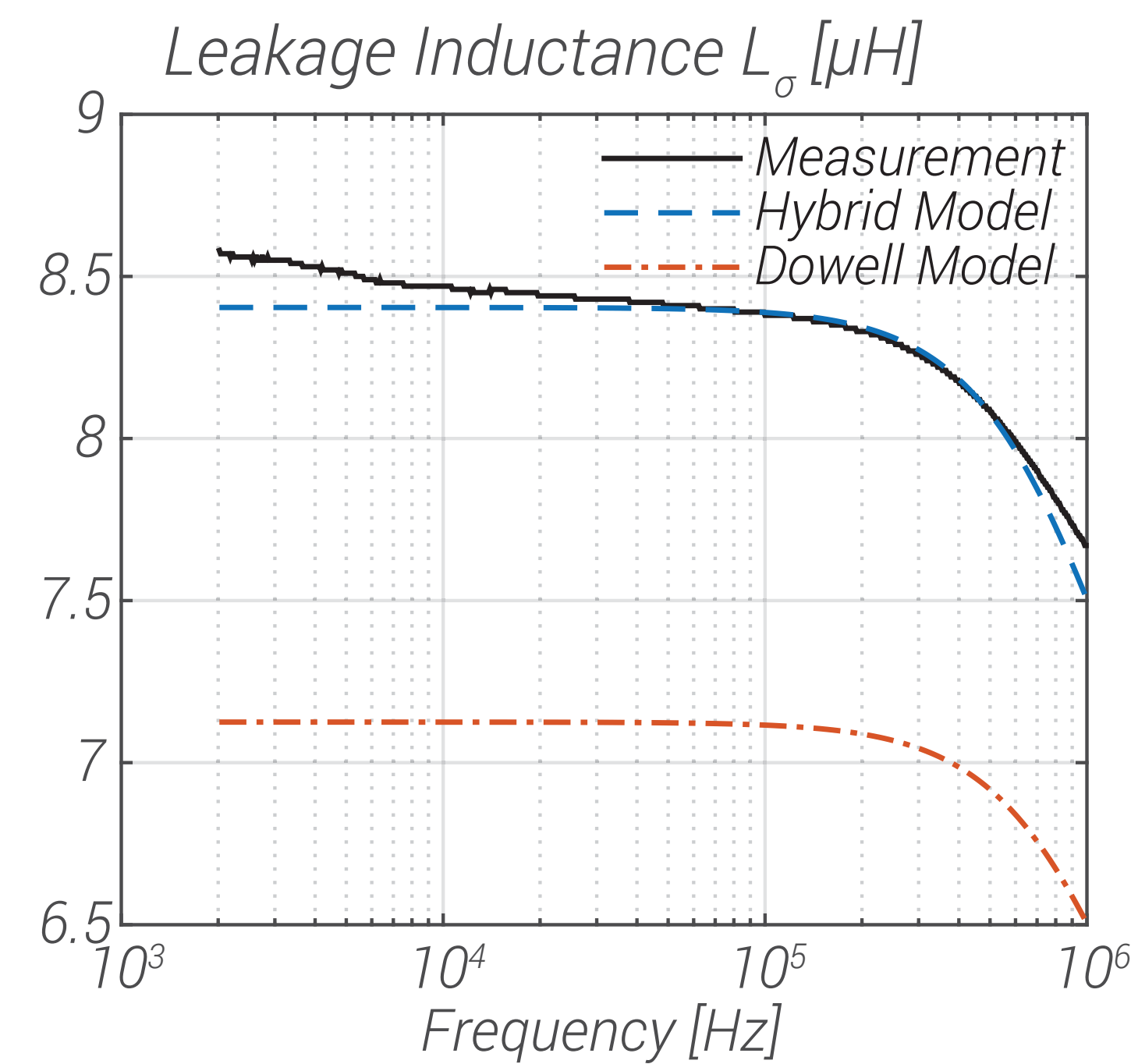


▲ Electrical measurements using Bode100

## Series Resistance Measurement:



## Leakage Inductance Measurement:



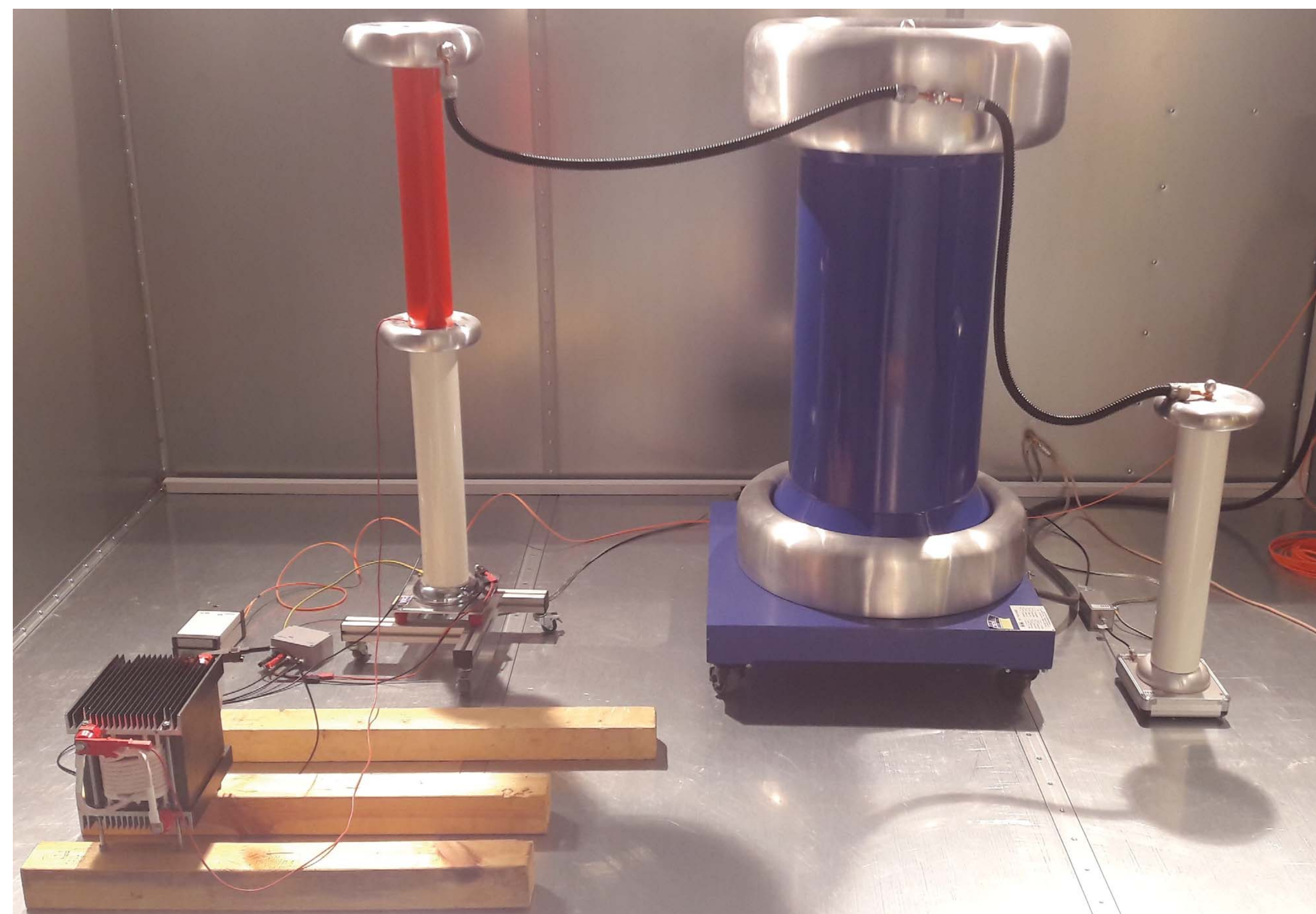


# MEASUREMENTS: DIELECTRIC PARAMETERS

## Dielectric Withstand Test:

- ▶ Partial Discharge measurement between all conductive parts
- ▶ High Voltage 50Hz source within a Faraday cage
- ▶ 10pC - between primary and secondary winding at 4kV

## HV Measurement Setup:

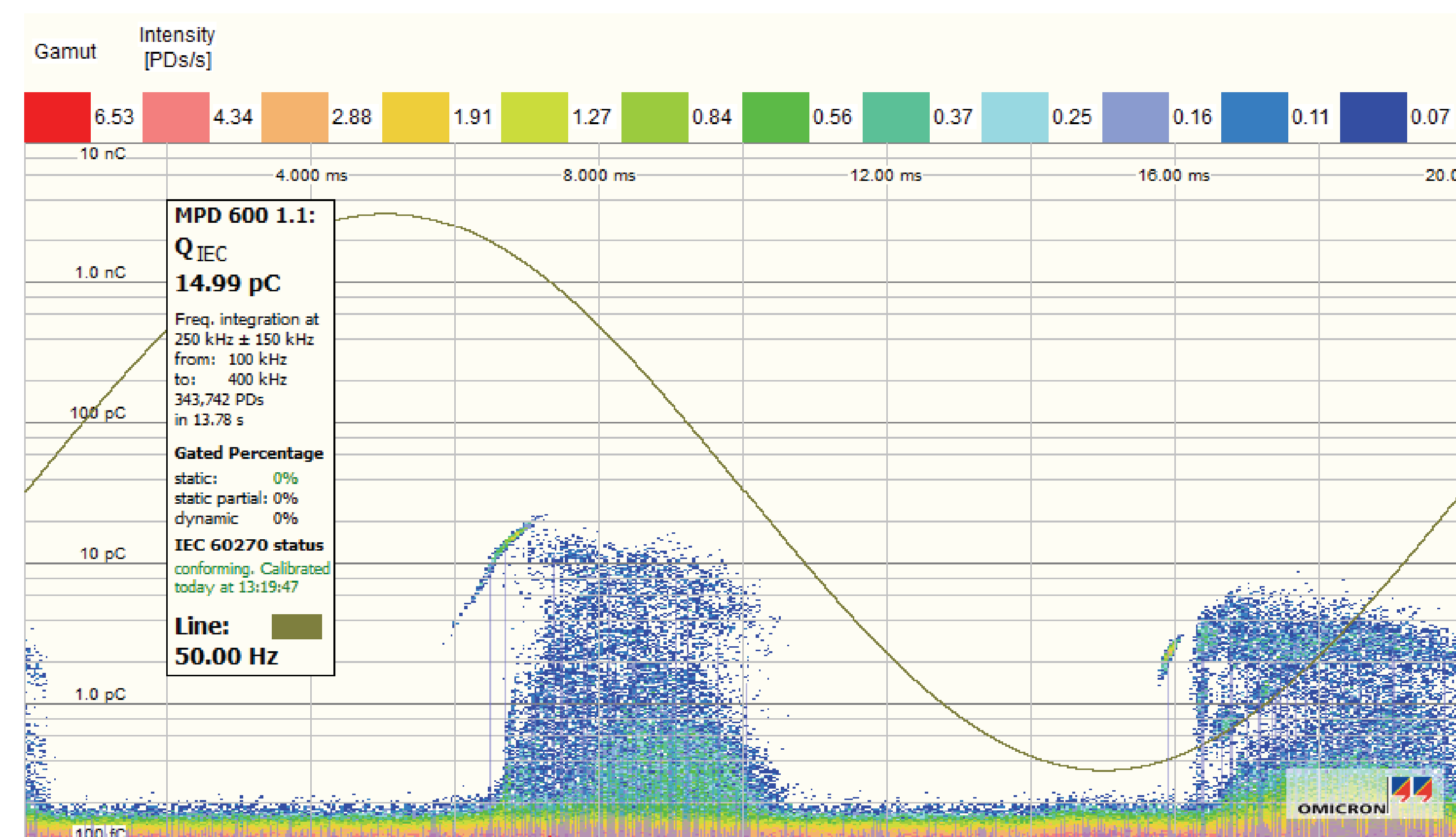


▲ MFT during AC test

## PD Test Settings:

- ▶ Front of the voltage profile:  $V = 6kV$
- ▶ Flat back of the voltage profile:  $V = 4kV$
- ▶ Peak PD at periods where  $|dV/dt|$  increases after the  $V$  peak
- ▶ PD is influenced by combination of  $V$  and  $|dV/dt|$

## Measured PD at flat back $V = 4kV$ :

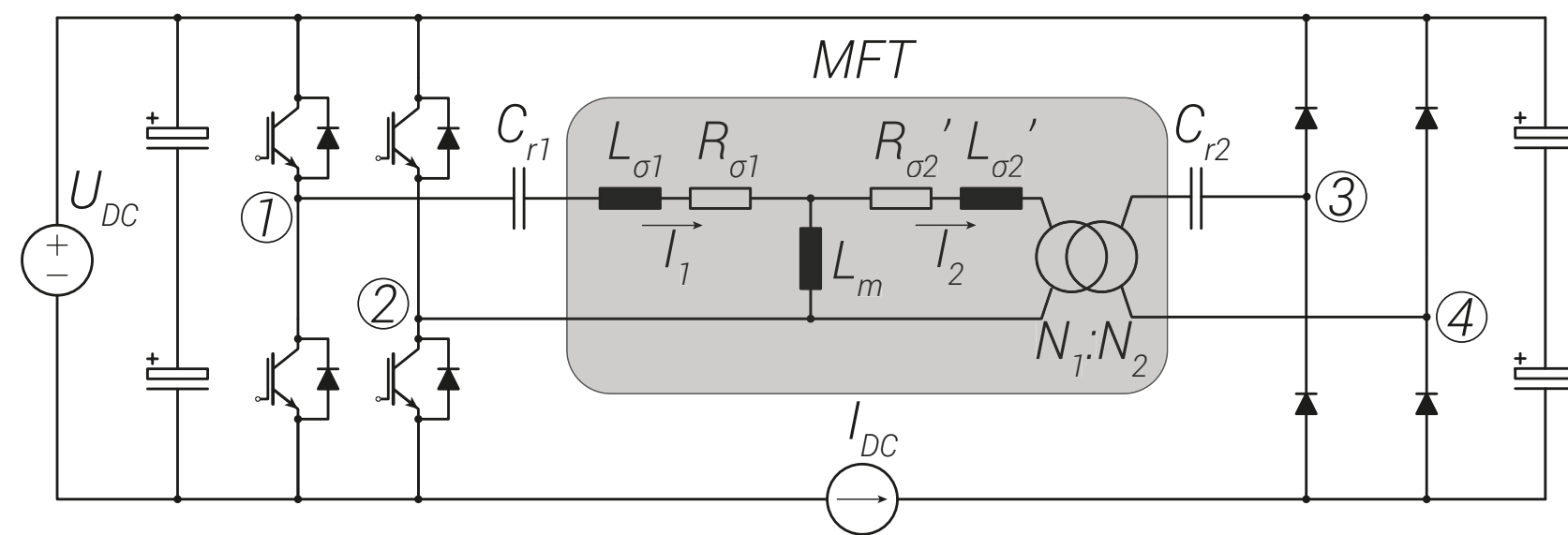


▲ MPD600 obtained measurement results

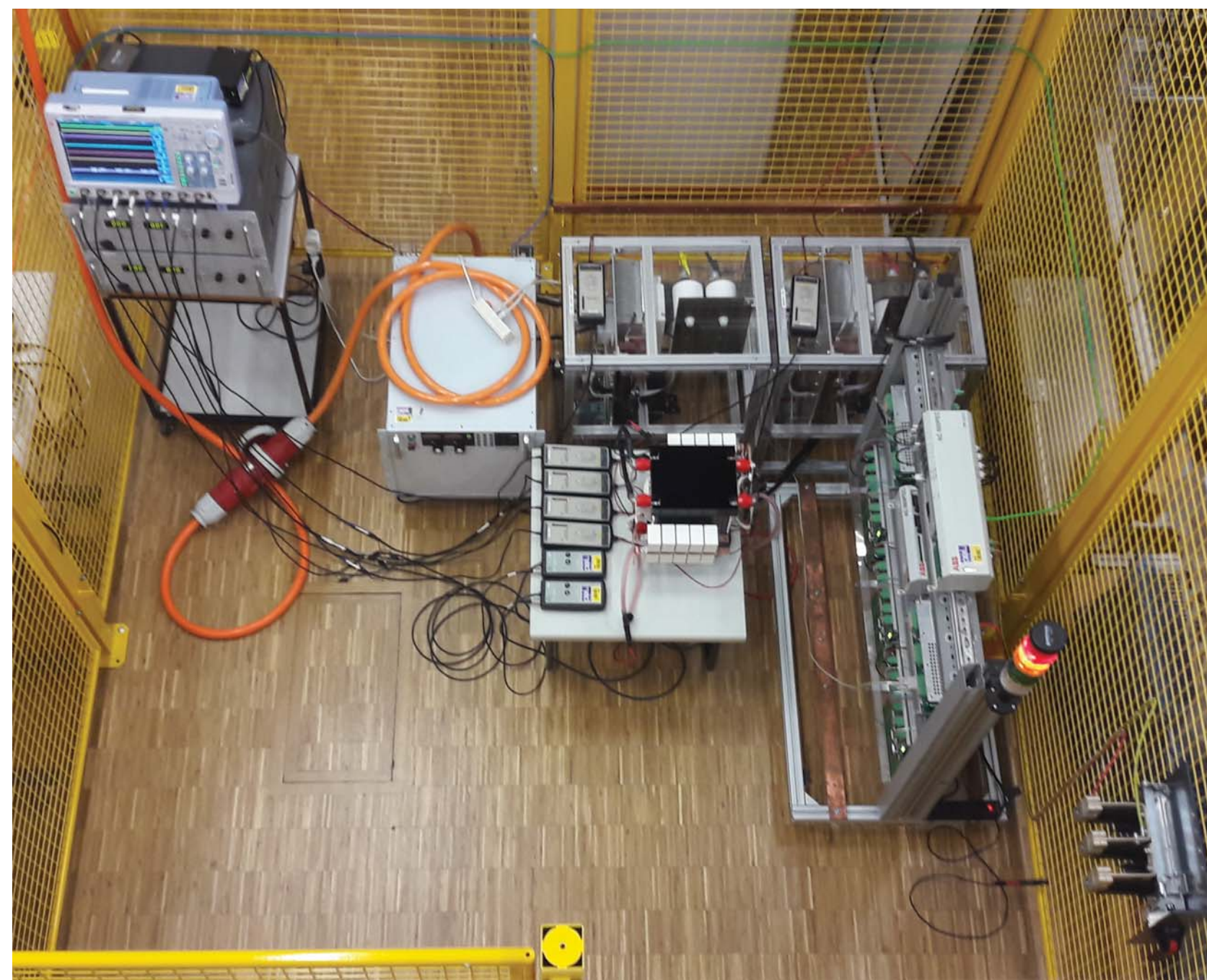
# MEASUREMENTS: LOAD TEST

## Test Setup Topology:

- ▶ B2B Resonant Converter
- ▶ Input voltage maintained by  $U_{DC}$
- ▶ Power circulation via  $I_{DC}$

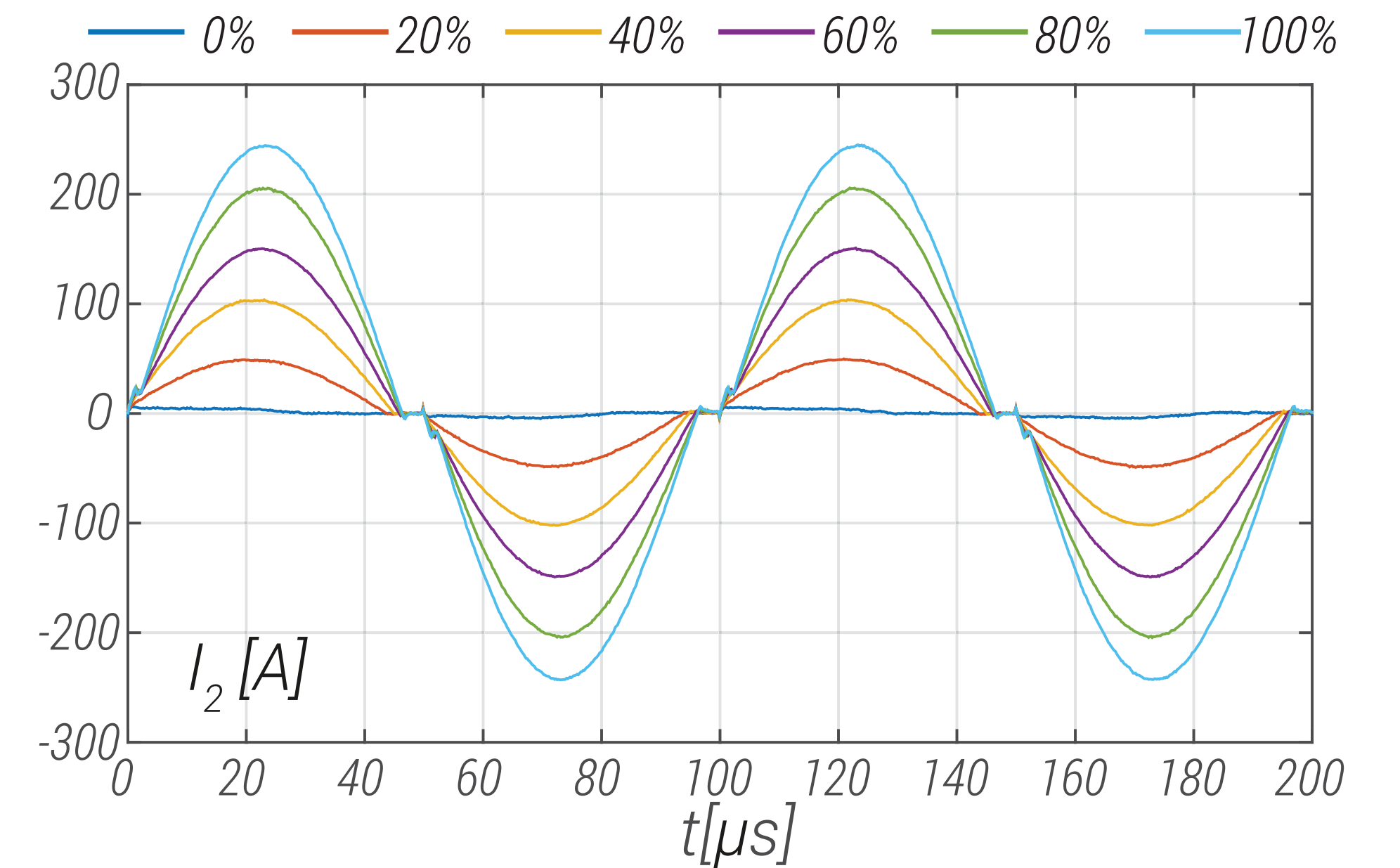
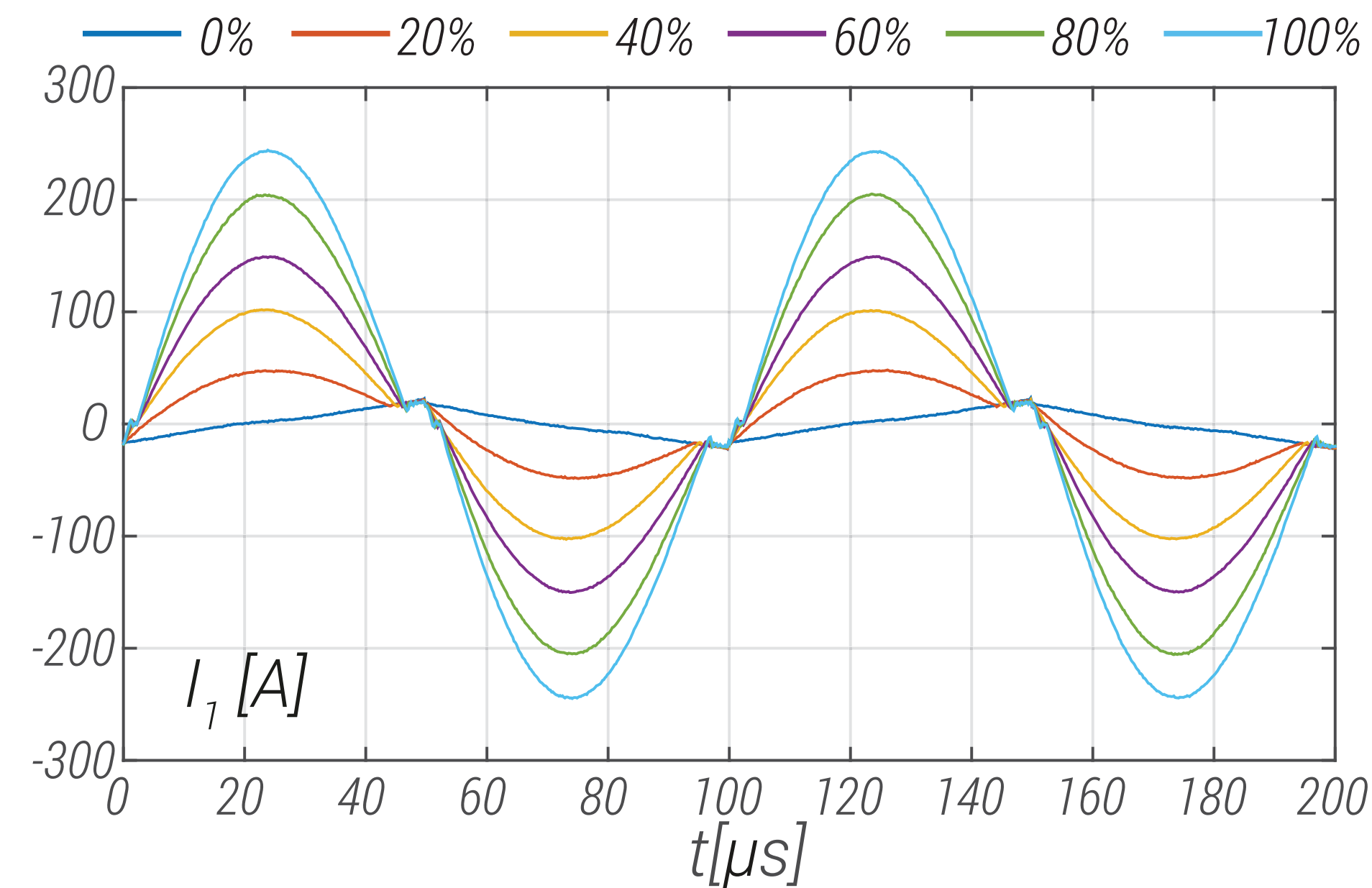
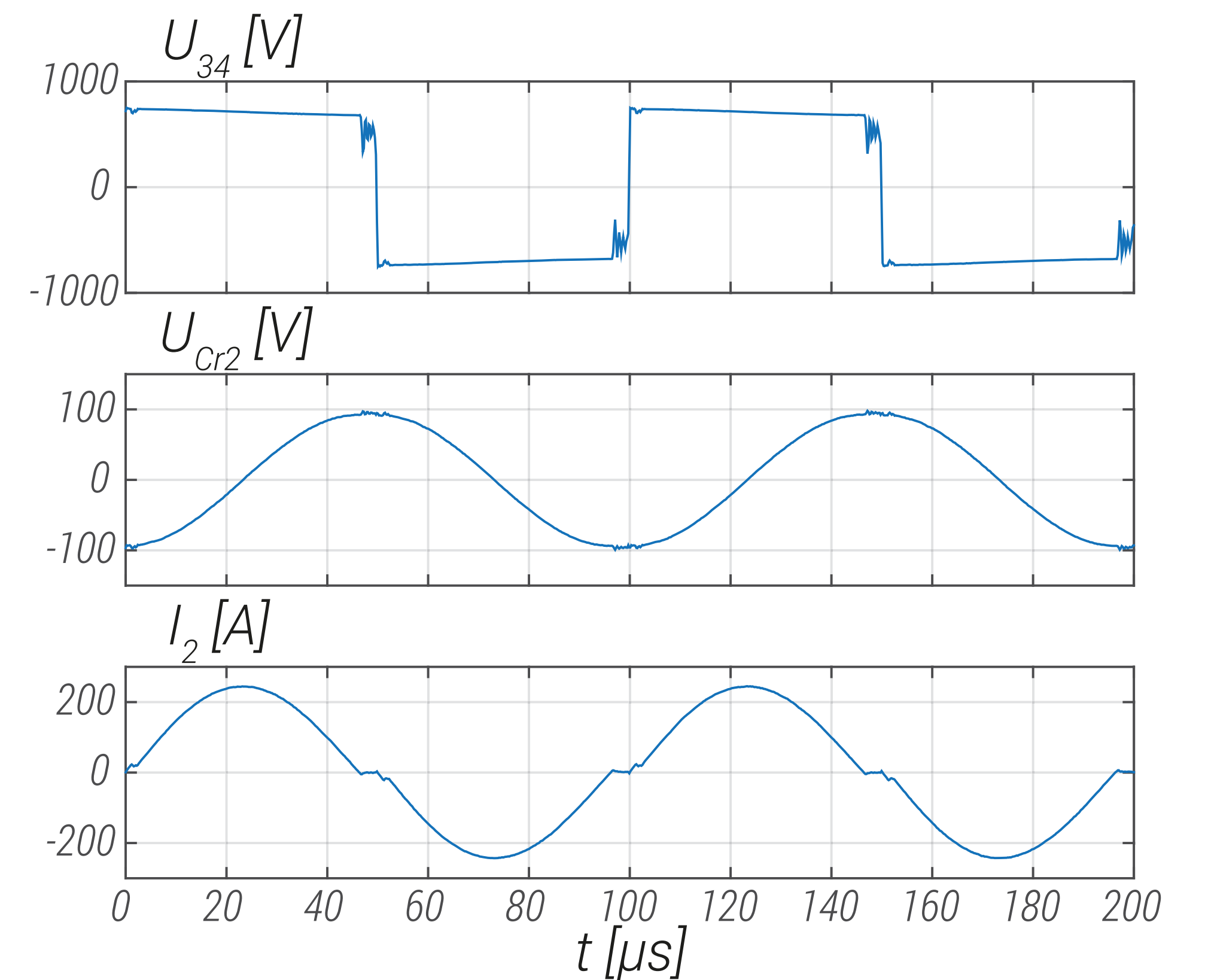
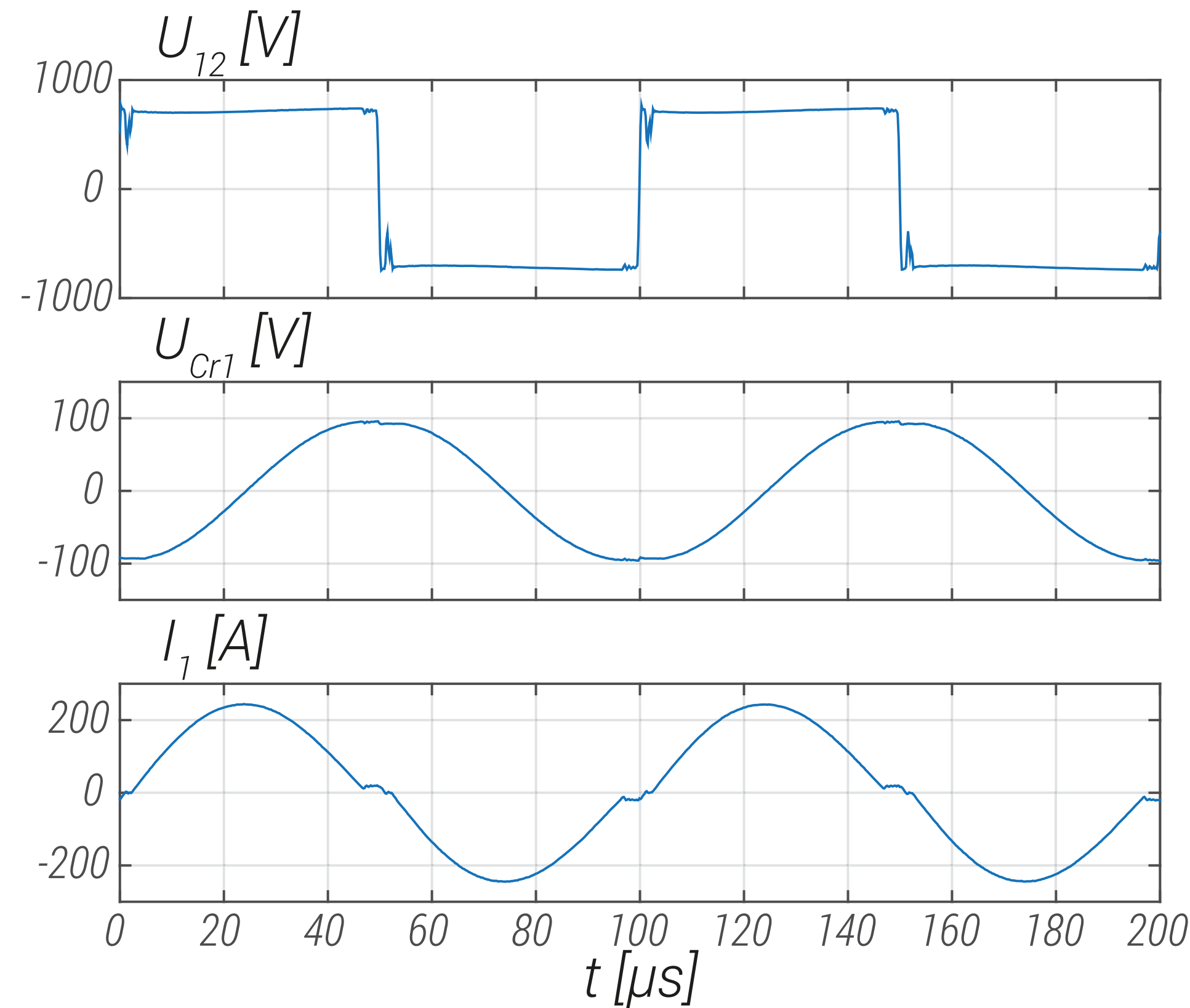


## Test Setup:



▲ B2B MFT test setup

## Measurement Results:

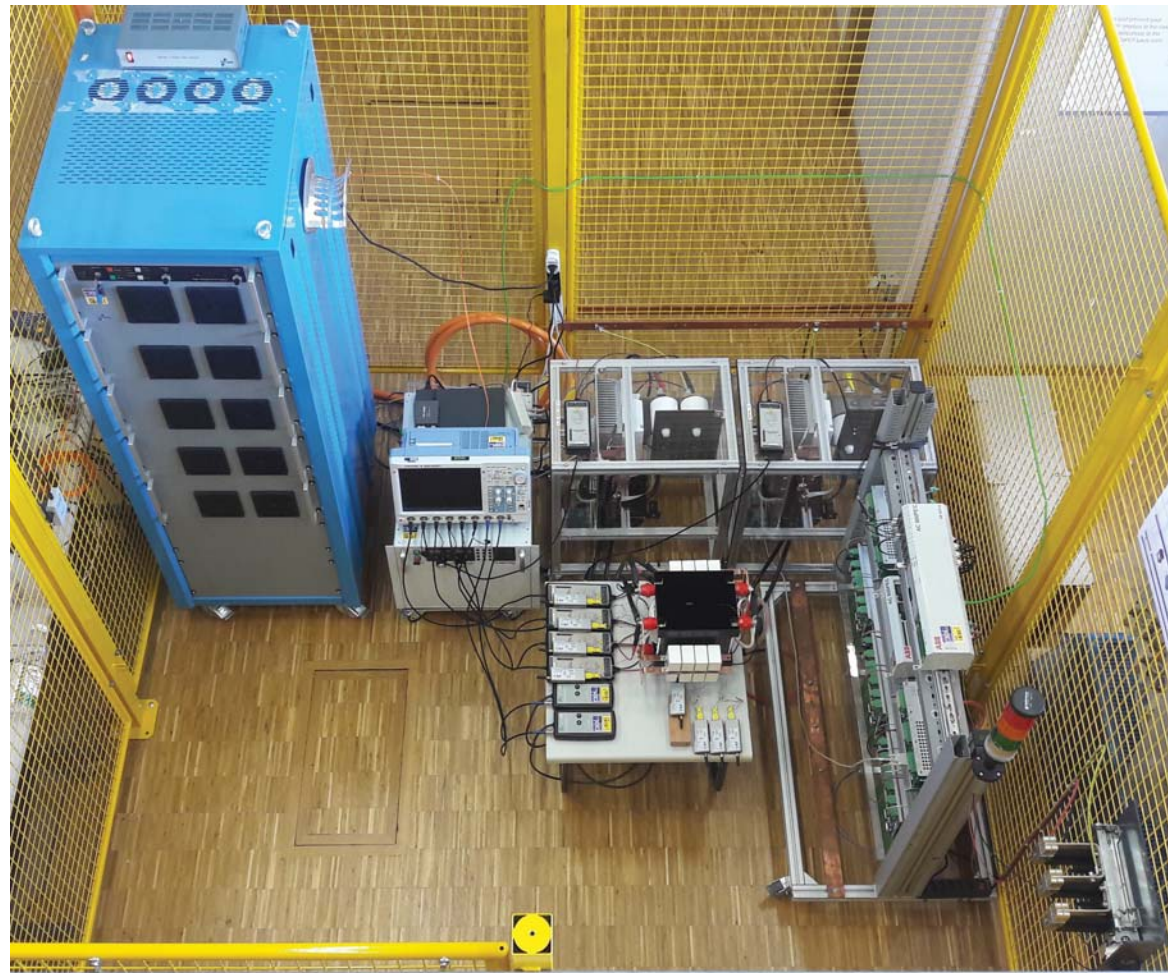


▲ Experimental results: left: MFT primary waveforms; right: MFT secondary waveforms

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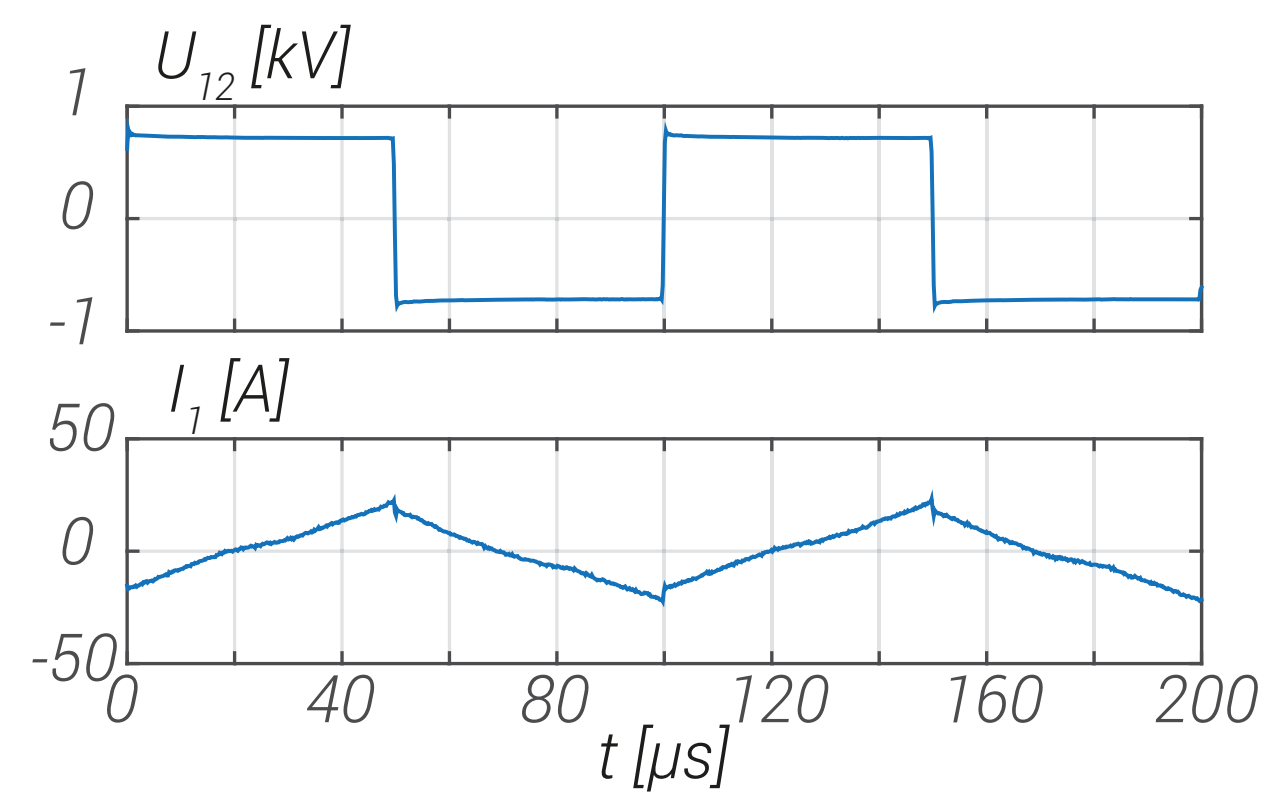
# MEASUREMENTS: THERMAL RUN

## Measurement Setup:

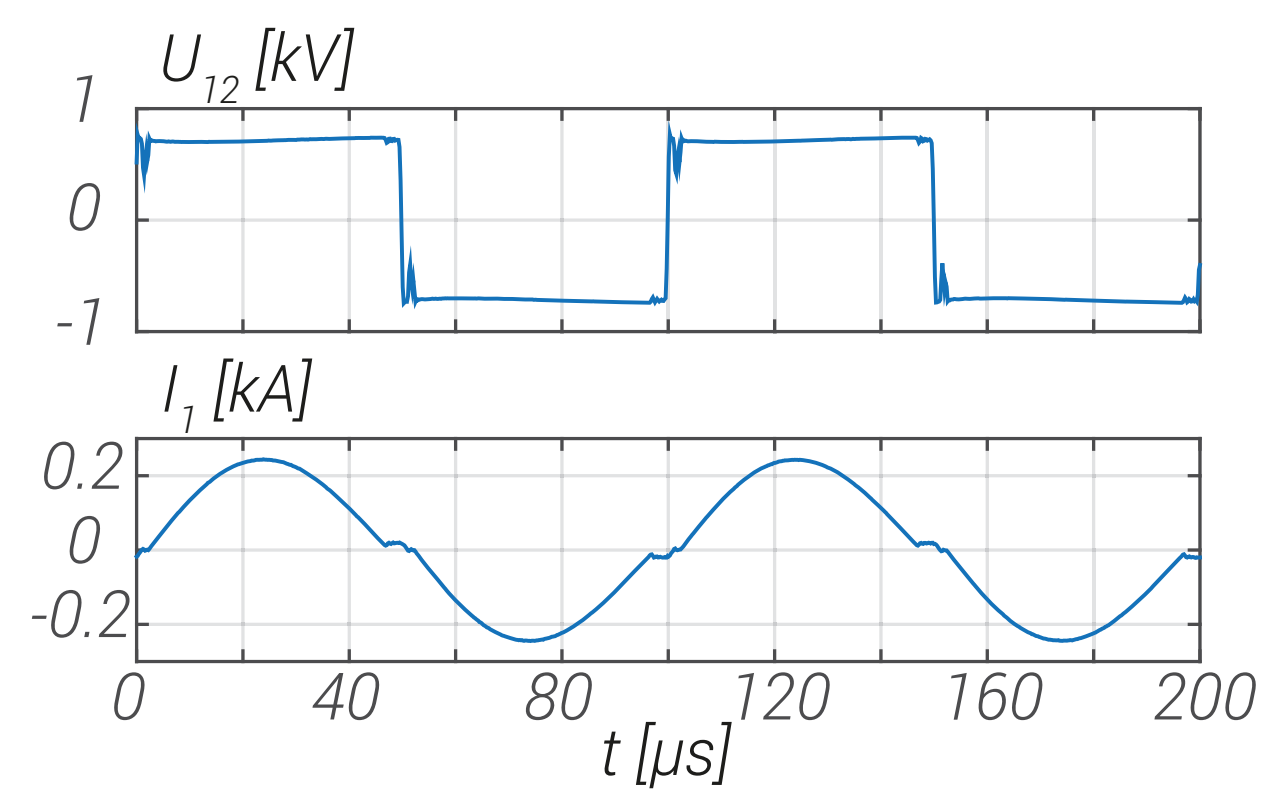


## Thermal Run:

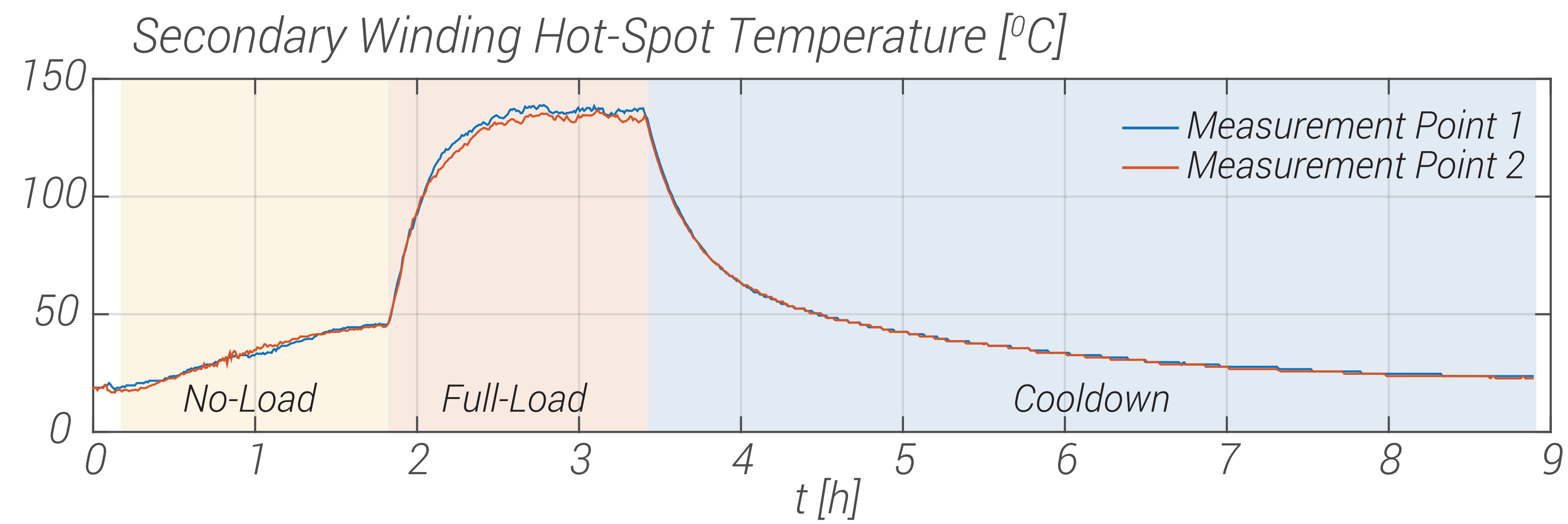
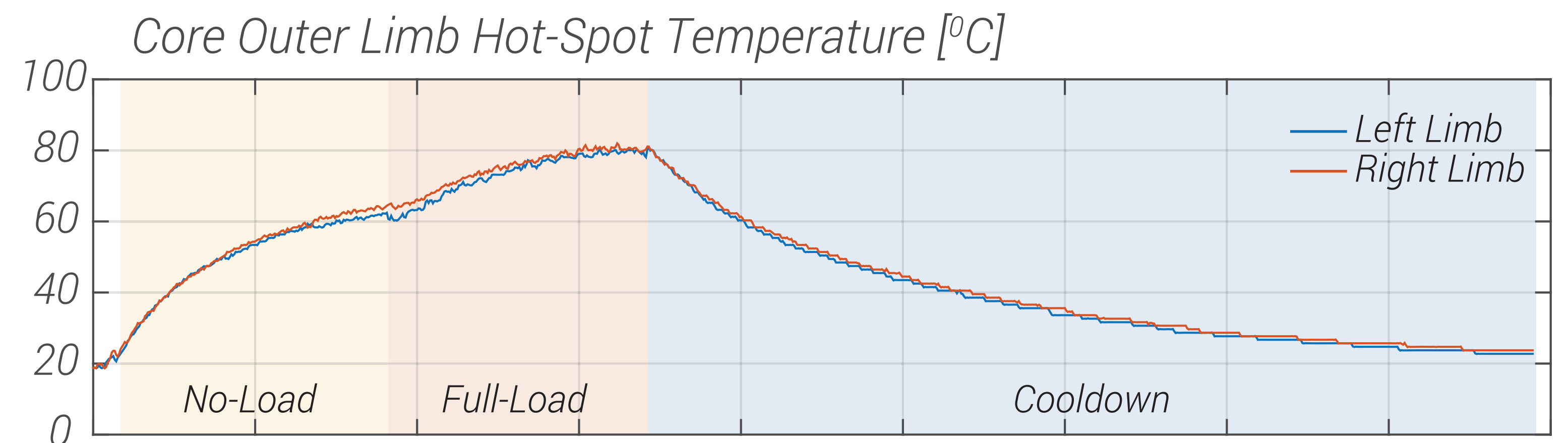
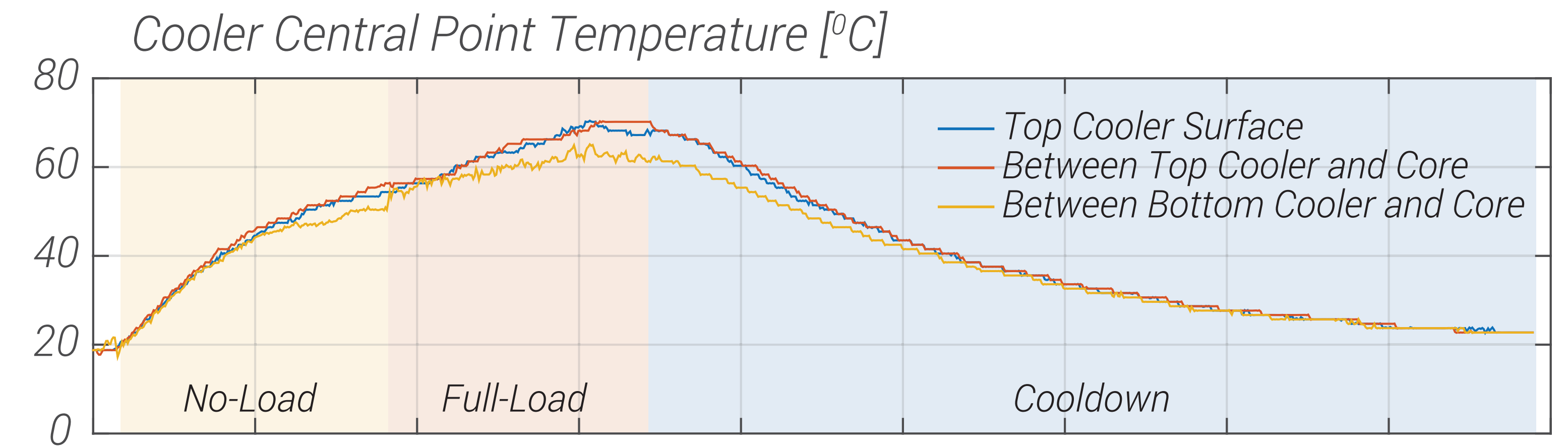
► No-Load Operation:



► Full-Load Operation:



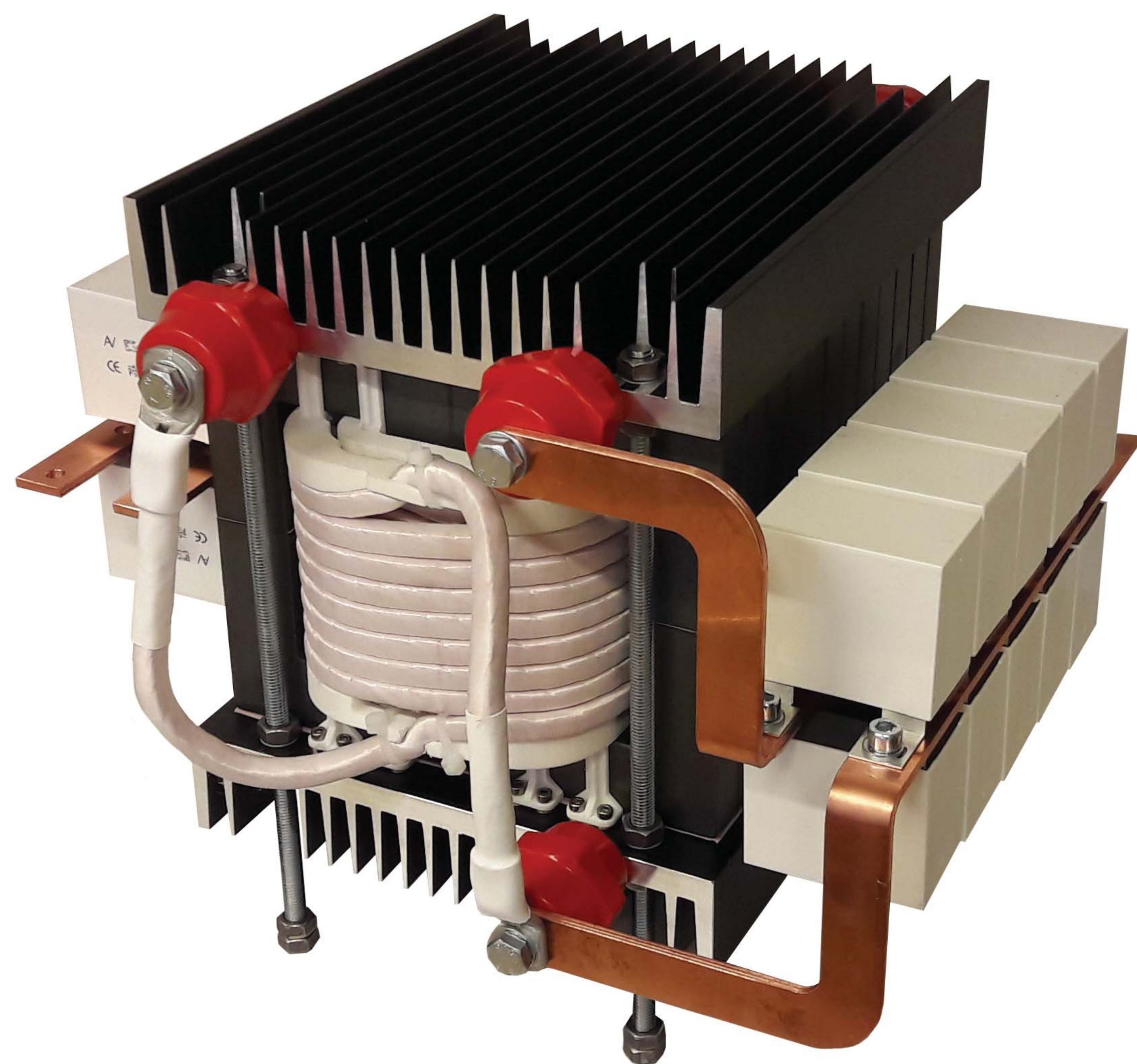
## Thermal Profile:



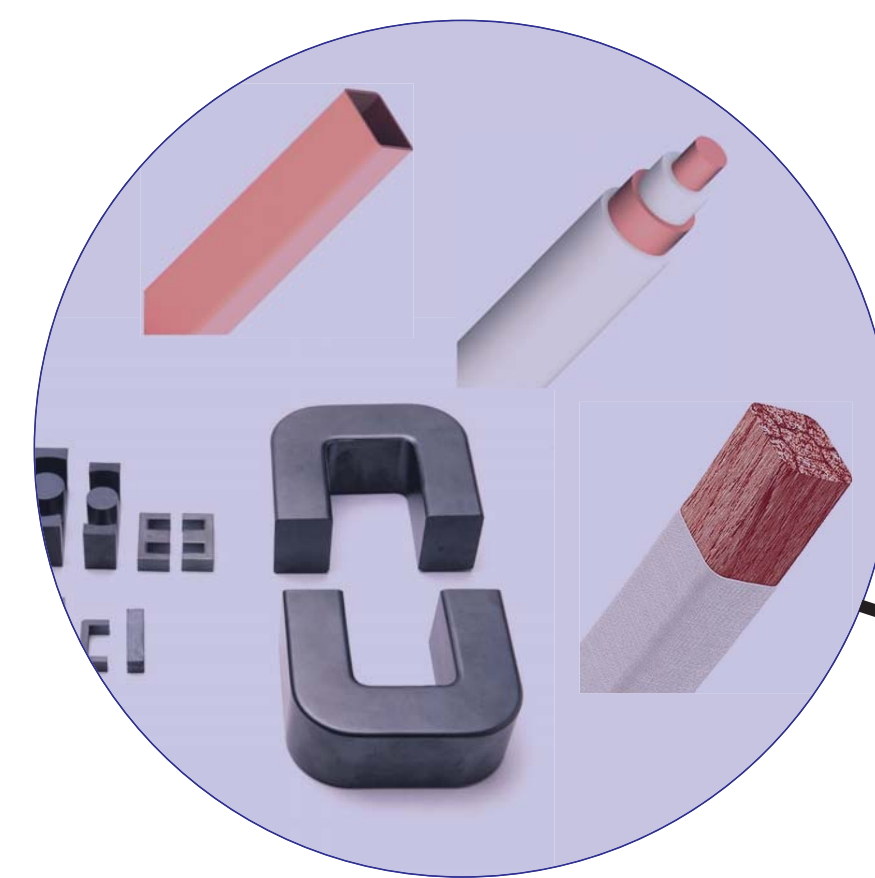
▲ Thermal heat run results

# CONCLUSION

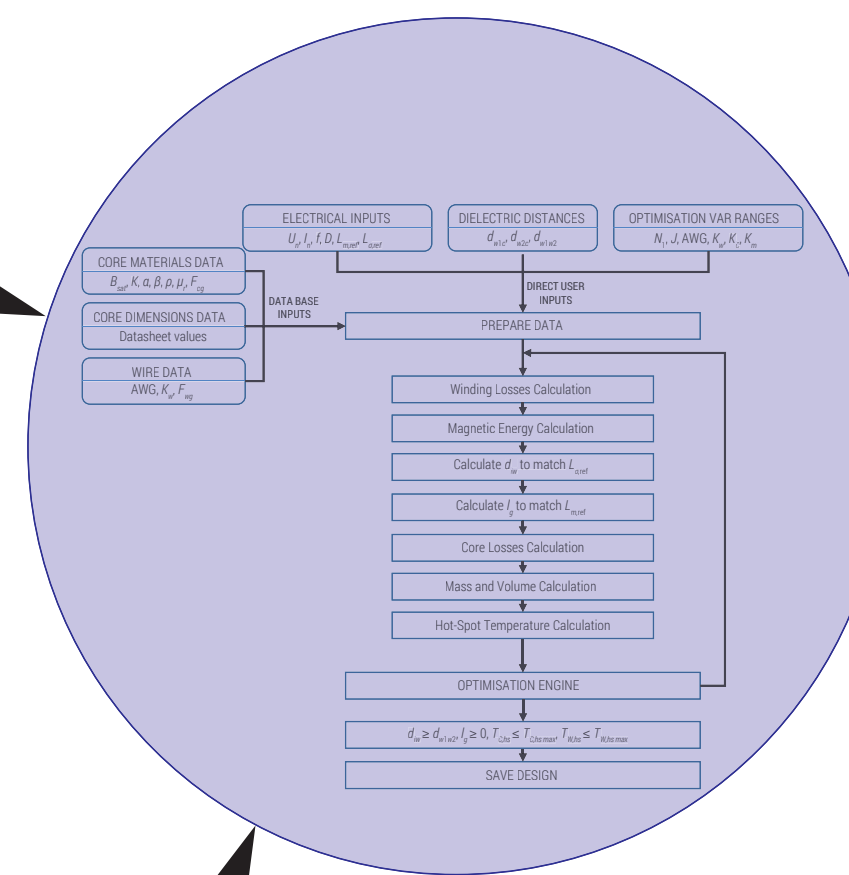
- ▶ Complex and challenging design optimization
- ▶ Large number of available materials
- ▶ Customized designs prevail
- ▶ Research opportunities...



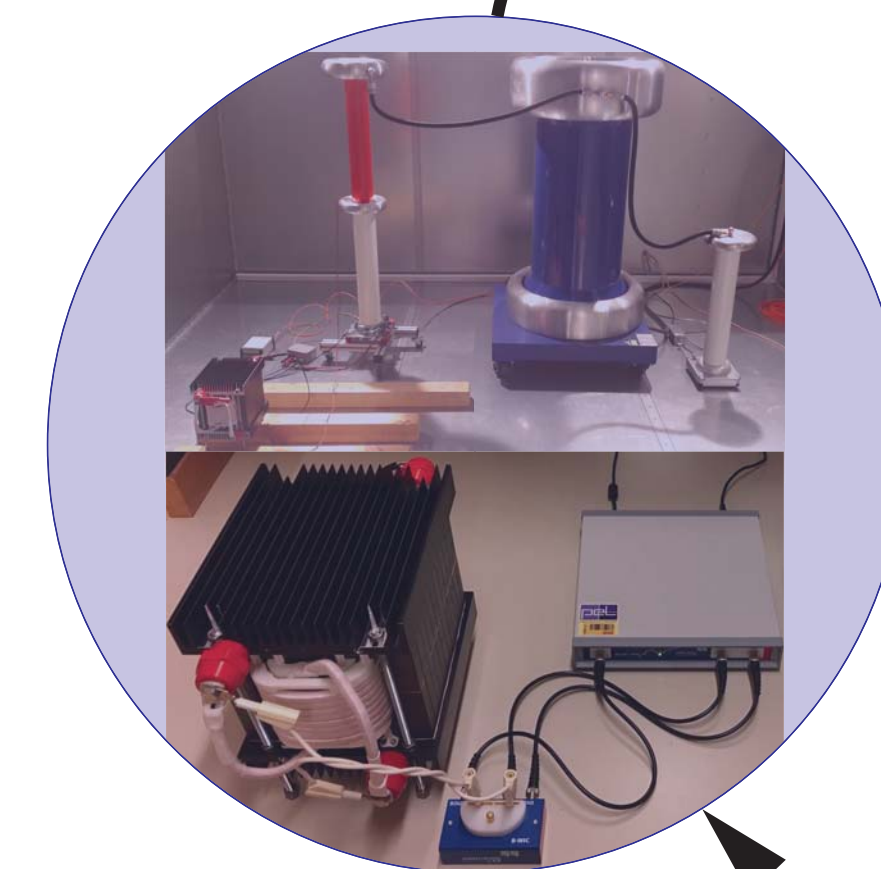
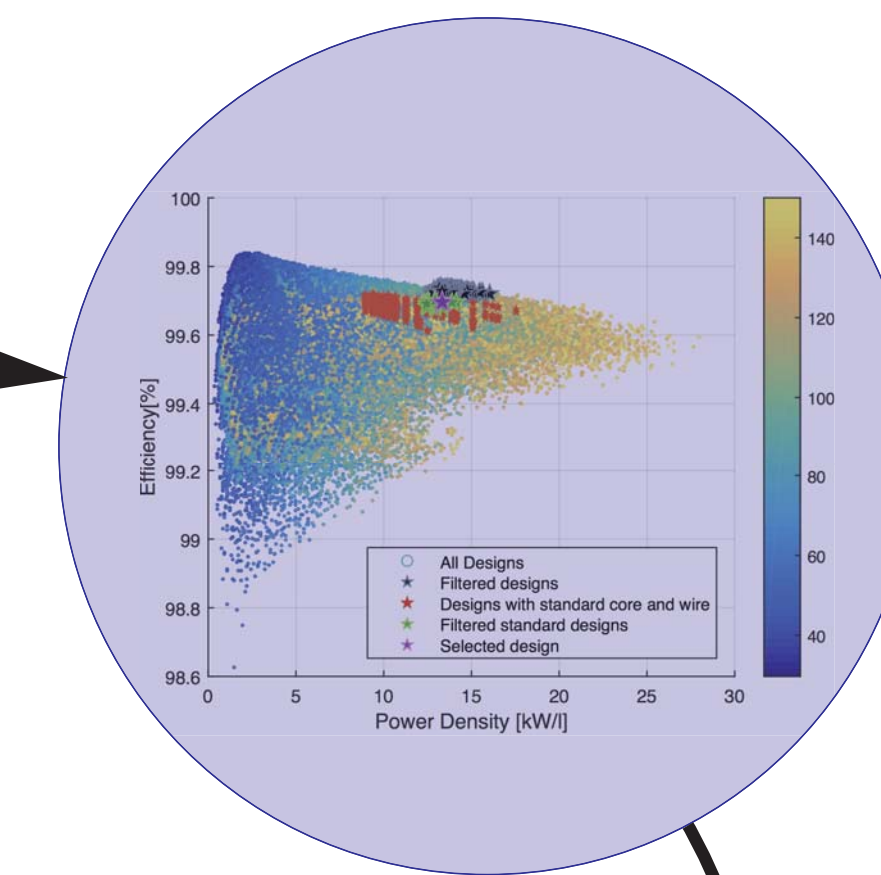
## Components & Materials



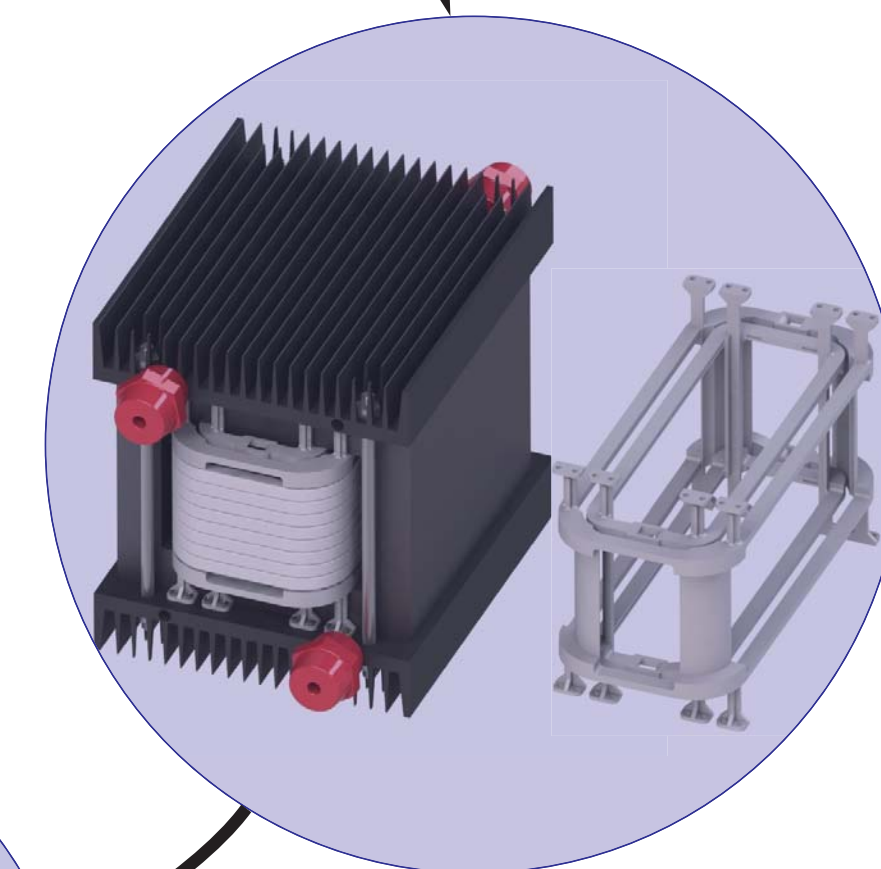
## Algorithm



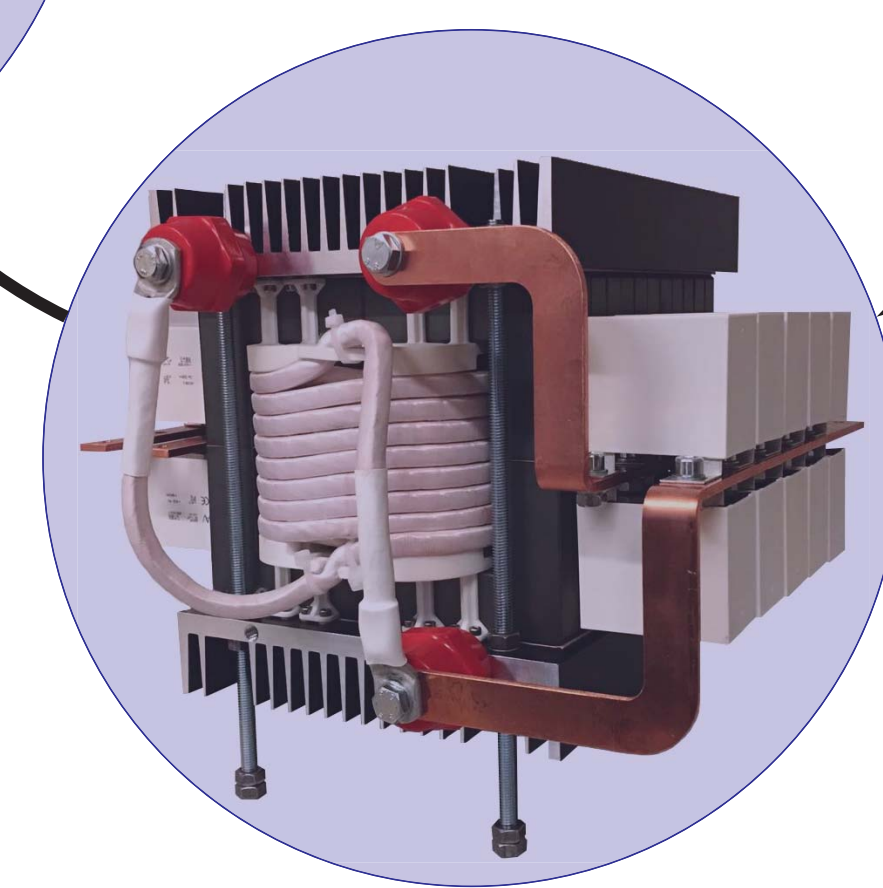
## Design Selection



## Testing



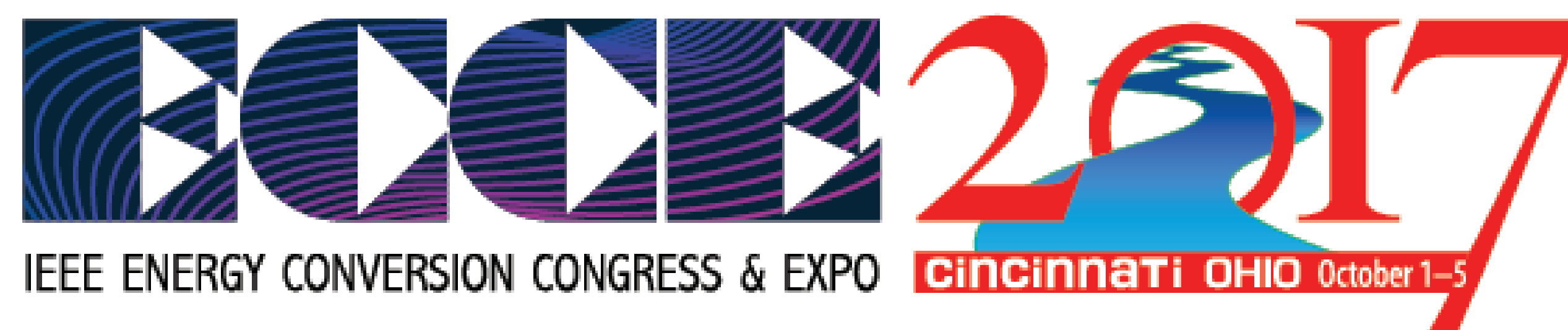
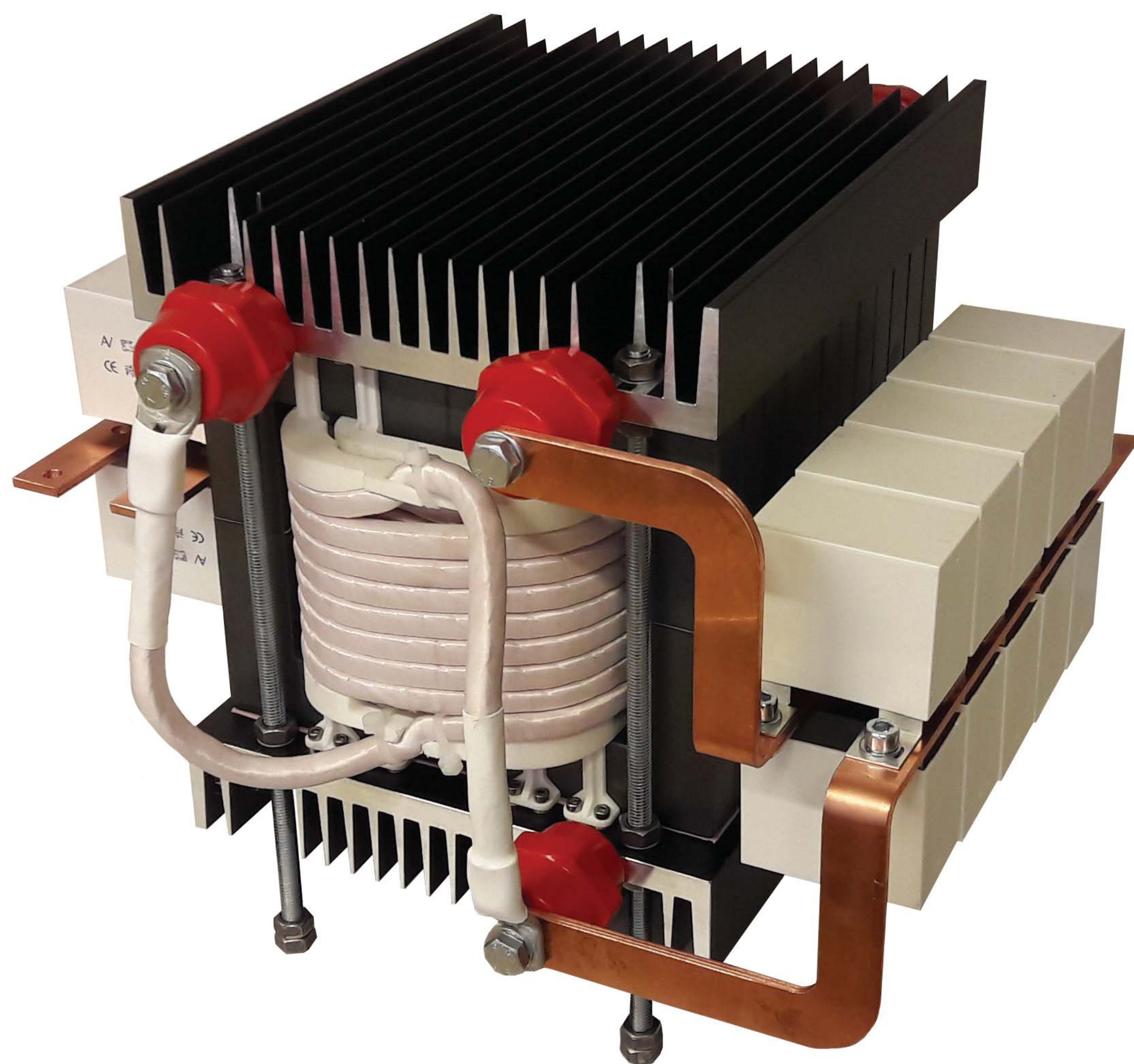
## 3D-Design



## Prototype

# CONCLUSION

- ▶ Complex and challenging design optimization
- ▶ Large number of available materials
- ▶ Customized designs prevail
- ▶ Research opportunities...



- ▶ **Tutorial:** "High Power Medium Frequency Transformer Design Optimization" - v2
- ▶ **Publication:** "Medium Frequency Transformer Leakage Inductance Modeling and Experimental Verification"



- ▶ **Tutorial:** "High Power Medium Frequency Transformer Design Optimization" - v3

# BIOGRAPHIES

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**Drazen Dujic** is an Assistant Professor and Head of the Power Electronics Laboratory at EPFL. He received the Dipl.Ing. and MSc degrees from the University of Novi Sad, Novi Sad, Serbia in 2002 and 2005, respectively, and the PhD degree from Liverpool John Moores University, Liverpool, UK in 2008. From 2003 to 2006, he was a Research Assistant with the Faculty of Technical Sciences at University of Novi Sad. From 2006 to 2009, he was a Research Associate with Liverpool John Moores University. After that he moved to industry and joined ABB Switzerland Ltd, where from 2009 to 2013, he was Scientist and then Principal Scientist with ABB Corporate Research Center in Baden-Dättwil, and from 2013 to 2014 he was R&D Platform Manager with ABB Medium Voltage Drives in Turgi. He is with EPFL since 2014.

His research interests include the areas of design and control of advanced high power electronic systems and high-performance drives, predominantly for the medium voltage applications related to electrical energy generation, conversion and storage. He has authored or co-authored more than 90 scientific publications and has filed eleven patents.

In 2014, he received The Isao Takahashi Power Electronics Award for Outstanding Achievement in Power Electronics, presented at International Power Electronics Conference, IPEC-Hiroshima 2014, Japan. He is Senior Member of IEEE, EPE Member, and serves as Associate Editor for IEEE Transactions on Power Electronics, IEEE Transactions on Industrial Electronics and IET Electric Power Applications.



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He is an IEEE Student Member and EPE Student Member.

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# HIGH POWER MFT DESIGN OPTIMIZATION

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