16th Annual Meeting

Highly compact magnetic transformer with dedicated thermal management for aerospace applications

Andrés Ferrer López
Alberto Delgado Expósito & Miroslav Vasić

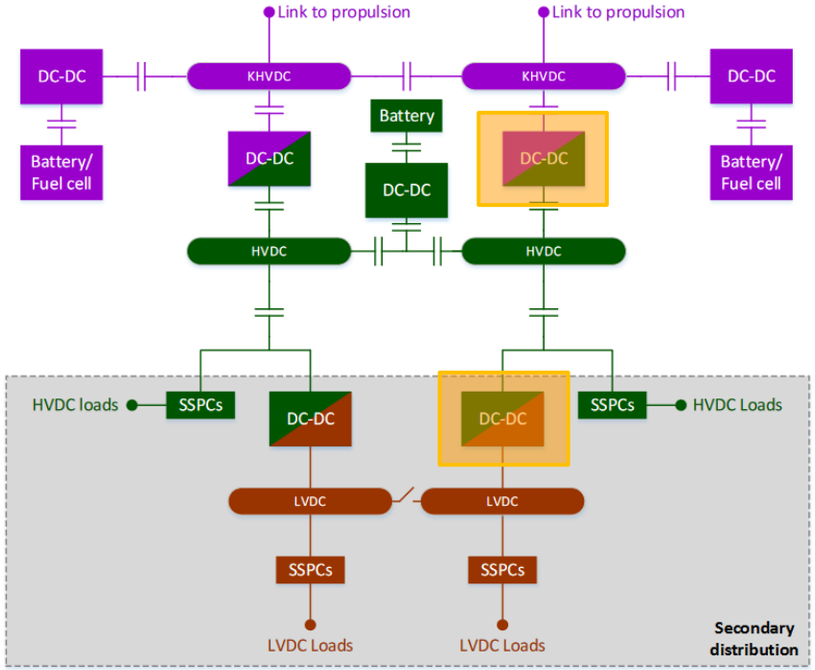
European Project:

34 M€ 37 partners

aerospaceHV · AALBORG UNIVERSITY · AIRBUS DEFENCE & SPACE · Collins Aerospace

- Climate **neutral air mobility** by 2050 set by ACARE (Advisory Council for Aeronautics Research in Europe)

- Requires aviation industry to do a **further step.** HECATE project is born.

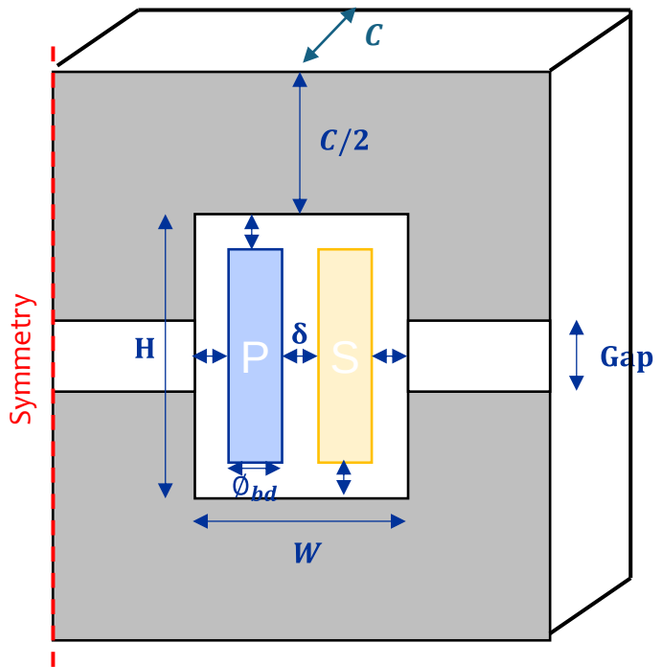


4 months!!

What did we did during discussion time?

C
Gap
H
W
$\emptyset_{bd}$
δ

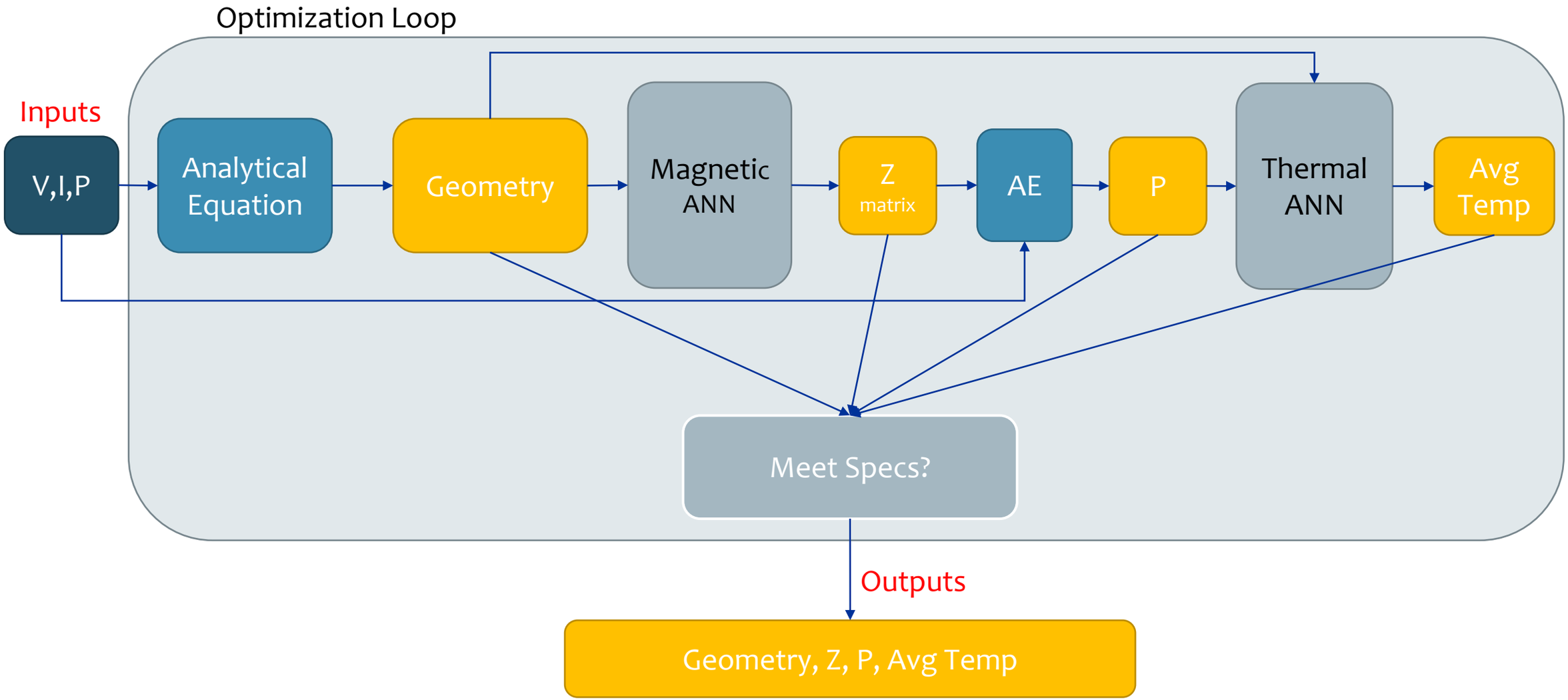
ANN based on FEM simulations



L_{mag}
L_{lk}
$P_{winding}$
P_{core}
T_{avg}

ANN
=
Fast Design
Response

What did we did during discussion time?



What did we did during discussion time?

Input Data

Topology:
- Switching Frequency
- N° Harmonics

Waveforms:
- Voltage
- Current

Ambient:
- T_{amb}
- $T_{coldplate}$ or V_{air}

Analytical Equations

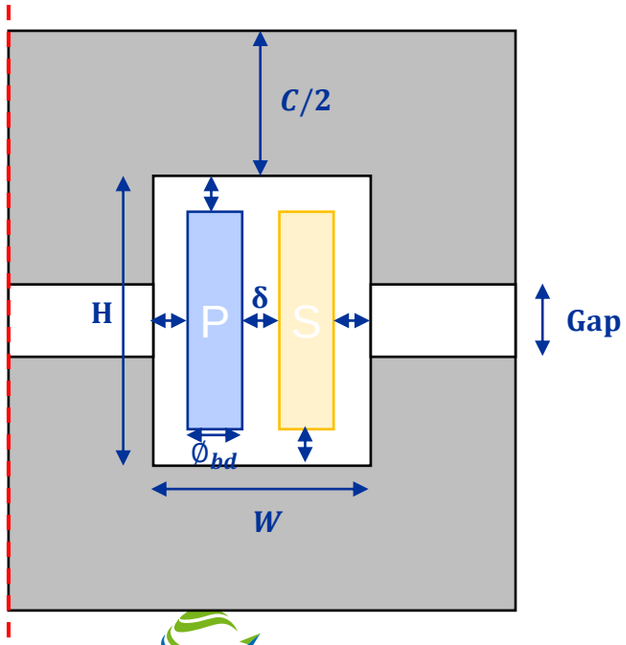
- $BA = \frac{\int V_p dt}{N_p}$
- $P_{core} = Steinmetz(B)$
- $A_{cu} = \frac{I}{J}$
- $L_{mag} = \frac{N_p^2}{R_{eq}}$

Finite Element

Sweep:
- $N \in [N = 1, N = 30]$
- $B \in [15mT, 150mT]$
- $C = \sqrt{A(B, N)}$
- $J \in [2, 10] A/mm^2$
- $\emptyset_{bd}(J)$

ANN

L_{mag}
$P_{winding}$
P_{core}



Geometry:

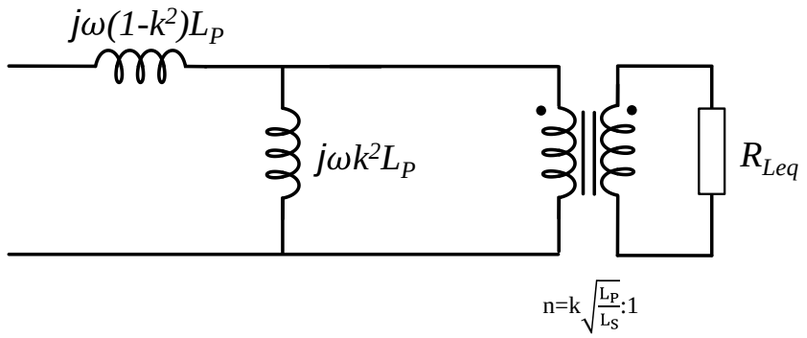
- $W = (N_{winding} + 1)\delta + \emptyset_{bd} N_{winding}$
- $H = 2\delta + \emptyset_{bd} N_{turns}$
- $H \in [W, 4W]$
- $l_{eff_{core}} = 2\left(H + \frac{C}{2}\right) + 2\left(W + \frac{C}{2}\right)$
- $HW \in \left[0.25 \frac{C}{2} l_{eff_{core}}, 0.5 \frac{C}{2} l_{eff_{core}}\right]$
- $Gap \in \left[0.001 l_{eff_{core}}, 0.05 l_{eff_{core}}\right]$

Fix:

- f_{sw}
- $Material(f_{sw})$
- $k_{LW} = 1/0.55$
- $k_w = 0.5 \rightarrow \delta$

Modelling

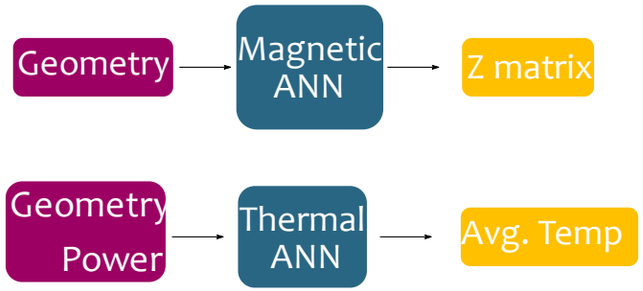
Parameters	Value
Power	100 - 300 kW
Frequency	25 – 100 kHz
Primary voltage (square)	800 V
Primary current (senoidal)	150 - 300 A_{RMS}
Secondary current (senoidal)	200 - 400 A_{RMS}
Turns ratio	??
Lmag	20 - 40 µH
Llk	1 - 5 µH

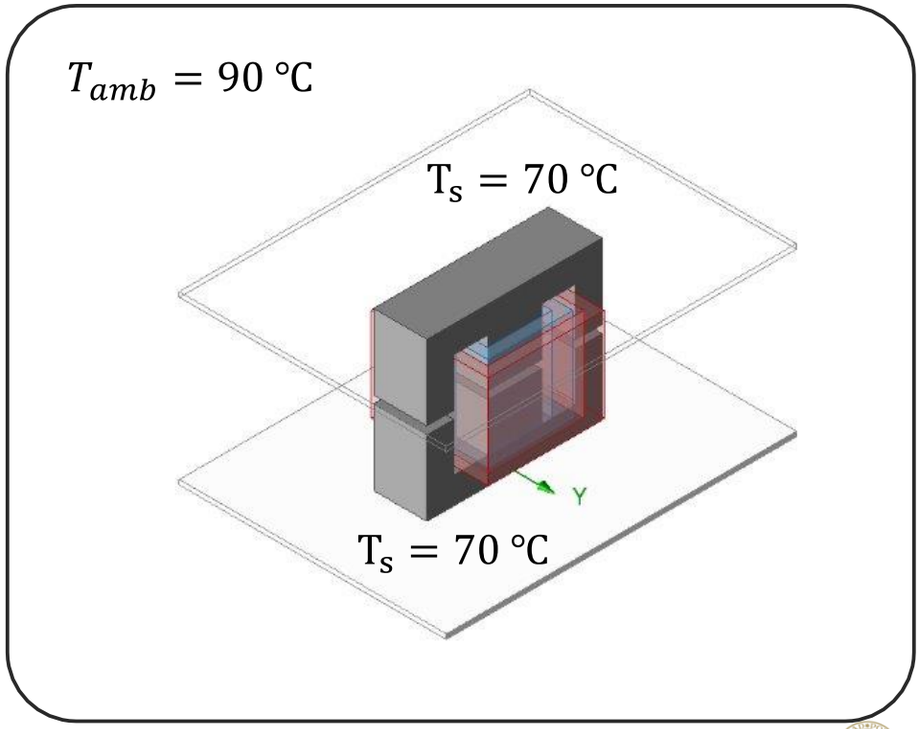


Training the ANN

Inputs: V, I, P
Outputs: Geometry, Z matrix, Power, Avg Temp.

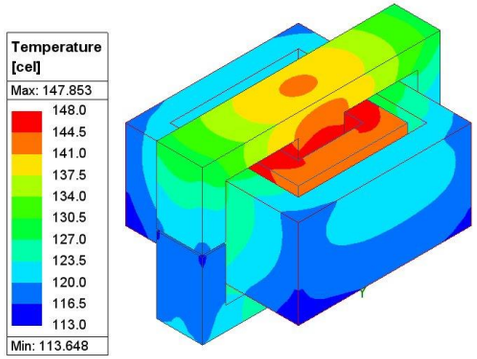
Using the ANN



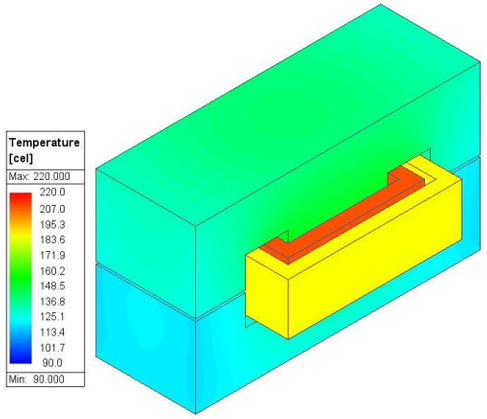


Practical case

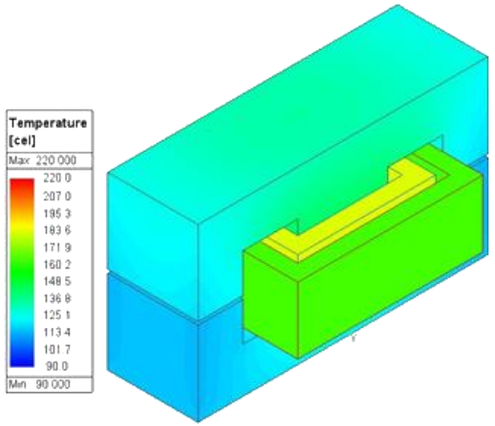
Technology must be changed!!



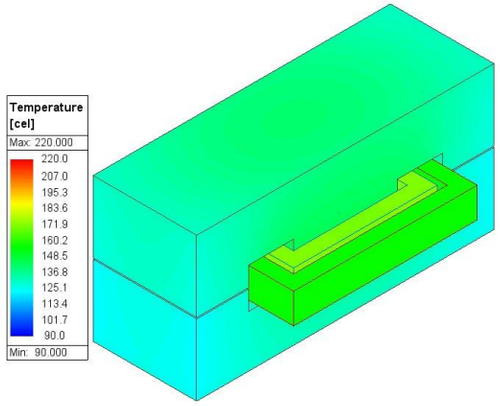
42 kg
6:4
$L_{mag} = 50\ \mu H$
$L_{lk} \approx 6\ \mu H$
$T_{max} \approx 148\ °C$
$J = 0{,}5\ A/mm^2$



11 kg
6:4
$L_{mag} = 65\ \mu H$
$L_{lk} \approx 4\ \mu H$
$T_{max} \approx 215°C$
$J = 5\ A/mm^2$



14 kg
6:4
$L_{mag} = 65\ \mu H$
$L_{lk} \approx 4\ \mu H$
$T_{max} \approx 185°C$
$J = 2{,}5\ A/mm^2$



20 kg
3:2
$L_{mag} = 52\ \mu H$
$L_{lk} \approx 2{,}1\ \mu H$
$T_{max} \approx 150°C$
$J = 2{,}5\ A/mm^2$

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Classical design: first iteration

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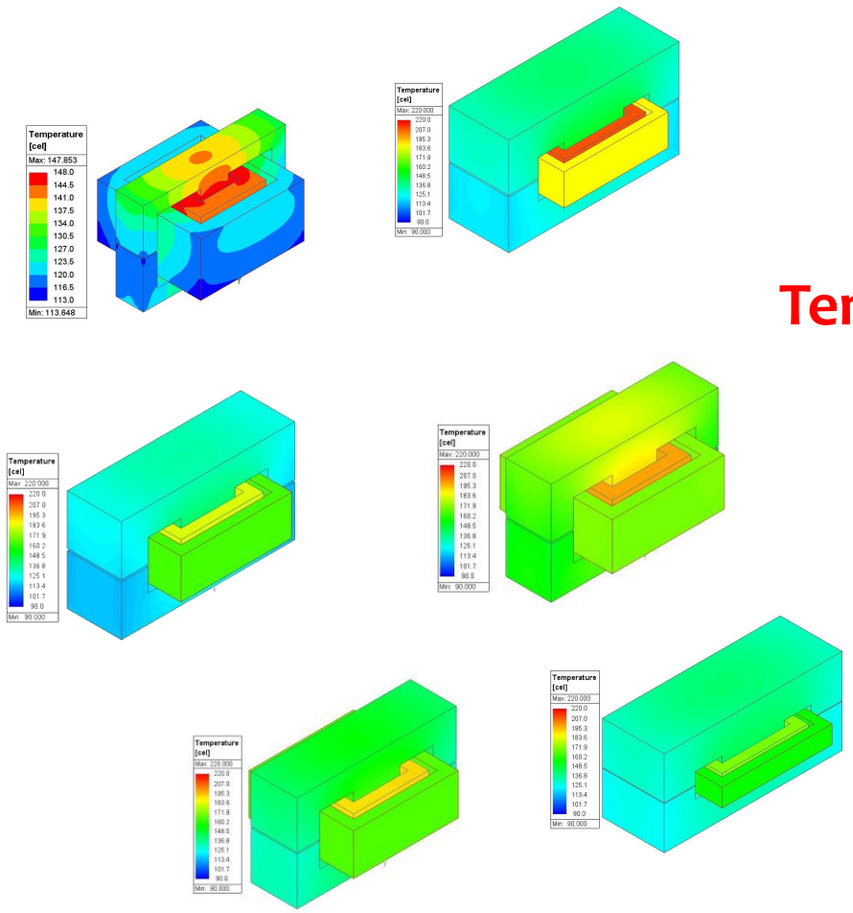
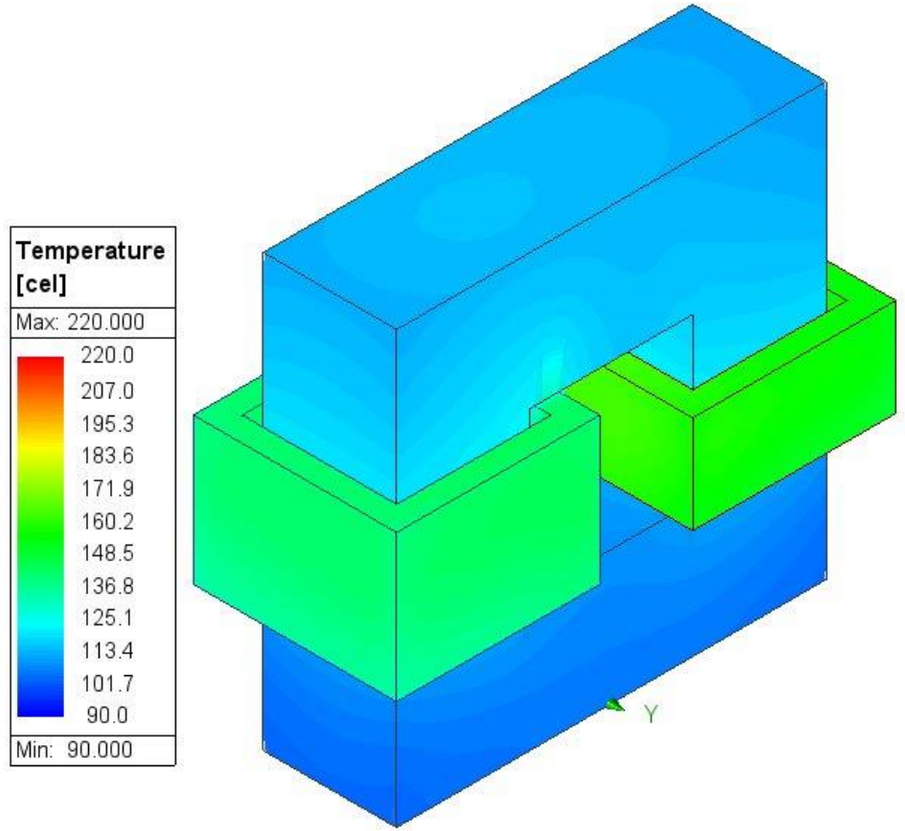
From E core to U core

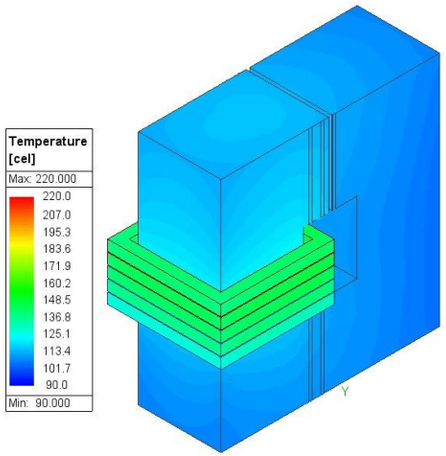


Temperature issues in the Inner winding

Solution?



U core first iterations



50 kg

3:2

$L_{mag} = 50\ \mu H$

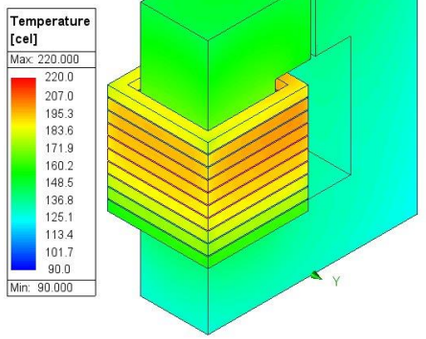
$L_{lk} \approx 3\ \mu H$

$T_{max} \approx 150°C$

$J = 2.5\ A/mm^2$

Decrease core by Increasing Nturns and Bmax

Increase power losses on: Core and winding



14 kg

6:4

$L_{mag} = 76\ \mu H$

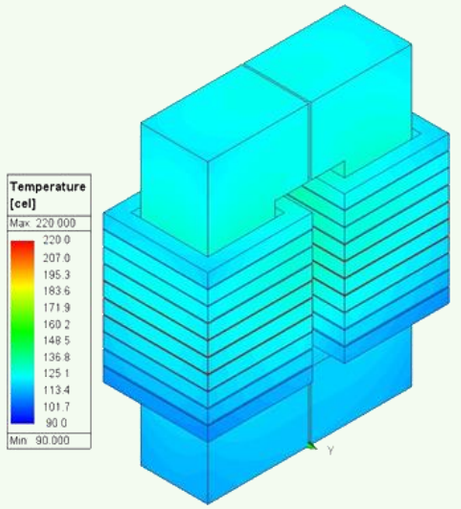
$L_{lk} \approx 4\ \mu H$

$T_{max} \approx 195°C$

$J = 5\ A/mm^2$

Parallel windings

Decrease winding losses and reduce the core temperature



21 kg

6:4

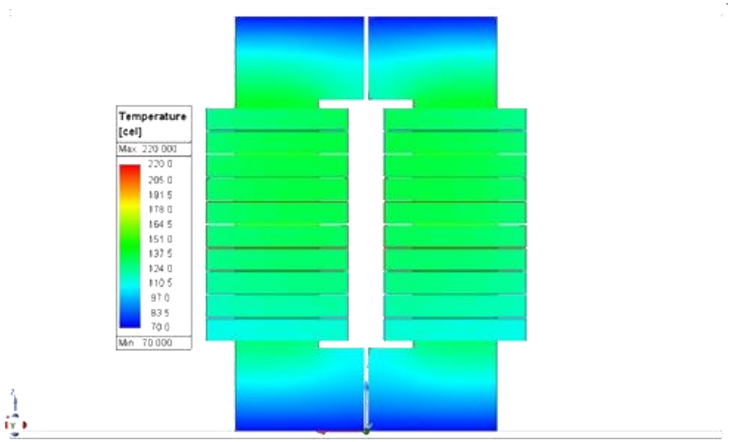
$L_{mag} = 65\ \mu H$

$L_{lk} \approx 2{,}8\ \mu H$

$T_{max} \approx 125°C$

$J = 2.5\ A/mm^2$

Reducing the weight of the transformer



16 kg

6:4

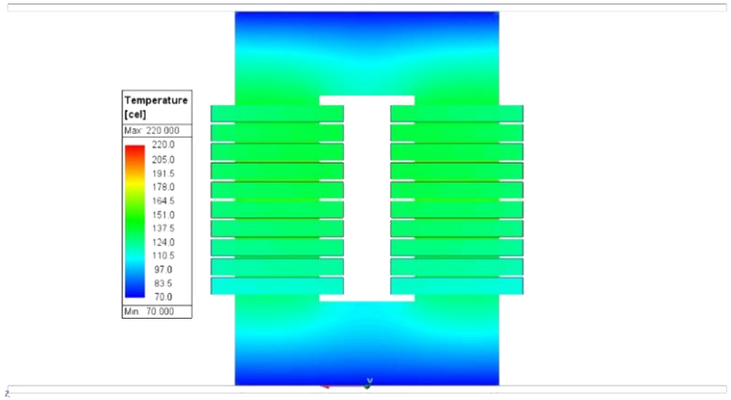
$L_{mag} = 31\ \mu H$

$L_{lk} \approx 2\ \mu H$

$T_{avg,w} = 131\ °C$

$T_{avg,c} = 127\ °C$

$Ø_{bd} =$ 15 mm x2



13 kg

6:4

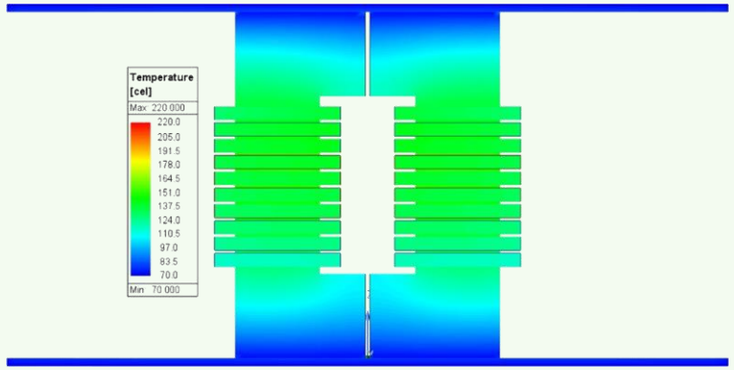
$L_{mag} = 31\ \mu H$

$L_{lk} \approx 2\ \mu H$

$T_{avg,w} = 131\ °C$

$T_{avg,c} = 120\ °C$

$Ø_{bd} =$ 11,25 mm x2



11,2 kg

6:4

$L_{mag} = 31\ \mu H$

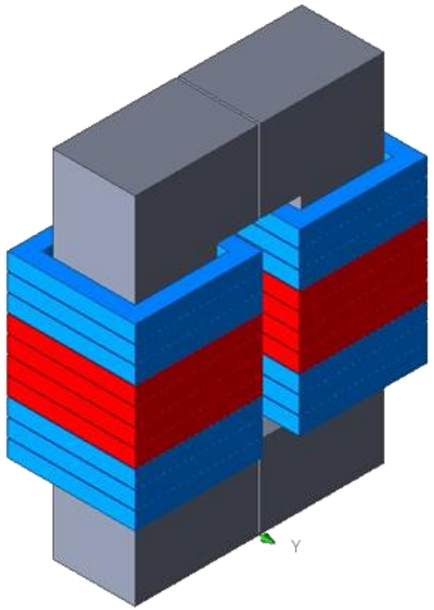
$L_{lk} \approx 2\ \mu H$

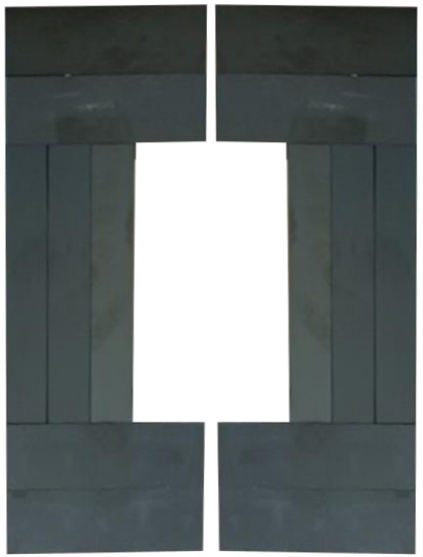
$T_{avg,w} = 135\ °C$

$T_{avg,c} = 118\ °C$

$Ø_{bd} =$ 9 mm x2

First prototype: Fabrication details





The core is made from **ferrite tiles**

$10\ kW/kg$

6:4

TORYTRANS

Primary winding perpendicular across secondary winding. Less losses.

First prototype: Characterization

$10\ kW/kg$

6:4

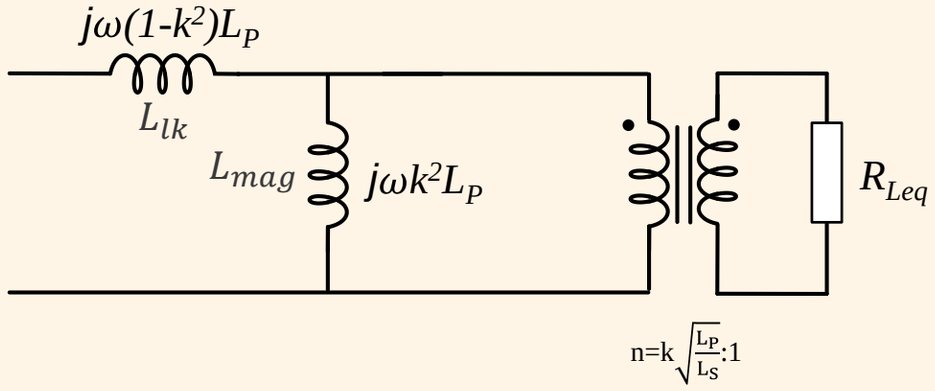
TORYTRANS

Transformer characterization:

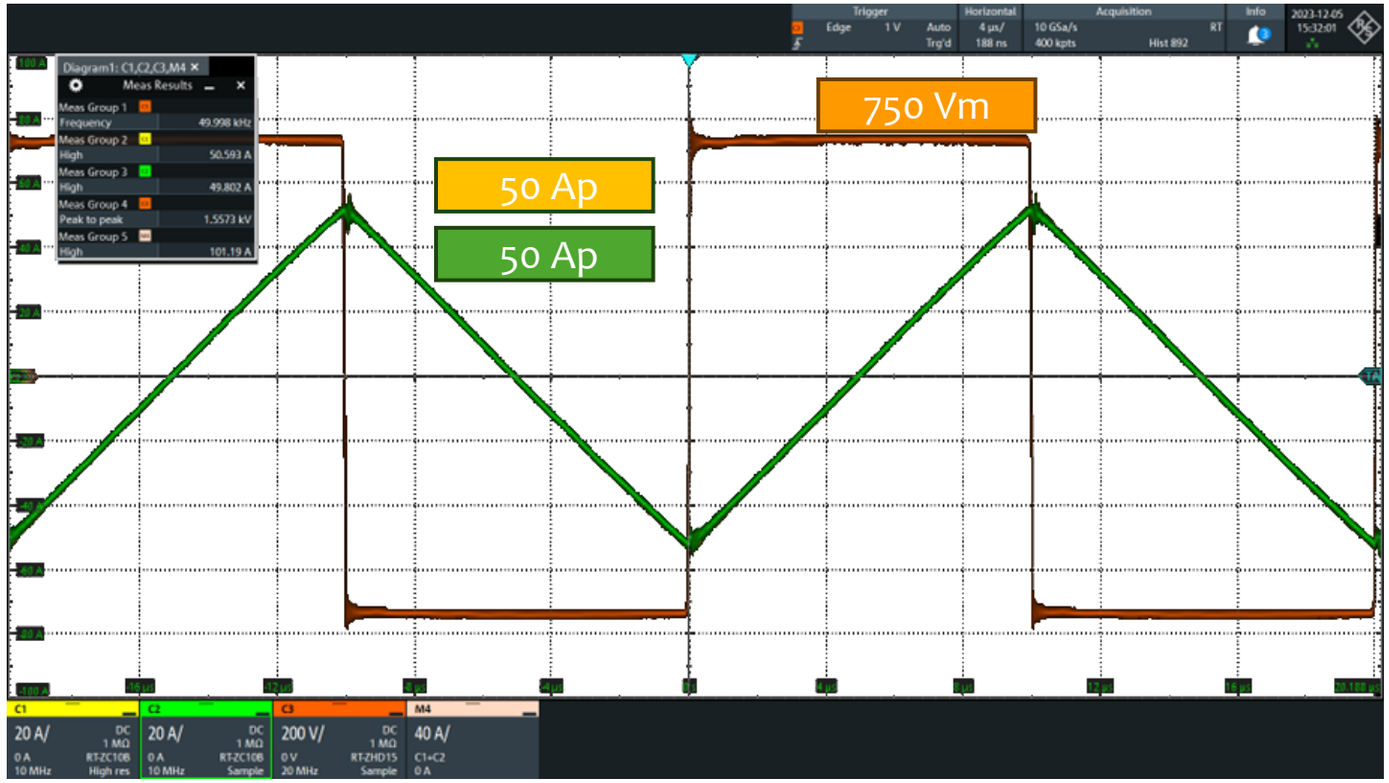
$$L = \begin{pmatrix} L_{11} & L_{12} \\ L_{12} & L_{22} \end{pmatrix} = \begin{pmatrix} 34{,}2\ \mu H & 22{,}74 \mu H \\ 22{,}74\ \mu H & 16{,}8 \mu H \end{pmatrix}$$

$$k = 94.89\%$$
$$\mathbf{L_{mag} = 30.8 \mu H}$$
$$\boldsymbol{L_{lk} = 3.4 \mu H}$$

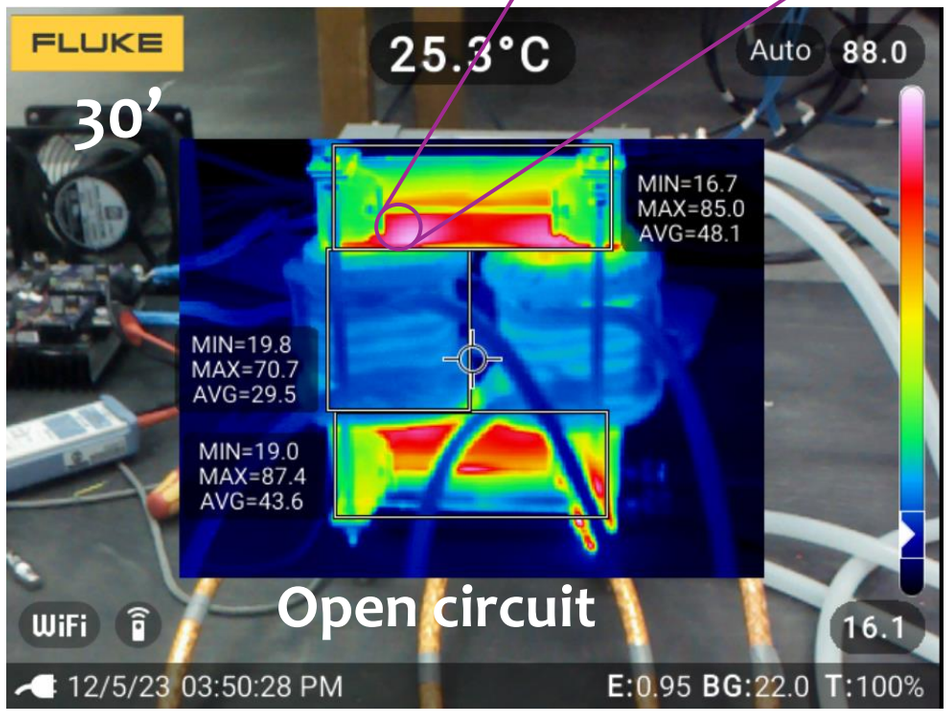
Parameter	Specification	Measured
Lmag	≈ 30 µH	30,8 µH
Llk	≈ 2 - 3 µH	3,4 µH



Test: Open-circuit (core losses)



Max 85°C



Thermal transfer conclusions:

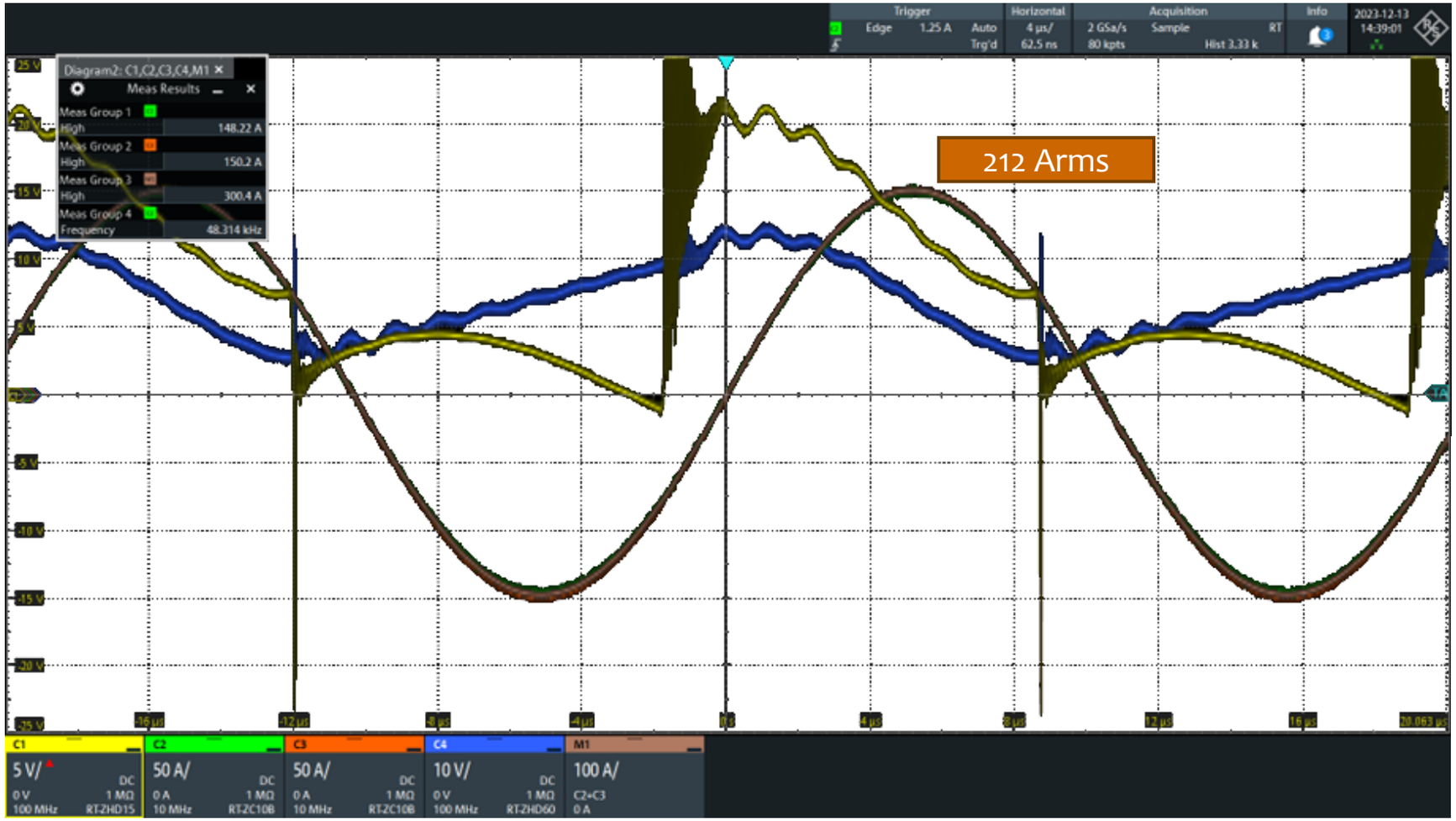
Between ferrite tiles. ✗ **Thermal Paste?**

Between heatsink and top ferrites. ✓

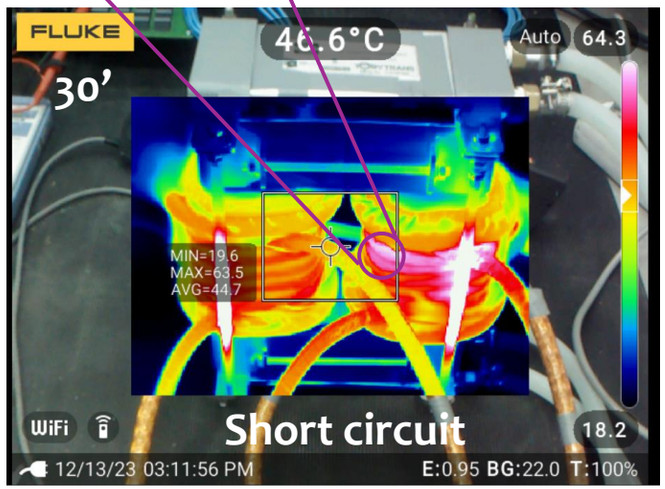
Max 81°C

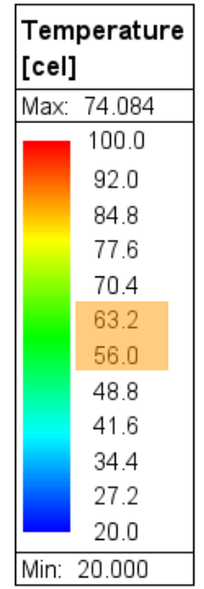
Almost no change.

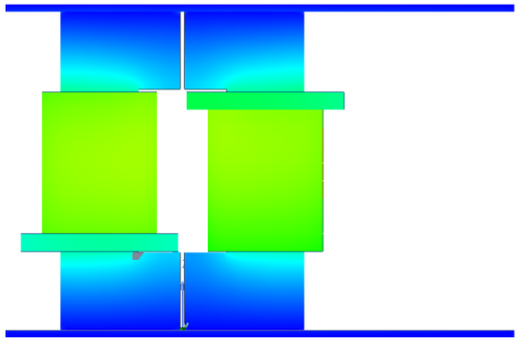
Test: Short-circuit (winding losses)



Max 63,5°C



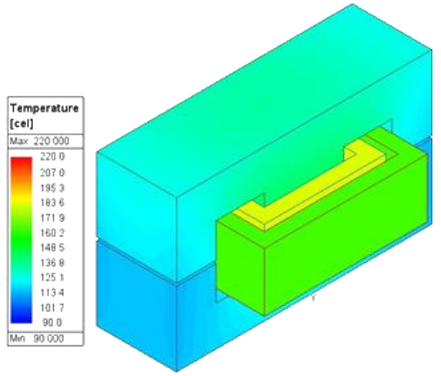




What have we learnt from the first prototype?

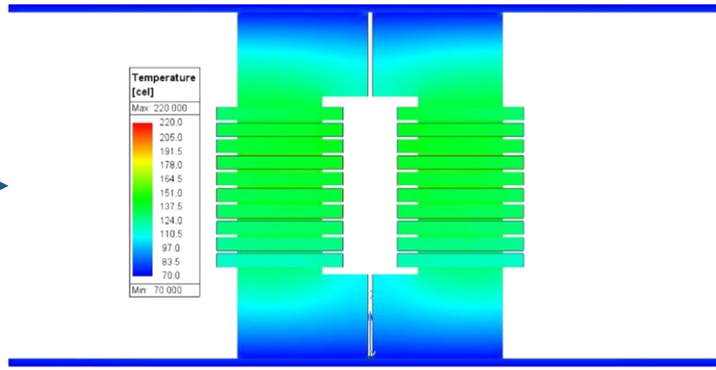
- ANN is a useful tool but E core **not suitable for this application.**
- Poor heat transfer between **ferrite tiles**.
- Due to Fringing effect the **metal structure** heats up.
- New iteration must have **less core stacking in vertical direction**.
- The prototype **performed as expected**.
- Parallel windings work.

14 kg

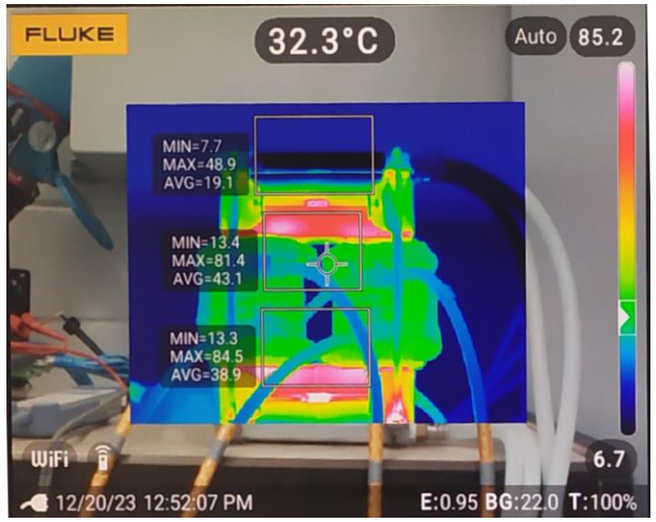


T_{max} ≈185°C

11,2 kg



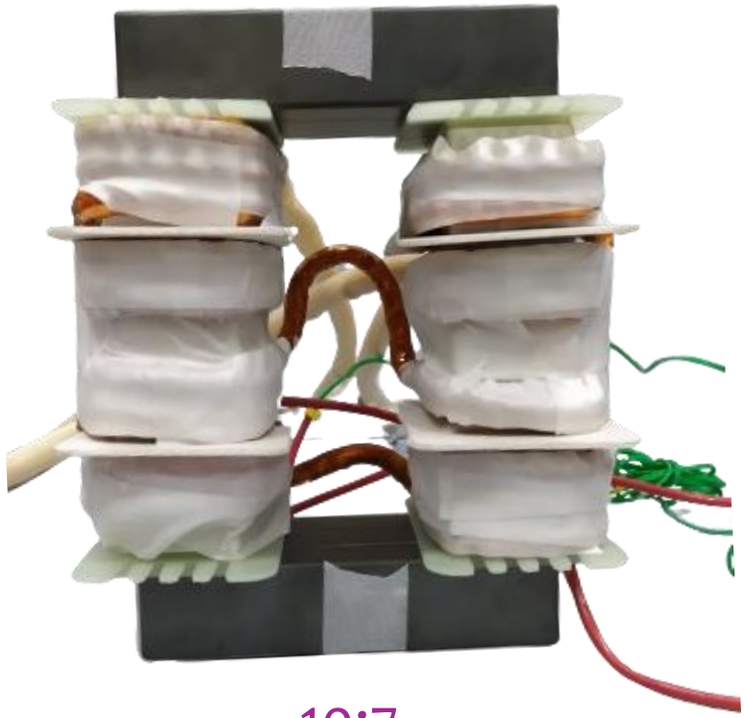
$T_{avg,w} = 135\ °C$



Second Iteration

Second prototype

$26\ kW/kg$



10:7

All turns in series !

$B_{peak} = 230\ mT$

$150\ mT\ (1^{st} Prototype)$

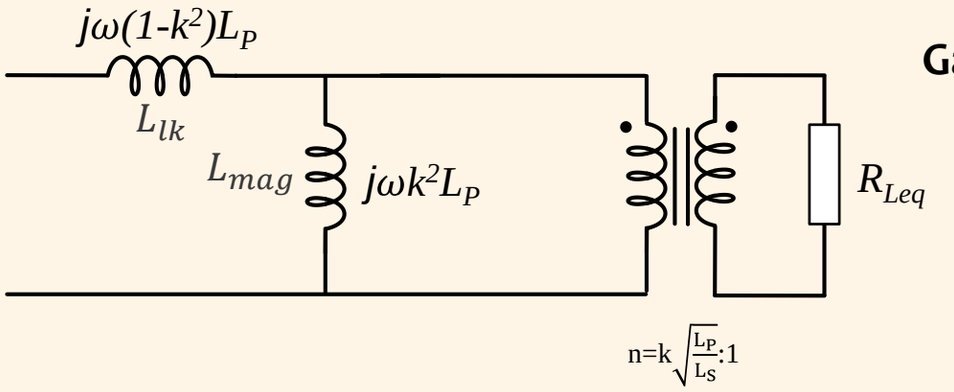
Transformer characterization:

$$L = \begin{pmatrix} L_{11} & L_{12} \\ L_{12} & L_{22} \end{pmatrix} = \begin{pmatrix} 36{,}4\ \mu H & 21\ \mu H \\ 21\ \mu H & 14{,}8 \mu H \end{pmatrix}$$

$$k = 89{,}84\%$$

$$\mathbf{L_{mag} = 30\ \mu H}$$

$$\boldsymbol{L_{lk} = 6.4 \mu H}$$

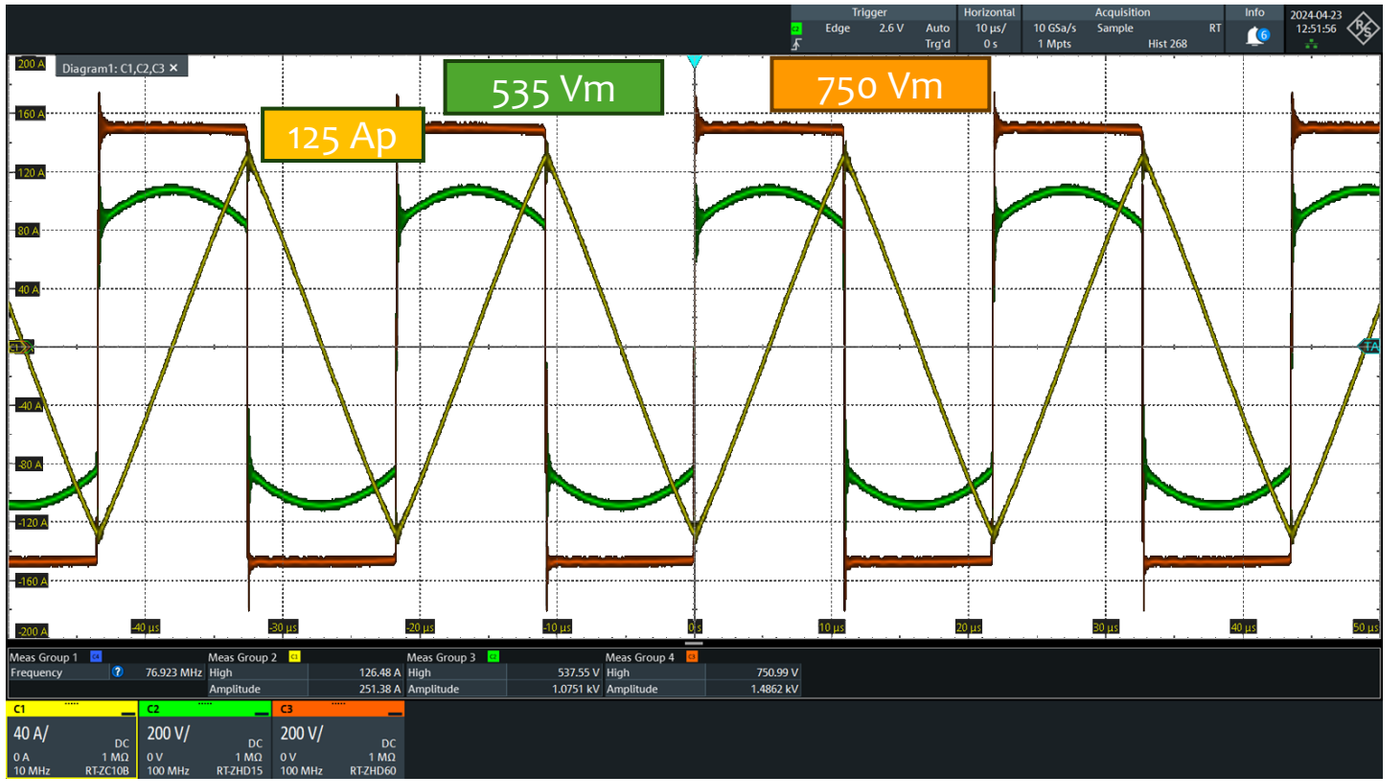


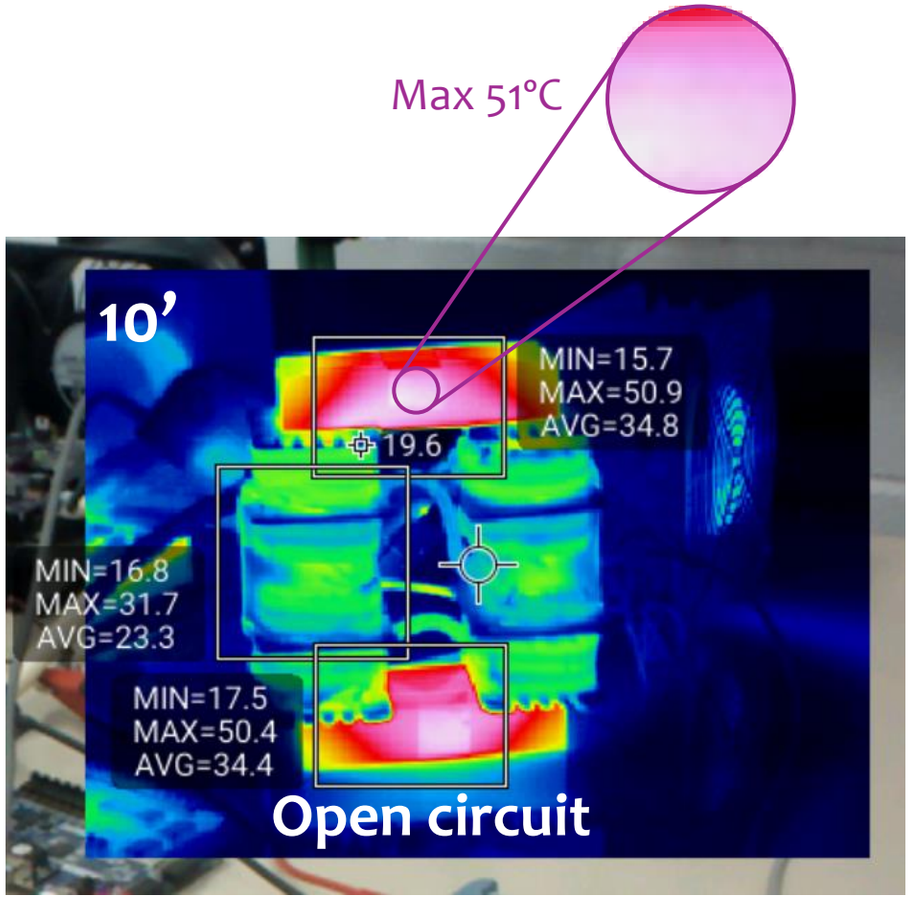
Parameter	Specification	Measured
Lmag	≈ 30 µH	30 µH
Llk	≈4,5 µH	6,4 µH

Leakage inductance a bit higher.

Gap needs to be **readjusted.**

Test: Open-circuit (core losses)





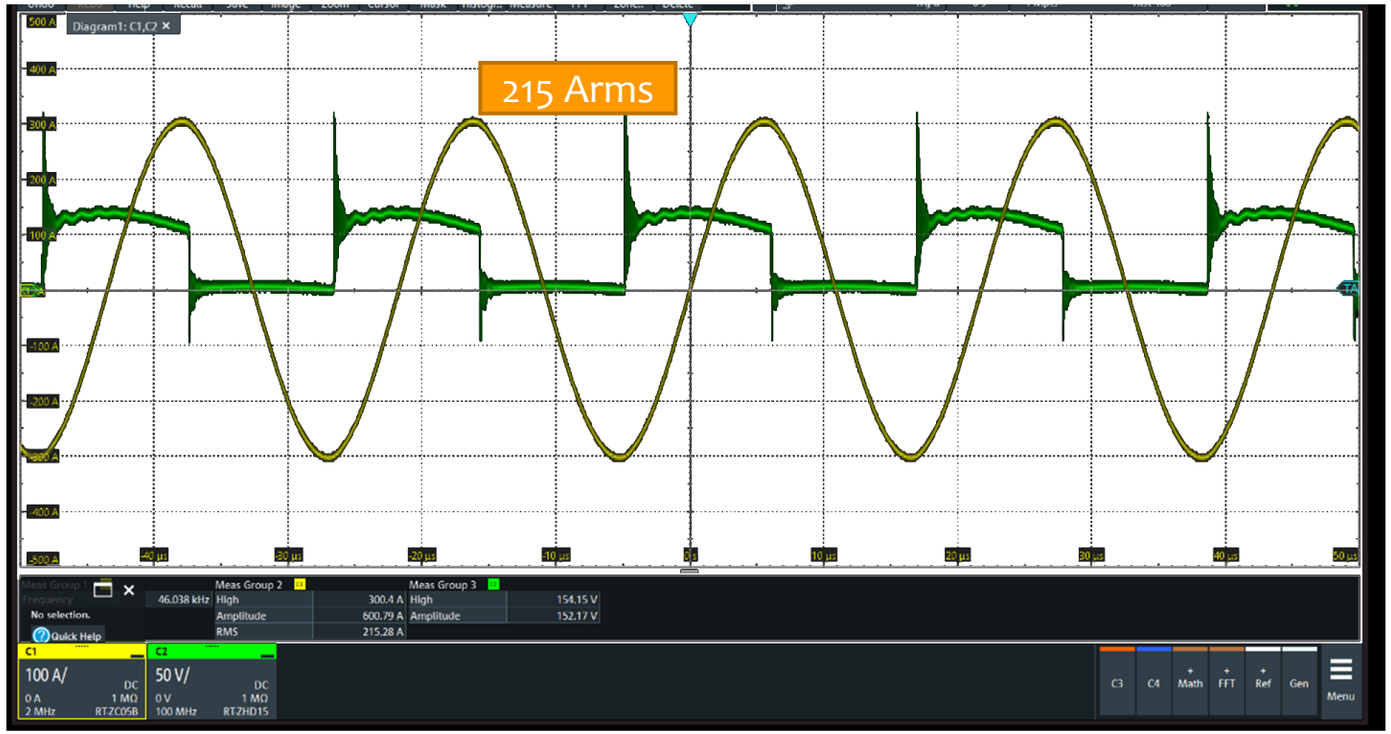
* Without cooling

Thermal transfer conclusions:

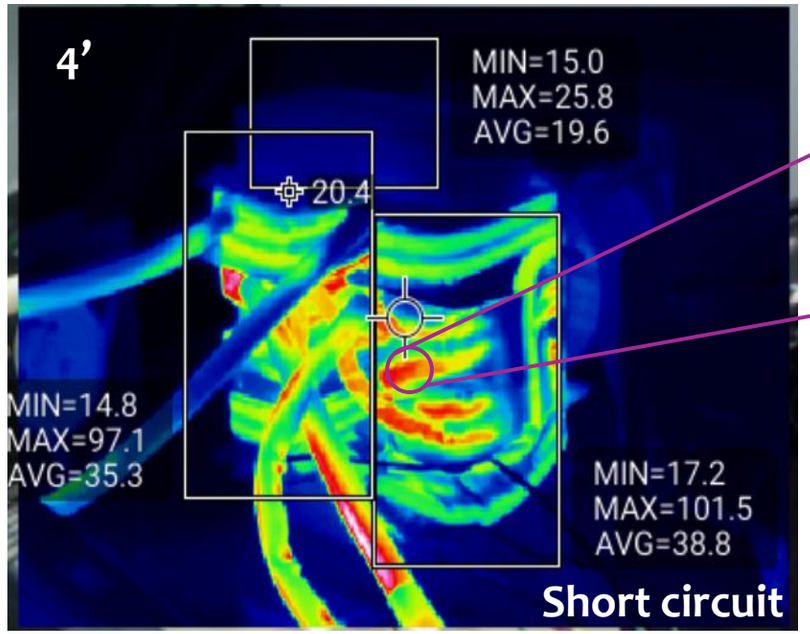
Uniform heat distribution in the core

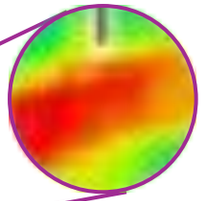
The field path can be clearly seen. Could corners be removed to reduce weight?

Test: Short-circuit (winding losses)



*Forced convection



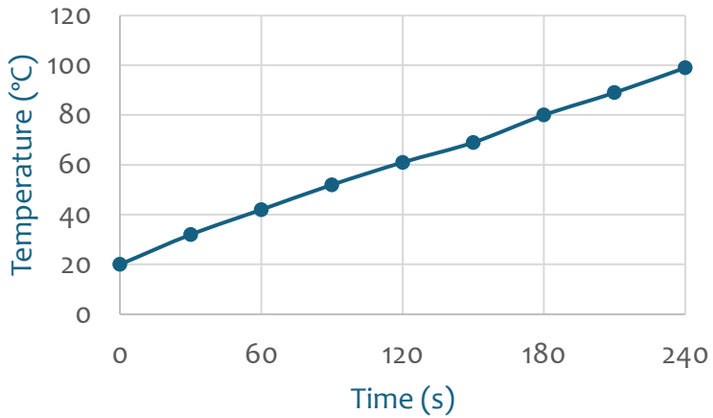


Max 102°C

Transformer is going to be embbeded in an aluminum case with high termal conductivity potting.

More tests must be done with the case.

Winding hot spot vs time



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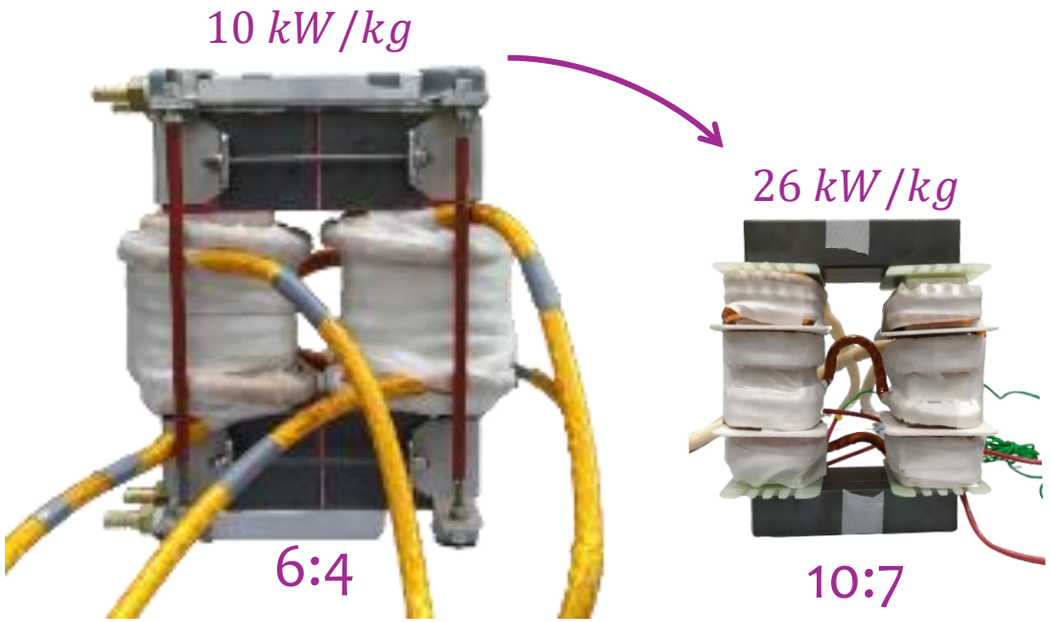
Summary and Conclusions

POLITÉCNICA

Summary and Conclusions



- **ANN** has been useful for the first design steps and determine that **E core** is not suitable for this application.
- **Ferrite tiles** stacking add complexity to the fabrication. Heat transfer between them is not good even if thermal paste is used.
- **Commercial core** stacking gives better manufacturability. Lower fabrication cost.
- U core stacking resulted in a **uniform and better heat distribution**.
- Both transformer prototypes performed as expected.

Thank you!

- Andrés Ferrer López

- **Coordinators**
  - Alberto Delgado Expósito
  - Miroslav Vasić