Scaled Prototype of a Redundantly Fed, Gearless PMSM Wind Generator with Tooth Coil Winding and Solid Rotor Yoke

VDE Antriebssysteme 2021

TECHNISCHE UNIVERSITÄT DARMSTADT

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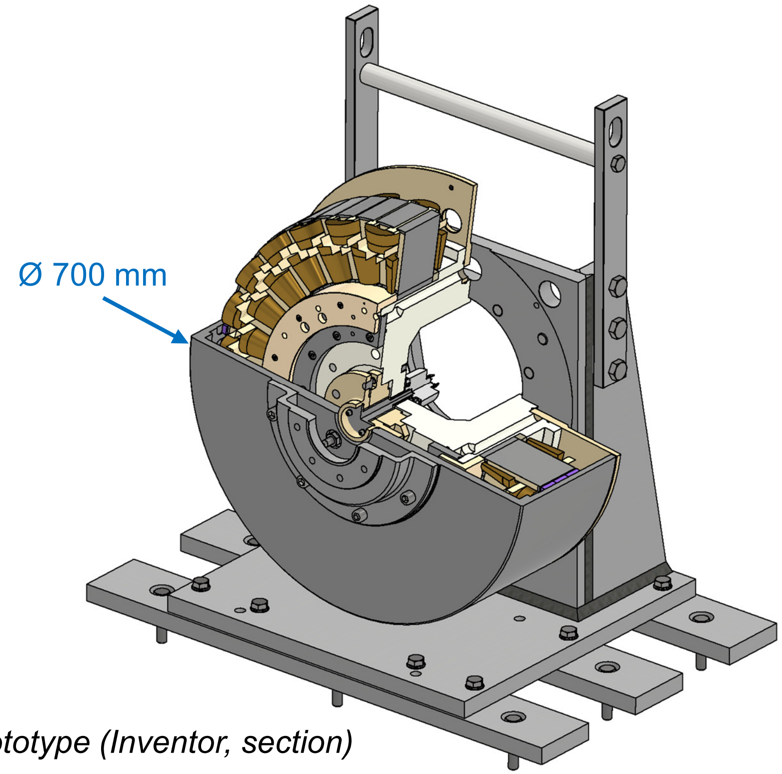

Prototype (Inventor, section)

Agenda

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- Introduction
- FEM Model and Results
- Thermal Simulation
  - Hybrid Model
  - Conductor Repositioning
  - Excess Temperature - End Winding
  - Results
- Conclusion

Introduction:
Gearless PMSM Wind Generators

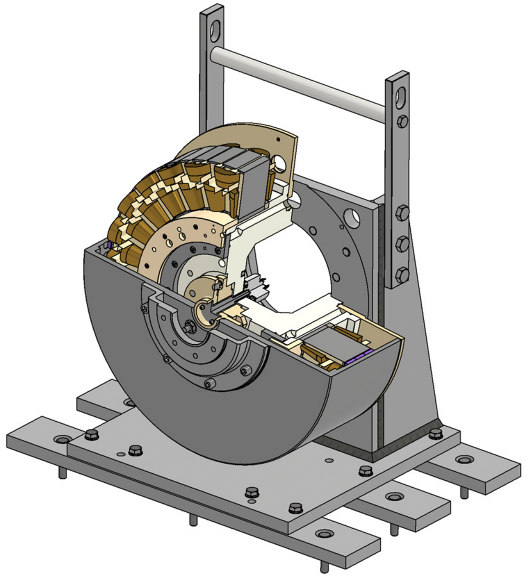
Wind Generator

[*Siemens Gamesa*]

Scaling

- Modular manufacturing
- Verify rotor loss models

Prototype



$q = 2/5$; $2p = 40$; $Q = 48$

$n_N = 60\ \text{min}^{-1}$ / $120\ \text{min}^{-1}$; $M_N = 2800$ Nm

Inner water jacket ; form-wound coils

- Outer rotor design: Solid rotor yoke
- Tooth coil winding (q = 2/5)
- Redundancy operation (sectorial stator feeding)

Stator field harmonics → Rotor eddy currents

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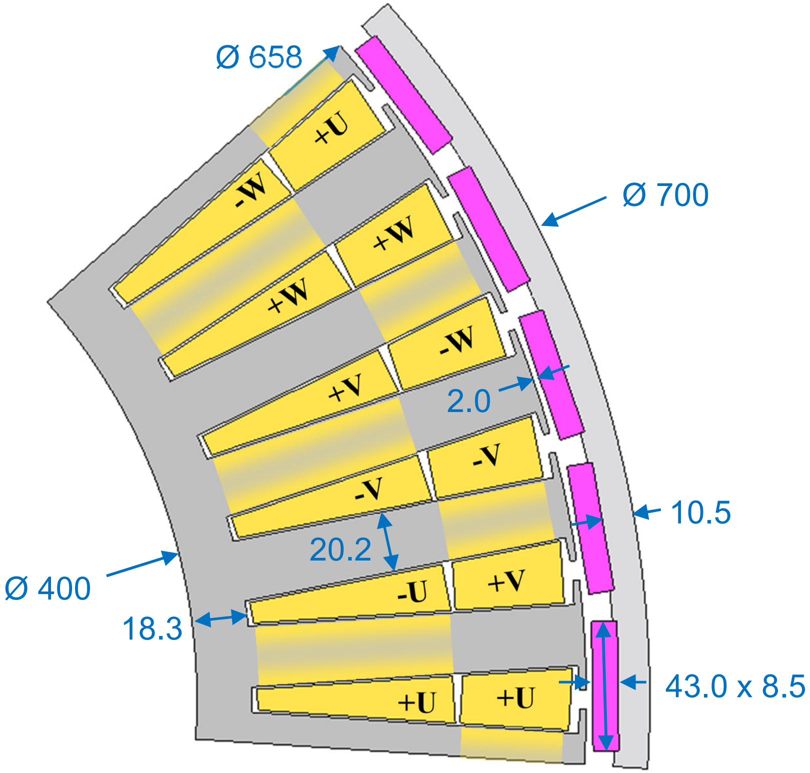
Demonstrator:
FEM Model and Results

2D *JMAG* Model (dimensions in mm)



axial stack length 90 mm

Simulation Results for Nominal Operation

Speed n_N, stator frequency f_s	60 min^{-1}, 20 Hz
Torque M_N	2828 Nm
Mechanical power P_{mech}	17.77 kW
Total losses P_d	2895 W (100 %)
Copper losses $P_{Cu,AC}$	2487 W (86 %)
Stator iron losses $P_{Fe,s}$	222.7 W (8 %)
Eddy current losses: Magnets P_{mag}	40.1 W (1 %)
Eddy current losses: Rotor yoke P_{rot}	145.3 W (5 %)
Stator current $I_{s,1}$	35.01 A
Stator voltage $U_{s,1}$	190.4 V
Efficiency	83.7 %
$\cos(\varphi_1)$	0.74 (ind.)

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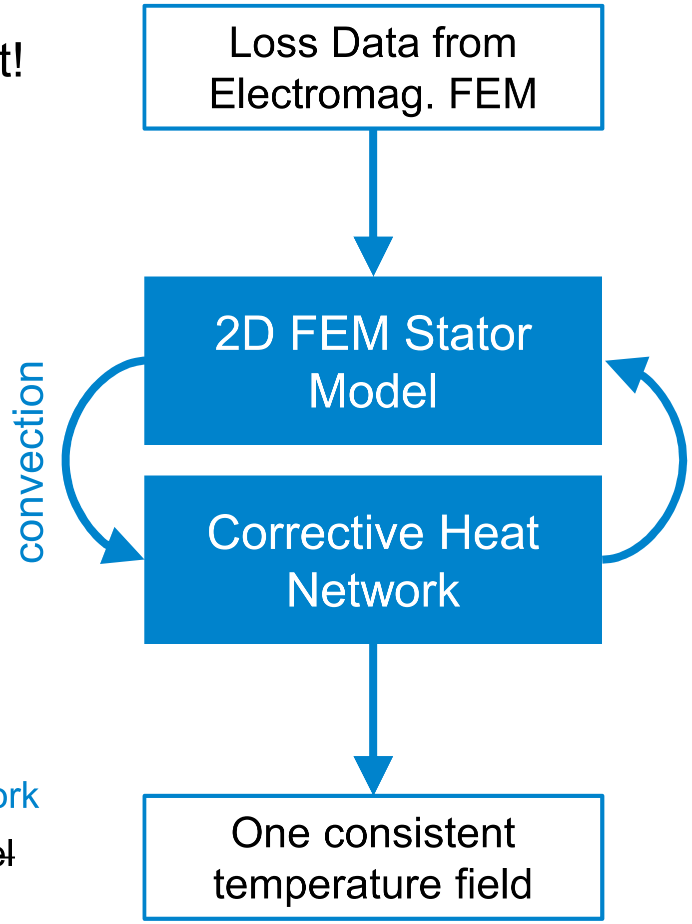
Thermal Modelling:
Motivation and Hybrid Model

- Stator winding temperature? Average and hot spot!
  - Deep slots and round wire winding
  - Inhomogeneous temp. distribution over winding
  - Complex but well known geometry
  - Model: 2D FEM (*FEMM*)
- Rotor magnet temperature?
  - Rotor losses and convective heat from stator
  - Dominated by convection heat transfer
  - Options:
    A) Fast analytical HTC calculation and simple thermal network
    ~~B) Precise HTC calculation from CFD and network/3D model~~



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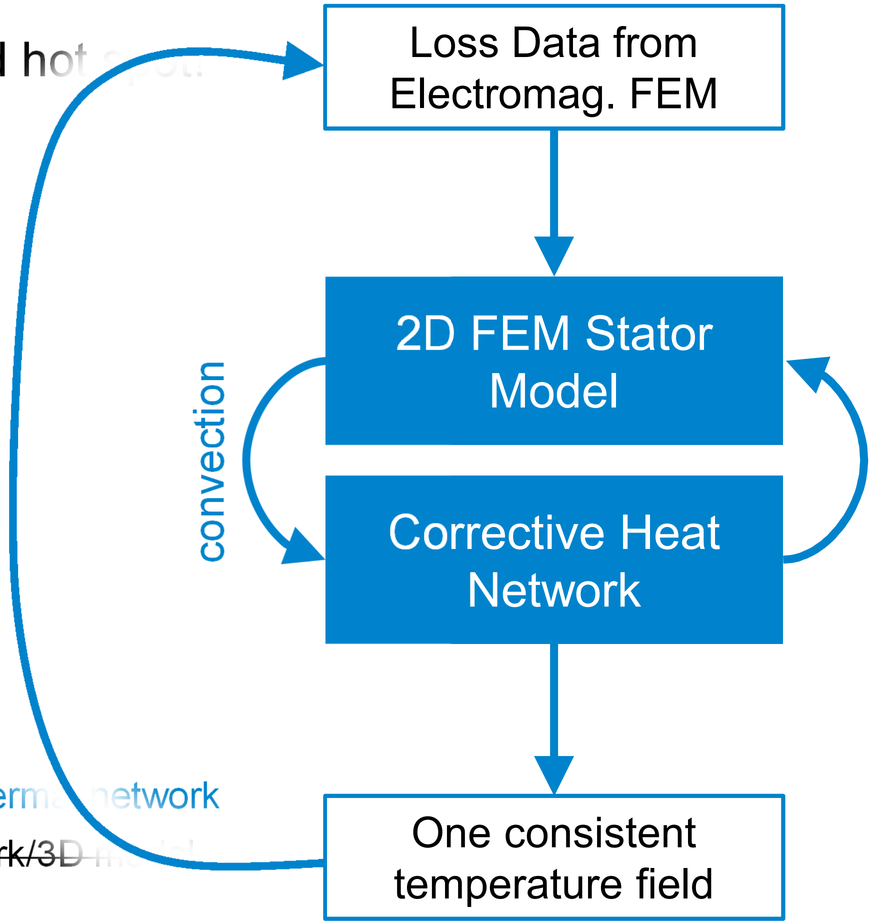
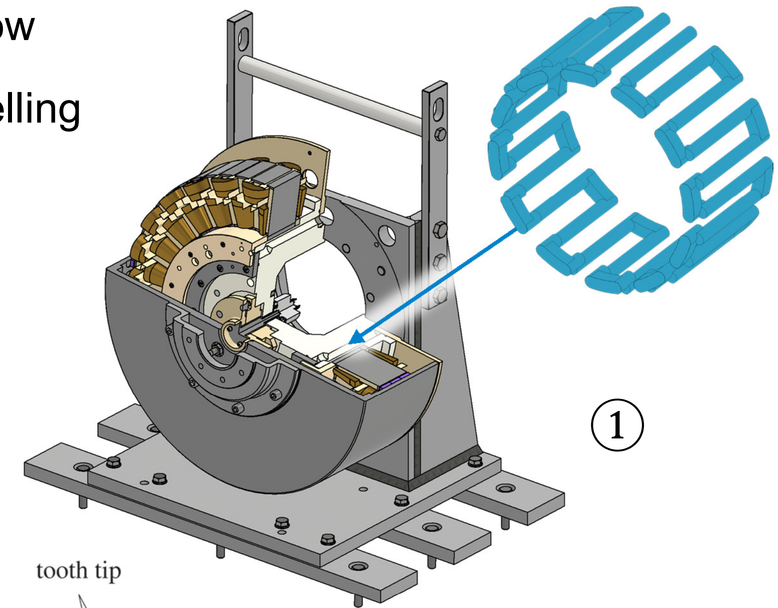
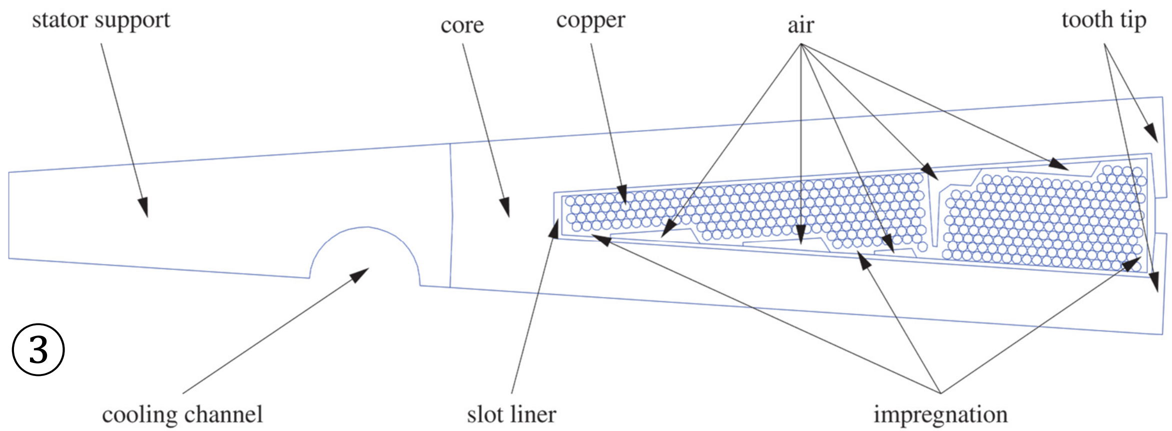
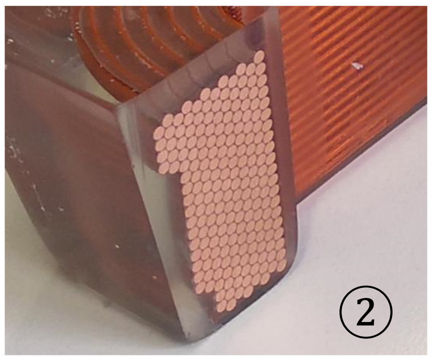


Thermal Modelling:
Stator – Cross Sectional 2D FEM

- ① Inner water jacket: Dominant transversal heat flow
- ② Prefabricated orthocyclic Winding: Precise Modelling
- ③ Cross sectional FE-Model (*FEMM*)
  - \+ Precision
  - \+ Modelling effort
  - \- all axial effects are neglected







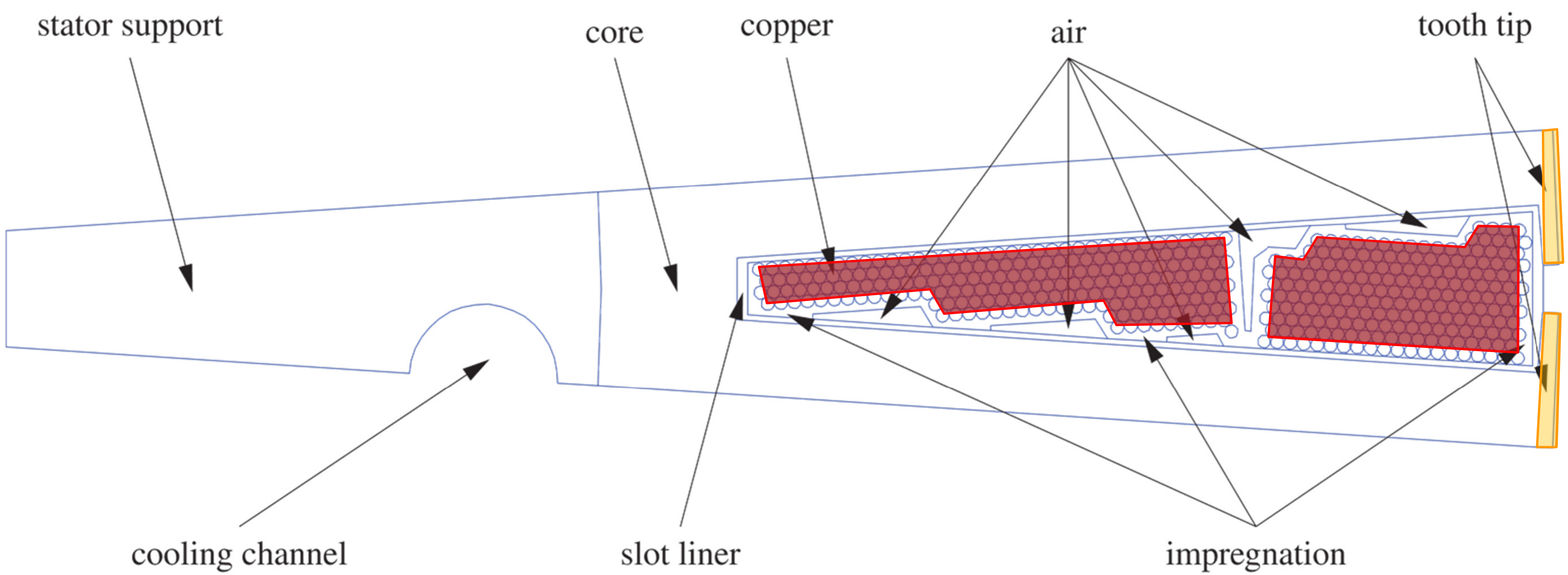
Thermal Modelling:
Stator – Cross Sectional 2D FEM: Coupling

- Heat from winding overhang to inner air

  Adjustment of heat generation in copper: 

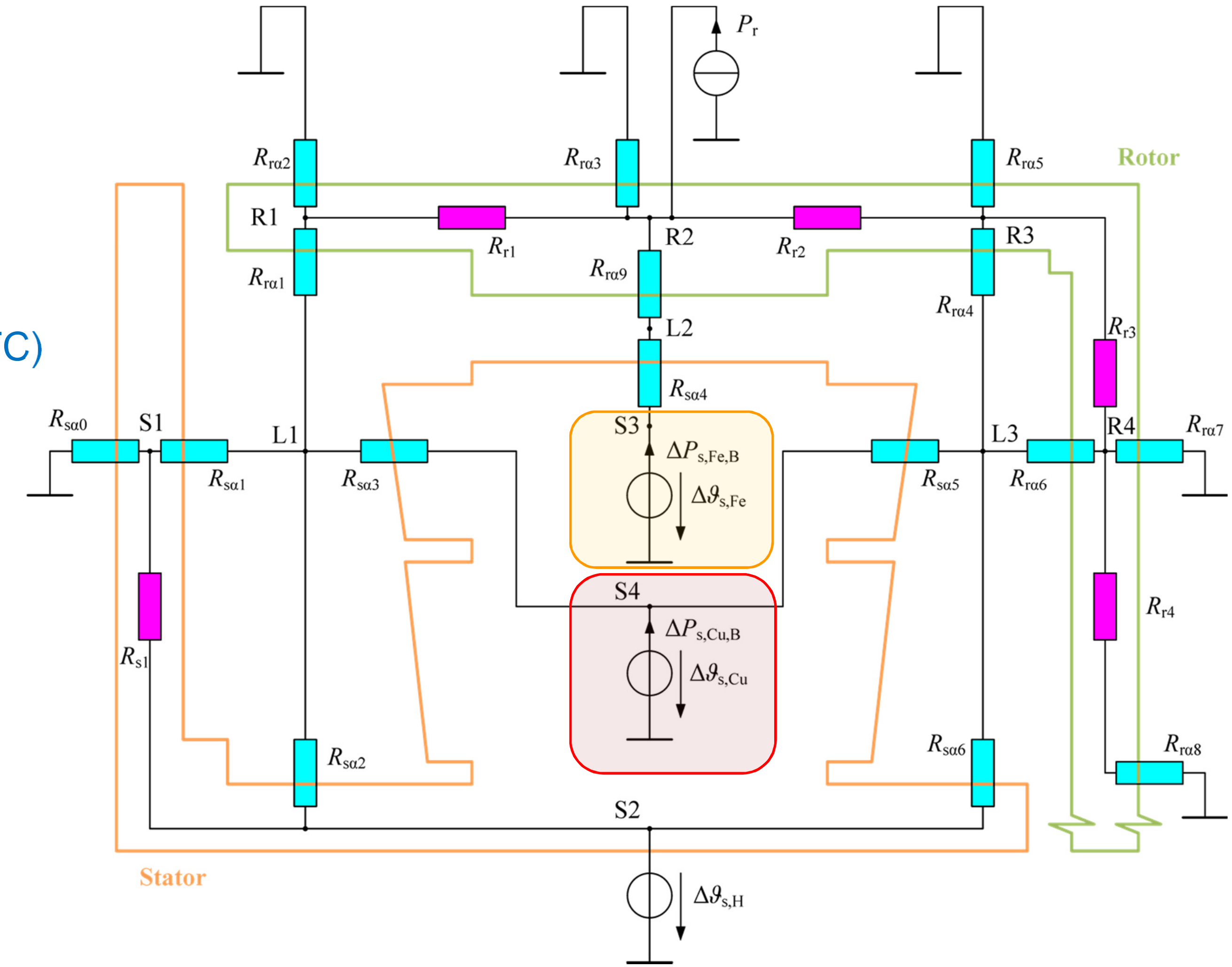
- Heat from stator tooth tips to air gap

  Adjustment of heat generation in tooth tip: 



Thermal Modelling:
Corrective Thermal Network

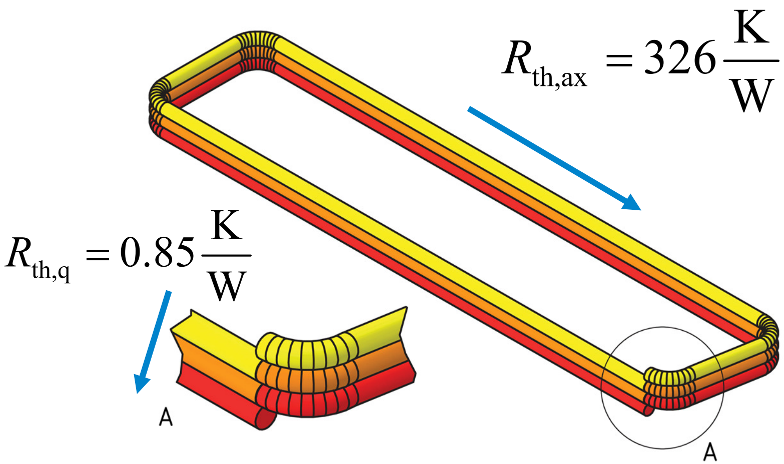
- Longitudinal section
- Thermal conduction
- Convection (Analytical HTC)
- Coupled to stator via:
  - Stator tooth tips
  - End winding



Thermal Modelling:
Assessment of Axial Effects

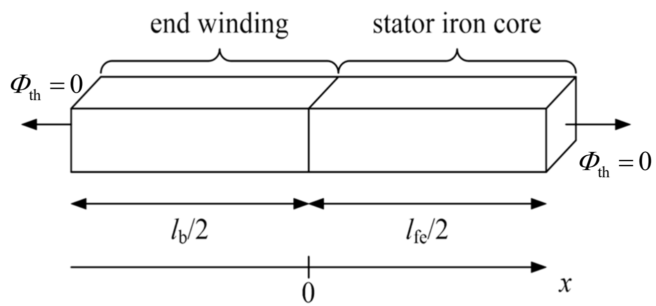
Repositioning of Wire from Turn to Turn

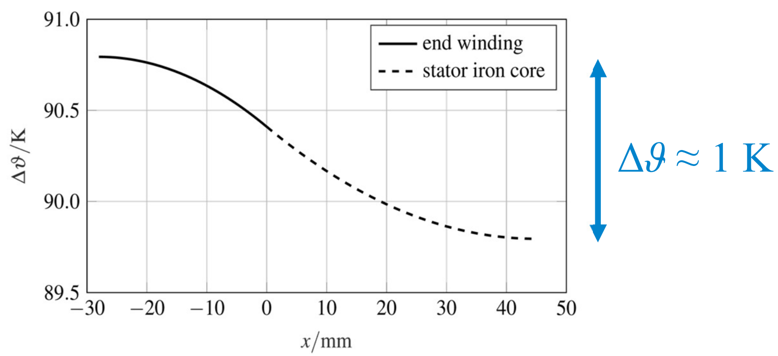
- Additional heat flow path along the wire
- Analytical assessment:
  Negligible additional heat resistance



Excess Temperature in End Winding

- End winding outside of cooled core
- Assuming thermal insulation
- Analytical 1D bar model: 1 K excess temp. rise

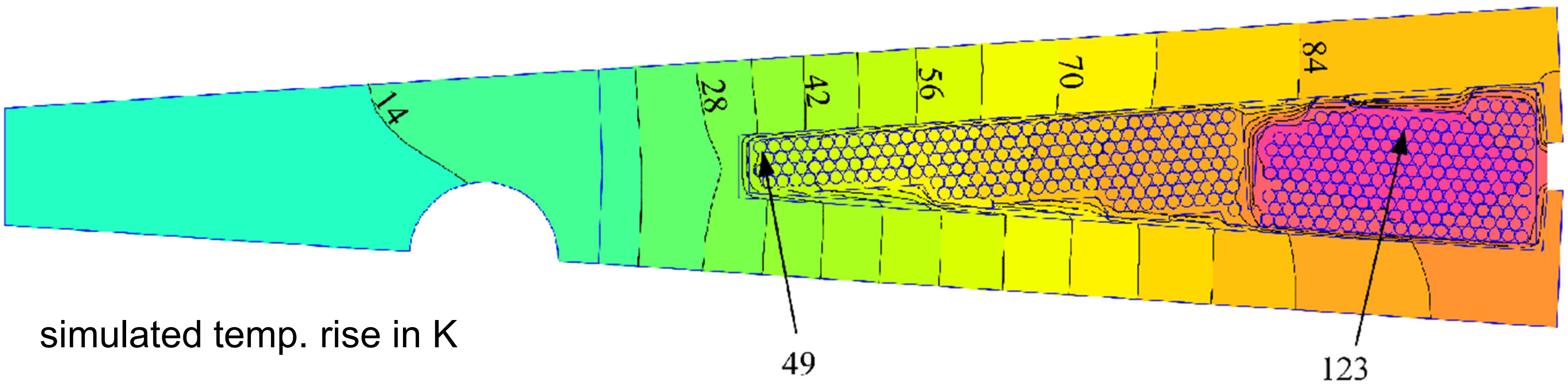




Thermal Simulation of Nominal Operation:
Coupling of Stator and Rotor – Results (I)

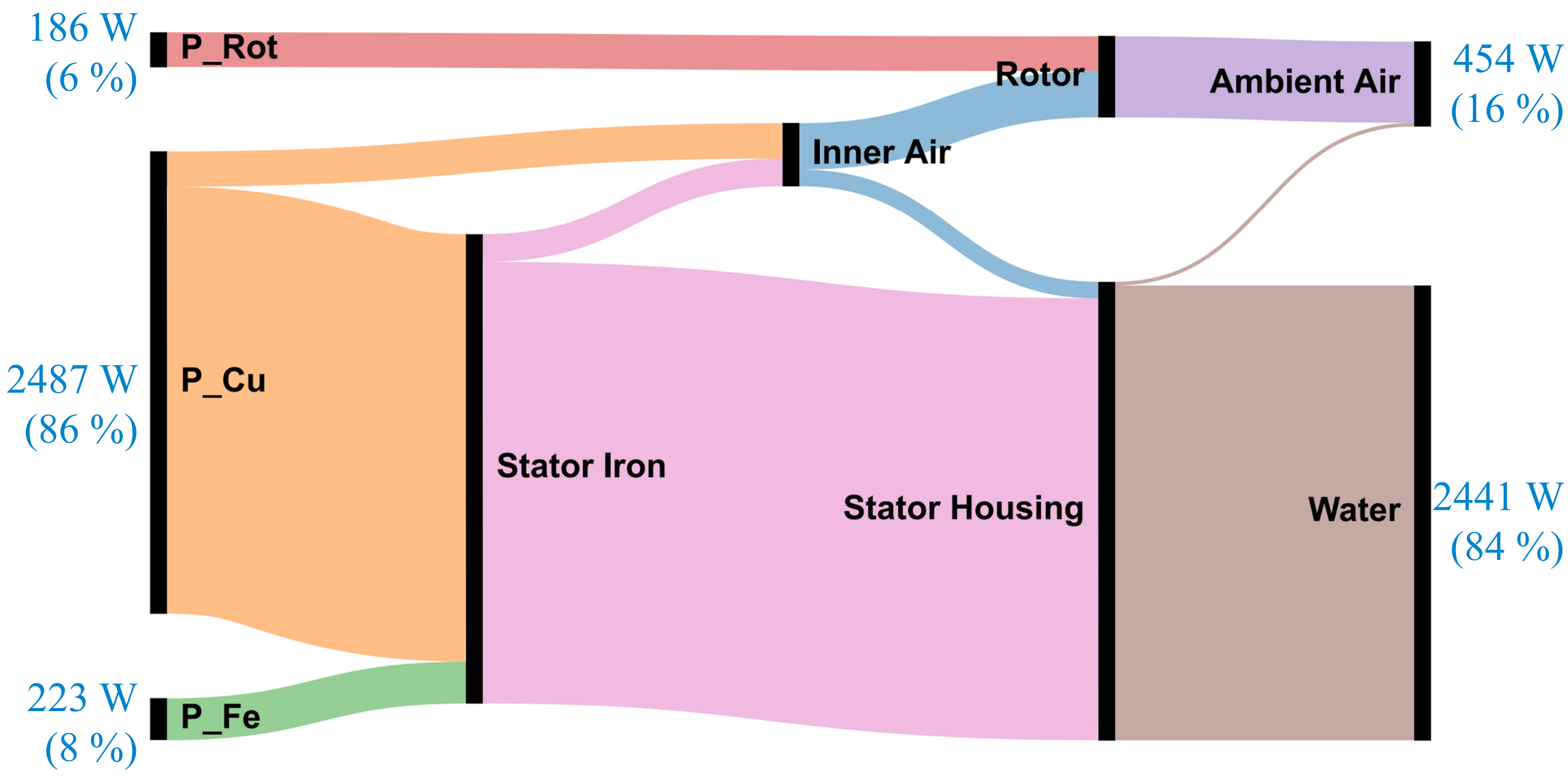
- Deep slots → inhomogeneous temp. distribution
- Utilization of insulation class 180 (H)

Amb. temp.	Avg. temp. rise coolant	HTC cooling channel	Avg. copper temp. rise	Max. copper temp. rise	Min. copper temp. rise	Avg. stator core temp. rise	Tooth tip temp. rise	Avg. stator support temp. rise
40°C	7 K	2282 $W/(m^2{\cdot}K)$	**100 K**	**123 K**	**49 K**	64 K	96 K	14 K



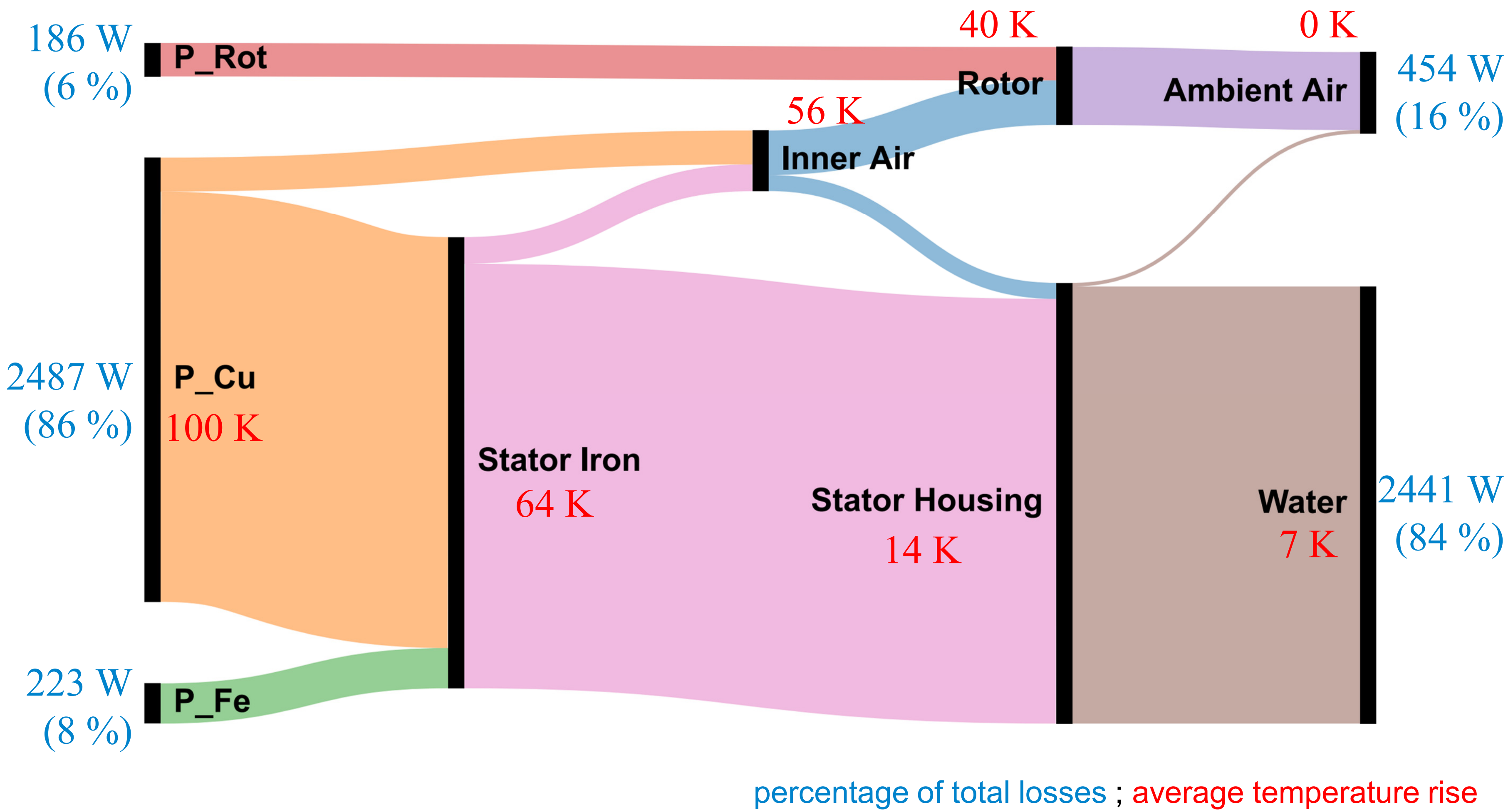
simulated temp. rise in K

Thermal Simulation of Nominal Operation:
Coupling of Stator and Rotor – Results (II)



percentage of total losses

Thermal Simulation of Nominal Operation:
Coupling of Stator and Rotor – Results (II)



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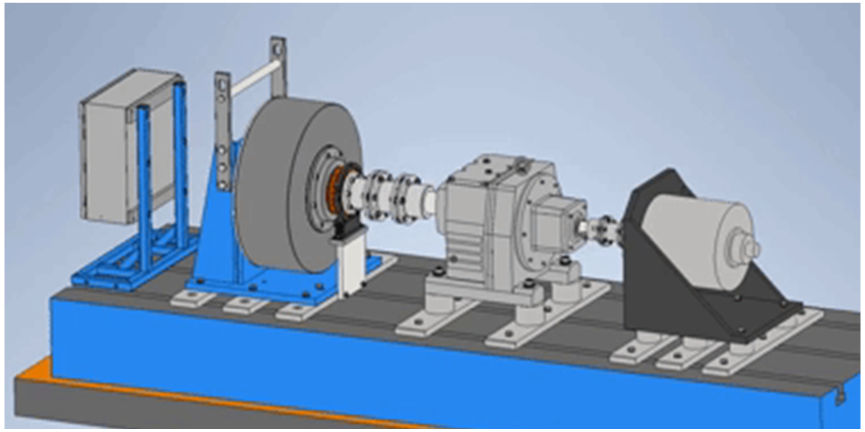
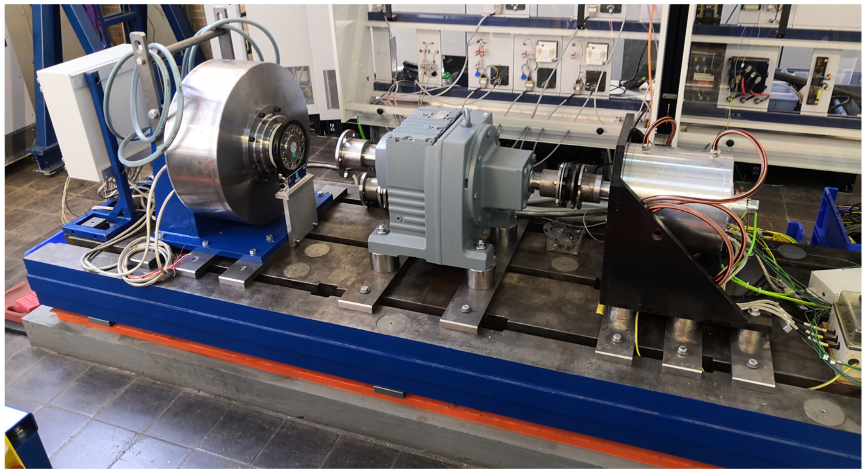
Conclusion

- FEM loss results
- Thermal modelling and results
- Discussion of axial side effects

- Deep slots (111 mm) combined with water jacket cooling:
- Copper: 49 K … 123 K temp. rise
- Magnets: 40 K temp. rise
- Significant heat flow from stator to rotor

- Outlook: Experimental temp. measurements on test bench

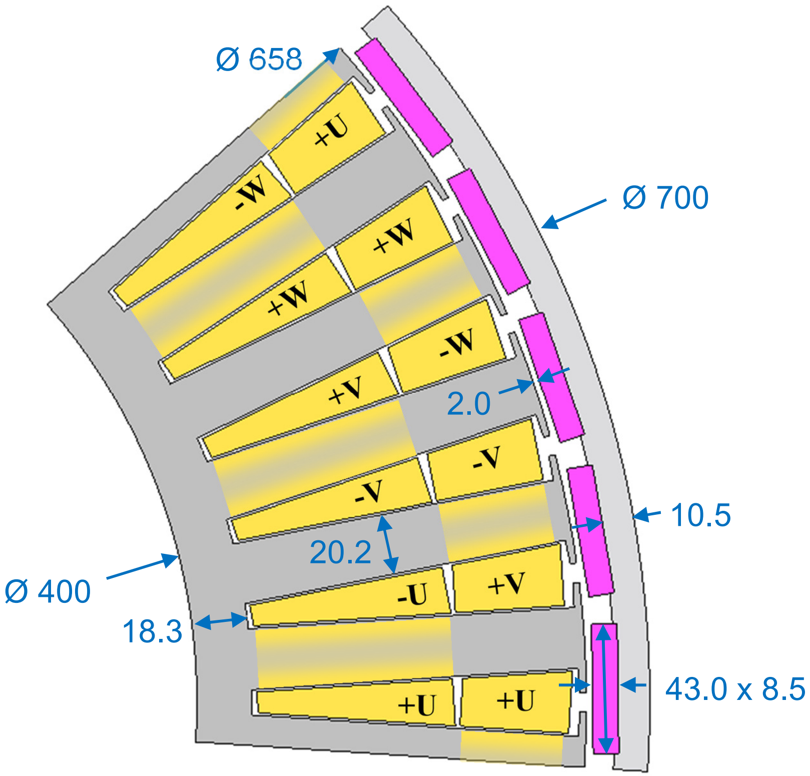




Thank you for your attention!

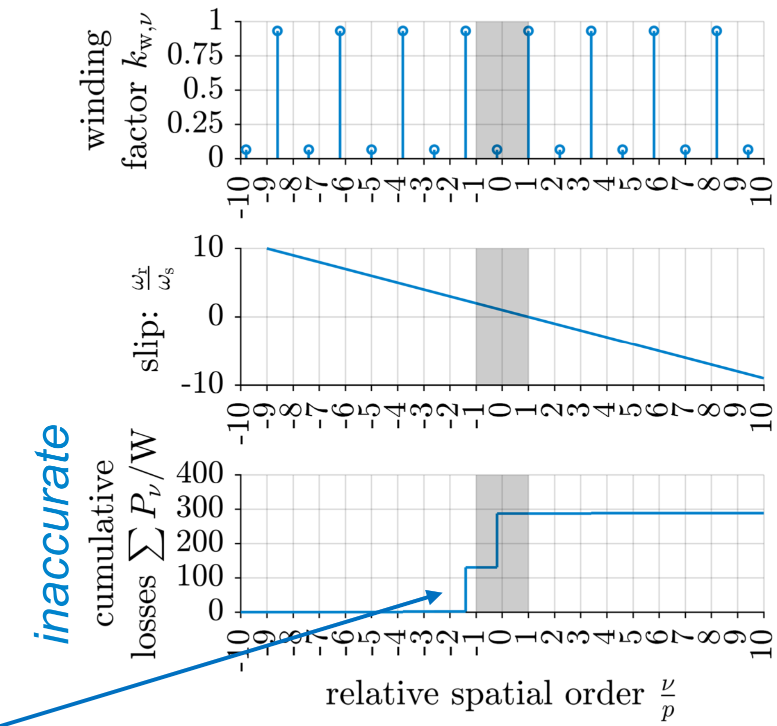
Demonstrator:
FEM Model and Meshing (I)

2D *JMAG* Model (dimensions in mm)



Analytical rotor yoke eddy current calculation

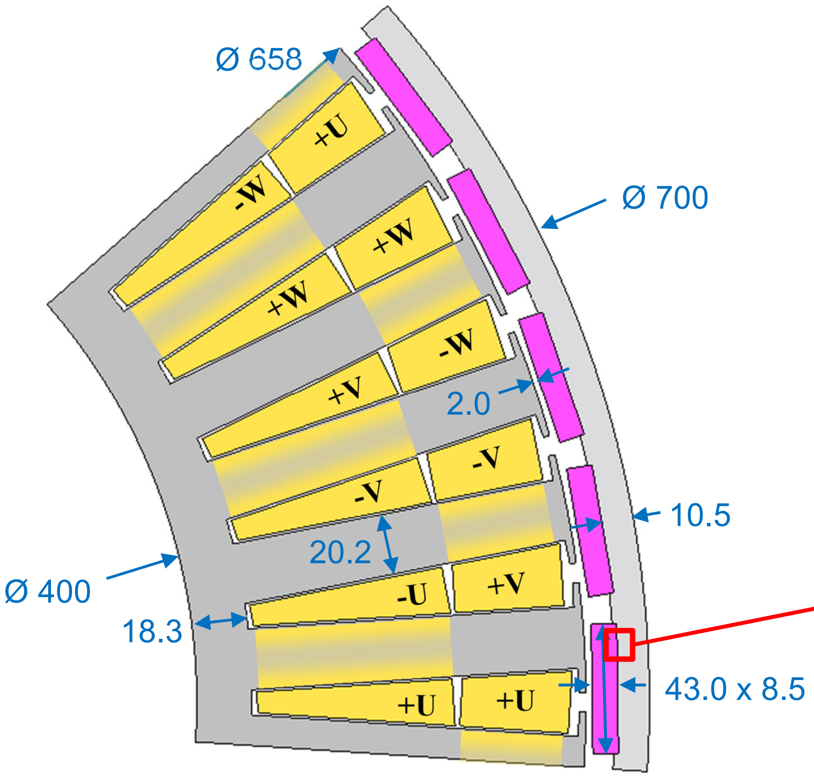
$A = 823\ \mathrm{A_{eff}/cm}$; $\kappa_{\mathrm{rot}} = 6.29\ \mathrm{MS/m}$; $\mu_{\mathrm{r,rot}} = 250$



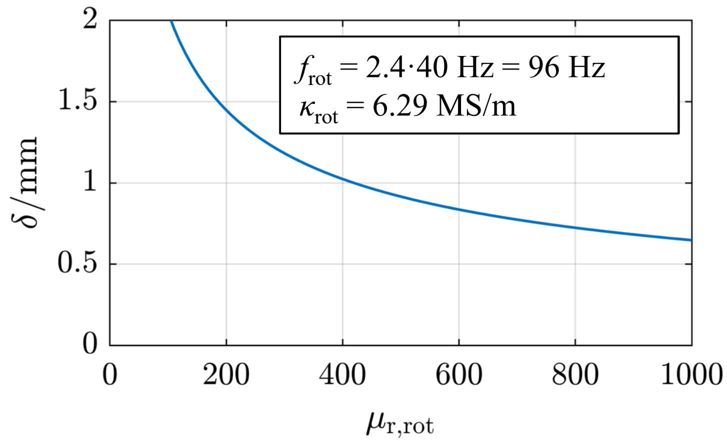
critical harmonic: $\nu/p = -1.4$ with $s = 2.4$

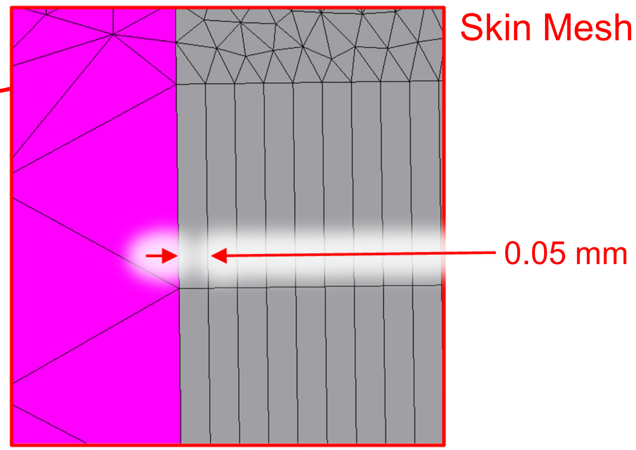
Demonstrator:
FEM Model and Meshing (II)

2D *JMAG* Model (dimensions in mm)



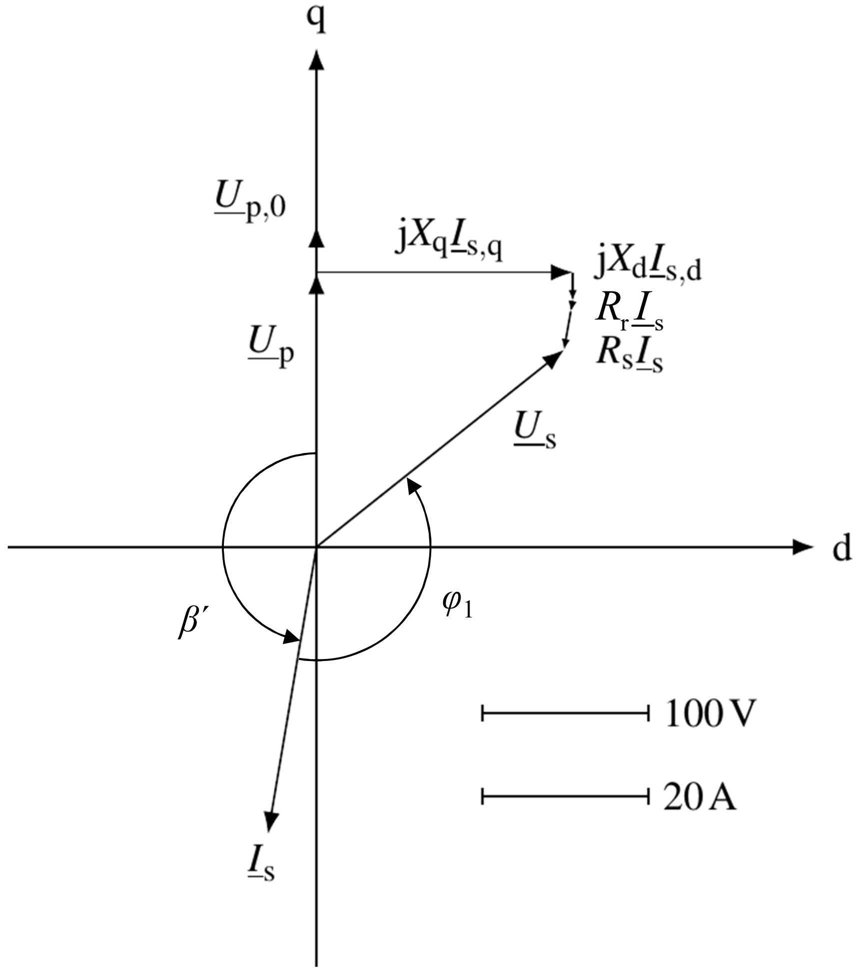
Rotor Skin Penetration Depth





Demonstrator:
Nominal Operation: Electromagnetical Simulation

Speed n_N, stator frequency f_s	60 min^{-1}, 20 Hz
Torque M_N	2828 Nm
Mechanical power P_{mech}	17.77 kW
Total losses P_d	2895 W (100 %)
Copper losses $P_{Cu,AC}$	2487 W (86 %)
Stator iron losses $P_{Fe,s}$	222.7 W (8 %)
Eddy current losses: Magnets P_{mag}	40.1 W (1 %)
Eddy current losses: Rotor yoke P_{rot}	145.3 W (5 %)
Stator current $I_{s,1}$	35.01 A
MTPA: Current angle β'	170°
Stator voltage $U_{s,1}$	190.4 V
Efficiency	83.7 %
$\cos(\varphi_1)$	0.74 (ind.)
Torque ripple	1.2 %

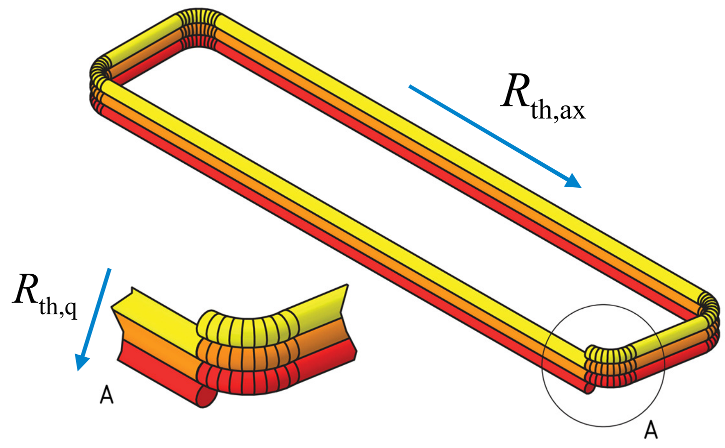


Tab. and phasor diagram:
2D, nonlinear, transient FEM (*JMAG*)

Thermal Modelling:
Repositioning of Wire from Turn to Turn

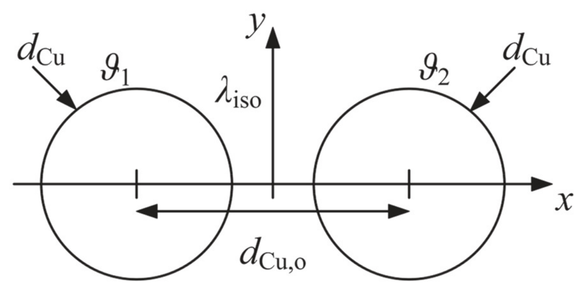
- Wire repositioning adds a thermal path for cooling with $R_{\mathrm{th,ax}} \rightarrow$ negligible compared to $R_{\mathrm{th,q}}$

$$R_{\mathrm{th,ax}} = \frac{l_{\mathrm{wdg}}}{\lambda_{\mathrm{Cu}} \cdot \frac{\pi}{4} \cdot d_{\mathrm{Cu}}^{\,2}} = 325.5\,\frac{\mathrm{K}}{\mathrm{W}}$$



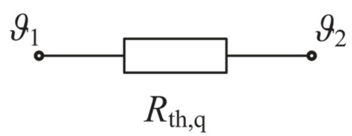
- Transversal main path for cooling with $R_{\mathrm{th,q}}$

$$R_{\mathrm{th,q}} = \frac{1}{\pi \cdot \lambda_{\mathrm{iso}} \cdot l_{\mathrm{wdg}}} \cdot \ln\left(\frac{d_{\mathrm{Cu,o}}}{d_{\mathrm{Cu}}} + \sqrt{\left(\frac{d_{\mathrm{Cu,o}}}{d_{\mathrm{Cu}}}\right)^2 - 1}\right) = 0.85\,\frac{\mathrm{K}}{\mathrm{W}}$$



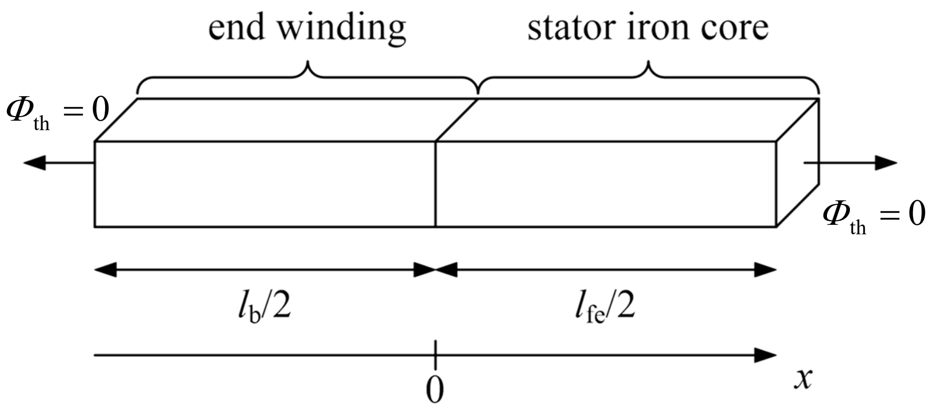
$$\lambda_{\mathrm{iso}} = 0.4\,\mathrm{W/(m \cdot K)} \quad \lambda_{\mathrm{Cu}} = 390\,\mathrm{W/(m \cdot K)}$$

$$l_{\mathrm{wdg}} = 293\,\mathrm{mm} \quad d_{\mathrm{Cu,o}} = 1.8\,\mathrm{mm} \quad d_{\mathrm{Cu}} = 1.72\,\mathrm{mm}$$



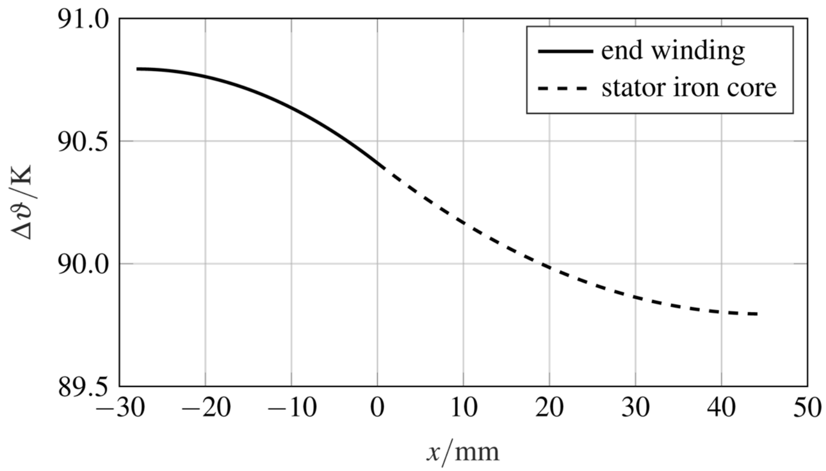
Thermal Modelling:
Excess Temperature in End Winding

- End winding not embedded in cool core
- Worst case: Total insulation from surrounding air
- Analytical Calculation from simple 1D bar model



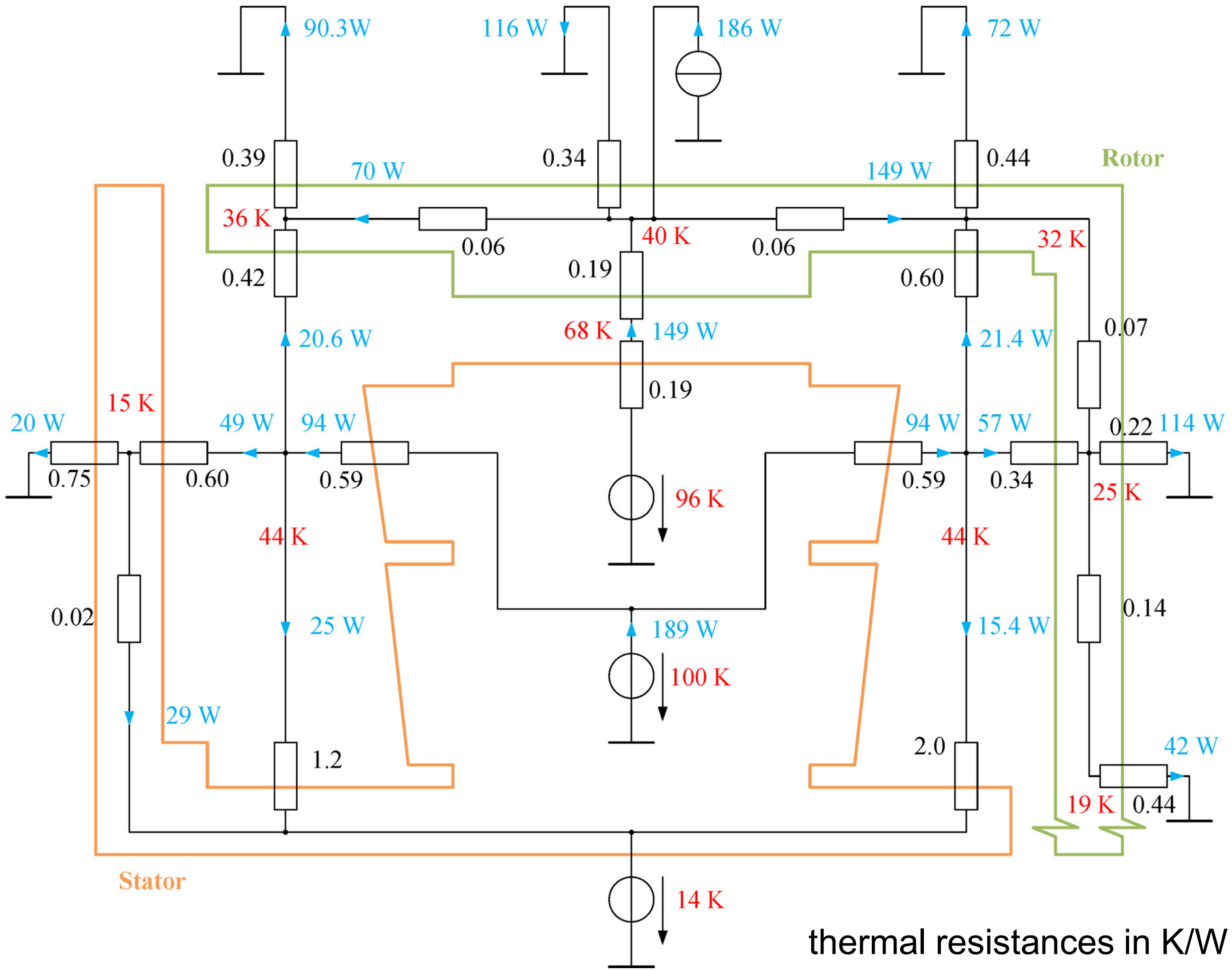
$$\frac{d^2\Delta\vartheta(x)}{dx^2} - \frac{r_{th,ax}}{r_{th,q}} \cdot \Delta\vartheta(x) = -r_{th,ax} \cdot p_L$$

- insignificant excess temperature of end winding $\Delta\vartheta \approx 1\ \mathrm{K}$



Thermal Simulation of Nominal Operation:
Coupling of Stator and Rotor – Results (II)

- Rotor losses 186 W
- Heat flux from stator to rotor: 248 W
- Air cooling: 454 W (16%)
- Water cooling: 2441 W (84%)
- Rotor temp. rise 40 K
- Reserve of 20 K (rotor losses not critical)



thermal resistances in K/W