Design and Manufacturing of a High Torque PMSM with Tooth-Coil Winding and Solid Rotor Yoke

TECHNISCHE UNIVERSITÄT DARMSTADT

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EDPC 2021: Proceedings page 208-215

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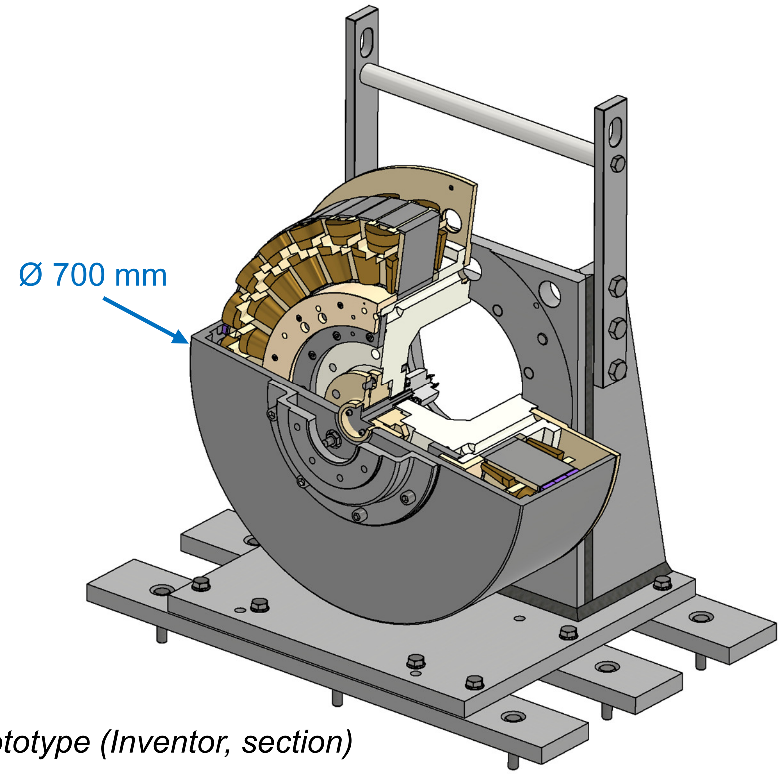


Prototype (Inventor, section)

Agenda

- Introduction
- Mechanical Machine Design
- Winding Design
  - Requirements
  - Design
  - Manufacturing
- Conclusion

Introduction:
Gearless PMSM Wind Generators

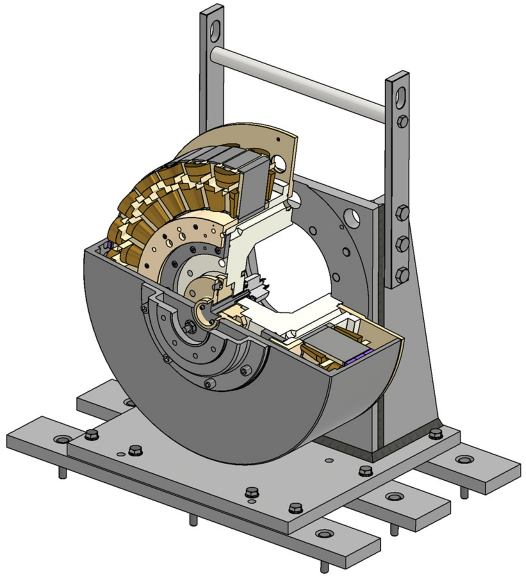
Wind Generator

[*Siemens Gamesa*]

Scaling

- Modular manufacturing
- Verify rotor loss models

Prototype



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

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

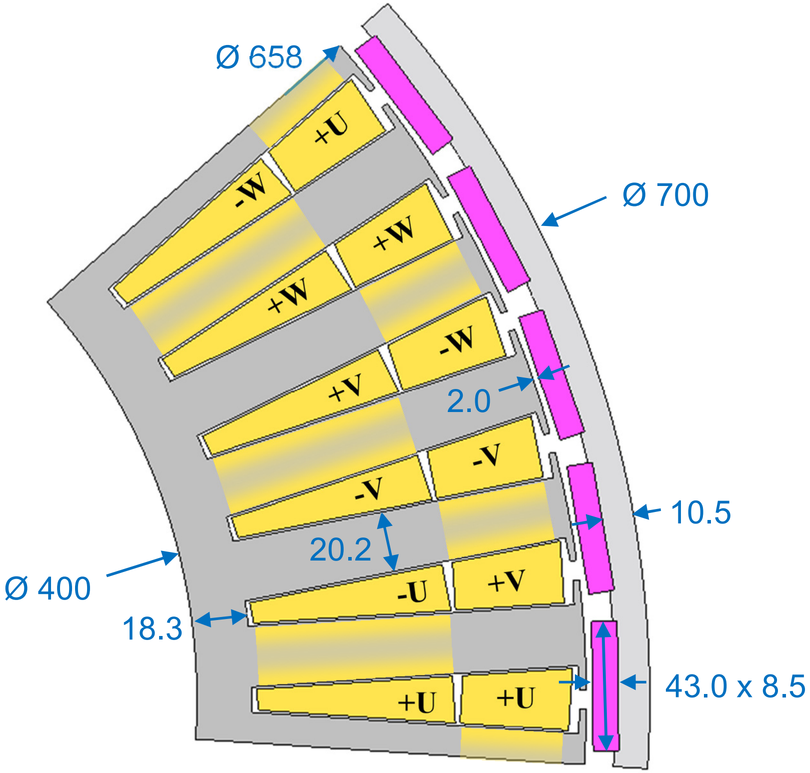
Inner water jacket ; form-wound coils

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

Stator field harmonics → Rotor eddy currents

Demonstrator Simulation:
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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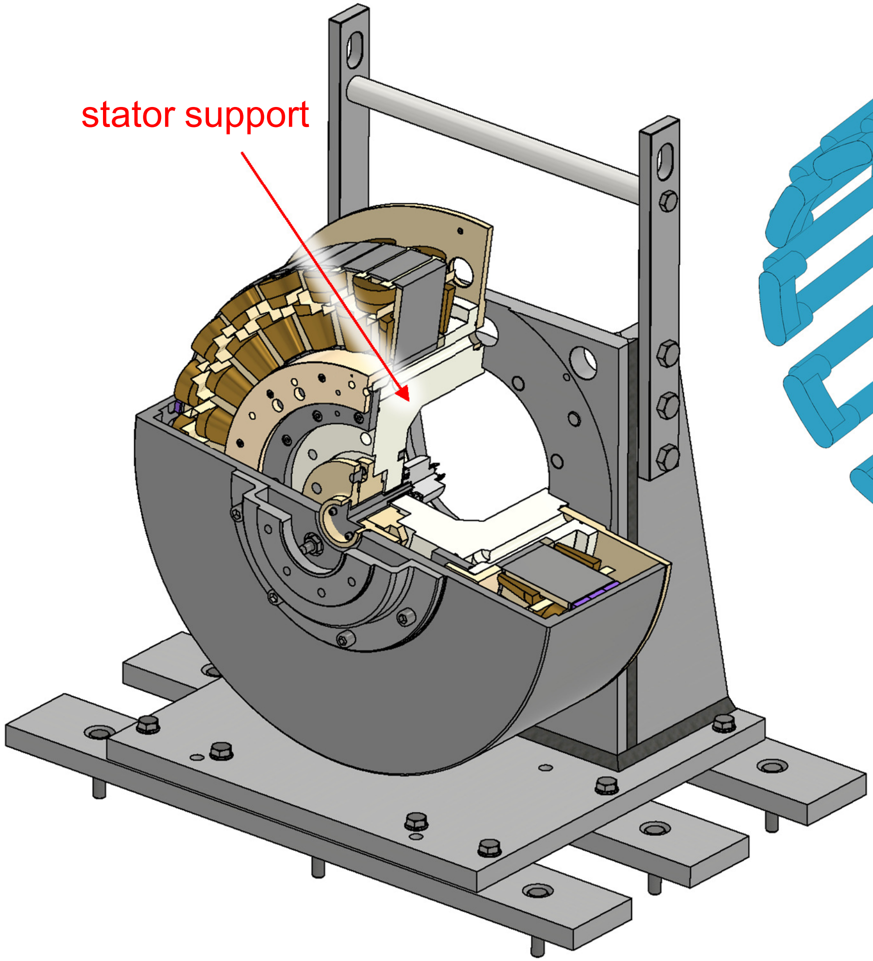
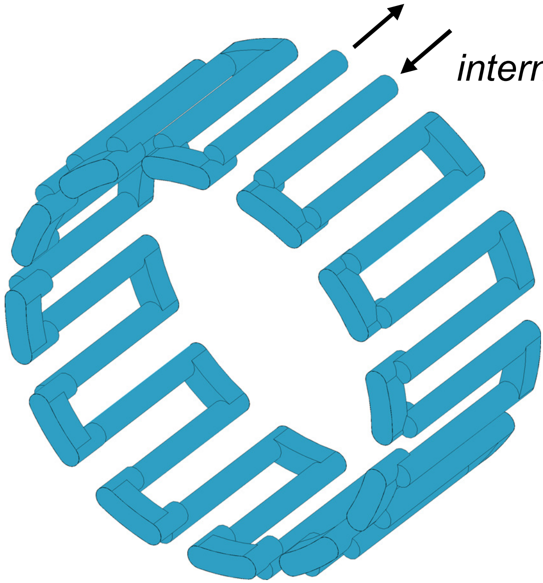
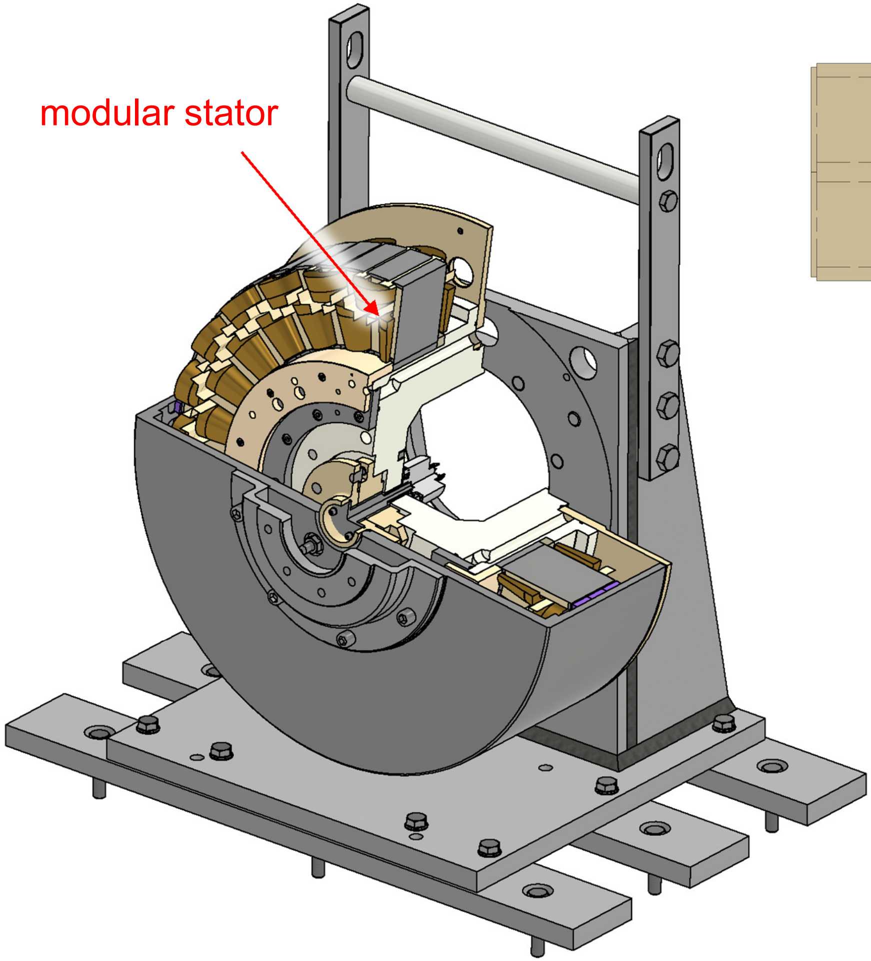
Machine Design:
Stator Support with internal water jacket

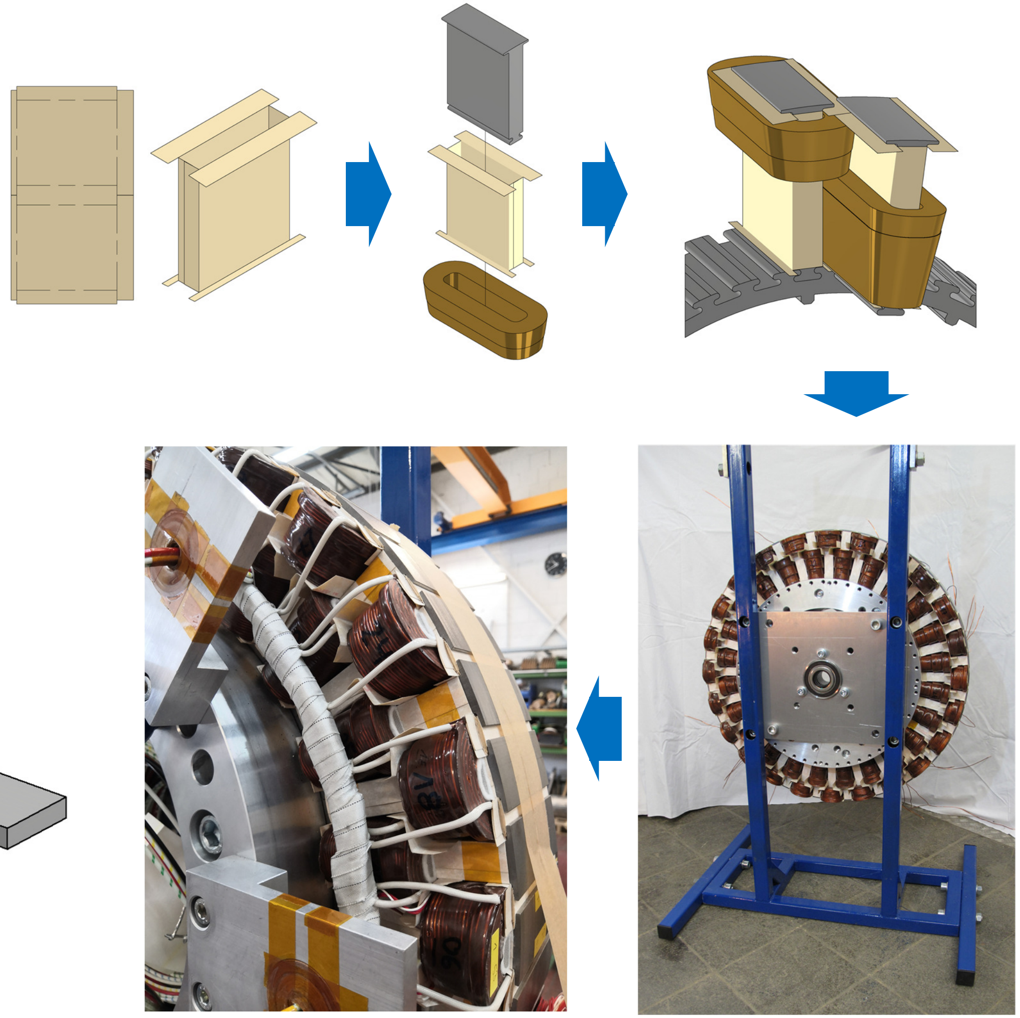




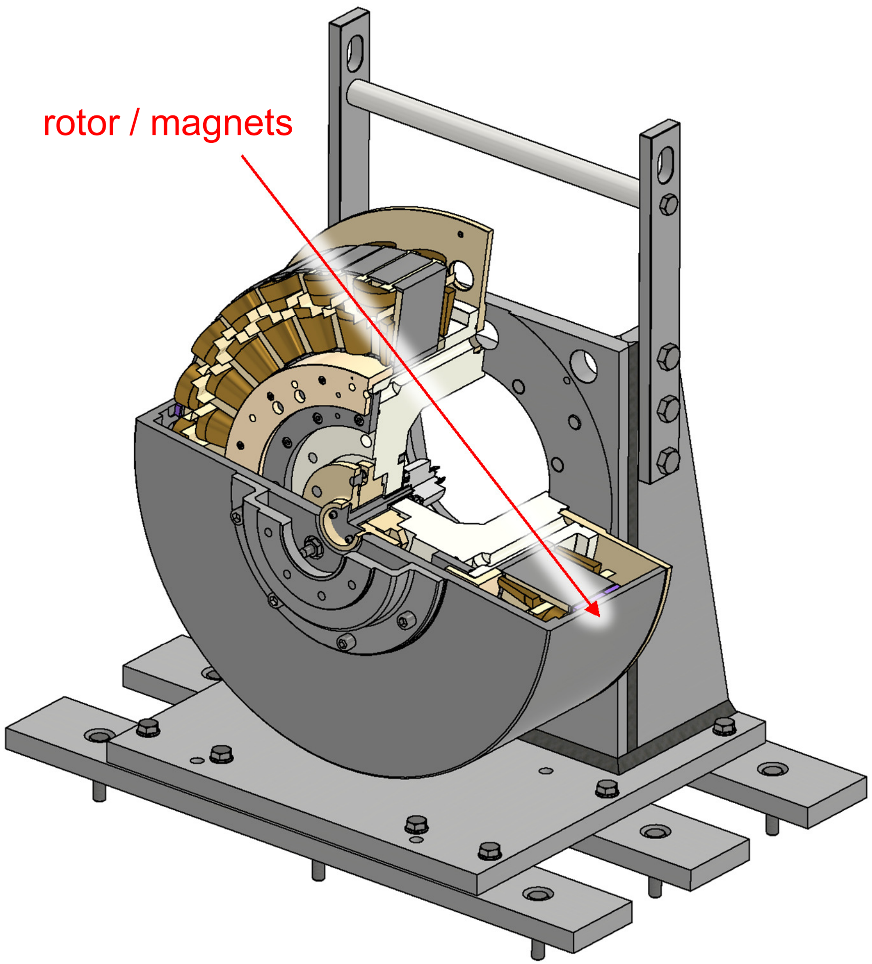
machined stator support

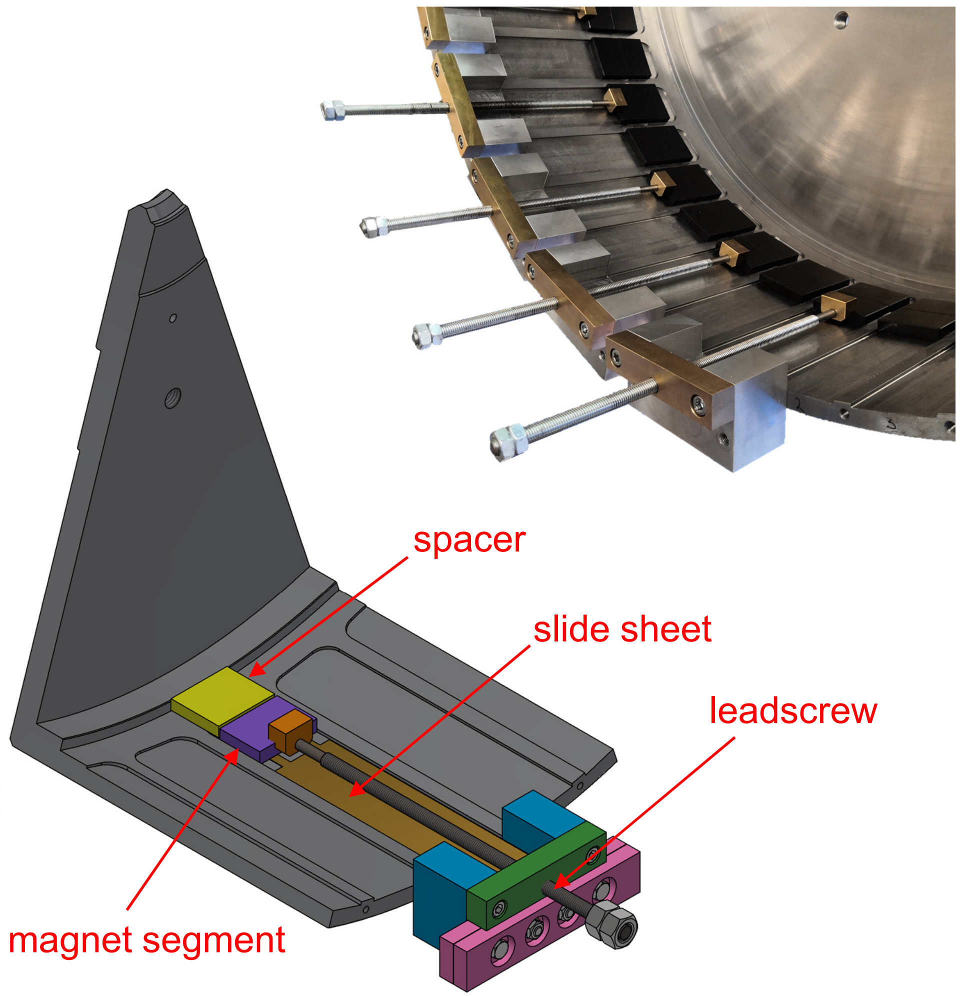
Machine Design:
Modular Stator





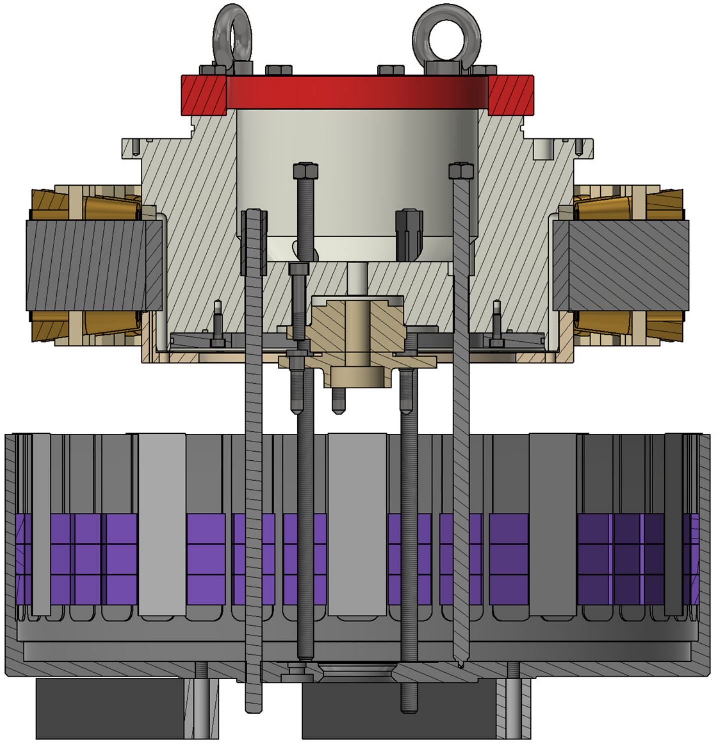
Machine Design:
Rotor and Permanent Magnets





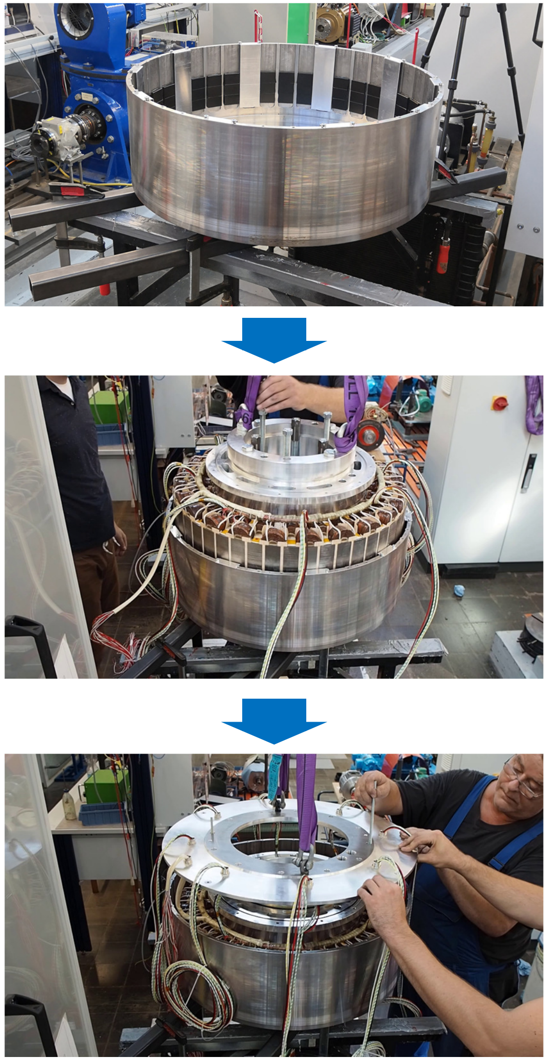
Demonstrator Assembly: Stator Insertion

- Insertion by 6 leadscrews (3 pull rods, 3 push rods)
- axial magnetic pull max. 7000 N
- 10 cover plates for magnet surfaces



left: sectional view of stator insertion (Inventor)

right: insertion steps



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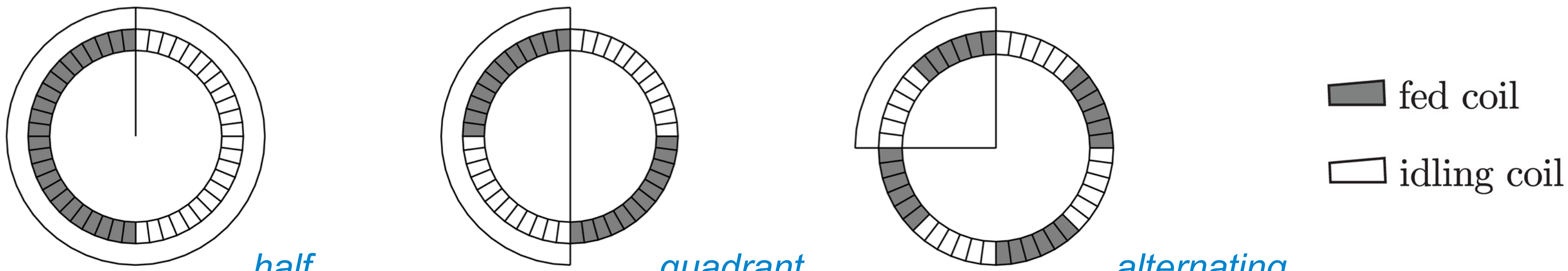
Winding Design:
External Interconnection

Two-layer, tooth-coil with $m = 3,\ q = 2/5,\ 2p = 40$ – Influence of stator field harmonics

A) 3 Implemented redundancy operation patterns:

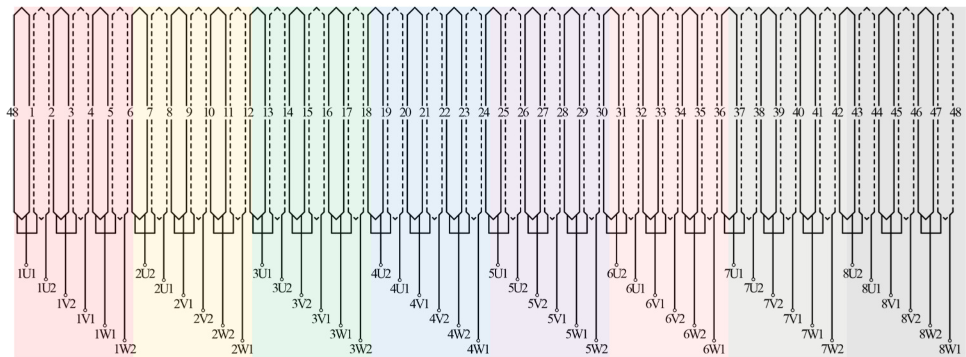


half *quadrant* *alternating*

B) Two different speeds / stator frequencies:

Switchable number of parallel branches

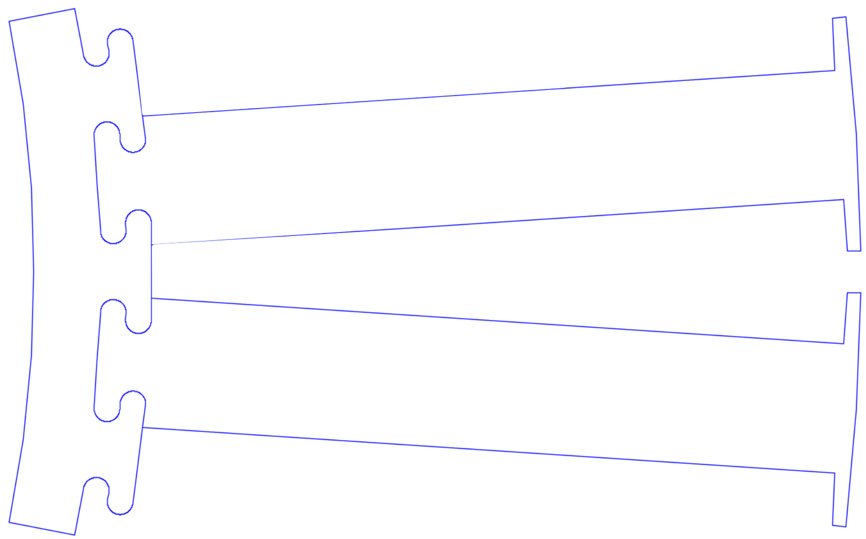
($a = 8$ or $a = 4$)



A) and B) → External interconnection of fundamental winding schemes

Winding Design:
Orthocyclic Round Wire Winding

- Two layers reduced inter-phase insulation area
  (compared to side-by-side coils)
- Adaption of coil cross-section to trapeze slot area:
  Reduction of turns in odd winding layers (forward winding direction)



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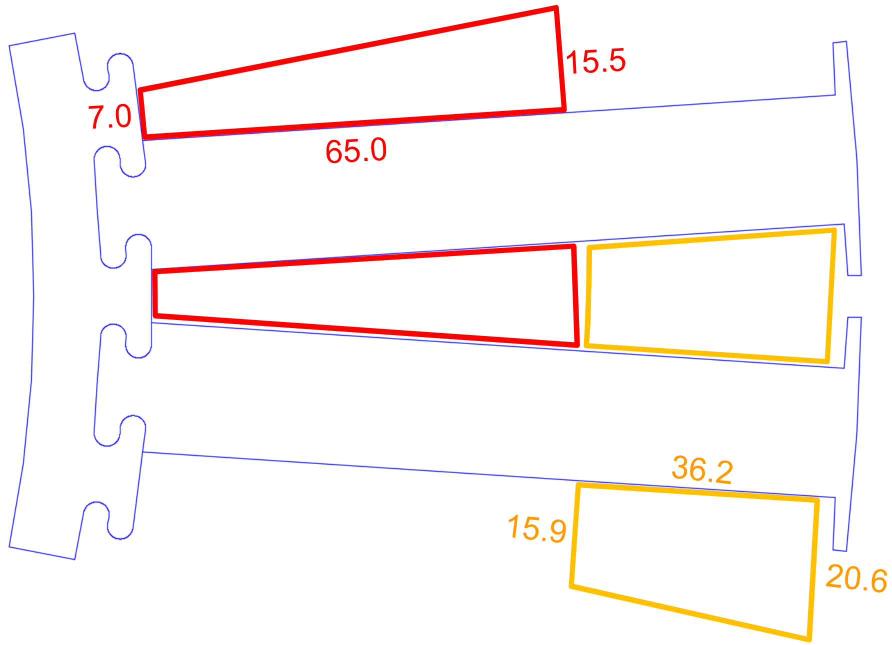
$d_{Cu} = 1.80$ mm



dimensions in mm

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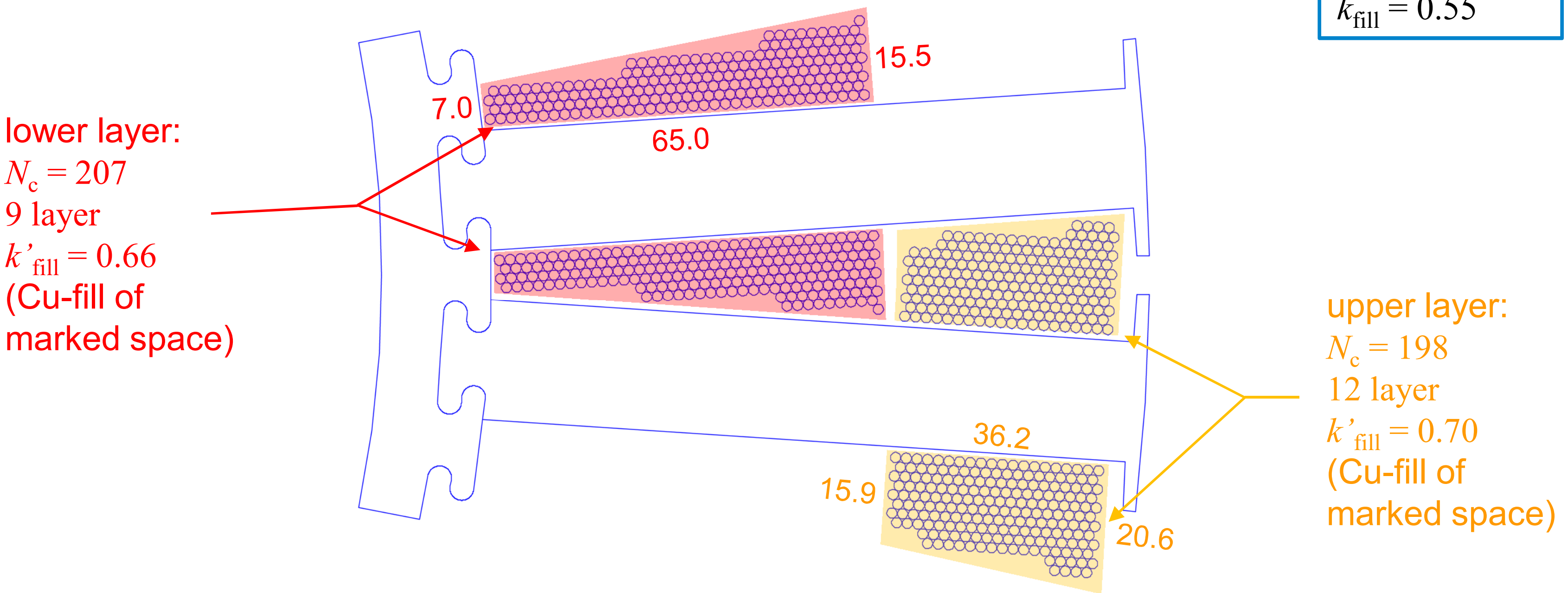
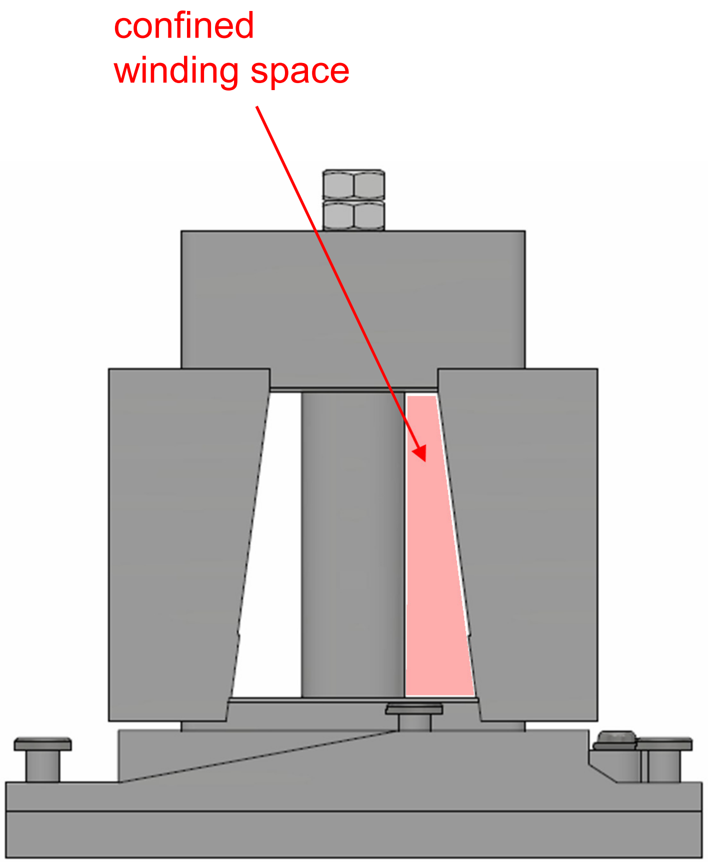
electrical slot fill factor k_{fill} = 0.55

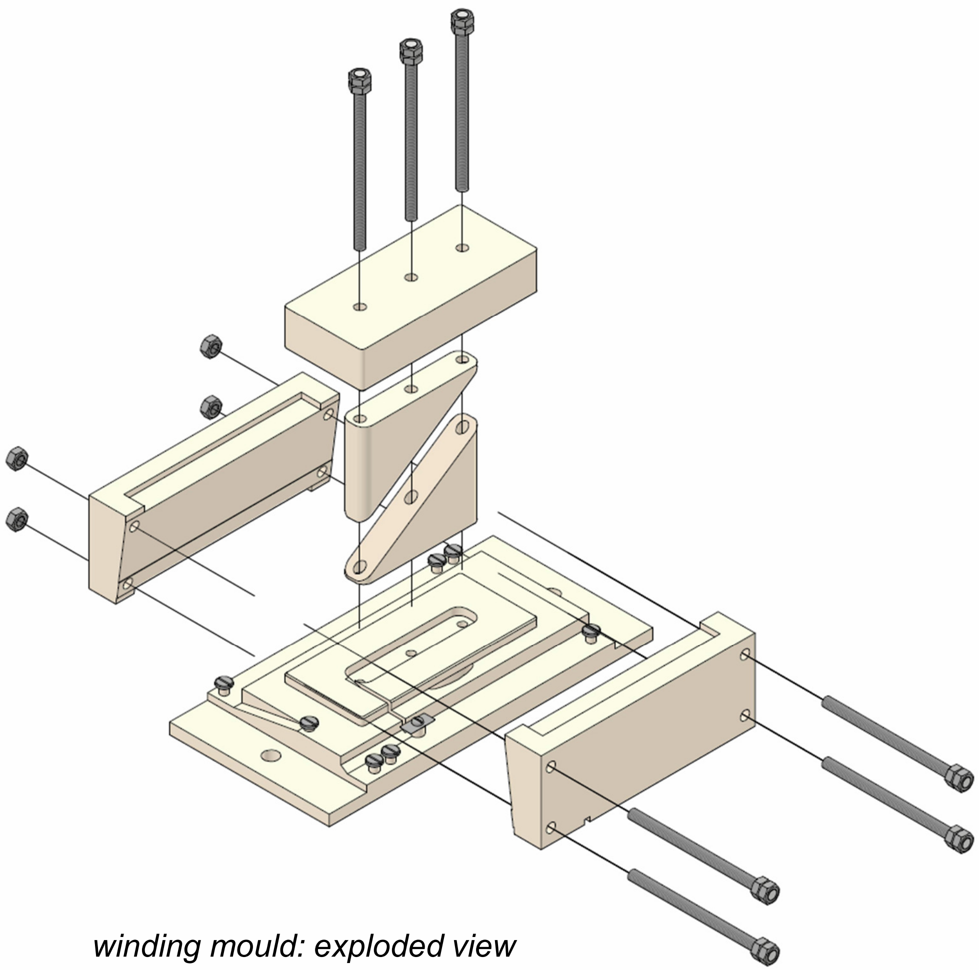


dimensions in mm

Winding Manufacturing:
Equipment: Winding Mould



winding mould: front view



winding mould: exploded view

Winding Manufacturing:
Winding process

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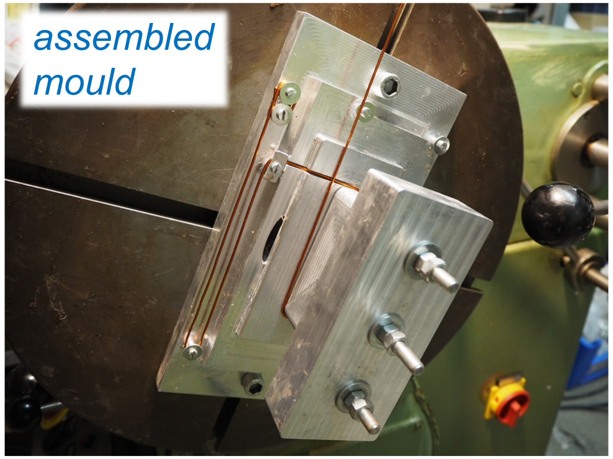

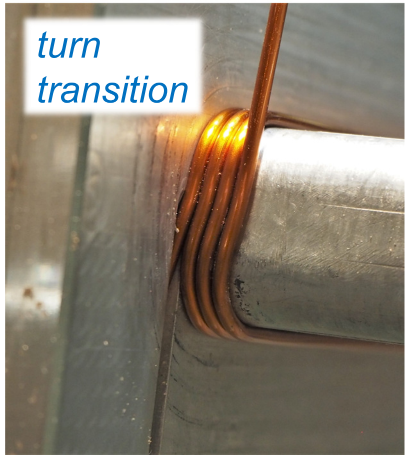

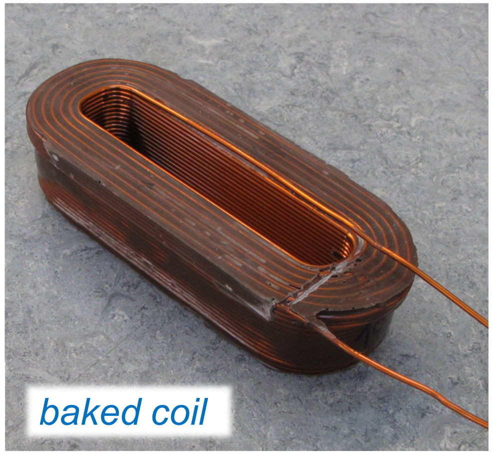

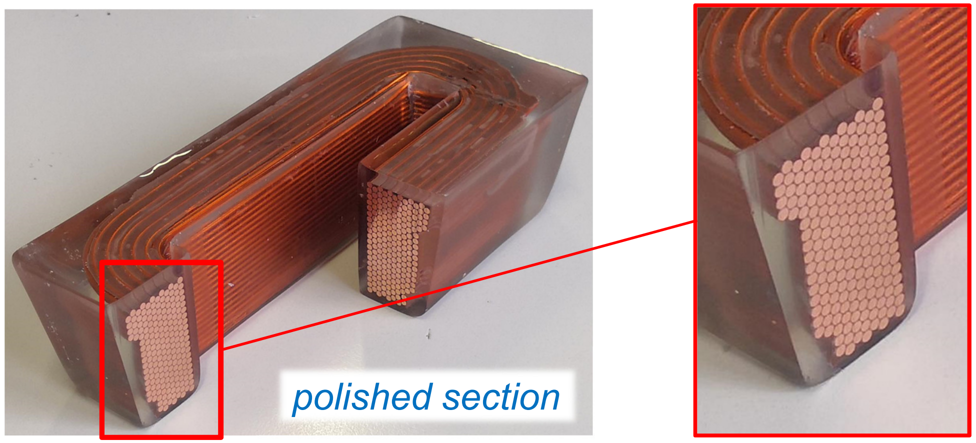

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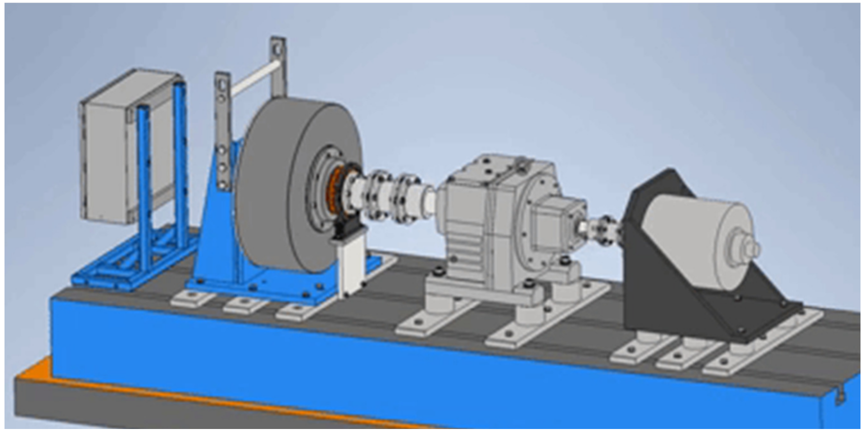
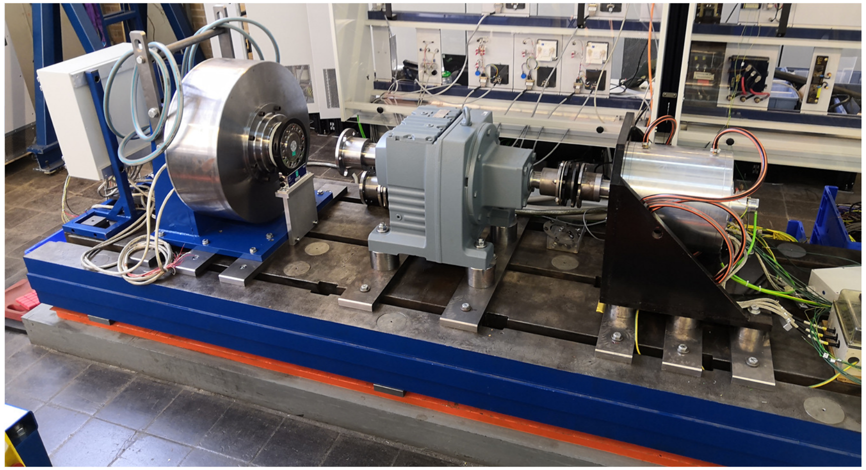
Conclusion

- FEM simulation: Nominal operation
- Mechanical machine design
- Winding manufacturing
- Machine assembly

- Economical modular manufacturing
- Copper fill factor 55 %
- Resin fill of premanufactured coil > 80 %

- Outlook: Experimental measurements on test bench





Research Funding and Supplier

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