Innovative Winding and Stator Architectures for High Torque and Lightweight Electrical Machines

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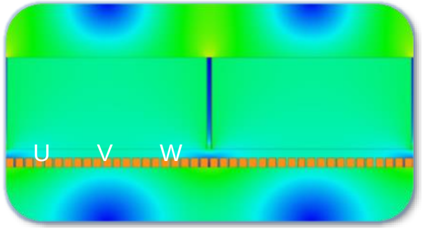
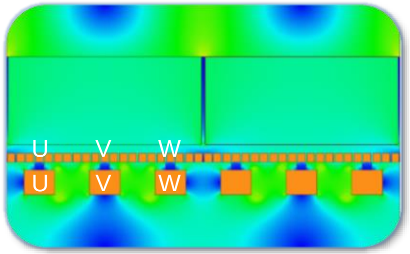
Content

- Introduction ➡ demands and opportunities

Air-gap windings

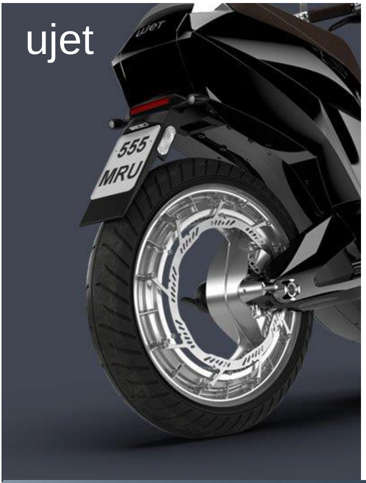


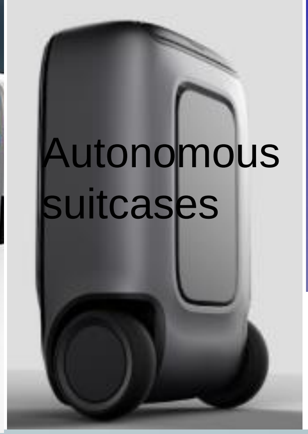
Combined windings

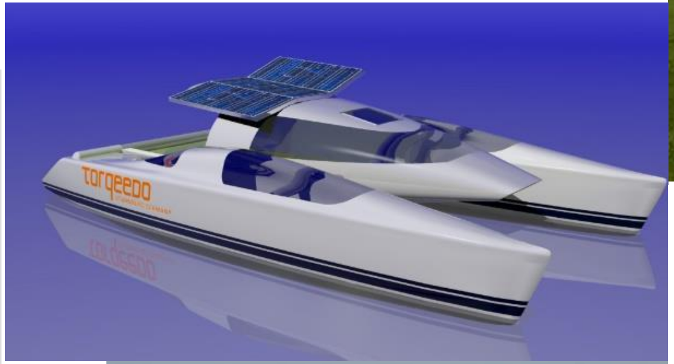


- Architectures and lightweight potential
- Design and manufacturing
- Cooling considerations
- View of new materials for lightweight electrical machines
- Applications
- Overview and outlook

Low Weight, High Efficiency E-Machines







State of the Art

Demands from Applications

- Compact
- Low weight
- Low cost
- Efficient
- High power
- Scalable
- Adaptable

Available designs

- Permanent magnets for high power
- Bulky coils to lead current and to build magnetic field ➡ **copper**
- Slotted stator back-iron to carry coils and lead magnetic field ➡ **iron**
- Sums up to
  - **weight**,
  - **cost** and
  - **losses**

Faulhaber

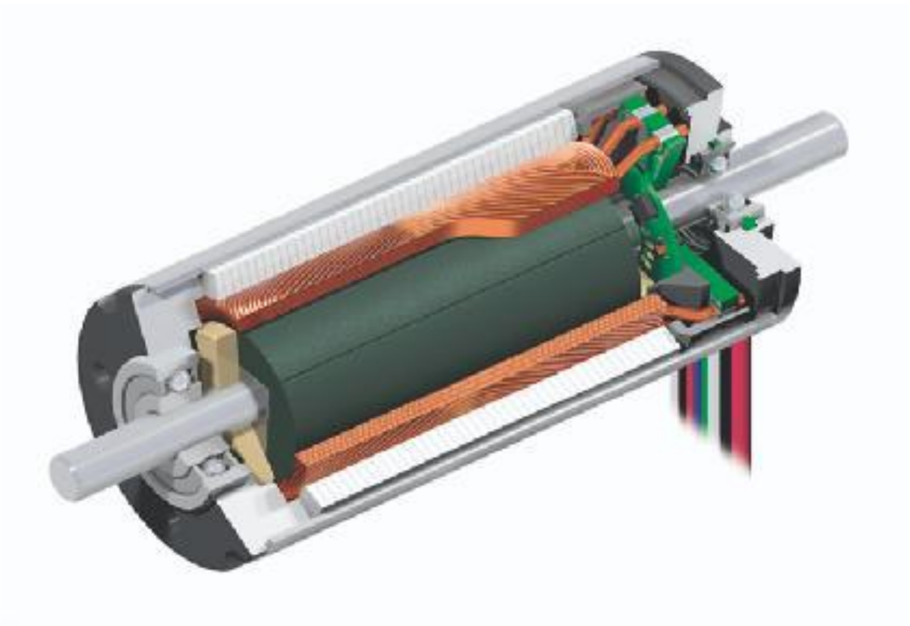
Basic design

- Totally ironless winding
- Self-sustaining winding
- Number of turns > 1
- Air-cooled winding

Example 3272...CR

- Ø 32 mm, length 72 mm
- 5500 rpm, 120 mNm torque
- 120 Watt, 24 V
- 87% efficiency
- Mechanical time constant < 3 ms
- Weight 312 g

Maxon



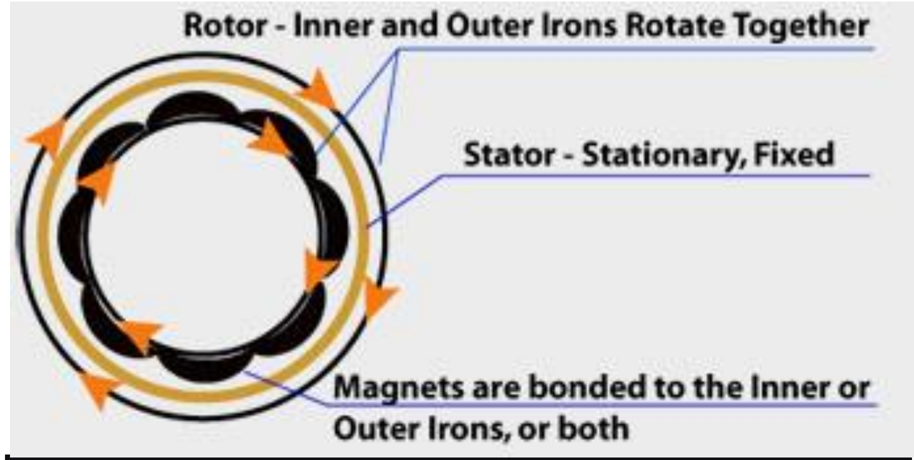
Basic design

- Knitted winding
- Number of turns > 1
- Low loss back-iron to limit iron losses
- Back-iron cooled winding

Example EC 4-pole

- Ø 30 mm, length 64 mm
- 16100 rpm, 95.6 mNm torque
- 200 Watt, 24 V
- 90% efficiency
- Weight 300 g

Thin Gap Motors



Basic design

- Air-gap winding fixed by polymer
- Totally iron-free stator
- Double air-gap
- Air-cooled winding

Example TG715X

- Ø 190 mm, length 39 mm
- 10,600 rpm
- 4.8 Nm torque
- 4 kW power
- 91% efficiency
- Weight 1.5 kg

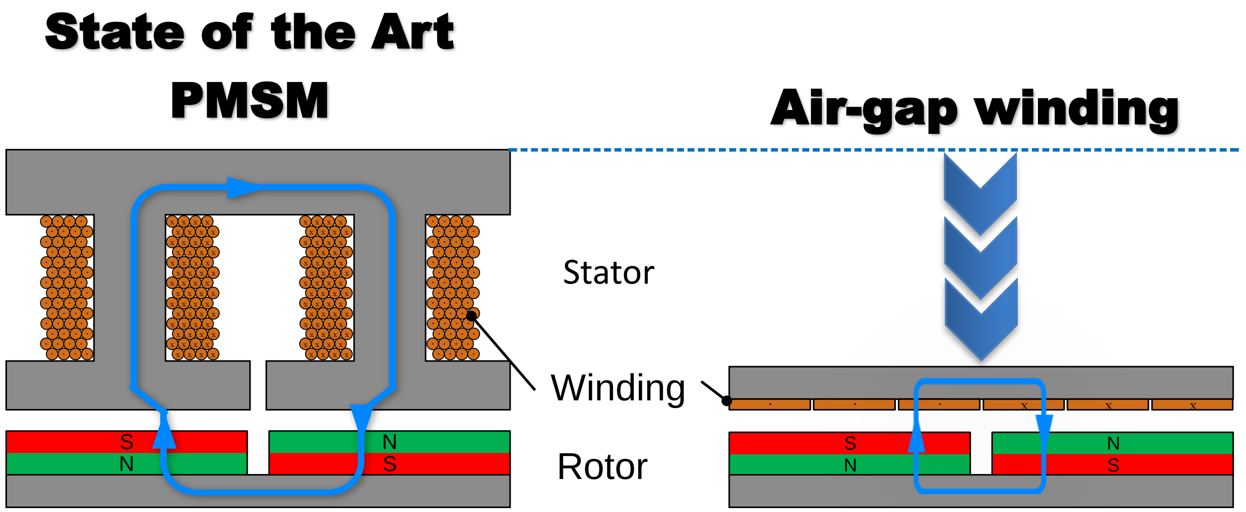
Features Slotless Air-gap Winding

Basic

- Low weight
- No cogging torque
- Very compact

Additional

- High torque
- Excellent cooling
- High power
- Metal formed winding technology
  - High fill factor ➡ low losses
  - Low cost



Magnetic Circuit Air-gap Winding

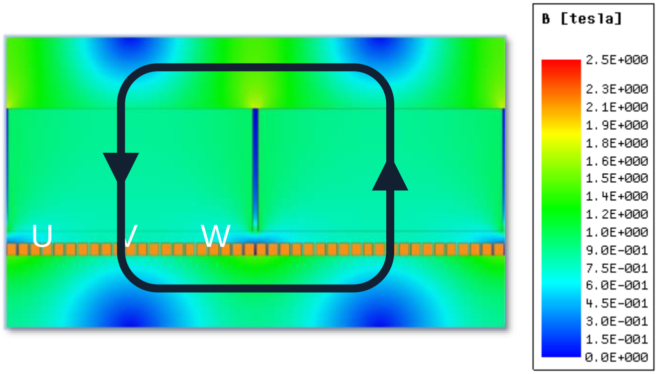
Compact magnetic circuit

- High B field in air-gap + axial wires
  ➡ high torque by Lorentz force
- Extremely thin stator back-iron without saturation
  ➡ low weight
  ➡ small iron losses
- Low need of copper for winding
  ➡ low weight
  ➡ low cost

ANSYS magnetic field simulation for 0.5 mm air-gap

- Single wires in phase to avoid eddy currents

rotor



stator

Patented Design Slotless Air-gap Winding

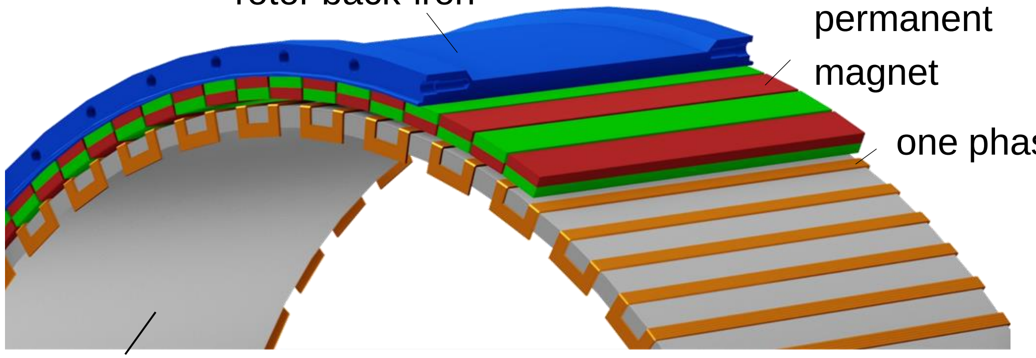
DE 10 2011 111 352 B4, US 9.685.830 B2, RU 2 603 680 C2, CN 103931085 B, EP 2751906 A2, WO 2013029579 A2

Meandering multi wire air-gap winding attached on stator back-iron

- Simple slotless ring geometry
- Flexible adaptable design

- Applicable to all motors and generators with external rotor
  ➡ automated winding technology available

- Internal rotor machines possible
  ➡ improved winding technology
  under development



Prototype Design Electric Power Wheel EPW I

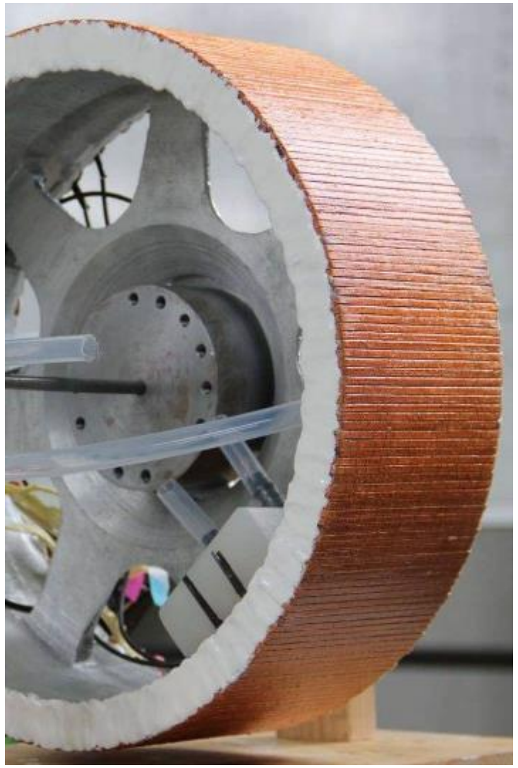
Integrated into 15“ rim

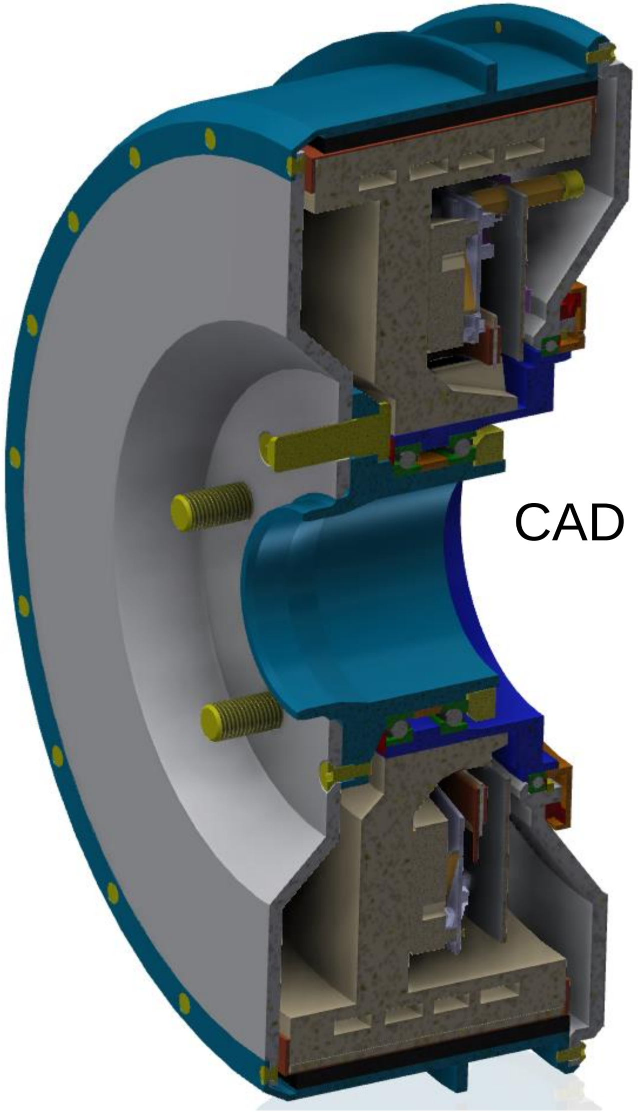
- ∅ app. 300 mm
- Width 100 mm
- Weight 20 kg

- Nominal
  - torque 300 Nm
  - speed 1350 rpm
  - voltage 400 V
  - power 40 kW ➧ 2 kW/kg

- Max. efficiency ≥ 93 %
- Excellent cooling

Stator



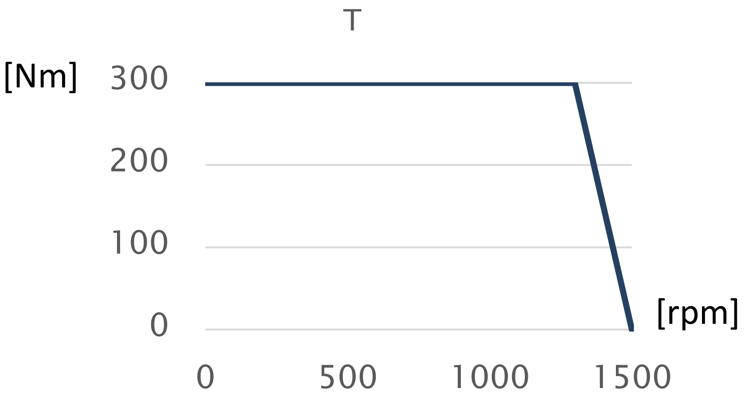


CAD

Prototype EPW I - Test I

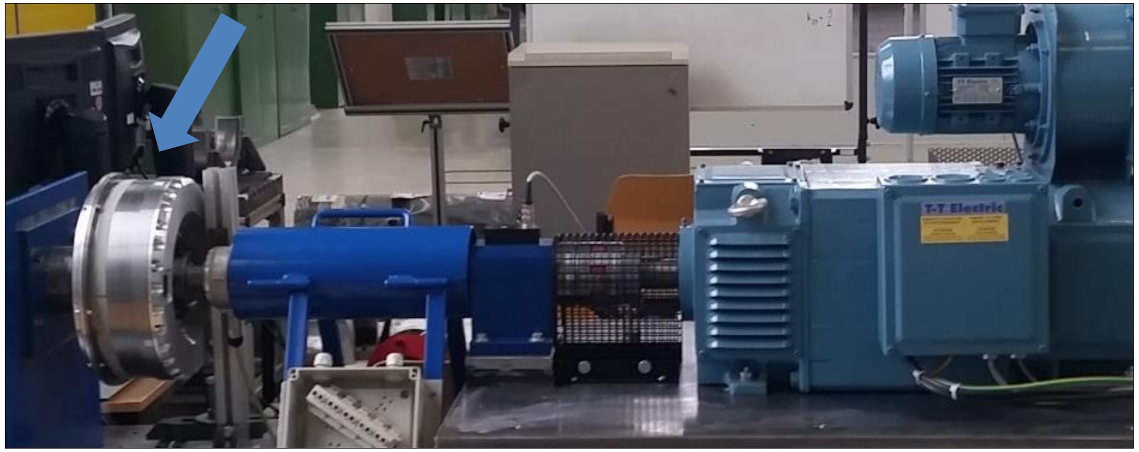
General results

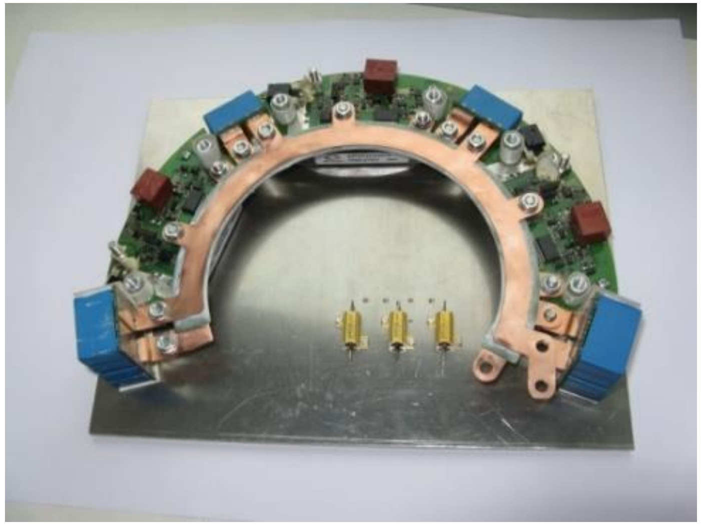
- DC Motor behavior
- Constant torque for all speed
- No weakening of B-field



Integrated electrical control unit

- Small phase inductance 10 µH
- Complex 2-stage electronic control





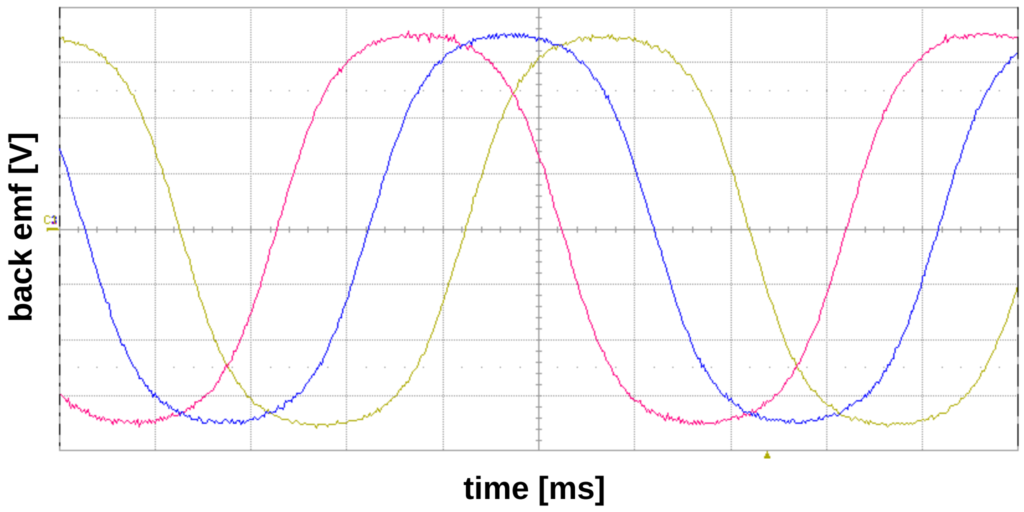
Prototype EPW I - Test II

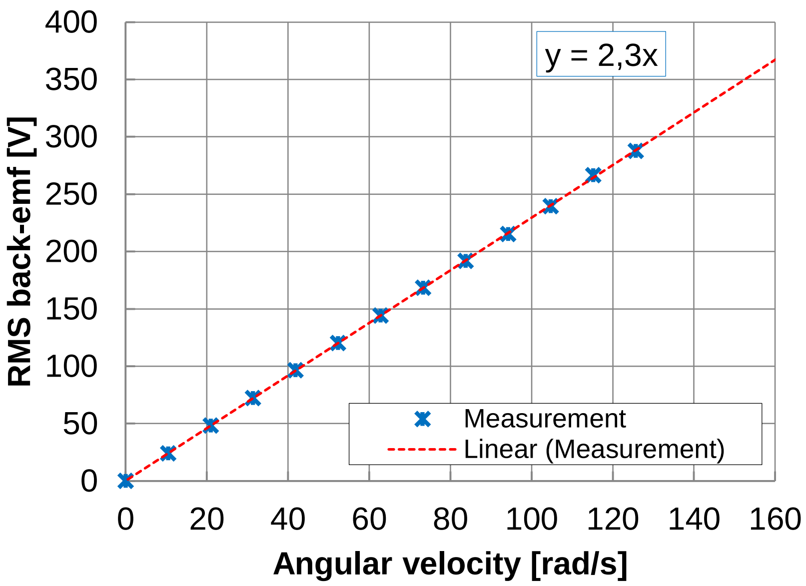
- EMF

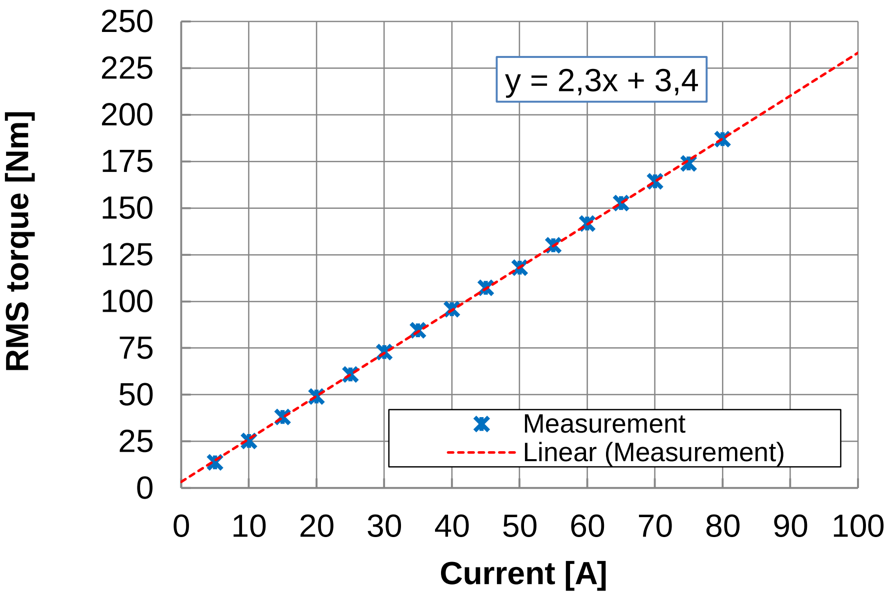
  $e = \sum_{k=1}^{n} a_k \cdot \sin(k \cdot \omega \cdot t)$

- Torque

  $T = k_M \cdot \sum_{k=1}^{3} B_k \cdot i_k$



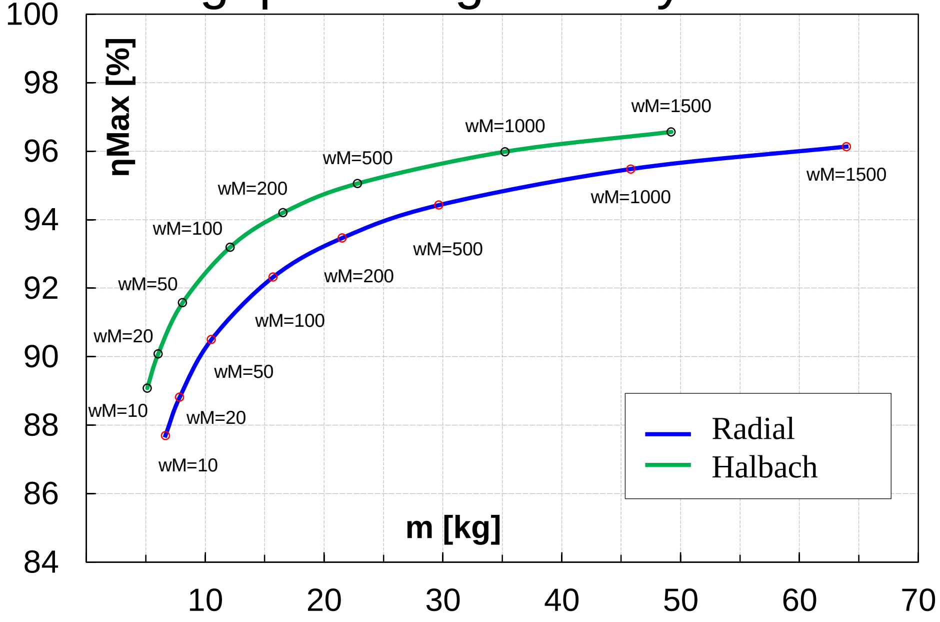




Electromechanical Design Flow

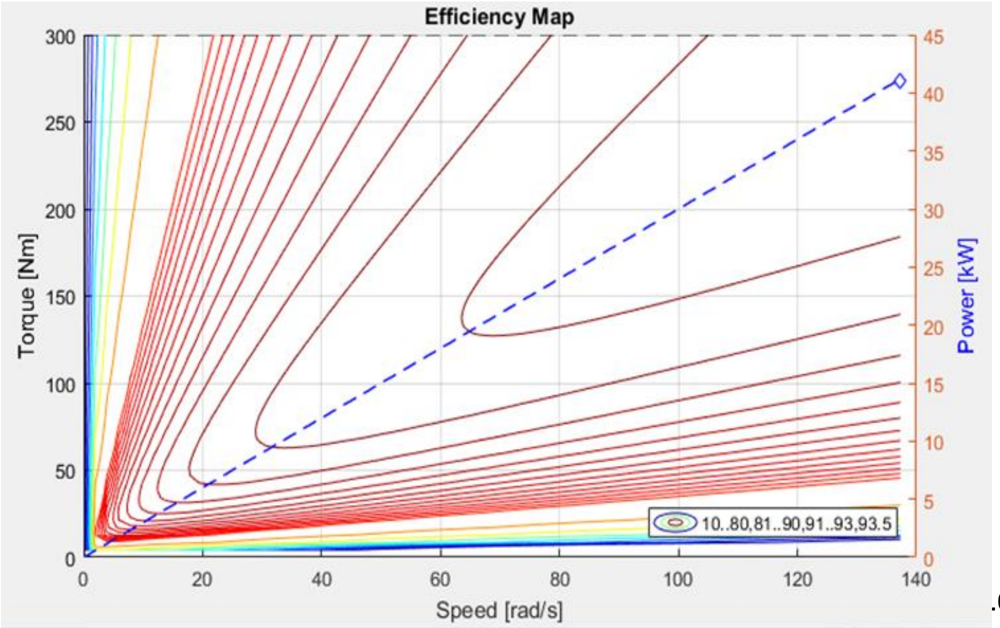
MAXWELL

- 2/3D-model fixed parameters
- Function
  - B, EMF, torque, U, I, …
- Losses
  - Stator ➡ Eddy, Remagnetization
  - Air-gap winding ➡ Eddy



Matlab/Simulink

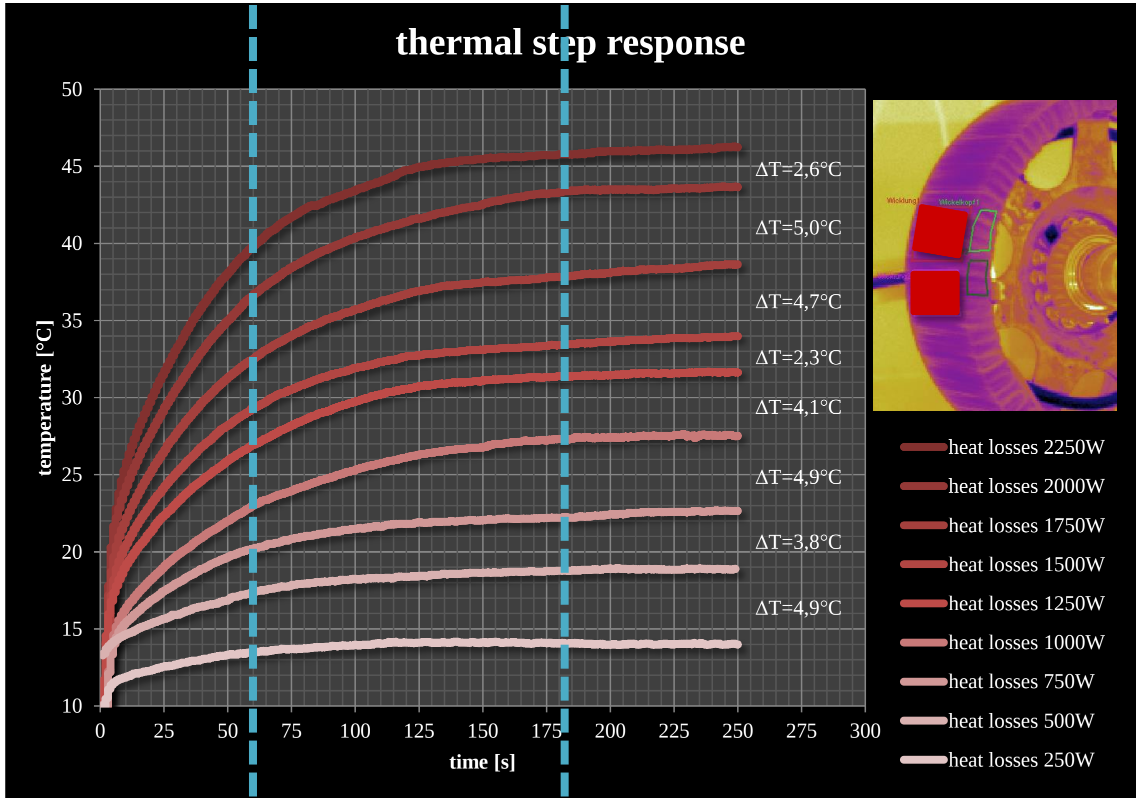
- Table based model variable parameters
  - System simulation
    - Control, Test, …
  - Optimization
    - e.g. efficiency ⬅➡ weight



Prototype EPW I - Test III

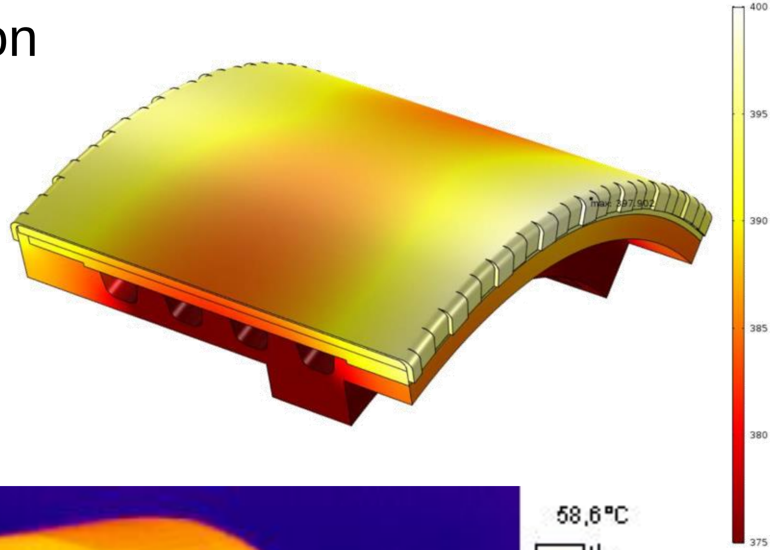
Heating-up experiment

- Very good heat transfer
- Uniform temperature distribution
- No hot spots

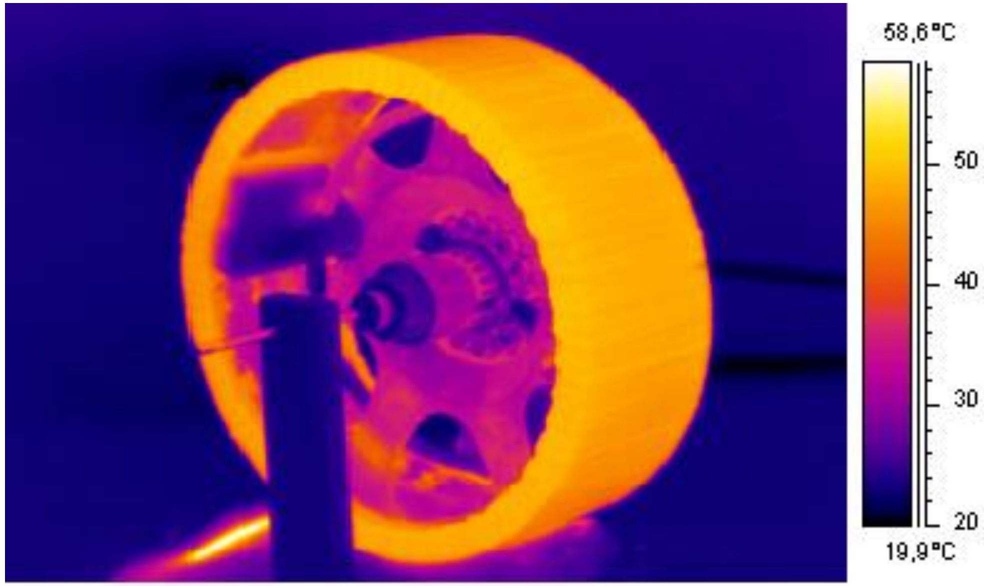


Temperature distribution

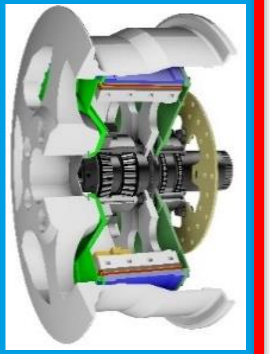
- FE simulation



- Experiment



Competition Wheel-Hub-Motor
Air-gap Winding

						
	General Motors	*Schaeffler AG*	*Siemens AG*	*Fraunhofer*	*Protean Electric*	*EPW I*
Rim Size [inch]	17	16	17	17	18	**15**
Weight [kg]	30	53	50	42	34	**20**
Power [kW]	16	33	63	55	54	**40**
Power/Weight [kW/kg]	0.53	0.62	1.26	1.31	1.59	**2**

Air-gap Winding Applications I

E-Scooter

- Power 4.5 kW
- Speed 500 rpm
- Torque 85 Nm
- Extreme lightweight construction
  - Scooter total: 32 kg
  - Motor: 2.7 kg
- Driving test successful (spring 2016)

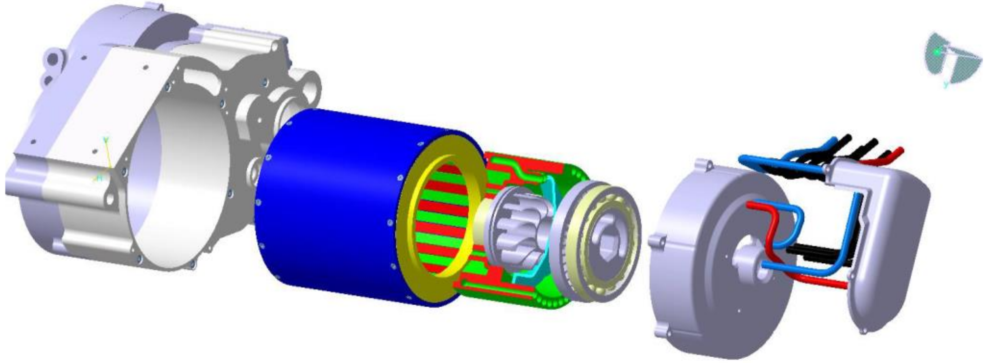
ePower Wheel-Generator Trailer

- Recuperation power 30 kW
- Speed 350 rpm
- Air-cooled
- IAA commercial vehicles Hannover 2016 (2. award)
- Test stand evaluation successful (fall 2016)

Air-gap Winding Applications II

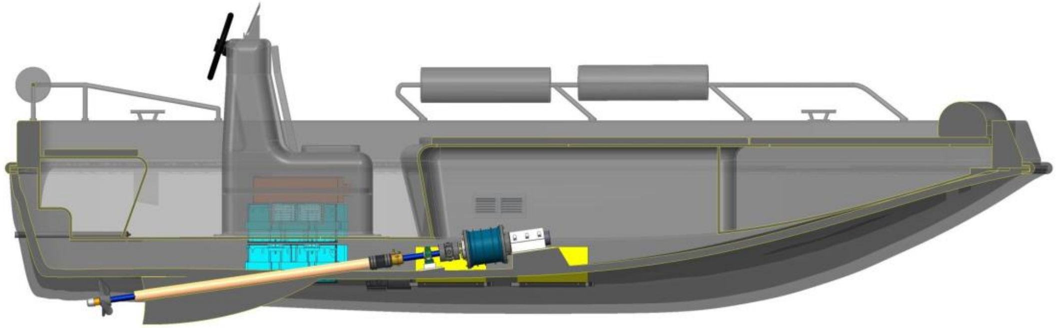
E-Motorcycle

- Integration into existing engine block/gearbox
- Power 12 kW
- Speed 6000 rpm
- Weight app. 8 kg
- Integrated water cooling system
- Design study (2017)



E-Flyboat

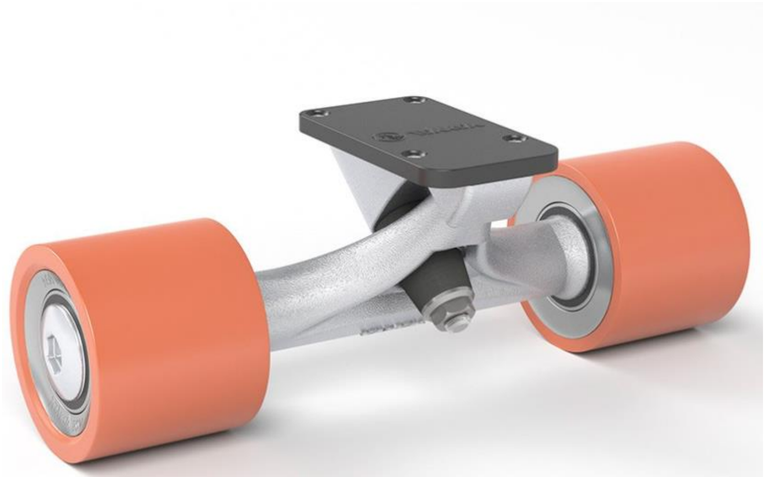
- Low weight
- High efficiency
- Power 2 x 5.5 kW
- Integration into hull
- Speed 600 to 2600 rpm
- Weight app. 8 kg
- Prototype (spring 2018)



Air-gap Winding Applications III

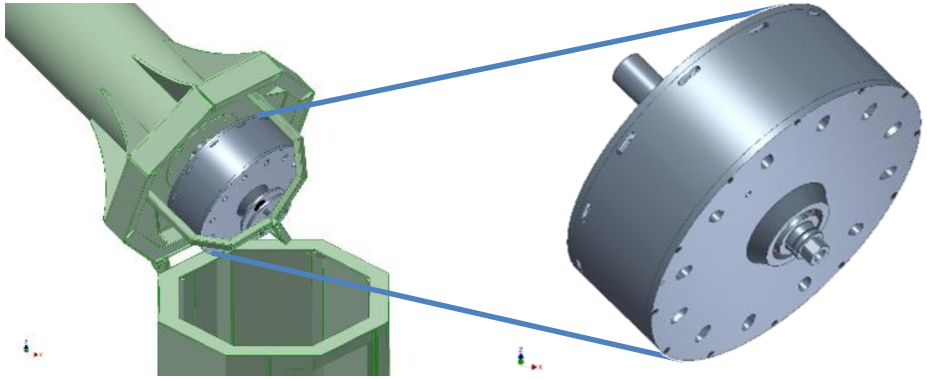
E-Longboard

- Integration into standard axle
- Usable for any kind of rack
- Power 250 W
- Speed 2500 rpm
- Range 12 km



Darrieus Windmill Generator

- Integration into tower
- Power 2.75 kW
- Speed 180 rpm
- Ø 350 mm
- Length 100 mm



COMO Test Vehicle with EPW I

Electrified Smart

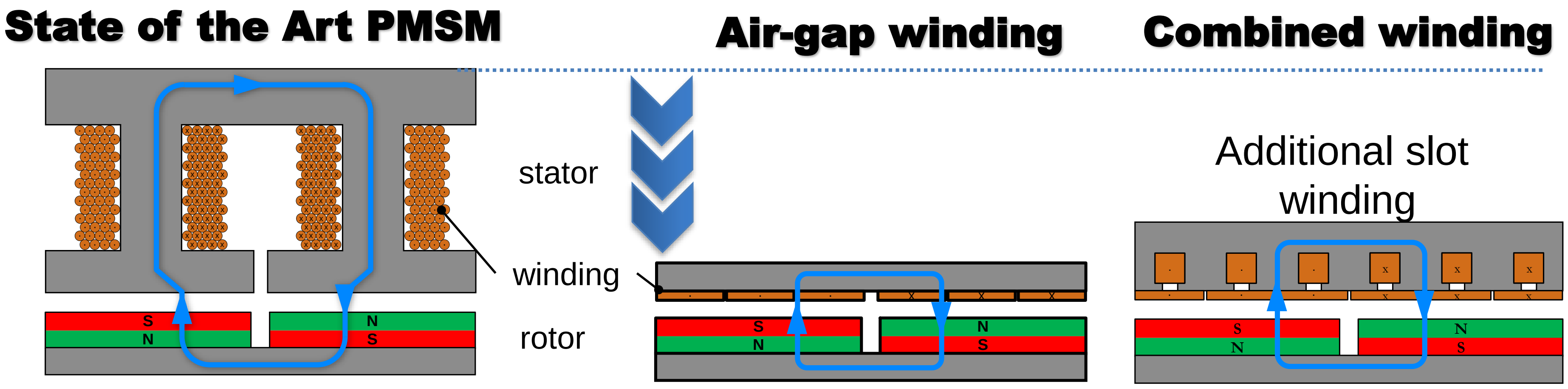
- ICE replaced by battery
- Range 150 km
- Voltage 400 V

Integrated Wheel-Hub-Motors

- 2 back wheels
- Re-use wheel-suspension
- Re-use brake

➡ Need for torque

Features Combined Winding



All advantages of air-gap winding + Nearly double power and torque

- Windings share permanent magnet field ➡ re-use of magnets
- Windings do not interfere besides adding torque and emf

Magnetic Circuit Combined Winding

Compact magnetic circuit

- 2 windings working together
  ➡ approx. double torque

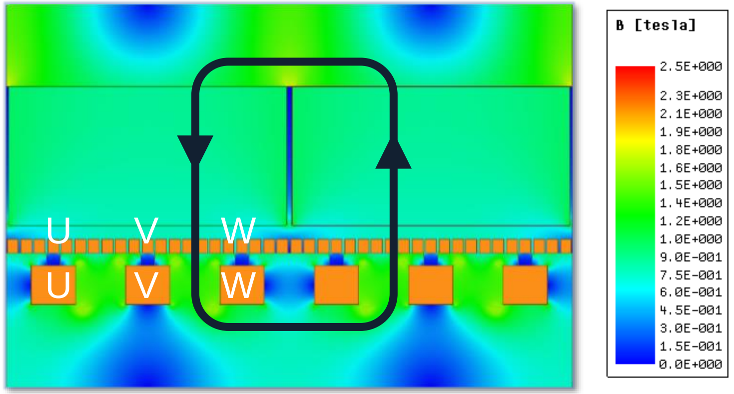
- Only slightly higher stator back-iron without saturation
  ➡ low weight
  ➡ small iron losses

- Only slightly higher need for copper of slot winding
  ➡ low weight
  ➡ low cost

ANSYS magnetic field simulation for 0.5 mm air-gap

- 1 wire to maximize fill factor

rotor



stator

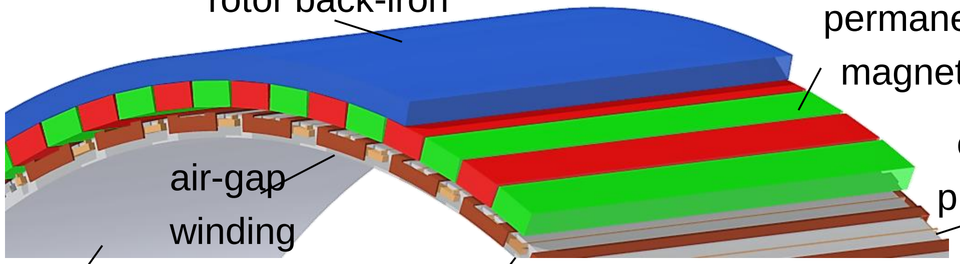
Patented Design Combined Winding
DE 10 2016 100 744, WO 2017/125416 A1

Meandering 1 wire slot winding in series to air-gap winding

- Simple weakly slotted ring geometry
- Special slot winding technology
  - High fill factor ➡ low losses
  - Low cost

- Customization of cogging torque and inductance by slot geometry

- Can use modified existing slot winding technology

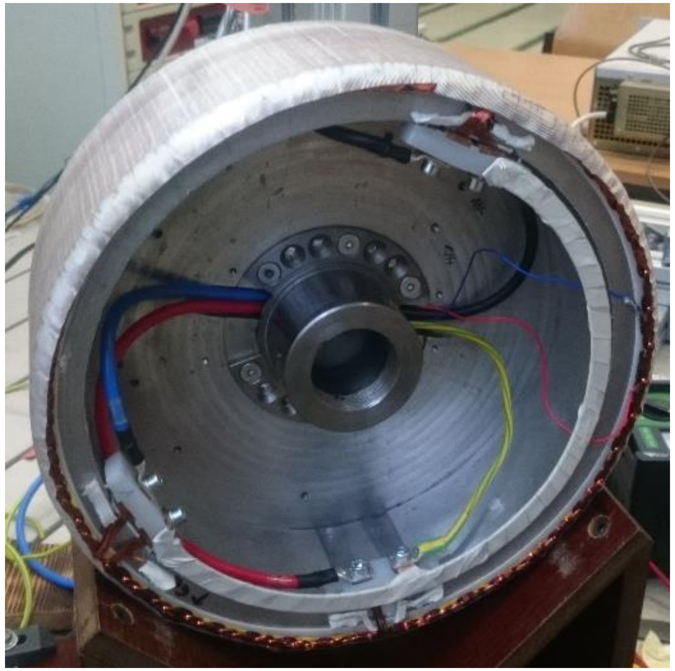


First Prototype EPW I➡II

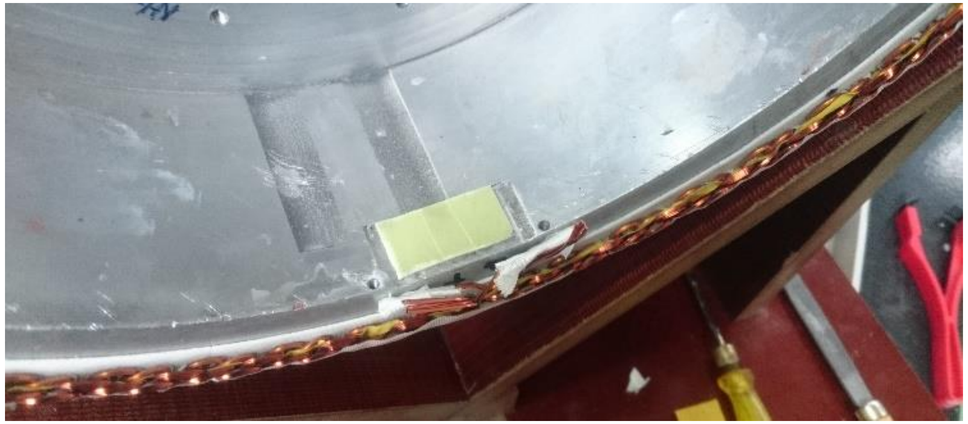
Design Parameters

- Extension of air-gap winding with slot winding using existing 15“ EPW I prototype
- Torque 480 Nm
- Nominal power 62 kW
- Weight 21 kg
- Power/Weight ca. 3 kW/kg
- Max. efficiency ≥ 94 %
- Completion February 2017

Stator



Winding Heads

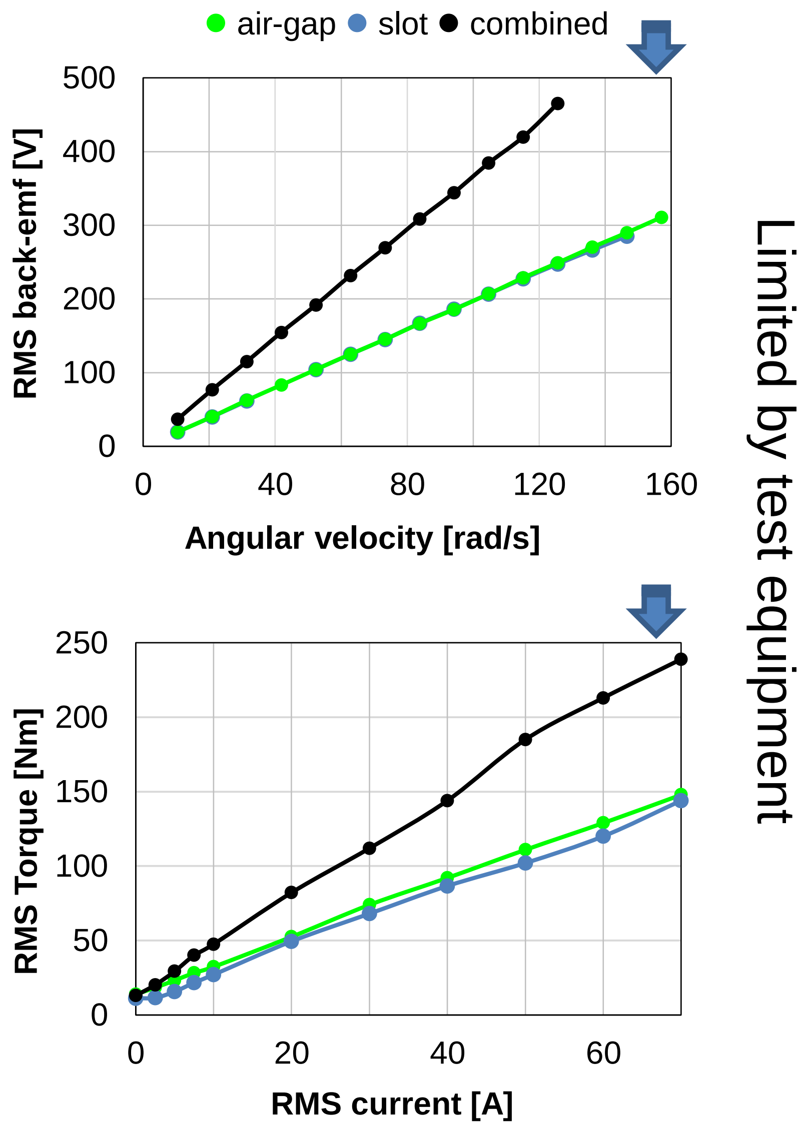


Proof of Combined Winding Principle

Experimental Parameters EPW I➡II

- Voltage (EMF) of combined winding sums up
- Torque of combined winding sums up
- No mutual interference of windings

➡ **Proof of principle of combined winding**



Regular Prototype EPW II
Exploiting Full Potential of Combined Winding

- Rim size 16 inch
- Width 100 mm

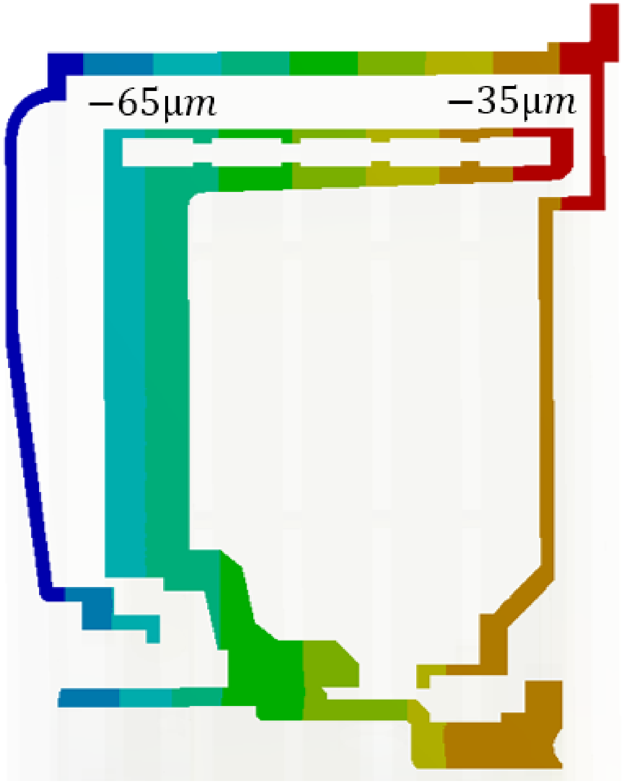
- Nominal
  - Torque 600 Nm
  - Power 64 kW

- Weight 16 kg
- Power/Weight 4 kW/kg

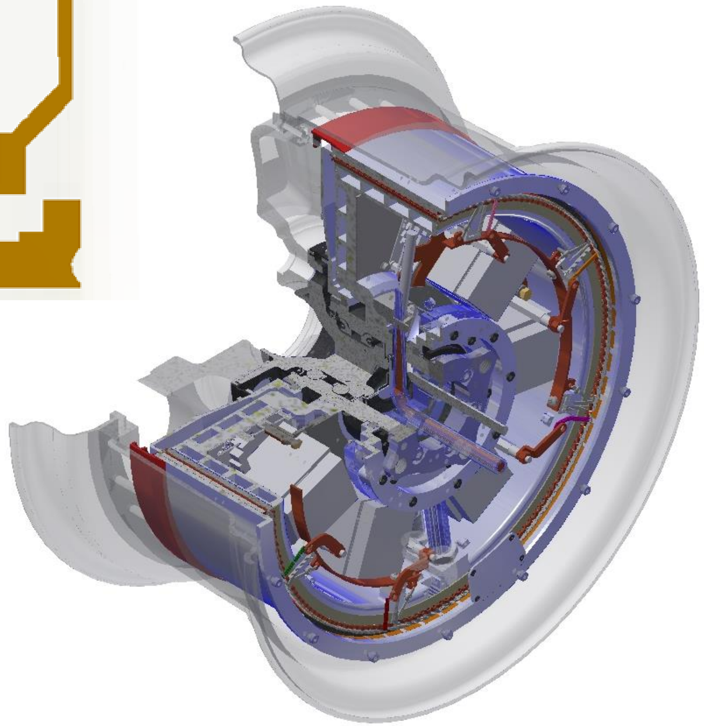
- Max. efficiency ≥ 95 %
- Larger inductance
  ➡ standard FOC

Regular Prototype EPW II - Additional Features

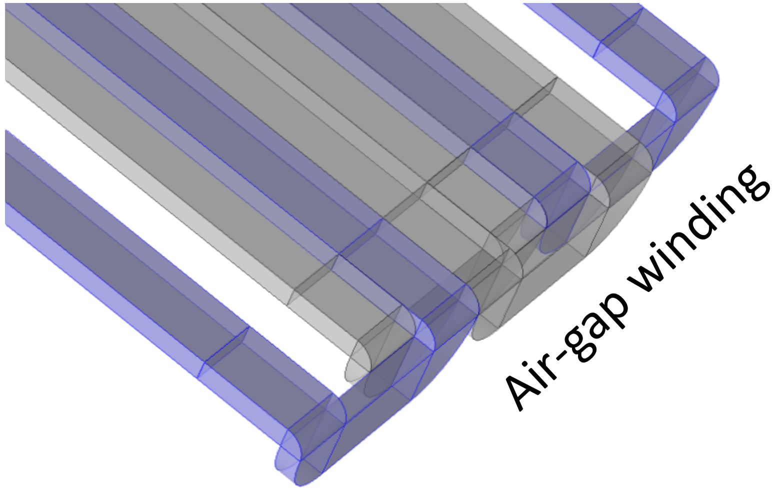
- New method of integration of motor into rim tolerating misuse of **15 kN** on rim
- Lightweigth materials (BMWi project LeiRaMo)
  - Al-foams
  - Carbon fibers
  - Hybrid = Al-foam + carbon
- Lightweight completely integrated power control unit

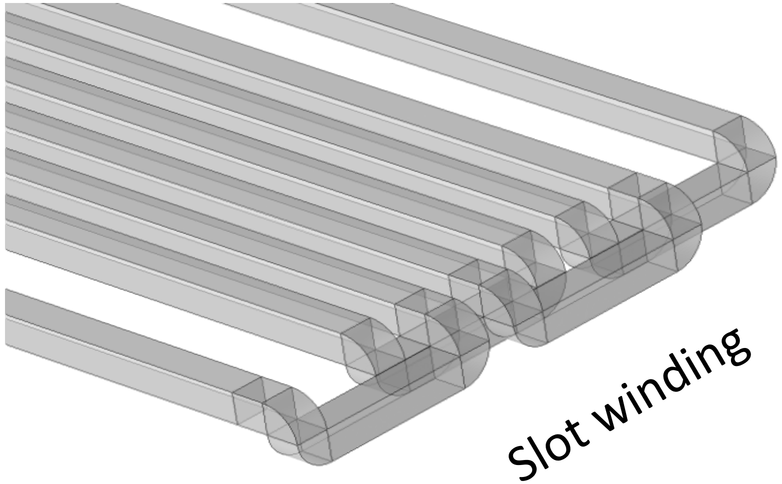


air-gap reduction



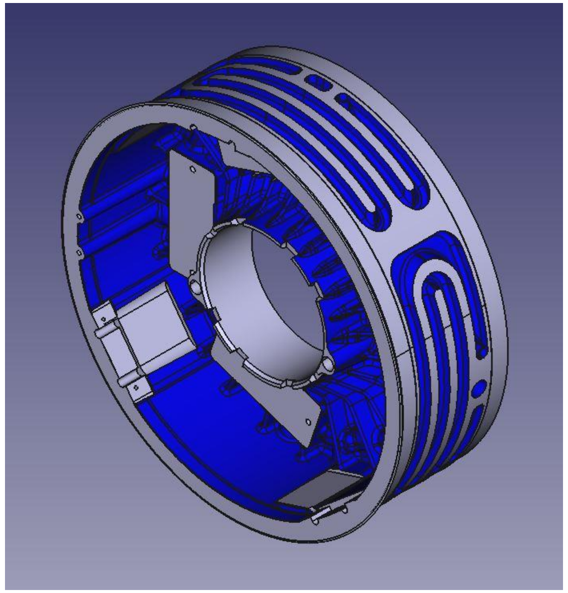
Regular Prototype EPW II - Thermal FE Design

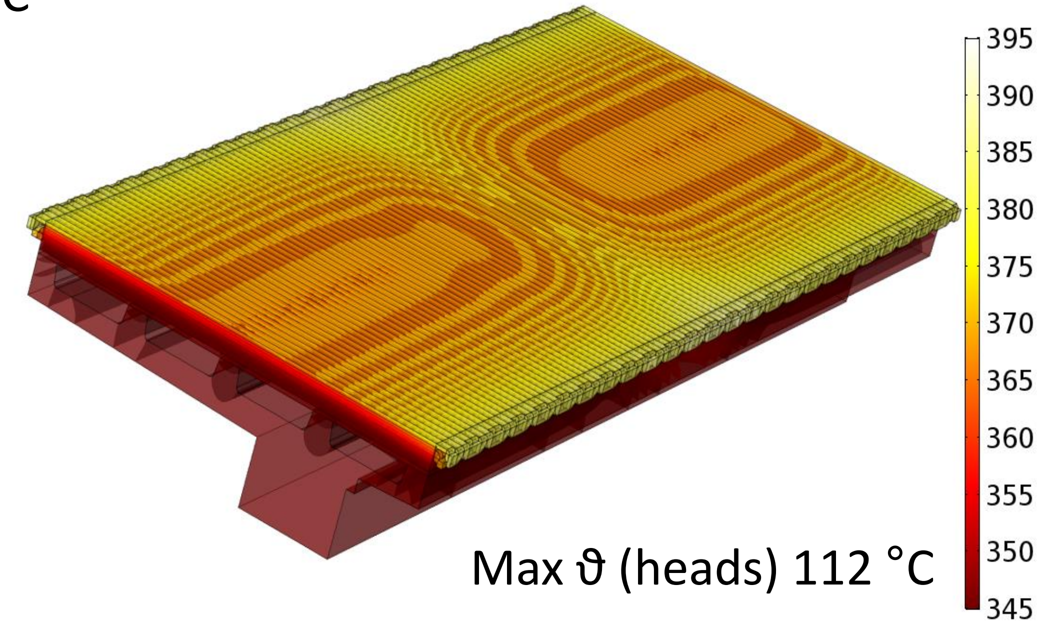




8 kW lost heat,
inflow 65°C

Pump power < 20W





Max ϑ (heads) 112 °C

Comparison Wheel-Hub-Motor EPW II

						
	General Motors	*Schaeffler AG*	*Siemens AG*	*Fraunhofer*	*Protean Electric*	*EPW II*
Rim Size [Zoll]	17	16	17	17	18	**16**
Weight [kg]	30	53	50	42	34	**16**
Power [kW]	16	33	63	55	54	**64**
Power/Weight [kW/kg]	0.53	0.62	1.26	1.31	1.59	**4**
Torque [Nm]	200	350	500	700	650	**600**
Torque/Weight [Nm/kg]	6.67	6.60	10	16.67	19.12	**37.5**

Combined Winding Applications

Hybrid motor

- Power 90 kW
- Speed 7000 rpm
- Integration into gear
- Active weight app. 6 kg
- ∅ reduction by 20%
- Simulation study for OEM

(picture similar)

Lightweight sports vehicle

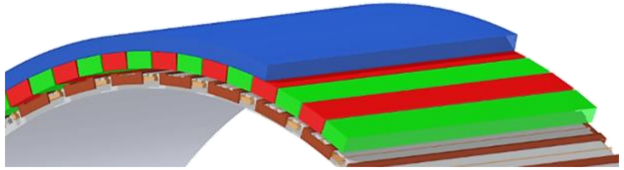
- 4WD wheel hub motors
- Vehicle dynamics control
- Total vehicle weight 700 kg
- Unlimited range with range extender
- New project

(picture similar)

Summary

New motor technology

- Lightweight
- High power
- Compact
- Cost efficient
- Scalable



Rim [inch]	13	16	19	21	23
T [Nm]	400	600	850	1000	1200

- Design environment

Air-gap winding offers

- Minimum iron/copper
- Small losses iron/copper
- Excellent cooling/overload
- Thin ring motor
- No cogging torque
- Automated winding application

Combined winding adds

- Double torque
- Best power/ and torque/weight
- Compactness

Outlook

Technology

- Optimization of production
  - of air-gap and slot winding
  - wound stator back-iron

- Improved architecture for higher power and torque

Rim [inch]	13	16	19	21	23
T [Nm]	400	600	850	1000	1200

+ 50%

Applications

- Automotive
  - Hybrid motor
  - Electric drive axle
  - Non-powertrain e-drives

- Non-automotive
  - Wind- and watermill generators
    1-250 kW
    6-300 rpm
  - Pump motors
    2-20 kW
    2000-3000 rpm

Innovative Winding and Stator Architectures for High Torque and Lightweight Electrical Machines

Thank you

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