Verlustberechnung und experimentelle Validierung bei hochausgenützten Permanentmagnet-Synchronmaschinen mit Zahnspulenwicklungen und Feldschwächbetrieb

Andreas Binder & Csaba Deak

Darmstadt University of Technology
Dept. of Electrical Energy Conversion

Landgraf-Georg-Strasse 4, D-64283, Darmstadt

E-Mail: abinder@ew.tu-darmstadt.de
cdeak@ew.tu-darmstadt.de

Overview

- Introduction
- Considered PM synchronous motors
- Basic design
- Electromagnetic performance
- Thermal analysis
- Built prototypes
- Rotor loss calculation methods
- Loss estimation from thermal measurements
- Conclusions

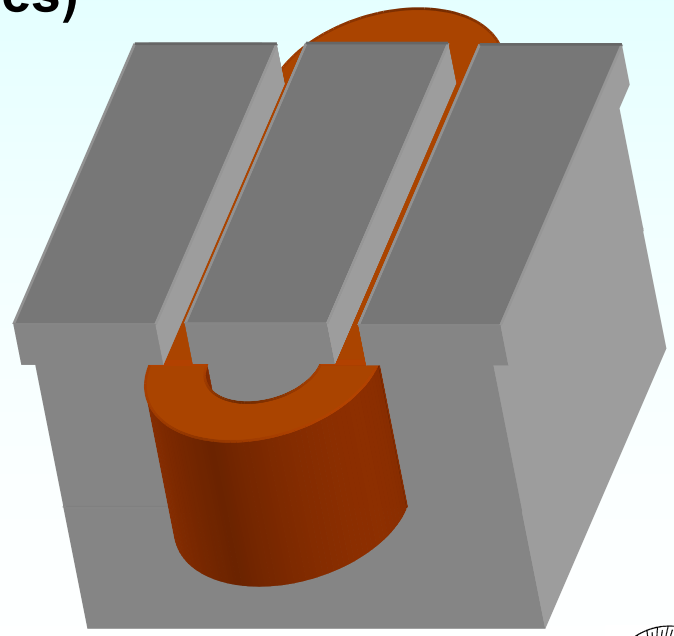
Modular synchronous machine

Permanent - Magnet motors:
- high torque
- reduced active mass
- reduced rotor losses

Tooth-wound coils:
- short winding overhang
- small resistance (reduced stator losses)
- compact design

Design of 3 PM motors:

- Constant power: 45 kW
- Phase voltage: 230V
- Rated speed: 1000 /min
- Maximum speed: 3000 /min

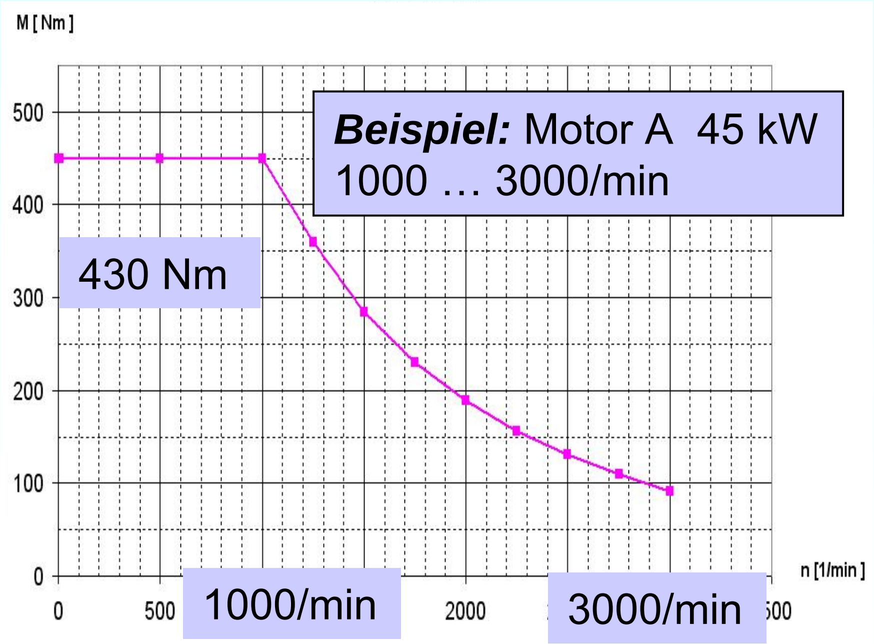


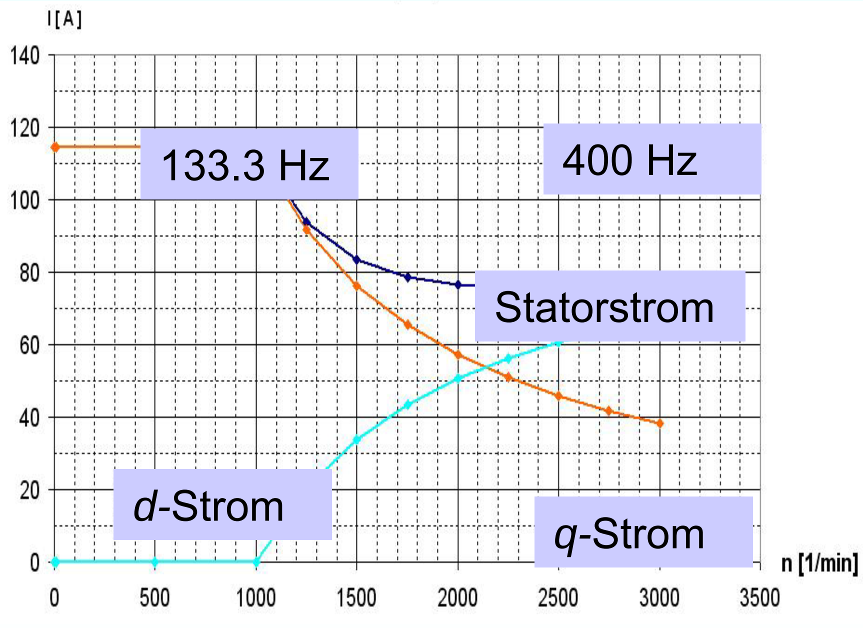
High-torque Antriebe für höhere Drehzahlen

- Zahnspulentechnologie und Permanentmagnetläufer :
    - kompakte Statoren
    - niedrige Stromwärmeverluste
    - hohe Induktivität für gute Feldschwächbarkeit
    - hohe Kraftdichte

- Genutzt für Servoantriebe, High-torque-Antriebe !

- Auch nutzbar für Industrieantriebe mit höheren Drehzahlen ?

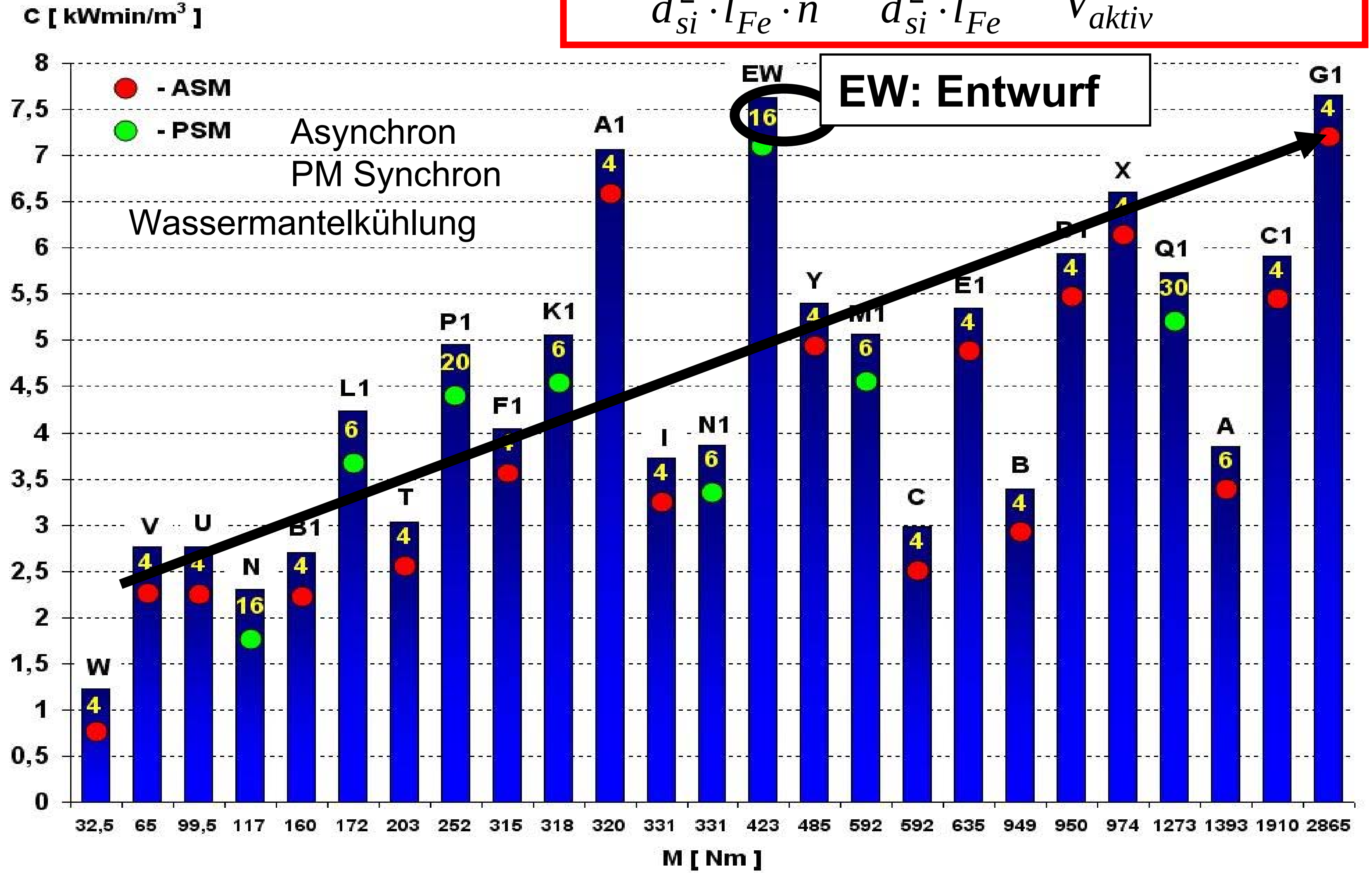




High-torque Antriebe für höhere Drehzahlen

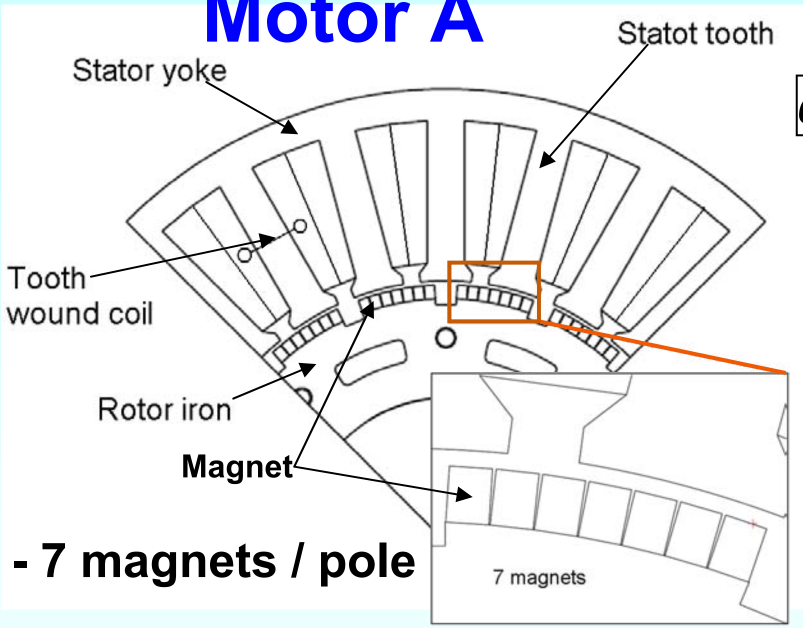
- Hohe Ausnützung im Vergleich

$$C = \frac{P_N}{d_{si}^2 \cdot l_{Fe} \cdot n} = \frac{2\pi \cdot M_N}{d_{si}^2 \cdot l_{Fe}} \sim \frac{M_N}{V_{aktiv}} \sim k_w \cdot A \cdot B$$



Considered PM synchronous motors

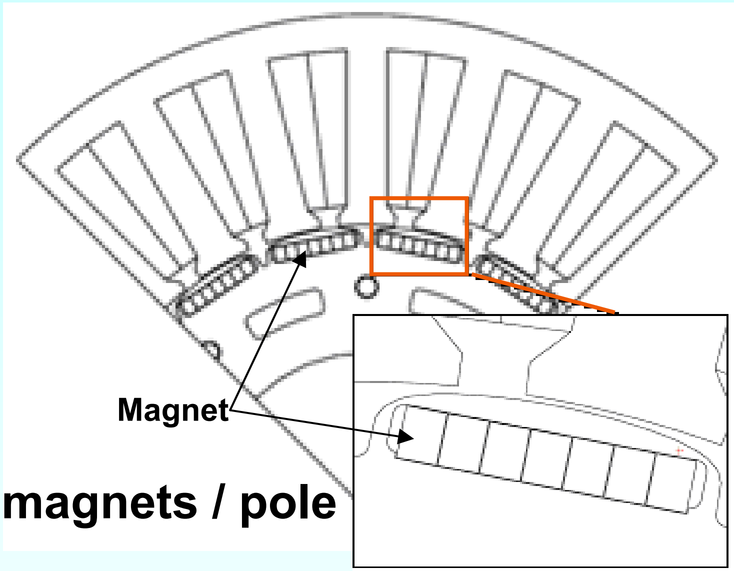
Motor A



- 7 magnets / pole

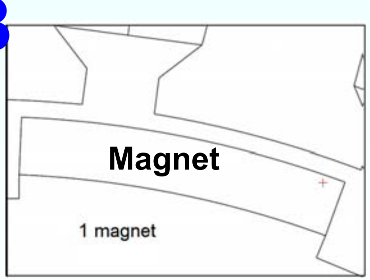
$q = \frac{1}{2}$

Motor C



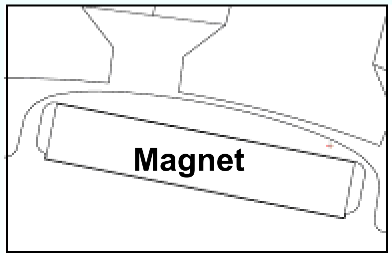
- 7 magnets / pole

Motor B



- 1 magnet / pole

Motor D



- 1 magnet / pole

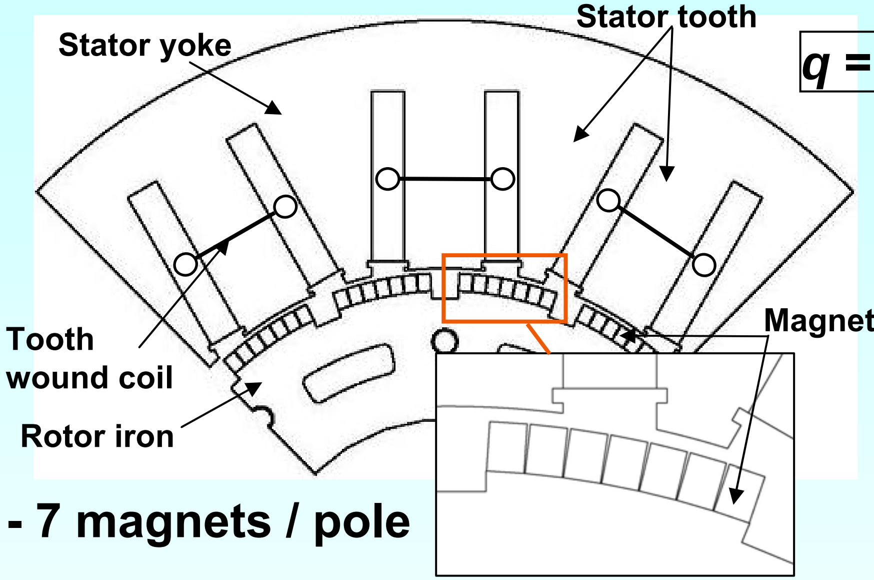
Surface mounted magnets

Buried magnets

24 semi-closed stator slots / 16 poles

Considered PM synchronous motors

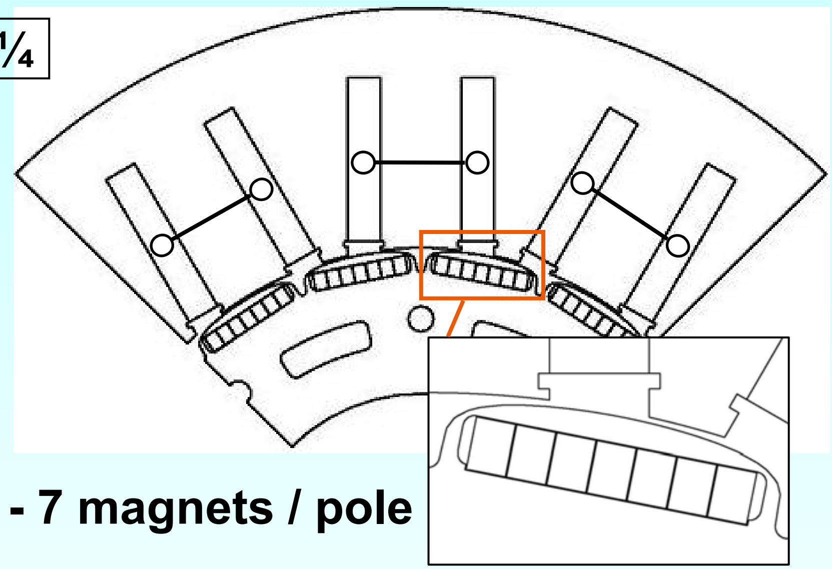
Motor E



- 7 magnets / pole

$q = \frac{1}{4}$

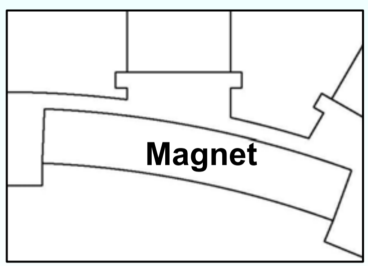
Motor G



- 7 magnets / pole

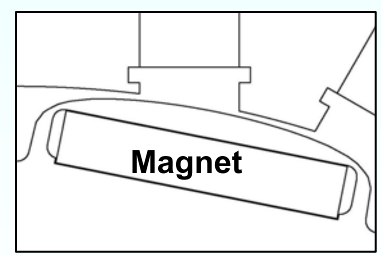
Motor F

- 1 magnet / pole



Motor H

- 1 magnet / pole

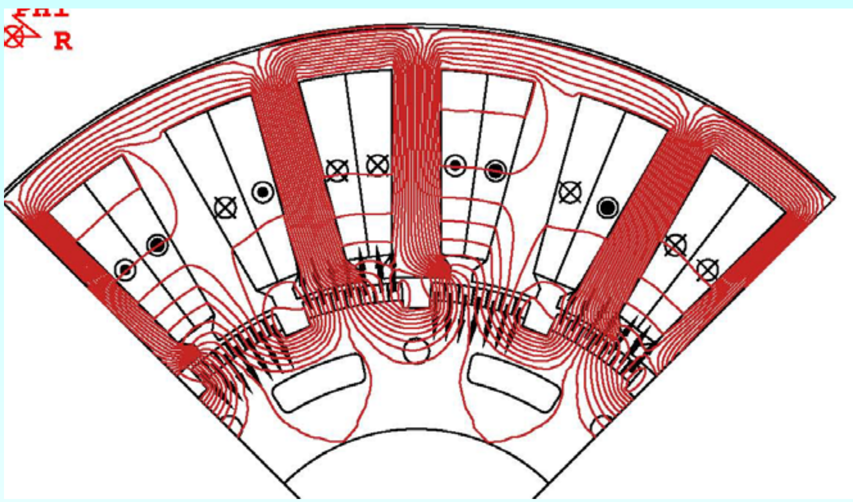


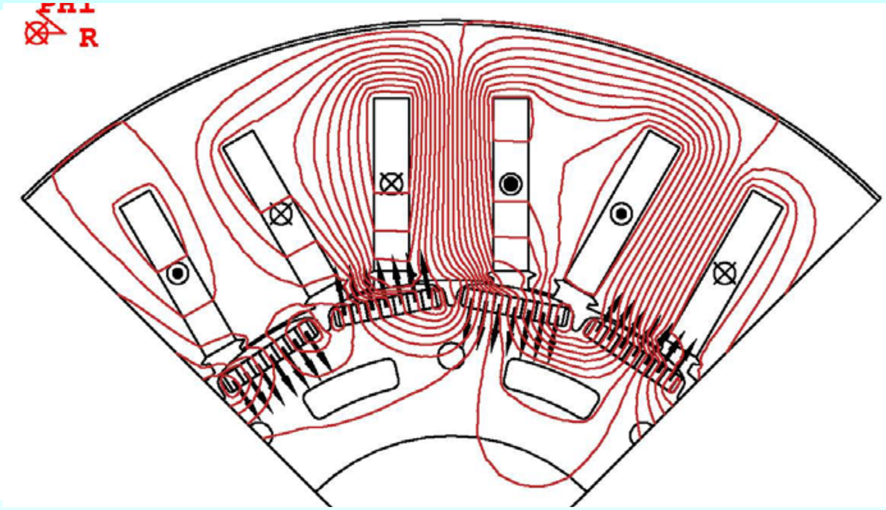
Surface mounted magnets

Buried magnets

24 open stator slots / 16 poles

High-torque Antriebe für höhere Drehzahlen





Alternative Motorkonzepte: 16-polige Statoren

	Variante A: q = 0.5	Variante G: q = 0.25
Wirkungsgrad *)	93.7% / 95.3 %	92.8 % / 93.3 %
bei 45 kW	1000 / 3000/min	1000 / 3000/min
Magnettemperatur	87°C	115°C

*) gemessen direkt bei:
Umrichterspeisung, Wärmeklasse F, 45 °C Kühlwasser

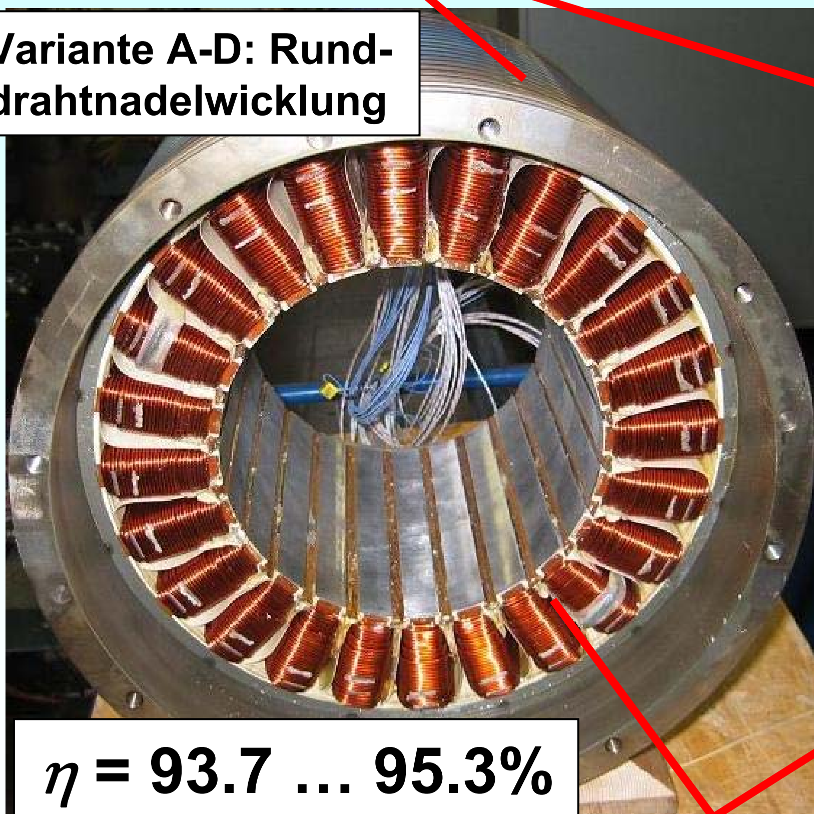
Zwei alternative Motorkonzepte: 16-polige Statoren
A-D: q = 0.5 (links)   E-H: q = 0.25 (rechts)

Kompakte Stator-Kupfer-Wicklung –
<u>geringere</u> Stromwärmeverluste

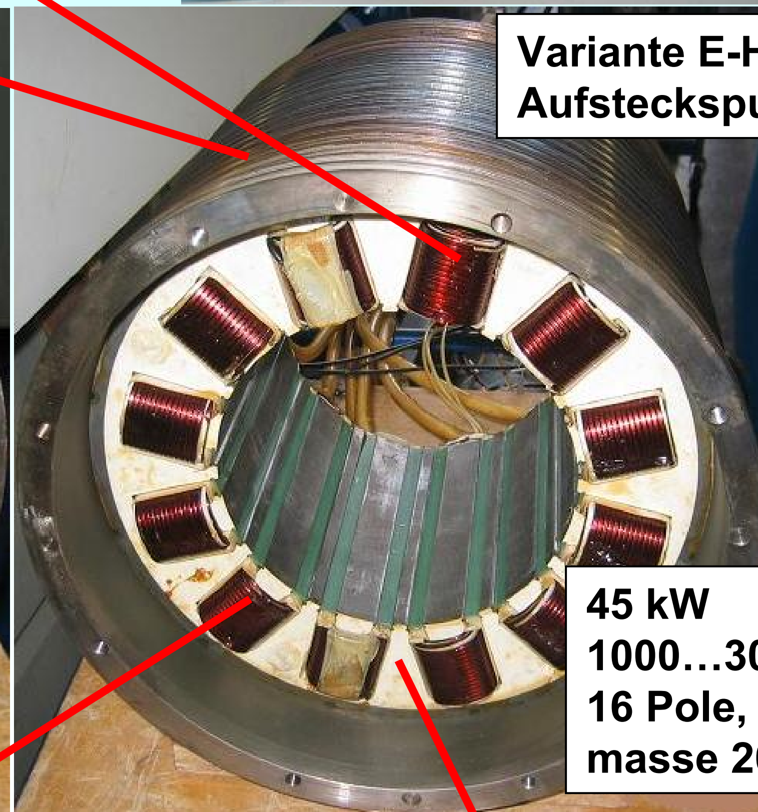
Kühlmantel

Zahnspule

Variante A-D: Runddrahtnadelwicklung



Variante E-H: Aufsteckspulen



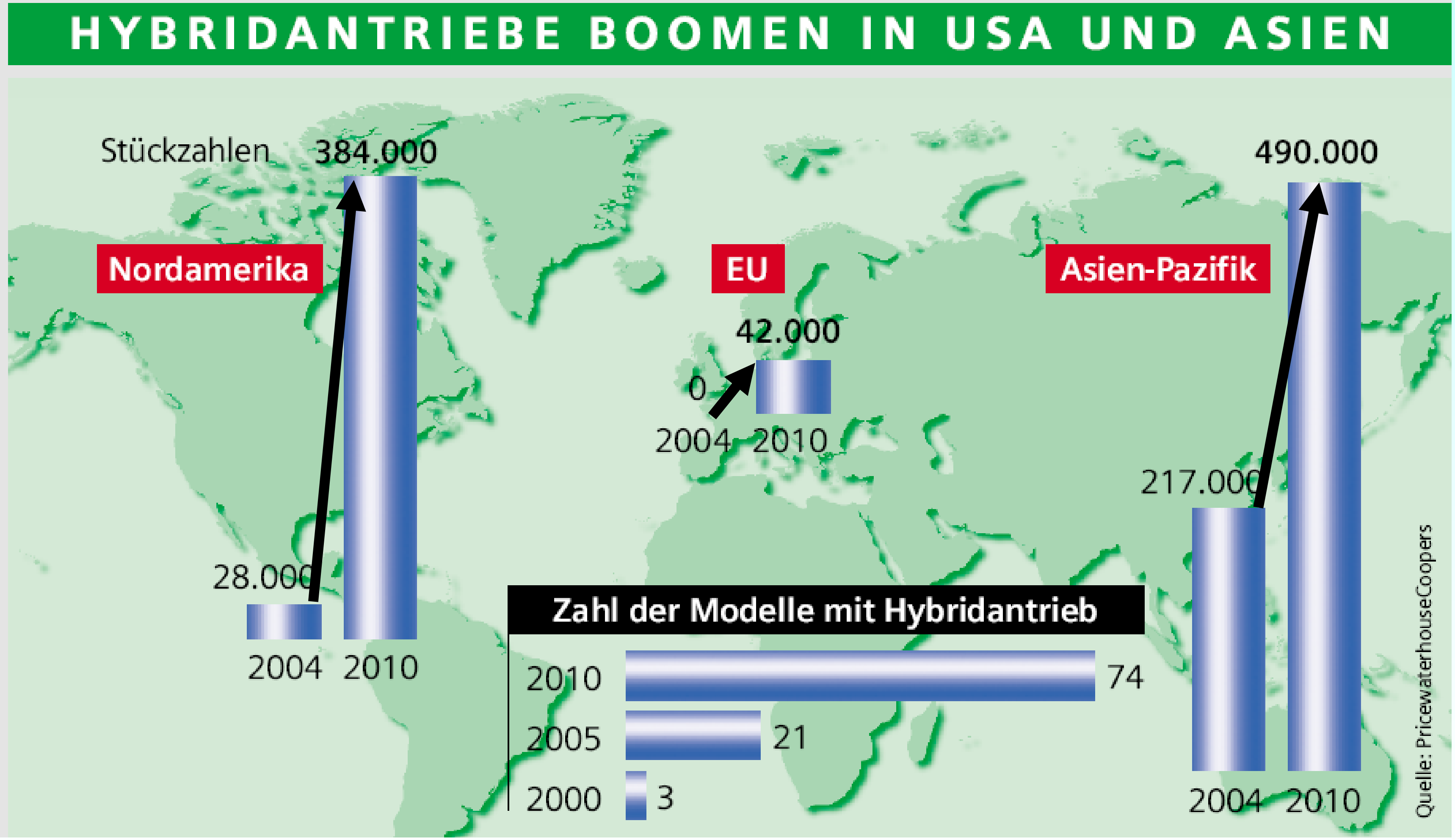
η = 93.7 … 95.3%

45 kW
1000…3000/min
16 Pole, Motormasse 200kg

Stator-Wicklung

Blechpaket

Zukunftsmarkt: E-Antriebe für Hybrid-Automobile ?



2004 → 2010

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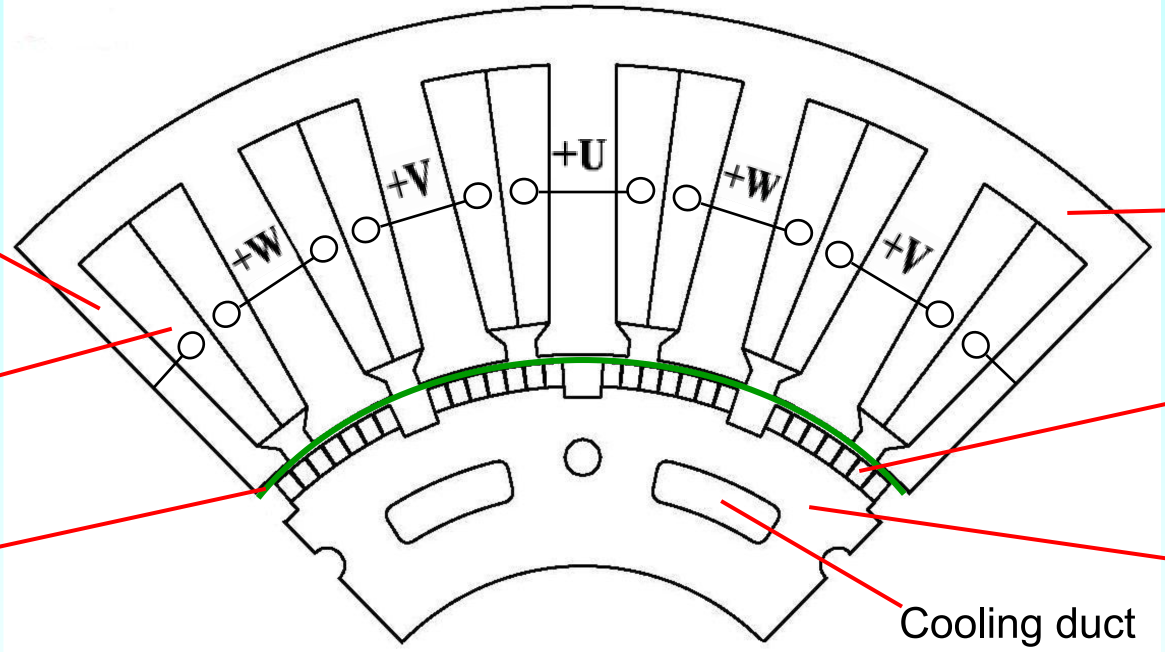
Geometry and winding design

Motor A



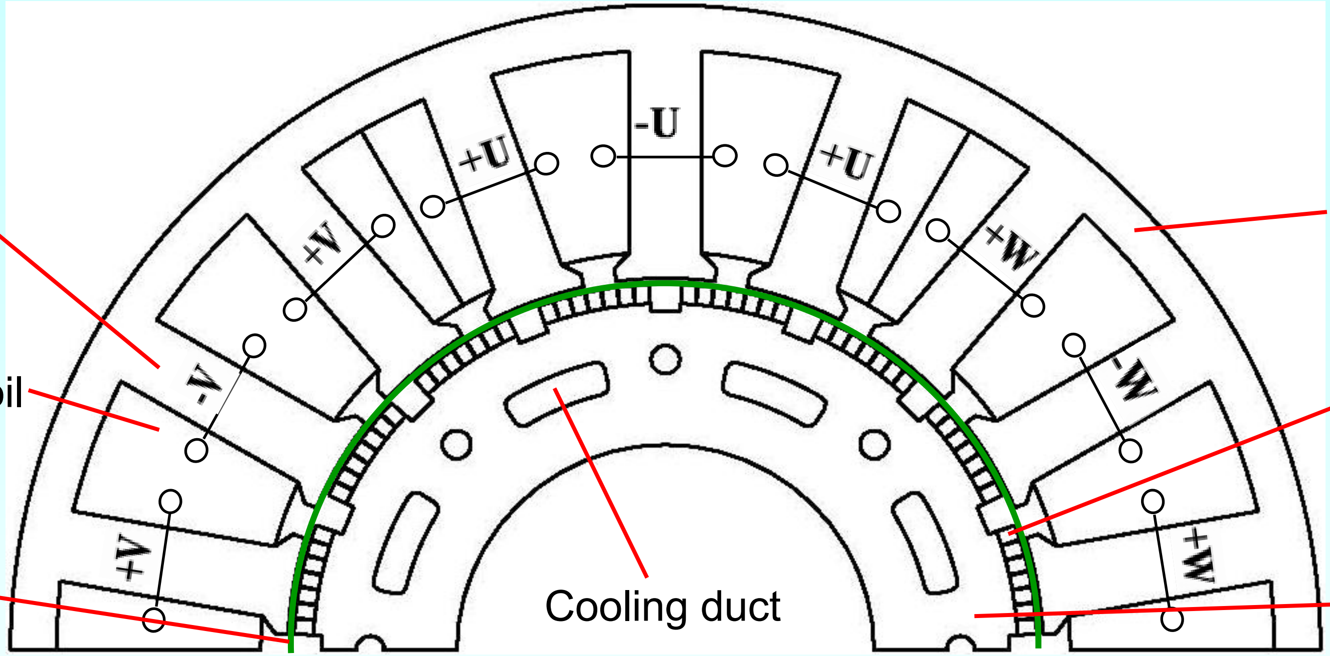
Motor	A	X	G
Stator outer diameter (mm)	314	314	314
Stator bore diameter (mm)	181	181	181
Active length (mm)	180	180	180
Number of stator slots	24	18	24
Number of poles	16	16	16
Air gap (mm)	0.7	0.7	0.5 $(=\delta_0)$
Bandage (mm)	0.7	0.7	-

Motor	A	X	G
Nr. of turns per phase	96	81	60
Nr. of parallel connections	8	2	4
Coils per pole and phase	0.5	0.38	0.25
Slot fill factor	0.41	0.39	0.59
Winding factor ($\nu = 1$)	0.866	0.94	0.98
Phase resistance (mΩ)*	70	57	48

* At 145° C

Geometry and winding design

Motor X



Motor	A	X	G
Stator outer diameter (mm)	314	314	314
Stator bore diameter (mm)	181	181	181
Active length (mm)	180	180	180
Number of stator slots	24	18	24
Number of poles	16	16	16
Air gap (mm)	0.7	0.7	0.5 (= δ_0)
Bandage (mm)	0.7	0.7	-

Motor	A	X	G
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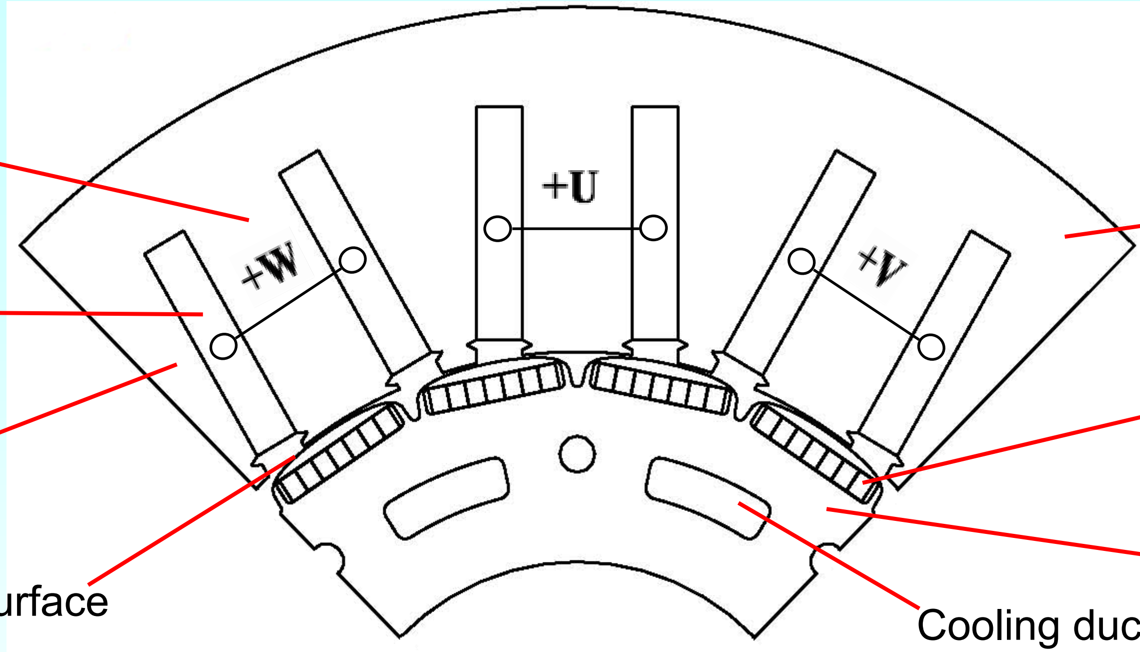
Geometry and winding design

Motor G



Motor	A	X	G
Stator outer diameter (mm)	314	314	314
Stator bore diameter (mm)	181	181	181
Active length (mm)	180	180	180
Number of stator slots	24	18	24
Number of poles	16	16	16
Air gap (mm)	0.7	0.7	0.5 ($=\delta_0$)
Bandage (mm)	0.7	0.7	-

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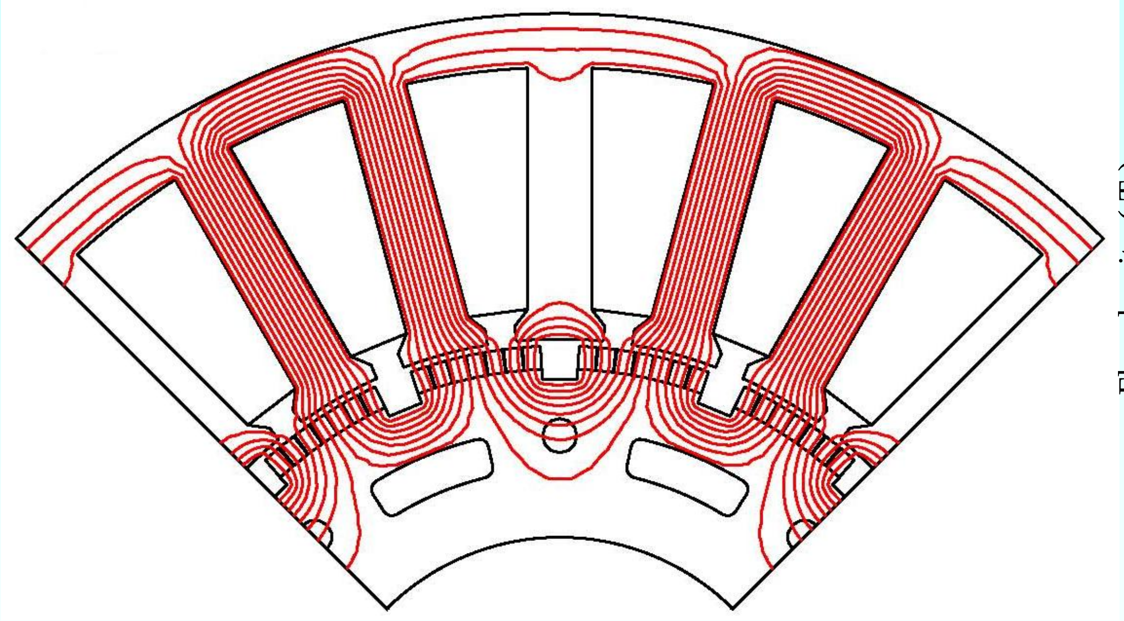
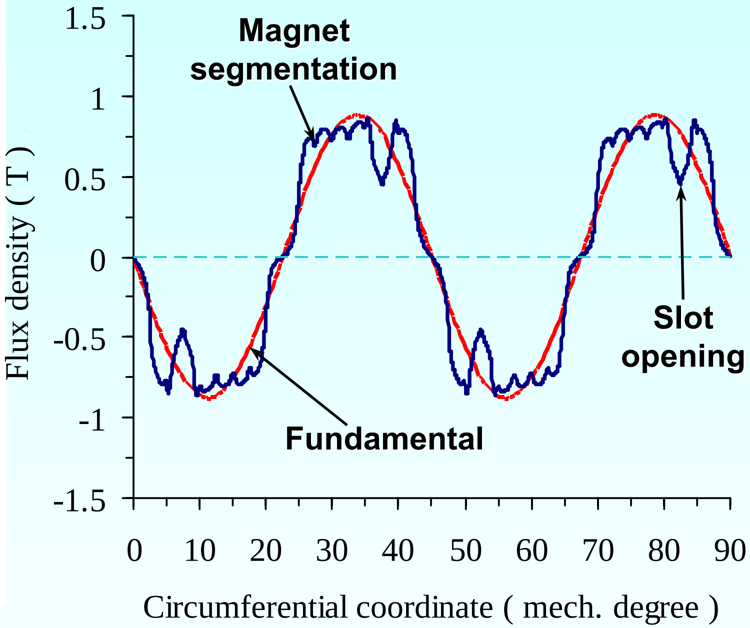
No-load operation

Motor A

Field distribution



Air gap flux density

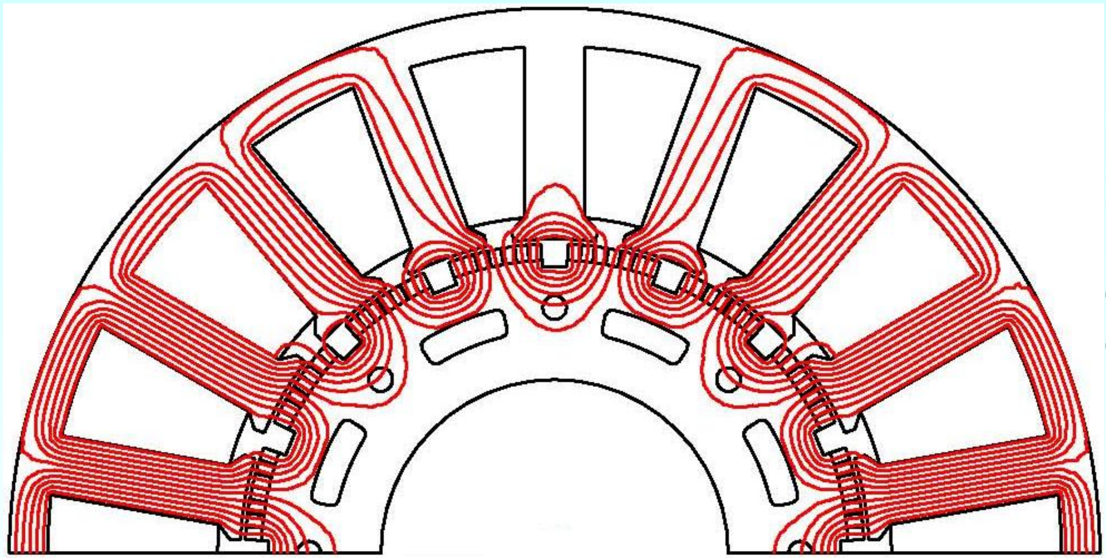


$B_{\delta0(1)} = 0.875$ T

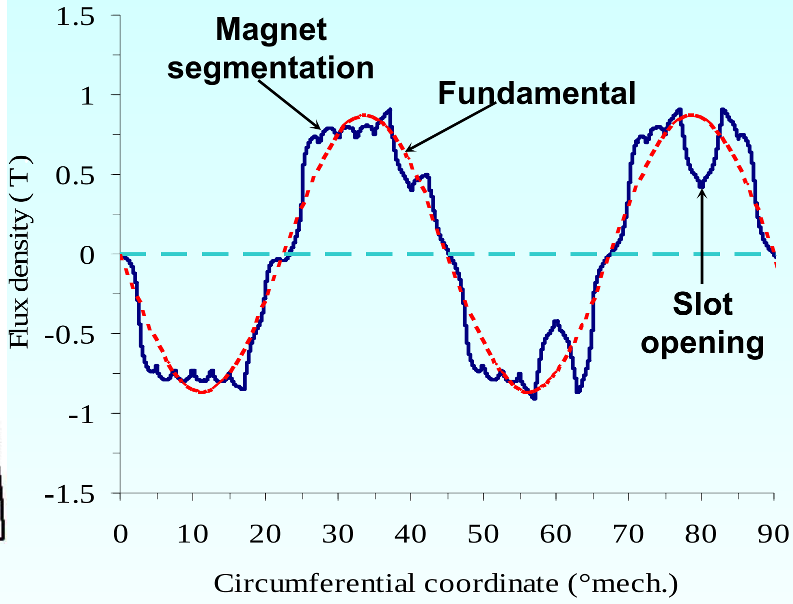
No-load operation

Motor X

Field distribution



Air gap flux density

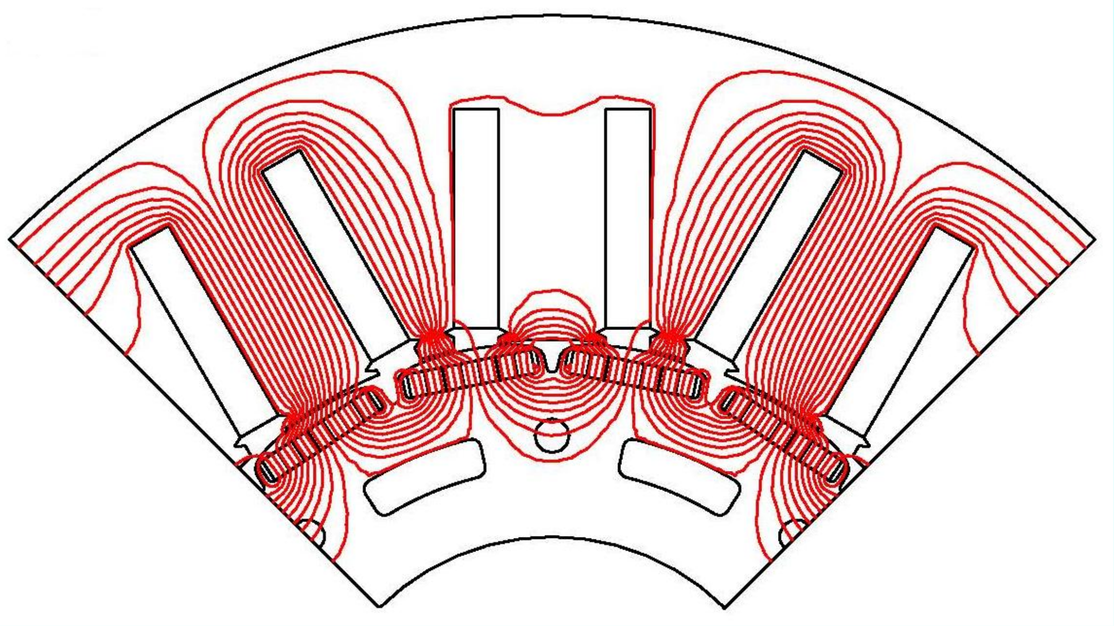


$$B_{\delta 0(1)} = 0.868 \text{ T}$$

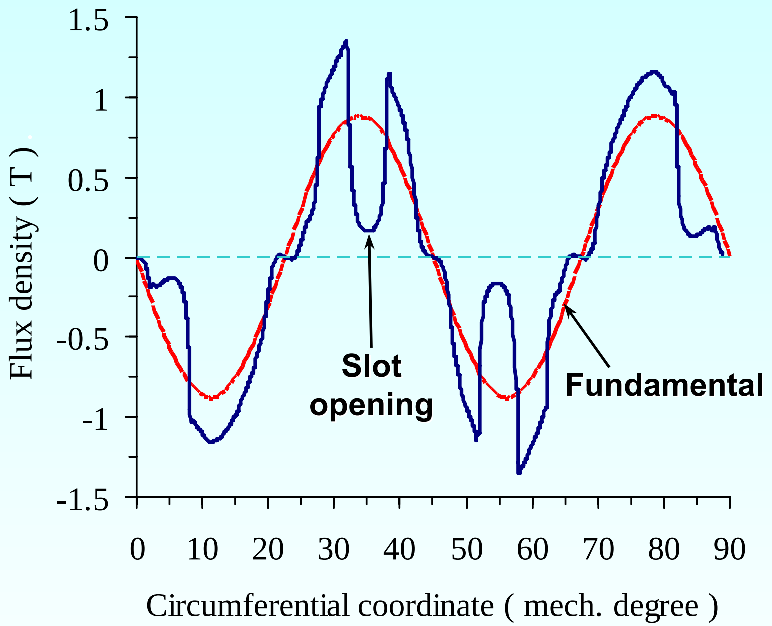
No-load operation

Motor G

Field distribution



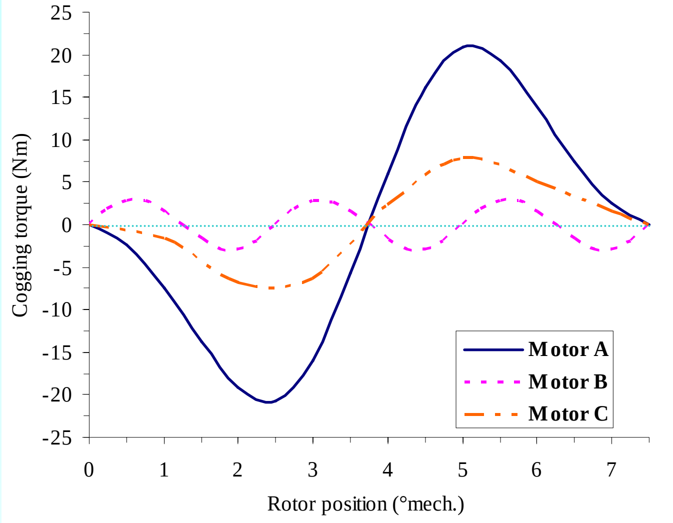
Air gap flux density



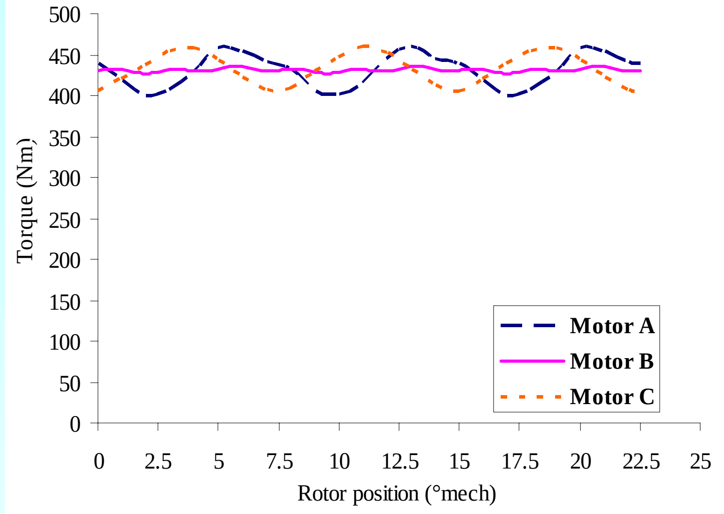
$B_{\delta 0(1)} = 0.87\ \mathrm{T}$

No-load and load torque

Cogging torque

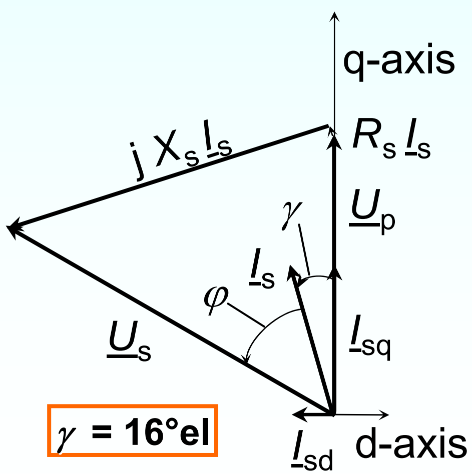


Torque ripple at rated speed



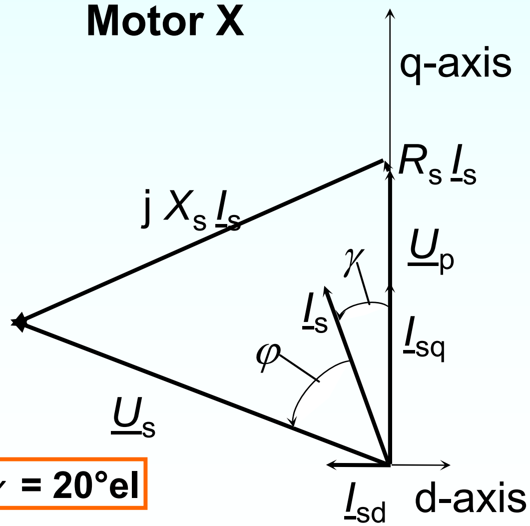
Phasor diagrams at rated speed

Motor A



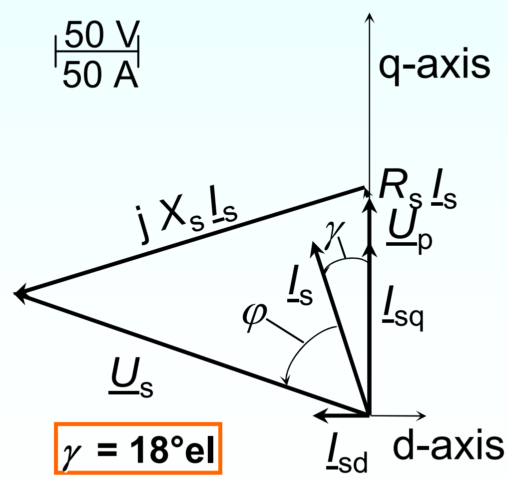
γ = 16°el

Motor X



γ = 20°el

Motor G



γ = 18°el

Comparison of the designed motors

	Motor A		Motor X		Motor G	
Speed (1/min)	1000	3000	1000	3000	1000	3000
Constant power (kW)	45	45	45	45	45	45
Phase voltage (V)	230	230	230	230	230	230
Phase current (A)	95	67	103	67	114	68.5
Power factor	0.72	1	0.66	0.98	0.6	0.97
Torque (Nm)	430	143	430	143	430	143
Torque density / active mass (Nm/kg)	5.56	1.85	5.56	1.85	4.77	1.59
Power density / active mass (kW/kg)	0.58	0.58	0.58	0.58	0.5	0.5
Torque ripple (% of rated torque)	7	7.3	1.04	0.7	6.4	2.7
Thermal load $A \cdot J$ (A/cm · A/mm^2)	5683	2827	5131	2156	5142	1834

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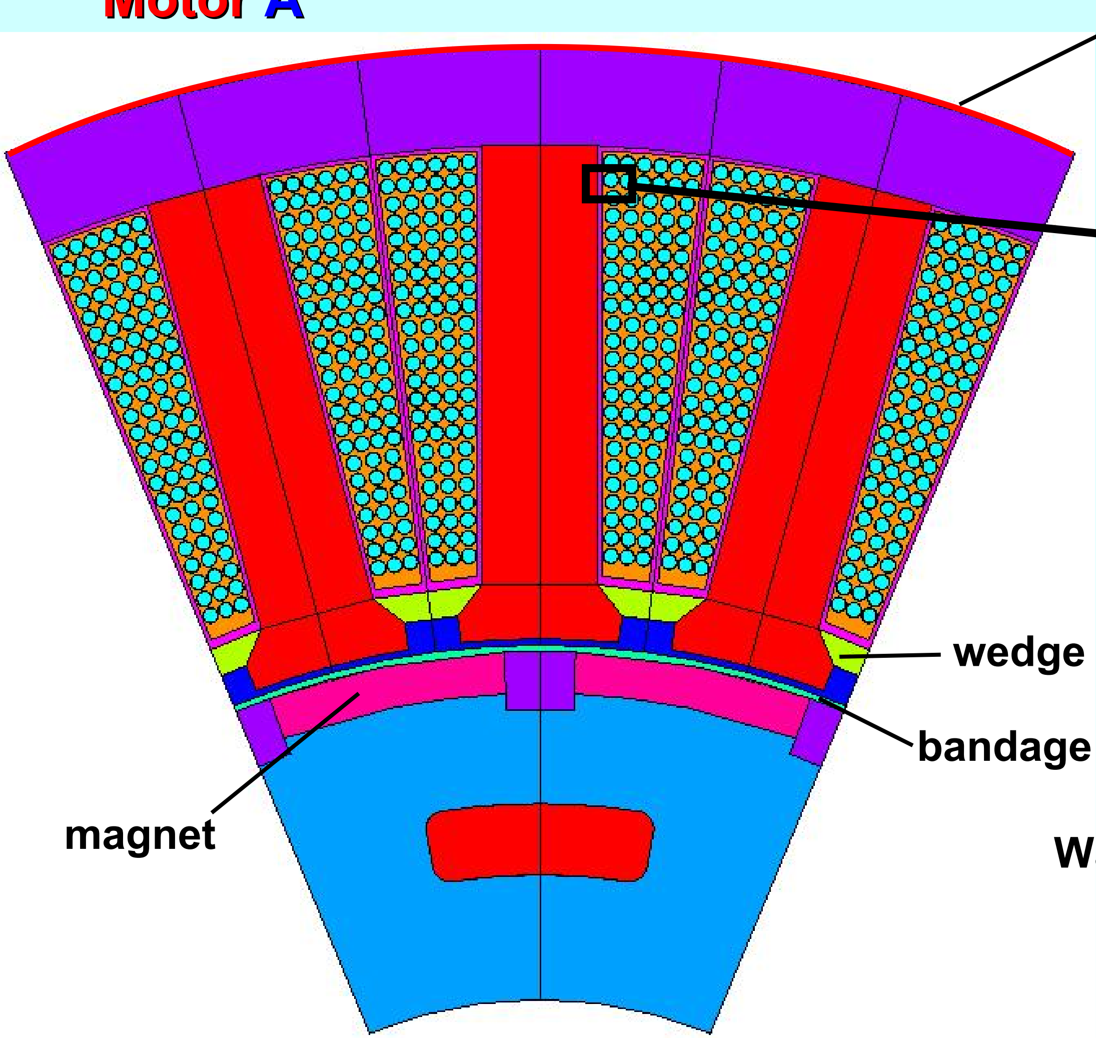
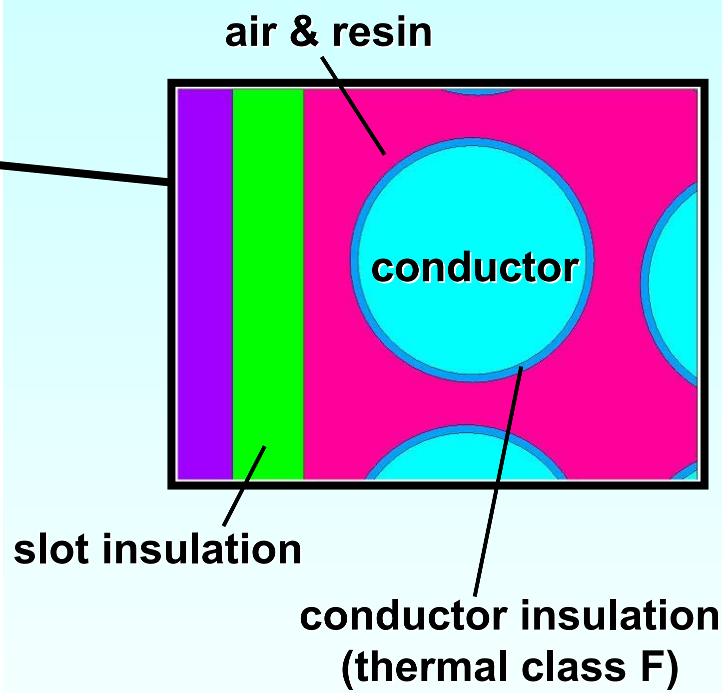
2D thermal Models

Motor A



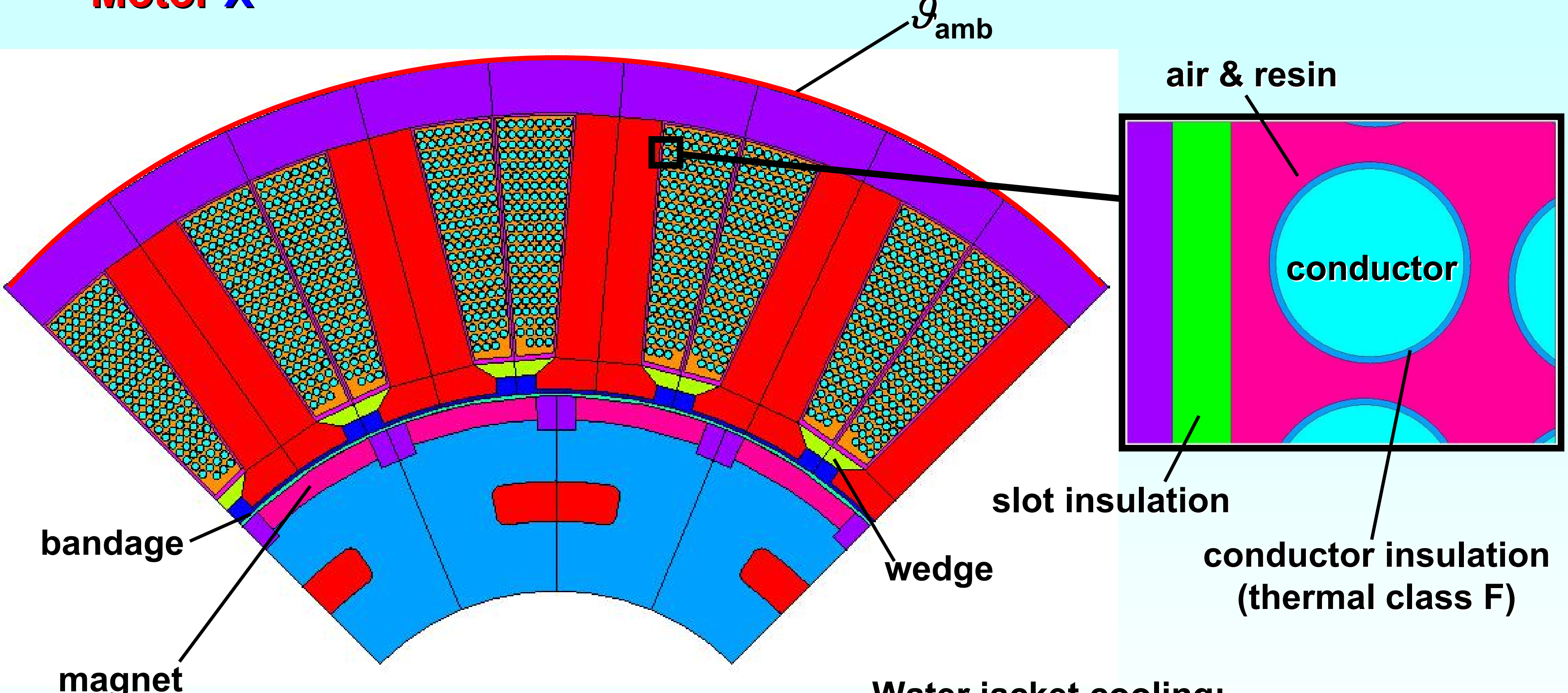


Water jacket cooling:

- inlet temperature ϑ_{in} = 38°C
- outlet temperature ϑ_{out} = 43.3 °C
- ambient temperature ϑ_{amb}= 44.2 °C

2D thermal Models

Motor X

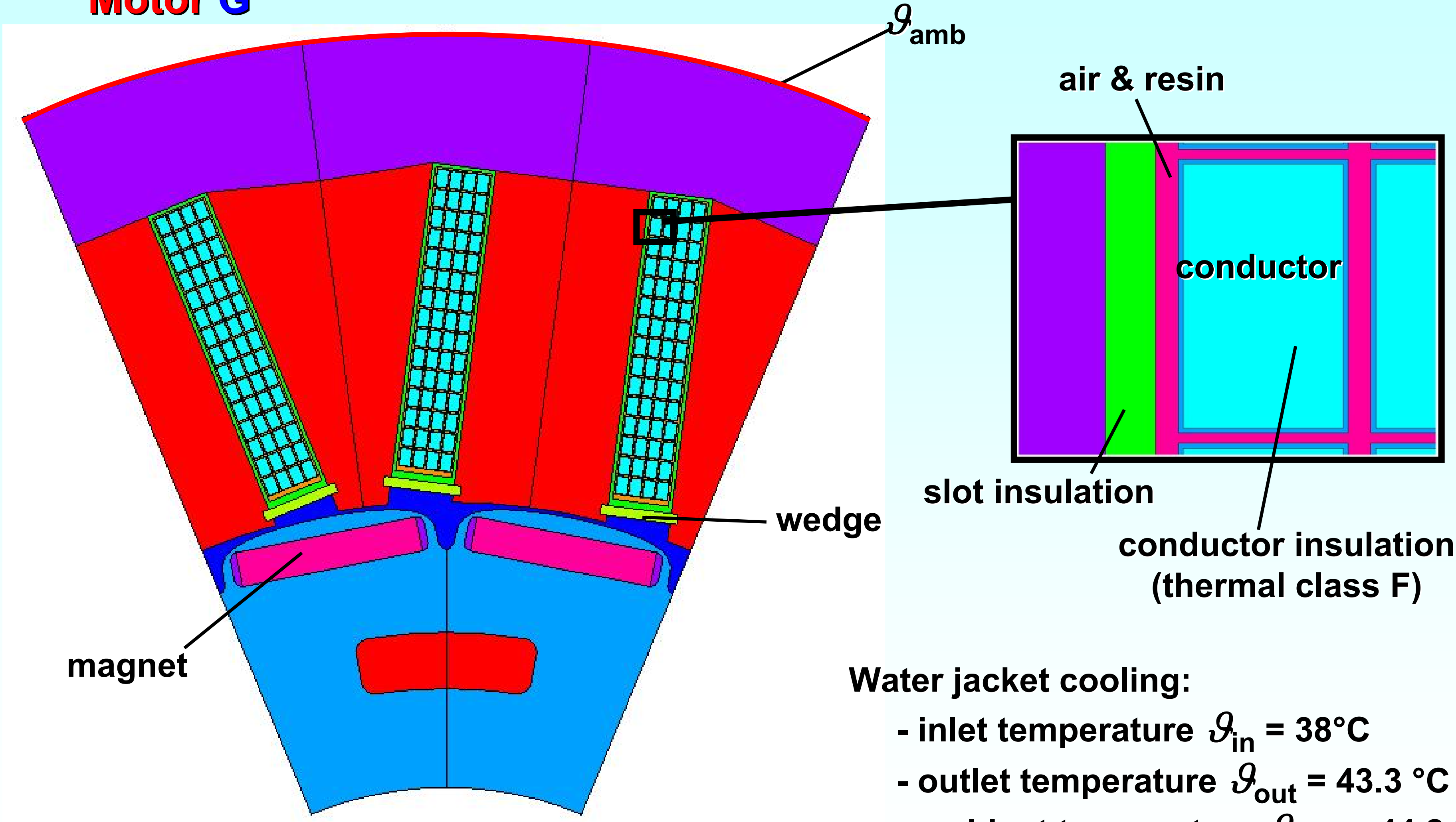


Water jacket cooling:

- inlet temperature ϑ_{in} = 38°C
- outlet temperature ϑ_{out} = 43.3 °C
- ambient temperature ϑ_{amb}= 44.2 °C

2D thermal Models

Motor G



Water jacket cooling:

- inlet temperature ϑ_{in} = 38°C
- outlet temperature ϑ_{out} = 43.3 °C
- ambient temperature ϑ_{amb}= 44.2 °C

Loss distribution

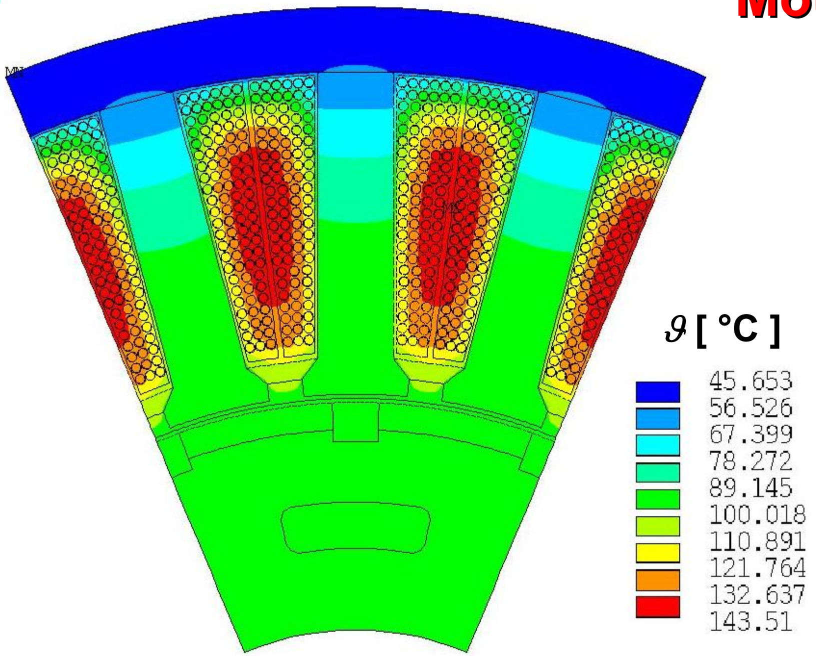
	Motor A		Motor X		Motor G	
Speed (1/min)	1000	3000	1000	3000	1000	3000
Copper Losses (at 145 °C) * (W)	2171	1846	2523	3042	2142	1470
Iron losses in teeth * (W)	800	845	669	875	698	1052
Iron losses in yoke * (W)	250	392	284	470	249	346
Magnet losses * (W)	47	158	53	184	32	77
Friction losses (W)	-	-	-	-	-	-
Total losses	3268	3241	3529	4571	3121	2945

* Sinus + inverter supply: Analytical calculation

Heat distribution at rated speed & torque

Motor A

Rated speed



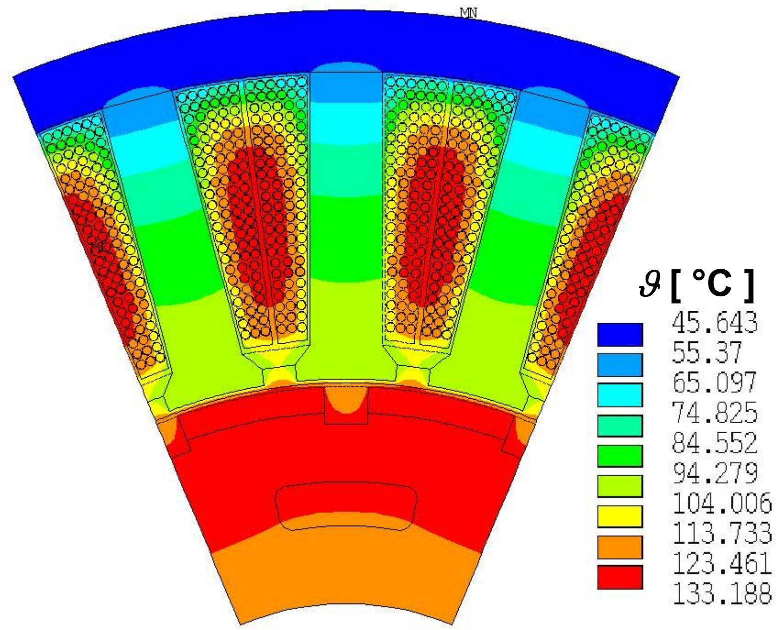
Hotspot: $\vartheta_{hotspot}$ = 144 °C

$\Delta\vartheta_{hotspot}$ = 104 K

Average: $\vartheta_{average}$ = 119 °C

$\Delta\vartheta_{average}$ = 79 K

Maximum speed



Hotspot: $\vartheta_{hotspot}$ = 133 °C

$\Delta\vartheta_{hotspot}$ = 93 K

Average: $\vartheta_{average}$ = 112 °C

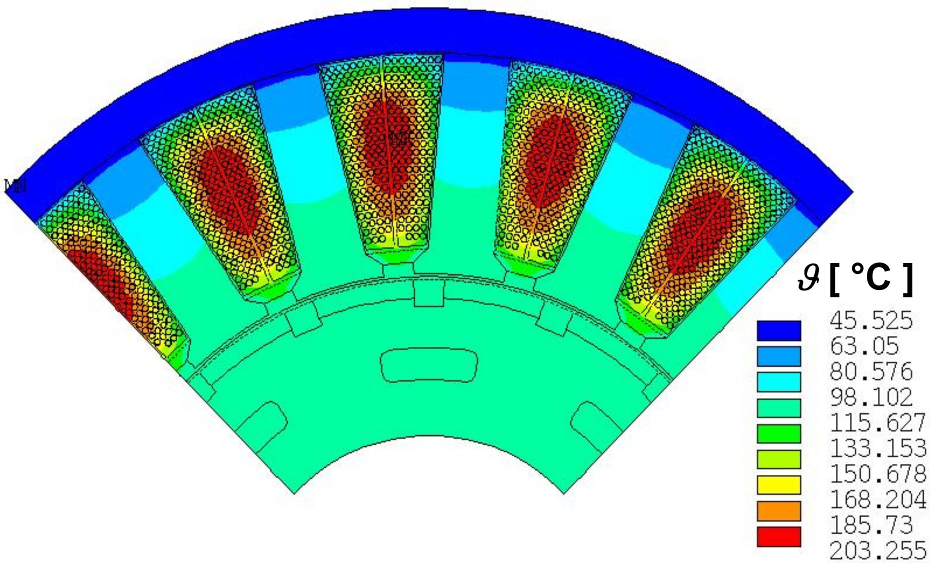
$\Delta\vartheta_{average}$ = 72 K

Thermal class F: $\Delta\vartheta_{average,lim}$ = 105 K; $\vartheta_{average,lim}$ = 145 °C; $\Delta\vartheta_{hotspot,lim}$ = 115 K; $\vartheta_{hotspot,lim}$ = 155 °C

Heat distribution at rated speed & torque

Motor X

Rated speed



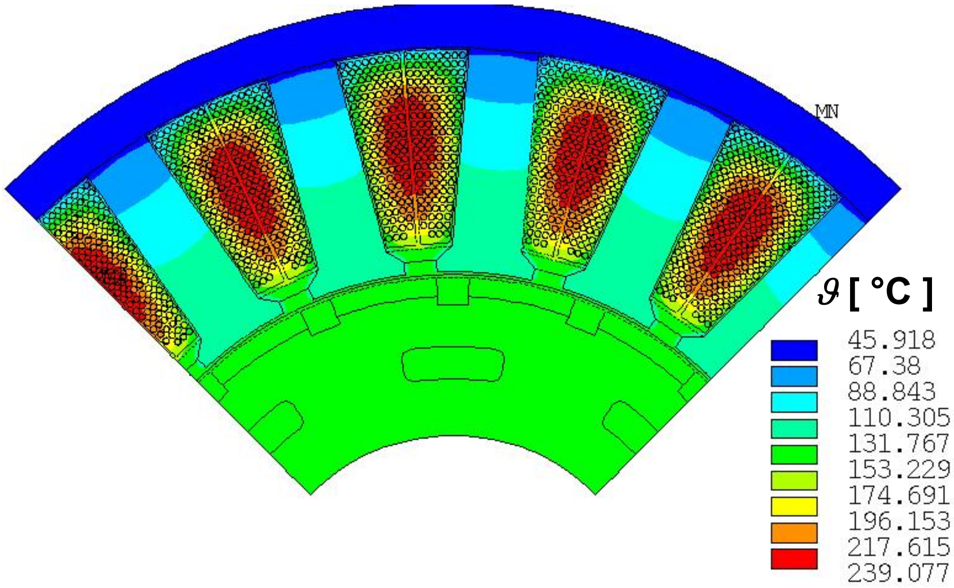
Hotspot: $\vartheta_{hotspot}$ = 203 °C

$\Delta\vartheta_{hotspot}$ = 163 K

Average: $\vartheta_{average}$ = 155 °C

$\Delta\vartheta_{average}$ = 115 K

Maximum speed



Hotspot: $\vartheta_{hotspot}$ = 239 °C

$\Delta\vartheta_{hotspot}$ = 199 K

Average: $\vartheta_{average}$ = 181 °C

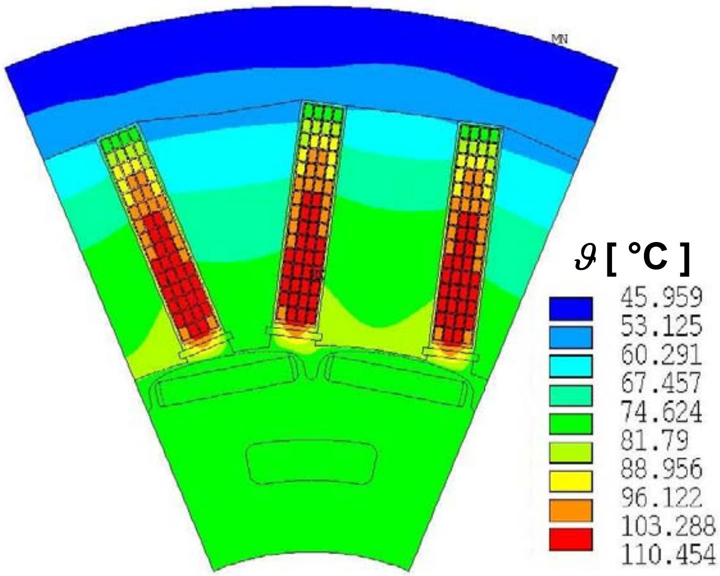
$\Delta\vartheta_{average}$ = 141 K

Thermal class F: $\Delta\vartheta_{average,lim}$ = 105 K; $\vartheta_{average,lim}$ = 145 °C; $\Delta\vartheta_{hotspot,lim}$ = 115 K; $\vartheta_{hotspot,lim}$ = 155 °C

Heat distribution at rated speed & torque

Motor G

Rated speed



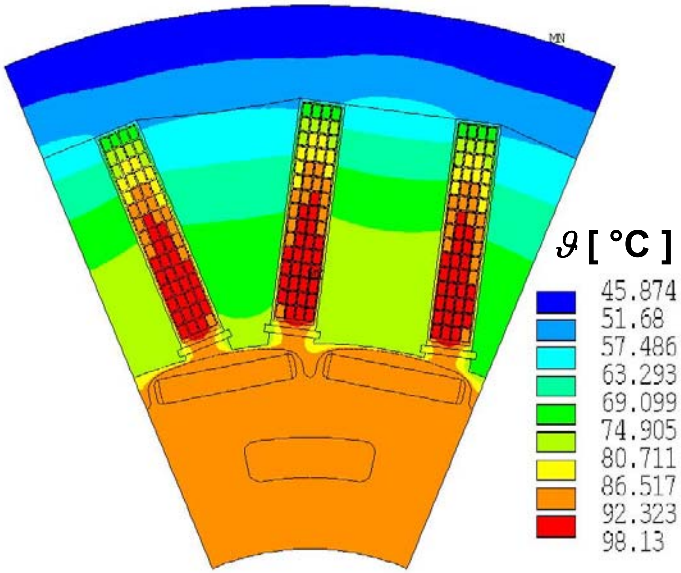
Hotspot: $\vartheta_{hotspot}$ = 110 °C

$\Delta\vartheta_{hotspot}$ = 70 K

Average: $\vartheta_{average}$ = 100 °C

$\Delta\vartheta_{average}$ = 60 K

Maximum speed



Hotspot: $\vartheta_{hotspot}$ = 98 °C

$\Delta\vartheta_{hotspot}$ = 58 K

Average: $\vartheta_{average}$ = 89 °C

$\Delta\vartheta_{average}$ = 49 K

Thermal class F: $\Delta\vartheta_{average,lim}$ = 105 K; $\vartheta_{average,lim}$ = 145 °C; $\Delta\vartheta_{hotspot,lim}$ = 115 K; $\vartheta_{hotspot,lim}$ = 155 °C

Design features

- Torque density: 5.56 Nm/kg (motor A & X), 4.77 Nm/kg (motor G)
- Power density: 0.58 kW/kg (motor A & X), 0.5 kW/kg (motor G)
- Increased power factor due to negative d-current supply:
    - 0.64 →0.72 (motor A), 0.58 →0.66 (motor X), 0.52→0.6 (motor G)
- 2D thermal models (overhang losses in slots included):
    - temperature reserve: 10 K (motor A)   & 45 K (motor G)
    - overheating by motor X

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Built prototype rotors

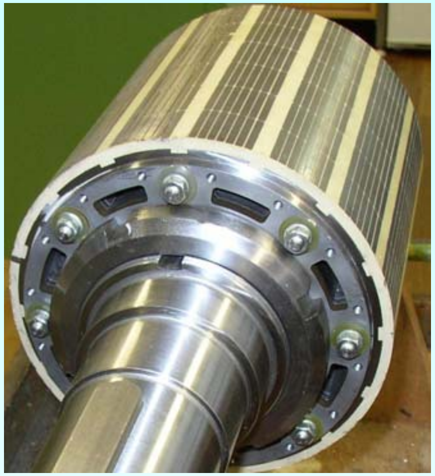
Rotor 1 with surface mounted segmented magnets

Magnets

Rotor lamination

Gluing of the magnets

Filling the pole gaps



Bandage

Rotor 3 with buried segmented magnets

Magnets

Rotor lamination

Inserting the magnets

6 x

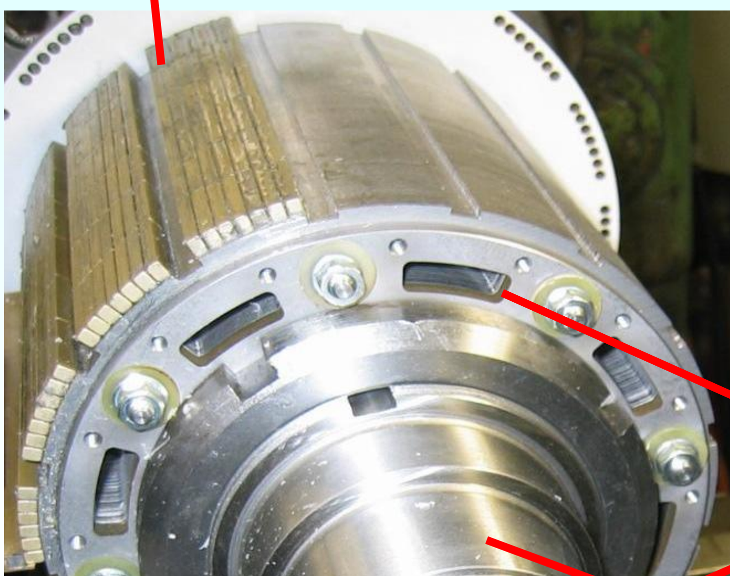
6 Packages

Assembling

Vermeidung von Magnetverlusten: Segmentierte NdFeB-Magnete, Rotor 1

Permanentmagnete erzeugen verlustfrei das Magnetfeld

Magnete

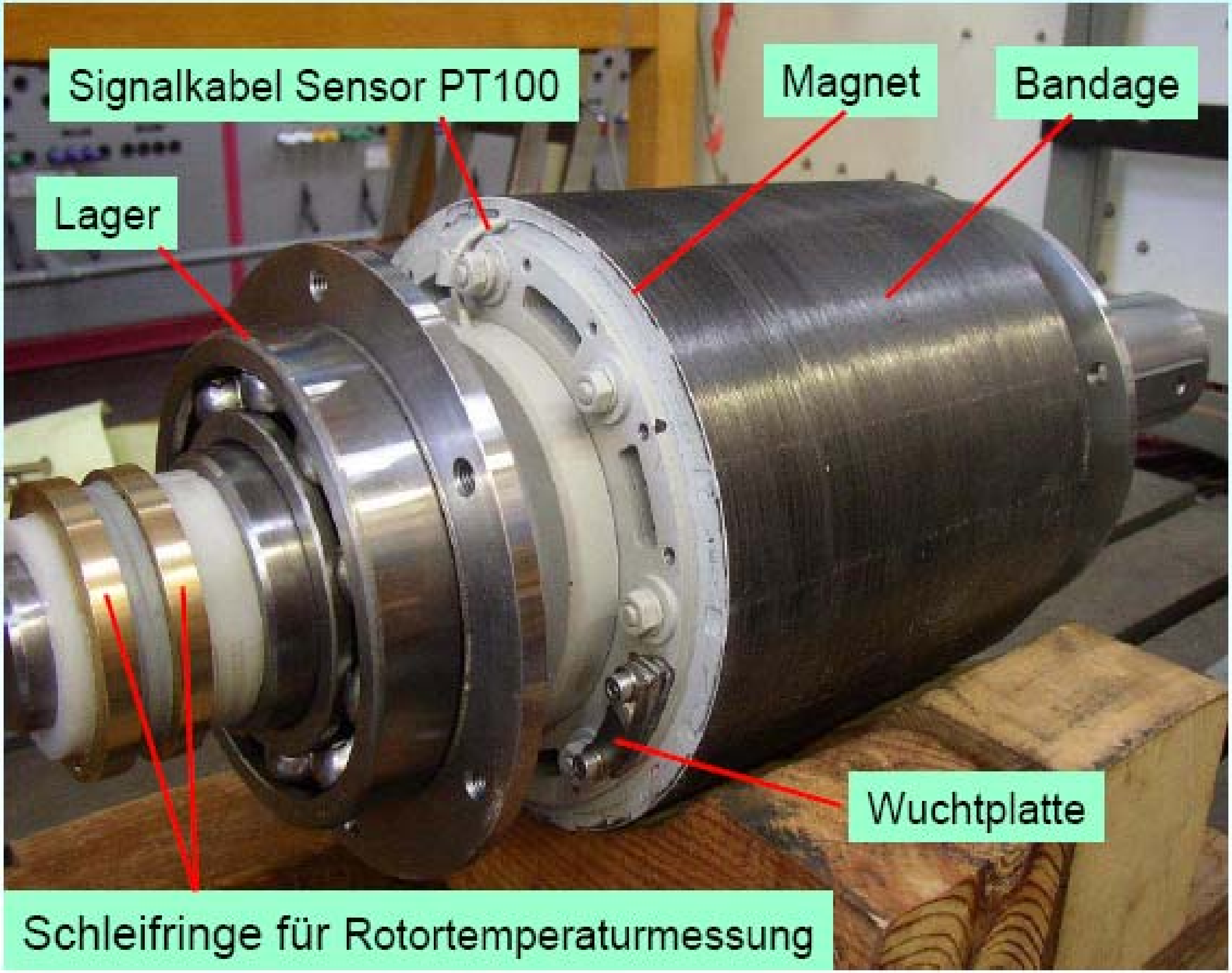


Kohlefaserbandage

Welle **Rotorblechpaket**

Built prototype rotors

Rotor 2 with surface mounted non-segmented magnets



Magnetpol nur in axiale Richtung segmentiert: 4 x 45 mm statt 6 x 30 mm (Rotor A und C)

Built prototypes

Stator A-D

Cu-wire

Stator lamination

Winding

Cooling jacket

Heating of the cooling jacket and mounting it on the stator lamination

Stator E-H

Preformed coil

Stator lamination

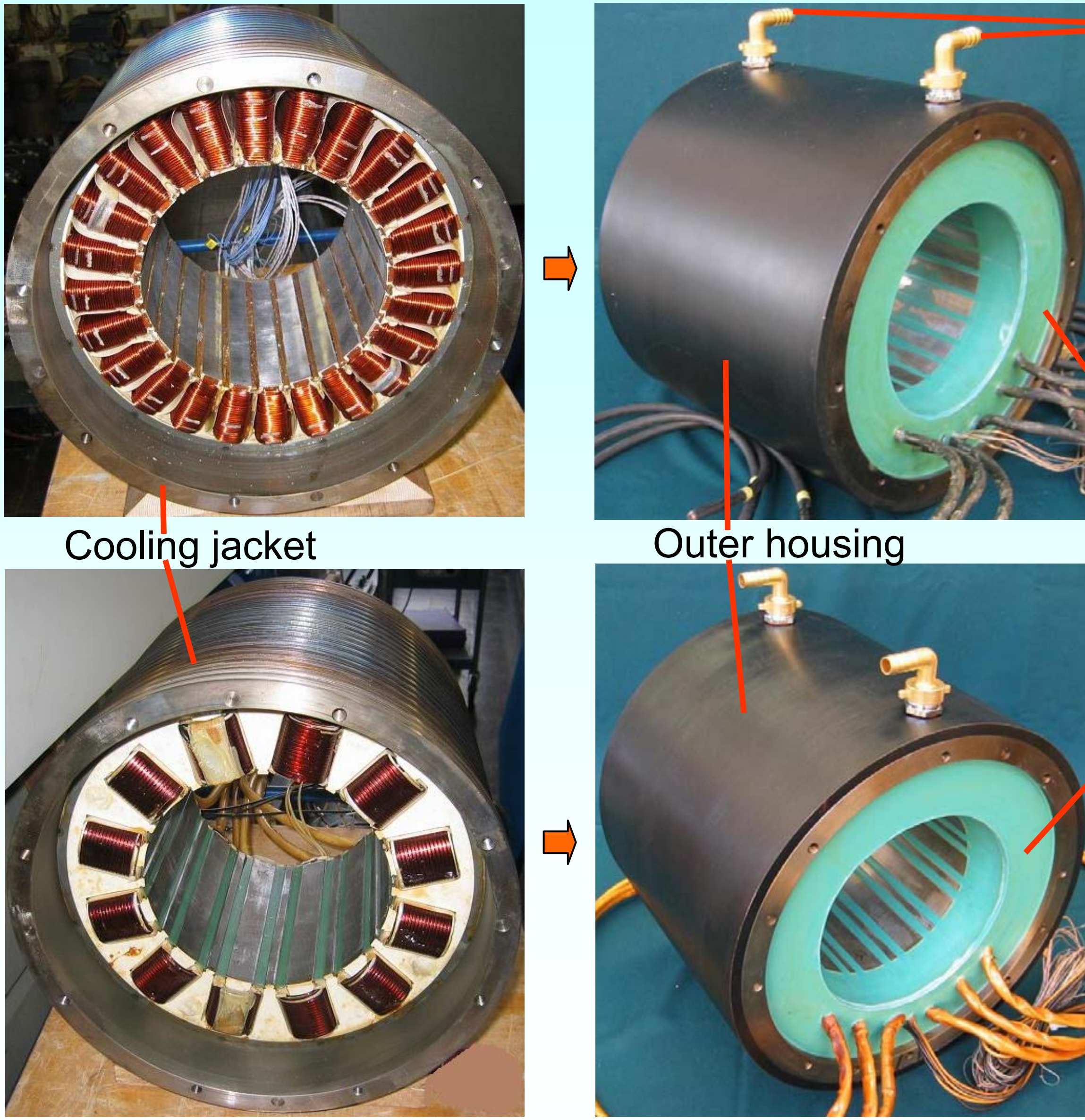
Winding

Cooling jacket

Built prototype stators

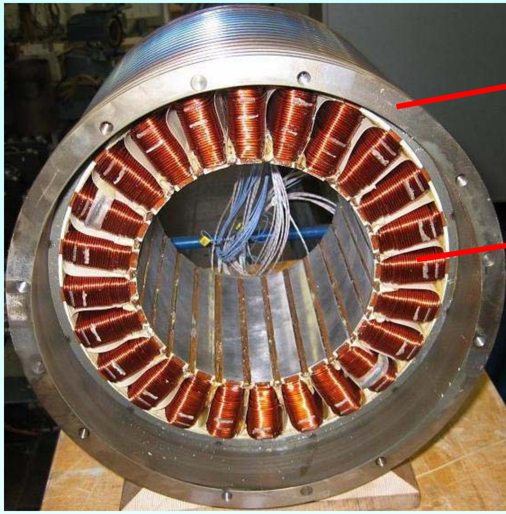
Stator A-D

Stator E-H



Gemessene Motoren

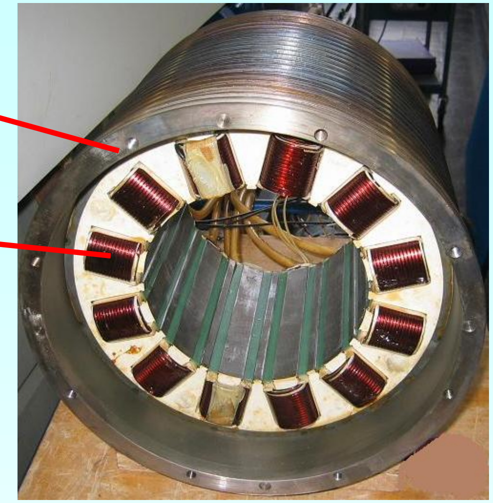
Stator A-D



Kühlanlage

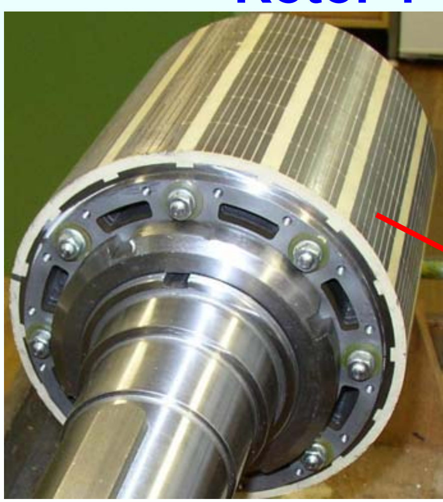
Wicklung

Stator E-H



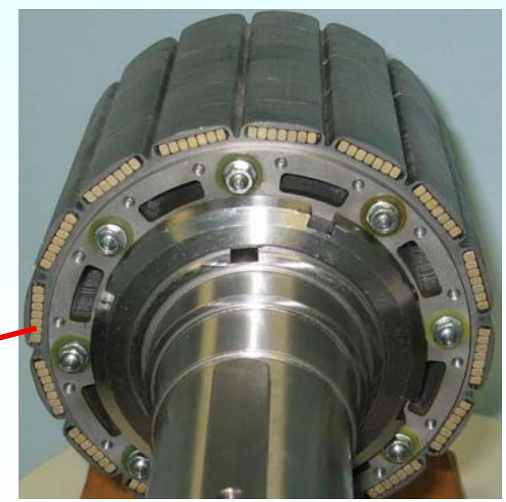
	Rotor		
Stator	1	2	3
A-D	A	B	C
E-H	E	F	G

Rotor 1



Magnet

Rotor 3

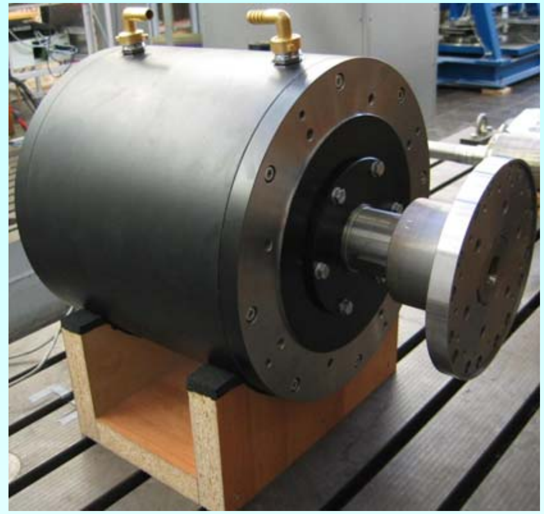


Built prototype machines

Stator A-D **Stator E-H**

Rotor 1 with surface segmented magnets

Rotor 3 with buried segmented magnets



End shields

Bearing

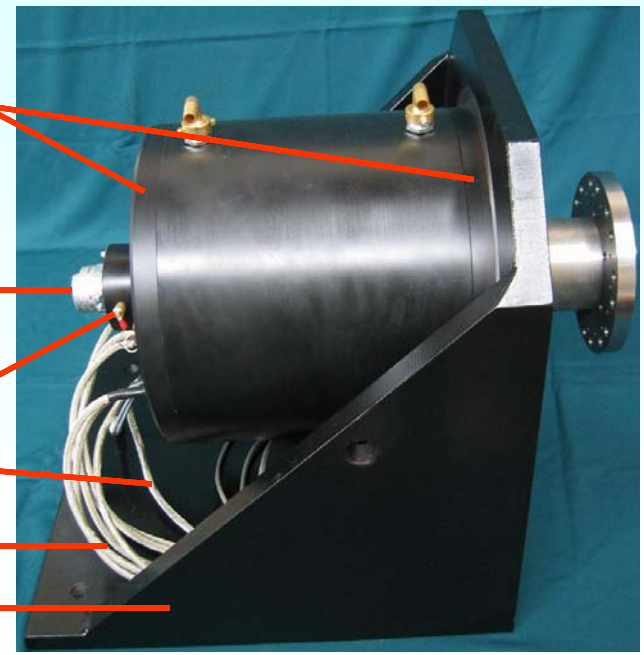
Encoder

Cu- Brushes

Thermal sensors

Supply cables

Support



Overview

- Introduction
- Considered PM synchronous motors
- Electromagnetic performance
- Thermal analysis
- Built prototypes
- Rotor loss calculation methods
- Loss estimation from thermal measurements
- Conclusions

Rotor losses

Permanent - Magnet motors with concentrated windings

Increased eddy current losses in the rotor magnets:

- air gap field pulsations due to the slot openings
- flux pulsations in the magnets at load operation

Segmented Magnets

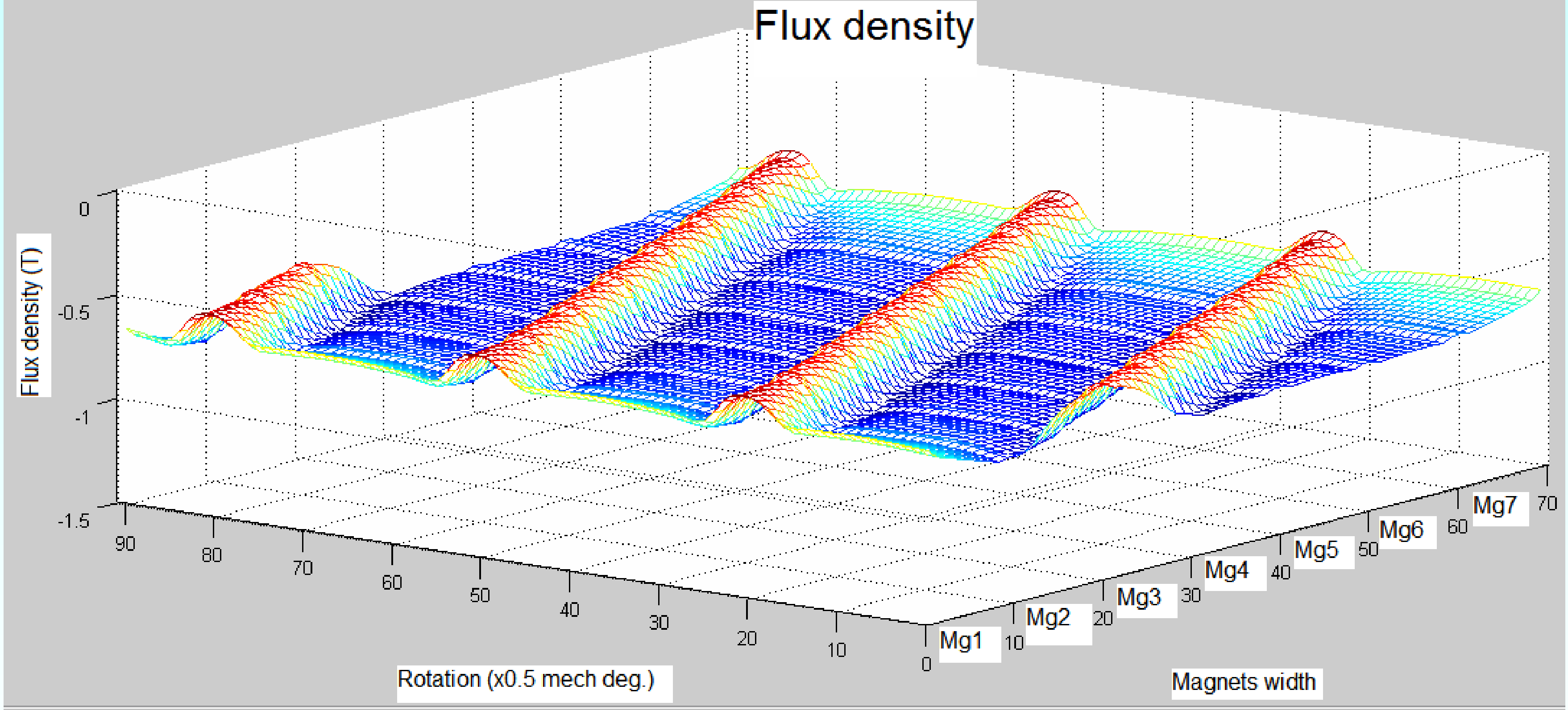
7 PM segments

1 Pole

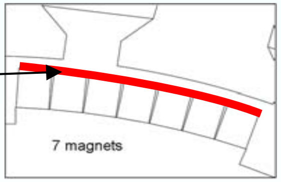
Calculated: 8 PM motors A, B, C, D, E, F, G, H; Measured: 6!
(2 Stators & 4 Rotors): **Constant power: 45 kW**
Rated speed: 1000 rpm
Maximum speed: 3000 rpm

Flux density for Motor A

1000 rpm, no-load operation



***B*(*x*) at upper surface**

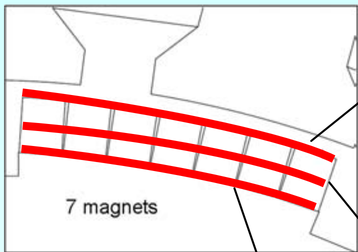


FEMAG-DC (no eddy currents considered!)

Flux density for Motor A

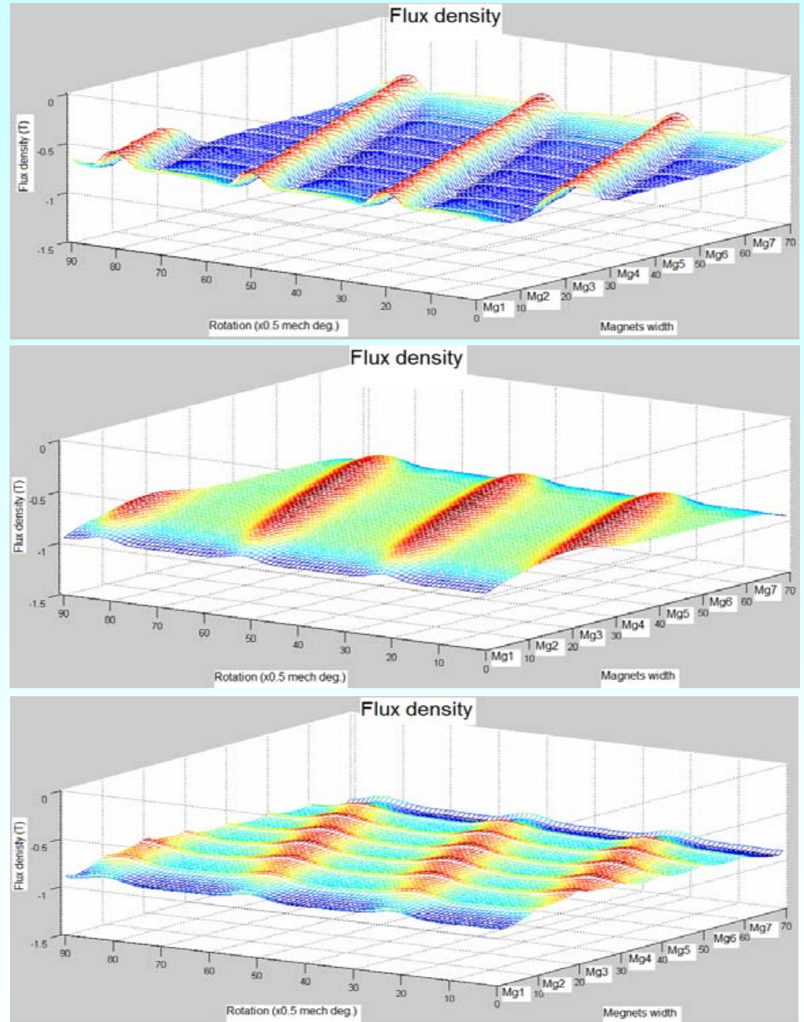
1000 rpm, no-load operation

Upper surface



Middle surface

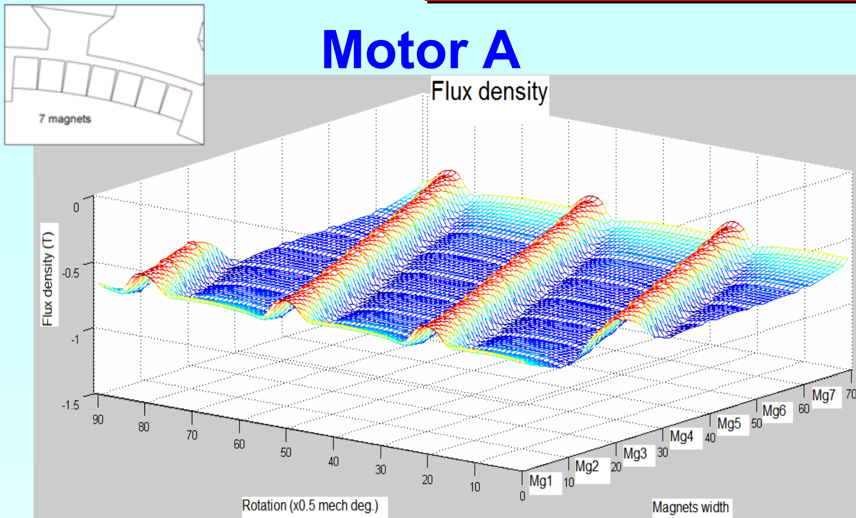
Bottom surface



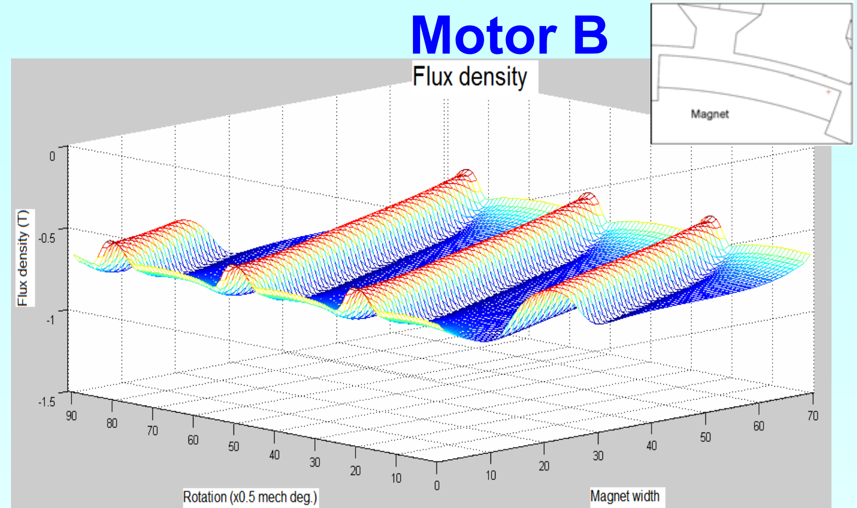
FEMAG-DC (no eddy currents considered!)

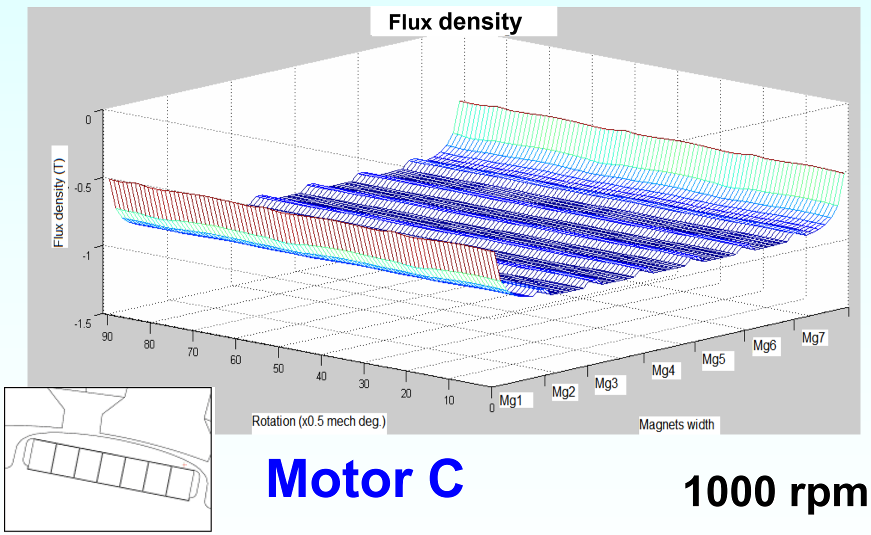
Flux density at no-load operation

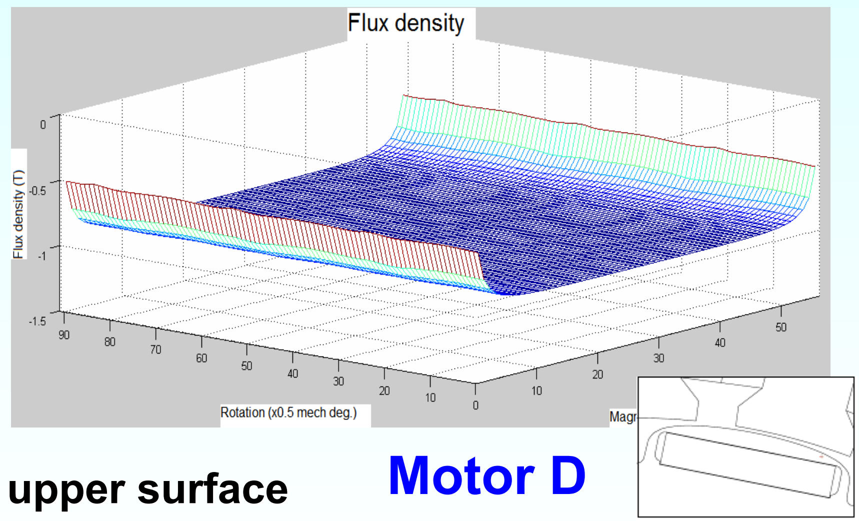
Motor A



Motor B







Motor C

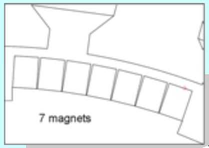
1000 rpm, upper surface

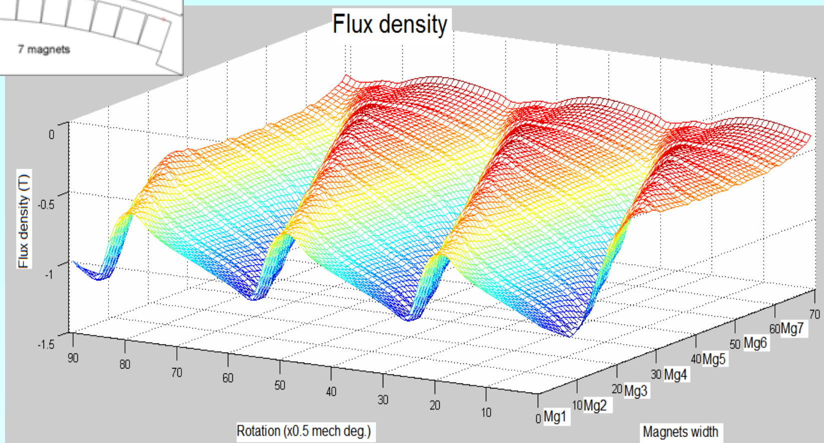
Motor D

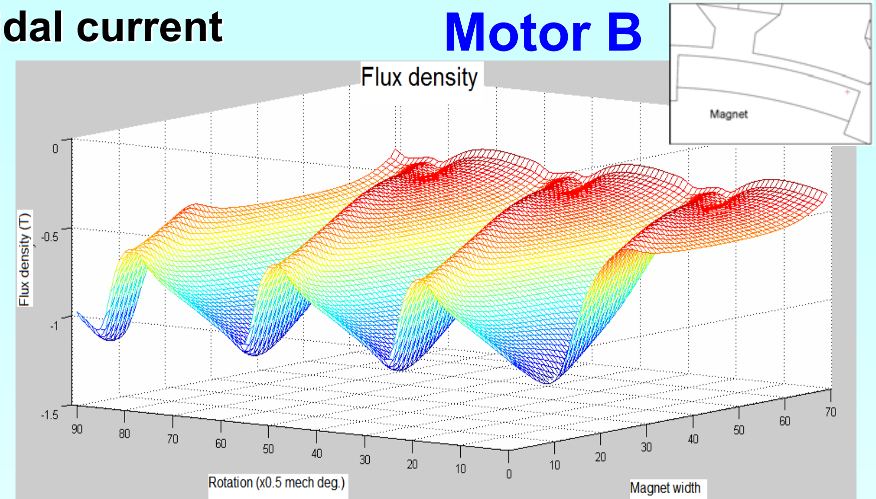
FEMAG-DC (no eddy currents considered!)

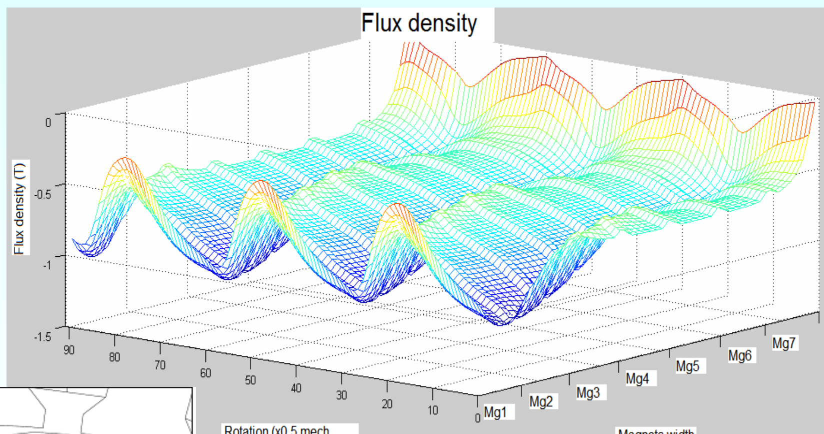
Flux density at load operation

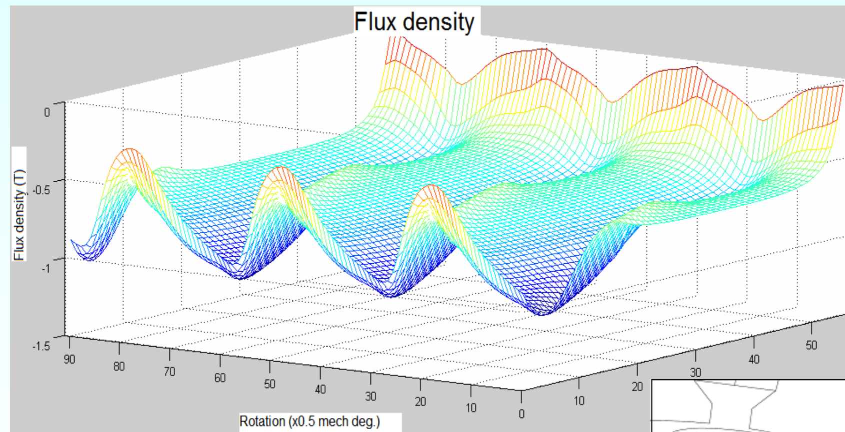
Motor A **Sinusoidal current** **Motor B**

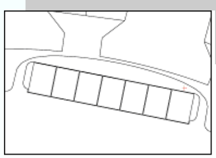


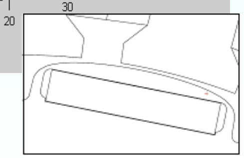












Motor C **Motor D**

1000 rpm, upper surface

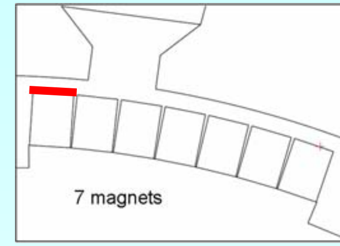
FEMAG-DC (no eddy currents considered!)

Loss calculation methods

Method 1: FEMAG-DC & Analytical Formula

Vector potential

$$A_z = \sum_{i=0}^{k} B_r(i) \cdot \Delta x, \quad k = 0 \dots n$$



Current density

$$J_z(k, t_{j+1}) = -\kappa_{Meff} \cdot \frac{A(k, t_{j+1}) - A(k, t_j)}{\Delta t}$$

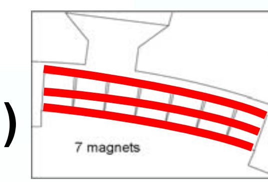
Alternating current density

$$\int_{b_M} J_z(x) \cdot dx = 0 \qquad J_{z\sim}(k, t_{j+1}) = J_z(k, t_{j+1}) - \overline{J_z}(t_{j+1})$$

Losses in magnets

$$P_{Mu,m,b} = \int_V \frac{J_{z\sim}^2}{\kappa_{Meff}} dV = \sum_{u,m,b} \left(h_M \cdot \Delta x \cdot l_M \cdot 1/\kappa_{Meff} \cdot \sum_{k=1}^{n} J_{z\sim}^2(k, t_{j+1}) \right)$$

Considered in each of the three surfaces (upper, middle, bottom)



Loss calculation methods

Method 2: FEMAG DC - Version 05/2007

- No reaction field of eddy currents considered

- Maxwell equations $\quad rot\vec{E} = -\partial\vec{B}/\partial t \qquad \vec{J} = \kappa\vec{E}$

- Fast calculation

- For magnets with rather low conductivity (small eddy currents)

Method 2 is similar to Method 1, but $\int\limits_{A_M} J_z(x,y)\cdot dx\cdot dy = 0$

is considered over the magnet cross section and not only

in the three surfaces

Loss calculation methods

Influence of eddy current reaction field

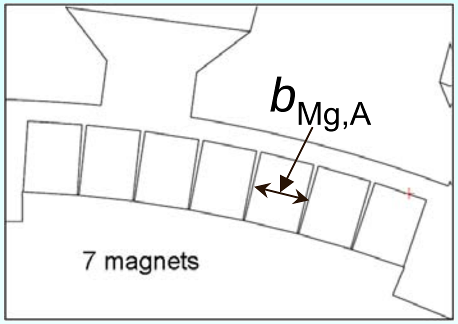
Penetration depth: $$d_E = \frac{1}{\sqrt{\kappa_{Mg} \cdot \pi \cdot f_{B,Mg} \cdot \mu_{Mg}}}$$

Ratio $b_{Mg} / d_E \leq 1 \rightarrow$ no eddy current reaction field

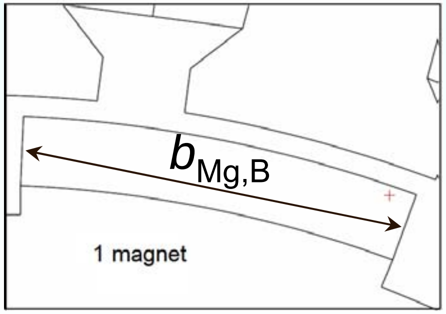
Ex.: $n = 3000$ rpm; $f_s = 400$ Hz; $f_{B,Mg} = 1200$ Hz ($q = ½$)

Motor A	Motor B
$b_{Mg,A} = 3.6$ mm	$b_{Mg,B} = 27.3$ mm
$\kappa_{Mg,A} = 0.62 \cdot 10^6$ S/m	$\kappa_{Mg,B} = 0.43 \cdot 10^6$ S/m
$d_{E,A} = 17.8$ mm	$d_{E,B} = 21.6$ mm
$b_{Mg,A} / d_{E,A} = \underline{0.2}$	$b_{Mg,B} / d_{E,B} = \underline{1.26}$

Motor A



Motor B



Loss calculation methods

Method 3: 2D Time-step calculation

- Reaction field of eddy currents considered

- Full set of Maxwell equations

$$rot\vec{E} = -\partial\vec{B} / \partial t$$

$$\vec{J} = \kappa \cdot \vec{E}$$

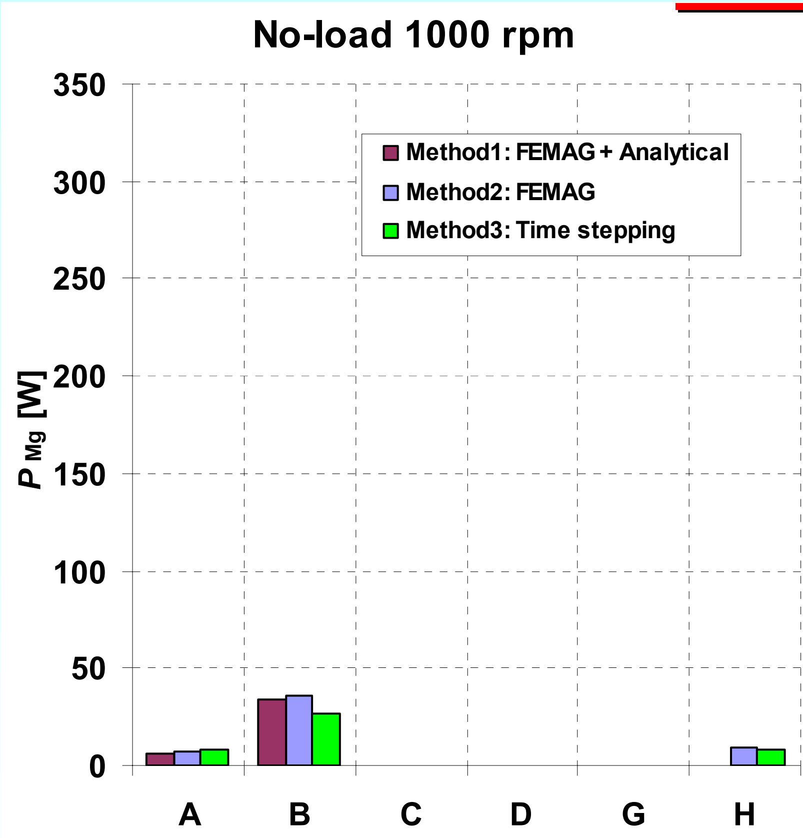
$$rot\vec{H} = \vec{J} \quad \vec{B} = \mu\vec{H}$$

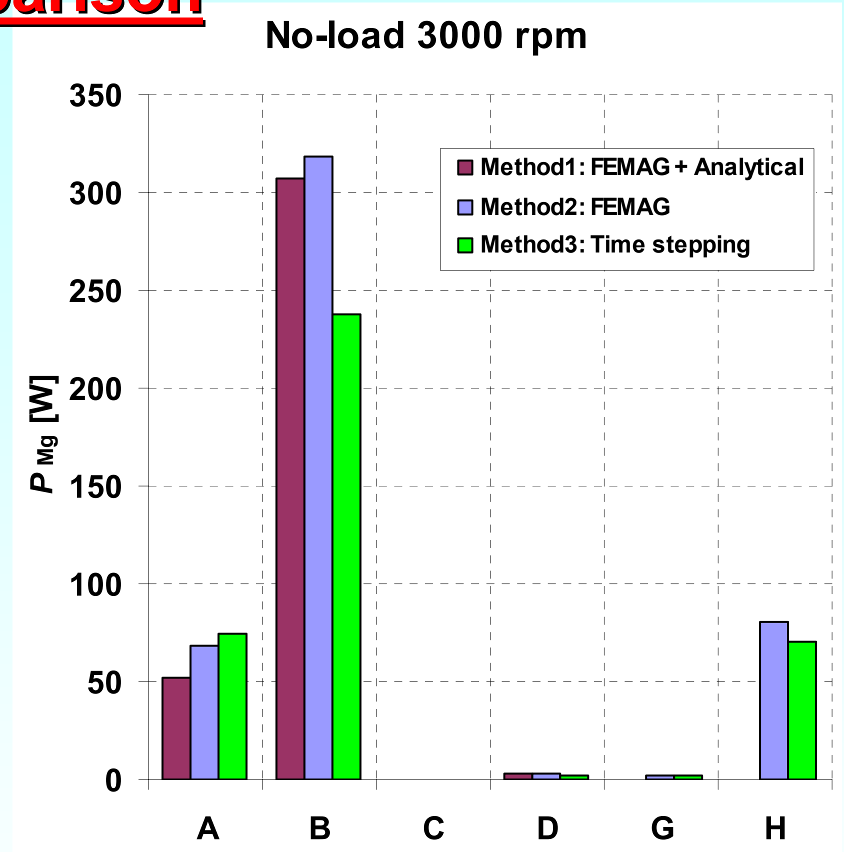
- For general purpose up to medium frequencies valid

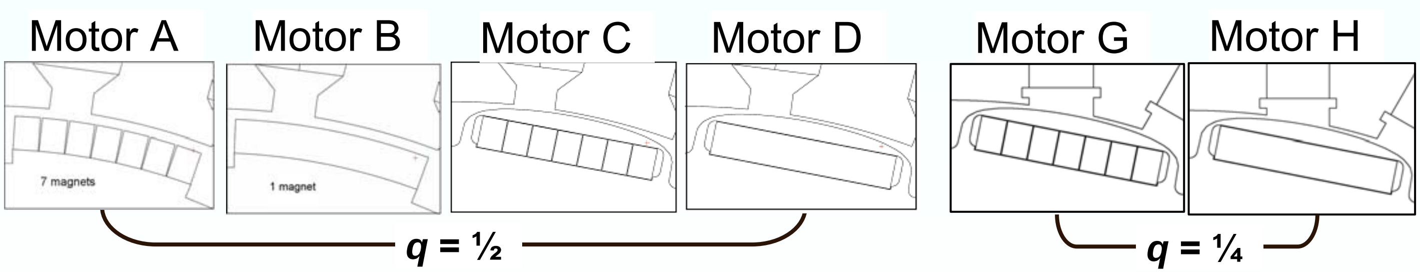
- Very time consuming

Loss calculation methods

Comparison



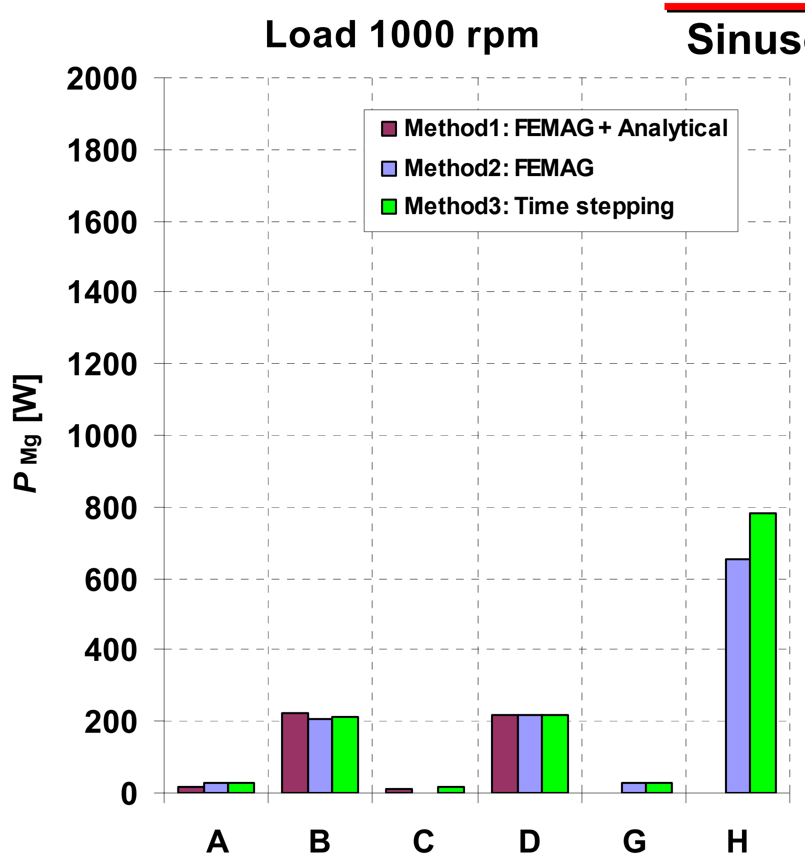


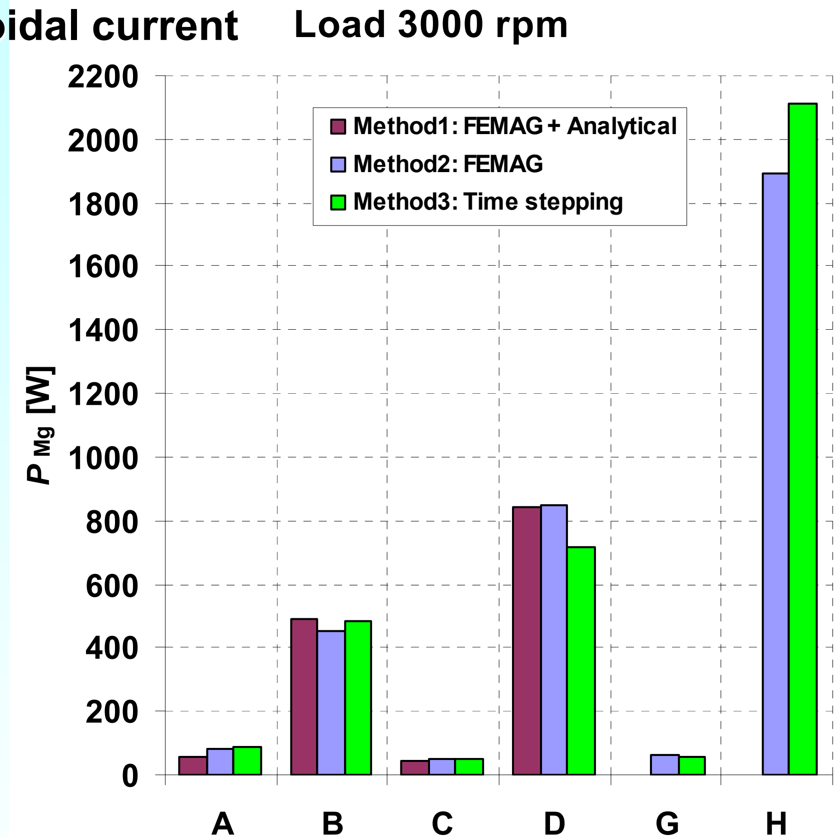


Loss calculation methods

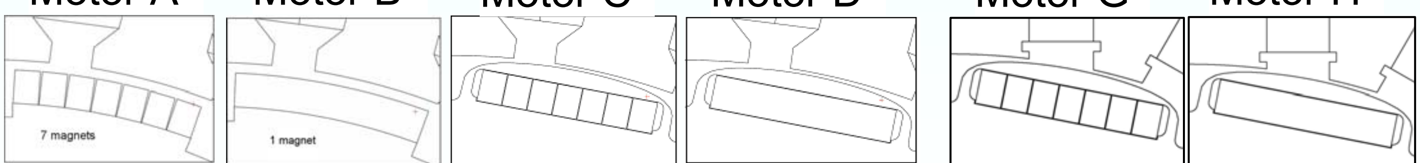
Comparison

Sinusoidal current





Motor A Motor B Motor C Motor D Motor G Motor H



$q = ½$ $q = ¼$

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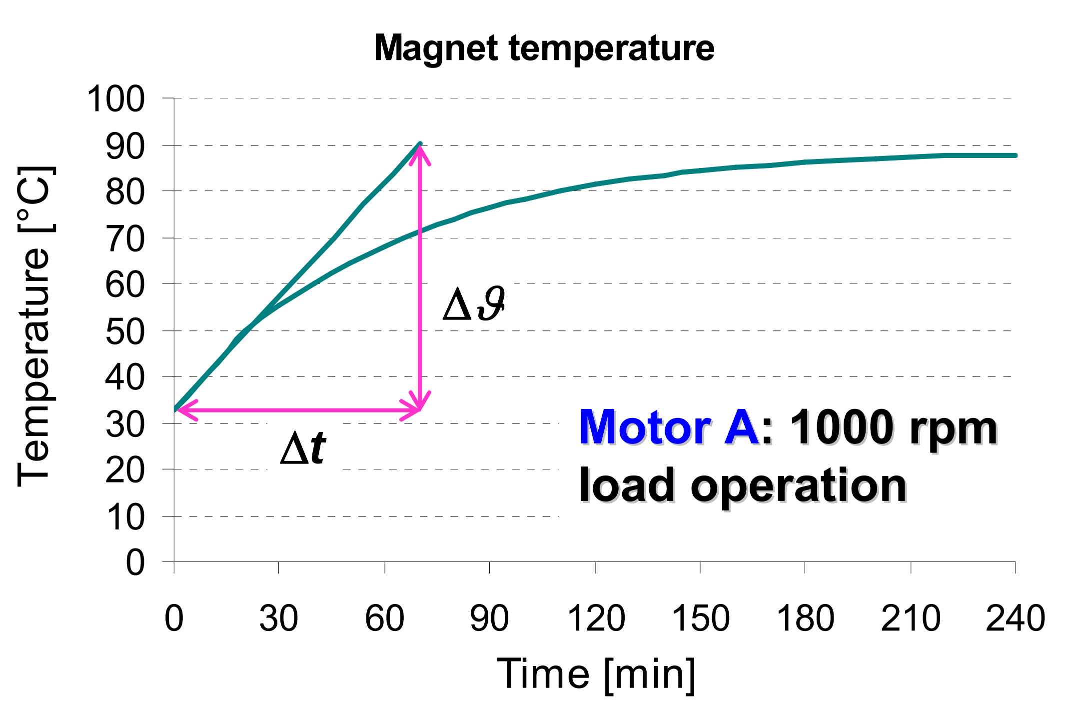
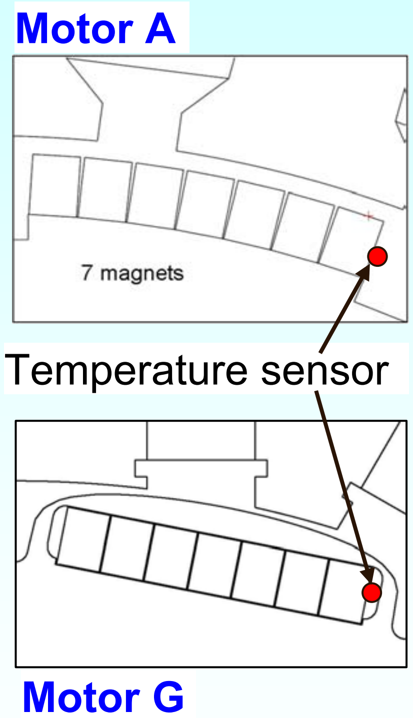
Loss estimation from thermal measurements

Losses at adiabatic heating





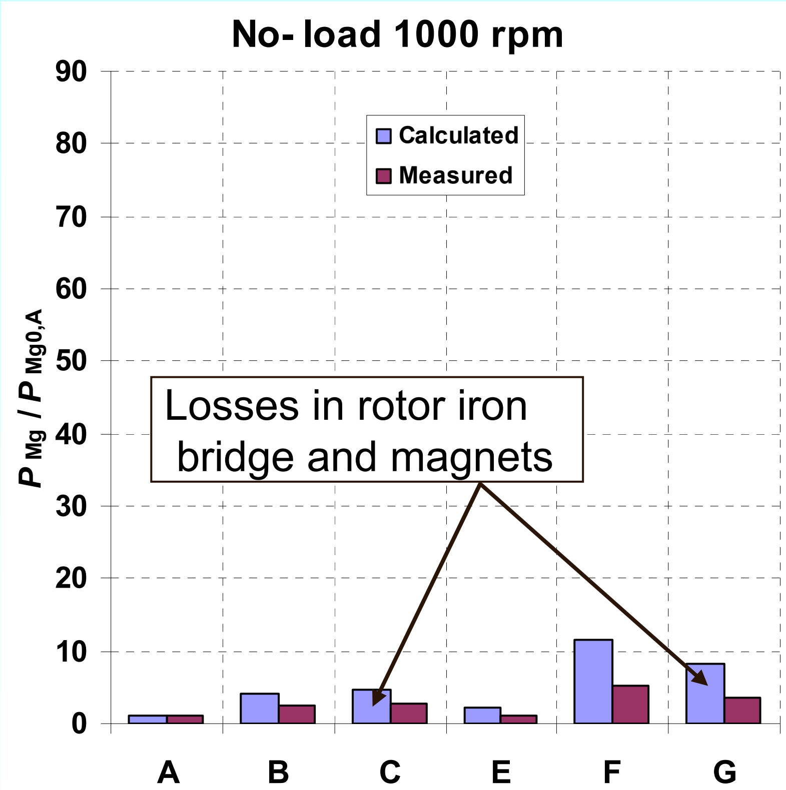
Losses: $P = m \cdot c \cdot \mathrm{d}\vartheta / \mathrm{d}t$

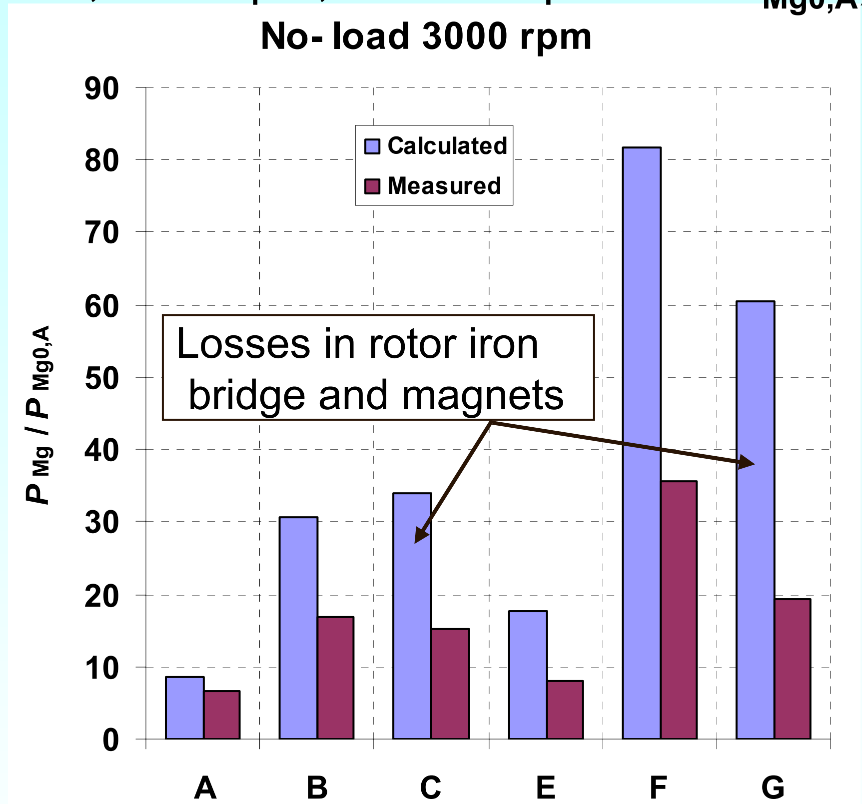
Useful only as the ratio of the dϑ/dt values by the different motor configuration!!

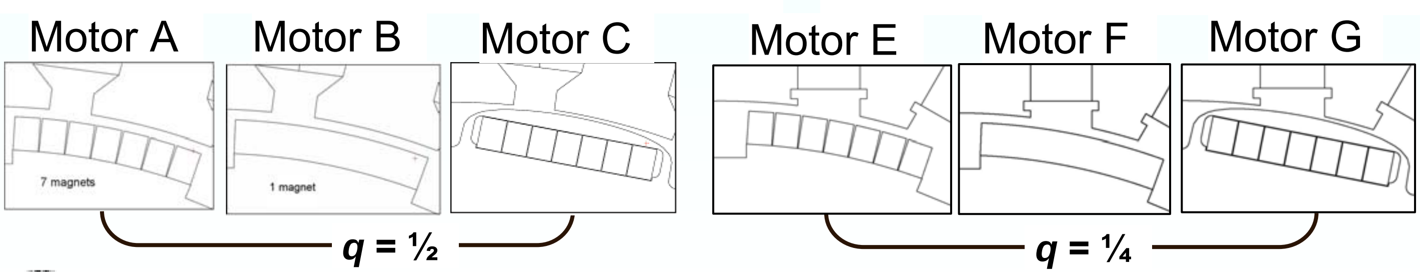
Loss estimation from thermal measurements

Comparison

(all values related to **Motor A**, 1000 rpm, no-load operation $P_{Mg0,A}$)



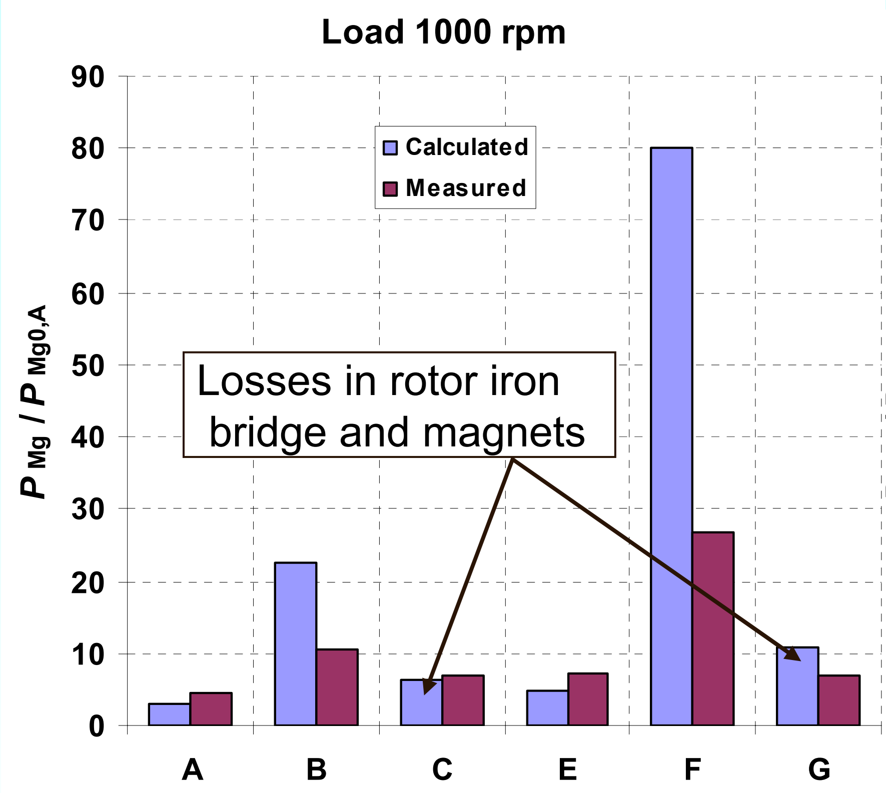


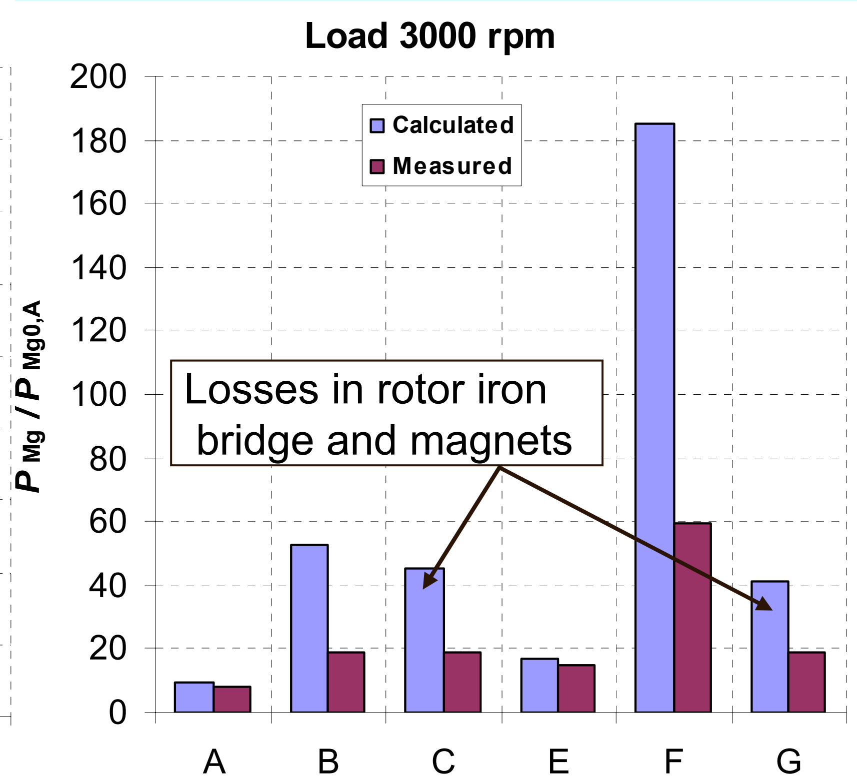


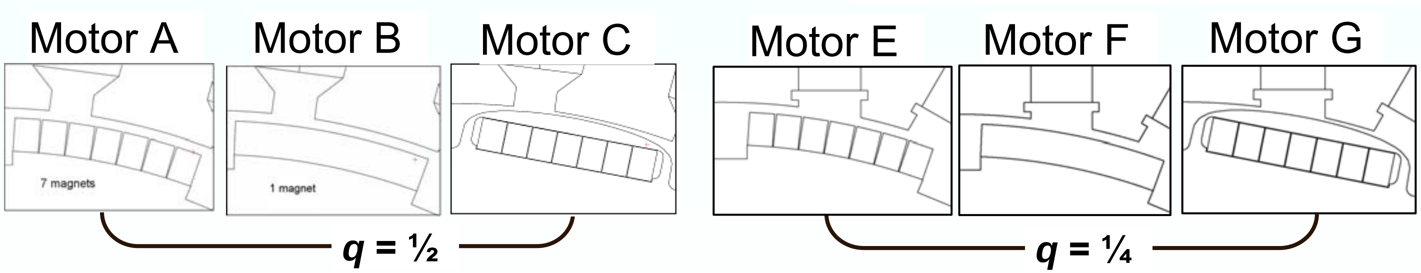
Loss estimation from thermal measurements

Comparison

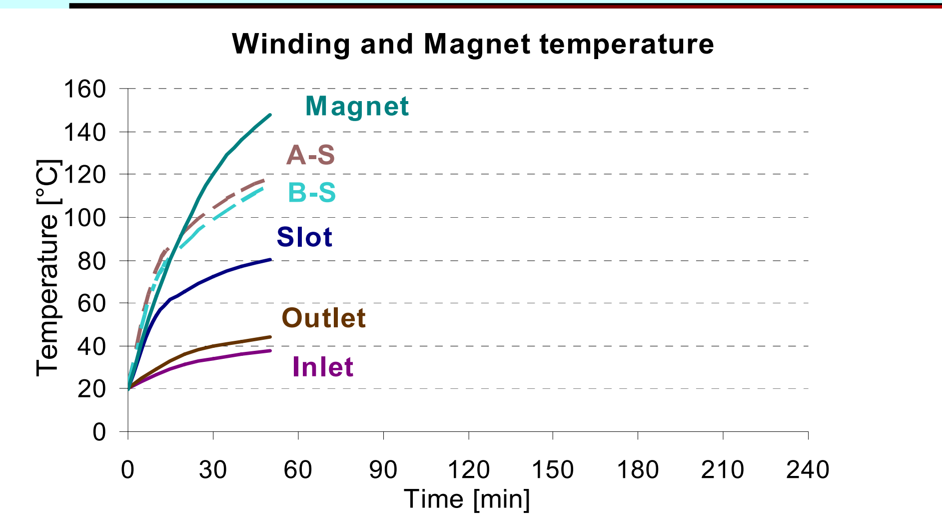
(all values related to **Motor A**, 1000 rpm, no-load operation $P_{Mg0,A}$)

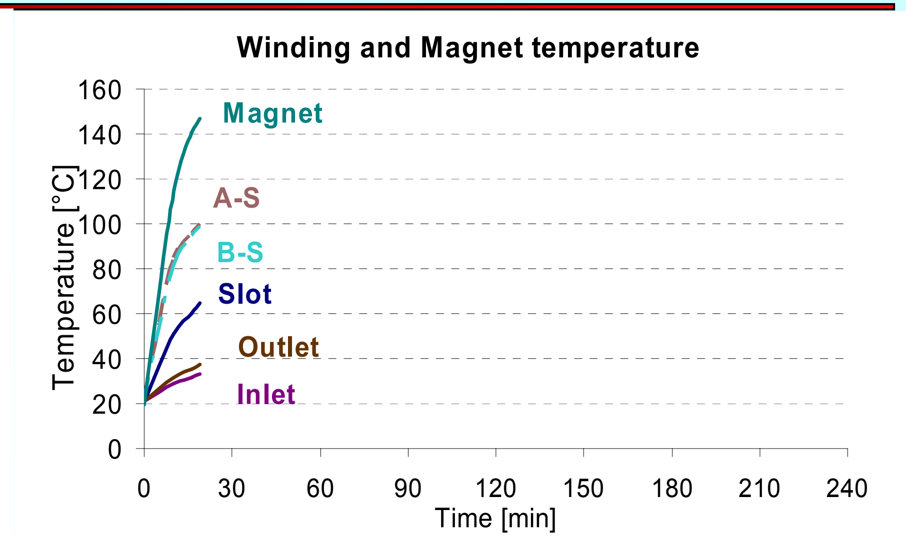


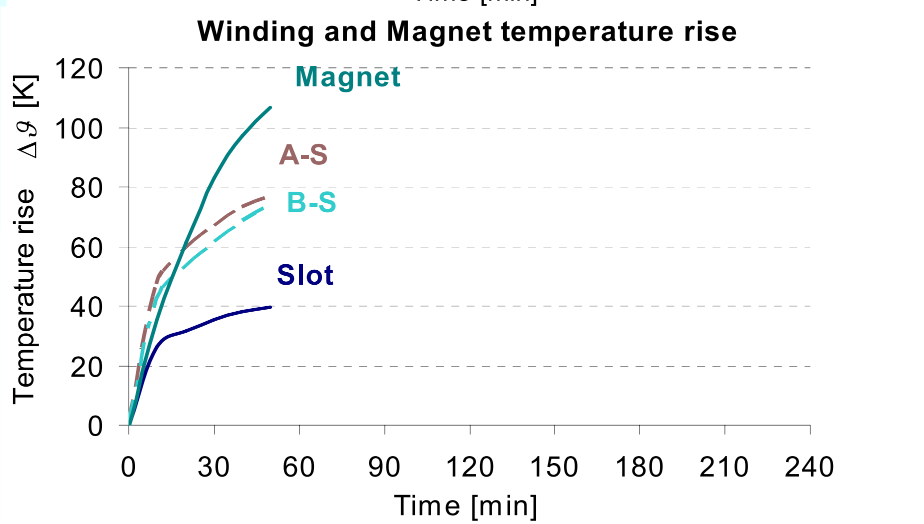


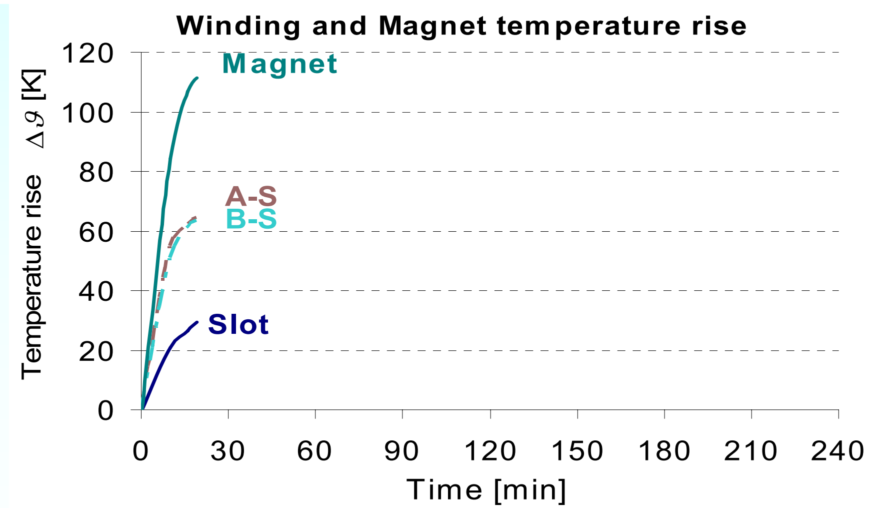


Erwärmung bei Nennleistung : Motor F









I_s = 128.1 A; U_s = 203.2 V; cosφ = 0.64;
M = 430.7 Nm; P_{mech} = 45.1 kW; P_d = 5.34 kW

I_s = 73.9 A; U_s = 231 V; cosφ = 0.99;
M = 143.6 Nm; P_{mech} = 45.1 kW; P_d = 6.19 kW

n = 1000 / min - Kühlung: 6.6 l/min n = 3000 / min

Conclusions

- 3 loss calculation methods: FEMAG-DC & analytical formula

  FEMAG-DC

  Time stepping

- 8 motors : 2 Stators ($q = 1/2$; $q = 1/4$)

  4 Rotors (segmented/non-segmented; surface/buried)

- Eddy-current losses in magnets are possible to be calculated with DC method (no eddy current reaction field) due to the rather low conductivity of rare-earth magnets

- Loss estimation from adiabatic thermal heating is possible mainly for surface-mounted permanent magnets

- For buried magnets: influence of bridge losses to be investigated further

Verlustberechnung und experimentelle Validierung bei hochausgenützten Permanentmagnet-Synchronmaschinen mit Zahnspulenwicklungen

Thank you for your attention!