Skalierung und Auslegung von lagerlosen Miniatur-Scheibenläufermotoren für hohe Drehzahlen

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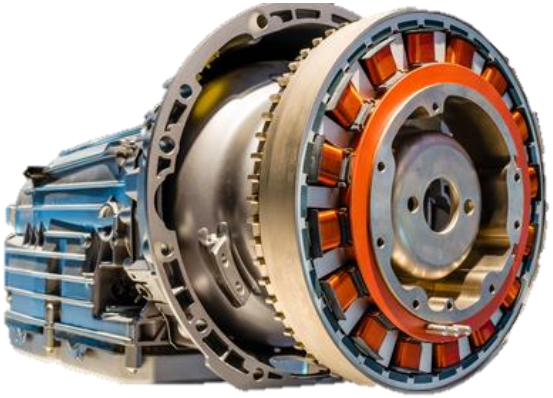

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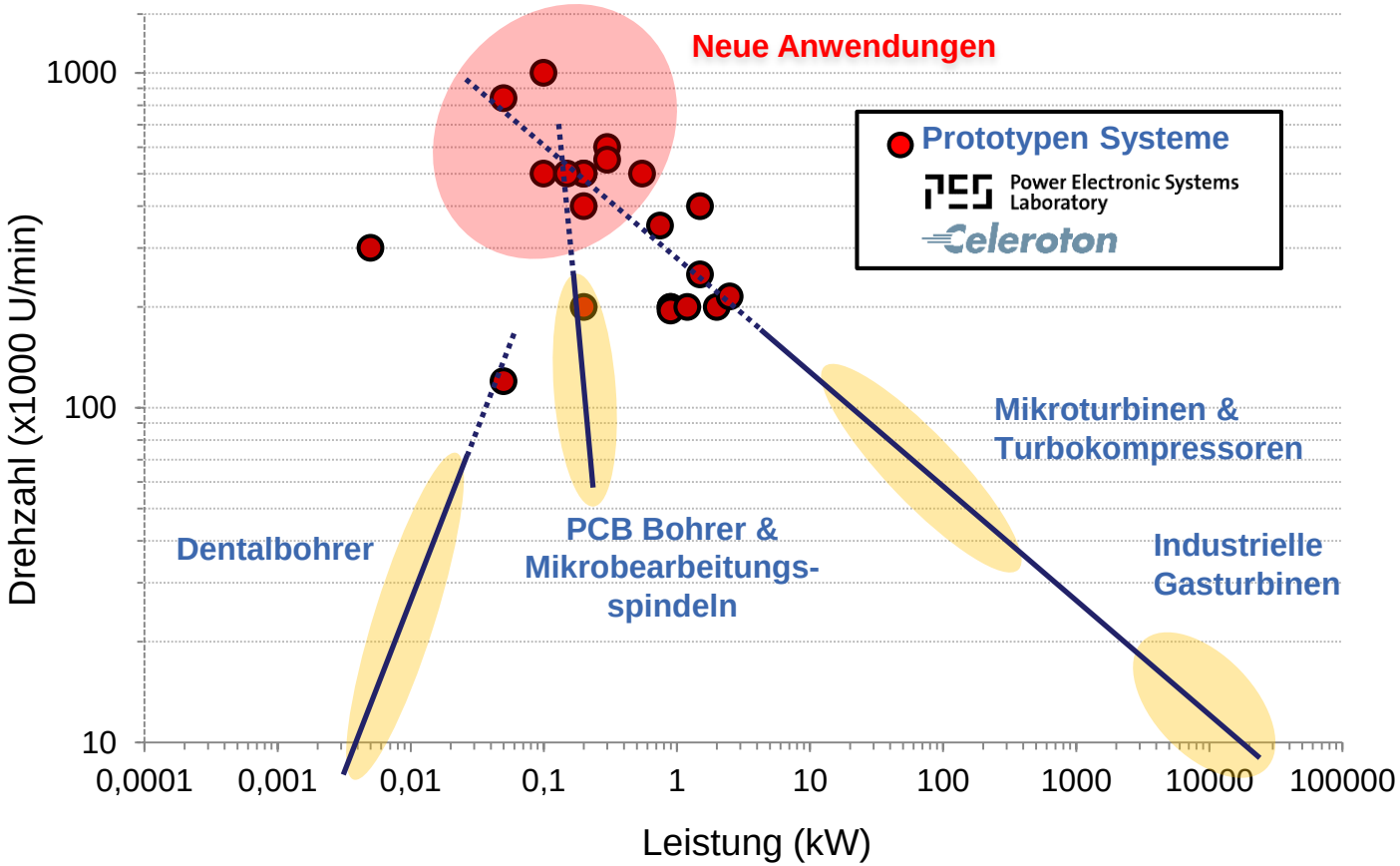
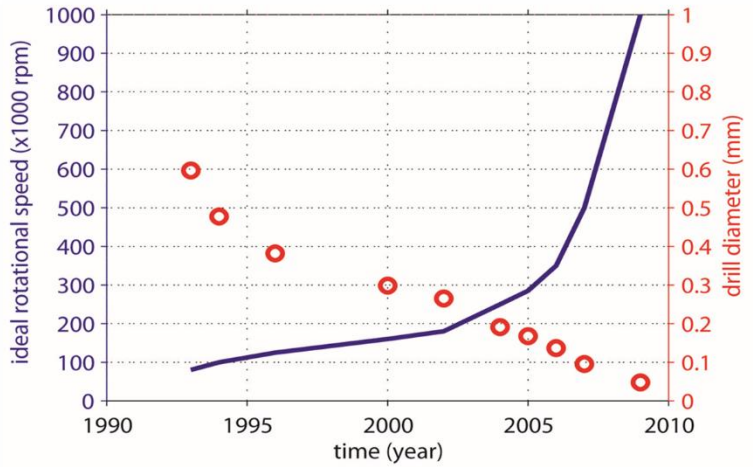
- Anwendungsgebiete von Hochdrehzahlantrieben



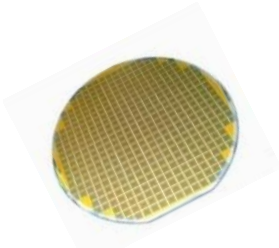
Source: Zwyssig et. al., Megaspeed Drive Systems: Pushing Beyond 1 Million r/min, IEEE Transactions on Mechatronics 2009

Anwendungen von Hochdrehzahlantrieben

- Drehzahlen von 250’000 – 1‘000‘000 U/min
  - µ-Vias für PCB Produktion
  - Hohe Genauigkeit für Mikrofertigung
  - Beschleunigter Fertigungsprozess



Source: Kolar et al., Beyond 1 000 000 rpm Review of Research on Mega-Speed Drives, COBEP 2007



Waferbearbeitung

µ- Vias für PCBs

Dentalbohrer

Uhrenindustrie

Winkelfrequenz

Drehmoment

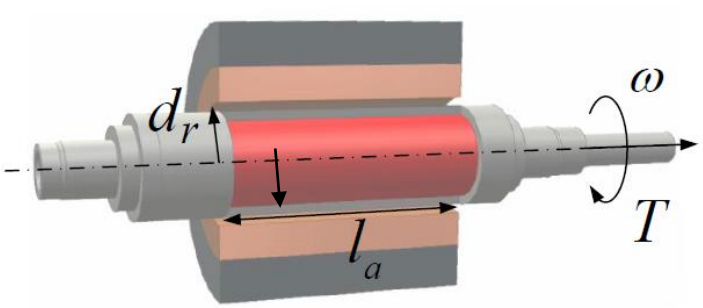
Mechanische Leistung $P_m = \omega T$

Drehmoment $T = C\, l_a d_r^2$

Rotordurchmesser

Axiale Länge

Maschinengröße



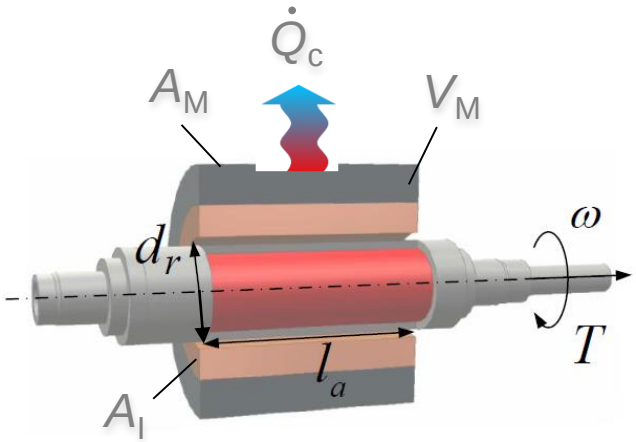
Essonsche Ausnutzungsziffer

- Motortopologie
- Materialien
- Herstellungsprozess
- Kühlung

- Erhöhung der Leistungsdichte

Skalierungsfaktor x_d

Konstante Größenverhältnisse



Motor Radius Axiale Länge

Oberfläche $A_M = 2\pi r_M^2 + \pi r_M l \propto \boldsymbol{x_d^2}$

Volumen $V_M = \pi r_M^2 l \propto \boldsymbol{x_d^3}$

$T = B_\delta I\, l_a r_w \propto \boldsymbol{x_d^{3.5}}$

Mechanische Leistung $P_m = \omega T \propto \boldsymbol{x_d^{2.5}}$

$\omega = v_c / r_r \propto \boldsymbol{1/x_d}$

Kupferverluste

$P_I = R I^2$ mit $R = \rho \frac{l}{A_I} \propto \frac{1}{x_d}$ $P_I \leq \dot{Q}_c$ (!)

→ $I \propto \boldsymbol{x_d^{1.5}}$

Leistungsdichte

$p_m = P_m / V_M \propto \boldsymbol{x_d^{-0.5}}$

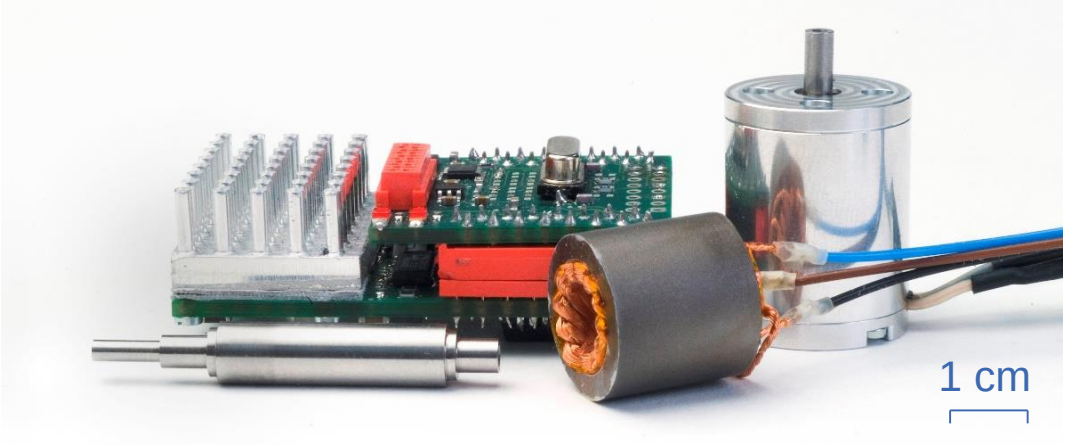
- Demonstratorsystem für 100 W @ **1’000’000 U/min**

d Rotor PM 3 mm

Motorverluste 9 W

Lagerverluste **44 W** (!)

→ **Geringe Lebensdauer**



176’000 rpm

275’000 rpm

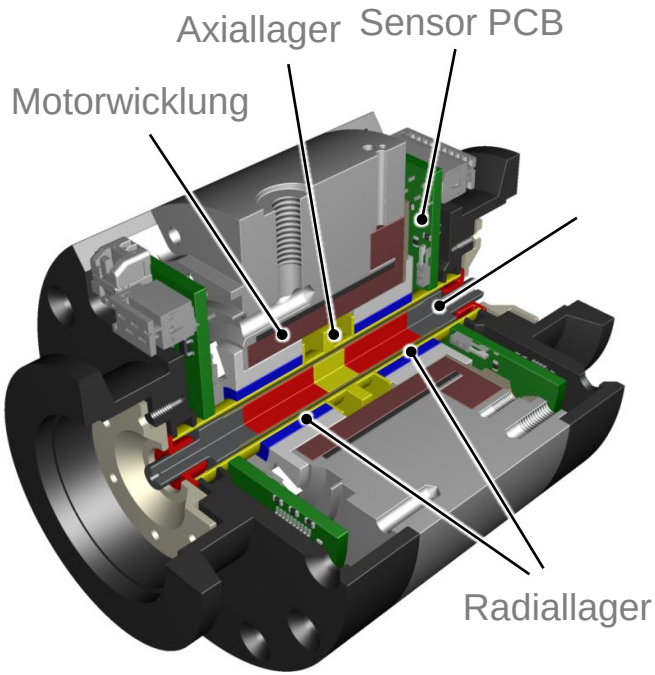
858’000 rpm

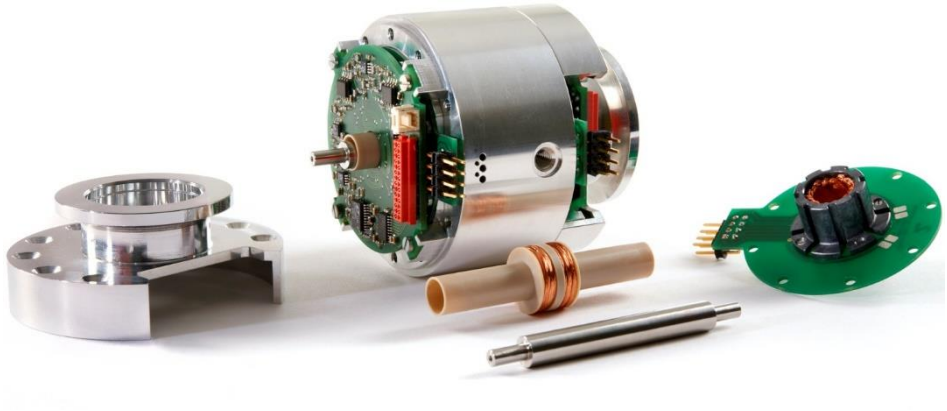
Biegeeigenschwingungen innerhalb des Drehzahlbereichs

Source: Zwyssig et al., Megaspeed Drive Systems: Pushing Beyond 1 Million r/min, IEEE Transactions on Mechatronics 2009

- Demonstratorsystem für **500’000 U/min** mit Magnetlagern

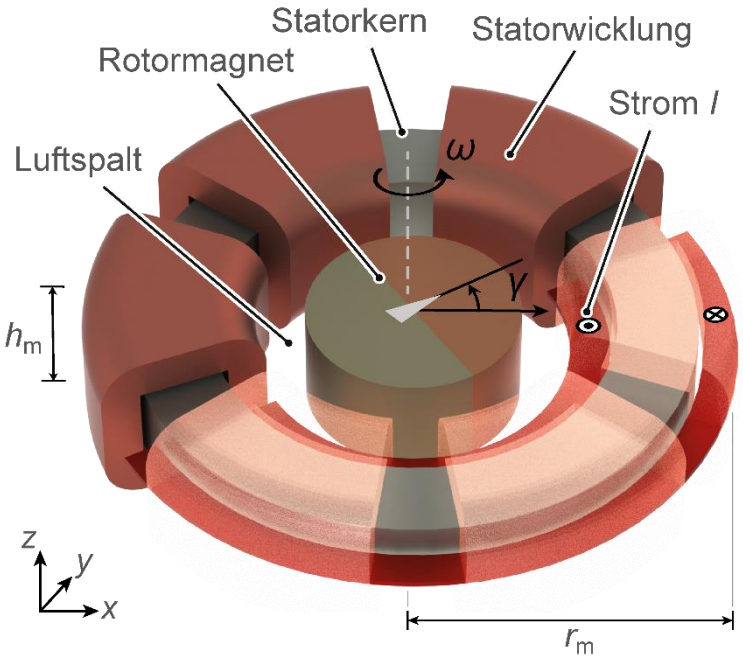
  - Aktive Magnetlager
    - + Keine Abnutzung, Lange Lebendauer
    - + Regelbare Rotordynamik
    - - Begrenzte Lagerkraft
    - - Hoher Kontrollaufwand
    - - Positionssensor notwendig

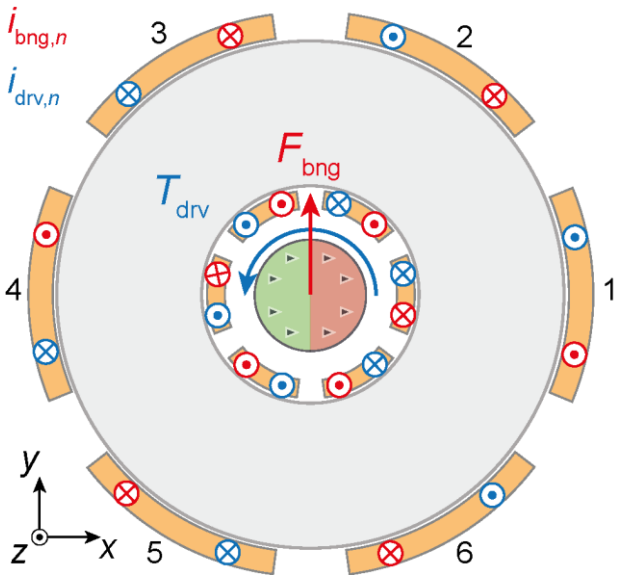




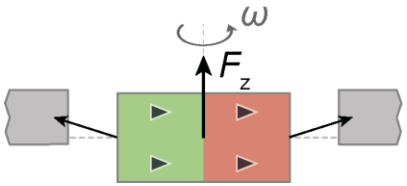
Source: Baumgartner et al., Analysis and Design of a 300-W 500 000-r/min Slotless Self-Bearing Permanent-Magnet Motor, IEEE Transactions on Industrial Electronics 2014

Magnetgelagerter Scheibenläufermotor

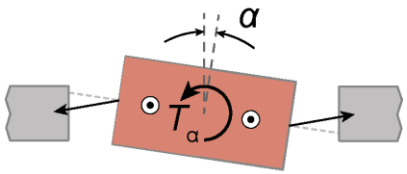




Passive Axialstabilität



Passive Kippstabilität

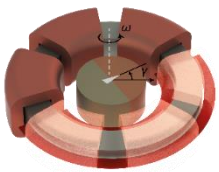


Kombinierte Wicklungen

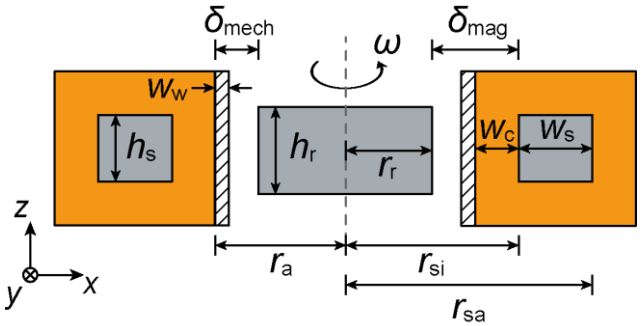
Radiale Lagerkraft und Drehmoment werden mit gleichen Spulen erzeugt

$p_{drv} = p_{pm} = 1$

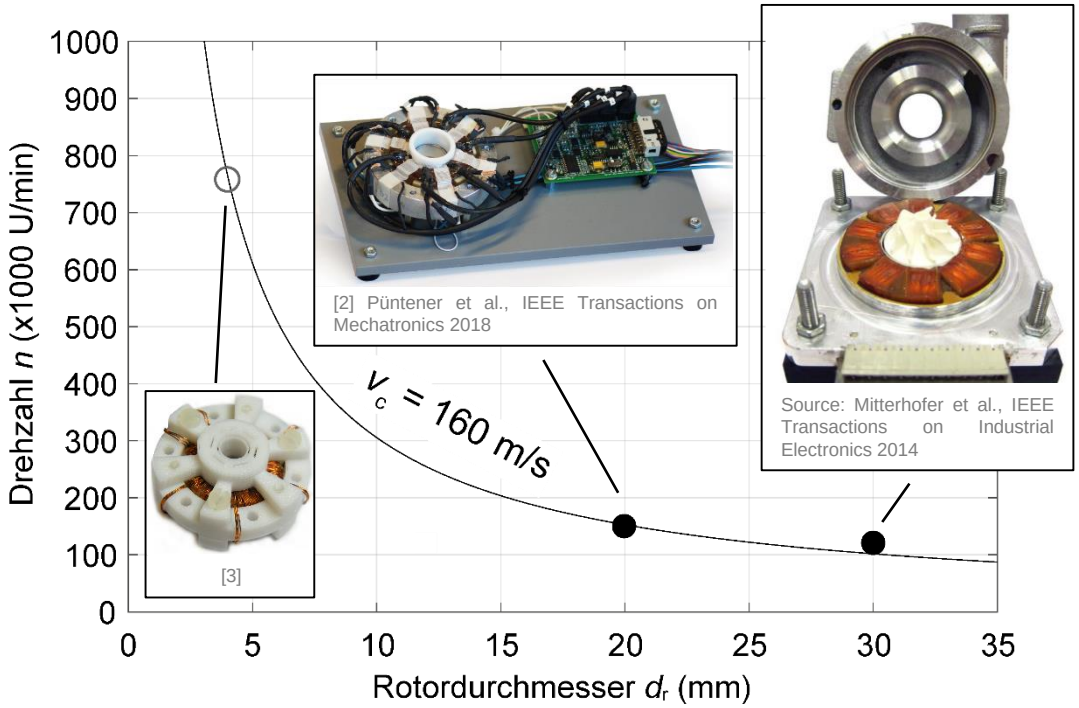
$p_{bng} = p_{pm} + 1 = 2$



Auslegung



$$\sigma_{max} = C_s \rho_r \omega^2 r_r^2$$



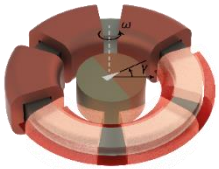
Skalierung von Geometrieparametern nutenloser Scheibenläufermotoren

	d_r	δ_{mech}	h_r/r_r	h_s/h_r	δ_{mag}/r_r	n_{max}
[1]	102 mm	2 mm	0.29	0.83	0.19	20‘000 U/min
[2]	22 mm	1.4 mm	0.82	0.89	0.41	150‘000 U/min
[3]	4 mm	1 mm	**1**	0.75	**0.88**	760‘000 U/min

[1] Steinert et al., Slotless Bearingless Disk Drive for High-Speed and High-Purity Applications, IEEE Transactions on Industrial Electronics 2014

[2] Püntener et al., A 150 000-r/min Bearingless Slice Motor, IEEE Transactions on Mechatronics 2018

[3] Schuck et al., A High Speed Millimeter-Scale Slotless Bearingless Slice Motor, IEEE International Electric Machines & Drives Conference (IEMDC) 2017

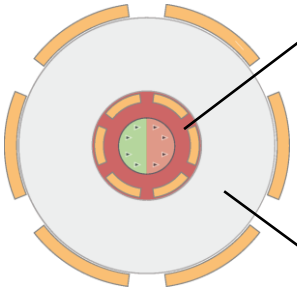


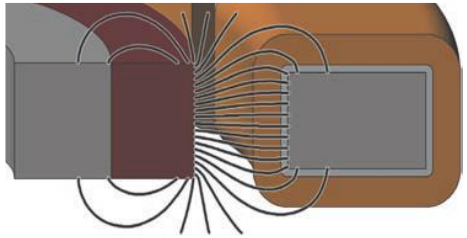
Flussdichteverteilung

Magnetischer Luftspalt

$$B_{a,r}(r,\varphi) = \frac{B_{rem}}{2}\left(\frac{r_r}{r_{si}}\right)^2\left[1+\left(\frac{r_{si}}{r}\right)^2\right]\cos(\varphi)$$

$$B_{a,\varphi}(r,\varphi) = \frac{B_{rem}}{2}\left(\frac{r_r}{r_{si}}\right)^2\left[1-\left(\frac{r_{si}}{r}\right)^2\right]\sin(\varphi)$$



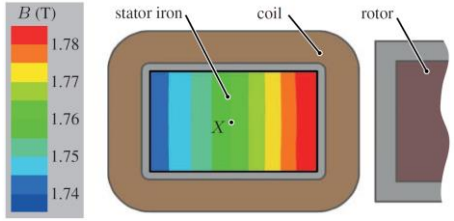


Axialer Streufluss

Statorrückschluss

$$B_{s,r}(r,\varphi) = \left(\frac{B_{rem}r_r^2}{r_{sa}^2-r_{si}^2}\right)\left[1-\left(\frac{r_{sa}}{r}\right)^2\right]\cos(\varphi)$$

$$B_{s,\varphi}(r,\varphi) = \left(\frac{B_{rem}r_r^2}{r_{sa}^2-r_{si}^2}\right)\left[1+\left(\frac{r_{sa}}{r}\right)^2\right]\sin(\varphi)$$



Flussdichte im Rückschluss

Source: Steinert et al., Loss investigation of slotless bearingless disk drives, IEEE Energy Conversion Congress and Exposition (ECCE) 2015

Drehmoment

Füllfaktor Wicklungsfaktor

$$T = h_s\frac{B_{rem}}{2}\left(\frac{r_r}{r_{si}}\right)^2 k_f k_w \hat{J}\pi\left[\frac{r_{si}^3-r_a^3}{3}+r_{si}^2(r_{si}-r_a)\right]$$

Verluste

Kupferverluste

$$P_{\mathrm{cu},k} = \underbrace{I_k^2 R_{\mathrm{dc}}}_{P_{\mathrm{cu,R}}} + \underbrace{\frac{\pi^3 N p d_{\mathrm{cu}}^4 \sigma_{\mathrm{cu}} f^2}{32} \int_L \hat{B}_{\mathrm{rem}}^2 \mathrm{d}l}_{P_{\mathrm{cu,ed}}}$$

Kernverluste

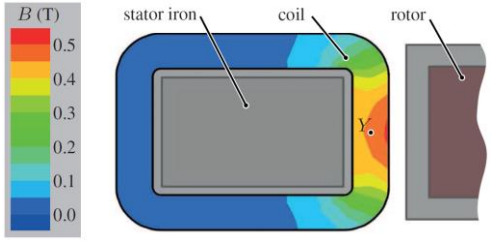
$$P_{\mathrm{c}} = C_{\mathrm{m}} h_{\mathrm{s}} \int_0^{2\pi} \int_{r_{\mathrm{si}}}^{r_{\mathrm{sa}}} f^{\alpha} \hat{B}^{\beta} r \, \mathrm{d}r \, \mathrm{d}\varphi$$

Luftreibung

$$P_{\mathrm{air}} = C_{\mathrm{f}} \rho_{\mathrm{air}} \omega^3 \left(\pi h_{\mathrm{r}} \left(\frac{d_{\mathrm{r}}}{2} \right)^4 + \left(\frac{d_{\mathrm{r}}}{2} \right)^5 \right)$$

Zylinderflächen Deckflächen

Rotorverluste (Wirbelstromverluste)

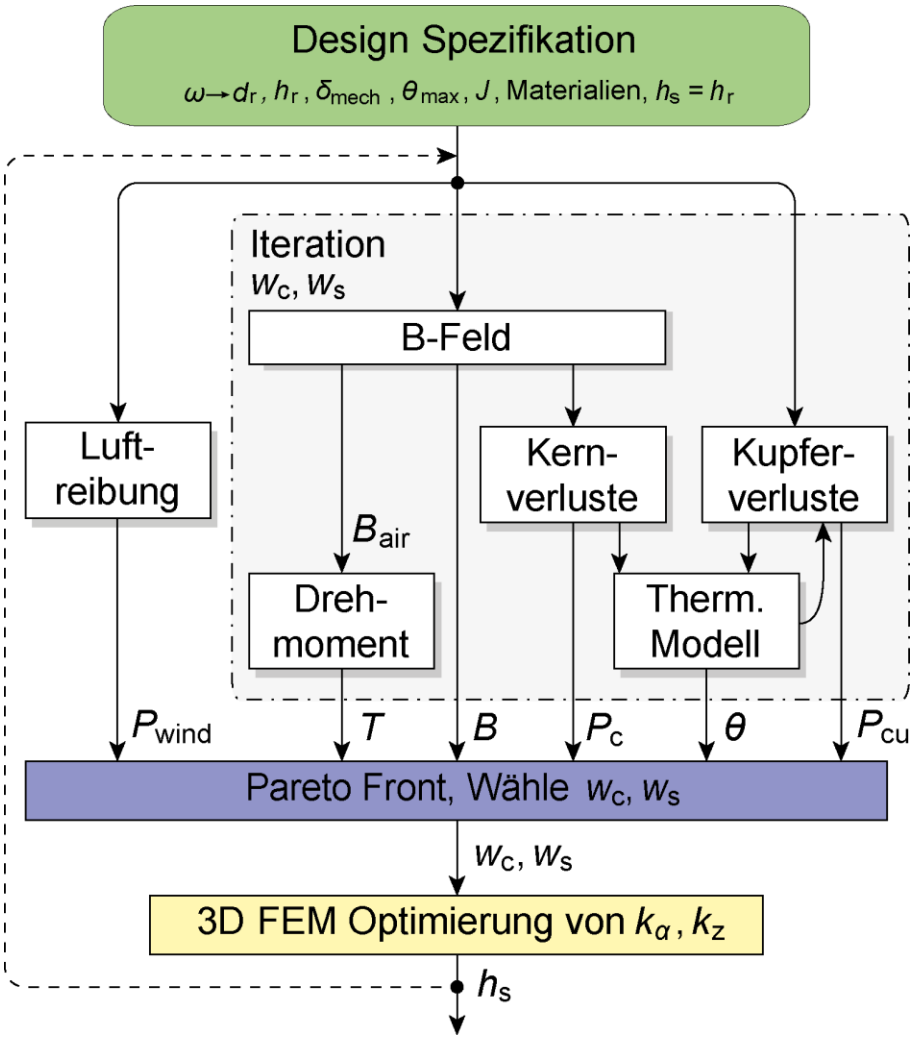


Wirbelstromverluste in Spulen

Source: Steinert et al., Loss investigation of slotless bearingless disk drives, IEEE Energy Conversion Congress and Exposition (ECCE) 2015

Metglas 2605SA1	
C_{m}	0.94 W/m³
α	1.53
β	1.72
B_{sat}	1.56 T

Optimierungsverfahren

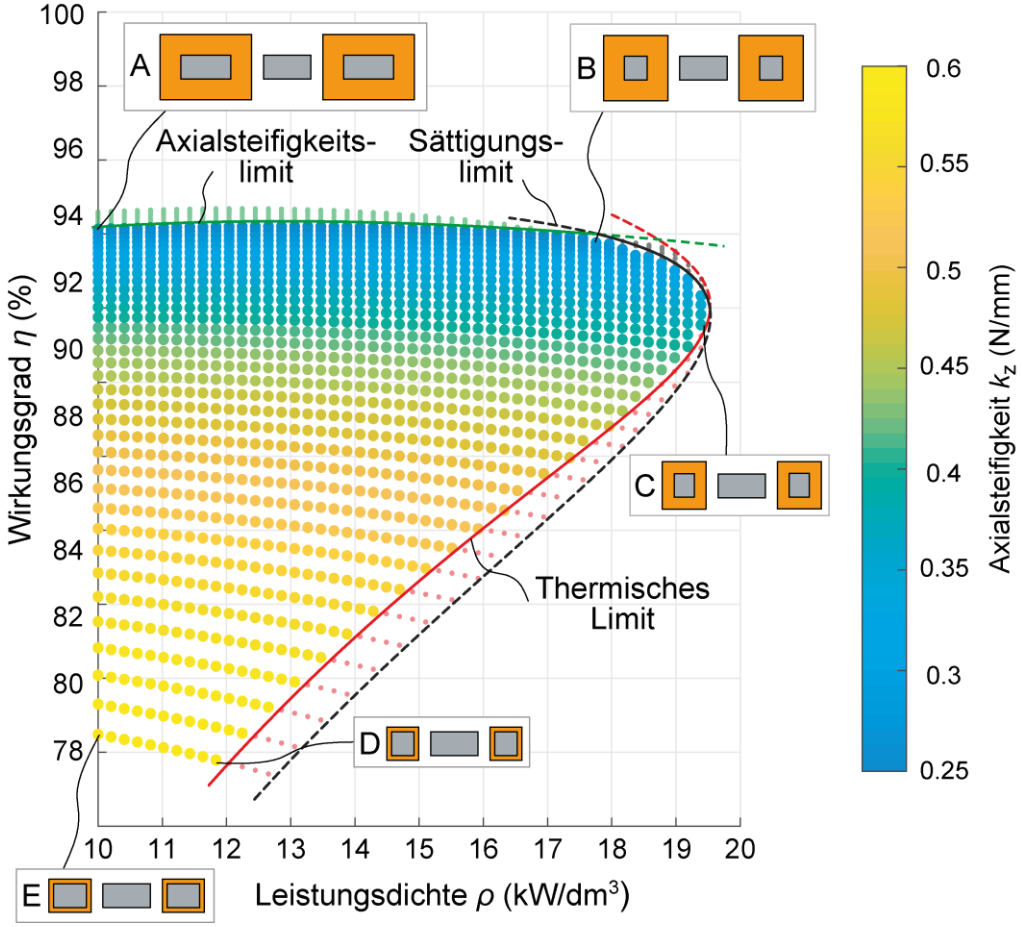


Limitierungen

- Verluste / Temperatur
- Sättigung (Rückschluss)
- Passive Axialsteifigkeit

Auslegungsparameter	
n_{max}	750‘000 U/min
h_r	2 mm
δ_{mech}	1 mm
θ_{max}	65 °C
J	5 A/mm^2

Optimierungsergebnis – Pareto Front



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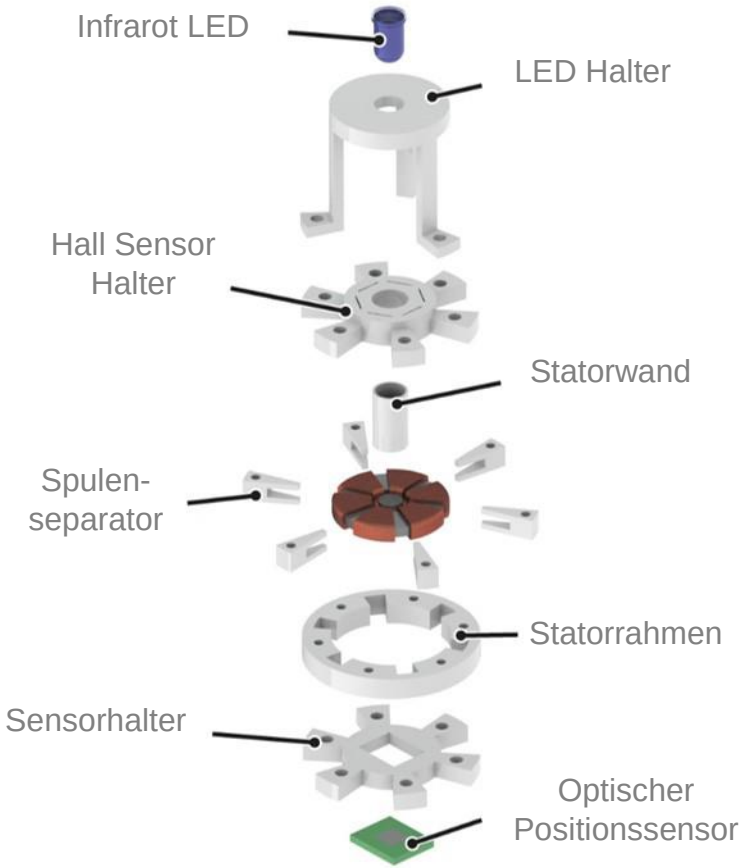
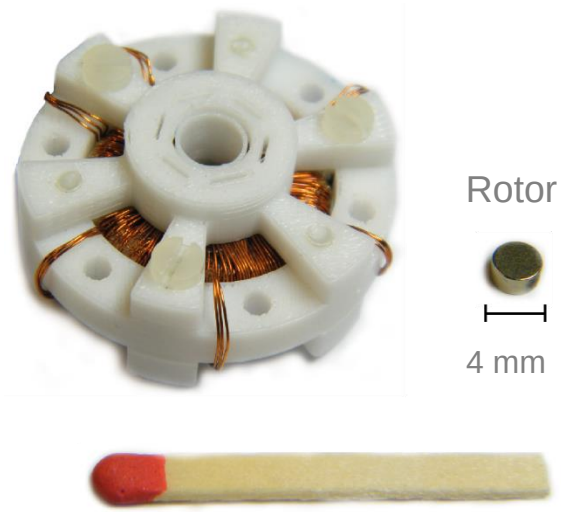
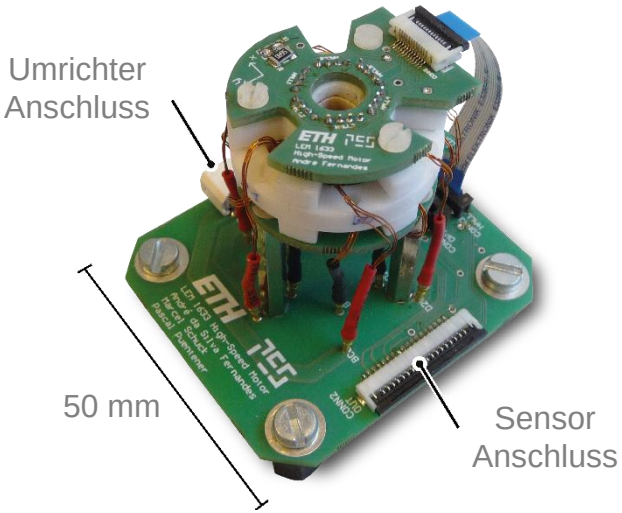
Hochdrehzahl Scheibenläufer – Prototyp

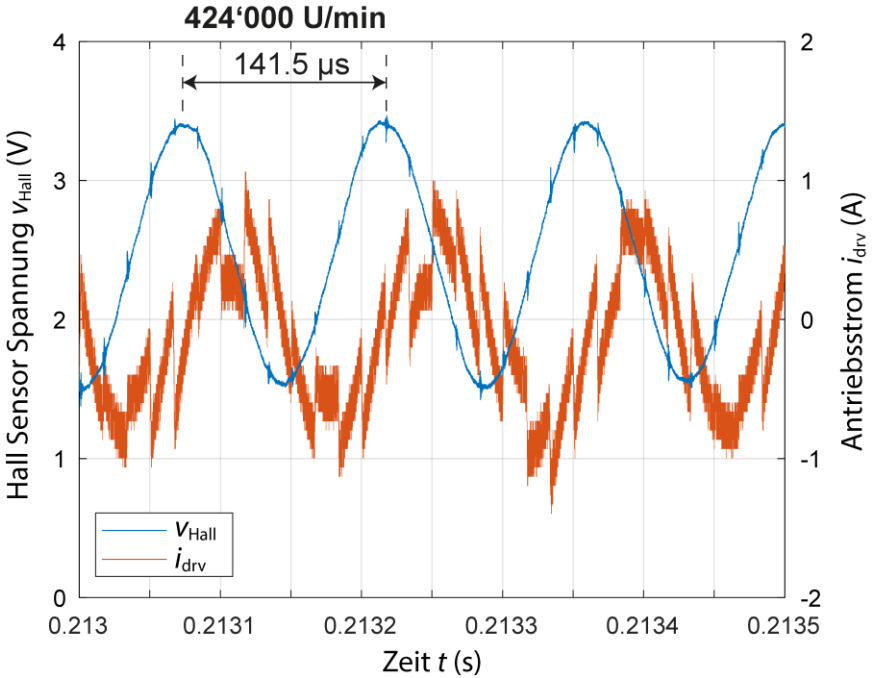


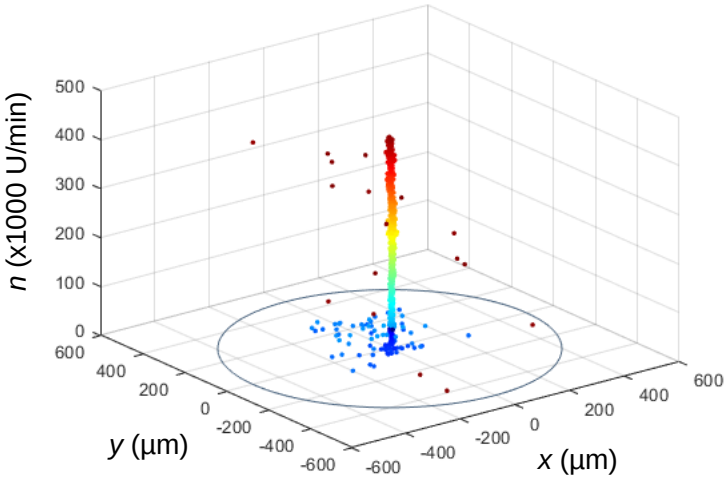


- Implementierung mittels 3D Druck
- Diametral magnetisierter Scheibenmagnet
- Winkelmessung mittels Hall Sensoren
- Kontaktlose optische Positionssensorik

Hochdrehzahl Scheibenläufer – Prototyp

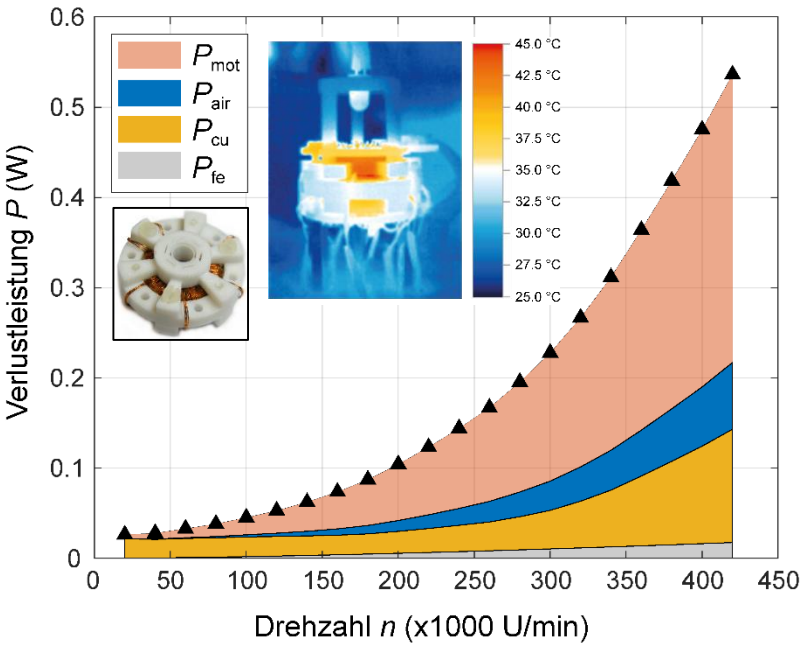


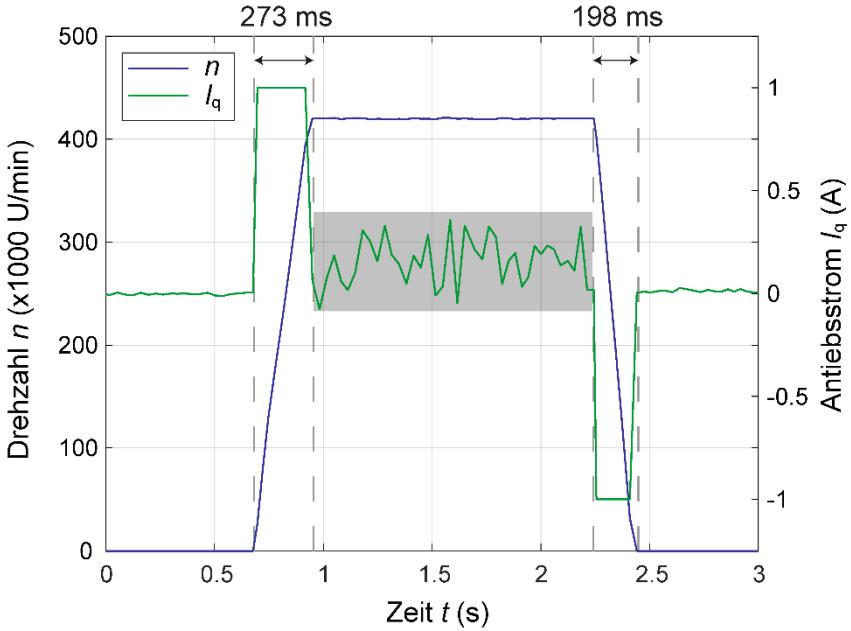




- Stabiles magnetisches Schweben bis **420‘000 U/min**
- Limitiert durch Regelbandbreite

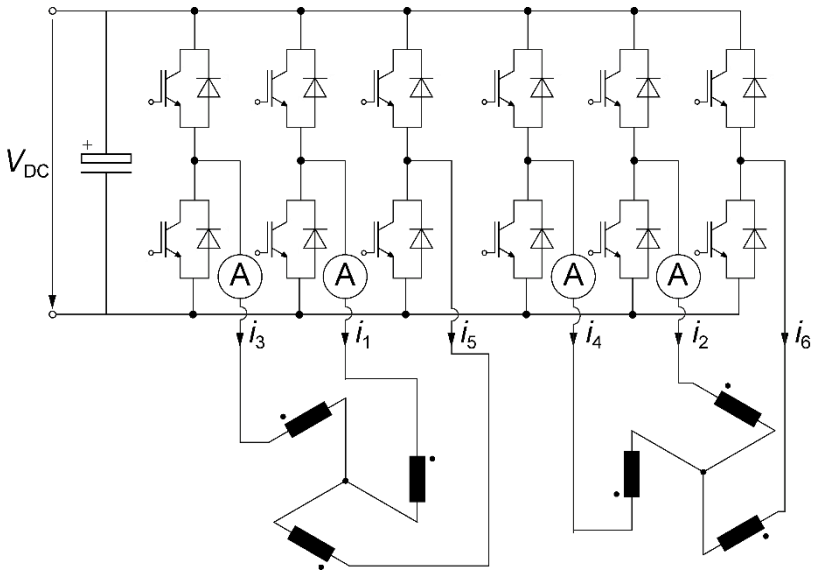
Hochdrehzahl Scheibenläufer – Messungen

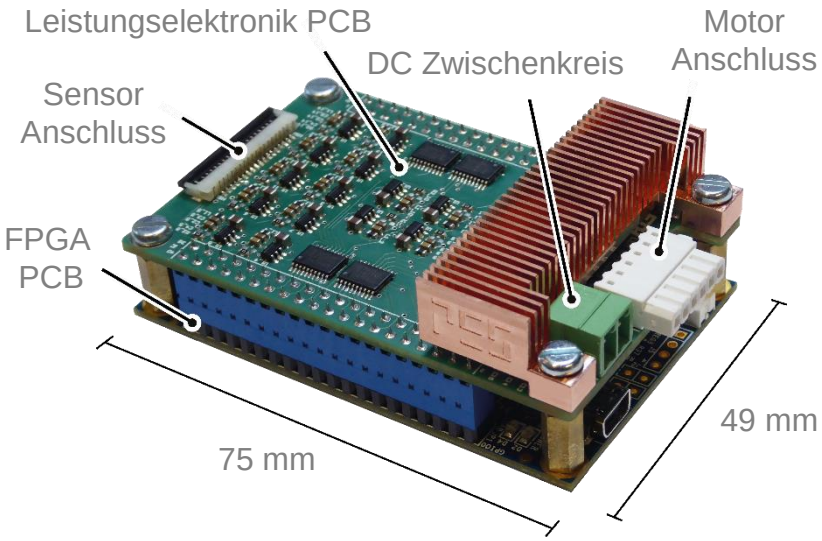


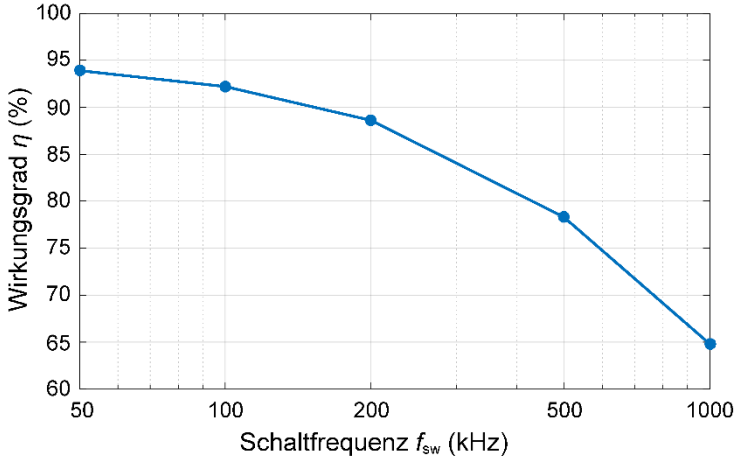


- Verluste **< 1 W @ 420‘000 U /min**
- Harmonische Verluste (Stator + Rotor)
- Hohe Rotordynamik / Geringes Trägheitsmoment
- **0 - 420‘000 U/min in 273 ms @ I_q ≤ 1 A**

Hochdrehzahl Scheibenläufer – Umrichter



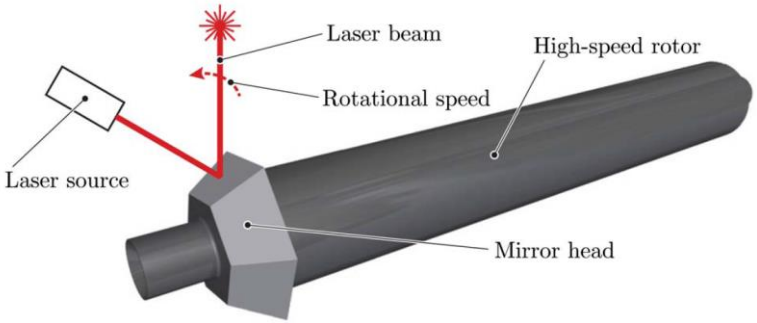


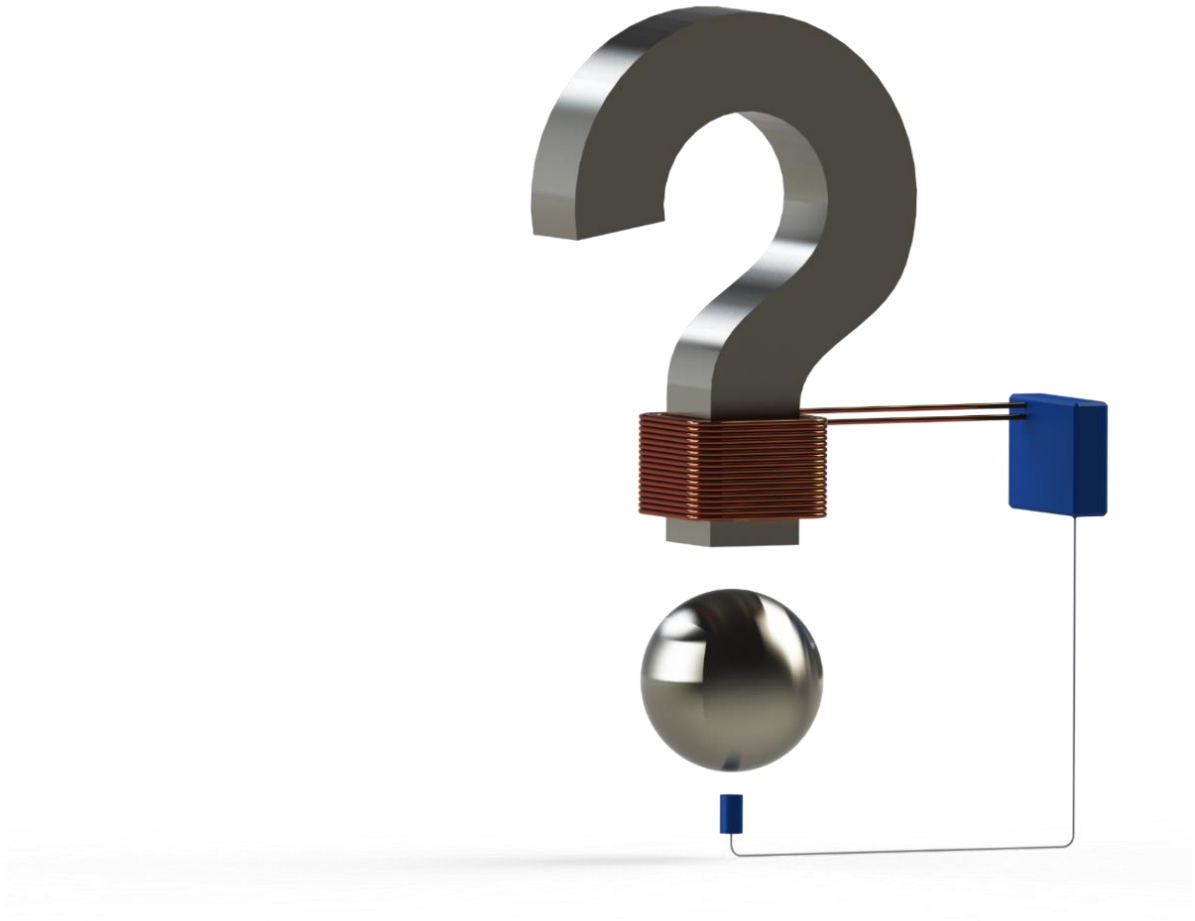


- Sechs integrierte Halbbrücken
- FPGA Regelung
- Digitale Schnittstelle zu Sensoren

Zusammenfassung

- Anwendungsgetriebener Entwicklungstrend elektrischer Maschinen hin zu hohen Leistungsdichten
- Hohe Leistungsdichten erzielbar für Hochdrehzahlmaschinen kleiner Baugröße
- Verschleißfreie Lagerung des Rotors mittels Magnetlagern
- Passive Stabilisierung von Axialverschiebungen und Verkippung durch Scheibenläufertopologie
- Auslegungs-/Optimierungsverfahren basierend auf analytischen Modellen & 3D FEM Simulationen für Scheibenläufermotoren notwendig
- Pareto-optimales Motordesign für Drehzahlen bis zu 750‘000 U/min & experimentelle Demonstration bis **420‘000 U/min**
- Umrichter mit FPGA Regelung notwendig
- Anwendungsmöglichkeiten in optischen Systemen



Source: Baumgartner et al., Analysis and Design of a 300-W 500 000-r/min Slotless Self-Bearing Permanent-Magnet Motor, IEEE Transactions on Industrial Electronics 2014

Herzlichen Dank für Ihre Aufmerksamkeit!