Elektrische Hochdrehzahlantriebe-Auslegungsgrundlagen und Beispiele aus der Praxis

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Technische Universität Darmstadt
Institut für Elektrische Energiewandlung

Andreas Binder

abinder@ew.tu-darmstadt.de

Rotor of PM synchronous machine with magnetic bearings, 40 kW, 40000/min

Source: TU Darmstadt, Germany

Contents

Basics on High Speed Drives

Why High-Speed Drives ?

Advantages of high rotational speed *n*:

High power *P* = Low torque *M*

$$P = 2\pi \cdot n \cdot M$$

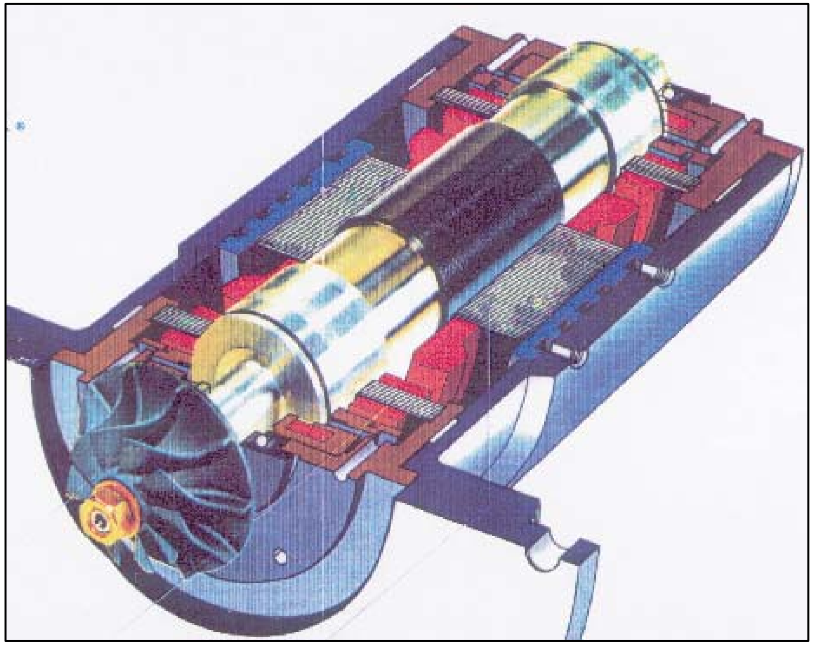
$$M = P/(2\pi \cdot n)$$

“Size“ of a machine (volume *V*):

Determined by **„torque density” *m* = *M*/*V***

$$V = M/m \sim P/(n \cdot m)$$

High power *P* $\Rightarrow$ low torque *M* = low volume *V*



Cut-view: Maglev turbo-compressor rotor

Source: Piller, Germany

Motor power determined by speed $P \sim n$

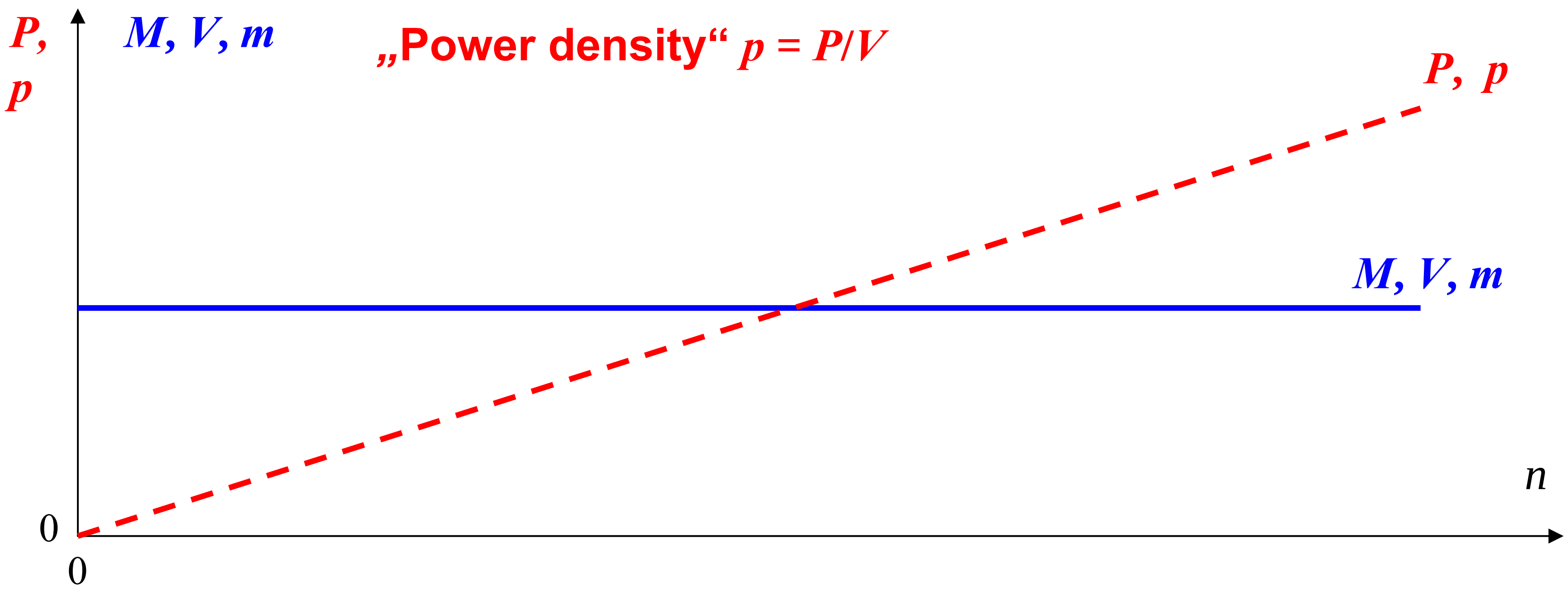
- **Mechanical system = „machine":**

  Torque *M* determines machine volume *V* via torque density *m*

  Small torque *M* = small machine size *V*

  "Power determined by speed" $P \sim n$

  „Power density" $p = P/V$



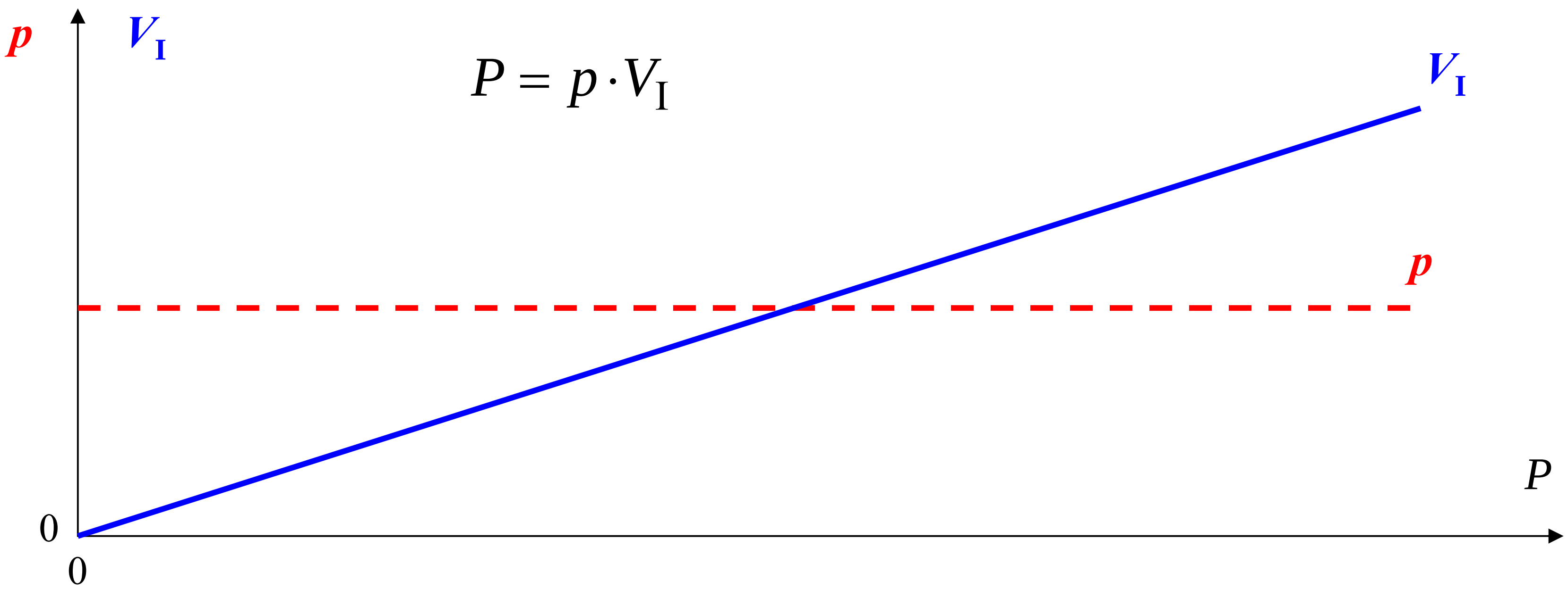
Inverter size determined by power $V_I \sim P$

- **Electronic system = feeding inverter:**

"Power from voltage *U* & current *I* ": $S \sim U \cdot I$

Apparent power $S = P / \cos\varphi$ determines inverter size (volume V_I) via *p*

Small power S = small inverter size V_I



Why “High-Speed” E-Machines?

- Small volume/power V/P ratio advantageous = “high power density $p = P/V$“

- Gearless drive system = reduced maintenance & vibrations

- Wide rated “power/speed”-range P_N/n_N:
  (1 000 000 … 500 000 /min), 0.1 kW … 3000 /min, 1000 MW

- Increasing field of applications as
  pumps,
  compressors,
  small gas turbines,
  direct coupled air-craft generators,
  high speed cutting drives, …

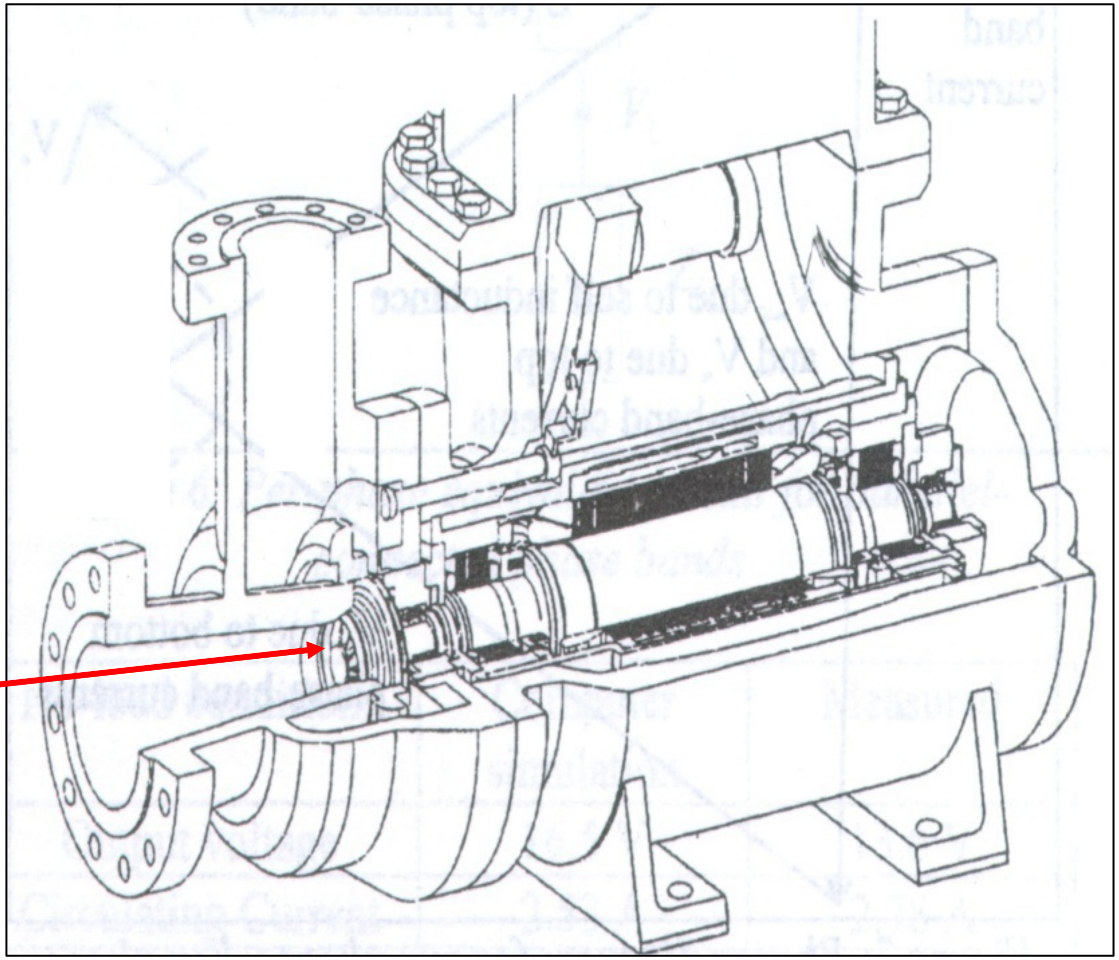
Typical High-Speed Drive Application

High-Speed PM generator with single stage turbine

<u>Natural gas expansion turbine:</u>

- *Small volume* at high power
- *Less mass*
- *Gearless direct drive*
- *Low maintenance* (magnetic bearings)

Small single-stage turbine runner for 500 kW at high speed 32 000 /min!



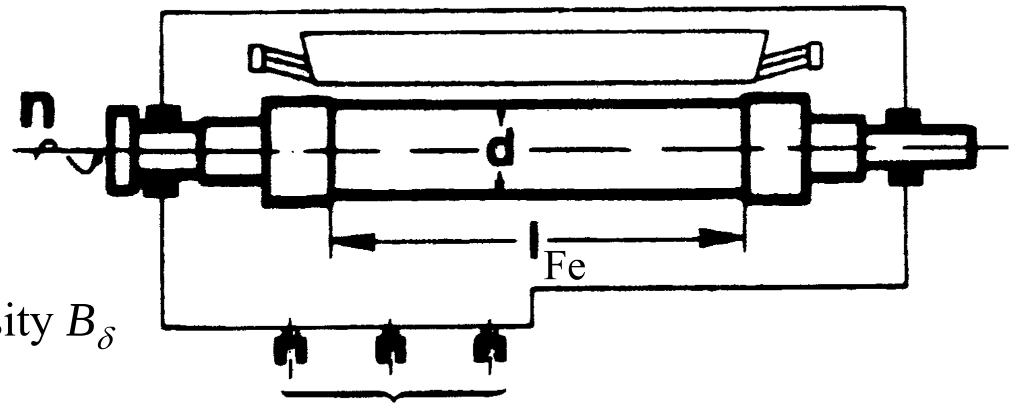
Source: Piller, Germany

Torque density *m*

- Motor "active volume" V determined by rotor diameter d & active rotor length l_{Fe}
- *LORENTZ*-force: $F = I \cdot B_\delta \cdot l_{Fe}$ Torque: $M = z \cdot F \cdot \frac{d}{2} = z \cdot I \cdot B_\delta \cdot l_{Fe} \cdot \frac{d}{2}$
- Three-phase winding, N_s turns per phase = z conductors: $z = 3 \cdot 2N_s$
- **Torque density:** $m = \frac{M}{V} = \frac{z \cdot I \cdot B_\delta \cdot l_{Fe} \cdot \frac{d}{2}}{d^2 \cdot l_{Fe} \cdot \pi / 4} \sim \frac{z \cdot I}{d \cdot \pi} \cdot B_\delta = A \cdot B_\delta$

$$m \sim A \cdot B_\delta$$

Current loading A Air gap flux density B_δ



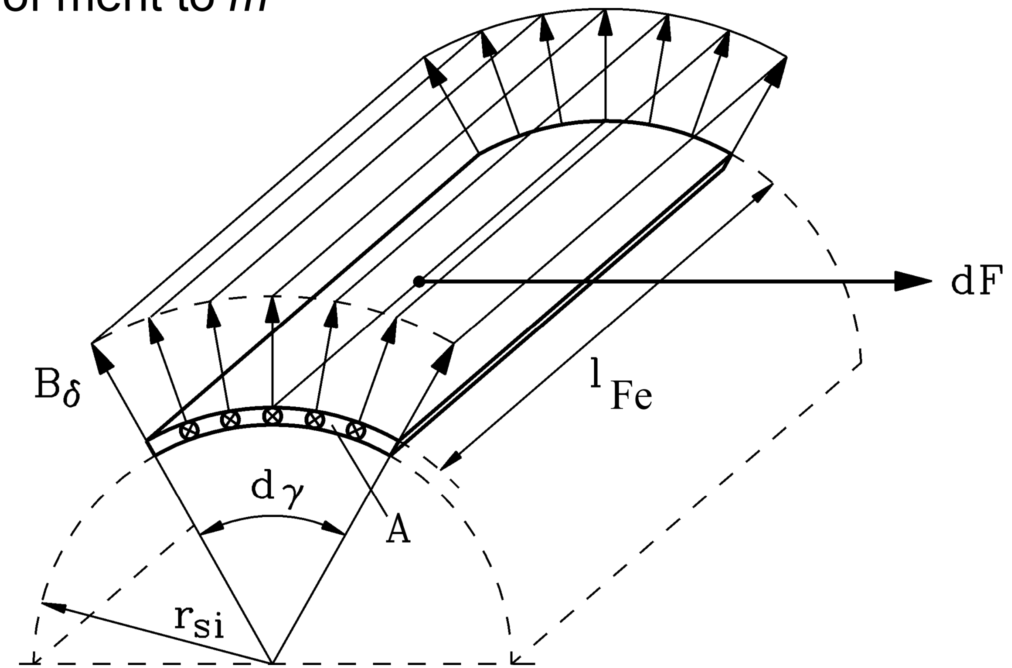
$$\bar{P} = 3 \cdot U \cdot I \cdot \cos\varphi$$

Source: Bohn, T. (Hsg.): El. Energietechnik

Specific thrust τ

„Specific thrust“: $$\tau = \frac{z \cdot F}{d \cdot \pi \cdot l_{Fe}} = \frac{2M}{d^2 \cdot \pi \cdot l_{Fe}} = \frac{m}{2}$$

τ: Alternative figure of merit to *m*



Contents

Mechanical challenges of High-speed drives

- Challenge 1: Rotor integrity at high speed due to high centrifugal forces

- Challenge 2: Rotor vibrations, excited by rotating imbalance forces
  $\Rightarrow$ Elastic vibration behaviour of rotor
  = **rotor dynamics**

$\Rightarrow$ Rotor strength and rotor dynamics
dominate the High-speed-machine design !

Challenge 1: What means “High-Speed” ?

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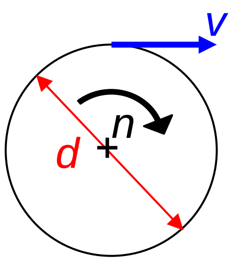
- NOT ONLY: High “revolutions per second” *n* !

  BUT:

  High rotor circumference speed *v*



$$v = d \cdot \pi \cdot n \cong 100 \ \ldots \ 250 \ \mathrm{m/s}$$

(*d*: Rotor outer diameter)

- High mechanical (tangential) stress σ_t due to high centrifugal forces !

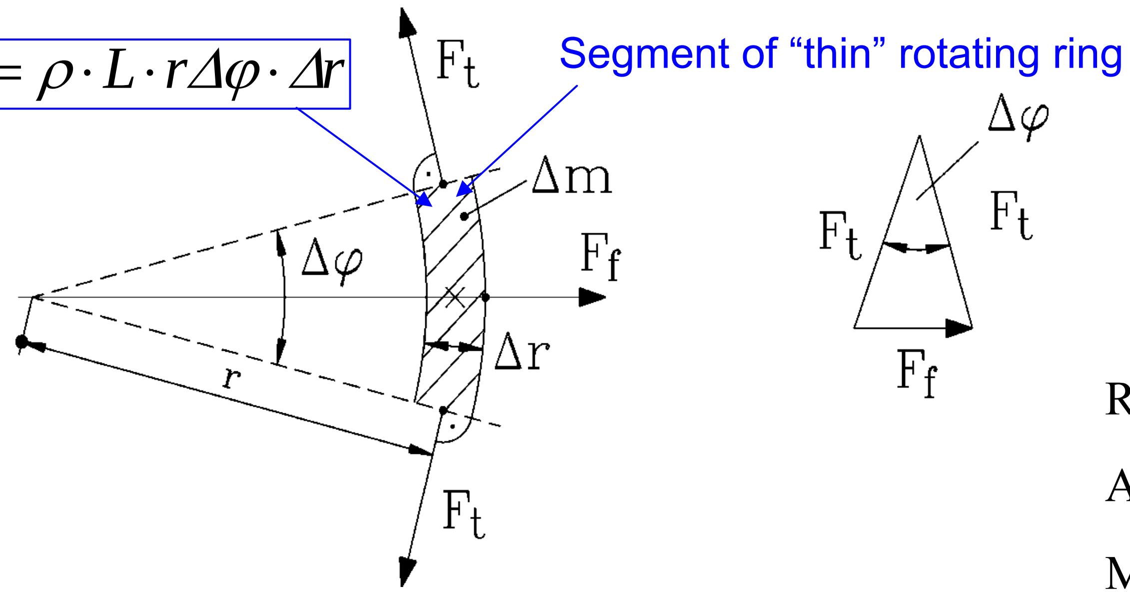
$\Rightarrow$ Stress σ proportional to mass density ρ and to *v* !

$$\sigma_t \sim \rho \cdot v^2$$

Example:

Tangential stress σ_t in a "thin" rotating ring

$$\Delta m = \rho \cdot L \cdot r \Delta\varphi \cdot \Delta r$$



$$F_f = \Delta m \cdot r \cdot (2\pi n)^2$$

$$F_f \approx F_t \cdot \Delta\varphi$$

Ring diameter $d = 2r$

Axial length L

Mass density ρ

Tangential stress σ_t : $\sigma_t = \frac{F_t}{L \cdot \Delta r} \approx \frac{F_f / \Delta\varphi}{L \cdot \Delta r} = \rho \cdot r^2 \cdot (2\pi n)^2 = \rho \cdot v^2$

$$\sigma_t = \rho \cdot v^2$$

Rotor stress distribution

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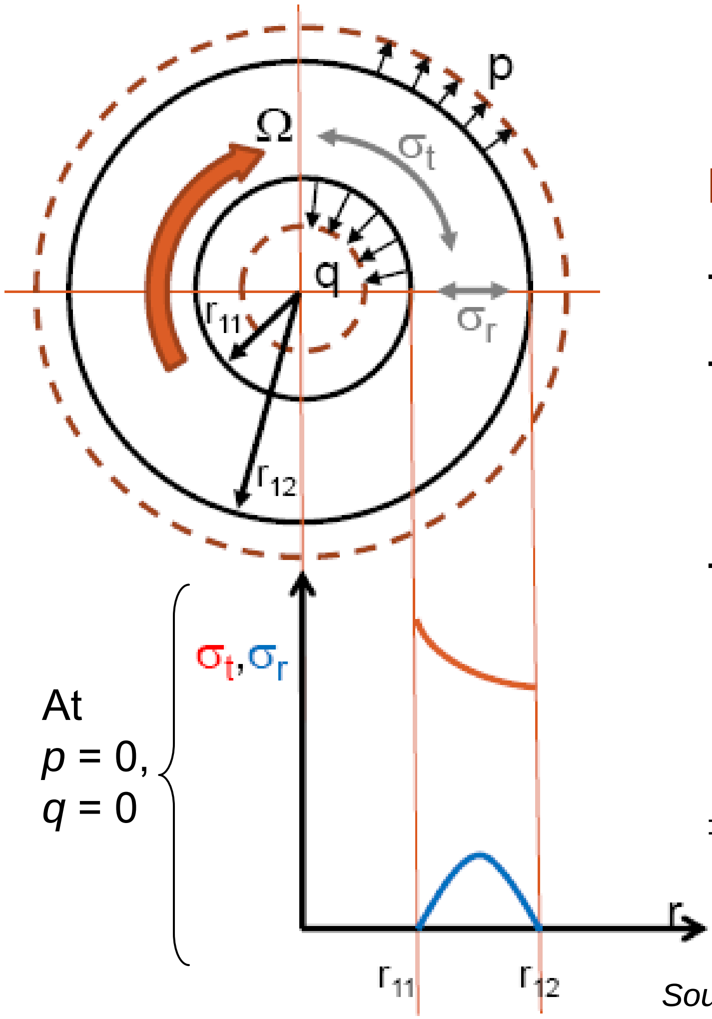


$$\Omega = 2\pi \cdot n$$

Rotor model as rotating „thick“ ring:

- Tangential and radial stress

- General loading:
  Centrifugal load (Ω), shrink fit load (p, q), thermal expansion stress load (p, q)

- At pure centrifugal load: $p = 0$, $q = 0$:

$$\sigma_t \sim \rho \cdot v^2 \qquad \sigma_r \sim \rho \cdot v^2 \qquad \sigma_t >> \sigma_r$$

$\Rightarrow$ Dominating tangential stress

Source: Canders, W.-R.: TU Braunschweig, 2014

Example: "High-Speed" stress

$$\sigma_t \sim \rho \cdot v^2$$

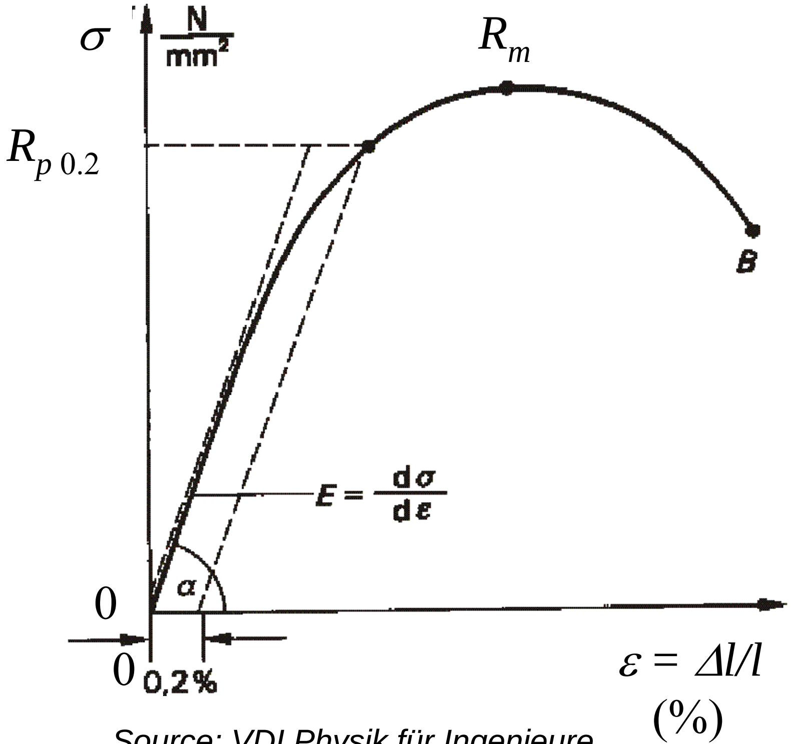
Yield strength of steel sheet:
$R_{p,0.2}$ = 350 N/mm²

ROTATING "thin" steel ring (ρ = 7850 kg/m³)
at v = 211 m/s

Tangential stress reaches yield strength
at which ring diameter d?

a) At d = 1.3 m: n = 3 000 /min

b) At d = 90 mm: n = 45 000 /min



Source: VDI Physik für Ingenieure

⇒ BOTH speed levels 3000/min & 45 000/min are **"high-speed" cases!**

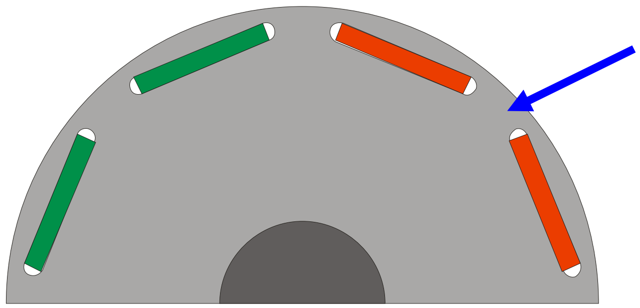
Typical “High-Speed” limits

- Circumferential speed *v* is the „characteristic“ parameter for rotor strength
- „High speed“ means typically: $v \geq 100 \text{ m/s}$

Typical circumferential speed limits for different E-machine designs:

Permanent magnet synchronous machine	Permanent magnet synchronous machine	Synchronous machine, el. excitation	Synchronous machine, el. excitation	Induction motor
Buried magnets	Surface magnets, carbon fibre bandage	Salient pole	Cylindrical massive rotor	Massive cage rotor with end caps
80 m/s	280 m/s	90 m/s	220 m/s	200 m/s

Fixing buried magnets at high speed (1)



- No bandage ⇔ magnets are fixed by rotors sheets
- Small magnetic air gap
- Less magnet material in case of flux concentration
- Segmented magnets per pole with radial iron bridges for higher centrifugal force capability

Fixing buried magnets at high speed (2)

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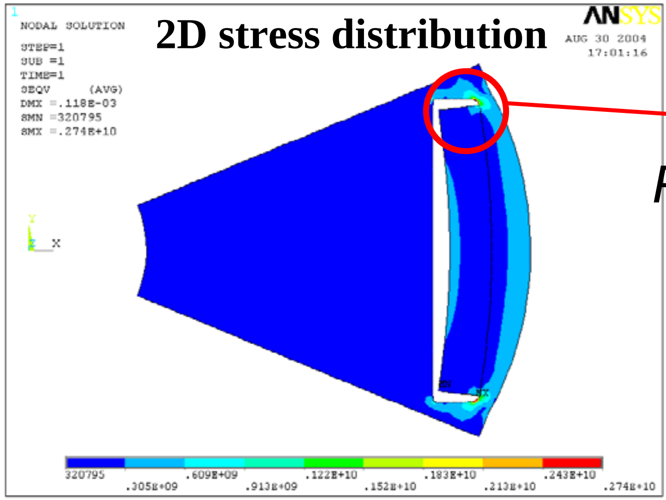
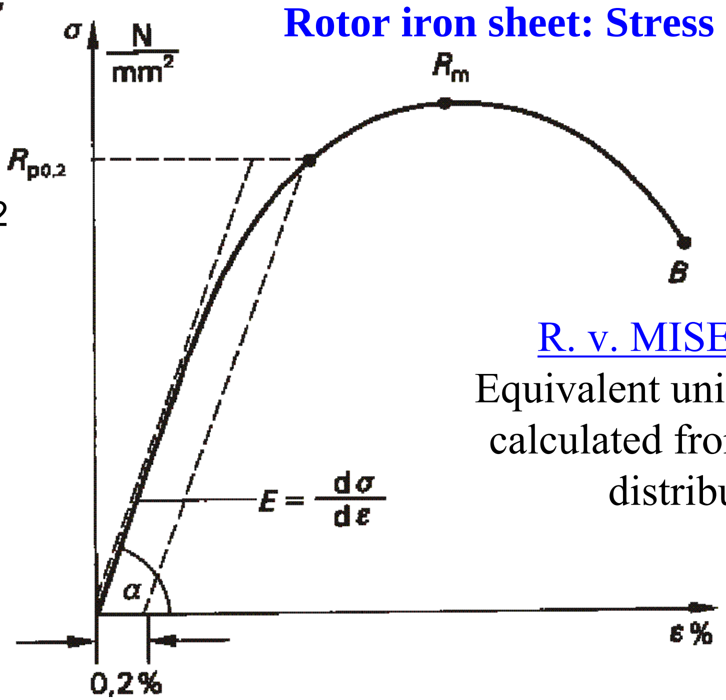
- Detailed mechanical calculation necessary, requires Finite Element Calculation
- Max. tensile strength must stay below 0.2%-deformation limit of sheet $R_{p0,2}$



$R_{p0,2}$

Rotor iron sheet: Stress σ vs. strain ε



R. v. MISES-stress:
Equivalent uni-axial stress, calculated from 2D stress distribution

Source: VDI Physik für Ingenieure

Fixing of magnets by bandage

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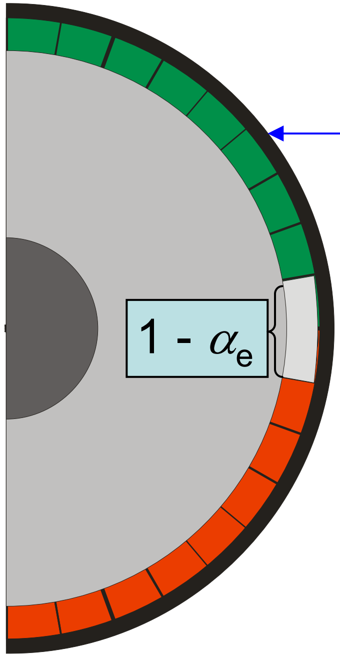
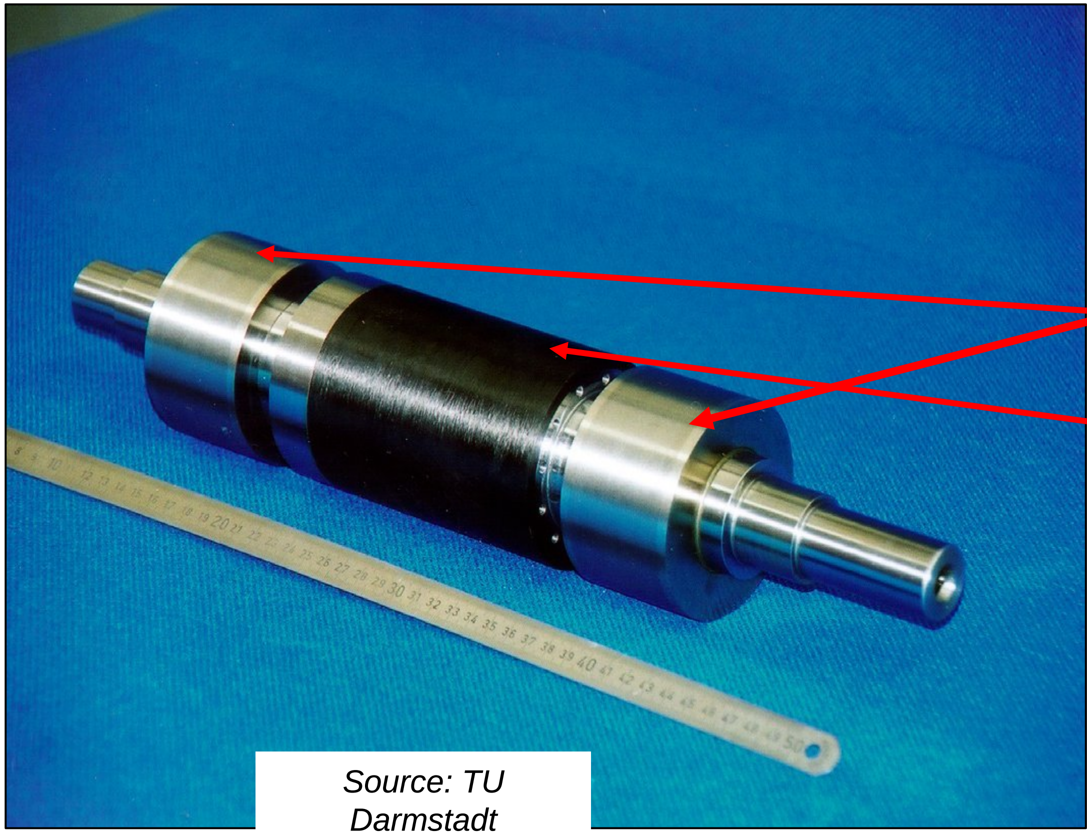


- **4-pole rotor**
- **Pole coverage ratio $\alpha_e = 8/9 < 1$**

Surface mounted magnets $\alpha_e < 1$ "dangerous"!

Pre-fabricated CFC bandage, pressed onto rotor



Source: TU Darmstadt

PM-Rotor

40 kW, 40000/min

Magnetic bearings

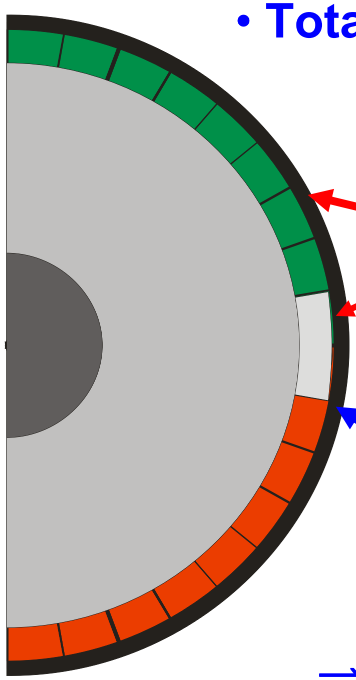
Carbon fiber bandage

Outer diameter: ca. 90 mm

Example:
Damaged Rotor due to Magnet Edge Pressure

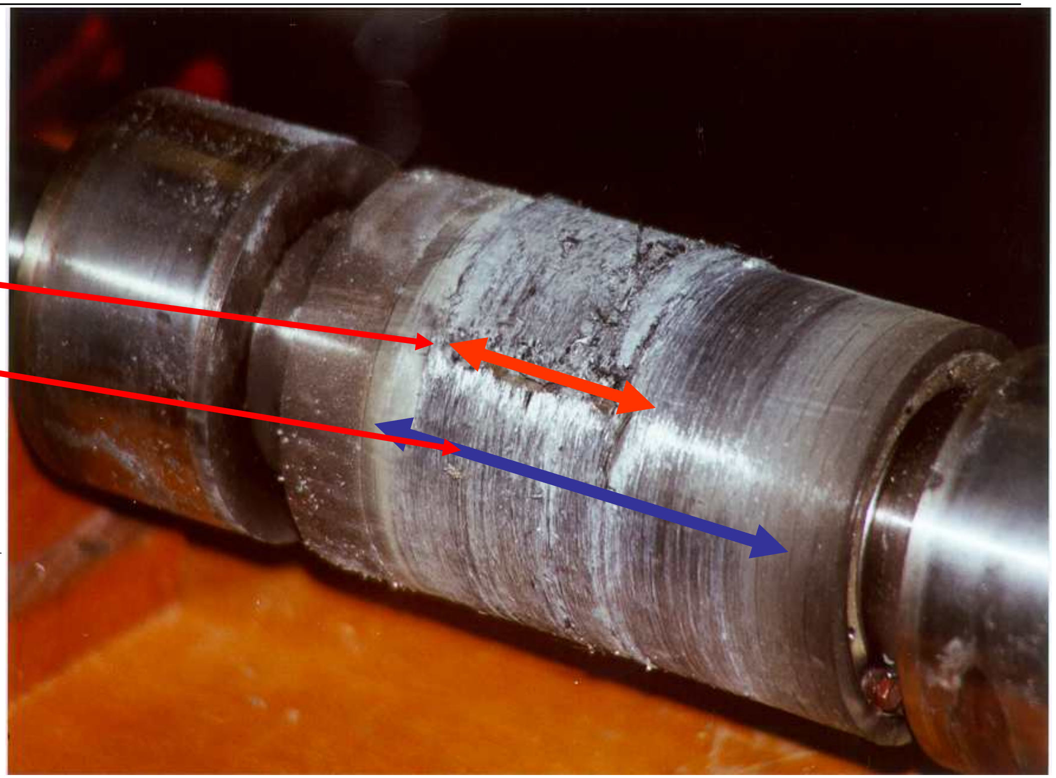
Breaking of bandage at 35 000/min

- **Break length**
- **Total active length**



Different centrifugal forces in magnets and inter-pole gap

Magnet edges cut into carbon fiber bandage



4-pole rotor with PM, carbon fiber bandage and magnetic bearings

Source: TU Darmstadt

⇒ 100% pole coverage ratio recommended $\alpha_e = 1$!

PM synchronous rotor, 100% coverage

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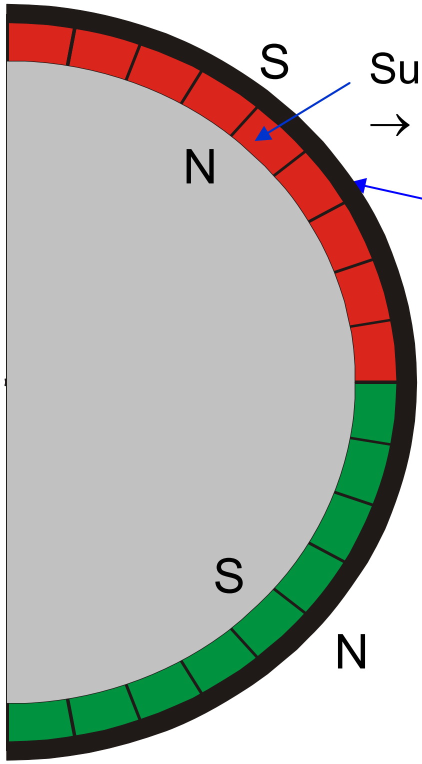
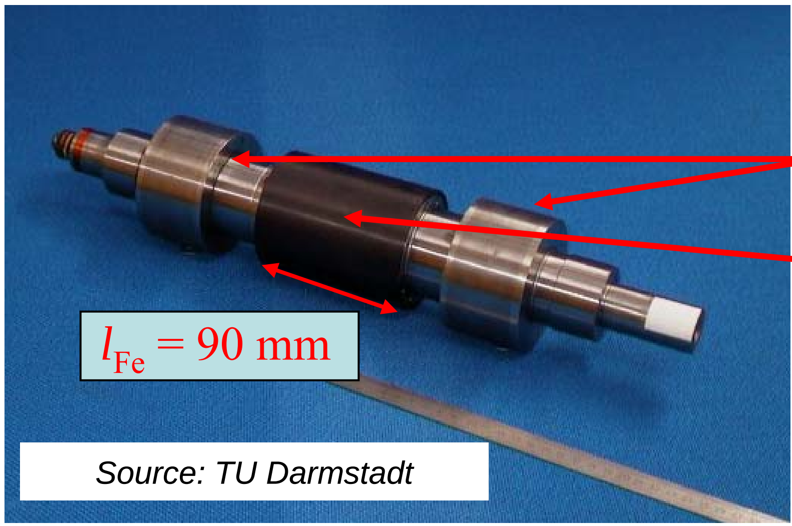
Example: Distributed double-layer integer-slot stator winding, semi-closed stator slots, 4-pole rotor, pole coverage ratio 100%



Surface mounted radial magnetized segmented magnets
$\rightarrow$ low eddy currents

Pre-fabricated CF bandage is pressed onto rotor with force



PM-Rotor:

P_N = 40 kW, n_N = 40 000/min
over-speed (OS) 120%:
48 000/min

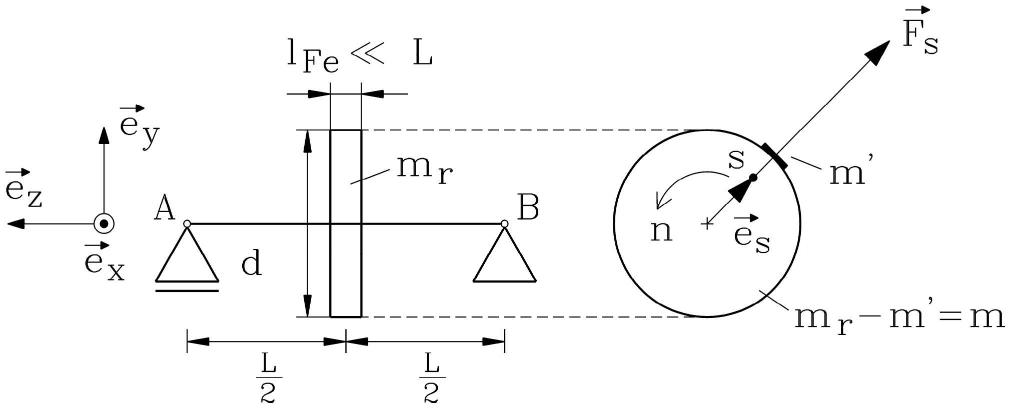
Magnetic bearings

Carbon fiber bandage

Outer rotor diameter:
d = 90 mm

v = 188 m/s (OS: 225 m/s)

Challenge 2: Rotor dynamics: Residual rigid rotor imbalance

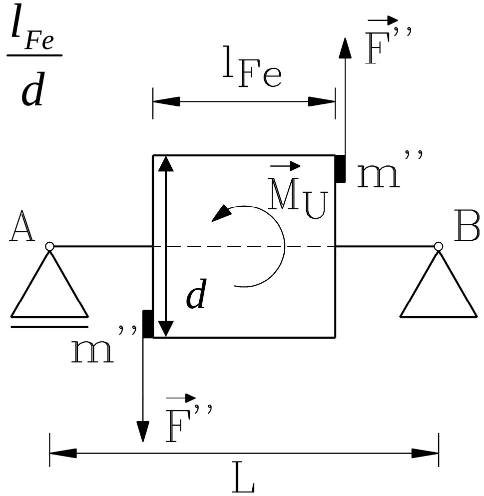


1) „Static" imbalance U_S
at disk-like rotor ($l_{Fe} << L$)
leads to imbalance force F_S

$$\vec{U}_S = m_r \cdot \vec{e}_S \Rightarrow \vec{F}_S = m_r \cdot \vec{e}_S \cdot \Omega^2$$

$$\Omega = 2\pi \cdot n$$

$$\lambda = \frac{l_{Fe}}{d}$$



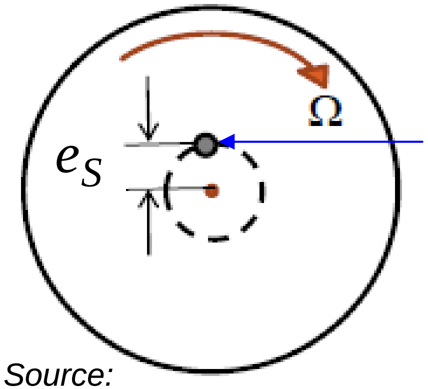
S: Center of gravity
m', m'': Imbalance mass
m_r: Rotor mass
F_S: Centrifugal force

2) „Dynamic" imbalance M_U
at „long" rotor ($l_{Fe} \sim L$)
leads to imbalance torque $M'' = F'' \cdot l_{Fe}$

$$M_U = m'' \cdot \frac{d}{2} \cdot l_{Fe} \rightarrow M'' = F'' \cdot l_{Fe} = m'' \cdot \frac{d}{2} \cdot l_{Fe} \cdot \Omega^2$$

Quality class *G* of rotor imbalance

- Imbalance forces: Counter-balanced by balancing masses in two rotor planes for static and dynamic imbalance = “rotor balancing”
- Residual imbalance after “rotor balancing” NOT zero $\Rightarrow$ “Imbalance class” *G*



Source: Canders, W.-R.: TU Braunschweig, 2014

Orbiting centre of gravity with Ω

$v_S = G$: Orbiting circumference velocity $\quad v_S = \Omega \cdot e_S$

G = Quality class of imbalance (ISO 1940)

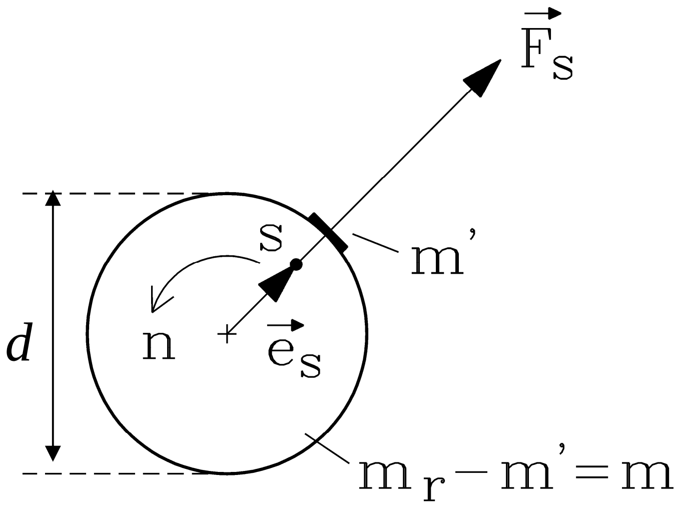
Typical for high speed machines: *G* = 1 mm/s or 0.4 mm/s

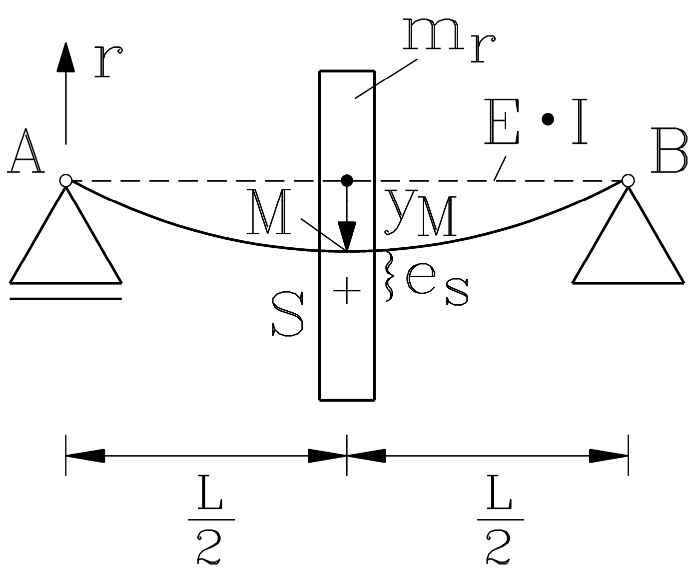
Example: „Static“ imbalance U_S:

$$e_S = 0.24\ \mu\text{m},\ n = 40\,000/\text{min} \Rightarrow G = 1\ \text{mm/s}$$

Rotating imbalance forces excite rotor vibrations (1)

- The rotating residual imbalance forces excite rotor vibrations with rotational speed *n*, because a) the bearings are not rigid, but elastic,
  b) the rotor is elastic and allows bending deformation y_M



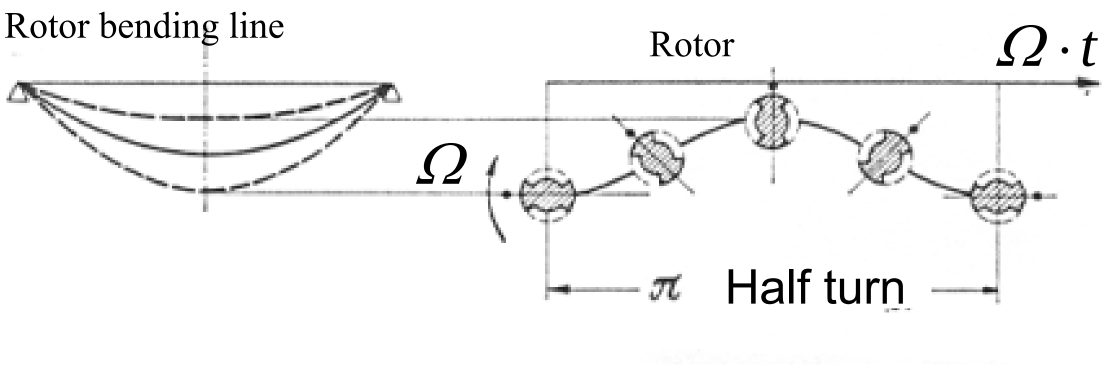


Rotating imbalance forces excite rotor vibrations (2)

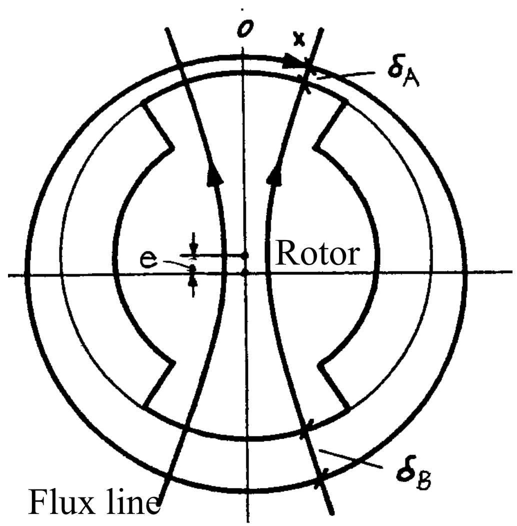
Different additional vibration excitations exist:
- Misaligned coupling,
- Anisotropic rotor stiffness,
- Rotor eccentricity *e*:

  (i) Static and (ii) dynamic (Ω-depending) rotor eccentricity value *e*;
  In combination with single-sided unbalanced magnetic pull !

Source: Wiedemann, E.; Kellenberger, W.; Springer-Verlag, 1968



Anisotropic rotor stiffness

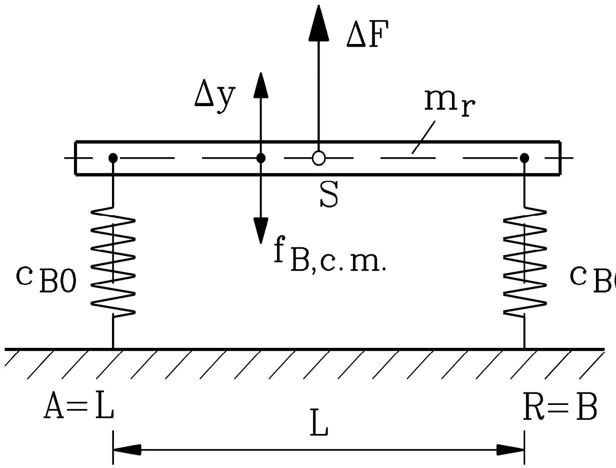


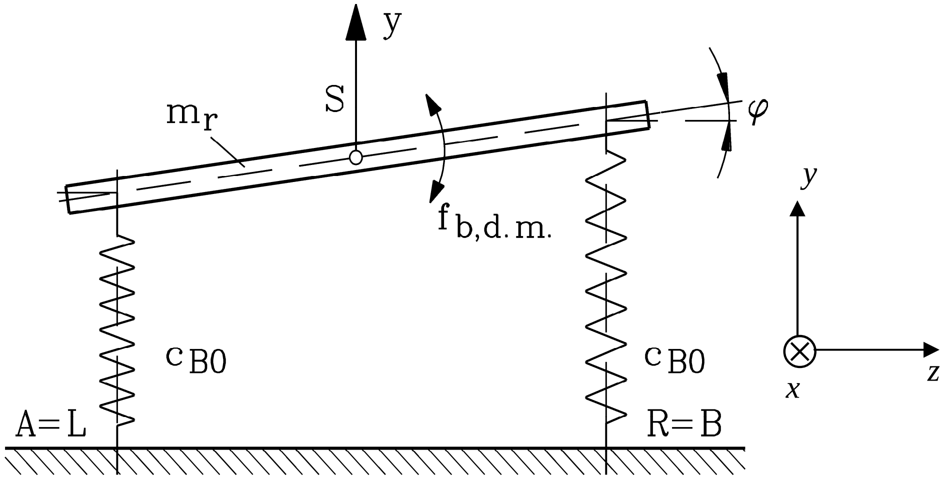
Rotor eccentricity *e*

Rigid rotor vibrates in elastic bearings: „Rigid body mode vibration"

- Elastic bearings are represented by spring constant c_{B0} ⇒ Two vibration modes

Common mode vibration | **Differential mode vibration**





$$f_{B,c.m.} = \frac{1}{2\pi} \cdot \sqrt{\frac{c_{B0}}{m_r}}$$

$$f_{B,d.m.} = \frac{1}{2\pi} \cdot \frac{L}{2} \cdot \sqrt{\frac{c_{B0}}{J_x}} > f_{B,c.m.}$$

J_x: Angular momentum around x-axis

Source: Parkus Mechanik fester Körper, Springer, Vienna

Bending of elastic rotor in rigid bearings

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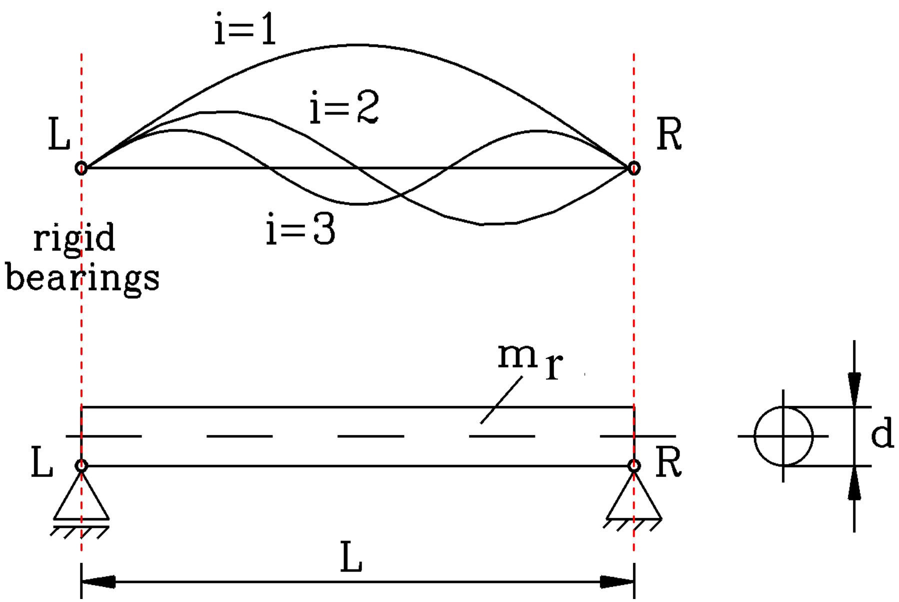
- **Simplified approach: Rotor (shaft) considered as elastic cylindrical beam:** Diameter *d*, length *L* between bearings, mass density ρ, *Young´*s modulus *E*
- **Bending vibrations with "eigen"-frequencies f_b** (at rigid bearings):

$$f_{b,i} = \frac{1}{2\pi} \cdot \left(\frac{i \cdot \pi}{L}\right)^2 \cdot \sqrt{\frac{E}{\rho} \cdot \frac{d}{4}} \qquad i = 1,2,3,... \qquad \textbf{mode number } i \qquad m_r = \rho \cdot L \cdot d^2 \cdot \pi / 4$$



Example:

$i = 1$: 703 Hz

$i = 2$: $2^2 \cdot 703 = 2812$ Hz

$i = 3$: $3^2 \cdot 703 = 6327$ Hz

a) Real frequencies are lower!

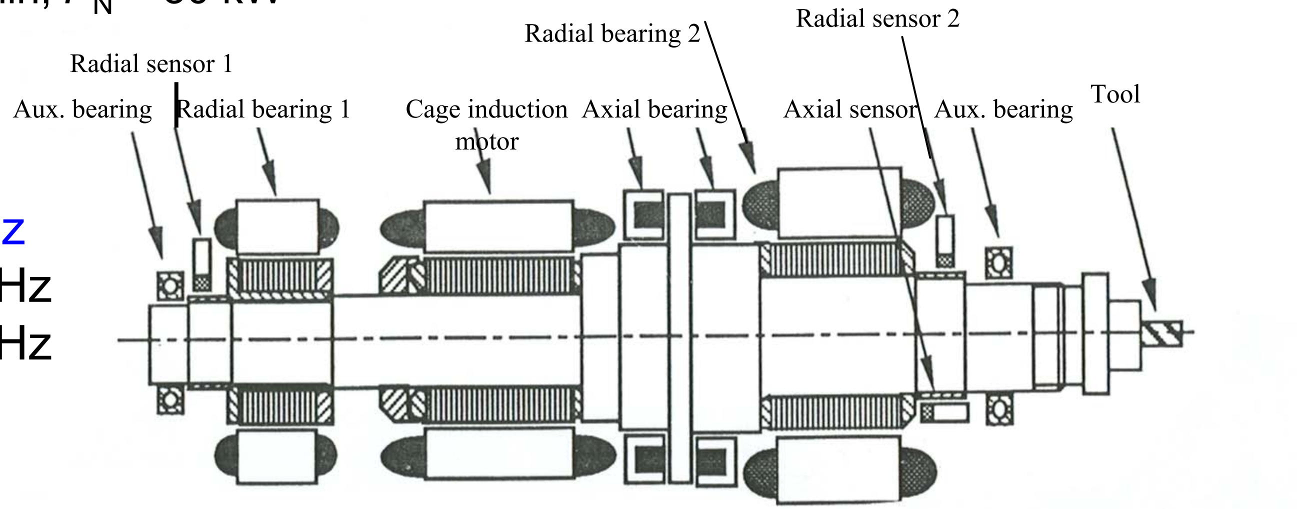
b) Exciting n below $0.7 \cdot f_{b,1}$:

Rotor "behaves" rigid!

Example: Natural bending vibration modes of a milling spindle rotor

2-pole "High-Speed" Aluminum-squirrel cage rotor: 2 radial & 1 axial magnetic bearing

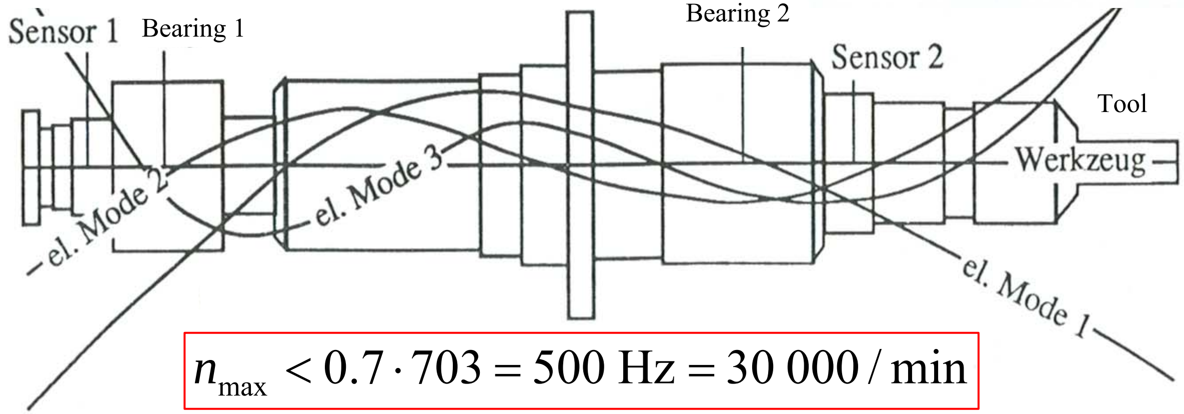
n_N = 35 000 /min, P_N = 30 kW



$k = 1$: 703 Hz

$k = 2$: 1758 Hz

$k = 3$: 2990 Hz



$$n_{max} < 0.7 \cdot 703 = 500\ \text{Hz} = 30\,000\ /\ \text{min}$$

Source:

Schweitzer, G. et al.: Active magnetic bearings

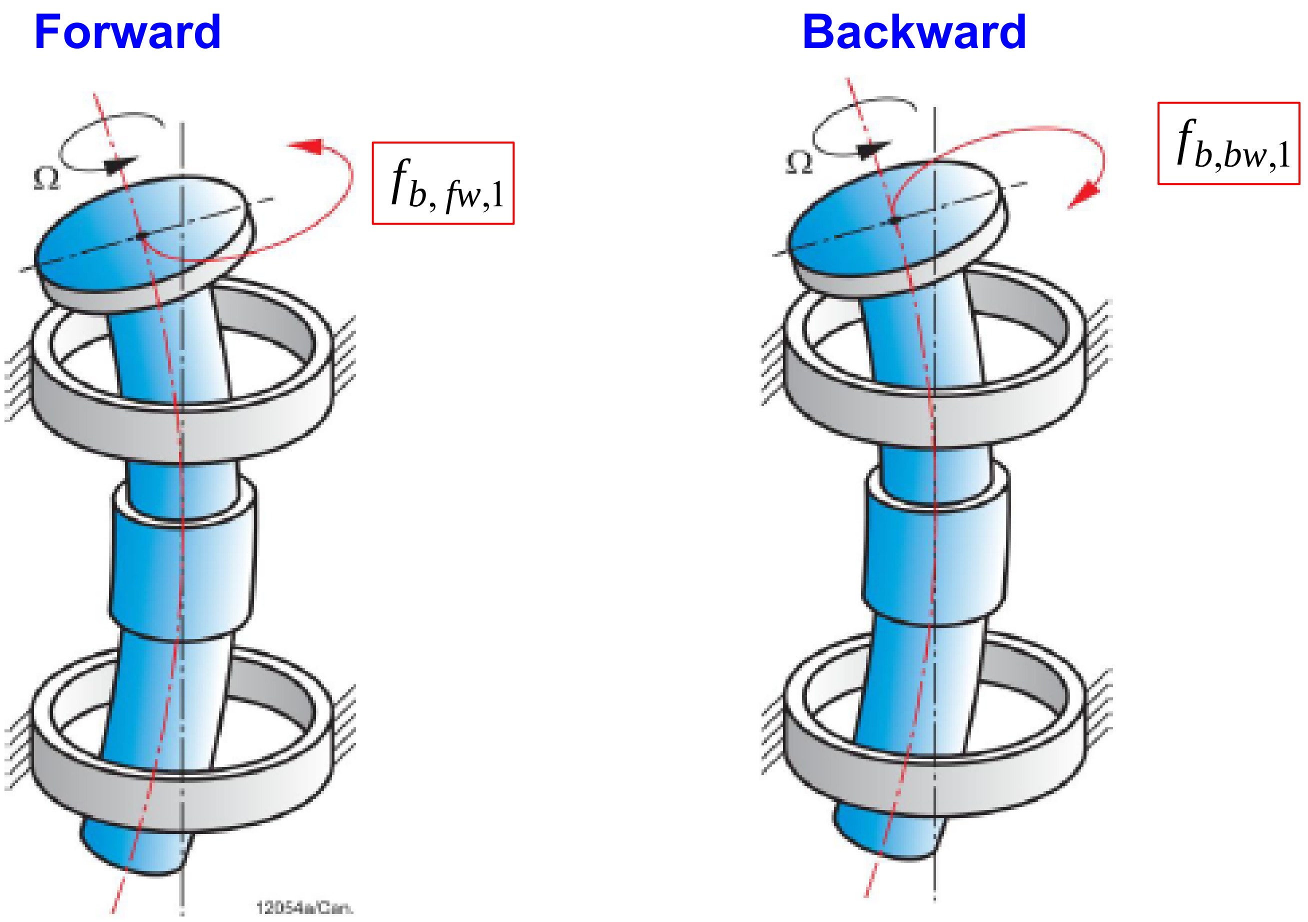
Influence on rotor bending frequencies

- Bigger (longer) rotors have lower bending frequencies $f_b \sim d / L^2$
- Real rotor geometry $\Rightarrow$ more complicated f_b-calculation
- Equivalent *Young´s* modulus of stacked rotor iron:
  How to determine? $\Rightarrow$ Mainly be experiment!
- Finite stiffness of rotor bearings c_{B0}
  a) reduces bending frequencies and
  b) shifts nodes of bending modes
- Unbalanced magnetic pull reduces $c_B < c_{B0}$ $\Rightarrow$ Reduction of bending frequency
- Rotor gyroscopic effect $\Rightarrow$ Rotor "swirls" in
  a) forward swirling mode (fw)
  b) backward swirling mode (bw)

$\Rightarrow$ Bending frequency splits up into two "eigen-frequencies" per bending mode i

$$f_{b,i} \Rightarrow f_{b,fw,i} \quad \text{and} \quad f_{b,bw,i}$$

Forward and backward swirling

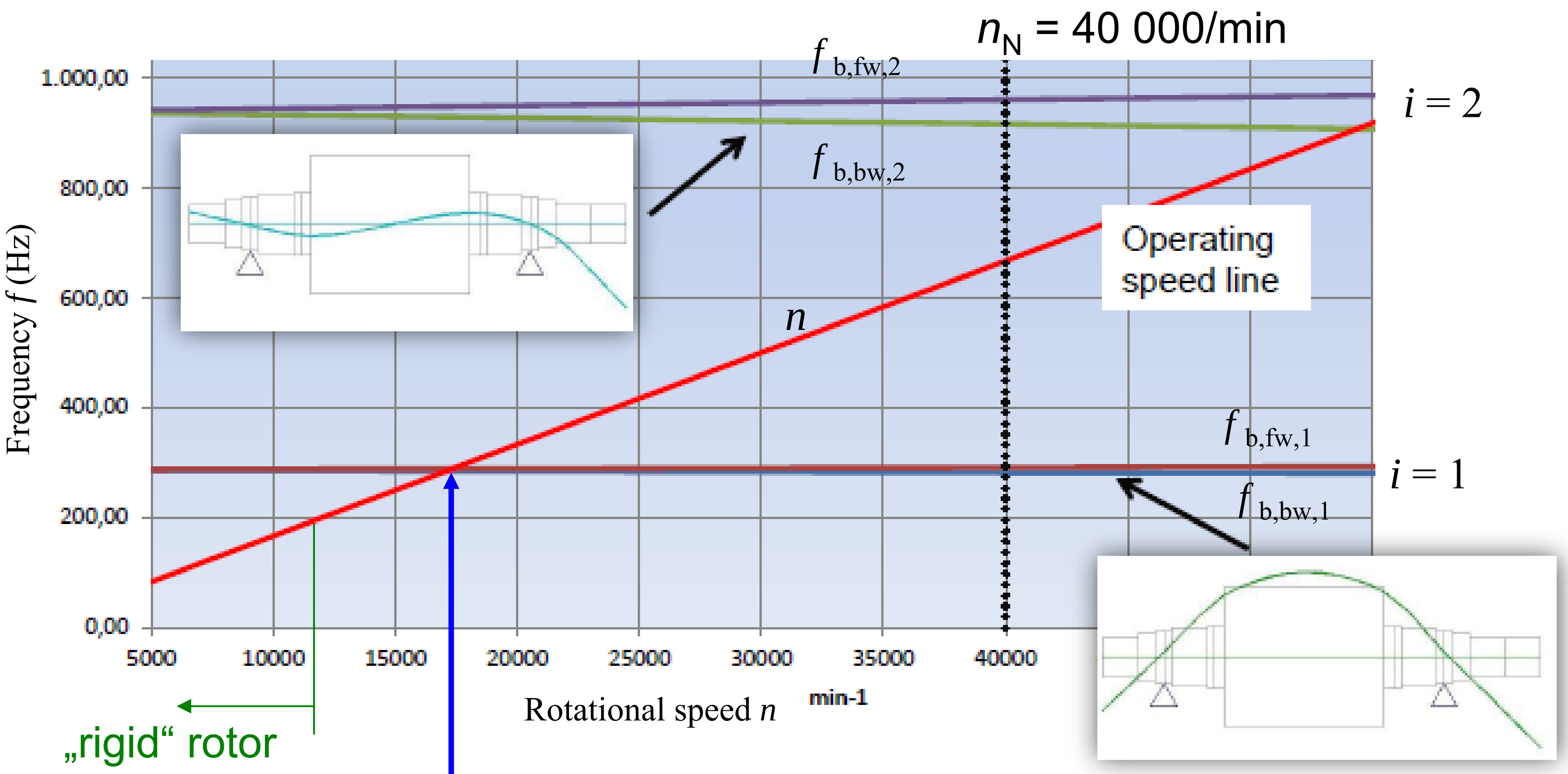


Source: Canders, W.-R.: TU Braunschweig, 2014

Example: *Campbell* diagram

PMSM, laminated rotor yoke, surface magnets, carbon fibre bandage:

P_N = 60 kW, d = 86 mm, v = 180 m/s, l_{Fe} = 90 mm



Bending resonance at 17000/min = 1st critical speed

Source: Canders, W.-R.: TU Braunschweig, 2014

Elastic rotor balancing

- If rotational speed n above e.g. second bending frequency $f_{b,2}$, an elastic rotor balancing in two additional rotor planes is necessary
- Elastic balancing needed to minimize rotor bending amplitude y_M at the resonance points

$$n = f_{b,1} \text{ and } n = f_{b,2}$$

- At smaller rated power the rotor length L is small enough, so that the bending natural frequencies are higher than the maximum operation speed n_{max}

$$n_{max} < f_{b,1}$$

- If possible, keep n_{max} below $0.7 \cdot f_{b,1} \Rightarrow$ Rotor "behaves" as rigid body !

Mechanical limits for rotor volume $V \sim l_{Fe} \cdot d^2$ at “high-speed” and rigid rotor

- Max. surface velocity v_{max} at rated speed n_N determines max. rotor diameter d_{max}:

$$d_{max} = v_{max} / (n_N \cdot \pi) \sim (\sqrt{\sigma_{max} / \rho}) / n_N \qquad \sigma_{max} \sim \rho \cdot v_{max}^2$$

- Rotor diameter-length ratio λ (“slimness“): $\lambda = l_{Fe} / d$

- 1st Rotor bending frequency limits the length:

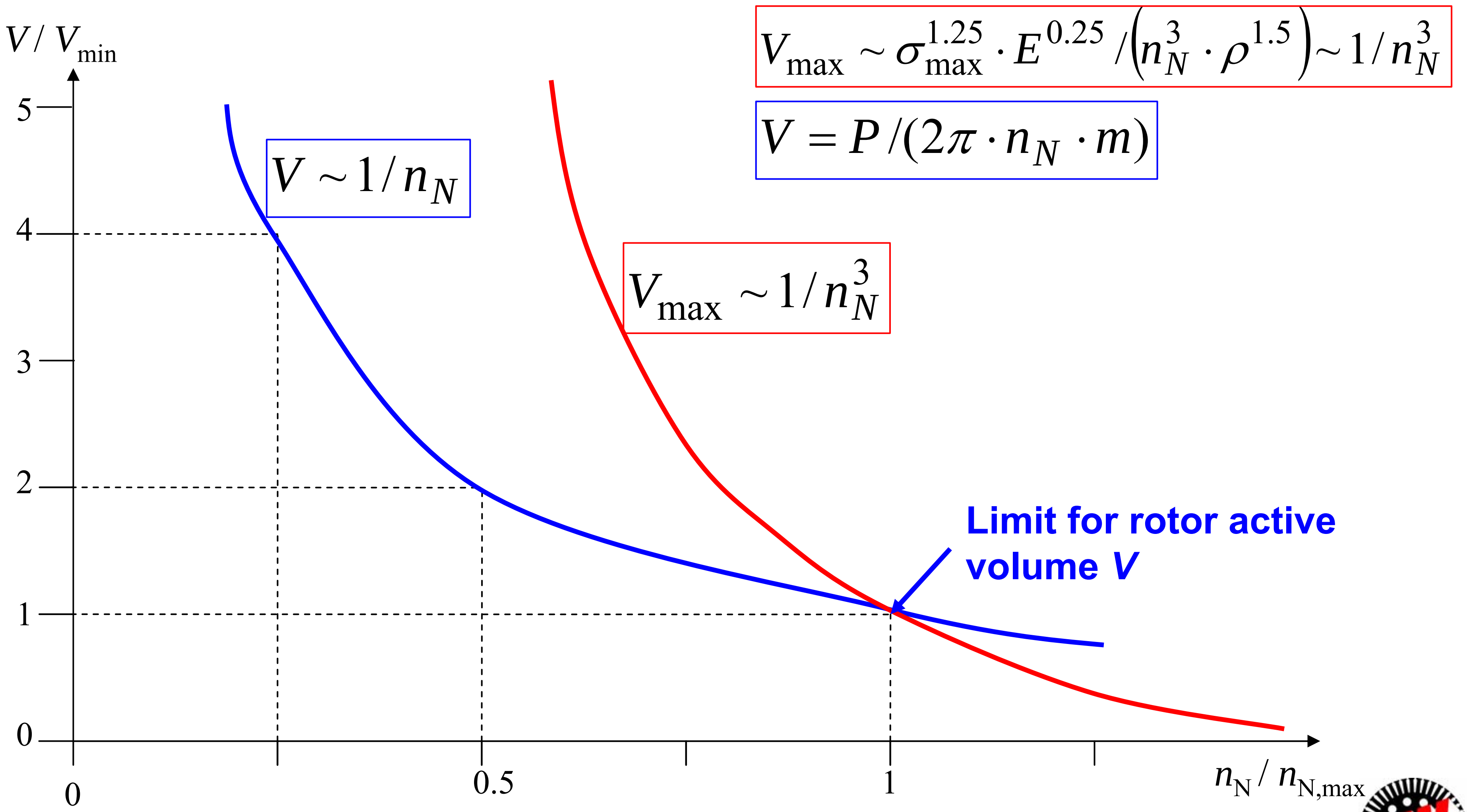
$$f_{b,1} = \frac{n_N}{0.7} \Rightarrow L_{max} \sim \sqrt{\frac{d_{max}}{n_N}} \cdot \sqrt[4]{\frac{E}{\rho}} \sim l_{Fe,max} \Rightarrow \lambda_{max} = l_{Fe,max} / d_{max}$$

- **Limit for rotor active volume *V*:**

$$V_{max} \sim d_{max}^2 \cdot l_{Fe} \sim \sigma_{max}^{1.25} \cdot E^{0.25} / \left(n_N^3 \cdot \rho^{1.5}\right)$$

The higher the speed n_N and mass density ρ, the lower the maximum admissible rotor volume V_{max} at given maximum stress σ_{max}

Limits for rotor volume $V \sim l_{Fe} \cdot d^2$ at "high-speed" and rigid rotor



Reduced maximum speed n with increased rated power P_N

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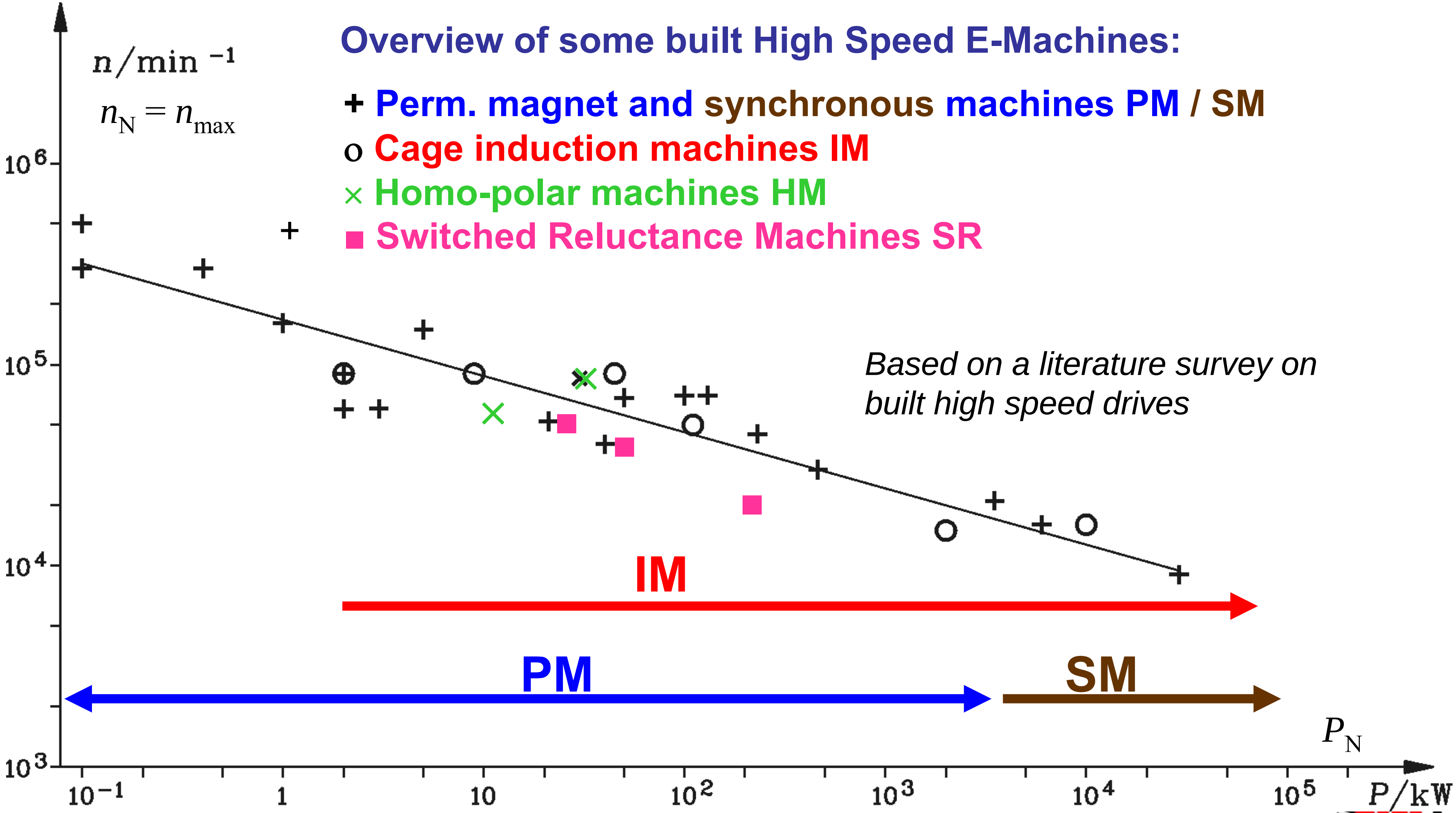

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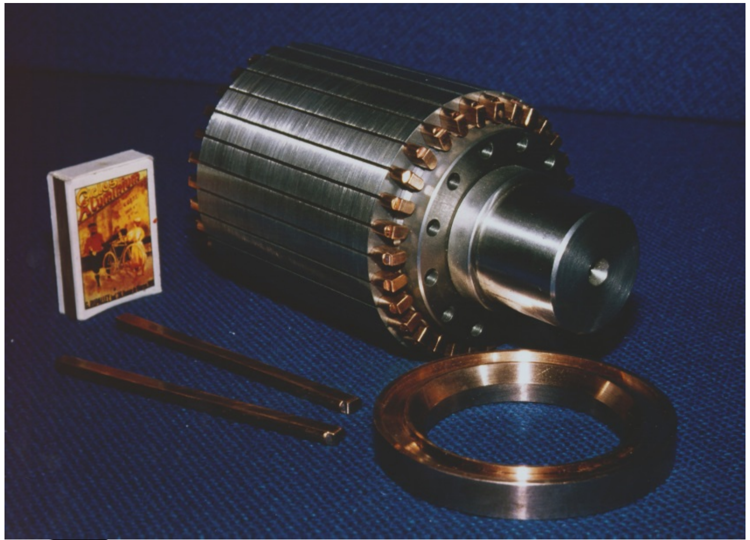
Contents

Types of High Speed Motors

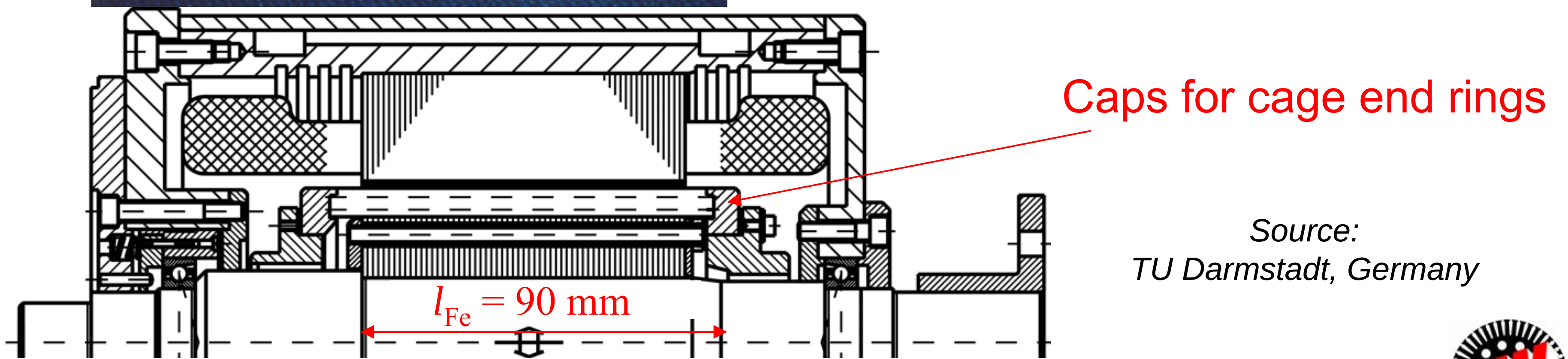
- **PM synchronous machines**
  Rotor magnet fixation essential
- **Electrically excited synchronous machines**
  At higher rated power of interest (MW-range)
- **Cage induction machines (e.g. with massive iron rotor)**
  Cage centrifugal forces needs end caps
- **Cage-less massive rotor induction machines**
  Robust rotor, but slip-dependent losses big in massive iron
- **Homo-polar machines**
  Special machine design, additional losses in massive rotor iron
- **Switched Reluctance Machines**
  Rotor cog-wheel losses, additional iron losses in rotor

Cage induction machine with laminated rotor

Example: 4-pole rotor



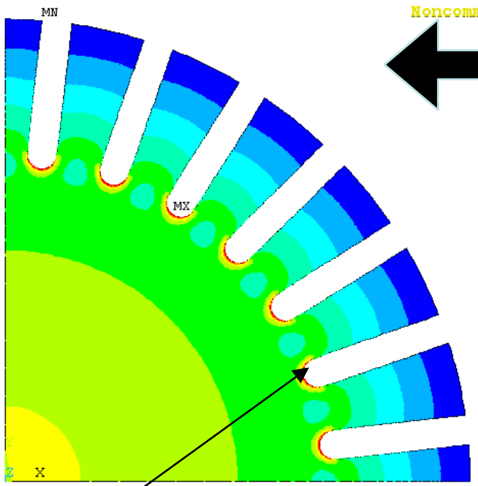
- Squirrel cage rotor winding
- Retaining caps for end rings
- Laminated rotor for low additional losses
- P_N = 30 kW, n_N = 24 000/min (OS: 120%)
- Spindle ball bearings
- Outer rotor diameter d = 90 mm, v = 113 m/s
  OS: 136 m/s



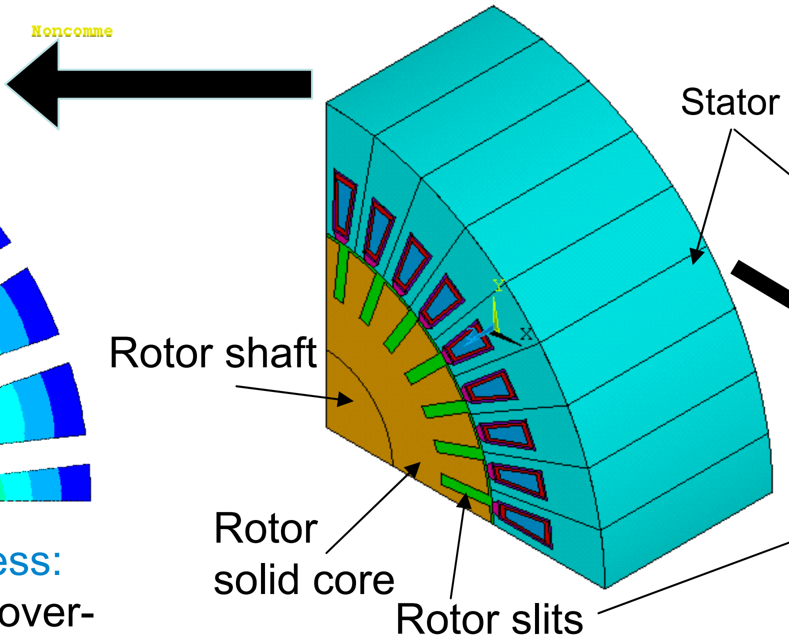
Source:
TU Darmstadt, Germany

Cage-less massive rotor induction machine

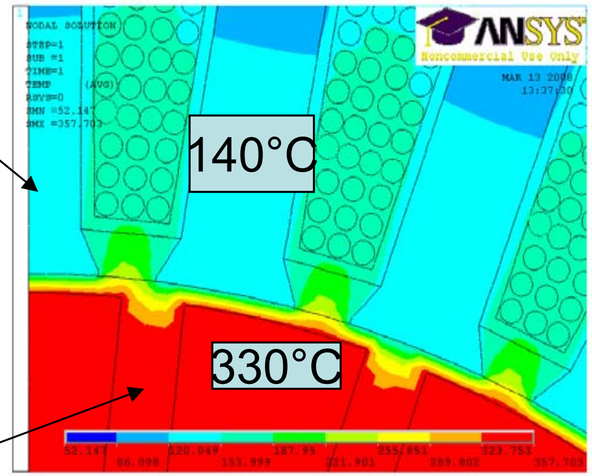
Example: 2-pole massive slit rotor with copper end rings, n_{max} = 29000/min, $d = l_{Fe} = 90$ mm, low power factor, high rotor slip-dependent losses ⇒ special rotor cooling needed for P_N = 24 kW, spindle bearings



Max. tangential stress:
128 N/mm² at 120% over-speed 34800/min



Model of solid slit rotor



Temperature distribution:
Max. temperature in the air-cooled rotor due to the big rotor losses

Source:
TU Darmstadt, Germany

Homo-polar synchronous machine (*ARCO*)

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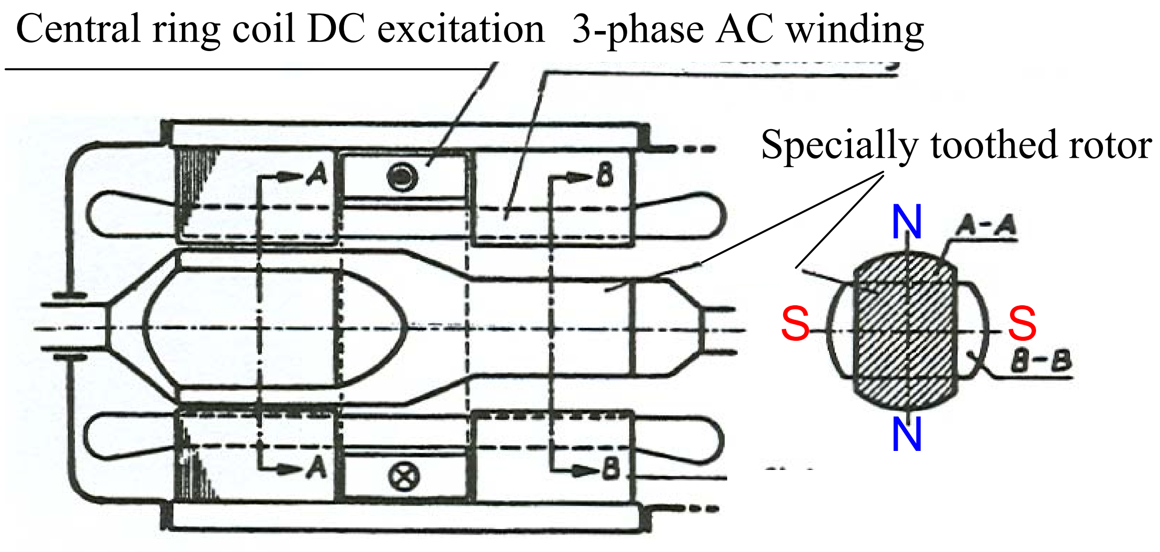
Example: Three-phase electrically excited synchronous machine:
4-pole massive rotor with stator-side DC excitation



Two-halves stator

- No winding or magnet in the rotor
- Variable DC excitation or PM axial excitation
- No slip rings
- Massive rotor: additional surface eddy current losses due to stator slotting
- Low iron saturation needed!

Source: H. Kleinrath, Stromrichtergespeiste Drehfeldmaschinen, Springer, Wien, 1980

Homo-polar synchronous machine (*ARCO*)

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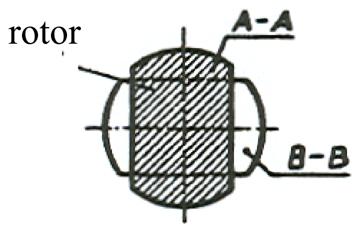
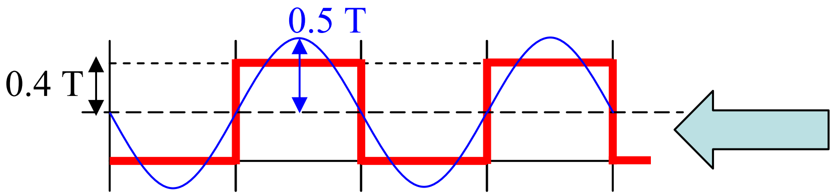


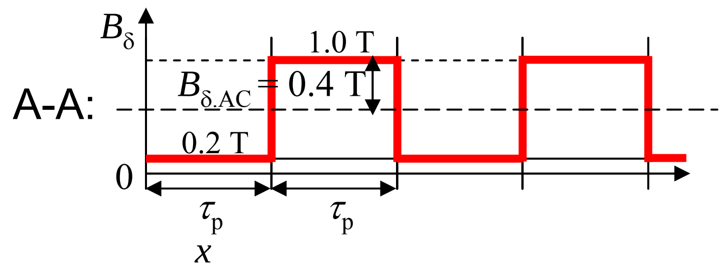


The fundamental wave of the AC air gap field component $B_{\delta,AC}$ induces the stator 3-phase winding with the back EMF $U_p(I_f)$ like in conventional synchronous machines

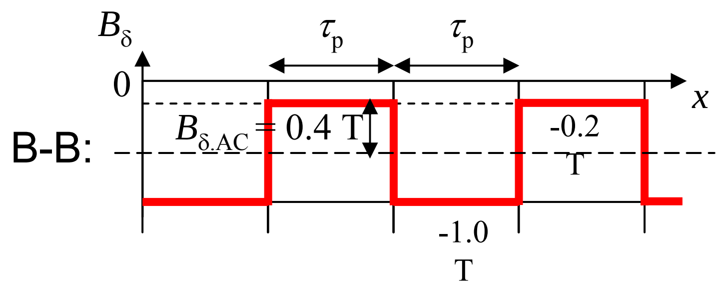
Source: H. Kleinrath, Stromrichtergespeiste Drehfeldmaschinen, Springer, Wien, 1980

Radial air gap flux density $B_\delta(I_f)$ at no-load ($I_s = 0$):

a) Rotor half A-A: Homo-polar positive field



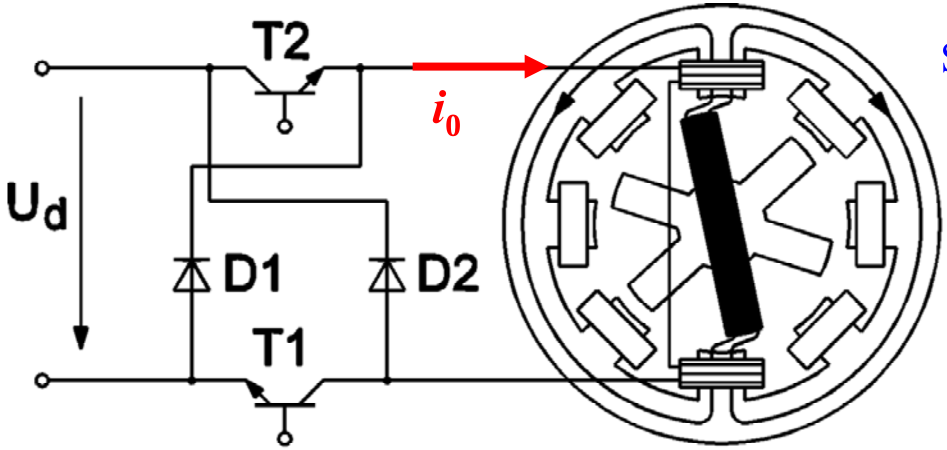
b) Rotor half B-B: Homo-polar negative field



The modulation of the air-gap field B_δ by the rotor reluctance yields an AC air gap field component $B_{\delta,AC}$, which for both motor halves A-A, B-B is IN PHASE

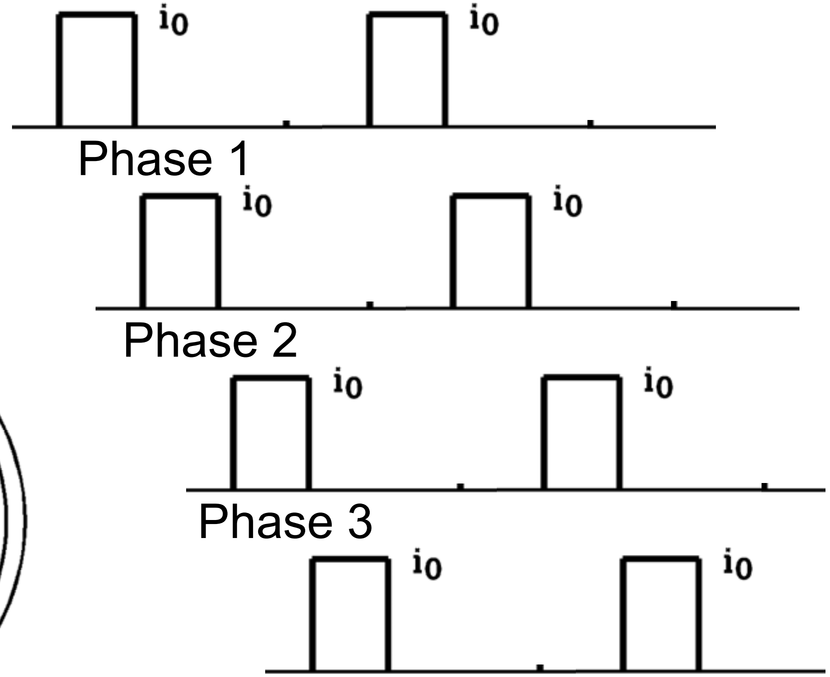
Switched Reluctance Machines

Example: 2-pole laminated rotor with 4-phase stator AC excitation, Q_r = 6 rotor teeth

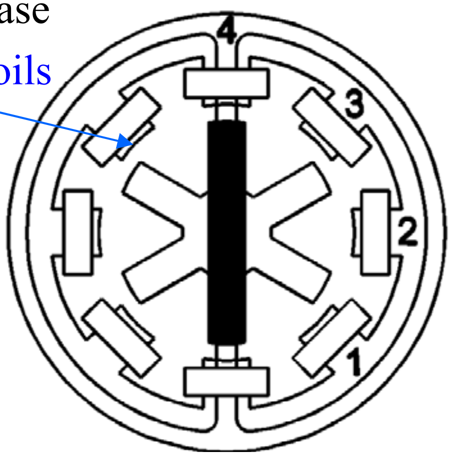


Half-H-Bridge inverter per phase

Stepwise uni-polar current feeding:



Stator tooth coils



- Inter-tooth rotor gaps should be filled to reduce windage losses
- Rather high stator frequency $f_s = n \cdot Q_r$ needed
- Rotor iron losses

Source: E. Hopper, MACCON, Germany

Stator frequency and pole count

El. excited synchronous & induction machines:

Low pole count $2p \Rightarrow$ low electrical frequency $f_s \Rightarrow$

$\Rightarrow$ low iron losses & low inverter frequency: $2p = 2$ poles

e.g. $n_{max} = 40\,000$ /min, $2p = 2$ poles, $f_s = 667$ Hz

PM synchronous machines:

Pole count 2 or better 4 poles $\Leftrightarrow$

Limit by rotor PM demagnetization due to stator field

e.g. $n_{max} = 40\,000$ /min, $2p = 4$ poles, $f_s = 1.33$ kHz

$$f_s = n \cdot p$$

Switched reluctance machines:

Rotor tooth count Q_r:

SRM behaves like a synchronous machine with $2Q_r$ poles

e.g. $n_{max} = 40\,000$ /min, $Q_r = 4$, $f_s = 2.66$ kHz

$$f_s = n \cdot Q_r$$

Contents

Different bearing types (Selection)

- Oil-lubricated high-speed ball bearings (spindle bearings):
  Highest stiffness, but mechanical speed limit
- Oil-lubricated sleeve bearings, at high rotor mass:
  Coupling of vertical and horizontal vibration movement ⇒
  ⇒ Upper speed limit due to bearing instability
- Air cushion sleeve bearings, at low rotor mass:
  Reduced stiffness, bearing instabilities
- Magnetic bearings (MB): No mechanical friction and wear
  Controlled MB: Lower dynamic stiffness due to controller delay
  Self-stable MB: Limited magnetic forces ⇒ Low static stiffness

Bearings for high speed operation

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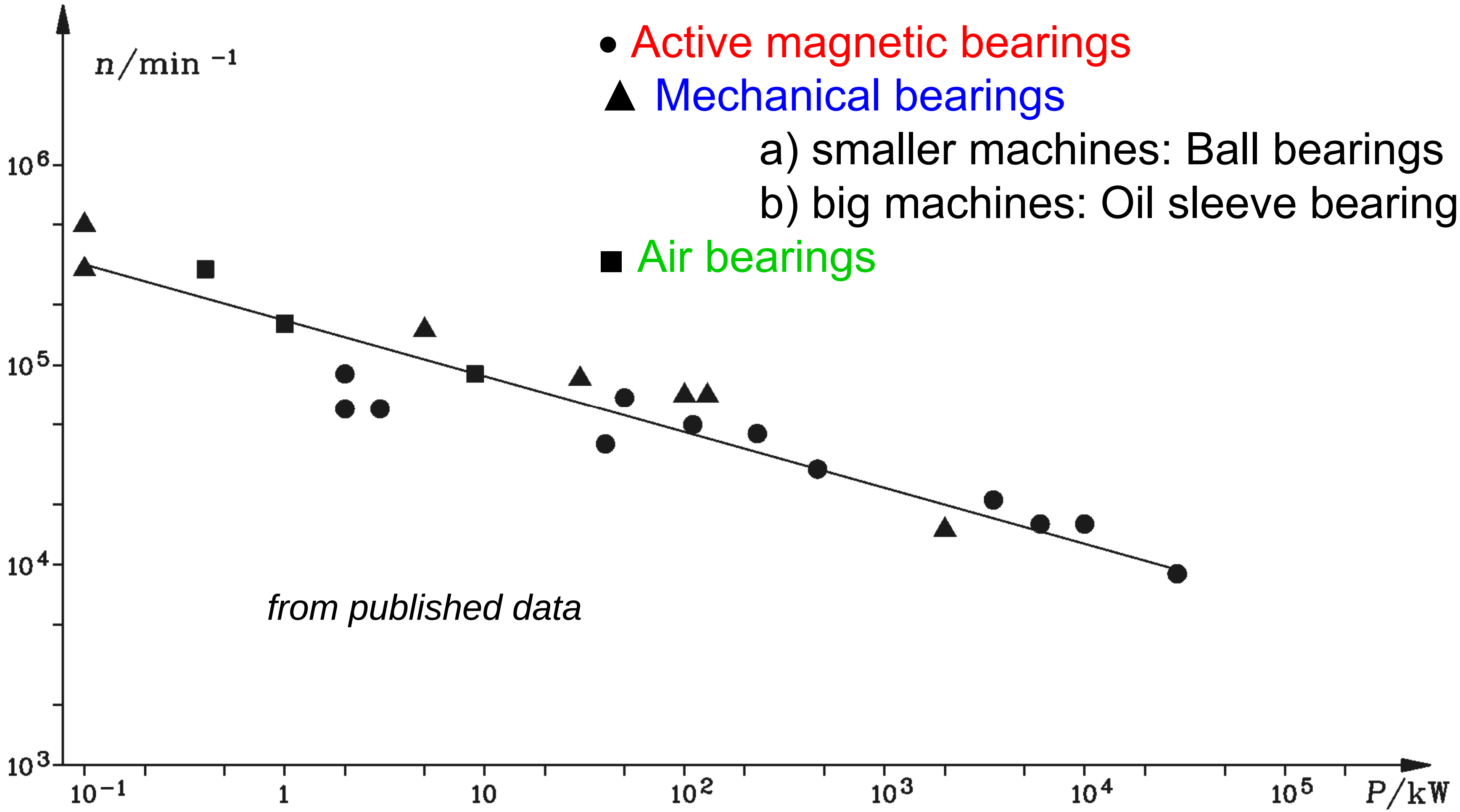
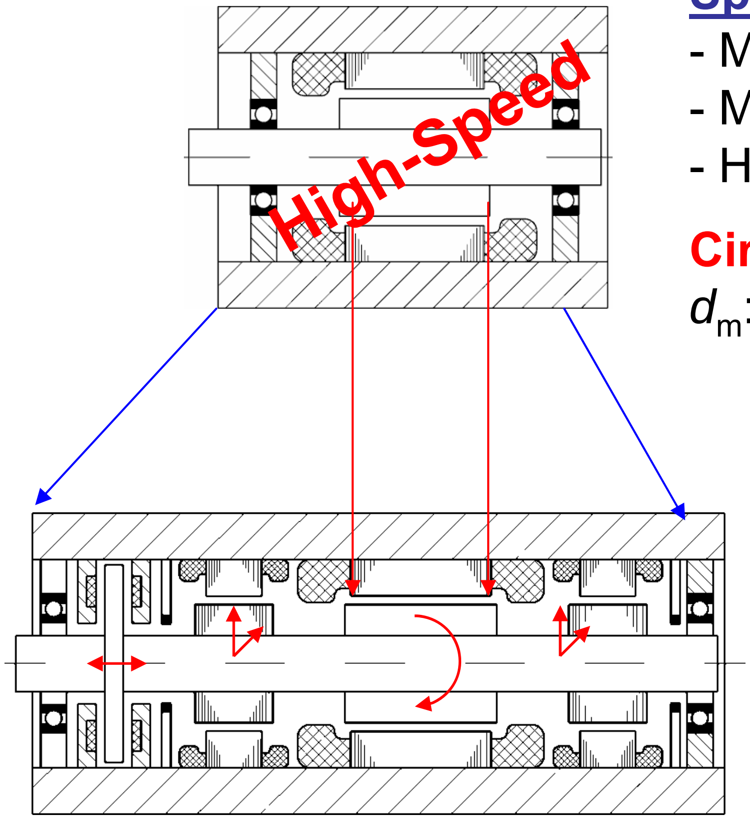


Ball bearings vs. active magnetic bearings



Usually longer machine with AMB

Spindle ball bearings:

- More, but small balls = low centrifugal force per ball
- Minimum oil lubrication = minimum friction
- Hybrid bearings = Ceramic balls = higher stiffness

Circumference velocity $v_B \sim d_m \cdot n : (1 \ldots 2) \cdot 10^6$ mm/min

d_m: Average bearing diameter n: Rot. speed

Active magnetic bearings (AMB):

Plus: + No contact
+ No lubricant
+ No maintenance
+ Same high speed v as motor

Need: - DC-Chopper & DC-Control,
- Position sensors & auxiliary bearings
- Bearing actuators

Active radial magnetic bearings for High-Speed

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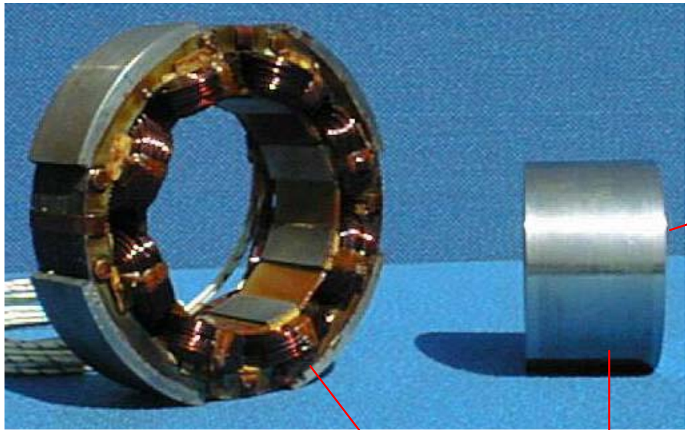
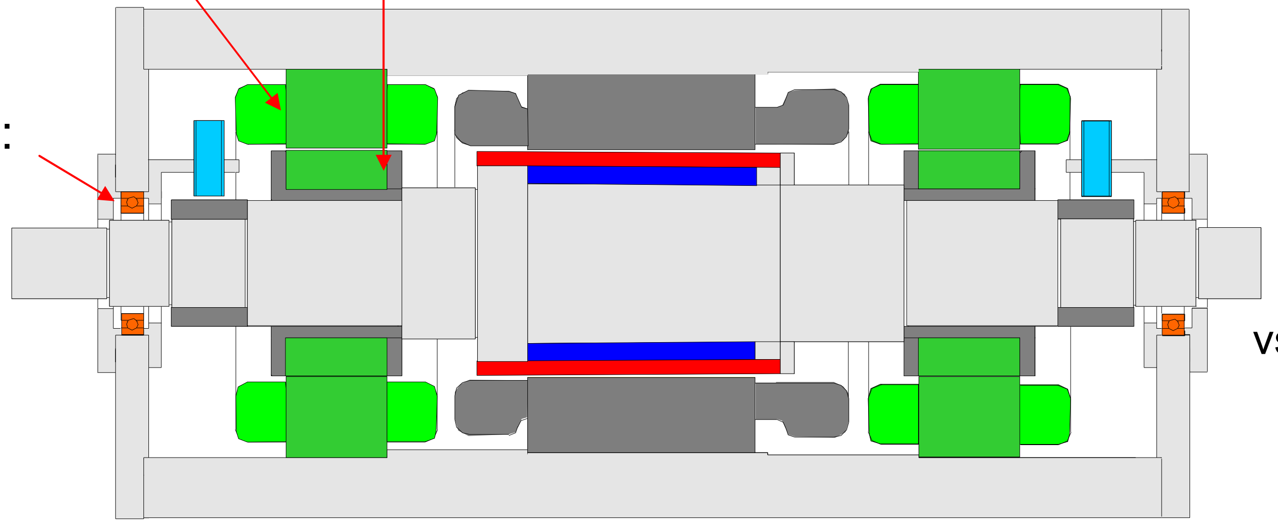


Radial magnetic bearing: gap **0.4 mm**

Two radial magnetic bearings, PM rotor

Auxiliary bearing gap: **0.2 mm**



Motor air gap: **0.7 mm**

Bearing force vs. weight force: **600 %**

40 kW, 40000/min

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Contents

Loss components in High Speed E-Machines

Dominating loss components in "high-speed" motors:

- Iron losses P_{Fe} = Eddy current & hysteresis losses in iron sheets

- Air friction losses P_{fr}

- Additional losses (= eddy current losses) P_{ad} in massive, conductive parts

I^2R-losses $P_{Cu,s}$ are usually less decisive!

⇒ **Low loss iron sheets** may reduce iron losses
e.g.: 2 W/kg losses at 1.5 T, 50 Hz such as HF-sheets (0.1 mm thickness)

⇒ **Twisted litz wires** may reduce eddy current losses in slot conductors

⇒ **Segmented, insulated rotor magnets** reduce there eddy currents

⇒ Slot-less stator windings (= "**air-gap winding**") approximates sine-wave air-gap field distribution ⇒ reduces rotor eddy current losses

⇒ Stator AC currents should have **minimum ripple** due to inverter switching

Loss components in
PM Synchronous High Speed E-Machines

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No-load losses:

a) Stator iron losses: $P_{Fe,s} \sim B_\delta^2 \cdot f_s^x \sim B_\delta^2 \cdot n^x$

x = ca. 1.8, considering eddy-current and hysteresis losses

b) Friction losses at the rotor surface: $P_{fr,w} \sim \rho_{air} \cdot d^4 \cdot l_{Fe} \cdot n^3$

Depending on rotor and stator surface condition & bearings: $y = 2 \ldots 3$

$P_{fr,b} \sim d_m \cdot n^y$

Load losses:

c) Armature winding losses (I^2R- losses): $P_{Cu,s} = 3 \cdot R_s \cdot I_s^2$

d) Additional losses $P_{M+Fe,r} = f(n,\ \text{current shape}) \sim I_s^2 \cdot n^z$

- In stator winding: $P_{ad,s}$ due to eddy currents of high frequency current
- In rotor magnets and rotor iron $P_{M+Fe,r}$, z = ca. 1.5 ... 2, depending on rotor geometry and stator current wave shape

B_δ: Air-gap flux density amplitude, I_s: Stator phase current rms,
f_s: Stator frequency, R_s: Stator ohmic winding resistance per phase

Inverter Operation for High Speed

- Voltage: $U_i \sim n \cdot N_s \cdot k_w \cdot d \cdot l_{Fe} \cdot B_\delta$ → high $n \Rightarrow$ low $N_s \sim 1/n$

  N_s: Number of turns per phase, k_w (≈ 0.9) fundamental winding factor

- High fundamental frequency:
  e. g. $n = 200\,000$ /min, two-pole motor: $f_s = 3.3$ kHz $= n$
  high switching frequency $f_T \approx 5 f_s$ (e.g. 16.5 kHz)

- Motor stator inductance L_d per phase rather small: $L_d \sim \mu_0 \cdot N_s^2 \cdot l_{Fe}$

- Current ripple amplitude I_T rather big: $I_T \sim U_T / (f_T \cdot L_d) \sim f_s$
  (U_T: Switching voltage harmonic amplitude)

Need: Low current harmonics I_T to reduce additional losses

Solutions:
a) Very high switching frequency f_T
b) 3-level-inverter
c) (Active) output sine wave filter

Torque density *m* at "High-Speed"

- Increased iron, friction and additional losses at high speed $P_{\mathrm{Fe+fr+ad}}$!
- $P_{\mathrm{Fe+fr+ad}}$ must be limited $\Rightarrow$ Reduction of *A* and *B* necessary
- Reduction of *A* and *B* leads to certain reduction of *m*: $m \downarrow \Leftrightarrow n_N \uparrow$

$$P/V = 2\pi \cdot n_N \cdot M_N / V = 2\pi \cdot n_N \cdot m$$

Note:
If torque density *m* decreases inverse with raising rated speed n_N: $m \sim 1/n_N$
then high speed drives would have no benefit
from increased power per volume *P*/*V* at elevated speed!

BUT:
With special "high speed technology" B_δ and *A* may be kept
at reasonable high values!

Design features of High Speed E-Machines

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- Necessary at high speed:

⇒ Low loss iron sheets: (e.g. 0.1 mm HF sheets):
Reduction of B_δ^2 less than $1/n$!

$$B_\delta(n) > 1/\sqrt{n}$$

⇒ Special stator windings for low additional losses (e.g. twisted litz wire):
Reduction of $A^2 \sim I_s^2$ less than $1/n$!

$$A(n) > 1/\sqrt{n}$$

- Increased power density $P/V \Rightarrow$ Less volume $V \Rightarrow$
Increased loss density $P_d/V \Rightarrow$ Improved cooling system necessary !

e.g. Stator water jacket cooling:
Increased heat transfer coefficient $\alpha \Rightarrow$ temperature rise $\Delta\vartheta$ kept within limits!

$$\Delta\vartheta_{\mathrm{Cu,s}} \sim P_\mathrm{d} / \alpha \Rightarrow \Delta\vartheta_{\mathrm{Cu,s}} \le \Delta\vartheta_{\mathrm{lim}}$$

Contents

- Basics on High-speed Drives
- Mechanical challenges of High-speed drives
- Which type of E-machine for high speed?
- Bearing concepts for high speed
- Electromagnetic design for High-Speed
- Examples for High-Speed drives
- Conclusions

Examples for High-Speed drives

Permanent-magnet synchronous machines

a) with different rotor magnet fixation,

b) different power & speed rating,

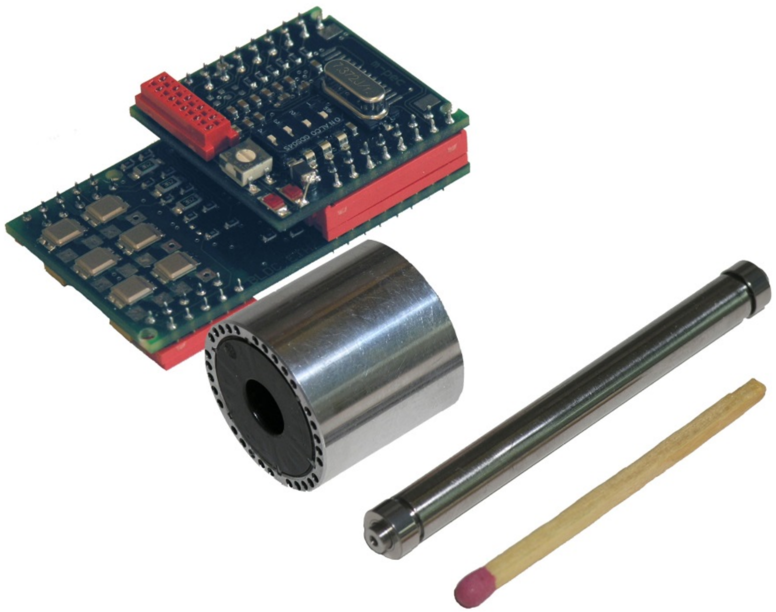
c) different cooling system and motor utilization,

d) different bearing systems,

e) different stator winding technology

High-Speed PM Synchronous Machine

"Ultra high-speed" motor for a meso-scale gas turbine



100 W, 500 000/min

Torque	M_N	2 mNm
Phase voltage	U_N	11 V
Current	I_N	3 A
Frequency	f_N	8.3 kHz
Rotor diameter	d	6 mm
Stack length	l_{Fe}	15 mm

Source: ETH Zurich, Switzerland

$$P = 2\pi \cdot n \cdot M_N =$$

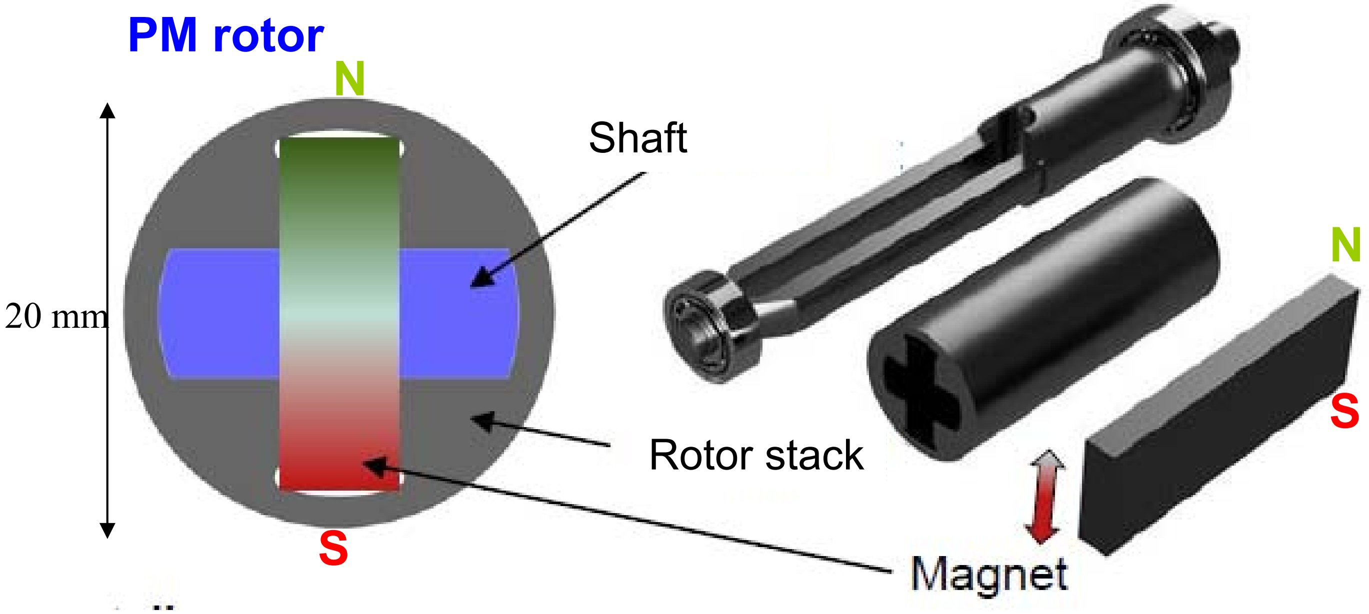
$$= 2\pi \cdot \frac{5 \cdot 10^5}{60} \cdot 2 \cdot 10^{-3} = 100\mathrm{W}$$

$$m = \frac{M_N}{d^2 \cdot l_{Fe} \cdot \pi / 4} = 0.5\ \mathrm{N/cm^2}$$

- Two-pole PM motor, six-step voltage feeding
- Titanium rotor sleeve
- Circumference speed: 157 m/s
- Mechanical bearings $n \cdot d_m \cong 2 \cdot 10^6\ \mathrm{mm/min}$

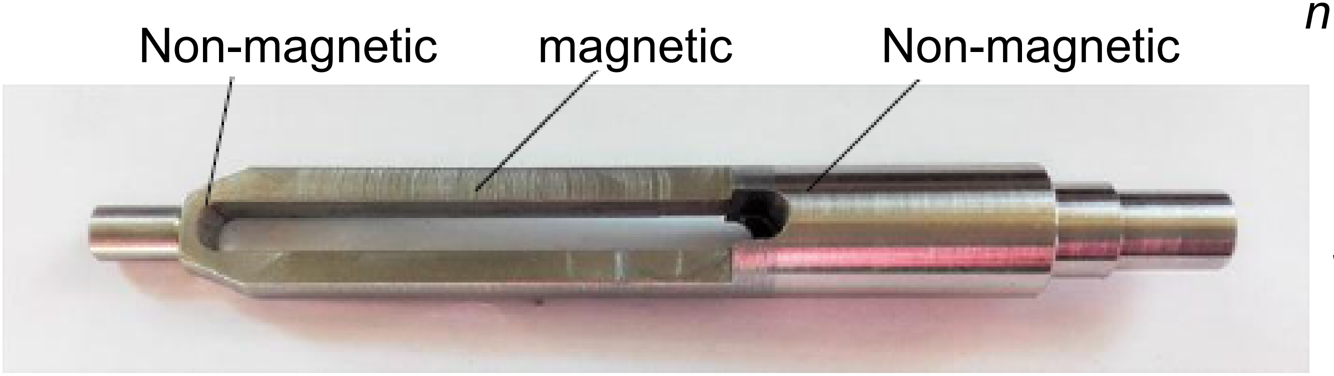
High-Speed PM Synchronous Machine

Two-pole PM synchronous motor with buried magnets (1)



f_s = 2083 Hz

n = 125 000/min



Source: Schiefer, M.: Antriebssysteme 2017, VDE/Karlsruhe, Germany

High-Speed PM Synchronous Machine

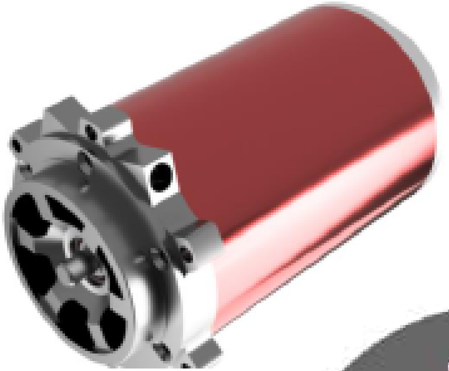
Two-pole PM synchronous motor with buried magnets (2)

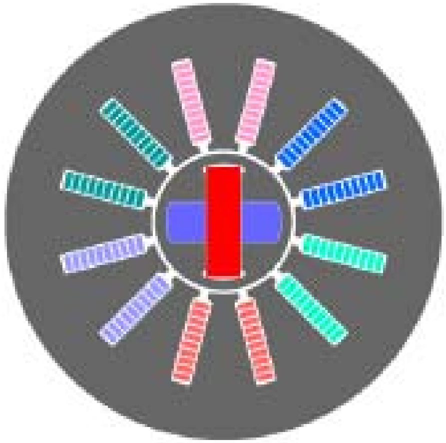
High slot fill factor 65%

Water jacket cooling 50°C

High current loading → high *m*-value
A = 688 A/cm

Rated power P_N (Th. Cl. F)	15.7 kW
Rated phase current $I_{s,N}$	45 A
Rated DC link voltage $U_{d,N}$	600 V
Speed	125 000/min
Rotor diameter	d = 20 mm
Active iron length	l_{Fe} = 50 mm
Rotor mass	Ca. 2 kg
Max. efficiency	95%





$$v = d \cdot \pi \cdot n = 130\ \text{m/s}$$

$$A = \frac{2 \cdot 3 \cdot N_s \cdot I_s}{d \cdot \pi} = \frac{6 \cdot 16 \cdot 45}{2 \cdot \pi} = 688\ \frac{\text{A}}{\text{cm}}$$

$$m = \frac{M_N}{d^2 \cdot l_{Fe} \cdot \pi / 4} = 7.6\ \text{N/cm}^2$$

Source: Schiefer, M.: Antriebssysteme 2017, VDE/Karlsruhe, Germany

High-Speed PM Synchronous Machine

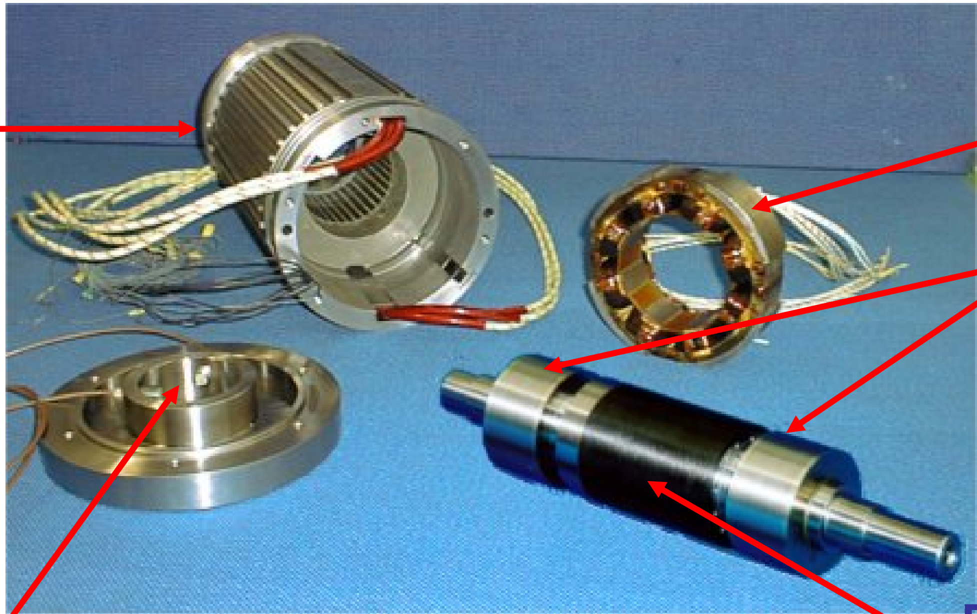
4-pole PM synchronous machine with carbon fibre bandage

Surface magnets (Sm_2Co_{17}), 16 magnet segments / pole, carbon fiber bandage, radial magnetic bearings

P_N = 40 kW
n_N = 40 000 min^{-1}

d = 88.6 mm rotor diameter, l_{Fe} = 90 mm
v_{max} = 222 m/s rotor surface velocity at 120% over-speed

$$m = \frac{M_N}{d^2 \cdot l_{Fe} \cdot \pi / 4} = $$
$$= 1.8\ \mathrm{N/cm^2}$$



$$"d_m" \approx 60\ \mathrm{mm}:$$
$$n \cdot d_m = 2.4 \cdot 10^6\ \mathrm{mm/min}$$

Source: TU Darmstadt

High-Speed PM Synchronous Machine

PM 4-pole synchronous generator for micro gas turbine

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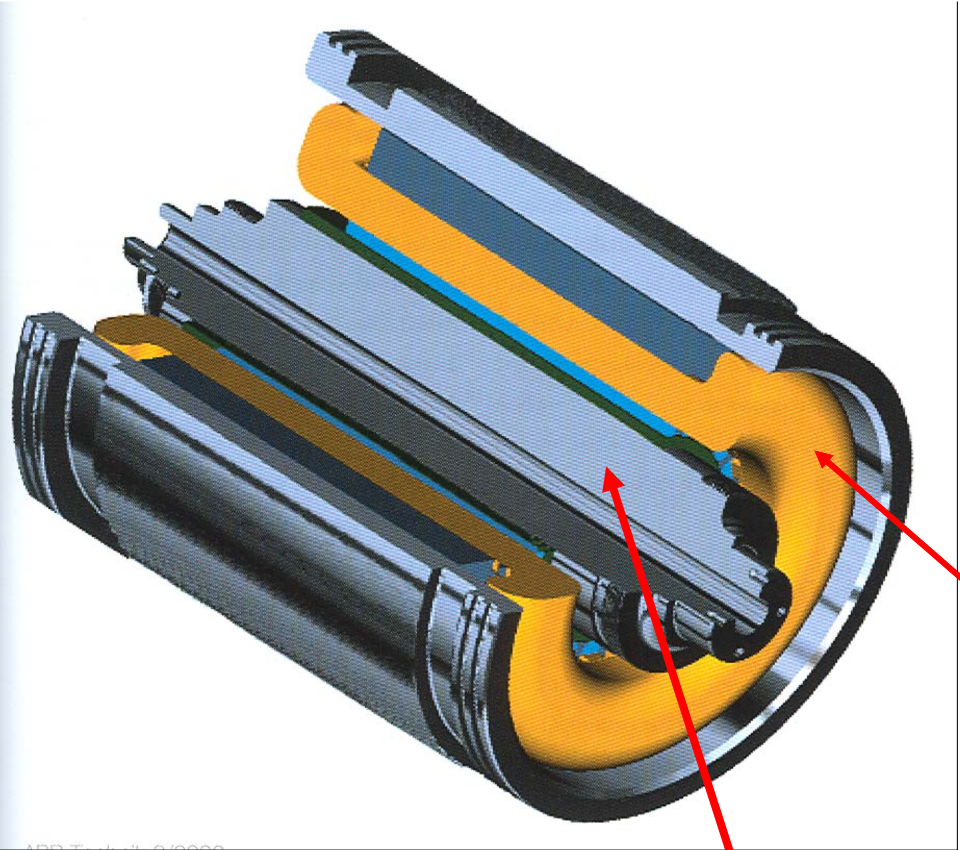
70 000/min, 2300 Hz, four pole PM-machine



Four pole PM-rotor, Carbon fiber bandage

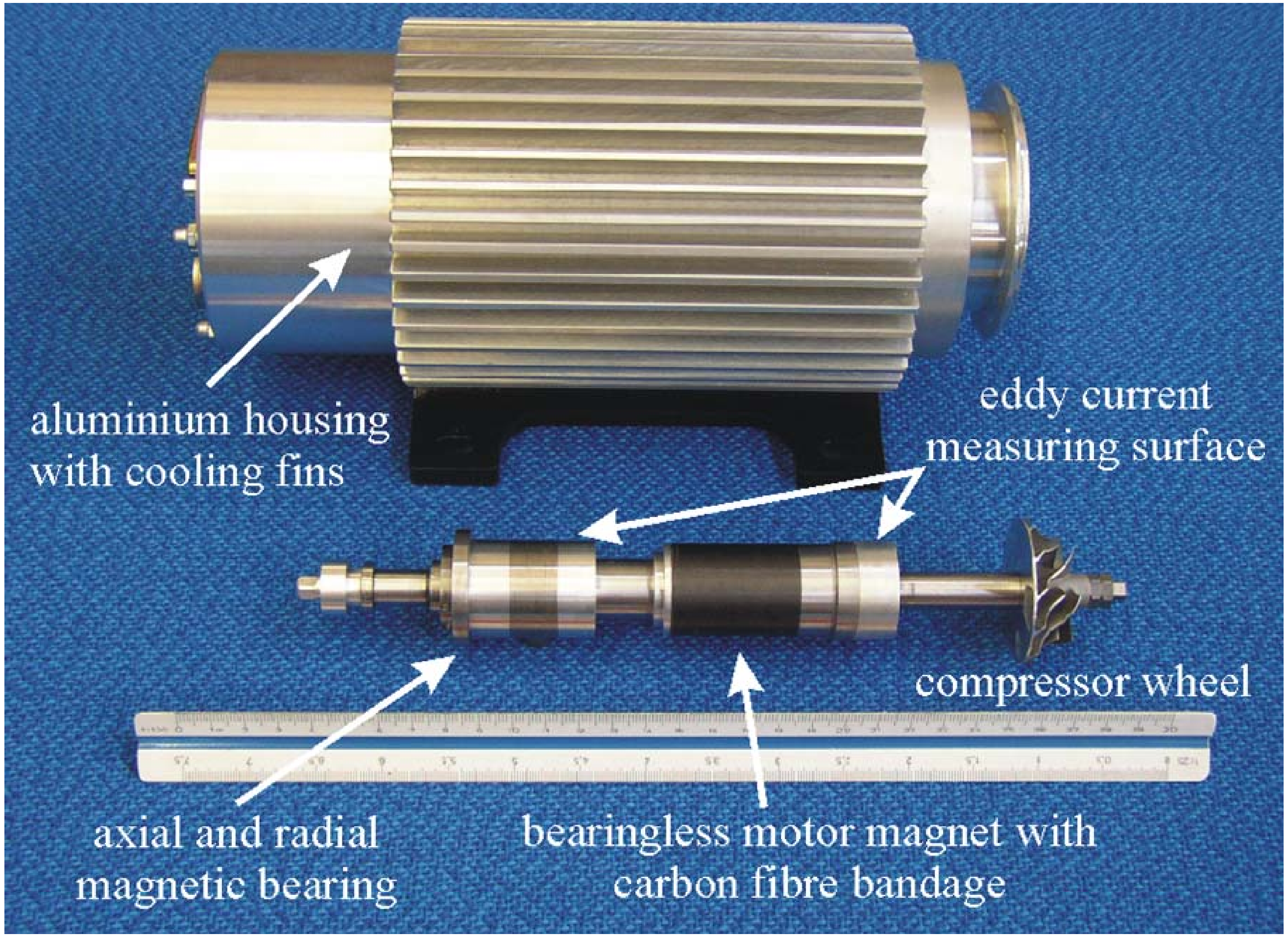
Stator with four pole three phase winding, fully encapsulated in resin for good heat transfer to iron

Massive rotor iron, special air bearings

Source: ABB, Sweden

High-Speed PM Synchronous Machine

Bearing-less high-speed PM motor 500 W, 60 000/min



n_N = 60 000/min

P_N = 500 W

Two-pole motor:
$2p$ = 2

f_s = 1000 Hz

v = 100 m/s

4-pole levitation winding

Air self-cooling

$$m = \frac{M_N}{d^2 \cdot l_{Fe} \cdot \pi / 4} =$$

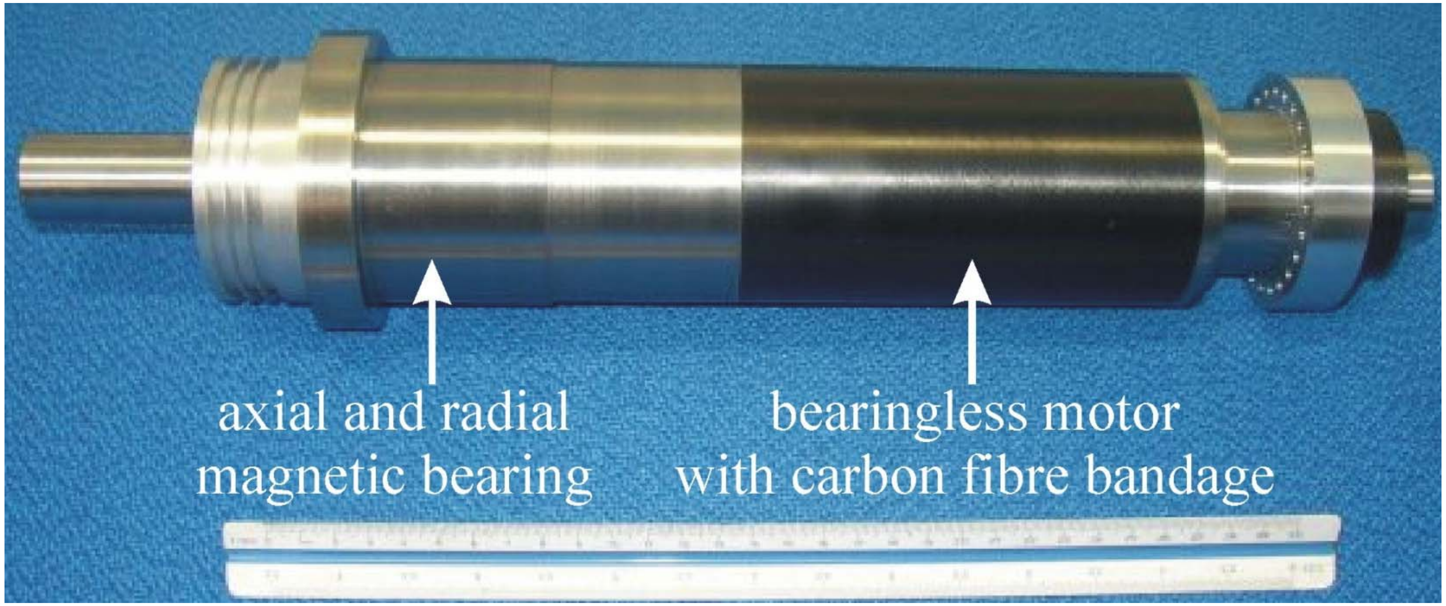
$$= 0.33\ \mathrm{N/cm^2}$$

Source: TU Darmstadt,

In co-operation with LTI, Lahnau, Germany

High-Speed PM Synchronous Machine

Bearing-less high-speed PM motor 40 kW, 40000/min



$n_N = 40000/\text{min}$

$P_N = 40\ \text{kW}$

Four-pole:
$2p = 4$

$f_s = 1333\ \text{Hz}$

$v = 167\ \text{m/s}$

$d = 80\ \text{mm}$

$l_{Fe} = 90\ \text{mm}$

BEARINGLESS concept:

***Two* 3- phase stator windings:**

- **Four-pole drive winding $2p_1 = 4$**
- **Six-pole levitation winding $2p_2 = 6$**

Source: TU Darmstadt,

In co-operation with LTI, Lahnau, Germany

$$m = \frac{M_N}{d^2 \cdot l_{Fe} \cdot \pi / 4} = 2.2\ \text{N/cm}^2$$

- Rotor successfully tested at 44000/min (185 m/s)

- Water-jacket cooling

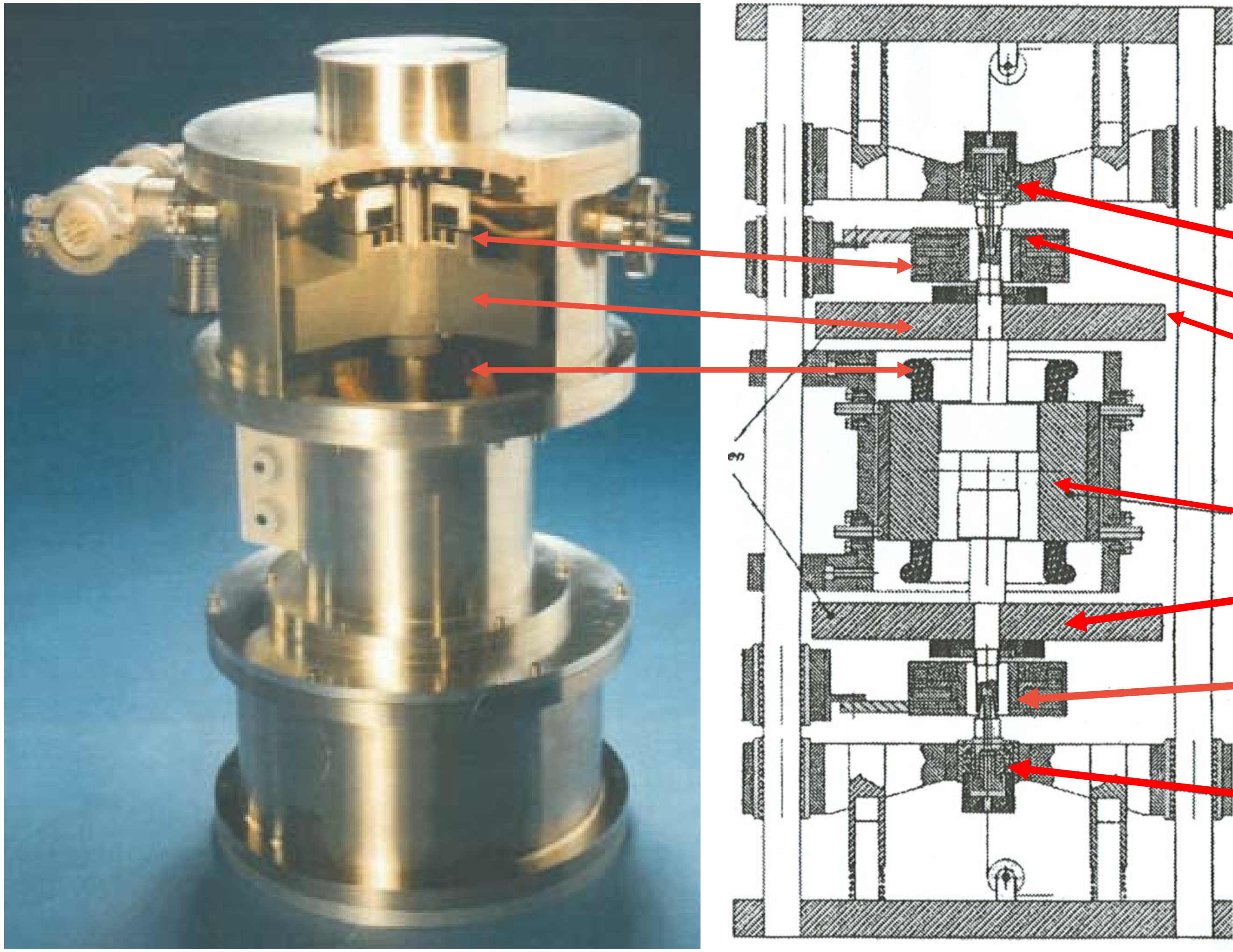
Examples for High-Speed drives

Homo-polar synchronous machine

Massive rotor cage induction machine

Cylindrical rotor synchronous machine

Homo-polar generator for flywheel



10 kW, 50 000/min
Vacuum operation
0.21 Pa !

Auxiliary bearing

HTSC magnetic bearing

Carbon fibre
fly-wheel disc

4-pole homo-polar synchronous generator

Carbon-fibre fly-wheel disc

HTSC magnetic bearing

Auxiliary bearing

Source: FSZ Karlsruhe, Germany

Cage induction machines with massive rotor

Operation above 2nd bending eigen-frequency

Air-water cooler

Example: 2-pole rotor, 15000/min, 4 MW

Source: Siemens AG, Dynamowerk, Berlin, Germany

- Gas pipe line compressor motor series
- Motor series 4 MW / 15000/min / 2.5 kNm … 16 MW / 6000 /min / 25.5 kNm
- Copper cage, 2-pole motors, solid iron rotor, ca. 240 m/s circumferential speed
- 2 radial Active Magnetic Bearings; axial magnetic bearing at compressor wheel
- Medium voltage IGBT-PWM-voltage source converter

Two-pole electrically excited high-speed solid steel rotor

Motor operation at thyristor synchronous converter with block current wave form

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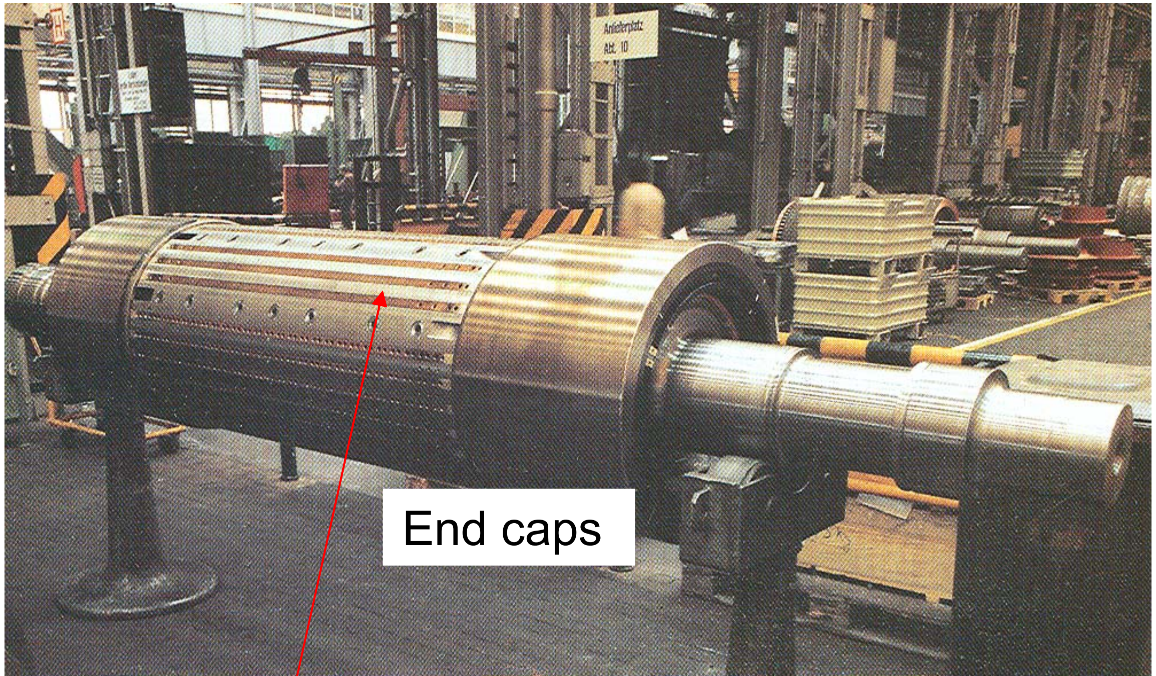
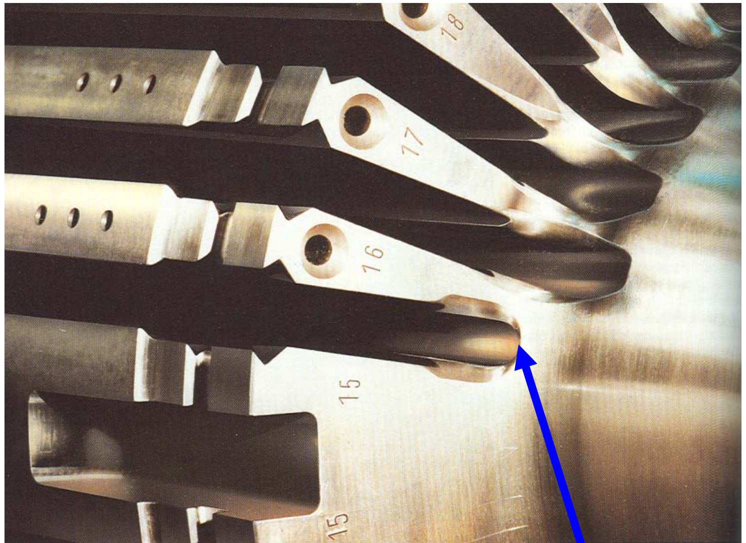
17 MW, 6100/min, high speed converter-fed synchronous motor as compressor drive, oil sleeve bearings: Operation between 1st and 2nd bending frequency



Conducting rotor slot wedges as damper bars



Highest mechanical stress here

Milled rotor slots prior to mounting of rotor DC excitation winding

Source: Siemens AG, Dynamowerk, Berlin, Germany

Selected Examples of High-Speed Machines

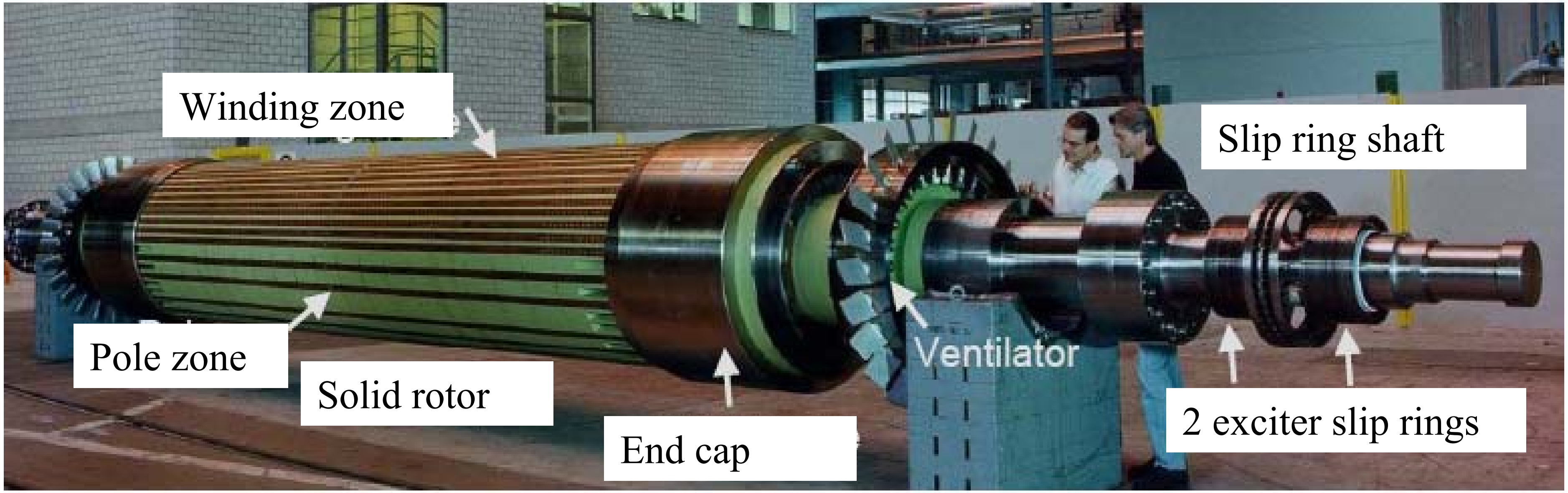
Largest High-Speed Machines are Two-Pole Turbine Generators

Example: f_s = 50 Hz: Largest possible power: 1 GW at 50 Hz, n = 3000/min

Rotor diameter: d = 1.25 m: v = 188 m/s = 676 km/h at $2p = 2$, l_{Fe} = 8 m m = 32.4 N/cm^2

⇒ Bigger rotor diameters not possible due to limited strength of steel

⇒ Longer rotors not possible due to strong rotor bending: 5 balancing planes



Manufacturing of Hydrogen gas-cooled two-pole Rotor, 1 GW, *Lippendorf/Germany*

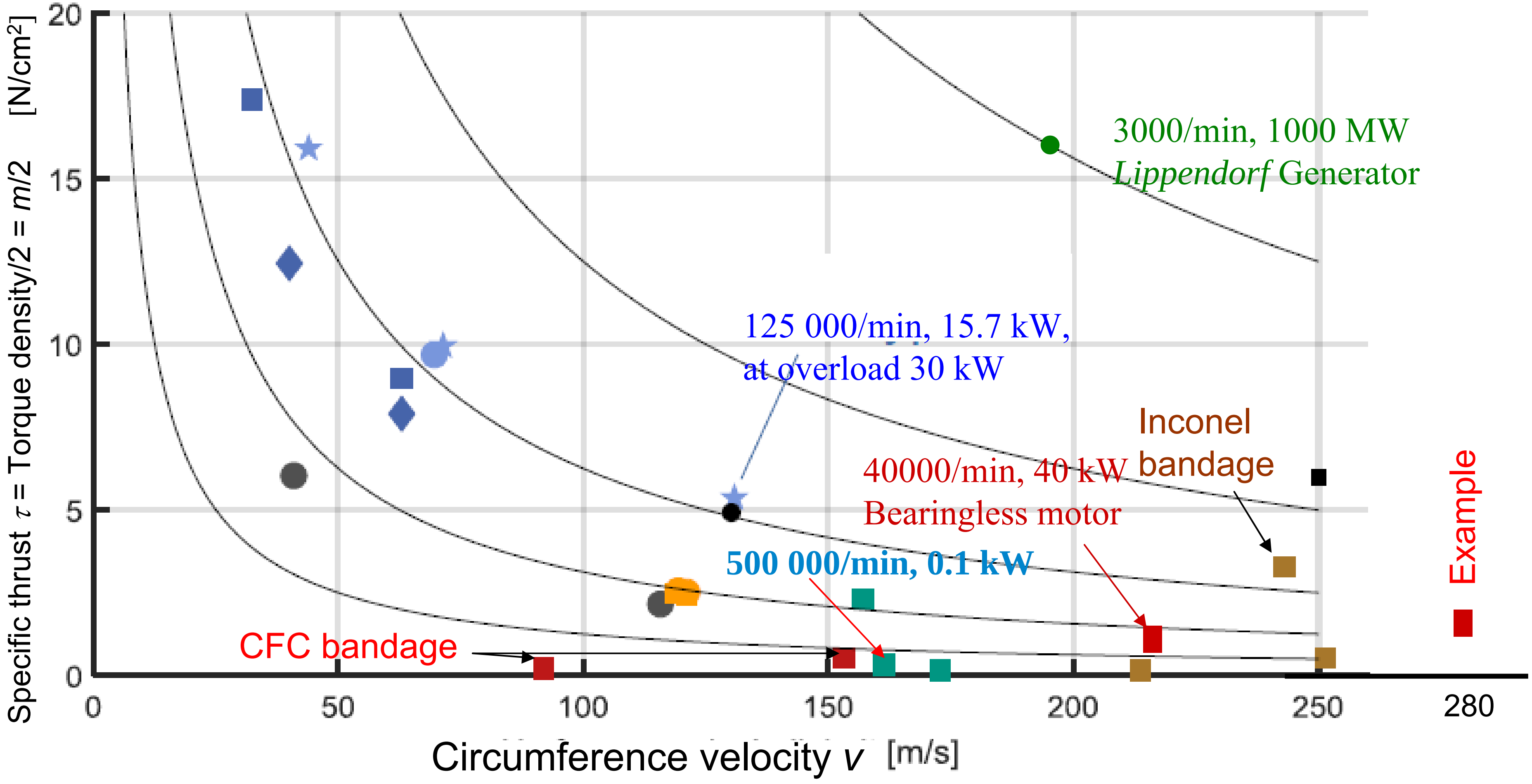
Source: Alstom Power Generation, Mannheim

PM synchronous High-speed machines

Literature	Sleeve type	Maximum speed (rpm)	Power (kW)	Rotor diameter (mm)	Sleeve thickness (mm)	Air-gap length (mm)	Stator diameter (mm)	Stack length (mm)
L. Zhao et al.	Hollow shaft	200,000	2	22	-	0.8	35	21
C. Zwyssig et al.	Titanium	500,000	1	10	0.5	-	25	30
P. D. Pfister et al.	Titanium	200,000	2.19	16.48	2	1.36	-	30
A. Tüysüz et al.	Titanium	280,000	1	11	-	0.75	27.5	33
C. Zwyssig et al.	Titanium	500,000	0.1	6	-	-	16	15
D. K. Hong et al.	Inconel 718	120,000	15	34	4.5	1	120	50
J. H. Ahn et al.	Inconel 718	400,000	0.5	11.6	-	0.35	30	19
T. Abe et al.	Inconel	240,000	5	20	2	0.5	74	40
S. Jumayev et al.	Stainless steel	80,000	0.05	5.5	0.25	0.7	22	16
T. Noguchi et al.	Carbon fiber	220,000	2	25	5 (sleeve + air-gap)		110	29
T. Schneider et al.	Carbon fiber	60,000	0.5	29.2	1	1.4	60	36
T. Noguchi et al.	Glass fiber	150,000	1.5	19.5	4.25 (sleeve + air-gap)		70	30

Source: Schiefer, M.: Antriebssysteme 2017, VDE/Karlsruhe, Germany

"Specific thrust" $\tau = m/2$ (~ torque density m) vs. circumference velocity $v \sim \sqrt{\sigma}$ of high-speed machines



Source: Schiefer, M.: Antriebssysteme 2017, VDE/Karlsruhe, Germany

Example:

Experts only

High-Speed PM generator with single stage turbine

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$$500\ \mathrm{kW},\quad 32000/\mathrm{min},\quad d = 167\ \mathrm{mm}: \quad v = d\cdot\pi\cdot n = 280\ \mathrm{m/s}$$

$$\text{Outer motor diameter (with water-jacket)}: d_{so} = 320\ \mathrm{mm},\quad l_{Fe} \approx 200\ \mathrm{mm}$$

$$\text{Total rotor length (overall)}: L = 520\ \mathrm{mm}$$

$$M = 149\ \mathrm{Nm},\quad m = \frac{M}{d^2 l_{Fe}\pi/4} = 3.4\ \mathrm{N/cm^2}$$

$$B_\delta \approx 0.7\ \mathrm{T},\quad m \sim A\cdot B_\delta \Rightarrow A = 377\ \frac{\mathrm{A}}{\mathrm{cm}} = \frac{6\cdot N_s\cdot I_s}{d\cdot\pi} \Rightarrow N_s\cdot I_s = 3300\ \mathrm{A}$$

$$U_i = \sqrt{2}\cdot\pi\cdot n\cdot N_s\cdot k_w\cdot d\cdot l_{Fe}\cdot B_\delta \Rightarrow \frac{U_i}{N_s} = 50.4\ \mathrm{V}$$

Fundamental winding factor $k_{\mathrm{w}} \cong 0.9$

$$\text{Check: Power (at } \cos\varphi = 1): 3\cdot U_s\cdot I_s \approx 3\cdot U_i\cdot I_s = 3\cdot\frac{U_i}{N_s}\cdot N_s I_s = 500\ \mathrm{kW}$$

$$\text{e.g.}: N_s = 6, U_i\cdot\sqrt{3} = 533\ \mathrm{V}, I_s = 550\ \mathrm{A}$$

Based on: Source: Piller, Germany

Contents

- Basics on High-speed Drives
- Mechanical challenges of High-speed drives
- Which type of E-machine for high speed?
- Mechanical integrity at high speed
- Bearing concepts for high speed
- Electromagnetic design for High-Speed
- Examples for High-Speed drives
- Conclusions

Conclusions

- High speed = high circumference speed 100 … 250 m/s
- Small volume/power ratio & gearless drive system
- Wide rated "power/speed"-range:
  (500 000 … 1 000 000)/min, 0.1 kW … 3000 /min, 1 000 MW
- Different bearing systems
- PM & electrically excited synchronous machines,
  induction, homo-polar synchronous & switched reluctance machines
- Inverter fundamental frequency several kHz;
  output filters / three-level voltage source / elevated switching frequency
- Wide field of applications:
  Increasing numbers of high-speed drives expected in the future

Thank you for your attention !

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