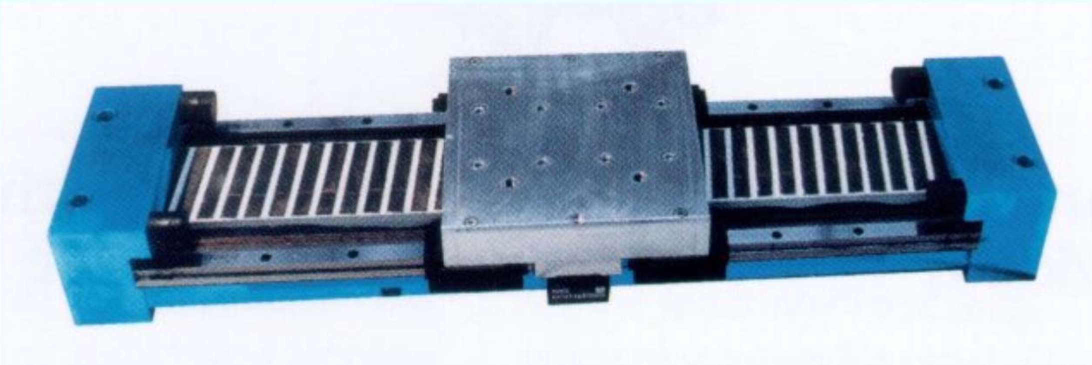
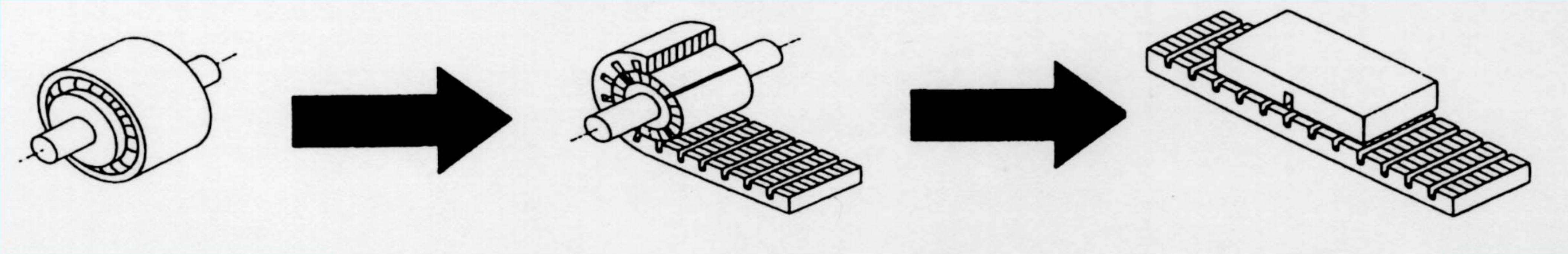
1. Permanent magnet synchronous machines as “brushless DC drives”

1.4 Linear PM machines



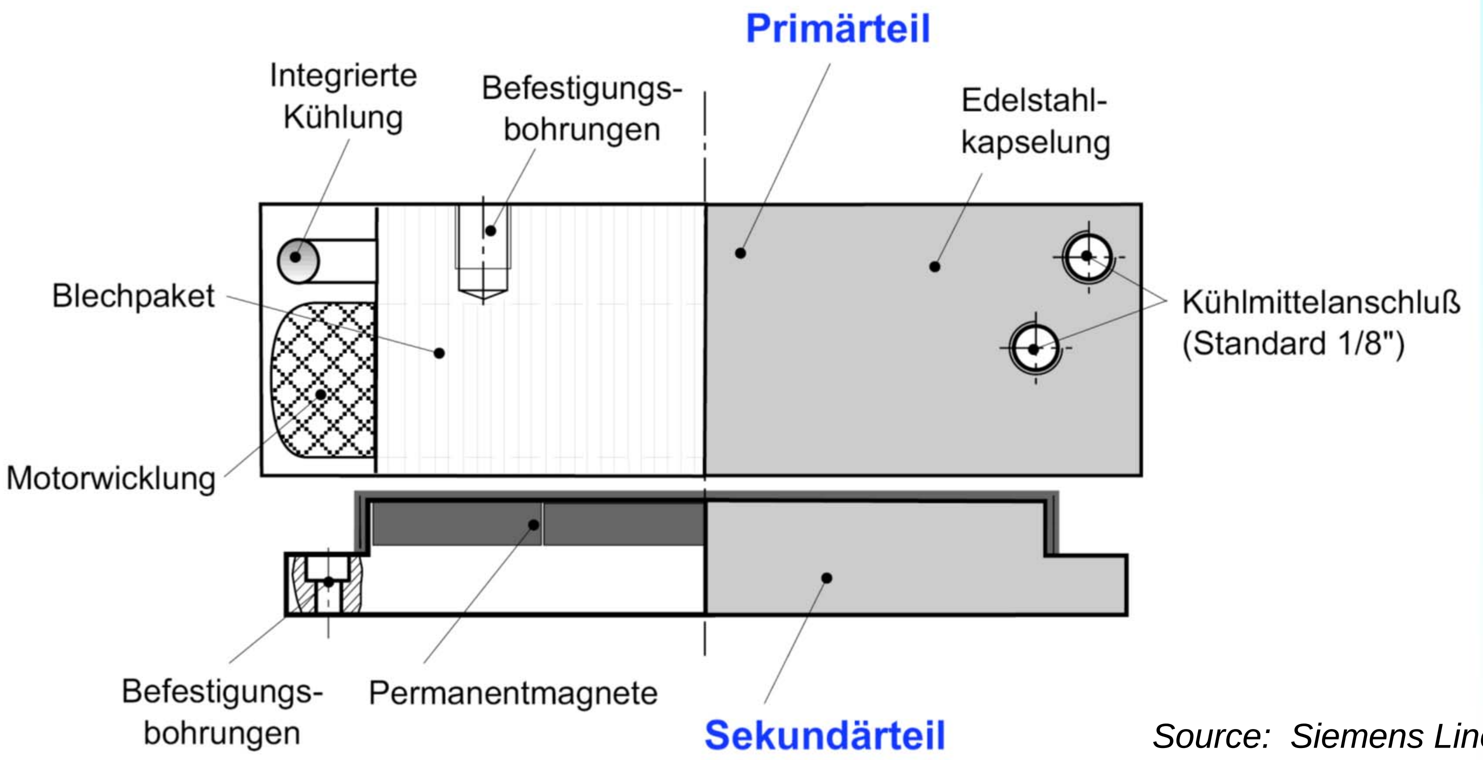
Source: Oswald, Miltenberg, Germany

Linear PM machine principle

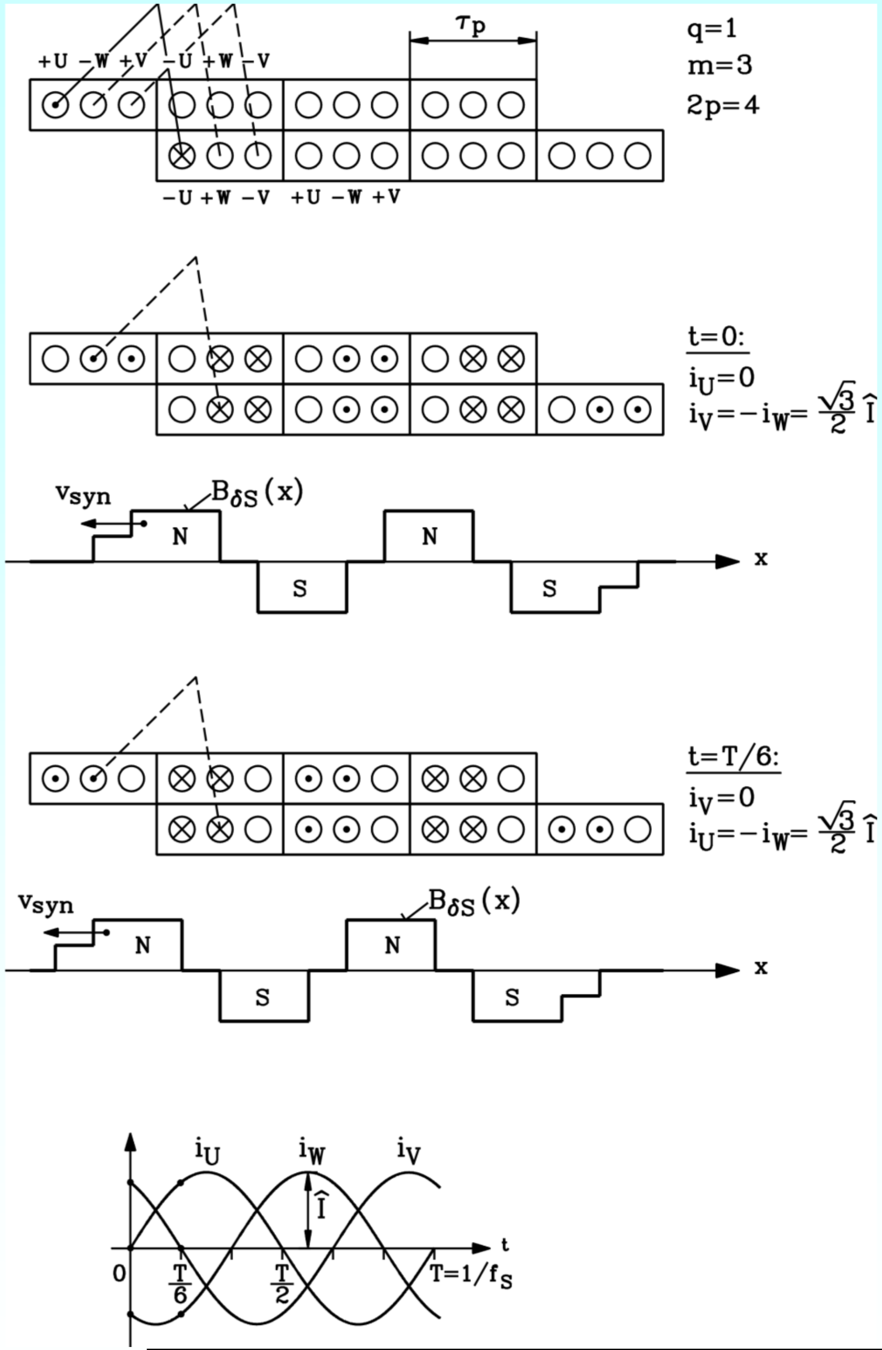


"Unrolling" rotating machine yields linear machine

Cross section of PM linear motor



Source: Siemens Linear Motors



Travelling wave in linear machines

Three phase primary linear winding generates travelling stator field with synchronous velocity !

Example: $q = 1$, $m = 3$, 4-pole two-layer winding

Field emerges at the right and vanishes at the left side of machine.

Five pole pitches are needed, as the end poles contain only half of the coils (upper OR lower layer)

Example:

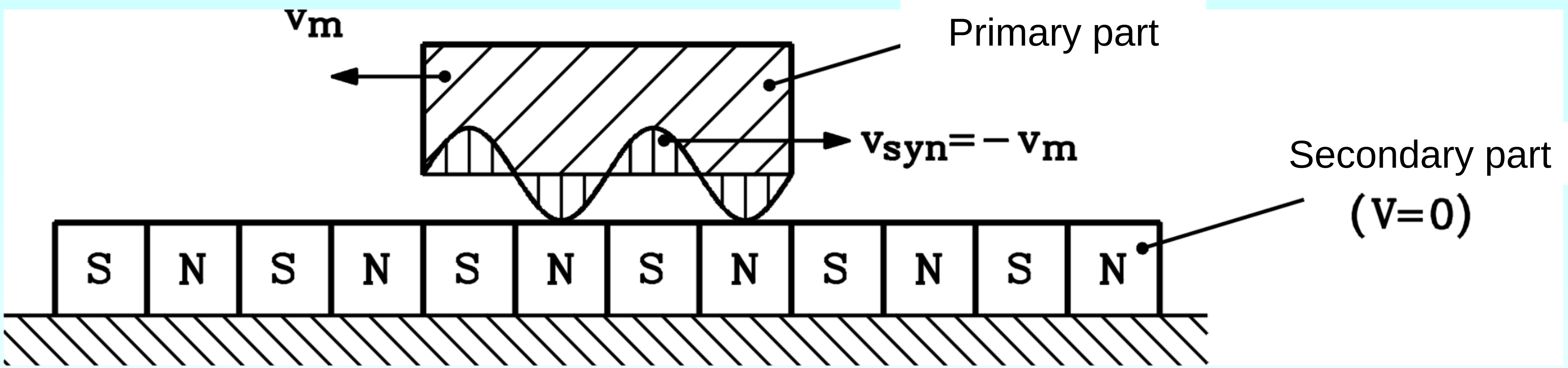
Pole pitch $\tau_p = 62{,}5$mm, Slot pitch $\tau_Q = \tau_p/(m \cdot q) = 20{,}8$mm.

Stator frequency $f_s = 16$ Hz :

Synchronous velocity

$$v_{syn} = 2 \cdot \tau_p \cdot f_s = 2 \cdot 16 \cdot 62{,}5 \cdot 10^{-3}\,\text{m/s} = 2\,\text{m/s} = 120\,\text{m/min}$$

Linear movement of primary



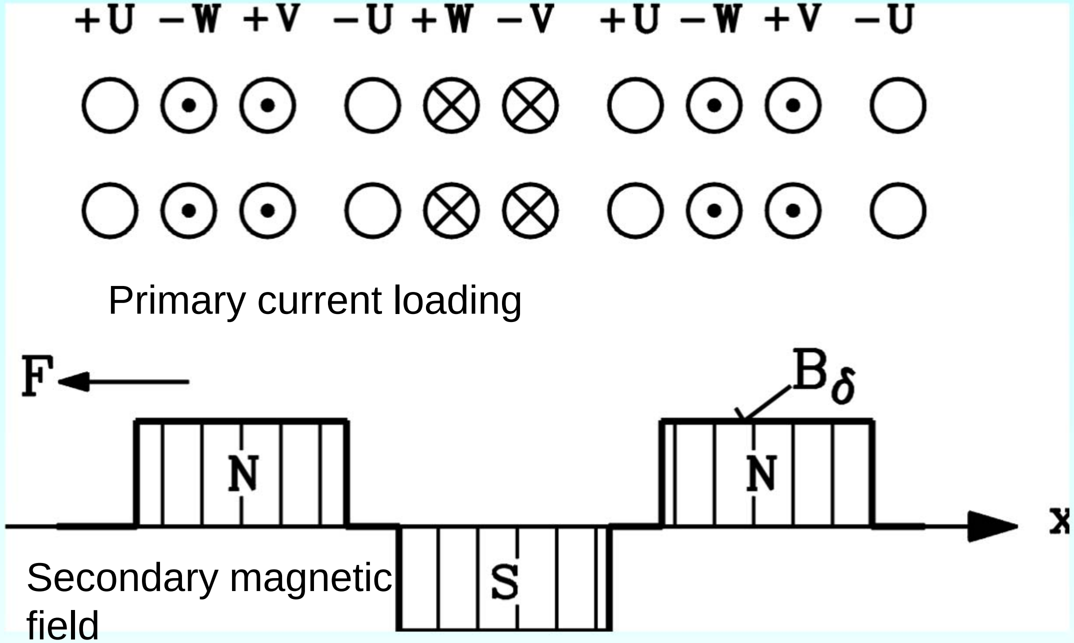
Primary is short in order to get low stator resistance = low losses !

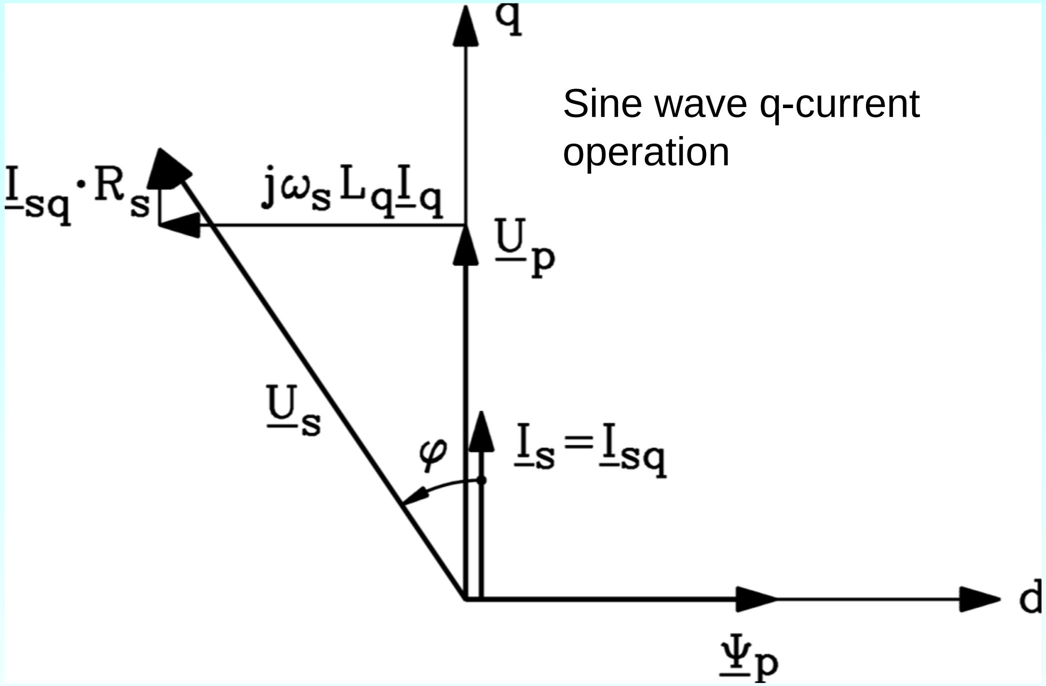
Hence primary has to move !

Primary moves in opposite direction as travelling wave does !

Primary energy has to be fed by flexible stator cables from inverter !

Tangential force (thrust) in linear PM machine





- Linear position sensor determines primary position relative to secondary fields´s d-axis.
- Inverter supplies q-current to maximize tangential force.
- Hence current flows with the same direction under each pole to give maximum force.
- Force per conductor: $F_c = i_{q,c} \cdot B_\delta \cdot l_{Fe}$

Calculation of thrust of fundamental wave

Total force: $F = k_w \cdot z \cdot I_{q,c} \cdot \frac{B_{\delta,1}}{\sqrt{2}} \cdot l_{Fe} = k_w \cdot \frac{z \cdot I_{q,c}}{2p \cdot \tau_p} \cdot \frac{B_{\delta,1}}{\sqrt{2}} \cdot (l_{Fe} \cdot 2p \cdot \tau_p)$

Current load: $A = \frac{z \cdot I_{q,c}}{2p \cdot \tau_p}$ *z*: total number of conductors

Motor surface: $A_{mot} = 2p \cdot \tau_p \cdot l_{Fe}$

$$F = \frac{k_w}{\sqrt{2}} \cdot A \cdot B_{\delta,1} \cdot A_{mot}$$

Thrust of linear motor

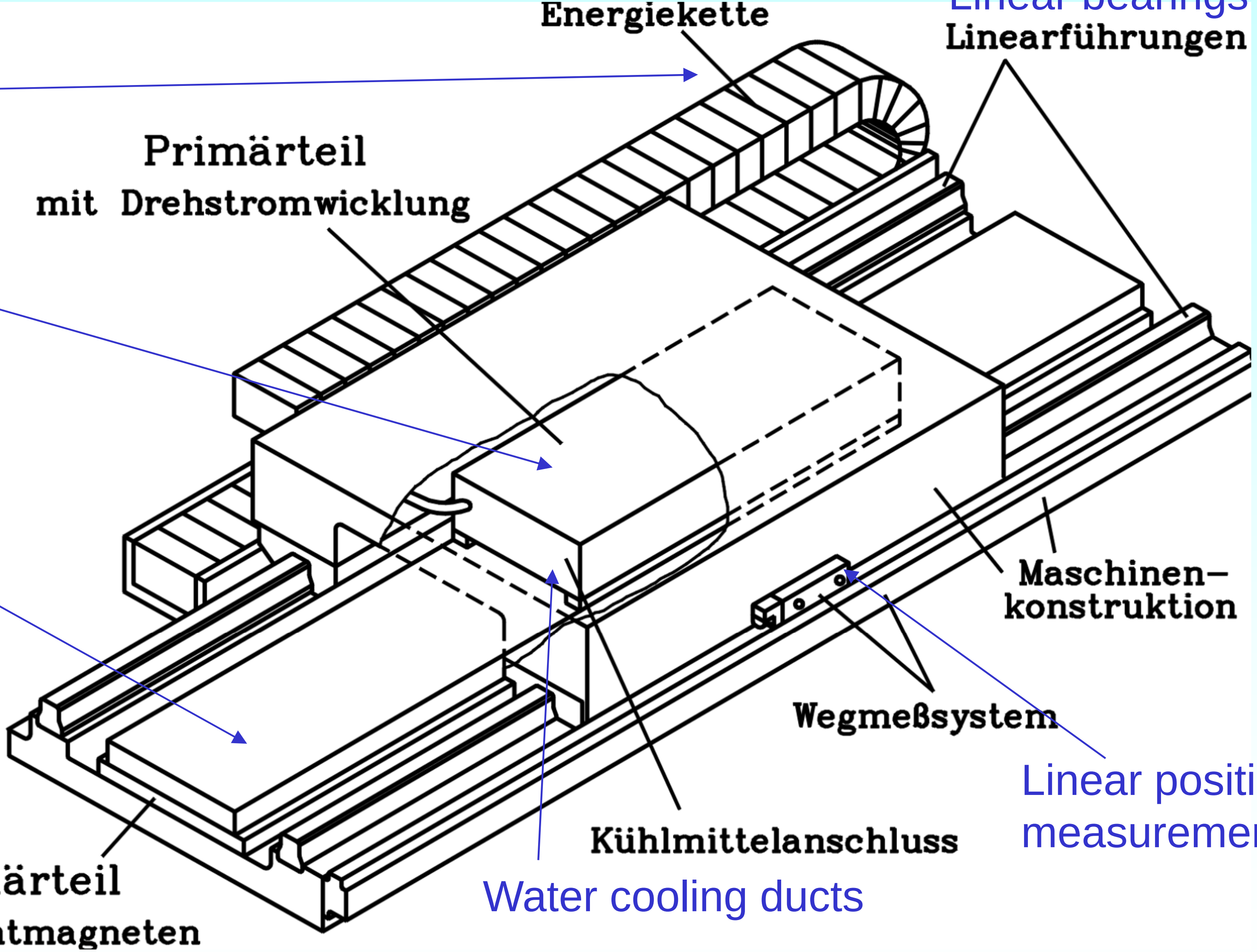
Example:

Indirect water cooling: A = 1000 A/cm (r.m.s.). $B_{\delta,1}$ = 0,7 T (amplitude)
Winding factor: k_w = 1 (q = 1, full-pitched)
Motor surface: A_{mot} = 376,8 cm^2

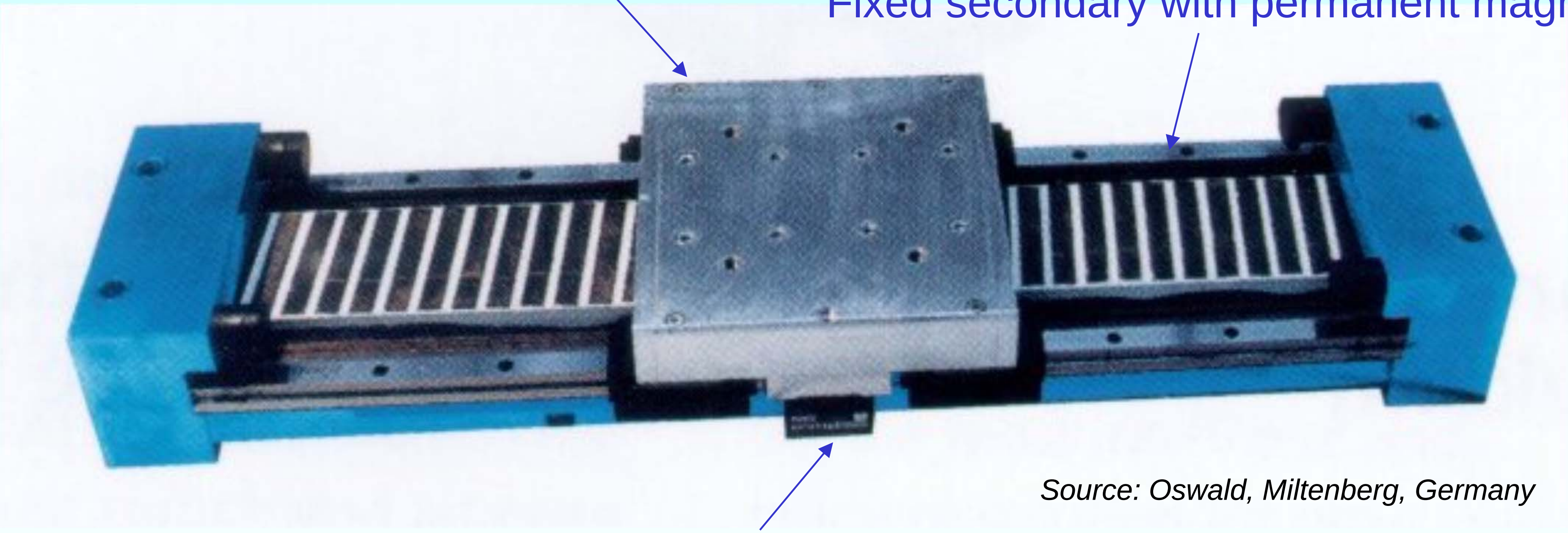
$$F = \frac{1}{\sqrt{2}} \cdot 1000 \cdot 0{,}7 \cdot 376{,}8\,N = 1865\,N \quad \Rightarrow \quad \frac{F}{A_{mot}} = \frac{1865\,\mathrm{N}}{376{,}8\,\mathrm{cm}^2} = 5\,\mathrm{N/cm}^2 = 0.5\mathrm{bar}$$

Short time duty: Increased current and thrust: 10 N/cm^2 !

Linear PM machines



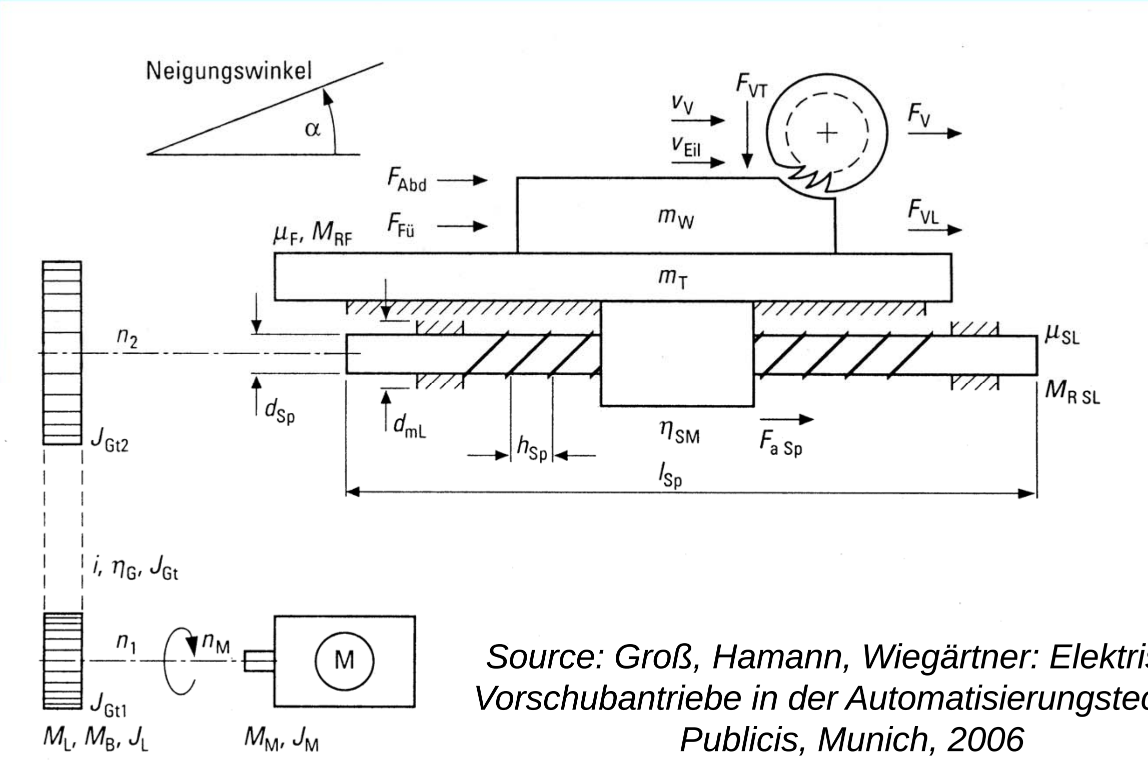
Basic elements of linear PM motors



Source: Oswald, Miltenberg, Germany

Short stator PM linear synchronous motor, skewed PM rows visible

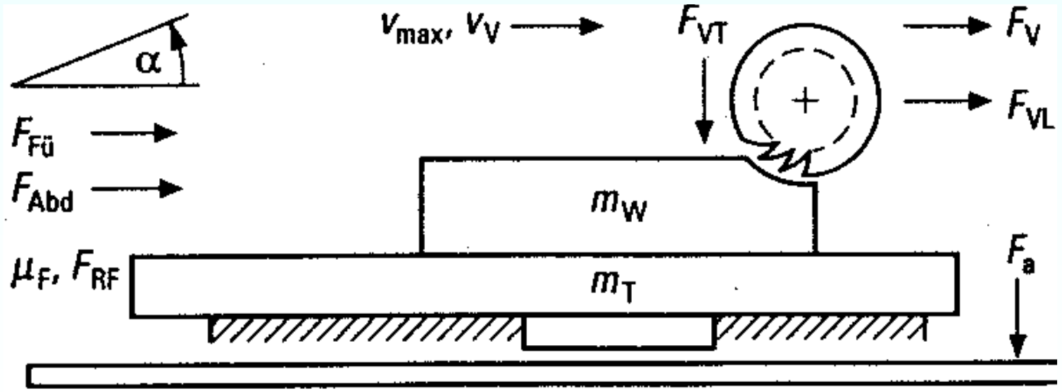
Comparison of rotating and linear drive in tooling machinery



Source: Groß, Hamann, Wiegärtner: Elektrische Vorschubantriebe in der Automatisierungstechnik, Publicis, Munich, 2006

Linear movement of a table (mass m_T) with a workpiece (mass m_W) during a milling process.

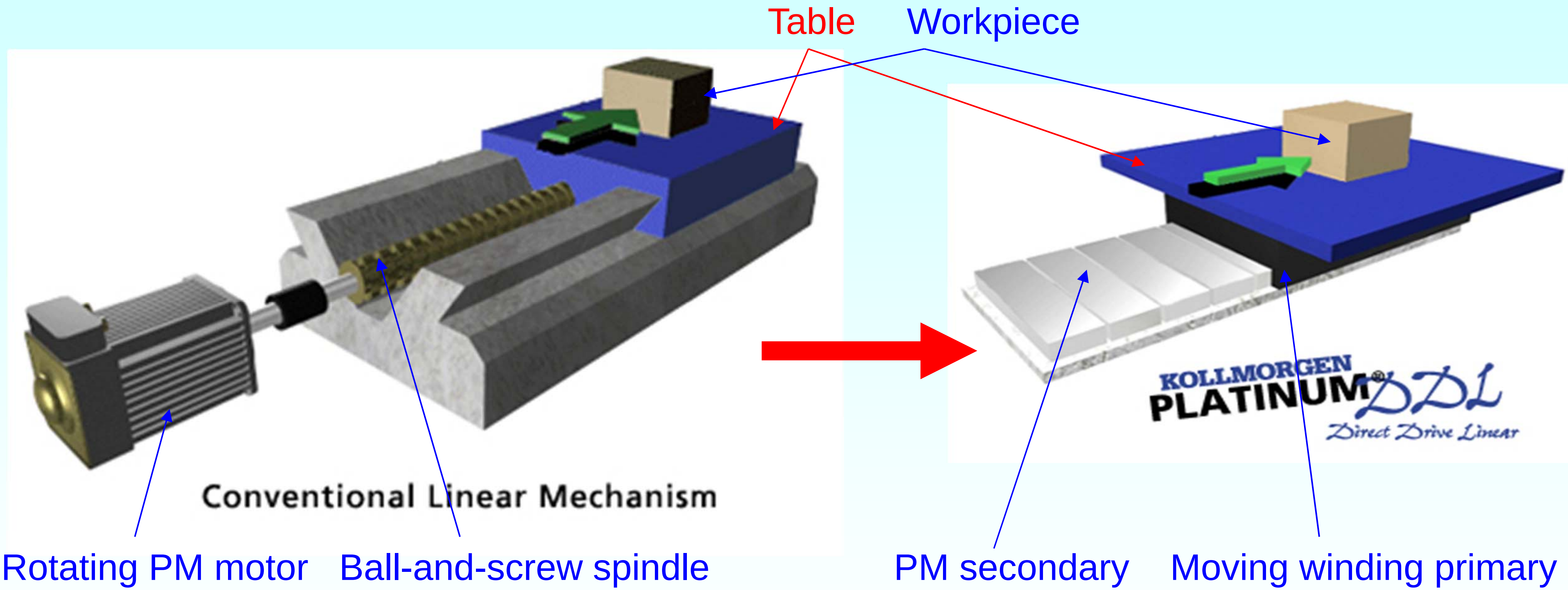
A) Rotating drive: A rotating servo motor M with belt gear (gear ratio i) drives a ball-and-screw spindle, which converts rotating movement into linear movement.



B) Linear motor: A linear PM servo motor moves a working table for milling process. No spindle elasticity, increased stiffness.

Comparison of spindle drive and direct linear drive

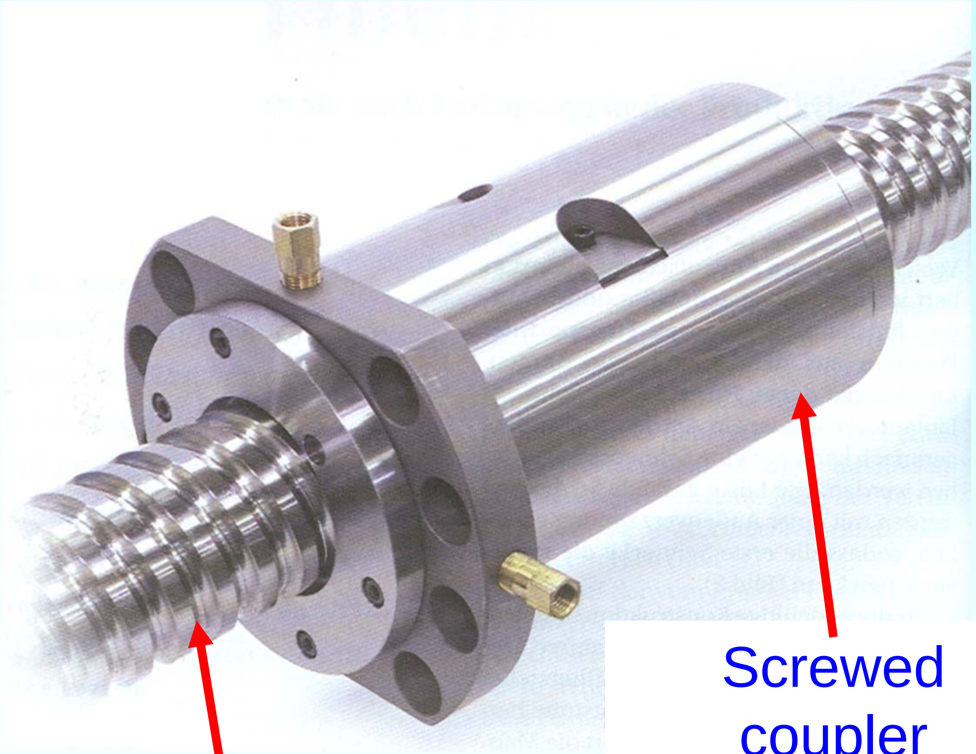
- Linear Motor: Direct coupling of the load to the motor



Ball-and-screw spindle drive | **Direct linear drive**

Source: Dr. Krah/ Danaher Motion, Germany

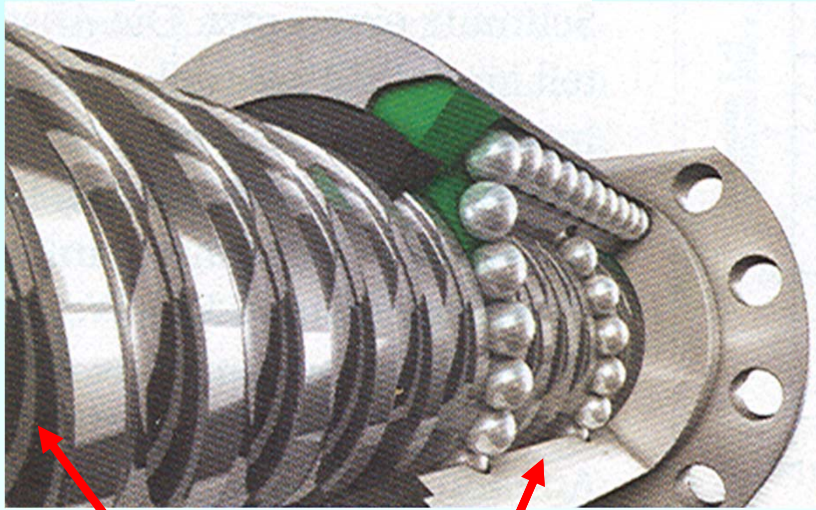
Ball-and-screw spindle drive



Screwed coupler

Screwed spindle

Cut view



Screwed spindle

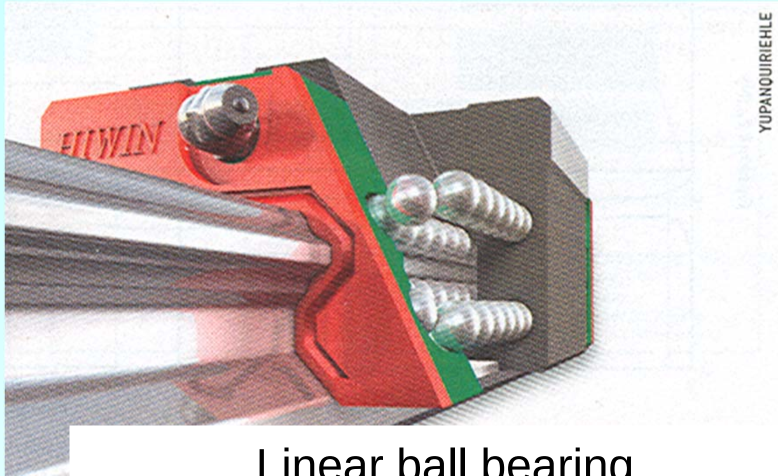
Screwed coupler with oil-lubricated balls in grooves

Source: NSK Deutschland GmbH, Ratingen, antriebstechnik 4/2011, p. 40

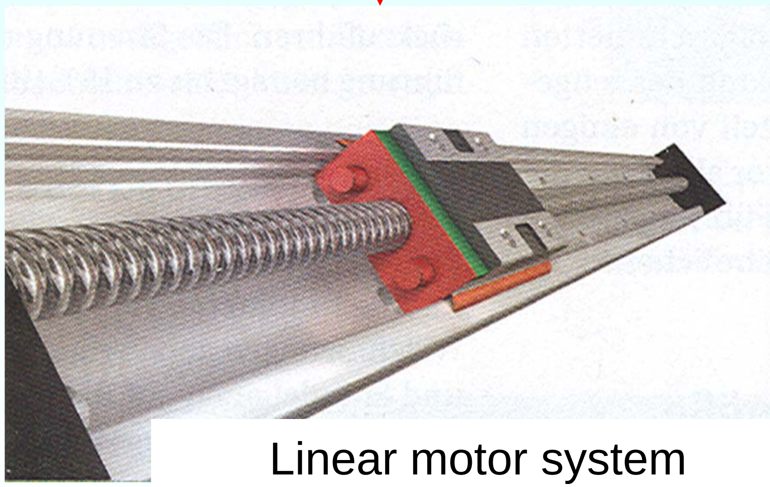
Source: HIWIN motion control systems, Germany

Overview on linear mechanical systems

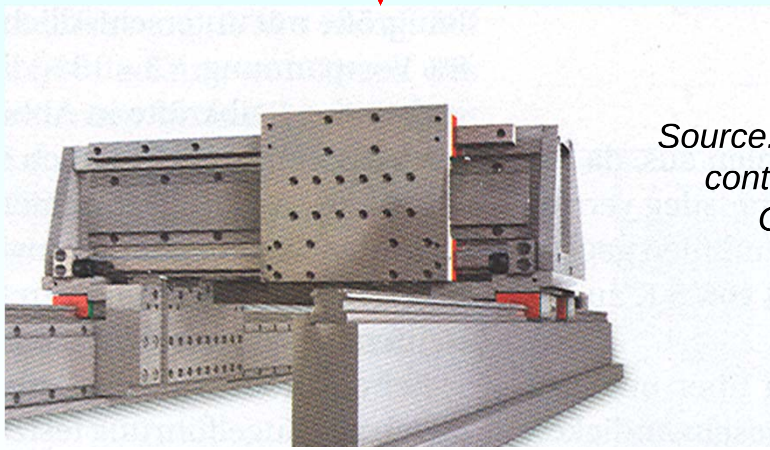
Ball-and-screw spindle



Linear ball bearing



Linear motor system

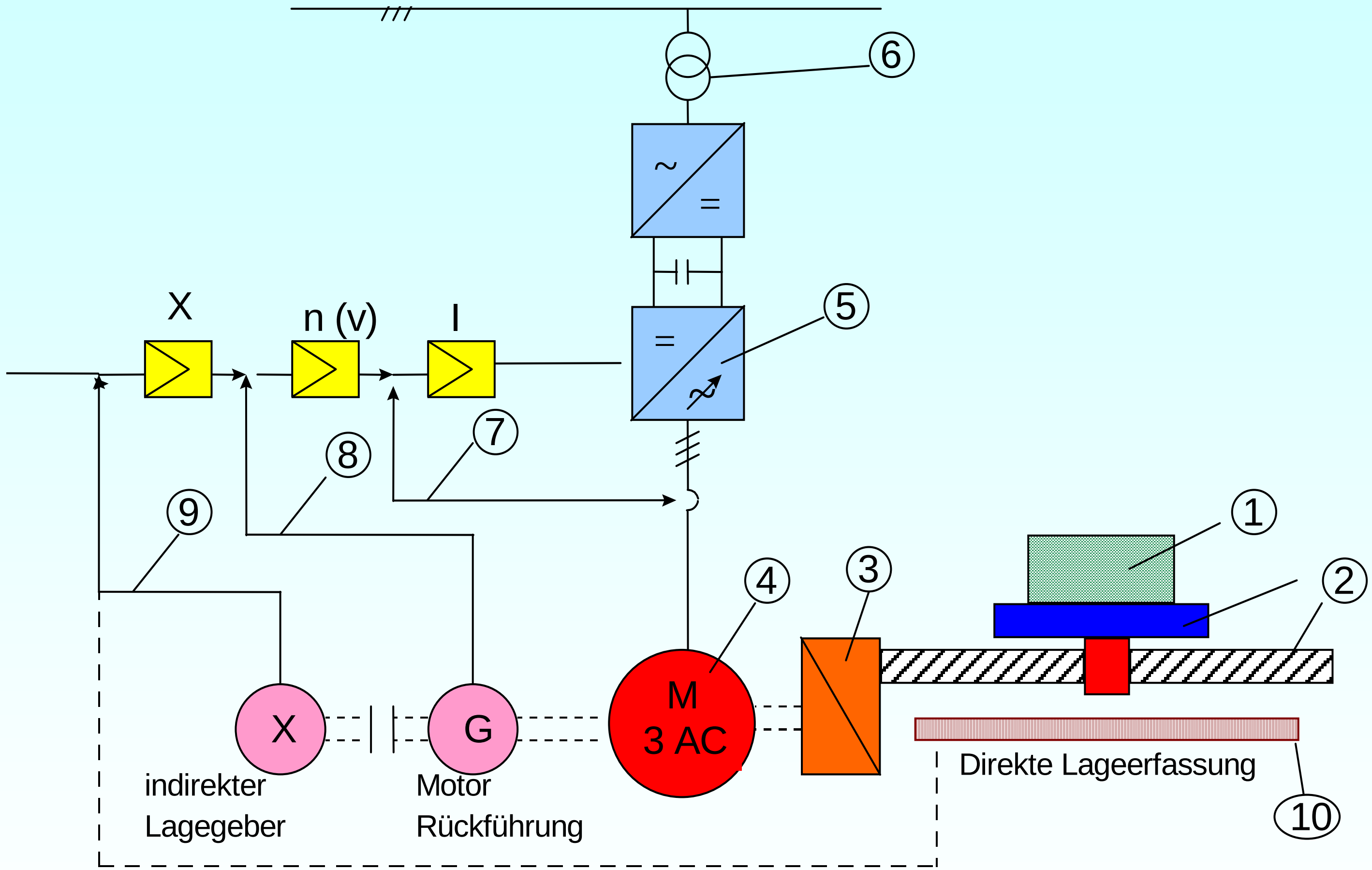


Linear axis with ball-and-screw spindle

Source: HIWIN motion control systems, Germany

Linear movement with ball-and-screw spindle drives

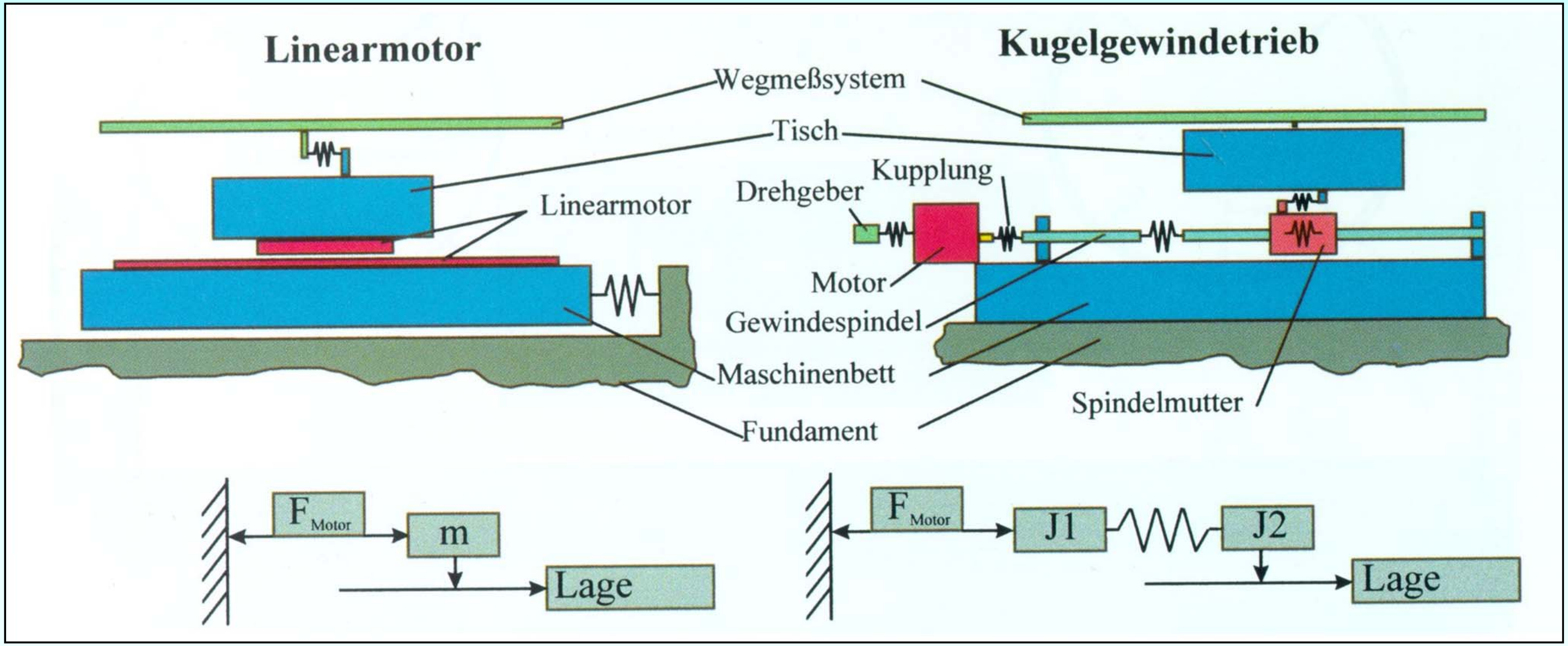
- Rotating motor turns screw ball spindle, which moves table and working piece linear !



1	Load: Workpiece
2	Table and screw spindle
3	Gear to operate with fast rotating (=small) motor
4	Servo motor
5	Three-phase inverter
6	Transformer and grid
7	Motor current measurement
8	Voltage measurement
9	Rotor Position measurement
10	Linear Position measurement

Source: Dr. Krah/ Danaher Motion, Germany

Tooling machine: Linear motor vs. screw ball drive



Source: Siemens Linear Motors

Linear motor:

Stiff drive, few oscillations

Increased accuracy of surface of workpiece (~ 1 μm)

High dynamic control possible = high accelerations

Ball-and screw spindle drive:

Elasticity of screw spindle - increased oscillations

Less accuracy at workpiece surface (~ 10 μm)

Smaller accelerations

Comparison of linear drive performance

Example: Comparison of manufacturing accuracy for positioning of cutting edge and workpiece

a) conventional with ball-and-screw spindle   b) linear motor positioning.

Data: Moved mass of workpiece: 1.2 t, velocity: 4m/min.

Result: The out-of-roundness of a circular shape of 300 mm diameter is

a) 5 μm.   b) only 0.4 μm

Advantages of linear drives

Advantages:

- no play between mechanical parts such as teeth of gear
- less mechanical components = increased stiffness of mechanical system
- less low resonance frequencies allow higher gain of position controller, leading to higher dynamic response of controlled system
- smaller process and shape errors in tooling application
- reduction of time for manufacturing
- reduced mechanical wear

Disadvantages:

- more expensive than the conventional solution
- special cooling systems must prohibit the heating of the workpiece by the motor losses.

Performance of linear PM machines

Speed of travelling wave: $v_{syn} = 2 f_s \tau_p$

a) **TRANSRAPID** high speed magnetically levitated train:
Long stator linear synchronous motor with electric excitation of moved secondary, which is the train cabin:
pole pitch 258 mm, max. frequency 270 Hz, maximum speed: **139.3 m/s = 500 km/h**

b) **PM short stator linear motor** for tooling machinery:
pole pitch 40 mm, max. frequency 125 Hz, maximum speed: **10 m/s = 36 km/h = = 600 m/min**

c) **Rotating PM servo motor** (six poles, 120 mm rotor diameter):
Rotor surface speed = speed of rotating field:
pole pitch 63 mm, max. frequency 150 Hz, maximum surface speed: **18.9 m/s**, corresponding with rotational speed **3000/min**

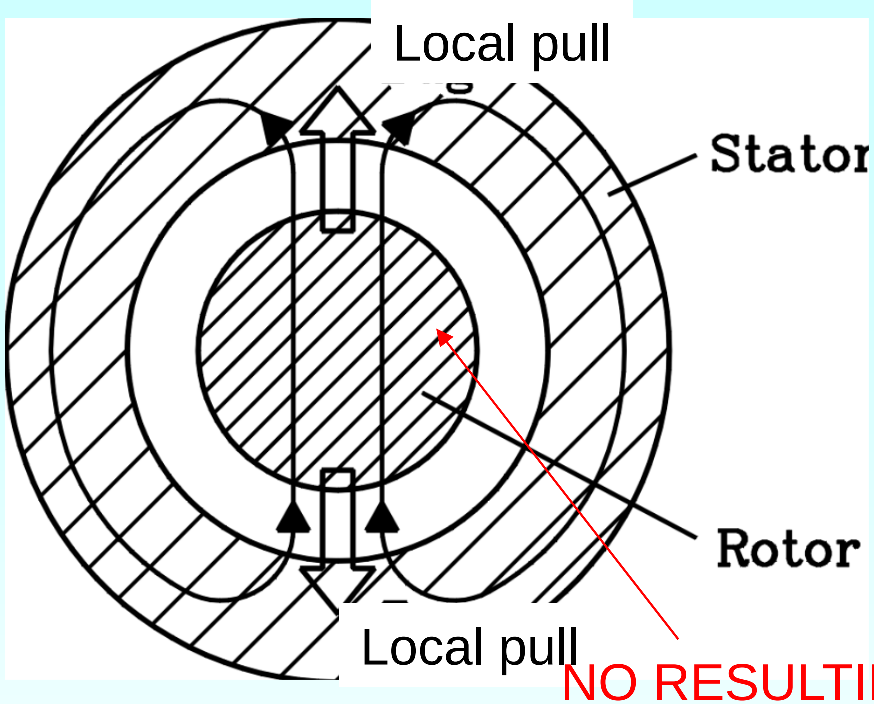
Maximum acceleration of linear motors:

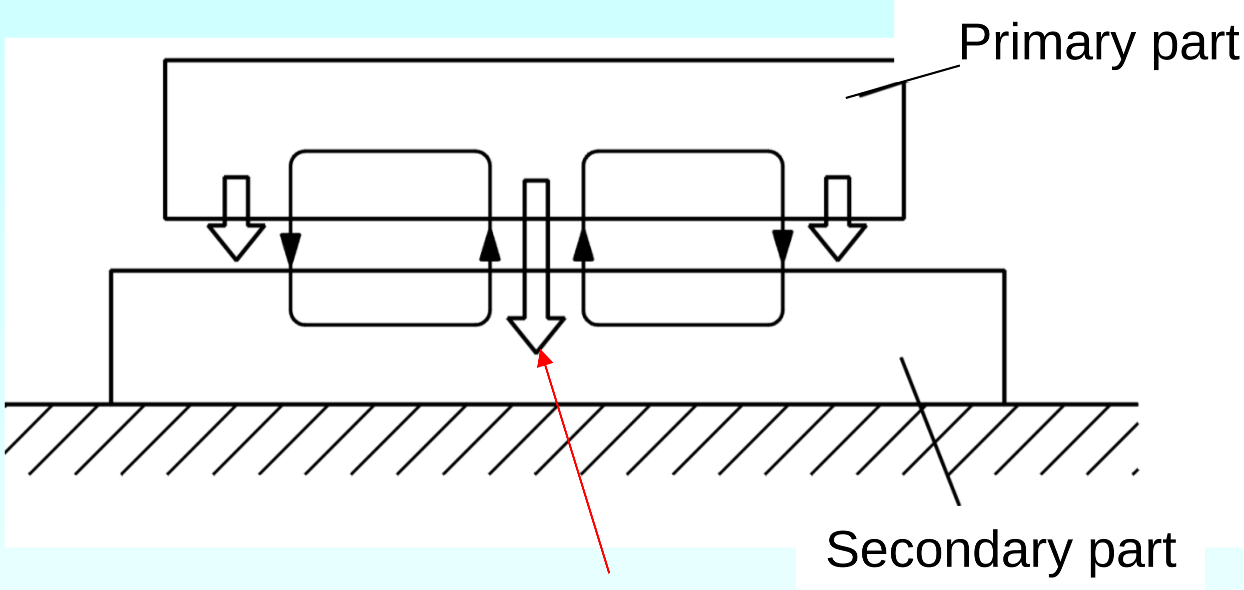
a) **TRANSRAPID:** For personnel transportation maximum acceleration of typically **1 m/s^2** is recommended.

B) **PM short stator linear motor** for tooling machinery:

self acceleration up to **600 m/s^2** possible.

Normal force in linear PM machines





- Magnetic air gap field pulls magnetized iron sides together.
- In rotary machines without any eccentricity the local pull is equalized, so total pull on rotor is zero !
- In linear machines this pull is full in action on the rotor and loads the linear bearings heavily !

Calculating Normal Force (Pull) in Linear PM machines

Normal force per area (*Maxwell* stress): $\sigma = \frac{B_{\delta,n}^2 - B_{\delta,t}^2}{2\mu_0} \approx \frac{B_{\delta,n}^2}{2\mu_0}$

Sinus fundamental field in air gap: $B_\delta(x) = B_{\delta,1} \cdot \sin \frac{x\pi}{\tau_p}$

Normal force of fundamental:

$$F_N = l_{Fe} \int_0^{2p\tau_p} \sigma dx = l_{Fe} \cdot \frac{B_{\delta,1}^2}{2\mu_0} \int_0^{2p\tau_p} \sin^2 \frac{x\pi}{\tau_p} dx$$

$$F_N = l_{Fe} \cdot \frac{B_{\delta,1}^2}{2\mu_0} \cdot p \cdot \tau_p = A_{mot} \cdot \frac{1}{2} \cdot \frac{B_{\delta,1}^2}{2\mu_0}$$

Tangential and normal force

Single sided linear motor :

$B_p \cong B_{\delta,1} = 0.7$ T; winding factor $k_w = 0.93$

a) Normal force per motor surface: *Maxwell* stress: $f_n = F_n/A_{mot} = B_{\delta,1}^2/(4\mu_0) = 9.8$ N/cm^2

b) Tangential force per motor surface = *Lorentz* thrust: $f_t = F_t/A_{mot} = k_w B_{\delta,1} \cdot A/\sqrt{2}$

Current loading A depends on the permissible temperature rise of the winding !

Steady state current loading and tangential thrust:

Cooling of primary	Direct air cooling	Indirect water jacket cooling
Current loading *A*	**400 A/cm**	**1000 A/cm**
***Lorentz* thrust f_t**	**1.8 N/cm^2**	**4.5 N/cm^2**
Ratio f_n/f_t	**5.4**	**2.2**

Short time overload S3-25%, 1 s cycle time (= 0.25 s overload, 0.75 s no-load, periodically)

Cooling of primary	Indirect water jacket cooling
Current loading *A*	**2000 A/cm**
***Lorentz* thrust f_t**	**9 N/cm^2**
Ratio f_n/f_t	**1.1**

Forces in linear PM motors - Loading of linear bearings

Example:

$A_{\mathrm{mot}} = 3768\ \mathrm{cm}^2,\ B_{\delta,1} = 0.7\ \mathrm{T}$:

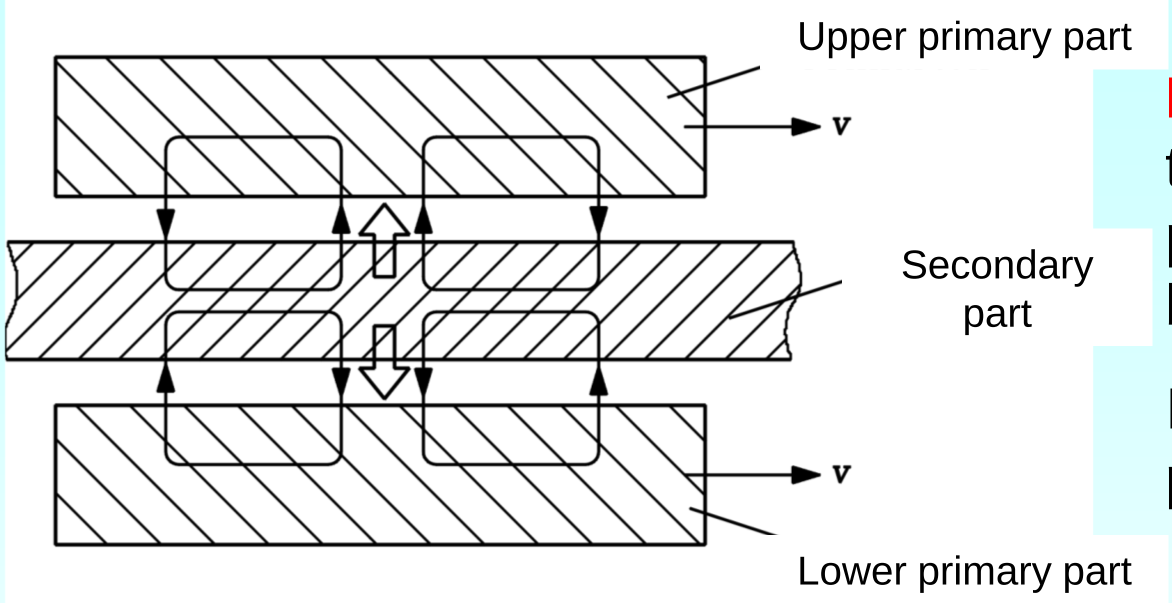
Normal force per area: $\frac{F_N}{A_{mot}} = \frac{1}{2} \cdot \frac{0{,}7^2}{2 \cdot 4\pi \cdot 10^{-7}}\ \mathrm{N/cm}^2 = 9.75\ \mathrm{N/cm}^2$

Normal force: $F_N = 9.75\ \mathrm{N/cm}^2 \cdot 3768\ \mathrm{cm}^2 = 36800\ \mathrm{N}$ **!!!**

- Steady state thrust force demand: 17 000 N,
- Single sided, water jacket cooling: f_t = 4.5 N/cm² (= 45000 N/m²)
- Necessary motor surface: $A_{mot} = F_t / f_t = 17000 / 45000 = 0.38$ m²,
- mass: motor primary + moving cables: m_{mot} = 220 kg
- mass of table and workpiece: $m_{\mathrm{W+T}}$ = 1500 kg

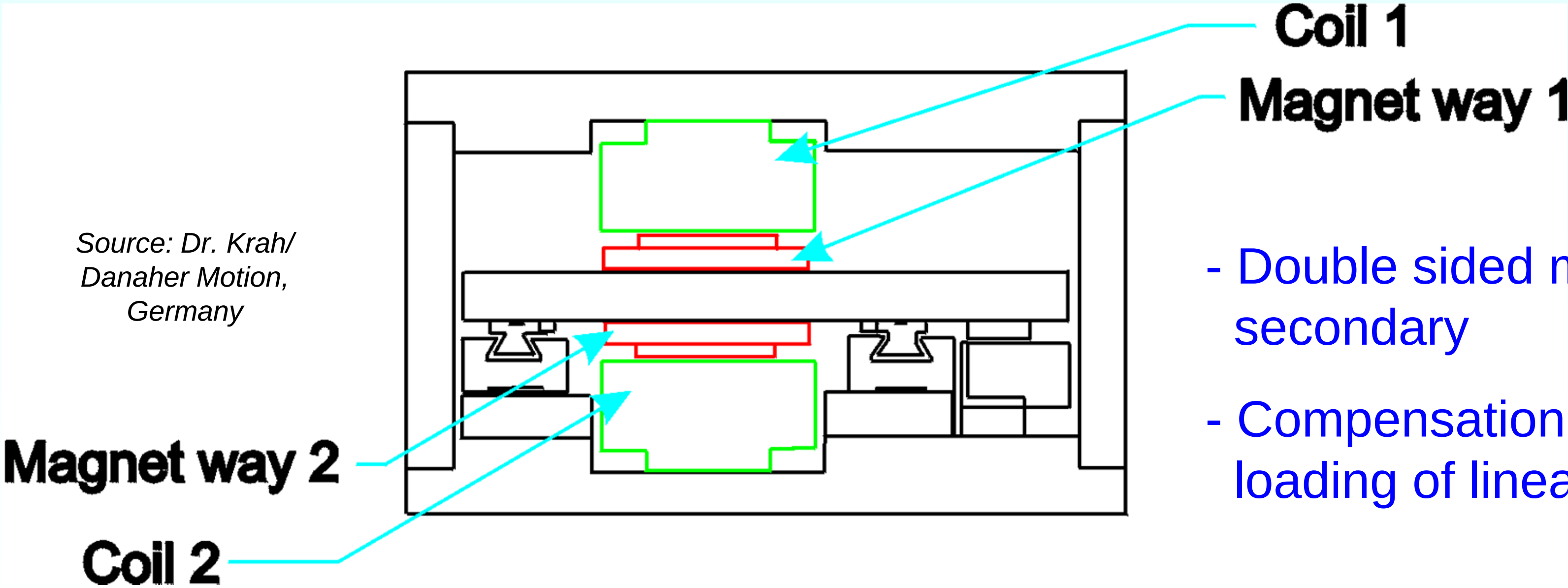
Weight force	Magnetic pull
$(m_{W+T} + m_{mot}) \cdot g = 16870\,N$	$f_n \cdot A_{mot} = 36800\,N$

Double sided linear PM synchronous motors



In double sided linear motors the magnetic pull of both motor parts compensates. The linear bearings are relieved.

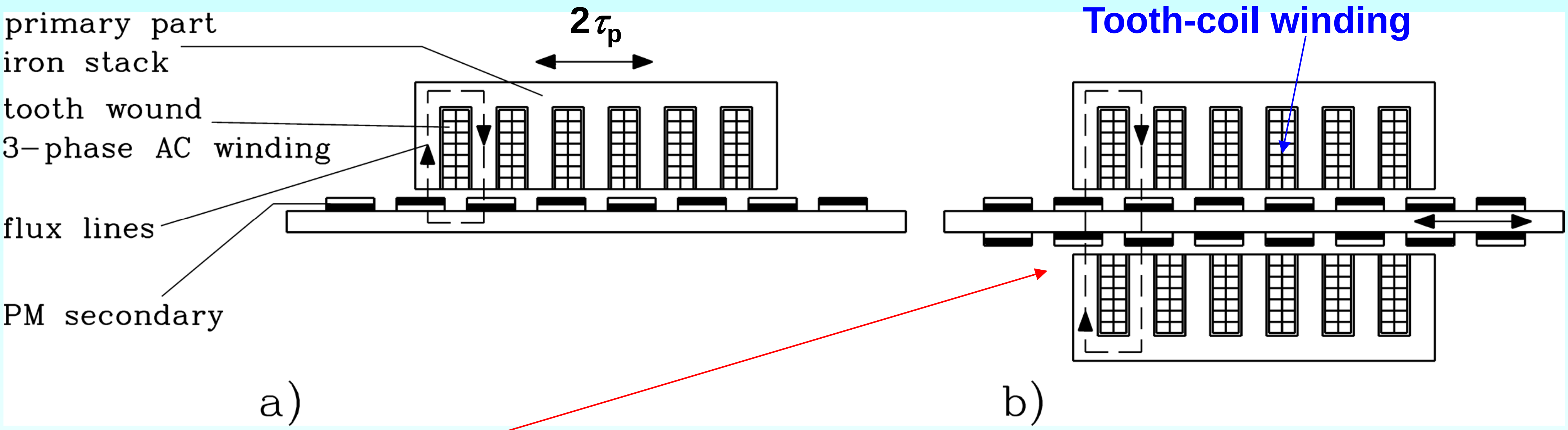
Inside the machine of course the pull loads the primary to bend !



Source: Dr. Krah/ Danaher Motion, Germany

- Double sided motor with moved secondary
- Compensation of normal forces to avoid loading of linear bearings

Single and double sided linear PM motors



- **In double sided linear motors** the magnetic pull of both motor parts compensates. The linear bearings are relieved.
- **Tooth-coil winding** (see *"Modular synchronous machines, Chapter 1.5.2"*) is a linear modular PM machine, which has slot pitch nearly pole pitch and allows

a) very short winding overhangs and

b) low cogging torque, if least common divider of number of slots and poles is very high, e.g. 8 poles & 9 slots (q = 3/8), but not 8 poles and 24 slots (q = 1).

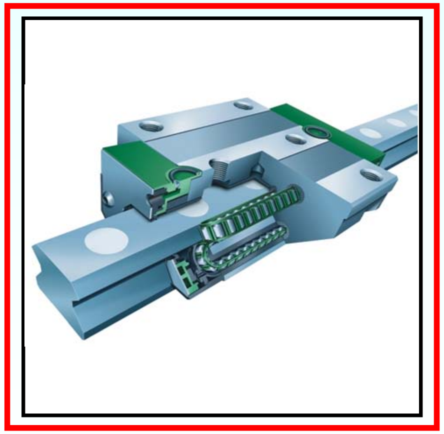
Influence of motor cooling on overload capability

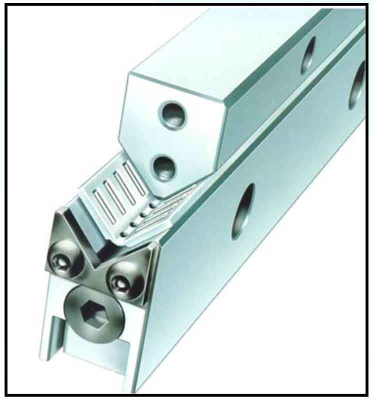
	• Cooling system	• F_{peak}/F_{cont} Overload capability	• Remarks
• Air-cored linear motors	Air cooling	$F_{peak}/F_{cont} = 3$	Small thermal time constant
• Iron PM motors	Air cooling	$F_{peak}/F_{cont} = 2.5$	Big thermal time constant
• Iron PM motors	Water cooling	$F_{peak}/F_{cont} = 1.3$	Heavy duty

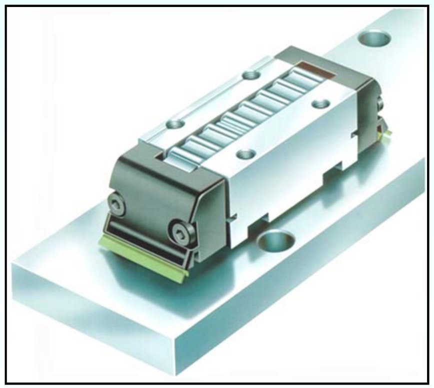
Overview on mechanical bearings

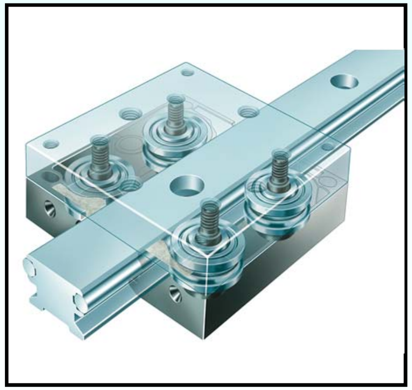
Source: Rudy /INA Schaeffler, Herzogenaurach, Germany

- **Guidance**
  - **Rolling**
    - **Linear motion**
      - Profiled rails with rolling moving elements as "endless chain"
      - Flat cage with rolling elements in fixed position
      - Flat rails with rolling moving elements as "endless chain"
      - Wheel guidance
      - ´Linear moving shaft guidance
    - **Rotational motion**
  - **Aerostatic**
  - **Hydrostatic**
  - **Hydrodynamic**



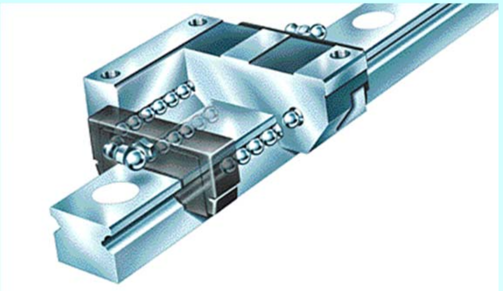


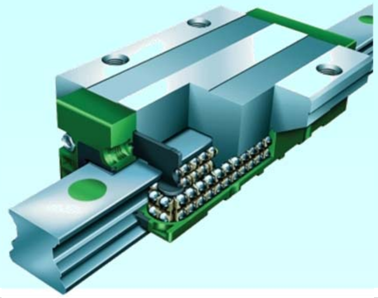


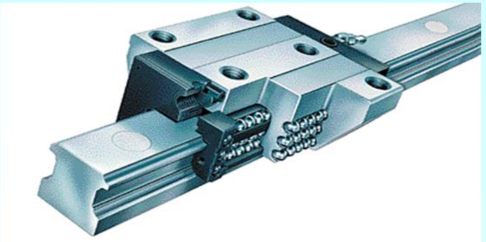


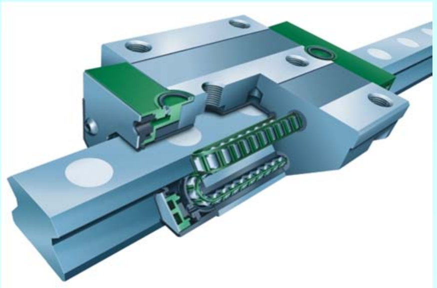
Linear bearings with rolling, moving elements as "endless chain"

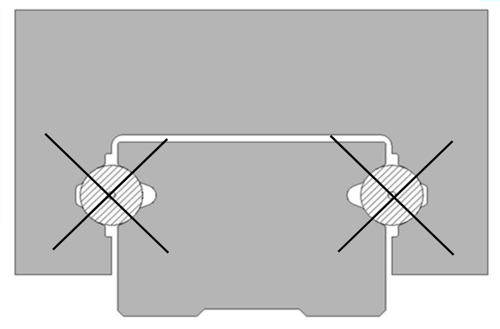
Source: Rudy /INA Schaeffler, Herzogenaurach, Germany

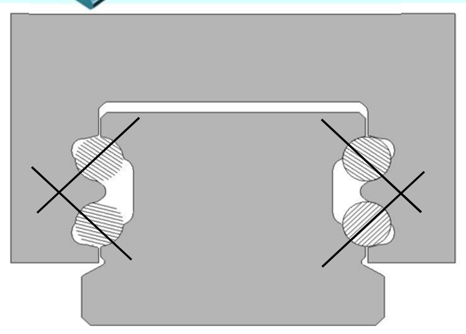


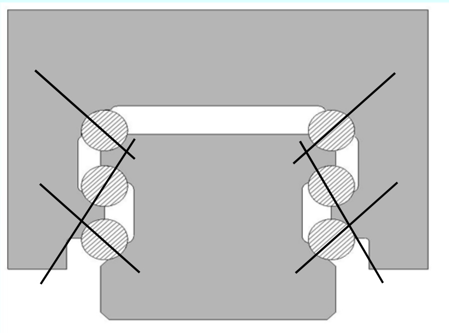


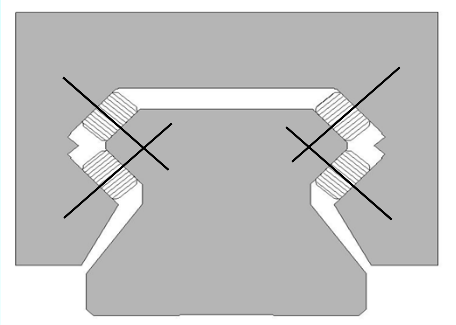












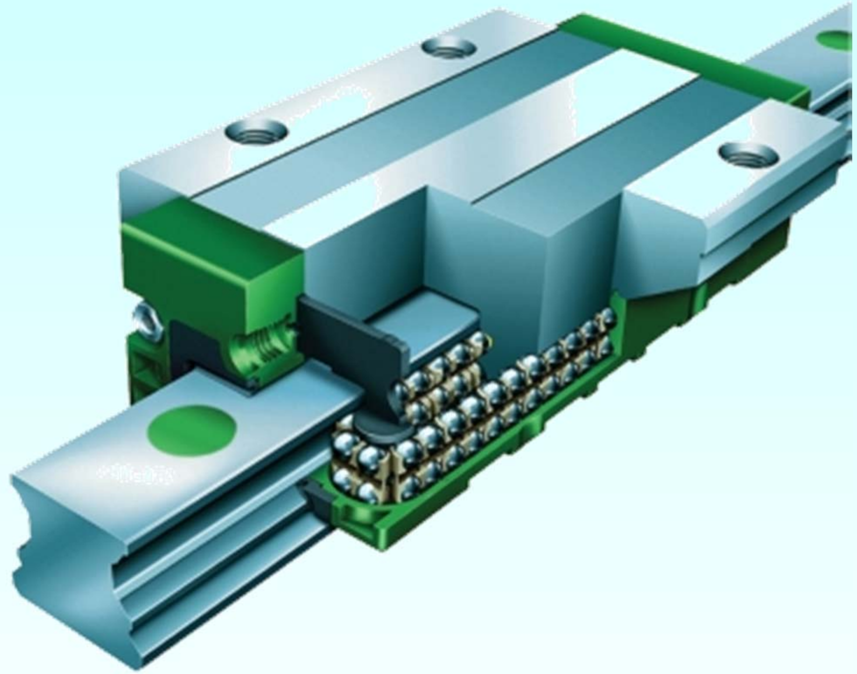
Balls: in single row | double row | triple row | **Rollers:** in double row

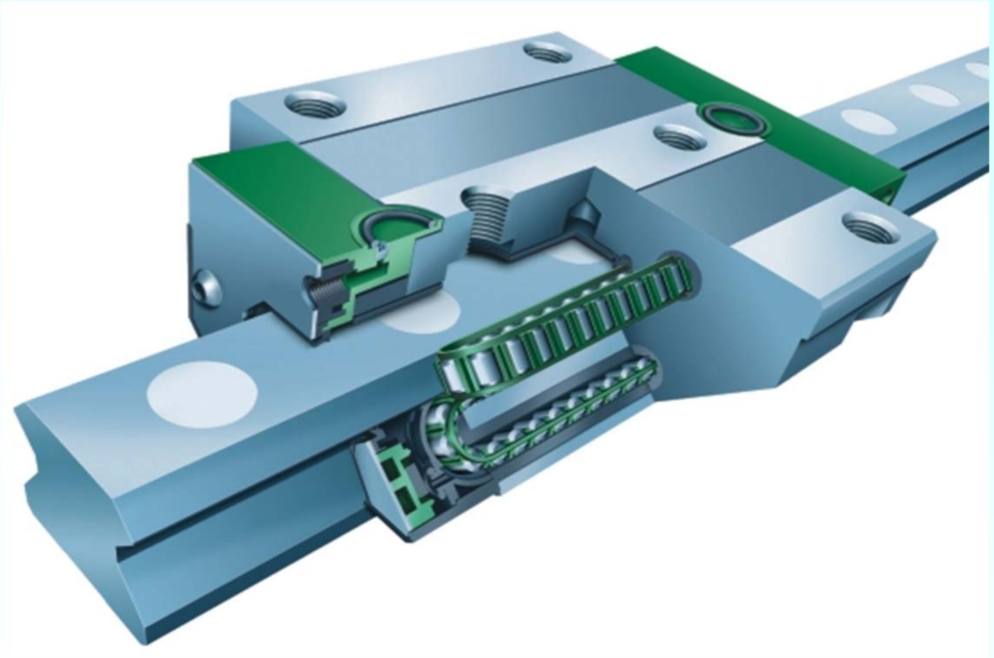
→ Load capability increases →

15 .. 35 mm | **15 .. 55 mm** | **20 .. 55 mm** | **25 .. 100 mm**

Dimensions standardized: DIN 645-2

Linear bearings with rolling, moving elements as "endless chain"





Balls: in double row

Rollers: in double row

Source: Rudy /INA Schaeffler, Herzogenaurach, Germany

Acceleration of linear PM machines

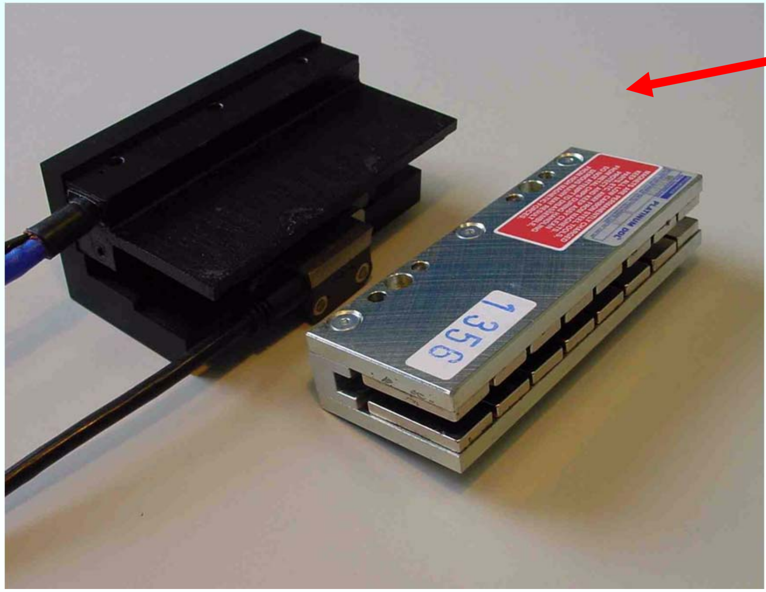
Self acceleration *a* with maximum thrust $F_{t,max}$:
Only motor primary mass and motor cables m_{mot} have to be moved.

$$a = F_{t,\max} / m_{mot}$$

Example:

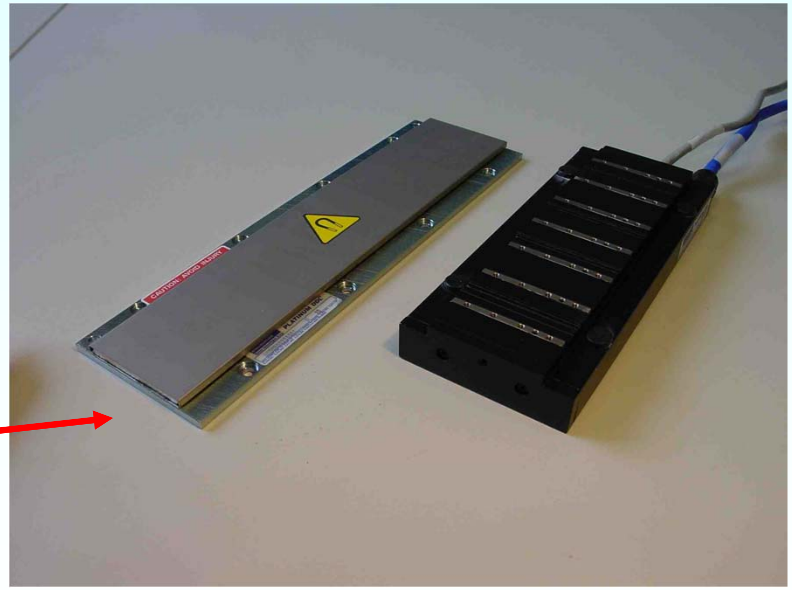
- Single sided motor: m_{mot} = 220 kg, steady state thrust force: 17 000 N
- Maximum thrust: 200% of steady state value

$$a = F_{t,\max} / m_{mot} = 34000 / 220 = 155 \text{ m/s}^2$$



Double sided ironless linear PM motor: low force, lower mass, *big acceleration*, nearly no cogging force

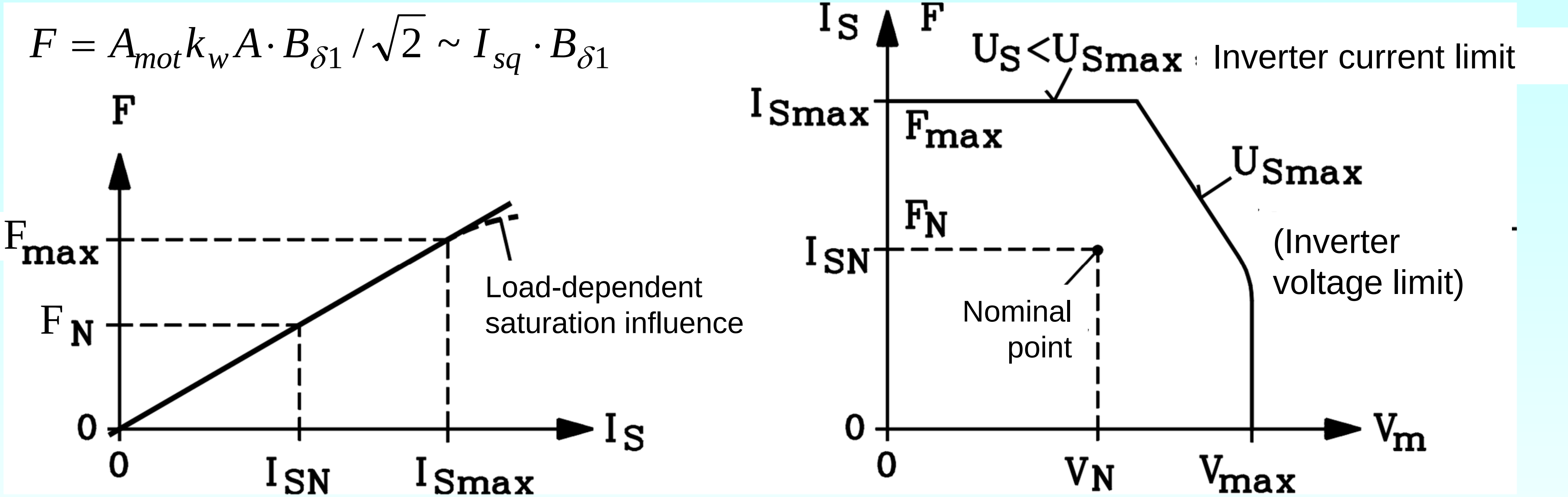
Single sided linear motor with iron back



Source: Dr.Krah: Danaher / Kollmorgen

Characteristics of Linear PM machines at q-current operation

$$F = A_{mot} k_w A \cdot B_{\delta 1} / \sqrt{2} \sim I_{sq} \cdot B_{\delta 1}$$



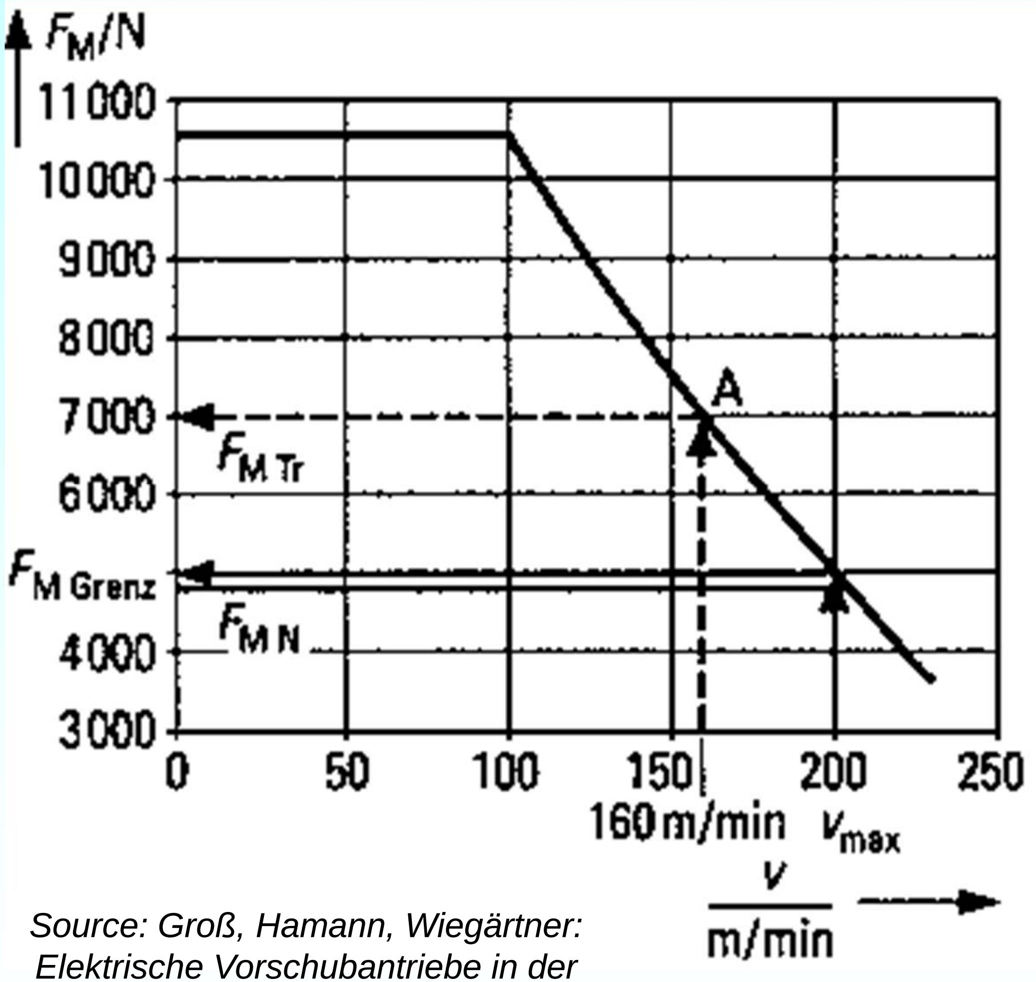
- In q-current operation the thrust is linear proportional with current, as long as the iron does not saturate !

- Like with rotary PM servo drives, there exists “current limit”, “voltage limit”, “thermal limit”, “overload limit” !

Example: *F(v)*-limits of PM linear motor

Current limit:
Force is limited to 10500 N
Voltage limit:
Speed at full force 10500 N
is limited to 100 m/min
Maximum speed: (I_q-current operation):
250 m/min at 3000 N

e.g. at 200 m/min only a force of 5000 N is possible, at 160 m/min an increased force of 7000 N !



Source: Groß, Hamann, Wiegärtner: Elektrische Vorschubantriebe in der Automatisierungstechnik, Publicis, Munich, 2006

Cooling of linear motors in tooling machines

Demand: Only very small thermal expansion of workpiece is allowed to achieve high accuracy of manufacturing process in the micron region.

Solution: Motor winding is cooled with water jacket, **using two cooling systems**.

a) **Power cooler**: directly mounted on the primary iron stack, takes off about 85% of total primary losses.

b) **Precision cooler** mounted on top with controlled coolant flow, taking away 15% of total losses. Keeps change of table surface temperature within $\Delta\vartheta = 2$ K (!).

Example:

Working piece: main dimension: l = 400 mm at 20°C

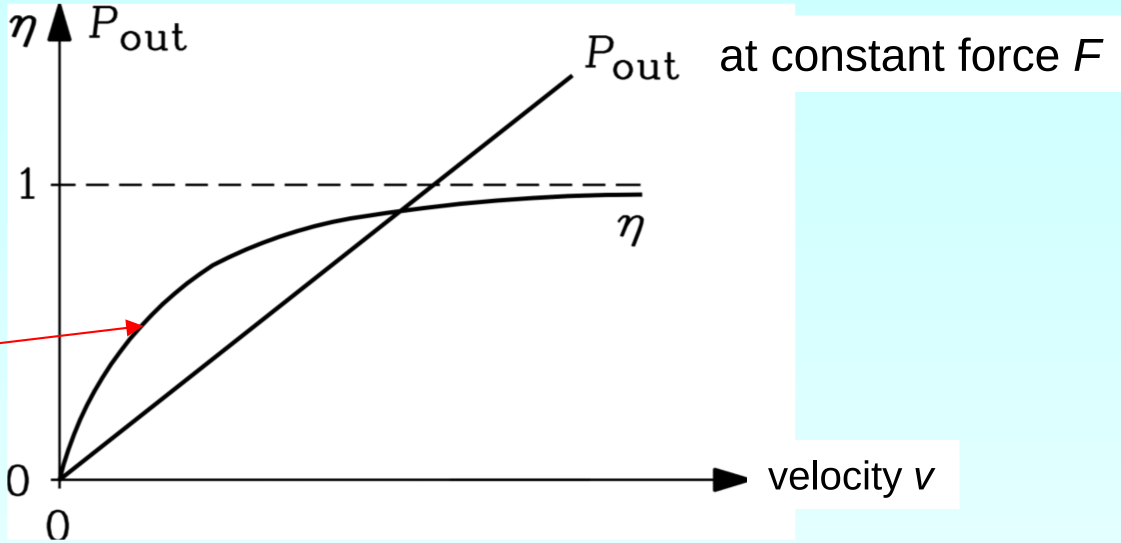
At 22°C (when motor is hot) the additional length is $\Delta l = l \cdot \alpha_\vartheta \cdot \Delta\vartheta$

Material of working piece	Aluminium	Iron
Linear expansion coefficient	$\alpha_\vartheta = 23.8 \cdot 10^{-6}$ / K	$\alpha_\vartheta = 12.0 \cdot 10^{-6}$ / K
Δl	19 μm	10 μm

Efficiency of linear motors

$$\eta = \frac{P_{out}}{P_{out} + P_d} = \frac{F \cdot v}{F \cdot v + 3 \cdot R \cdot I_q^2}$$

$$\eta = \frac{v}{v + k \cdot I_q}$$



- Constant tangential force (or torque): $F \sim I_q = \text{const.}$
- Constant losses $P_d \sim I_q^2 = \text{const.}$
- Output power $P_{out} \sim F \cdot v$
- Efficiency $\eta = P_{out} / (P_{out} + P_d)$ decreases with decreasing velocity v

Efficiency at rated velocity: Typically 60% to 70%,
- Rather low, compared with rotating PM synch. motors (typically up to 95%)
- Rather low velocity of moving part causes rather low efficiency.

Comparison: Linear & rotating PM motors

	Linear motor	*Rotating motor 2p = 6*
		d_r = 120 mm, l_{Fe} = 37 mm
Motor surface A_{mot}	140 cm^2	140 cm^2 = $d_r \cdot \pi \cdot l_{Fe}$
Rated speed	120 m/min	1500/min ($\leftrightarrow v$ = 565 m/min)
Tangential force $F_t = A_{mot} f_t$	630 N	630 N
Frequency f_s	16 Hz	75 Hz
Output power $P_{out} = F \cdot v$	1260 W	5930 W
Input power $P_{in} = P_{out} + P_{Cu}$	1585 W	6255 W
Efficiency $\eta = P_{out} / P_{in}$	**79.5%**	**94.8%**

Assumptions: Identical water jacket cooling system

- identical current load A & flux density B_δ = identical specific thrust f_t = 4.5 N/cm^2
- identical ohmic winding losses P_{Cu} = 325 W (further losses neglected)

Note: This linear motor, operated at only 60m/min with the same force and losses, produces only 630 W output power and therefore only 66% efficiency !

Features of linear PM machines

(i) Maximum thrust f_t:
Single sided motor: 5...8 N/cm^2. **Double sided motor:** 10...16 N/cm^2.

(ii) Self acceleration (without cable mass): 150...300 m/s^2. **double sided stator:** 600 m/s^2

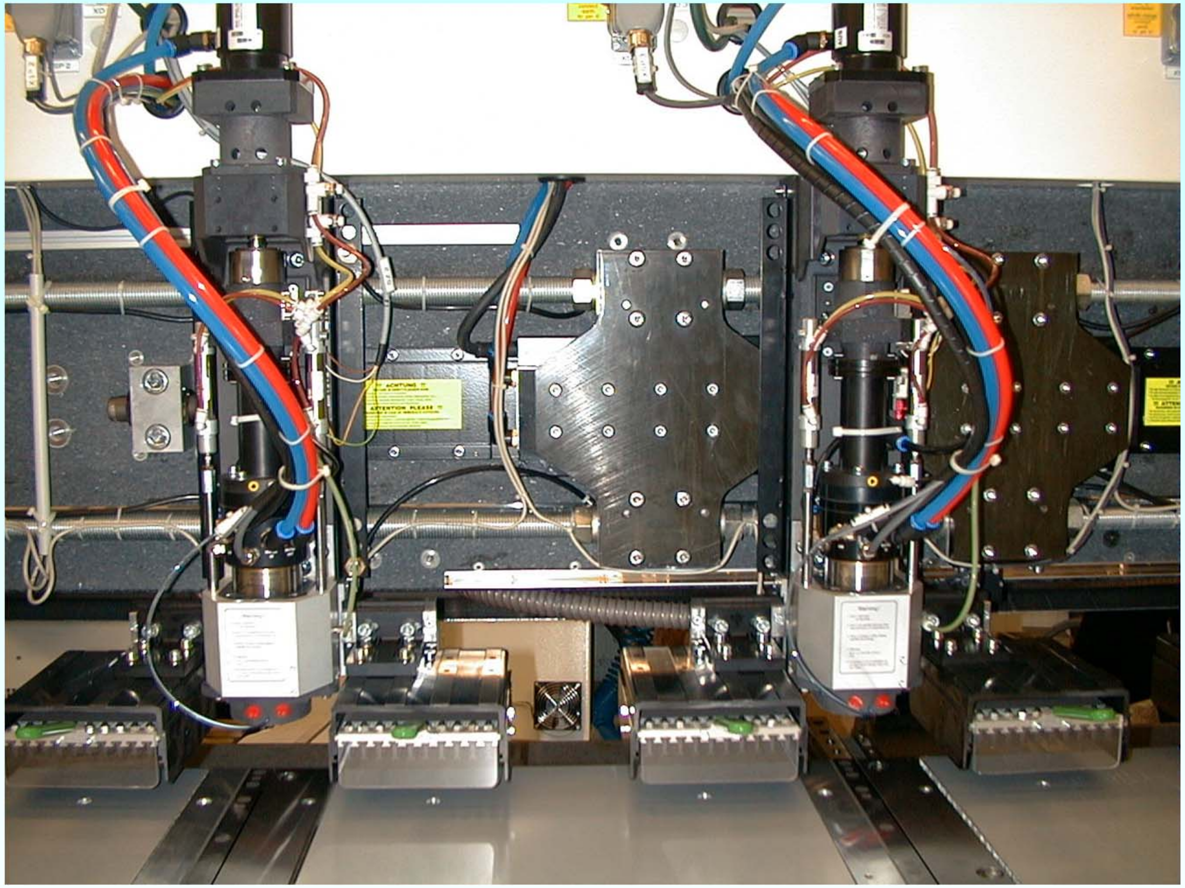
(iii) Steady state thrust:
About 50% of maximum thrust = overload capability: 200%.

(iv) Maximum speed: up to 600m/min = 36 km/h

(v) Position control: (high precision drive systems)
Resolution of position: Linear optical position sensors: 1nm is possible.
Control steps: about 0.5μm !

(vi) Efficiency at maximum speed: typically 60% to 70%

PM Linear Motor: Application 1: Drilling printed circuit boards



Drilling holes in printed circuit boards (PCBs)

Moved mass: 300kg, acceleration: a = 12m/s², velocity: v =1m/s

Facts:

400 holes /min

Benchmark: 2,54 mm Step/60ms

Position-window 2µm

Accuracy +/-8µm

Solution:

PM Linear Motor with stator and rotor iron stack and stator water cooler

Reasons for this solution:

- Small cogging force,
- high force density
- External cooler must keep surface temperature independent of motor load

Advantage:

40% higher drilling rate as with rotating motor and screw ball spindle drive

Source: Dr. Krah/ Danaher Motion, Germany

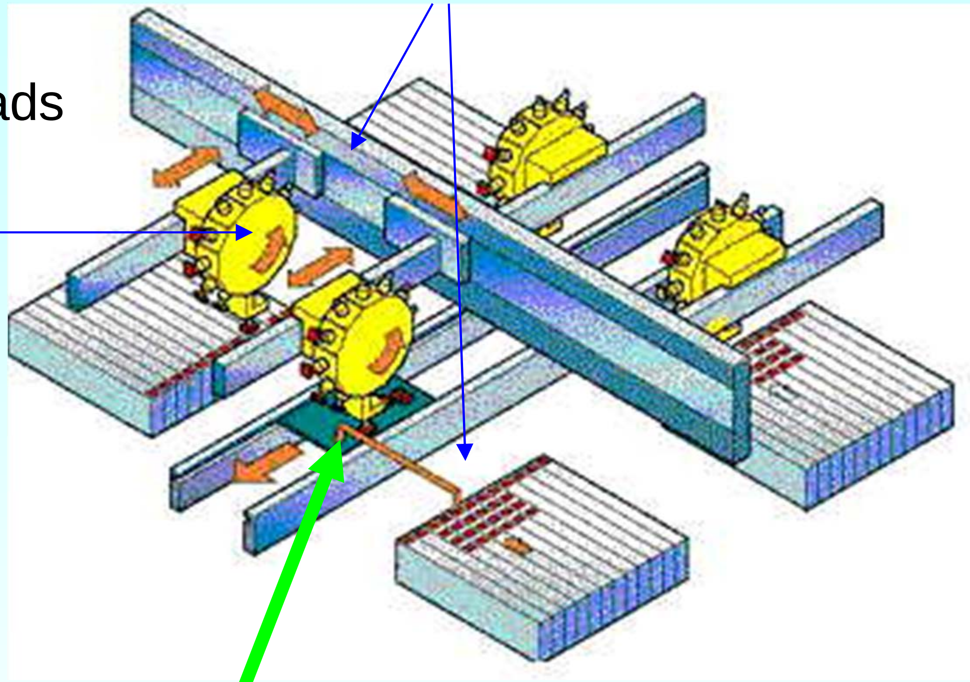
Application 2: Pick & and place of electronic devices on PCBs

Leiterplattenbestückung

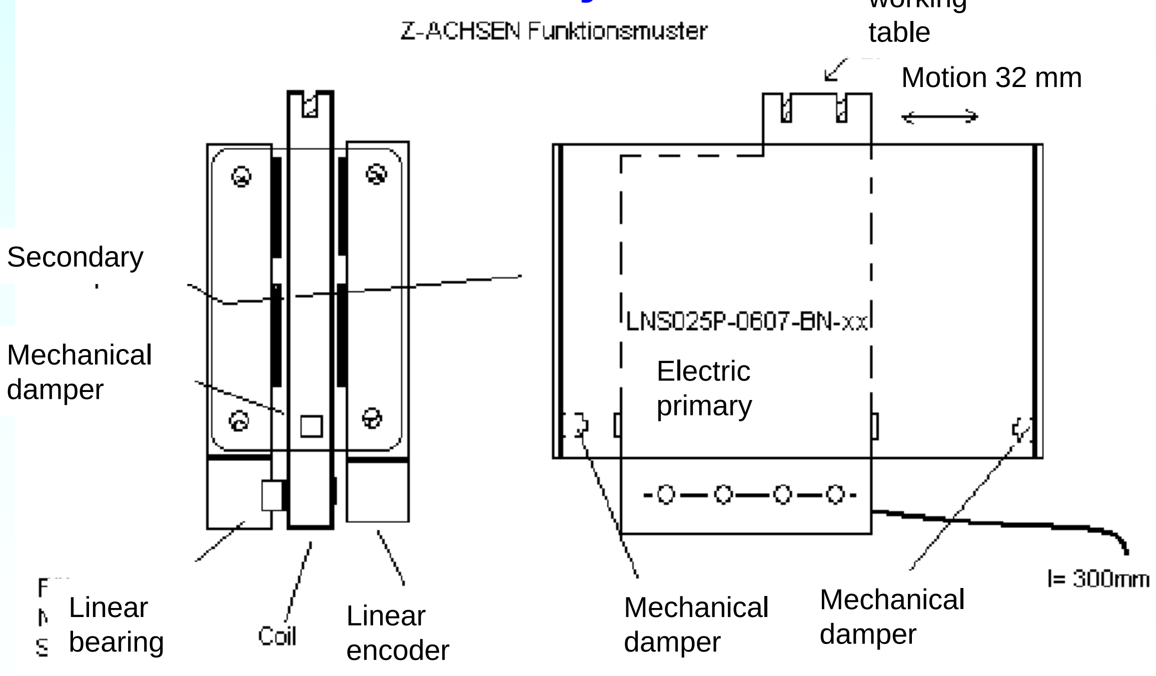
- Revolving head positions the electronic devices
- Ironless PM linear motors move the revolving heads

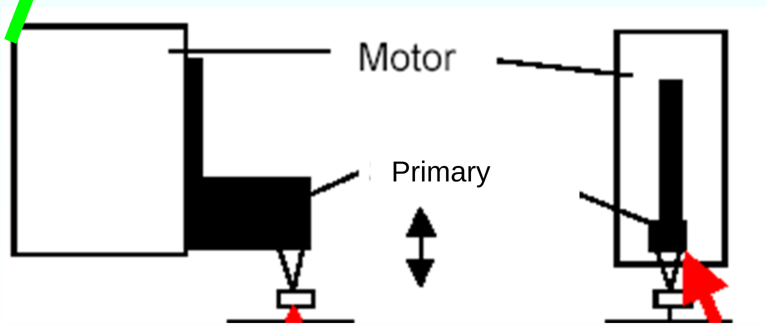
Ironless linear motor

Revolving head



Ironless linear motor with double secondary:



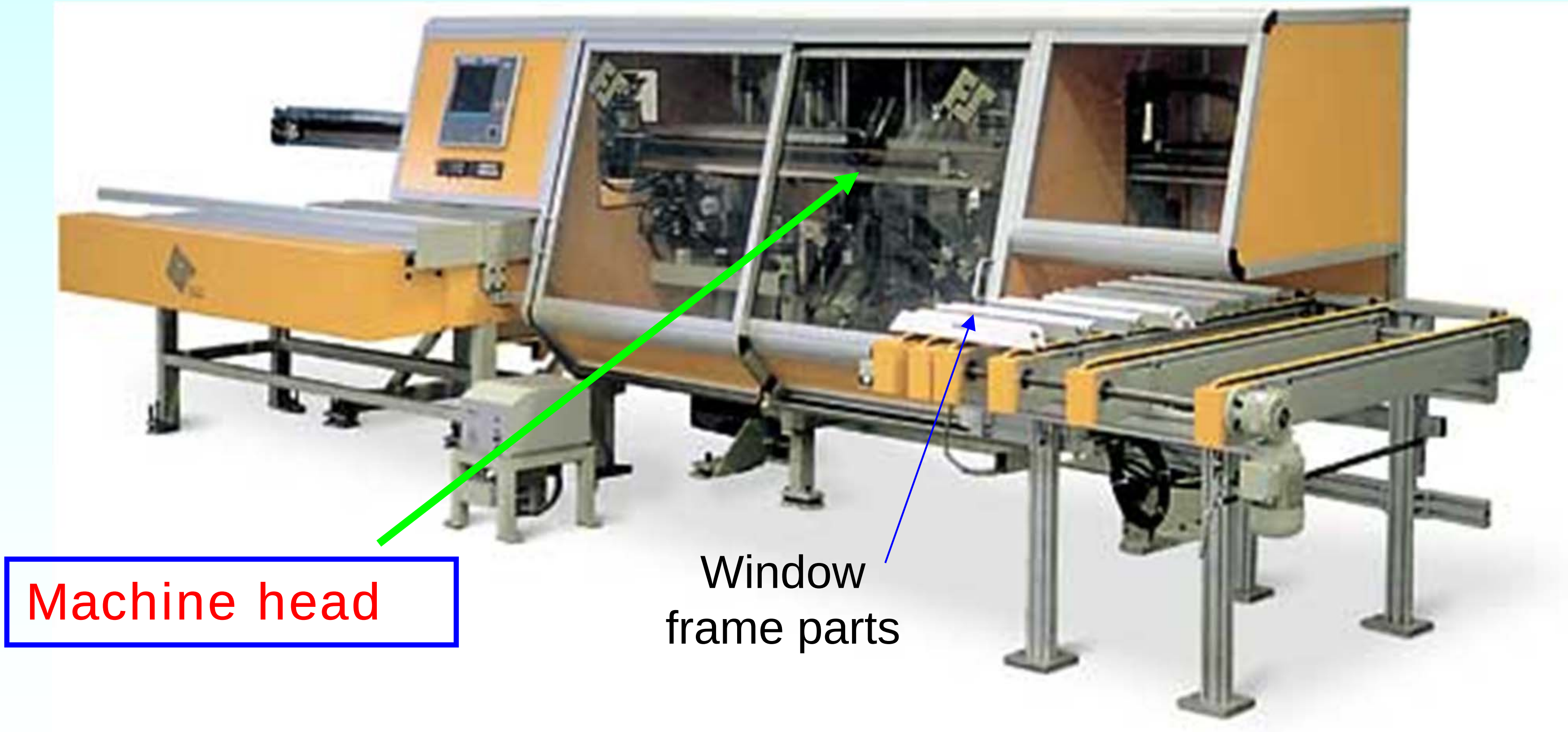


Source: Dr. Krah/ Danaher Motion, Germany

Application 3: Manufacturing window frames

Fensterrahmenmaschine

- Linear movement of a machining head for profiling the frame parts of the windows
- Moving distance up to 6m with high accuracy and thermal stability



Source: Dr. Krah/ Danaher Motion, Germany

Application 4: High velocity drilling unit

Hochgeschwindigkeits-Bohrer

Linear motor

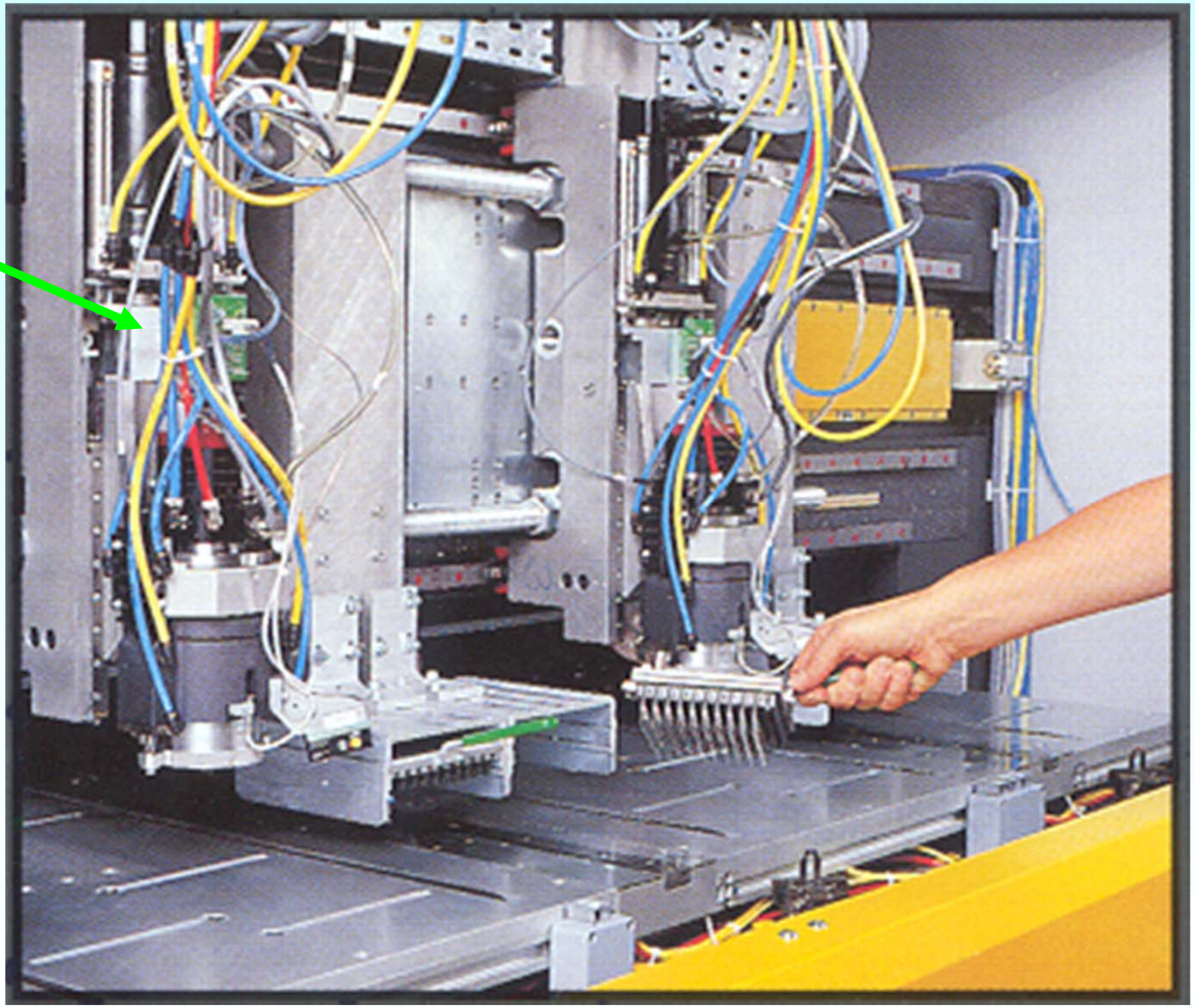
Features:

- acceleration 4g,
- 200 ms drilling rate

Only achievable due to:

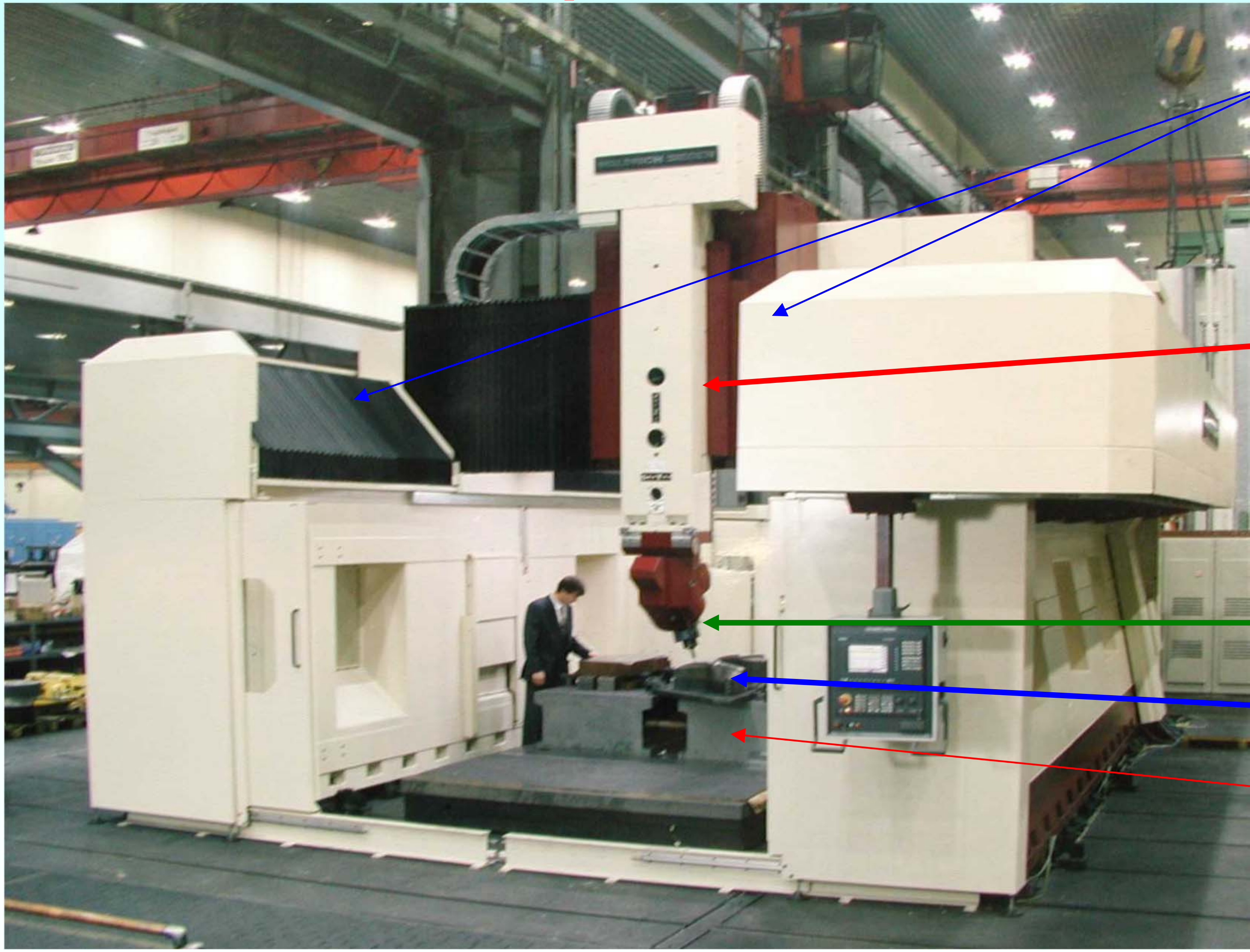
High force density = high force per moved mass

A LINEAR MOTOR IS NEEDED !



Source: Dr. Krah/ Danaher Motion, Germany

Application 5: Twin linear motors for gantry milling unit for aircraft parts (Portalfräsmaschine)



Twin linear motors for horizontal movement

One linear motor for perpendicular movement

Milling head

Working piece

Table

Source:

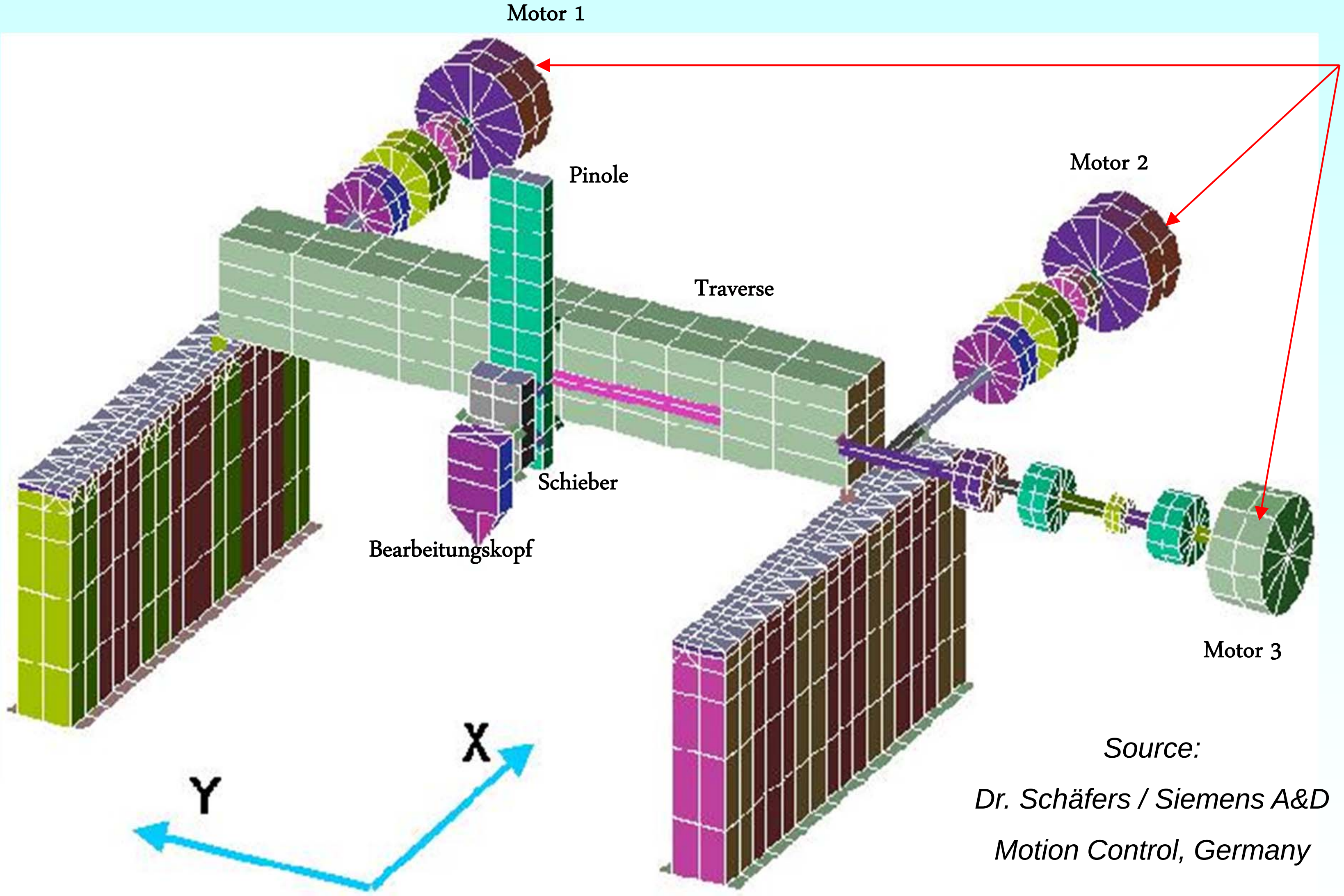
Dr. Schäfers

Siemens A&D

Motion Control

Germany

Mechanical finite element model for calculating vibration resonance frequencies



Linear motors are represented by rotating motors with ball-and-screw spindle for mechanical modeling

Source:

Dr. Schäfers / Siemens A&D

Motion Control, Germany

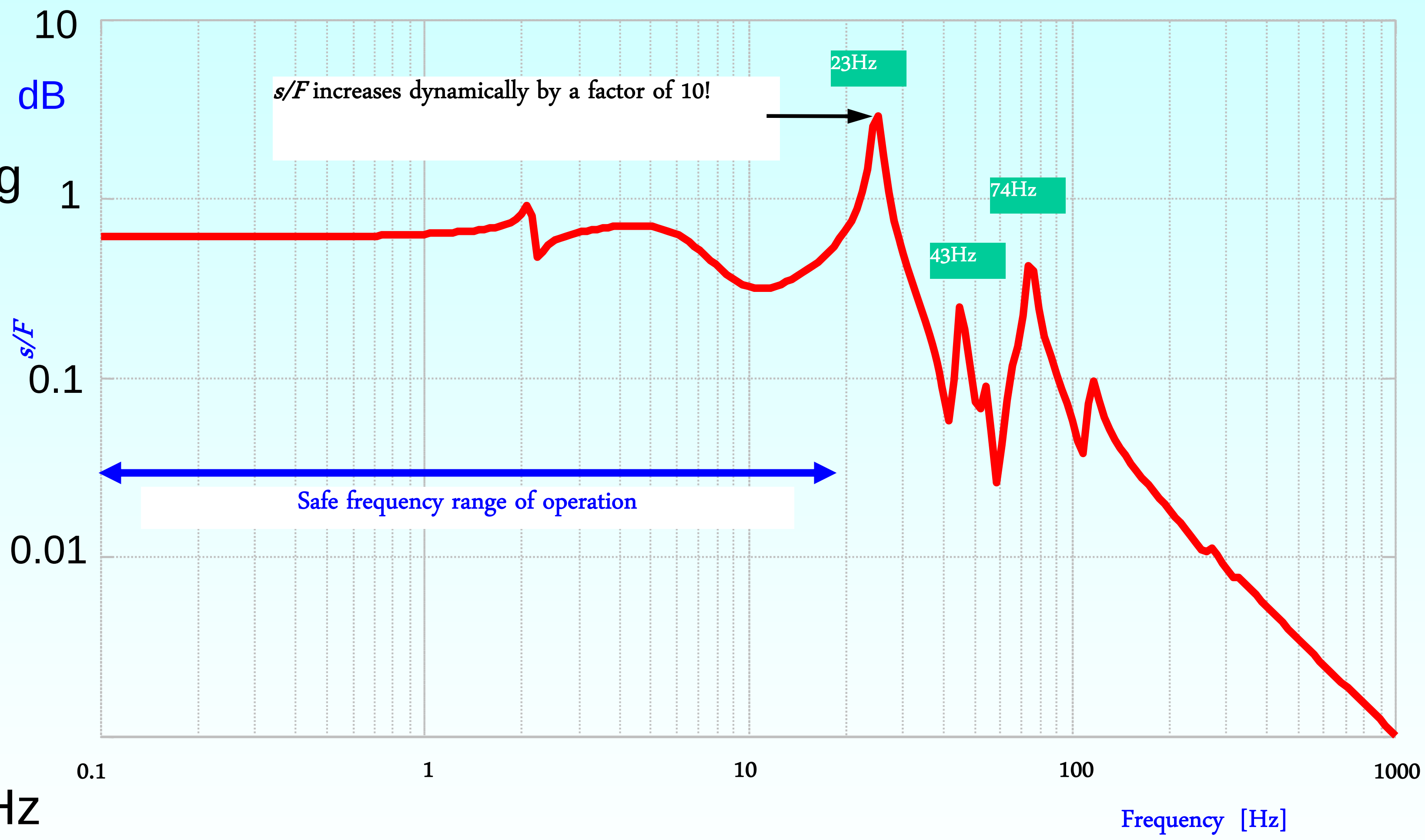
Calculated ratio of “vibration amplitude/exciting force”

- *s/F* = vibration amplitude/exciting force, depending on exciting frequency *f*

s(f): Vibration amplitude of milling head

- Three major resonance frequencies, belonging to three different vibration eigen-modes:

23 Hz, 43 Hz, 74 Hz



Source: Dr. Schäfers / Siemens A&D, Motion Control, Germany