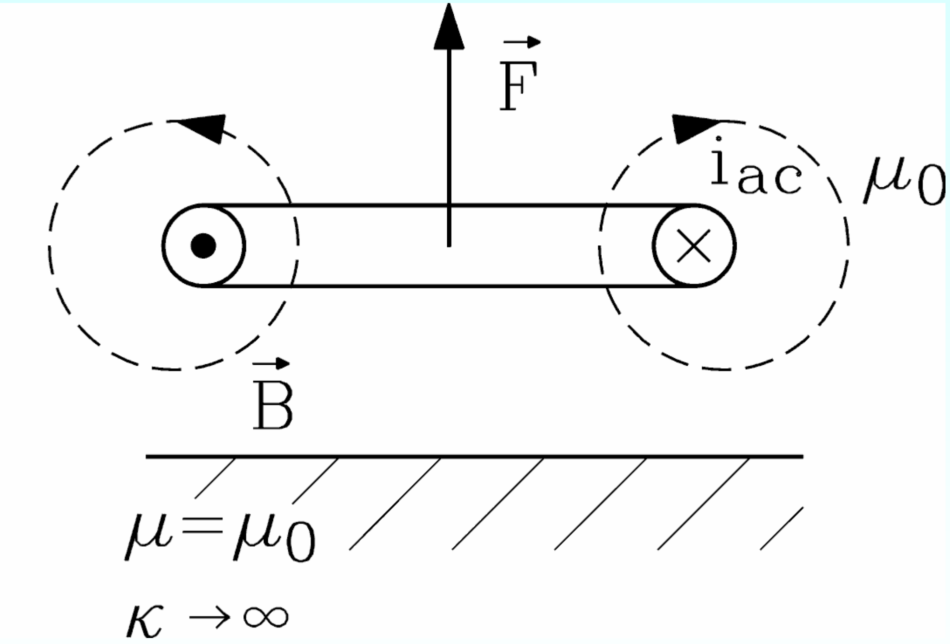
New technologies of electric energy converters and actuators

3. Magnetic bearings („magnetic levitation“)

3.3 Electro-dynamic levitation

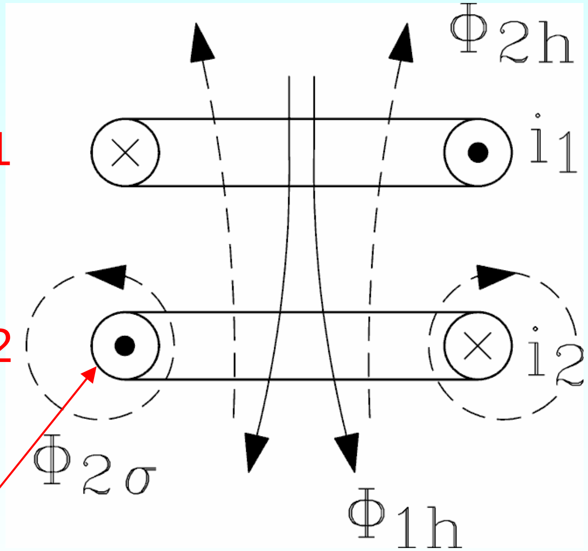


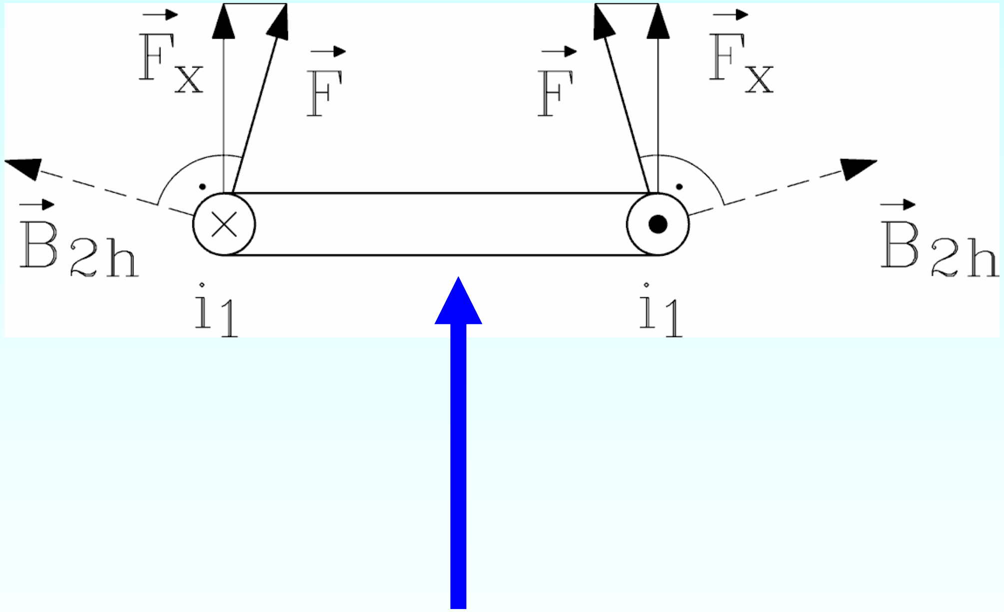
Basic principle of the Electro-dynamic levitation

- A primary AC-fed coil 1 excites a magnetic field, which induces eddy currents in a short-circuited coil 2 as a „circular current“.
- The circular current i_2 creates via it self-field B_2 a repulsive (levitating) force F_x on the primary coil 1

primary coil 1

secondary coil 2





Current in secondary coil in opposite phase = repelling force !

Levitating force F_x on the primary coil 1

Calculation of the induced circulating current i_2

- **Mutual inductance M_{12} between coils 1 and 2:** $u_{i,2} = -N_2 \frac{d\Phi_{1h}(i_1)}{dt} = -M_{12}\frac{di_1}{dt}$
- **Short circuited coil 2** (number of turns N_2): voltage $u_{i,2}$ drives current i_2, which excites a main flux Φ_{2h}, that is opposing the change of flux $d\Phi_{1h}/dt$.
  ⇒ **The direction of current i_2 nearly opposite to i_1!**

$$u_{i,2} = R_2 i_2 + N_2\frac{d\Phi_2}{dt} = R_2 i_2 + N_2\frac{d(\Phi_{2h}+\Phi_{2\sigma})}{dt} = R_2 i_2 + L_{2h}\frac{di_2}{dt} + L_{2\sigma}\frac{di_2}{dt}$$

$$-M_{12}\ddot{u}\frac{di_1}{dt} = -L_{1h}\frac{di_1}{dt} = R_2' i_2' + L_{2h}'\frac{di_2'}{dt} + L_{2\sigma}'\frac{di_2'}{dt} = R_2' i_2' + L_{1h}\frac{di_2'}{dt} + L_{2\sigma}'\frac{di_2'}{dt}$$

- **Neglecting the stray flux and resistance of coil 2:** $L_{2\sigma} = 0,\ R_2 = 0$

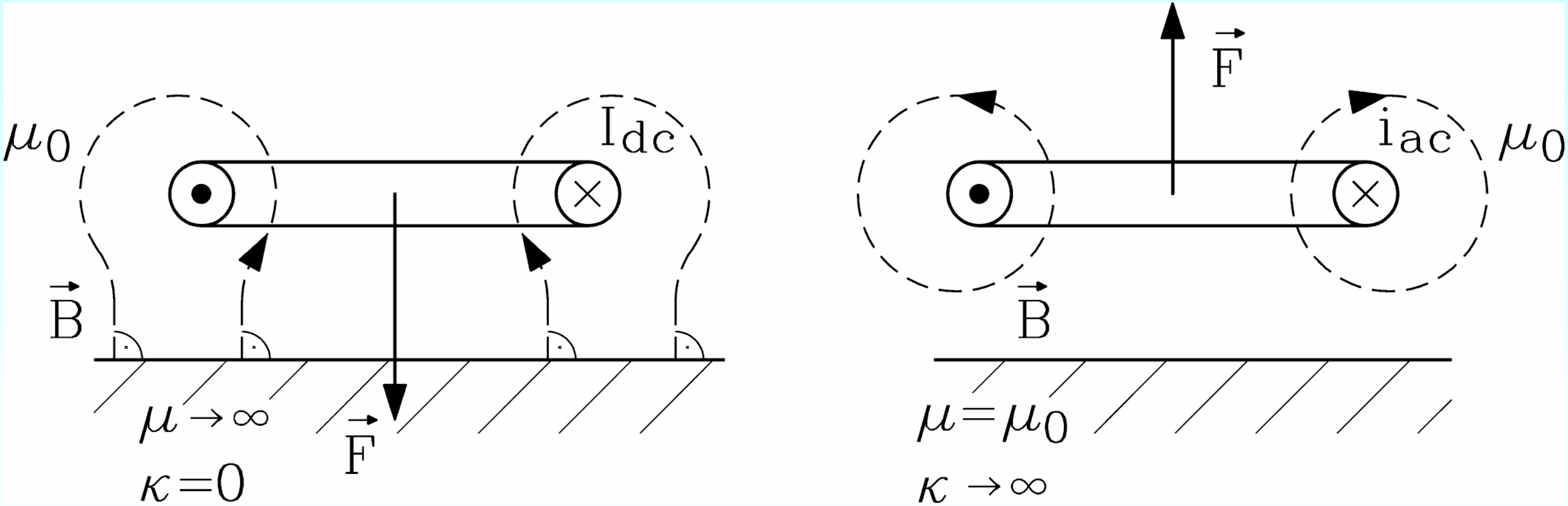
$$L_{1h}\frac{d(i_1+i_2')}{dt} = 0 \quad\Rightarrow\quad i_1 = -i_2' = -\frac{N_2}{N_1}\cdot i_2$$

⇒ ***Currents have opposite signs, causing a repulsing force F between coils 1 and 2 !***

EML and EDL compared

Electro-magnetic levitation

Electro-dynamic levitation



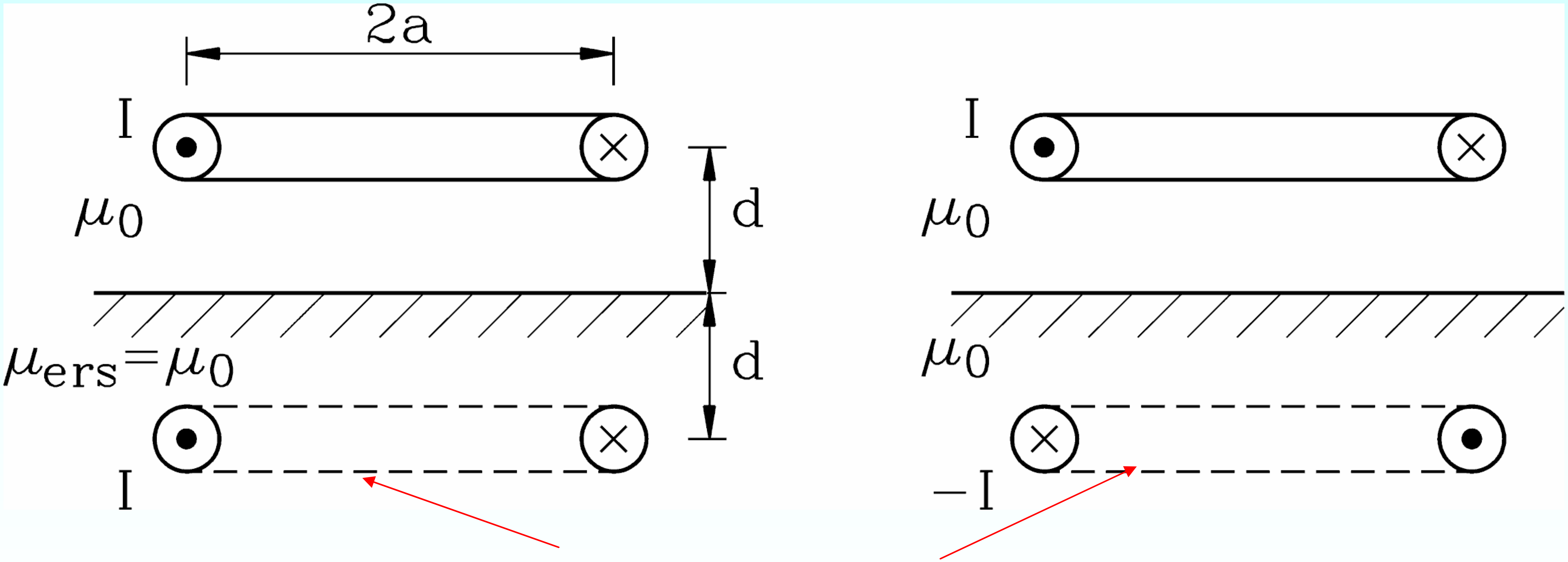
Attractive force due to ferromagnetism

Repulsing force due to eddy currents

3.3 Electro-dynamic levitation

Mirror principle for calculating forces

- **Mirrored current flow** in lower half space for calculation of EML and EDL forces



Mirrored current flow

Example for mirror calculation: *Miyazaki* track

- **Infinitely long pair of parallel line conductors, distance 2*a*, distance *d* of primary coil above the conducting surface yields a repulsing vertical force:**

$$F/l = \mu_0 \frac{I^2}{4\Delta\pi} \cdot \left(\frac{\Delta}{d} - \frac{d}{\Delta} \right) \qquad \Delta = \sqrt{a^2 + d^2}$$

- ***Example:***

Long moving superconducting DC excited coils as primary coils for the *Japanese* high speed train with EDL (7 km *Miyazaki*-test track, *Kyushu*)
Coil length *l* = 1.7 m, width 2*a* = 0.5 m, number of turns/coil *N* = 1167, coil current *i* = 600 A, levitation distance *d* = 10 cm: $\Delta = 0.269$ m, $I = N \cdot i = 700.2$ kA

$$F = 1.7 \cdot 4\pi \cdot 10^{-7} \cdot \frac{700200^2}{4 \cdot 0.269\pi} \cdot \left(\frac{0.269}{0.1} - \frac{0.1}{0.269} \right)$$

= 718.3 kN per coil side

Idealized levitation force per coil: 1436.5 kN (equals 146.4 tons)

Electro-dynamic levitation – *Miyazaki*-test track/*Japan*

Guiding and driving winding coils on both sides of the track

Short circuited coils in the track in driving direction for MAGLEV

Vehicle mass 20 t

Max. speed 420 km/h

Source: RTRI/Japan

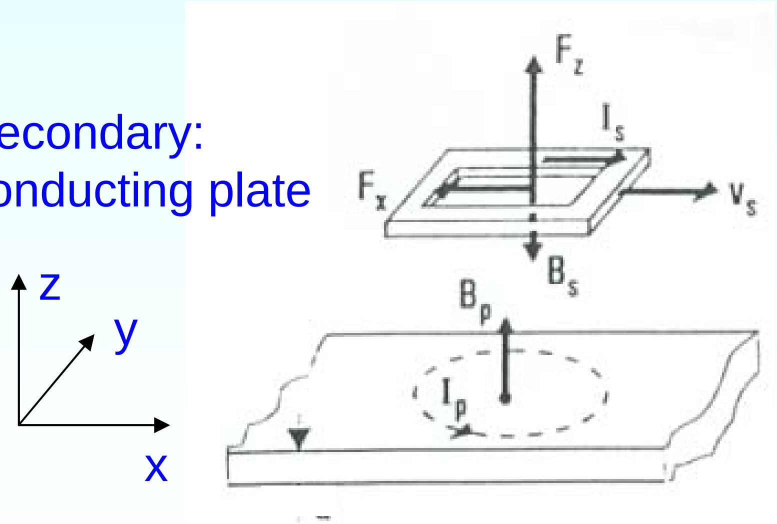
MAGLEV train high speed test vehicle with aerodynamic emergency brakes, test track distance 7 km

D.C. operated levitated coil

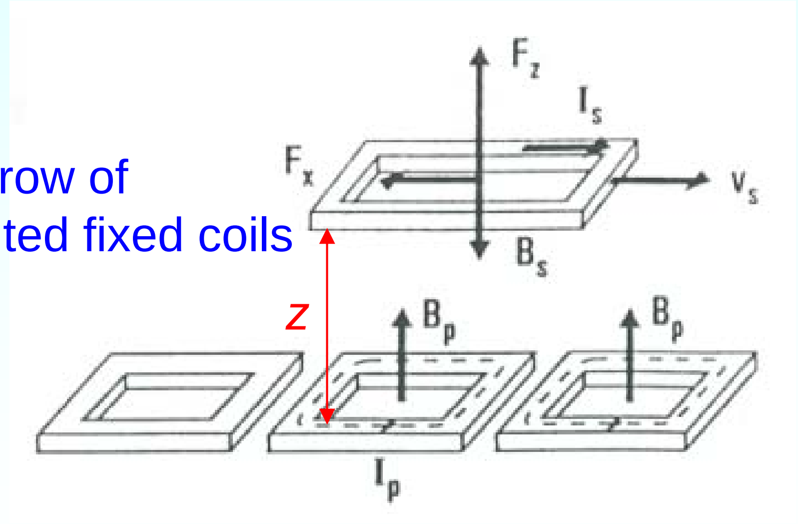
- Moving coil, excited with DC current I_s (e.g. superconducting current). Moves with velocity v_s in x-direction over a conducting plate or a row of short-circuited fixed coils

- Coil field B_s induces in the fixed short-circuited coils an eddy current I_p, which creates with B_s a levitation (repulsing) force F_z, that gives a stable levitation to the moving coil. A (disturbing) braking force F_x on the coil occurs a the same time.

Secondary: conducting plate



Secondary: row of short-circuited fixed coils

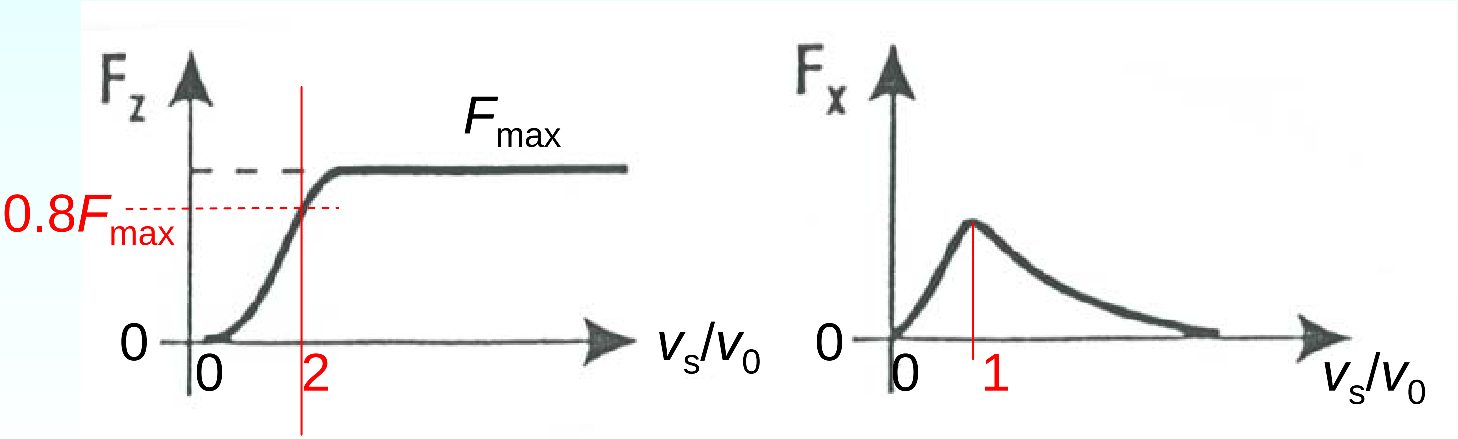


Komarek, P.: Teubner, Stuttgart, 1995

Levitation force F_z and braking force F_x

- Coils excited with DC current I_s are moving with v_s over a sequence of short-circuited fixed coils and induce an eddy current I_p per coil, which gives a levitation (repulsing) force F_z and braking force F_x.

Levitation force F_z Braking force F_x



Komarek, P.: Teubner, Stuttgart, 1995

$R_m = v_s/v_0$: magnetische *Reynolds*-Zahl

Braking force F_x and loss of energy $P(v_s)$

- Frequency of induced voltage (in coils): $f_p = v_s/(2\tau_p)$
- Moving DC coils replaced by non-moving AC coils: Current i_s with frequency f_p:

$$-j\omega_p L_{sh}\underline{I}_s = R'_p\underline{I}'_p + j\omega_p L_{sh}\underline{I}'_p + j\omega_p L'_{p\sigma}\underline{I}'_p$$

Current in short circuited coil: $\underline{I}'_p = -\dfrac{j\omega_p L_{sh}\underline{I}_s}{R'_p + j\omega_p(L_{sh} + L'_{p\sigma})}$

- I^2R losses P in the secondary coil as current heat ($L'_{p\sigma} \approx 0$): ⇒ Power balance ⇒ Braking force F_x

$$\underline{\underline{P}} = R'_p I'^2_p = \frac{R'_p\cdot(\omega_p L_{sh} I_s)^2}{R'^2_p + (\omega_p L_{sh})^2} = \frac{(\pi v_s/\tau_p\cdot L_{sh}/R'_p)^2}{1 + (\pi v_s/\tau_p\cdot L_{sh}/R'_p)^2}\cdot R'_p\cdot I_s^2 = \underline{\underline{F_x}}\cdot v_s$$

with $v_0 = (R'_p/L_{sh})\cdot(\tau_p/\pi)$ gives: $\boxed{\underline{\underline{F_x = \dfrac{v_s/v_0^2}{1 + (v_s/v_0)^2}\cdot R'_p\cdot I_s^2}}}$

Influence of coil dimensions on braking force

- **Coil inductance:** $L_{sh} \sim \mu_0 N_s^2 \cdot \tau_p \cdot l / z$ ***z*: vertical distance of coils**

  Coil resistance: $R'_p \approx (N_s / N_p)^2 \cdot \dfrac{N_p \cdot 2(\tau_p + l)}{\kappa \cdot (A_{coil} / N_p)}$

- **Magnetic *Reynolds*-number $R_m = v_s/v_0$: with** $v_0 = \dfrac{R'_p}{L_{sh}} \cdot \dfrac{\tau_p}{\pi} \sim \dfrac{2\tau_p}{\mu_0 \kappa \pi \cdot A_{coil}} \cdot \dfrac{z}{l}$

Magnetic *Reynolds*-number is free of units & describes relative coil velocity.

- **Braking force:** $F_x = \dfrac{R'_p I_s^2}{v_0} \cdot \dfrac{R_m}{1 + R_m^2} \sim \underline{\underline{B_s^2 \cdot \dfrac{R_m}{1 + R_m^2}}}$

The braking force F_x is zero near very low and very high R_m and has its maximum at $R_m = 1$.

Calculation of levitation force F_z

- **Field of DC coil:** $B_s \sim \mu_0 I_s / z$, mathematical model as AC field for alternating current: $\underline{B}_s \sim \mu_0 \underline{I}_s / z$

  Short circuited current $\underline{I}_p'$: Component $I'_{p,real}$ in phase with $\underline{B}_s$: It creates a repulsing force F_z: $F_z \approx 2N_s I'_{p,real} B_s \cdot (\tau_p + l)$

  With $L_{p\sigma} \cong 0$ we get: $$I'_{p,real} = -\mathrm{Re}\left(\frac{j\omega_p L_{sh} I_s}{R'_p + j\omega_p (L_{sh} + L'_{p\sigma})}\right) = -\frac{\omega_p^2 L_{sh}^2 I_s}{R_p'^2 + \omega_p^2 L_{sh}^2} = -\frac{(v_s / v_0)^2 \cdot I_s}{1 + (v_s / v_0)^2}$$

- **Repulsing (levitating) force:**

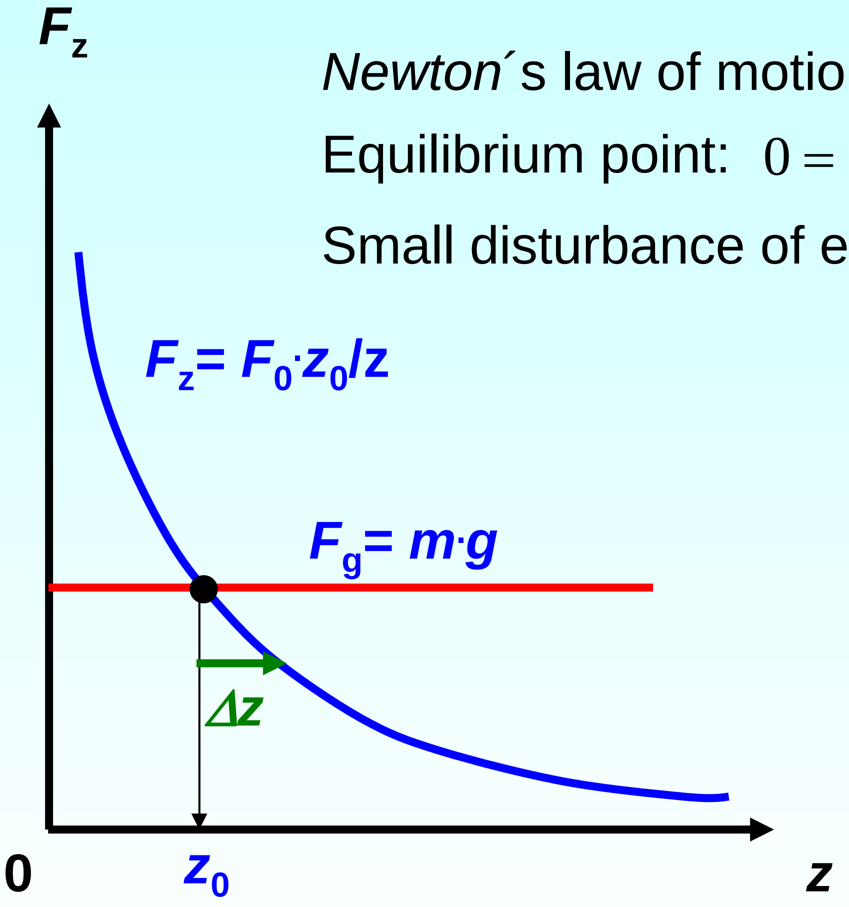
$$F_z \sim I'_{p,real} \cdot B_s \sim \mu_0 I'_{p,real} \cdot (I_s / z) \sim -\frac{I_s^2}{z} \cdot \frac{(v_s / v_0)^2}{1 + (v_s / v_0)^2} = \underline{\underline{-\frac{I_s^2}{z} \cdot \frac{R_m{}^2}{1 + R_m{}^2}}}$$

- High R_m : Maximum levitation force ⇒ at $R_m = 2$ already 80% of max. force
- v_0 must be low: Low resistance R_p of secondary coils: $N_p = 1$, high conductivity κ, big coil conductor cross section $A_{Cu} = A_{coil}$.
- High mutual inductance L_{sh} ⇒ Low levitation distance z necessary

Condition for electro-dynamic levitation

- Levitation force depends on square of I_s resp. flux density B_s: high coil-flux density B_s e.g.: 5 – 6 T necessary for big z
- Big B_s demands big excitation current I_s: Therefore low-loss excitation essential: Solution: Superconducting DC coil excitation
- "Magnetic spring curve" $F_z(z) \sim 1/z$. At low levitation distance strong rising of repulsing force: typical levitation distance $z = 10$ cm
- Minimum speed of moving DC coils necessary for levitation
- Magnetic rail way with electro-dynamic levitation needs wheels for acceleration and braking. „Take-off" at minimum speed (*Yamanashi*: Take-off at about 100 km/h)

Self-stable electro-dynamic levitation



Newton´s law of motion for vertical axis: $m \cdot \ddot{z} = F_z - F_g = F_0 \cdot \frac{z_0}{z} - m \cdot g$

Equilibrium point: $0 = F_z - F_g \Rightarrow z = z_0 : F_0 = m \cdot g$

Small disturbance of equilibrium: $z = z_0 + \Delta z \quad \Delta z / z_0 << 1$

$$m \cdot \Delta\ddot{z} - \frac{F_0 z_0}{z_0 + \Delta z} = -m \cdot g$$

$$m \cdot \Delta\ddot{z} - F_0 \cdot (1 - \Delta z / z_0) \approx -m \cdot g$$

$$m \cdot \Delta\ddot{z} + (F_0 / z_0) \cdot \Delta z = 0$$

Solution of homogeneous 2nd order linear differential equation: $\Delta z(t) = \hat{Z} \cdot \cos \omega t$

$$\omega = \sqrt{F_0 / (m \cdot z_0)}$$

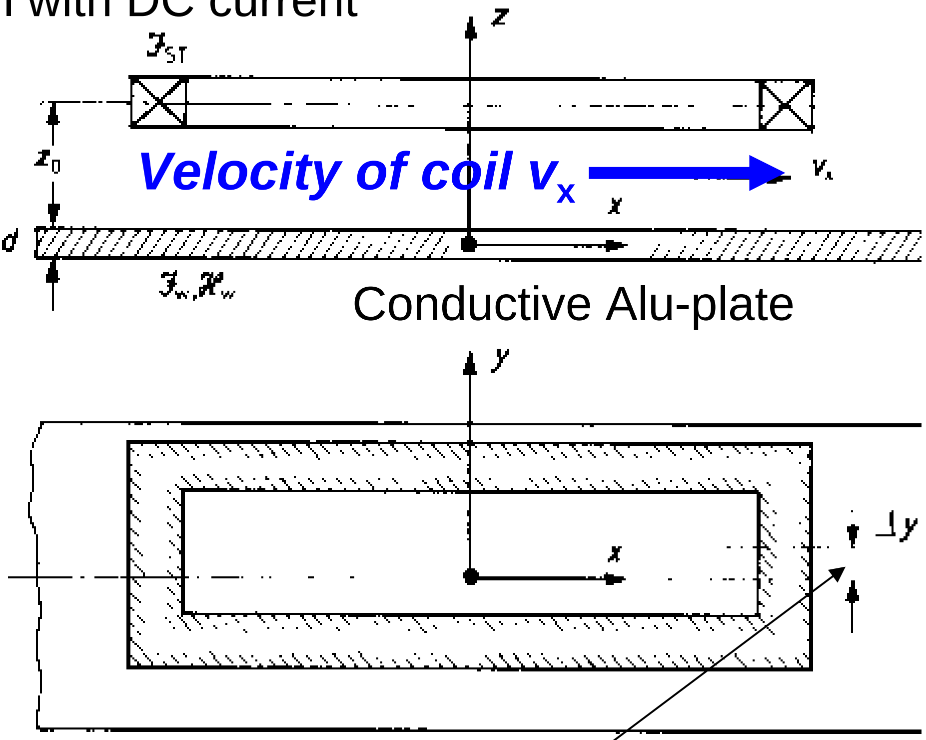
Un-damped, but stable oscillation of the levitated body after disturbance $\Delta z(0) = \hat{Z}$

3.3 Electro-dynamic levitation

Numerical field calculation for electro-dynamic levitation

Model geometry

Coil with DC current

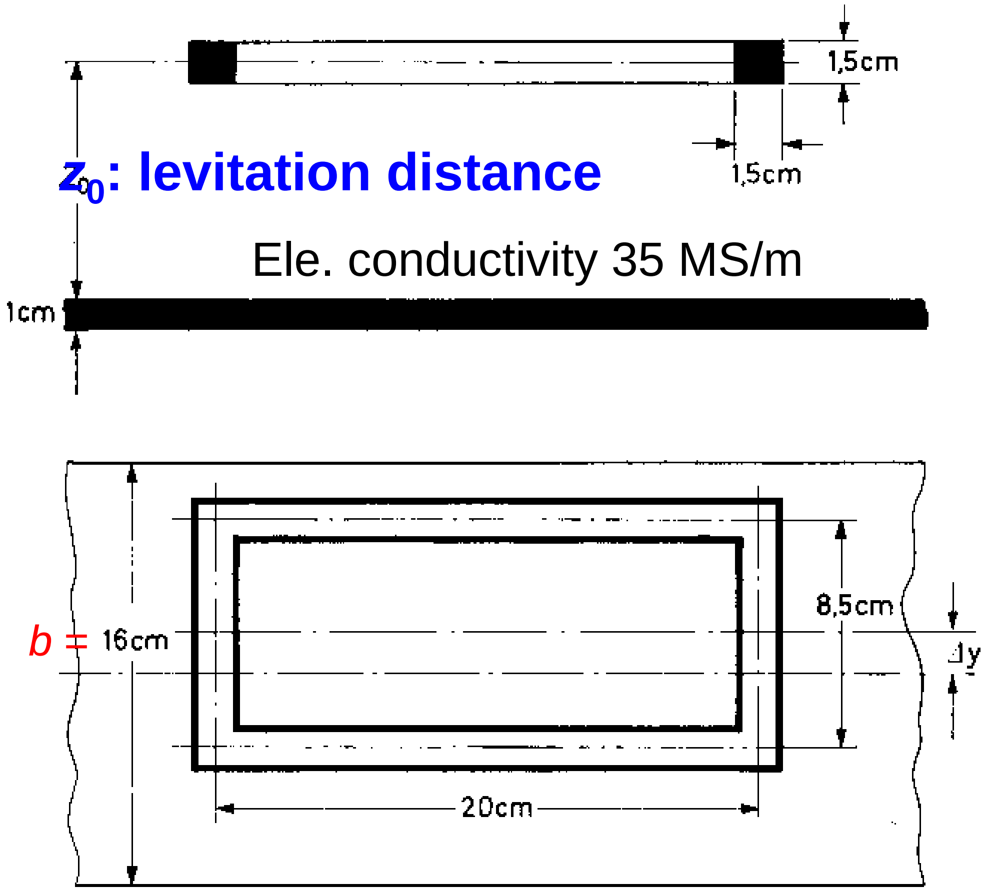


Velocity of coil v_x

Conductive Alu-plate

Lateral dislocation of the coil Δy

Model dimensions



z_0: levitation distance

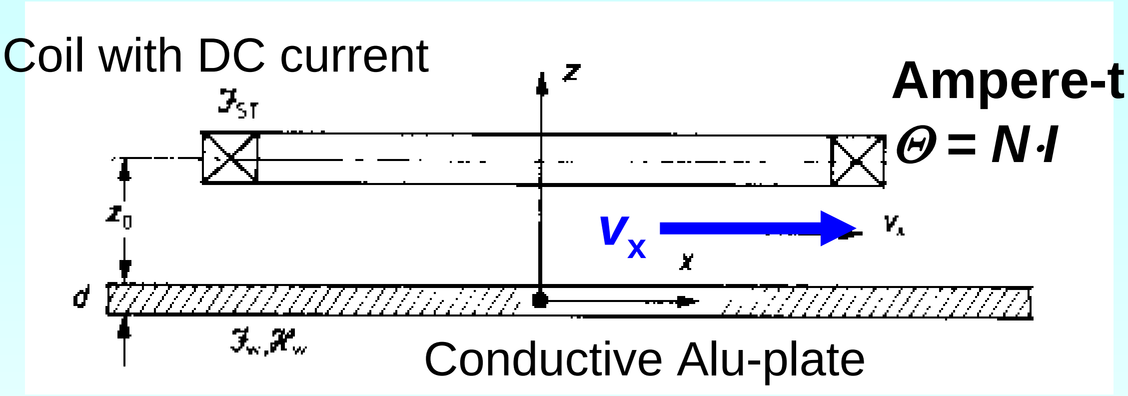
Ele. conductivity 35 MS/m

$b =$ 16cm

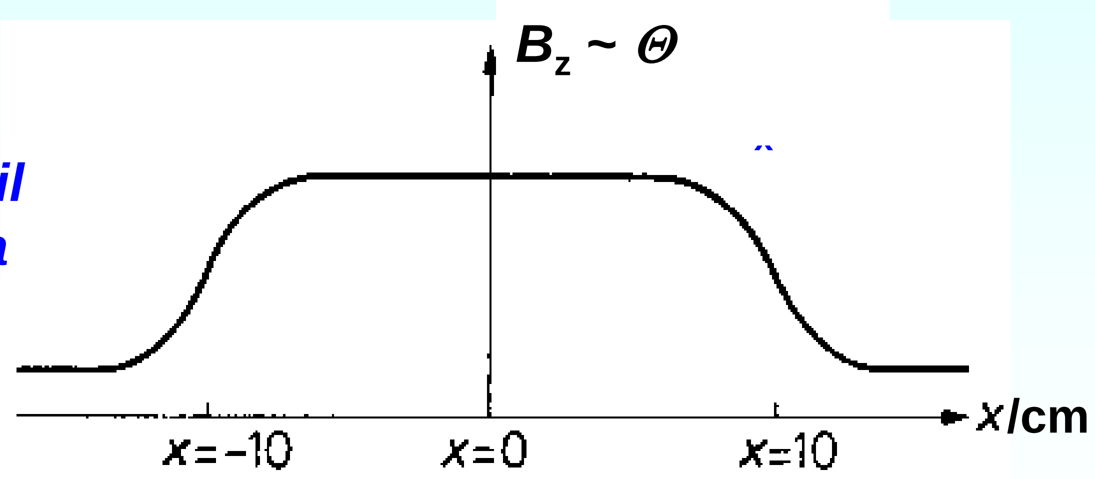
Source: AEG, Germany

3.3 Electro-dynamic levitation

Sketch of the distribution of the normal component of the magnetic field of the DC coil at the plate surface



Ampere-turns:
$\Theta = N \cdot I$

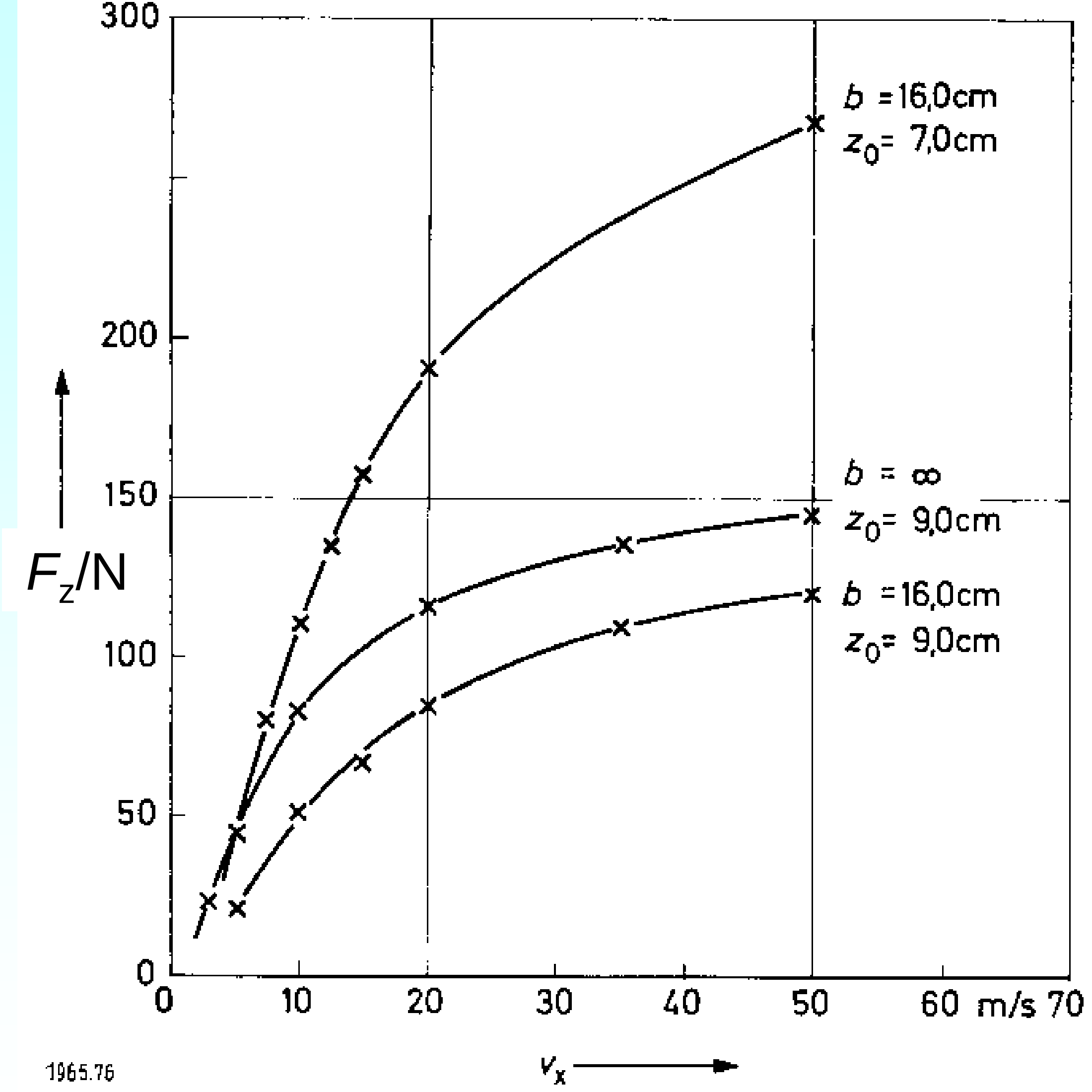


Result:
The DC excited coil field has at $v_x = 0$ a symmetrical distribution!

So no longitudinal braking force exists!

Source: AEG, Germany

Repulsive normal force F_z in dependence of the coil velocity v_x



Levitation distance z_0 = 70 mm:

b) Alu plate breadth b = 160 mm

Maximum force at $v_x \rightarrow \infty$: ca. 330 N

Levitation distance z_0 = 90 mm:

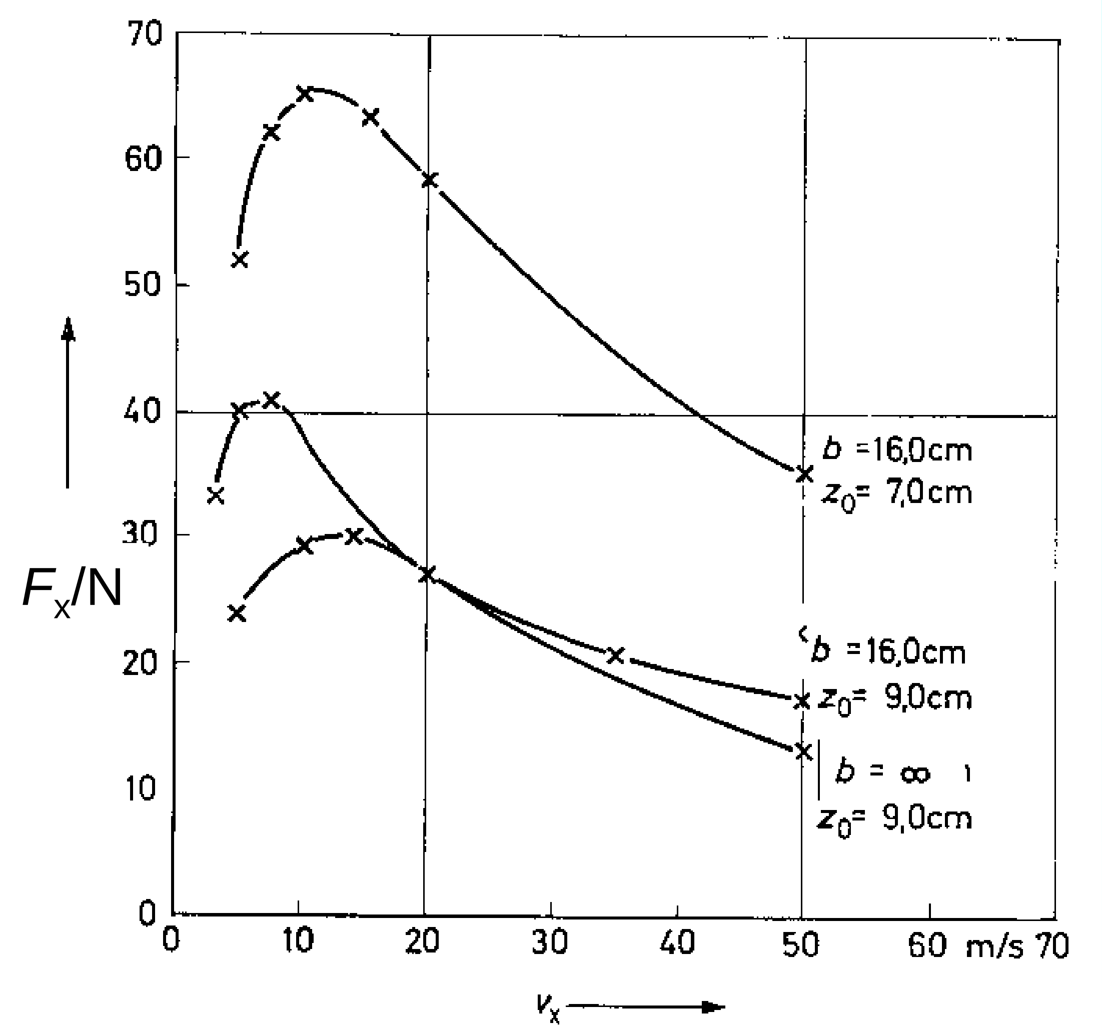
a) Infinitely broad Alu plate

b) Alu plate breadth b = 160 mm

Maximum force at $v_x \rightarrow \infty$:
a) 160 N, b) ca. 130 N

Source: AEG, Germany

Braking longitudinal force F_x in dependence of the coil velocity v_x



Result:

Maximum braking force at small velocities: ca. 8 … 12 m/s

Levitation distance z_0 = 70 mm:

b) Alu plate breadth b = 160 mm

Levitation distance z_0 = 90 mm:

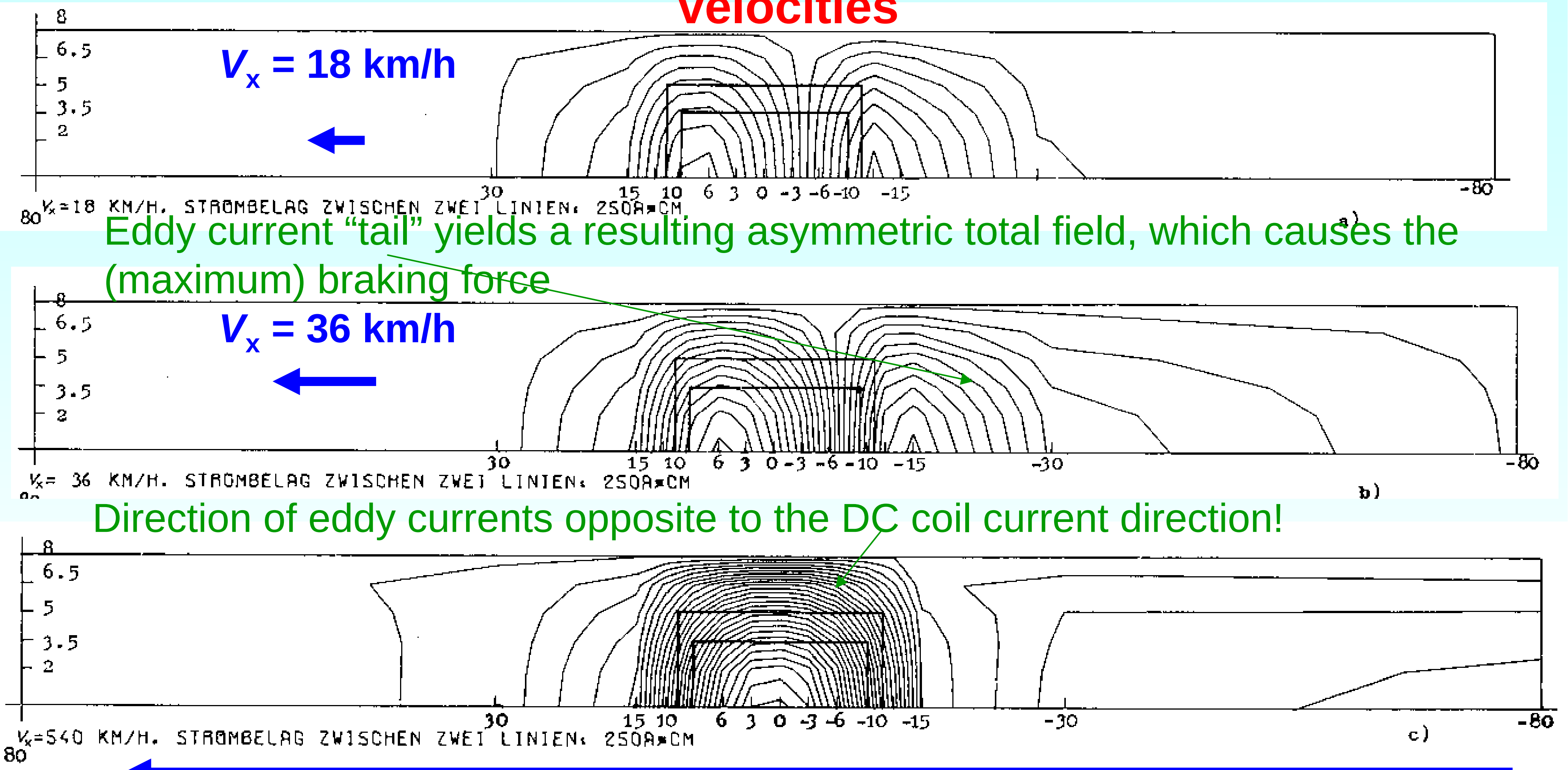
b) Alu plate breath b = 160 mm

a) Infinitely broad Alu plate

Source: AEG, Germany

3.3 Electro-dynamic levitation

Calculate eddy current density in the Aluminum plate at rising coil velocities



V_x = 18 km/h

Eddy current “tail” yields a resulting asymmetric total field, which causes the (maximum) braking force

V_x = 36 km/h

Direction of eddy currents opposite to the DC coil current direction!

V_x = 540 km/h

Source: AEG, Germany

New technologies of electric energy converters and actuators

Summary:
Electro-dynamic levitation

- Repulsive force due to induced eddy currents used as levitation force
- No ferro-magnetics allowed due to their counteracting attracting force
- AC or moving DC coils used as exciter
- Self-stable levitation
- Superconducting moving DC coils as exciter
- With SC rather large levitation gaps possible

New technologies of electric energy converters and actuators

3. Magnetic bearings („magnetic levitation“)

3.1 Basics of magnetic levitation

3.2 Electro-magnetic levitation

3.3 Electro-dynamic levitation

3.4 High speed trains with magnetic levitation

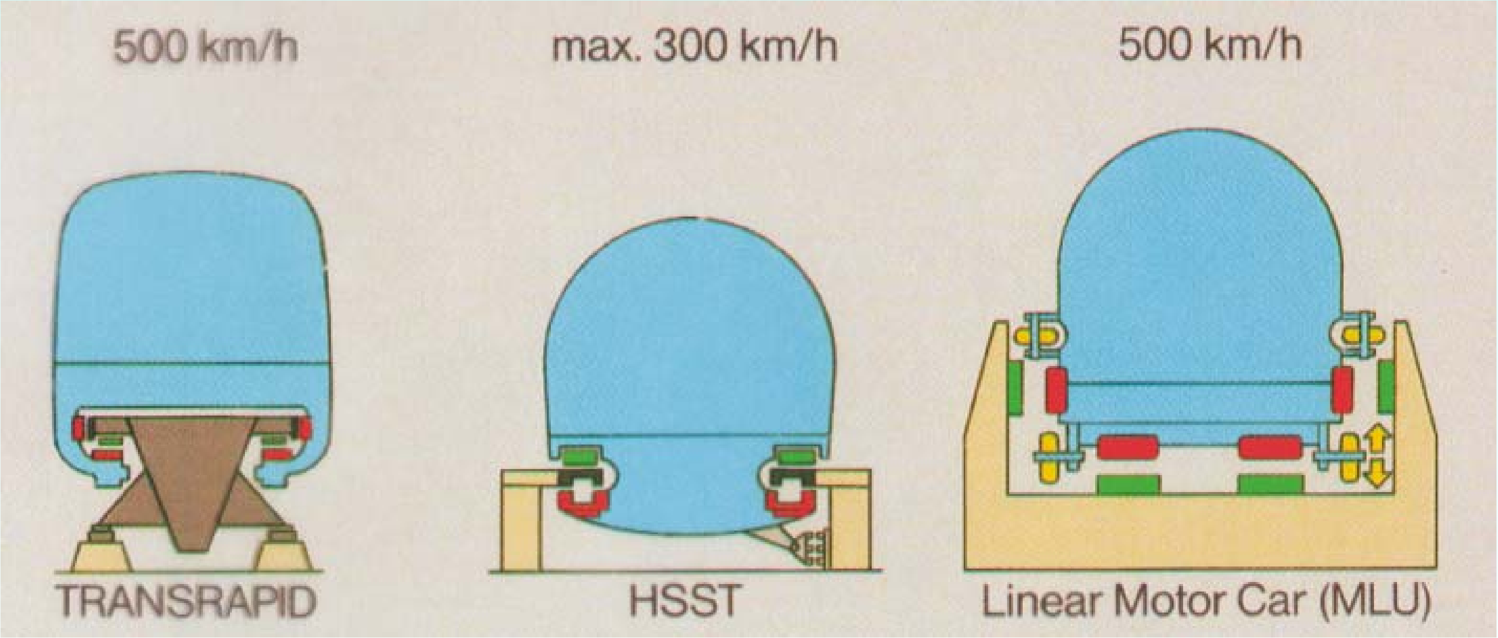
3.5 Superconducting magnetic bearings

3.4 High speed trains with magnetic levitation (MAGLEV)

Source: Siemens AG, Germany

Magnetic levitation railways (MAGLEV) - overview

Long linear motor in the track Attractive force	Short linear motor in the vehicle Attractive force	Long linear motor in the track Repulsive self-stable force



Source: Thyssen Krupp, Germany

TRANSRAPID/Germany **HSST/*Japan*** ***Yamanashi/Japan***

Long stator motor **Short stator motor** **Long stator motor**

$\underbrace{\hspace{6em}}$

Electromagnetic levitation **Electro-dynamic levitation**

3.4 High speed trains with magnetic levitation

3.4.1 Active magnetically levitated high-speed train TRANSRAPID

3.4.2 Japanese electro-dynamically levitated high-speed train YAMANASHI

TRANSRAPID – Magnetic railway

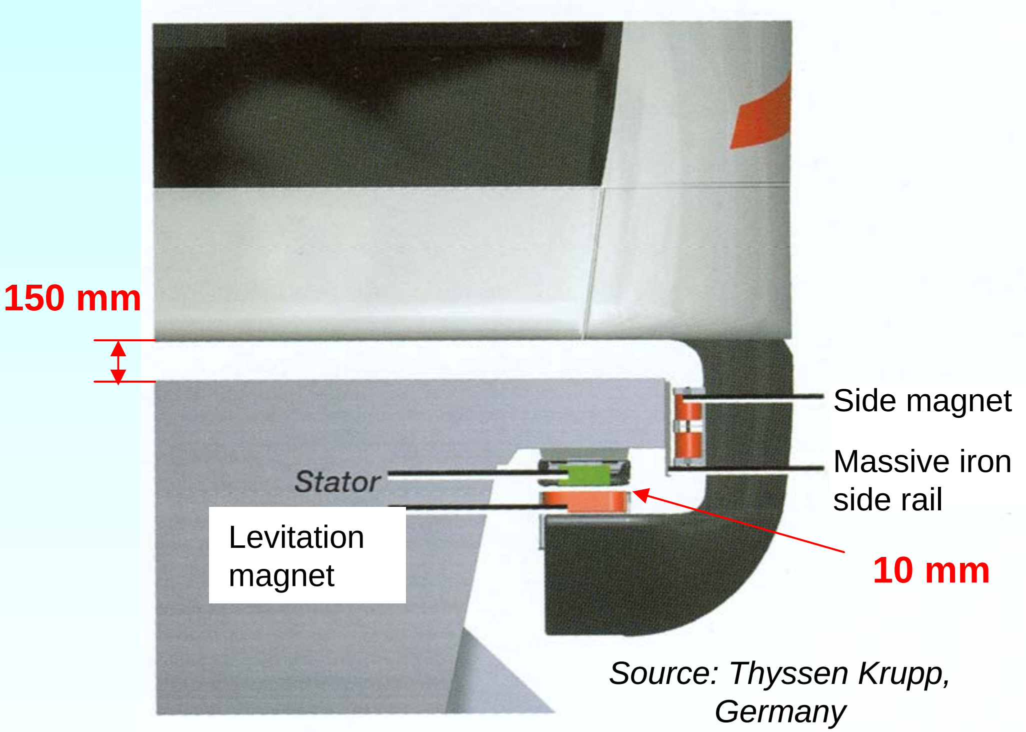
Source: Thyssen Krupp, Germany

TRANSRAPID – System TR07

- Electromagnetic levitation: DC magnets under T-formed vehicle with levitation gap of about 10 mm. Vehicle distance to track 15 cm.
- Levitation DC-excited magnets are electrical secondary excitation of a synchronous linear long-stator motor: $N_{f,Pol}$ = 230 turns per coil/magnet.
- Guiding side-magnetic forces to keep the vehicle on centre of the track
- Long stator: Travelling wave long-stator 3-phase, AC winding $q = 1$, $m = 3$, $N_c = 1$ (cable winding) with stator iron core with open slots, winding section feeding by inverters, position detection of train via radio
- Linear synchronous generator in „medium frequency"-layout: Generator 2-phase AC winding ($q = 1$, $m = 2$, single layer) in slots in the secondary magnet pole-shoes: the open stator slots "modulate" the secondary DC field, yielding a slot-frequent AC component, which induces the generator winding with a voltage with „slot frequency“. Above 85 km/h this rectified voltage is big enough for loading of the 440 V-board battery.

Magnetic levitation of high speed train TRANSRAPID

Source: Siemens AG, Germany

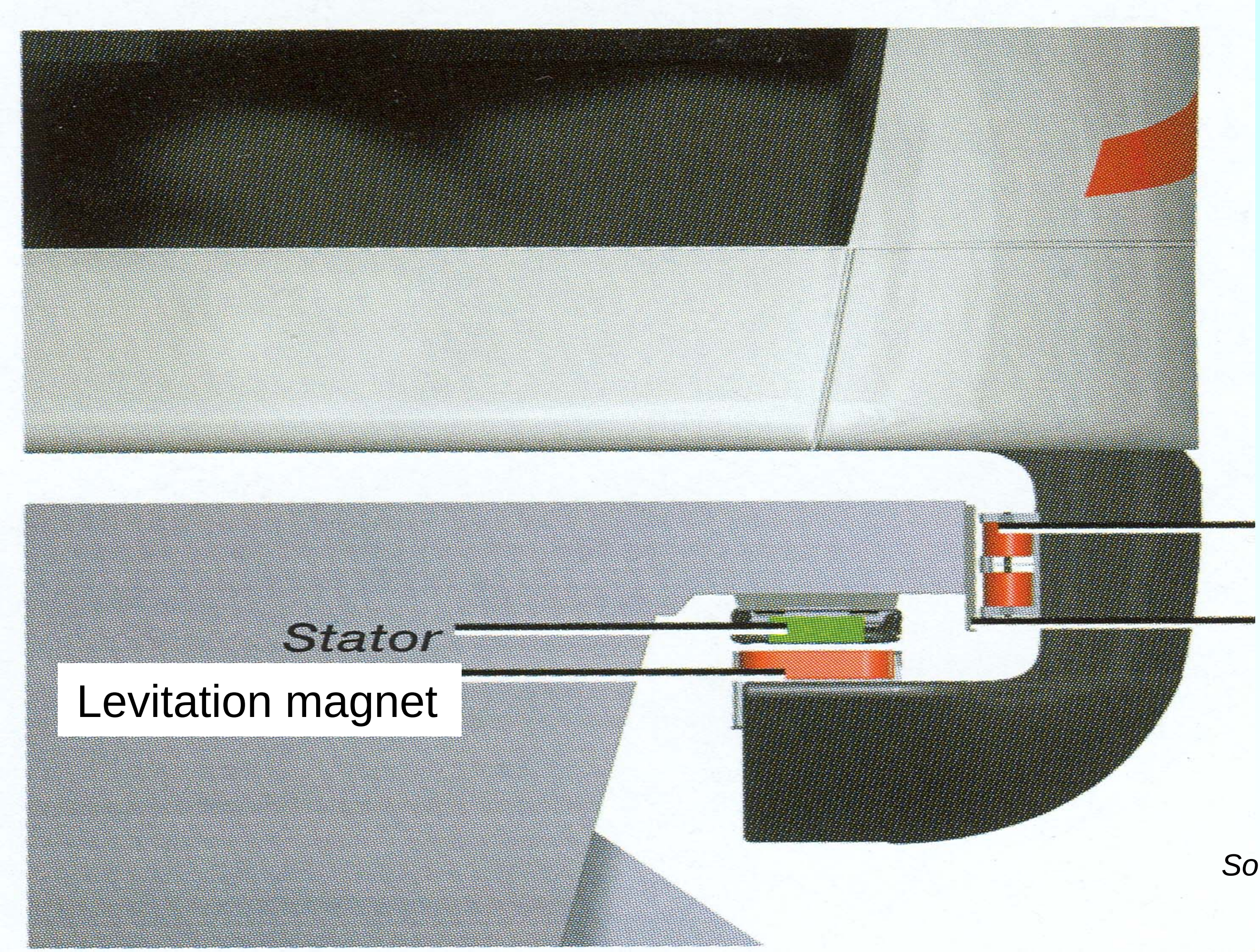


Source: Thyssen Krupp, Germany

- **Active controlled magnetic levitation and guidance system**
- **Electrical linear synchronous motor for thrust**

3.4 High speed trains with magnetic levitation

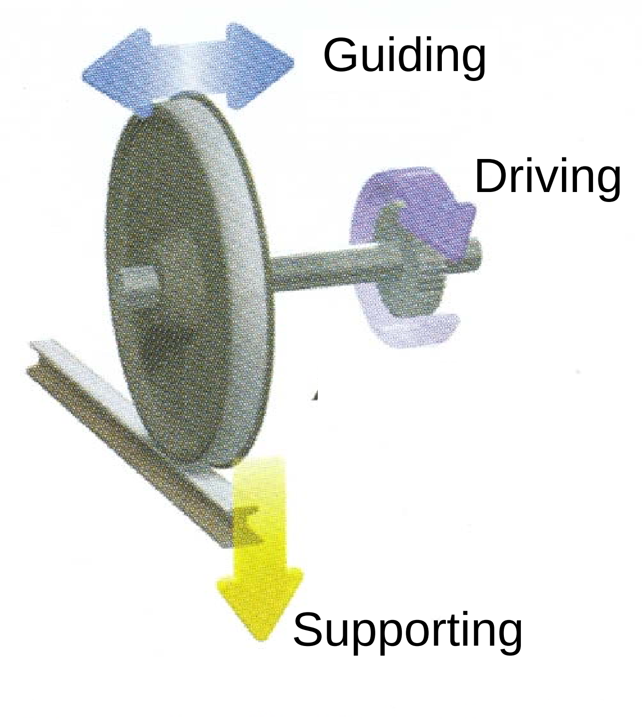
TRANSRAPID – Levitation, guidance and propulsion system



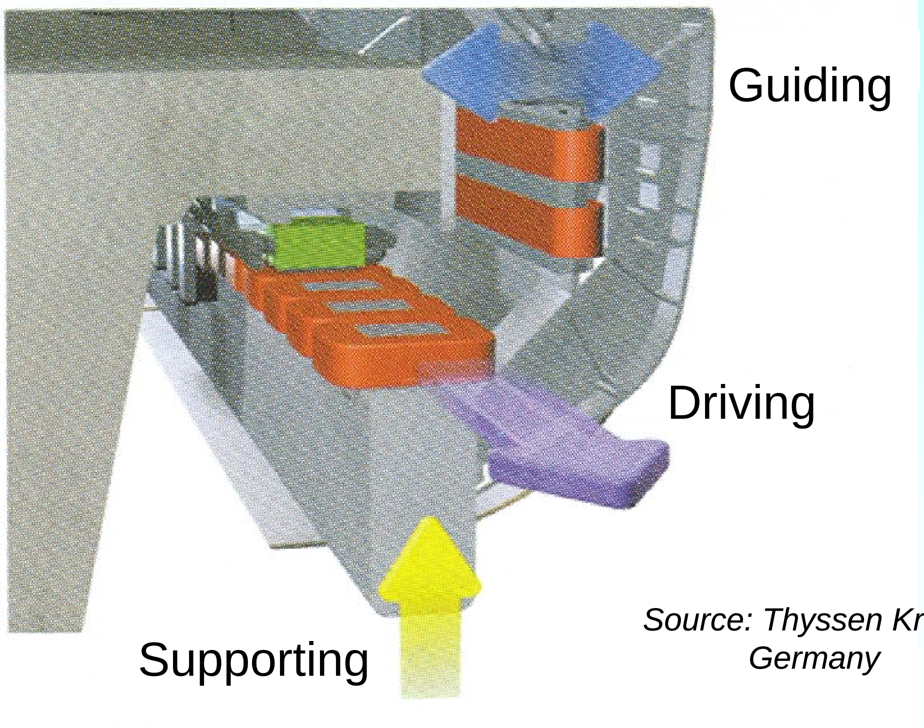
Source: Thyssen Krupp, Germany

Wheel-rail-system (ICE 3) versus Linear drive (TRANSRAPID)

Wheel-track system



Magnetic levitation

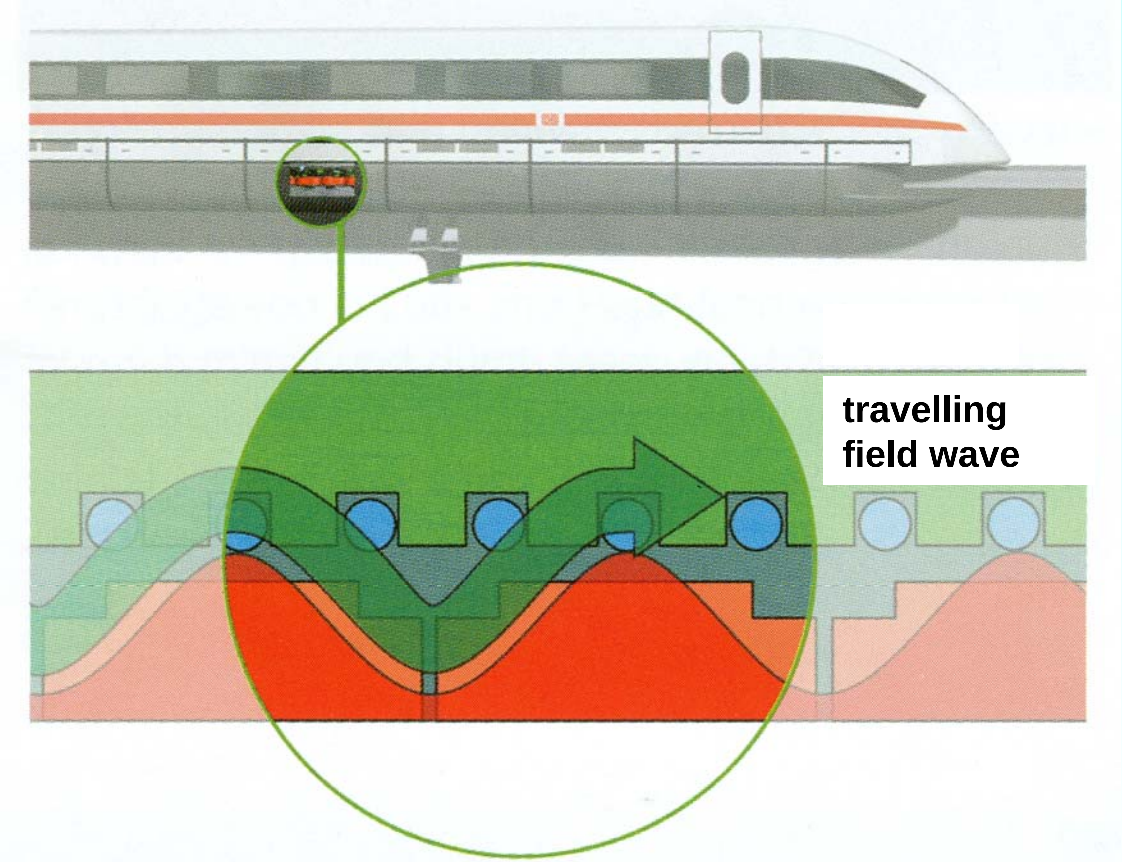


Source: Thyssen Krupp, Germany

ICE 3 – Wheel-rail contact force

TRANSRAPID – Combined magnetic levitation, guidance, propulsion

Magnetic travelling field „pulls“ the vehicle „synchronously“



Instead of a rotary field in rotary motor, we have a travelling field of a „linear“ long-stator winding

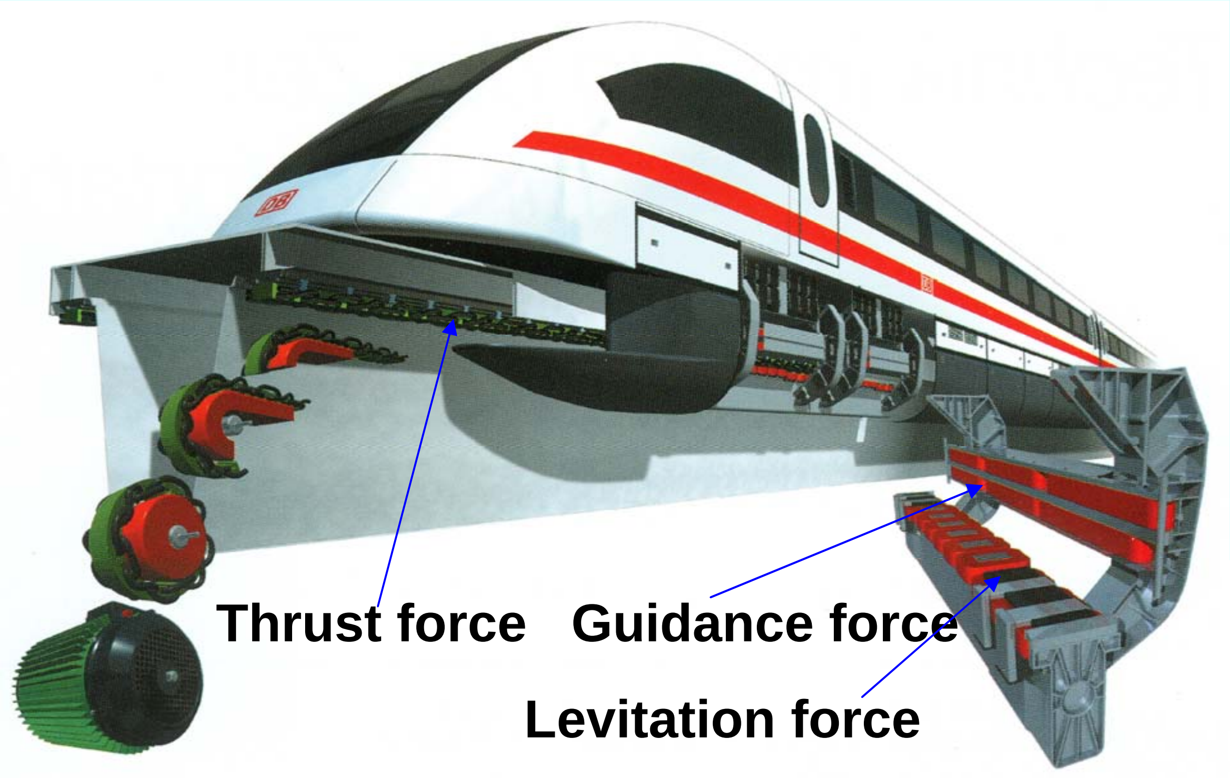
DC magnets of the magnetic bearing are the poles, that are pulled by the travelling stator field “synchronously“ = SYNCHRONOUS LINEAR MOTOR.

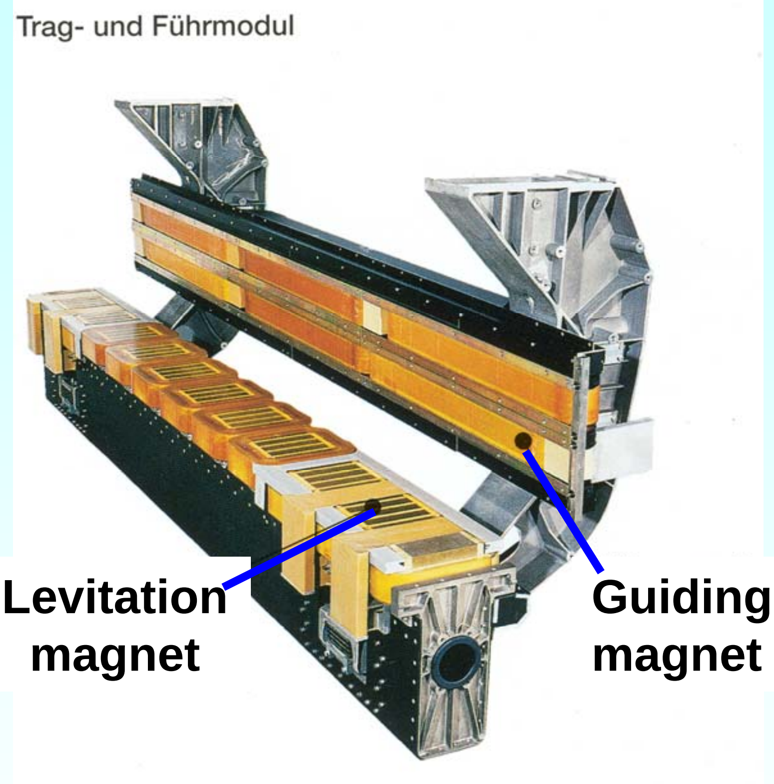
Source: Thyssen Krupp, Germany

Velocity of stator travelling field wave = Speed of vehicle

$v = 2 f \tau_p = 2 \cdot 215 \cdot 0.258 = 111$ m/s = 400 km/h (*Shanghai / Pudong*)

Levitation and guidance of TRANSRAPID



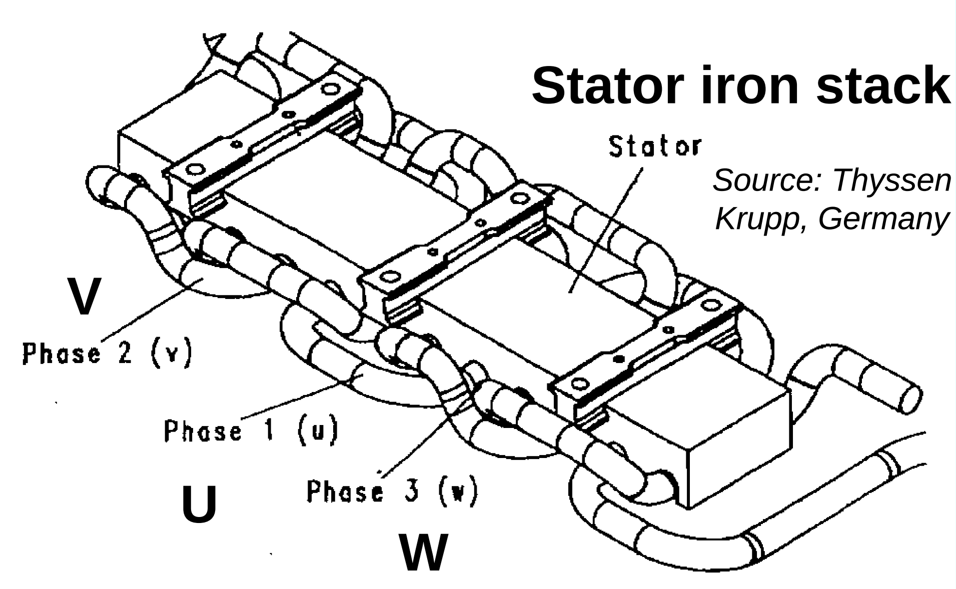


Levitation magnets pull from below at a gap distance 10 ...13 mm the vehicle to the stator iron of the linear motor, which lies fixed in the track. So the vehicle gets ABOVE the track a clearance of 150 mm.

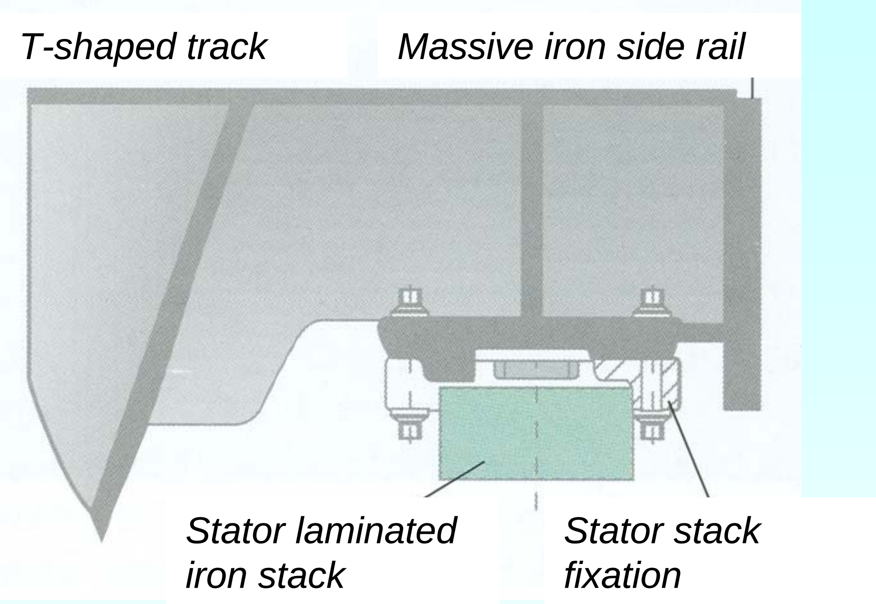
Source: Thyssen Krupp, Germany

3.4 High speed trains with magnetic levitation

Three phase long stator winding in stator iron stack



Source: Thyssen Krupp, Germany



- Three-phase windings U, V, W: Wave-wound winding, made from aluminum MV cable
- Pole pitch: 258 mm, units of 4 poles = 1032 mm, 24 units = 1 section = 24.768 m, iron width 185 mm, two motors left and right of the track
- Several coupled sections create a “supply section”: In *Shanghai*: 0.9 ... 5.0 km
- About 180 poles fit under one total vehicle length (= 46 m length)

TRANSRAPID-07-long stator winding

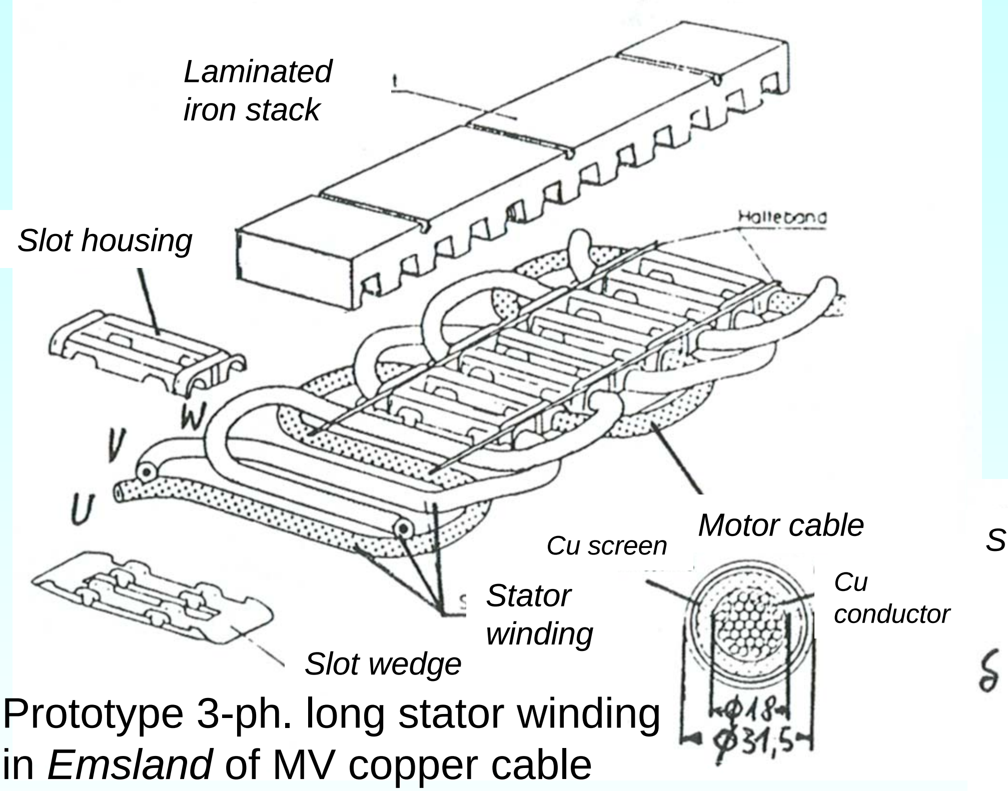
Synchronous long stator winding:

Laminated stator iron stack, open slots and three-phase AC travelling field wave winding, made of MV aluminum cables as wave winding = 1 coil per pole and phase

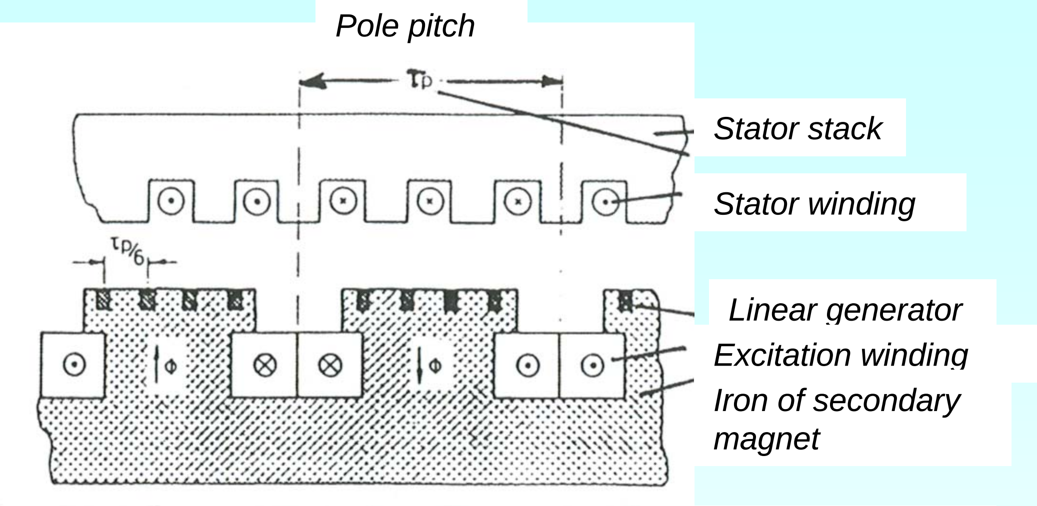
TRANSRAPID test track in *Emsland, Germany*

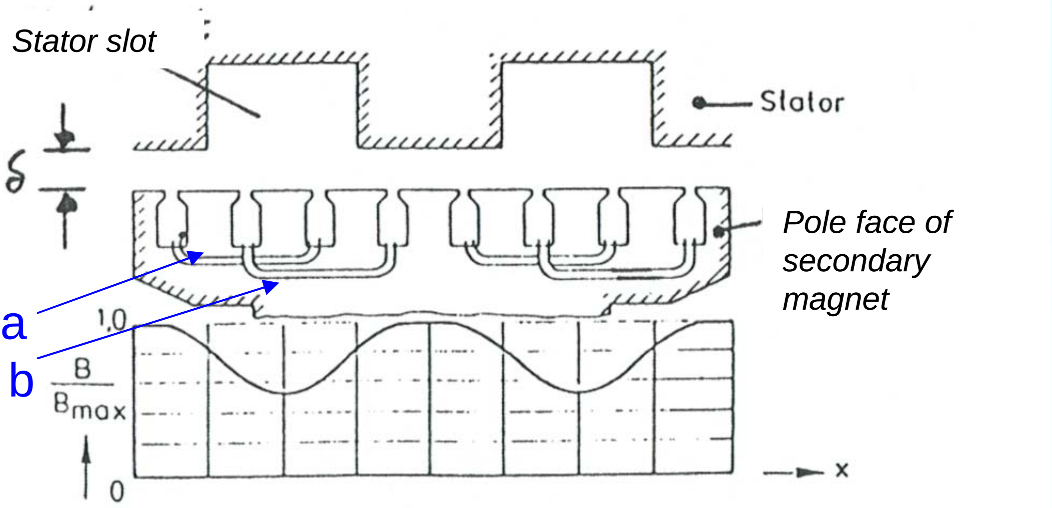
Source: Thyssen Krupp, Germany

Linear 3-ph. syn. motor and linear 2-ph. syn. generator



Prototype 3-ph. long stator winding in *Emsland* of MV copper cable





Linear generator: Phase a

Phase b

Coil width = half stator slot pitch $\tau_{Qs}/6 = \tau_p/6$

Source: PhD Thesis Dr. Fürst,
TU Berlin

Design of the TRANSRAPID linear drive

- **Pole pitch τ_p small to have small flux per pole:** Small iron yoke height = small iron masses, short winding overhangs = small conductor masses = saving of material. BUT: Small pole-pitch: High max. fundamental frequency f_s for high train speed: τ_p = 258 mm: $v_{syn,\max} = 2 f_{s,\max} \tau_p = \underline{\underline{500}}\ \mathrm{km/h} \Rightarrow \quad f_{s,\max} = \underline{\underline{269}}\ \mathrm{Hz}$
- Air-gap flux density ca. 0.64 T demands exciting Ampere-turns $N_{f,pole} \cdot I_f$.

- Vehicle length 46 m: 46/0.258 = about 180 pole pitches (= 90 pole pairs) covered by the vehicle.

  Number of turns per stator winding phase: $N = p \cdot q \cdot N_c / a = 90 \cdot 1 \cdot 1/1 = 90$

- **Nominal current I_s = 1200 A**, electric loading: $A_s = \frac{2mNI_s}{2p\tau_p} = \frac{2 \cdot 3 \cdot 90 \cdot 1200}{2 \cdot 90 \cdot 25.8} = \underline{\underline{139.5}}\ \mathrm{A/cm}$

  Cable diameter 18mm: current density: $J_s = \frac{I_s}{q_{Cu}} = \frac{1200}{18^2 \cdot \pi / 4} = \underline{\underline{4.7}}\ \mathrm{A/mm^2}$

- **Thermal loading:** $A_s \cdot J_s = \underline{\underline{660\,\mathrm{A/cm} \cdot \mathrm{A/mm^2}}}$

  Short time operation with natural air cooling by convection

Propulsion and levitation system of TRANSRAPID

- **Electromagnetic thrust/surface:** $\tau = k_w \frac{A_s B}{\sqrt{2}} = \frac{13950 \cdot 0.64}{\sqrt{2}} = 6313\ \mathrm{N/m^2} \quad k_w = 1$

  Thrust force *F* **per vehicle at 2x150 secondary magnets: l_{Fe} = 185 mm**

  $$F = \tau \cdot 2p\tau_p l_{Fe} \cdot 2 = 6313 \cdot 150 \cdot 0.258 \cdot 0.185 \cdot 2 = 90.4\ \mathrm{kN}$$

  U_s = 4675V: Constant thrust up to v_{max} = 370 km/h: $P_{\max} = F \cdot v_{\max} = \underline{\underline{9.3}}\ \mathrm{MW}$

- **Levitation system: Vehicle mass: *m* = 100 t ⇒ Weight force: *m·g* = 981 kN**

  Levitation force per magnet: $F_{Lev} = \frac{B^2}{2\mu_0} \cdot A = \frac{0.64^2}{2 \cdot 4\pi \cdot 10^{-7}} \cdot 20400 \cdot 10^{-6} = 3.3\ \mathrm{kN}$

  (Pole surface *A* = 20 400 mm²)

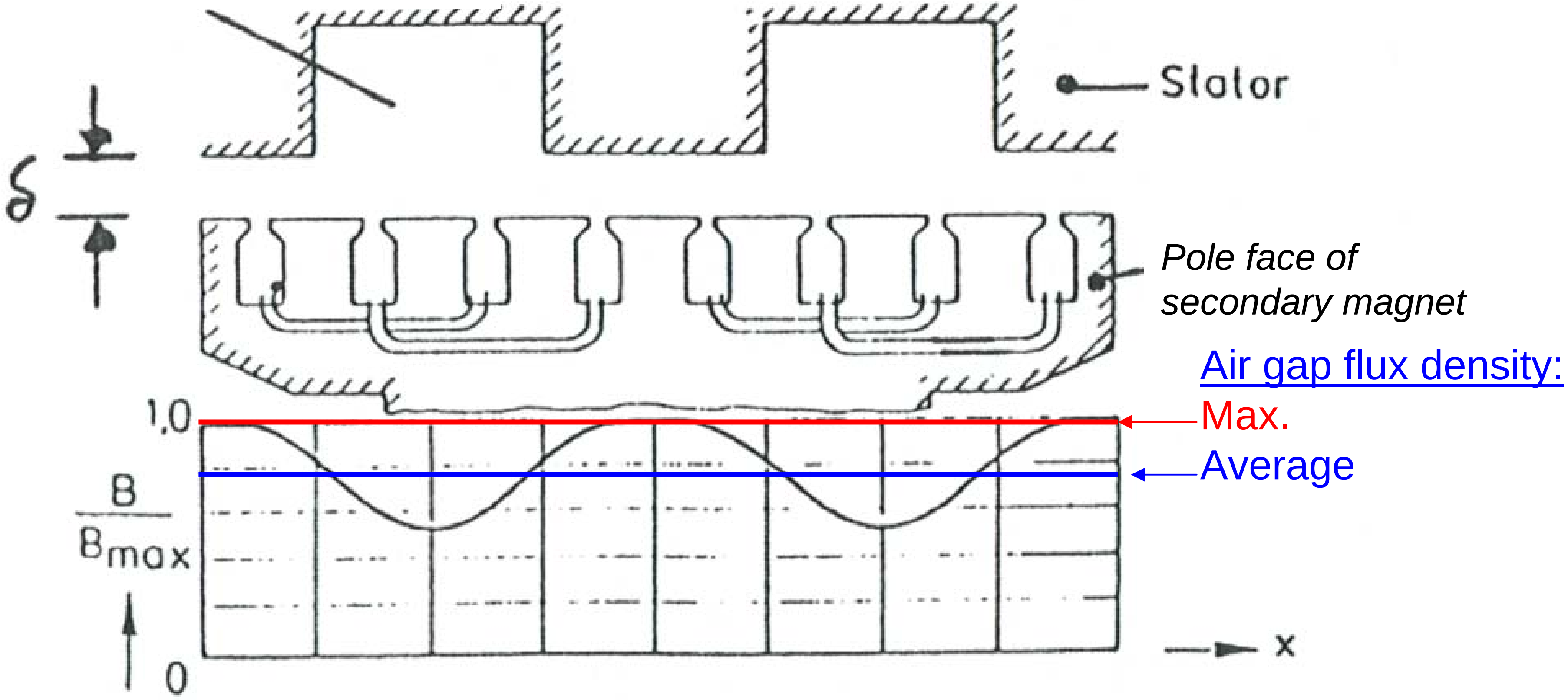
  Levitation force per vehicle: $F_{Lev,tot} = 150 \cdot 2 \cdot 3.3 = \underline{\underline{990}}\ \mathrm{kN}$ **sufficient!**

  Exciting Ampere-turns: $V_f = N_{f,Pol} I_f = \frac{B}{\mu_0} \delta \cdot k_C = \frac{0.64}{4\pi \cdot 10^{-7}} \cdot 0.01 \cdot 1.4 = \underline{\underline{7133}}\ \mathrm{A}$

  Field current I_f per magnet: $I_f = \frac{V_f}{N_{f,Pol}} = \frac{7133}{230} = \underline{\underline{31}}\ \mathrm{A}$

Influence of open stator slots on the air gap field

Stator open slot



Source: PhD Thesis Dr. Fürst, TU Berlin

Ratio of maximum/average air gap flux density: $k_C = 1.4$
CARTER-coefficient

Secondary pole shifting to reduce force oscillations

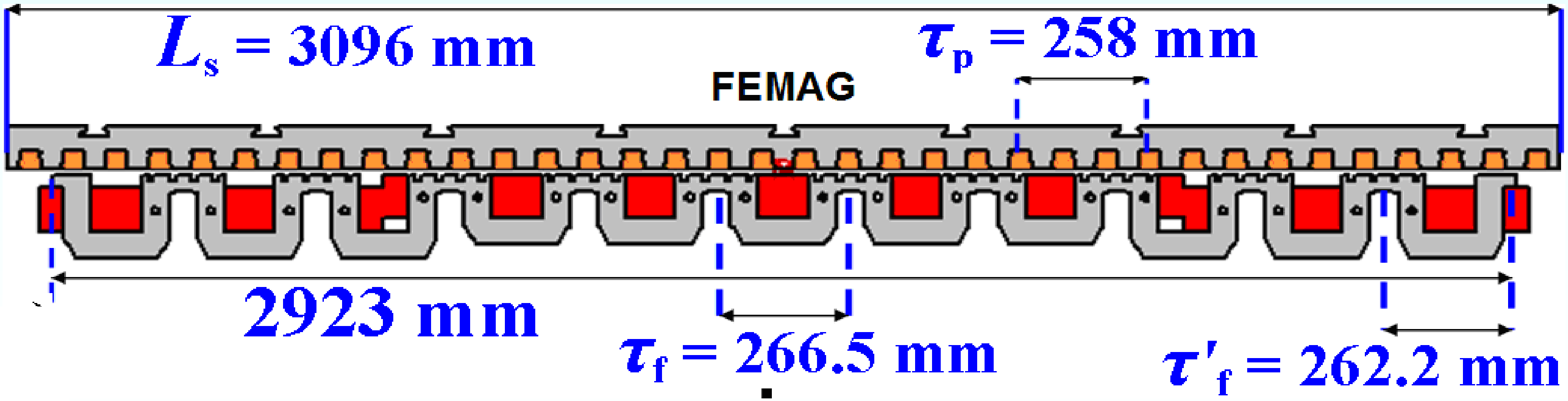
- Stator integer slot winding & secondary poles un-skewed, so slot openings cause field and hence force ripple, when the car is moving.
- A skewing by one slot pitch τ_s is recommended to reduce this ripple.

- By having a secondary pole pitch τ_f different to the stator pole pitch τ_p, a pole shifting by one slot pitch per 12 poles occurs, which can also equalize the force ripple.

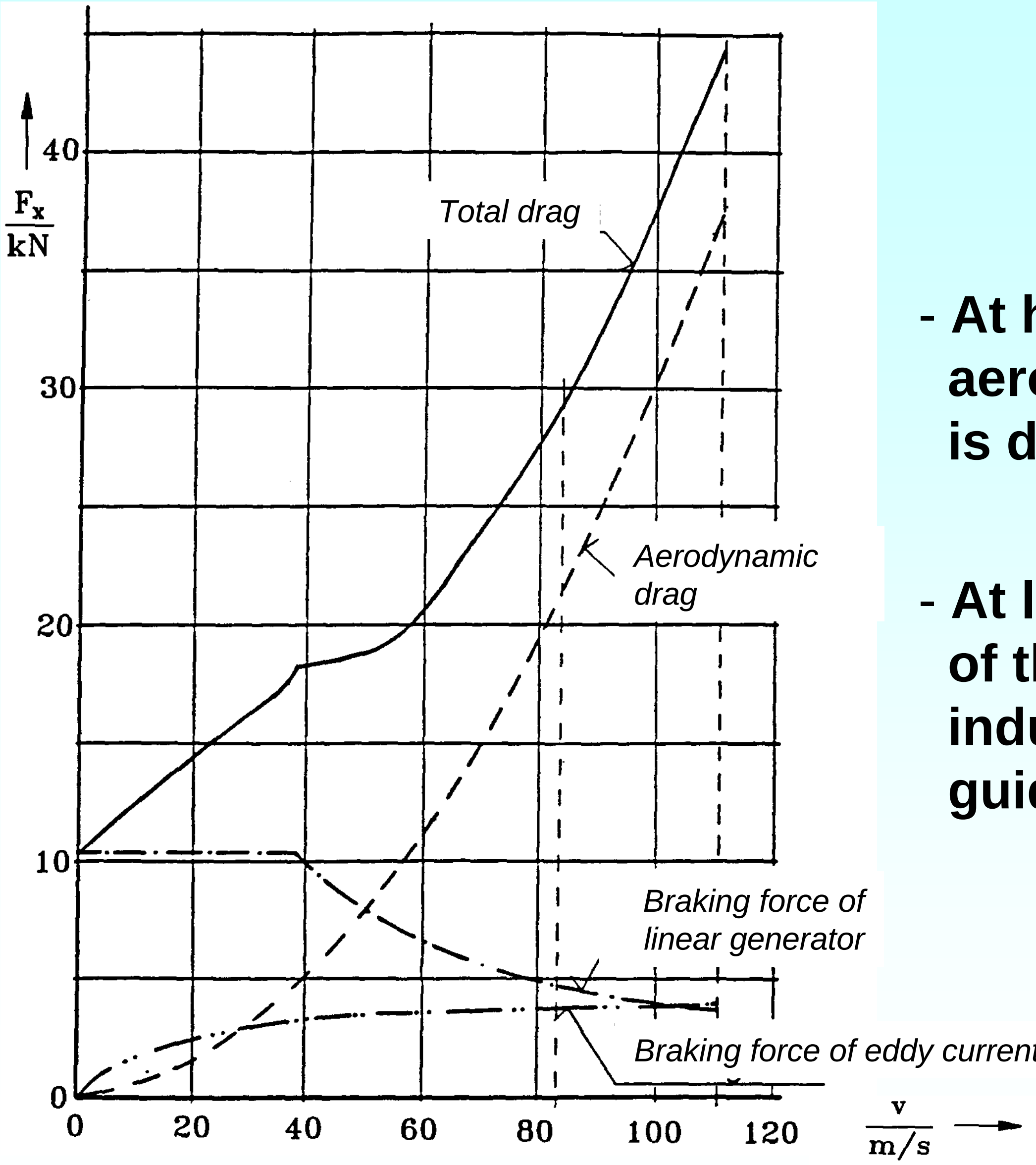
- A secondary pole module comprises 10 centre poles and 2 half end poles, with different pole pitch: centre poles: τ_f = 266.5 mm, end poles: τ'_f = 262.5 mm

- Resulting shift: $x_{shift} = 9(\tau_f - \tau_p) + 2(\tau'_f - \tau_p) = 84.9\ \text{mm} \approx \tau_s = 86\ \text{mm}$

Source: Thyssen Krupp, Germany



TRANSRAPID: Motional drag



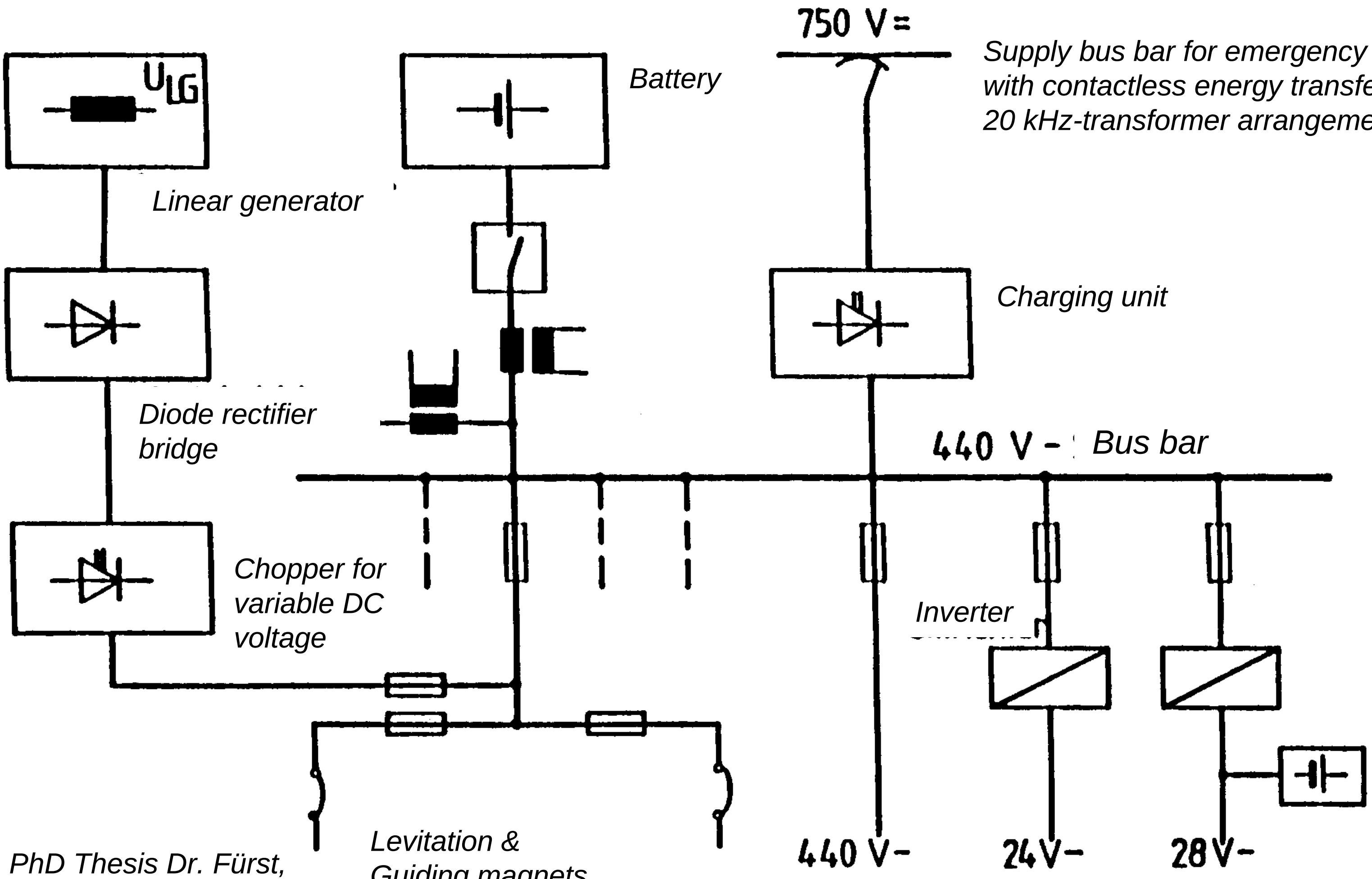
- At high velocities only the aerodynamic resistance (drag) is dominating

- At low velocities the braking forces of the linear generator and of the induced eddy currents due to the guiding magnets are also essential

Source: PhD Thesis Dr. Fürst, TU Berlin

3.4 High speed trains with magnetic levitation

Transrapid: On board current supply



Linear generator

Diode rectifier bridge

Chopper for variable DC voltage

Battery

Supply bus bar for emergency (now with contactless energy transfer via a 20 kHz-transformer arrangement)

Charging unit

Bus bar

Inverter

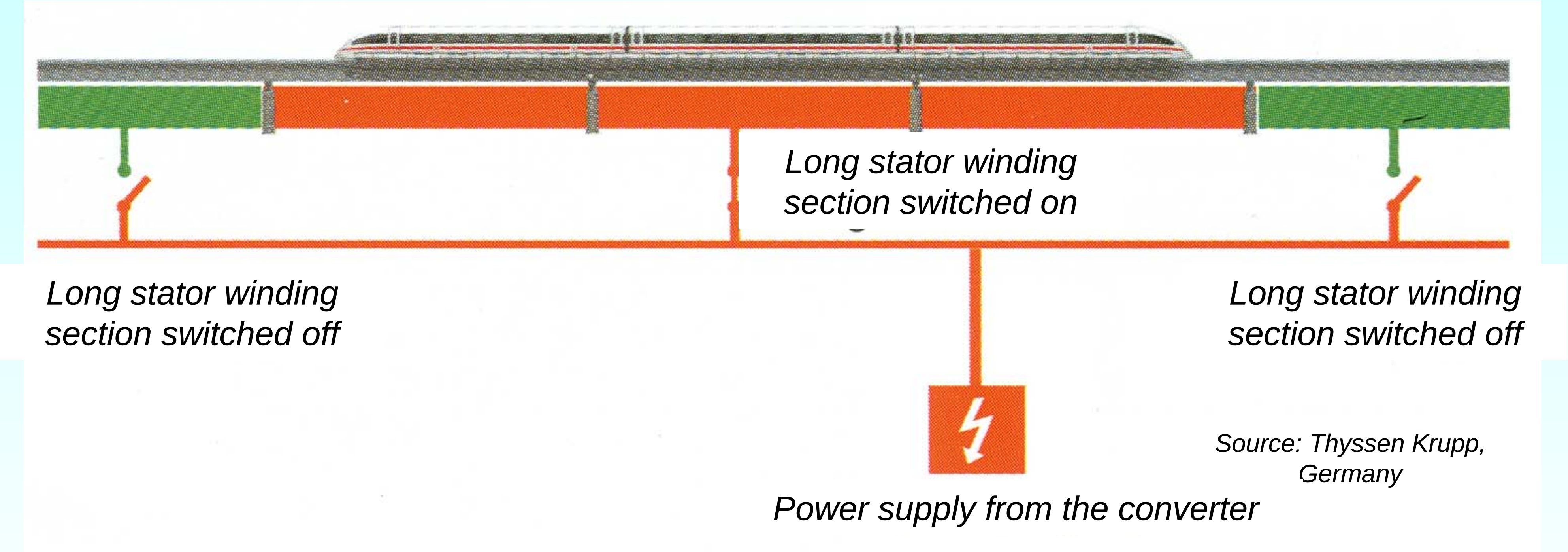
Levitation & Guiding magnets

Load e.g. Air condition

Low voltage supply bar

Source: PhD Thesis Dr. Fürst, TU Berlin

Commutating of feeding winding sections

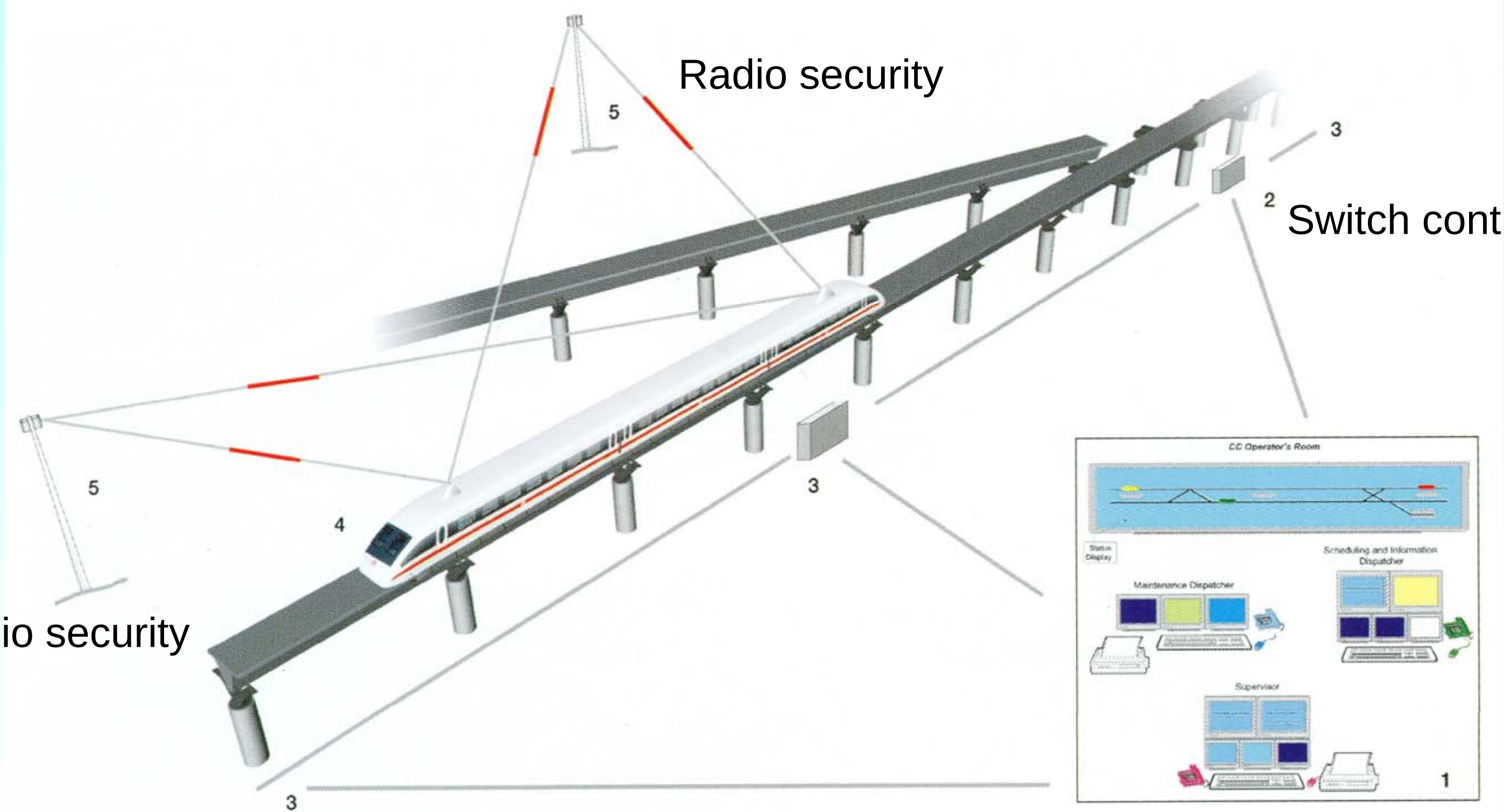


Source: Thyssen Krupp, Germany

- Installed GTO or HV-IGBT-frequency-converter supplies linear motor winding sections via parallel cables and power switches.
- Position of vehicle captured via radio and only the corresponding winding section is energized

3.4 High speed trains with magnetic levitation

Long distance system for train controlling and vehicle-securing



Radio security

Switch control

Radio security

Track security

Source: Thyssen Krupp, Germany

Control area

3.4 High speed trains with magnetic levitation

Electrical supply of the linear stator winding

- *Emsland* test track*:* 50 Hz/110 kV-grid, 110 kV/20 kV-power transformers, along the track at different stations: Feeding points via PWM-voltage source converters, built with GTO-modules

- Converter transformers 20 kV/1120 V create two 30°el phase-shifted 3-ph. AC voltage systems, which are rectified = 12 pulse controlled rectification of the grid voltage via thyristors!

- *Voltage source inverter:* DC link voltage 2.6 kV, PWM-output voltage up to 55 Hz (= 102 km/h), 1170 V phase voltage (r.m.s.).

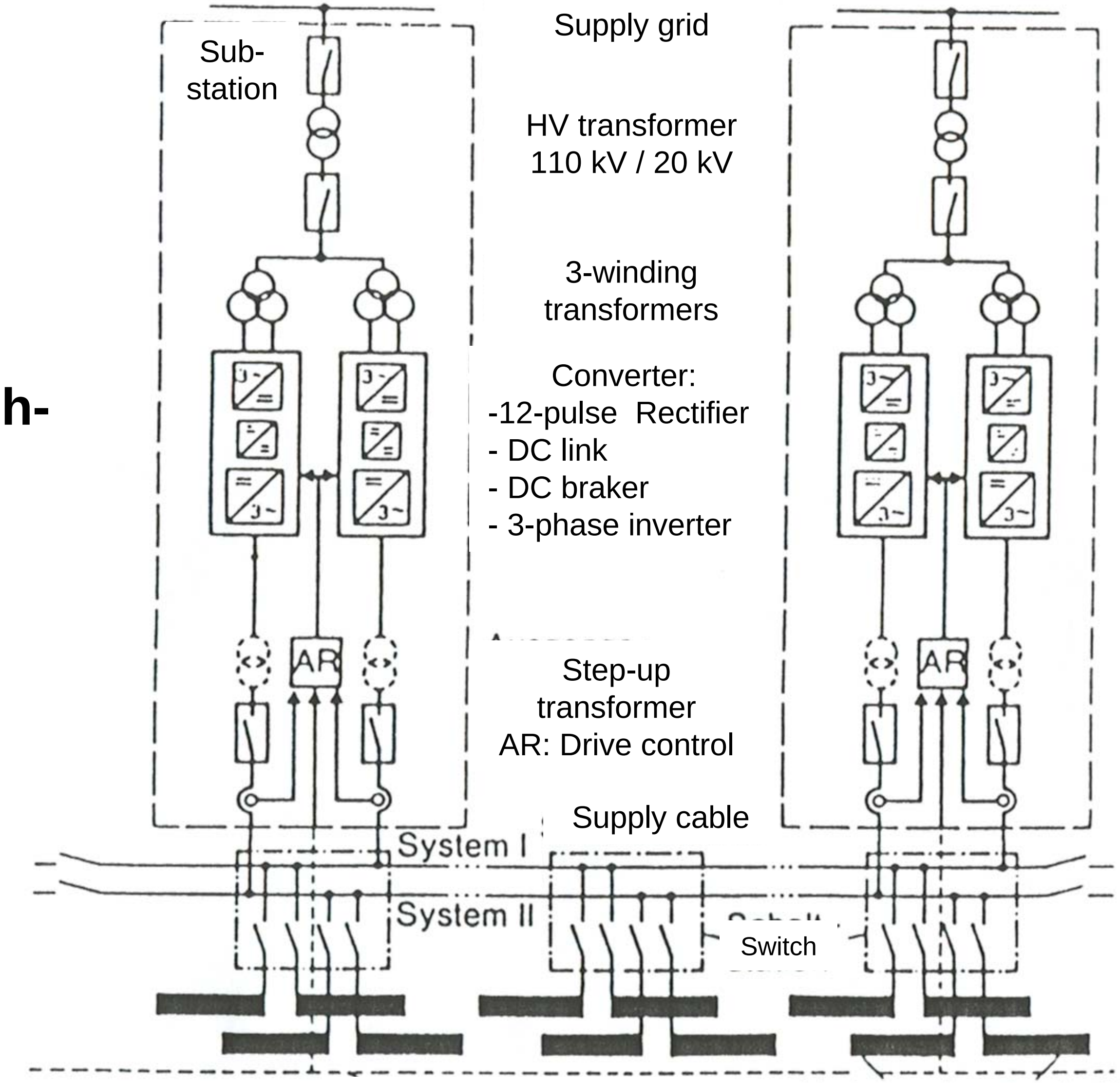
  Between 55 … 270 Hz: Block-voltage operation, but phase shifted by the four output transformers to reduce the harmonic content of the output voltage and the stator current harmonic in the linear motor winding.
  Output voltage raised with these transformers up to 4x1170 = 4675 V ⇒ up to 370 km/h constant thrust possible

- Switching of feeding sections in “Alternate step mode”: Left and right linear motor winding changed from section to section time-shifted!

Energy supply of TRANSRAPID in *Emsland* test track

- **1995: GTO-converters**
- **Since 2006: Replaced by High-Voltage IGBT-technology**

Source: Siemens AG, Germany



Sub-station

Supply grid

HV transformer 110 kV / 20 kV

3-winding transformers

Converter:
-12-pulse Rectifier
- DC link
- DC braker
- 3-phase inverter

Step-up transformer
AR: Drive control

Supply cable

Switch

Vehicle position detection

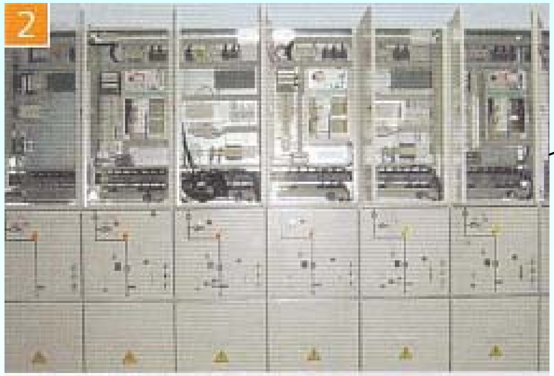
Motor winding feeding section

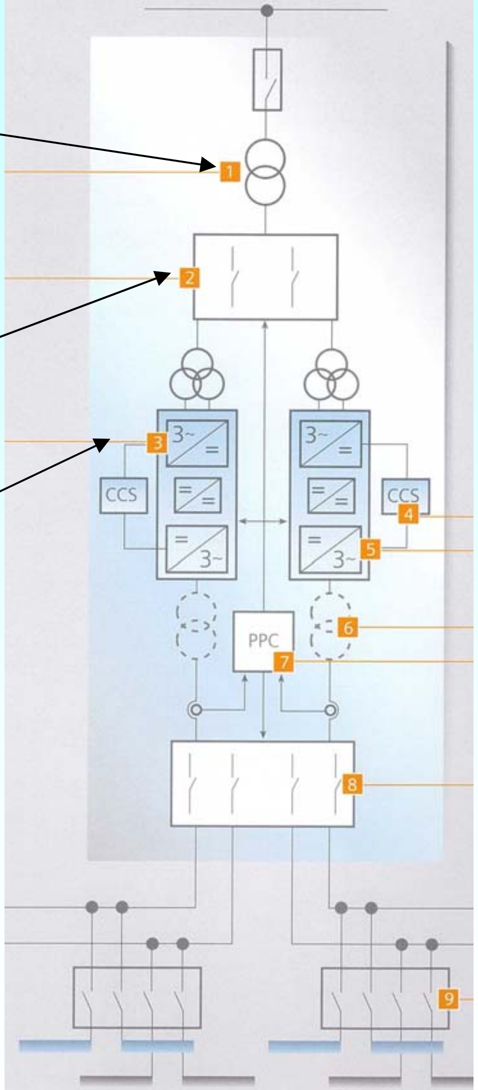
3.4 High speed trains with magnetic levitation

Energy supply of TRANSRAPID in *Emsland* test track

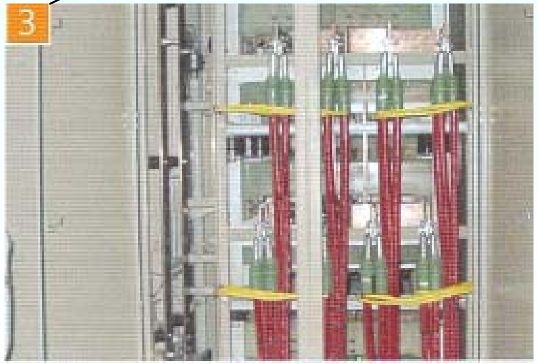
High voltage switchgear
with transformer
110 kV/20 kV

Input switchgear





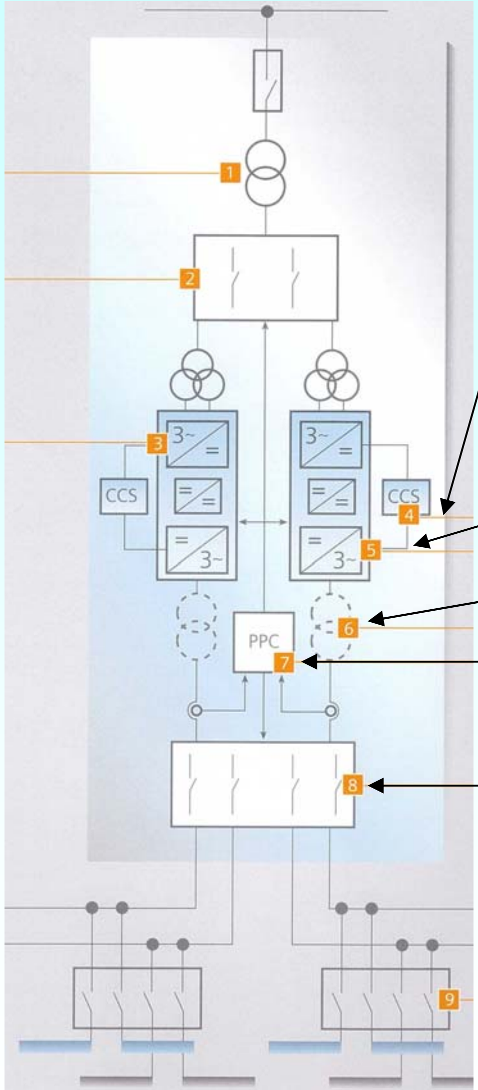
Line side thyristor
converter for dual
power flow



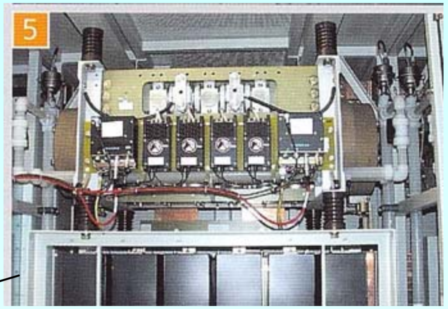
Source: Siemens AG, Germany

3.4 High speed trains with magnetic levitation

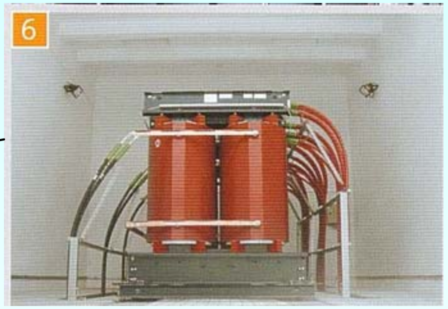
Energy supply of TRANSRAPID in *Emsland* test track



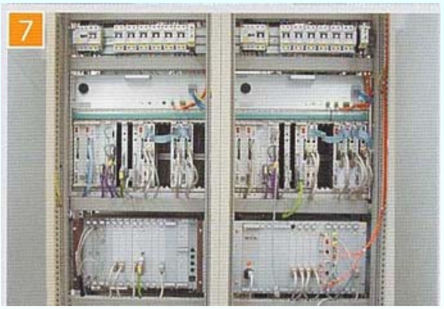
converter water cooling system



GTO motor converter



Epoxy-resin step-up transformer

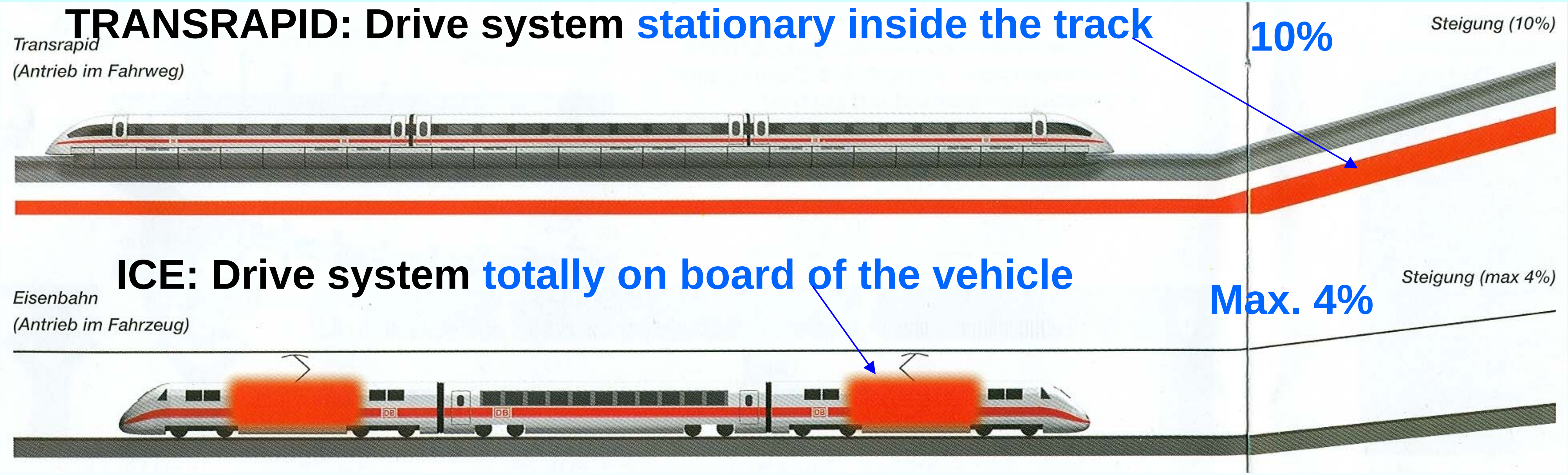


Propulsion regulation and control system

20 kV vacuum contactor output switch gear

Source: Siemens AG, Germany

Slope climbing ability of TRANSRAPID up to 10%



TRANSRAPID: Drive system stationary inside the track

10%

ICE: Drive system totally on board of the vehicle

Max. 4%

TRANSRAPID has higher climbing capability than ICE3, because:

Source: Thyssen Krupp, Germany

- **No wheel rail system, so no friction contact force as limit**
- **Thrust power of converter inside the track, so locally higher power supply possible**

Maximum acceleration for ICE 3 and TRANSRAPID

	ICE 3	TRANSRAPID
0 ... 250 km/h	0.59 ...0.18 m/s^2	0.74 m/s^2
300 ... 350 km/h	0.03 m/s^2	0.57 m/s^2
350 ... 400 km/h	v_{max} already surpassed	0.44 m/s^2

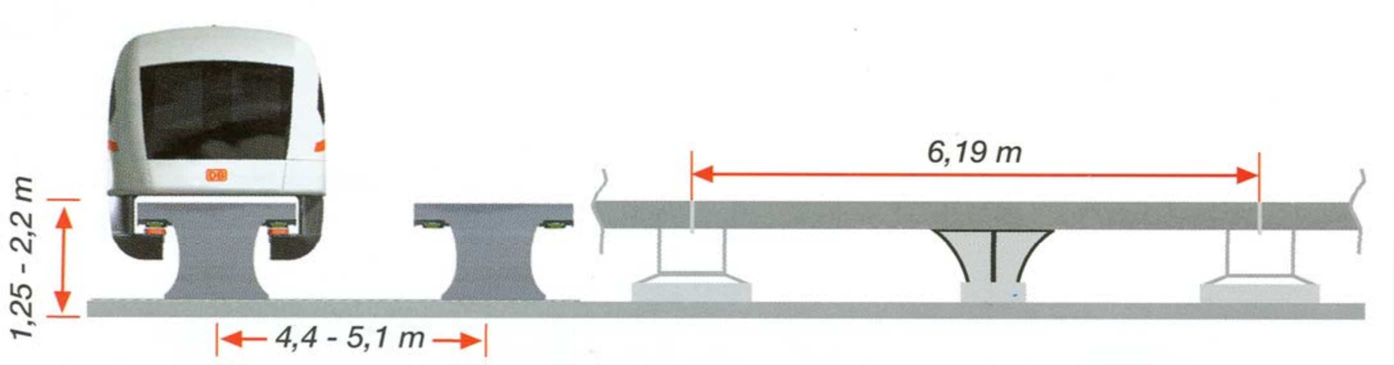
Source: Thyssen Krupp, Germany

Travelling time - ICE 3 compared to TRANSRAPID

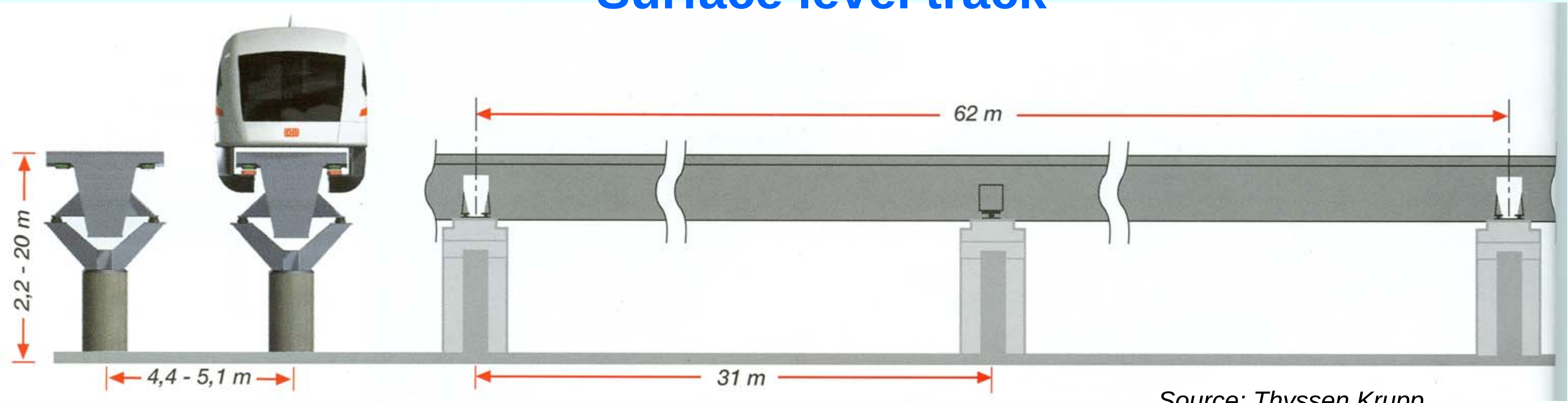
Source: Thyssen Krupp, Germany

	ICE 3	TRANSRAPID
v_{max}	300 km/h	400 km/h
Distance 20 km	7 min	6 min
v_{max}	330 km/h	400 km/h (possible: 450 ... 500 km/h)
Distance 200 km	44 min	35 min (ca. 29 min)

Track layout of TRANSRAPID



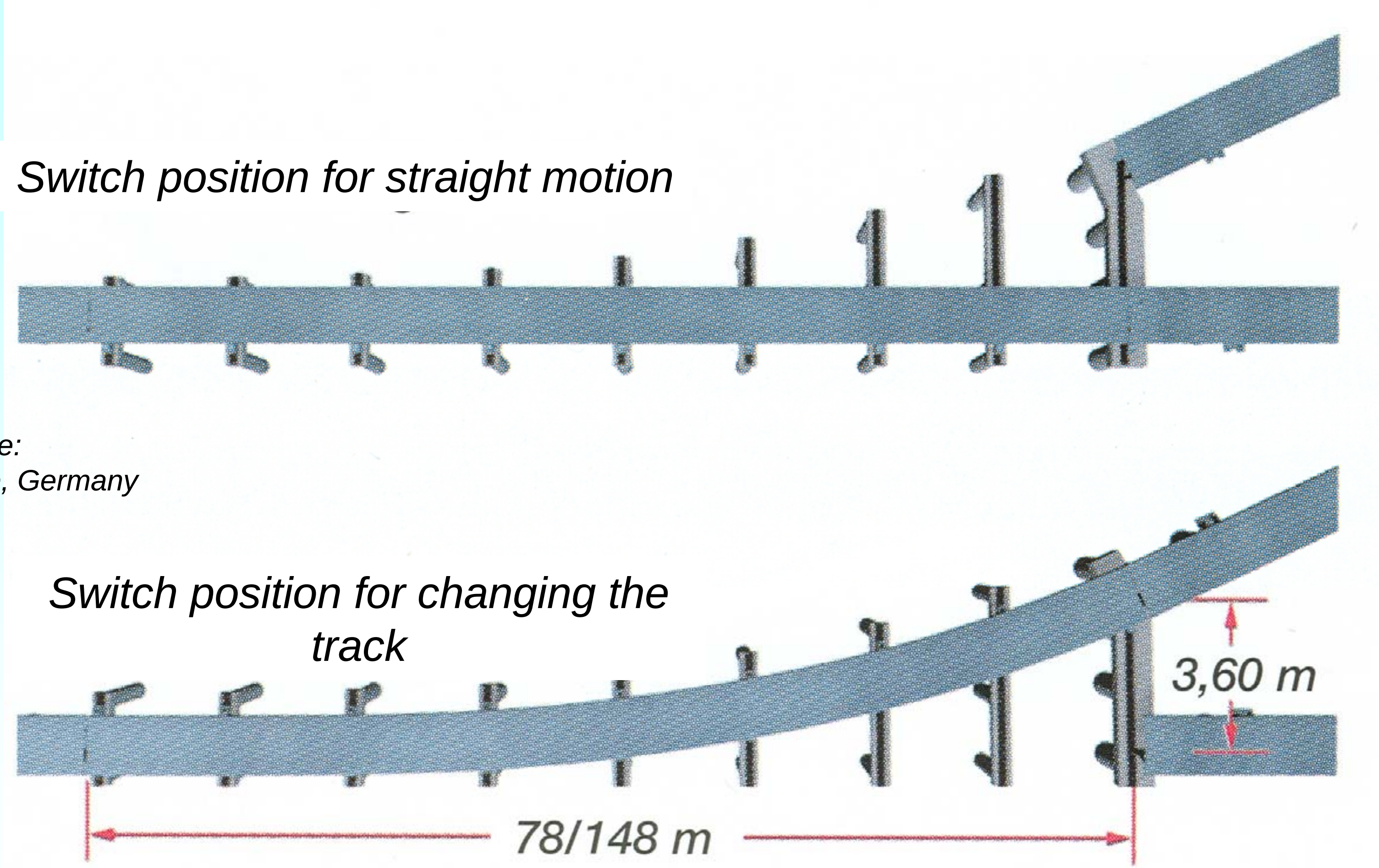
Surface level track



Mounted track

Source: Thyssen Krupp, Germany

Bent steel as switches for TRANSRAPID



Switch position for straight motion

Switch position for changing the track

Source:
Thyssen Krupp, Germany

Electromagnetic drives bend elastically 78 ... 148 m long steel beams

3.4 High speed trains with magnetic levitation

TRANSRAPID: Serial used vehicle

- *Vehicle:*

  Length: End section: 27 m, middle section: 24.8 m, *width:* 3.7 m, *height:* 4.2 m
  empty weight per section: 53 tons, *persons:* 92/126 end-/middle section

- *Track:*

  Necessary *area:* in tunnel (length > 150 m, v = 450 km/h):
  single track tunnel: 120 m^2, double track tunnel: 225 m^2
  Maximum slope: 10% (ICE: max. slope ca. 4 %).

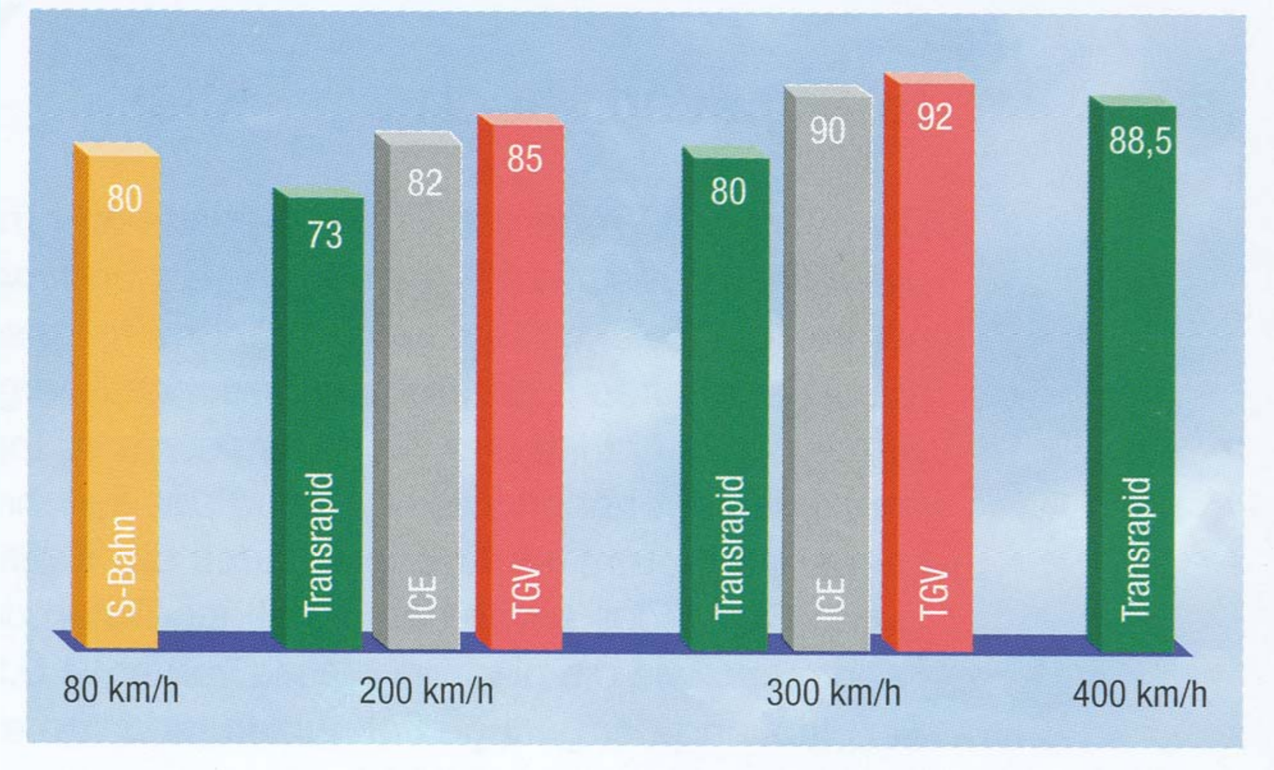
- *Acoustic noise:*

  Above 250 km/h purely aerodynamic noise!
  No rolling or motor drive noise (e.g. gears or motor fans)!
  At 25 m lateral distance: v = 200 / 300 / 400 km/h: L_{pA} = 73 / 80 / 88.5 dB(A)
  (Measurements from the mounted track system of the *Emsland* test track)
  (Normal street traffic noise: 70 dB (A), trucks: 5 m distance: 90 dB(A) !)

- *Magnetic field* in the cabin with 100 µT very low: Because the magnetic flux is guided within the iron cores and is rather small in the magnetic air-gaps
  (Compare: earth magnetic field ca. 50 µT)

Acoustic noise of ICE3 and TRANSRAPID

Sound pressure level of by-passing vehicle at 25 m distance
dB(A)



TGV: French high speed train ("train a grande vitesse")

ICE: German high speed train (Inter city express)

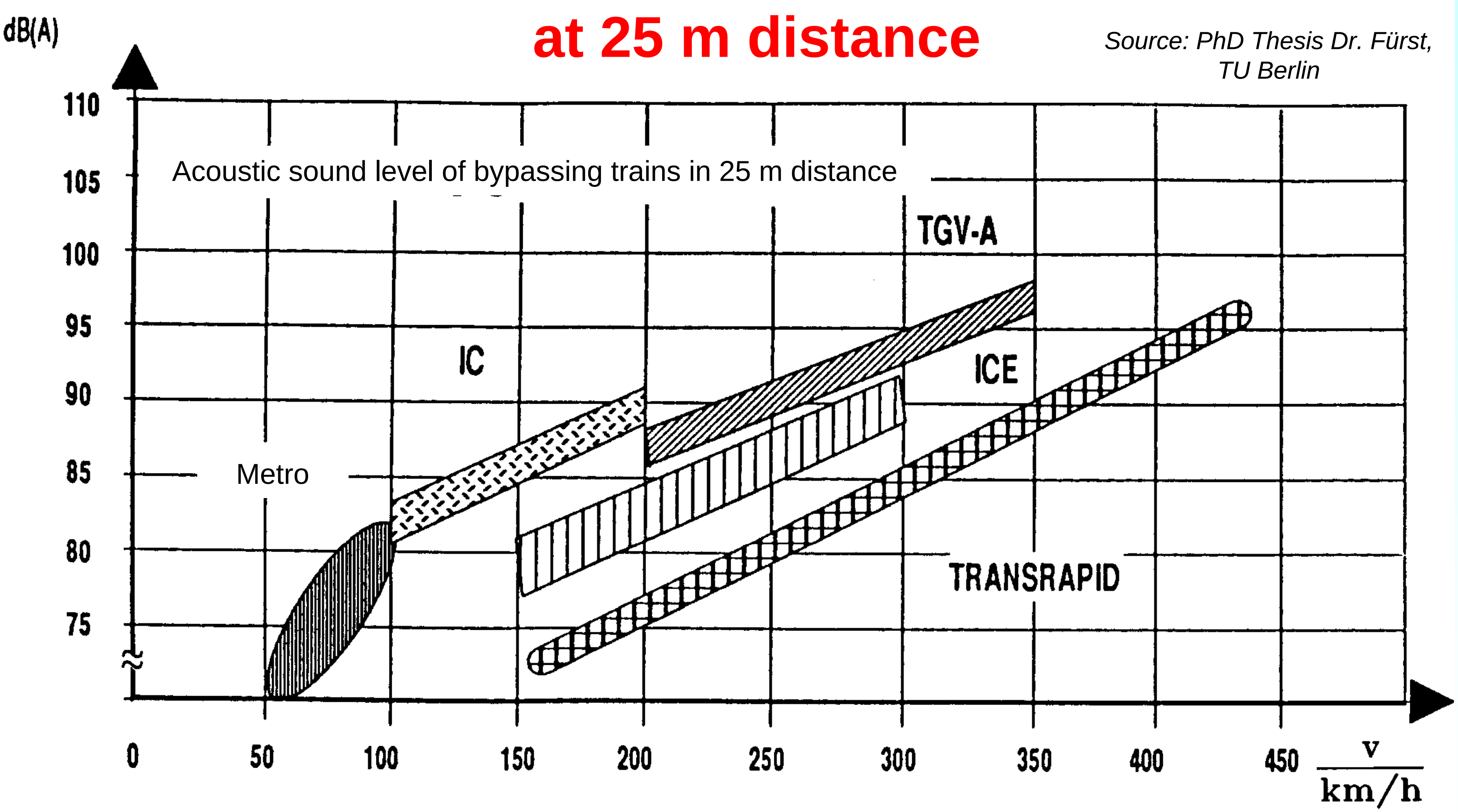
TRANSRAPID has no rolling noise, so its acoustic noise is lower than that of ICE and TGV

Source: Thyssen Krupp, Germany

Above 250 km/h the aerodynamic noise dominates in TRANSRAPID

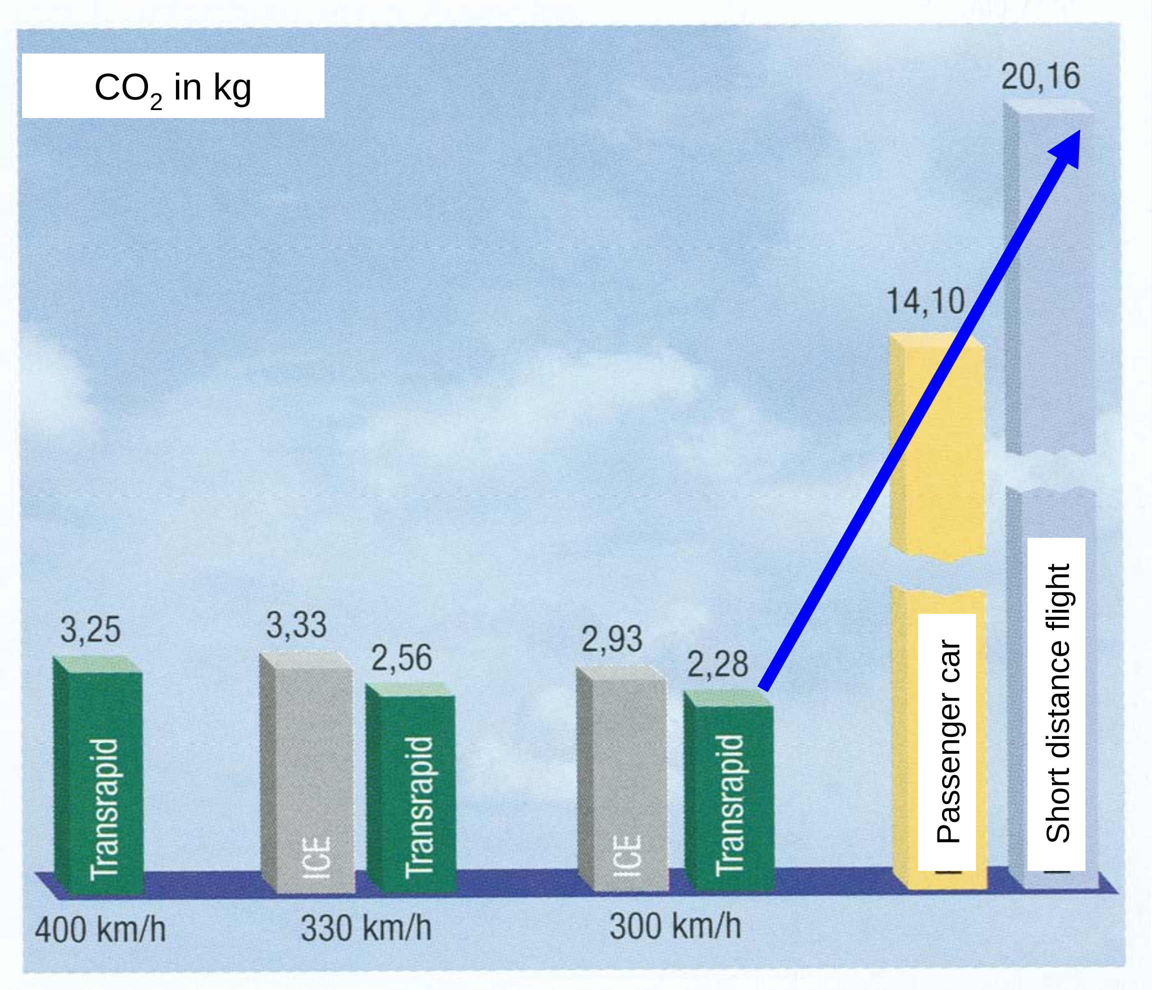
Comparison: Acoustic sound level of bypassing trains at 25 m distance

Source: PhD Thesis Dr. Fürst, TU Berlin



3.4 High speed trains with magnetic levitation

CO_2-emission in kg per 100 persons and per kilometer



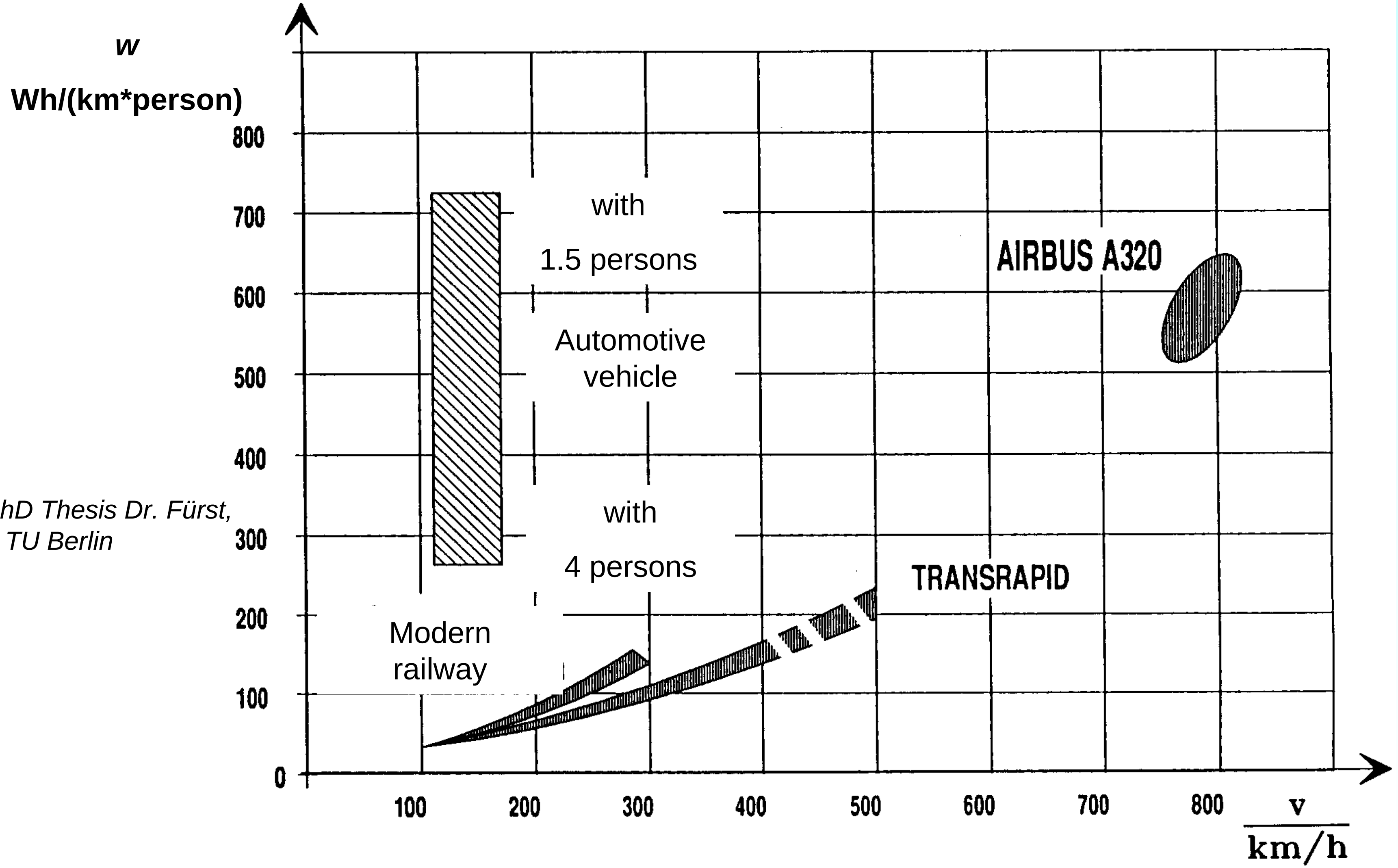
Specific need of energy per person and kilometer:

	ICE 3	TRANSRAPID
200 km/h	29 Wh	22 Wh
300 km/h	51 Wh	34 Wh
400 km/h	-	52 Wh

TRANSRAPID will be a future low energy competitive to short-distance flights

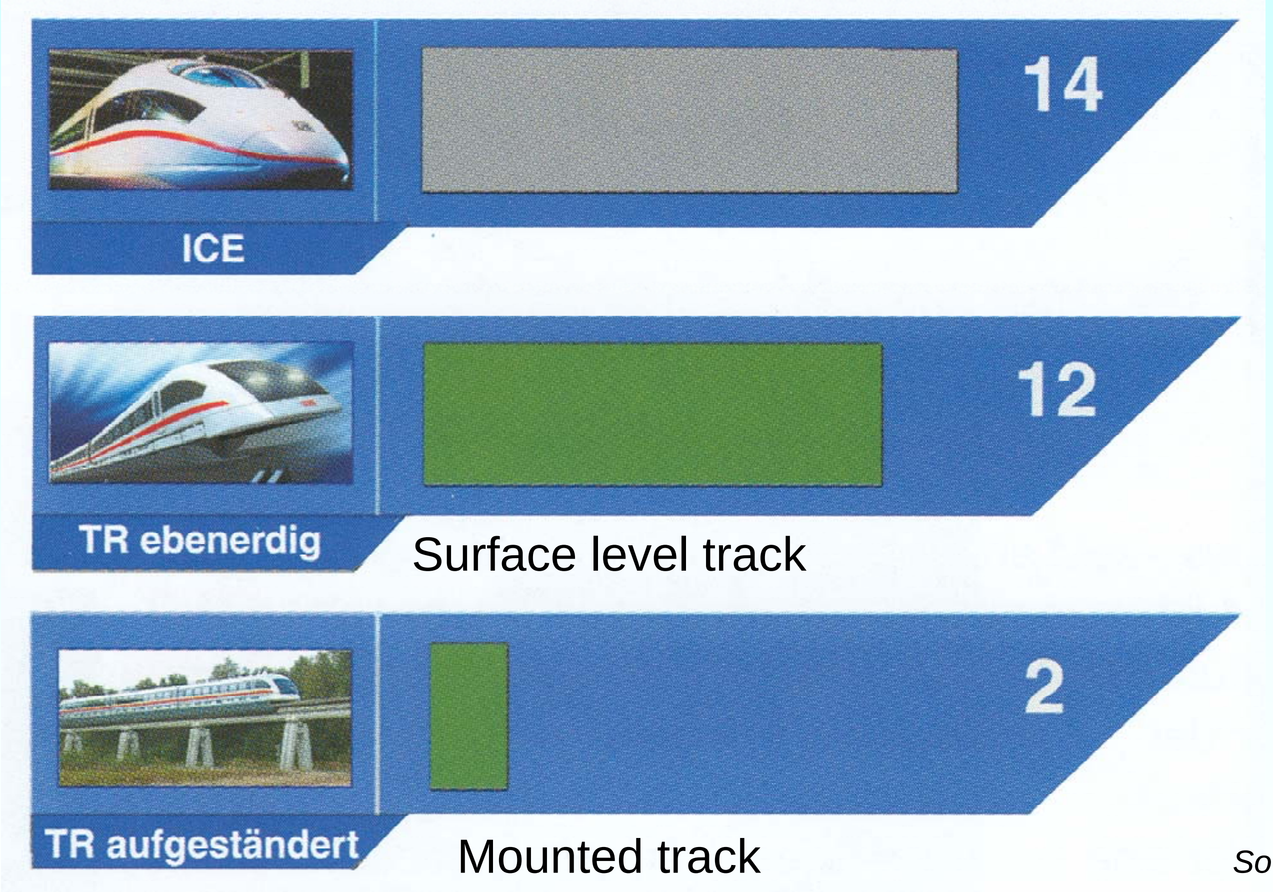
Source: Thyssen Krupp, Germany

Comparison: Energy consumption per km & passenger



Source: PhD Thesis Dr. Fürst, TU Berlin

Need of area for the high speed track in m^2 per m of vehicle length (inclusive substations)



Source: Thyssen Krupp, Germany

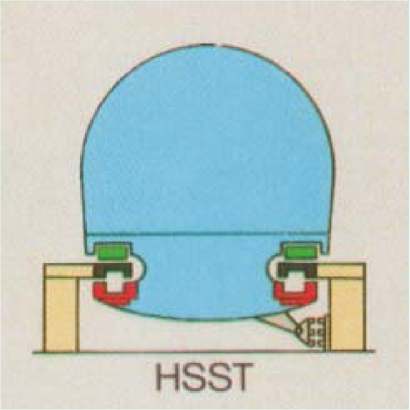
Summary:
Active magnetically levitated high-speed train TRANSRAPID

- Synchronous long-stator linear motor at both sides of the track
- Electromagnetic levitation with controlled air-gap
- Motor secondary is also used as levitating magnet system
- Up to 500 km/h until now feasible
- Less energy consumption per person and km than competing air-plane
- Well suited for long distance fast surface transport

HSST – Magnetic railway

Source: Wikipedia: Maglev

HSST magnetic levitation rail way, *Japan*



Source: HSST Corporation, Japan

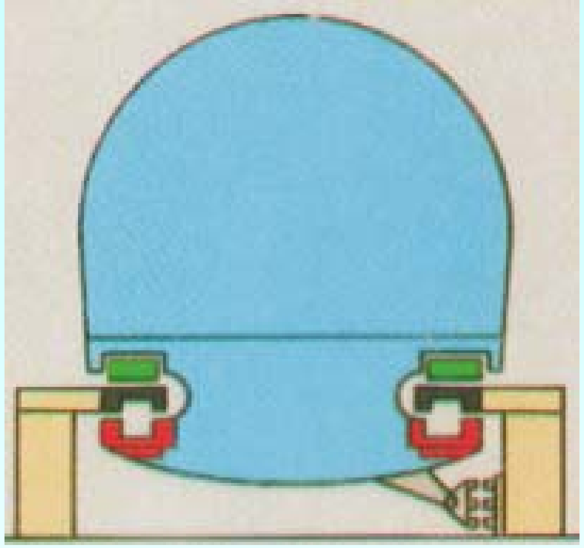
High Speed Surface Transport System (HSST)
500 m track at the *Yokohama* exposition 1989

Electromagnetic levitation (EML), short stator asynchronous linear drive
v_{max} = 300 km/h, fast local traffic

3.4 High speed trains with magnetic levitation

HSST vehicle data

Aluminum reaction rails



- Cheap short stator asynchronous linear drive on both sides with aluminum reaction rail as secondary
- Aluminum short stator three-phase windings
- Three-phase pantograph for stator current feeding limits maximum speed to v_{max} = 300 km/h; rigid aluminum conductor trolley
- 2-car train, 158 seats, 1.26 mio. passengers carried during 8 months, weight per car 15 tons

- DC magnets for levitation, 8 … 10 mm air gap
- Side stabilization via reluctance forces
- Gap sensors needed for gap control

Source: HSST Corporation, Japan

HSST vehicle as “Urban Maglev” system LINIMO

- Commercial operation since March 2005 at suburbs of *Nagoya* (*Aichi*), *Japan*
- Nine-station 9 km long *Tobu-kyuryo* Line (Linimo)
- Minimum operating radius of 75 m
- Maximum gradient 6%
- Top speed: 100 km/h
- Trains designed by *Chubu HSST Development Corporation*,
  which also operates a test track in *Nagoya*

Aluminum reaction rails

Linimo approaching *Banpaku-Kinen-Koen*, towards *Fujigaoka* station

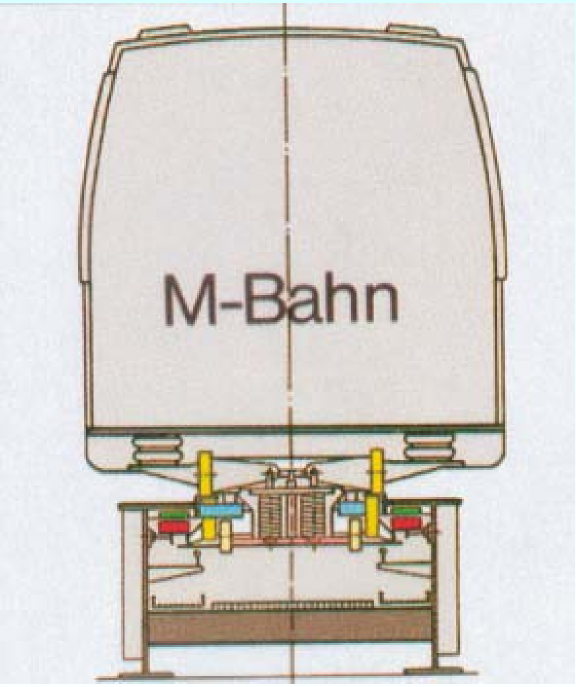
Source: Wikipedia: Maglev

Literature:
THE FIRST HSST MAGLEV COMMERCIAL TRAIN IN JAPAN

Y. Yasuda, M. Fujino, M. Tanaka: *Chubu HSST Development Corporation,*
S. Ishimoto: *Aichi Kosoku Kotsu Corporation, Japan*

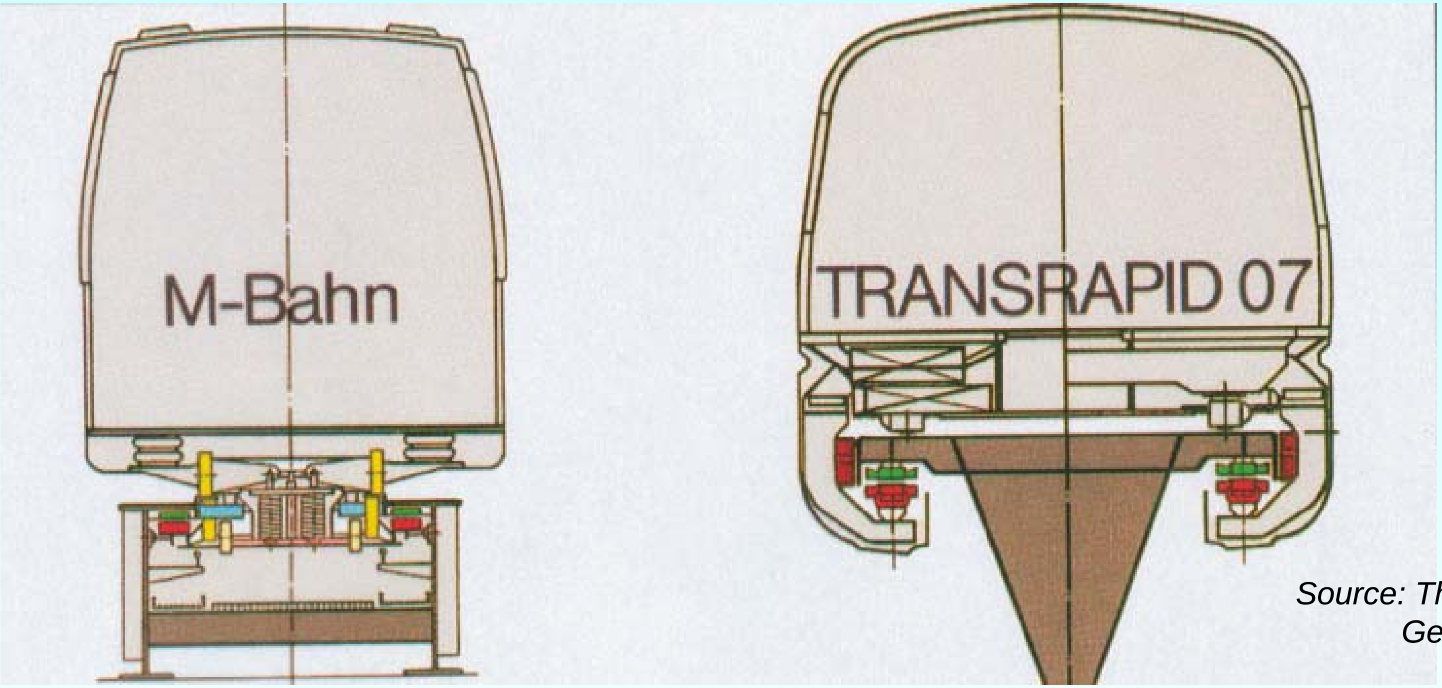
3.4 High speed trains with magnetic levitation

M-Bahn, *Berlin*



Source: Thyssen Krupp, Germany

Past project: Magnetic railway – *Magnetbahn Berlin* (until 1991)



Source: Thyssen Krupp, Germany

Magnetic rail: Passive magnetic levitation reduces pressure on the guiding and stabilizing wheel-rail system by the magnetic pull, but no real levitation occurs

Permanent magnets create the levitating force and are the „secondary“ of a PM synchronous long-stator motor

Still the major part of the gravity force and the total guiding force are accomplished via the wheel-rail system

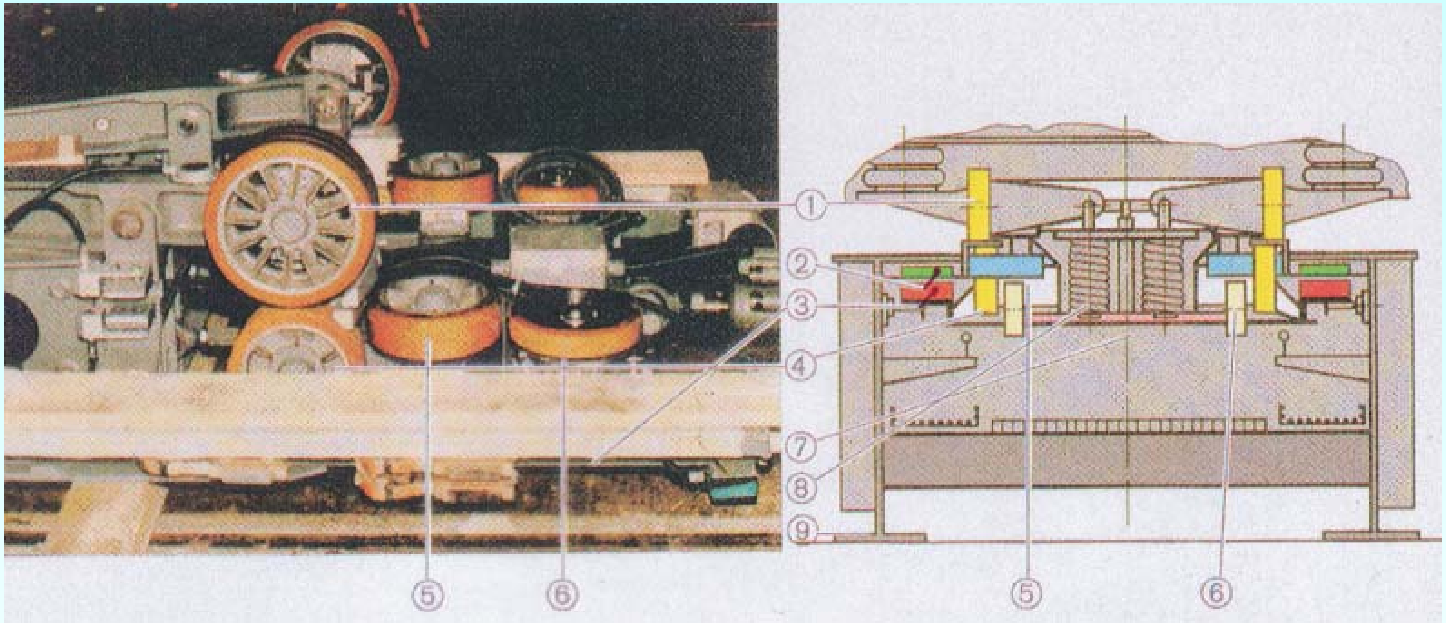
Supporting and guiding wheels of the *Magnetbahn Berlin*

Low noise operation

Low energy consumption

Autonomous vehicle operation

BUT: Complicated wheel system



1, 4: Vertical wheels 2: Stator with winding, 3: Permanent magnets,
5: Guiding wheels, 6: Wheels for switches, 7: Wheel bogie,
8: Primary spring, 9: Track

Magnetic rail: Several years of testing at the track „Gleisdreieck" *Berlin West*

Disassembly of the train after the re-union of *Eastern* and *Western Germany*

Source: AEG and Thyssen Krupp, Germany