New technologies of electric energy converters and actuators

Contents

1. Superconductors for power systems

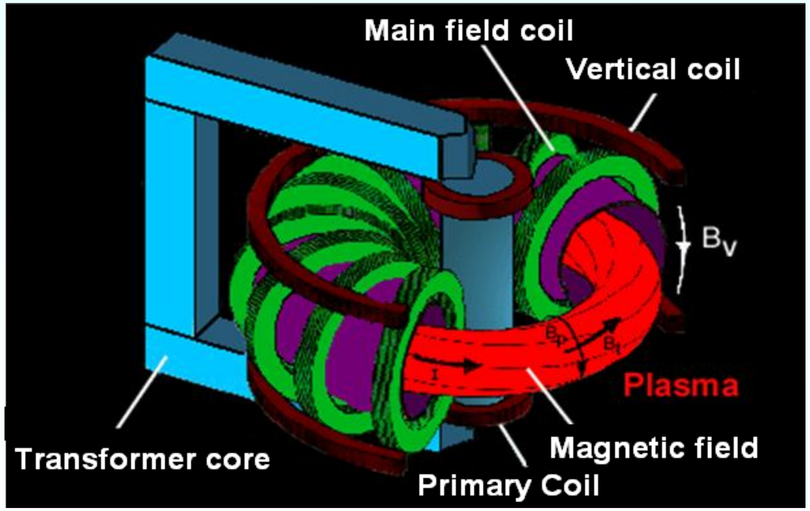
2. Application of superconductors for electrical energy converters

3. Magnetic bearings („magnetic levitation")

4. *Magneto-h*ydro*d*ynamic (MHD) energy conversion

5. Fusion research

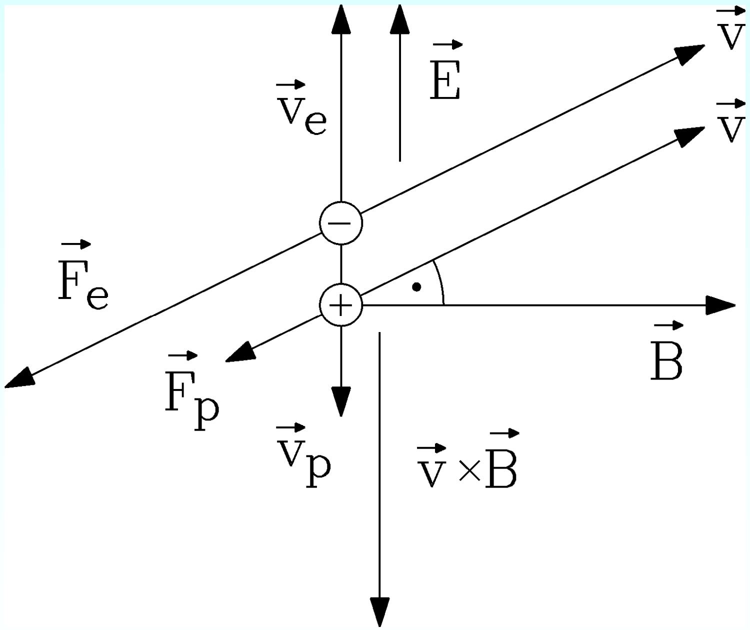
Source: Internet



4. *M*agneto-*h*ydro*d*ynamic (MHD) energy converters

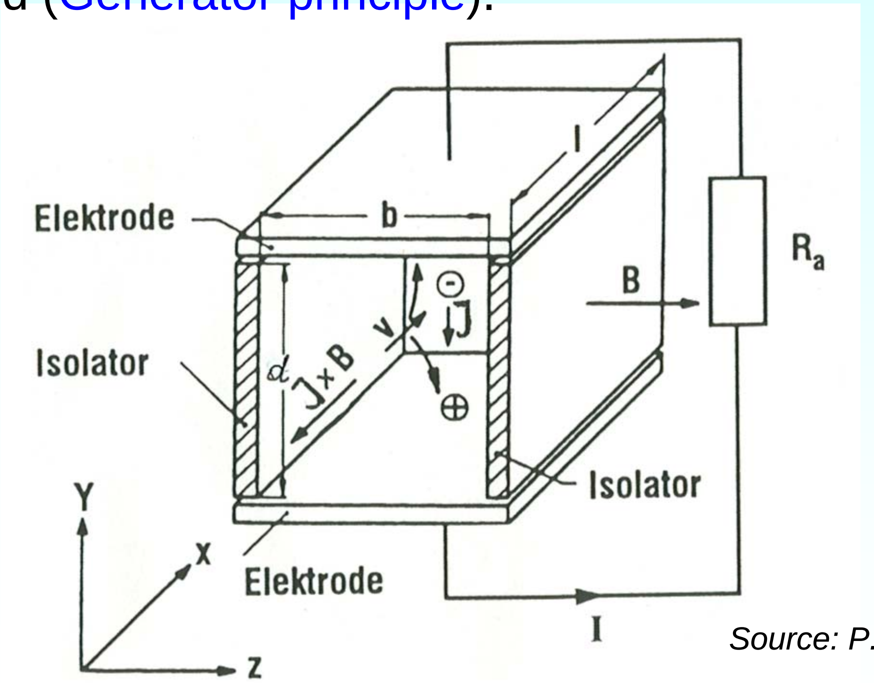
& Electric satellite drives

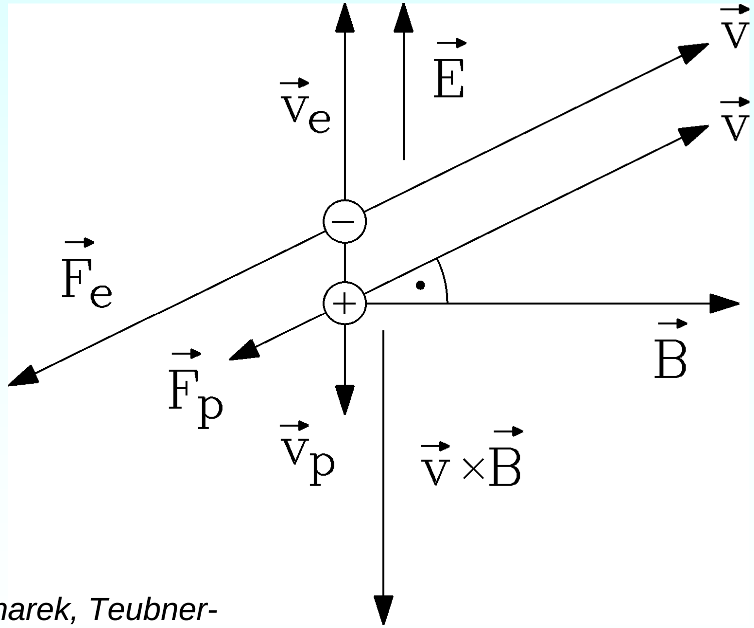
4.1 Physical basics of MHD energy conversion



Magnetic hydrodynamic (MHD) Generator - principle

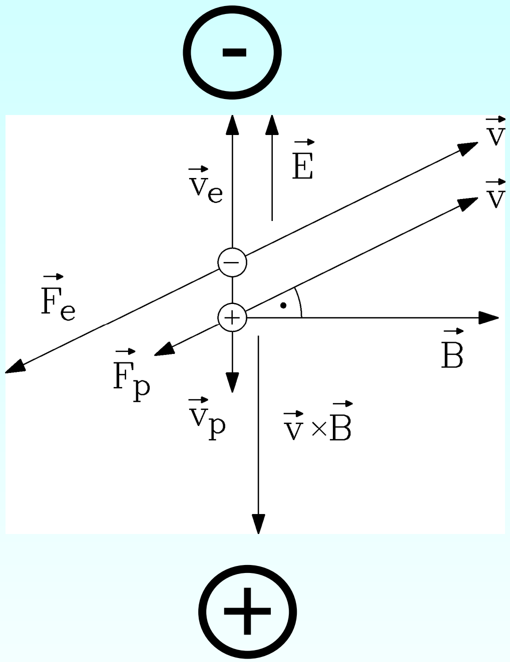
- Electrically conducting fluid flows in a channel with velocity *v*. Flux density *B* separates positively and negatively charged ions to up- and downside (= voltage induction). Between + & - electrode a DC current *I* may flow via a load resistance with the current density *J* in the channel.
- A braking LORENTZ-force *F* ~ *J* x *B* occurs in the channel, which acts against the flowing fluid (Generator principle).

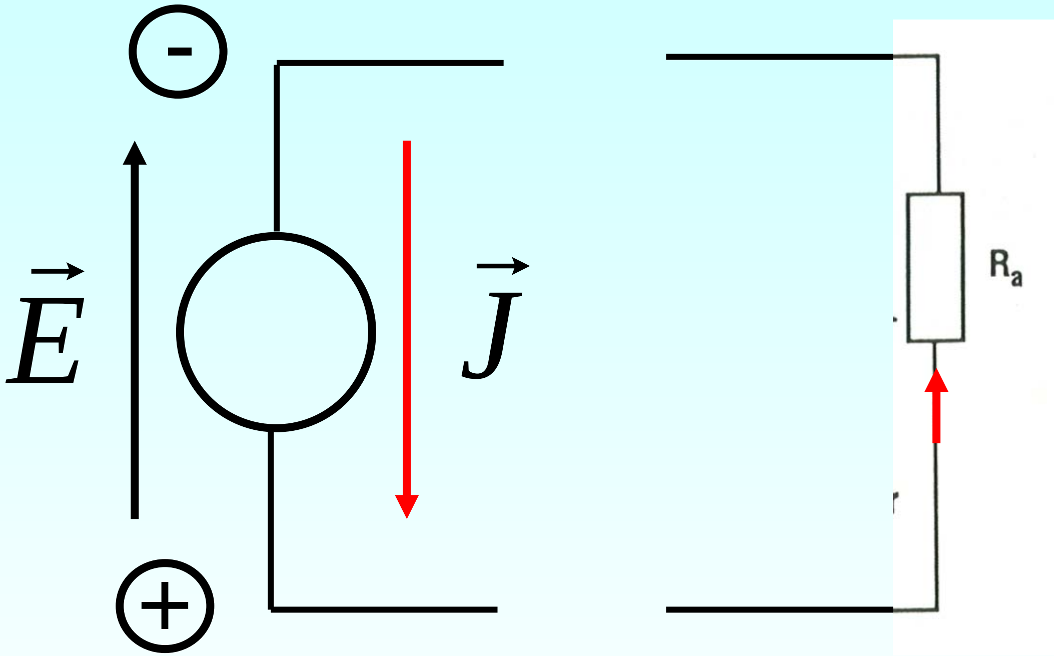




Source: P. Komarek, Teubner-Verlag

Equivalent circuit of DC voltage source





Mobility law for charged particles

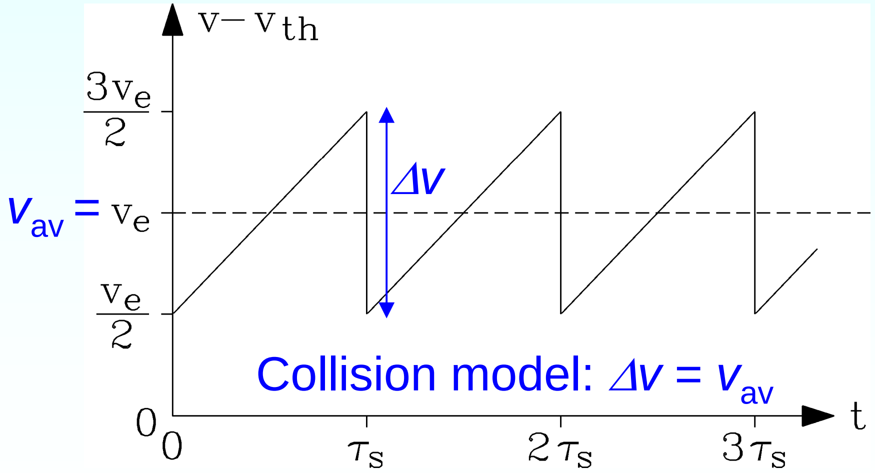
NEWTON´s law: $\vec{F} = m \cdot d\vec{v} / dt \Rightarrow q \cdot \vec{E} = m \cdot d\vec{v} / dt$

DRUDE theory on collisions: regularly occurring collisions with collision time τ_s

$$\vec{F} = m \cdot d\vec{v} / dt \approx m \cdot \Delta\vec{v} / \tau_s = m \cdot \vec{v} / \tau_s = q \cdot \vec{E} \quad \Rightarrow \quad \vec{v}_{av} = \vec{v} = \mu \cdot \vec{E}$$

$$\boxed{\vec{v}_e = \mu_e \vec{E}, \vec{v}_p = \mu_p \vec{E}, \quad \mu_e = q_e \cdot \tau_s / m_e, \mu_p = q_p \cdot \tau_s / m_p}$$

v_{th}: average thermal velocity of the particles in the hot gas



charged particle mobility: $\mu_e < 0 \quad \mu_p > 0$

Due to the collisions force is on average not proportional to accelaration, but to (average) velocity = OHM´´s law for gases!

Due to the much higher ion mass m_p the mobility of the ions is much smaller than of the electrons!

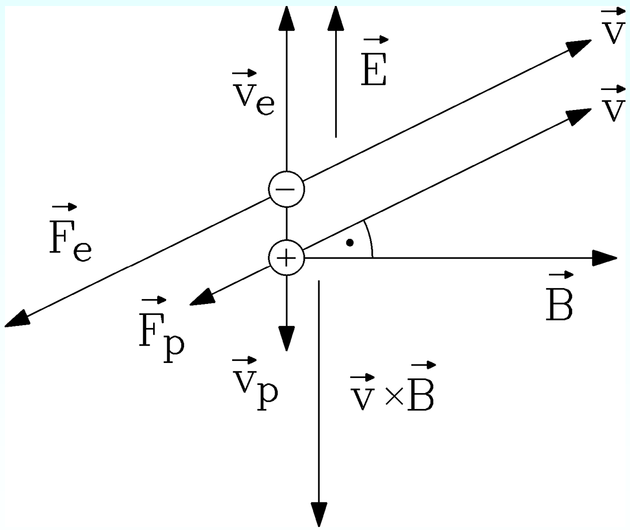
Forces on charge carrier in fluid

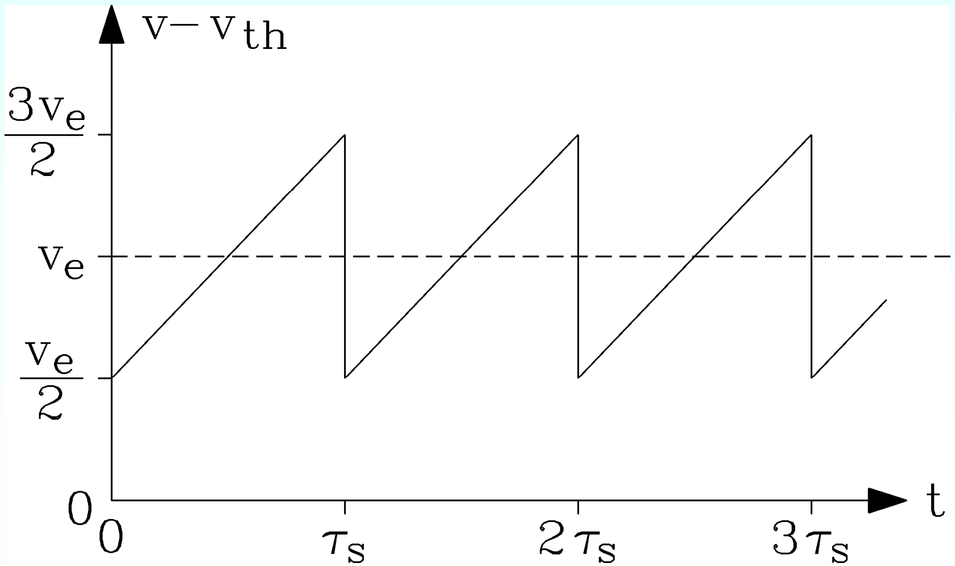
- **Singly ionized gas:** $q_e = -e, q_p = e$ **. Force** $\vec{F} = q \cdot (\vec{v} \times \vec{B})$ **on ions and electrons has same, but opposite value. Ion mass *m_p* >> electron mass *m_e*, so transversal velocity *v_e* >> *v_p*, so electron density *J_e* higher than ion current density *J_p*. Hence in the channel mostly electron conduction.**

  $\vec{J}_e = q_e \cdot n_e \cdot \vec{v}_e, \vec{J}_p = q_p \cdot n_p \cdot \vec{v}_p$ ***n_e*, *n_p*: number of charged carriers/volume**

- $\vec{v}_e = \mu_e \vec{E}, \vec{v}_p = \mu_p \vec{E}, \quad \mu_e = q_e \cdot \tau_s / m_e, \mu_p = q_p \cdot \tau_s / m_p$ **„mobility"**

  τ_s: Collision time (corresponds to „average free path of motion“ in ionized gas)





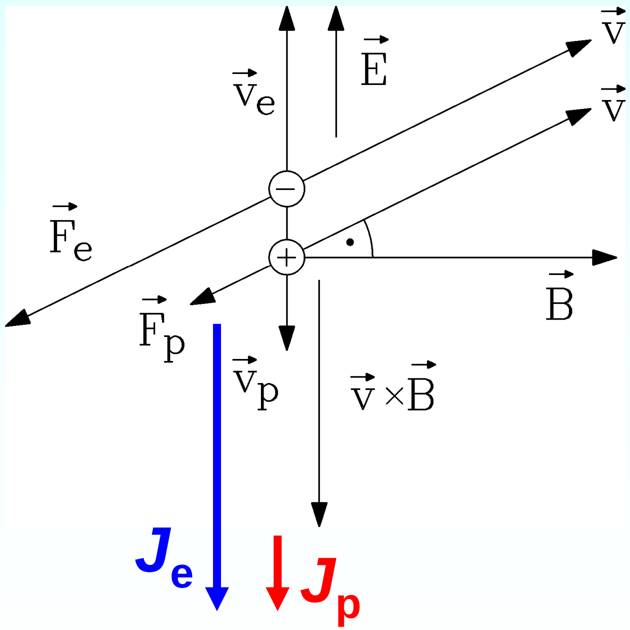
OHM´s law for ionized gas

- Current density of positive and negative charged particles:

$$\vec{J}_e = q_e \cdot n_e \cdot \vec{v}_e,\ \vec{J}_p = q_p \cdot n_p \cdot \vec{v}_p \qquad \vec{J}_e \uparrow\uparrow \vec{J}_p \quad \Leftrightarrow \quad q_e < 0, \supset \vec{v}_e \downarrow\uparrow \vec{v}_p$$

- Total current density:

$$\vec{J} = \vec{J}_e + \vec{J}_p \qquad \vec{J}_e >> \vec{J}_p \ (|\mu_e| >> \mu_p \Leftrightarrow m_e << m_p) \qquad \boxed{\vec{J} \approx \vec{J}_e}$$



OHM´s law:

$$\vec{J}_e = q_e \cdot n_e \cdot \vec{v}_e = q_e \cdot n_e \cdot \mu_e \cdot \vec{E} = \kappa_e \cdot \vec{E} \approx \kappa \cdot \vec{E}$$

Gas conductivity κ determined mainly by electron parameters: $q_e = -e$

$$\kappa = |\mu_e| \cdot n_e \cdot e = \frac{e^2 \cdot n_e \cdot \tau_s}{m_e}$$

Equations of MHD-Generator (1)

- $\vec{v}_e = \mu_e \cdot \left[\vec{E} + \vec{v} \times \vec{B} + \vec{v}_e \times \vec{B}\right]$ (1) $\qquad \vec{J}_e = -e \cdot n_e \cdot \vec{v}_e \approx \vec{J}$ (2)
- From (1), (2): $\vec{J} = \kappa \cdot \left[\vec{E} + \vec{v} \times \vec{B} - \vec{E}_H\right]$ *HALL*-field strength: $\vec{E}_H = \dfrac{\vec{J} \times \vec{B}}{e \cdot n_e}$

$\kappa = |\mu_e| \cdot n_e \cdot e$: electrical conductivity of the gas

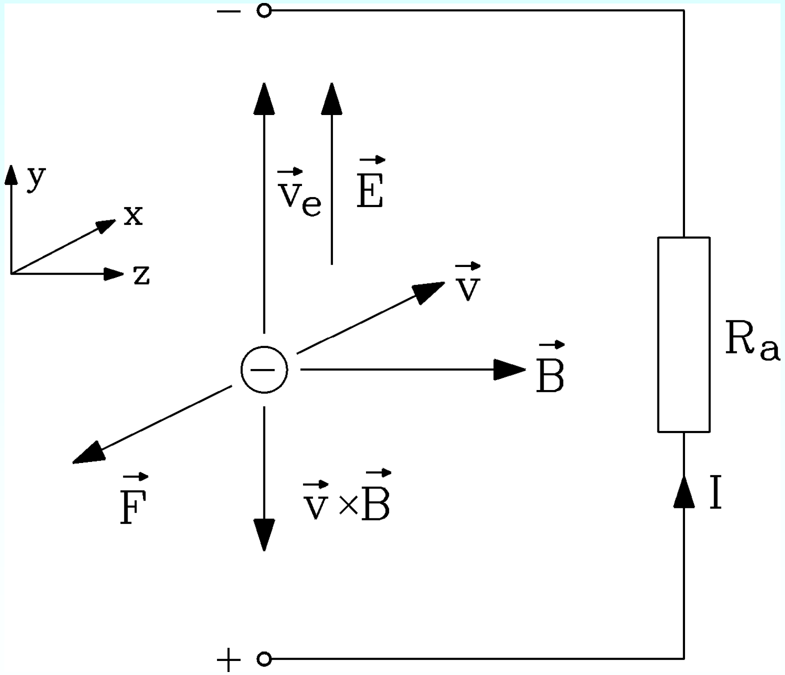
$$\vec{B} = (0,0,B), \vec{v} = (v,0,0) \Rightarrow \vec{J} = (J_x, J_y, 0)$$

$$\Rightarrow \vec{E} = (E_x, E_y, 0)$$

$$J_x = \frac{\kappa}{1+\beta^2} \cdot \left[E_x - \beta \cdot (E_y - v \cdot B)\right]$$

$$J_y = \frac{\kappa}{1+\beta^2} \cdot \left[E_y - v \cdot B + \beta \cdot E_x\right]$$

$\beta = \dfrac{e \cdot \tau_s \cdot B}{m_e} = |\mu_e| \cdot B$: *HALL*-Parameter



Equations of MHD-Generator (2)

$$\vec{B} = (0,0,B),\ \vec{v} = (v,0,0) \Rightarrow \vec{J} = (J_x, J_y, 0)$$

$$\vec{J} = \kappa \cdot \left[\vec{E} + \vec{v} \times \vec{B} - \frac{\vec{J} \times \vec{B}}{e \cdot n_e} \right] \quad \Rightarrow \quad \begin{pmatrix} J_x \\ J_y \\ 0 \end{pmatrix} = \kappa \cdot \begin{pmatrix} E_x \\ E_y \\ 0 \end{pmatrix} + \kappa \cdot \begin{pmatrix} 0 \\ -v \cdot B \\ 0 \end{pmatrix} - \frac{\kappa}{e \cdot n_e} \cdot \begin{pmatrix} J_y B \\ -J_x B \\ 0 \end{pmatrix}$$

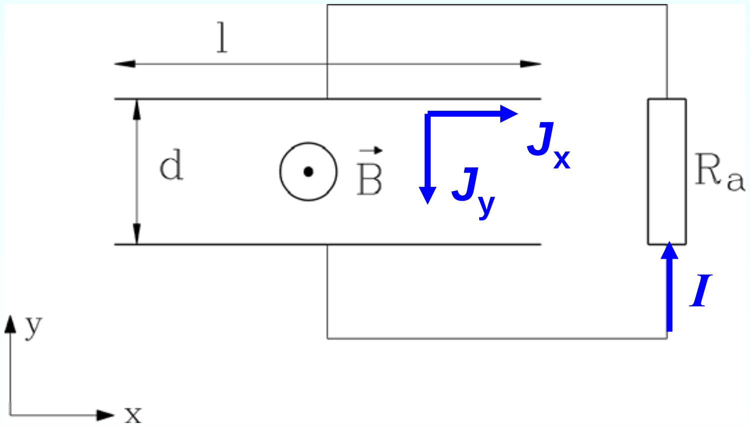
$$J_x = \kappa \cdot E_x - \frac{\kappa \cdot B}{e \cdot n_e} \cdot J_y$$

$$J_y = \kappa \cdot E_y - \kappa \cdot v \cdot B + \frac{\kappa \cdot B}{e \cdot n_e} \cdot J_x$$

$$J_x = \frac{\kappa}{1+\beta^2} \cdot \left[E_x - \beta \cdot (E_y - v \cdot B) \right]$$

$$J_y = \frac{\kappa}{1+\beta^2} \cdot \left[E_y - v \cdot B + \beta \cdot E_x \right]$$

$$\beta = \frac{e \cdot \tau_s \cdot B}{m_e} = |\mu_e| \cdot B$$: *HALL*-Parameter



Summary:
Physical basics of MHD energy conversion

- Hot, partially ionized gases act as electrically conductive fluids
- Exposed to magnetic field: Magneto-hydrodynamic interaction (MHD)
- *Lorentz* force on moving conductive fluid separates charges = voltage induction (*Faraday* effect)
- Current flow at load is subjected to *Hall* effect
- Linear generator or linear motor operation

4. *M*agneto-*h*ydro*d*ynamic (MHD) energy converters & Electric satellite drives

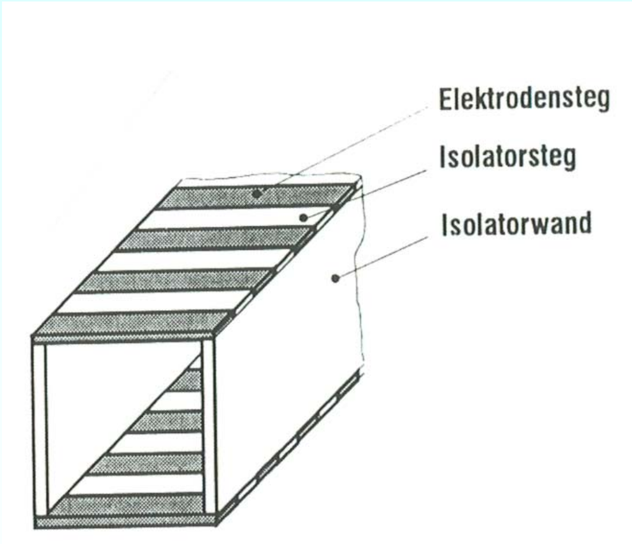
4.1 Physical basics of MHD energy conversion

4.2 FARADAY- and HALL-Generator

4.3 Future perspectives of MHD

4.4 Electric satellite drives

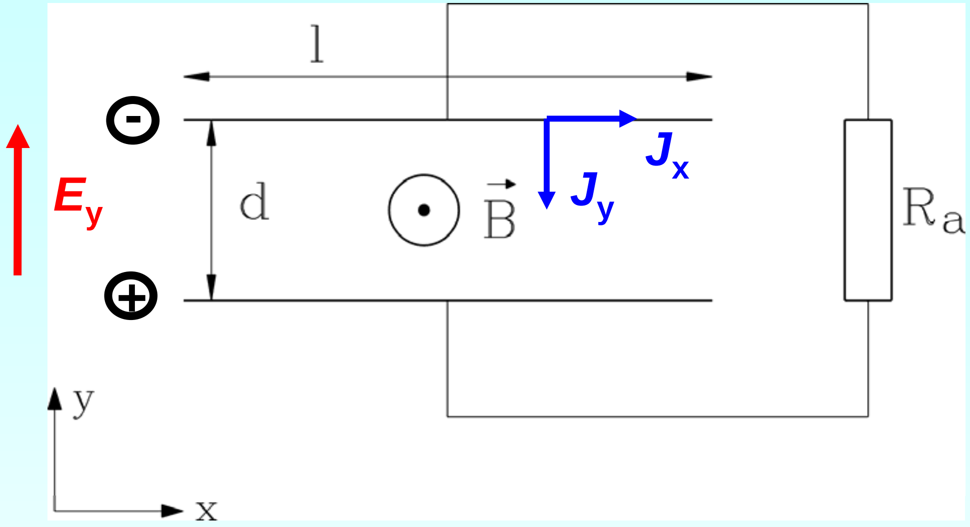
4.2 FARADAY- and HALL-Generator



Source: P. Komarek, Teubner-Verlag

(Non-segmented) *FARADAY*-Generator $\beta \le 0.5$ (1)

- E_x short circuited by electrodes:
  $E_x = 0$; J_x flows in direction of electrodes !



$$J_x = \frac{\kappa}{1+\beta^2} \cdot [0 - \beta \cdot (E_y - v \cdot B)]$$

$$J_y = \frac{\kappa}{1+\beta^2} \cdot [E_y - v \cdot B + 0]$$

$$J_y = \frac{\kappa}{1+\beta^2} \cdot [E_y - v \cdot B], \quad J_x = -\beta \cdot J_y$$

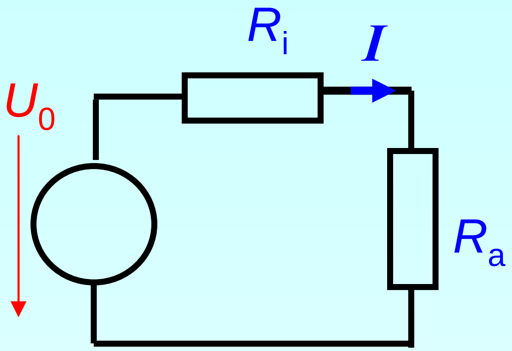
- No-load voltage U_0: $J_y = 0$: $J_y = 0 : E_y - v \cdot B = 0 \Rightarrow E_{y0} = v \cdot B \quad U_0 = v \cdot B \cdot d$

- Power density: $p = P/V$ $\quad p = -\frac{U \cdot I}{V} = -\frac{U \cdot I}{d \cdot A} = -\frac{U}{d} \cdot \frac{I}{A} = -E_y \cdot J_y > 0$

  Generator power in consumer reference frame:

$$p = -J_y E_y = \frac{-\kappa}{1+\beta^2} \cdot [E_y - v \cdot B] \cdot E_y = \frac{-\kappa}{1+\beta^2} \cdot \left[\frac{E_y}{v \cdot B} - 1\right] \cdot \frac{E_y}{v \cdot B} \cdot (v \cdot B)^2$$

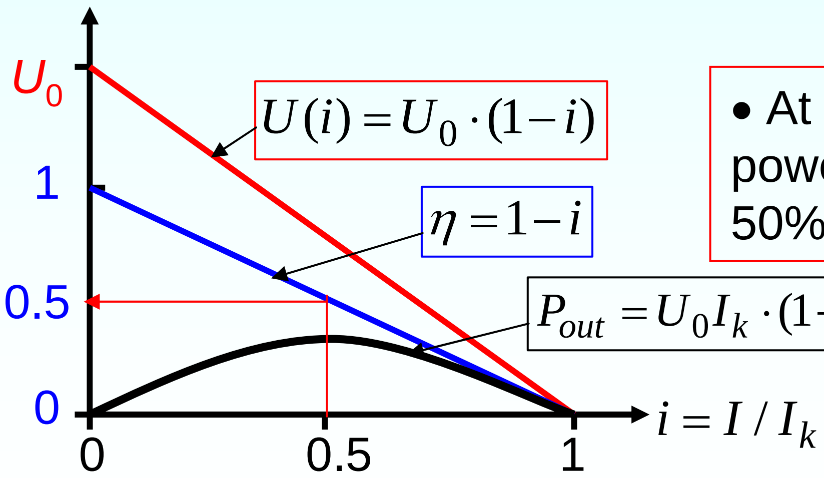
DC Voltage source equivalent circuit (1)



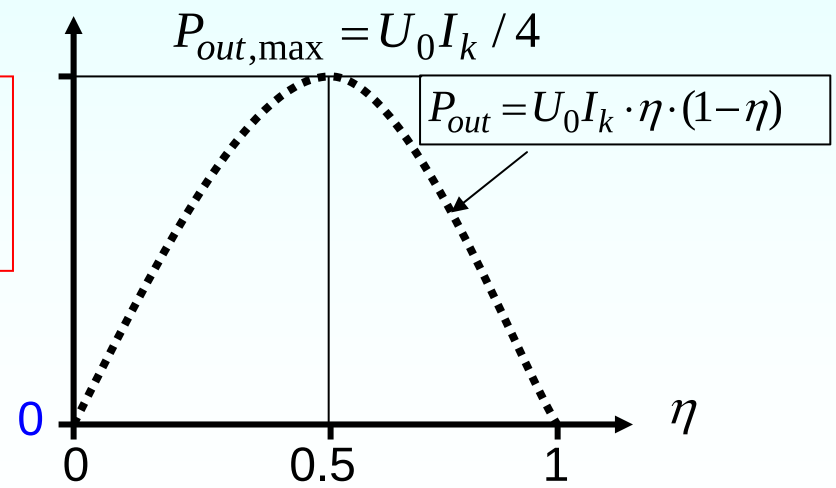
- Short-circuit current: ($R_a = 0$): $I_k = U_0 / R_i$
- Load current: $I = \dfrac{U_0}{R_i + R_a}$
- Relative load current: $i = I / I_k$
- Load characteristic:

$$U = U_0 - I \cdot R_i = U_0 \cdot (1 - I / I_k) = U_0 \cdot (1 - i)$$

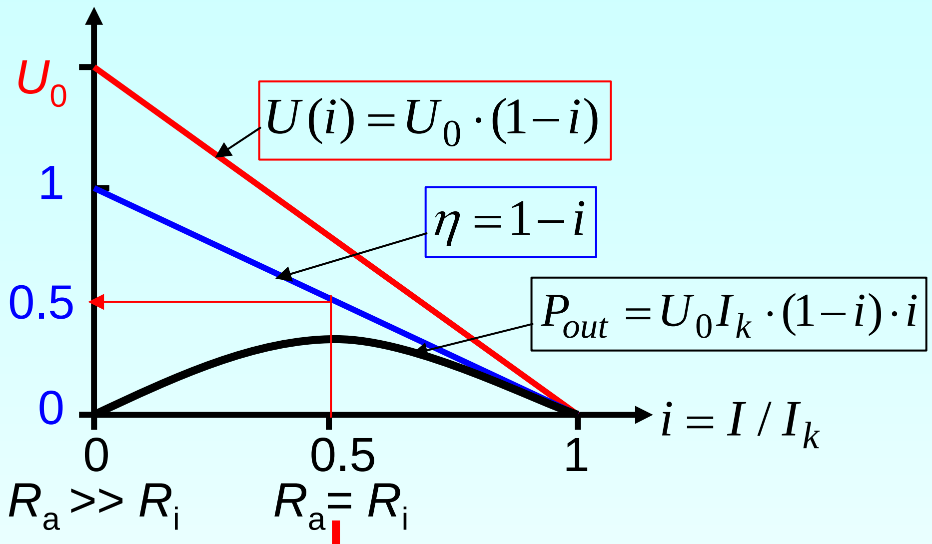
- Output power: $P_{out} = U \cdot I = U_0 I_k \cdot (1 - i) \cdot i$
- Efficiency: $\eta = P_{out} / P_{in} = (U \cdot I) / (U_0 \cdot I) = U / U_0 = 1 - i \quad \Rightarrow \quad P_{out} = U_0 I_k \cdot \eta \cdot (1 - \eta)$



- At maximum power output only 50% efficiency!



DC Voltage source output characteristic (2)



$R_a = R_i$:

MHD generator operation:
High output power aimed = high waste energy in the hot gas = second energy conversion stage required, e.g. steam turbine!

$R_a >> R_i$:

Typical operation condition for energy systems: high efficiency aimed!

But total system power (e.g. grid short-circuit power) much bigger than utilized power!

$R_a = R_i$:

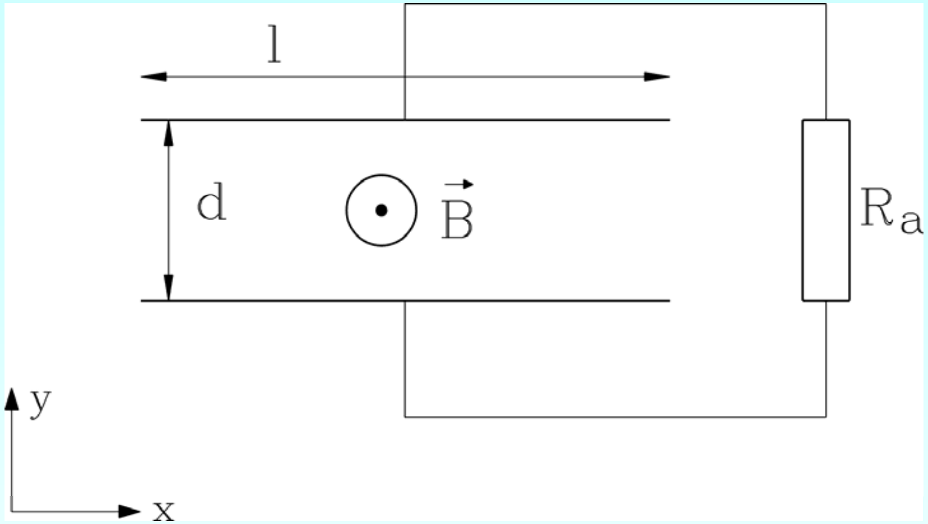
Typical operation condition for communication systems: high transmitted power output aimed!

But: poor system efficiency!

(Non-segmented) *FARADAY*-Generator $\beta \leq 0.5$ (2)

- E_x short circuited by electrodes:
  $E_x = 0$; J_x flows in direction of electrodes !

$$J_y = \frac{\kappa}{1+\beta^2}\cdot\left[E_y - v\cdot B\right],\quad J_x = -\beta\cdot J_y$$



- Efficiency: $\eta = P_{out}/P_{in} = R_a I^2/(U_0 I)$

$$\eta = R_a I/U_0 = E_y/(v\cdot B)$$

- Power density: $p = -J_y E_y = \frac{\kappa}{1+\beta^2}\cdot\eta\cdot(1-\eta)\cdot(v\cdot B)^2$

- ***Result:***

1) p is maximum at the condition: $R_a = R_i$, but then efficiency is only $\eta = 0.5$.

$$p_{max} = \frac{\kappa\cdot(v\cdot B)^2}{4\cdot(1+\beta^2)}$$

2) Power decreases strongly with increasing mobility μ_e: Hence β should be low.

3) Power density rises with v and B:
   - Design of supersonic channel shape for high v recommended,
   - Low temperature superconducting coils for DC excitation of high B necessary!

Segmented FARADAY-Generator 0.5 ≤ β ≤ 5 (1)

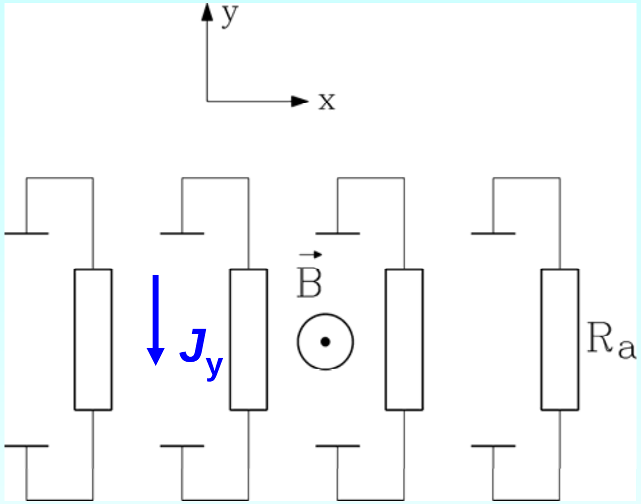
- J_x interrupted by segmented electrodes: $J_x = 0$!

$$J_x = 0 = \frac{\kappa}{1+\beta^2} \cdot \left[E_x - \beta \cdot (E_y - v \cdot B) \right]$$

$$E_x = \beta \cdot (E_y - v \cdot B)$$

$$J_y = \frac{\kappa}{1+\beta^2} \cdot \left[E_y - v \cdot B + \beta \cdot E_x \right] = \kappa \cdot \left[E_y - v \cdot B \right]$$

$$\boxed{J_y = \kappa \cdot (E_y - v \cdot B) \quad J_x = 0}$$



- No-load voltage U_0: $J_y = 0$: $J_y = 0 : E_y - v \cdot B = 0 \Rightarrow E_{y0} = v \cdot B \quad U_0 = v \cdot B \cdot d$

- Power density: $p = P/V$

Generator power in consumer reference frame:

$$p = -J_y E_y = -\kappa \cdot \left[E_y - v \cdot B \right] \cdot E_y = -\kappa \cdot \left[\frac{E_y}{v \cdot B} - 1 \right] \cdot \frac{E_y}{v \cdot B} \cdot (v \cdot B)^2$$

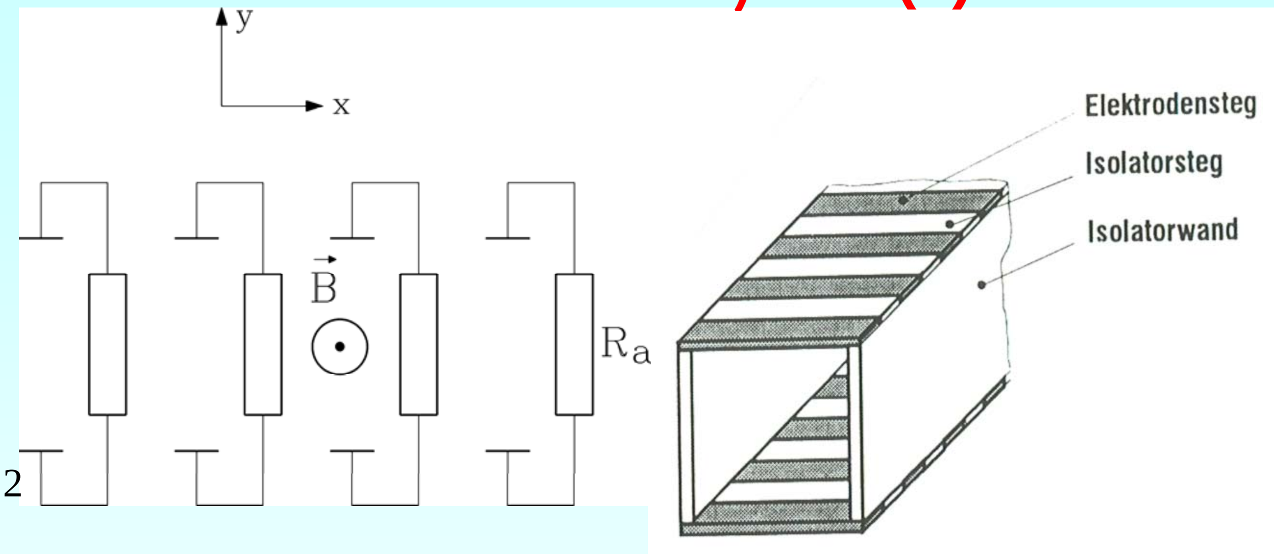
Segmented FARADAY-Generator $0.5 \leq \beta \leq 5$ (2)

- **J_x interrupted by segmented electrodes: $J_x = 0$!**

$$J_y = \kappa \cdot (E_y - v \cdot B)$$

- **Power density:**

$$p = -J_y E_y = \kappa \cdot \eta \cdot (1-\eta) \cdot (v \cdot B)^2$$



- ***Result:*** $p_{max} = \kappa \cdot (v \cdot B)^2 / 4$

Source: P. Komarek, Teubner-Verlag

1) Maximum power density *p* of all different MHD generator configurations!

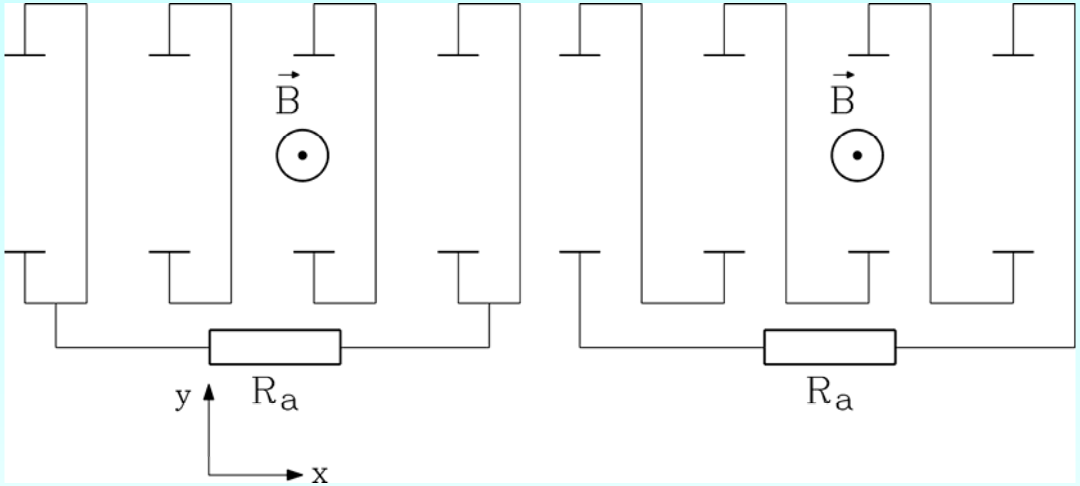
2) Although β might be high, the HALL-effect has no influence due to the segmented electrodes.

3) Segmentation by insulation must not be bridged by conductive gas remnants such as particles from burnt coal!

4) High conductivity (= high mobility) allows high power density.

MHD-Hall-Generator β > 5 (1)

- E_y short circuited by electrodes: $E_y = 0$



$$J_x = \frac{\kappa}{1+\beta^2}\cdot\left[E_x - \beta\cdot(0 - v\cdot B)\right]$$

$$J_y = \frac{\kappa}{1+\beta^2}\cdot\left[0 - v\cdot B + \beta\cdot E_x\right]$$

$$J_x = \frac{\kappa}{1+\beta^2}\cdot\left[E_x + \beta\cdot v\cdot B)\right]$$

- Power density: $p = P/V$

Generator power in consumer reference frame:

$$p = -J_x E_x = \frac{-\kappa}{1+\beta^2}\cdot\left[\frac{E_x}{\beta\cdot v\cdot B} + \frac{\beta\cdot v\cdot B}{\beta\cdot v\cdot B}\right]\cdot\frac{E_x}{\beta\cdot v\cdot B}\cdot(\beta\cdot v\cdot B)^2$$

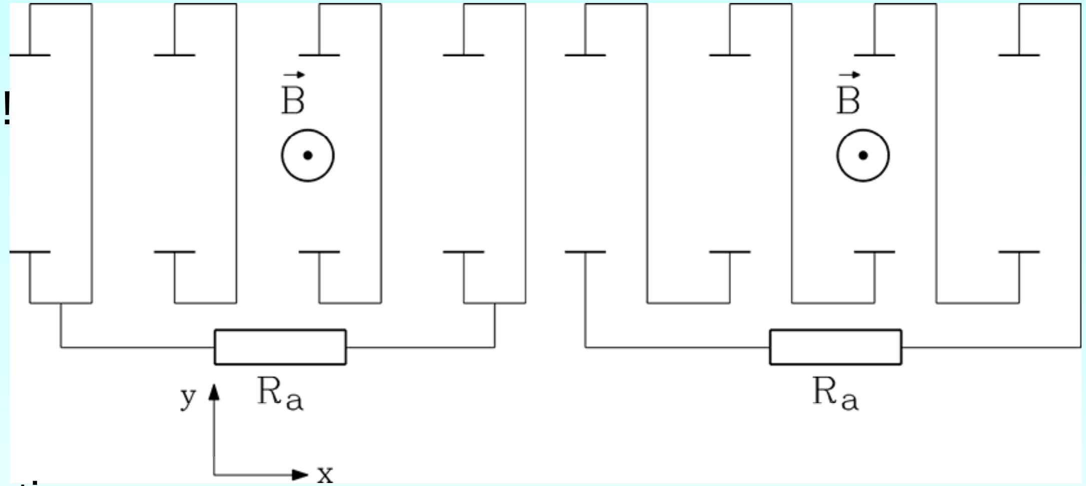
MHD-Hall-Generator β > 5 (2)

- *HALL*-effect dominates: $U_H >> v \cdot B$

- E_x dominates over E_y and is therefore used!

- E_y short circuited by electrodes: $E_y = 0$

$$J_x = \frac{\kappa}{1+\beta^2} \cdot [E_x + \beta \cdot v \cdot B]$$



- J_x interrupted in electrodes by segmentation.
- No load voltage at $J_x = 0$: $E_{x0} = -\beta \cdot v \cdot B, \quad U_{H0} = E_{x0} \cdot l$
- Efficiency: $\eta_H = P_{out} / P_{in} = R_a I^2 / (U_{H0} I) = R_a I / U_{H0} = -E_x / (\beta \cdot v \cdot B)$
- Power density: $$p = -J_x E_x = \frac{\kappa \cdot \beta^2}{1+\beta^2} \cdot \eta_H \cdot (1-\eta_H) \cdot (v \cdot B)^2$$ $$p_{\max} = \frac{\kappa \cdot \beta^2}{1+\beta^2} \cdot \frac{(v \cdot B)^2}{4}$$
- *Result:* Maximum power density is lower for same β than in the segmented *FARADAY*-generator, but it is higher than in the non-segmented *FARADAY*-generator

MHD-Generator overview

$0 \le \beta \le 0.5$

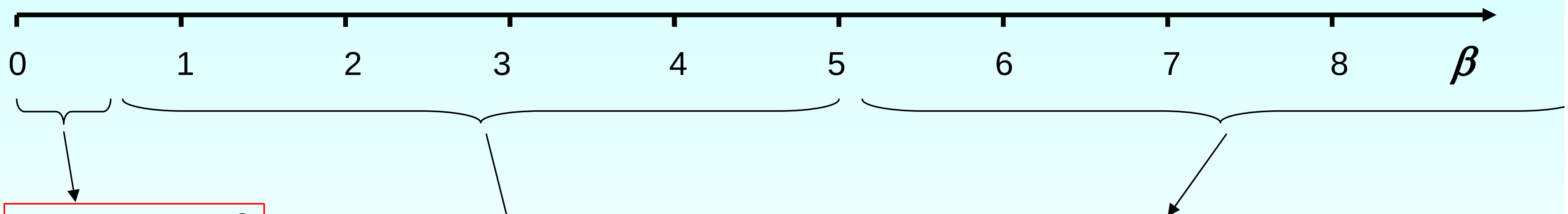
Non-segmented FARADAY-Generator

$0.5 \le \beta \le 5$

Segmented FARADAY-Generator

$\beta \ge 5$

HALL-Generator



$$p_{\max} = \frac{\kappa \cdot (v \cdot B)^2}{4 \cdot (1+\beta^2)}$$

$$\frac{1}{1+\beta^2} \ge \frac{1}{1+0.5^2} = 0.8$$

$$p_{\max} = \kappa \cdot (v \cdot B)^2 / 4$$

$$1$$

$$p_{\max} = \frac{\kappa \cdot \beta^2}{1+\beta^2} \cdot \frac{(v \cdot B)^2}{4}$$

$$\frac{\beta^2}{1+\beta^2} \ge \frac{5^2}{1+5^2} = 0.96$$

Summary:
FARADAY- and HALL-Generator

- Dominating use of *Faraday* effect or *Hall* effect leads to either *Faraday*- or *Hall*-MHD-generator
- MHD-generator is a DC voltage source
- Segmented electrodes are necessary for high efficiency
- Segmented Faraday generator has highest power density

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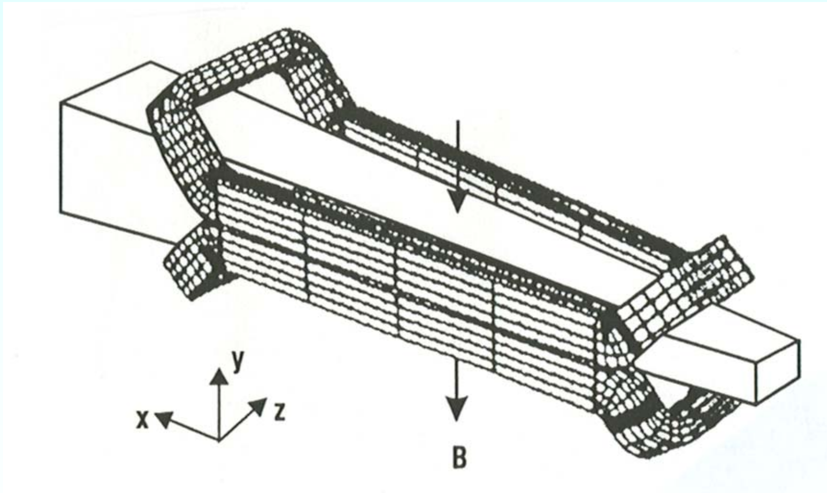
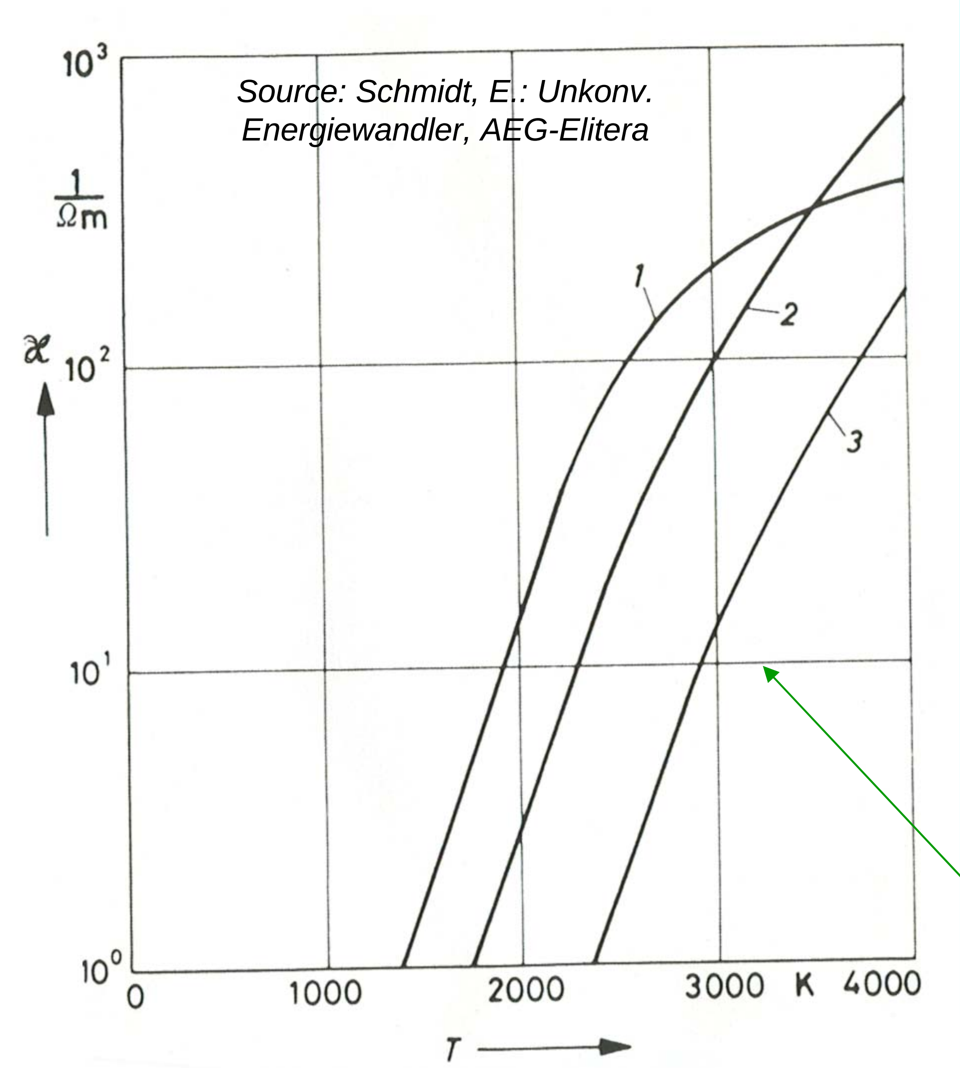
4.3 Future perspectives of MHD



Source: IEEE PES magazine

Performance of MHD-generators

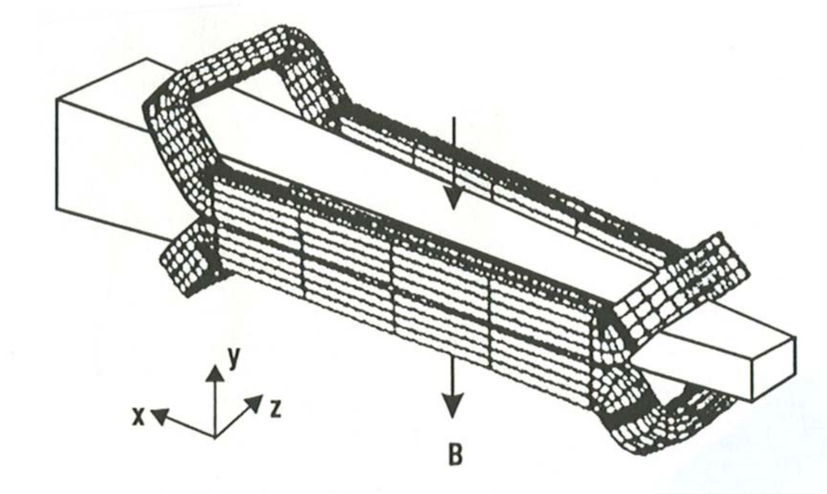


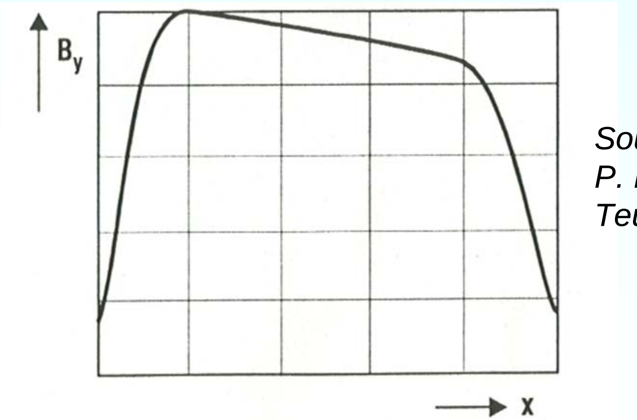
- For high power density: $p \sim \kappa \cdot (v \cdot B)^2$
- a) high B = superconducting exciter coils
- b) high κ = hot, specially doped gases
- c) high v = supersonic flow of the gas
- Hot doped gases: Cesium has the lowest ionizing energy, but is very expensive
- Rare gas, mixed with Cesium, demands a closed gas circulation to avoid gas loss, but needs a heat exchanger (for T > 2500 K !)
- Open gas circulation with carbon burning = cheap gas, but exhaust gas cleaning necessary to regain the doping gas Cs.

<u>Conductivity</u> κ of ionized doped rare gases:
1: Argon + 0.1% Cs, 2: He + 2% Cs
3: Argon + 1% K (100 bar !)

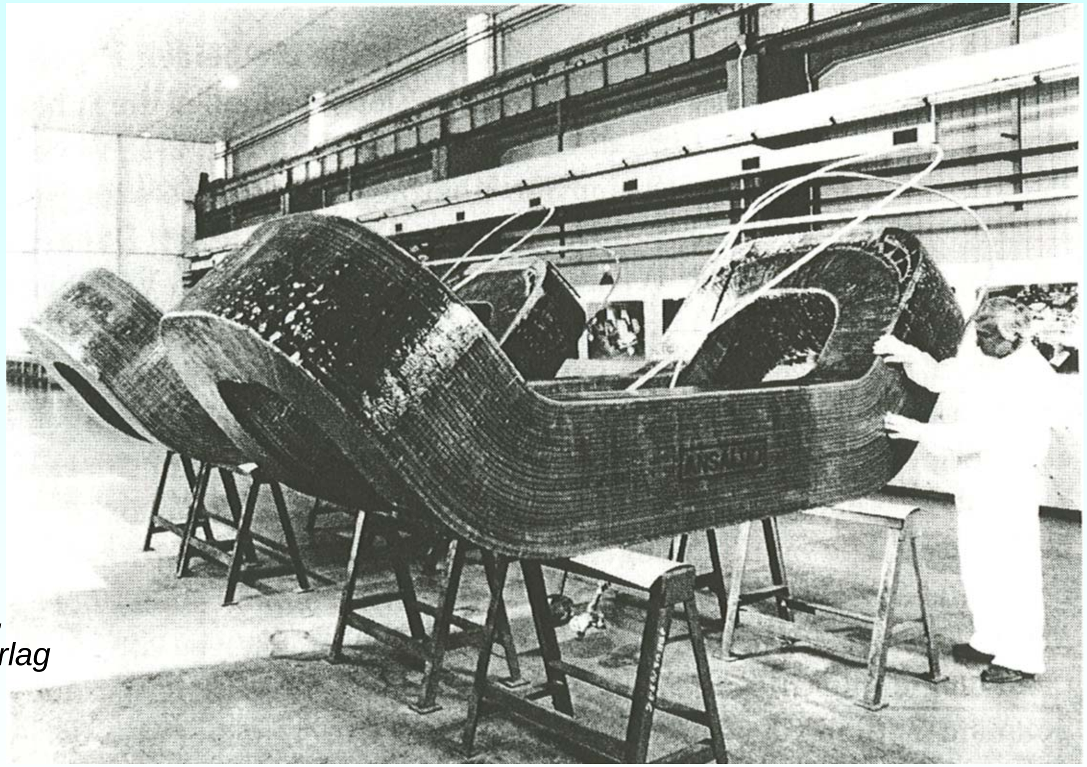
Prototype example: Rectangular channel cross section

- Supersonic channel shape needs increase of cross-section, hence *B* decreases.
- LTSC NbTi-coils in copper matrix, in austenitic steel housing: current I_s = 9 kA, $I_{s,c}$ = 16 kA, 5 T





Source:
P. Komarek,
Teubner-Verlag



Source: IEEE PES magazine & Ansaldo, Genova, Italy

Design example of a MHD generator

- ***FARADAY*-MHD-Generator, segmented electrodes**

  Closed gas circulation: Ar + 0.1% Cs: 2000 K, κ = 10 S/m at the channel inlet

  ***Mach-number*: *Ma* = 0.8, *v* = 800 m/s, *B* = 5 T,**

  Channel length *l* = 10 m, diameter *d* = 1 m, cross section area *A* = 1 m^2

- **No-load voltage:** $U_0 = v \cdot B \cdot d = 800 \cdot 5 \cdot 1 = 4\ \mathrm{kV}$

  Efficiency at $R_i = R_a$ for max. power: $\eta = 0.5$

  Power density at channel inlet:

  $$p_{max} = \kappa \cdot \eta \cdot (1-\eta) \cdot (v \cdot B)^2 = 10 \cdot 0.25 \cdot (800 \cdot 5)^2 = 40\ \mathrm{MW/m^3}$$

  At channel outlet already reduced temperature & power: $p = p_{max} / 10$

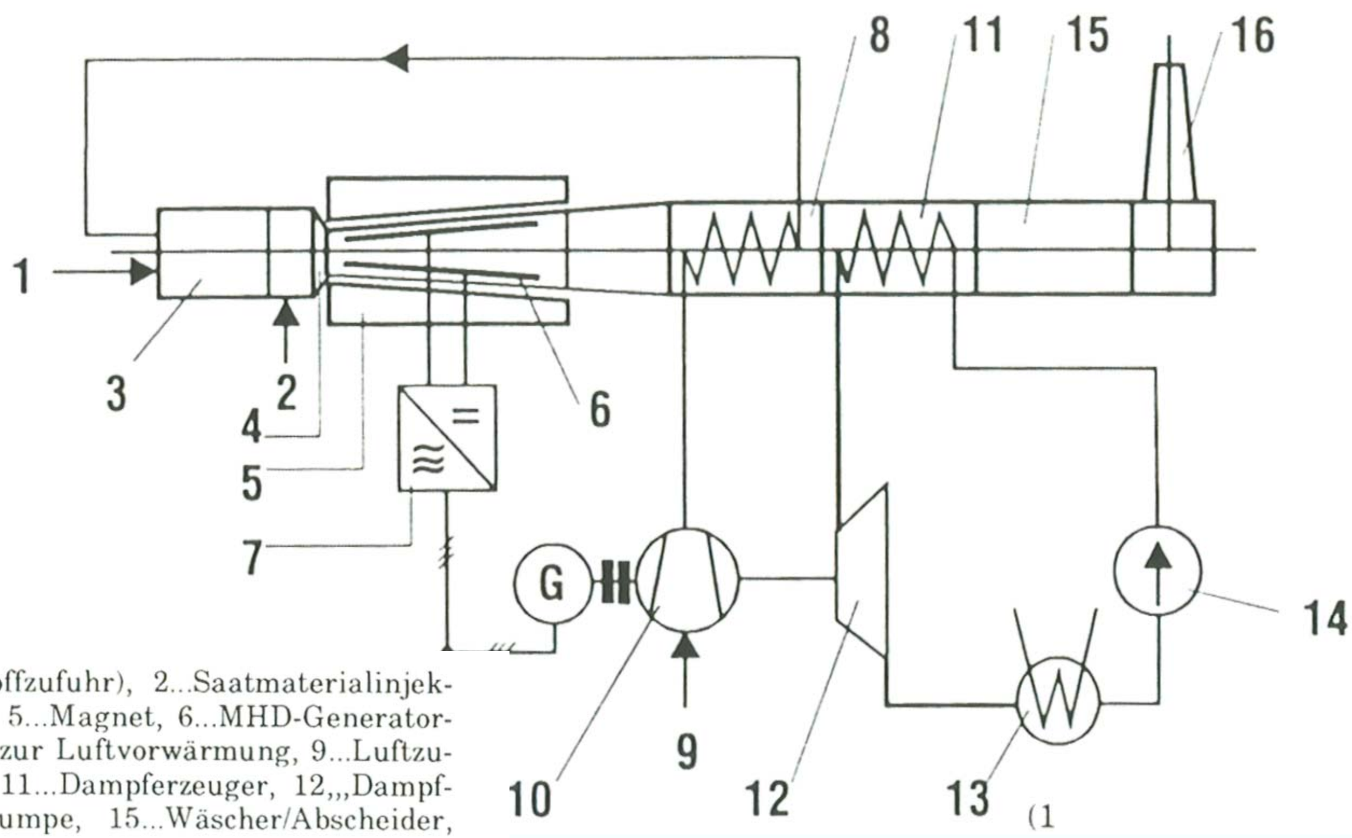
  Power: $P = (p_{max} + p)/2 \cdot (A \cdot l) = (40 + 4)/2 \cdot (1 \cdot 10) = 220\ \mathrm{MW}$

  10 segments: Current per segment: $I = P/(10 \cdot U_0) = 220/(10 \cdot 4) = 5.5\ \mathrm{kA}$

- **Below 2000 K conductivity falls rapidly, so *p* gets too low. Exhaust gas must still be very hot, so its energy should be used for steam generation in a conventional thermal plant (MHD-combined plant !)**

MHD-combined power plant

Source: Schmidt, E.: Unkonv. Energiewandler, AEG-Elitera



(1...Brennstoffzufuhr), 2...Saatmaterialinjektion, 3...Verbrennungskammer, 4...Düse, 5...Magnet, 6...MHD-Generatorkanal, 7...Umrichter, 8...Wärmetauscher zur Luftvorwärmung, 9...Luftzufuhr, G...Generator, 10...Luftverdichter, 11...Dampferzeuger, 12,,,Dampfturbine, 13...Kondensator, 14...Wasserpumpe, 15...Wäscher/Abscheider, 16...Kamin).

- Disadvantage of MHD-plants: Extremely high gas temperatures 2500 K ... 3000 K cause ageing problems for electrodes and isolators. So no long time operation until now possible!

Result: Different prototypes since 30 years investigated, but no industrial use until now!

Summary:
Future perspectives of MHD

- High temperatures of 2500 … 3000 K lead to fast destruction of the electrodes
- Insulation barriers between segmented electrodes may be bridged by conductive gas deposits
- Superconducting coils necessary for magnetic field excitation
- Thermal insulation against 3000 K needed
- MHD generators as primary stages of a thermal power plant at the moment not feasible due to material problems at long-term operation

4. *M*agneto-*h*ydro*d*ynamic (MHD) energy converters & Electric satellite drives

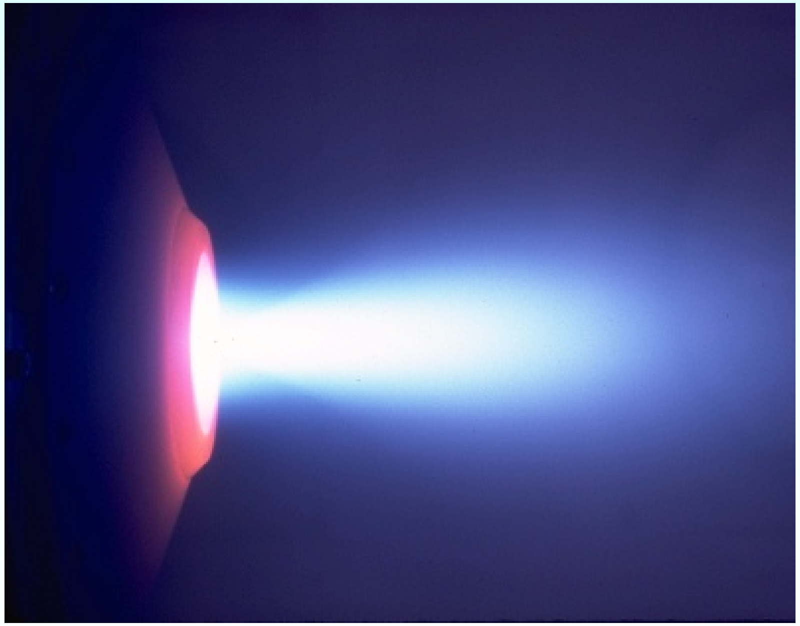
4.1 Physical basics of MHD energy conversion

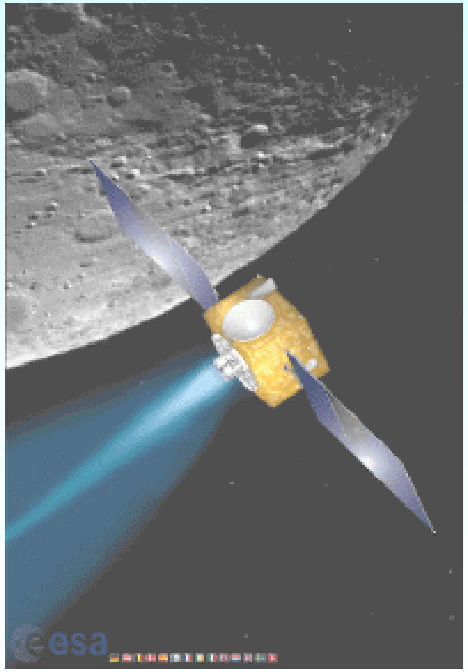
4.2 FARADAY- and HALL-Generator

4.3 Future perspectives of MHD

4.4 Electric satellite drives

4.4 Electric satellite drives





Source: esa, European Space Agency

4.4 Electric satellite drives

Electrical positioning drive for satellites

- Low forces can adjust (geostationary) broadcasting satellites in space, which are operating transceivers/receivers. Normally thermal thrust drives are used, but they need high amount of fuel (load mass of satellite!).

- Alternative: Electrical drives: Ionized gas is accelerated in electrical or magnetic field, and pushes the satellite into the opposite direction. Low need of gas (Rare gas Xenon, which is stored at a pressure 80 ... 150 bar).

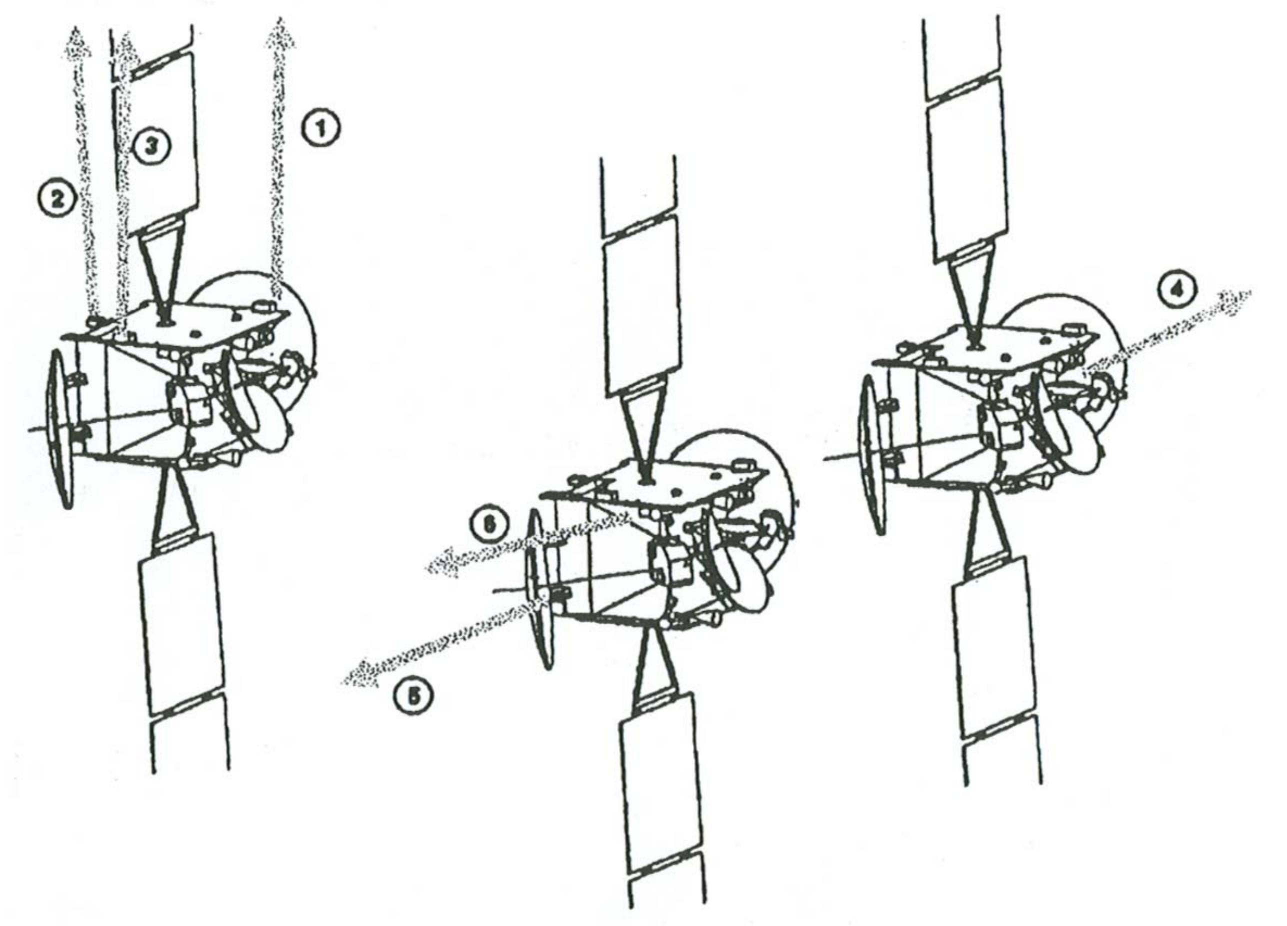
- Different principles:

Electrostatic ion drive AND electromagnetic plasma drive

Geo-stationary satellite TELECOM 2

State-of-the-art technology:

- Positioning of the satellite with thermal thrust drive (burning of fuel = chemical engine)
- 6 drives for different space directions
- Satellite mass 2.3 tons
- 10 years „life time“
- Mass of thrust-engines: 100 kg
- Mass of fuel for 10 years: 1150 kg (hydrazine+oxygen)



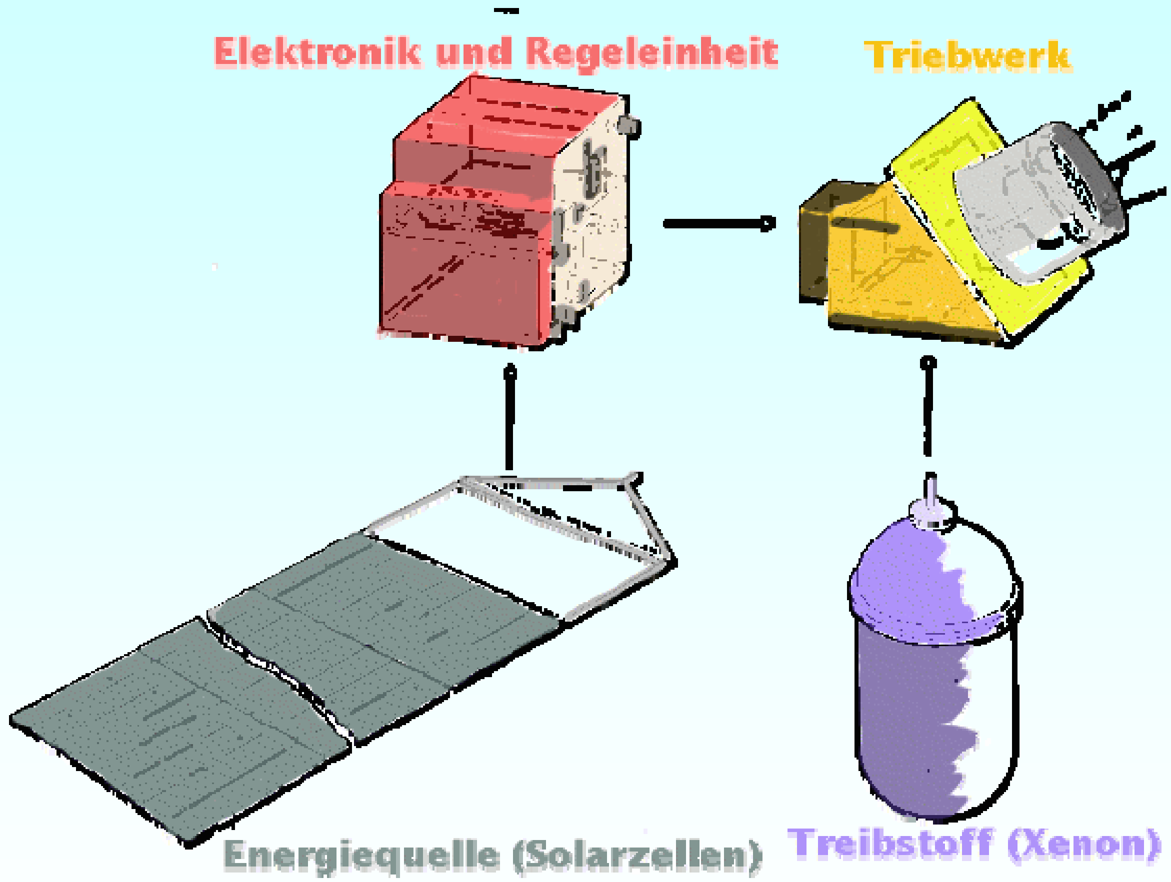
Source: Revue electrique REE, France

Definition of electrical space drive

- Engine creates thrust by direct exhausting a hot ionized gas ("support medium") with a high velocity by the usage of electrical energy
- Primary energy source for ionizing the gas is not involved in the creation of thrust, but gives only the operational energy. So it can be low.
- Compared to chemical engines:
  Burning energy is not carried in the engine and released through burning

Primary energy for ionizing – electrical interaction - kinetic energy of gas jet

Electrical satellite drive system - overview



Source: Univ. Gießen, Germany

Overview on electrical space drive

Electro-thermal drive
[Electric arc engine]

- *Resistojet*
- *Arcjet*

Electrostatic drive
[*Ion drive*]

- Bombardement-ion drive
- *Hall*-ion drive
- Radiofrequency-ion-drive

Electromagnetic drive
[*Plasma-drive, magneto-gasdyn. ~*]

- MPD-self field engine
- MPD-external field engine

4.4 Electric satellite drives

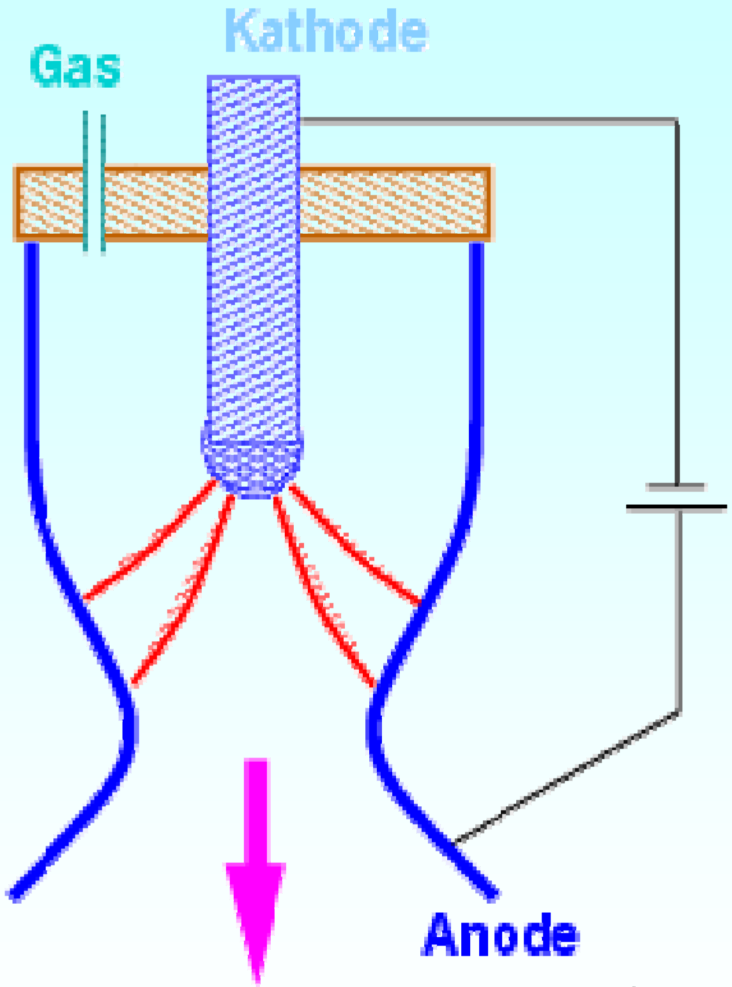
Electro-thermal drive (Arc engine)

- Heating of fuel (e.g. hydrogen H_2, which is stored at high pressure)
- Expanding the gas via a *Laval*-channel for supersonic flow = Generation of high flow velocity

Arcjet:

- Heating of fuel (Hydrazine $H_2N\text{-}NH_2$) with an electric arc to 10 000 K
- Cylindrical cathode inside the burning cell, *Laval*-shaped channel acts as anode

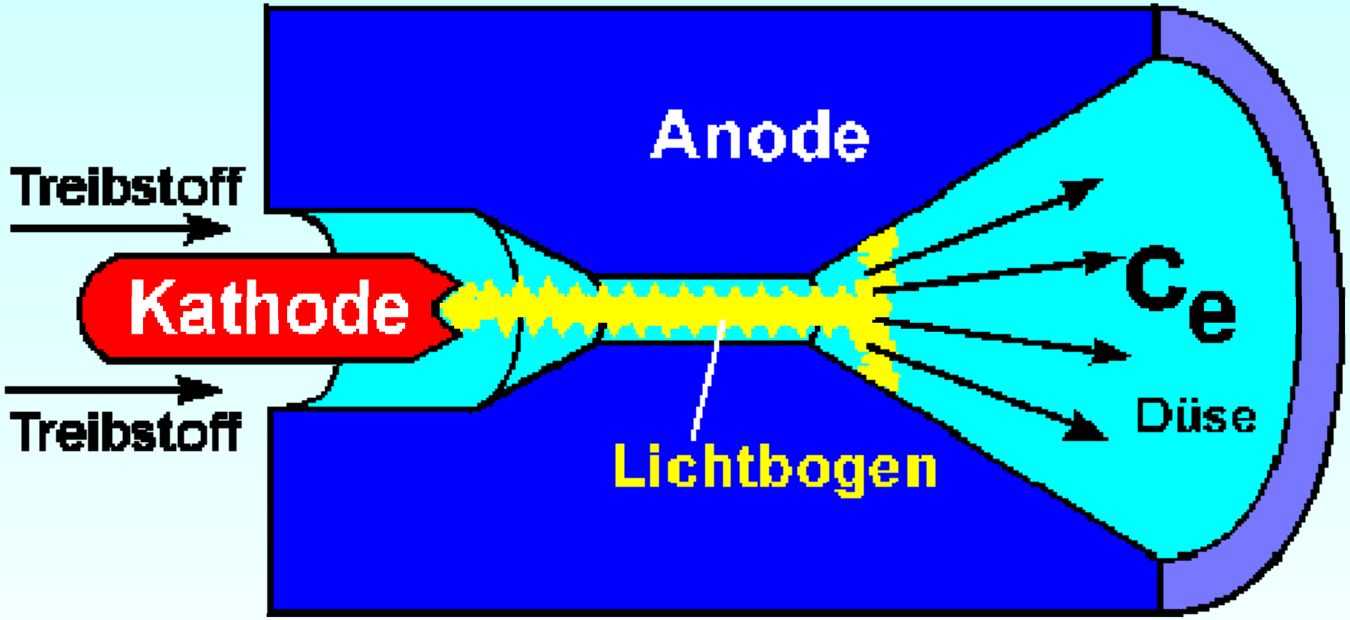
- Advantage: Simple layout
- Disadvantage: Jet velocity only about 10 000 m/s; hence low efficiency ca.30%



***Arcjet*-drive**

Source: Univ. Gießen, Germany

Arcjet drive



Source: Univ. Gießen, Germany

4.4 Electric satellite drives

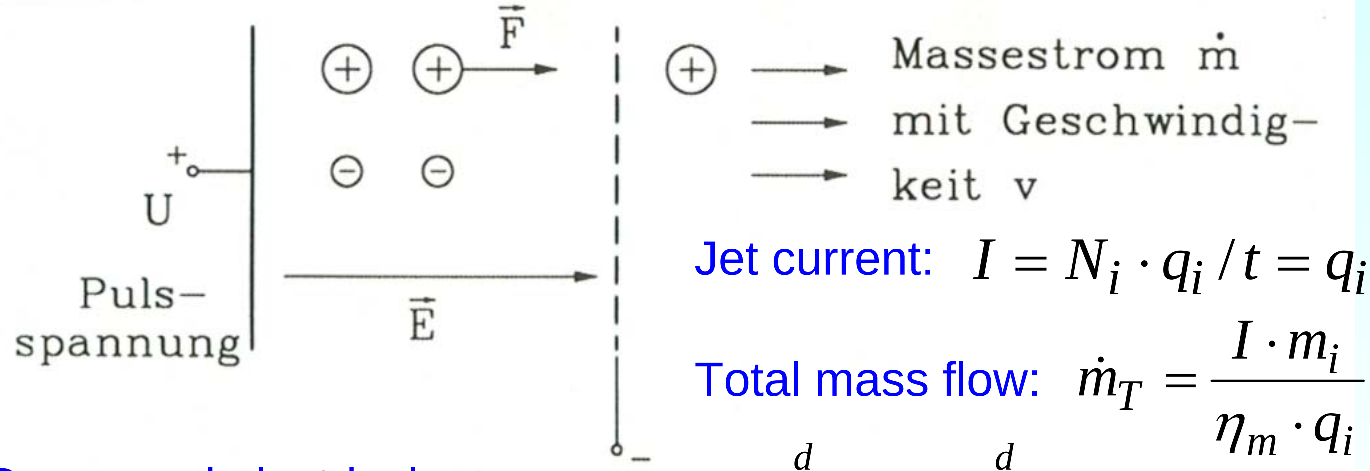
4.4 Electric satellite drives

4.4.2 Electrostatic propulsion system

- *Kaufman*-engine
- RIT-engine
- *Hall*-Ion-propulsion system

Electro-static drive = Ion drive: Thrust generation

- Ion drive: Ionized Xe gas is generated via a gas discharge. Ions are accelerated in the electrostatic field E: Electrostatic force $F_i = q_i \cdot E$.
- The ion flow passes through the perforated anode electrode and leaves the satellite, thus creating a thrust F.
- The ion jet is neutralized afterwards with electrons to avoid satellite charging.



m_i: Ion mass

Jet current: $I = N_i \cdot q_i / t = q_i \cdot \dot{m}_I / m_i$

Total mass flow: $\dot{m}_T = \frac{I \cdot m_i}{\eta_m \cdot q_i} \quad \eta_m < 1$

Consumed electrical energy = kinetic jet energy:

$$W_e = \int_0^d F_i dx = q_i \int_0^d E(x) dx = q_i U = m_i v_i^2 / 2 \rightarrow v_i = \sqrt{2 q_i U / m_i}$$

Thrust: $F = \dot{m}_T \cdot v_T = \frac{m_i I}{\eta_m q_i} \cdot \eta_m \sqrt{2 q_i U / m_i} = I \cdot \sqrt{\frac{2 m_i U}{q_i}}$

$$\boxed{F = I \sqrt{2 \cdot m_i \cdot U / q_i}}$$

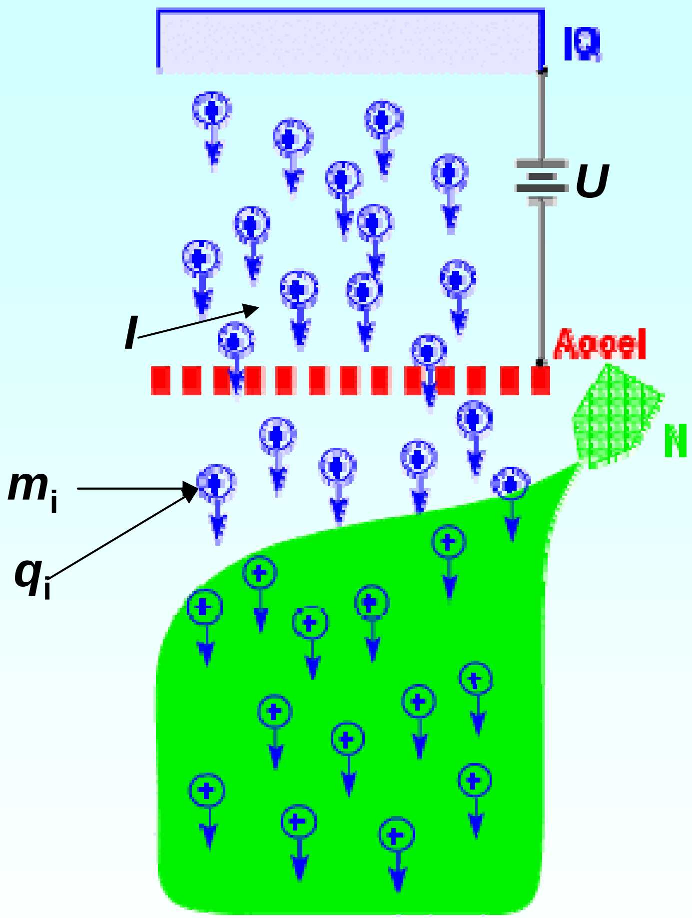
Electro-static drive (Ion drive)

- Ionizing of fuel e.g. by gas-exhausting (IQ: ion source)
- Heavy positive ions extracted and accelerated (no neutral plasma)
- After the accelerated ion beam has left the satellite, it is neutralized with electrons (source *N*)
- Efficiency up to 90%
- Jet velocity up to 100 000 m/s
- Thrust: $$F = I\sqrt{2 \cdot m_i \cdot U / q_i}$$
- Conditions for ideal fuel:
  - High atom weight for heavy ions
  - Easy ionization and vaporization:

  Hence a good candidate is ➔ *Xenon*

  Disadvantage: expensive

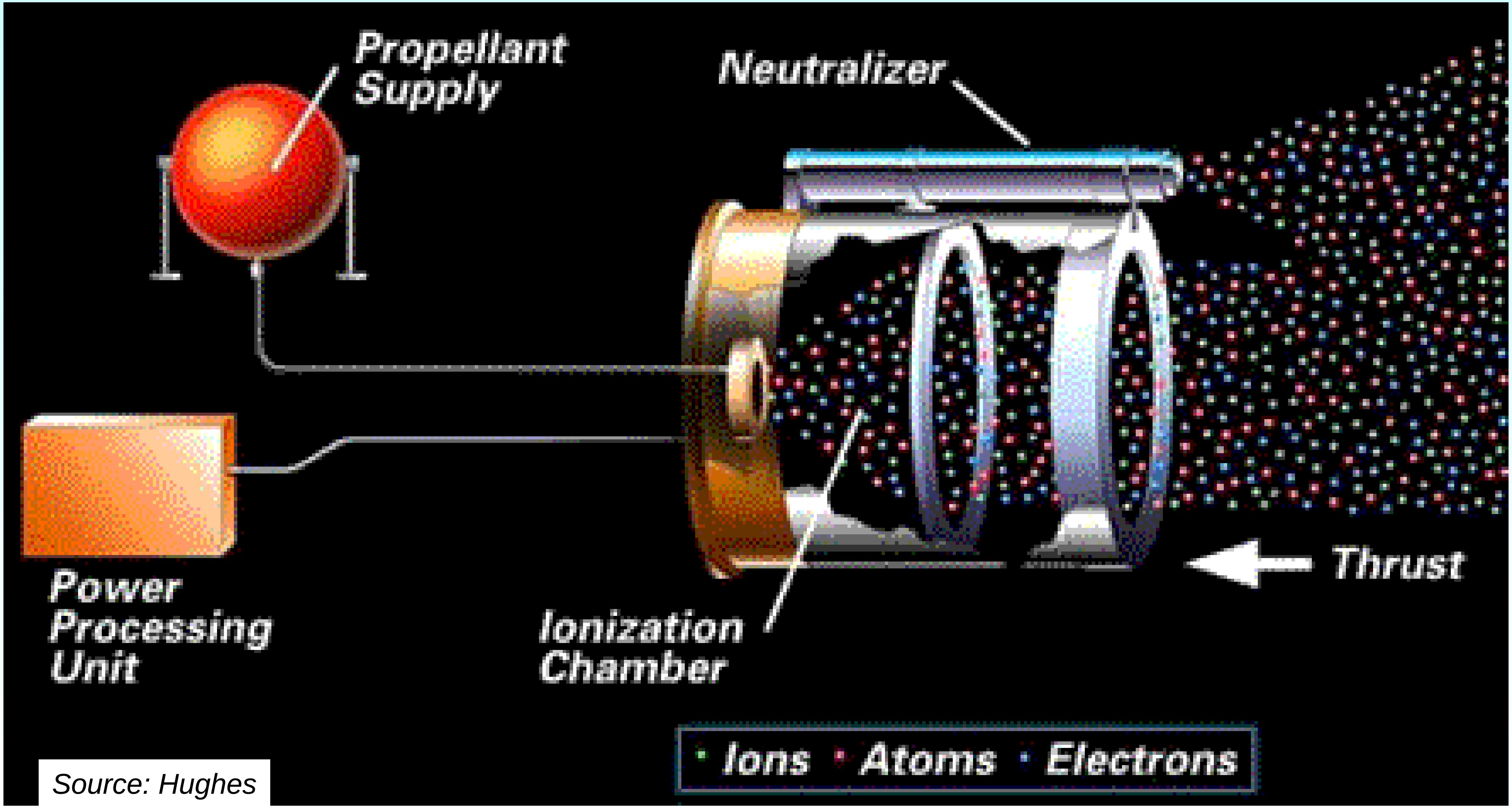
  Advantage: No contamination like with Hg



Source: Univ. Gießen, Germany

Schematic ion drive

Ion drive – Basic principle



Source: Hughes

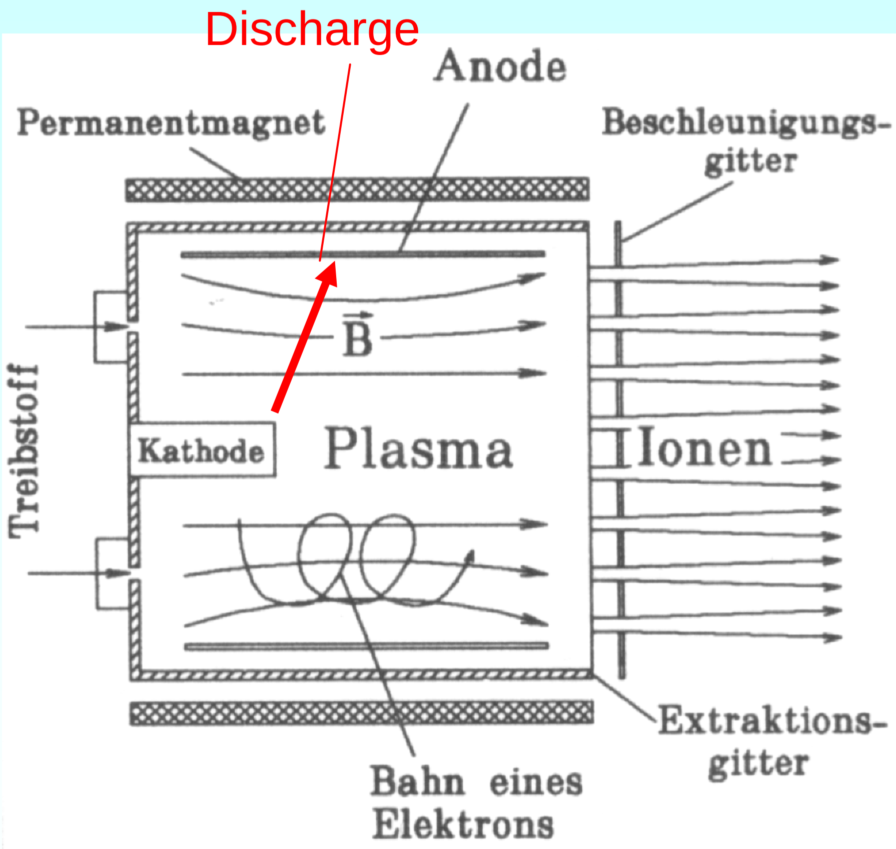
4.4 Electric satellite drives

4.4.2 Electrostatic propulsion system

- *Kaufman*-engine
- RIT-engine
- *Hall*-Ion-propulsion system

Ion drive: Bombardement-Engine

- Creation of electrons by e.g. thermionic emission between central hollow cathode and anode ring
- Ionization by impact between colliding atoms ("Bombardement")
- Impact probability raised by spiral-shaped orbits of electrons. Spiral orbit generated by a permanent magnet field via the *LORENTZ*-force.
- 2 high voltage electrodes as grids allow passing of the accelerated ions
- Up to 200mN thrust
- High efficiency, but not very robust system
- Developed in USA, UK, Japan, mid 1960

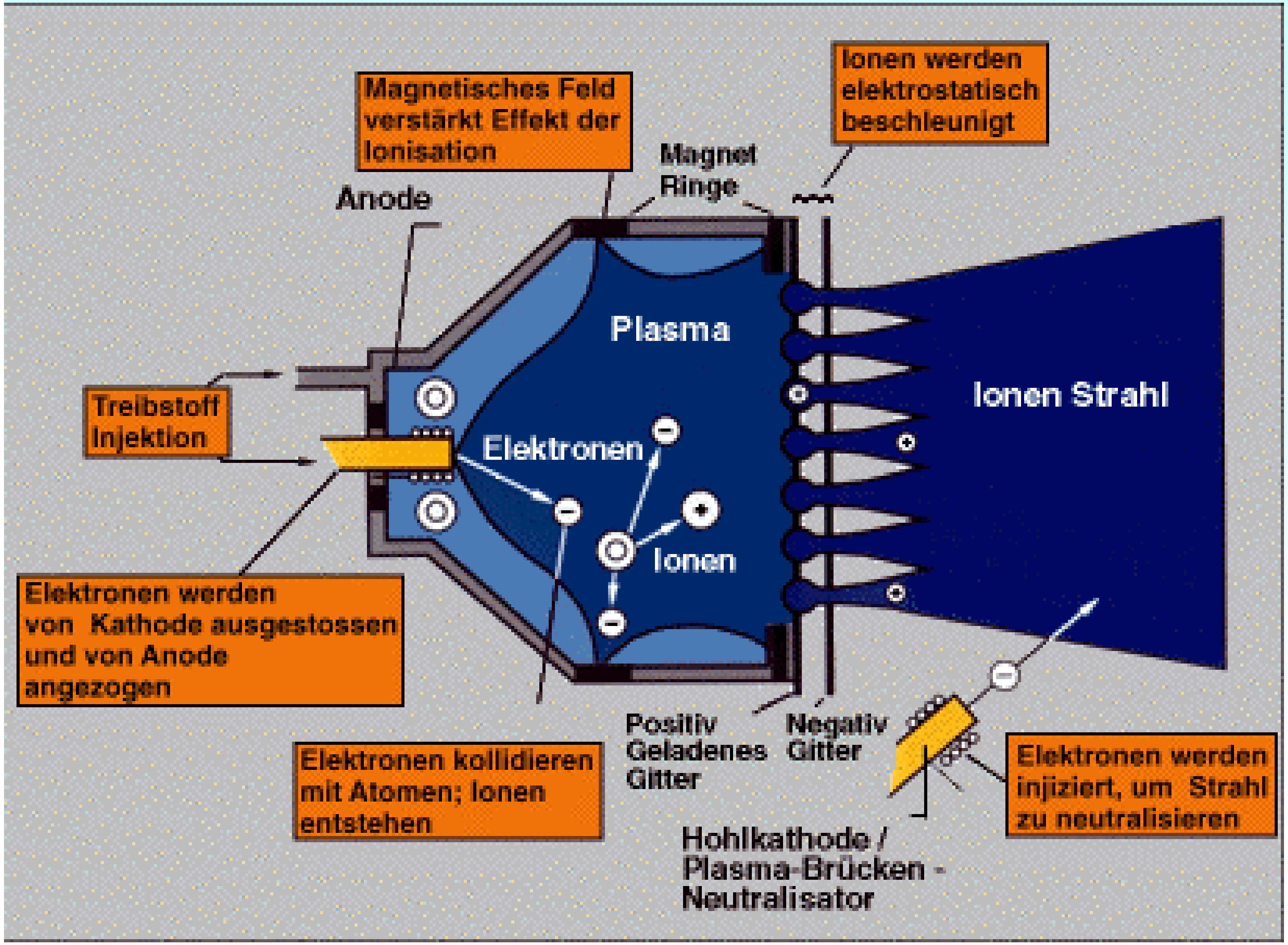


***Kaufman*-engine**

Source: Auweter-Kurtz

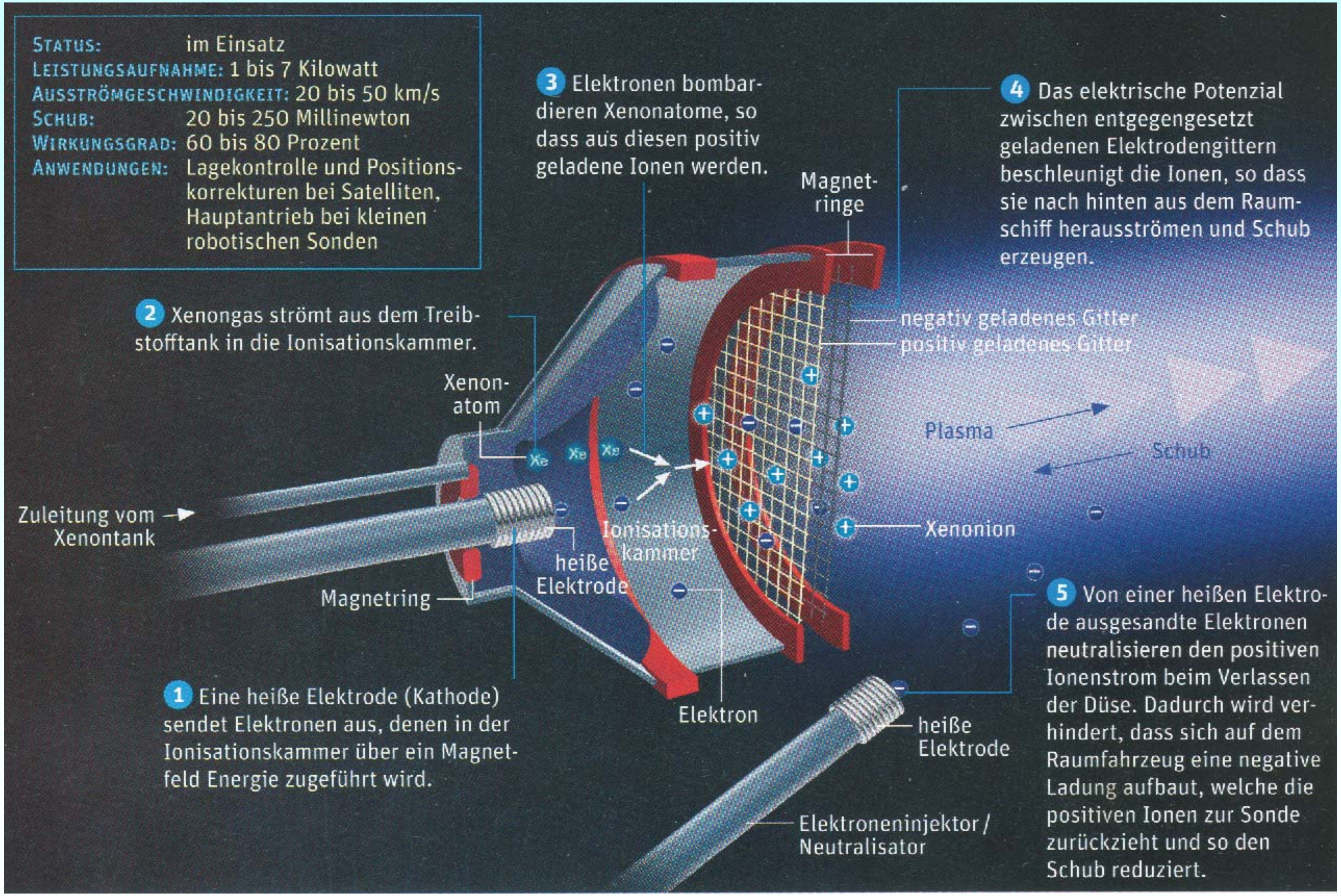
Ion drive: Bombardement engine *(Kaufman)*

Source: Spektrum der Wissenschaft Jan. 2010



Ion drive, ∅ 40 cm, ignited in a test vacuum chamber. The Xe-ions cause a blue light emission.

Ion drive: Overview

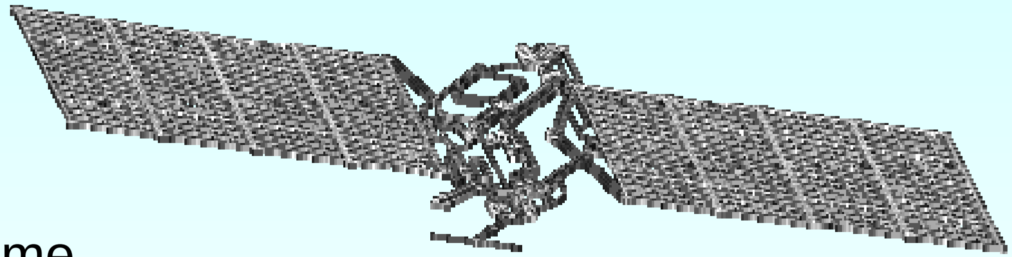


Source: Spektrum der Wissenschaft Jan. 2010

Kaufman Ion drive for *Deep Space 1*

Project *Deep Space 1*:

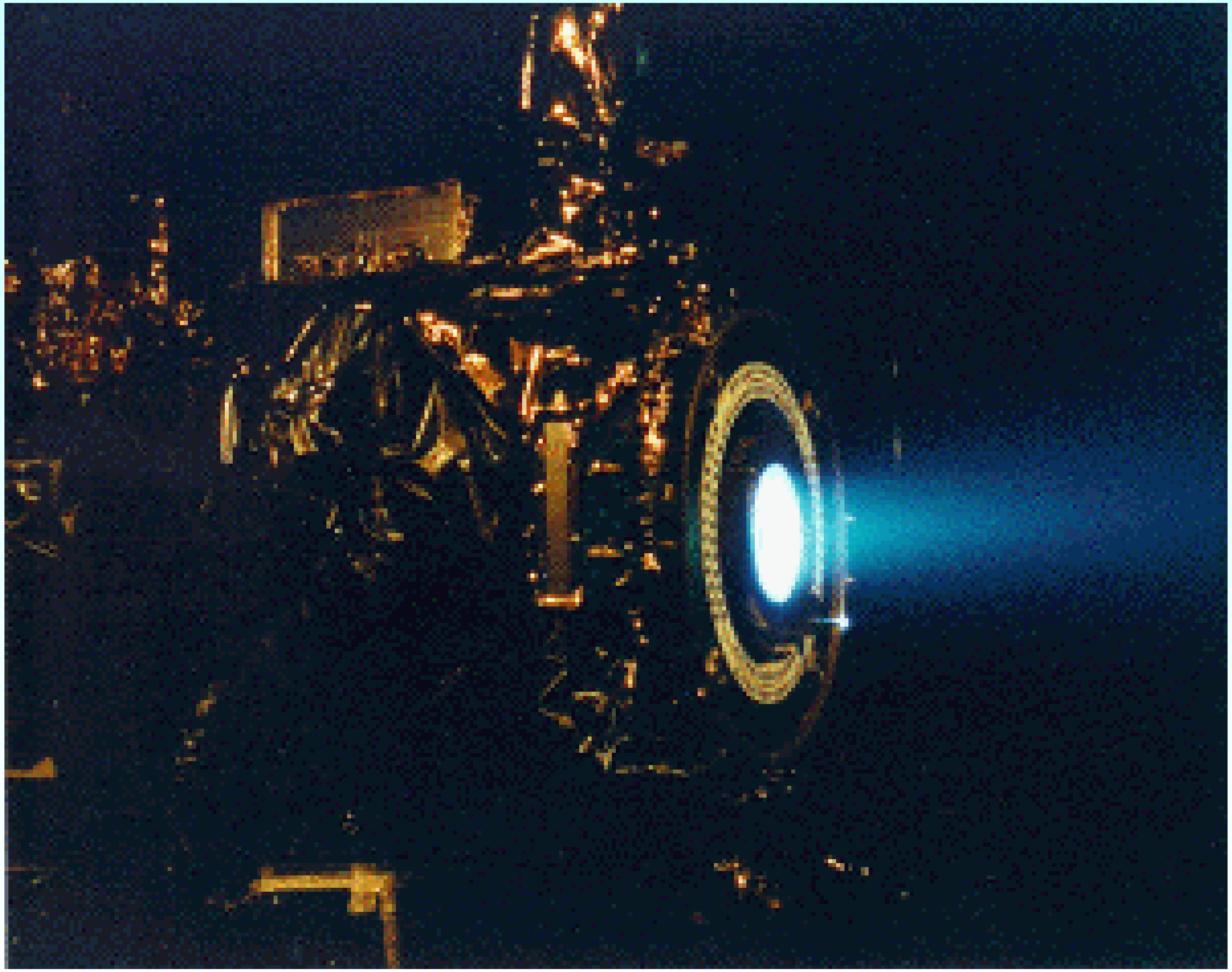
- First time use of a ion drive, energized by sun (photovoltaic) energy
- Solar cells with 23,4 % efficiency and peak power 2,3 kW
- Start 24.10.98 ➔ asteroid *Braille* (27.07.99) ➔ comic *Borrelly* (22.09.01)



Source: Internet

- Mass of space ship 486,3 kg
- Fuel: 81,5 kg Xenon: 8000h burning time
- *Kaufman-engine* with variable throttling gives 20…92 mN thrust
- Space ship has been accelerated up to 13 000km/h in 300 days
  ➔ 10 times faster than chemical driven space ship
- High efficiency (determined as space ship momentum per gram fuel)
- ➔ Less need of fuel than with chemical drive
  (A chemical drive would have a 6-tons engine and 1000 kg of fuel!)

Test of the *Deep Space 1*- Bombardement-Engine



Source:
Homepage of
Project Deep Space

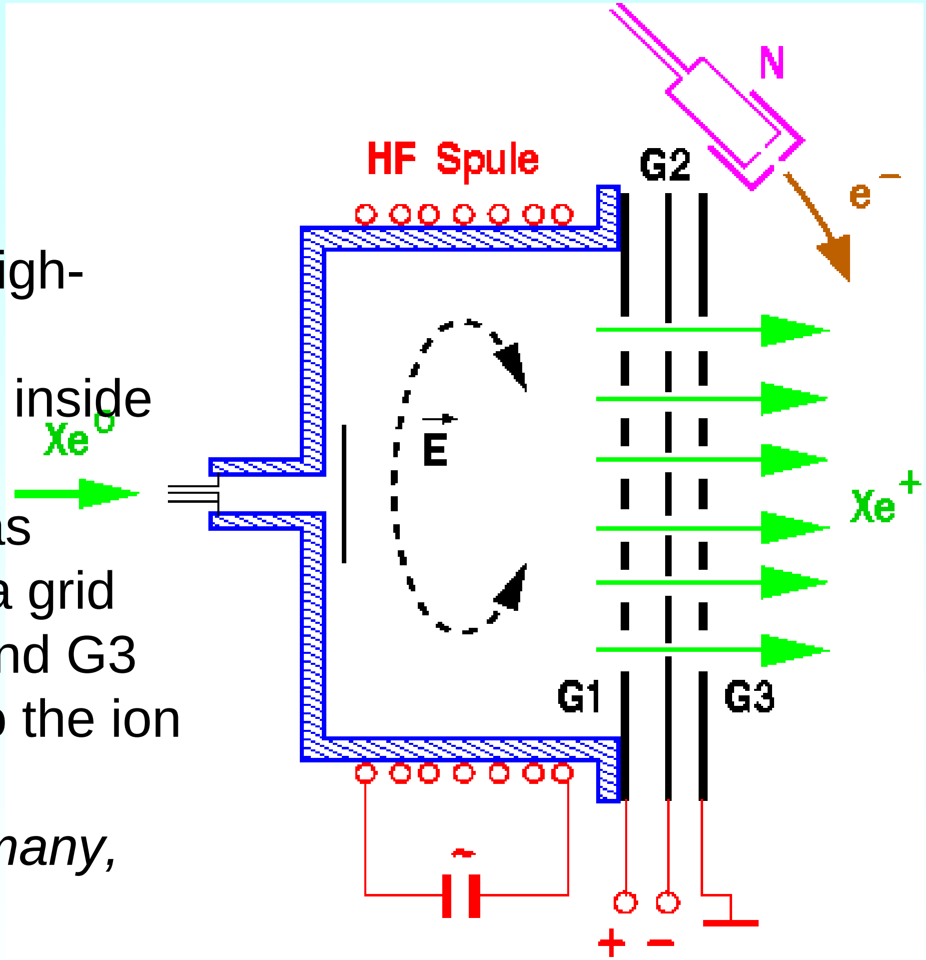
4.4 Electric satellite drives

4.4.2 Electrostatic propulsion system

- *Kaufman*-engine
- RIT-engine
- *Hall*-Ion-propulsion system

Radio frequency-Ion drive (RIT)

- Neutral Xenon gas filled into a discharge chamber
- HF copper coil around chamber couples high-frequency electric curl field *E*
- Curl field drives initial ions. By ion impacts inside chamber ignition of an electrode-less HF-ring discharge ➔ partly ionizing the gas
- Ions extracted from discharge chamber via grid electrodes and accelerated between G1 and G3
- Neutralization source *N* sends electrons to the ion jet
- RIT-drive developed at *Univ. Gießen/Germany, Prof. Löb*

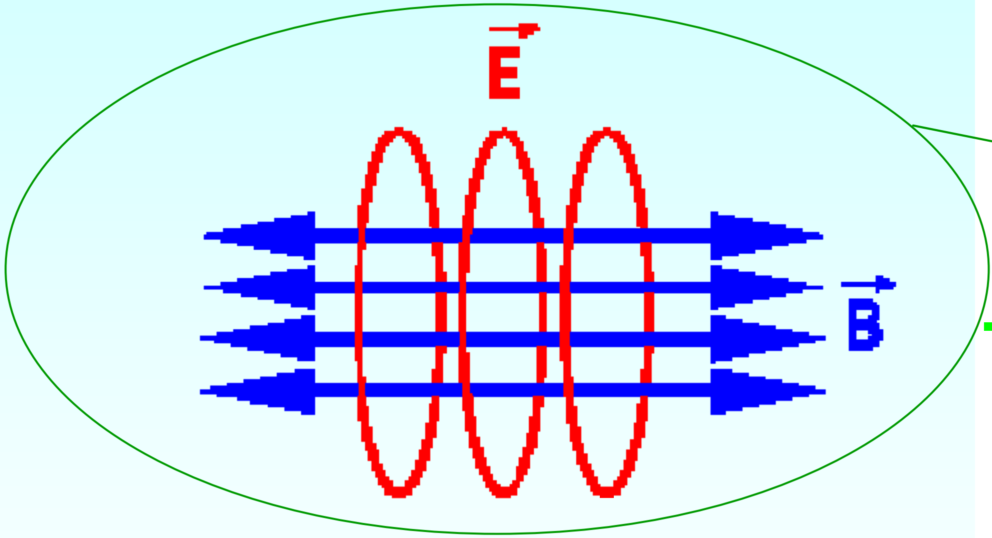


Source: Univ. Gießen, Germany

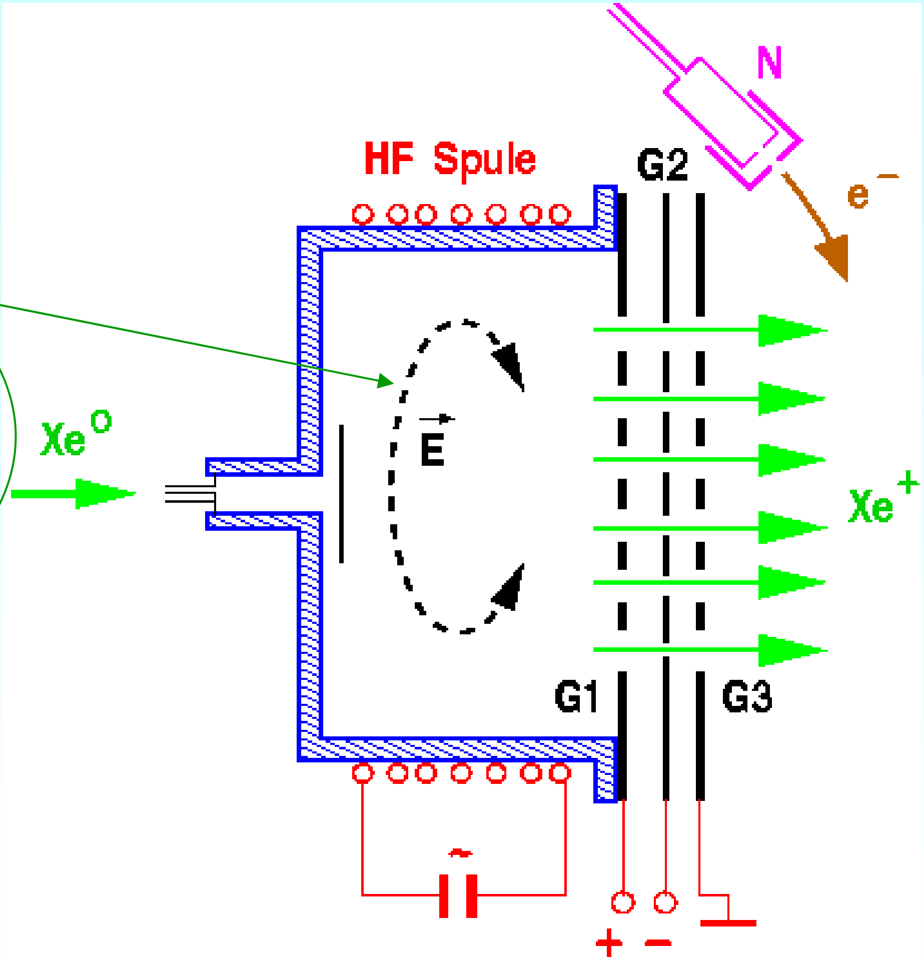
Layout of RIT

Radio frequency (HF): Coupled *E* and *B*-field

Coupled HF *E* & *B*-field according to *Maxwell´s* equations!

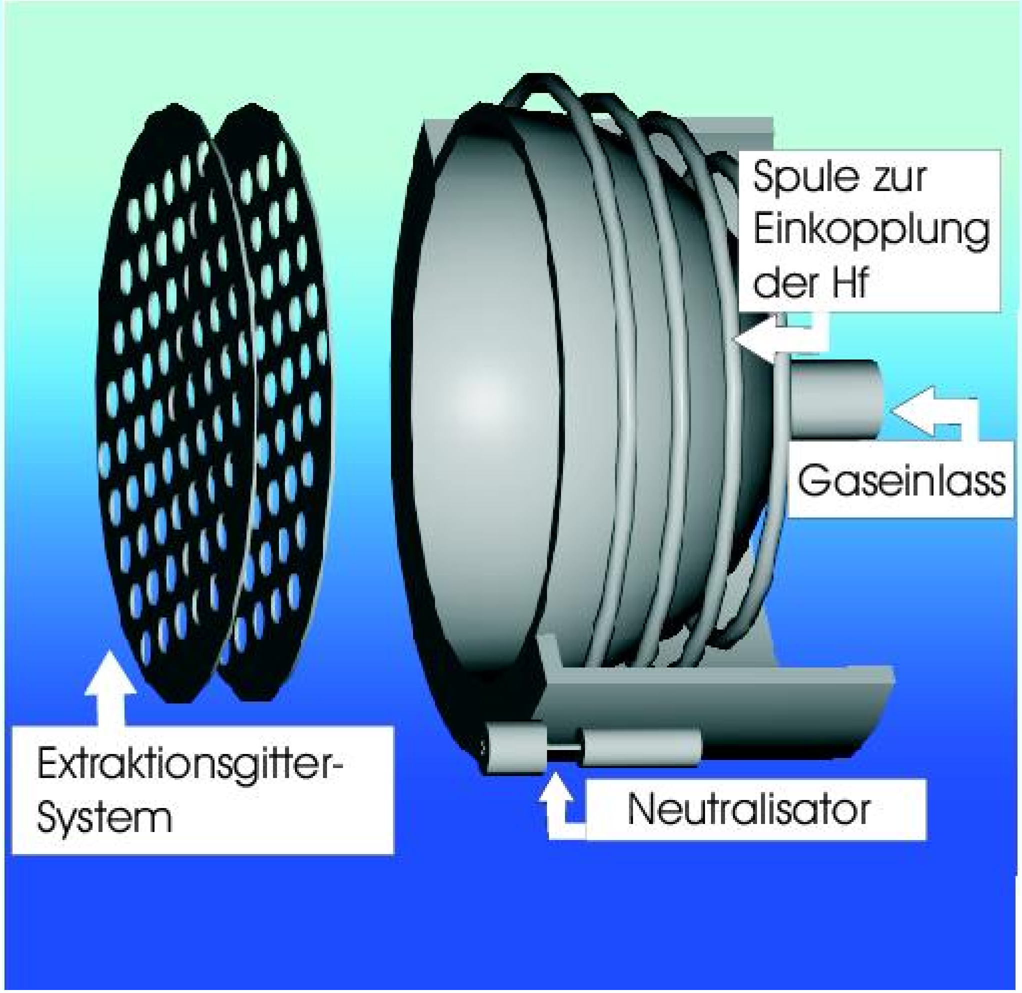


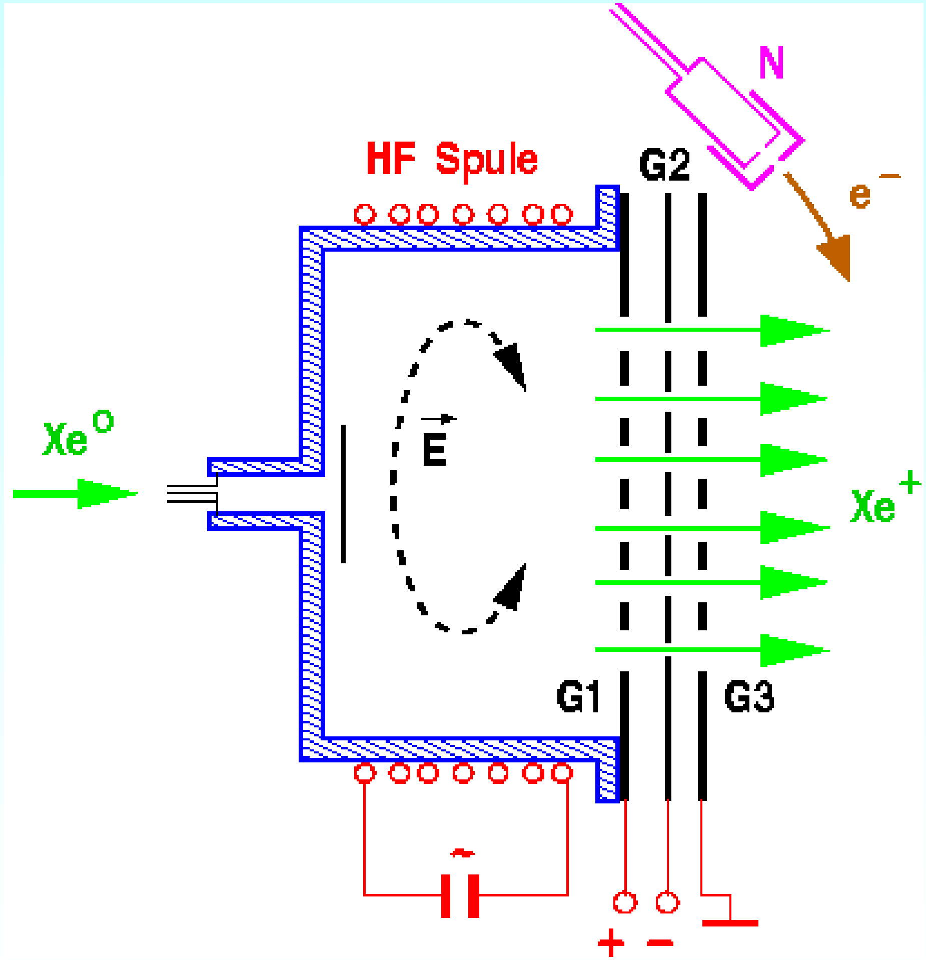
$$rot\vec{E} = -\frac{\partial \vec{B}}{\partial t} \qquad rot\,\vec{B} = \mu_0 \varepsilon_0 \cdot \frac{\partial \vec{E}}{\partial t}$$



Source: Univ. Gießen, Germany

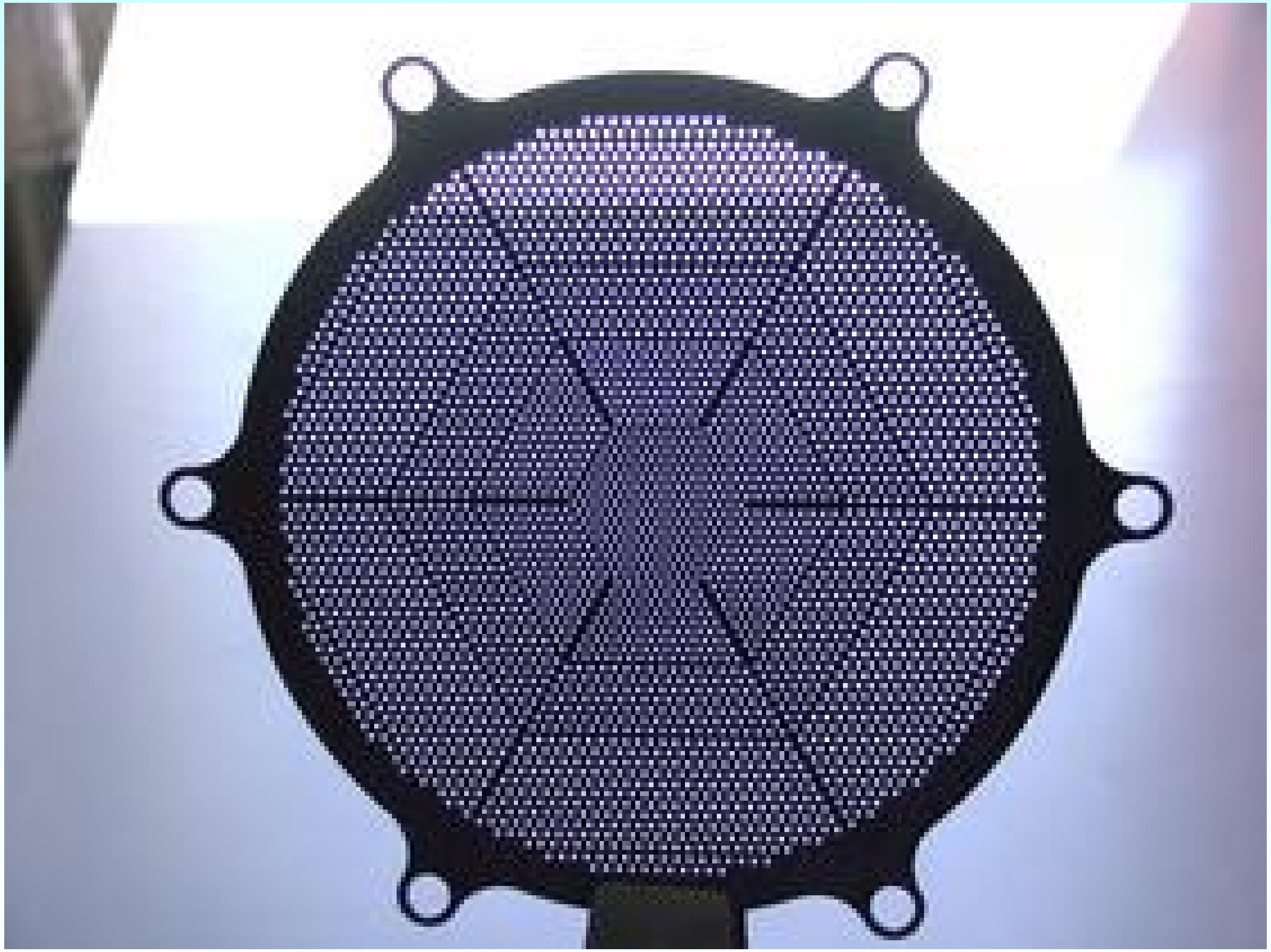
RIT-Drive: basic design





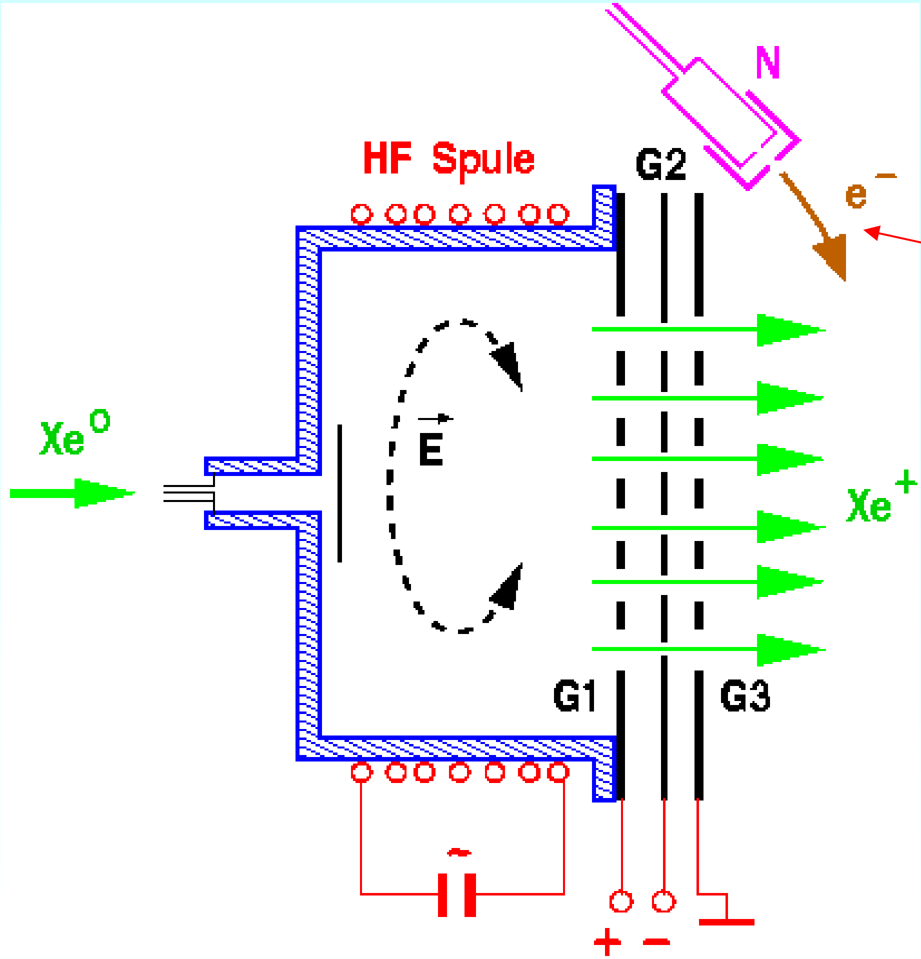
Source: Univ. Gießen, Germany

Extraction grid electrode of RIT-drive



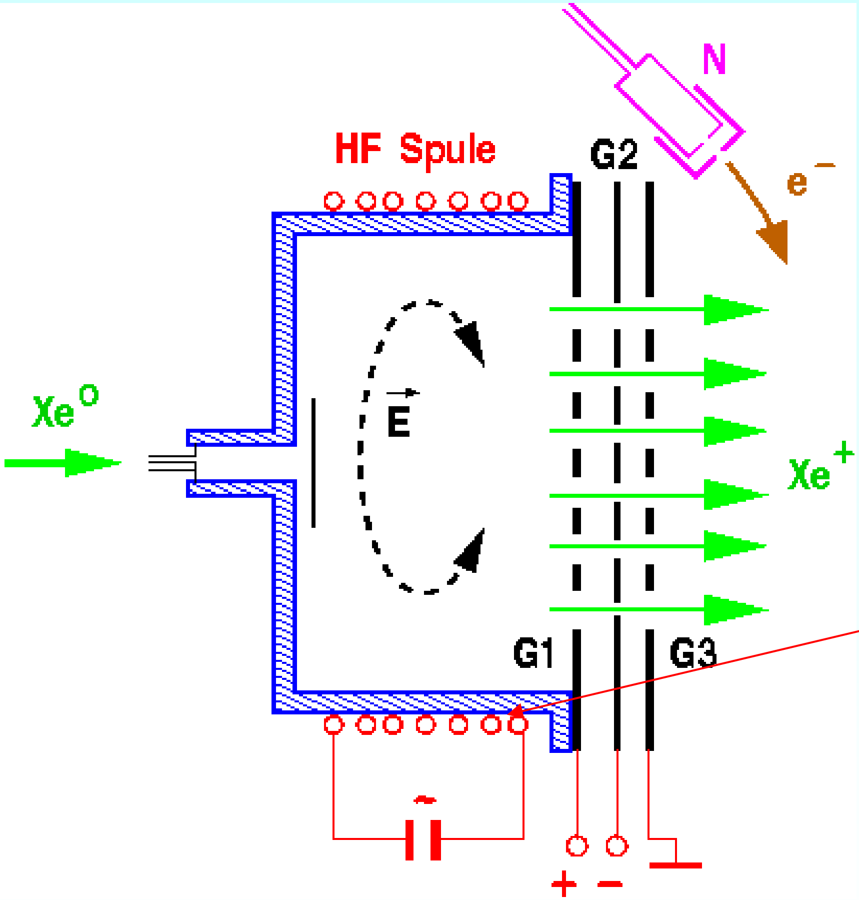
Source: Univ. Gießen, Germany

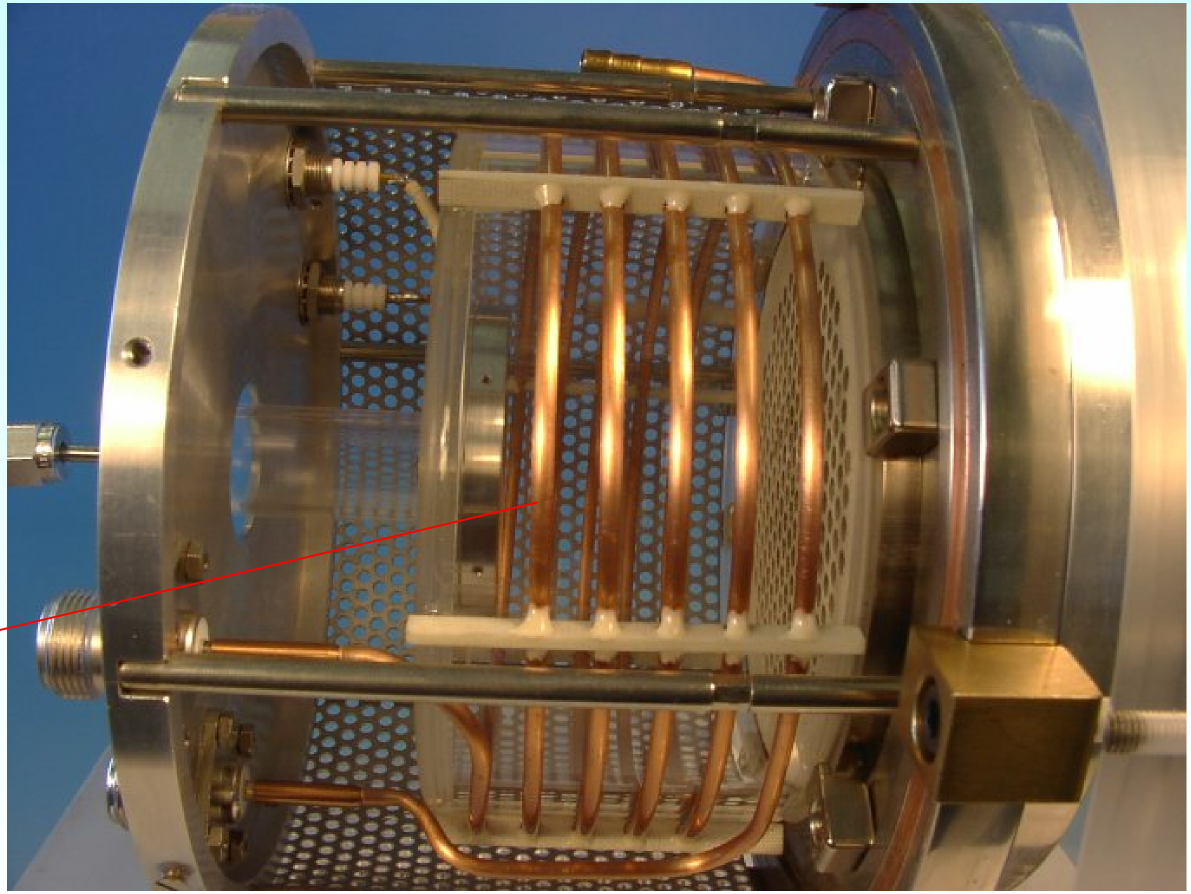
RIT-Drive: Neutralization source *N*



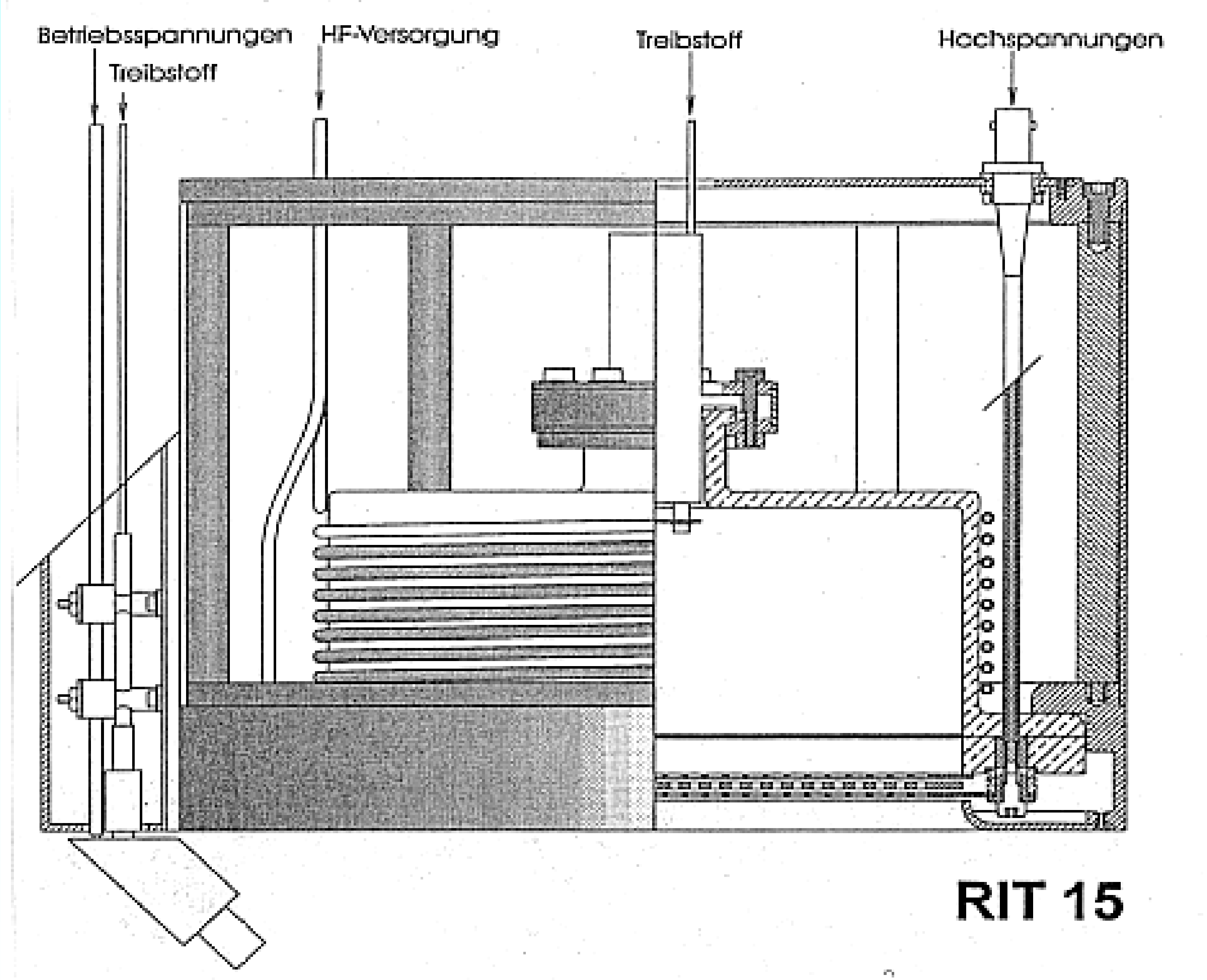
Source: Univ. Gießen, Germany

RIT-Drive: HF-Coil (Copper hollow conductor)





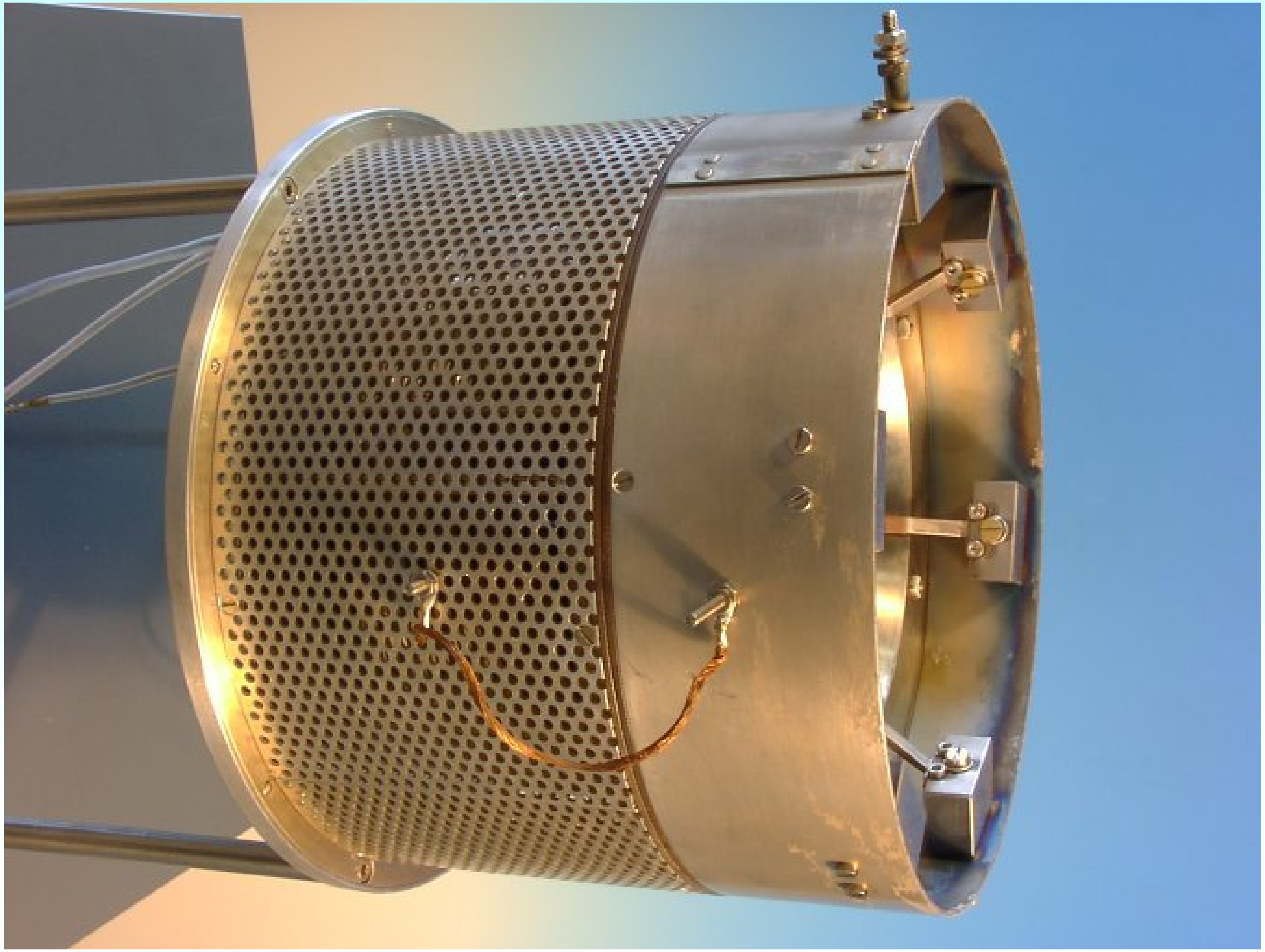
Source: Univ. Gießen, Germany



RIT-Drive Prototype RIT 15 cross section

Source: Univ. Gießen, Germany

RIT-Drive – Prototype *Univ. Gießen*



Source:

Univ. Gießen, Germany

RIT-Ion drive *Artemis*

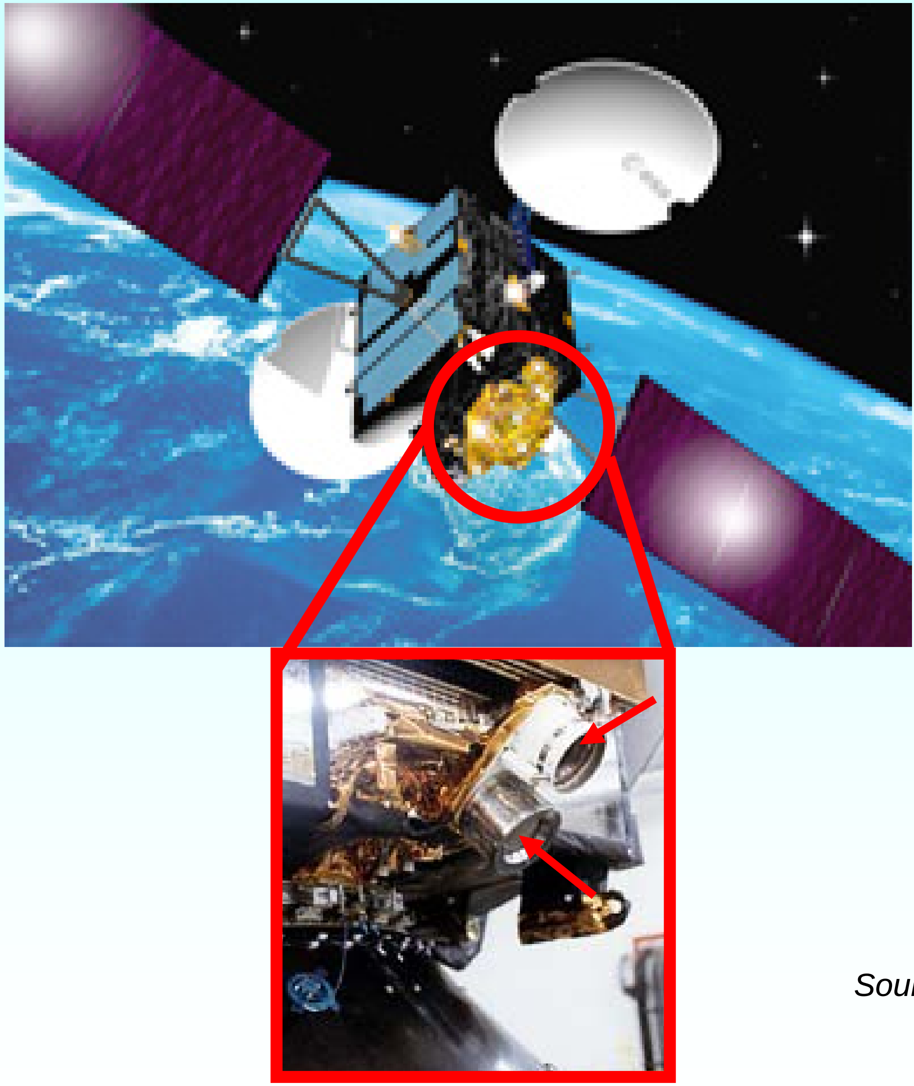
Artemis:

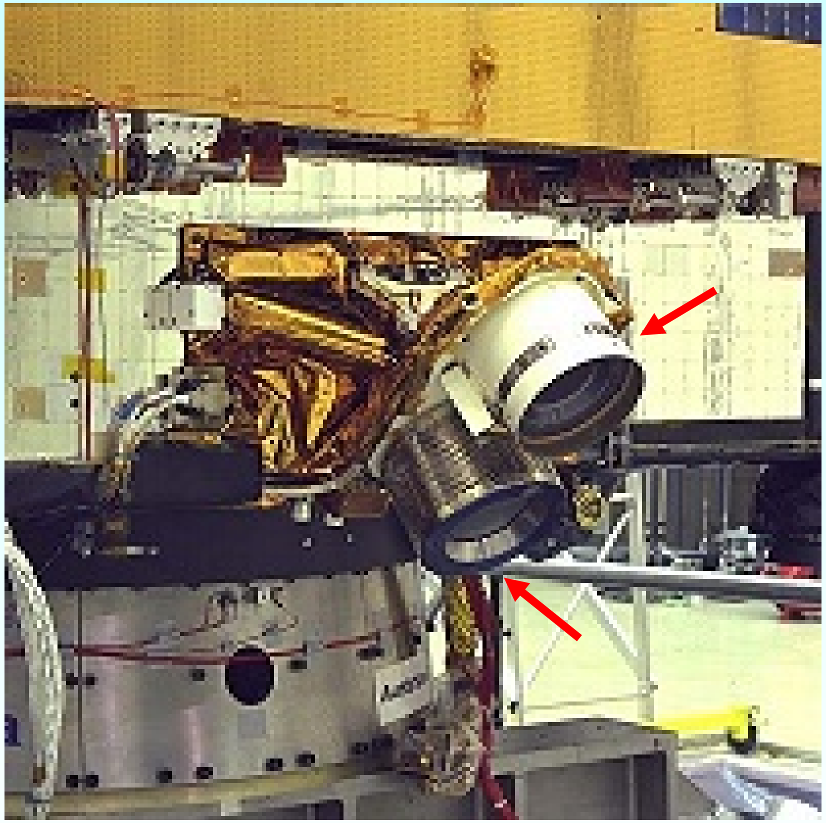
- Communication satellite (*ESA*), equipped with four RIT ion drives for north-south-correction (Start 2001)
- Stranded in 31000 km distance due to malfunction of the *Ariane* 5-stage at 31 000 km
- One RIT-10-Ion drive (the other three failed) was used to bring the satellite on 5000 km higher orbit 36000km (geostationary orbit) during a period of 10 months, thus saving the mission.
- 20 kg of fuel were enough, due to the low thrust during the 10 month operation
- Notwithstanding this unplanned use of fuel, a 5 years duty time was possible ➔ otherwise the mission (cost 700 M€) would have failed. There is no insurance in satellite business.

RIT-10-Engine data:

- Mass: 1,2 kg
- Fuel type: Xenon
- Fuel consumption: 0,3 mg/s
- Thrust: 10 mN
- Electr. Power 340 W
- Jet velocity: 31000 m/s
- Efficiency: 53 %

Artemis RIT-Ion drive





Source: Artemis, European Space Agency, ESA

"High Power" RIT-Ion drive (*Airbus*)

- Rated power 5 kW (15-times of *Artemis* project)

- Peak thrust: 200 mN

- Maximum jet ejection velocity: 180 000 km/h = 50 000 m/s

$$P = F \cdot v = 0.2 \cdot 180000 / 3.6 = 10\mathrm{kW}$$

- Prototype tested (2015) at DLR test center, *Göttingen, Germany*

- RIT-Ion drive shall be used for orbit transfer actions

Source: VDI nachrichten, Düsseldorf, 30.10.2015

4.4 Electric satellite drives

4.4.2 Electrostatic propulsion system

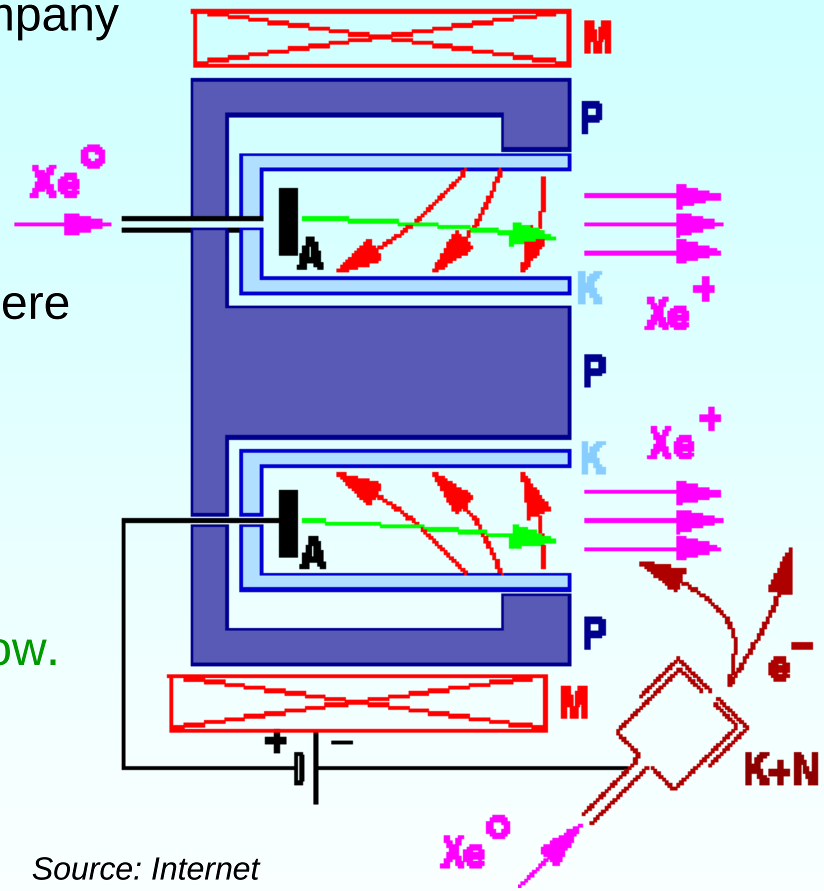
- *Kaufman*-engine
- RIT-engine
- *Hall*-Ion-propulsion system

Hall-Ion drive

- Developed in *Russia*, adopted in *France*, SNECMA company
- Between the outside cathode K and the anode A: ring-shaped insulated ionization chamber
- Thermionic emission of electrons at cathode K, accelerated to A
- Radial magnetic field forces electrons on ring orbits, where they flow as a *Hall*-current.
- Ionization of introduced Xe-gas by bombardment with the Hall current electrons, ions travel in the same ring current direction. *B*-field gives a outward force on them
- Outside ion are neutralized. By that the repelling space charge of the ions is compensated to keep up the ion flow.
- So a higher maximum ion current flow and hence a larger thrust force is possible
- Advantage: No extraction grids needed.
- Disadvantages:

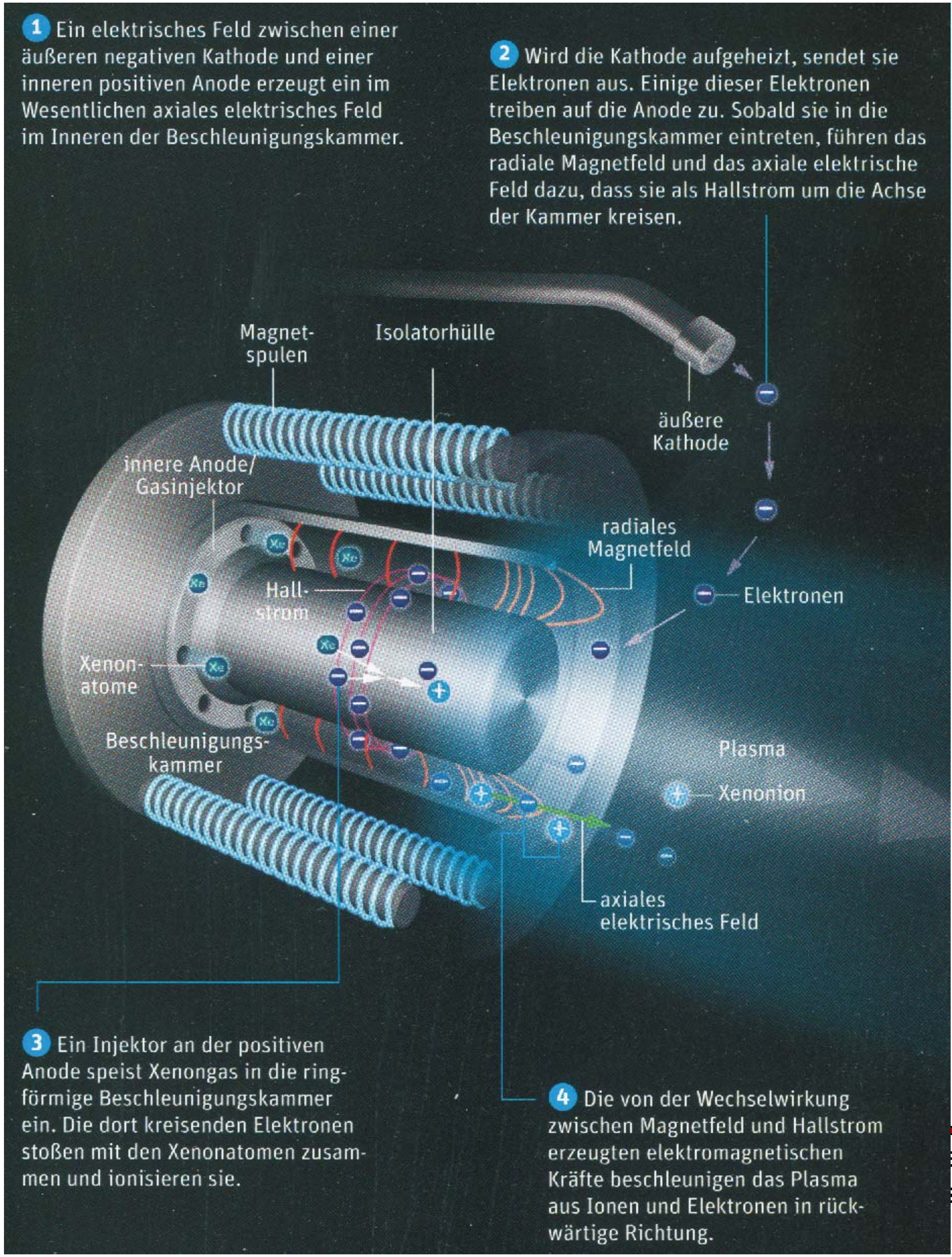
a) Only about 25000 m/s jet velocity

b) Lower efficiency and shorter life time than RIT drive



Source: Internet

Hall-ion-drive



Hall-Ion drive

Status:	In operation
Input power:	1.35 … 10 kW
Jet velocity:	10 … 50 km/s
Thrust:	40 … 600 mN
Efficiency:	45 … 60%

In use for:
Positioning & position correction of satellites; main drive for robotic medium-sized space craft

Source: Spektrum der Wissenschaft Jan. 2010

Hall-Ion drive PPS1350

- PPS 1350 (Plasma Propulsion System) SNECMA company

Thrust force: $F = \dot{m} \cdot v = 0.088\ \mathrm{N}$

Mass current (Xe): $\dot{m} = 5.22\ \mathrm{mg/s}$

Velocity: $v = 0.088/(5.22 \cdot 10^{-6}) = 16858 m/s$

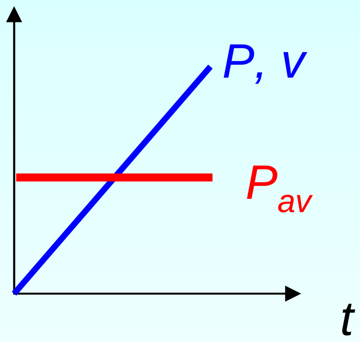
Power: $P = F \cdot v = 0.088 \cdot 16858 = 1500W$

Xenon-Mass: m = 141 kg,

Total burning time: $t = m/\dot{m} = 141/(5.22 \cdot 10^{-6}) = 7500$ hours

Mass of drive: 94 kg (without Xe-mass)

1350 W electrical input power

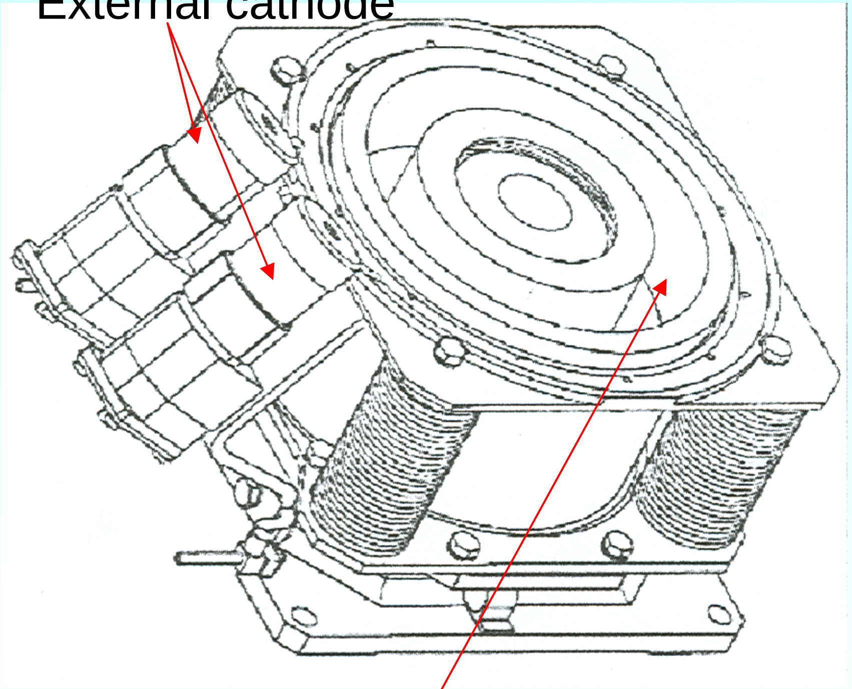


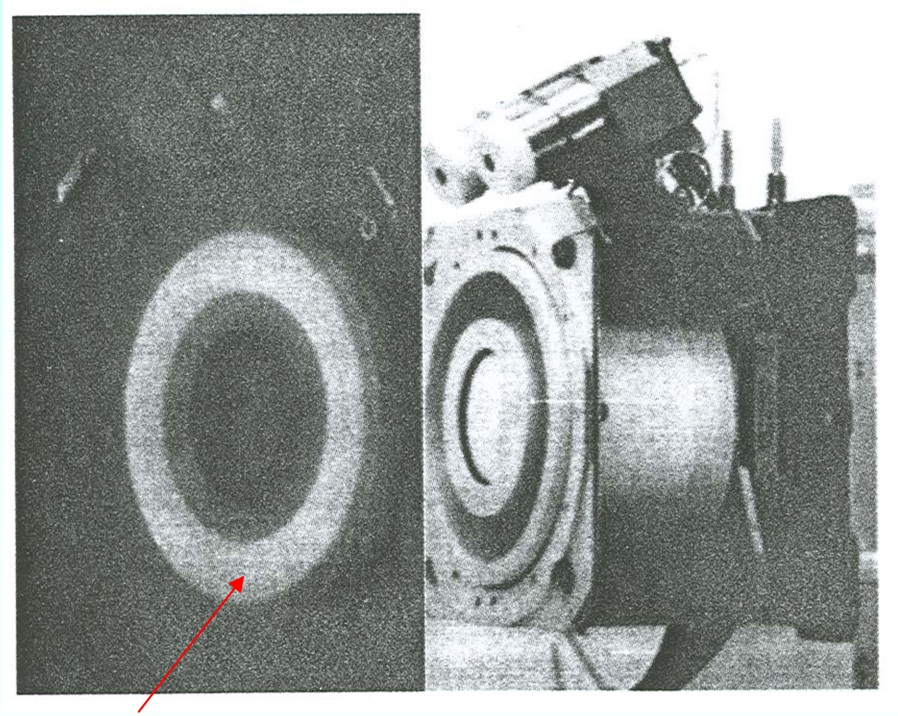
$P_{av} = F \cdot v/2 = 750W$ Efficiency: η = 750/1350 = 56%

Hall-Ion drive PPS 1350

- Satellite STENTOR (*France Telecom*), lift off in spring 2001

External cathode



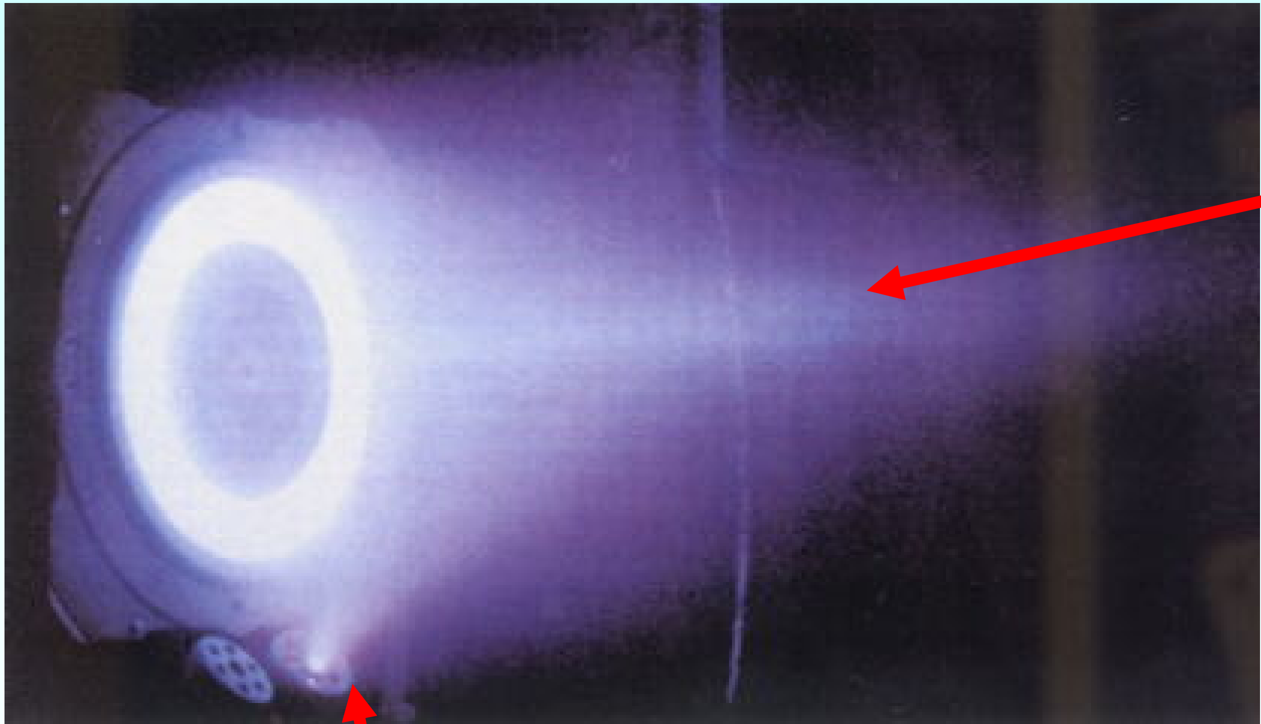


- Ring formed exhaust channel

- Ionized gas exhausting from ring channel

Source: Snecma comp./France

Operating *Hall*-Ion drive



Source: Snecma comp./France

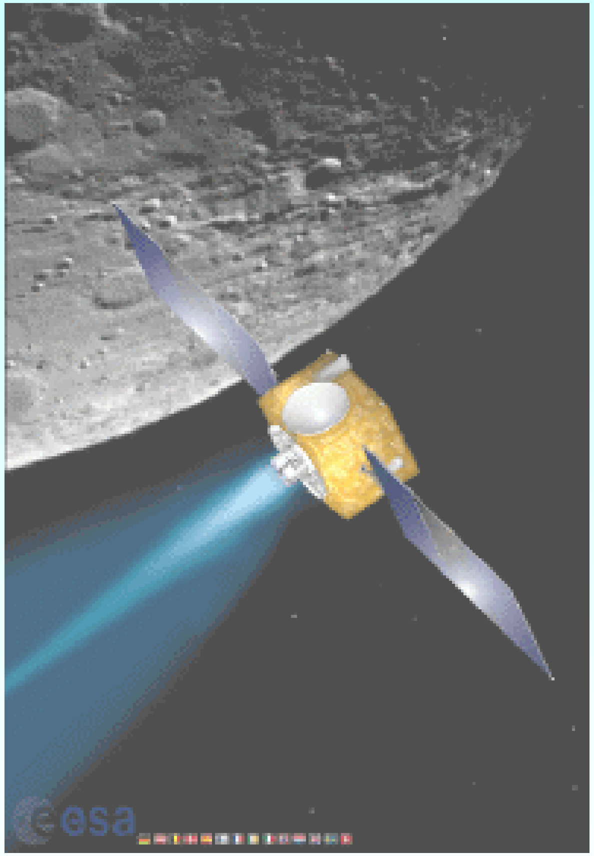
Satellite projects with electrostatic drives

Smart-1-Mission:

- Moon space ship (350 kg) of ESA with a *Hall*-Ion drive
- *Hall*-Ion-Drive PPS-1350 of *SNECMA*
- ➔ Thrust 70 mN; 1350 W electric power consumption

Bepi-Colombo:

- *Mercury*-Orbiter of *ESA*
- Start in 2014, arrival 2020, 1 year mission
- Transportation of Planetary and of Magnetospheric Orbiter with ion drive system



Mock up of *Bepi-Colombo* orbiter

Source: ESA

4.4 Electric satellite drives

4.4.1 Electric propulsion systems for satellites

4.4.2 Electro-thermal propulsion system

4.4.3 Electrostatic propulsion systems

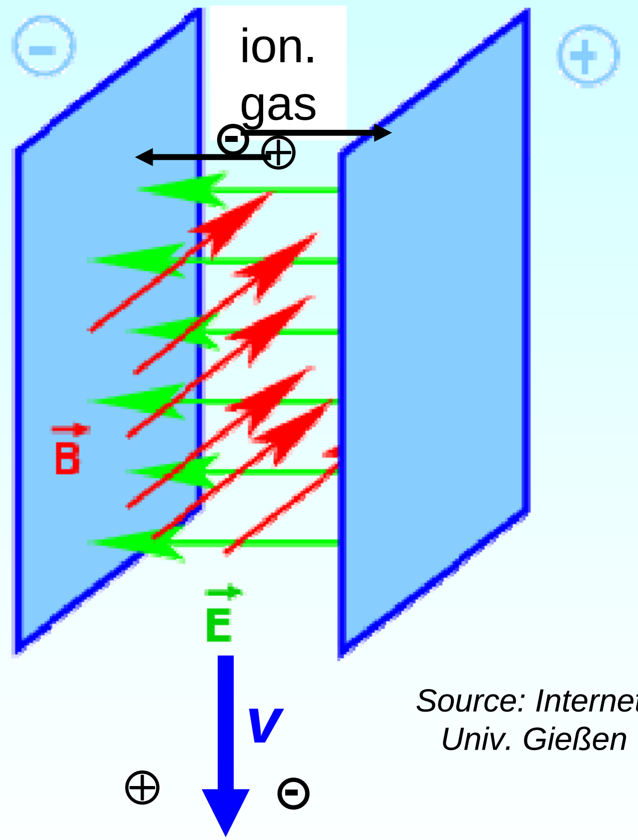
4.4.4 Electromagnetic propulsion systems

4.4.5 Advantage and disadvantage of electrical satellite drives

Electromagnetic drive (MPD) with external field

(MPD: Magneto-plasma-dynamic drive)

- Ionizing of fuel
- Acceleration of plasma by *Lorentz*-forces within *Laval*-shaped channel



Source: Internet, Univ. Gießen

MPD-external field drive:

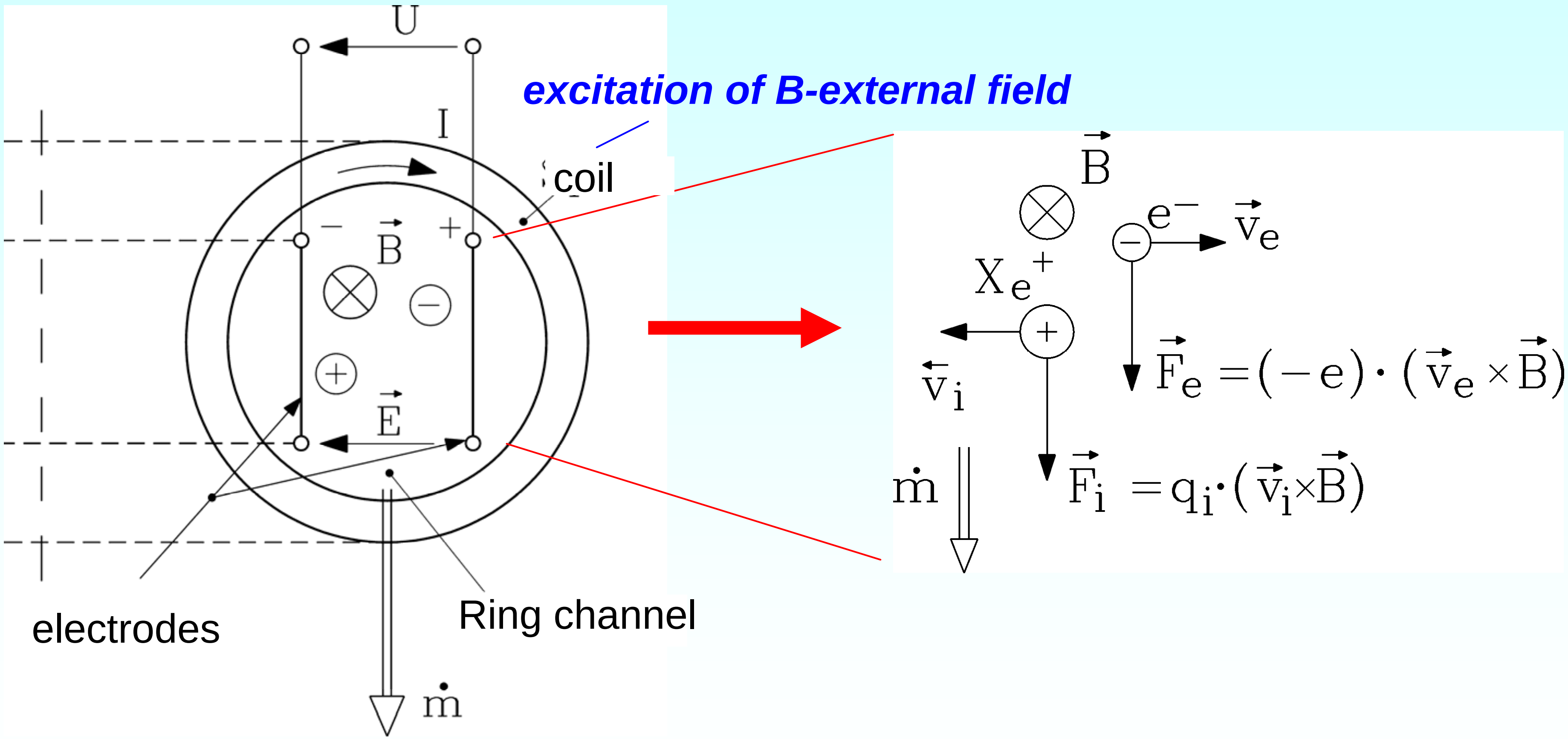
- Charge separation by an electrical field *E*
- Vertical to resulting current, we have a magnetic field *B*, so a *Lorentz-force* exists. By that electrons and ions are accelerated into the same direction *v*

- Efficiency about 20%; high thrust density

Electromagnetic drive MPD

Principle of plasma drive

- Li-Ion current gets Hall-effect due to the *B*-field : Electrons and ions accelerated into same direction. Both are leaving the electrodes as a mass flow. So no neutralization of jet necessary !

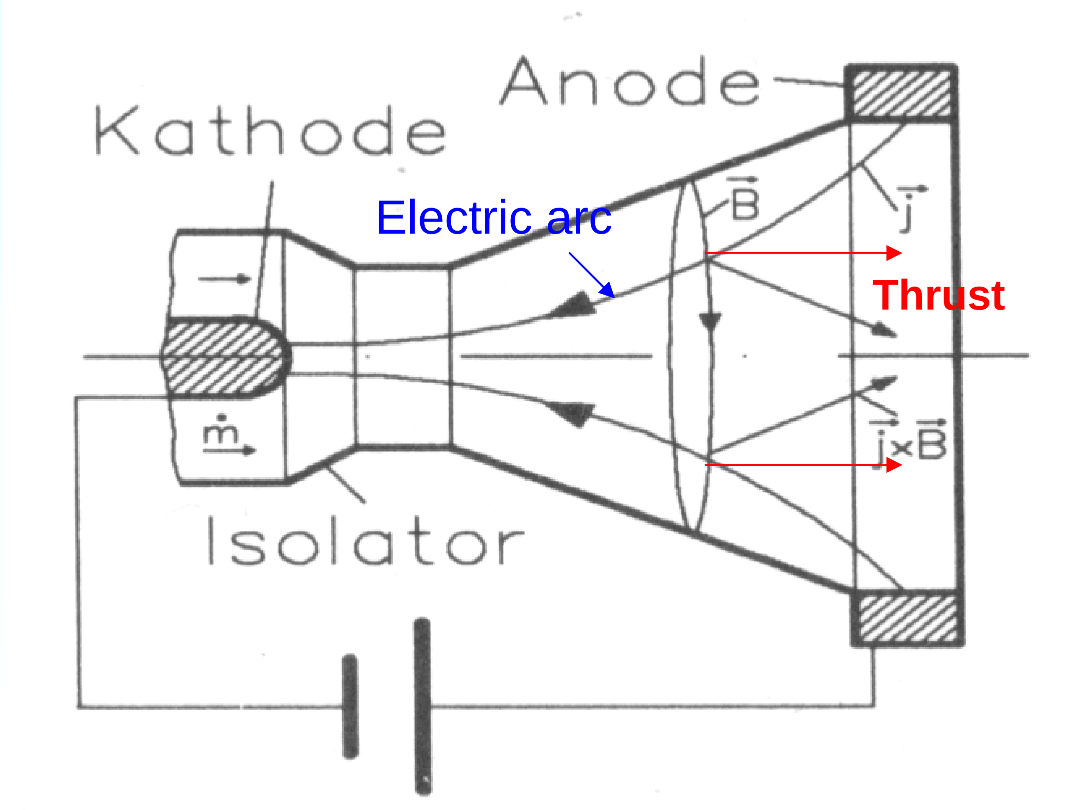


MPD-Electro magnetic drive with self field

MPD-self field accelerator:

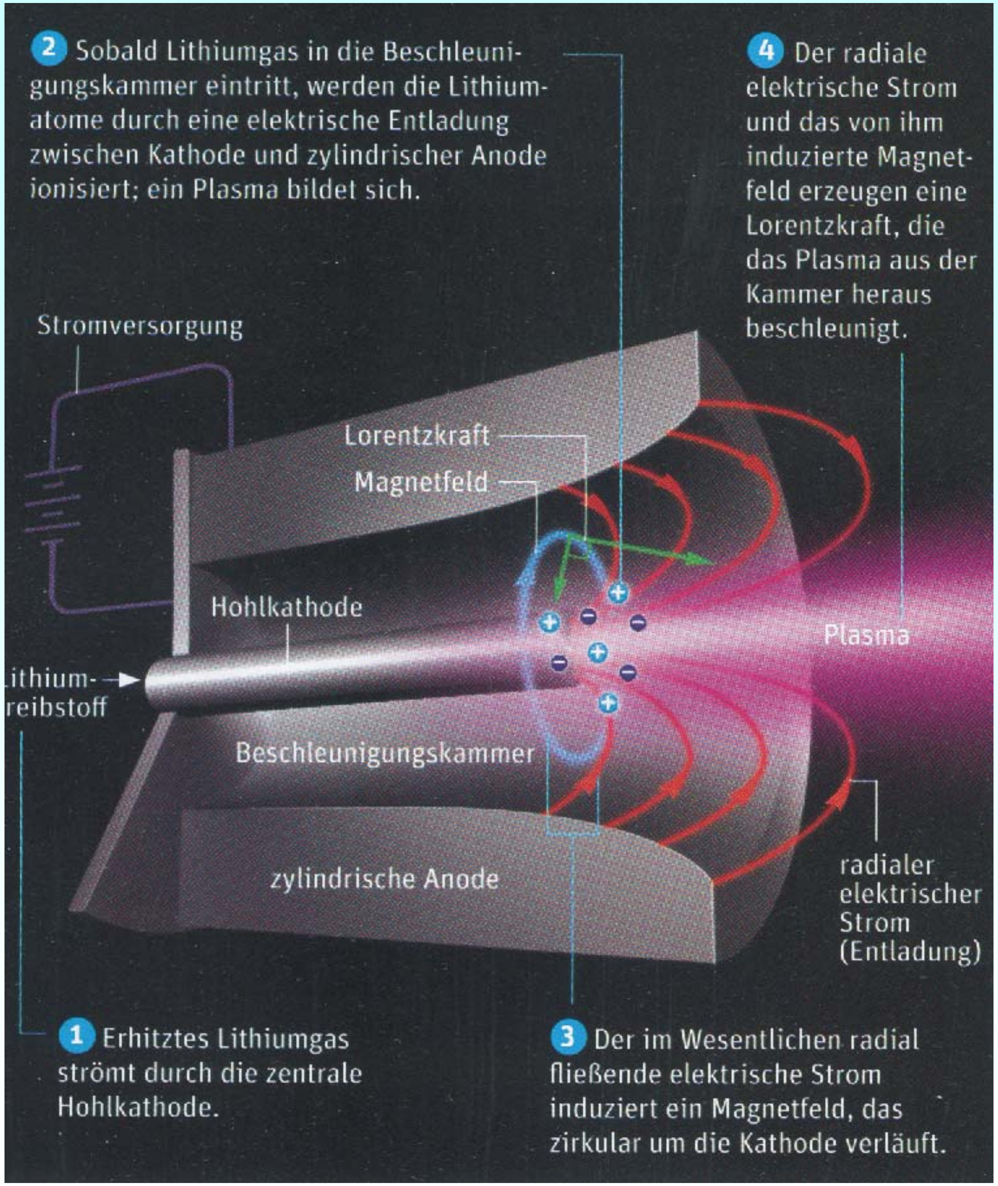
- Fuel heated and ionized by an electric arc. The arc current excites a magnetic field = arc "self-field"
- *Lorentz*-force in (*J* x *B*)-direction has an axial component, that creates a magneto-plasma-dynamic thrust
- Efficiency about 50%

Source: Auweter-Kurtz



MPD-self field accelerator

MPD-Electro magnetic drive with self field



Status:	Tested during flight, but not in operation till now
Input power:	100 kW … 1 MW
Jet velocity:	15 … 60 km/s
Thrust:	2.5 … 25 N
Efficiency:	40 … 60%

Future use:
Main drive for unmanned and manned heavy space ships

Source: Spektrum der Wissenschaft Jan. 2010

4.4 Electric satellite drives

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4.4.5 Advantage and disadvantage of electrical satellite drives

Advantages and disadvantages of electrical satellite drives

Disadvantages:

- Short time orbit- or direction correction are not possible, as the electrical engines work over a long time (month) due to the low thrust
- Fuel is not energy carrier, but “support mass”, so a power source for ionization is needed ➔ Limiting of power by photovoltaic generators
- Due to low thrust electrical engines can only be used in vacuum of outer space. No starts from earth possible
- Low thrust = Raised resting time in radiation (*van Allen*) belt, while climbing to higher orbit

Advantages:

- No rocket stage principle necessary, where only small parts of starting mass arrive at the mission destination (e.g.: *Apollo*-mission 0,16% of starting mass)
- No detours by swing-by-operation necessary, like in chemical rockets
- About 10 times higher jet velocity as in chemical rockets (max. 4 800 m/s), which is limited by the stored chemical energy
- For the same fuel amount at 10-times higher thrust is possible (which is prop. to the jet velocity), compared to chem. rockets
- This saving of fuel allows an increased rocket payload

Application of electrical satellite drive

- Electrical engines only for positioning tasks
- In long mission times in space, the mentioned disadvantages are irrelevant
- Doubling of useful load and flight time halved

- *Result:*
  Compensation of orbit problems (gravitation attraction of sun, moon) can be done by electrical engines.

Correction momentum =
= mass of fuel gas * gas jet velocity

Future perspectives

Use of electric drives in space till now:

- Used to transport satellites into the final geostationary orbit position
- First test missions to inter-planetary regions in the solar system with ionic drive
- MPD also used as plasma source for simulation of re-entry of space ships in earth atmosphere
- Electrostatic drives have reached so far highest development level:

  e.g.: ➔ RIT-10-drive of Prof. *Löb*: 20 000 h full load in testing

Future use:

- Drive system for moving space ships after lift-off from earth with chem. rocket.
- Inter-planetary flights with long mission time and high velocity
- *Arcjet* engines with ratings 5 … 100 kW as primary drive for future space programs (research field of the *University Stuttgart*)
- Periodic transport of supplies to the moon

➔Special tasks, where fine thrust control and high end velocity are needed, but no high acceleration is needed.

New technologies of electric energy converters and actuators

Summary:
Electric satellite drives

- Electrostatic or magneto-hydrodynamic force generation as propulsion force
- Very weak forces, but may act over very long time
- Forces too small for launching rockets from earth
- Forces big enough for propulsion in free space
- Since ca. 10 years increased use of electric satellite drives in commercial satellites
- Further prospects very promising for future satellite projects