Plasma Thrusters

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https://www.iter.org/newsline/-/3303

Overview

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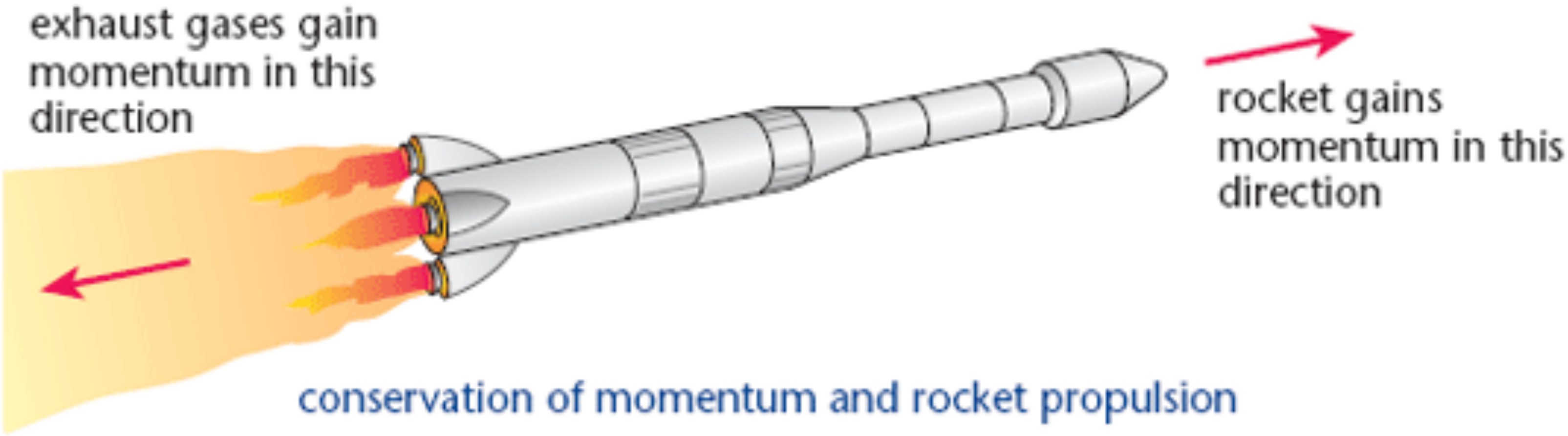
3. Limits of Chemical Rockets
4. Electric Propulsion
5. Why Plasma Thrusters?
6. General Physics of Plasma Propulsion
7. Different Types of Plasma Thrusters
8. Conclusion

Rocket Principle
Actio et Reactio



https://revisionworld.com/a2-level-level-revision/physics/force-motion/momentum-second-law/momentum-second-law-0

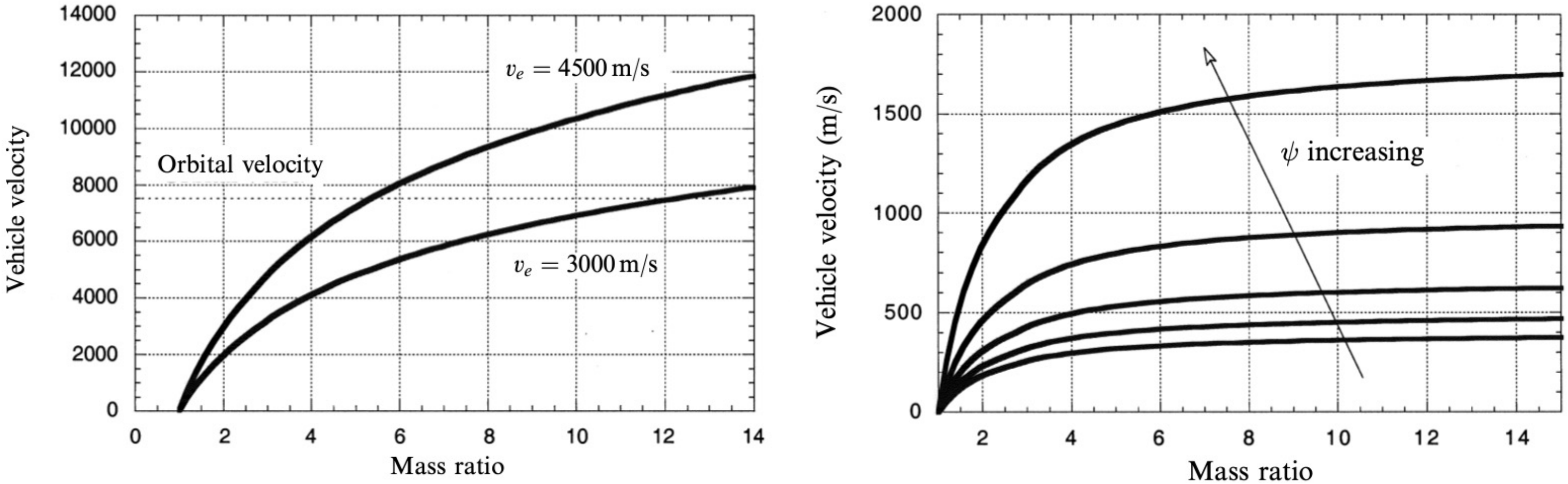
Rocket Principle

Newton's Law and the Rocket Equation

$F = m \cdot v_{ex}$	Thrust developed by the exhaust (2nd law) , $m = \frac{dM}{dt}$
$v_{ex} = u_{ex} + \left(\frac{p_e A_e - p_a A_e}{m}\right)$	Effective exhaust velocity
$\frac{dv}{dt} = \frac{F}{M}$	Acceleration of the rocket (2nd law)
$\frac{dv}{dt} = -v_{ex} \cdot \frac{dM}{dt} \cdot \frac{1}{M}$	Substituting for F, from the first equation
$v_{rocket} = v_{ex} \cdot \log_e\left(\frac{M_0}{M}\right)$	Tsiolkovsky‘s equation (ideal rocket equation)

Rocket Principle

Newton's Law and the Rocket Equation



Turner (2009)

Vehicle velocity strongly depends on the exhaust velocity!

Power, Thrust and Specific Impulse

Engine Parameters

$P = F \cdot v_{ex}$	Power of the rocket engine
$F = m \cdot v_{ex}$	Thrust of the rocket engine
$I_{sp} = \frac{v_{ex}}{g}$	Specific impulse of the rocket engine, $g \approx 9.81\ \frac{\mathrm{m}}{\mathrm{s}^2}$

Power, Thrust and Specific Impulse

Specific Impulse I_{sp}

$I = F\ dt = m \cdot v_{exhaust}\ dt$ Impulse given to the rocket, $m = \frac{dM}{dt}$

$I_{sp} = \frac{I}{m \cdot g\ dt} = \frac{v_{exhaust}}{g}$ Impulse given to the rocket by *weight* of propellant

I_{sp} is an efficiency quantity!

Limits of chemical rockets

Maximum exhaust velocity of chemical rockets

”Lets just build rockets with higher exhaust velocities!”

For a chemical rocket the maximum exhaust velocity is $v_{ex} = 4.5\ {}^{\text{km}}/_{\text{s}}$!

Electric Propulsion

Plasma Thrusters as a Subset of Electric Propulsion Systems

Electric Propulsion

Electric Thrusters

“Using electricity to heat the propellant”

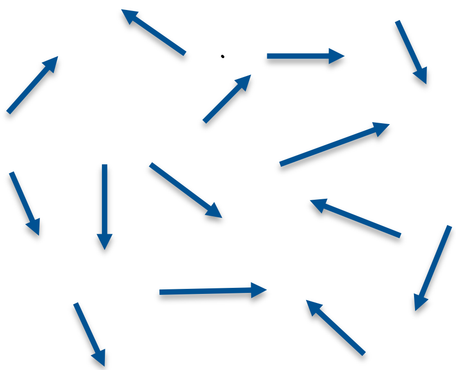
Electrostatic/ -magnetic Thrusters

“Using electric and magnetic fields to accelerate particles”

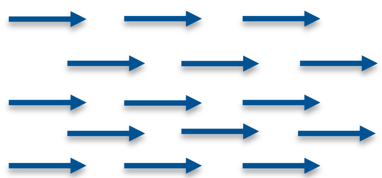
General Physics of Plasma Propulsion

What is different?

Molecules after chemical reaction



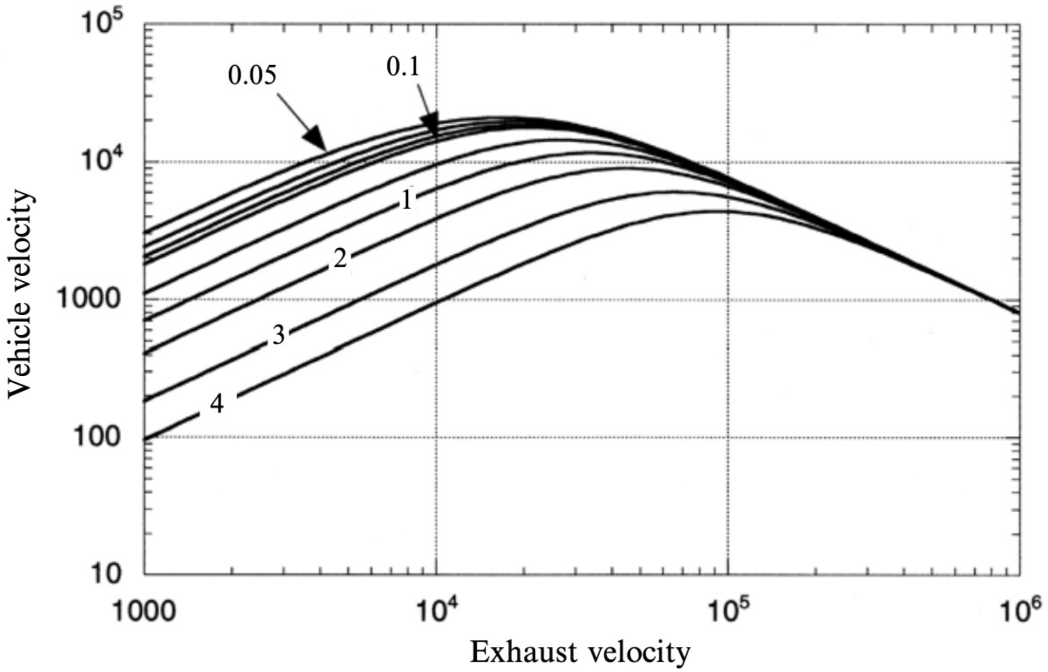
Plasma particles in
e.g. electrostatic field



Propulsion is no longer based on thermodynamic effects.

General Physics of Plasma Propulsion

What is different?

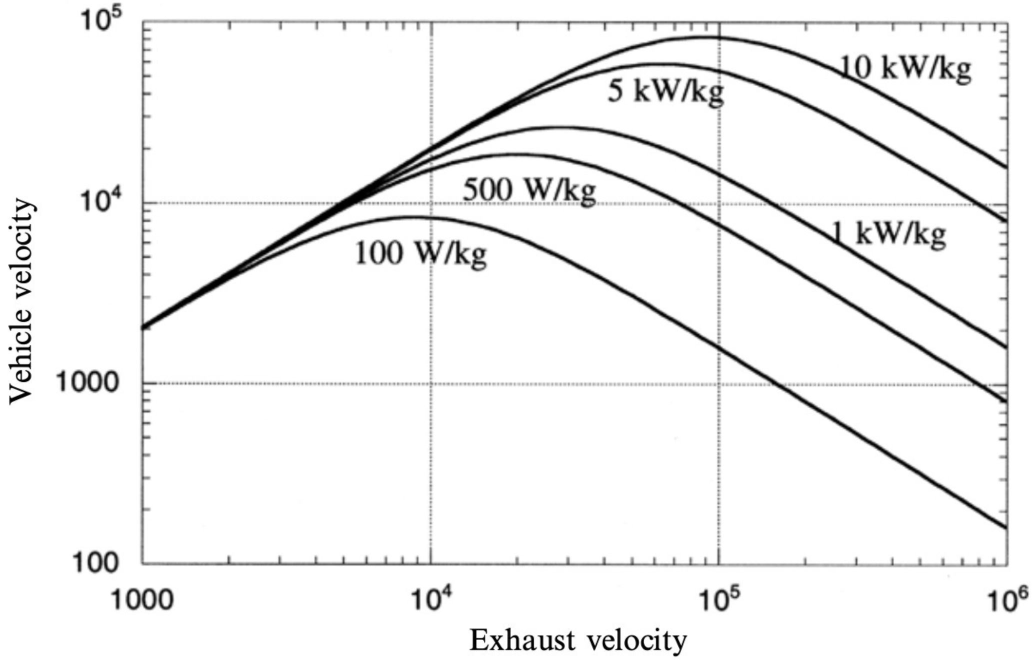


Turner (2009)

$$v = v_{ex} \cdot \log\left(1 + \frac{2\eta\xi t}{2\eta\xi t \frac{M_S}{M_P} + v_{ex}^2}\right)$$

General Physics of Plasma Propulsion

What is different?

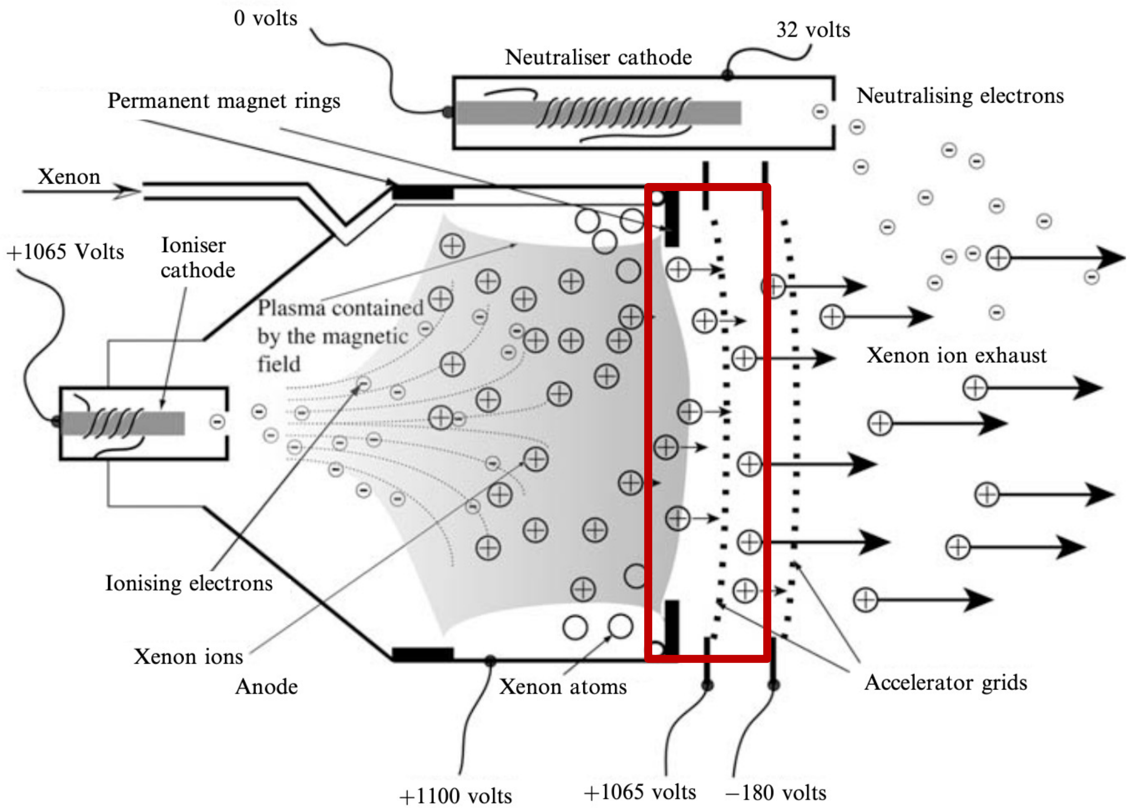


Turner (2009)

A too high exhaust velocity reduces the vehicle velocity!

General Physics of Plasma Propulsion

Ion Thrusters



Turner (2009)

General Physics of Plasma Propulsion

Ion Thrusters – The Space Charge Limit

Ions partially shield the first grid

$$\frac{d^2V}{dx^2} = -\frac{\rho_i}{\epsilon_0} = -\frac{j}{\epsilon_0 v_i}$$

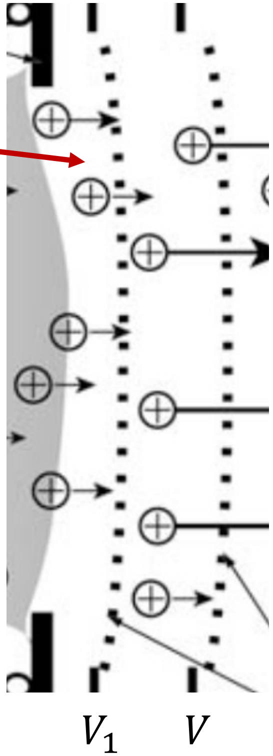
$$E = \frac{dV}{dx} = 2\left(\frac{j}{\epsilon_0}\right)^{1/2}\left(\frac{M}{2q}\right)^{1/4} \cdot (V_1 - V)^{1/4}$$

$$v_i = \sqrt{\frac{2q(V_1 - V)}{M_i}}$$

$$V = V_1 - \left[\frac{3}{2}\left(\frac{j}{\epsilon_0}\right)^{\frac{1}{2}}\left(\frac{M}{2q}\right)^{\frac{1}{4}} d\right]^{4/3}$$

$$j = \frac{4\epsilon_0}{9}\left(\frac{2q}{M} \cdot \frac{E_0^3}{d}\right)^{1/2}$$

$$E_0 = \frac{V_1 - V}{d}$$



Turner (2009)

The current density of an ion thruster is limited.

General Physics of Plasma Propulsion

Ion Thrusters – The Thrust Dilemma

$$\boldsymbol{F} = m \cdot v_{ex} = \underbrace{j \cdot \frac{M_i}{q} \cdot A}_{m} \cdot \underbrace{\sqrt{\frac{2q(V_1 - V)}{M_i}}}_{v_{ex}} = \frac{\mathbf{8}}{\mathbf{9}} \cdot \boldsymbol{\epsilon_0 E_0^2} \cdot \boldsymbol{A}$$

$$E_0 = \frac{V_1 - V}{d}$$

$$v_i = \sqrt{\frac{2q(V_1 - V)}{M_i}}$$

Ion thrusters are high exhaust velocity and low thrust devices.

General Physics of Plasma Propulsion

Plasma Thrusters – Acceleration Mechanism

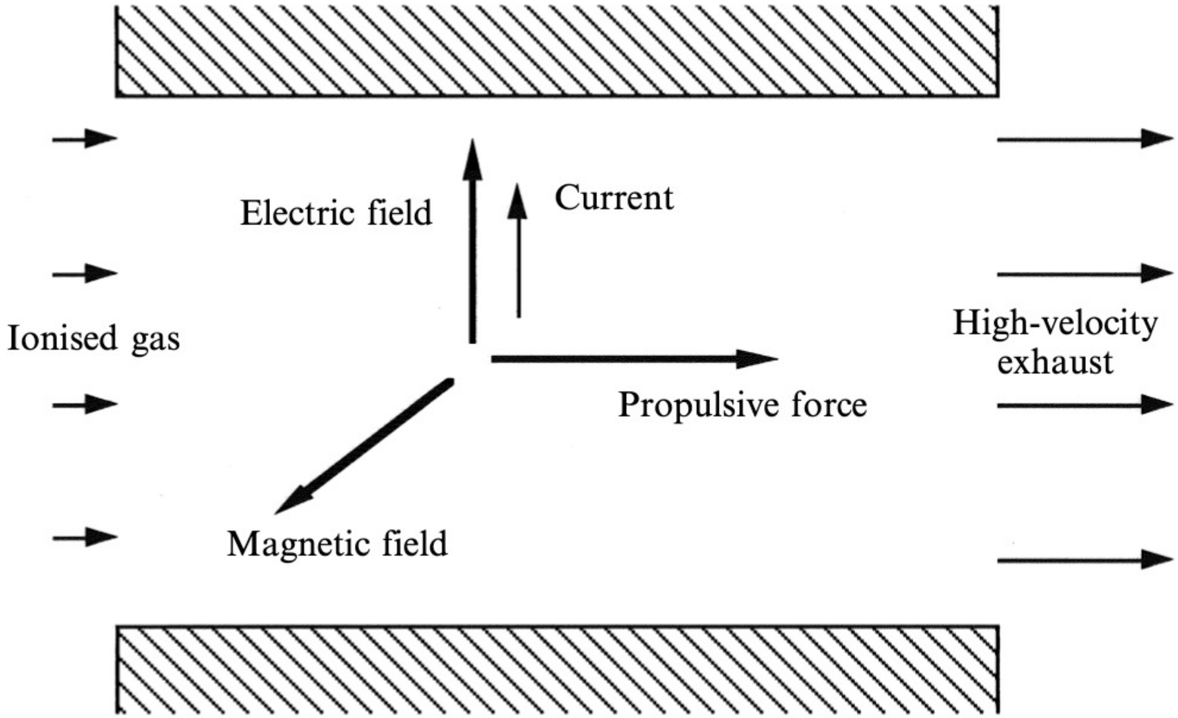
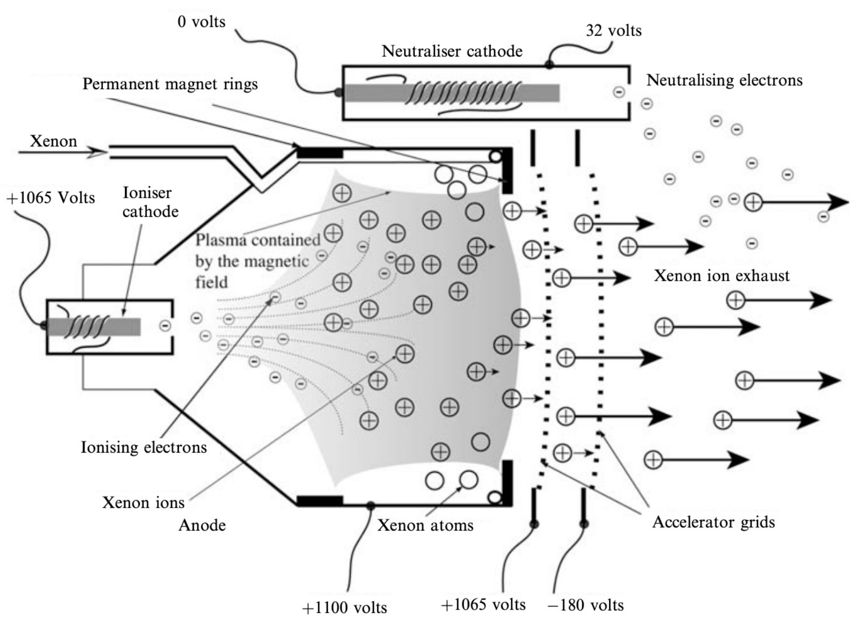


Figure 6.14. Principle of the plasma thruster.

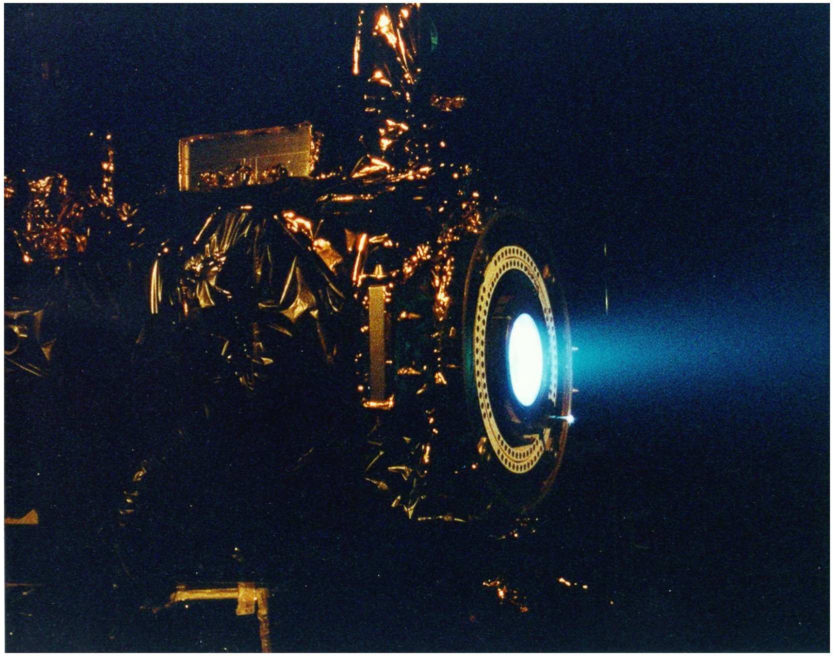
Turner (2009)

Different Types of Plasma Thrusters

Ion Thrusters



Turner (2009)

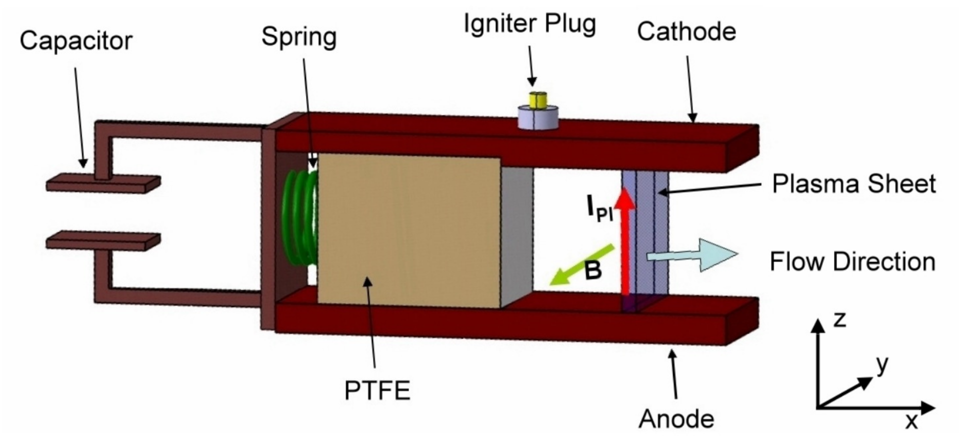


https://www.jpl.nasa.gov/images/pia04247-deep-space-1s-ion-engine

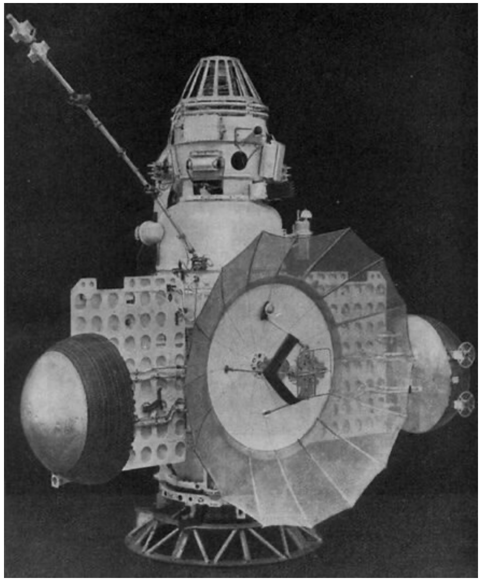
NSTAR ion thruster, as used on Deep Space 1

Different Types of Plasma Thrusters

Pulsed Plasma Thruster



Lau et al. (2013)



https://de.wikipedia.org/wiki/Zond

Pulsed Plasma Thruster, as used on ZOND 2

Different Types of Plasma Thrusters

Hall Effect Thrusters (HET)

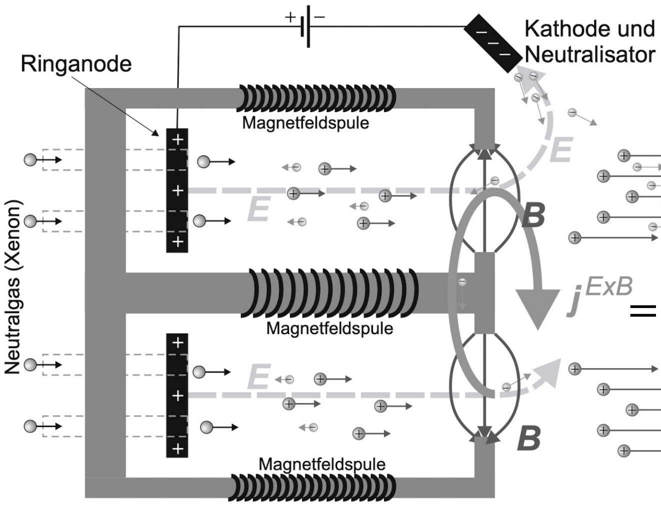
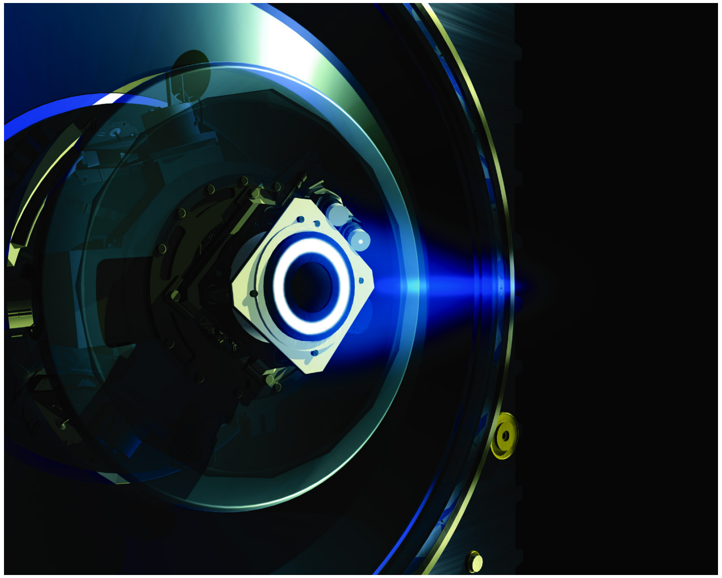


ABBILDUNG 3.30: Aufbau eines Hall-Triebwerks.

Stroth (2011)

$$j^{ExB} = -\sigma_H \cdot \frac{\vec{E}\times\vec{B}}{B}$$

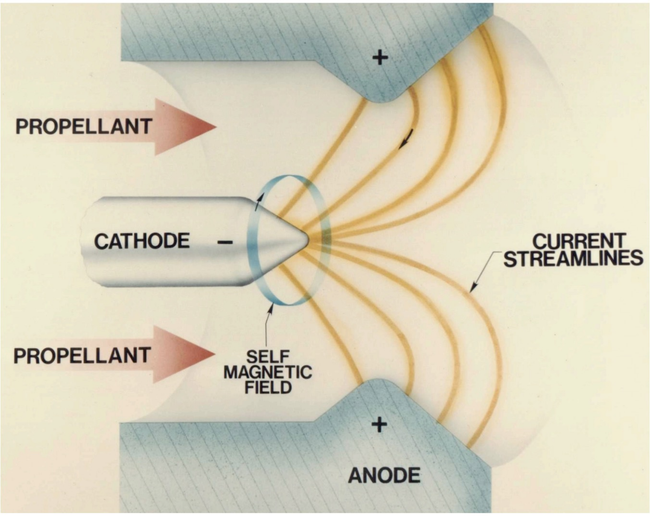
Hall current



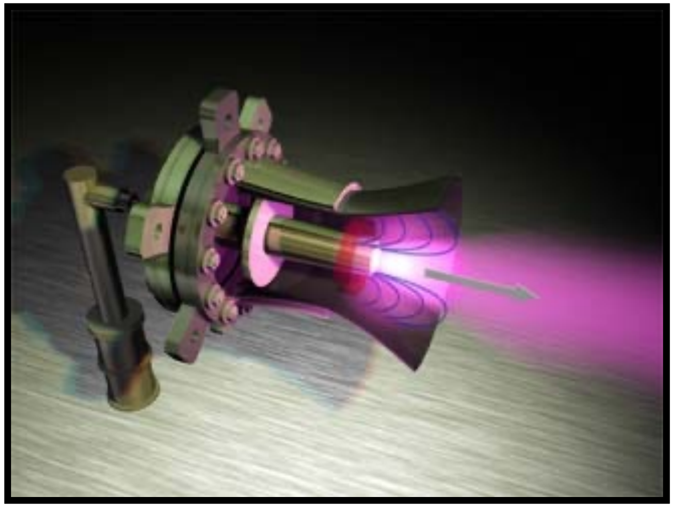
https://www.esa.int/ESA_Multimedia/Images/2003/04/Close-up_view_of_SMART-1_s_stationary_plasma_thruster

Hall Effect Thruster, as used on SMART-1

Different Types of Plasma Thrusters
Magnetoplasmadynamic Thrusters



Gilland et al. (2003)

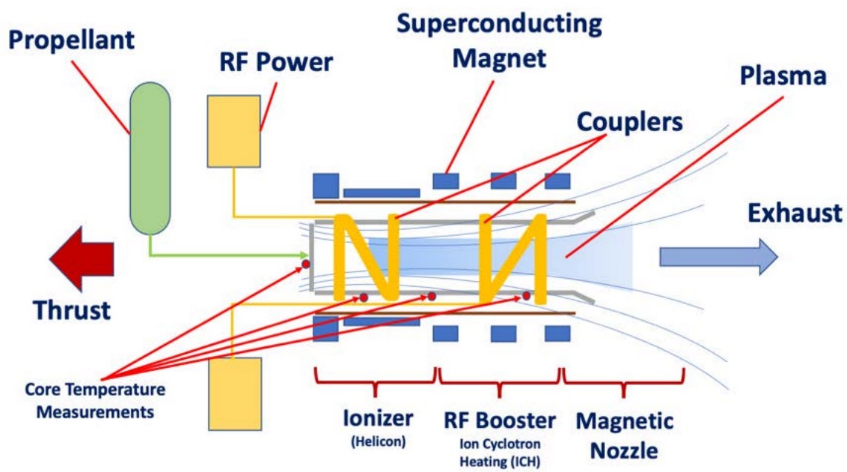


https://en.wikipedia.org/wiki/Magnetoplasmadynamic_thruster

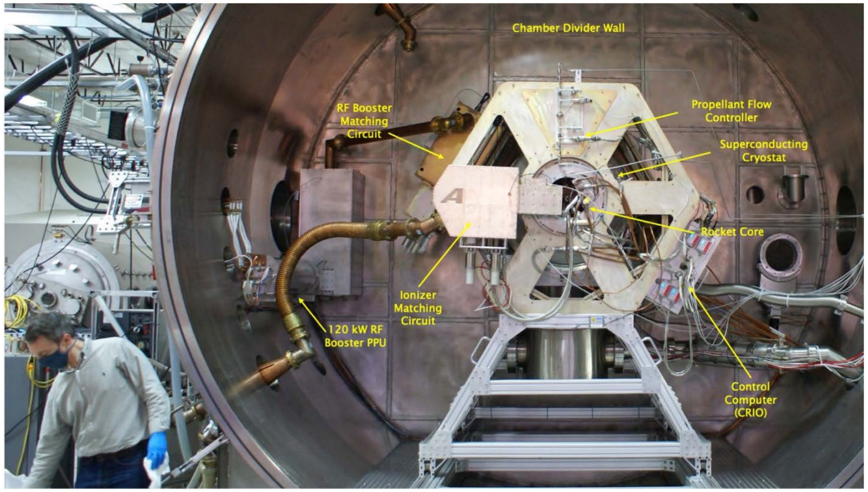
Currently being studied by e.g. NASA Jet Propulsion Laboratory

Different Types of Plasma Thrusters

VASIMR



Chang-Diaz et al. (2022)



Chang-Diaz et al. (2022)

VASIMR, Ad Astra Rocket Company (in progress)

Conclusion

Sky is not the Limit

Promising benefits

- highly efficient
- heavier payloads
- ideal for long term missions
- addition/ alternative to chemical rockets

Challenges

- generating more thrust
- power requirements
- erosion of components

Applications

- interplanetary and deep space mission
- adjusting of satellite trajectories

Sources

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