Electric Propulsion

An short introduction to plasma and ion spacecraft propulsion

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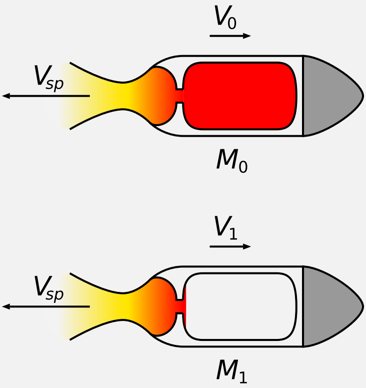
Tsiolkovsky's equation:

$$M_0 = M_1 \exp\left(\frac{V_1 - V_0}{V_{sp}}\right)$$

$M_0,\ V_0$: initial mass and velocity
$M_1,\ V_1$: final mass and velocity
V_{sp} : specific velocity $(= g_0 I_{sp})$

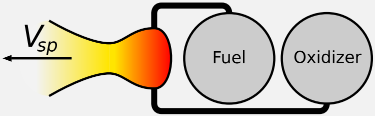


How to decrease M_0?

$$M_1 \approx \text{payload}$$
$$\Delta V = V_1 - V_0 \approx f\,(\text{orbit})$$

$\Rightarrow V_{sp}$ must be as high as possible

Chemical vs. electric propulsion (1/2)



Chemical propulsion

$V_{sp} \sim \sqrt{\frac{C_p T}{M}}$ limited by nozzle temperature & molecular mass of gases

$V_{sp} \sim \sqrt{Q}$ limited by the chemical specific energy of propellants

In practice, $V_{sp} < 4500\ \mathrm{ms}^{-1}$

Electric propulsion

no intrinsic limit on V_{sp}, but

$$V_{sp} \propto \frac{P}{F}$$

$\Rightarrow$ V_{sp} constrained by the available electrical power (P) and/or requirered thrust (F)

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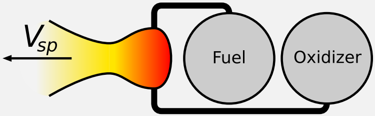

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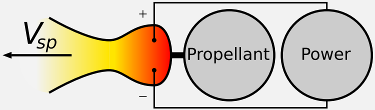

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Chemical vs. electric propulsion (2/2)

Available chemical power:
3000 MW

Available electrical power:
13 kW

Typical performances & use

Thrust:	0.1μN – 200mN
Input Power:	0.5mW – 10 kW
Efficiency:	5% – 90%

Missions

- Orbit correction (NSSK in particular)
- Deep space propulsion
- Drag cancellation
- LEO-LEO and LEO-GEO Orbit raising
- Deorbiting

A short summary of the (long) EP history

1906	Robert Goddard	First known hand-writtent notes on EP
1911	Konstantin Tsiolkowsky	First published mention of the EP concept
1929	Hermann Oberth	Full chapter in *Wege zur Raumschiffahrt*
1949	Shepherd & Cleaver	Considerations on nuclear-electric propulsion
1951	Lyman Spitzer	Demonstration of the feasability of EP
1954	Ernst Stuhlinger	In-depth analysis of EP system
1964	US and Russia	First succesful EP tests in space
1980's	US and Russia	Commercial use (resistojets, Hall thrusters)
1998	US	First deep space probe with EP (Deep Space I)

Definition

*"A **plasma** is a quasi-neutral gas of charged and neutral particles which exhibits a collective behavior"* [F. C. Chen]

Why is a plasma quasi-neutral?

Being very light, electrons tend to move so as to screen out electric field perturbations (electrodes, walls, ...). The screening distance is called the **Debye length**:

$$\lambda_D = \sqrt{\frac{\varepsilon_0 \kappa T_e}{n_e q_e^2}}$$

- ε_0 : permitivity of free space
- κ : Boltzmann constant
- T_e : temperature of electrons
- n_e : density of electrons
- q_e : charge of an electron

A plasma is thus macroscopically neutral over Debye length scales:

$$n_i \approx n_e$$

- n_i : density of ions

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Particle motion in an electrostatic field

Force on a free particle

$$\vec{F} = q\vec{E}$$

q : electric charge
E : electric field

Ohm law

Electrons also often experience a significant drag force, $\vec{F}_{drag} = -m_e \nu_e \vec{V}_e$, related to frequent collisions with heavy species (ions and neutrals). In such a case the pulling and drag forces approximately cancel:

$$\vec{V}_e \approx \frac{q_e}{m_e \nu_e}\vec{E}$$

m_e : mass of an electron
ν_e : collision frequency

from which Ohm law for a plasma is obtained

$$\vec{J}_e = q_e n_e \vec{V}_e = \left(\frac{n_e q_e^2}{m_e \nu_e}\right)\vec{E}$$

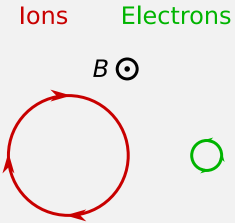
J_e : electron current density
n_e : density of electrons

Particle motion in uniform E and B fields

Lorentz force

$$\vec{F} = q\left(\vec{E} + \vec{V} \times \vec{B}\right)$$

V : particle velocity
q : electric charge
E : electric field



- For $E = 0$, particles rotate on a circle of radius

$$r_L = \frac{mV}{qB} \qquad \text{(Larmor radius)}$$

$\Rightarrow$ **light particles are easily magnetized**

- For $E \neq 0$, charged particles additionally drift perpendicularly to E and B, at velocity

$$\vec{V}_d = \frac{\vec{E} \times \vec{B}}{B^2}$$

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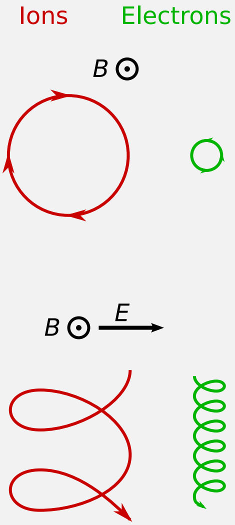


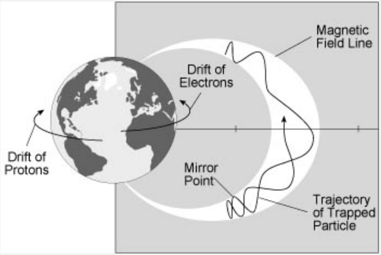
Magnetic mirror force

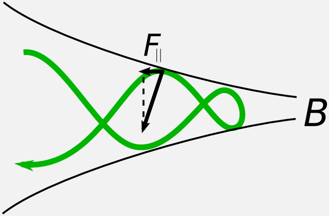
The projection of the Lorentz force along the gradient of B gives

$$\vec{F}_{\parallel} = -\mu \; gradB$$

$\mu = \frac{mV_\perp^2}{2B}$:	magnetic moment	$= const$
m :	particle mass	
$V_\perp$:	velocity perp. to B	

$\Rightarrow$ **charged particles are reflected by strong magnetic gradients**





Electrothermal

The propellant is heated (resistor/arc discharge) and expanded in a nozzle to velocity:

$$V < \sqrt{\frac{2C_pT}{M}}$$

C_p : specific heat
T : max. nozzle temperature

Electrostatic

Ions are accelerated directly by an electric field qE up to velocity:

$$V_i \approx \sqrt{\frac{2q_iU}{m_i}}$$

U : acceleration potential

Electromagnetic

A plasma is accelerated using a combination of electric and magnetic fields.
The plasma is quasineutral ($\sum q = 0$) thus $\sum qE = 0$:

$$\vec{F} = \vec{J} \times \vec{B}$$

J : current density

Categorization of EP devices

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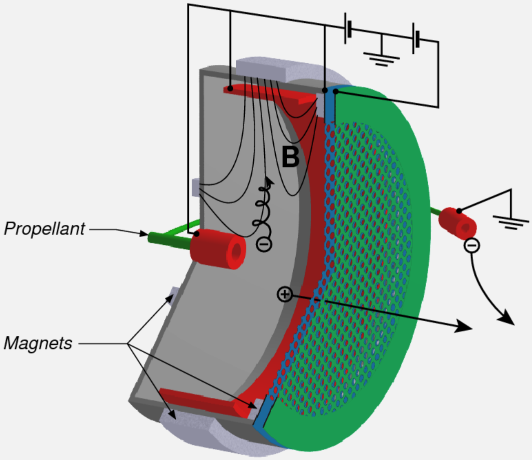


Characteristics

- electrostatic thruster
- xenon propellant
- limited thrust/area:

$$\frac{F}{A} < \frac{8\epsilon}{9}\left(\frac{U}{d}\right)^2$$

- ionization methods:
  - ion bombardment (US, UK)
  - μwave heating (Germany, Japan)

Performances

- specific impulse:

  $$Isp = 2500 - 4000 \text{ s}$$

- thrust:

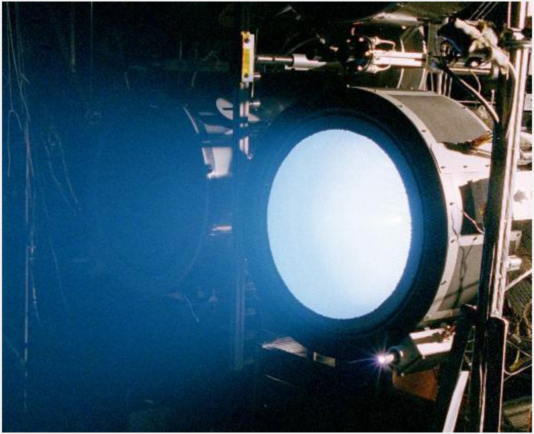
  $$F = 10 - 40 \text{ mN}$$

- efficiency:

  $$\eta \approx 60\%$$

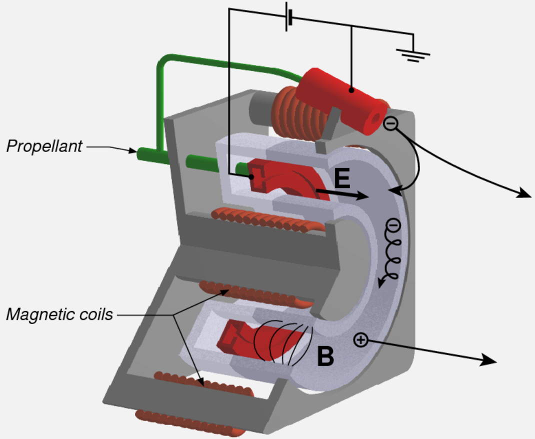
- complex Power Processing Unit
- flight experience:

  $$> 70 \text{ flights}$$



NEXT ion engine (Credit: NASA GRC)

The Hall thruster (1/2)



Characteristics

- electromagnetic thruster
- xenon propellant
- electrons "trapped" in azimuthal $E \times B$ drift $\Rightarrow$ improves ionization
- two main types:
  - Anode Layer Thruster (metal walls)
  - Stationary Plasma Thruster (ceramic walls)

Performances

- specific impulse:

$$Isp = 1500 - 2500 \text{ s}$$

- thrust:

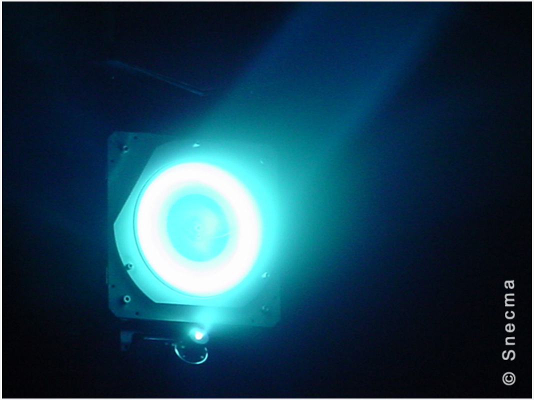
$$F = 20 - 200 \text{ mN}$$

- efficiency:

$$\eta \approx 50\%$$

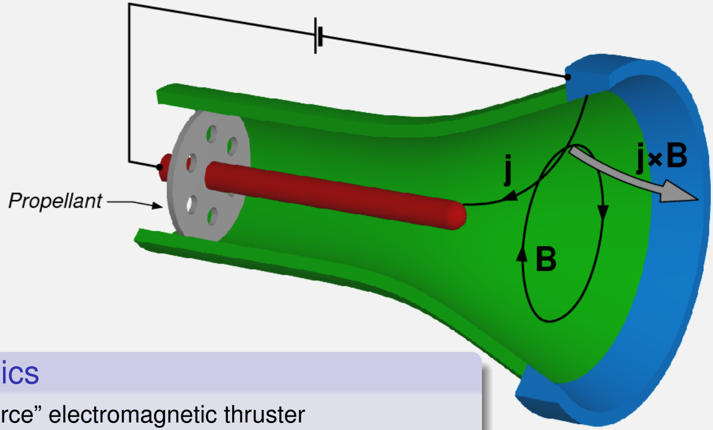
- moderately complex Power Processing Unit
- relatively wide beam ($\Rightarrow$ S/C contamination)
- flight experience:

$$> 120 \text{ flights}$$



PPS® 5000 Hall thruster (Credit: Snecma)

The magnetoplasmadynamic thruster (1/2)



Characteristics

- “Lorentz force” electromagnetic thruster
- nobles gases, hydrogen or lithium propellant
- several types: *continuous* or *quasi-stationary* (pulsed), *self field* or *applied field*
- close parent: pulsed plasma thruster (solid propellant)

Performances

- power:

  up to 1 MW!

- specific impulse:

  $Isp = 4000 - 10000$ s

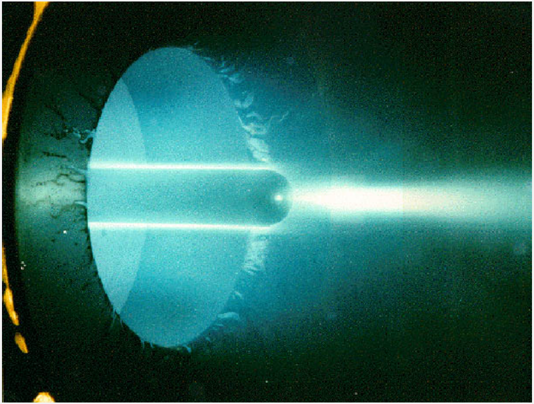
- thrust:

  $F = 10$ mN $- 100$ N

- efficiency:

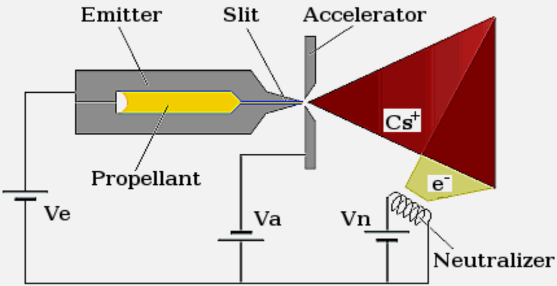
  $\eta \approx 20 - 40\%$

- flight experience:
  very few flights



(Credit: unknown)

Field Emission Electric Propulsion (1/2)



(Credit: Centrospazio)

Characteristics

- electrostatic thruster
- propellant: cesium or indium
- uses field-enhanced ion emission
- very low thrust/high Isp
- close parent: colloid thruster

Field Emission Electric Propulsion (2/2)

Performances

- specific impulse:

$$Isp = 6000 - 10000 \text{ s}$$

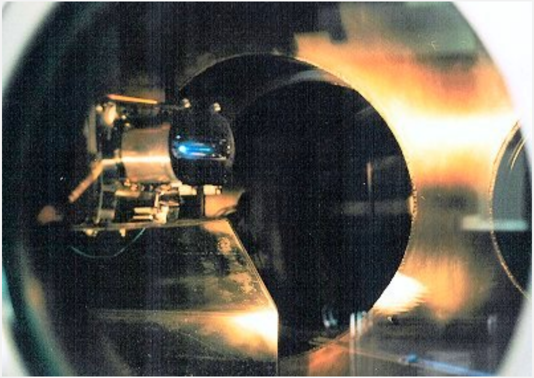
- thrust:

$$F = 0.1\mu\text{N} - 5 \text{ mN}$$

- efficiency:

$$\eta \approx 90\%$$

- S/C contamination issues with Cesium
- flight experience: none



Alta FEEP-50 (Credit: ESA)

Derivation of an "ideal" I_{sp} (1/2)

Assumptions

- the mission is *time-constrained*: the time t to achieve a given ΔV is prescribed
- *the available power P and the thrust F are constant* during the mission
- the mass of the propulsion subsystem is proportional to the power: $M_{ps} = \alpha P$

Starting from:

$$P = \frac{1}{2}\dot{M}\frac{V_{sp}^2}{\eta} = \frac{1}{2}\frac{M_{prop}}{t}\frac{V_{sp}^2}{\eta}$$

$\dot{M}$: mass flow rate
V_{sp} : specific velocity ($= g_0 I_{sp}$)
M_{prop} : initial mass of propellant
η : propulsion system efficiency

one obtains:

$$\frac{M_{pl}}{M_0} = \exp\left(-\frac{\Delta V}{V_{sp}}\right) - \frac{\alpha V_{sp}^2}{2\eta t}\left[1 - \exp\left(-\frac{\Delta V}{V_{sp}}\right)\right]$$

M_{pl} : payload mass
M_0 : initial mass

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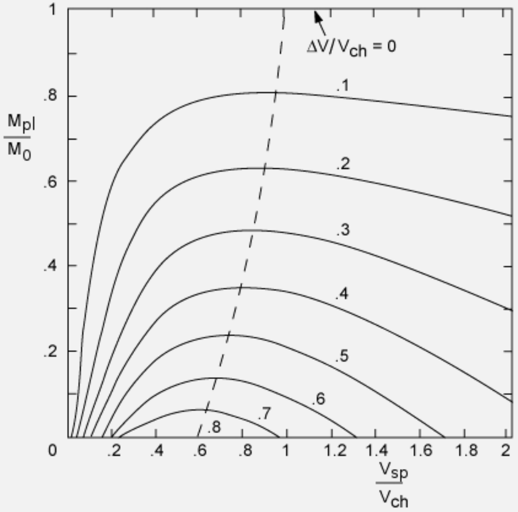

Payload fraction vs. V_{sp} for $\Delta V \ll V_{ch}$

(Credit: MIT)

Conclusion

The optimal V_{sp} scales roughly as:

$$V_{ch} = \sqrt{\frac{2\eta t}{\alpha}}$$

The choice of the propellant follows from a variety of technical considerations: storage requirements, spacecraft contamination, handling hazards, etc, and from its impact on thruster efficiency.

Assumptions

- the propellant related energy loss is mainly due to ionization (realistic for ion and Hall thrusters, less for MPDs and FEEPs)
- the effective ionization cost is proportional to the single ionization energy

The ratio of the effective ionization power to the usefull power:

$$\frac{P_{ioniz}}{P_{useful}} \approx \frac{\gamma \epsilon_i}{\frac{1}{2} m_i V_{sp}^2}$$

γ : effective ionization cost factor
ϵ_i : ionization cost
m_i : mass of an ion
V_{sp} : specific velocity

suggests that for given V_{sp} the parameter $\frac{\epsilon_i}{m_i}$ must be minimized

Choice of the propellant (1/2)

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Propellant	ϵ_i [e.V]	m [u]	ϵ_i/m
Cs	3.9	132.9	0.029
Li	5.9	6.9	0.855
Bi	7.3	209.0	0.035
Hg	10.4	200.6	0.052
Xe	12.1	131.3	0.092
H	13.6	1.0	13.600
Kr	14.0	83.8	0.167
Ar	15.8	39.9	0.396

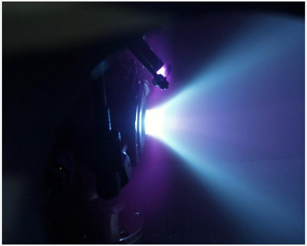
Short and mid-term R&D

- high power (P>5kW) and low power (P<200W) Hall thrusters
- high I_{sp} Hall thrusters (I_{sp}>2000s)
- high power (P>5kW) ion thrusters
- erosion-resistant grid and channel materials for ion and Hall thrusters
- indium FEEP, colloid thrusters, μ-size field emission thruster arrays
- applied field MPDs

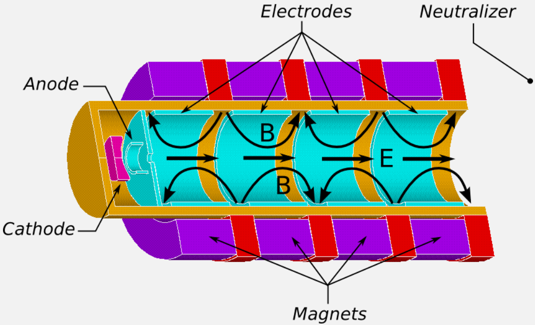
Long term R&D

- lithium MPDs
- Nuclear-Electric Propulsion (NEP)
- new thruster concepts

Highly Efficient Multistage Plasma thruster (HEMP)



HEMP DM3a (Credit: Thales)

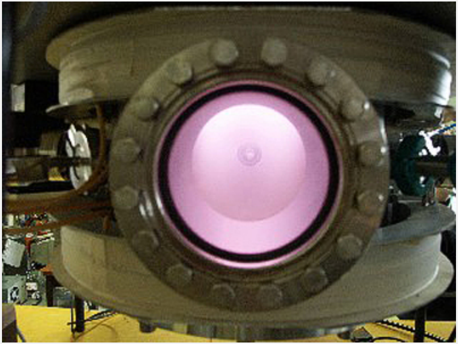


Characteristics

- specific impulse $\approx 2000 - 3000$s
- thrust $\approx$ 100mN
- very low erosion $\Rightarrow$ long lifetime
- large beam angle still an issue

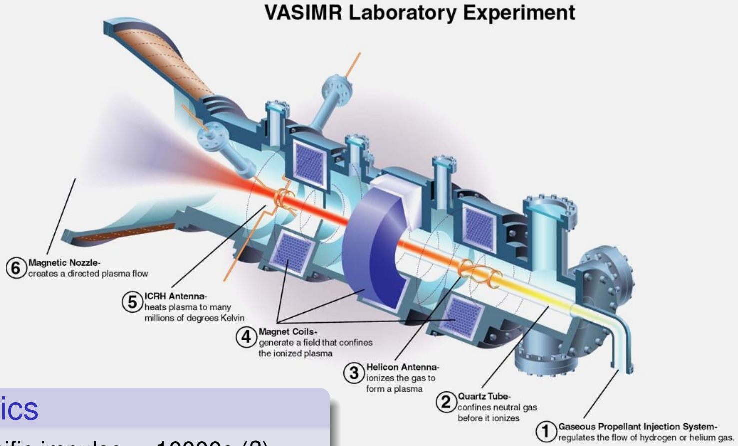
Characteristics

- very efficient ionization using an helicon antenna
- no electrodes
- early development stage (ongoing evaluation at ESA)



ANU's HDTL (Credit: ESA)

Variable Specific Impulse Magnetoplasma Rocket



Credit: NASA ASPL

Characteristics

- target specific impulse $\approx$ 10000s (?)
- target power: up to few MW
- extremely complex
- very early development stage