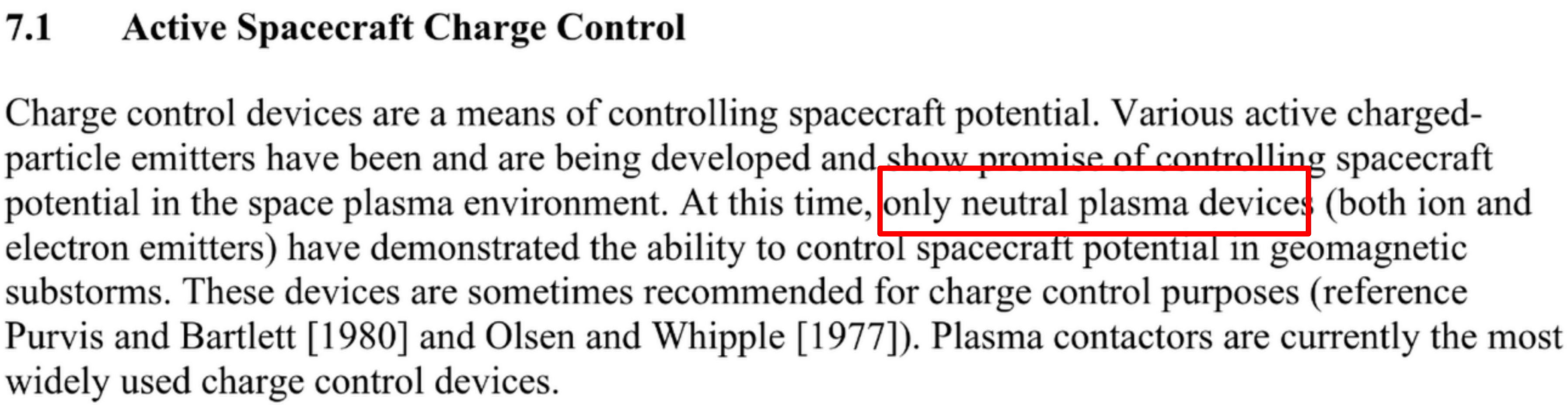
Máster Universitario en Ingeniería Aeronáutica

The Space Environment

Artificial plasmas in space. Plasma propulsion

Jorge González Muñoz
Based on the work by Luis Conde
Personal website: http://plasmalab.aero.upm.es/~lcl/
Departamento de Física Aplicada

Charge control at the ISS

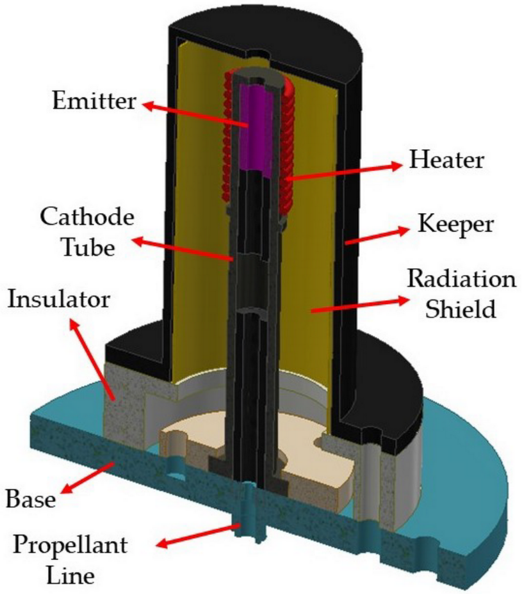


7.1 Active Spacecraft Charge Control

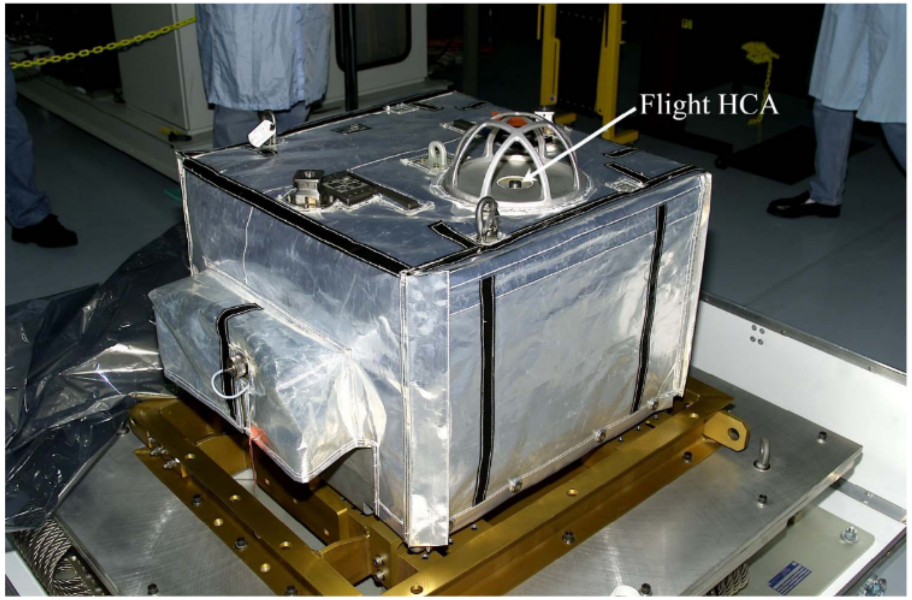
Charge control devices are a means of controlling spacecraft potential. Various active charged-particle emitters have been and are being developed and show promise of controlling spacecraft potential in the space plasma environment. At this time, only neutral plasma devices (both ion and electron emitters) have demonstrated the ability to control spacecraft potential in geomagnetic substorms. These devices are sometimes recommended for charge control purposes (reference Purvis and Bartlett [1980] and Olsen and Whipple [1977]). Plasma contactors are currently the most widely used charge control devices.

NASA: Mitigating In-Space Charging Effects—A Guideline

Use of a Hollow Cathode to avoid charging of ISS: Plasma Contactor Unit (PCU)



Kokal, Ugur, Nazli Turan, and Murat Celik. "Thermal analysis and testing of different designs of lab6 hollow cathodes to be used in electric propulsion applications." Aerospace 8.8 (2021): 215.



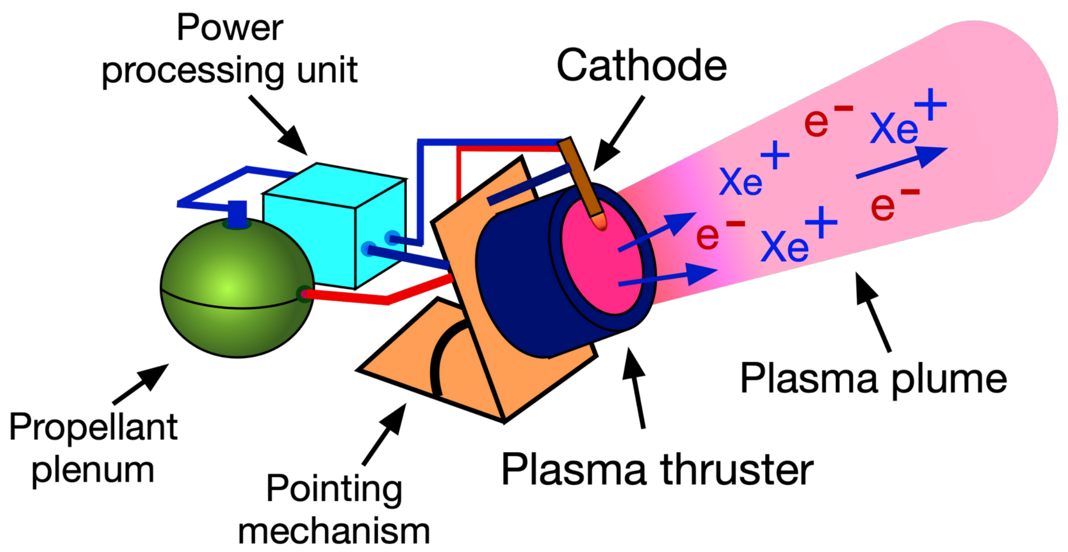
Carpenter, Christian. "On the operational status of the ISS plasma contactor hollow cathodes." 40th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit. 2004.

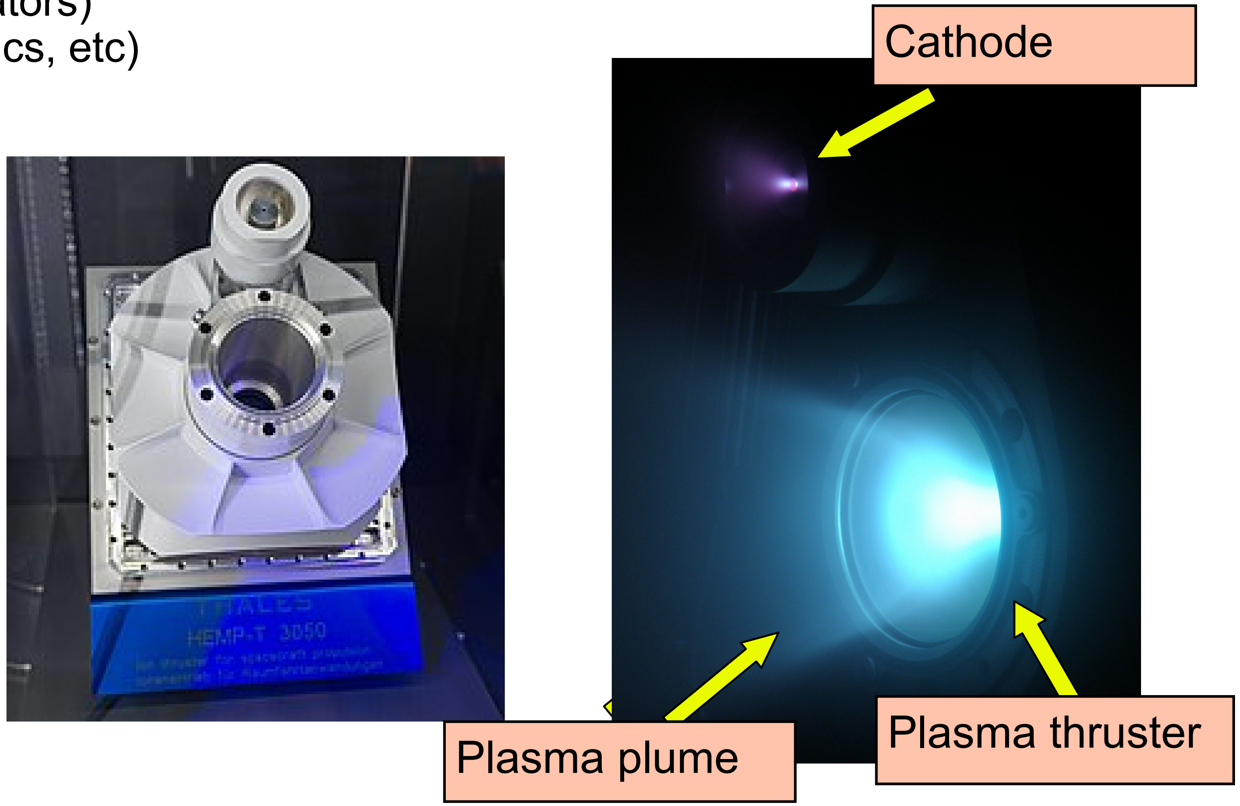
Commercial propulsive systems in Europe

Plasma thrusters are different from other propulsive systems. In the following I will concentrate in electrostatic thrusters using fast plasma streams that are considered as mature technologies in Europe.

Subsystems

- Thruster (plasma accelerator)
- Gas Control System (gas, valves, regulators)
- Power Processing Unit (control electronics, etc)
- Pointing Mechanism





Thales HEMPT 3050 (courtesy Thales Group. Germany)

Increase in EP systems in orbit

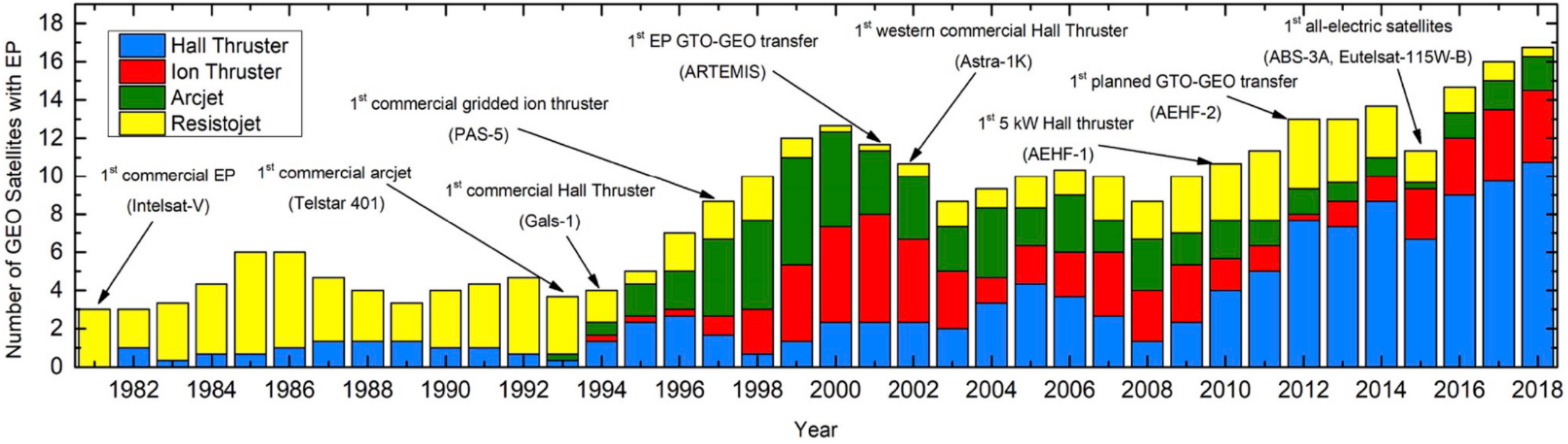


Fig. 3. Number of EP-based GEO satellites launched in the years 1981–2018 (3-year moving average), divided into electric thruster subclasses.

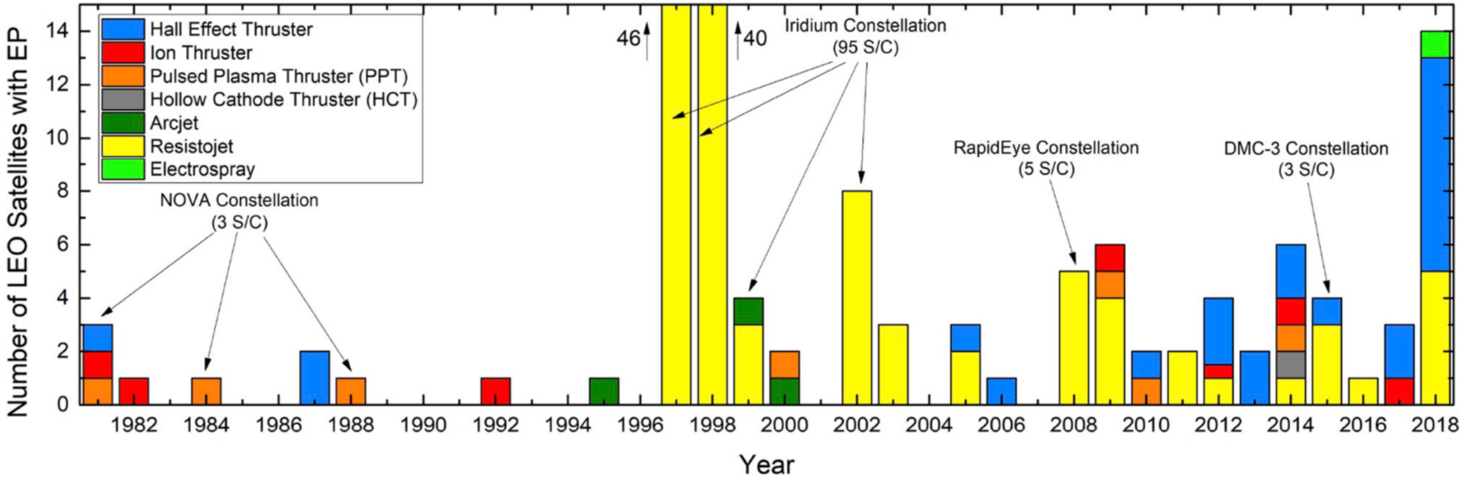
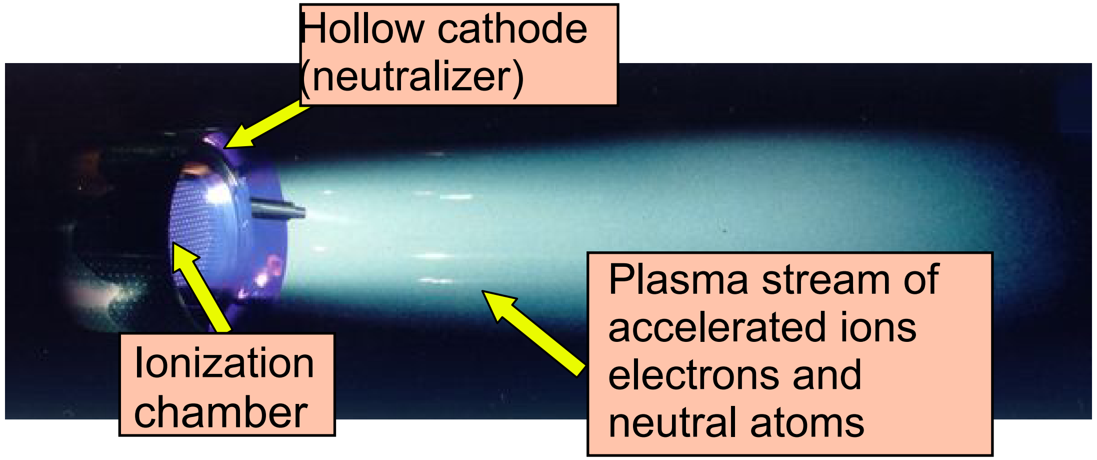


Fig. 7. Number of LEO satellites incorporating electric propulsion systems by year and by thruster technology subclass. Total number of LEO satellite incorporating EP is 167.

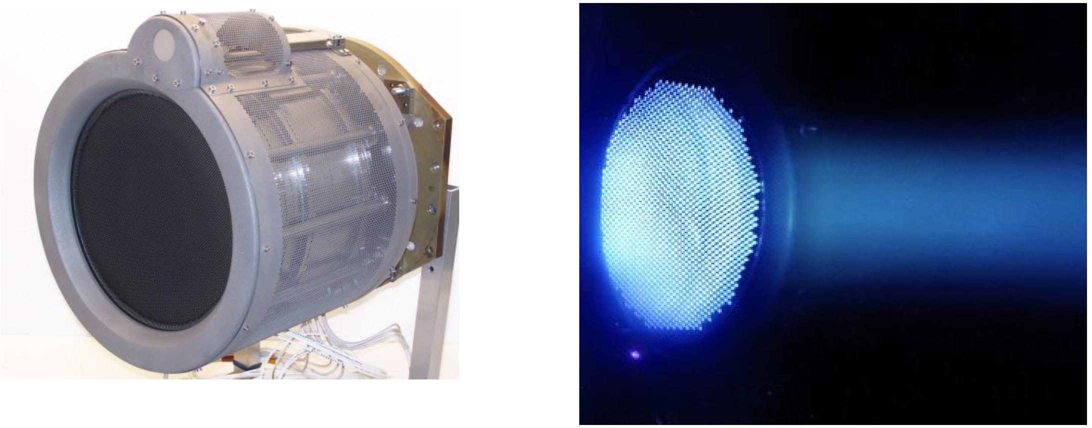
Lev, D., Myers, R. M., Lemmer, K. M., Kolbeck, J., Koizumi, H., & Polzin, K. (2019). The technological and commercial expansion of electric propulsion. Acta Astronautica, 159, 213-227.

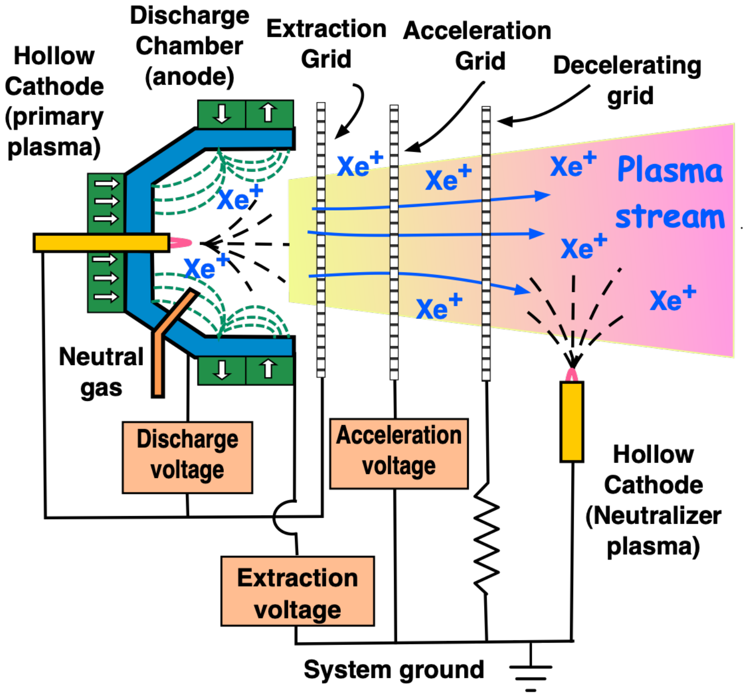
INCREASING WITH CONSTELLATIONS

The gridded ion engine



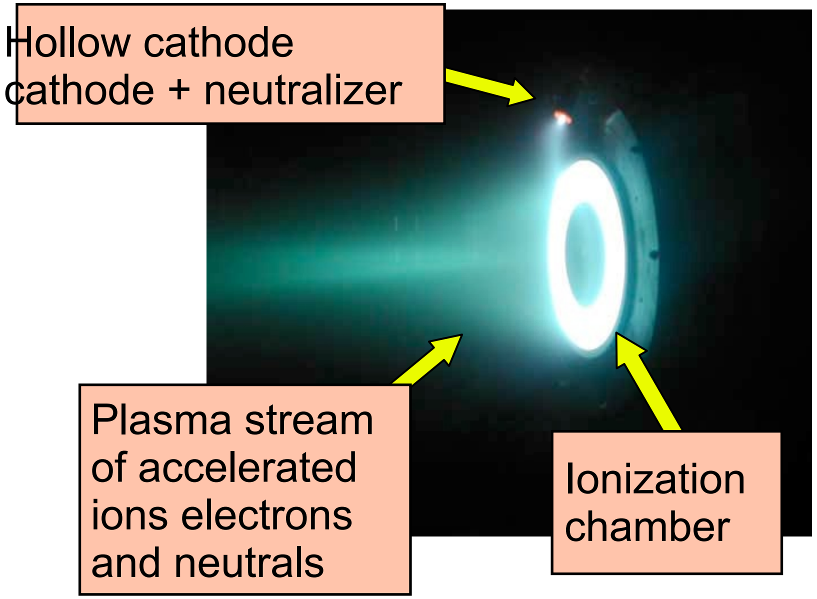
Quinetiq T6 Ion Engine Thruster
courtesy Quinetiq Inc. UK)





- This thruster is the classical ion engine (Kaufman). The ions are produced inside the plasma chamber by electrons from a cathode and later extracted by a multigrid system. The exhausted ion beam is neutralized by electrons from a second cathode located outside.
- Only ions are transported through the grids (ion optics) and this current is essentially limited by the Child-Langmuir law.
- The T5 and T6 ion engines (photographs) manufactured by Quinetiq (UK) have been flown in the GOCE and Beppi-Colombo missions

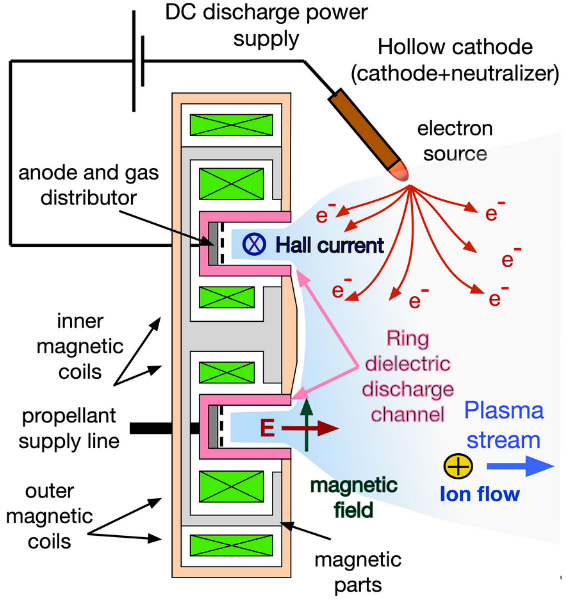
The Hall effect thruster



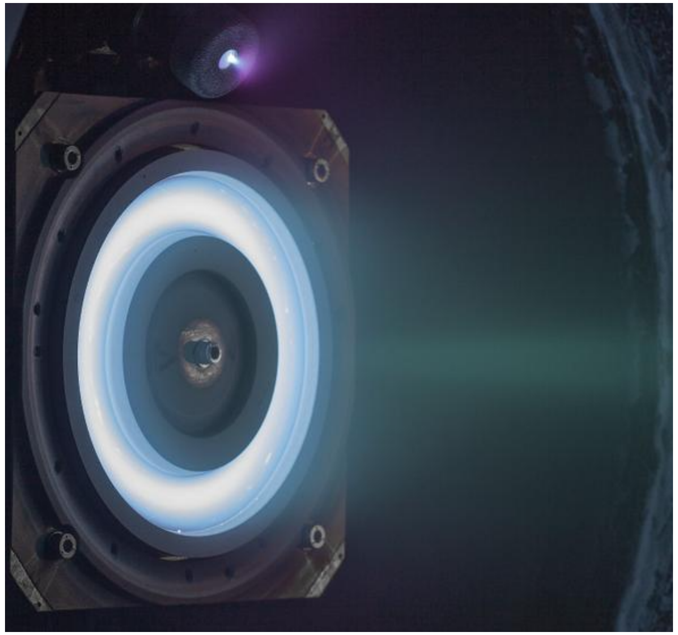
Hollow cathode
cathode + neutralizer

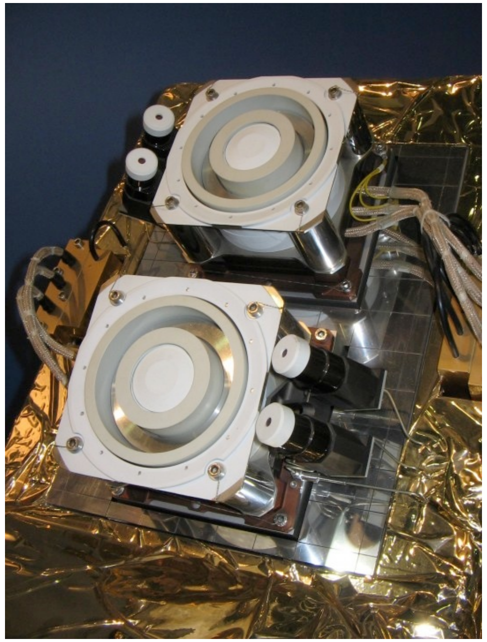
Plasma stream
of accelerated
ions electrons
and neutrals

Ionization
chamber



Safran PPS 1350 Hall Thruster
(courtesy Safran-Snecma. France)

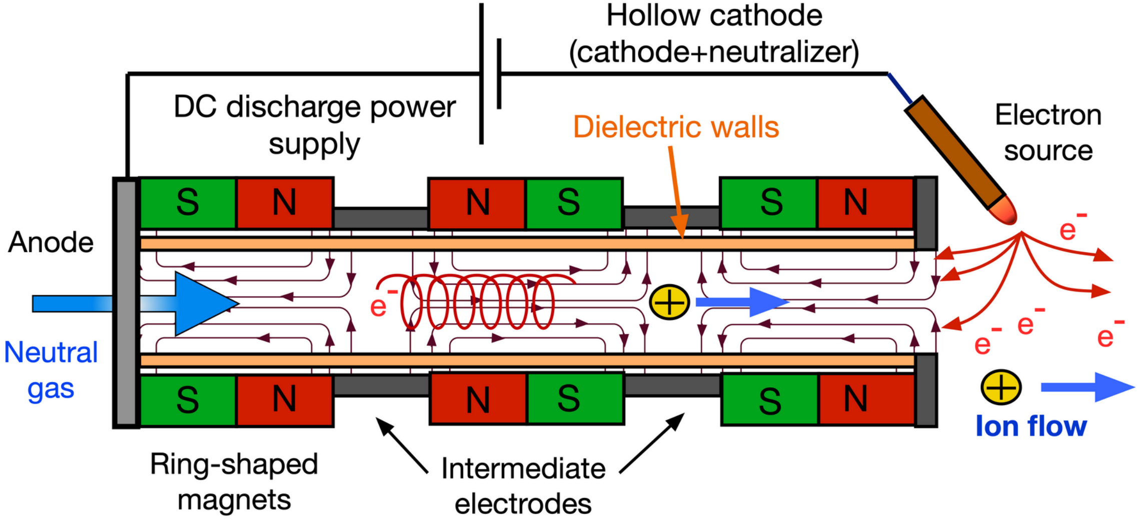




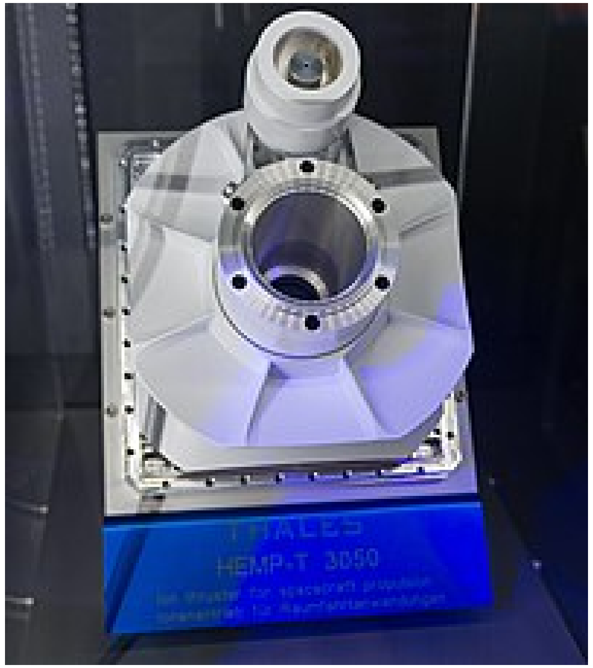
- The Hall effect thruster (HET) usually have ceramic ionization chambers and ions are extracted from a plasma with by a "crossed" electrostatic and magnetic fields. The only external hollow cathode is employed for both ion production and neutralization.
- Since the first Russian commercial thrusters from Fakel STP-100 HETs are flying since more than 15 years mainly in telecommunications satellites and for station keeping purposes.

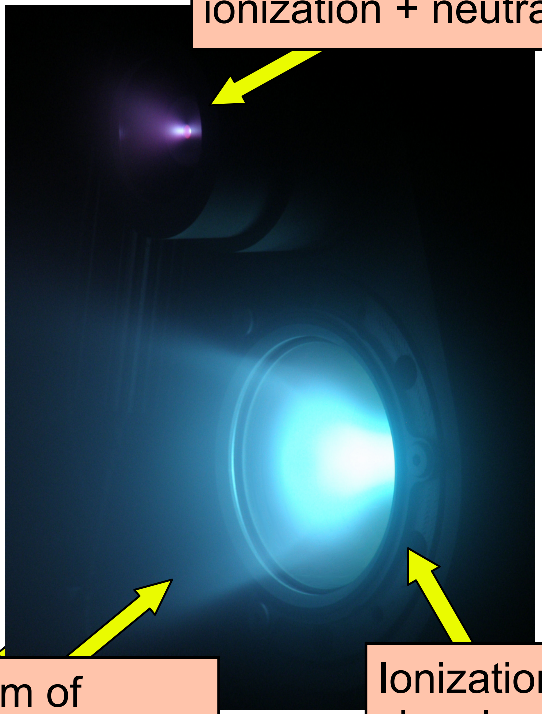
The HEMPT

- The Highly Efficient Multistage Plasma Thruster has ceramic wall, and the ion acceleration is produced by a multi-stage longitudinal electric field. The magnetic field (red lines) confines the electrons along the radial direction (red helix) and only one hollow cathode is used for both plasma production and ion beam neutralization.
- The electrons from the external hollow cathode are attracted towards the anode and the end one the cylindrical cavity and produce the ionization of the neutral gas.



Thales HEMPT 3050 (Courtesy Thales Group. Germany)





Hollow cathode ionization + neutralizer

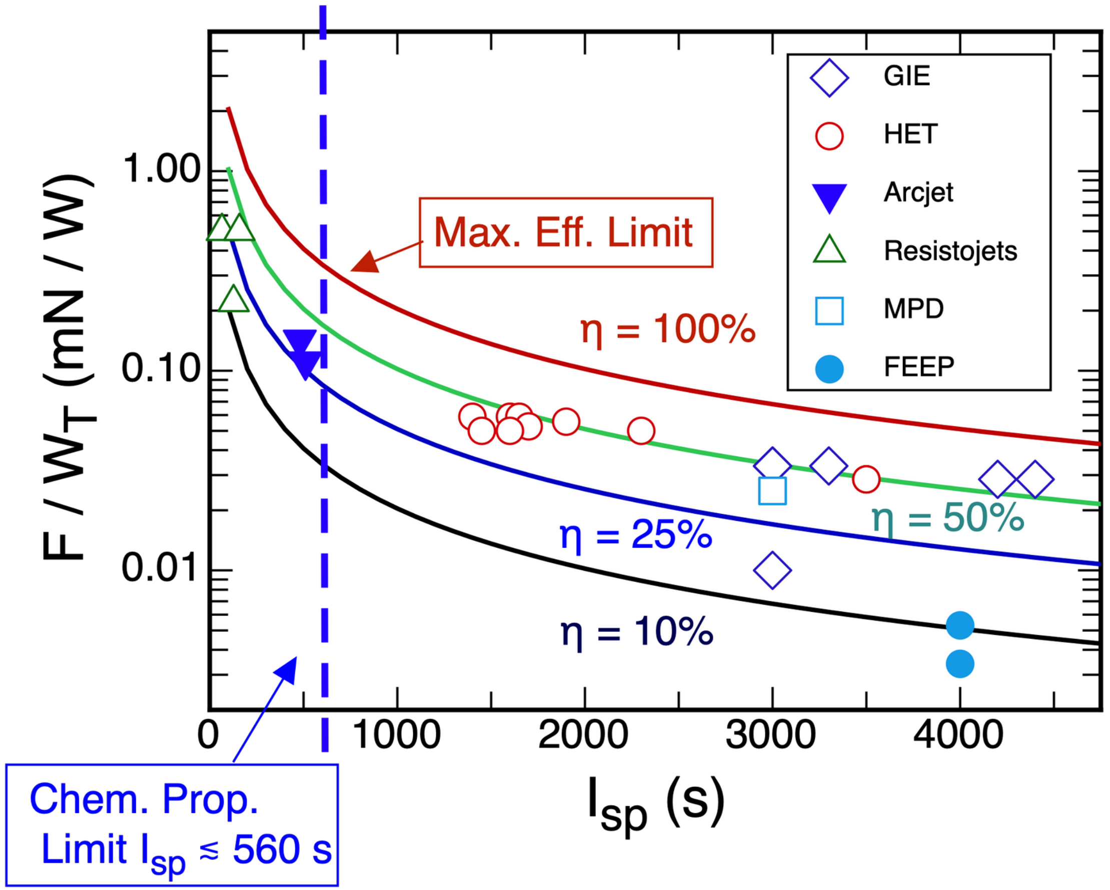
Plasma stream of accelerated ions electrons and neutrals

Ionization chamber

- The ion acceleration is produced by a set of ring-shaped intermediate electrodes that produce an axial electric field.

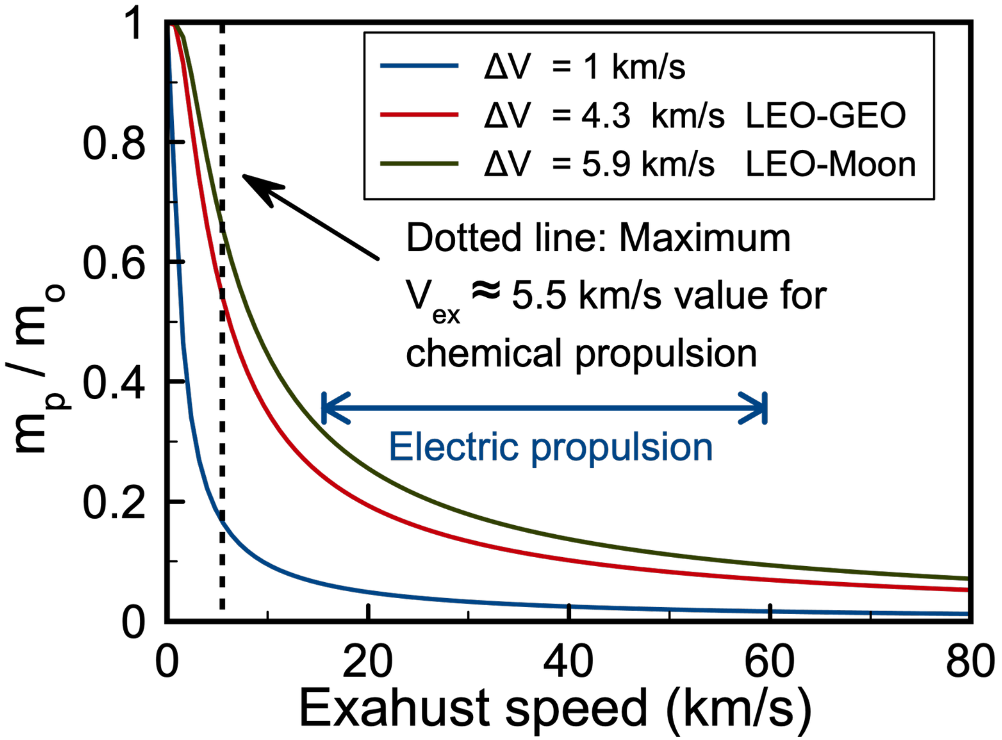
Electric thruster performance

$$\frac{F}{W_T} = \eta_T \times \frac{\dot{m}_i\, v_{ex}/2}{\dot{m}_i\, v_{ex}^2/2} = 2\,\frac{\eta_T}{v_{ex}} \qquad v_{ex} = I_{sp} \times g_o$$



Max. Eff. Limit

Chem. Prop.
Limit $I_{sp} \lesssim$ 560 s



Dotted line: Maximum $V_{ex} \approx$ 5.5 km/s value for chemical propulsion

Electric propulsion

The Tsiolkovsky equation gives the ratio m_p/m_o between the propellant mass m_p necessary to increment in $\Delta v = v_f - v_i$ the dry mass m_f of a system with initial mass $m_o = m_f + m_p$

$$\frac{m_p}{m_o} = 1 - e^{-\Delta v/v_{ex}} \qquad \text{or,} \qquad \frac{m_p}{m_f} = e^{\Delta v/v_{ex}} - 1$$

The speed of one Argon ion accelerated by a 500 V voltage is 49 km/s compared to 5.5 km/s of conventional chemical propulsion limit.

The in-space electric propulsion

Advantages

- Powered by solar panels.
- Propelled by chemically inert gases (xenon) of easy long-term stowage.
- Important propellant/weight savings allow heavier payloads.
- High efficiency, high specific impulse allow long term missions.
- Today indispensable for economic competitiveness of telecommunication satellites.

Drawbacks

- Are complex systems (materials, electronics, etc) with demanding requisites.
- Low levels of thrust, in the order of 0.1-200 mN.
- Orbital maneuvers take long.
- Electric power consumption can be an issue.
- The large electric power (typically few kW) of thrusts for telecommunication satellites limits the use of these to with large solar panels (up to 20 kW).

The electric propulsion is nowadays a growing field where new thrusters and improvements of the existing continuously appear. The physics involved in ion production and plasma acceleration to high exhaust velocities is still unclear in some thruster configurations.

Plasma propulsion: ion backflow

A plasma thruster emits ions, electrons and neutrals.

Charge-exchange between ions and neutrals in the plume can lead to slow ions.

$$\mathrm{A}_{\mathrm{slow}} + {\mathrm{A}_{\mathrm{fast}}}^{+} \longrightarrow {\mathrm{A}_{\mathrm{slow}}}^{+} + \mathrm{A}_{\mathrm{fast}}$$

These can be attracted to areas of the spacecraft with lower voltage (with respect to the plasma plume): solar panels, antennas, scientific instruments...

Issues of ion bombardment, surface charging, secondary emission...

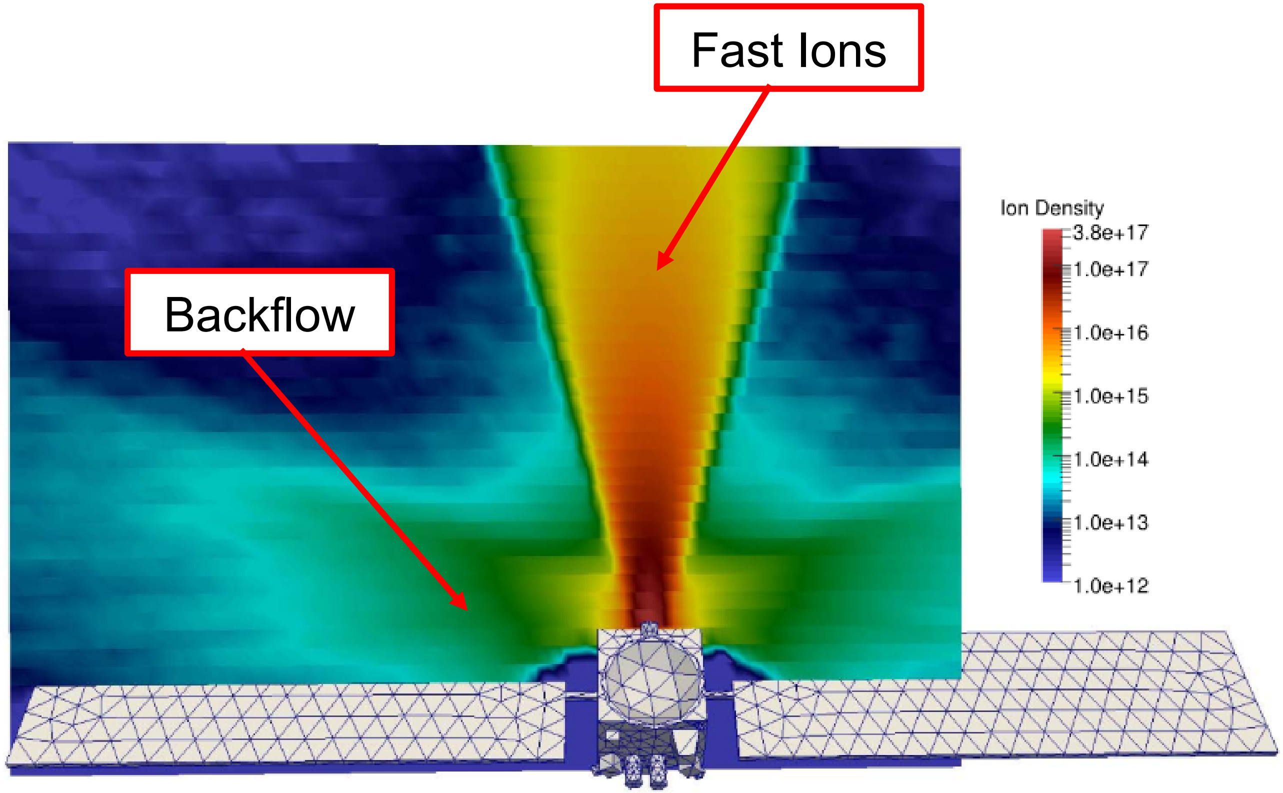


Fig. 11. Ion density (m^{-3}) on a plane perpendicular to the thruster's exit plane.

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