Plasma Propulsion in Space

Eduardo Ahedo

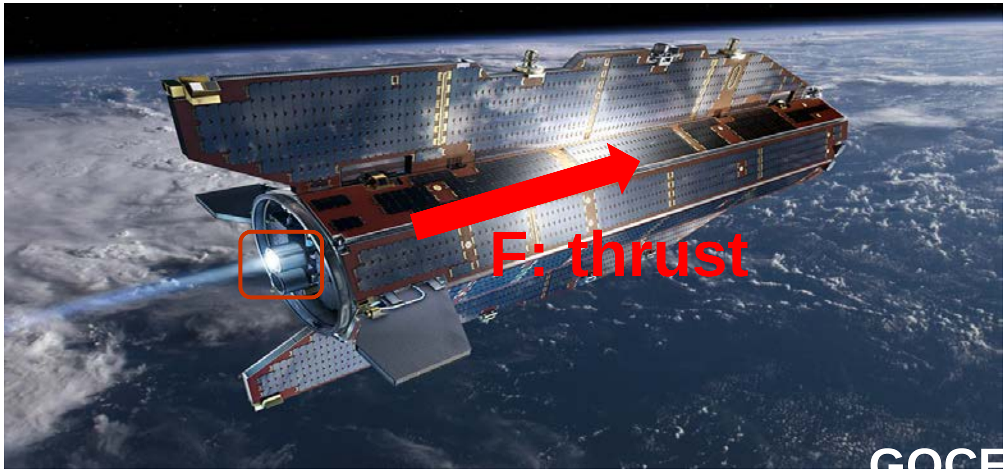
Professor of Aerospace Engineering

Plasmas and Space Propulsion Team

Universidad Carlos III de Madrid, Spain

Outline

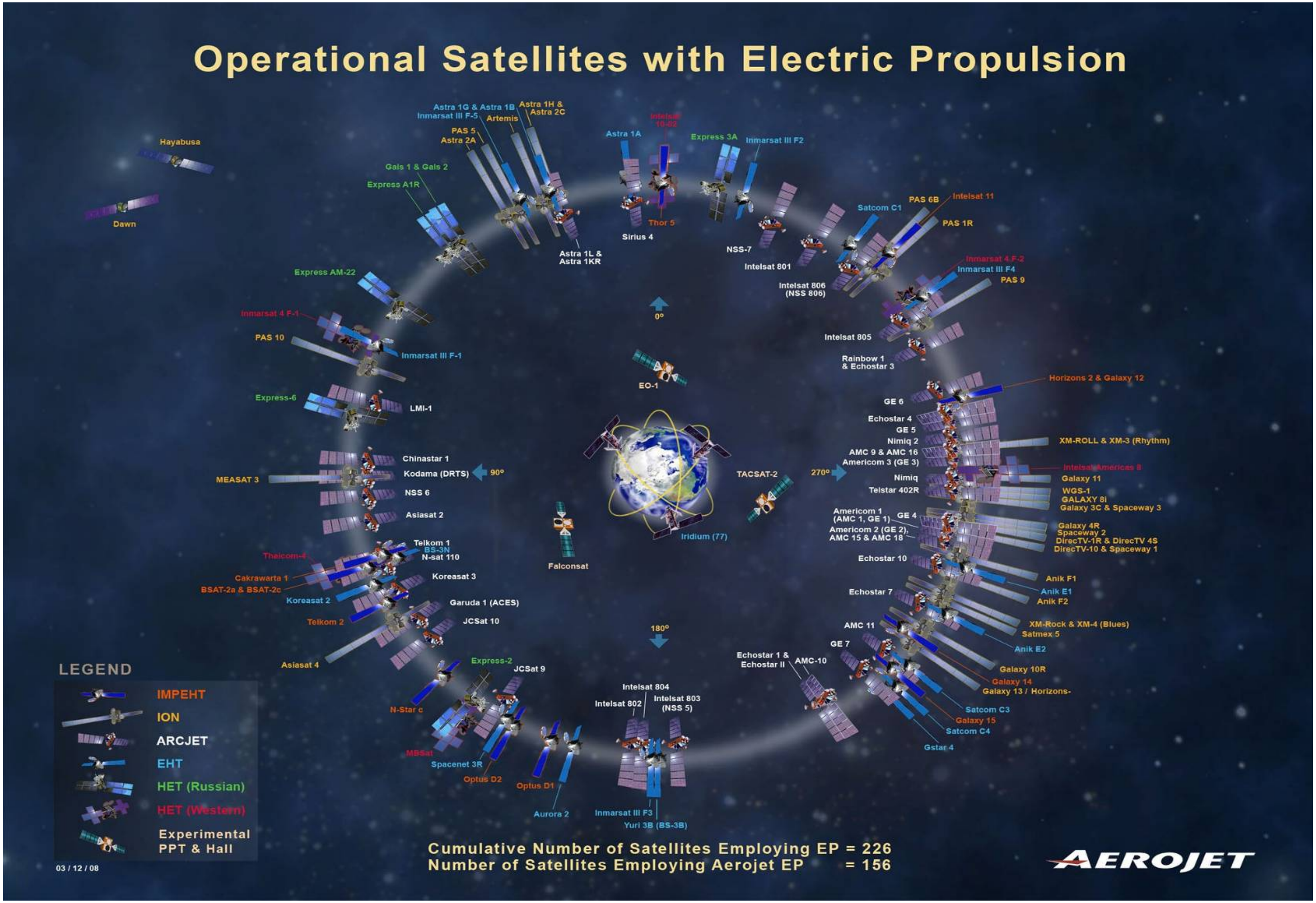
- Space propulsion has been the domain of chemical propulsion (CP)
- Plasma/Electric Propulsion (EP) is an emergent group of technologies, in the path to get an important share of **in-space propulsion** missions
  - Launchers will continue to be the domain of chemical propulsion
- In this presentation we will show
  - Main figures-of merit for plasma thrusters
  - Short review of main devices and operational principles



In-space propulsion: constraints

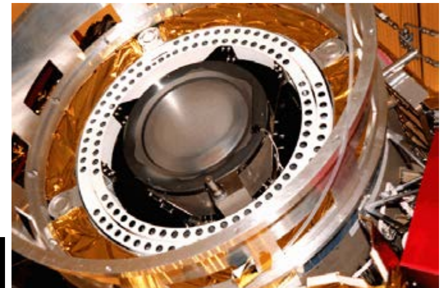
- **No repair shop**: Spacecraft subsystems and parts must be highly <u>reliable</u> and durable $\rightarrow$ long and costly qualification tests
- **No fuel station**: spacecraft must carry all fuel they need at launch
- **Launching costs** ~ 20.000€/kg $\rightarrow$ **500 kg ~ 1M€**
- Electric Propulsion uses much less fuel than Chemical Propulsion
  - Advantages: initial mass ↓, payload ↑, longer mission ↑
  - Lower initial mass ⇒ Smaller launcher ⇒ Double savings
- Implementation of Plasma Propulsion **save several M€**

EP: significant ComSat heritage

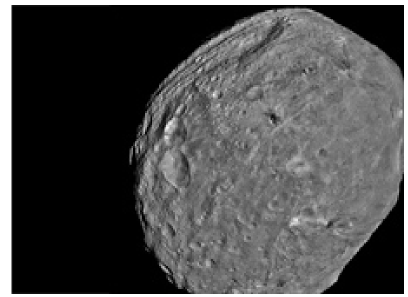


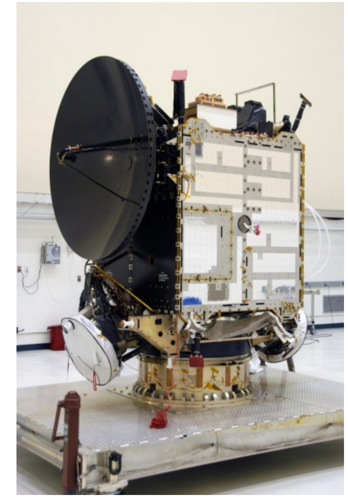
EP: successful interplanetary missions

DEEP-SPACE-1

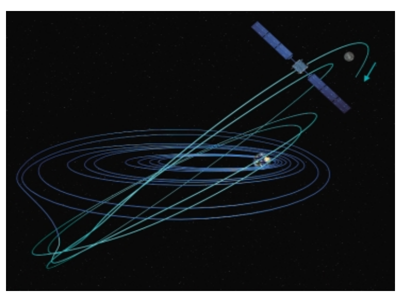


DAWN

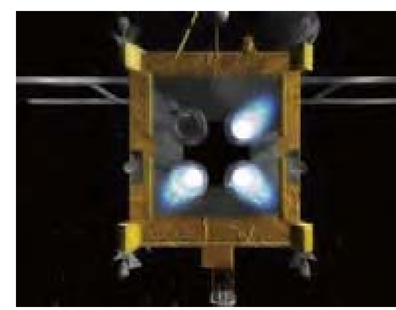




SMART-1



HAYABUSA



The mass budget

$$\frac{M_{payload}}{M_{initial}} = \exp\left(-\frac{\Delta V}{I_{sp}}\right) - \frac{M_{dry}}{M_{initial}}$$

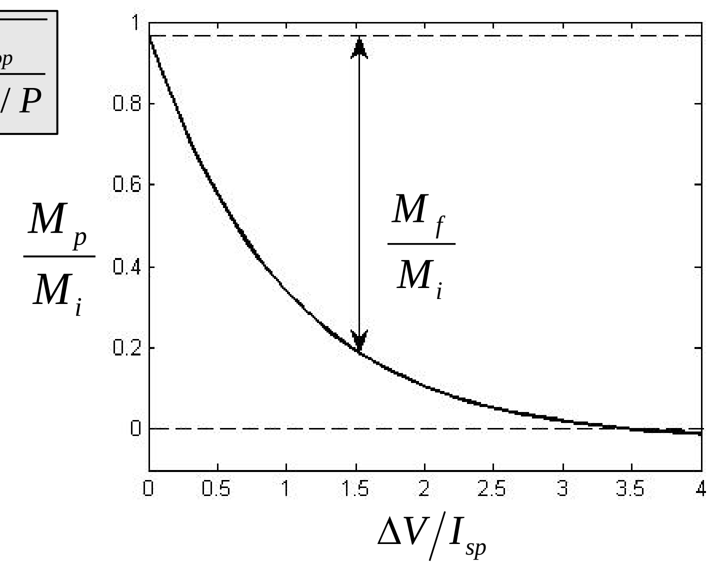
- ΔV = sum of velocity changes required by mission
  - GEO sat, 15year SK, $\Delta V \sim 0{,}8$ km/s
  - Dawn Mission, $\Delta V \sim 11$ km/s
- I_{sp} = specific impulse

  = impulse per fuel mass unit

  ≈ exhaust velocity of gas jet
- $M_{dry} = M_{initial} - (M_{payload} + M_{fuel})$

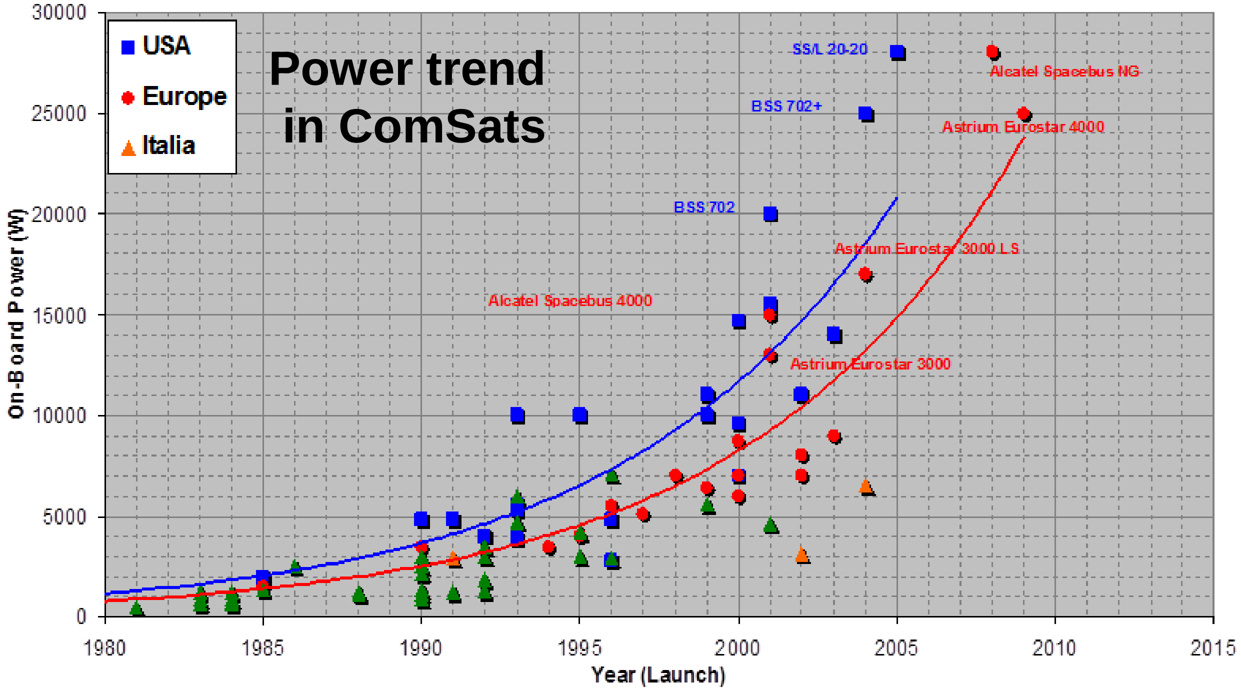
- **High I_{sp} thruster**
  - CP: $I_{sp} \sim$ 2 km/s ≡ 200 s
  - EP: $I_{sp} \sim$ 20 km/s ≡ 2000s
- EP offers **irresistible cost savings**
  - but high development costs
- **Light thruster**
  - Plasma thrusters can be heavy
  - There is an optimal Isp for the mass budget
- **Other contraints must be considered**
  - Mission propulsion time
  - Minimum acceleration or thrust/power
  - Solar array sharing with payload

$$Isp_{opt} \propto \sqrt{\frac{\tau_{prop}}{M_{thr}/P}}$$



Power and efficiency

- On-board power (e.g. solar arrays) limits the range of missions for EP
- Fortunately, installed power is growing fast, mainly in ComSats
- Additionally, Microsatellites and Satellite Precise Control are becoming a relevant part of the space business → MicroPropulsion
- Today, EP technologies are trying to cover the 1W-25kW range



Thruster figures of merit

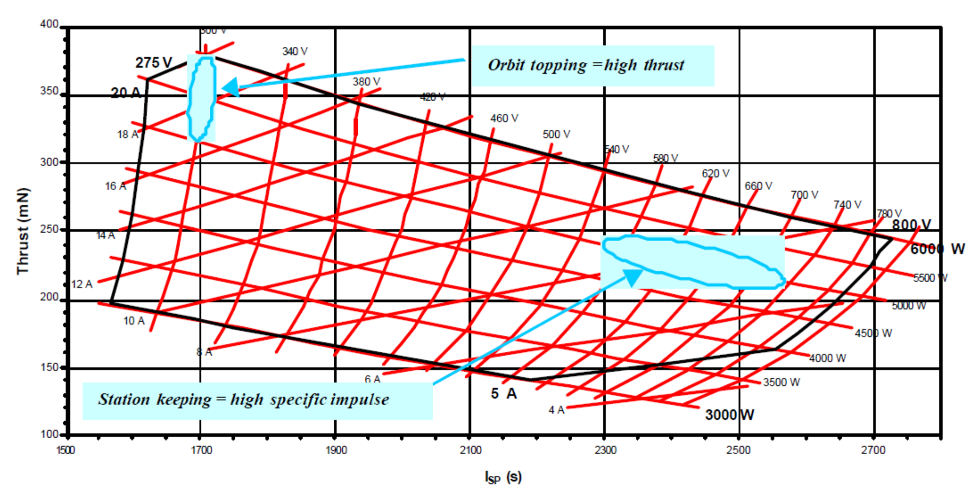
- Specific Impulse
- Thrust Efficiency, η
  - Limits on $P \Rightarrow$ EP is <u>low-thrust</u> , <u>long-firing</u>
  - At system level: PCPU efficiency is important
- Throttlability $\rightarrow$ dual-mode

  $\rightarrow$ trade-off between F/P and I_{sp}
- Lifetime $\rightarrow$ slow deterioration
- Lightness $\rightarrow$ low M_{dry}/P
- Small jet divergence
- Scalability of technologies
- Compactness
- Reliability

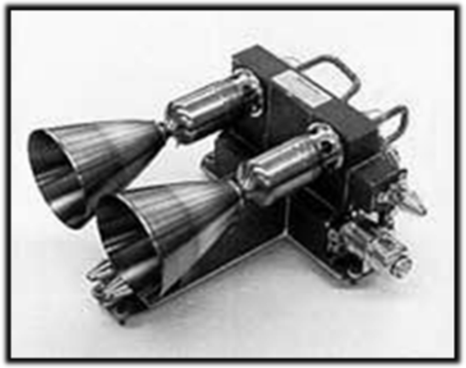
$$\eta = \frac{I_{sp}F}{2P} \approx \frac{P_{useful}}{P}$$

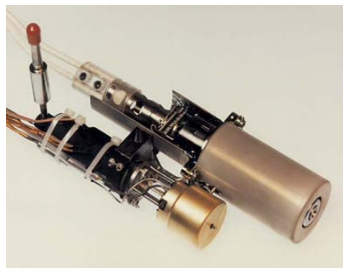
$$\downarrow$$

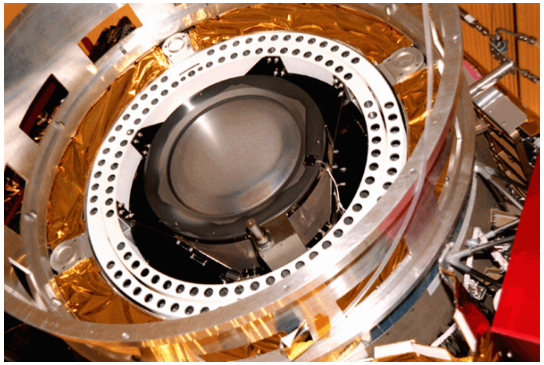
$$I_{sp} \times \frac{F}{P} = 2\eta \approx 1$$

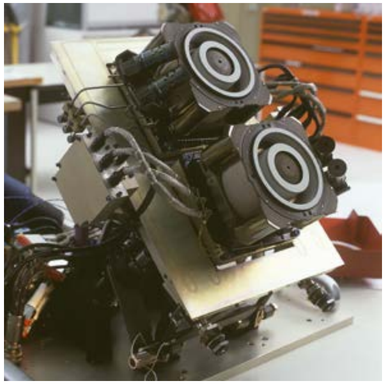


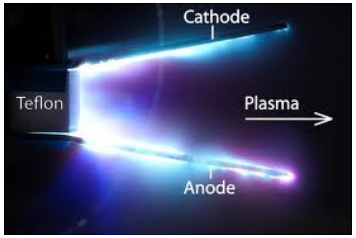
EP: family portrait

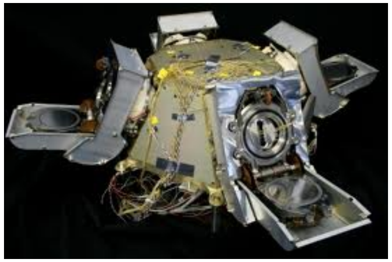


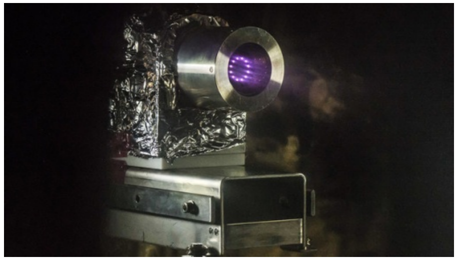


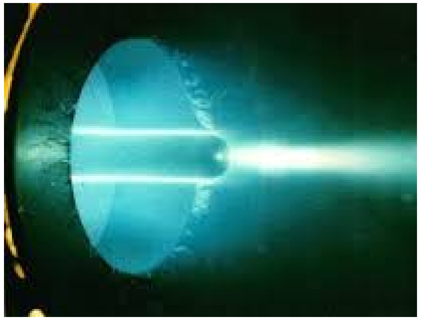


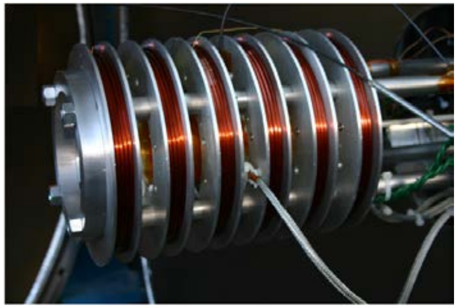










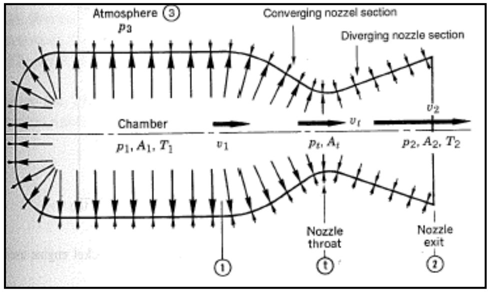


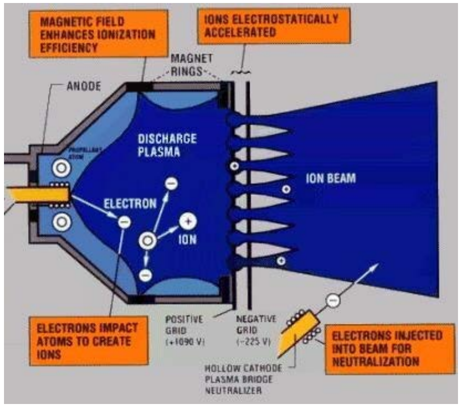
Multifaceted plasma processes

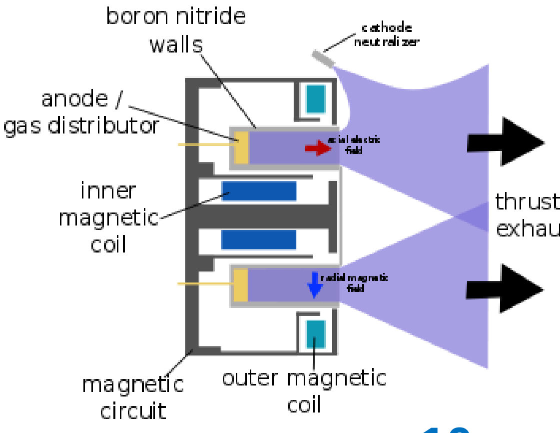
- **Plasma production & heating:**
  - DC electrodes versus AC antennas
  - Different propellants types
- **Plasma acceleration & thrust transmission**
  - Electrothermal, electrostatic, or electromagnetic

$$\text{Thrust} \approx \int_{chamb+plume} [-\nabla_z p + \rho_e E_z + (\vec{j}\times\vec{B})_z] dV$$

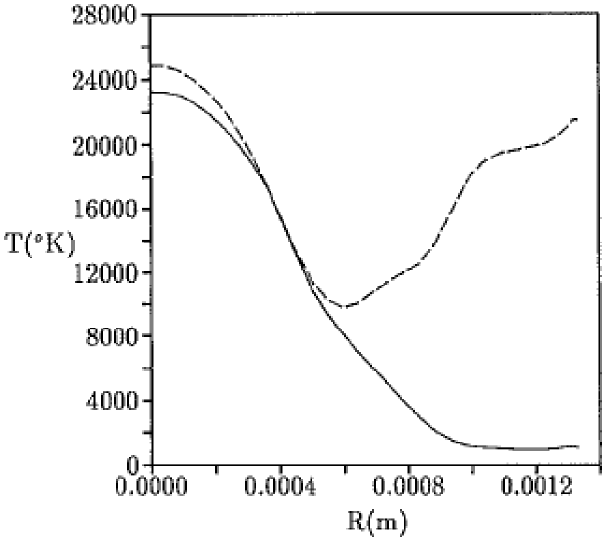
  - Jet expansion and divergence
- Plasma-surface interaction
  - Sheaths, surface emission, grids, confinement
  - Heat loads, wall erosion, recombination
- Magnetized, weakly-collisional plasmas
  - Non local thermodynamic equilibrium
  - Instabilities, turbulence
  - Radiation

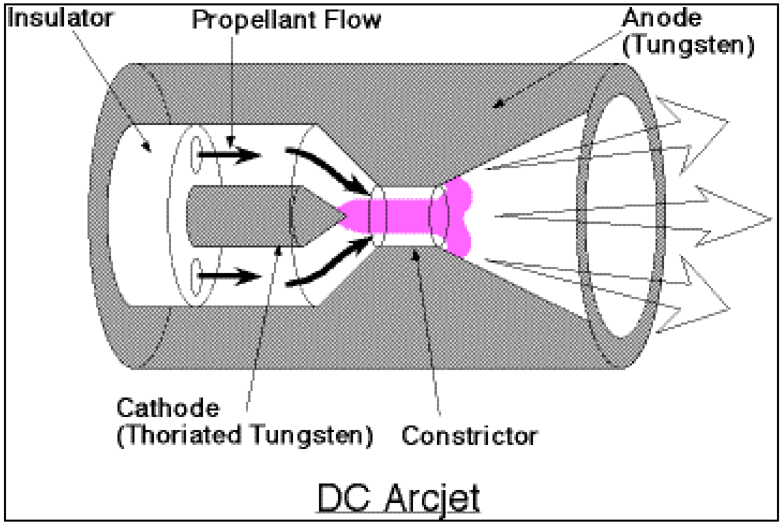






Arcjet





- Operational since 1984
- *Isp* (N_2H_4) ~ 6 km/s ~ 600 s
- lifetime ~ 1000 h
- η ~ 35%

DC Ion thruster

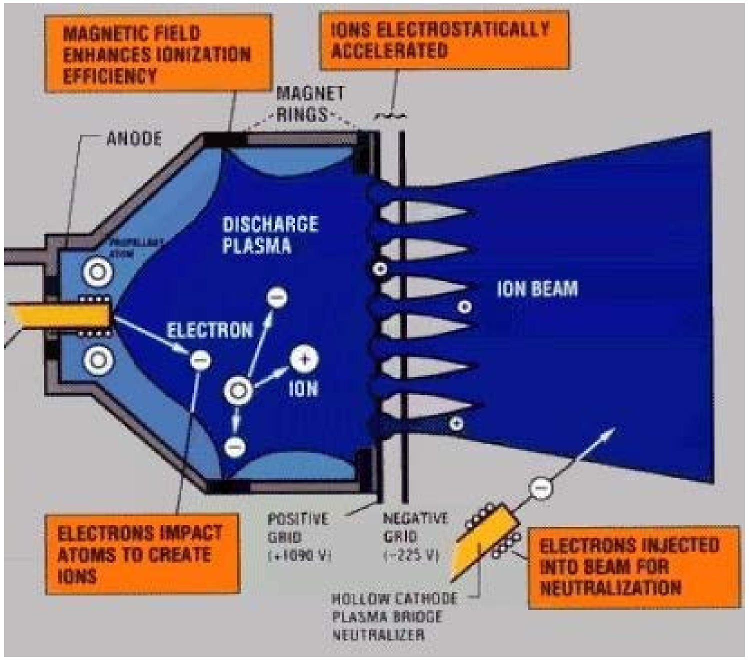
- <u>Discharge chamber</u>: plasma produced by e-n impact
  - <u>Hollow cathode</u>: injects high-energy electrons (10-20eV)
  - <u>Magnetic screening</u> of walls: for efficient ionization

- <u>Grid system</u>: Ion acceleration
  - prevents two-side electron transit
  - 3rd grid mitigates CEX ion impact

- <u>External hollow cathode</u>:

  Ion beam neutralization

NASA Evolutionary Xenon Thruster (NEXT) ion thruster in operation.



DC ion thruster

- Grids pose severe challenges:
  - High transparency & good ion focusing
  - Grid erosion ends in fatal failure
  - I_{beam} limited by charge-saturation

$$I_{beam} \propto A\frac{V^{3/2}}{d^2} \quad \text{(Child's law)}$$

- small grid separation (~ 0.5-1mm)
- high voltage (~1-2kV)

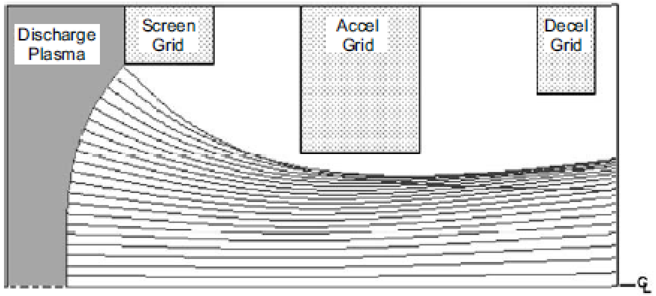
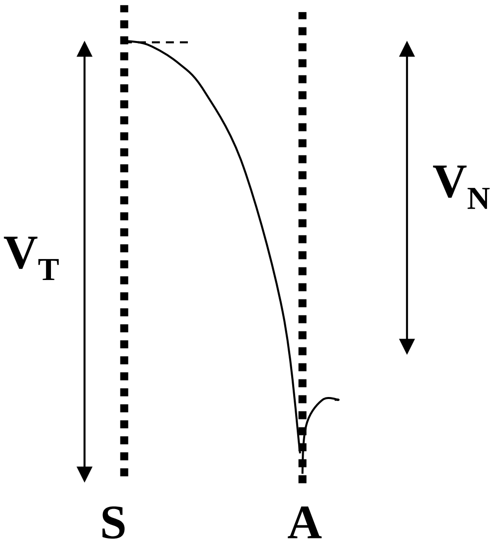


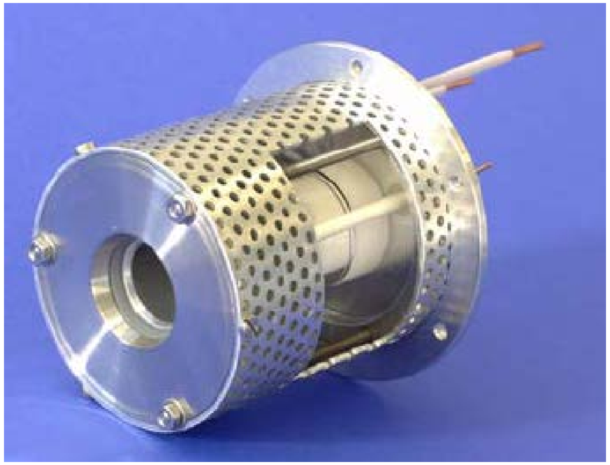
Fig. 5-4. Ion trajectories from a plasma sheath (on the left) in a half-beamlet inside an example three-grid accelerator.

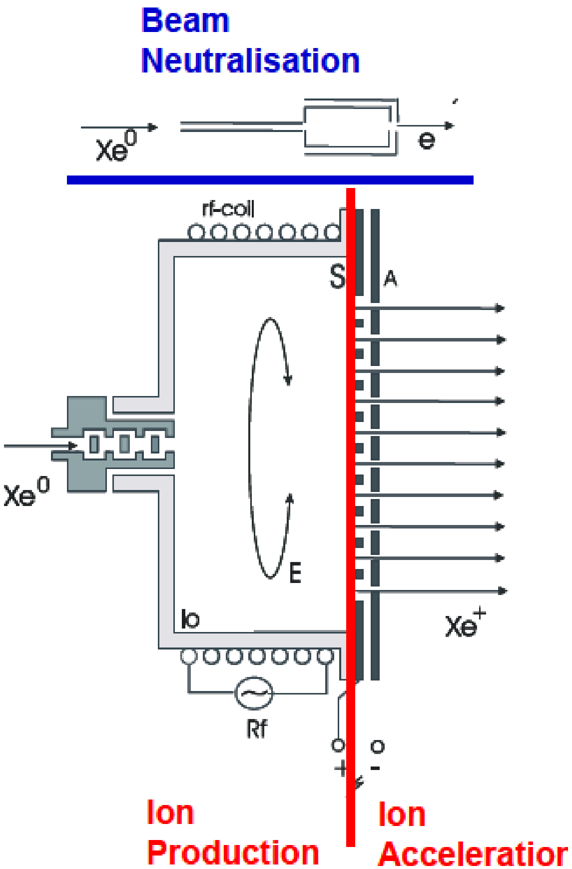


- Operational (1964, 1997)
- Very good efficiency η ~ 65-75%
- Very good lifetime ~ 30000 hours
- High I_{sp} ~ 30-50 km/s
- Issues: heavy, bulky, complex PPU

RF ion thruster

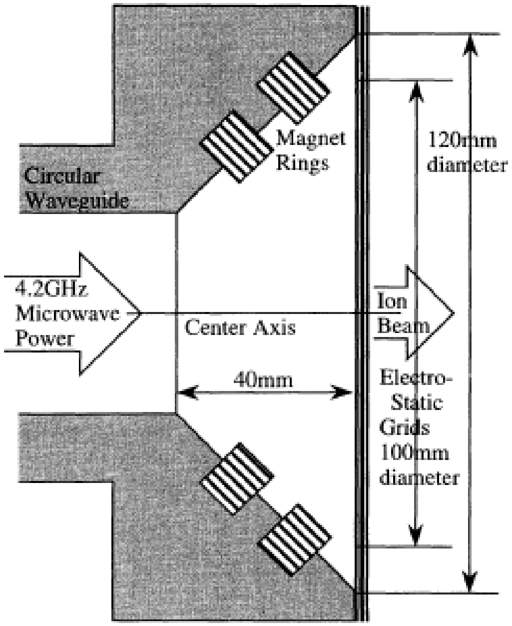
- Internal hollow cathode is substituted by a RF discharge (1-2Mhz)
- Energy deposition through inductive plasma-wave coupling
- Operational (in Eureca, Artemis missions)
- Advantages:
  - Simpler electric circuit
  - Cooler plasma, lower wall losses
    - No magnetic confinement
  - No contamination issue on internal cathode

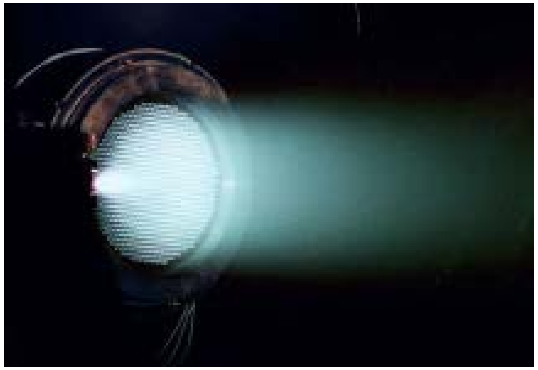


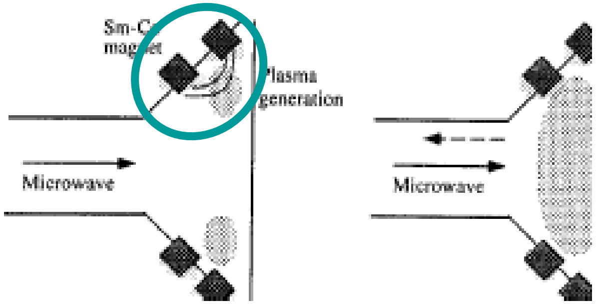


ECR ion thruster

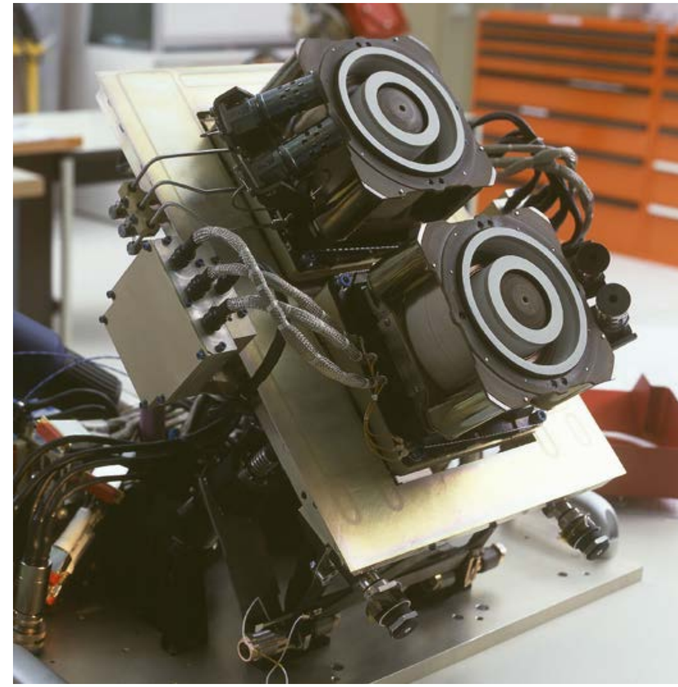
- Experimental technology
- Flown in Hayabusa mission ($\Delta V \sim 4$km/s)
- Sm-Co magnet rings → 0.3T
- 4.25 Ghz wave is absorbed at 0.15T region via ECR: $\omega = \omega_{ce} > \omega_{pe} \sim n_e^{1/2}$
- Thrusters performed well, $\eta \sim 45\%$
- To avoid wave reflection: ring shaped plasma peaking at ECR region →lower thrust density
- Issue: EMI with communication link







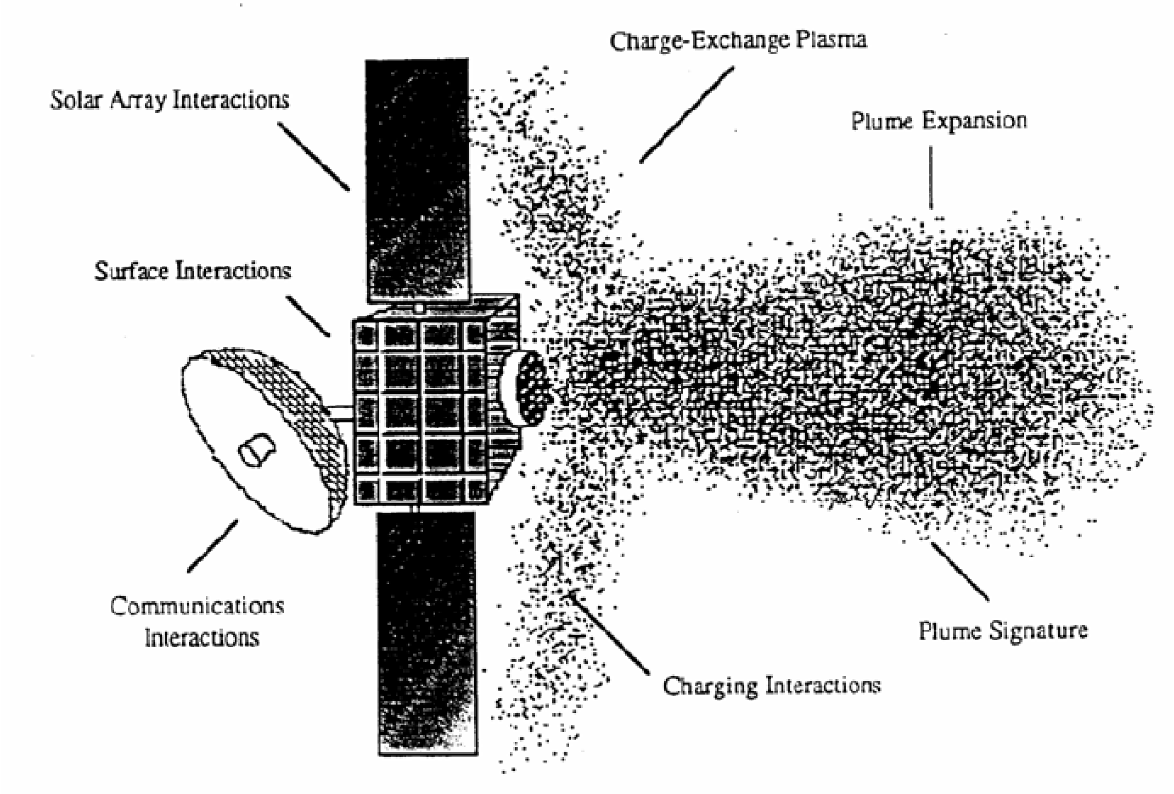
Hall effect thruster (HET)



- Large Russian flight experience (1970)
- Comparison with ion thrusters
  - Similar power range
  - Lower $V_d \rightarrow$ Lower Isp $(\sim 15-25\text{km/s})$
  - Optimal for GEO stationkeeping
  - No limitation on I_{beam}
  - Simpler, lighter, more compact
  - Larger throttling capability
  - Lower thrust efficiency $(70\% \rightarrow 50\%)$
  - Lower lifetime $(30000\text{h} \rightarrow 15000\text{h})$
  - Worse plume divergence $(40^{\circ} \rightarrow 20^{\circ})$

Plume divergence concern

- Highly-energetic divergent plume can damage solar panels, sensors, …
- Reduction of plume divergence is of principal interest
- Low-energy CEX ions are the worse; more abundant with external cathode

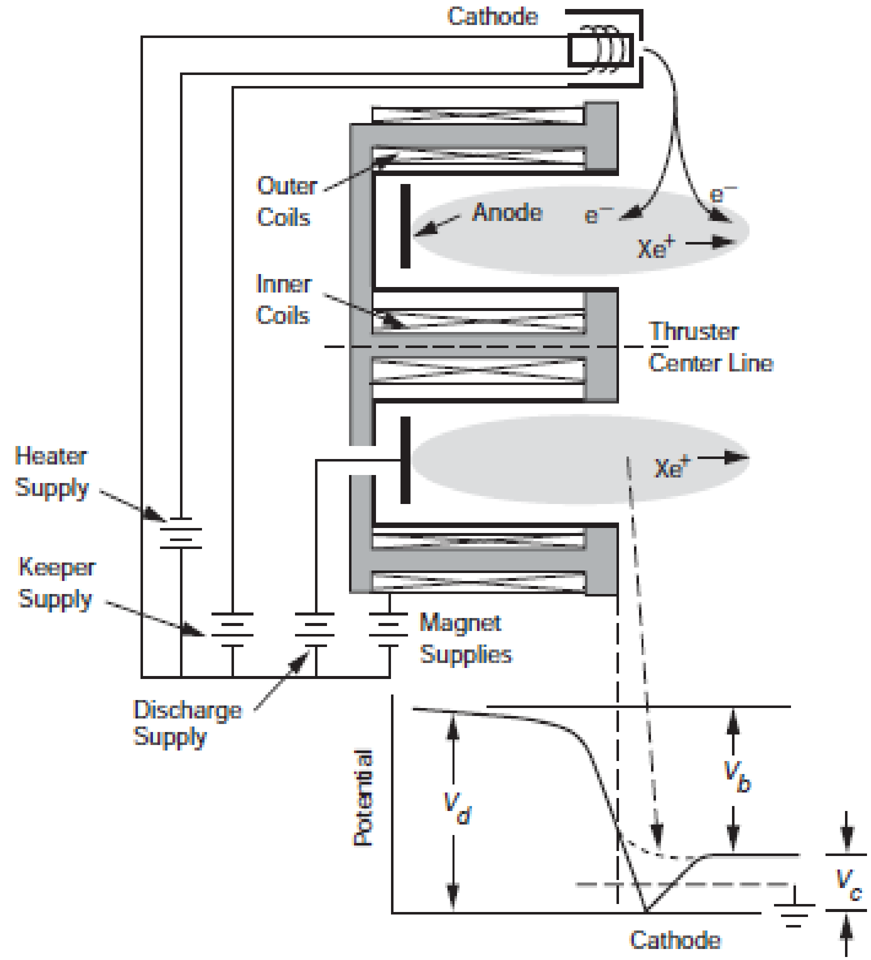


Hall effect thruster

- Discharge voltage V_d between internal anode and external hollow cathode.

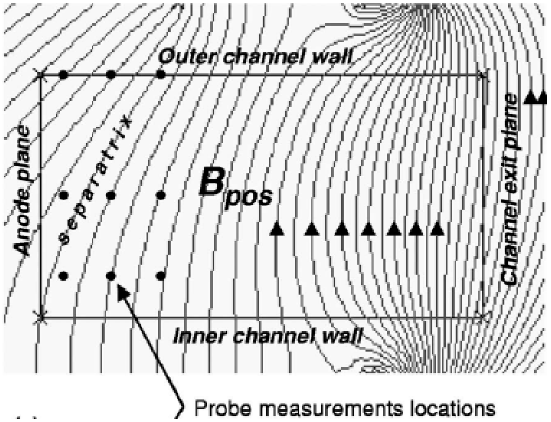
- Ambipolar electric field drives counterstreaming ions and electrons

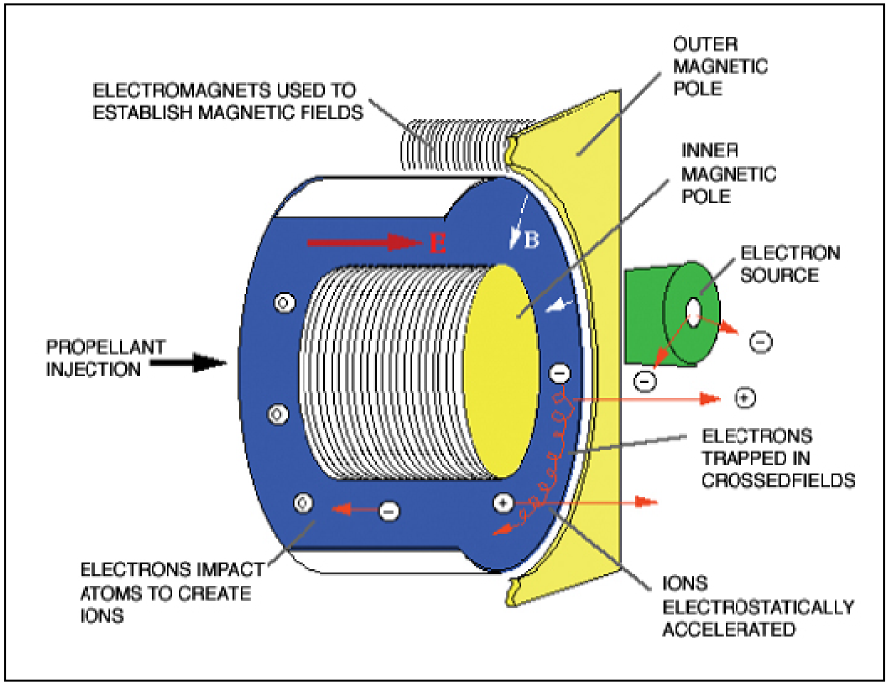
- Electron-emitting cathode (I_d) acts as:
  a) neutralizer of ion beam ($\sim 0.7 I_d$)
  b) source of primary backstreaming electrons ($\sim 0.3 I_d$):
    – neutralize plasma in chamber
    – start gas ionization



Hall effect thruster

- Radial magnetic field inhibits
  axial transport of electrons
  ⇒ efficient ionization
- However, radial transport is not inhibited
  ⇒ large heat losses
  ⇒ large chamber erosion
- New designs try to solve this working with more complex magnetic topologies
- Magnetized electron flow is helicoidal
  * dominated by $E_z \times B_r$ azimuthal drift
  * axial transport via collisions/turbulence
- Ions (unmagnetized and weakly collisional) are free-accelerated by $\vec{E}$





HET: plasma-wall processes

- High **e⁻ secondary emission** + lack of **lateral confinement** hinder performances
- **Wall sputtering** by ion impact is main life limitation factor in HET
- Wall sputtering depends on
  - ceramic sputtering yield: poorly known, very dependent of fabrication process
  - ion energy flux at walls ➔ very dependent on magnetic confinement
- Reliable **simulation of sputtering** would save many hours&money on lifetime tests

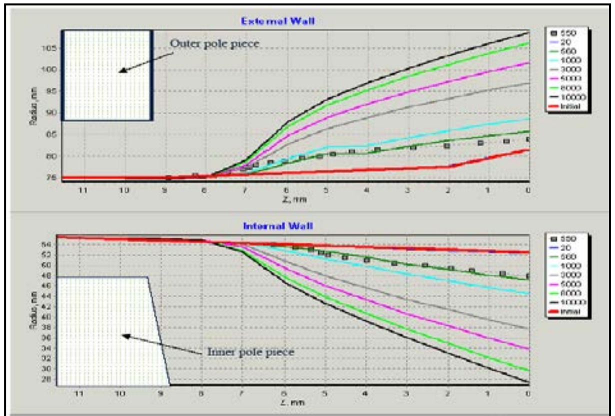


Figure 14. Measured, calculated and predicted ceramic erosion profiles for the PPS®X000.

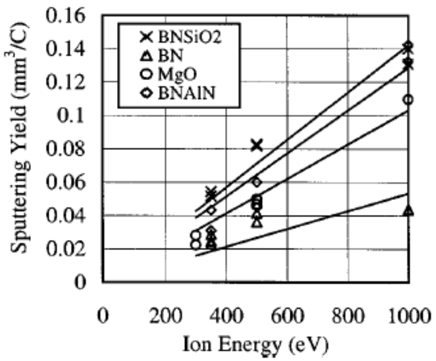


FIG. 8. Sputtering yield of four ceramics at normal incidence vs ion energy.

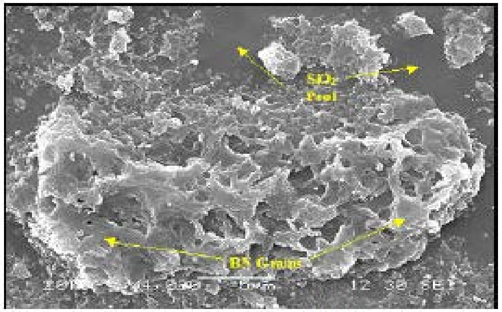


Figure 9. Sputtered Area (X4000). Xenon to Borosil, 5000 eV, 0°. INASMET-Tecnalia

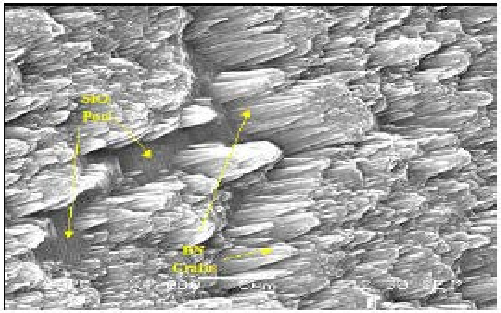


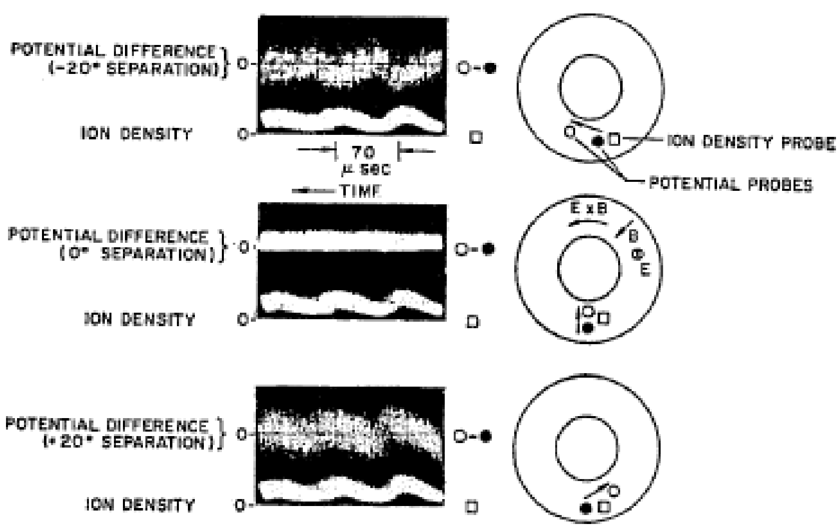
Figure 10. Sputtered Area (X4000). Xenon to Borosil, 5000 eV, 60°. INASMET-Tecnalia

HET: Turbulent diffusion

- There is experimental evidence of correlation-based turbulence, $F_{\theta,turb} \approx \langle e n_e E_\theta \rangle_{time}$ driving perpendicular electron transport but there is
  - no agreement on whether it comes from low- or high-frequency modes
  - no established theory/model of F_{turb}
- This is the main obstacle for building a predictive code of the HET discharge

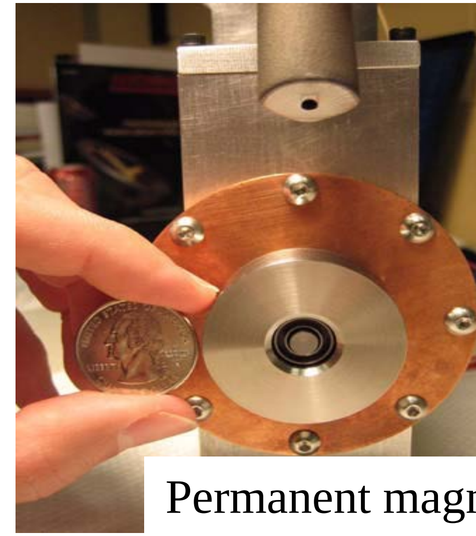
Correlation between n_e and E_θ fluctuations

- HET plasma subject to many instabilities: longitudinal/azimuthal, low-/high-frequency
- Only a few longitudinal modes are reasonably understood:
  - breathing mode (10-30kHz)
  - transit-time mode (100-500kHz)𝔐
- Azimuthal modes are less amenable to analytical treatment (2D modes)

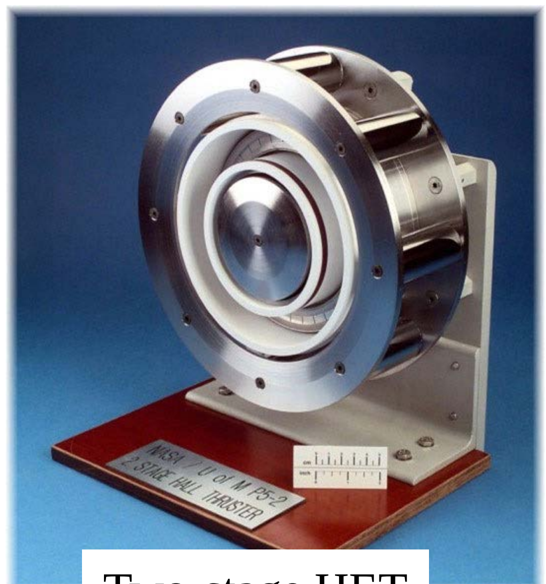


Alternative HET designs

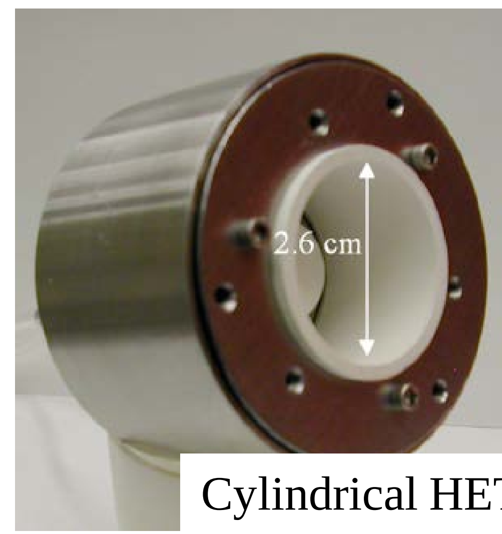
- Main goals:
  (i) to reduce wall energy losses to walls
  (ii) to reduce plume divergence,
  (iii) to improve ionization/acceleration processes
- HET scale bad to low powers (< 300W)


Permanent magnet mini-HET


TAL-type HET



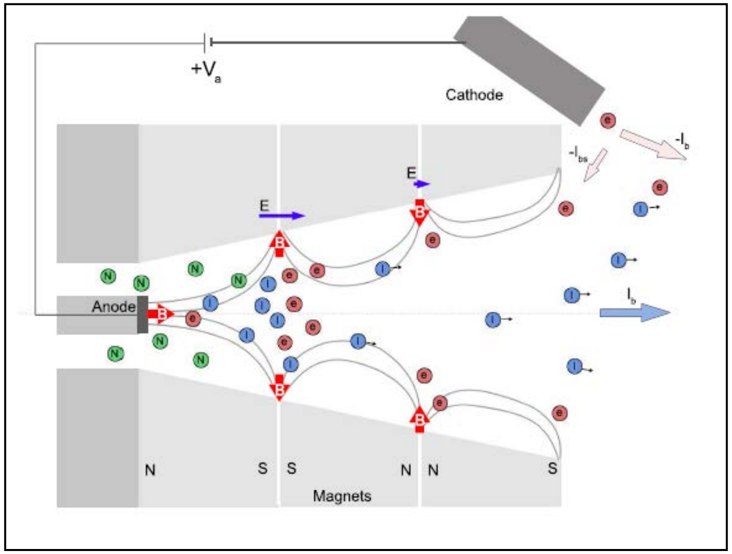
Two-stage HET

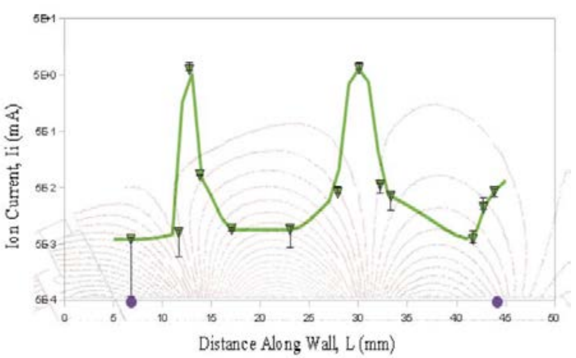


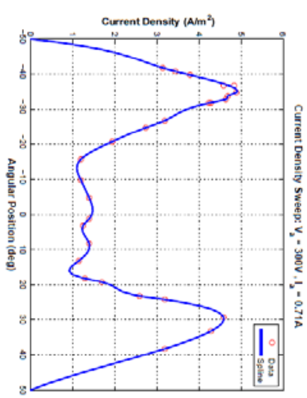
Cylindrical HET

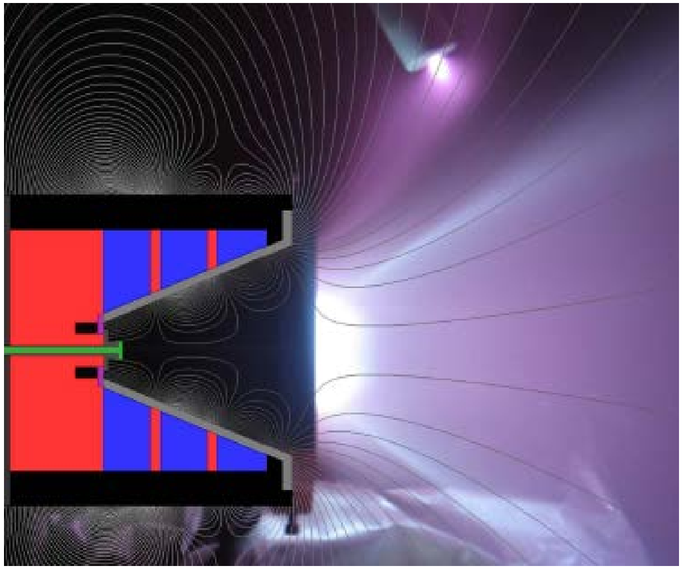
HET with magnetic cusps

- Most recent development (HEMP, DCFT)
- Ringed permanent magnets create magnetic screening of walls $\rightarrow$ reduction of wall losses
- Still, B-field in cusp regions is radial
- This smart topology provides at a time
  - strong radial confinement
  - strong-enough inhibition of axial transport
- Detailed internal physics pending of analysis and diagnosis

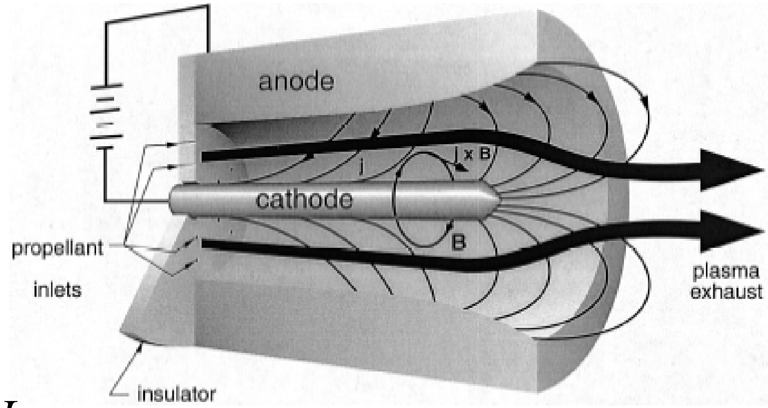








Magnetoplasmadynamic thruster (MPDT)



- MPDT is radically different to HET

- Radial E-field ($\sim V_d / r_A$) between 2 coaxial
electrodes drives a near-radial plasma current I_d

- I_d creates induced, azimuthal B-field: $B_\theta \propto \mu_0 I_d$

- Plasma acceleration and thrust based on $j_r B_\theta$

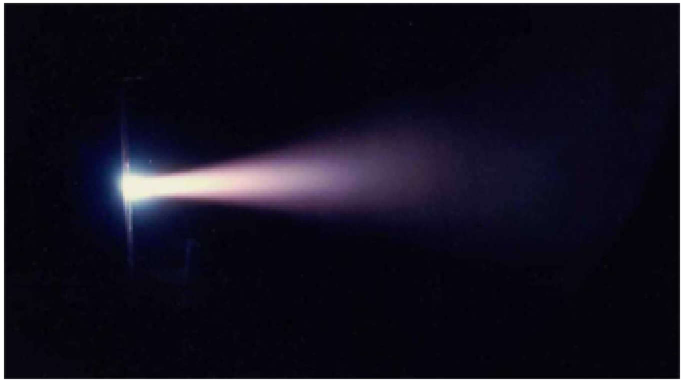
- High-power ($\sim$ 1MW) : $F \sim \dfrac{\mu_0 I_d^{\ 2}}{4\pi}, \quad \eta \propto I_d^3$

- Current-free, high-density plasma:

  no need of beam-neutralizer

Magnetoplasmadynamic thruster (MPDT)

- Pros (at 1MW): Compact, simple, lightweight
- Cons:
  - Only works well at megawatt level
  - Short lifetime (electrode erosion)
  - Onset instability at full ionization: plasma arc becomes unstable: $\Rightarrow$ filamentation, huge erosion



- Applied-field MPDT
  - Alternative for 20-100kW range
  - Applied magnetic field is added
  - $F \propto (j_r B_\theta) + (-j_\theta B_r)$
  - Complex physics, not mastered yet

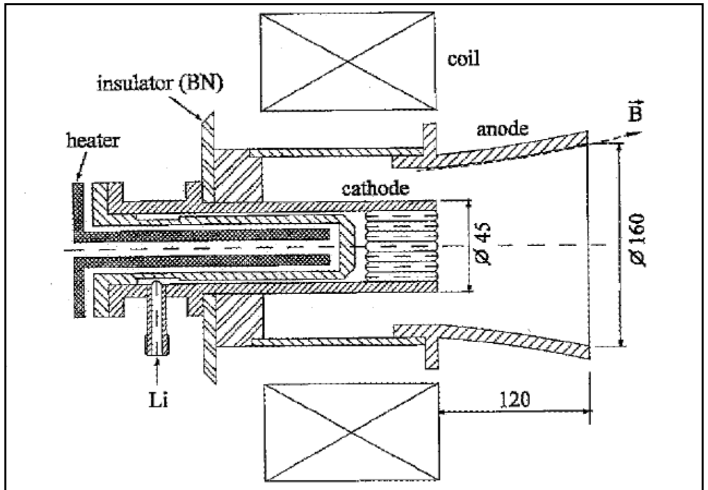
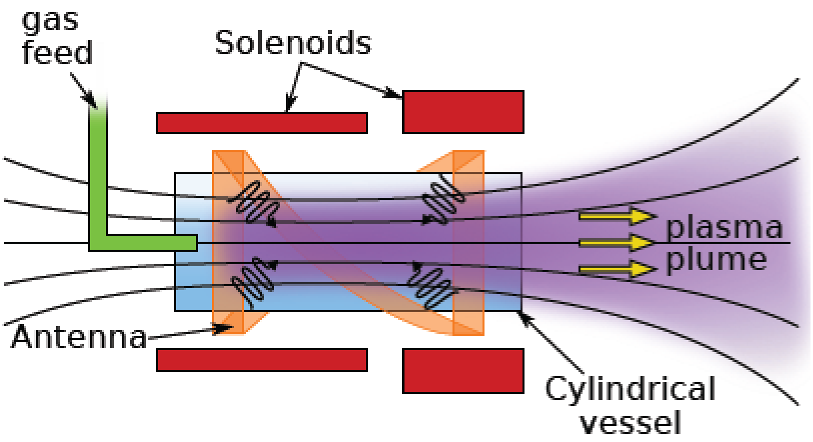


Fig. 9 Schematic of Russian high-power AF-MPD thruster operated with Li propellant.[34]

Helicon thruster

- **Cylindrical plasma Chamber + Gas Feeding subsystem**
- **Magnetic circuit SS (MCSS)** generates
  - Near-axial B-field inside
    - Magnetizes electrons
    - Confines plasma from walls
    - Allows RF penetration
  - Gently-divergent B-field outside
    - Channels the plasma beam
- **RF antenna + power subsystem (RFSS)**

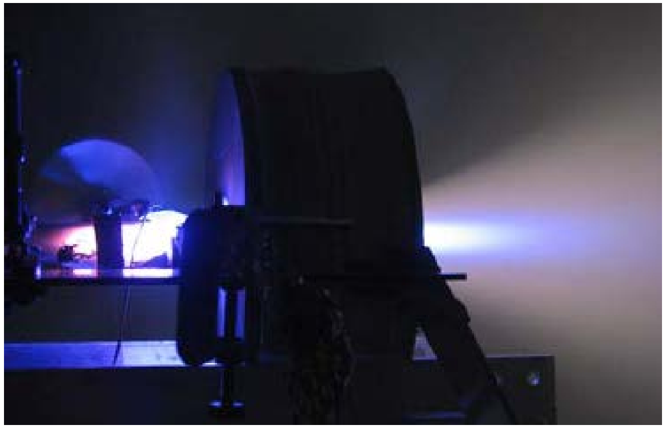


Basic processes

- RF emission propagates inside plasma column and deposit energy into electrons
- Energetic electrons ionize neutral gas
- Rest of electron energy (i.e. plasma internal energy) is converted into ion directed energy through expansion with ambipolar electric field
- Supersonic expansion facilitated by external, wall-less magnetic nozzle (MN)

Helicon thruster

- **Main HPT characteristics**
  - No grids, no electrodes, no neutralizer, no material nozzle
  - Magnetic confinement and guiding of plasma
- **Potential benefits of HPT technology**
  - Long lifetime
  - Simplicity, robustness
  - Wall-less acceleration
  - Variety of propellants
  - Compactness → high thrust density
  - Throttlability (power, mass flow, MN shape)
  - Low plume divergence
  - Thrust-vector steering (MN)
- **Potential limitations**
  - High Isp could be feasible only for light propellants
  - High efficiency requires efficient energy transfer to plasma
  - Too heavy at low-power

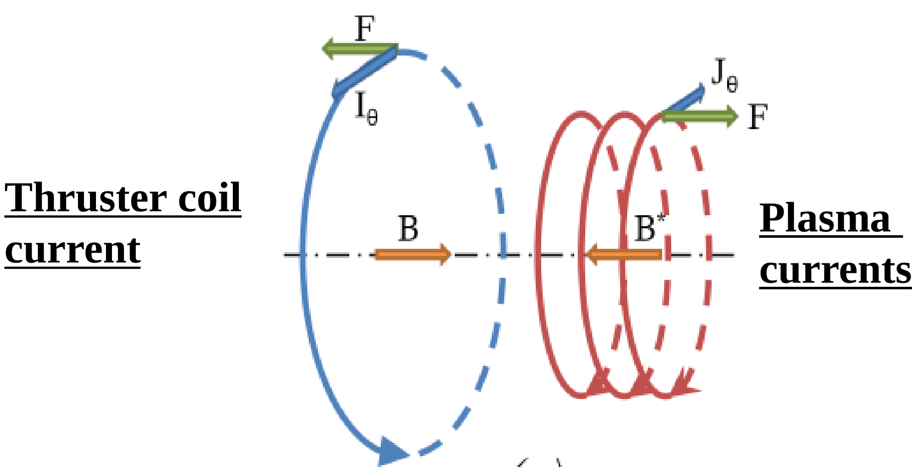


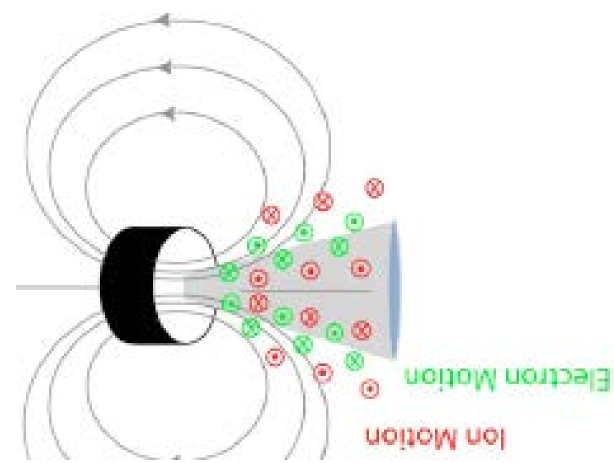
Magnetic nozzle

- What is it ? A convergent-divergent magnetic field that guides a plasma
- From gas expansion in solid nozzles (i.e. chemical thrusters), we know:
  - There is <u>energy conversion</u> of 'internal' into 'axial kinetic'
    $\rightarrow$ supersonic gas in divergent nozzle
  - There is a <u>thrust gain</u> from the gas pressure on the divergent walls
- We expect similar phenomena in magnetic nozzle
- Magnetic nozzle has no walls:
  - No energy losses, no thermal limits !!
  - No thrust gain ?

Magnetic nozzle: peculiar features

1. Different sources of internal energy: Ions or electrons, isotropic or not
2. Meso-magnetized plasma (in general)
3. Plasma jet sustains azimuthal current
4. Nozzle shape can be altered (via applied or induced field)
5. Thrust gain & transmission are electromagnetic, based on diamagnetic j_θ
6. <u>Detachment</u> of plasma from magnetic lines before these turn back.

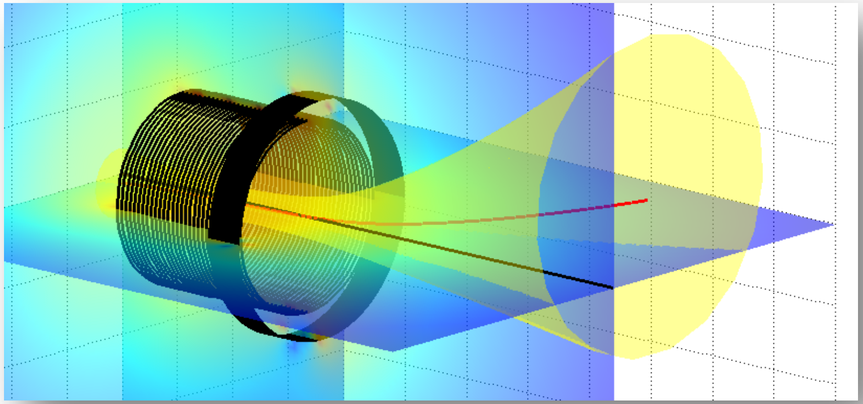




Thrust vector control with MN

VecMan – Vectorial Magnetic Nozzle

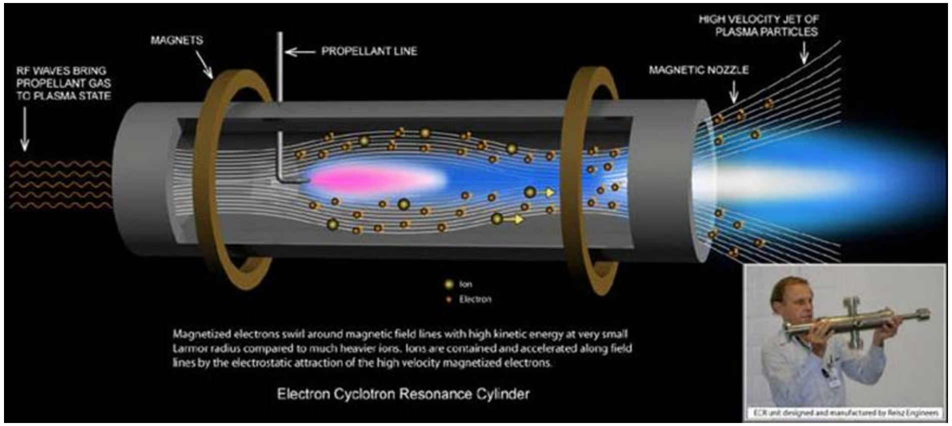
Simple solution to control the thrust vector direction in space plasma thrusters, with no moving mechanical parts, without affecting the internal operation and efficiency of the thruster or the satellite operation.



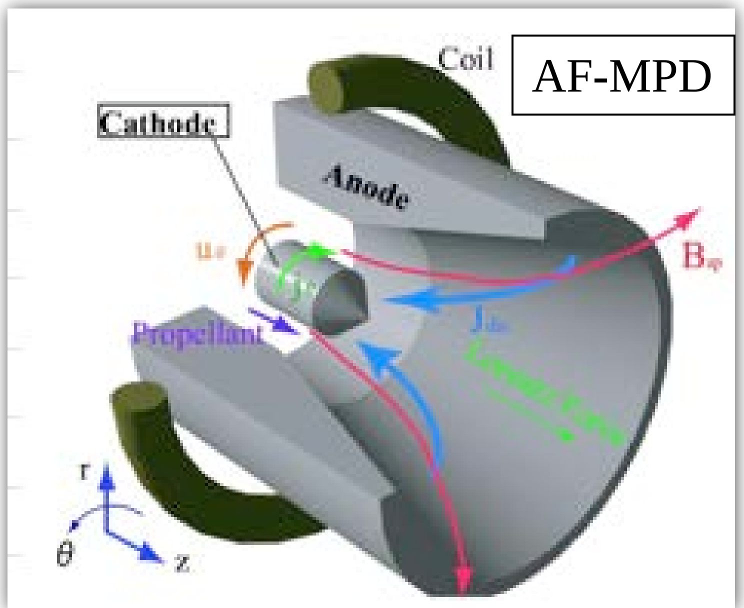
IPR

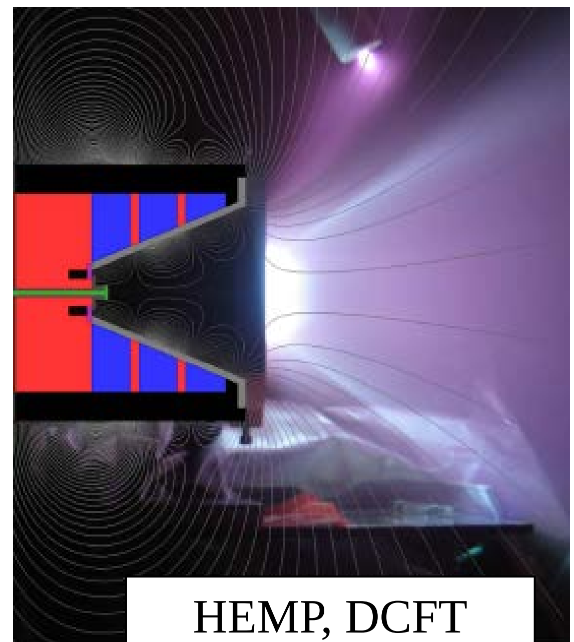
- Patent pending [P201331790]

Magnetic nozzles in other thrusters



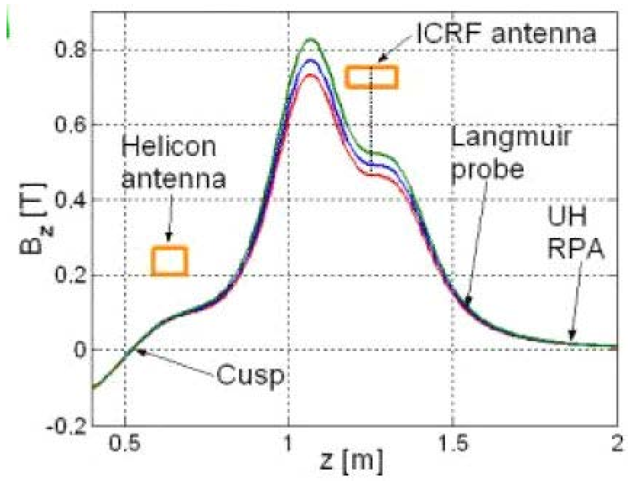
ECR-thruster

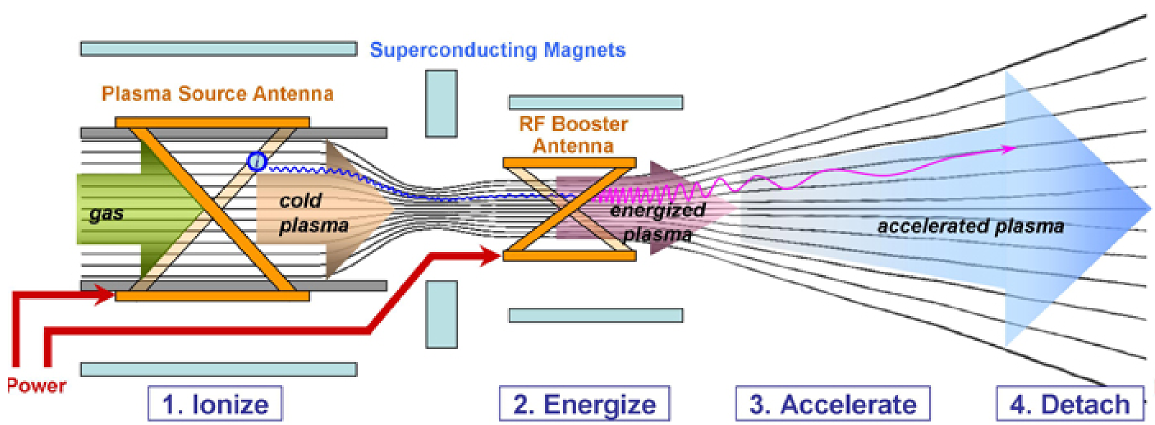


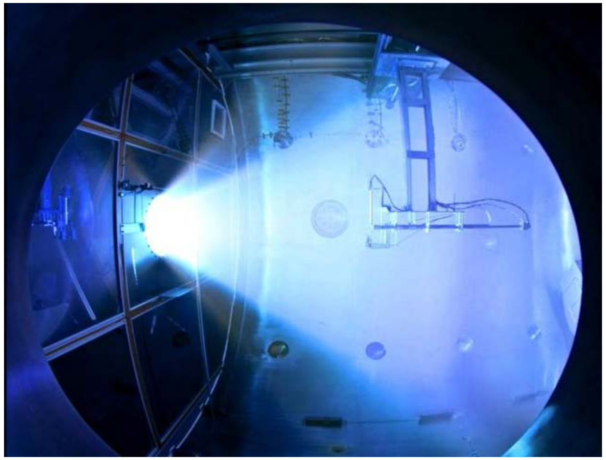


VASIMR

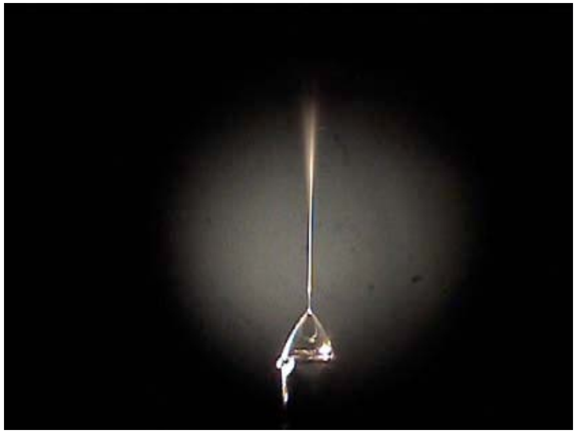
- A high-power thruster, promoted for interplanetary missions
- Similar to helicon thruster, but plasma is heated in an intermediate stage through ion-cyclotron-resonance antenna (1.85Mhz)
- Magnetic nozzle physics are somehow different

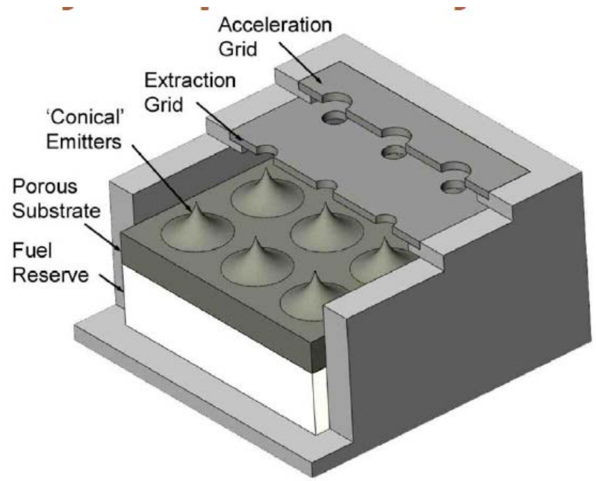


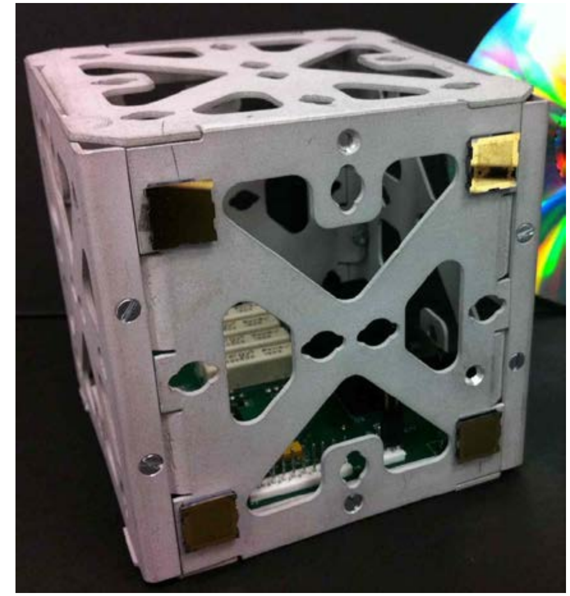




Micropropulsion

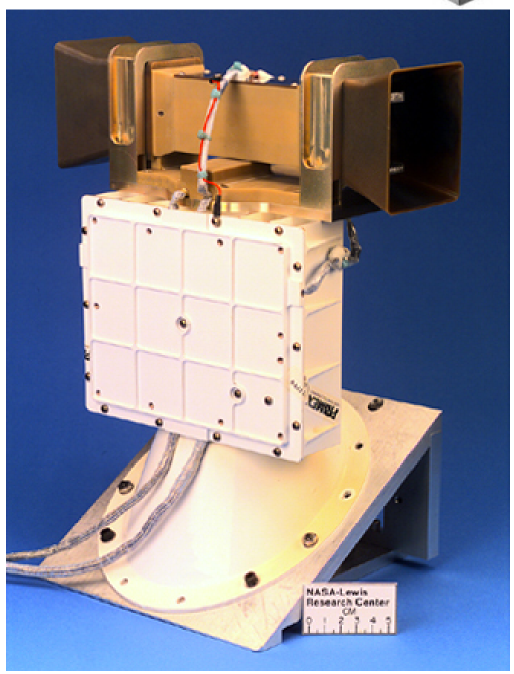


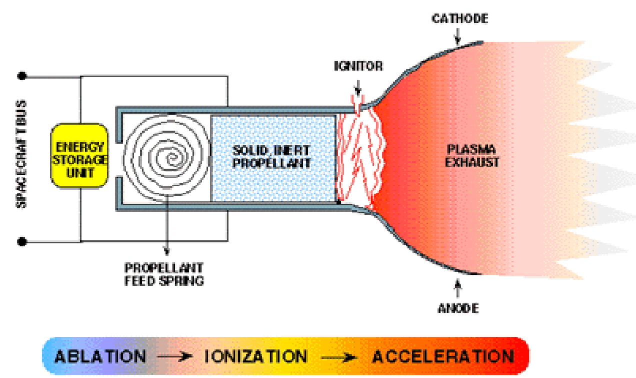




Electrospray

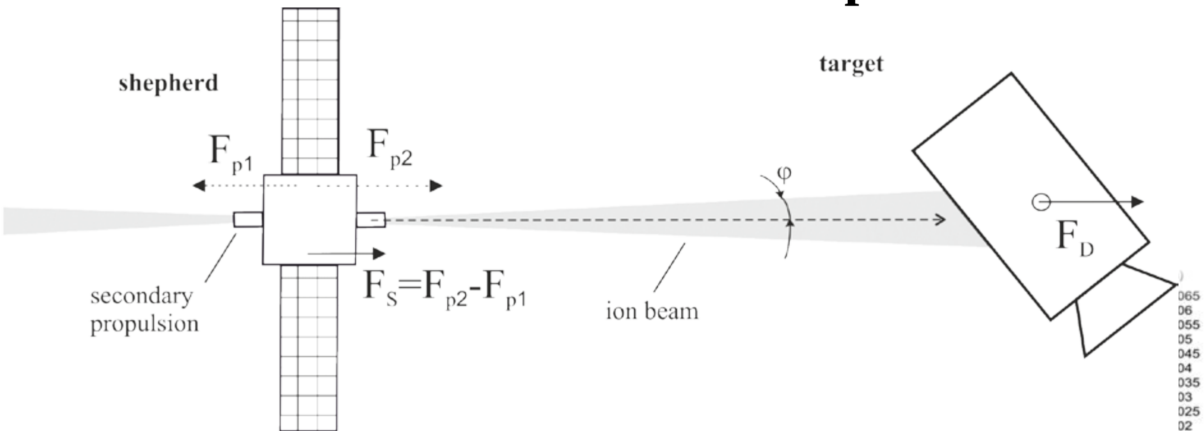
PPT

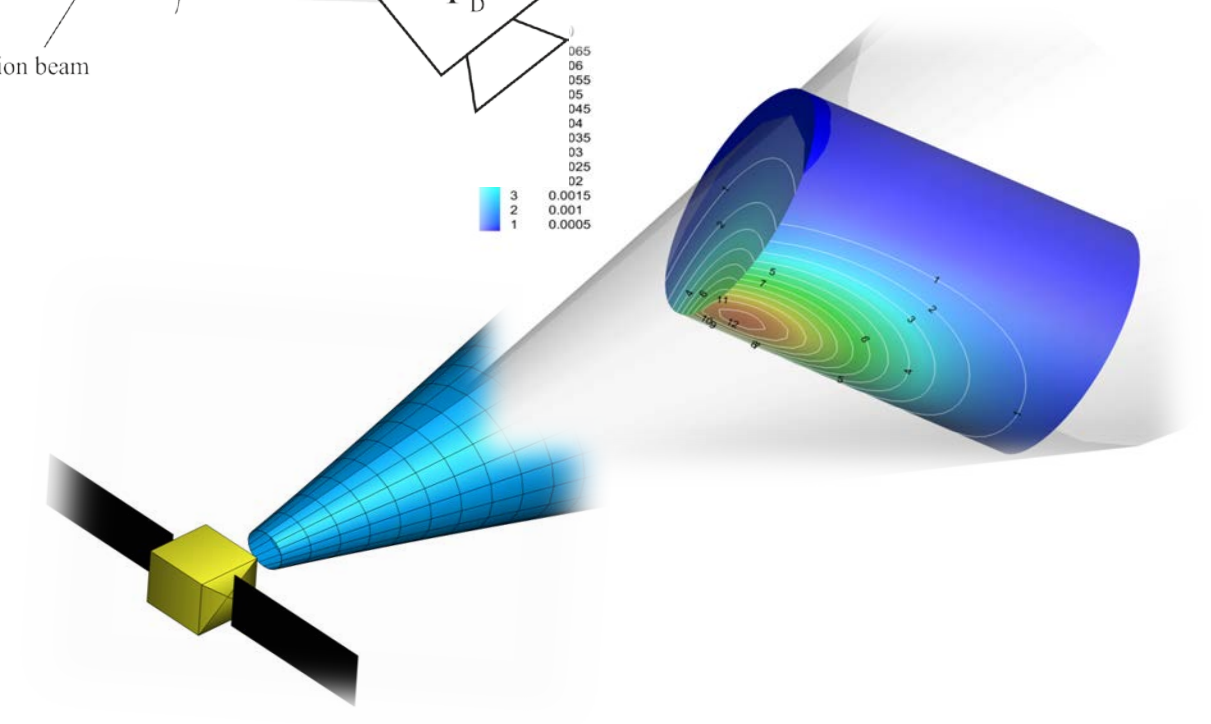




To end: a non-propulsive application

Ion beam shepherd (IBS) concept
for contactless space debris removal





FP7 LEOSWEEP project

SENER
POLITÉCNICA
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ITM
Universidad Carlos III de Madrid
DLR
deimos ENGENHARIA
YUZHNOYE design office
LPP
UNIVERSITY OF Southampton

Thank you