SPACE TRIPS SUMMER SCHOOL

Theme 9: SPACE

Riga Latvia
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HALL THRUSTERS FOR SATELLITE PROPULSION

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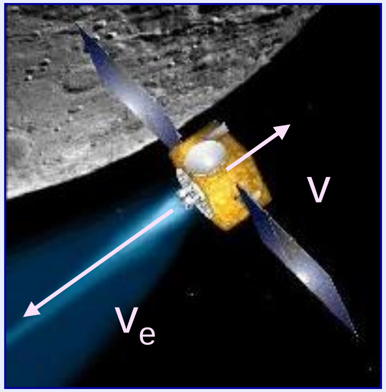
Outline

1. **Electric Propulsion & Hall Thrusters**
   - Electric propulsion
   - Principle of Hall Effect Thrusters

2. **Research on Hall thrusters**
   - Simulation and plasma diagnotics
   - Physics and technical issues
   - Examples of recent achievements in France

3. **Conclusion**

- **Total velocity increment Δv** required for a given mission or manoeuvre is an indication of the energetic difficulty of that mission or operation



- **Momentum conservation** for a spacecraft $$\frac{d\left[m\mathrm{v}\right]}{dt}=0$$

$$m\frac{d\mathrm{v}}{dt}=-\mathrm{v}_e\frac{dm}{dt}$$

time varying mass of the vehicle → m

acceleration of the vehicle → $\frac{d\mathrm{v}}{dt}$

velocity of the exhaust stream → v_e

rate of change of spacecraft mass due to propellant expulsion → $\frac{dm}{dt}$

- Integration of this equation gives the propellant mass needed for a given velocity increment (i.e. for a given mission)

- **Electric propulsion** can provide large exhaust velocity of the propellant (acceleration of the propellant by electric force) but generally with small thrust
  → ***adapted to satellite station keeping or interplanetary missions***

- **Chemical propulsion** provides small exhaust velocity (thermal expansion of the propellant) but large thrust is possible
  → ***adapted to fast orbit transfer***

- **Specific Impulse** is a measure of the propellant velocity

$$I_{sp} = \frac{v_e}{g}$$

- **Thrust** is a measure of the force exerted on the satellite

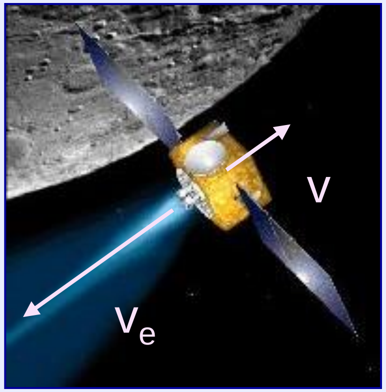
$$T = v_e \frac{dm}{dt}$$

Propellant mass consumption

$$m\frac{d\mathrm{v}}{dt} = -\mathrm{v}_e\frac{dm}{dt}$$

- Integration over the whole duration of the mission

$$\frac{m_D}{m_0} = \exp\left[-\frac{\Delta \mathrm{v}}{\mathrm{v}_e}\right]$$



m_D = delivered mass
m_0 = initial mass = delivered mass + propellant mass = $m_D + m_P$
Δv = total velocity increment needed for the mission

$$\frac{m_D}{m_D + m_P} = \exp\left[-\frac{\Delta \mathrm{v}}{\mathrm{v}_e}\right]$$

$$\frac{m_P}{m_D} = \exp\left[\frac{\Delta \mathrm{v}}{\mathrm{v}_e}\right] - 1$$

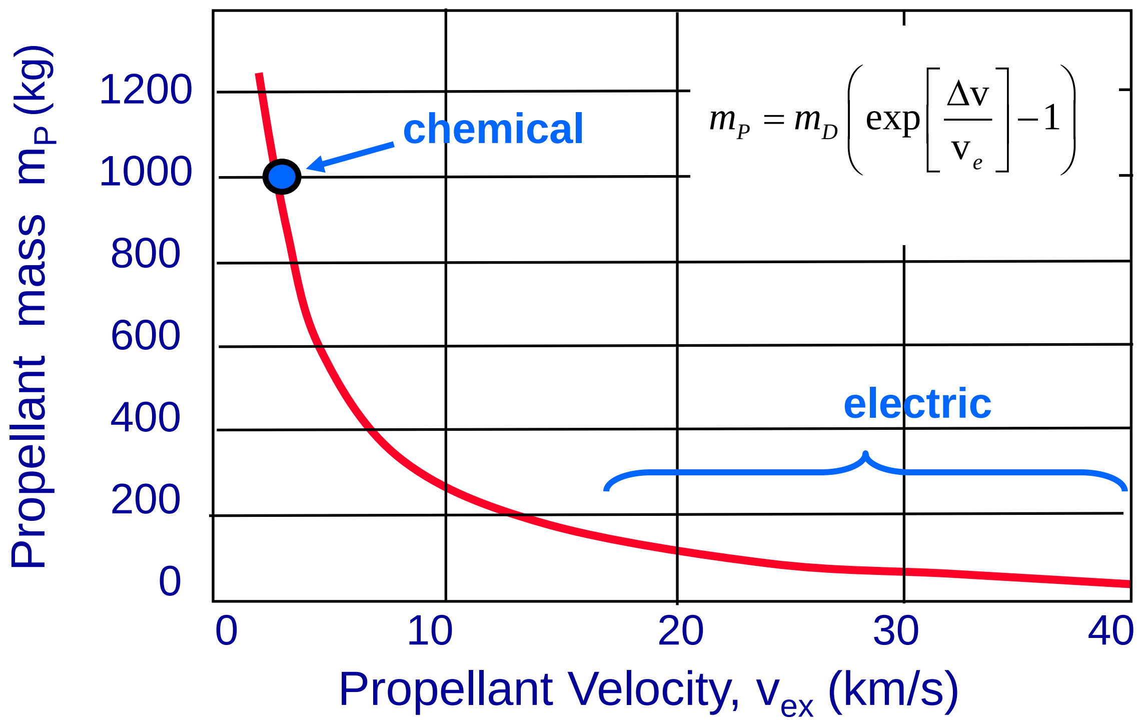
For a given total velocity increment of the vehicle, propellant mass consumption is smaller for larger propellant exhaust velocity

Propellant Consumption – Electric vs Chemical Propulsion

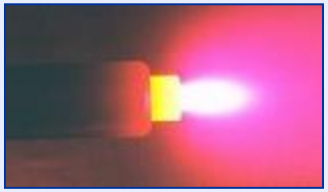
- Propellant mass consumption decreases exponentially with propellant exhaust velocity
- High propellant velocity can be reached with electric thrusters
- Electric propulsion saves more than 800 kg of propellant to keep a 3 tons satellite on geo orbit

→ Cost reduction of millions of Euros

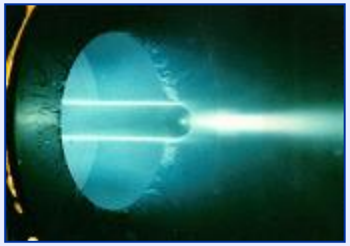
m_P (kg) for maintaining a 3 tons satellite on orbit for 15 years
i.e. total incremement velocity ~ 750 m/s



- **Electrothermal**
  - Gas heating + expansion
    - *Arc Jet, resistojet, microwave*



- **Electromagnetic** (MPD, MagnetoPlasmaDynamic)
  - Plasma acceleration by Lorentz force + expansion
    - *Pulsed Plasma Thruster*
    - *Lorentz Force Accelerator*



- **Electrostatic** (Ion thrusters)
  - Plasma source + ion extraction
    - *Gridded ion thruster*
    - *Field Emission Electric Thruster*

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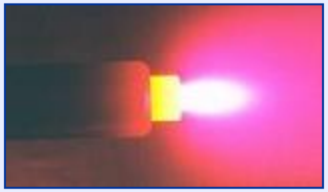

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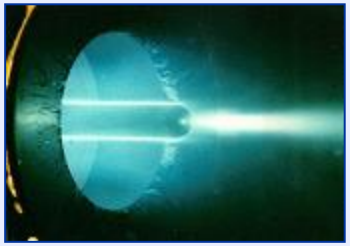
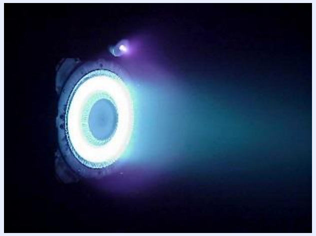


Hall Effect Thruster →



- **Electrostatic** (Ion thrusters)
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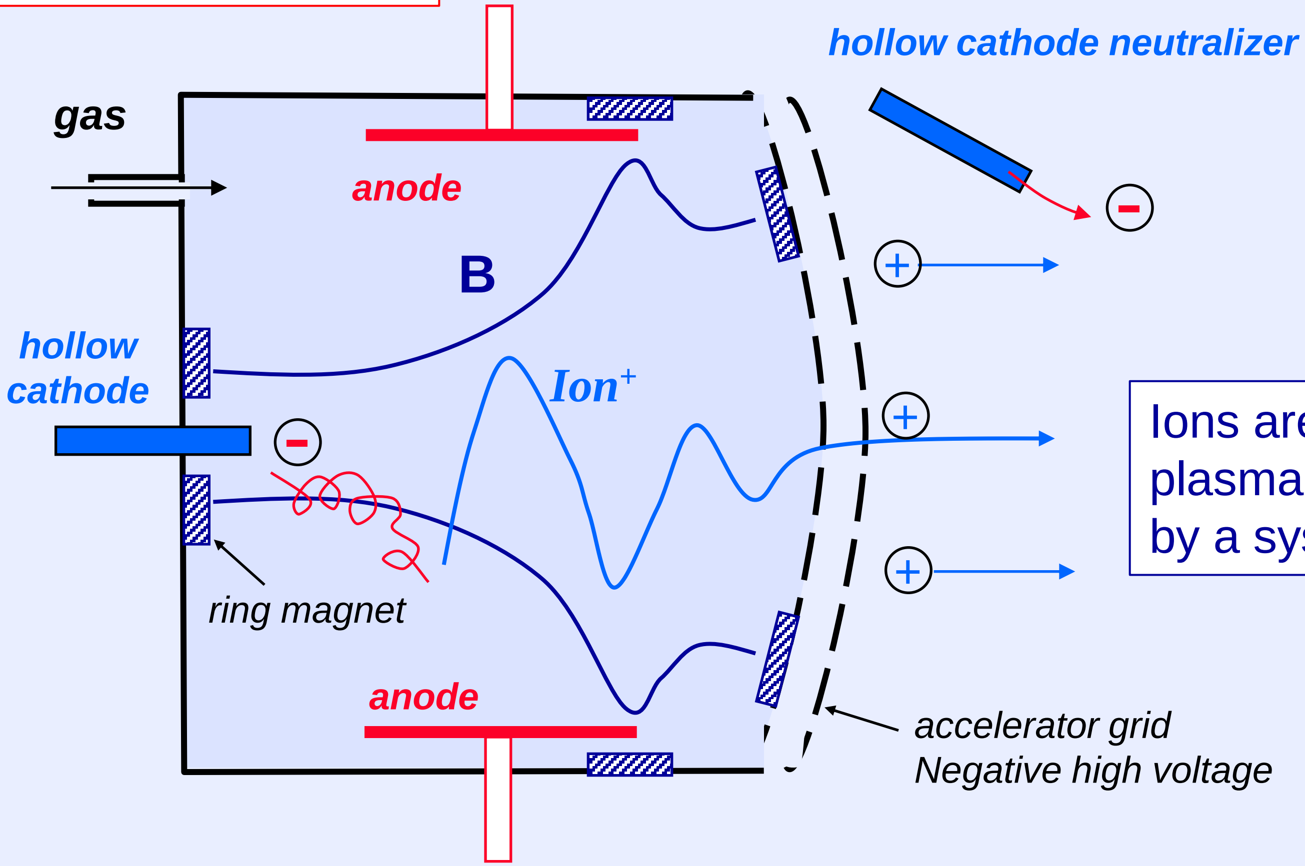
    - *Field Emission Electric Thruster*

- Plasma = ionized gas
- Contains gas molecules, free electrons and positive ions with densities n_g , n_e and n_i
- In a plasma n_e and n_i must be sufficiently large to have **quasi-neutrality** $n=n_e \sim n_i$
  (non-neutrality generate electric fields and forces that keep negative and positive charges together)
- If plasma density n is large enough plasma can be a **good conductor**
  → Plasma tends to be equipotential (low electric field in plasma)

- Plasma is sustained by **ionization** by electron impact of the molecules
- Ionization must be sufficient to compensate for the charged particle losses (eg to the walls)
- To increase ionization electron energy must be increased
- Electron energy is increased by applying external field (DC, AC, microwave, etc…)

- At very low pressure, eg 1 Pa, the electron mean free path (distance between collisions with the molecules) can be larger than the dimensions of the plasma source
  → Ionization of the molecules is difficult (no collisions)
  → Magnetic field generally used to confine the electrons at low pressure

Gridded Ion Thruster

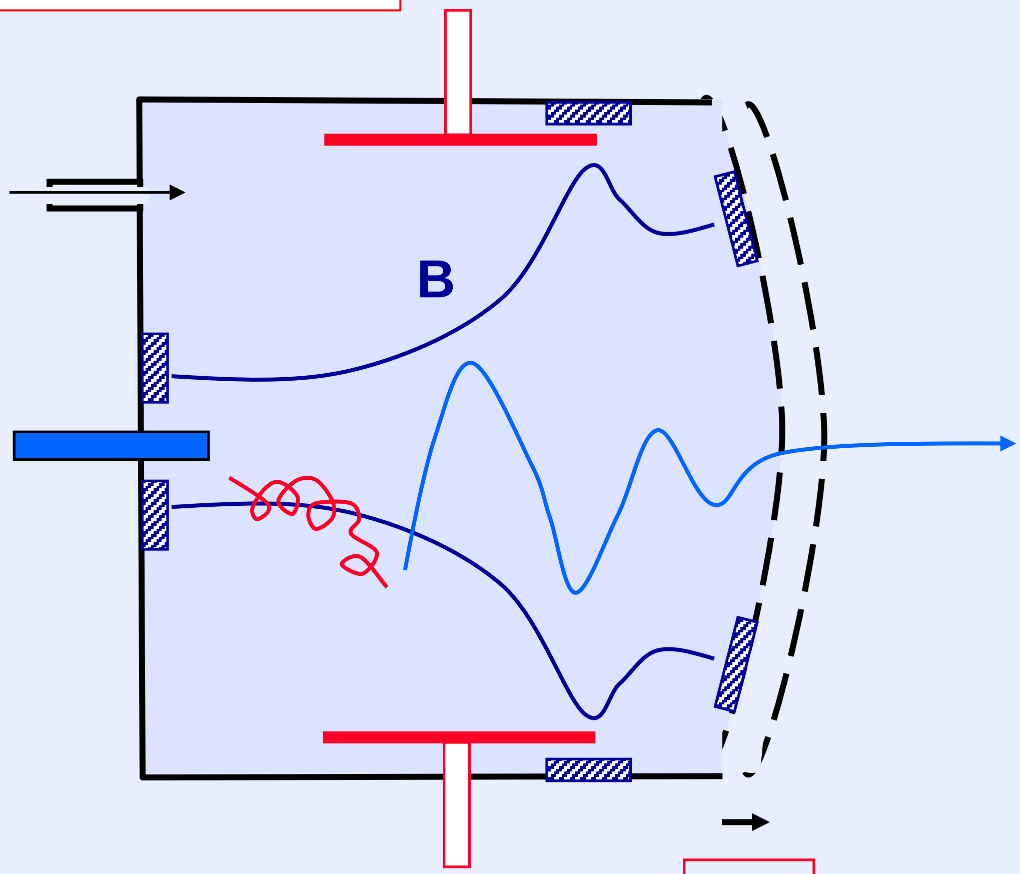


Ions are extracted from the plasma and accelerated out by a system of biased grids

Ring cusp configuration

- **cathode : hot filament or hollow cathode**
- **magnetic confinement**
- **~100 V between cathode and anode**

Gridded Ion Thruster



Ring cusp configuration

Ion current density limited by Child Langmuir law

$$j_i = \frac{4\varepsilon_0}{9}\left(\frac{2e}{m_i}\right)^{1/2}\frac{V^{3/2}}{d^2}$$

Xenon, 1 kV, 1 mm $\rightarrow$ j_i =0.01 A/cm^2
- to get an ion current of 6 A
- need an extracting area of 600 cm^2
  i.e. 30 cm diameter

few 10s mA/cm^2

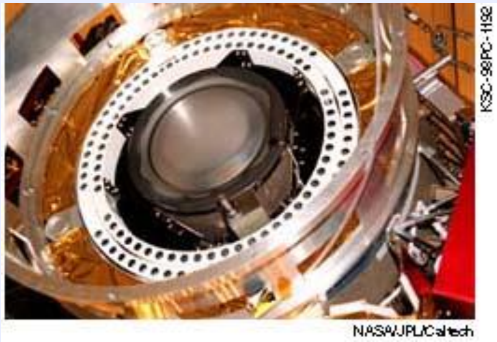
Maximum Thrust/Unit Surface

$$\frac{T}{A} = \frac{\dot{m}_i \mathrm{v}}{A} = \frac{m_i}{e} j_i \mathrm{v} \qquad \mathrm{v} = \sqrt{\frac{2e}{m_i}V}$$

$$\frac{T}{A} = \frac{8}{9}\varepsilon_0\left(\frac{V}{d}\right)^2$$

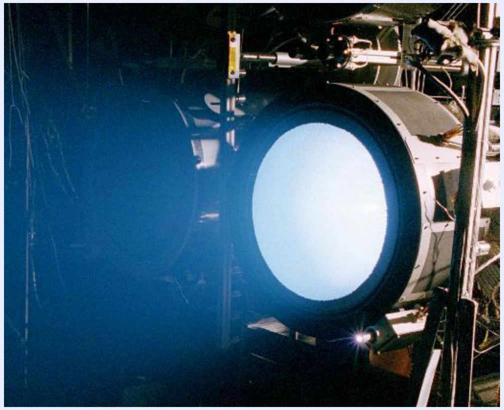
few N/m^2

➢ Examples of gridded ion thruster



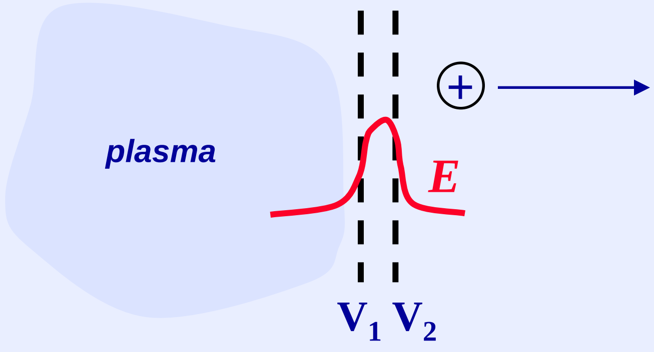
- **NSTAR**: used on the NASA Deep Space 1 mission (1998)
  30 cm diameter, P=2.3 kW, Isp=3100 s, T=20-90 mN

- **NEXT**: **N**ASA **E**volutionary **X**enon **T**hruster
  40 cm diameter, P=1-6 kW, Isp=2000-4000 s, T=50-240 mN



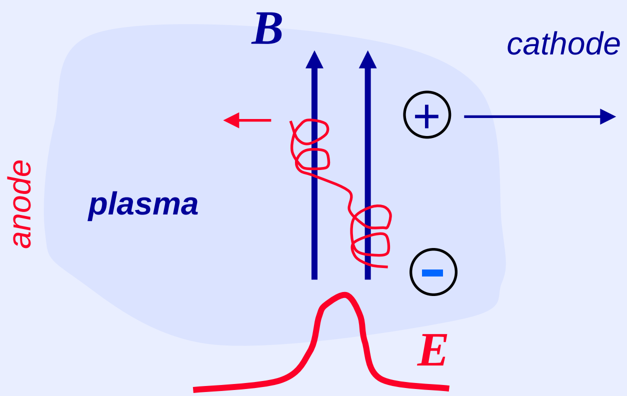
Gridded ion source

- Space charge limited current density (Child Langmuir)
  Large thrust → large thruster area
- Sputtering limits the life time of the grids

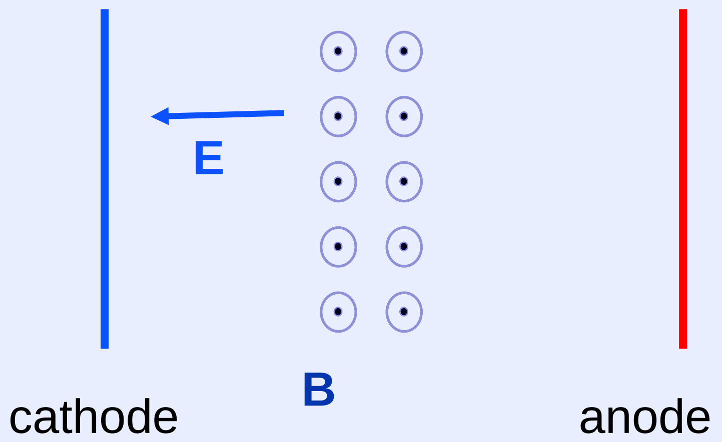


Gridless ion source – Hall Thruster

- Large electric field generated in the plasma
- How to create large electric field in the plasma ?
- Decrease electron conductivity locally $E = \dfrac{J}{\sigma}$
- Can be done by perpendicular magnetic field
  « **magnetic field barrier** »
- No limitation on current density



- **Magnetic barrier between cathode and anode in a plasma source**
- Perpendicular to electron flow from cathode to anode
- Increase electron residence time and ionization
- Ions are ~ not magnetized (not sensitive to magnetic field because of large mass)



- Electron drift // to $\boldsymbol{E}$ is considerably reduced
- Electron drift in the $\boldsymbol{E} \times \boldsymbol{B}$ direction with large velocity (Hall current)

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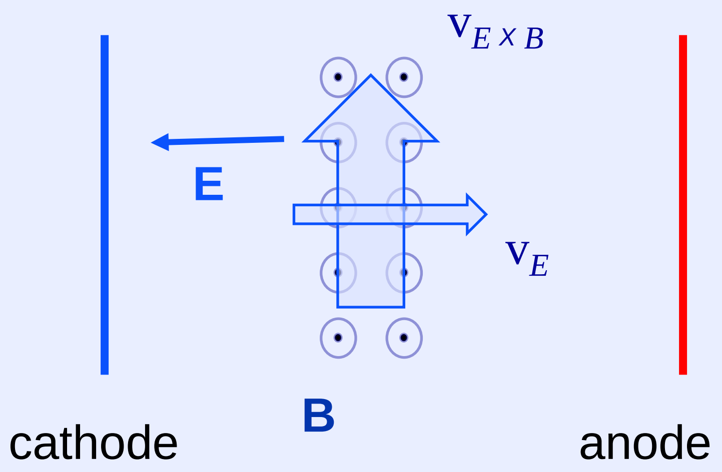

- Electron drift // to $\boldsymbol{E}$ is considerably reduced
- Electron drift in the $\boldsymbol{E} \times \boldsymbol{B}$ direction with large velocity (Hall current)

$\boldsymbol{E} \times \boldsymbol{B}$ drift velocity: $v_{E \times B} = E/B$
$\boldsymbol{E}$ drift velocity: $v_E = E/B \ \nu/\omega$

ν electron collision frequency
ω electron cyclotron frequency = eB/m
ν/ω can be ~ 10^{-3} in a Hall thruster

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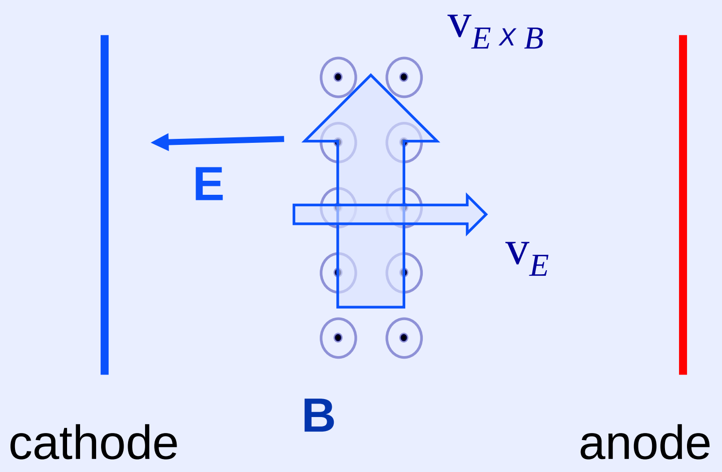


E x ***B*** drift velocity: $v_{E \times B} = E/B$

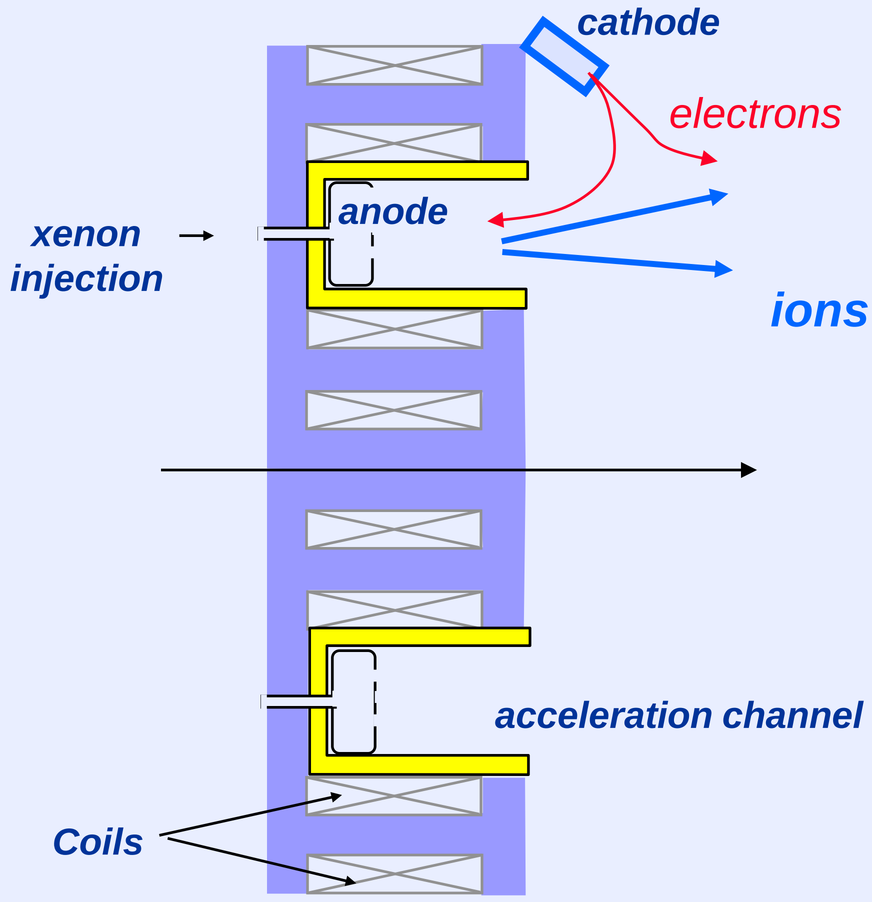
E drift velocity: $v_E = E/B\ \nu/\omega$

- Because of electron flux in the ***E*** x ***B*** direction, there should be no walls in this direction

→ Closed drift geometry (i.e. cylindrical with ***E*** x ***B*** in the azimutal direction)

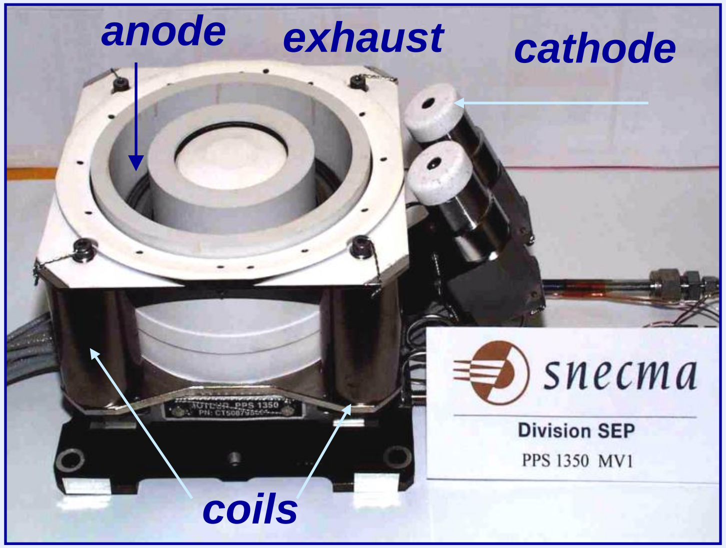
→ Hall thrusters

Hall thruster

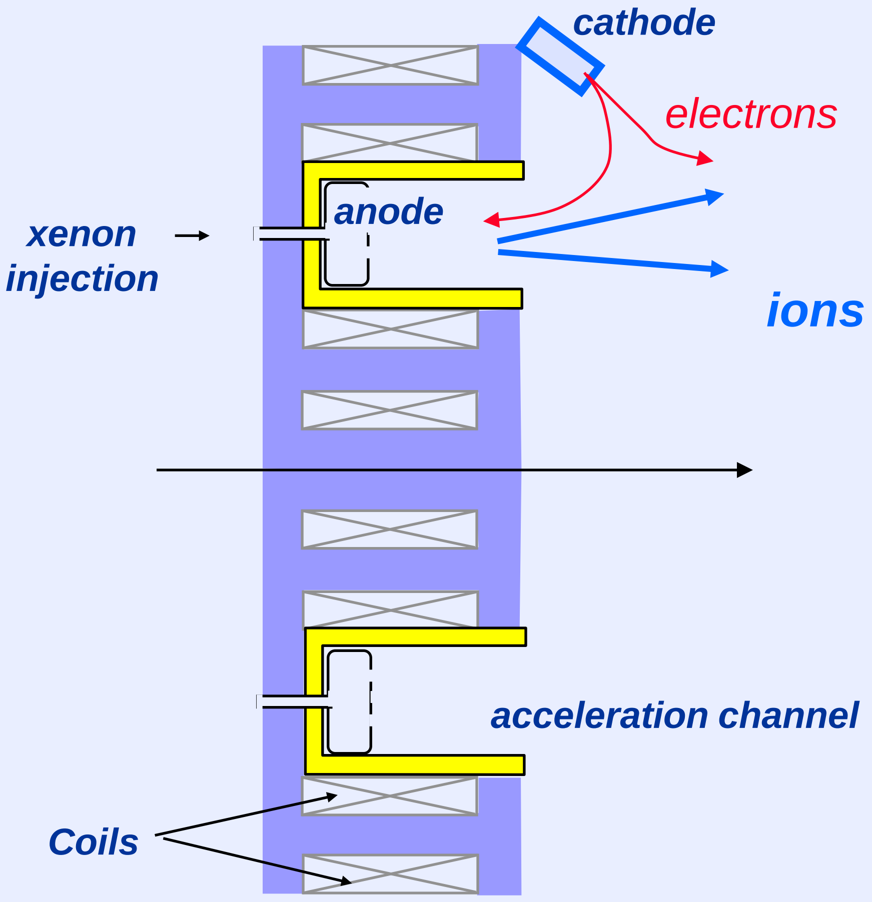


- High Thrust Efficiency > 50 %
- High propellant velocity ~20 km/s
- Thrust to Power Ratio ~ 70 mN/kW

E *x* ***B*** drift in the azimutal direction



Hall thruster



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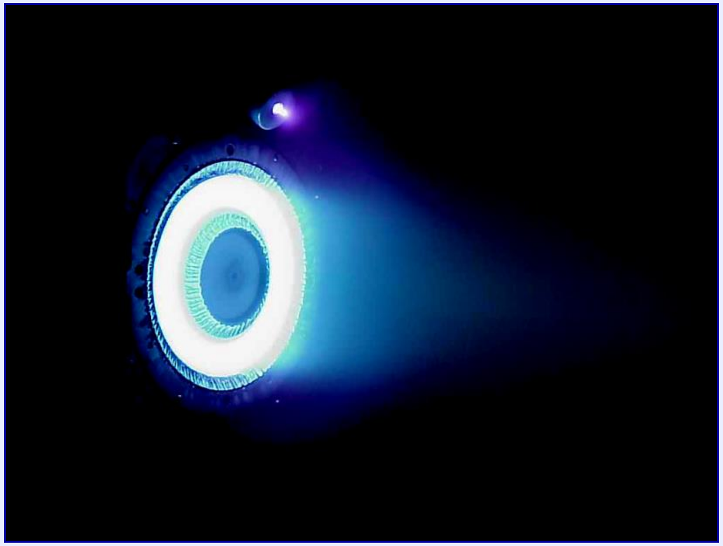
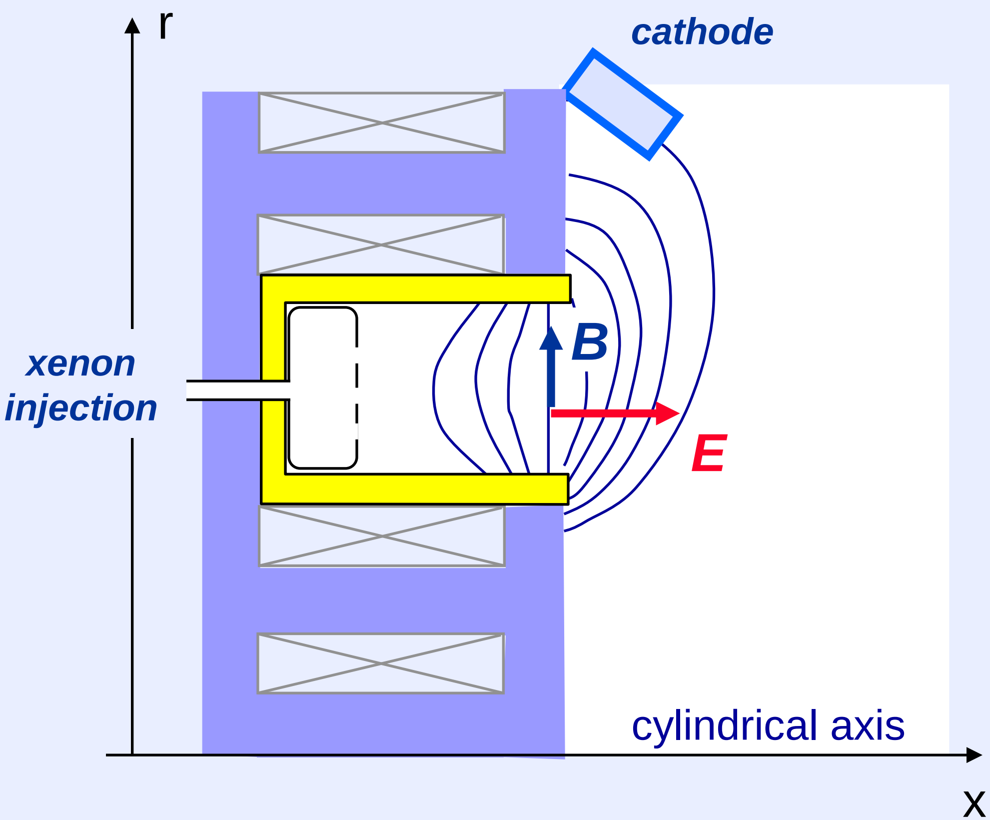


European lunar probe SMART 1

Hall thruster



Principles

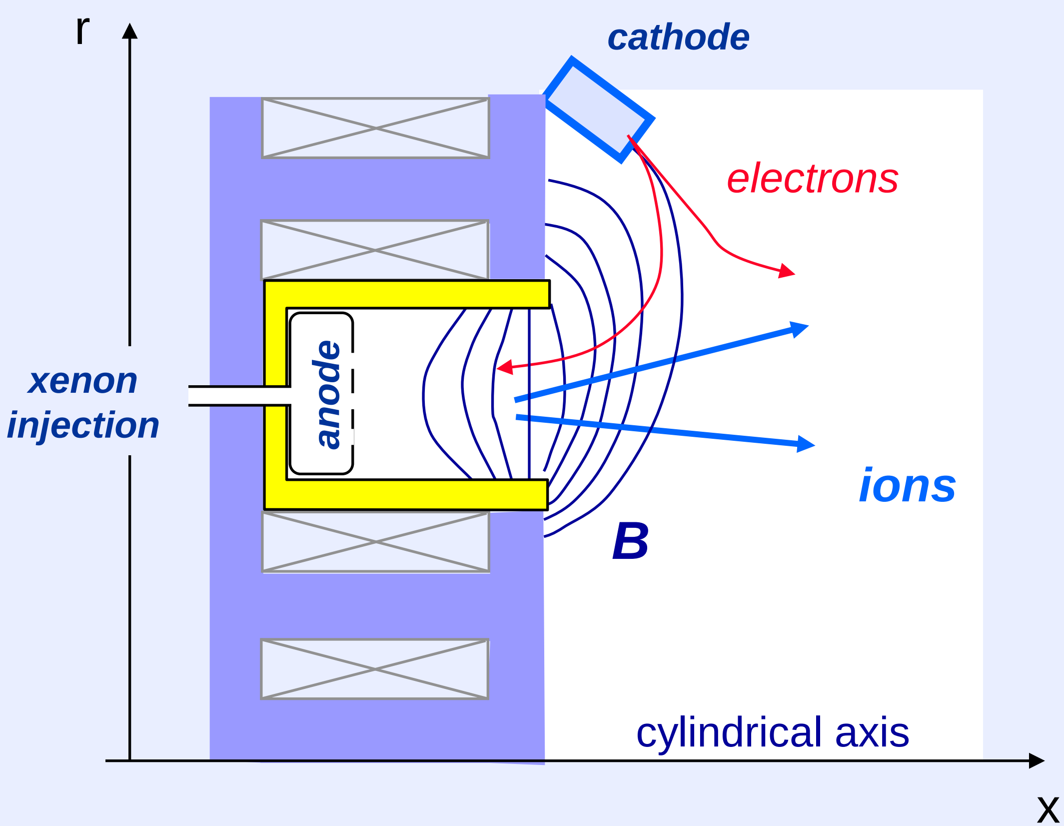
- Radial magnetic field B
- Axial electric field E
- ***E*** x ***B*** drift in the azimutal direction

➢ **Existence of large electric field in the plasma because of low electron conductivity in the magnetic barrier:**

$$J = \sigma E$$

If conductivity σ is low, electric field $E=J/\sigma$ must increase for a given current

Hall thruster



Principles

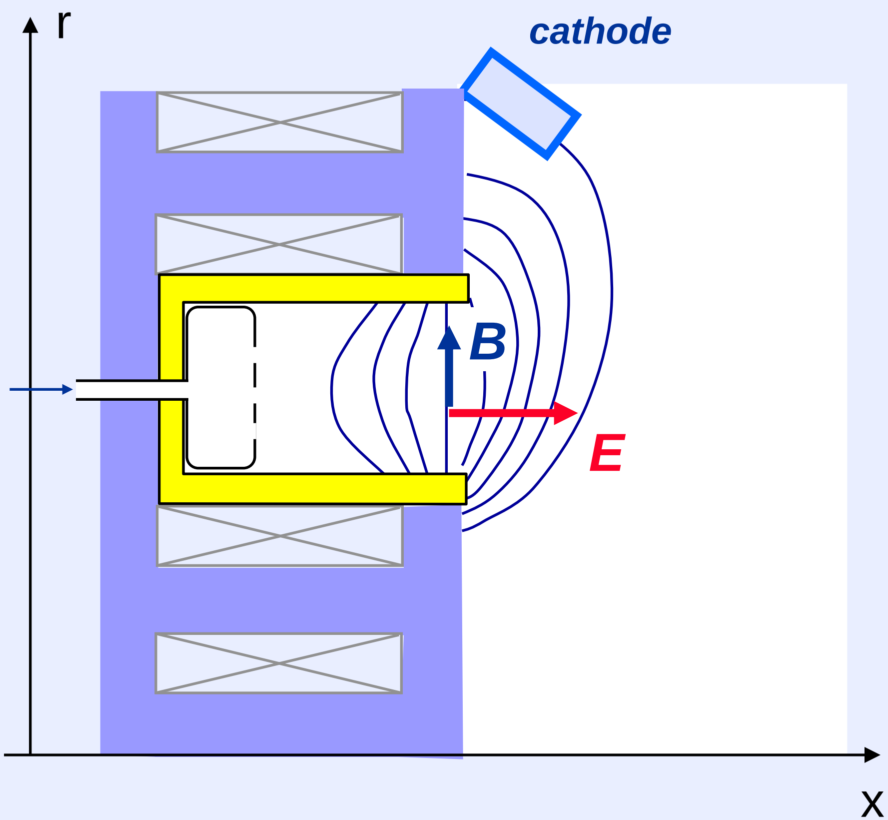
- Mean free paths >> dimensions
- Large radial B field at exhaust (**2 10^{-2} T**)
  → increase residence time of electrons
  → **Magnetized, collisional electrons**
- **Unmagnetized**, **Collisionless ions**
- Neutral flow ~ fully ionized (80-90%)

Typical numbers

- Voltage **300 V**, current **4 A**
- Xenon mass flow rate 5 mg/s
- Typical dimensions ϕ 10 cm, L 3 cm
- gas density at anode $10^{13\text{-}14}$ cm^{-3}

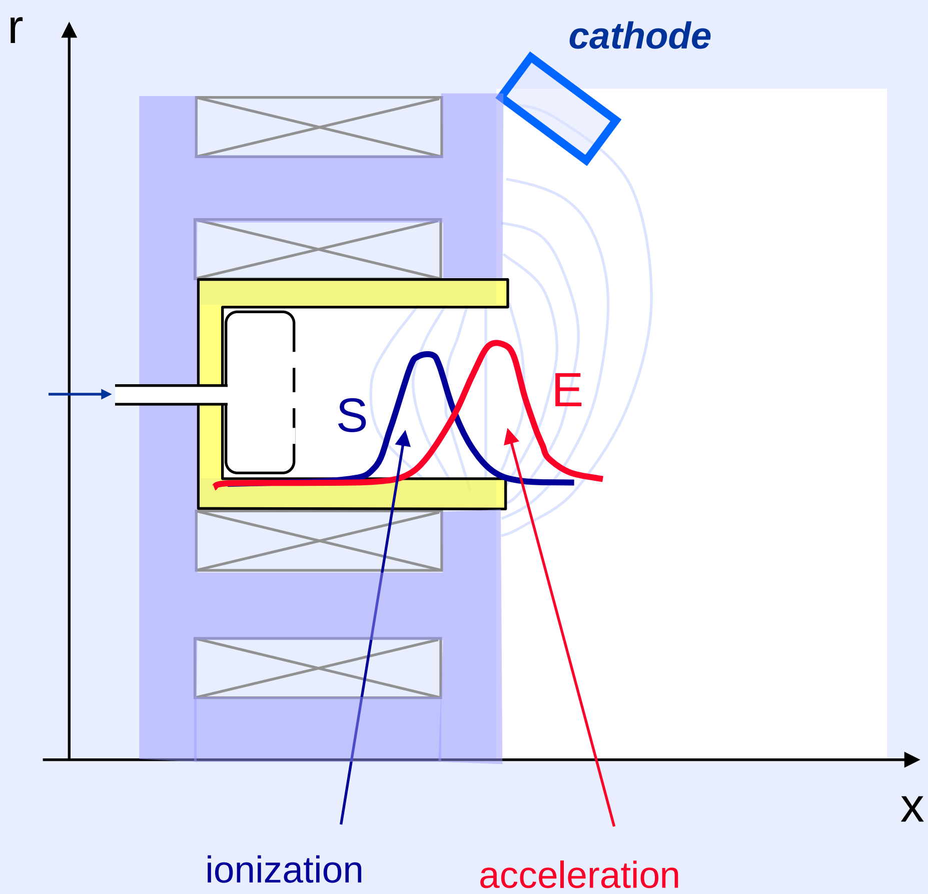
- Plasma density 10^{12} cm^{-3}
- Electron temperature 15 eV

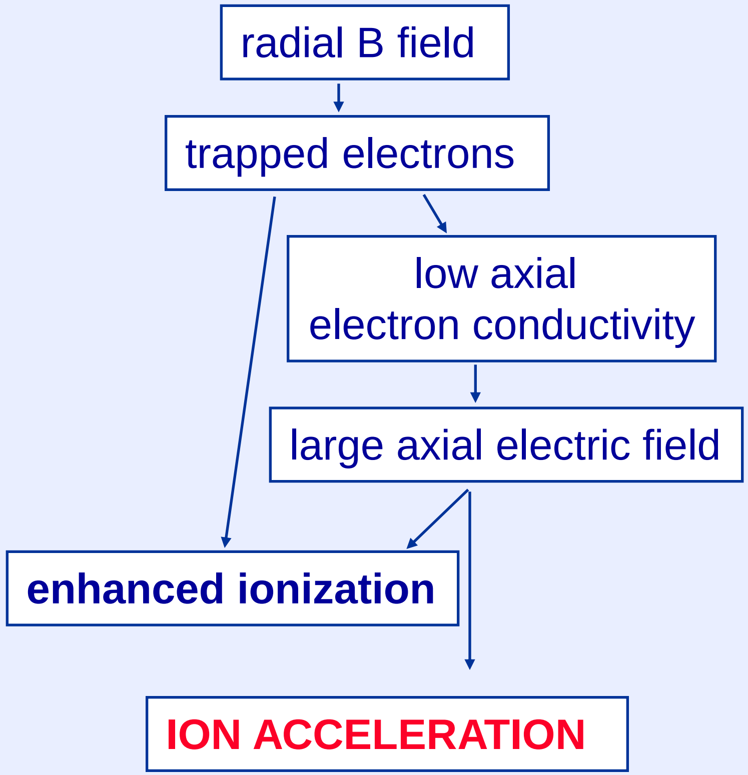
$E \times B$ configuration → **Hall (azimutal) current ~ 20 A**, larger than the discharge current ~ **4 A**



Two ways to describe thrust

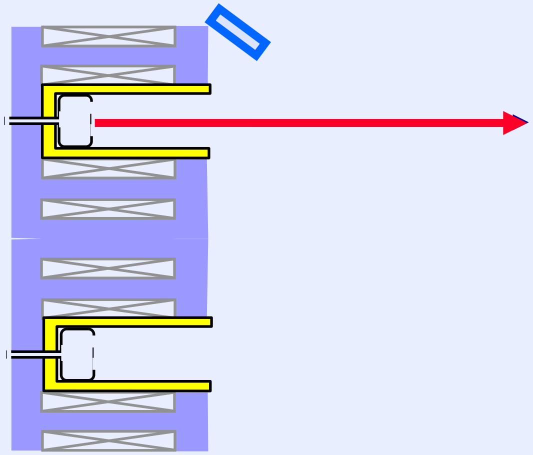
- Electric force acting on ions and due to the large electric field generated by the decrease of electron conductivity
- Lorentz force acting on the Hall current

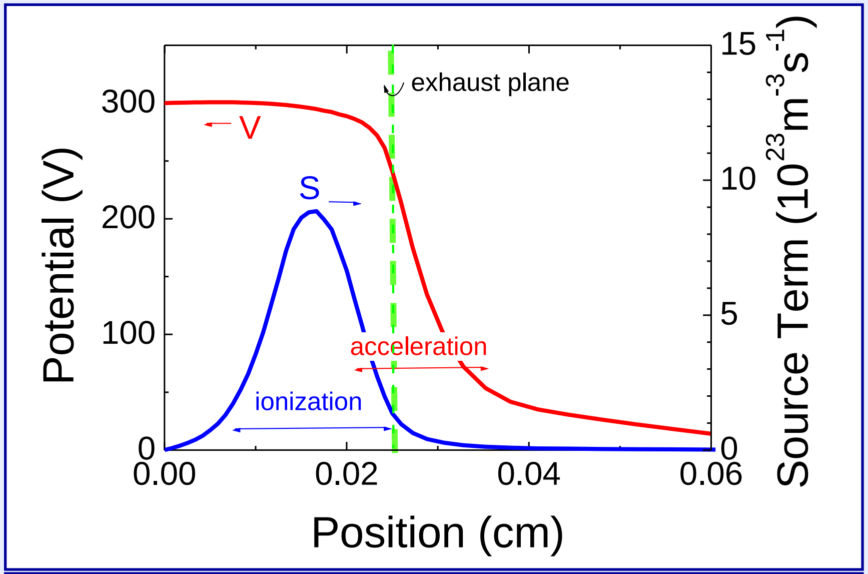

r
cathode
S
E
x
ionization
acceleration

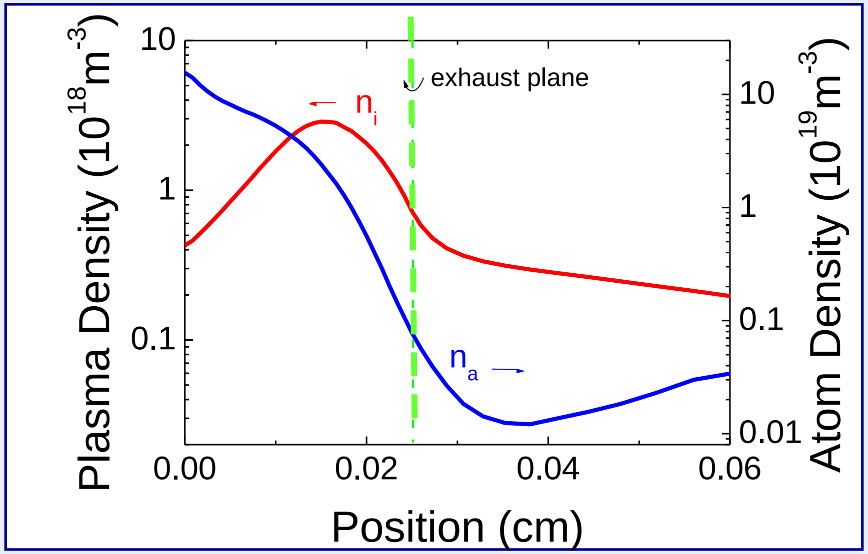

radial B field
trapped electrons
low axial electron conductivity
large axial electric field
enhanced ionization
ION ACCELERATION

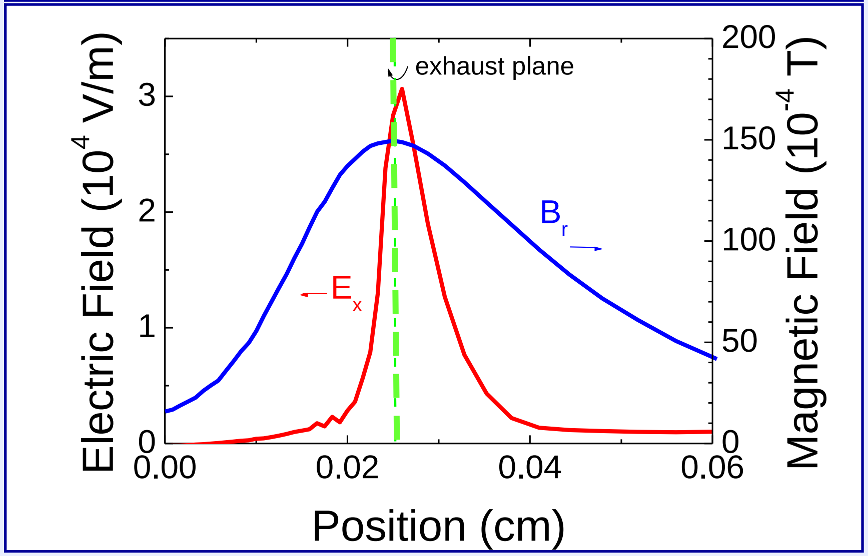
Research on Hall thrusters

Typical plasma properties from 2D Hybrid model









Hybrid model: fluid description of electrons, kinetic descritpion of ions

Research on Hall thrusters

Hybrid model predictions – Neutral density and current oscillations

- full ionization of the flow

⇩

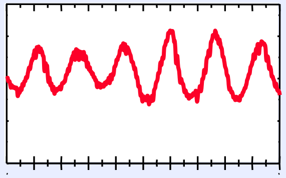
- Discharge extinction

⇩

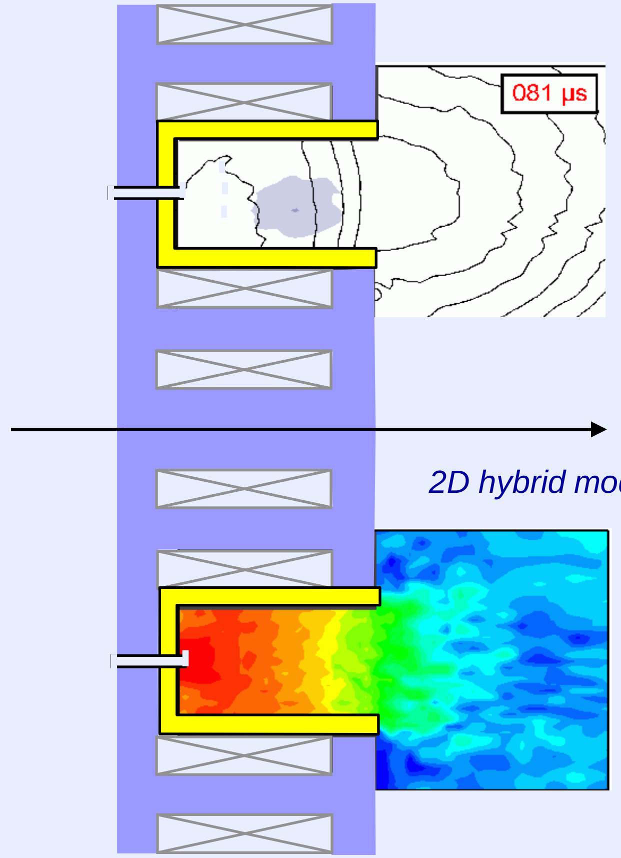
- Re-filling of the channel by the neutral flow

⇩

large amplitude (few A)
low frequency (10 kHz)
current oscillations



Potential & ionization rate



2D hybrid model (LAPLACE)

Atom density
10^{11} -10^{14} cm^{-3}

Bareilles et al. Phys. Plasma 11, 3035 (2004)

Research on Hall thrusters

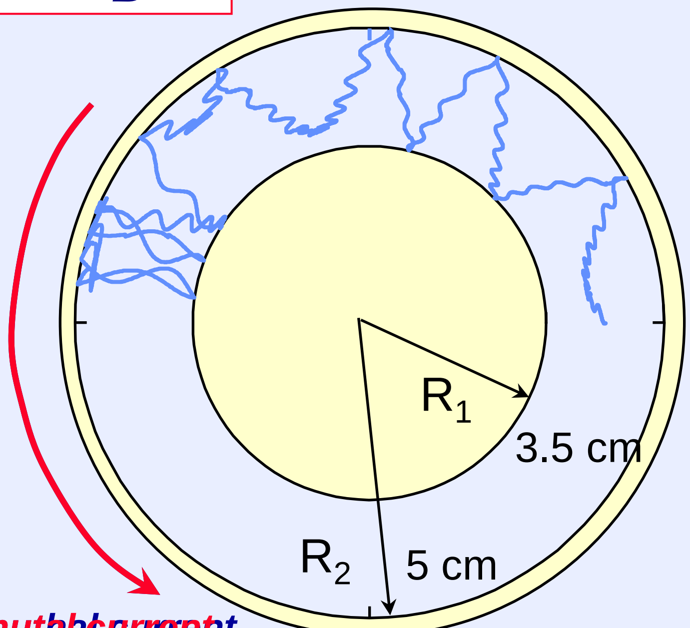
Classical, collisional transport – Axial and azimutal velocity

Azimutal electron current (Hall current)= 20 A
Axial electron current at channel entrance= 1A

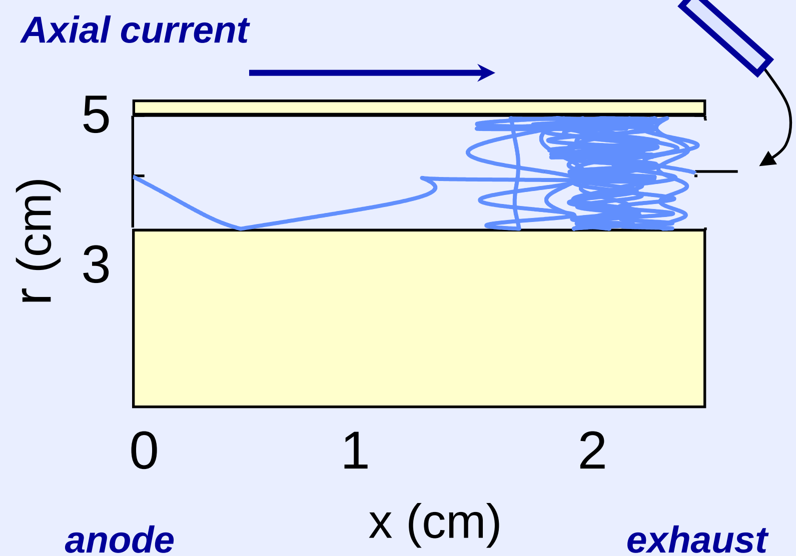
$$\omega = \frac{eB}{m}$$

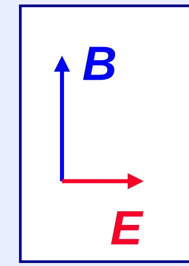
$$\overline{v}_E = \frac{E}{B}\frac{\nu}{\omega}$$

$$v_{E\times B} = \frac{E}{B}$$



azimutal current
hall current





Classical electron conductivity across B
- Axial velocity proportionnal to collision frequency i.e. to **gas density**
- No collisions → no « classical » axial transport

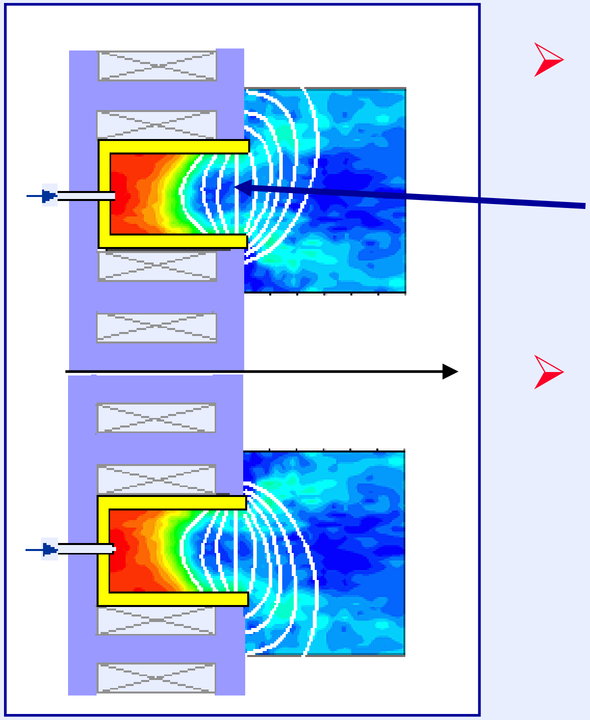
- **In classical theory electron current is proportional to electron-neutral collision frequency, i.e. to gas density**

$$\mathrm{v}_E = \frac{E}{B}\frac{\nu}{\omega}$$

electron current density $$J_e = en_e \mathrm{v}_E = en_e \frac{E}{B}\frac{\nu}{\omega}$$

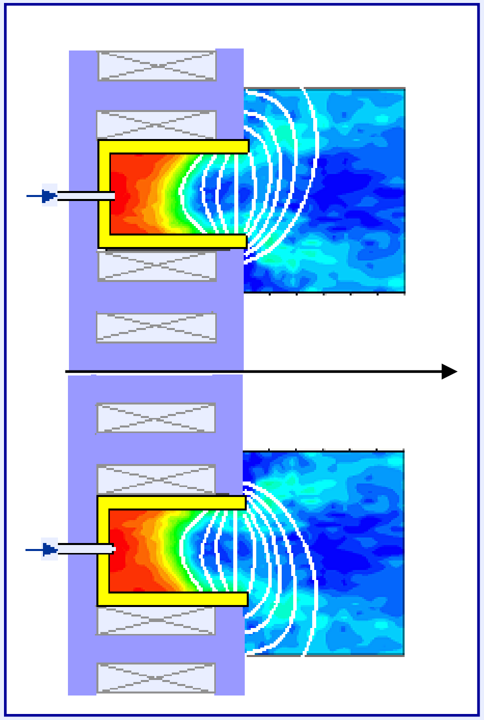
- **Problem**
  - experiments and models show that classical conductivity is not sufficient to explain observations
  - i.e. current density due to collisions between electrons and neutral gas is too low

Neutral atom density



- Because of ionization, neutral density is depleted in the exhaust region
  - Collisions with neutral atoms not sufficient to allow transport ⊥ B (especially outside the channel)
- Necessary to introduce supplementary scattering effects in hybrid models (« anomalous mobility »)
  - **Collisions with walls and secondary emission (« near wall conductivity »)**
  - **Turbulent transport**

Adam et al. Plasma Physics and Controlled Fusion 50 124041 (2008)



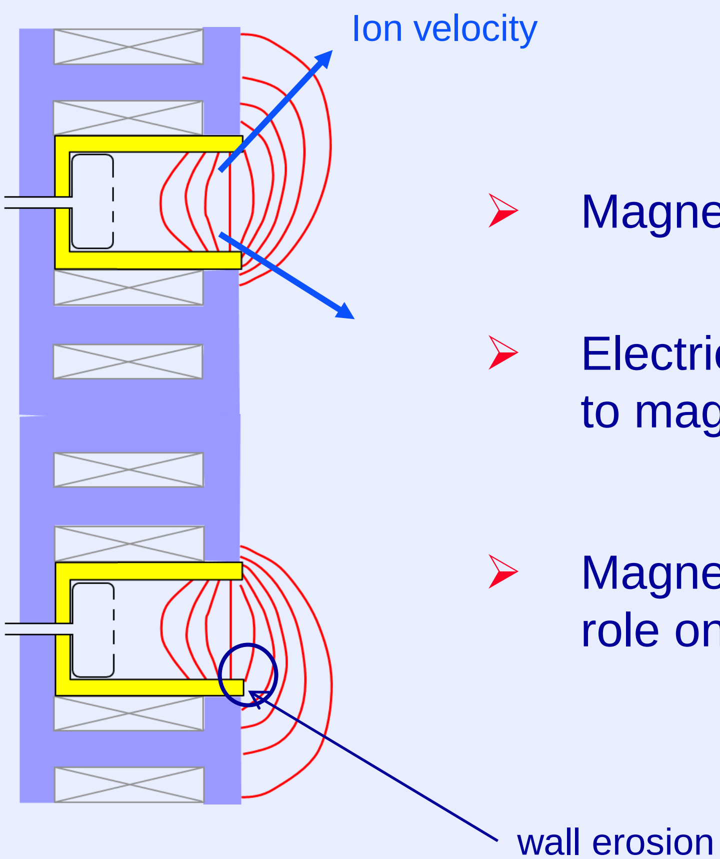
- Research efforts to understand and quantify electron transport across magnetic field
  - Particle In Cell simulation of turbulence
  - Possible to deduce turbulent transport coefficients for fluid models ?
  - Plasma diagnostics to measure plasma properties and quantify turbulence: Laser diagnostics (Laser Induced Fluorescence, Collective Thomson Scatering)
- Because of anomalous transport, the models are still not able to help efficiently the design of new Hall thrusters (larger power or different designs):

Hall thruster design is still empirical

Adam et al. Plasma Physics and Controlled Fusion 50 124041 (2008)

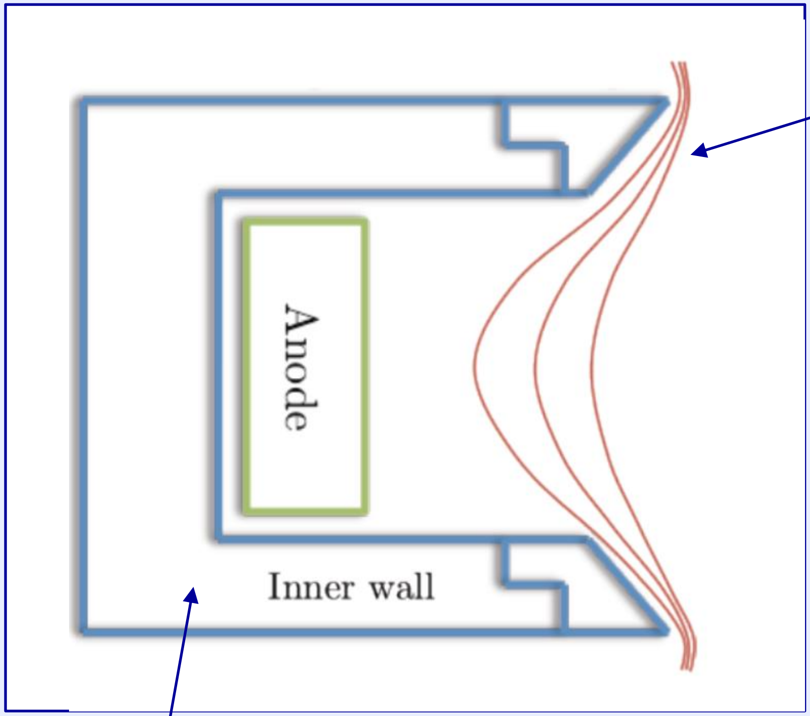
Research on Hall thrusters

Other Isssue: Ion divergence and wall erosion



- Magnetic field lines tend to be equipotential
- Electric field and ion trajectories ~ perpendicular to magnetic field lines
- Magnetic field configuration plays an important role on ion divergence and wall erosion

- Magnetic shielding configuration proposed by JPL to minimize wall erosion and increase lifetime



Magnetic field lines

Ceramic wall (Boron Nitride)

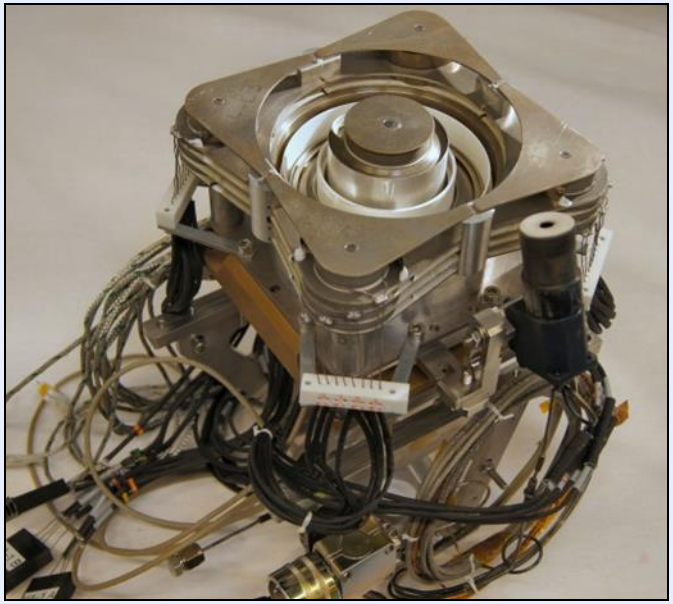
Hofer et al, IEPC-2013-033

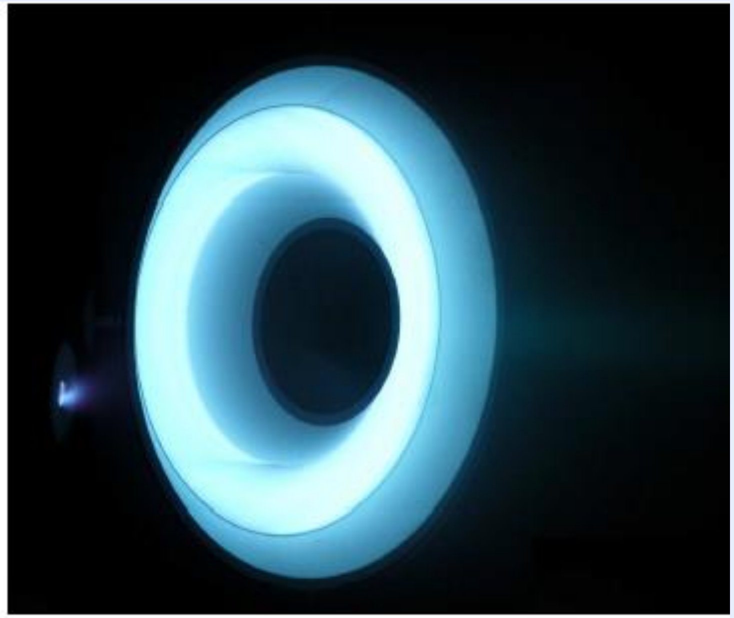
Research on Hall thrusters
Some important issues

- Better understand and quantify electron transport across magnetic field to build predictive simulation tools than can help the design of Hall thrusters
  - understand role of instabilities and turbulence on transport
  - understand role of electron interaction with walls on transport
- Understand the role of magnetic field distribution
  - on instabilities, turbulence and electron transport
  - on ion beam distribution and divergence – wall erosion – lifetime
- Improve materials
  - Development of new ceramic materials to increase lifetime
- Investigation of plasma surface interaction (eg secondary electron emission)
- Improve cathode (electron source)

PPS FLEX (French research group on electric propulsion)

- Design of a Hall thruster with Flexible magnetic field configuration: PPS FLEX
- Possible to test multiple magnetic field configurations on a single thruster
- Possible to change each parameter independantly (eg B gradient) to understand the role of each parameter on the thruster performance

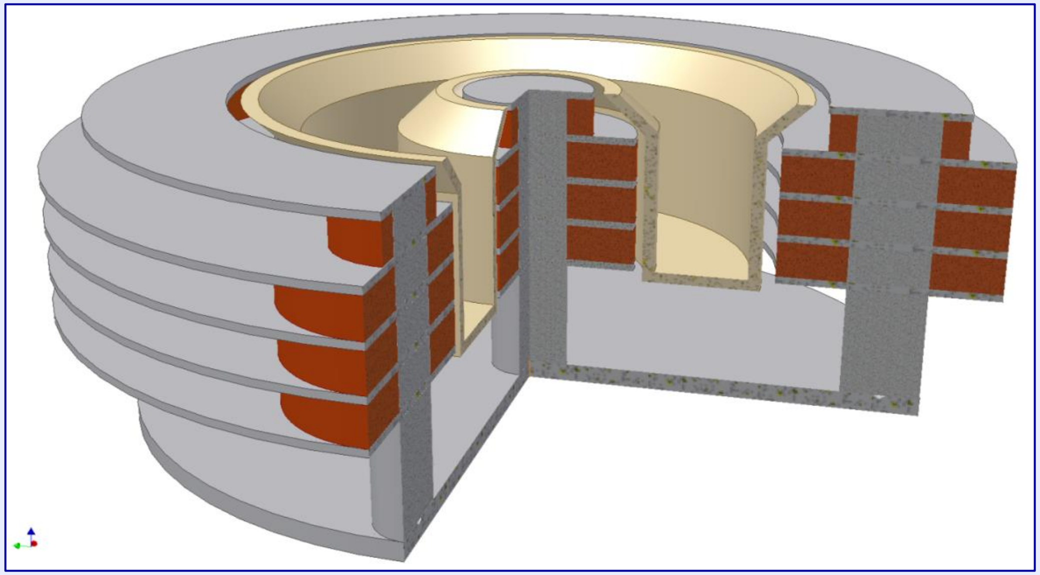




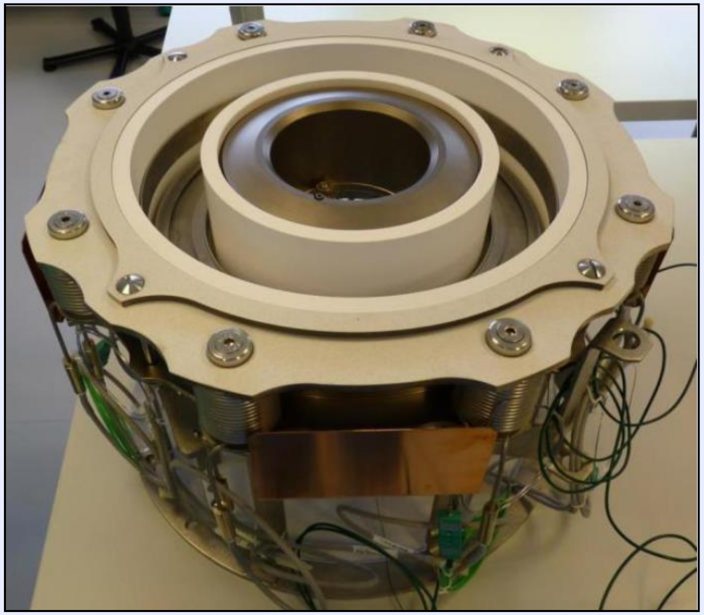
Hénaux et al, IEPC-2011-291

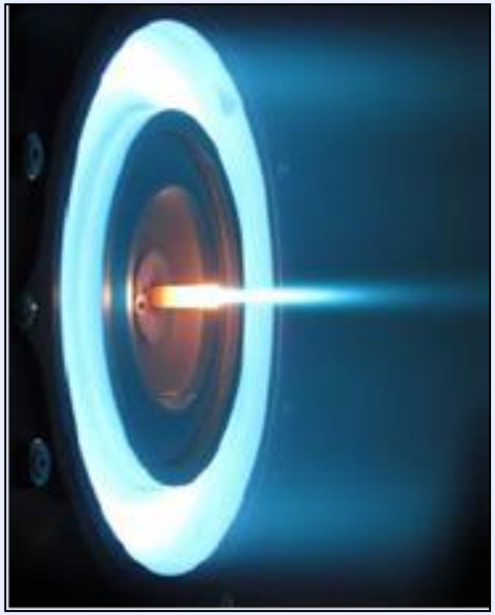
PPS FLEX (French research group on electric propulsion)

- Complex system of independant coils and magnetic circuit
- 8 degrees of freedom



PPS-20k ML (French research group on electric propulsion)

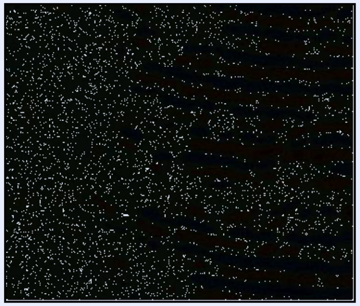




Hall effect thruster PPS-20k ML operating at 23.5 kW, developed in the frame of the FP7 HiPER

Simulations and diagnostics (French research group on electric propulsion)

- Evidence of the presence of azimutal instabilities (microturbulence) enhancing electron transport across the magnetic field by Particle-In-Cell simulations



- Measure of density fluctuations and turbulence by Collective Thomson Scattering

- Laser Induced Flurence measurements of ion velocity distribution function

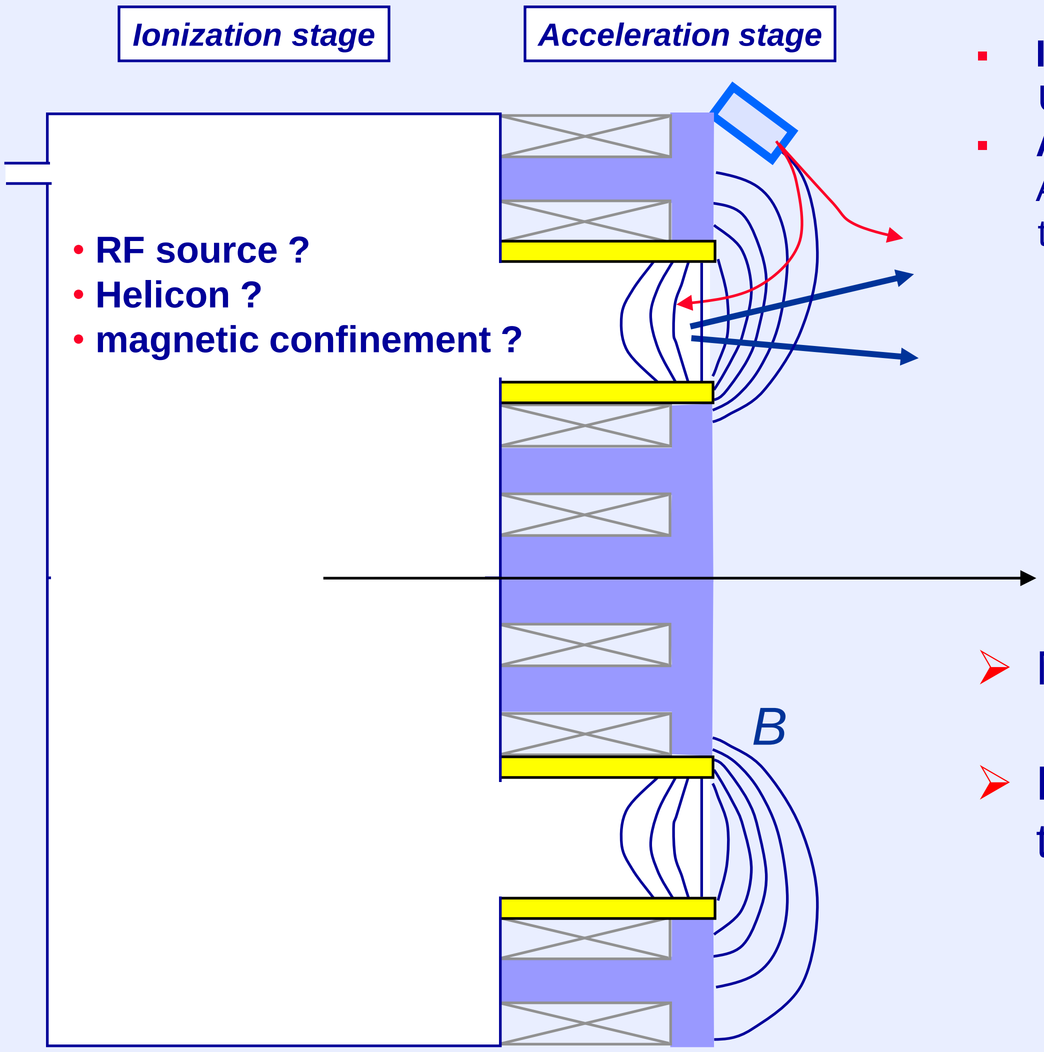
Need for more versatile Hall thrusters

- In a Hall thruster the same electric field is used to energize the electrons (allowing ionization) and to accelerate the ions
- ionization and acceleration are strongly linked so it is difficult to fix separately the power (thrust) and the ion velocity (Isp)
- **Need for versatile thrusters with variable Isp and thrust**
  - orbit top up – orbit raising
    - high thrust (reduction of mission duration)
    - high mass flow rate/low voltage (enhance ionization)
  - North/South Station Keeping
    - high Isp to minimise gas consumption
    - high voltage/low mass flow rate to enhance acceleration

→ **Double Stage Hall Thruster (DSHT)**

- Separation of ionization and acceleration processes
- promising candidate for multi-mode operation

Research on Hall thrusters
Double Stage Hall Thruster



- **Ionization Stage**
  Use a separate chamber for plasma generation
- **Acceleration Stage**
  Acceleration in chanel as in standard Hall thrusters

- Many attempts at developing DSHTs
- But results are not yet convincing in terms of performance and efficiency

Conclusion

1. **Interest in all-electric propulsion is increasing fast**

2. **EP will be used on all telecommunication satellites not only for station keeping but also for orbit raising**

3. **Hall thrusters are excellent candidates for EP and are already used on satellites – Still need for Research and Development**

4. **Principles of Hall thrusters are relatively simple but physics is quite complex**
   - Electron transport across magnetic field
   - Role of plasma-wall interactions
   - Design is stil empirical
   - Important progress made in the last years on physics and technical issues