Jet and Rocket Propulsion

AE4451

LECTURE 28

Sedina Tsikata – March 15, 2023

Overview

- what we saw in Lecture 27
    - electric propulsion: introduction to basic concepts

- today
    - electric propulsion: real systems

Electric propulsion

Classes of devices

examples

electrothermal

electrical heating of propellant
expansion of propellant across nozzle

- resistojet
- arcjet
- microwave heated thruster

electro~~static~~ magnetic

electromagnetic body forces (Lorentz forces, **j x B**) to accelerate ions

electrostatic

- Hall thruster
- gridded ion engine
- electrospray/colloidal thruster/ field emission electric propulsion (FEEP)

electro~~magnetic~~ static

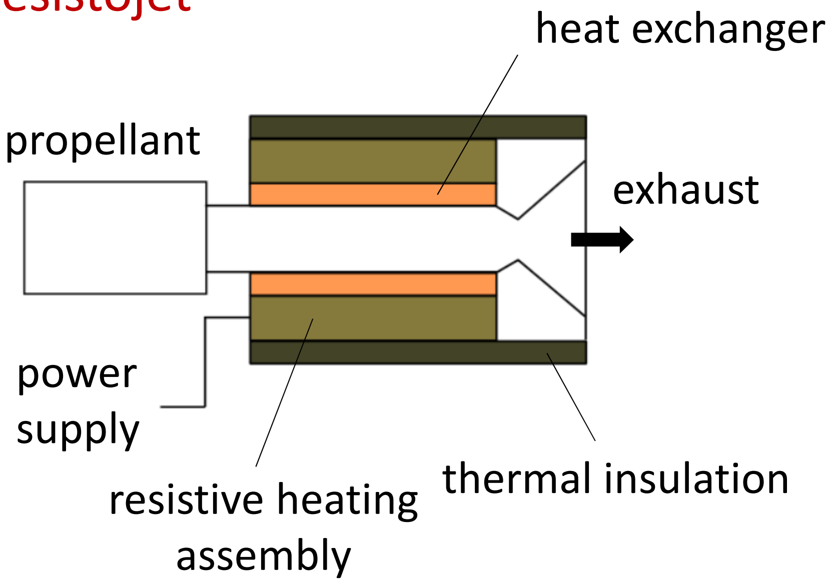
charge potential difference to accelerate ions (Coulomb forces)

electromag.

- pulsed plasma thruster
- magnetoplasmadynamic thruster

Electric propulsion: electrothermal devices

Resistojet



- propellant resistively heated via chamber or filament
- expansion of propellant and acceleration across nozzle
- virtually any propellant usable: Xe, Ar, H_2, N_2H_4, NH_4, N_2…

- temperature change in chamber due to added electrical energy

$$\Delta T_c = \frac{P_e}{\dot{m} c_p}$$

initial temperature: decomposition of e.g. N_2H_4 flowing over catalyst

$$I_{sp} \propto \sqrt{T_c / MW}$$

resistojet advantages

- simplicity of operation, low cost
- same architecture for all propellants
- high thrust and efficiency

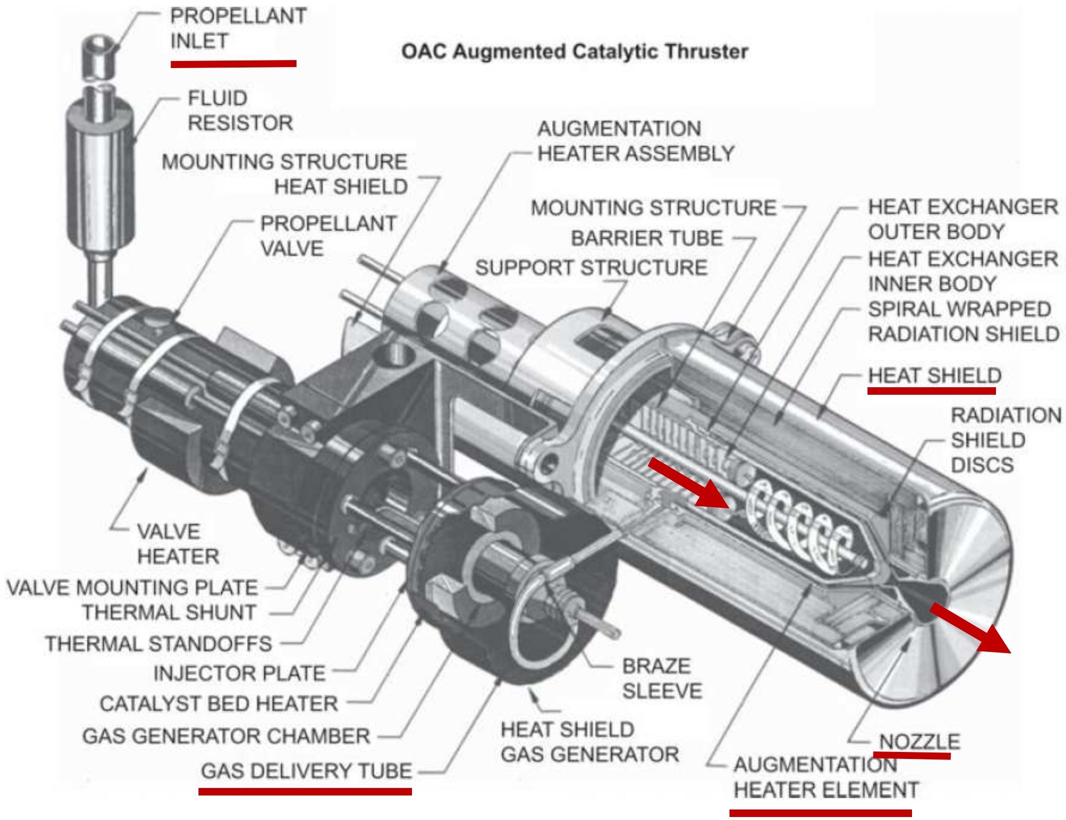
resistojet disadvantages

- lowest Isp compared to other EP methods
- thermal losses
- gas dissociation
- erosion

Electric propulsion: electrothermal devices

Resistojet

MR-501B (Aerojet Rocketdyne)

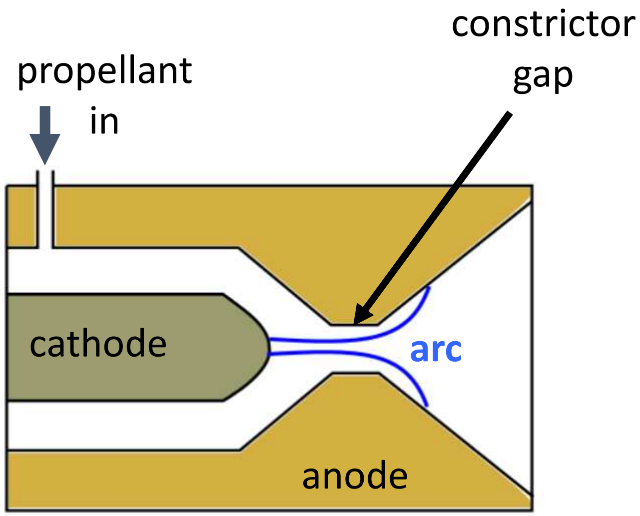


Design Characteristics of Aerojet Rocketdyne MR-502A

- propellant: hydrazine
- catalyst: S405
- thrust/Steady State: 0.80 – 0.36 N
- flow Rate: 0.28-0.12 g/sec
- mass: 0.87 kg (1.92 lbm)
- specific impulse: 303 – 294 sec
- total steady state firing: 2 hrs single firing / 370 hrs cumulative

Electric propulsion: electrothermal devices

Arcjet



- high current arc created between cathode and anode
- propellant fed across arc; ionized and heated
- acceleration across nozzle

- arc replaces the heat exchanger and heating coil of the resistojet

- first used on Telstar-401 telecommunications satellite in 1994; hundreds used since

advantages

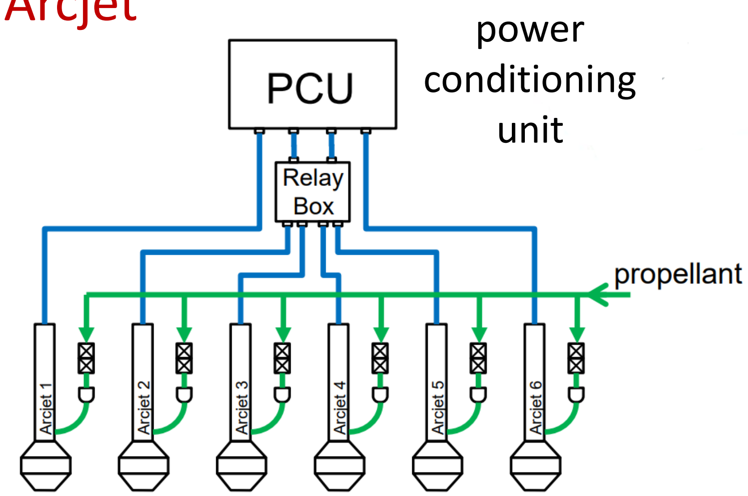
- relatively simple operation
- high thrust
- direct gas heating
- low voltage (tens of V)

disadvantages

- low Isp
- low efficiency
- erosion at high power (can add B field for confinement)
- heavy wiring

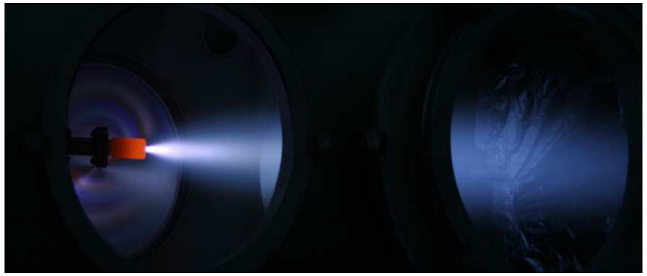
Electric propulsion: electrothermal devices

Arcjet



MR-512 Low Power Bus Arcjet System (Aerojet Rocketdyne)

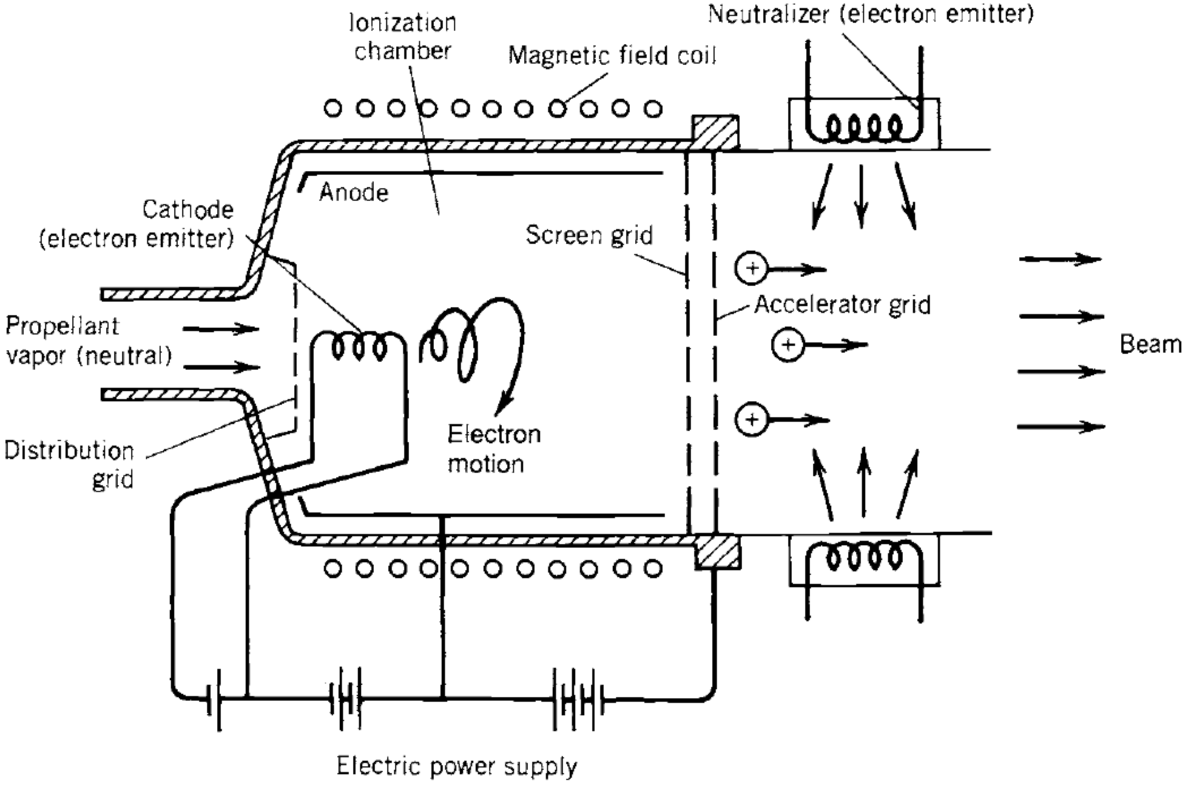
- propellant: hydrazine
- mass of arcjet thruster + 2000 mm cable: 1.4 kg
- arcjet dimensions: 240 x 125 x 90 mm^3
- PCU input power per arcjet: 1780 W
- PCU efficiency, avg: > 91%
- thrust: 254 – 213 mN
- specific impulse: > 502 s



1 kW AT 1k arcjet (SITAEL)
thrust = 50 - 150 mN
Isp = 134 – 605 s

Electric propulsion: electrostatic devices

Gridded ion engine / thruster GIE / GIT



Sutton and Biblarz

- electrons from emitter cathode are trapped in chamber

- ionizing collisions between electrons (constrained by radial B) and neutral gas

- radial electric field to remove electrons; axial electric field to accelerate ions

- beam neutralization from external electron emitter

with triple grid system:

screen grid: retains electrons in ionizing chamber
second grid: high voltage acceleration of ions
third grid: keeps out neutralizing electrons

Electric propulsion: electrostatic devices

Gridded ion engine

0.5 – 2.3 kW NSTAR gridded ion engine (NASA)
Φ = 300 mm
thrust = 19 - 92 mN
Isp = 1900 – 3100 s

assembled Deep Space 1 satellite (NASA)

advantages

- high Isp (NSTAR: 3200 s)
- high efficiency (> 60%)

disadvantages

- complex power conditioning
- heavy power supply
- optimized for a single propellant (Xe)
- arcing possible at high voltage

Electric propulsion: electrostatic devices

Performance of electrostatic devices

- we want the applied electrical energy to be transferred to kinetic energy of the species

$$qV_a = \frac{1}{2} m v_{ideal}^2$$

$$v_{ideal} = \sqrt{\frac{2qV_a}{m}}$$

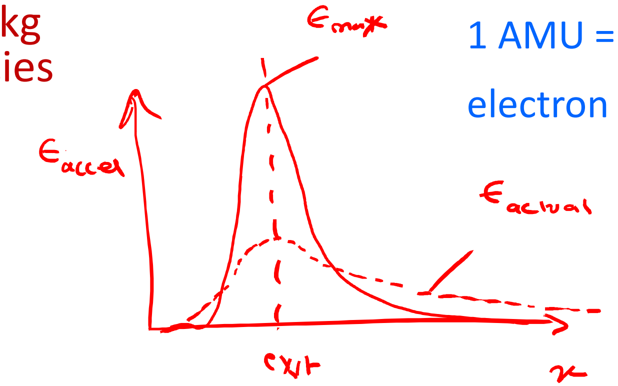
$$v_{ideal} = 13{,}890\sqrt{\frac{V_a}{MW}}$$

q = elementary charge, 1.602×10^{-19} C
V_a = accelerating voltage, V
m = particle mass, kg
v = velocity of species

Xe standard atomic weight = 131.3

1 AMU = 1.66×10^{-27} kg

electron mass = 9.109×10^{-31} kg



apply = 300V

- current across accelerator

$$J = \dot{m}\frac{q}{m}$$

assuming complete ionization, singly-charged species

- ideal thrust

$$\tau_{ideal} = \dot{m} v_{ideal} = \frac{mJ}{q} \times \sqrt{\frac{2qV_a}{m}} \quad \Rightarrow \tau_{ideal} = J\sqrt{\frac{2mV_a}{q}}$$

Electric propulsion: electrostatic devices

Performance of electrostatic devices

- an <u>upper limit</u> exists for the current density of a charged particle beam

  - a function of geometry and electric field

- at this limit, accumulated charges start to oppose applied field

  - e.g for electrons

$$\boxed{j = \frac{4\varepsilon_0}{9}\sqrt{\frac{2q}{m_e}}\frac{V_a^{3/2}}{d^2} = \frac{J}{A}}$$

Child-Langmuir limit

d = electrode separation
ε_0 = vacuum permittivity = 8.854 x 10^{-12} F/m

j is referred to as the maximum space-charge limited current

typical values of *j* for gridded ion assemblies: ~2 – 10 mA/cm^2

we get the maximum thrust based
on this current limit

$$\tau_{\max,ideal} = \frac{4\varepsilon_o}{9}\sqrt{\frac{2q}{m}}\frac{\Delta V_a^{3/2}}{d^2}A\frac{m}{q}\sqrt{\frac{2q}{m}\Delta V_a}$$

Electric propulsion: electrostatic devices

Performance of electrostatic devices

- maximum thrust

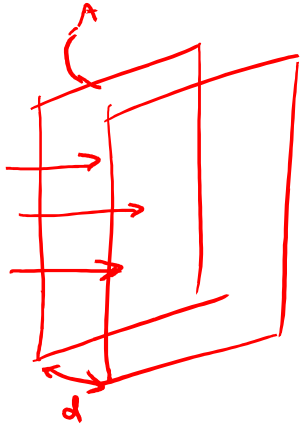
$$\tau_{\max,ideal} = \frac{4\varepsilon_o}{9}\sqrt{\frac{2q}{m}}\frac{V_a^{3/2}}{d^2}A\frac{m}{q}\sqrt{\frac{2q}{m}V_a}$$

$$\tau_{\max,ideal} = (8\varepsilon_o/9)AV_a^2/d^2$$

$$\tau_{\max,ideal} = (2\pi/9)\varepsilon_o(D/d)^2V_a^2$$

for circular cross section, diameter *D*

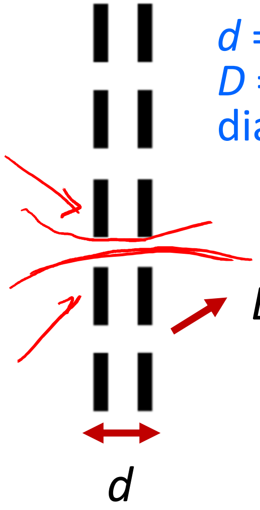
$$= 6.18\times10^{-12}(D/d)^2V_a^2$$



Electric propulsion: electrostatic devices

Performance of electrostatic devices

- aspect ratio for gridded ion engines



d = grid spacing
D = hole diameter (beam emitter diameter)

$$a = \frac{D}{d}$$

grid erosion (NASA)

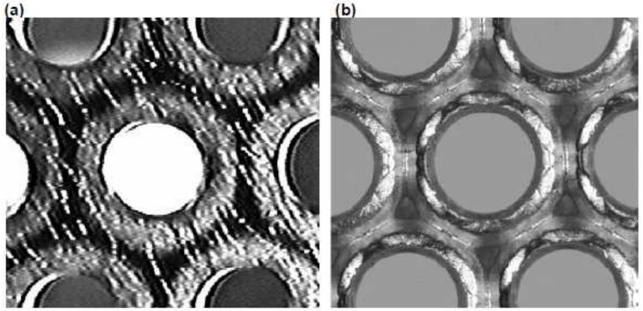


Fig. 5-22. NSTAR thruster accelerator grid at (a) 125 hours and (b) 30,352 hours.

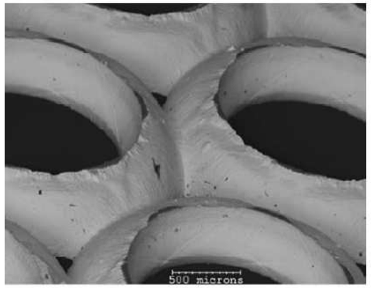


Fig. 5-23. SEM photograph shows that sputtering in the webbing between the holes had almost destroyed the structural integrity of the NSTAR grids.

$$a \leq 1$$

- for simple singly-charged ion beams (space charge limit)
- to increase thrust, would increase number of engines because current density is limited

$$\tau_{\max,ideal} = 6.18\times10^{-12}\left(D/d\right)^2 V_a^2$$

Electric propulsion: electrostatic devices

Performance of electrostatic devices: propellant considerations

$$\tau_{ideal} = \dot{m} v_{ideal}$$

$$= \frac{mJ}{q} v_{ideal} = \frac{mjA}{q} v_{ideal}$$

for gridded ion engine

$$j_{\max} \propto \sqrt{\frac{q}{m}} \Rightarrow \frac{\tau_{\max}}{A} \propto \sqrt{\frac{m}{q}}$$

so $\frac{\tau_{ideal}}{A} = j \frac{m}{q} v_{ideal}$ or in terms of Isp, $\frac{\tau}{A} = j \frac{m}{q} I_{sp} g$

$$\boxed{\frac{\tau}{A} \propto j \frac{m}{q}}$$

for fixed Isp

- maximize thrust/area by maximizing *m/q*
- e.g. heavy ion like Xe (MW = 131.3)
  stable, unreactive and readily stored
- singly-charged species preferred
- large charged particles (colloidal thrusters)

Xe^{+}

Xe^{2+}

Xe^{3+}

Xe^{4+}

Electric propulsion: electrostatic devices

Performance of electrostatic devices: thruster power

Jet power

$$P_j = \tfrac{1}{2}\dot{m}_b v^2$$ where $\dot{m}_b = \text{ion beam flow rate}$

beam flow rate

- propellant utilization not 100%
  - propellant utilization efficiency defined as $\underline{\eta_u} = \frac{\dot{m}_b}{\dot{m}}$

"actual" beam flow

mass flow rate (neutral propellant)

- thrust correction to account for divergence, multiple ionization, sputtering

real velocity

$$\underline{\gamma} \equiv v/v_{ideal} = \frac{\tau/\dot{m}_b}{\tau_{ideal}/\dot{m}_b}$$

Accelerator electrical power

$P_{elec} = P_{jet}$ ideally

$$\underline{\underline{P_{elec} = JV_a}}$$

- in reality, electrical power also goes towards:
  - ionization $P_{ion} = JV_{ion}$
  - neutralization $P_{neut} = JV_{neut}$

Electric propulsion: electrostatic devices

Performance of electrostatic devices: thruster power

- accounting for these effects

$$I_{sp} = \gamma \eta_u I_{sp,ideal}$$

real Isp

$$\tau = \dot{m}_b v \;\; = \eta_u \dot{m} \gamma I_{sp,ideal} g$$

real thrust

thruster efficiency

"actual" jet power

$$\eta_{th} \equiv \frac{P_j}{P_{th}} \qquad P_{th} = JV_{th} = J\left(V_{ion} + V_a + V_{neut}\right)$$

i.e. all of the channels to which electrical power goes

"P_{elec}"

thruster efficiency

$$\eta_{th} = \frac{\eta_u \gamma^2}{1 + \left(V_{ion} + V_{neut}\right) / V_{accel}}$$

typical values:

V_{ion}	100 - 300V (eV/ion)
V_{neut}	10 - 20V
γ	0.8 - 0.95
η_u	0.8 - 0.95

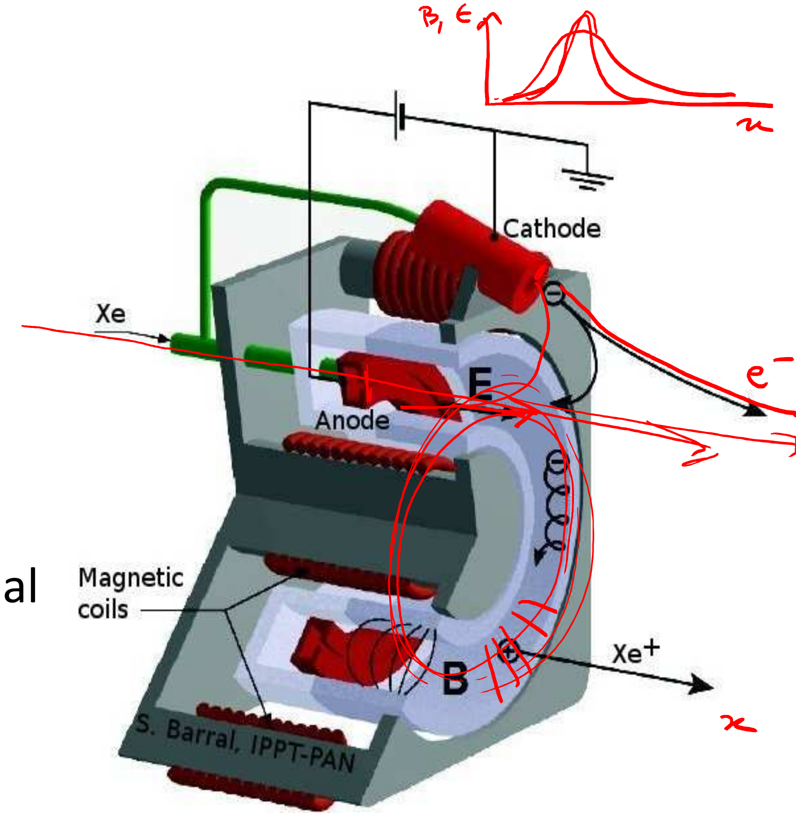
Electric propulsion: electrostatic devices

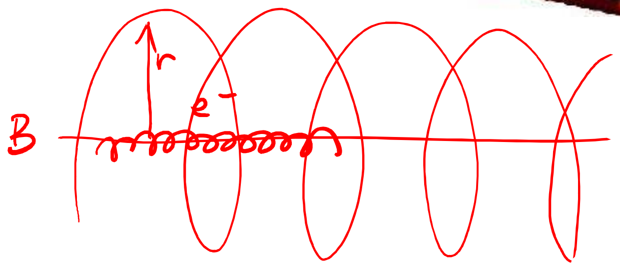
Hall "effect" thruster

- ionization
    - axial E and radial B generate azimuthal e- acceleration/motion (Hall current)
    - high energy e- ionize neutrals
    - heavy ions have larger Larmor radius, low deviation by B

- acceleration: two interpretations
    - electrons largely trapped by B, so negative plasma potential near exit accelerates ions
    - Hall effect from electron current, induced E ∝ j x B

- beam neutralization
    - external cathode





Electric propulsion: electrostatic devices

Hall effect thruster

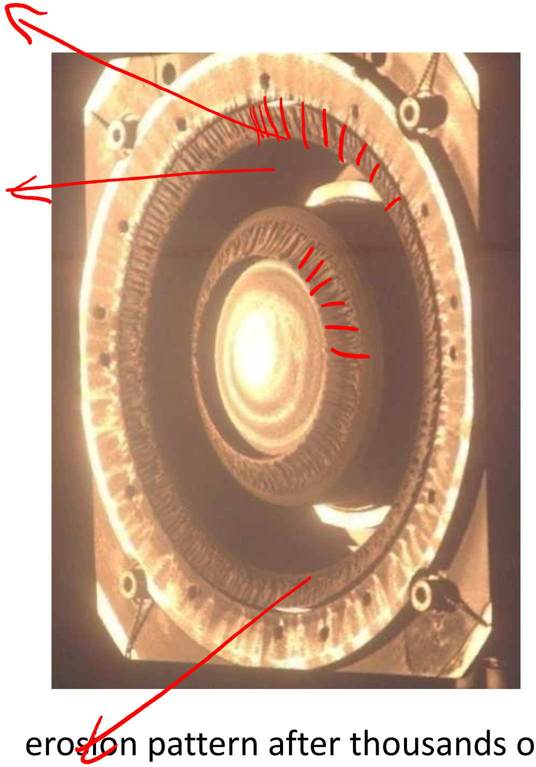
advantages

- simple architecture
- high Isp (1500 – 2500 s)
- very good efficiency (50%)
- compact and low mass

disadvantages

- erosion
- complex physics
- optimized for a single propellant (Xe)
- beam divergence

5 kW PPS-X000 thruster (Safran)
mean diameter 12.5 cm



erosion pattern after thousands of
hours of operation (Safran)