AE 330 Rocket Propulsion
Rocket Engine Schematics

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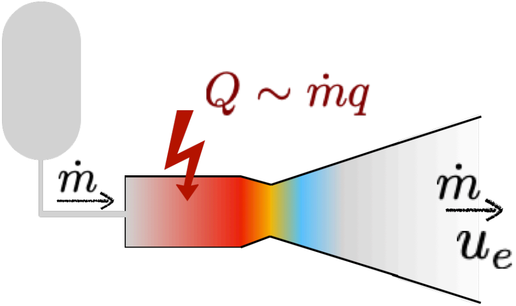
Rocket Propulsion



The added energy is giving this kinetic energy:

$$q \sim h_0 \sim \frac{1}{2}u_e^2$$

$$\frac{\gamma}{\gamma-1}\frac{\mathcal{R}_u}{\mathcal{M}_w}T_0 \sim \frac{1}{2}u_e^2 \implies u_e \sim \sqrt{\frac{2\gamma}{\gamma-1}\frac{\mathcal{R}_u}{\mathcal{M}_w}T_0}$$

Diwali Rocket

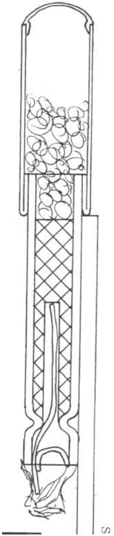


image from cyber-heritage.co.uk

Solid Propellant Rocket Motor (SRM)

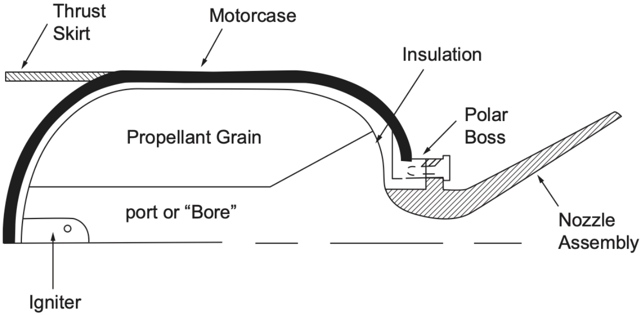


image from Heister

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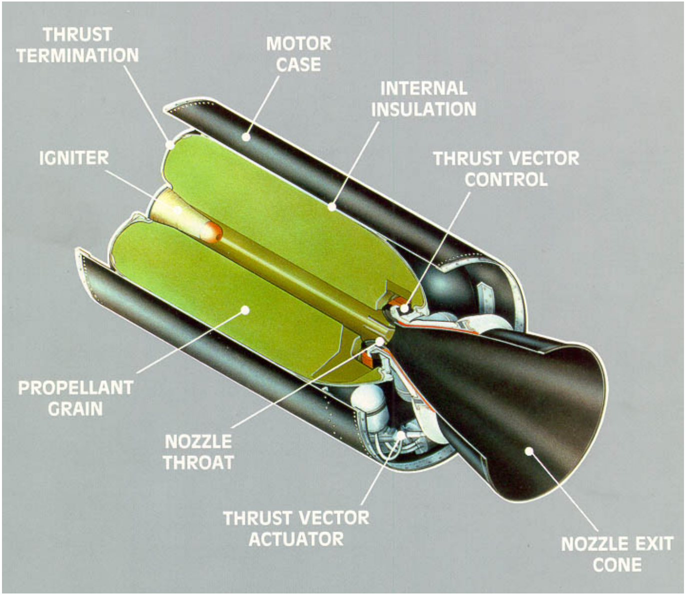


Liquid Propellant Rocket Engine (LRE)

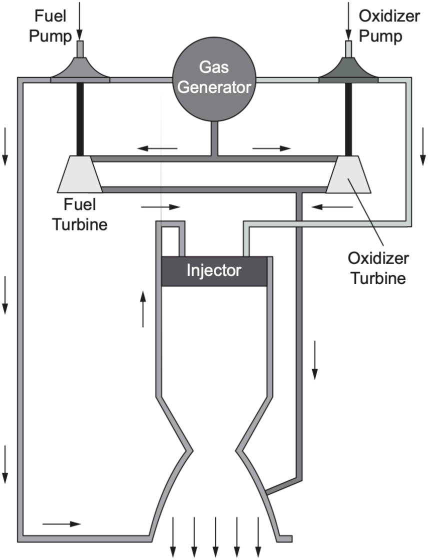
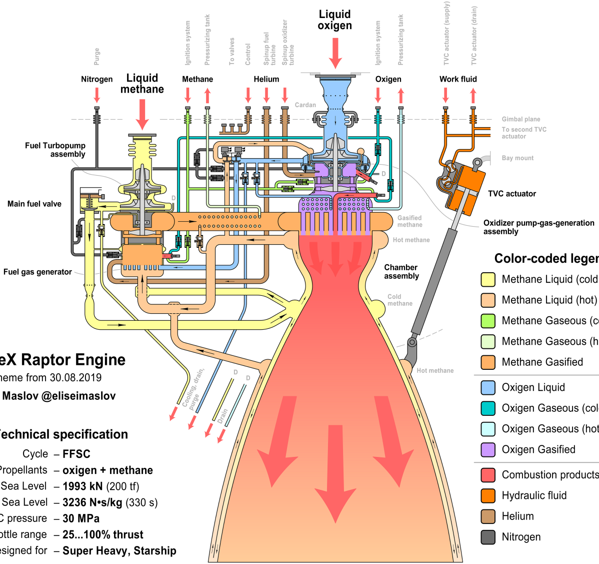


image from Heister

Raptor SemiCryo Engine (SpaceX)



SpaceX Raptor Engine

Scheme from 30.08.2019

Elisei Maslov @eliseimaslov

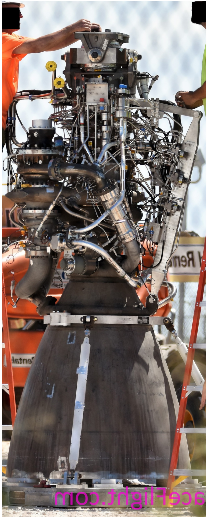
Technical specification

Cycle – **FFSC**
Propellants – **oxigen + methane**
Thrust Sea Level – **1993 kN** (200 tf)
ISP Sea Level – **3236 N•s/kg** (330 s)
CC pressure – **30 MPa**
Throttle range – **25...100% thrust**
Designed for – **Super Heavy, Starship**

Color-coded legend

- Methane Liquid (cold)
- Methane Liquid (hot)
- Methane Gaseous (cold)
- Methane Gaseous (hot)
- Methane Gasified
- Oxigen Liquid
- Oxigen Gaseous (cold)
- Oxigen Gaseous (hot)
- Oxigen Gasified
- Combustion products
- Hydraulic fluid
- Helium
- Nitrogen

Raptor SemiCryo Engine (SpaceX)



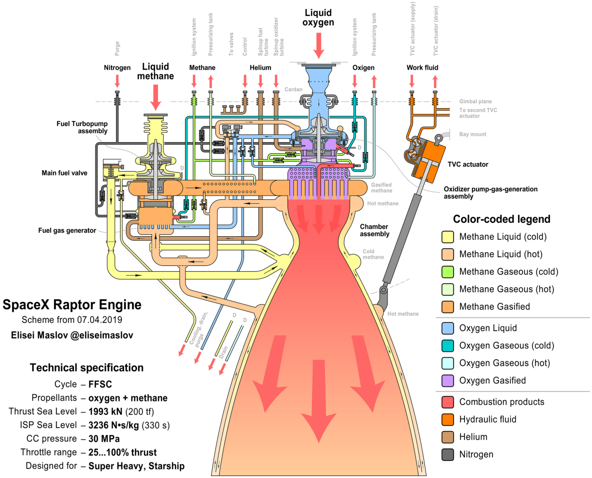


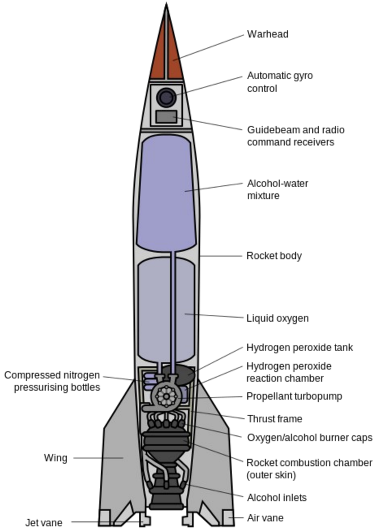
image from Elisei Maslov

V-2 Rocket

V-2 was the missile name

It was powered by a liquid rocket engine (LRE)

image from wikipedia



Hybrid Propellant Rocket Engine

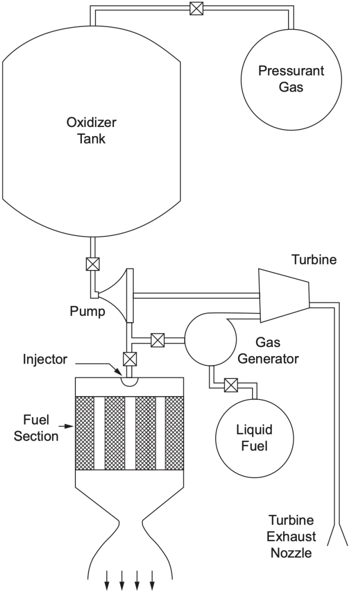


image from Heister

The Propulsion Problem

I_{sp} limited by the reaction heat release

Chemical rocket engines

Specific impulse, $I_{sp} = u_e/g_0$ is $\leq 500s$

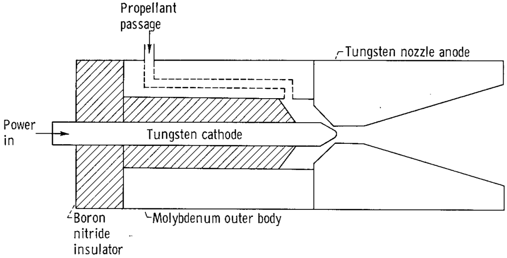
Can we cross this limit?

What if we further heat the propllant?

Electric energy can be used for this purpose

Arcjet Thruster

Heat propellant using an electric arc

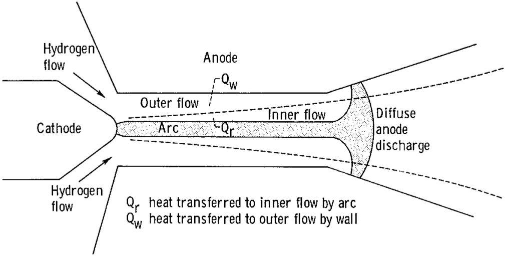


Wallner & Czika Jr, NASA TN D-2868

Hot gases can expand/accelerate and provide thrust

Arcjet Thruster

Heat propellant using an electric arc



Wallner & Czika Jr, NASA TN D-2868

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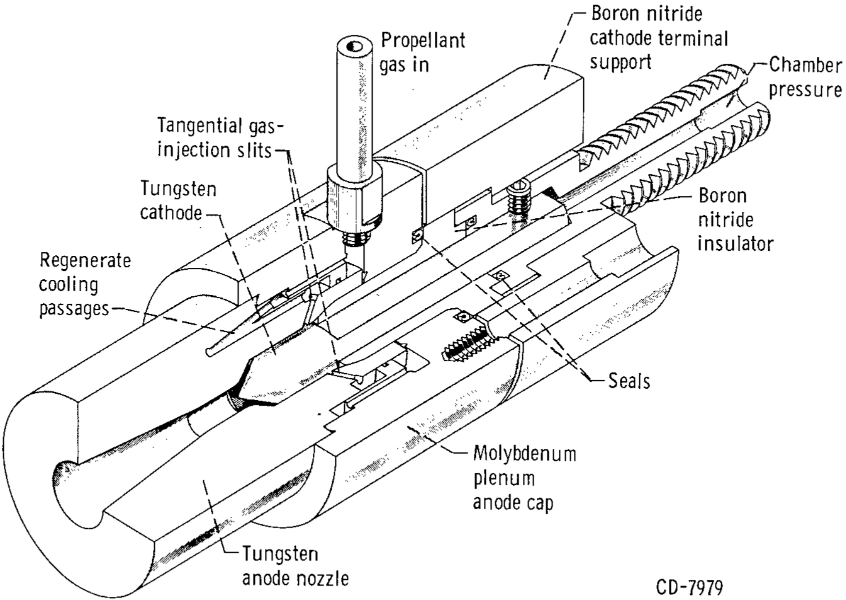

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Arcjet Thruster

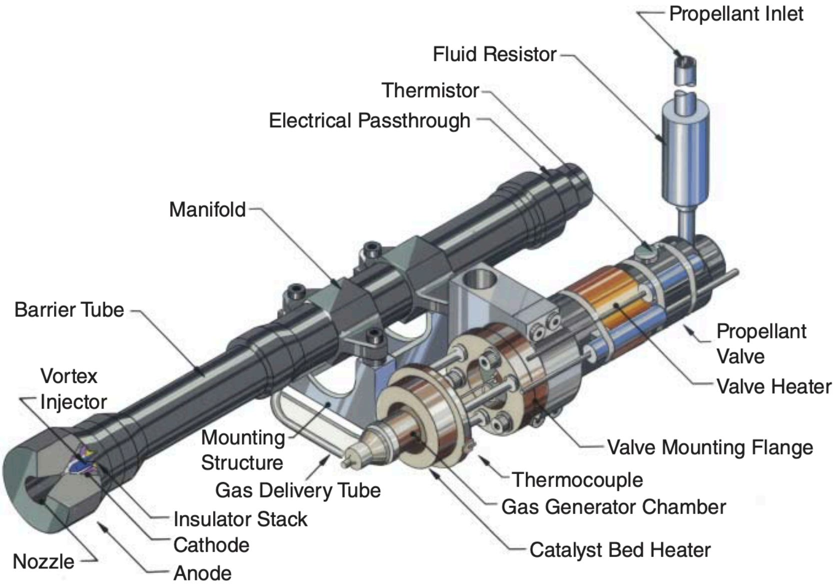


image from Sutton

Electrothermal thrusters

Electric energy is from a source external to propellants

Electric power storage system adds to propulsion unit weight
mass flowrate is limited by electric power storage capability

Propellant	Power (kW)	Thrust (mN)	I_{sp} (s)
Hydrogen	0.37-200	22-7000	800-2000
Ammonia	0.24-26	35-2000	350-800
Hydrazine	0.25-2	30-222	450-615

Electrode erosion is a constraint

Appropriate for Maneuver/Orbit corrections, NOT launch from ground

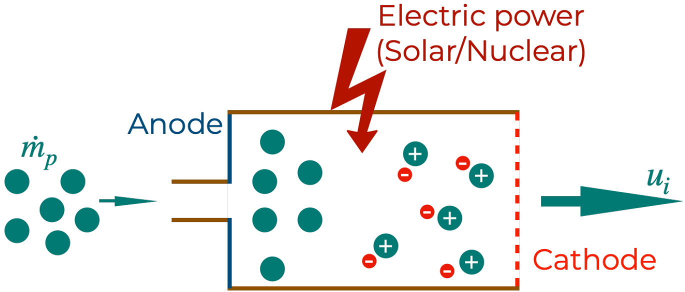
Beyond Electrothermal thrusters

One can achieve even higher I_{sp} even more heat by ionizing the propellant

Apply electric field to accelerate ions $\rightarrow$ Electrostatic Thrusters

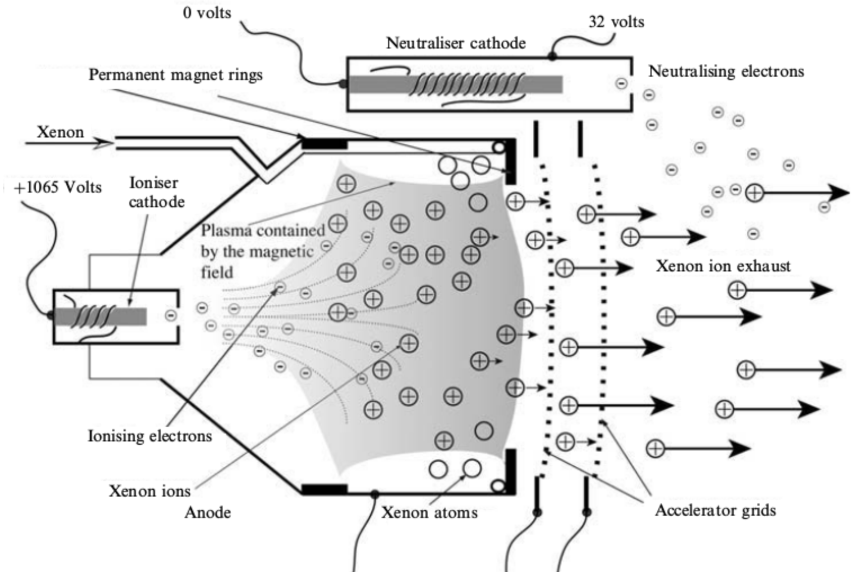
Electrostatic thruster Concept

Ionize, then accelerate Ions



Xenon is used due to its low ionization energy

Gridded Ion thrusters

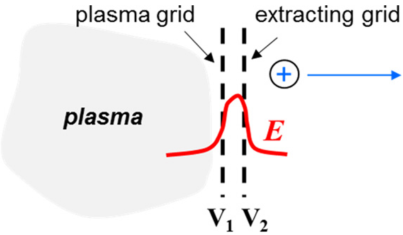


from Sutton

Gridded Ion thrusters

Acceleration between the grid electrodes

$$u_e \sim \sqrt{\frac{2V_{grid}}{\mathcal{M}_i}} \sim \sqrt{\frac{2\left(V_1 - V_2\right)}{\mathcal{M}_i}}$$



Gridded ion source

How much voltage can we sustain?

image from Boeuf, J. App. Physics 121, 011101 (2017)

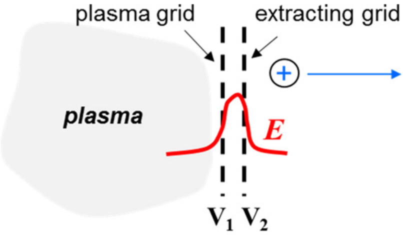
Gridded Ion thrusters

For a grid-spacing of d, with voltage difference of V,

$$I_b = \frac{4\varepsilon_0}{9} A_c \sqrt{\frac{2q}{\mathcal{M}_w}} \frac{V^{1.5}}{d^2}$$

Thrust is

$$\mathcal{T} = \sqrt{\frac{2\mathcal{M}_w}{q}}\, I_b \sqrt{V} = \frac{8\varepsilon_0}{9} A_c \frac{V^2}{d^2}$$



Gridded ion source

$$\mathcal{T} \sim 0.1 - 1.0\ N,\ I_{sp} \sim 2,000 - 10,000\ s$$

image from Boeuf, J. App. Physics 121, 011101 (2017)

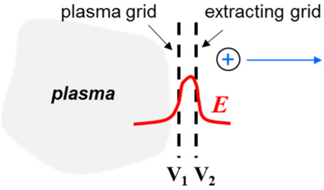
Gridded Ion Thrusters - Constraints

Erosion of the grids

Space Charge Effects constrain current density

 Need large cross-section area

Low thruster efficiency



Gridded ion source

image from Boeuf, J. App. Physics 121, 011101 (2017)

Avoid grid-facing electrodes

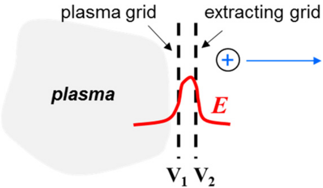
Gridded electrodes constrain electron flow into the chamber

and accelerate the extracted ions outward

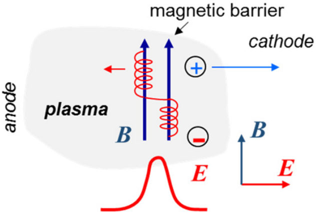
If the idea is the reduction of electron flow inwards

we can achieve this using a magnetic field

Only electrons are 'magnetised'



Gridded ion source



Griddless ion source

image from Boeuf, J. App. Physics 121, 011101 (2017)

Magnetisation of charged particles

For a charged particle in a magnetic field

$$\omega_c = \frac{qB}{m}$$

$$\rho_c = \frac{v_\perp}{\omega_c} \equiv \frac{mv_\perp}{qB}$$

where $v_\perp$ is the particle speed in the plane perpendicular to $\vec{B}$

$$\frac{\rho_{c_i}}{\rho_{c_e}} = \frac{m_i v_{\perp_i}}{m_e v_{\perp_e}}$$

Ions are much heavier than electrons
$m_p \approx 1836 m_e$.

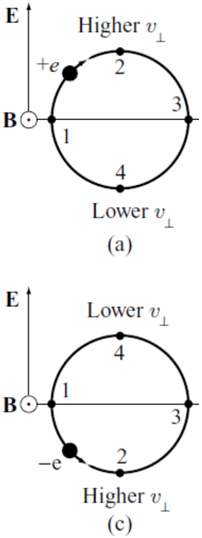


image from Freidberg

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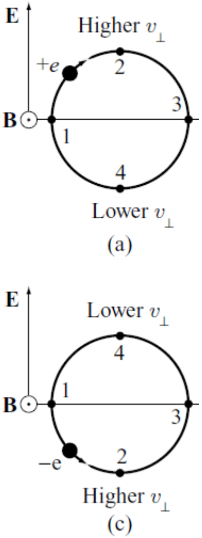


image from Freidberg

To magnetize electrons only

$$\rho_{c_e} \ll L \ll \rho_{c_i}$$

where $\rho_c = qB/m$ is the gyroradius

Particle motion in Electric & Magnetic fields

If an electric field $\vec{E}$ is imposed along with $\vec{B}$

$$m\frac{d}{dt}\vec{v} = q\left(\vec{E} + \vec{v} \times \vec{B}\right)$$

Split the particle velocity:
$\vec{v} = \vec{v}_c + \vec{v}_E$

$$m\frac{d}{dt}\vec{v}_c = q\vec{v}_c \times \vec{B}$$

$$0 = q\left(\vec{E} + \vec{v}_E \times \vec{B}\right)$$

Drift due to electric field is

$$\vec{v}_E = \frac{\vec{E} \times \vec{B}}{B^2}$$

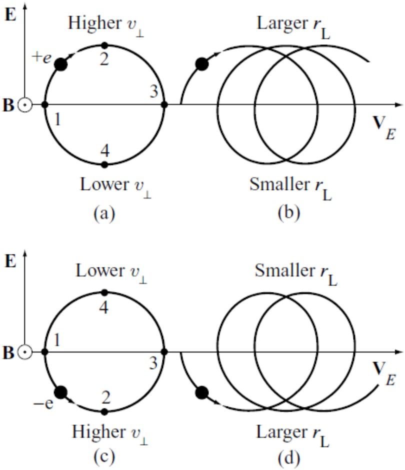


image from Freidberg

Details: SPT100 Hall thruster

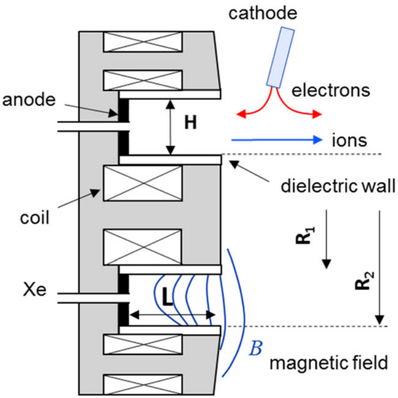


image from Boeuf, J. App. Physics 121, 011101 (2017)

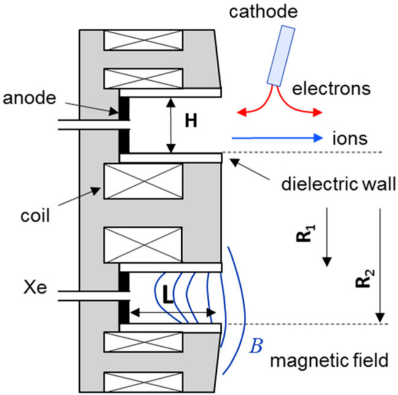
$R_1 = 3.5$ cm, $R_2 = 5.0$ cm
$L = 2.5$ cm, $H = 1.5$ cm

Discharge Current: $I_D = 4.5\ A$
Discharge Voltage: $V_D = 300\ V$

$\underline{m} = 5.3$ mg/s
$\mathcal{T} = 90.2$ mN
$I_{sp} = 1734$ s

Ion Beam Current: $I_b \approx 3.9\ A$

Details: SPT100 Hall thruster



$L = 2.5$ cm, $H = 1.5$ cm

Neutral density:

at anode: $n_a = 2 - 3 \times 10^{19}$ m^{-3}

at exhaust: $n_{ex} \sim 3 \times 10^{17}$ m^{-3}

Electrons, at anode:

$$T \approx 10 \text{ eV}$$

$$\lambda_{en} \approx 30 \text{ cm} \gg L$$

Drifts $\implies$ long trajectories

$\implies$ collisions, needed for ionization

Neutral density is small at the exhaust, further increasing λ_{en}

image from Boeuf, J. App. Physics 121, 011101 (2017)

Details: SPT100 Hall thruster

$$L = 2.5 \text{ cm}, \; H = 1.5 \text{ cm, and } B_{max} = 15 - 20 \text{ mT}$$

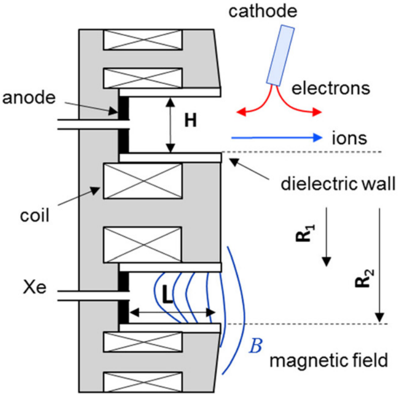


image from Boeuf

image from Boeuf, J. App. Physics 121, 011101 (2017)

Electrons:

$$\omega_{c_e} = \frac{eB}{m_e} \approx 2 - 3 \times 10^9 \text{ rad/s}$$

$$\rho_{c_e} = v_{th_e}/\omega_{c_e} \approx 1 \text{ mm} \ll L$$

Ions:

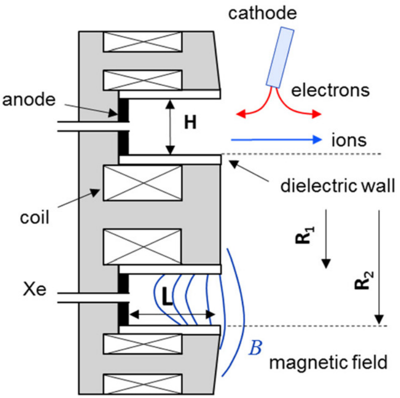
$$\omega_{c_i} = \frac{eB}{m_i} \approx 10^4 \text{ rad/s}$$

$$\rho_{c_i} = v_i/\omega_{c_i} \approx 0.2 - 2 \text{ m} \gg L$$

for ion velocities between

$2 - 20 \; m/s$

Hall Thrusters



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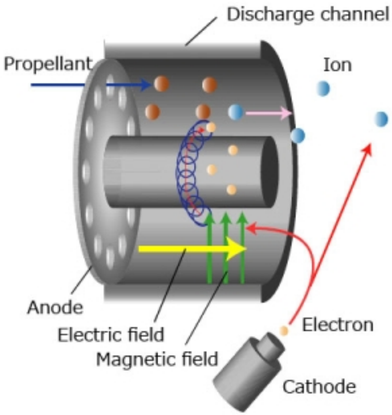
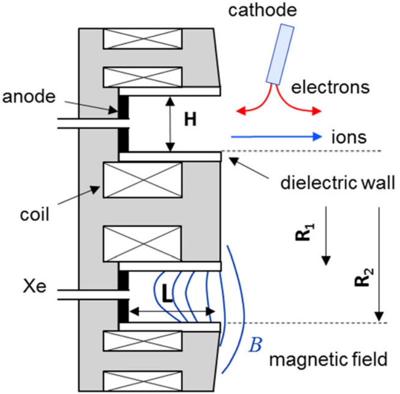


image from Univ. of Tokyo

Electron confinement using Electric & Magnetic fields



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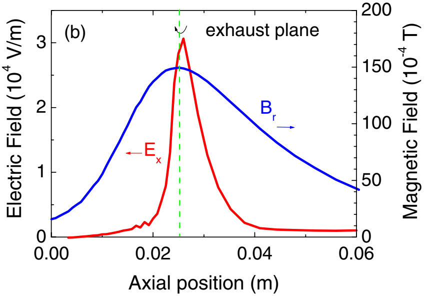
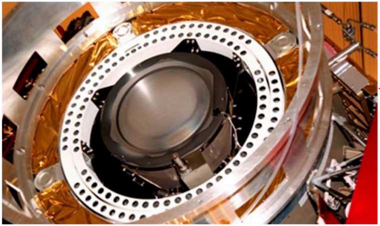
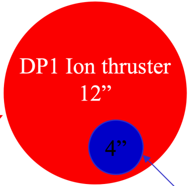
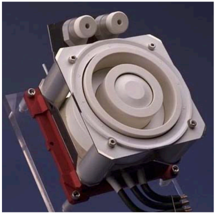


Comparing Gridded Ion and Hall thrusters

Deep Space Mission Ion thruster







SMART -1
Hall thruster:
PPS-1350: 1200 W
10 cm OD, 68 mN

image from Raitses

Comparing Electric Thrusters

Some representative values

	$I_s\ (s)$	Power (W)	Thrust (mN)
Resistojet	300	840	500
Arcjet	865	365	22,500
Ion Thruster	3,100	2,300	92
Hall Thruster	1,600	1,500	90