Electrostatic Propulsion

Ion Engines (Ion Thrusters)

Electrostatic Thrusters

- Thrust provided by “static” electric field in the direction of the acceleration
- Propellant is often an ionized gas
  - so often denoted **ion thruster**
- Typically operate at low pressure (near vacuum)
- Handful of different technologies
  - **gridded ion thruster** or ion engine
    - original development at NASA, 1950’s-60’s
  - Hall effect thruster (HET) or **Hall thruster** or ungridded ion thruster
    - original development in Russia (Stationary Plasma Thruster, SPT), 1950’s-60’s
  - electrospray (or colloidal) thruster
  - ….

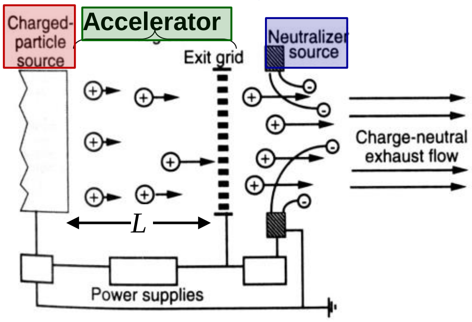
Missions and Lifetime

- **Satellite Station-keeping**
  - GEO communication satellites (including orbit raising as backup to chemical propulsion system)
  - LEO: ESA GOCE
- **Satellite orbit raising** (and station-keeping)
  - Boeing 702HP - XIPS ion engine
  - AEHF GEO comm. satellite, BPT-4000 HET
- **Lunar orbit**
  - ESA SMART-1 (2003) employed Hall thruster (PPS-1350-G)
- **Deep space exploration**
  - Deep Space 1 (1998), Dawn (2007) – asteroid belt protoplanets
  - JAXA Hayabusa (2014) - asteroid rendezvous and return
- **Lifetime**
  - NASA Evolutionary Xenon Thruster (NEXT), 7 kW ion engine, >43,000 hours (5 years) of continuous operation (ground test)

Components

- **Ion sources**
  - usually **electron bombardment** plasma
  - **RF discharge**
  - **ion contact**: liquid metal (e.g., Cs) flowing through hot porous tungsten
  - **field emission**: charged droplets/ particles
- **Accelerator**
- **Neutralizer**
  - electrons added to make exhaust charge neutral
  - typically thermionic emitters or hollow cathodes

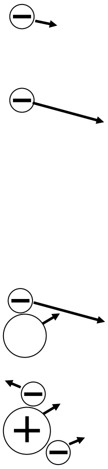
Gridded Ion Engine example



Space Propulsion Analysis and Design, Humble, Henry and Larson, 1995

Ionization by Electron Bombardment

1) produce seed electrons (e^-)
   - typically from thermionic source
2) accelerate e^- to high velocity/energy
   - E field or B field approaches
   - B field gyrate e^-
     - increased energy and frequency of collisions with neutrals
3) electrons collide with neutral gas molecules and ionize them
   - also produces majority of electrons used in ionization



Hollow Cathode Ionization Chamber

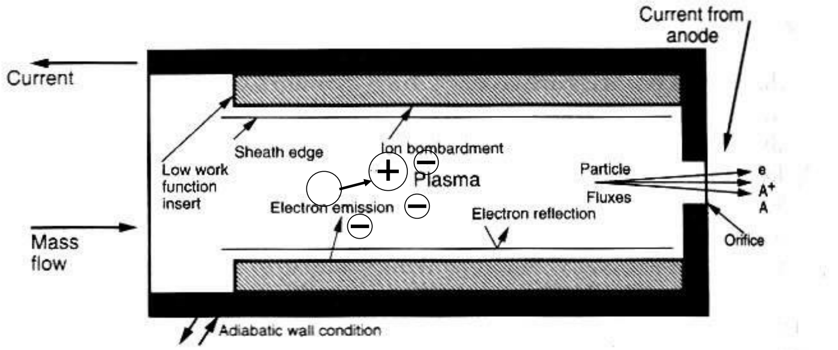


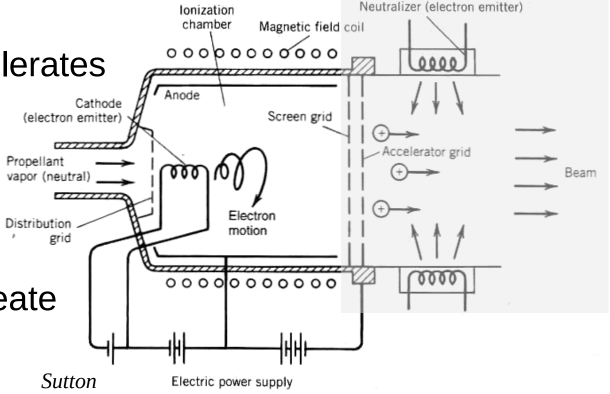
Fig. 9.38. **Schematic of a Hollow Cathode** [Salhi and Turchi, 1993]. Ions from the plasma heat the cathode surface, causing thermionic emission of electrons which ionize the mass flow and the neutral atoms returning from the cathode surface. Electrons, ions, and atoms are extracted through the orifice for use in the discharge chamber.

Space Propulsion Analysis and Design, Humble, Henry and Larson, 1995

Thermionic Emitter/B Field Ion. Chamber

- Electron emission from hot source with low work potential (ϕ_S)
  - filament example shown here
  - B field accelerates e^-
  - high KE e^- ionize neutral propellant flow and create more e^-

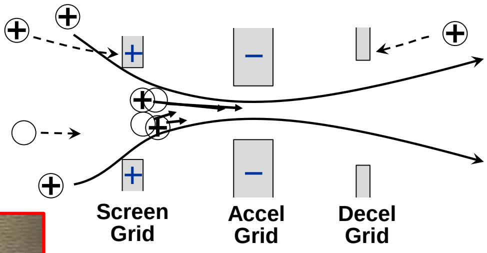
$$J = \frac{4\pi q_e m_e k^2}{h^3} T^2 e^{-q_e \phi_s / kT}$$



Sutton

Accelerator: Gridded Ion Thruster

- Acceleration E field provided by electrodes
  - propellant passes through many small cells
- Grid of multiple electrodes (forms ion optics)
  - 2-3 grids typical

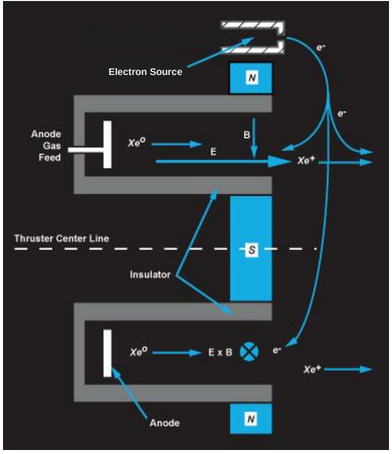


- screen and decel grids help prevent high energy ions from impacting accel grid (sputtering)
- decel grid reduces sputtering from backflow of charge-exchange ions

Hall (Effect) Thruster

- Uses applied magnetic (B) field (external magnets) to create ionization and acceleration in same chamber
- Typically axisymmetric geometry
  - apply radial B field
- E field created between internal anode and external cathode
  - but strongly influenced by plasma at open end

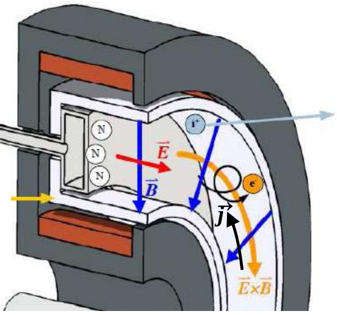
Azimuthal example



after *Space Travel Aided by Plasma Thrusters: Past, Present and Future* , DeFusco, Craddock, Faler, DSIAC Journal, 2017

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 radius of gyration, so less deflection by **B**
    - pick weak enough **B**
- **Acceleration**: two interpretations
  - electrons largely trapped by **B,** so negative plasma potential near exit accelerates ions
  - Hall effect from electron current, induced $\boldsymbol{E} \propto \boldsymbol{j} \times \boldsymbol{B}$



C. Mullins, *Non-invasive Hall Current Distribution Measurement System for Hall Effect Thrusters* (2015)

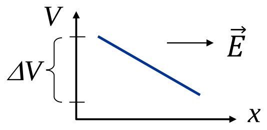
Electrostatic Propulsion

Ion Thruster Analysis

Electrostatics – Recall Definitions

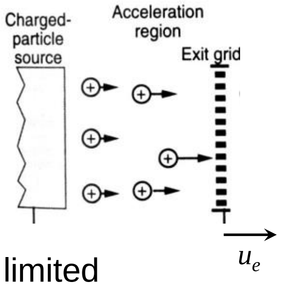
- V – potential or voltage (sometimes ϕ) ($Volts$)
- E – electric field (V/m, N/C)
- q – charge (C) ($q_{e^-}=1.602\times10^{-19}\ C$)
- Force, $\vec{F} = \vec{E}q$
- Potential Energy $\int F dx = \int qE dx = q\Delta V$
- J – current (A, C/s)
- j – charge current density (A/m^2, C/sm^2)
- n_q – number density charged part. ($1/m^3$)
- u – velocity of charged particles (m/s)

$$\vec{E} = -\nabla V \left(= -\frac{dV}{dx} \right)$$



$$j = n_q q u$$

Electrostatic Thruster Performance - u_e



- Specific impulse $I_{sp} = \dfrac{u_e}{g_o}$
- Find exhaust velocity from energy balance ***per particle*** $\frac{1}{2}mu^2 = q\Delta V$
- So maximum (ideal) specific impulse limited by voltage difference across accelerator

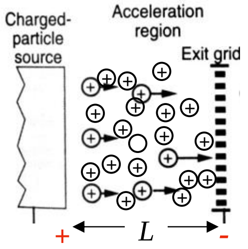
$$u_e = \sqrt{2\frac{q}{m}\left(V_{exit} - V_{inlet}\right)}$$

$$1AMU = 1.6605\times10^{-27}\,kg$$

$$= 13{,}890\sqrt{\frac{\Delta V_{accel}(\text{volts})}{MW}}\;\frac{m}{s}$$

for singly ionized
q=1.6022×10^{-19} C

Gridded Ion Thruster Performance - τ



accelerator electrode spacing

- Thrust $\tau = \dot{m}u_e$
- Mass flow rate related to current
  $j = nqu_e \quad n = \rho/m \quad \Rightarrow \dot{m}/A = j\dfrac{m}{q}$
- Maximum thrust limited by achievable current density
- For gridded ion engine, ion current limited by space-charge
  - field from dense ions creates "shield" from applied E field

Child-Langmuir Law $j_{\max} = \dfrac{4\varepsilon_o}{9}\sqrt{\dfrac{2q}{m}}\dfrac{\Delta V_{accel}^{3/2}}{L^2}$

permittivity of free space $\varepsilon_o = 8.854\times10^{-12}\,\dfrac{Farad}{meter}$

for singly ionized

$$j_{\max} = 5.467\times10^{-8}\,\frac{\Delta V_{accel}^{3/2}(\text{volts})}{\sqrt{MW}\,L^2(\text{m})}\;\frac{Amps}{m^2}$$

Gridded Ion Thruster Performance - τ

$$\tau = \dot{m} u_e = jA(m/q)u_e$$

A=cross-sectional flow area

- Maximum thrust

$$\tau_{\max} = j_{\max} A \frac{m}{q} u_e = \frac{4\varepsilon_o}{9}\sqrt{\frac{2q}{m}}\frac{\Delta V^{3/2}}{L^2} A \frac{m}{q}\sqrt{\frac{2q}{m}\Delta V}$$

$$\tau_{\max} = (8\varepsilon_o/9)A\Delta V^2/L^2$$

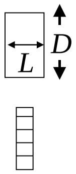
$\neq$ **f(q/m)**

for circular cross-section of diameter, D

$$\tau_{\max} = (2\pi/9)\varepsilon_o (D/L)^2 \Delta V^2$$

$$= 6.18\times10^{-12}(D/L)^2 \Delta V^2 \text{ in } Newtons$$

- High τ requires high ΔV and aspect ratio
  - space charge$\Rightarrow$$(D/L)_{\max}$~1
  - use many small ion beams to get more thrust



Electrostatic Thruster - Propellant

- Thrust performance

$$\frac{\tau}{A} = j\frac{m}{q}u_e = j\frac{m}{q}I_{sp}g_o$$

- For fixed I_{sp}

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

for gridded ion engine

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

- So choose propellant with high m/q
  - heavy molecules
    - xenon (Xe) good choice (MW=131.3) and noble gas, so easy to store
    - Cs, Hg heavier, but storage issues
  - singly ionized ions preferable
  - also macro particles (colloidal thrusters)

Electrostatic Thruster Power

- **Jet power** $P_j = \frac{1}{2}\dot{m}_b u_e^2 = \frac{1}{2}\tau g_o I_{sp}$ $\qquad \frac{1}{2}u_e^2 = \frac{q}{m}\Delta V_{accel}$

  Ion beam flowrate @ exit

  - at maximum current for gridded ion thruster

$$j_{\max} = \frac{4\varepsilon_o}{9}\sqrt{\frac{2q}{m}}\frac{\Delta V^{3/2}}{L^2}$$

$$P_j = \frac{4}{9\varepsilon_o}A\sqrt{\frac{2q}{m}}\frac{\Delta V_{accel}^{5/2}}{L^2} \qquad \dot{m}_{b,\max} = A\frac{4\varepsilon_o}{9}\sqrt{\frac{2m}{q}}\frac{\Delta V_{accel}^{3/2}}{L^2}$$

- **Accelerator electrical power**

$$P_{elec} = J\Delta V_{accel} = jA\Delta V_{accel}$$

ideally

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

- **Power supplied to thruster** (not just accel.)

$$P_{th} = P_j / \eta_{th}$$

η_{th} = thruster efficiency

not thermodynamically limited

Electrostatic Thruster Power - Losses

- **Ionization** losses
  - energy used to create ions (e.g., $Xe \rightarrow Xe^+$)
  - minimum loss given by ionization potential (ε_I) for atom (typically 4-20 eV, electron volts) times current

$$P_{ion\ loss} = \varepsilon_{ion} J = \varepsilon_{ion}\frac{\dot{m}}{m}q$$

- **Thrust correction**
  - beam divergence, multiple ionization, sputtering (ion impacts on grid)

$$\gamma = \frac{\tau}{\tau_{ideal}}$$

- **Propellant utilization efficiency** $\quad \eta_u = \dot{m}_b / \dot{m}$
- **Neutralization losses**
  - energy to create e^-

$$P_{neut} = J\Delta V_{neut}$$

Nonideal Performance and Typical Values

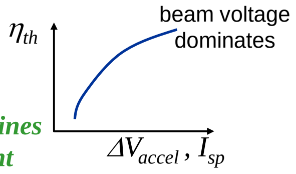
- Nonideal performance equations

$$I_{sp}=\gamma\eta_u I_{sp,ideal} \qquad \tau=\dot{m}_b u_e=\eta_u\dot{m}\gamma I_{sp,ideal}\,g_o$$

$$P_{th}=J\Delta V_{th}=J\left(\Delta V_{ion}+\Delta V_{accel}+\Delta V_{neut}\right)$$

$$\eta_{th}=\frac{P_j}{P_{th}}=\frac{\dot{m}_b u_e^2/2}{J\Delta V_{th}}=\frac{\dot{m}_b\left(\frac{q}{m}\Delta V_{accel}\gamma^2\right)}{\left(\dot{m}\frac{q}{m}\right)\Delta V_{th}}=\frac{\eta_u\gamma^2}{1+\frac{\Delta V_{ion}+\Delta V_{neut}}{\Delta V_{accel}}}$$

- Typical values
  - ε_{ion} ε_I up to 100-300 eV/ion
  - γ 0.8-0.95
  - η_u 0.8-0.95
  - ΔV_{neut} 10-20Vs



low Isp ion engines are inefficient

Example: Electron Bomb., Xe$^+$ Gridded Thruster

- Operating conditions
  - ΔV_{accel}=700 V, L=2.5 mm, 2200 holes (grids) each with D=2.0 mm
  - MW(Xe)=131.3, ε_I(Xe)=12.08 eV
- Determine
  - τ,
  - u_e, Isp
  - $\dot{m}_{prop}$
  - power required including only minimum needed for ionization and neutralization (10 V)

Solution

- $$\tau_{\max} = 6.18\times10^{-12}(D/L)^2\Delta V^2$$
  $$= 6.18\times10^{-12}(2/2.5)^2 700^2 = 1.94\times10^{-6}\,N/grid$$
- $$\tau_{\max,total} = 2200 grids\left(1.94\times10^{-6}\,N/grid\right) = 4.3mN$$
- $$u_e = 13{,}890\sqrt{\Delta V/MW}\ m/s = 13{,}890\sqrt{700/131.3}\,m/s$$
  $$u_e = 32{,}070\,m/s \Rightarrow I_{sp} = 3270\,s$$

ion mass

$$m = 1.66\times10^{-27}\,MW\ \ kg$$
$$= 2.18\times10^{-25}\,kg$$

assume η_u=1

- $$\dot{m} = \dot{m}_b = \tau/u_e = 1.34\times10^{-4}\ g/s$$
- $$P = P_{jet} + P_{ion} + P_{neut} = \dot{m}u_e^2/2 + (\varepsilon_I + \Delta V_{neut})q\,\dot{m}/m$$
  $$= 68.9W + 2.17W$$

$$q = 1.602\times10^{-19}C$$

for singly ionized molec.

$$P = 71.1W$$

maximum η_{th}**=68.9/71.1**
= 96.9%

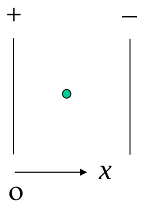
for ΔV_{ion}**=200eV,** η_{th} **= 77%**

Additional Slides

Child-Langmuir Law Derivation

- Poisson's Eqn. $\nabla^2 V = \frac{-\rho_q}{\varepsilon_o} = \frac{-n_i q_i}{\varepsilon_o}$
  - 1-d $\frac{d^2V}{dx^2} = \frac{-n_i q_i}{\varepsilon_o} = \frac{-j}{u\varepsilon_o}$

$$= \frac{-j}{\varepsilon_o}\sqrt{\frac{m}{2q}\frac{1}{V_o - V(x)}}$$



$$\frac{d}{dx}\left[\frac{1}{2}\left(\frac{dV}{dx}\right)^2\right] = \frac{dV}{dx}\left(\frac{d^2V}{dx^2}\right) = \frac{dV}{dx}\left[\frac{-j}{\varepsilon_o}\left(\frac{m}{2q}\right)^{1/2}(V_o - V)^{-1/2}\right]$$

$$\frac{d}{dx}\left[\frac{1}{2}\left(\frac{dV}{dx}\right)^2\right] = \frac{2j}{\varepsilon_o}\left(\frac{m}{2q}\right)\frac{d}{dx}(V_o - V)^{1/2}$$

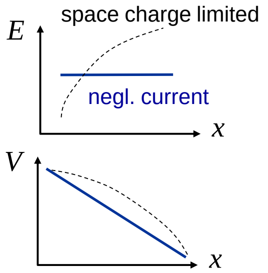
Integrate

$$\left(\frac{dV}{dx}\right)^2 - \underset{E_o^2}{\cancel{\left(\frac{dV}{dx}\right)_o^2}} = \frac{4j}{\varepsilon_o}\sqrt{\frac{m}{2q}(V_o - V)}$$

Assume
$E(0)=E_o=0$

Child-Langmuir Law Derivation

$$\frac{dV}{dx} = 2\left(\frac{j}{\varepsilon_o}\right)^{1/2}\left[\frac{m}{2q}(V_o - V)\right]^{1/4}$$



SOV and Integrate

$$\underbrace{\int_{V_o}^{V}(V_o - V)^{-1/4}dV'}_{\frac{4}{3}(V_o - V')^{3/4}} = 2\left(\frac{j}{\varepsilon_o}\right)^{1/2}\left(\frac{m}{2q}\right)^{1/4}x$$

Voltage reduced over applied voltage due to space charge

$$V = V_o - \left[\frac{3}{2}\left(\frac{j}{\varepsilon_o}\right)^{1/2}\left(\frac{m}{2q}\right)^{1/4}x\right]^{4/3}$$

$$j_{\max} = \frac{4\varepsilon_o}{9}\sqrt{\frac{2q}{m}}\frac{(\Delta V)^{3/2}}{(\Delta x)^2}$$

Maximum current density possible