

Operating Principles of Hall Effect Thrusters

Your Name

Electric Propulsion Overview

December 1, 2025

What is a Hall Effect Thruster?

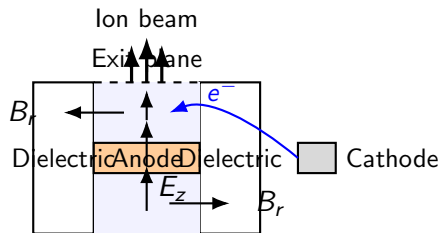
- A Hall Effect Thruster (HET) accelerates ions electrostatically using a crossed electric and magnetic field geometry.
- Key feature: **electrons are magnetized, ions are not.**
- Electrons undergo an azimuthal $\mathbf{E} \times \mathbf{B}$ Hall drift.
- Unmagnetized ions are accelerated axially by the electric field and exit at $\sim 10\text{--}20$ km/s.
- Quasi-neutral plasma throughout; no grids.

Hall Thruster Geometry (Annular Channel)

- Ceramic discharge channel with:
 - Radial magnetic field B_r
 - Axial electric field E_z
 - Neutral gas injection near anode
 - Cathode external to the channel
- Crossed-field configuration traps electrons, enabling efficient ionization and acceleration.

(See next slide for TikZ schematic.)

TikZ Schematic: Hall Thruster Cross-Section



Electron and Ion Magnetization

Electrons: strongly magnetized

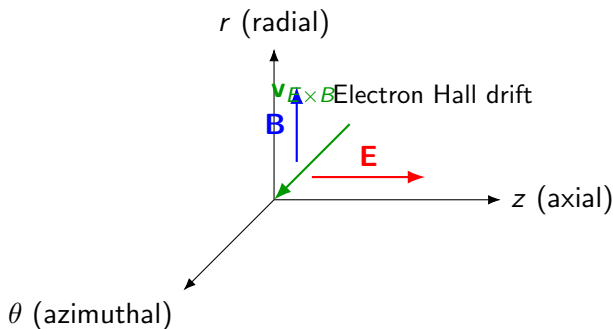
$$r_{L,e} = \frac{m_e v_{\perp}}{eB} \ll \text{channel size}$$

Ions: effectively unmagnetized

$$r_{L,i} = \frac{m_i v_{\perp}}{eB} \gg \text{channel size}$$

- Electrons are confined laterally by B_r , limiting axial motion.
- Ions move freely along the electric field.
- Magnetized electrons \rightarrow high ionization efficiency.

$\mathbf{E} \times \mathbf{B}$ Hall Drift (TikZ View)



- Crossed fields:

$$\mathbf{v}_{\mathbf{E} \times \mathbf{B}} = \frac{\mathbf{E} \times \mathbf{B}}{B^2}$$

- For HET:

$$\mathbf{E} = E_z \hat{z}, \quad \mathbf{B} = B_r \hat{r}$$

$$\Rightarrow \mathbf{v}_\theta = \frac{E_z}{B_r} \hat{\theta}$$

- Electrons experience crossed electric and magnetic fields:

$$\mathbf{v}_{E \times B} = \frac{\mathbf{E} \times \mathbf{B}}{B^2}$$

- For HET geometry:

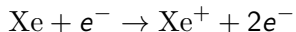
$$\mathbf{E} = E_z \hat{z}, \quad \mathbf{B} = B_r \hat{r}$$

$$\Rightarrow \quad \mathbf{v}_\theta = \frac{E_z}{B_r} \hat{\theta}$$

- This azimuthal electron drift current is the **Hall current**.
- Drift enhances electron residence time, boosting ionization.

Ionization and Acceleration

- Neutral xenon injected at the anode.
- Magnetized electrons drift azimuthally, colliding with neutrals:



- Ionization zone forms near the channel exit.
- Ions accelerate axially:

$$F = qE_z, \quad v_i = \sqrt{\frac{2qV_b}{m_i}}$$

- Typical ion energies: 200–300 eV.




Quasi-Neutral Plasma Acceleration

- Unlike gridded ion engines (GITs), HETs maintain **quasi-neutral plasma** throughout the acceleration region.
- No space-charge-limited extraction: electron confinement by B_r limits axial mobility.
- Very high ion current densities are achievable (\sim tens of mA/cm²).
- The thruster and cathode together produce a **neutralized ion beam**.

Cathode Functions

- Located outside the channel.
- Provides electrons for:
 - Beam neutralization
 - Sustaining the discharge current
 - Replacing electrons lost to the anode
- Cathode coupling is essential for efficiency and stability.

Hall Thrusters vs. Gridded Ion Thrusters (GIT)

| | Hall Effect Thruster | Gridded Ion Thruster |
|-------------------|---|--|
| Ion acceleration | Electrostatic, in quasi-neutral plasma; E_z in channel | Electrostatic, through grid apertures; strong sheath and space-charge region |
| Ion optics | No grids; plasma expansion at exit | Multi-grid optics (screen, accel, often decel); tightly controlled beam |
| Electron dynamics | Strongly magnetized; $\mathbf{E} \times \mathbf{B}$ Hall drift | Not strongly magnetized (typically); electrons confined by grids |
| Limiting physics | Cross-field electron transport | Child–Langmuir space-charge limit in grid gaps |
| Thrust-to-power | $\sim 60\text{--}70$ mN/kW | Typically lower, $\sim 30\text{--}50$ mN/kW |
| Efficiency | $\sim 50\text{--}65\%$ | $\sim 60\text{--}70\%$ (varies with design) |
| Lifetime limiters | Channel wall erosion,  | Grid  erosion  |

Advantages of Hall Thrusters

- High thrust-to-power ratio (60–70 mN/kW).
- Efficient: 50–65%.
- Long lifetime with magnetic shielding designs.
- Simple, robust design: no grids, tolerant to contamination.
- Widely used for Earth-orbit raising, station-keeping, and deep-space missions.

Summary of HET Operation

- Crossed E_z and B_r fields trap electrons and cause a strong $\mathbf{E} \times \mathbf{B}$ Hall drift.
- Trapped electrons enhance ionization efficiency near the channel exit.
- Ions, unmagnetized, are accelerated by the axial electric field.
- A cathode provides electrons to neutralize the ion beam.
- Result: efficient, stable, quasi-neutral plasma acceleration.