INTRODUCTION TO SPACE PLASMA PROPULSION

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Electric propulsion (EP) devices utilize a constantly renewable on-orbit resource (electric power from solar arrays or a nuclear source) to minimize the consumption of non-renewable on-board propellant. The EP techniques group broadly into three categories: electrothermal propulsion, wherein the propellant is electrically heated, then expanded thermodynamically through a nozzle; electrostatic propulsion, wherein ionized propellant particles are accelerated through an electric field; and electromagnetic propulsion, wherein current driven through a propellant plasma interacts with an internal or external magnetic field to provide thrust. Such systems can produce a range of exhaust velocities and payload mass fractions an order of magnitude higher than that of the most advanced chemical rockets, which can thereby enable or substantially enhance many attractive space missions. The attainable thrust densities (thrust per unit exhaust area) of these systems are much lower, however, which predicates longer flight times. This talk will focus mainly on the electrostatic and electromagnetic propulsion techniques, also called plasma propulsion, due to the nature of the propellant. Principles of operation, key issues, and commonly used diagnostics are discussed in detail for such complex devices as magnetoplasma dynamic thruster (MPDT), pulsed plasma thruster (PPT), ion thruster (IT), Hall thruster (HT), cylindrical Hall thruster (CHT), VASIMR, and others. Key physical questions specific to Hall thrusters are also elucidated.
Outline

- Basic Concepts and Equations of Propulsion
- Types of Plasma Propulsion
- Electrothermal propulsion
- Electrostatic Propulsion: Ion Thrusters
- Electromagnetic Propulsion: MPD, PPT, TAL, VASIMR, HT, CHT
- Hall Thruster Diagnostics: plume divergence, electron temperature, etc
- Anode Sheath in Hall Thrusters
Rocket Equation

Time = t

\[ \begin{align*}
M(t) & \rightarrow V(t) \\
V(t) & \rightarrow V_{\text{jet}} - V
\end{align*} \]

Time = t + \Delta t

\[ \begin{align*}
M - \Delta m & \rightarrow V + \Delta V
\end{align*} \]

Momentum Conservation: \( P(t) = \text{Const} \)

\[ P_x(t) = M V \]

\[ P_x(t + \Delta t) = (M - \Delta m) (V + \Delta V) - \Delta m (V_{\text{jet}} - V) = M V + M \Delta V - \Delta m V_{\text{jet}} \]

\[ \Delta m = \mu \Delta t \]

\[ M \frac{dV}{dt} = \mu V_{\text{jet}} \quad \text{– Rocket (Mescherskii’s) Equation} \]

\[ V(t) = V_{\text{jet}} \ln \left[ \frac{M_0}{M(t)} \right] \quad \text{– Tsiolkovskii’s Formula} \]
Electric Propulsion = Large Exhaust Velocity

\[ V_{\text{jet (plasma)}} \sim 10 - 100 \text{ km/s} \gg V_{\text{jet (chemical)}} \sim 3 \text{ km/s} \]

Interplanetary Missions:

\[ M_{\text{fuel}} \approx \sqrt{2 M_{\text{sat}} \eta P S / V_{\text{jet}}^3} \]

\[ t_{\text{flight}} \approx \sqrt{2 V_{\text{jet}} M_{\text{sat}} S / \eta P} \]

Higher \( V_{\text{jet}} \rightarrow \) LESS FUEL (but longer time)
Limit on Exhaust Velocity

On-Orbit Station Keeping

mN-level plasma thrusters are perfect for orbit correction tasks (precise, short-duration kicks)

\[ \Delta V = T \frac{\Delta t}{M_{sat}} \]

\[ T = 2\eta \frac{P}{V_{jet}} \]

Limit on \( V_{jet} \) is set by mission time requirements
Types of Electric Propulsion

1. **Electrothermal propulsion**, wherein the propellant is heated by some electrical process, then expanded through a suitable nozzle
   - a. Resistojets
   - b. Arcjets
   - c. *Inductively and radiatively heated devices*

2. **Electrostatic propulsion**, wherein the propellant is accelerated by direct application of electrostatic forces to ionized particles
   - a. *Ion Thrusters (IT)*
   - b. *Field Emission Electric Propulsion (FEEP)*
   - c. *Colloidal Thrusters*

3. **Electromagnetic propulsion**, wherein the propellant is accelerated under the combined action of electric and magnetic fields
   - a. *MagnetoPlasmaDynamic (MPD) Thrusters*
   - b. *Hall Thrusters (HT)*
   - c. *Pulsed Plasma Thrusters (PPT)*
   - d. *Inductive Thrusters*
Electric Propulsion in US and USSR

- Ernst Stuhlinger’s book “Ion Propulsion for Space Flight”
- Hall thrusters have been used on Soviet and Russian spacecraft since the mid-1970s
- Resistojets became common options for station keeping and attitude control
- Electrothermal arcjets were adopted for NSSK of many communication satellites in GEO
- 1st use of ion thrusters for NSSK
- DEEP SPACE 1

- 1960
- 1970
- 1980
- 1990
- 1994
- 1998

- < 10
- > 10
- 10s
- > 100
Heat is transferred to propellant (hydrazine) from some solid surface, such as chamber wall or heater coil

Power level: 750 Watts
Thrust level: 300 mN
Exhaust velocity: 3.5 km/s
Efficiency: 80 %
**Electrothermal Arcjet**

*Propellant (hydrazine) is heated by an electric arc driven through it*

- Cathode (emitter)
- Tangential gas flow
- Anode (nozzle)

- Power level: 1.5 kW
- Thrust level: 200 mN
- Exhaust velocity: 5 – 6 km/s
- Efficiency: 40 %
Glossary of Plasma Propulsion

THRUST

\[ T[mN] = V_i \cdot \langle \cos \Theta \rangle \cdot I_i \cdot \frac{M_i}{e} = \mu \eta_{\text{ioniz}} V_{\text{jet}} \]

SPECIFIC IMPULSE

\[ I_{sp}[s] = \frac{V_{\text{jet}}}{g} \]

IONIZATION EFFICIENCY

\[ \eta_i = \frac{I_i}{I_m} \]

ENERGY EFFICIENCY

\[ \eta_W = \frac{1/2 \cdot M_iV_i^2 \cdot I_i \cdot < \cos^2 \Theta >}{P_{\text{in}}} \]

THRUST EFFICIENCY

\[ \eta = \eta_i \cdot \eta_W \cdot \eta_c \approx \frac{1}{2} \cdot \frac{T^2}{m \cdot P_{\text{in}}} \]

PLUME DIVERGENCE

\[ \langle \cos^n \Theta \rangle \overset{\text{def}}{=} \frac{2\pi(\text{outwards})}{2\pi(\text{outwards})} \int d\Omega(\Theta, \varphi) \cdot j_i(\Theta, \varphi) \cdot \cos^n \Theta \]
Ion Thrusters (Xe, Ar, Kr)

In the US, ion engines were developed at NASA’s Lewis Research Center in the late 50-s under the guidance of Dr. Harold Kaufman. Flight experiments started from 1965.

$\text{I}_{sp} = 1500 - 4000 \text{ s} \quad \text{Diam} = 2.5 - 150 \text{ cm} \quad P = 50 \text{ W} - 200 \text{ kW}$

Deep Space-1 Ion Engine Images

launched from Cape Canaveral on October 24, 1998.
Electrostatic Acceleration of Ions by Applied DC Voltage

Child-Langmuir law limits maximum ion current density that can be extracted from ionization stage (ion source)

\[ j = \frac{4\varepsilon_0}{9} \left( \frac{2q}{M} \right)^{1/2} \frac{V^{3/2}}{d^2} \]

Maximum thrust density does not depend on the mass flow rate

\[ T \frac{mV_{jet}}{A} = \frac{jM_{ion}V_{jet}}{q} = \frac{8\varepsilon_0}{9} \left( \frac{V}{d} \right)^2 \]
Key Issue of Ion Thrusters

**Accelerator grid**

- **Upstream side**
  - Normal
  - Damaged

- **Downstream side**
  - Normal
  - Damaged

**Screen grid**

- **Downstream side**
  - Normal
  - Damaged

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Soulas, G. C., “Improving the Total Impulse Capability of the NSTAR Ion Thruster with Thick-Accelerator Grid Ion Optics,” IEPC-01-081

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Grid erosion due to ion bombardment limits thruster lifetime
Ion Thruster Diagnostics (Non-Intrusive)

**Laser-Induced Fluorescence** — for measurements of ion velocity and energy

**Laser Interferometry** — for measurements of electron, ion, and neutral densities

**Spectrographic analysis** of quartz crystal microbalances and fused silica samples placed in the plume — for determining the content and origin of the non-propellant flux coming out (erosion assessment)
Double and single Langmuir probes were employed at **PDEPL (Michigan)** to measure 2-D electron temperature and density profiles inside the IT, which can give an insight to the issue of Discharge Cathode Assembly (DCA) erosion – another lifetime limiting process in IT.
E&M Propulsion: MPD Thrusters

$lsp = 1500 - 8000 \text{ sec}$

Efficiency $> 40\%$

Power: 200 kW – 1 MW

Thrust Density: $10^5 \text{ N/m}^2$

Princeton 100 kW-class Lithium Lorentz-Force Accelerator (MPD-T)
Simple Thrust Formula for MPD Thrusters

\[ T = \frac{\mu_0}{4\pi} I_{\text{tot}}^2 \left( \ln \frac{r_c}{r_a} + A \right) \]

\( A \leq 1 \) – geometrical factor

1. \( dF_z = -j_r(z,r) B_\theta(z,r) \, dV \)

2. \( B_\theta(z,r) \approx \frac{\mu_0 I(z)}{2\pi r} \)

3. \( \frac{dI}{dz} = j_c 2\pi r_c \)

4. \( j_r(z,r) \approx \frac{j_c(z) r_c}{r} \)

5. \( T = \int_0^L dz \int_{r_c}^{r_a} 2\pi r \, dr \left( j_r \, B_\theta \right) = \frac{\mu_0}{2\pi} \int_0^L dz \frac{dI}{dz} \int_{r_c}^{r_a} \frac{dr}{r} = \frac{\mu_0}{4\pi} I_{\text{tot}}^2 \ln \frac{r_c}{r_a} \)
In **Ablative Pulsed Plasma Thruster (APPT)**, the surface of a Teflon® block is successively eroded by intermittent arc pulses driven across its exposed face, and the ablated material is accelerated by a combination of thermal expansion and self-field electromagnetic forces.
1. Neutral gas (hydrogen) is injected into the **forward cell**, where it is ionized.
2. The resulting plasma is then heated in the **central cell**, to the desired temperature and density, by use of radio-frequency excitation and ion cyclotron resonance.
3. Once heated, the plasma is magnetically and gas-dynamically exhausted by the **aft cell** (asymmetric magnetic mirror = magnetic nozzle) to provide modulated thrust.
Hall Thrusters

Power = 0.2 – 3 kW
Voltage = 0.1 – 1 kV
Current = 2 – 5 A
\( \mu (Xe) = 2 – 5 \text{ mg/s} \)

\( V_{jet} = 15 – 25 \text{ km/s} \)
Thrust = 40 – 80 mN
Efficiency ~ 50%
Hall Thruster is an ExB Discharge Device

\[ r_{Li} \gg L_{channel} \gg r_{Le} \]
Hall Thruster Experiment at PPPL

- 2 kW Hall Thruster
- Planar Probe for Plume Measurements
- Two-Plate Energy Analyzer
- Probe Apparatus for Near-Anode Measurements
- Fast-Reciprocating Probe Apparatus
Hall Thrusters Diagnostics (LIF and HF)

Laser-Induced Fluorescence apparatus was developed and used at Stanford Hall Thruster Facility (Plasma Dynamic Laboratory) for neutral velocity measurements in the near plume to gain a better understanding of the charge exchange process in Hall Thrusters.

High-Frequency (HF) probe diagnostics were developed and employed at HTX (PPPL) to characterize 1 – 100 MHz plasma density oscillations through measuring ion saturation current near the thruster exit.
PPPL 9 cm-Diameter Cylindrical Hall Thruster

Power range: 200 – 1000 W
Discharge voltage: 200 – 300 V
Xenon mass flow rate: 1 – 3 mg/s
Thrust: 13 – 40 mN
Efficiency: 30 – 45 %
Channel OD = 9 cm
Cylindrical Hall Thruster has larger volume to surface ratio than conventional thrusters

- Electron drift is azimuthal $\Rightarrow$ closed drift
- Ion axial acceleration $\sim I_e \theta \times B_r$
- In a short annular part the density of neutrals is higher $\Rightarrow$ better for ionization
- Length of the annular region $\sim \lambda_{ion}$
- Compared to a conventional (annular) Hall thruster, the CHT has lower surface-to-volume ratio $\Rightarrow$ potentially smaller wall losses in the channel
Key Problem of Hall Thrusters

Large plume divergence (~90 deg) decreases thrust and efficiency. Most importantly, it limits lifetime of the satellite – ion bombardment damages solar panel dramatically. Outgoing plasma jet may also interfere with radio-communication between the ground control and the satellite.
Controlling Plume with Segmented Electrodes

Segmented Electrode

Grooves (anti-sputtering)

Anode

Cathode

Discharge Voltage, V

Half Plume angle, deg

Anode mass flow rate = 1.7 mg/s

Single electrode configuration

Probe

1 kW HT

Segmented electrodes (localize potential drop - reduce beam divergence)
Temperature Profile in Hall Thrusters

1. In acceleration region:
   \[ T_e = \beta \phi_{pl} \]
   \( \beta = 0.08 - 0.14 \)

2. Maximum electron temperature saturates with discharge voltage
Anode Sheath = Adjoint Space-Charge Layer

Positive Anode Fall = Electron-attracting Anode Sheath

Negative Anode Fall = Electron-repelling Anode Sheath
Decreasing Anode Area Reverses Anode Fall

CLEAN ANODE = NEGATIVE ANODE FALL

COATED ANODE = POSITIVE ANODE FALL

At channel median $\dot{m} = 5 \text{ mg/s}$ $\varphi_{an} = 0$, biased probe
Decreasing Anode Collecting Surface Area Manifests Itself

Negative anode fall

Positive anode fall

CLEAN ANODE

COATED ANODE
Hall thruster operation appears to be MORE STABLE WITH COATED ANODE (i.e. with Electron-Attracting Anode Sheath or Positive Anode Fall)

Discharge Current Oscillations Measurements

- Relative Oscill Ampl vs. Discharge Voltage, V
- Discharge Current Oscillations Measurements
- 3 mg/s Coated
- 5 mg/s Coated
- 3 mg/s Clean
- 5 mg/s Clean

Graph showing the relationship between discharge voltage and the relative oscillation amplitude for both coated and clean conditions at different discharge currents.
Formation of an electron-repelling anode sheath (negative anode fall) is required to repel an excessive electron thermal flux from the anode.

Electron-neutral collisions are very weak near the anode, so is the magnetic field in the conventional configuration. \( \Lambda_{en} \sim \Lambda_{nn} \approx 12 \text{ cm} \)
Positive Anode Fall Formation Mechanism

Additional electron flux gets drawn into the anode by the electron-attracting sheath that appears at the inner, metal anode surfaces.

Positive Anode Fall Formation Mechanism

- Additional electron flux drawn by electron-attracting sheath at inner metal anode surfaces.
- Stainless steel anode, $\Phi_{an} = 0$.
- Conductive surface.
- Dielectric coating.
- Thermal electron current constitutes only 40% of discharge current.

$\Lambda_D \sim 0.075 \text{ mm}$
$\Delta_B = 0.6 \text{ mm}$

$\Phi_{plasma} \sim -6 \text{ V}$

Axis of symmetry
Zero-B-Field Configuration = Reversed Fall

\[ V_d = 300 \, V; \quad m = 3 \, \text{mg/s}; \quad Z = 0 = \text{Anode}; \quad \Phi = 0 = \text{Anode} \]
1. Input parameters:

\[ V_d = 300 \text{ V} \quad \dot{m} = 3 \text{ mg/s} \]

3 profiles \( B_r(z) \), \( I_d \), \( n_0 \), \text{sheath} = Experimental values

2. System of fluid equations for 3-species (\( e \), \( i \), \( n \)) quasineutral plasma. Includes ion wall losses terms \( \rightarrow \) “quasi-1D”

3. Fitting parameter, \( \alpha \), for electron cross-field mobility, \( \mu_e \):

\[ \mu_e = \frac{\alpha}{16 |B_r(z)|} \]
Boundary Conditions

- Reduced system:
  \[ dJ_i/dz = F(J_i, n, I_d, \mu_e) \]
  \[ dn/dz = G(J_i, n, I_d, \mu_e)/(1-V_i^2/V_s^2) \]

- \( I_d, n_0 = \text{Experimental} \)

- \( \mu_e = \frac{\alpha}{16 |B_r(z)|} \)

There is only one value of \( \alpha \), which allows a solution to be regular at the sonic transition point: \( V_i = V_s \).

- \[ \int_0^{L_{\text{cath}}} E(z) \, dz = V_d \quad \Rightarrow \quad L_{\text{cathode}}(V_d) \]