Plasma Propulsion for Satellites

Yevgeny Raitses

PPPL

SULI, Princeton, June 2020
Operational Satellites with Electric/Plasma Propulsion (2008)

Legend:
- IMPEHT
- ION
- ARCJET
- EHT
- HET (Russian)
- HET (Western)
- Experimental
- PPT & Hall

Cumulative Number of Satellites Employing EP = 226
Number of Satellites Employing Aerojet EP = 156

AEROGJET
French-Israeli Vegetation and Environment Monitoring Micro-Satellite (VENµS) with Hall thrusters, launched by Vega from French Guiana in 2017
Plasma propulsion research at PPPL

- Hall Thruster Experiment (HTX) in 1998 by N.J. Fisch and Y. Raitses and graduate students L. Dorf, A. Smirnov, A. Litvak and D. Staack
- Goal: to develop scientific understanding of plasma thruster physics


Interplanetary Travel Between Satellite Orbits

By LYMAN SPITZER, JR.
Princeton University Observatory, Princeton, N. J.

An analysis is given of the performance to be expected of a rocket powered by nuclear energy, and utilizing an electrically accelerated ion beam to achieve a gas ejection velocity of 100 km/sec without the use of very high temperatures in the propellant gases. While such a rocket travel particularly feasible. It is well known that one of the chief limitations on a conventional rocket is the temperature which the rocket tubes can tolerate without melting or evaporating. A nuclear-powered

http://htx.pppl.gov
Direct Fusion Drive: power and propulsion

Princeton Field Reversed Configuration (PFRC)
Quasi-toroidal plasma: Closed magnetic field lines
Goal: PFRC fusion reactor (truck-sized), 1-10 MW
High $\beta$ required to burn D-$^3$He
$^3$He supply ~ 100 MW/year
Low neutron damage - Long component lifetime
Thrust 10 N/MW

Remote planet exploration

Derek Sutherland’s lecture on alternative concepts, 06/18
✓ Personal and Group introduction

  • Plasma propulsion - why and what for
  • Fundamental limits on thrust density for ion and Hall thrusters
  • Superior Hall thruster technology – what is beyond?
Stimulus for electric/plasma propulsion

Konstantin Tsiolkovsky
Rocket equation, 1903

Robert Goddard
Electric propulsion, 1906

Propellant mass \( \frac{M_p}{M_i} = 1 - e^{-\Delta V/V_{ex}} \)

\( V_{ex} \approx 4 \text{ km/s} \)

\( V_{ex} \approx 50 \text{ km/s} \)

\( M \frac{dV}{dt} = \text{thrust} = -\frac{dM}{dt} V_{ex} \)
**Electric/plasma propulsion**

**Acceleration of gases for propulsion by electrical heating and/or by electric and magnetic forces**

**Chemical rocket:**
Energy source is in fuel/oxidizer chemical reactions

\[ V_{ex} \text{ limited by the propellant energy density} \]

For \( \text{H}_2 + \text{O}_2, V_{ex}^{\text{max}} \approx 4 \text{ km/s} \)

**Solar electric rocket:**
Energy source and fuel are separate

\[ V_{ex} \text{ limited by the on-board power} \]

\[ V_{ex} \approx 5 - 100 \text{ km/s} \]

Dawn’s Delta 2, 2007

Robert G. Jahn, *Physics of Electric Propulsion*
New York, McGraw-Hill (1968)
Electric propulsion: *fuel efficient, power limited*

Convert input electric power, $P_e$, to output thrust power:

$$\eta P_e = \frac{mV_{ex}^2}{2} = \frac{TV_{ex}}{2}$$

Solar power from 10 W to 10's kW
Near future available $P_e \geq 10^2$ kW

Electric thrusters – low thrust propulsion
Low thrust – low acceleration
Low acceleration – longer mission time
Longer mission time – longer thruster lifetime (needed)

Efficiency $\eta < 1$

Space mission: $\Delta V \approx a\Delta t = \frac{T}{M}\Delta t$
Use of electric thrusters

High ΔV space missions

1998
Ion thruster

NASA Deep Space 1

1998
Ion thruster

2019
Hall thruster

High precision control

Planned: 2034
2015-Pathfinder
Electrospray thruster

Station keeping and orbit rising

Drag compensation at low orbits

Airbreathing space missions

SpaceX Starlink

ESA

XXXX
XXXXXXXXX

ESA-NASA LISA

ESA
Propulsion: Electric vs Plasma (*)
Hall thruster and Ion thruster

Hall thruster:
• Scale dim. (diameter) 1-50 cm
• Power 0.1-100 kW
• Propellant Xe, Kr
• Efficiency 20-70%

Ion thruster:
• Scale dim. (diameter) 1-40 cm
• Power 0.1-10 kW
• Propellant Xenon
• Efficiency 60-80%

Ion thruster – electrostatic thrust force on electrodes

From ion energy conservation, $v_i(x = 0) = 0$, the maximum $Isp$ is the ion velocity at the accel grid:

$$Isp^{max} \approx \frac{v_{max}}{g} = \frac{1}{g} \left( \frac{2eV_d}{M_{ion}} \right)^{1/2}$$

Child-Langmuir space charge limit on the ion current density at $E_s = 0$:

$$J_{i max} = J_{CL} = \frac{4\varepsilon_0}{9} \left( \frac{2e}{M_{ion}} \right)^{1/2} \frac{V_d^{3/2}}{d^2}$$

Maximum thrust density when $E_s = 0$,

$$\frac{T_{max}}{A} = M_{ion} \frac{J_i}{e} v_i = -\frac{\varepsilon_0}{2} E_a^2 \approx -\frac{\varepsilon_0 V_d^2}{2d^2}$$
Hall thruster invented in 60’s, flown in 70’s

- Applied DC (stationary) fields: \( \mathbf{E} \times \mathbf{B} \)
- Quasineutral plasma: \( n_e \approx n_i \)
- Electrons \( \mathbf{E} \times \mathbf{B} \) drift in azimuthal direction
- Heavier ions almost unaffected by B-field

\[
\frac{r_{Le}}{r_{Li}} \ll L = \frac{m_i v \perp}{eB}
\]

- Equipotential magnetic field surfaces

\[
\mathbf{E} = -\mathbf{V}_e \times \mathbf{B}
\]

- Ions are accelerated by electric field
- Accelerated ion flux is neutralized by electrons
  ion flux = electron flux

Xenon, Krypton
V \sim 100-1000 V
B \sim 10^2 \text{ Gauss}

Dimensions:
L < 10 \text{ cm}
D \sim 1-50 \text{ cm}

Low gas pressure < 1 \text{ mtorr}
– ions move without collisions

Will Fox’s lecture on 6/16
Hall thruster –thrust force on magnet

- Force on ions (q=e):
  \[
  F_{ion} = 2\pi \int \int en_i E r dr dz
  \]

- Forces on electrons (q=-e):
  \[
  F_e = -2\pi \int \int en_e E r dr dz - 2\pi \int \int en_e v_e \times B r dr dz = 0
  \]

- Thrust is a reaction force to the ion acceleration applied to electromagnet:
  \[
  T = -F_{ion} \approx I_{Hall} \times B (2\pi r_m)
  \]

- The maximum achievable thrust density in Hall thruster is limited not by space charge, but by the magnetic field:
  \[
  \left( \frac{T}{A} \right)_{max} \sim \frac{B_{max}^2}{2\mu_0}
  \]
Comparing thrust densities for Hall and ion thrusters

Deep Space 1 NSTAR Ion thruster

At 1.5 kW, thrust ≈ 50 mN
At 2.3 kW, thrust ≈ 90 mN

Hall thrusters are also advantageously simpler than ion thrusters

DP1 Ion thruster
30 cm

HT
10 cm

SMART -1, ESA
Hall thruster:
PPS-1350:
Power: 1500 W
OD = 10 cm
Thrust= 90 mN
World’s largest and most powerful Hall thruster: X-3

- **Power**: 2-200 kW
- **Efficiency**: > 60%
- **Thrust**: 0.2 N–10 N
- **Isp**: 1550 – 3500 s for Xe
- **Diameter**: 0.80 m
- **Thrust density**: Up to ≈ 20 N/m²
- **Mass**: 250 kg

At higher power levels (over 600 kW, provided by a few X3s clustered together), the X3 has the potential to actually carry astronauts to Mars

*Courtesy Prof. Ben Jorns of Univ. Michigan Ann Arbor*
Thrust Density Limits: *achieved vs feasible*

- For Hall thrusters, $B_{\text{max}} \sim 0.1$ T (magnetic core material saturation)
- For FRC, MPD, $B_{\text{max}} \sim 1$ T

- $E_{\text{max}} \sim 10^6$-$10^7$ V/m (breakdown of gap)
Is Hall thruster a mature technology?

For the same thrust, we could make much more compact thruster if it could operate at the fundamental thrust density limit, with $B_{\text{max}} = 1 \text{kGauss}$!
Key obstacles for the development of high thrust density, compact Hall thrusters

• **Plasma-wall interactions**: Ion-induced erosion of the thruster channel and the thruster heating – both limiting the thruster lifetime, scaling down of thruster dimensions (i.e. thruster compactness, high thrust density)

• **Turbulent fluctuations and related anomalous transport phenomena, and plasma structures** critically affecting the thruster performance and lifetime

  • Typical operation is limited to $B_{\text{max}} \sim 100-200$ Gauss, because of violent instabilities developed at stronger magnetic fields
Ion-induced erosion of the thruster channel

1.35-kW SPT-100 New

1.35-kW SPT-100 5,700 Hrs

Ceramic channel, 10 cm OD diameter

Operational Cathode

Non-operational cathode

7 mm

Courtesy: L. King, F. Taccagona, Y. Mikellides
Magnetic shielding has been shown to dramatically reduce discharge channel wall erosion

Central pole piece erosion is still a concern!
Cylindrical Hall thruster

- Diverging magnetic field topology
- No central channel wall
- Closed $\mathbf{E}\times\mathbf{B}$ drift (like in conventional Hall thruster)
- Electrons confined in a magneto-electrostatic trap
- Ion acceleration in a large volume-to-surface channel
- Plume focusing controlled by the cathode mode

Maximum thrust density: 15 N/m²

Plasma structures and anomalous cross-field current

12 cm diameter, 2kW Hall thruster

Plasma non-uniformity
Current conducting ExB rotating “spoke”
Fast frame imaging 60 kfps

Xenon operation

Thruster efficiency
\[ \eta \equiv \frac{TV_{jet}}{2P_e} \propto \frac{I_i}{I_i + I_{e\perp}} \]

Electron cross-field current

- Spoke frequency $\sim 10$ kHz
- 10’s times slower than E/B
- Conduct $> 50$-$70\%$ of the discharge current
Hall thruster DC inputs, but highly oscillatory operation

Powerful breathing oscillations of the discharge current due to ionization instability affects temporal evolution of ion velocity distribution

Towards understanding and control of electron ExB transport

Lifetime Plasma Energy Density Throughput, MJ/cm³

- Theories & measurements of gradient driven instabilities
- Mesoscale structures (spoke)
- Spoke Mode transition
- First principles validated modeling capabilities & Predictive design & Control

Diffusion Scale, m²/s
- Mesoscale structures, $L > \lambda > R_{Le}$
- Since 60's, theories helped to double thruster efficiency and plasma energy density in 00's
- PIC simulations predict anomalous transport
- Interplay of small and mesoscale instabilities

Small-scale instabilities, $\lambda < R_{Le}$
- Discovery and characterization of plasma structures in plasma thrusters and ExB devices
- PIC & measurements of kinetic small-scale instabilities

Timeline
- 80's
- 90's
- 00's
- 10's
- 20's

MHz

kHz
Critical challenges of modern Hall thruster technology

• How to make predictive Hall thruster designs for various power levels of interest (space mission relevant)?
  • Need experimentally validated predictive modeling capabilities (e.g. 3-D kinetic codes for plasma, atomistic simulations for materials)

• How to make accelerated thruster lifetime tests (e.g. 10’s -100’s hours instead of 1000’s hours)?
  • Need experimental validated physics models and codes

• How to mitigate/suppress plasma instabilities?
  • Advance understanding of instabilities, develop active and passive engineering solutions (e.g. electrical circuitry, segmented electrodes)
Hall thruster of the future?

• How to make much more compact, higher thrust density Hall thruster than state-of-the-art counterparts?
  • Need to explore operating regimes relevant to the fundamental limit/s (e.g. strong B-fields > 1 kGauss, high plasma density, > $10^{12}$ cm$^{-3}$)
  • Revisit physics of instabilities, transport for these extreme regimes
  • Develop experimentally validated predictive modeling capabilities
  • May require new thruster materials (e.g. diamond or cubic boron nitride for channel walls, high temperature permanent magnets)
Miniaturized PPPL Hall thruster for nano/micro satellites, (1-50 kg)

Princeton University TigerSat

- Supercluster of 100 CubeSats to measure magnetic reconnection

Thruster development by Princeton PhD student Jacob Simmonds and Dr. Y. Raitses

Under development by Princeton students supervised by Prof. Daniel Marlow
**Pluto Orbiter and Lander mission**

### Mission parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Payload</td>
<td>1000 kg</td>
</tr>
<tr>
<td>Fusion Power</td>
<td>2 MW</td>
</tr>
<tr>
<td>Total Trip Time</td>
<td>4 years</td>
</tr>
<tr>
<td>Acceleration Time</td>
<td>292 days</td>
</tr>
<tr>
<td>Specific Power</td>
<td>0.7 kW/kg</td>
</tr>
<tr>
<td>Thrust Efficiency</td>
<td>0.5</td>
</tr>
<tr>
<td>Total $\Delta V$</td>
<td>74 km/s</td>
</tr>
<tr>
<td>Thrust</td>
<td>16.2 N</td>
</tr>
<tr>
<td>Isp</td>
<td>12,554 s</td>
</tr>
<tr>
<td>Total Mass</td>
<td>7158.7 kg</td>
</tr>
<tr>
<td>Engine Mass</td>
<td>2857.1 kg</td>
</tr>
<tr>
<td>Fuel Mass</td>
<td>3236.9 kg</td>
</tr>
<tr>
<td>Quantity $^3$He</td>
<td>0.4 kg</td>
</tr>
</tbody>
</table>

DFD rocket engine with PFRC-5

- Place roving lander on surface
- Provide power to lander
- Beam back data
SFS Z-Pinch Fusion Space Propulsion System

Operating at 1 Hz with a 0.001% duty cycle, a 4 MA (Q=10) SFS Z-pinch fusion thruster could deliver a 2,100 kg payload to a 125 AU orbit (interstellar space) in 9 years with a 70,000 kg spacecraft.

Towards SFS Z-Pinch thruster: Need to maintaining plasma stability and control at higher pinch currents (MA’s)

\[ \frac{T}{A} \approx \frac{B^2}{2\mu} \]

Steve Cowley’s lecture, June 6

Adam Sefkow’s lecture on pinches, June 19
Supplemental material
Ion thruster – electrostatic thrust force on electrodes

Ion current

Ion flux = electron flux

Poisson's equation

\[ \nabla \cdot E = \frac{\rho}{\varepsilon} \]

In 1-D

\[ \frac{dE}{dx} = \frac{qn_i(x)}{\varepsilon_0} \]

Force on ions, \( q = e \)

\[ F_{ion}/A = e \int_{0}^{d} n_i(x)E(x)dx \]

\[ \int_{0}^{d} \frac{dE(x)}{dx}E(x)dx = \varepsilon_0 \int_{E_s}^{E_a} EdE \]

Ion thrust – the reaction force to acceleration of ions applied to the thruster electrodes

\[ T = -F_{ion} = -\frac{\varepsilon_0}{2} (E_a^2 - E_s^2)A \]

Dan M. Goebel and Ira Katz
Fundamentals of Electric Propulsion
JPL series (2008)
Space charge-limited thrust density

Maximum thrust density when $E_s = 0$,

$$
\frac{T_{\text{max}}}{A} = M \frac{J_i}{e} v_i = -\frac{\varepsilon_0}{2} E_a^2 \approx -\frac{\varepsilon_0 V^2}{2 d^2}
$$

Child-Langmuir space charge limit on the ion current density:

$$
J_{i,\text{max}} = J_{CL} = \frac{4\varepsilon_0}{9} \left( \frac{2e}{M_{\text{ion}}} \right)^{1/2} V_d^{3/2} \frac{d^{3/2}}{d^2}
$$

From ion energy conservation, $v_i(x = 0) = 0$, the maximum Isp is the ion velocity at the accel grid:

$$
I_{sp,\text{max}} \approx v_{\text{max}} / g = \frac{1}{g} \left( \frac{2eV_d}{M_{\text{ion}}} \right)^{1/2}
$$