Plasma Instabilities in Electric Propulsion Devices

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There are key aspects of the thruster plasma that we do not understand

- What are these anomalous processes?
- What drives them?
- Can we model them?

Thesis: Plasma instabilities are a major driver
Overview

• Hall thruster principle of operation

• Anomalous processes in Hall thruster operation

• Role of plasma instabilities
Hall thruster principle of operation
Hall thruster principle of operation
Hall thruster principle of operation

Hollow cathode heated until thermionically emitting electrons
Electric field applied between anode and cathode
Electrons follow electric field and current flows between cathode and anode.
Magnetic field is applied in the radial direction. Electrons are trapped in $\mathbf{E} \times \mathbf{B}$ azimuthal drift: Hall effect
Neutral gas (xenon) flows through thruster anode.
Electron azimuthal drift “buzz saw” ionizes neutral xenon. Plasma is created.
Ions are unmagnetized and therefore follow electric field lines directly. Accelerated ions are neutralized by electrons in plume.
Hall thrusters work and currently fly on hundreds of spacecraft on orbit
Hall thruster principle of operation

- High specific impulse: $I_{sp} \propto \sqrt{V_D}$, 1000-3000 s
- High thrust density: $\sum q_s n_s = 0$, 30-500 mN
- Simple PPU and control logic: 1-13 kW

Hall thrusters work and currently fly on hundreds of spacecraft on orbit

However, there are key aspects of their operation that we do not understand
Anomalous Processes in Hall Thruster Operation

Onset of coherent, oscillatory modes
Anomalous Processes in Hall Thruster Operation

Unexplained erosion of downstream surfaces

Anomalous Processes in Hall Thruster Operation

Anomalously high electron cross-field transport that cannot be predicted by classical theory.
Unexplained erosion and electron transport in region of hollow cathode

Anomalous Processes in Hall Thruster Operation

Onset of coherent, oscillatory modes

Cross-field transport

Thruster surface erosion

Cathode erosion and electron transport
Anomalous Processes in Hall Thruster Operation

Onset of coherent, oscillatory modes

Cross-field transport

Each of these mechanisms is related to the onset of plasma instabilities

Thruster surface erosion

Cathode erosion and electron transport
Anomalous Processes in Hall Thruster Operation

Onset of coherent, oscillatory modes

Cross-field transport

Thruster surface erosion

Cathode erosion and electron transport

![Graph showing current and time](image1)

![Diagram of thruster operation](image2)
Anomalous processes in the hollow cathode plume:

Cathode erosion

Non-classical electron resistivity
Anomalous ion heating leading to cathode erosion

- Cathode is an electron source
Anomalous ion heating leading to cathode erosion

- Cathode is an electron source
- Plasma is quasineutral: electrons stream against background of ions
Anomalous ion heating leading to cathode erosion

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Anomalous ion heating leading to cathode erosion

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- Classically, background ions should be low energy
- However, some unknown process in plume accelerates ions to high and damage-causing energy
Anomalous ion heating leading to cathode erosion

• Cathode is an electron source

• Plasma is quasineutral: electrons stream against background of ions

• Classically, background ions should be low energy

• However, *some unknown process* in plume accelerates ions to high and damage-causing energy

Fig. 2  Front view of the DHC keeper at various times during the 30,000 h ELT of a 30-cm ion thruster.
Anomalous electron resistivity
Anomalous electron resistivity

- Plasma current carried by electrons.
Anomalous electron resistivity

- Plasma current carried by electrons.
- Plasma has an inherent resistance which is classically due to collisions slowing down electron motion.
Anomalous electron resistivity

- Plasma current carried by electrons.
- Plasma has an inherent resistance which is classically due to collisions slowing down electron motion.
- Some unknown mechanism provides additional drag on electrons: $R_{\text{classical}} \ll R_{\text{experimental}}$. 
Anomalous electron resistivity

- Plasma current carried by electrons.
- Plasma has an inherent resistance which is classically due to collisions slowing down electron motion.
- Some unknown mechanism provides additional drag on electrons: $R_{\text{classical}} \ll R_{\text{experimental}}$.
- Plasma potentials higher in experiment than estimates based on classical, collisional theory.

Anomalous processes in hollow cathode

Unknown mechanism heats the ions

Unknown mechanism induces drag on electrons
Anomalous processes in hollow cathode

Hypothesis (2013): both mechanisms can be explained by the onset of ion acoustic turbulence in the cathode plume

Unknown mechanism heats the ions

Unknown mechanism induces drag on electrons
**Ion Acoustic Turbulence**

**Ion**  ---  Low frequency (1-5 MHz), electrostatic modes carried by ion motion

**Acoustic**  ---  Waves propagate with linear dispersion relation (frequency vs. wavenumber) at ion sound speed

**Turbulence**  –  Spectrum of incoherent modes excited concurrently in plume
Overview of Investigation into IAT Hypothesis (2013-2017)

- Start with a physical description of how IAT could lead to anomalous cathode plume effects
- Experimentally determine if described process actually occurs in cathode plume
- Incorporate findings into first-principles model to determine if anomalous effects can be explained self-consistently by IAT
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Ion Acoustic Turbulence (IAT) interaction with cathode plume

1) Electron drift exceeds ion sound speed

2) IAT grows at expense of electron drift

\[ V_e \gg c_s \quad T_e \gg T_i \]

3) Growth of IAT slows electrons

4) IAT energy absorbed by ions through collisionless and collisional processes
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Experimental investigation into role of IAT

Diagnostics

<p>| | |</p>
<table>
<thead>
<tr>
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<tbody>
<tr>
<td>RPA</td>
<td>Ion energy</td>
</tr>
<tr>
<td>Single Langmuir probe</td>
<td>n_e, T_e</td>
</tr>
<tr>
<td>I_sat probe array</td>
<td>Wave dispersion</td>
</tr>
<tr>
<td>Laser Induced Fluorescence (LIF)</td>
<td>T_i and ion drift velocity</td>
</tr>
</tbody>
</table>

100-A LaB₆ Hollow Cathode

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
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</thead>
<tbody>
<tr>
<td>Discharge Current</td>
<td>20 – 180 A</td>
</tr>
<tr>
<td>Flow rate</td>
<td>5, 8, 10, 12, 15, 20 sccm</td>
</tr>
<tr>
<td>Gas</td>
<td>Xe</td>
</tr>
<tr>
<td>Applied Magnetic Field</td>
<td>None</td>
</tr>
<tr>
<td>P_B</td>
<td>1-4 × 10⁻⁴ T</td>
</tr>
</tbody>
</table>
Experimental investigation into role of IAT

1) Electron drift exceeds ion sound speed

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Cathode conditions

\[ V_e \gg c_s \quad T_e \gg T_i \]
1) Electron drift exceeds ion sound speed

Cathode conditions

\[ V_e \gg c_s \quad T_e \gg T_i \]

\[ \checkmark \quad \checkmark \]

Photo

Density

Electron temp.

140 A and 15 sccm xenon

2) IAT grows at expense of electron drift

\[ \omega \propto k \]

\[ \frac{dE_T}{dt} \propto V_e E_T \]

1) Measurement of dispersion relation in plume

2) Evolution of IAT energy in plume


3) Growth of IAT slows electrons

Quasi-linear theory

1) $\nu_{IAT} \propto E_T$
2) $\nu_{IAT} > \nu_{\text{classical}}$

1) Use measured energy to infer effective collision frequency

2) Compare IAT driven collision frequency to classical collisions


4) IAT energy absorbed by ions through collisionless and collisional processes

Quasi-linear theory

$$\Delta T_i \propto E_T$$

Measured wave energy and ion temperature as functions of position

4) IAT energy absorbed by ions through collisionless and collisional processes

Quasi-linear theory

$$\Delta T_i \propto E_T$$ ✔

Measured wave energy at single point

Measured ion energy at single point

Correlational and causal relationship between IAT and energetic ions persists over wide parameter space
Experimental investigation into role of IAT

1) Electron drift exceeds ion sound speed

2) IAT grows at expense of electron drift

3) Growth of IAT slows electrons

4) IAT energy dissipated by ions through collisionless and collisional processes
Overview of Investigation into IAT Hypothesis (2013-2017)

• Start with a physical description of how IAT could lead to anomalous cathode plume effects

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Modeling impact of IAT on plasma properties

Simulation

Governing equations

Continuity

\[ \frac{dn_s}{dt} + n_s \nabla \cdot V_s = 0, \]

Momentum

\[ m_s n_s \frac{dV_s}{dt} + \nabla \cdot p_s - e_s n_s (E + V_s \times B) = F_{s1} + F_{s(AN)}(E_T) \]

Energy

\[ \frac{3 dp_s}{2 \, dt} + \frac{3}{2} p_s \nabla \cdot V_s + p_s : \nabla V_s + \nabla \cdot q_s = W_s + W_{s(AN)}(E_T) \]

Wave energy

\[ \frac{\partial E_T}{\partial t} + \vec{v}_g \cdot \nabla E_T = \omega_0 E_T \left[ \zeta_e - \zeta_i - \frac{\nu_i}{\omega_0} \right] \]

“Drag”

“Heating”

Derived from quasilinear theory


Validating IAT-based terms on plasma properties

Drag

\[ F_{S(AN)}(E_T) \]

Heating

\[ W_{S(AN)}(E_T) \]


Wave energy

\[ \frac{\partial E_T}{\partial t} + \vec{v}_g \cdot \nabla E_T = \omega_0 E_T \left[ \zeta_e - \zeta_i - \frac{\nu_i}{\omega_0} \right] \]


B. Jorns et al. Physical Review E. Submitted
Analytical terms for impact of IAT on governing equations have been validated experimentally.
Self-consistent predictive model that includes anomalous effects

140 A and 10 sccm

Density on centerline

Temperature on centerline

A. Lopez Ortega, B. Jorns, and I. Mikellides. Journal or Propulsion and Power. Submitted
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Anomalous processes in hollow cathode

**Validated theory (2017):** both mechanisms can be explained by the onset of ion acoustic turbulence in the cathode plume.
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- Onset of coherent, oscillatory modes

- Cross-field transport

- Thruster surface erosion

- Cathode erosion and electron transport
Anomalous Processes in Hall Thruster Operation

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Cross-field transport

Thruster surface erosion

Cathode erosion and electron transport
The Problem of Anomalous Electron Transport
Anomalous electron transport in Hall thruster

$I_e/I_D = 0$

Ideal (collisionless)
Anomalous electron transport in Hall thruster

\[ I_e/I_D = 0 \]
\[ I_e/I_D = 0.1\% \]

Ideal (collisionless)  
Classical transport from particle collisions
Anomalous electron transport in Hall thruster

$I_e/I_D = 0$
Ideal (collisionless)

$I_e/I_D = 0.1$
Classical transport from particle collisions

$I_e/I_D = 10$
Anomalous transport

Ideal ($\text{collisionless}$)

Classical transport from particle collisions

Anomalous transport
Anomalous electron transport in Hall thruster

How do electrons get across field lines?

Ideal (collisionless)  Classical transport from particle collisions  Anomalous transport
Anomalous electron transport in Hall thruster

• In magnetized plasmas, electron transport across field lines is driven by collisions

\[ I_{ez} \propto E_0z \nu_{eff} \]

• Classical collision frequency in Hall thruster is too low to allow observed electron transport

• Models account for transport as an effective collision frequency
In magnetized plasmas, electron transport across field lines is driven by collisions.

\[ I_{ez} \propto E_{0z} \nu_{eff} \]

Classical collision frequency in Hall thruster is too low to allow observed electron transport.

Models account for transport as an effective collision frequency.

Problem of anomalous electron transport  

\[ I_{ez} \propto E_{0z} \nu_{eff} \]

Problem of anomalous collision frequency
• Problem of anomalous electron collision frequency is 50 years old.

  – Recent advances in diagnostics and theory have enabled new progress on problem.

  – Popular theory that has emerged in analog to hollow cathode processes: acoustic-like turbulence may drive the collision frequency
Ion Acoustic Turbulence (IAT) interaction with cathode plume

1) Electron drift exceeds ion sound speed

$V_e > c_s$

$T_e > T_i$

2) IAT grows at expense of electron drift

$\omega \propto k$

3) Growth of IAT slows electrons

$V_e' < V_e$

4) IAT energy dissipated by ions through collisionless and collisional processes

$Xe^+$

$Xe^+$
Mechanism for effective collision frequency in Hall thrusters

\[ V_e = \vec{E} \times \vec{B} \]

1) Strong \( E \times B \) drift between electrons and ions

2) Azimuthal wave driven unstable by drift through inverse cyclotron or Landau damping

\[ V'_e < V_e \]

3) Electrons slowed in \( E \times B \) direction by wave growth leads to effective collision frequency

4) Wave convected out of channel by ion axial drift
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QL model for collision frequency as a function of wave action

\[ \nu_{AN} = \left[ \frac{e}{n_e0} \right] \left( \frac{\pi}{8} \right)^{1/2} \left( \frac{1}{m_im_e} \right)^{1/2} k^2 N \]

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Mechanism for effective collision frequency in Hall thrusters

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Convective model for wave energy

\[
\frac{\partial N_k}{\partial t} + \frac{\partial}{\partial \vec{r}} \left[ \frac{\partial \omega}{\partial k} N_k \right] - \frac{\partial}{\partial k} \left[ \frac{\partial \omega}{\partial \vec{r}} N_k \right] = 2\gamma_k N_k
\]

4) Wave convected out of channel by ion axial drift
Results from model for collision frequency
Results from model for collision frequency

I. Katz, I. Mikellides, B. Jorns, and A. Lopez-Ortega. 34th IEPC. Kobe, Japan. IEPC-2015-402.
However there are still many open questions about the process:

Is the turbulence actually dominant?

Does it propagate in the way we think it should?

What is the correct way to model its interaction with the electrons?

I. Katz, I. Mikellides, B. Jorns, and A. Lopez-Ortega. 34th IEPC. Kobe, Japan. IEPC-2015-402.
On-going work into examining role of turbulence in cross-field transport

Re-evaluating theory for effective collision frequency

\[ \nu_{AN} = \left[ \frac{e}{n_{e0}} \right] \left( \frac{\pi}{8} \right)^{1/2} \left( \frac{1}{m_i m_e} \right)^{1/2} \frac{k^2 N}{N} \]

Developing new experimental tools to characterize turbulence growth

Re-examining governing hierarchy for turbulent energy in simulations

\[ \frac{\partial N_k}{\partial t} + \nabla \cdot (N_k \bar{v}_g) - \nabla \cdot (N_k \nabla \omega_r) = N_k [2 \omega_i + \mathcal{C} (N_k)] \]
Anomalous Processes in Hall Thruster Operation

Onset of coherent, oscillatory modes

Cross-field transport

Thruster surface erosion

Cathode erosion and electron transport
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The Problem of Magnetic Pole Erosion in Hall Thrusters
Iron poles of the Hall thruster are sputtered


6-kW Hall effect thruster at JPL
Measurements show ion trajectories intersect pole pieces

6-kW Hall effect thruster at JPL

Measured ion trajectories

B. Jorns et al. AIAA-2016-4839
Measurements show ion trajectories intersect pole pieces

6-kW Hall effect thruster at JPL

Ion kinetic energy too low to explain measured erosion rate

B. Jorns et al. AIAA-2016-4839
Measurements show ion trajectories intersect pole pieces

6-kW Hall effect thruster at JPL

Ion temperatures are anomalously high and can explain most of the erosion

Ion heating in this region is non-classical and is possibly driven by turbulent heating or low-frequency ionization modes

B. Jorns et al. AIAA-2016-4839
Anomalous Processes in Hall Thruster Operation

- Onset of coherent, oscillatory modes
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Anomalous Processes in Hall Thruster Operation

Onset of coherent, oscillatory modes

Current (arb.)

Time (us)

Cross-field transport

Thruster surface erosion

Cathode erosion and electron transport

0 hrs

30352 hrs
The Problem of Hall Thruster Stability
Coherent large scale oscillations in plume and discharge current occur on the 10-100 kHz scale
Global Hall thruster stability (breathing mode)

The stability of the thruster depends strongly on operating condition.

There has been some work on explaining these trends with numerical work.*

We are actively investigating a first-principles description of this oscillation.


Anomalous Processes in Hall Thruster Operation

Onset of coherent, oscillatory modes

Cross-field transport

Instabilities can cause problems!

Thruster surface erosion

Cathode erosion and electron transport
Summary

- Electric propulsion is a key enabling technology for commercialization and exploration of space

- Hall thrusters are particularly attractive form of EP

- Although Hall thrusters are currently flown, there are key aspects of operation that we do not understand. This poses a challenge for qualifying this technology for more ambitious missions. Anomalous aspects of operation include
  - Stability
  - Erosion of thruster face
  - Cross-field transport
  - Cathode erosion and resistivity

- In all cases, plasma instabilities play a role (if the anomalous effects were classical, we would have predicted them already!)

- Previous and on-going work seeks to understand these instabilities from first-principles in such a way as to model and potentially mitigate the anomalous processes
Acknowledgement of collaborators

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Mr. Zach Brown, PEPL
Mr. Matthew Byrne, PEPL