Characterization of the plasma plume in the current overrun regime of cylindrical Hall thrusters

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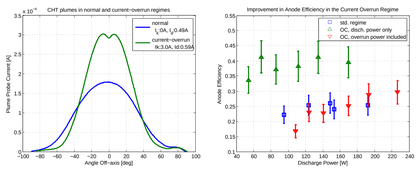
Abstract

Cylindrical Hall thrusters (HTs)[1] may be more promising than annular HTs for low-power scaling due to a smaller surface-to-volume ratio. High plasma plume divergence is a main drawback to cylindrical HTs as decreased efficiency and spacecraft integration issues may result. Recent measurements of the plume angle show that overrunning the discharge current above its self-sustained value can significantly decrease plume divergence. In this "current-overrun" regime, the half-plume angle of the cylindrical HT was reduced to 55°. Thrust measurements demonstrate that the current-overrun regime can have an anode efficiency of up to 35–40% at 100–200 W discharge power levels: an improvement of over 60%. Measurements of the ion energy distribution function in the plasma plume using a retarding potential analyzer reveal both increased ion current density and ion energy on-axis, indicating that these ions are ionized in a region of higher plasma potential. Also, the average energy of off-axis ions is substantially reduced, resulting in improved performance and lowered risk of damage to spacecraft components.

Motivation: Reduce Plume & Enhance Efficiency



Typical improvement in the thruster anode efficiency and plume angle in the current overrun (OC) regime. Note that no effort was made to minimize the overrun power ($P_{overrun} = I_{keeper}V_{keeper-cathode}$), and performance can still be enhanced using little overrun power.

Goals

- Charaterize performance improvement of current overrun regime: thrust enhancement, possible saturation of plume-narrowing effect, ion energy distribution in the plume
- Determine if the current overrun regime is due to internal physics of the hollow cathode or physics of the thruster discharge
- Determine if the performance improvement is due to plume physics or physics in the thruster channel

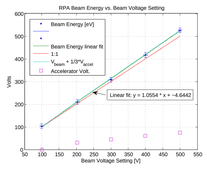
Diagnostics

Facilities:

- hollow cathode neutralizer: Large Hall Thruster Facility ($P_{background} \leq 6\mu$torr during operation)
- filament cathode neutralizer: Small Hall Thruster Facility
  CHT typically operated at low Xenon flow rates (about 0.2 mg/s) to keep $P_{background} \leq 10\mu$torr

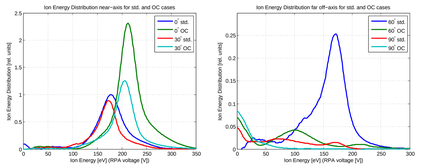
Ion Energy Diagnostics:

- LHTF: 2-grid Retarding Potential Analyzer
  transmission: 15.4%, collecting area: 0.785 cm^2, distance: 72.3 cm
  collector can be biased to -9V to reduce SEE current
- SHTF: 4-grid Retarding Potential Analyzer
  transmission: 2.5%, collecting area: 0.785 cm^2, distance: 15 cm
  Optimum grid voltages determined by calibration with Ar: grid 1: floating, grid 2: -7V (repel plasma electrons),
  grid 3: ion retarting potential, grid 4: -20V (repel SEE electrons), collector: -15.9V



Ion Energy

Retarding Potential Analyzer used to measure the Ion Energy Distribution Function (IEDF) reveal **on-axis ion energy is typically 10–20 eV higher in the current-overrun regime** compared to normal operation. Also, **off-axis ion energy is substantially reduced**.



Possible explanations for shift to higher ion energy

- Ambipolar potential changing thruster floating potential with respect to ground
  Langmuir probe measurements in the plume region indicate that: $V_f \approx 0.5$V, $T_e \approx 0.4$eV, and $V_p \approx 2.6$eV. These parameters remain unchanged in the current-overrun regime.
- Shift in ionization region due to increased T_e or n_e
- Decrease in cathode-plume resistance
  Positive shift in the cathode potential sufficiently accounts for the increased ion energy on-axis. This could be due to a decreased cathode-plume resistance as a consequence of the higher electron emission current.

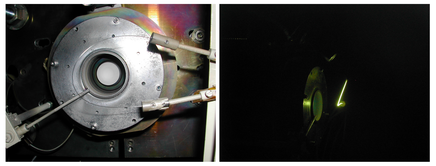
CHT operation with filament cathode

Motivation:

- Eliminate complex internal physics of the hollow cathode
- Direct control of electron emission source via heater current

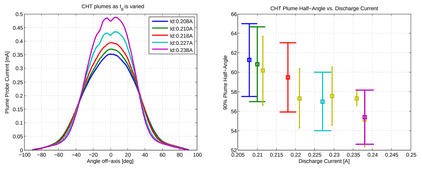
Diagnostics:

- biased graphite probe to measure plume ion current
- 4-grid RPA to measure ion energy distribution
- Langmuir probe to measure V_f at channel exit
- digital oscilloscopes to measure fluctuations in V_d, I_d, V_f



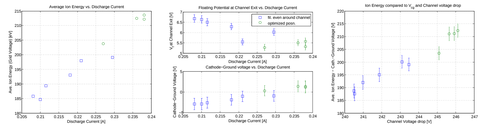
CHT filament operation: plume

- Source electron emission ($I_{emission}$) increased with heater current.
- Discharge current (I_d) increases with $I_{emission}$; plume angle decreases.
- I_d saturates to maximum; increase of $I_{emission}$ does not increase I_d or improve plume angle: I_d can be electron **source-limited** or **mobility-limited**
- saturated I_d depends on **position** of filament cathode



CHT filament operation: ion energy

- Ion energy (E_i) near-axis increases with I_d
- E_i enhancement is greater than increased channel voltage drop, cathode voltage
- indicates that ionization must be taking place closer to the anode, in a region of higher V_p
- Ion energy does not increase with additional $I_{emission}$ once I_d is saturated (the mobility-limited regime)
- if the filament position is moved and I_d changes, E_i continues to vary linearly with I_d



Exercise: Can a simple model estimate ion energy?

Assuming constant $\mathbf{E}$ field in the channel, the potential at a position x from the anode is given by:

$$\phi(x) = V_a - \frac{V_a - V_{fp}}{d}x = V_a - Ex$$

Since ions are collisionless, neglecting wall losses, the average ion energy is merely V_p one ionization mean-free-path from the anode. Giving a voltage difference between the anode and average ion energy of:

$$V_a - <\phi>= \frac{E}{n_e < \sigma_i v_e >}\frac{u_0}{} = \frac{E}{\lambda_i}$$

In the expressions above, u_0 is the neutral velocity (assumed constant), $\sigma_i(T_e)$ is the ionization cross-section,[3] and λ_i is the ionization mean-free-path. In principle, λ_i could be estimated from the measured propellant utilization (η_P); however, for Xenon gas, η_P is often above 1 indicating the presence of multiply-ionized species which are not taken into account by the calculation.

Exercise: Can cross-field diffusion be estimated?

Steady-state electron momentum equation[2]:

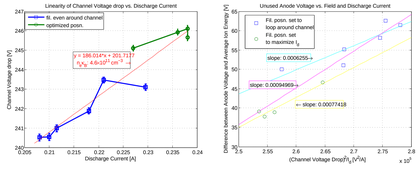
$$m_e n_e u_e \nu_c = e n_e \frac{d\phi}{dx} - \frac{d(n_e T_e)}{dx}, \quad \nu_c = \Omega_e^2/\nu_e, \quad \nu_e = \nu_{en} + \nu_{ew} + \kappa_B \Omega_e/16$$

For each quantity, the average value across the channel is used. The electron pressure term can be neglected, since $T_e \leq 20$eV. Estimating the magnitude of the various contributions to the effective collision frequency ν_e: for the wall collision frequency ($\nu_{ew} = \frac{\delta v_{th}}{h}\frac{\gamma}{1-\gamma}$), using typical CHT parameters gives $\nu_{ew} \leq 2.1 \times 10^7 \mathrm{s}^{-1}$. For an average radial magnetic field of 200Gauss, the Bohm collision frequency is $\nu_B \sim 2.2 \times 10^8 \mathrm{s}^{-1}$. The maximum electron-neutral collision frequncy occurs at the anode, where $n_a = 7.0 \times 10^12 \mathrm{cm}^{-3}$ (assuming cylindrical geometry, 3cm diameter, 2 sccm Xe flow rate). This collision frequency is $\nu_{en} = n_a \sigma_a v_{te}$, which is a maximum of about $5.1 \times 10^8 \mathrm{s}^{-1}$ for $T_e = 12$eV, $\sigma_a \approx 50\mathrm{cm}^2$. Since the Bohm collision frequency is the dominant contribution, other terms will be ignored. This gives a relation between current density and the electric field in the channel:

$$J_e = \frac{e^2 n_e E \nu_e}{m_e \Omega_e^2} = \frac{e^2 n_e E \kappa_B}{16 m_e \Omega_e}$$

This implies that for the same coil currents, nonlinear dependence of I_d on E indicates a change in n_e or κ_B. Combining with the equation for ion energy above, gives:

$$V_a - <\phi>= \frac{E^2}{J_e}\frac{u_0 e^2 \nu_e}{<\sigma_i v_e> m_e \Omega_e^2} = \frac{(V_a - V_{fp})^2}{I_e}\frac{u_0 e^2 \kappa_B A}{16 <\sigma_i v_e> m_e \Omega_e d^2}$$

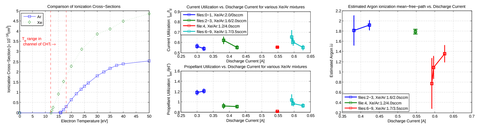


CHT filament operation: Xenon/Argon gas mixtures

The initial motivation for operating the CHT with Argon was to determine sensitivity of thruster operating paramteters to gas species properties (mass, ionization potential). Difficulty in discharge startup and maintenance changed the focus of the investigations to utilize Xenon/Argon mixtures. At typical T_e in the thruster channel, Argon has a significantly smaller ionization cross-section, coupled with its lower mass, cause it to have a much larger ionization mean-free-path, severely reducing its propellant utilization efficiency. The goal of these experiments was a "proof-of-principle" of using small amounts of Argon gas as a means to monitor shifts in average T_e and n_e in the thruster channel. Discounting wall losses in the channel and indirect losses due to charge exchange in the thruster plume, the ion current can be written as:

$$I_i = \sum_\alpha I_{i\alpha} = \sum_\alpha e\Gamma_\alpha \left(1 - e^{-\frac{L}{\lambda_{i\alpha}}}\right)$$

In the expression above, Γ_α and $\lambda_{i\alpha}$ are the source rate and ionization cross-section of species α. By measuring the total ion current for discharges enriched with various small fractions of Argon gas, changes in $\lambda_{i\mathrm{Ar}}$ due to changes in average T_e and n_e can be inferred. In practice, it is assumed that adding a small amount of Argon gas does not change the Xenon ion current, so by subtracting the ion current measured while operating with Xenon only, the Argon contribution can be estimated.



The drop in $\lambda_{i\mathrm{Ar}}$ in the rightmost graph may likely be due to a higher T_e in the channel due to increased Joule-heating from the larger current density. Future experiments would operate with much lower Argon/Xenon ratios where it would be legitimate to assume that the small amount of Argon gas would not perturb the discharge parameters. These experiments successfully demonstrated that the main discharge can be operated reliably with large ratios of Argon gas.

Conclusions

- Ion energy is about 10–20 eV higher in the current-overrun regime than in the normal regime.
  - Decreased cathode-plume voltage drop accounts for this shift in hollow cathode experiments at 0.4 mg/s Xenon flow rate.
  - A shift in the ionization location relative to equipotential surfaces in the channel is necessary to explain this shift in the experiments with a filament cathode at 0.2 mg/s Xenon flow rate.
- Two regimes of thruster discharge operation have been identified: the electron current can be source-limited or mobility-limited.
  - Without increasing electron current by driving current to a segmented electrode, driving a current to the hollow cathode keeper, or increasing electron emission from a filament emitter, the CHT typically operates in the source-limited regime
  - Plume angle is reduced as I_e increases until saturation; this saturation corresponds to the mobility-limited regime.
  - Further increases in electron emission from the source do not increase discharge current, nor improve plume angle or ion energy.
- Discharge operating parameters are sensitive to the position of electron emission
  - $\mathbf{B}$ outside the channel is sufficiently strong to magnetize the electrons $\rho_e \leq 1$mm
  - electrons are deposited on particular field lines
  - moving the filament position radially or axially can affect I_d and cause a transition between regimes

Future Direction

- Characterize fluctuations in the CHT to determine if cross-field transport changes from one regime to another
- Confirm the presence of multicharged Xenon in the CHT discharge
- Use Langmuir probes mounted on the channel wall or a fast reciprocating probe inside the channel to directly measure changes in n_e, T_e.
- Perform numerical simulations to understand how the shape of equipotential surfaces (hence the ion acceleration directions) are modified inside the thruster channel as discharge current is varied. Can the regimes of source-limited and mobility-limited operation also be understood in this manner?
- Develop the usage of minority Argon species as a diagnostic technique for measuring average properties in the thruster channel; compare to direct measurements using Langmuir probes

References & Acknowledgements

We thank Artem Smirnov for his dissertation work on the CHT, his identification of the plume narrowing phenomena, his instruction in taking thrust data, and profitable discussions regarding thruster operation and data analysis. We also thank Martin Griswold for his assistance with CHT filament operation experiments and useful discussions.
This work was supported by the US AFOSR and DOE under contract No. DE-AC02-76CH03073.

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