PLASMA PROPERTIES IN THE FAR-FIELD PLUME OF A RADIOFREQUENCY PLASMA THRUSTER

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A radiofrequency plasma source was previously developed at the University of Michigan to study the behavior of ions downstream of a diverging magnetic field.\textsuperscript{1,2} A follow-up experiment investigates the performance of the plasma source operating as a thruster. During this experiment, simultaneous thruster performance and far-field plume measurements of the rf plasma source are taken in the Large Vacuum Test Facility (LVTF) at the University of Michigan. Thruster performance is measured using an inverted-pendulum thrust stand, and plume properties are investigated using a nude Faraday probe, a retarding potential analyzer, and a commercial rf-compensated Langmuir probe. The pressure in the LVTF is held below $5.5 \times 10^{-6}$ torr during operation of the thruster in order to reduce facility effects on probe measurements. The work presented here focuses on the results of the probe analysis.


Plasma Properties in the Far-Field Plume of a Radiofrequency Plasma Thruster

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Motivation

• Investigate physical mechanisms for thrust in an rf plasma thruster

• Experimentally study plasma detachment from magnetic field

• Provide measurements of plasma properties in an expanding magnetic field for comparison to computational results

• Develop diagnostics to measure rf power delivered
Facilities

• Large Vacuum Test Facility (LVTF) at PEPL
  ▪ Seven TM-1200 nude cryopumps = 500000 L/s on air
  ▪ Pressure remains below 5.0x10^{-6} Torr (6.7x10^{-4} Pa)
  ▪ http://pepl.engin.umich.edu/facilities.html
Thruster

- The Radiofrequency Plasma Thruster (RPT)
  - Twisted Nagoya antenna intended to excite $m = 1$ helicon mode
  - Capable of axial magnetic field up to 1100 Gauss.
Diagnostics – Efficiency Breakdown

• Thrust, telemetry, and plume measurements required to determine sources of inefficiency

• Beam current density map, ion velocity, thrust, and rf power measurements must all be accurately characterized

\[ T_{RF,i} = \dot{m}_i v_i \cos \lambda = \left( \frac{I_{beam} m_i}{Ze} \right) \left( \frac{2ZeV_a}{m_i} \right)^{1/2} \left( \frac{I_{axial}}{I_{beam}} \right) \]

\[ \eta_{RF} = \frac{T_{RF}^2}{2\dot{m}P_{RF}} = \Phi_M \eta_P \Psi_B \]

\[ \Phi_M = \left( \frac{I_{beam} m_i}{Ze m} \right) \quad \eta_P = \left( \frac{I_{beam} (V_{mp} - V_p)}{P_{RF}} \right) \quad \Psi_B = \left( \frac{I_{axial}}{I_{beam}} \right)^2 \]
Diagnostics – Thrust

- Null-type, inverted pendulum thrust stand measures force
- Operated in displacement-mode
  - Higher sensitivity (+/- 0.1 mN)
  - Easy check for EMC

\[
T_T = T_{CG} + T_{RF} \quad I_{sp} = \frac{T_T}{\dot{m} g_0}
\]

Graph showing the relationship between Argon Flow Rate (mg/s) and \(T_{CG}\) (mN).
Diagnostics – RF power

- Werlatone -60 dB dual-directional coupler and oscilloscope
- Coupler in vacuum at matching network input port

\[ P = \frac{|V_+|^2 - |V_-|^2}{Z_0} \]

\[ \overline{P} = \frac{(|V_+|(1 + \varepsilon_{V+}))^2 - (|V_-|(1 + \varepsilon_{V-}))^2}{Z_0}; \quad \varepsilon_{V\pm} \equiv \frac{\Delta V_\pm}{|V_\pm|} \]

\[ \varepsilon_p = \frac{\overline{P} - P}{P} = \frac{2\varepsilon_{V+} + \varepsilon_{V+}^2 - |\Gamma|^2 (2\varepsilon_{V-} + \varepsilon_{V-}^2)}{1 - |\Gamma|^2}; \quad |\Gamma| \equiv \frac{|V_-|}{|V_+|} \]

Diagnostics – Setup

- Faraday probe sweeps -90 to 90 degrees, constant 96 cm downstream radius
- RPA and Langmuir probe mounted to translation stage so that data can be taken at same location, 124 cm downstream
Diagnostics – Current Density

• Nude Faraday probe used in previous studies
  ▪ In a smaller chamber, different mode, showed “wings” at large angles

\[ I_{\text{beam}} = 2\pi r^2 \int_{0}^{\frac{\pi}{2}} \frac{I_c(\theta)}{A_c} \sin(\theta) d\theta \]

\[ I_{\text{axial}} = 2\pi r^2 \int_{0}^{\frac{\pi}{2}} \frac{I_c(\theta)}{A_c} \sin(\theta)\cos(\theta) d\theta \]

\[ \lambda = \cos^{-1}\left(\frac{I_{\text{axial}}}{I_{\text{beam}}}\right) \]
Diagnostics - Ion Velocity

- Three-grid Retarding Potential Analyzer (RPA)
  - Derivative is directly proportional to ion voltage distribution
  - Used previously for parallel and perpendicular measurements
- Hiden Langmuir probe (LP)
  - Peak in first derivative gives plasma potential

\[ T_e = \frac{(V_p - V_f)}{\ln \left( \frac{m_i}{2\pi m_e} \right)} \]
Diagnostics – Setup

- Thrust Stand
- Directional Coupler
- 2 thermocouples
- Faraday Probe (+/- 150°)
- Single Point RPA, LP
Results – Thruster operation

• Matching network inside LVTF provided visible evidence of dramatically improved power coupling
Results – Performance

- Thrust mainly increases with rf power and magnetic field strength

\[ I_{sp} = \frac{T_T}{mg_0} \]
Results – Faraday probe

• Assuming singly-charged species only, mass utilization and effective beam divergence are calculated:

\[ \Phi_M = \frac{\dot{m}_i}{\dot{m}} = \frac{I_{\text{beam}}}{e \left( \frac{\dot{m}}{M_i} \right)} \times 100 \% \]

\[ \lambda = \cos^{-1}\left( \frac{I_{\text{axial}}}{I_{\text{beam}}} \right) \]
Results – Ion Velocity

- From the RPA and Langmuir probe results, acceleration voltage can be determined
• Further examination suggests that ion most probable voltage correlates negatively with thrust
• Electron temperature most strongly affected by magnetic field, and negatively correlates with thrust
Summary

• Operation of the RPT was significantly improved by moving the matching network close to the antenna

• RF power uncertainty was quantified using calibrated measurement equipment

• Thrust negatively correlates both with far-field electron temperature, and RPA most probable potential

• Charge exchange may explain energy transport inside RPT source tube