Background Pressure Effects on the Plume of an ECR Thruster

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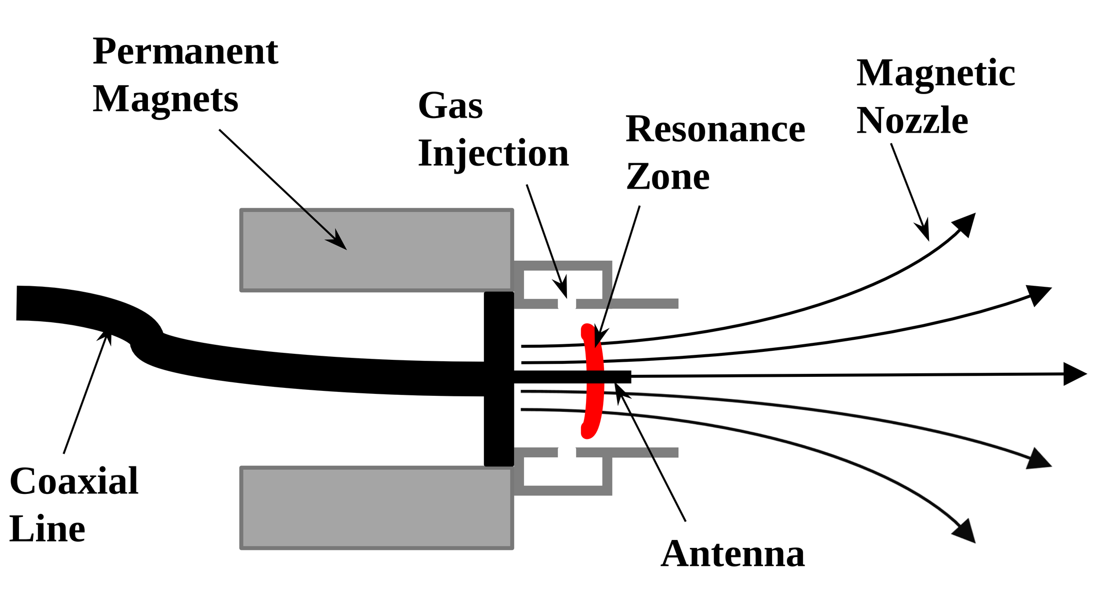
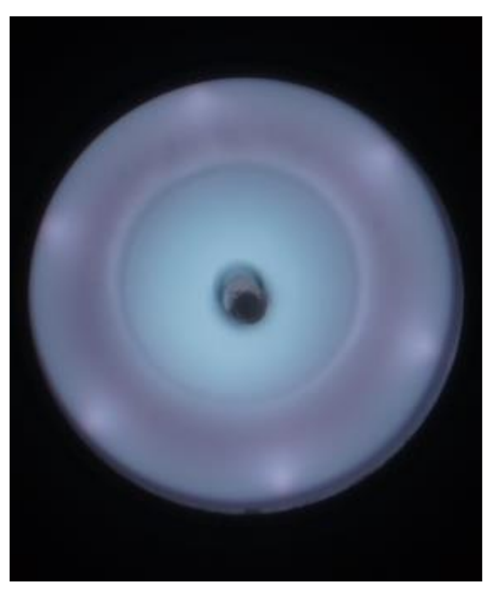
Motivation

Magnetic nozzle thrusters enable simple designs, low mass, and the ability to use many propellants [1]. However, their efficiency at low power has typically been less than 3%. Recent experiments using Electron Cyclotron Resonance (ECR) have shown efficiencies as high as 11% at powers under 50 Watts [2]. The experiments revealed that performance is highly dependent on background pressure, with thrust decreasing 70% as pressure increases from 1×10^{-5} to 5×10^{-5} torr-xe [3]. The physics underlying this decrease is not yet understood. Explaining these effects is essential to magnetic nozzle development and ensuring accurate ground testing results.

ECR Thruster

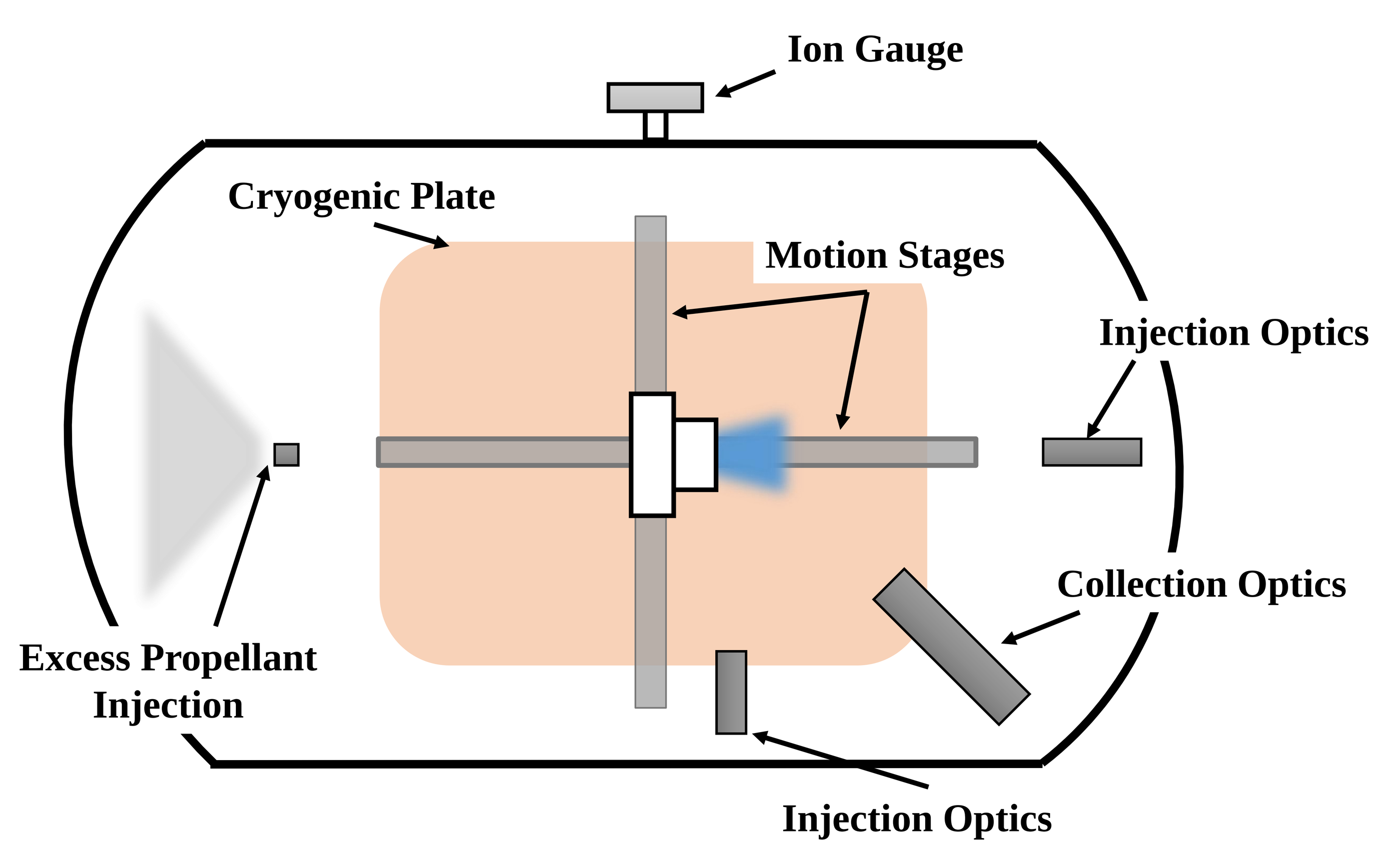
The thruster uses a coaxial design based on experiments at ONERA [2]. Xenon was used as a propellant. 30 watts of forward power at 2.4 GHz was used for all test cases.





Experimental Setup

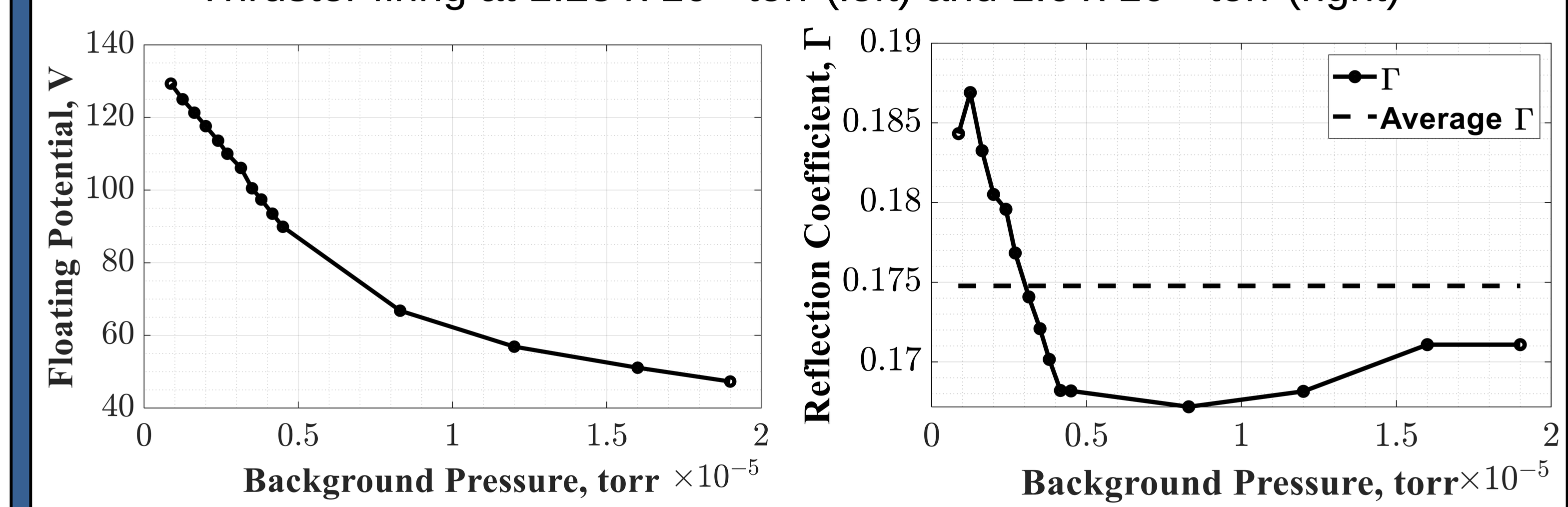
Xenon was injected upstream of the thruster to change background pressure. Plume properties were measured using Laser Induced Fluorescence (LIF), while changes in impedance were measured using diode power meters.



Pressure Study Results

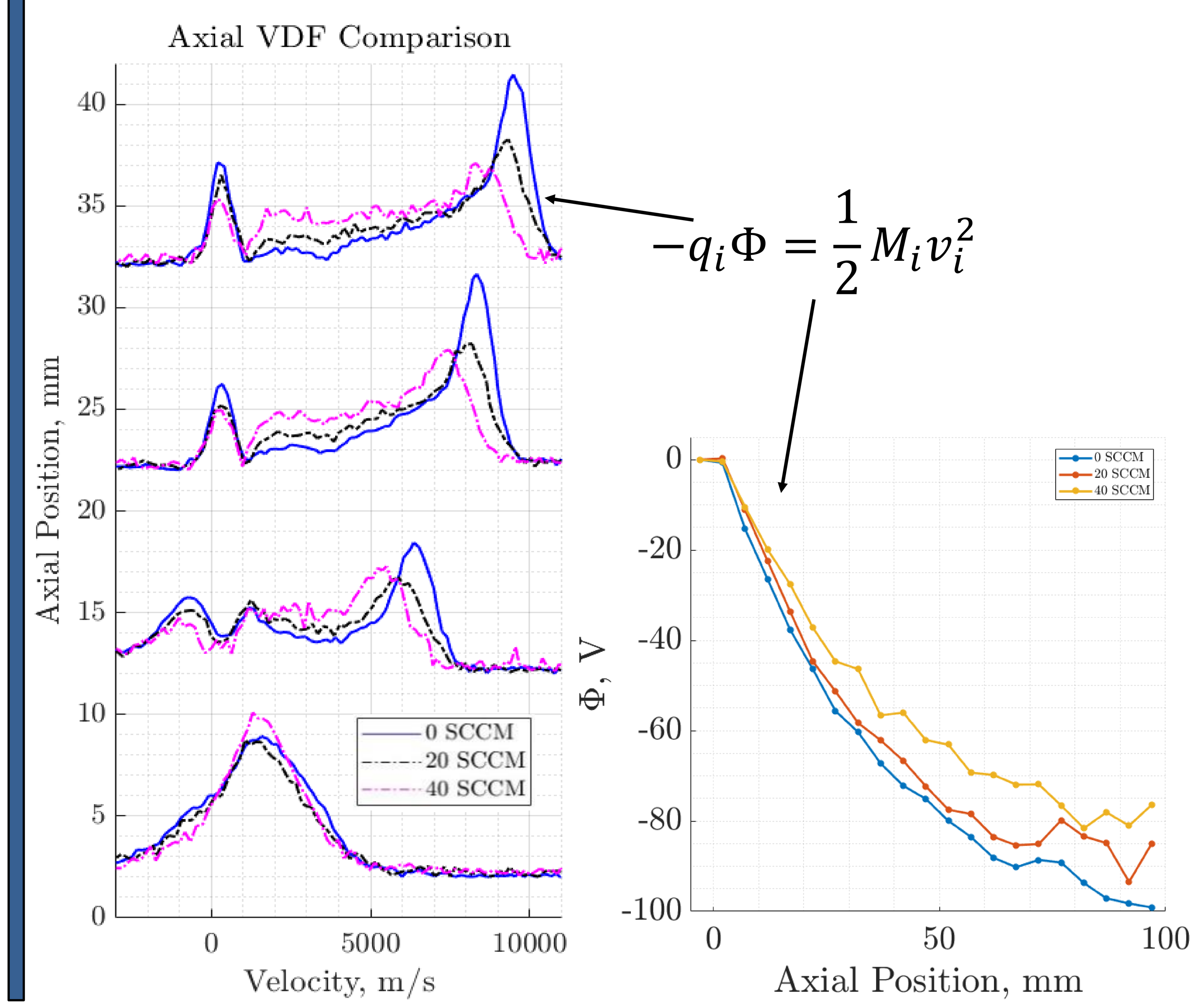
As pressure increased from 7×10^{-7} to 1.6×10^{-5} torr-xe, the plume changed color, and the thruster's floating potential dropped from 130 V. The microwave reflection coefficient, $\Gamma = \frac{P_{fwd}}{P_{rev}}$, was found to remain vary by less than 7% from 0.175.

Thruster firing at 1.25 x 10^{-6} torr (left) and 1.6 x 10^{-5} torr (right)



LIF Results

The Xe+ velocity distribution functions (VDF) were observed to spread to lower energies downstream of the thruster as pressure increased. By extrapolating the plasma potential from the VDFs the total potential drop was observed to decrease by 30% over the pressures tested.



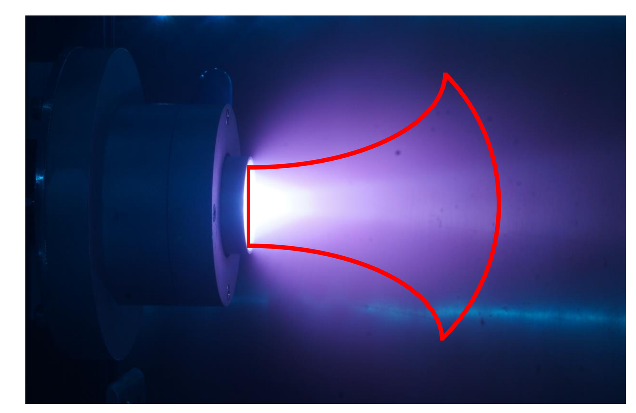
Collisions in the Plume

The ion-neutral mean free paths were calculated to be longer than the acceleration region for all conditions tested. Electron-neutral collisions were therefore thought to change the plume structure. By simulating neutral density, we can construct a global model of the thruster based on a particle and power balance:

$$n_0 u_B A_{eff} = K_{iz} n_g n_0 V_{eff}$$

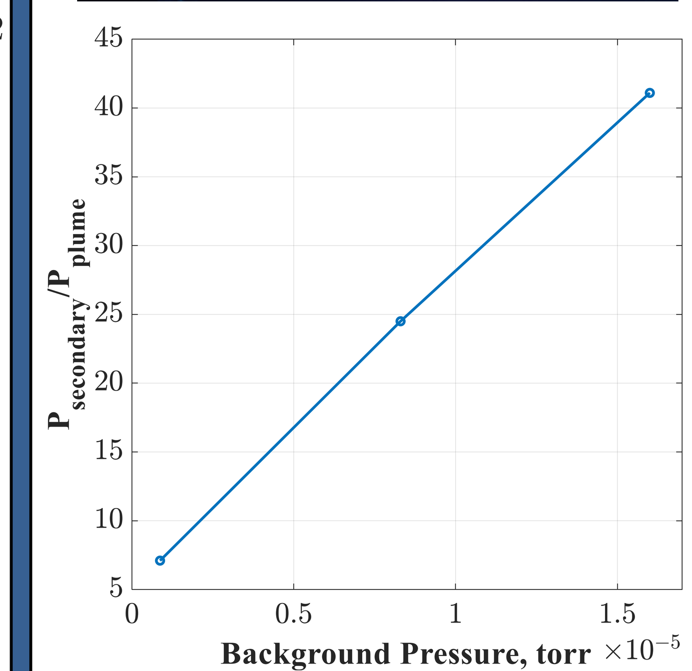
$$P_{abs} = q_e n_0 u_b\Big((\pi R^2 + 2\pi R l)(\varepsilon_c + \varepsilon_i + \varepsilon_e) + \pi R^2(\varepsilon_c + \varepsilon_{ie} + \varepsilon_e)\Big)$$

We can then estimate the plasma temperature and density in the plume by assuming that the plasma follows the magnetic field profile.



By averaging the plasma and neutral densities over the acceleration region, we can compute the energy lost to electron-neutral collisions in the plume:

$$\varepsilon_c = \varepsilon_{iz} + \frac{K_{ex}}{K_{iz}}\varepsilon_{ex} + \frac{K_{el}}{K_{iz}}\frac{3m_e}{m_{ion}}Te$$



Comparing this energy to the total energy entering the plume from the thruster, we show that >40% of the plume power is consumed by neutral collisions at high pressures (1.6×10^{-5} torr) vs. < 7% in the low pressure condition (7×10^{-7} torr).

Conclusions

Increasing background pressure broadens ion VDFs and decreases potential drop in the plume. Electron-neutral collisions were found to explain this decrease. Based on these results, we can conclude that accurate testing must be conducted with pressures less than 10^{-6} torr-xe.

Acknowledgments

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[2] F. Cannat, T. Lafleur, J. Jarrige, P. Chabert, P.-Q. Elias, and D. Packan, "Optimization of a coaxial electron cyclotron resonance plasma thruster with an analytical model," *Phys. Plasmas*, vol. 22, no. 5, p. 053503, May 2015.

[3] T. Vialis, J. Jarrige, and D. Packan, "Geometry optimization and effect of gas propellant in an electron cyclotron resonance plasma thruster," presented at the 35th International Electric Propulsion Conference, Atlanta, GA, 2017.