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Effect of Background Pressure on the Plasma Oscillation Characteristics of the HiVHAc Hall Thruster

Wensheng Huang, Hani Kamhawi

NASA Glenn Research Center

and

Robert B. Lobbia, Daniel L. Brown

U.S. Air Force Research Laboratory

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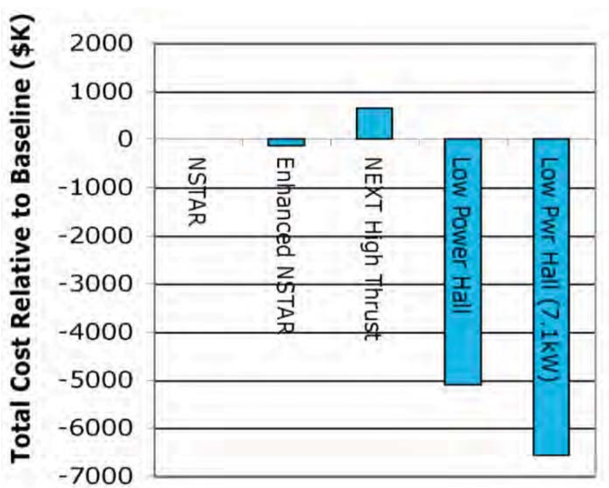
Introduction

- Two NASA studies[1,2] show that Hall thruster can provide considerable cost benefits compared to Ion thruster for Discovery class missions and a high-voltage Hall thruster outperforms current SotA Hall thrusters
  - SMD initiated the High-Voltage Hall Accelerator (HiVHAc) project
- Latest version of HiVHAc is EDU2
- Latest test of the EDU2 is a component compatibility test (CCT)
  - Also reported in: IEPC-2013-445, IEPC-2013-058
- This paper describes characterization of the plasma oscillation characteristics as the background pressure is varied during the CCT



↑ [1]Oh, D., JPC, AIAA-2005-4270, 2005.

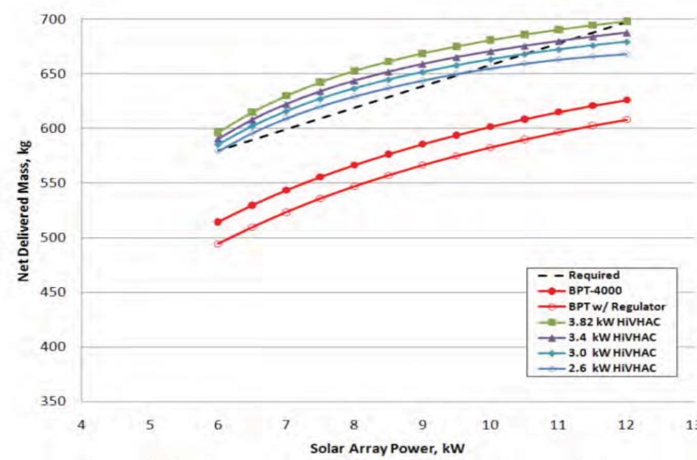


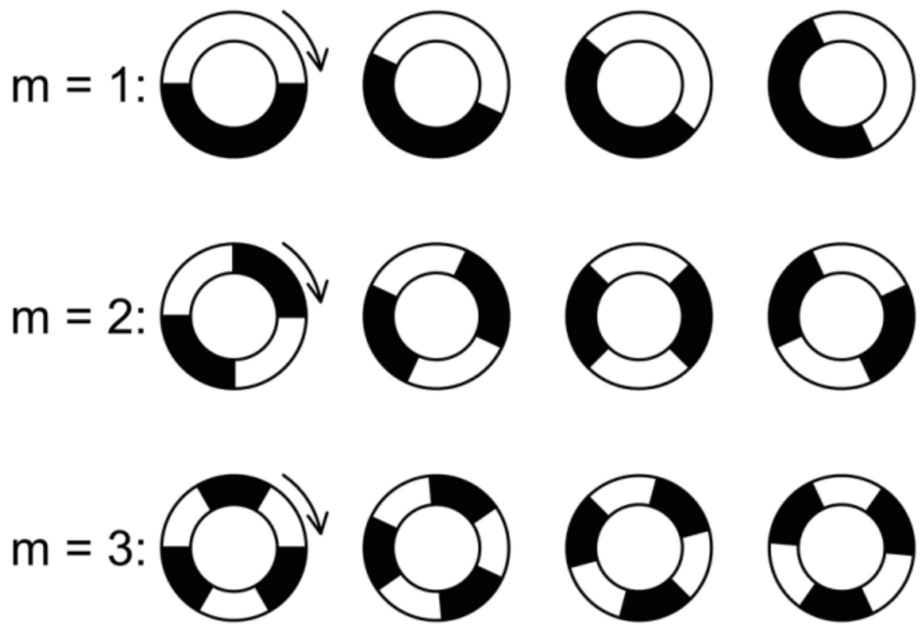
Figure 4. Performance comparison for the Dawn mission.

↑ [2]Dankanich, J. W., et al., IEPC, 2009-213, 2009.

Goal, Objective, and Oscillation Modes

- **Goal:** Determine the maximum acceptable background pressure for testing the HiVHAc EDU2 from the perspective of plasma oscillations
- **Objective:** Obtain data on how the characteristics (magnitude and frequency) of the plasma oscillations change with pressure
- Focused on breathing mode and spokes mode

Breathing mode video

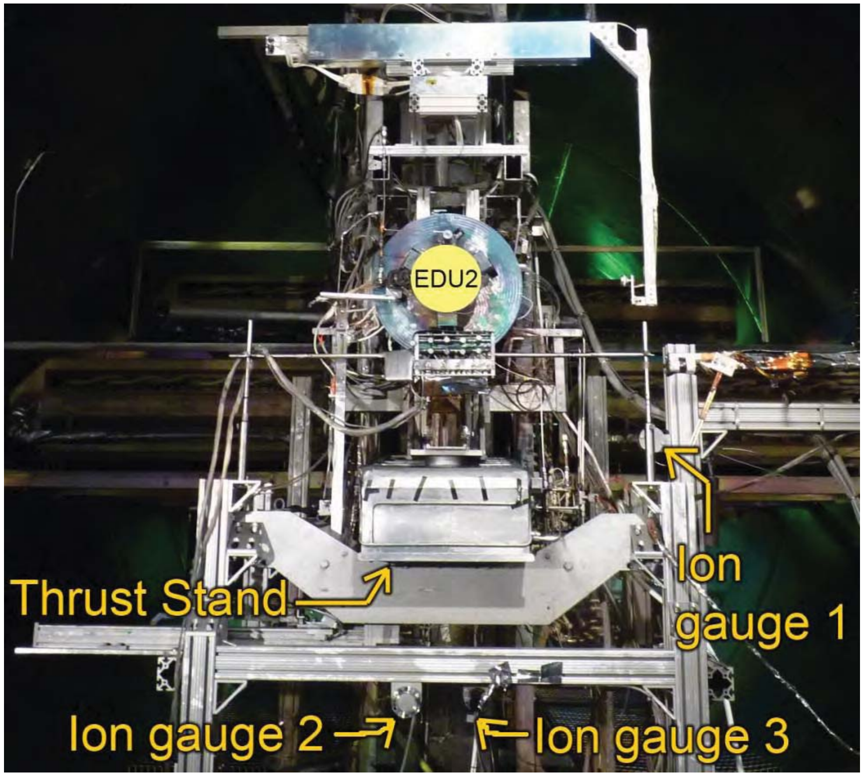


Spokes mode illustration

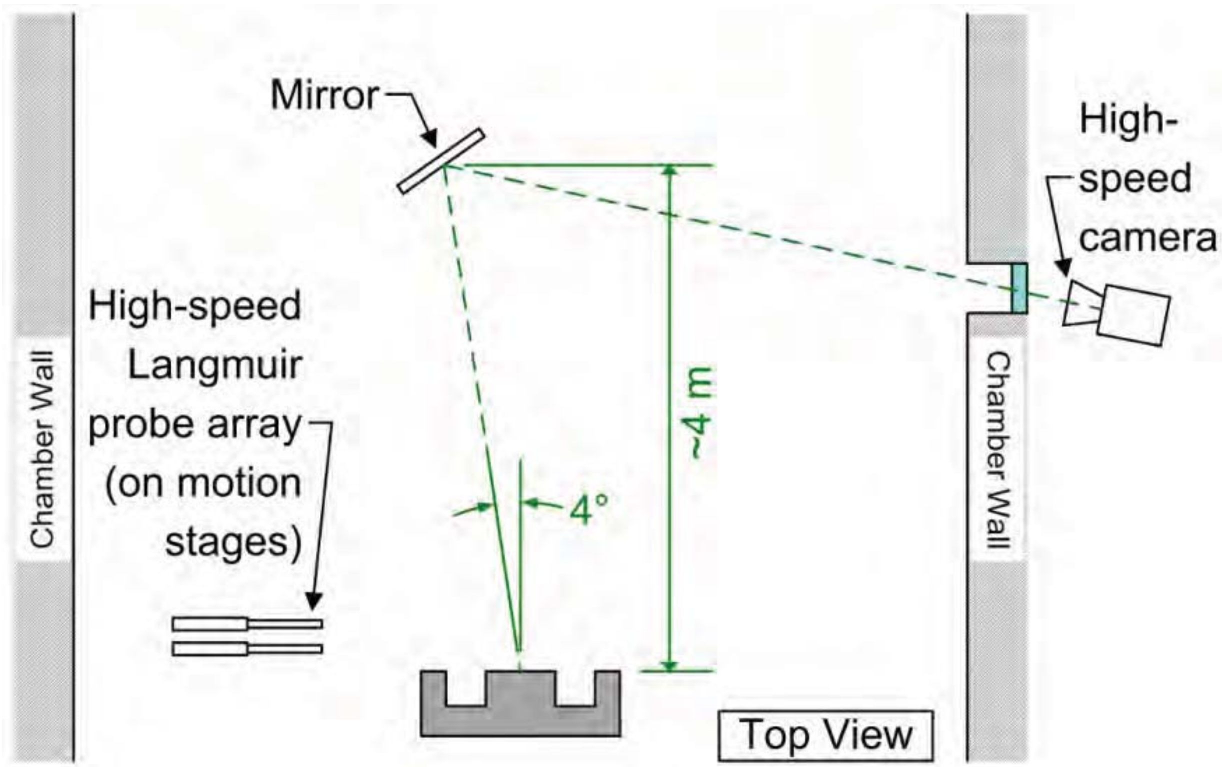
NASA HiVHAc EDU2 Hall thruster

- NASA HiVHAc EDU2 is a 3.9-kW Hall thruster
  - Can throttle from 200 to 650 V (1200 to 2700 sec); 0.3 to 3.9 kW
  - Magnetic lens topology symmetric about the channel centerline
  - Seven throttle points selected: 300 to 500 V, 1.5 to 3.9 kW

- Ion gauge 2 used to determine background pressure
- Label: vvv-k.k-Pnx (voltage-power-normalized pressure)
  - Pressure normalized by lowest achievable pressure
- Mass flow rates set while at lowest background pressure (P1x) and fixed for a given throttle point; CFF = 6.7%
- Magnetic field strength set to optimize efficiency at P1x

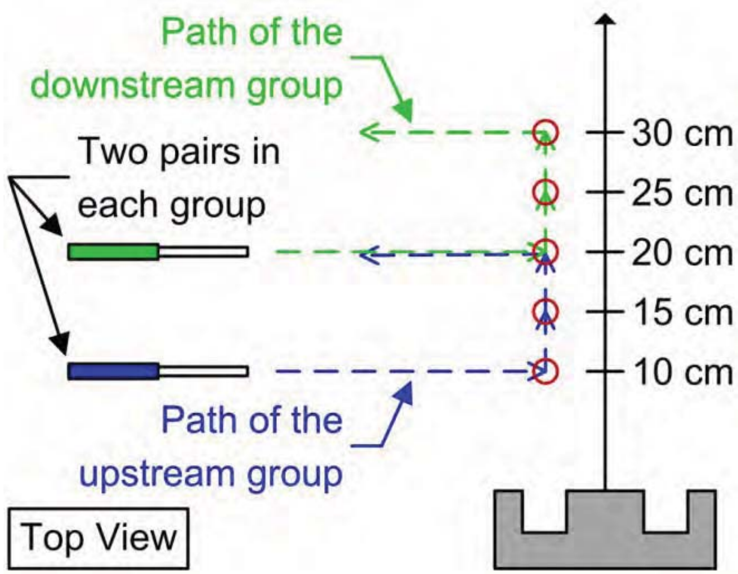


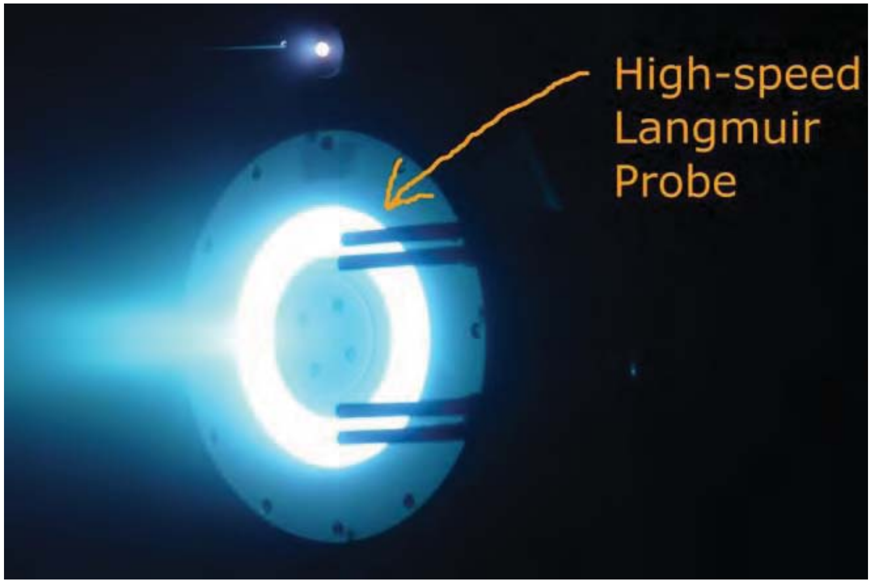
Experimental Setup: High-speed Camera



- High-speed camera filmed at ~80,000 fps
- Thruster occupy 100 x 100 pixels
- 4 degrees off-axis (to make room for an IR camera)
- High-speed video at various pressure collected only for 500 V conditions; video at lowest pressure available at other conditions

Experimental Setup:
High-speed Langmuir Probe

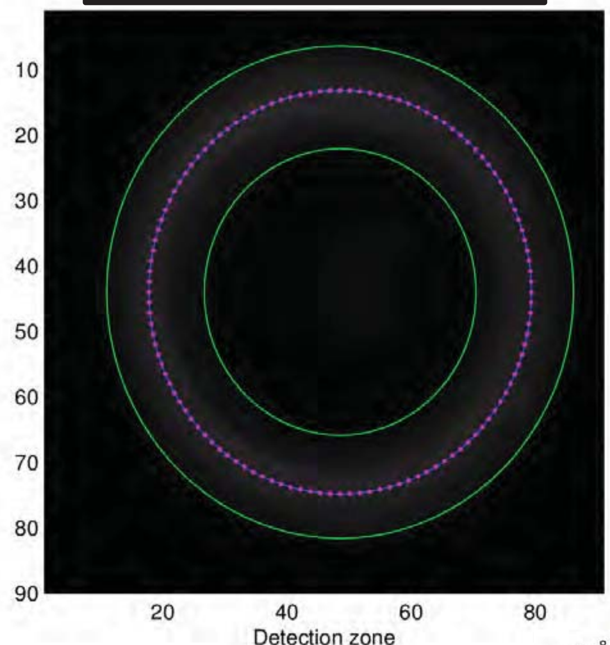




- Four pairs of Langmuir probes in a movable array
  - Each pair consist of an active and a null probe for high-speed sweeping
- Two pairs are axially upstream while the other two pairs are axially downstream, each pair is set azimuthally apart
- Sweep rate is 200 kHz
- Array moves to three axial locations along the channel centerline

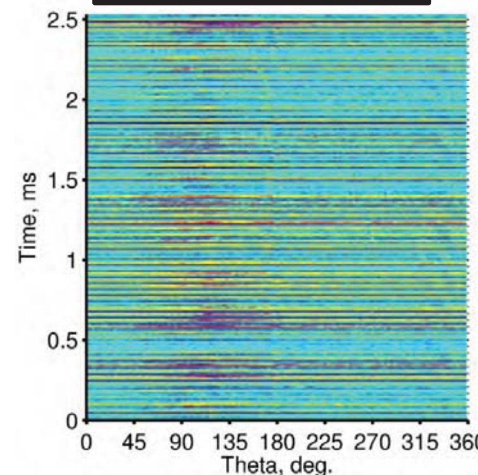
Data analysis:
High-speed Camera

Plot of crop & circle-fit



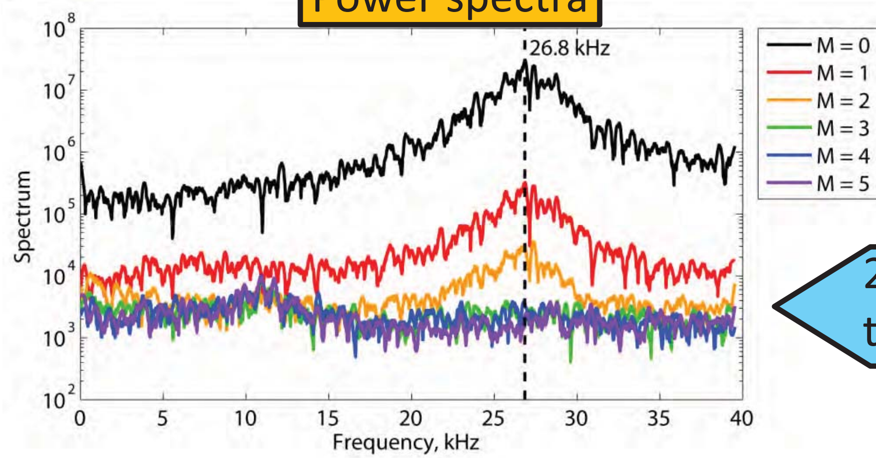
Bin data by azimuthal angle

Theta-t diagram



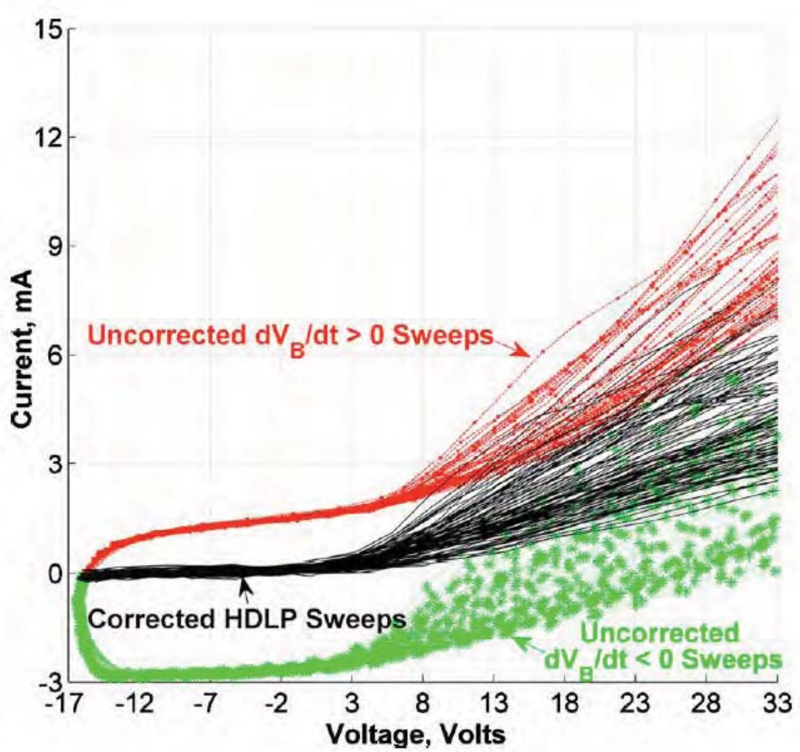
2D Fourier transform

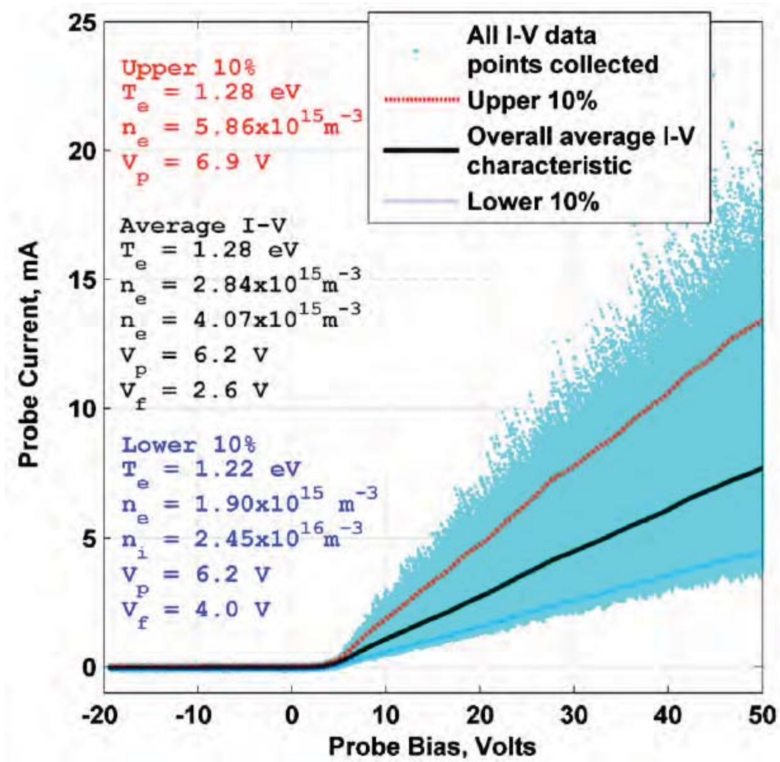
Power spectra



Data analysis:
High-speed Langmuir Probe

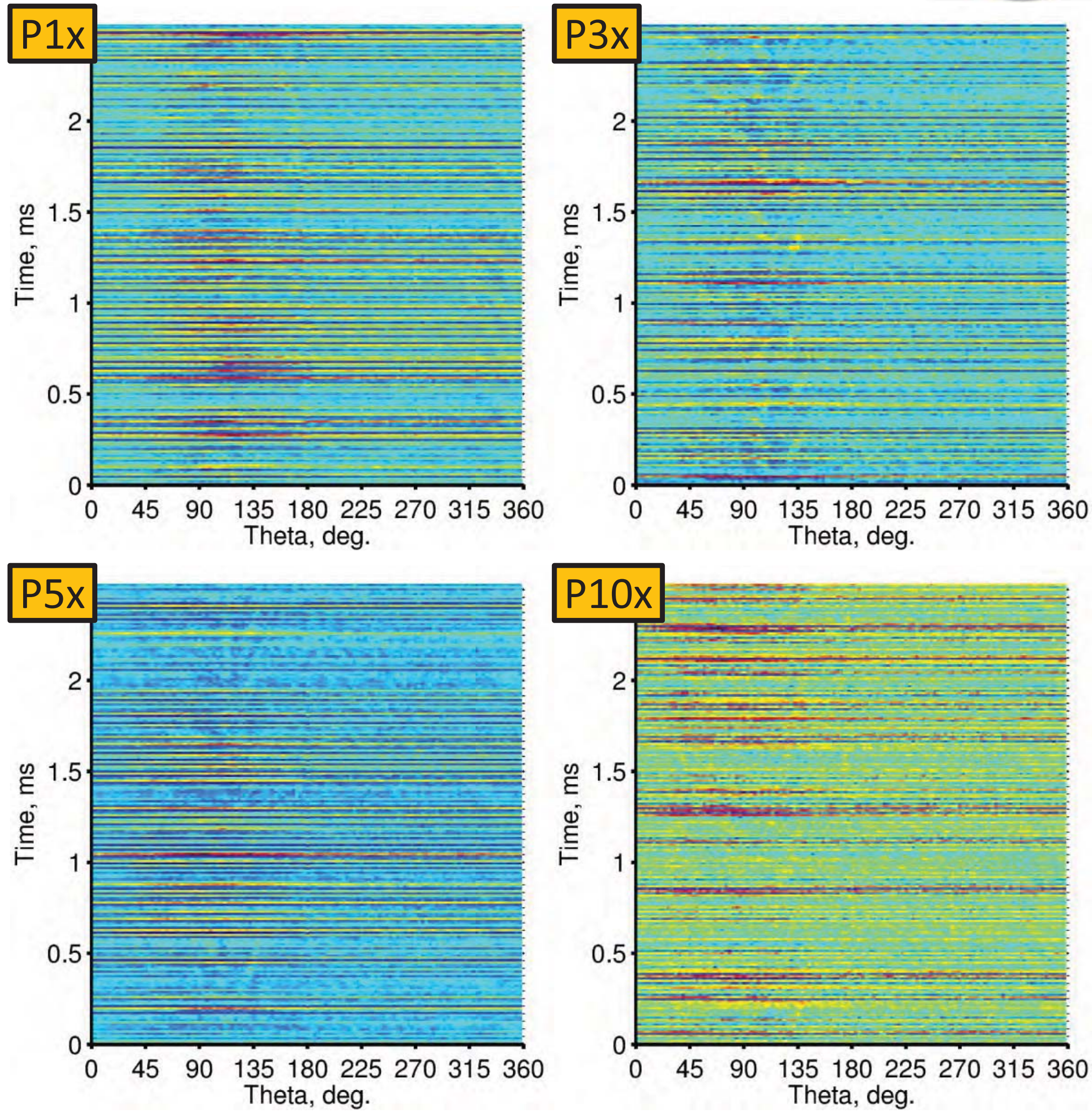
- Null probe data subtracted from active probe data to correct for capacitive effects associated with high-speed sweeping
- Analyzed using standard collisionless non-magnetized thin-sheath Langmuir probe theory





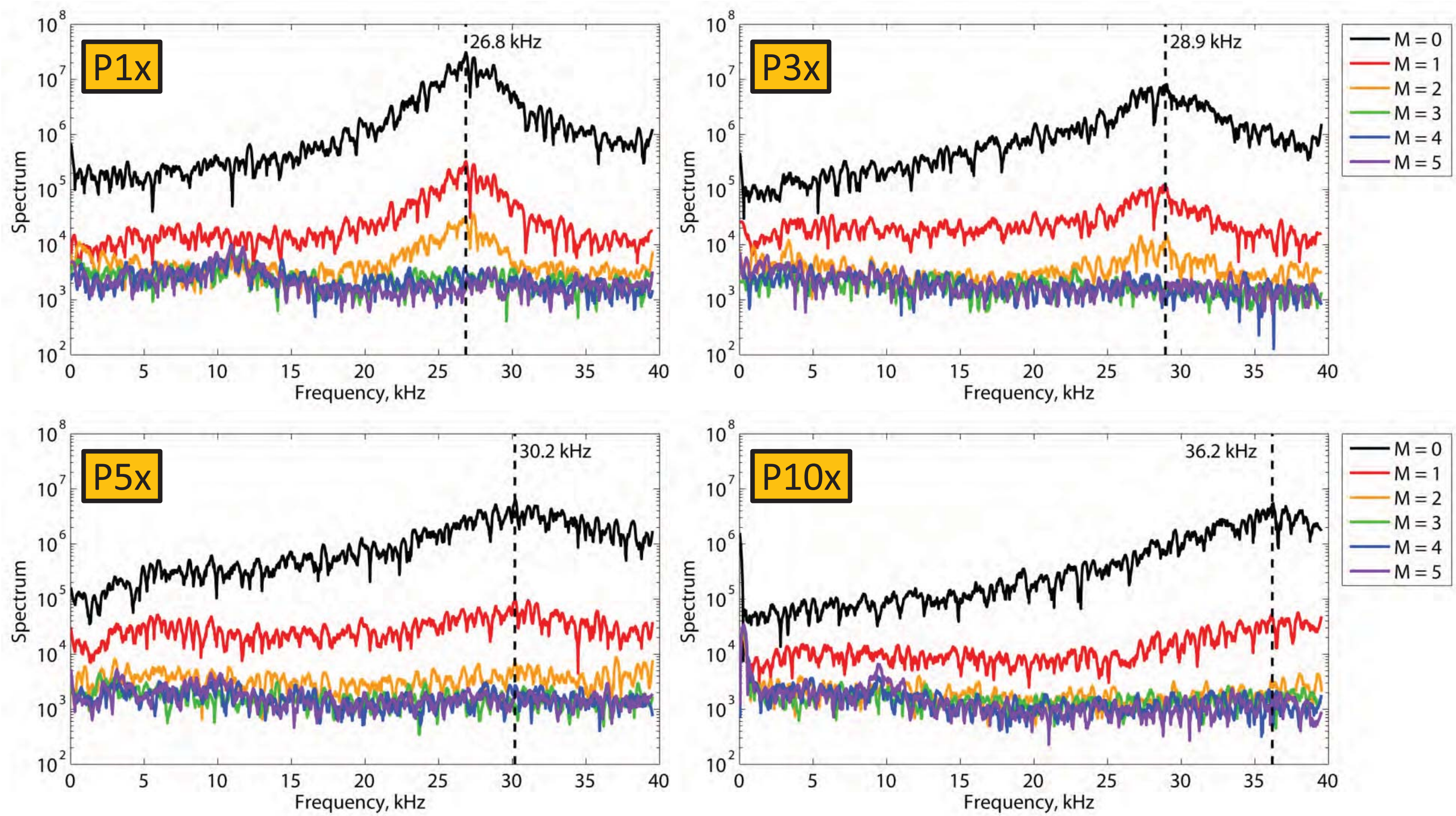
Results: High-speed Camera

- High-speed videos show mostly breathing mode oscillations
- Spokes occasionally appear but is not sustained
- Theta-t diagrams for the 500 V, 3.9 kW throttle point



Results: High-speed Camera

- Power spectra for the 500 V, 3.9 kW throttle point

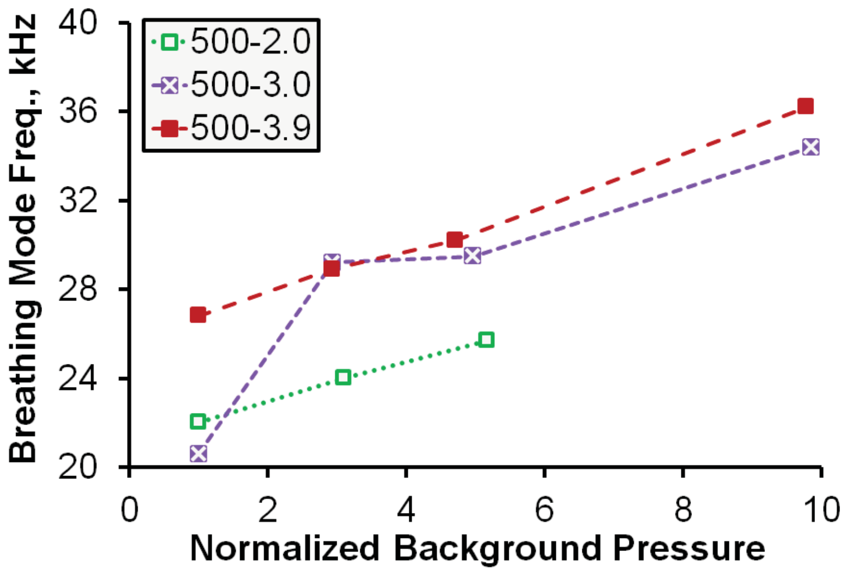


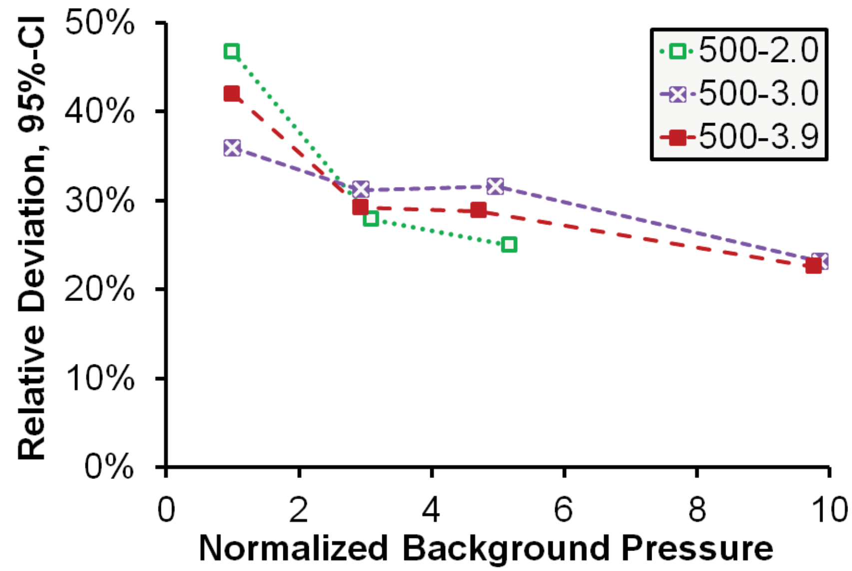
Results: High-speed Camera

- High-speed camera shows breathing mode frequency increases and magnitude decreases with rising background pressure
- Scaling relationship from Fife's work (AIAA-1997-3052) suggests that the characteristic axial length of the ionization/acceleration zone (I/AZ) decreases with rising background pressure

$$2\pi f_i = \frac{\sqrt{u_i u_n}}{L_i}$$

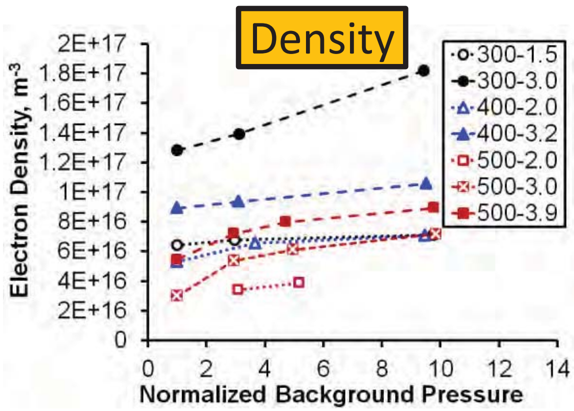
- Note the high-speed camera captures mostly light from I/AZ

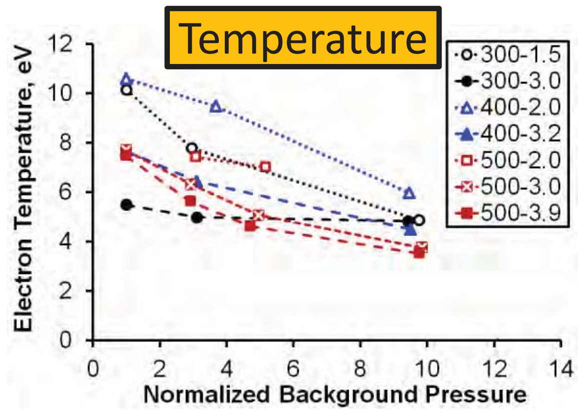


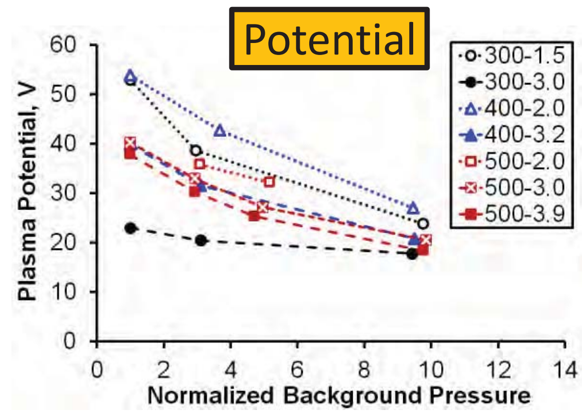


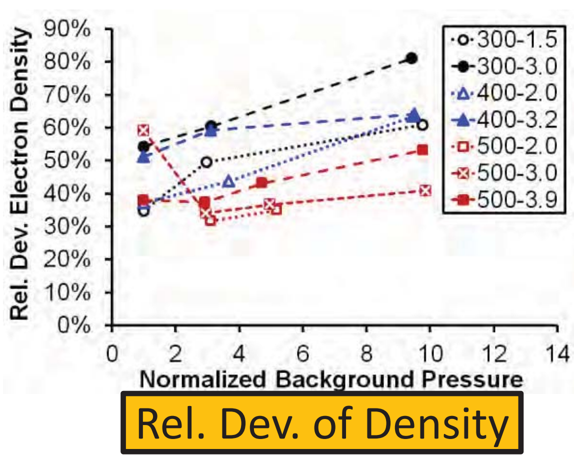
Results: High-speed Langmuir Probe

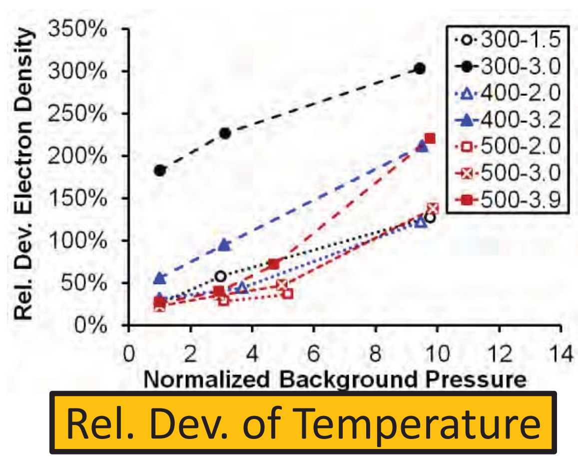
- Data shown is averaged of the two upstream probes at 10 cm axially downstream of the exit plane





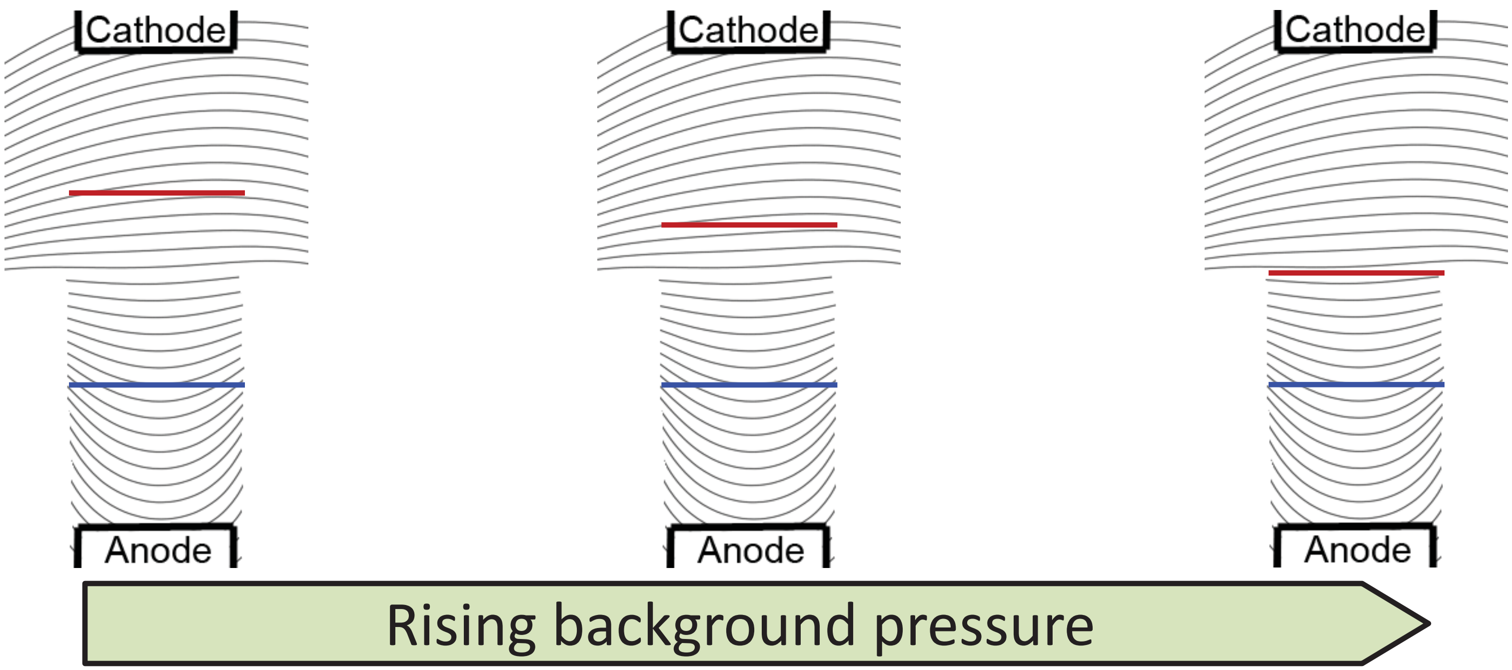






The ionization/acceleration zone is shortening with rising background pressure.

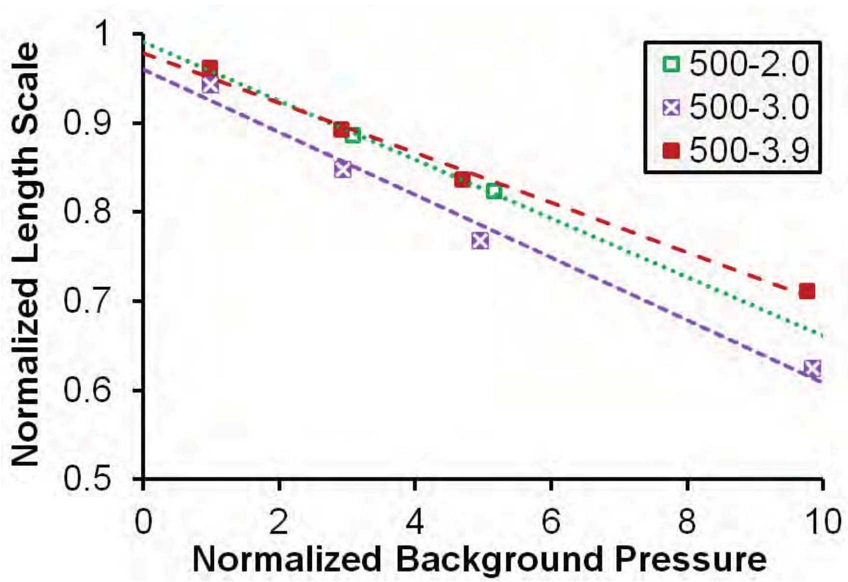
- Assumption: breathing mode enhance electron transport, upstream edge fixed by magnetic field and anode
- Downstream edge of I/AZ recedes into channel -> less field lines to cross between downstream and upstream edges -> lower breathing mode magnitude needed
- At the same time, more field lines to cross between downstream edge and cathode



***Red** line denote **downstream** edge of I/AZ, **blue** line denote **upstream** edge*

Engineering Analysis: Test Guidelines

- If preceding physical picture is correct, can formulate test guidelines by levying a requirement on the erosion band location
- Assume: I/AZ axial length of few tens mm (from probe and LIF data), impose a requirement that the erosion band shift by no more than a few mm (assumed design margin) -> I/AZ length cannot change by more than 10%
- Axial length scale change of 0.9 -> normalized pressure of 2-3
- Conservative estimate translates this normalized pressure to <u>1.2e-6 Torr per mg/s</u>



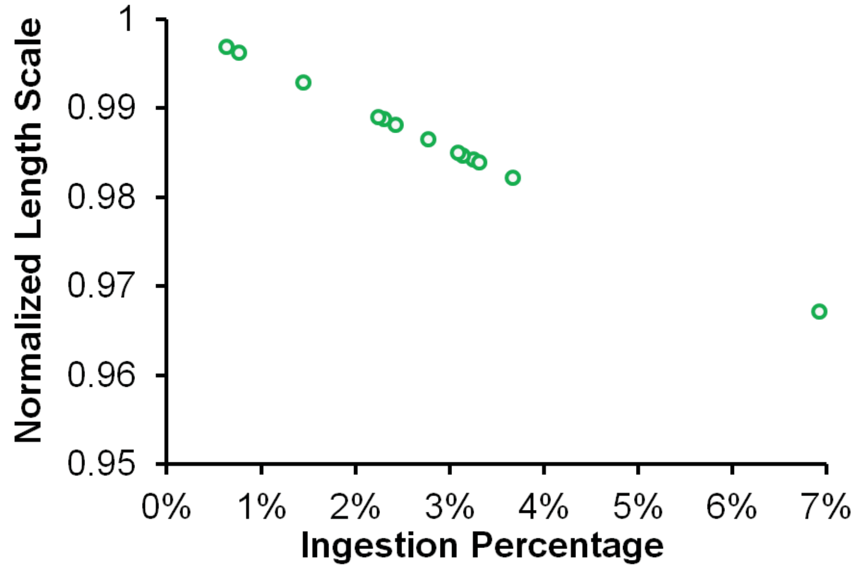
Dimensional Analysis: Shortening of Ionization/Acceleration Zone

- Try dimensional analysis to discover cause of I/AZ shortening
- Start with relationship between plasma potential and charge density
- Note Laplacian of Φ scales as V/L^2

$$\nabla^2 \Phi = -\rho/\varepsilon_0$$

$$L_i \sim \frac{1}{\sqrt{n_e}} \sim \frac{1}{\sqrt{MR_a + MR_i}}$$

- Assume ingested stream has same species composition, propellant utilization and current utilization as main propellant stream
- Use ratio of discharge current to mass flow rate and excess discharge current to calculated ingested mass flow rate
- Predicted change is about one order of magnitude too low



Conclusion

- Combined high-speed camera and Langmuir probe data suggests upstream movement of the ionization/acceleration zone with rising background pressure
- A physical model is proposed where the upstream edge is fixed while the downstream edge recedes into the channel with rising background pressure
  - Data is consistent with assuming that breathing mode oscillation enhances electron transport across magnetic field lines
- Assuming ionization/acceleration zone length inversely proportional to breathing mode frequency (from Fife's work), can convert requirement on erosion band location into requirement on maximum background pressure -> recommend at most **1.2e-6 Torr per mg/s** for HiVHAc EDU2 testing
- Previous work (IEPC-2013-058) suggested **5e-7 Torr per mg/s** for at most 2% increase in measured thrust, which is more stringent

Acknowledgment

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  - NASA Science Mission Directorate In-Space Propulsion project for funding this work,
  - Eric Pencil for managing this work,
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Questions