Thrust Characterization and Plasma Diagnostics for an Adamantane Thruster

Jonathan Fisher†, Nicholas Kiley‡, Marin Davis†, and Brian Phu‡

Advisors:
Lubos Brieda§; Matthew Gilpin¶

† Student in AME, University of Southern California

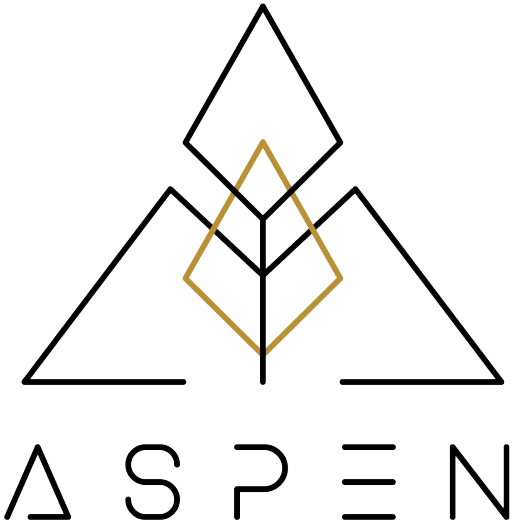
‡ Student in ASTE, University of Southern California

§ Part-time Lecturer of Astronautical Engineering, University of Southern California

¶ Associate Professor of Aerospace and Mechanical Engineering Practice, University of Southern California

Motivations

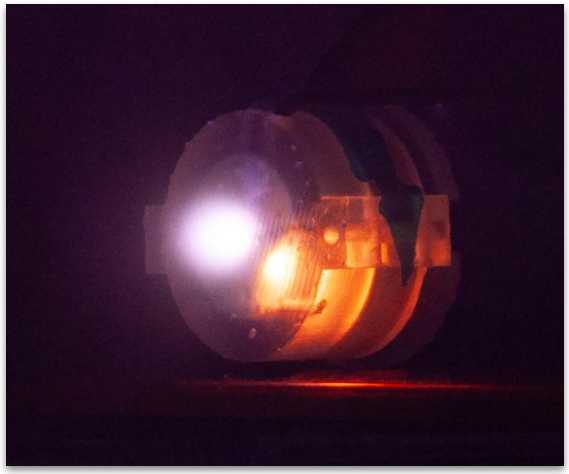
- Developing Adamantane-based ion thruster at USC ASPEN Lab
- Need to characterize the thrust and plasma to compare different iterations of the the thruster
- Constructing double langmuir probe and thrust stand for indirect and direct characterization

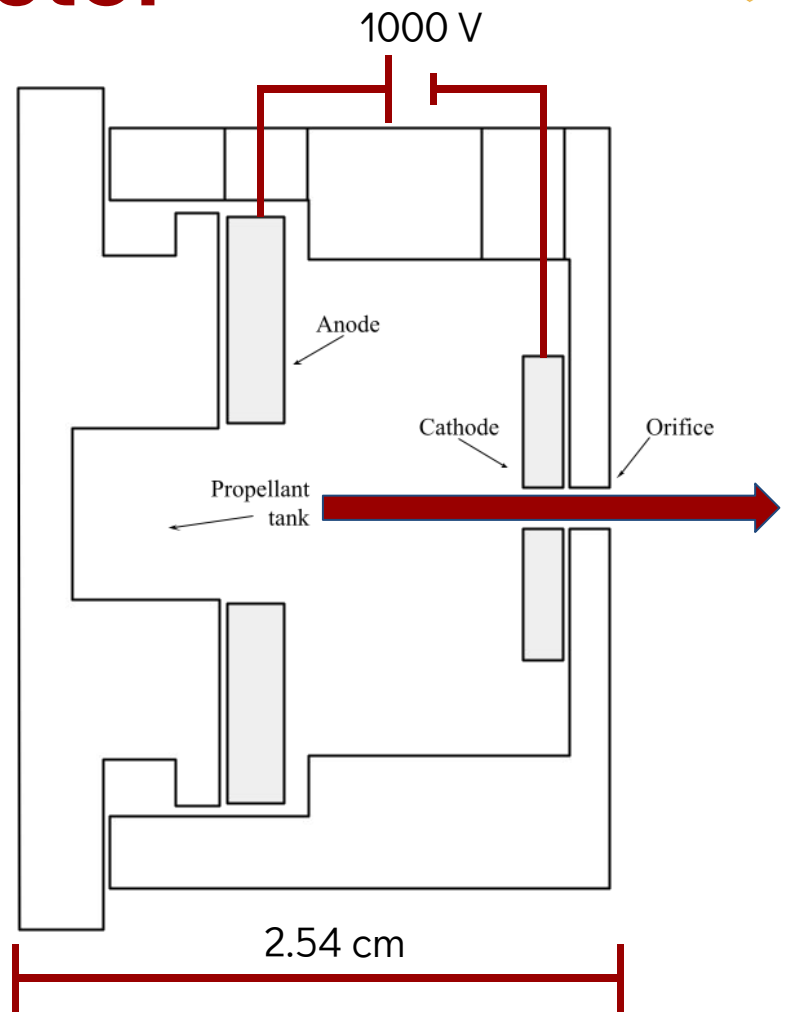


Advanced Spacecraft Propulsion & Energy Lab

Adamantane Thruster

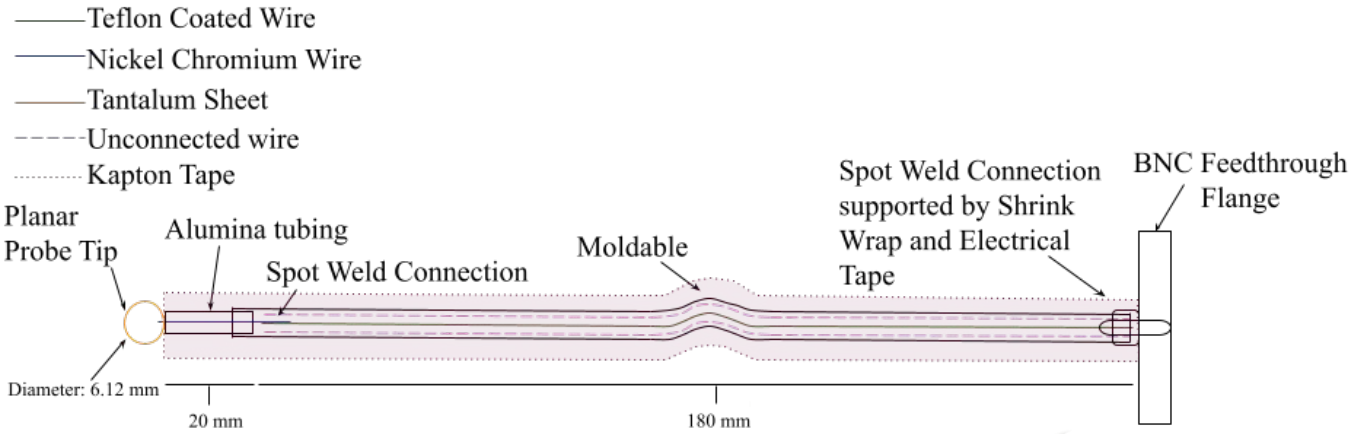
- 3D printed resin thruster
- Solid adamantane ($C_{10}H_{16}$) propellant that is sublimated under vacuum
- Neutral adamantane particles are simultaneously ionized by electrons emitted from the cathode and accelerated towards the orifice



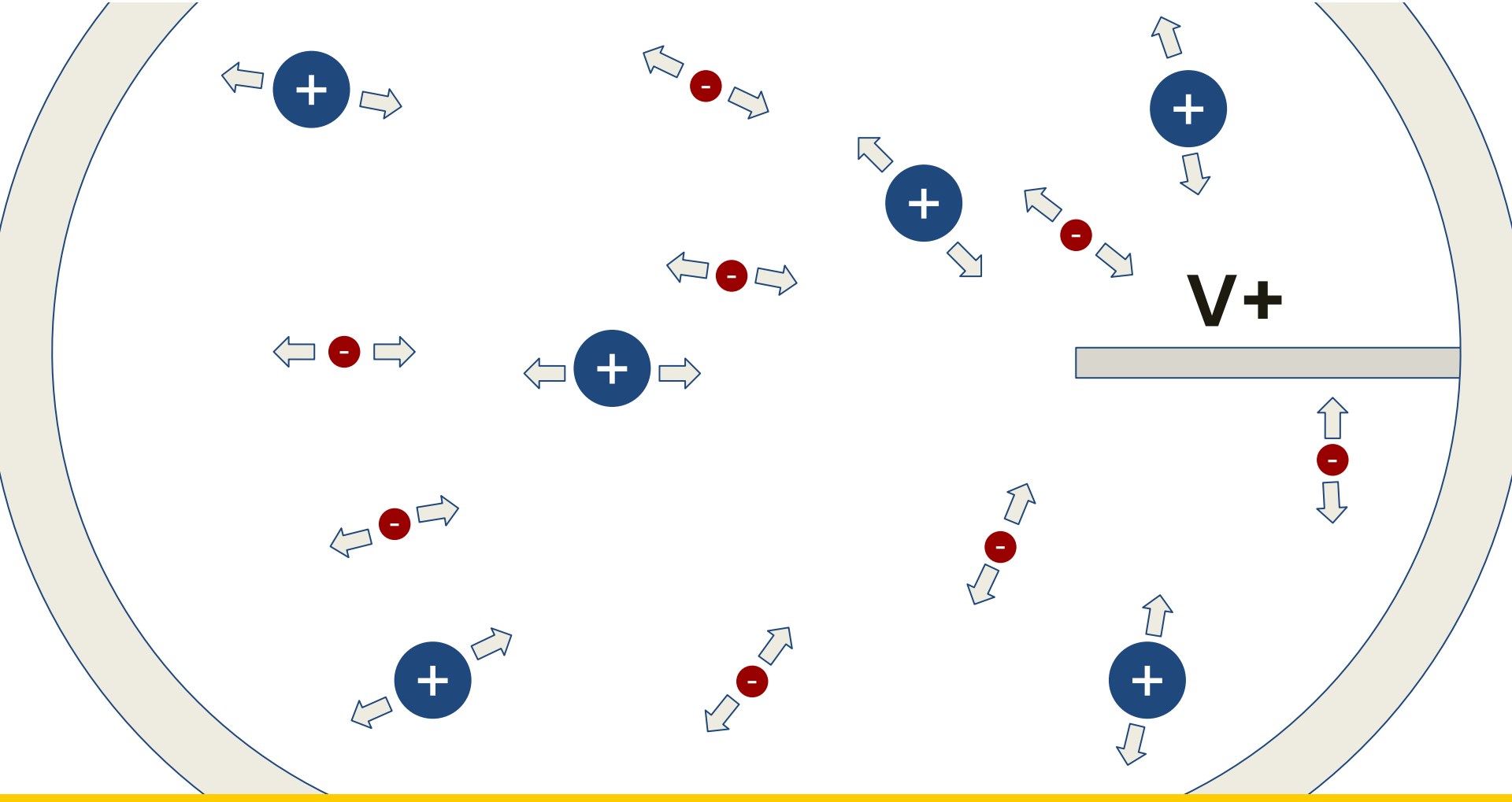


Langmuir Probe

- Previously, created and utilized Langmuir Probe

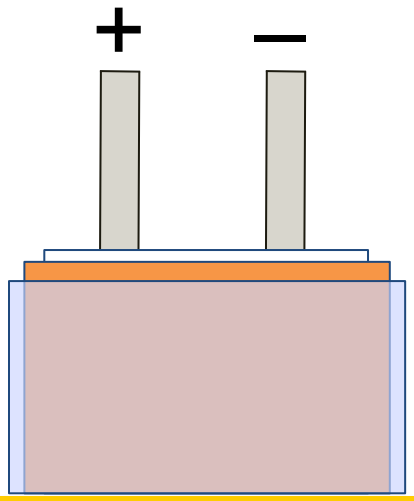


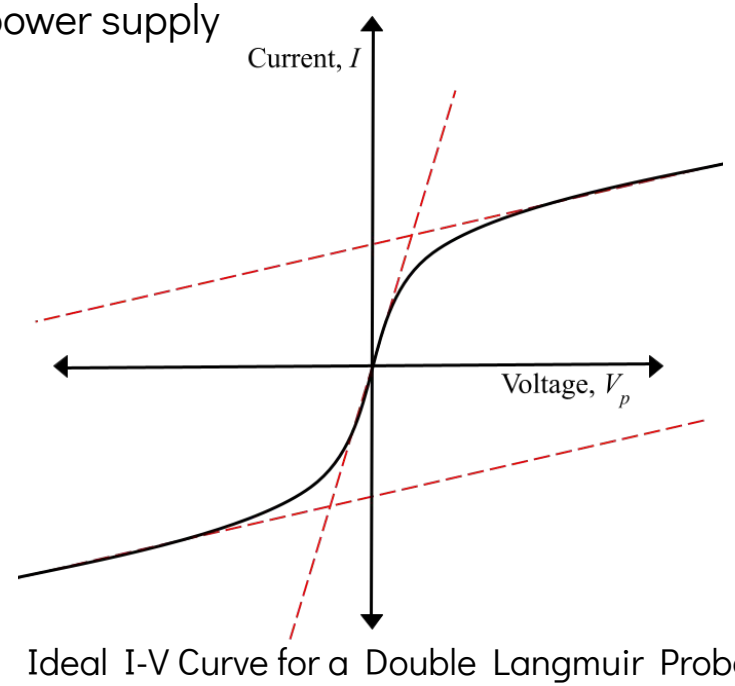
Plasma Characterization



Double Langmuir Probe

- Next step: double langmuir probe
  - Saturation and prevention of Debye sheath shielding
- Probe tips are biased against each other
  - One probe tip is connected to ground of variable power supply
  - Second probe tip is biased to voltage set by power supply

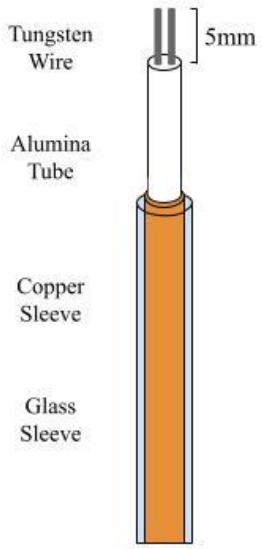


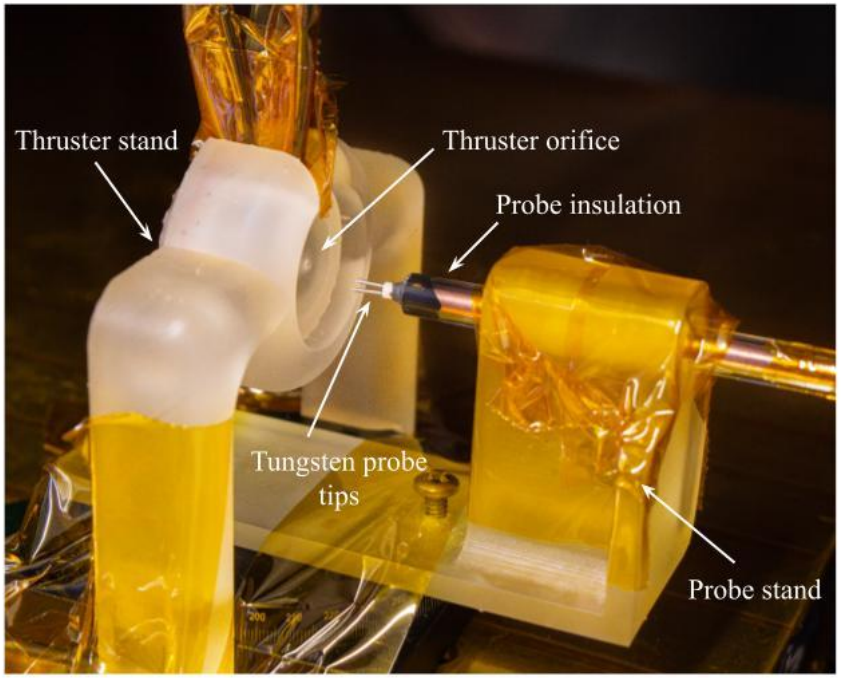


Ideal I-V Curve for a Double Langmuir Probe

Double Langmuir Probe Setup

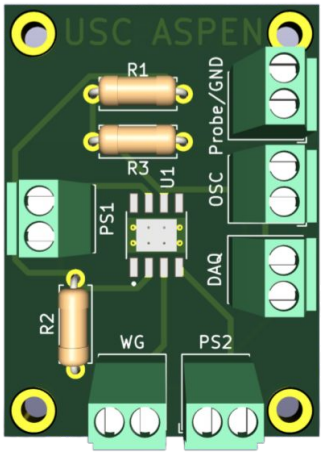
- Tungsten wire probe tips
- Concentric layers of alumina tube, copper, and glass
- Positioned probe tips near center of plume
- Probe tips close to plasma exit point on thruster

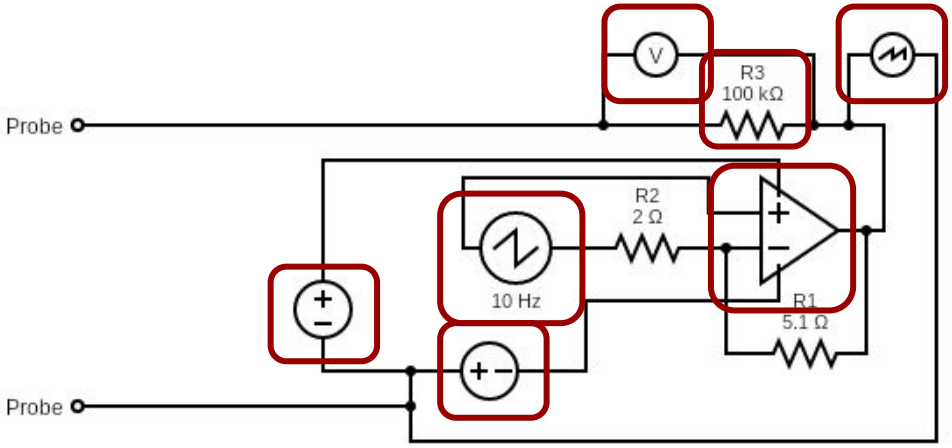




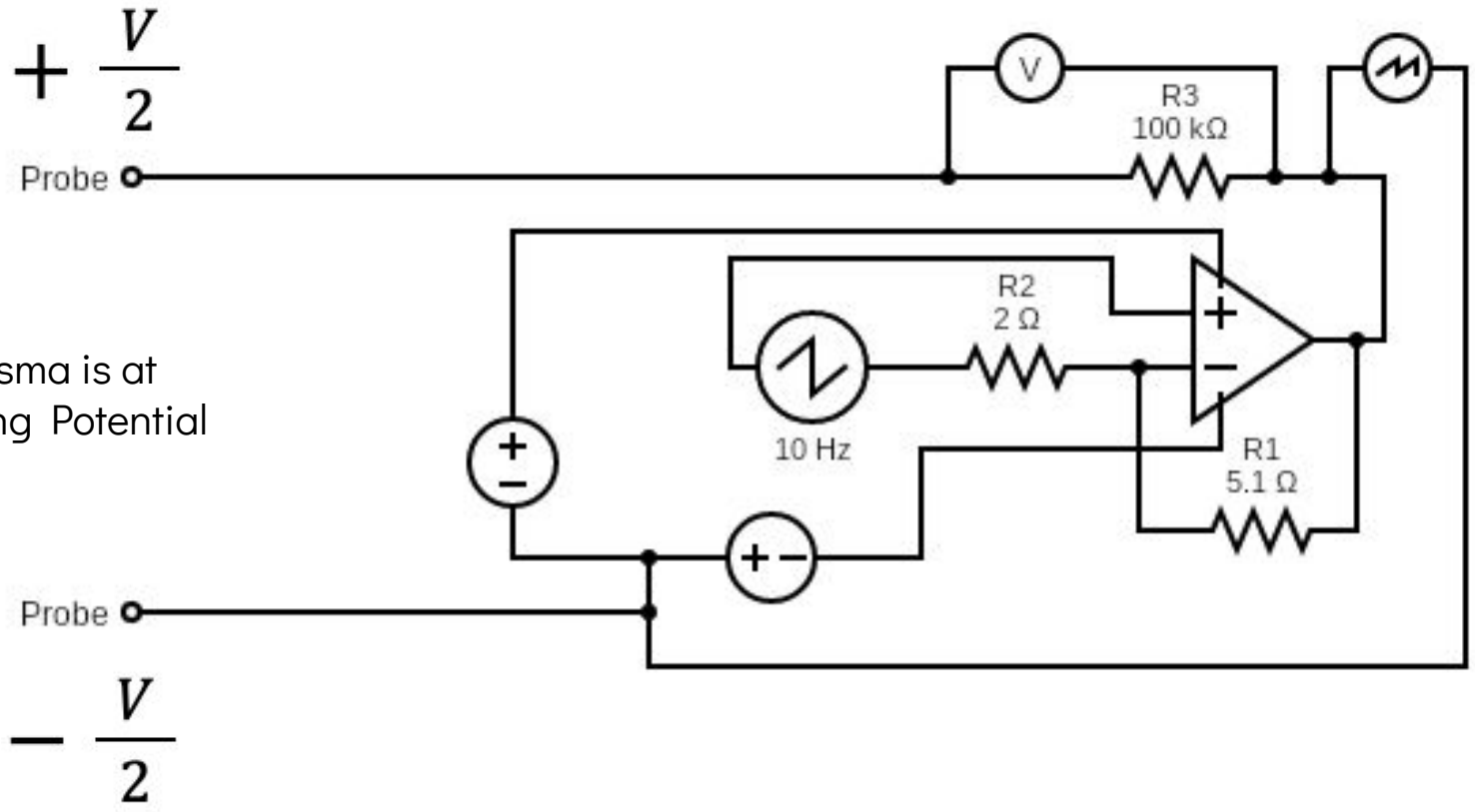
Probe Data Collection

- Non-Inverting Amplifier Circuit
- A waveform generator varies a voltage
- Voltage over a 100 kΩ resistor measured using an analog DAQ device
- Designed for PCB





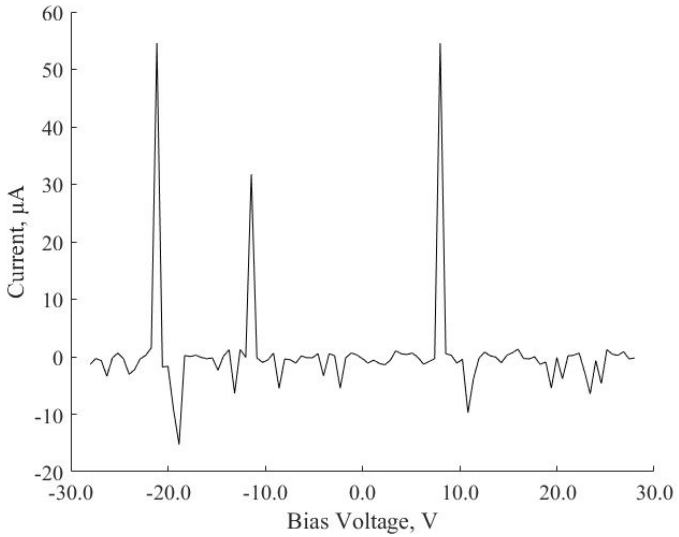
Probe Data Collection



Plasma is at Floating Potential

Double Probe Results

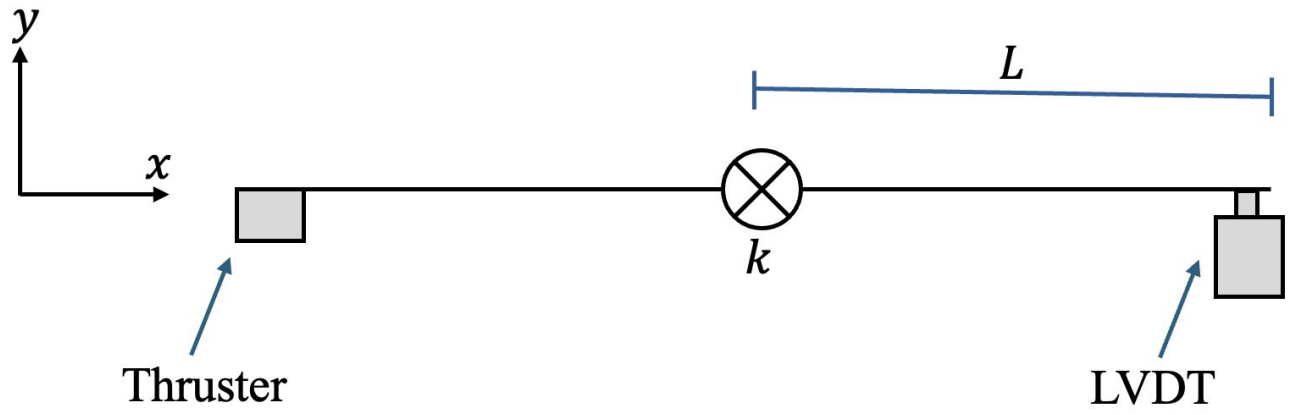
- Collected data with LabView
- Processed to create I-V curve
- Unusable results recorded



Data processed from ambient plasma

Thrust Stand Background

- EP produces low thrust that cannot be measured with typical load cells. Specialized measurement equipment is required to resolve μN forces.
- Torsional configuration uses moment arm to convert thrust F_t to torque about central frictionless pivot point
  - Length *L* and spring constant *k* can be adjusted to control resolution
    - *L*: 0.3 m
    - *k*: 0.311 N*m/rad
- Displacement measured with LVDT corresponds to thrust.

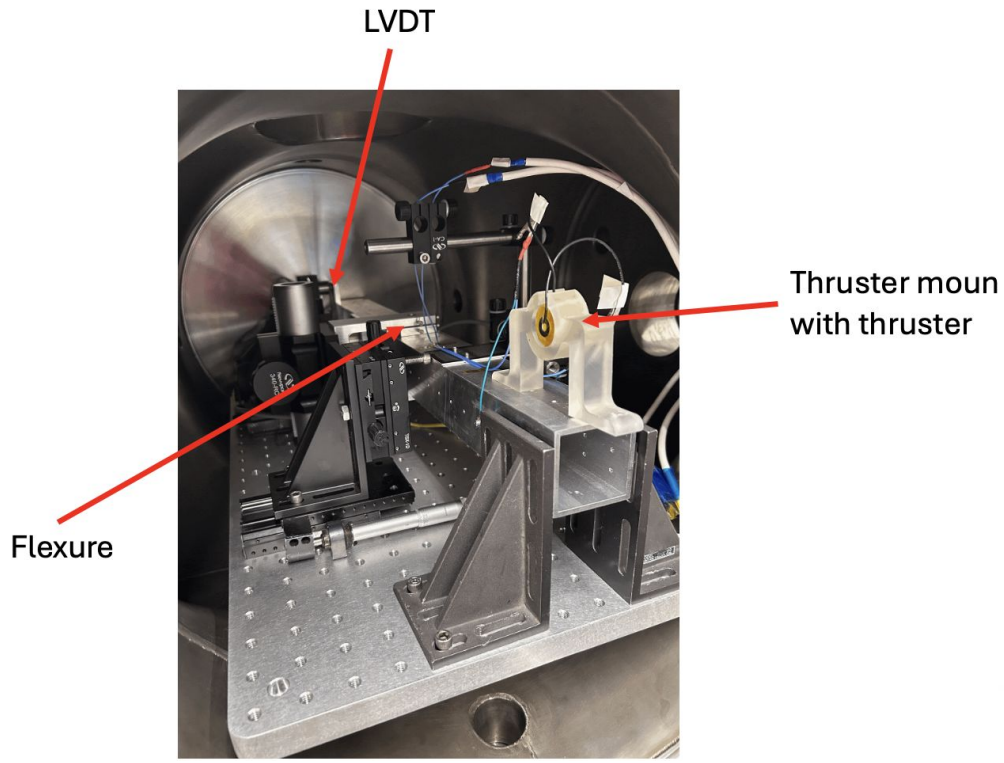


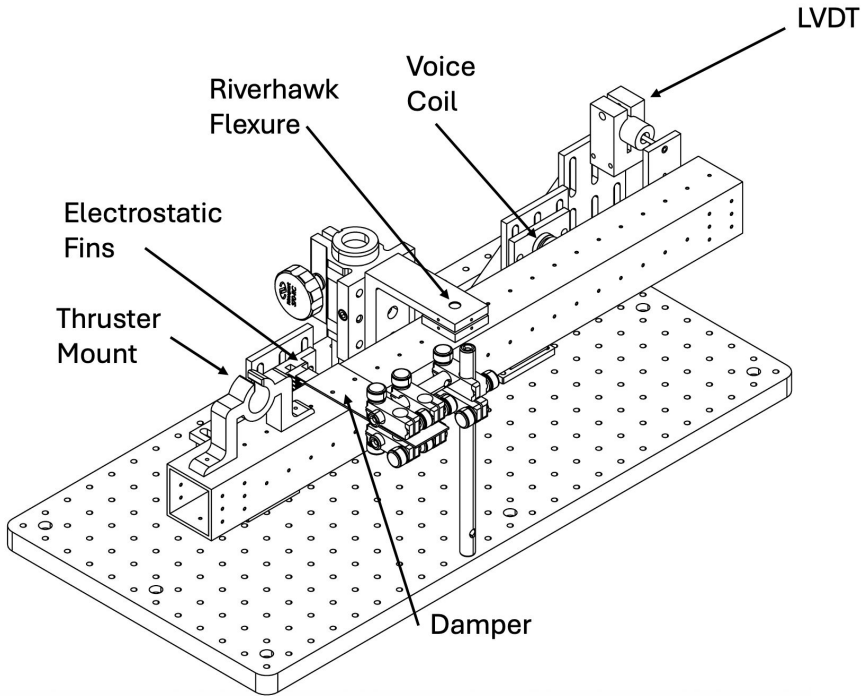
$$\delta = 0.000125 * V$$

$$F_t = \frac{2k * tan(\delta/L)}{L}$$

Thrust Stand Design

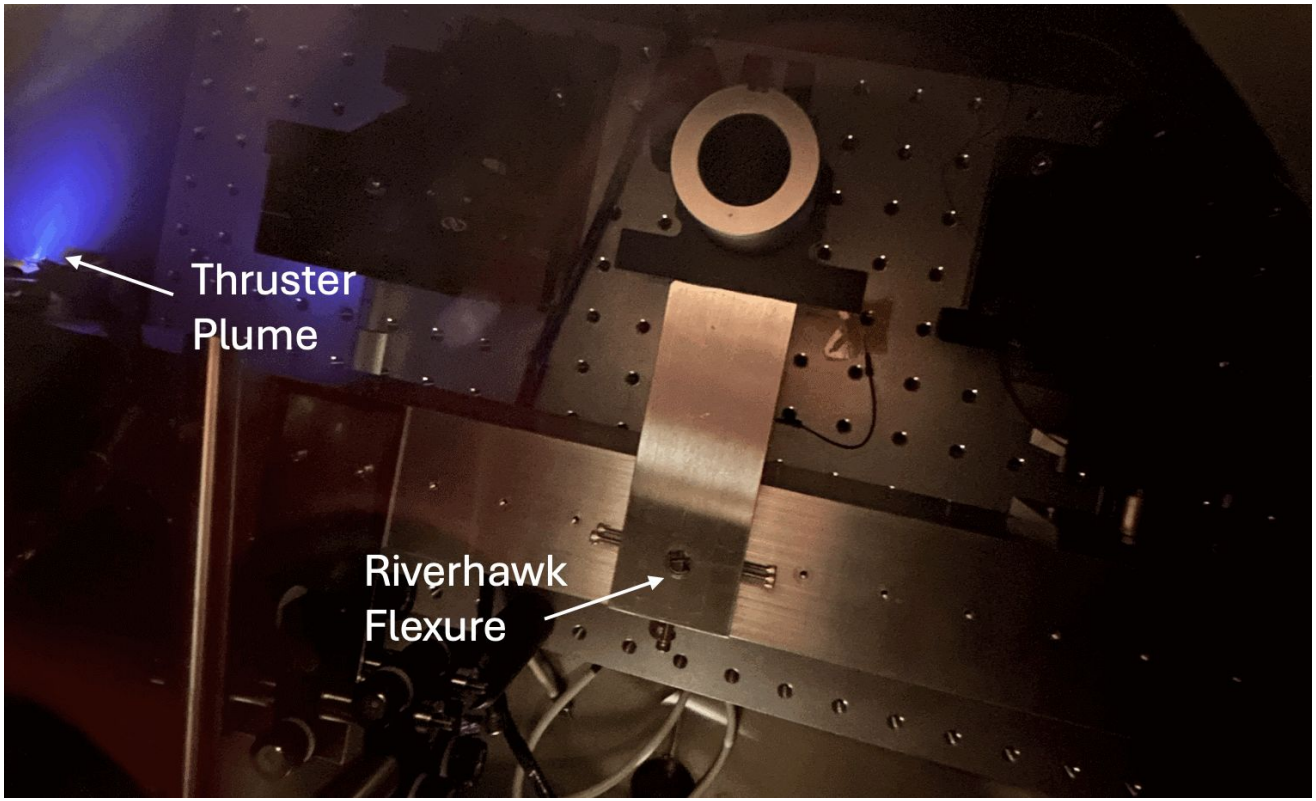
- Active/Passive Control
  - Active uses voice coil actuator to hold stand at 0 position
  - Passive measures displacement with LVDT





Thrust Stand Data Collection

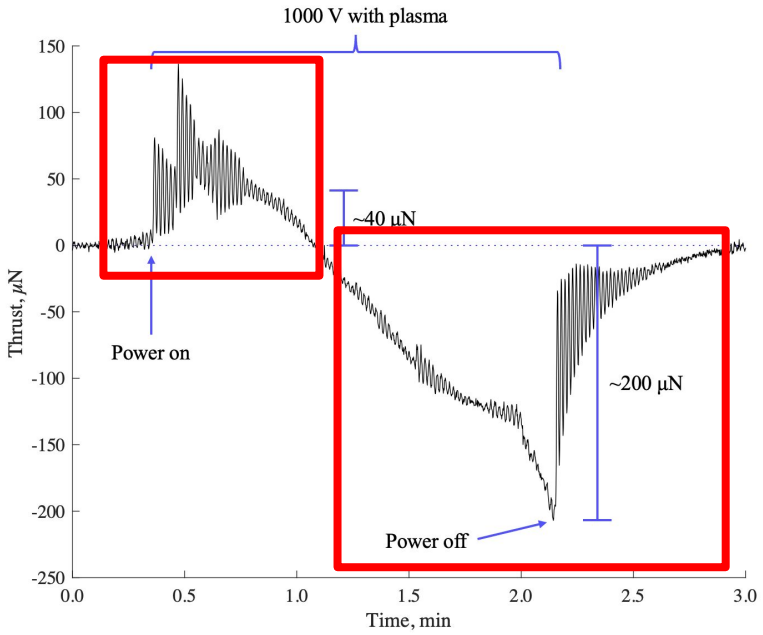
- Data collection with NI DAQ and LabView VI
- Testing conducted primarily at 15.7 Torr



$$\delta = 0.000125 * V$$

$$F_t = \frac{2k * tan(\delta/L)}{L}$$

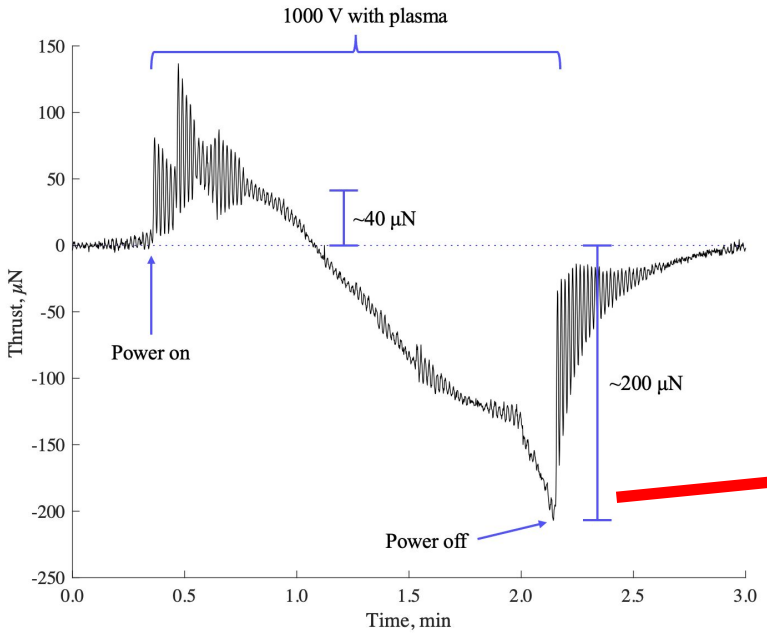
Thrust Stand Results

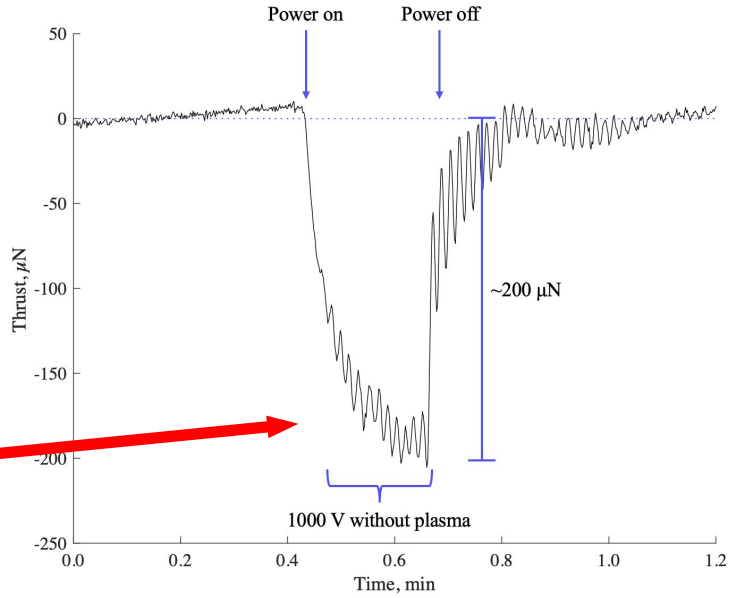


Plasma thrust test

- 15.7 Torr (Roughing Pump)
- No waterfall for wired connections
- Passive Configuration

Thrust Stand Results





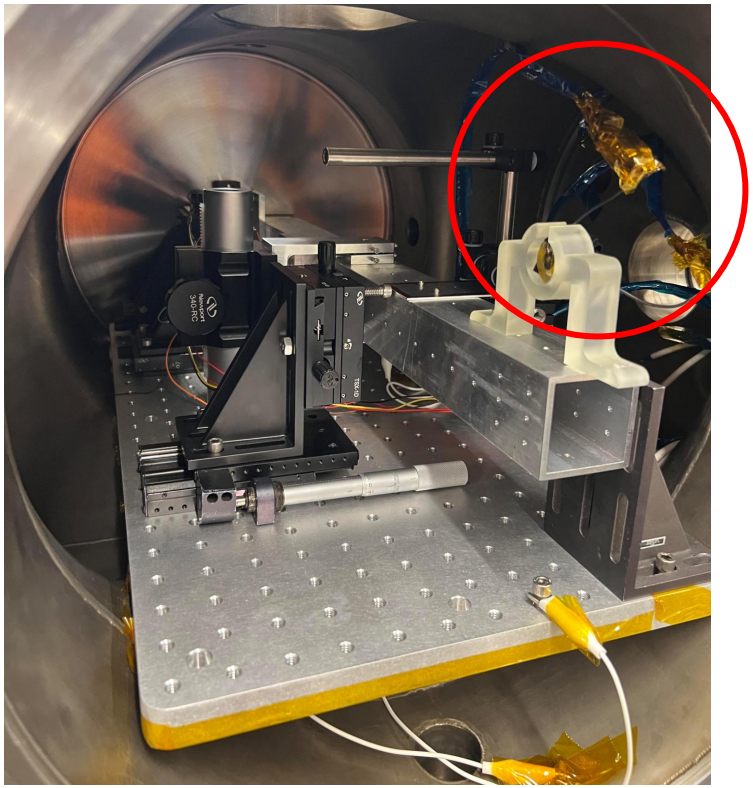
Plasma thrust test

- 15.7 Torr (Roughing Pump)
- No waterfall for wired connections
- Passive Configuration

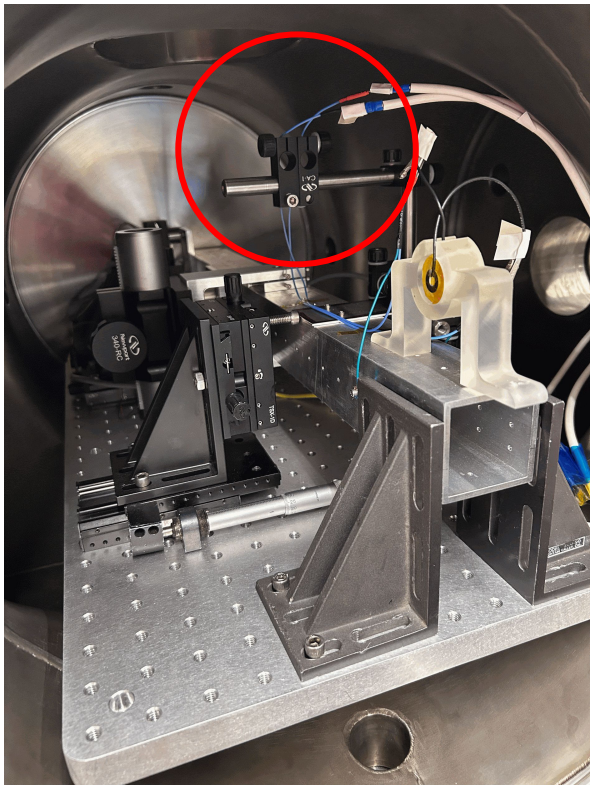
Electrostatic test

- 15.7 Torr (Roughing Pump)
- No waterfall for wired connections
- Passive Configuration

Thrust Stand Results

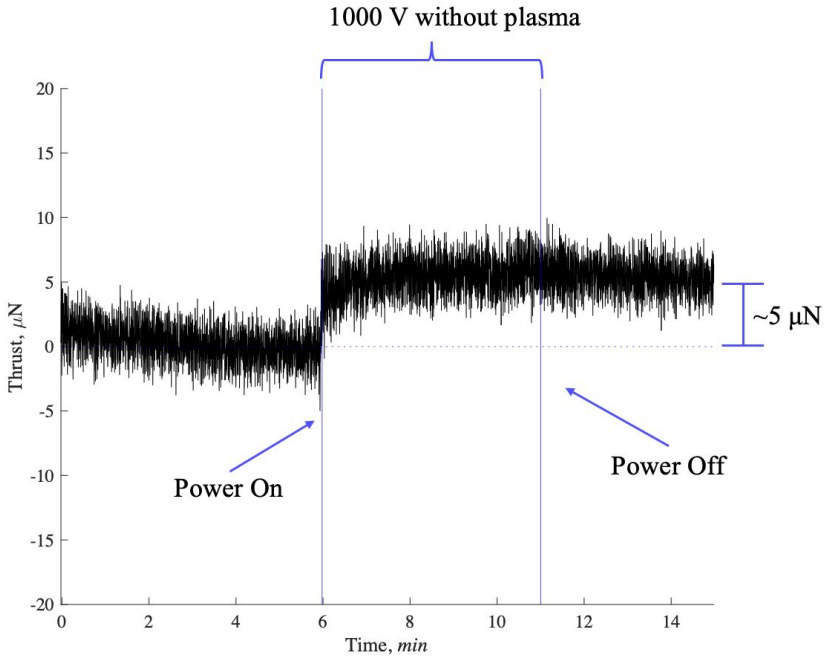


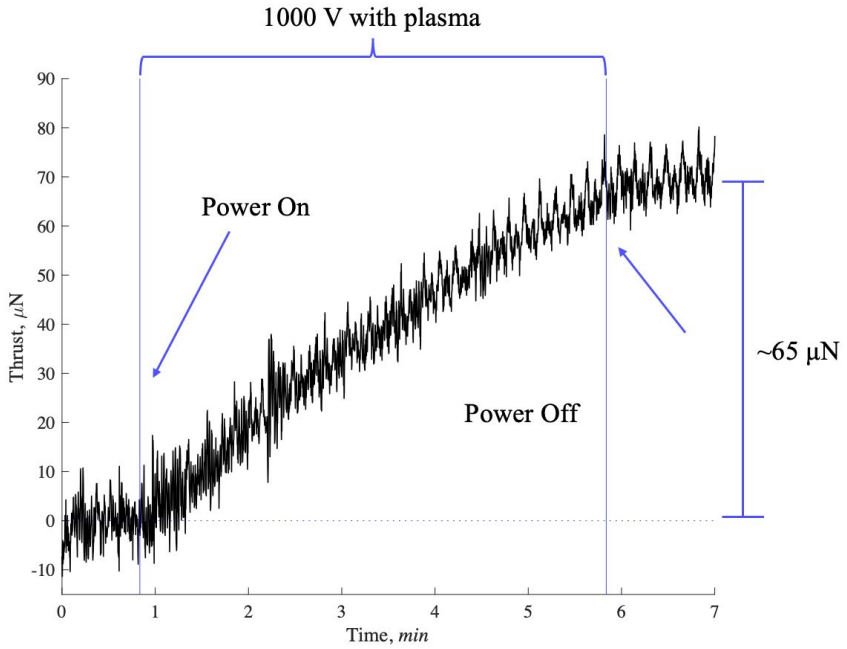
Initial Configuration



Current Configuration

Thrust Stand Results





Electrostatic test

- 0.22 mTorr (Turbo Pump)
- Coax waterfall for wired connections
- Passive Configuration

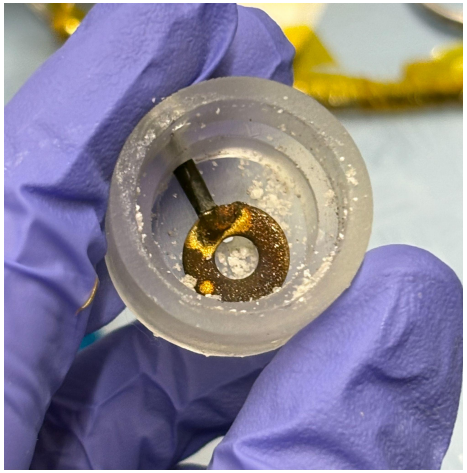
Plasma thrust test

- 15.7 Torr (Roughing Pump)
- Coax waterfall for wired connections
- Passive Configuration

Discussion

Double Langmuir Probe:

- Carbon buildup observed on cathode
- Probe showed significant contamination reducing measurements below observable resolution
- Resin thruster likely had outgassing
- Resin likely reacted with adamantane fragments

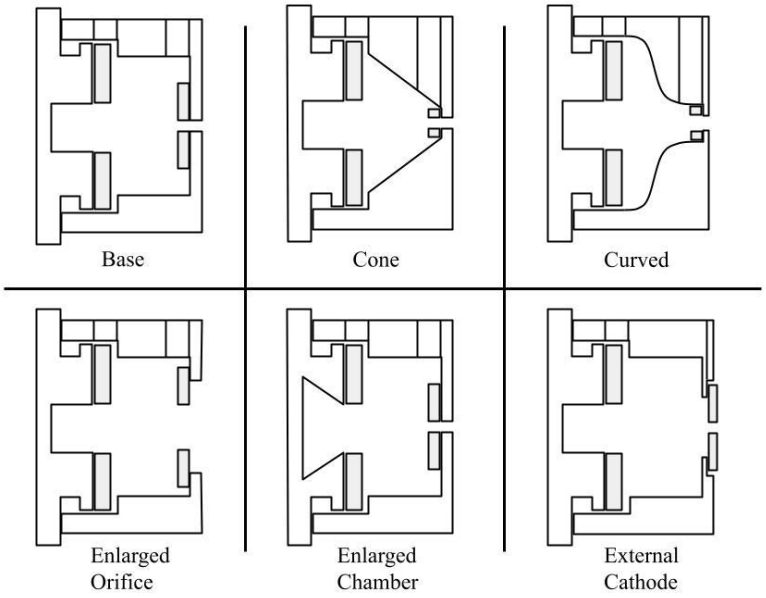


Thrust Stand:

- It it crucial to test the thruster under high vacuum
  - Adamantane sublimating too quickly
- Electrostatic issues mostly fixed
  - Significant electrostatic interference due to thruster power wires has been removed

Conclusion

- Thrust measured to on the order of 40 μN
  - Future plans to incorporate active control of stand
- Continued development of langmuir probe iterations
- New diagnostic tools to validate results
- Thruster redesign needed
  - Reduce outgassing and carbon buildup
  - Increase control of adamantane release in the ionization chamber



Q & A

Contact Information

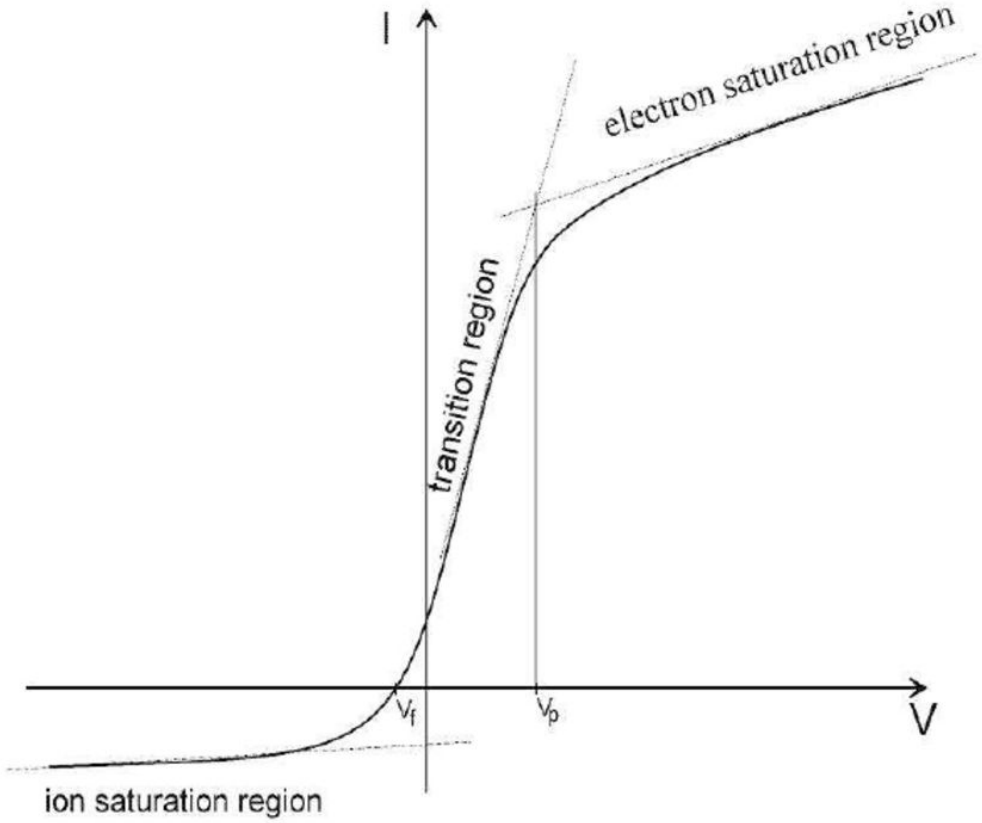
fisherjr@usc.edu ◆ nkiley@usc.edu ◆ mbdavis@usc.edu ◆ brianphu@usc.edu

Bonus slides

Previous measurements recorded

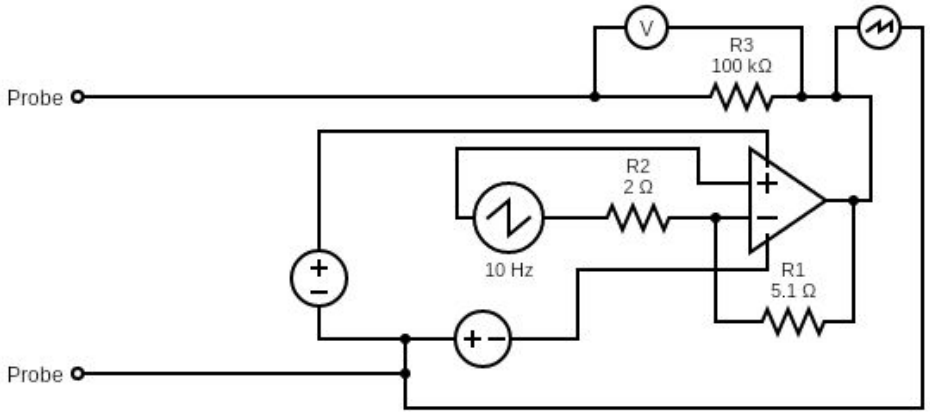
- Electron density of 4.17 1017 m-3
- Electron temperature of 2.9 eV
- Plasma potential of 12.63 V,
- Floating potential of 9.9 V

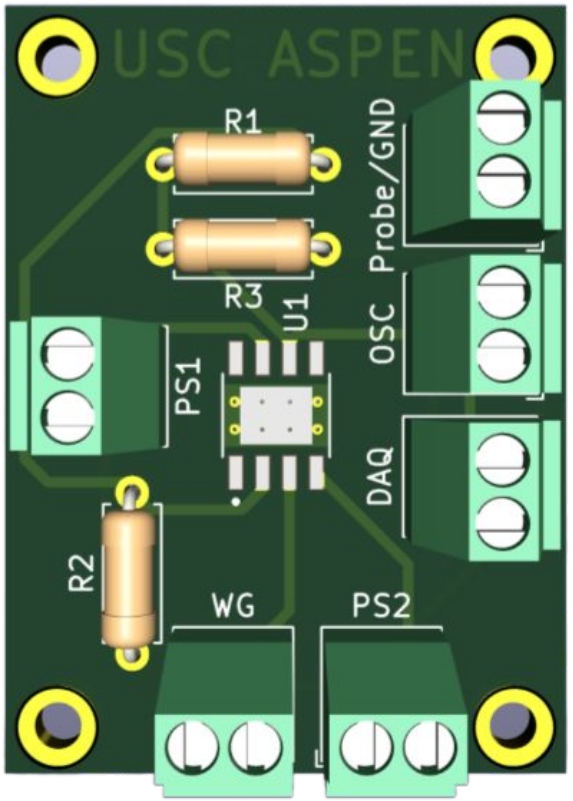
Bonus slides



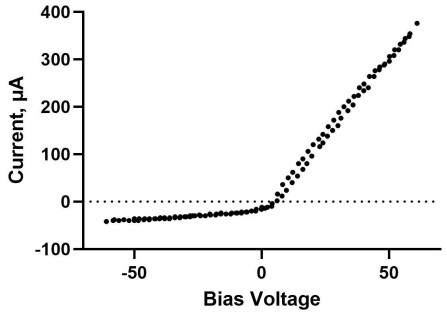
Merikallio, Sini. (2007). Analysis and visualisation software for Demeter Langmuir probe instrument.

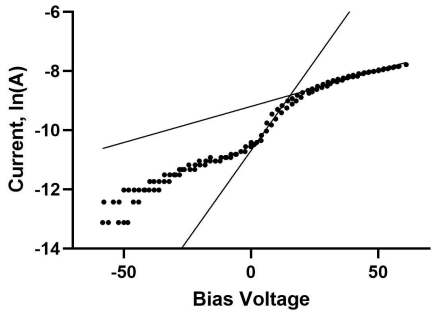
Bonus slides



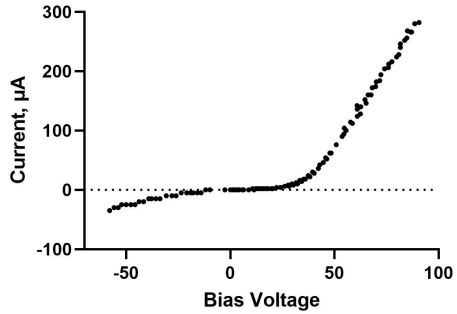


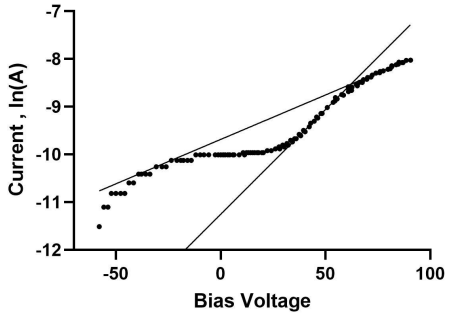
Bonus slides





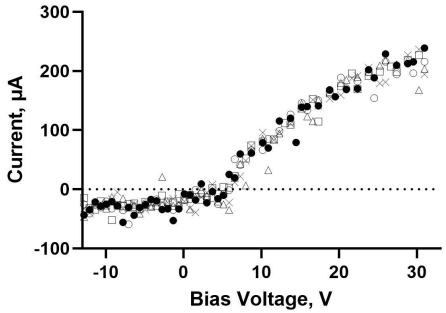
Data from automated method showing a) I-V trace of the probe in ambient plasma and b) $\ln(I_{probe}-I_{sat})$ plotted against bias voltage.

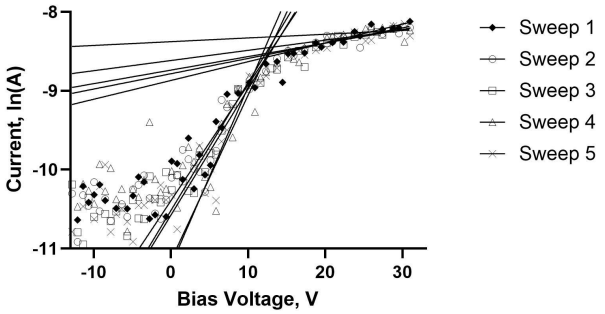




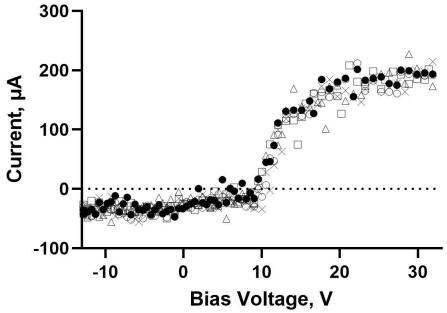
Data from manual method showing a) I-V trace of the probe in adamantane plasma and b) $\ln(I_{probe}-I_{sat})$ plotted against bias voltage.

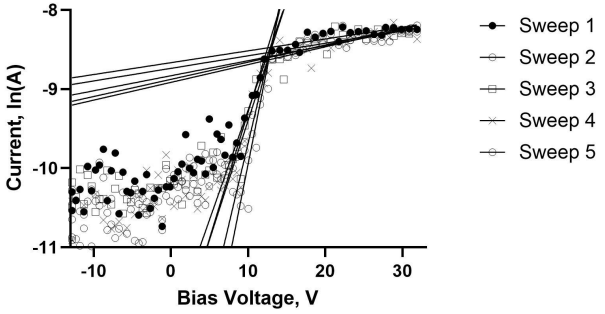
Bonus slides





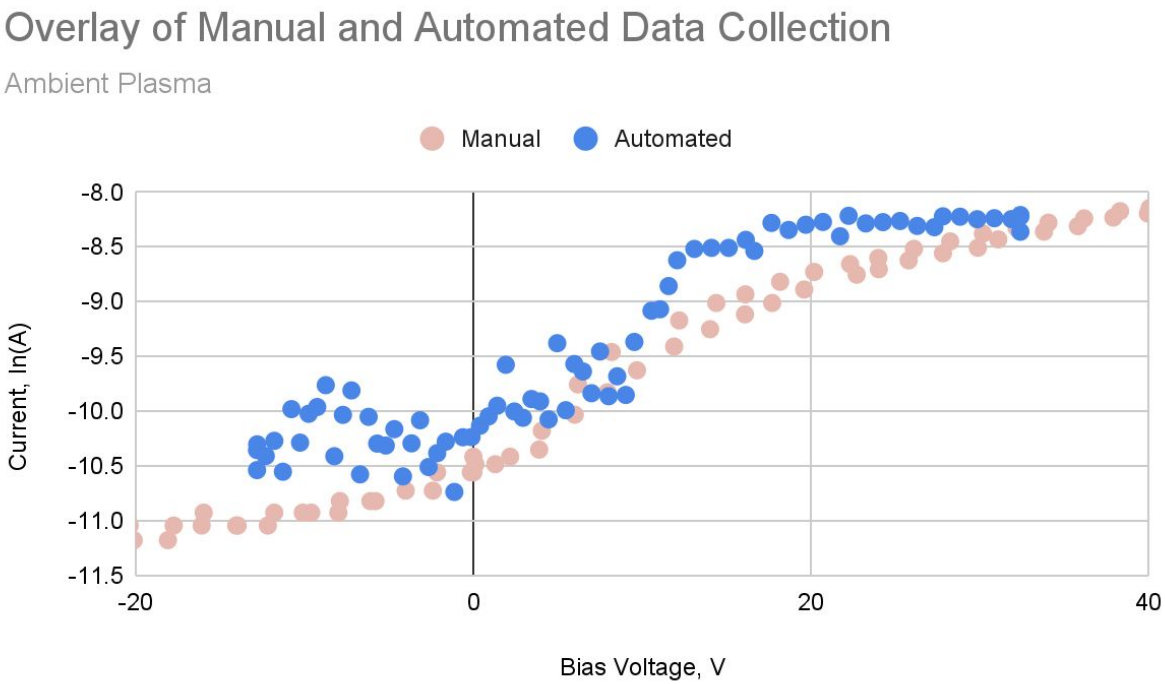
Data from automated method showing a) I-V trace of the probe in adamantane plasma and b) $\ln(I_{probe}-I_{sat})$ plotted against bias voltage.





Data from manual method showing a) I-V trace of the probe in ambient plasma and b) $\ln(I_{probe}-I_{sat})$ plotted against bias voltage.

Bonus slides



Bonus slides

$$I_{sat} = \quad - I_{probe} \tag{1}$$

$$ln(I_{probe} - I_{sat}) = q(V_{bias} - \phi_f)/kT_e \tag{2}$$

$$slope = \frac{q}{kT_e} \tag{3}$$

$$I_{sat} = I_{bohm} = 0.6qA_s qn_e \sqrt{\frac{k_b T_e}{M}} \tag{4}$$

$$n_e = \frac{I_{sat}}{qA_s 0.6} \sqrt{\frac{M}{k_b T_e}} \tag{5}$$

References

[1] Coen, C., Zaretsky, A., "Characterization of an Adamantane Thruster by a Langmuir Probe," *AIAA Aerospace Research Central*, 2024-80550, 2024 Regional Student Conferences, January 2024, https://doi.org/10.2514/6.2024-80550.

[2] Castro, R.M., Cirino, G.A., Verdonck, P., Maciel, H.S., Massi, M., Pisani, M.B. and Mansano, R.D, "A Comparative Study of Single and Double Langmuir Probe Techniques for RF Plasma Characterization," Contrib. Plasma Phys., 39: 235-246, 1999, https://doi.org/10.1002/ctpp.2150390305.

[3] Brown, Jordan, "Design and Implementation of a Double Langmuir Probe for an RF Plasma," *Princeton Plasma Physics Laboratory*, 14 Aug. 2017, https://w3.pppl.gov/ppst/docs/brown.pdf.

[4] Polk, J. E., Pancotti, A., Haag, T., King, S., Walker, M., Blakely, J., and Ziemer, J., "Recommended Practices in Thrust Measurements," *International Electric Propulsion Conference*, IEPC-2013-440, Washington, DC, Oct. 2013, https://hpepl.ae.gatech.edu/papers/2013_IEPC_Polk.pdf.

[5] Kukar, O., Elmer-Schurr, K., Cutchins, K., Fisher, J., Lo, E., Coen, C., Zaretsky, A., Wu, M., Brieda, L., Gilpin, M., "Design and Characterization of an Adamantane Thruster for Cubesat Applications," *International Electric Propulsion Conference*, IEPC-2024-163, June 2024, URL: https://electricrocket.org/IEPC_2024/163.pdf.

[6] Bhattarai, Shankar, "Interpretation of Double Langmuir Probe I-V Characteristics at Different Ionospheric Plasma Temperatures," Department of Physics, Patan Multiple Campus, Tribhuvan University, June 2017, https://doi.org/10.3844/ajeassp.2017.882.889.

[7] Chen, Francis F. "Lecture Notes on Langmuir Probe Diagnostics," Electrical Engineering Department, University of California, Los Angeles, June 2003, URL: https://www.seas.ucla.edu/~ffchen/Publs/Chen210R.pdf.

[8] Stenzel, R. L., Gruenwald, J., Ionita, C., and Schrittwieser, R., "Electron-rich sheath dynamics. I. Transient currents and sheath-plasma instabilities," *Physics of Plasmas* 18, 062112, 2011, https://doi.org/10.1063/1.3601858.