

Initial Operation of the CubeSat Ambipolar Thruster

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J. P. Sheehan*, Timothy A. Collard†, Frans H. Ebersohn‡ and Benjamin W. Longmier§
University of Michigan, Ann Arbor, MI, 48109, USA

The development progress of the CubeSat Ambipolar Thruster (CAT) is reported. Measurements of the magnetic nozzle field are in good agreement (to within 5%) of design values, demonstrating that permanent magnets can be used to generate a magnetic nozzle. CAT was fired using argon as a propellant at 5 – 220 W. Optimal operating conditions, as determined from plume observations, occurred at 15 W with a 10 sccm flow rate. A prototype additive-manufactured xenon tank is described, designed to utilize xenon’s supercriticality above 58.4 bar to increase the propellant mass at the cost of little additional tank pressure. A regulator and choked-flow orifices were paired to determine the propellant feed system elements required to provide the correct pressure and mass flow rate to CAT. Additionally, a low-thrust orbital simulation tool is described which allows rapid orbit change analysis to simulate CAT’s capabilities on orbit.

Nomenclature

I_{sp}	= specific impulse
m_e	= electron mass
m_i	= ion mass
p	= background neutral pressure
P_{dep}	= power deposited into the plasma
T_e	= electron temperature
V_{fl}^{cold}	= non-electron-emitting probe floating potential
V_{fl}^{em}	= electron-emitting probe floating potential
V_{COL}	= collector plate potential
V_{IR}	= ion retarding grid potential
V_{REP}	= electron repelling grid potential
V_{SE}	= secondary electron suppression grid potential
ϕ_p	= plasma potential

*Assistant Research Scientist, Aerospace Engineering, and sheehanj@umich.edu.

†PhD Candidate, Aerospace Engineering, and collardt@umich.edu.

‡PhD Candidate, Aerospace Engineering, and ebersohn@umich.edu.

§Adjunct Professor, Aerospace Engineering, and longmier@umich.edu.

I. Introduction

Propulsion is one of the most significant technology gaps for CubeSats and, more generally, nanosatellites. Developing propulsion technology for CubeSats is one of the main goals of NASA’s Cube Quest Centennial Challenge.¹ CubeSat propulsion is less advanced than other nanosatellite technologies because of the difficulties in miniaturizing conventional thruster designs. Monopropellant and bipropellant systems exist or are in development^{2–5} with thrusts of $\lesssim 1$ N and small ΔV capabilities of 10s of m/s. For moderate ΔV s (> 100 m/s) electric propulsion is needed. A wide variety of electric thrusters are in development, with predicted ΔV capabilities up to 300 m/s.^{6–14} These thrusters will be suitable for station keeping, formation flying, and deorbiting.

There are, however, exciting missions for CubeSats that can only be accomplished with 1000 m/s or greater ΔV . These mission include deep space exploration requiring earth escape or orbital insertion. Lunar capture from a trans-lunar trajectory can require between 700 and 1500 m/s, depending on the final lunar orbit.¹⁵ Long-lived low altitude orbits require such propulsion to compensate for drag. Meaningful orbit changes, including inclination changes, can require > 1000 m/s.

The CubeSat Ambipolar Thruster (CAT) is being developed to provide such levels of ΔV to CubeSats and other nanosatellites and this article describes the development progress made on the prototype thruster and propellant management system. The thruster has been operated on xenon and argon, with ion energy measurements identifying two different modes of operation. The first in-orbit demonstration of CAT will be aboard a 3U CubeSat and the design described here is suitable for that form factor and technology demonstration mission. The propellant management system has been designed to provide sufficient xenon for initial on-orbit testing and orbit change demonstrations. Together, the propulsion subsystem consisting of the thruster, propellant tank, propellant feed system, and power processing unit, will fit into 2U of the 3U satellite.

II. CubeSat Ambipolar Thruster

CAT is a helicon plasma thruster designed to provide small spacecraft with large ΔV ($\gtrsim 1$ km/s) for making significant orbit changes. Helicon plasma thrusters operate by using helicon waves, an electromagnetic wave, to efficiently heat electrons which ionize the propellant to a 95% ionization fraction or greater.^{16–23} A diverging magnetic nozzle expand the plasma, both ions and electrons, producing a stream of electrons and energetic (10s of eV) of ions.^{24,25} Benefits of this design include the high efficiency ionization mechanism of the helicon wave, the magnetic field which keeps plasma away from the walls which may reduce erosion, and zero net current so no neutralizing cathode is required.

Table 1: CAT parameters for xenon propellant.

Power	10 - 50 W
Flow Rate	5 - 15 sccm
I_{sp}	400 - 800 s
Efficiency	10% - 40%
Thrust	0.5 - 4 mN
Thrust/Power	50 - 80 mN/kW

Small spacecraft have stringent power limitations due to solar panel size, so CAT was designed to operate on 10 - 50 W. That power heats the electrons and ionizes the propellant via the helicon wave. At the design point the propellant flow rate is set to that which can be fully ionized by the input power. The magnetic nozzle expands the plasma and facilitates energy transfer from the electron thermal modes to the ion jet, so a higher electron temperature leads to a higher specific impulse (I_{sp}). Inefficiencies come principally from ionization costs, inelastic collisions, and losses to plasma-facing surfaces. Expected thrust can then be determined from power, efficiency, and specific impulse. A summary of the range of projected performance parameters for CAT using xenon propellant is shown in Table 1 but a more complete description of these calculations can be found in Ref. 25.

A notional diagram of CAT is shown in Fig. 1. Note that this figure is not to scale and is meant only to illustrate the key components. Propellant is fed into the plasma liner from the propellant management

system. It could be xenon, iodine, or some other propellant in gaseous form. The propellant is ionized in the plasma liner where RF energy is deposited via the helical half-twist helicon antenna.²⁶ On a spacecraft the RF power would come from an RF power processing unit (PPU) but in these experiments a laboratory power supply was used. Permanent magnets generate a magnetic nozzle which keeps the plasma away from the plasma liner and directs it out of the thruster. The magnetic field has a maximum strength of ~ 800 G in the throat and a far-field dipole moment of 12 A/m^2 . In the expanding region the ions accelerate and generating thrust, the physical mechanism of which is explained in greater detail elsewhere.²⁴ Within 40 cm the field strength decreases to 0.5 G, the strength of Earth's magnetic field.

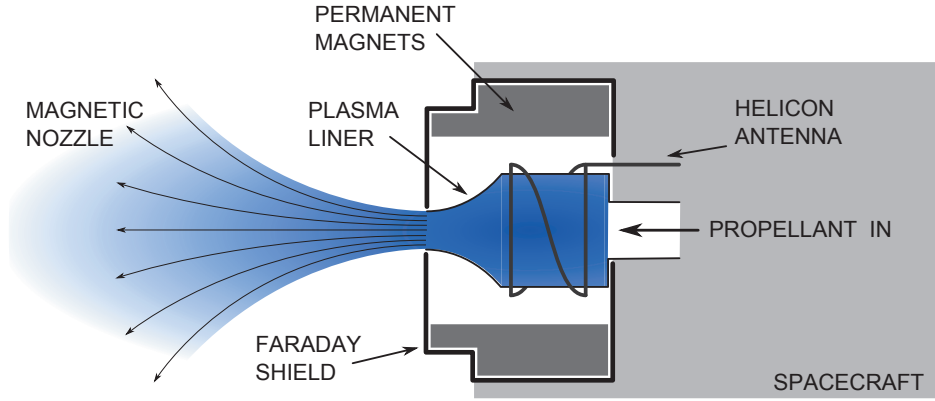


Figure 1: A schematic diagram of CAT operating, integrated with a 3U CubeSat. Not to scale.

Initial ground testing of CAT was performed in a 1 m diameter, 1 m long cylindrical vacuum chamber (shown schematically in Fig. 2). A scroll pump and a cryopump with a pumping speed of 1500 l/s on air and 1200 l/s on argon brought the chamber to a base pressure of $\sim 10^{-7}$ Torr. The thruster was mounted to a fixed stand on one end of the chamber. A two dimensional motion table with $5 \mu\text{m}$ precision was used to move probes in the chamber. In the experiments described below argon or xenon was fed to CAT from an external gas tank. A variable frequency RF signal generator was amplified to between 5 and 150 W by an RF amplifier. The amplifier was matched to the load outside of the chamber which made testing easier but resulted in some power being deposited in the transmission lines between the vacuum feedthrough and CAT. The power that was lost to the transmission lines was not quantified.

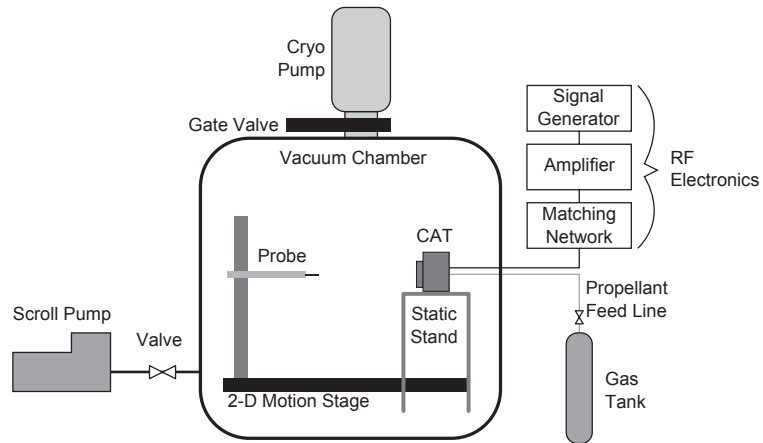


Figure 2: A schematic diagram of the experimental setup in which CAT was tested. (Not to scale.)

III. Diagnostics

The plasma discharge of CAT was analyzed with diagnostics including an emissive probe, a retarding potential analyzer (RPA), a residual gas analyzer (RGA), and a 3-axis magnetometer.

A. Magnetometer

A 3-axis magnetometer with a full scale range of up to 300 kG and a resolution of 0.01 mG was used to map the magnetic field of CAT prior to implementation of the above diagnostics. The probe tip dimensions were $\sim 7 \times 7 \times 15$ mm, allowing for mapping resolutions of up to 20 mm. Within this probe 3 independent gaussmeters record values in the 3 cardinal Cartesian directions, allowing for the local magnitude and streamline direction to be determined.

B. Emissive Probe

A emissive probe was used to measure plasma potential in the CAT plume using the floating potential in the limit of large emission technique.^{27,28} A hair-pin loop of 0.125 mm diameter thoriated tungsten wire extending from a dual bore alumina tube was used as a probe tip. Currents ranging from 2.2 – 2.8 A were used achieve thermionic emission and reach saturation at the plasma potential. Electron temperatures were estimated from the cold probe floating potential (V_{fl}^{cold}) and emitting probe floating potential (V_{fl}^{em}) assuming a planar probe model and a thin sheath:²⁹

$$T_e = \frac{e(V_{fl}^{em} - V_{fl}^{cold})}{- \left[\ln \left(0.61 \sqrt{\frac{2\pi m_e}{m_i}} \right) + 1.5 \right]} \quad (1)$$

Corrections were made to the plasma potential measured by the emissive probe using the electron temperature and the equation below:

$$\phi_p = V_{fl}^{em} + 1.5T_e/e \quad (2)$$

C. Retarding Potential Analyzer

The ion energy distribution was measured in the CAT plume using a retarding potential analyzer (RPA) which consists of a series of grids and a collector plate which act as a high pass filter for ions.³⁰ The microRPA developed at PEPL to study helicon plasma sources was used for these measurements.³¹ This RPA consists of four 316 stainless steel grids (floating, electron repelling, ion retarding, and secondary electron suppression) and a nickel collector. Each of the grids as well as the final grid and the collector plate are separated by 0.5 mm macor spacers.

The electron repelling and secondary electron grid biases were applied with Instek GPR-30H-10D power supplies. The voltages of these grids ranged from $V_{REP} = (-50, -30)$ V for the electron repelling grid and $V_{SE} = (-80, -48)$ V for the secondary electron suppression grid.³² The ion retarding and collector biases were applied with Keithley 2410 and 2400 sources respectively. The ion retarding voltages were swept from $V_{IR} = (-25, 150)$ V using a DAQ interface. The collector was biased negatively in the range of $V_{COL} = (-70, -40)$ V to insure collection of all ions. A range of biases was used for these measurements due to the wide range of operating conditions investigated. Currents at the collector were measured with a Keithley 6485 picoammeter.

Current-voltage traces were smoothed with locally weighted scatterplot smoothing (LOWESS) before derivatives ($-dI/dV$) were taken to determine the ion energy distribution function. A fourth-order central difference scheme was used in calculating the derivatives.

IV. Magnetic Field

CAT's magnetic nozzle was generated by annular neodymium magnets. These were specifically designed and manufactured to create a field that converged to a large magnetic flux of ~ 800 G at the throat of the nozzle and expanded with minimal divergence. The density of a helicon discharge scales linearly with magnetic field²⁶ so a larger magnetic field results in higher thrust. Peak electron temperatures are expected

to be on the order of 10 eV, based on past helicon experiments.^{24,33,34} Electrons with 10 eV of energy normal to the magnetic field in the throat would have a Larmor radius of ~ 0.01 cm, two orders of magnitude smaller than the throat diameter. The magnetized electrons follow the magnetic field lines and drag the ions with them via the electric field, exchanging energy and generating the ion beam.²⁴ At some point in the nozzle the plasma will detach from the magnetic field lines and continue moving away from the thruster, though this process is not well understood.^{35,36} Detachment is assumed to happen before the point where CAT's magnetic field strength falls below Earth's magnetic field strength (0.5 G). If detachment does not take place by before the plasma reaches Earth's magnetic field then it will follow Earth's magnetic field lines. At the point of detachment the electron temperature is expected to be reduced to $\lesssim 1$ eV, which results in a Larmor radius of ~ 10 cm, on the order of the diameter of the magnetic nozzle at that point. Large Larmor radii compared to the magnetic nozzle size are expected to contribute to detachment.^{35,37}

The magnetic field downstream of CAT is shown in Fig. 3 as measured by a 3-axis magnetometer. The thruster axis is located at the radial position of 0. The origin corresponds to the position as close to the throat of the magnetic nozzle that could be measured. Due to the size of the magnetometer probe tip and uncertainty in the precise position of the measuring elements within the probe tip, measurements could only be made up to ~ 0.5 cm downstream of the throat. The maximum measured magnetic field was 490 G while the maximum at the throat was projected to be 800 G. CAT's magnetic field falls below Earth's magnetic field approximately 40 cm downstream of the thruster. The magnetic field lines (shown as black lines in Fig. 3) expand uniformly and are in good agreement with the simulated magnetic field,²⁵ demonstrating that a magnetic nozzle can be generated by permanent magnets at this small scale. The field lines displayed represent those coming out of the plasma liner, so the plasma is expected to follow those field lines. In the worst case scenario, when the plasma remains attached to the field lines until Earth's magnetic field dominates, the divergent half-angle of the nozzle is 20° . If the plasma density is uniform across the nozzle then this would correspond to a nozzle efficiency of 97%. The slight asymmetry in the 40 – 50 cm downstream region is due to the influence of Earth's magnetic field and limitations to the precision with which the permanent magnets can be aligned. These measurements were made inside the vacuum chamber with the thruster mounted in the same location as it will be when it is operated. The vacuum chamber was not evacuated but the door was closed to correctly account for the effects of the steel vacuum chamber walls. The magnetic field measured with the vacuum chamber door closed was compared to that measured with the vacuum chamber door open to determine the effects of the vacuum chamber on Earth's magnetic field. The effect was a difference in magnetic field strength of ~ 0.05 G, a negligible difference in most of the nozzle and only a 10% difference in the 40 – 50 cm downstream region. Therefore, the effects of vacuum chamber on the magnetic field were assumed to be negligible for thruster performance evaluations.

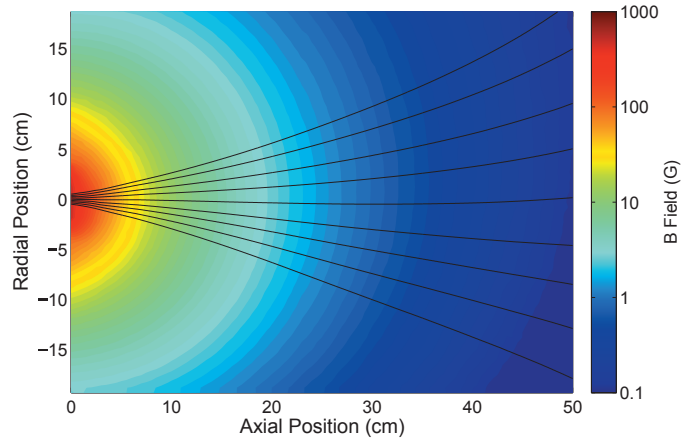


Figure 3: Measured magnetic field strength (color) and field lines (black) downstream of the exit plane of CAT.

V. Operating Conditions

A. Parameter Space Investigation

For these initial test of CAT the power-flow rate parameter space was explored to determine CAT's operational range with both argon and xenon. The power was varied from 3 to 220 W. The powers reported for the various conditions are the powers deposited to the circuit consisting of the antenna and its wire leads. Some fraction of that power was deposited into the plasma (P_{dep}) but some was lost in the leads. For this reason we report powers as being less than the deposited value (e.g. < 15 W) to remind the reader of this caveat. The volumetric flow rate ranged from 0.2 sccm to 50 sccm.

A photo of CAT at nominal operation with 10 sccm and 14.9 W is shown in Fig. 4. The propellant feed line delivers argon to the plasma liner (obscured) where it is ionized by the RF energy deposited by the helical half-twist antenna (obscured). The glow of the argon discharge can be seen through the holes in the Faraday shield. There is also some glow in the propellant feed line, though it is unclear if that is due to ionization in the propellant feed line or light coming from the plasma liner being diffused by the translucent feed line. The plasma is ejected by the thruster, forming a plasma plume shaped by the magnetic field lines.

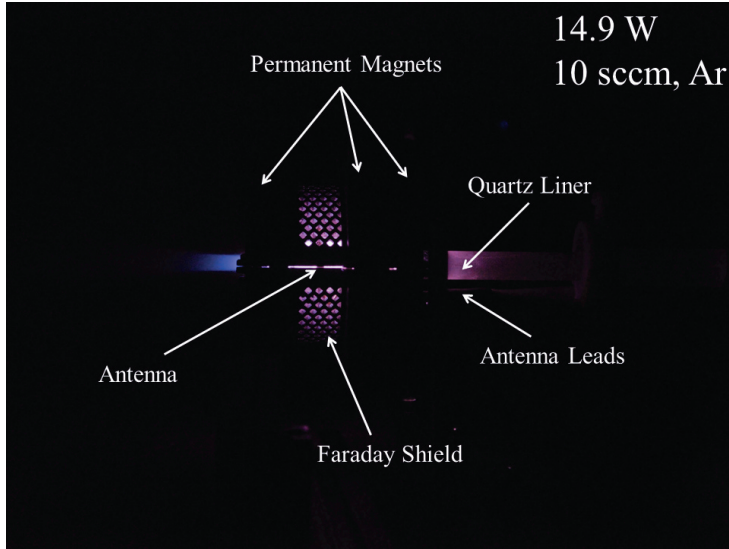


Figure 4: A photograph of CAT firing, including identification of the major components.

The plume exhibited a desirable, well-collimated structure while CAT was operating at flow rates of 5 – 20 sccm argon and deposited power levels of 5 – 15 W, as shown in Figure 5. For xenon the range of powers to achieve the collimation was 3 – 10 W and the flow rates were 2 – 8 sccm. The maximum flow rate at which the collimation could be achieved became smaller as the power was increased. At powers below 5 W and 3 W with argon and xenon, respectively, CAT was not able to light consistently. Similarly, at flow rates below 5 sccm argon and 2 sccm xenon CAT was either starved of propellant or was barely able to light, but no plasma could be seen outside of the thruster. At flow rates above 20 sccm for argon and 8 sccm for xenon the plume was no longer well-collimated. Neutral gas was exhausted in addition to the ions, disrupting the plume via charge-exchange collisions. At these higher flow rates the neutral background pressure within the chamber increased, and if power exceeded 15 W, led to secondary plasma formation around the antenna leads. This secondary plasma formation typically occurred when the background pressure (p) exceeded 5×10^{-4} Torr. Future tests in larger vacuum facilities with higher pumping speeds, such as the Large Vacuum Test Facility at the University of Michigan's Plasma Dynamics and Electric Propulsion Laboratory, will enable investigation of higher power levels by mitigating this background pressure issue.

When the plume was well-collimated it exhibited a bluish hue, in contrast to a pinkish hue inside of the thruster, while running on both argon and xenon. For the plume in Figure 5 it is possible that the difference in color is due to argon ion emission. However, it is also possible that this color shift is caused by sputtering of material from CAT or due to CAT-chamber interactions. To investigate this color shift of the argon discharge a residual gas analyzer (RGA) was attached to the chamber. The RGA provides an

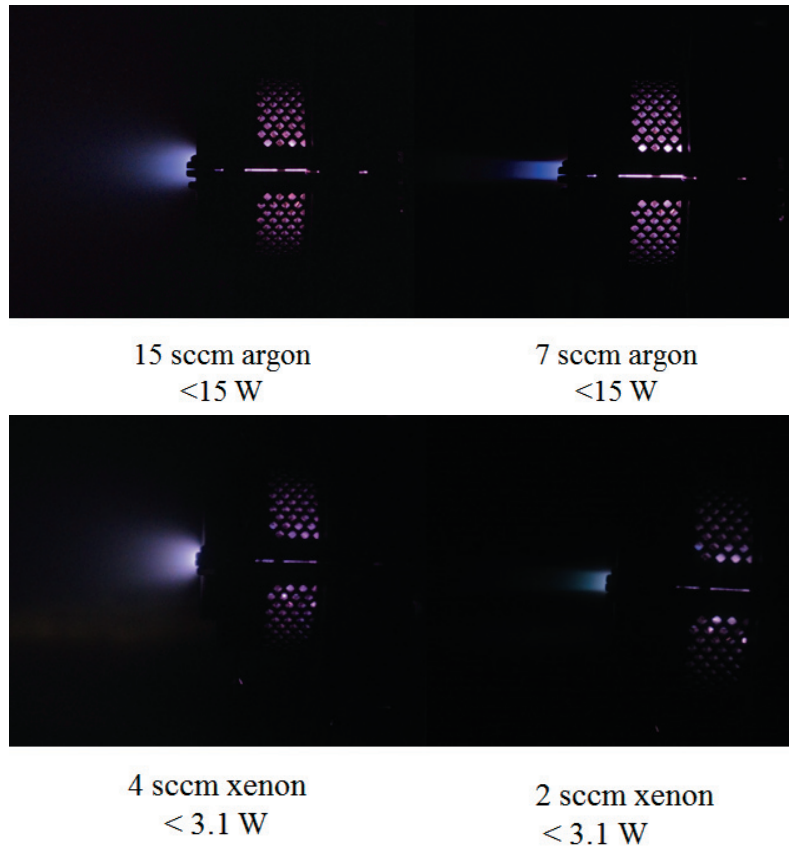


Figure 5: Photographs of CAT operating at 14 MHz on argon (top) and xenon (bottom) at various flow rates power levels. Note the visible change in plume structure.

approximate gas composition by bombarding the gas in the chamber with 70 eV electrons that collide with the neutral species and produce ions. These ions are then collected within the probe and a charge-to-mass ratio is measured. As shown in Figure 6, there was no noticeable difference in the RGA traces between flowing argon through CAT and CAT firing, which implies that the color shift in the plume is likely not due to sputtering of material originating from CAT or the vacuum facilities.

While these RGA traces matched well, interpreting the trace to determine the gas composition can be difficult. Since the RGA measures the charge-to-mass ratio of ions generated by collisions with 70 eV electrons some doubly-ionized species are created and many complex molecule break into segments that have several masses as other common gases. This issue is illustrated in Fig. 6 where N_2 and CO, typically generated by the breakdown of CO_2 , correspond to the same peak, requiring a basic, a priori knowledge of what materials are expected. While CAT is firing on argon the expected materials are atmospheric gases, argon isotopes, and sputtered materials. The possible sputtered materials include titanium (47.9 amu) from the Faraday shield, quartz (60.1 amu) from the liner, silver (107.9 amu) from the antenna, and Teflon (C_2F_4 – 100 amu) from the liner centering ring in the thruster face. Based on Figure 6 titanium from the Faraday shield is not being sputtered. It is not clear if quartz or silver is being sputtered. The peaks corresponding to quartz would be overshadowed by the presence of N_2 and O_2 while the high mass of silver means it could not be measured. Even if the silver antenna is being sputtered these particles are unlikely to be present in the plume at the thruster throat because the Faraday shield blocks the line-of-sight. Teflon is also not being sputtered. Based on the structure of Teflon during electron bombardment a C-F bond is likely to be broken, which would result in a peak in the RGA trace the corresponds to fluorine (19.0 amu). In Figure 6 there is not a distinct peak at 19.0 amu. While this analysis does not conclusively prove that the plume is comprised of primarily argon ions it provides evidence that suggests the color shift is not due to sputtering of the thruster. Planned optical spectroscopy measurements may provide definitive evidence to prove the

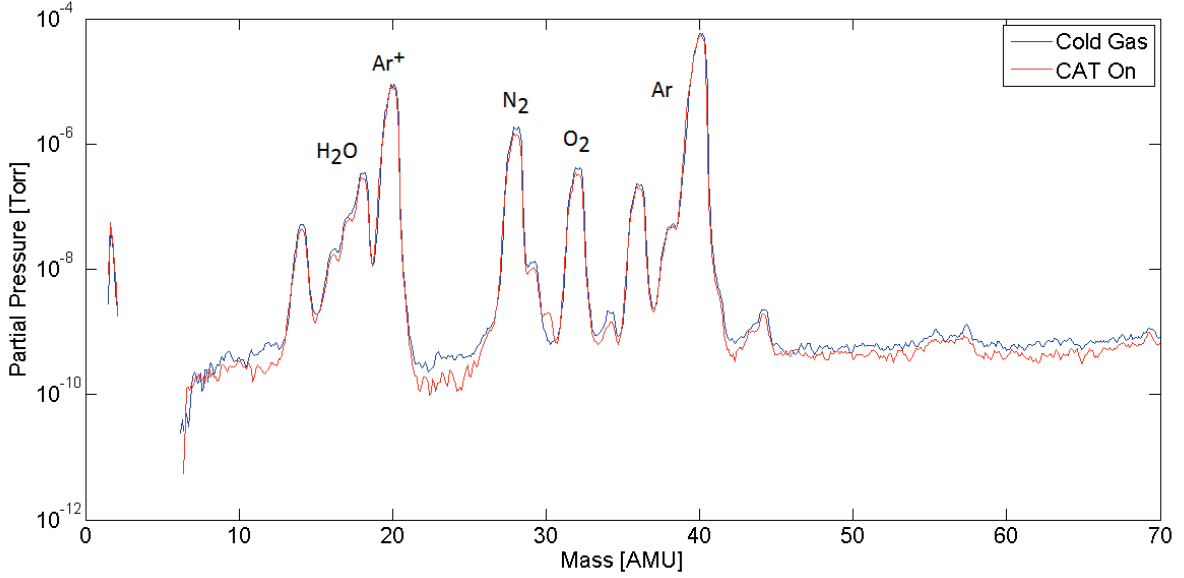


Figure 6: A comparison of the RGA traces for CAT while operating on argon in a cold gas mode, i.e. no power was being deposited into the gas, and while CAT was firing.

plume is composed of argon ions.

B. Argon

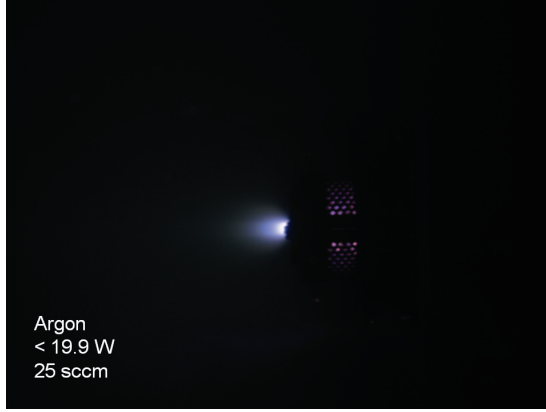
The diffuse and collimated operating modes for argon were investigated with more detail using the emissive probe and RPA diagnostics presented earlier. The diffuse pink plume is shown in Fig. 7. This operating condition was achieved with a flow rate of 25 sccm and a net deposited power (P_{dep}) of ≤ 19.9 W. The background pressure at this condition was 2.74×10^{-4} Torr. The emissive probe and RPA were located 40 cm downstream of the thruster exit. The RPA trace corresponding to this mode is shown in Fig. 7. The RPA trace for this operating condition shows a single peak near the plasma potential with no indication of any beam electrons. Either the thruster does not produce a beam of ions under those conditions or the ions have charge-exchanged with neutrals and

A second mode with a collimated blue plume, shown in Fig. 8, was obtained at flow rates of 9.0 sccm and net deposited powers of ≤ 15.6 W. The background pressure at this operating conditions was 1.01×10^{-4} Torr. The emissive probe and RPA were positioned 25 cm downstream of the thruster exit. The RPA trace corresponding to this mode is shown in Fig. 8. This trace shows a slight peak near the plasma potential measured by the emissive probe and then a broad range of higher energy ions with a peak energy of ~ 55 eV after correcting for the plasma potential. These higher energy ions indicate that the ions were accelerated by CAT. The broad peak may be due to the large collection area of the RPA compared to the size of the plume or due to ion-neutral collisions.

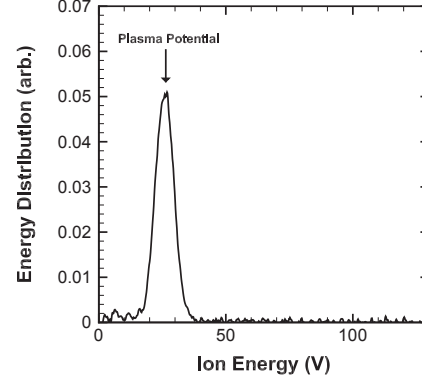
C. Xenon

Xenon operating conditions were investigated in greater detail with the RPA and emissive probe diagnostics. A diffuse mode with a collimated pink plume is shown in Fig. 9 achieved with a flow rate of 4 sccm and a net deposited power of ≤ 51.7 W. The background pressure for this operating condition was 3.96×10^{-4} Torr. The emissive probe and the RPA were positioned 30 cm downstream of the thruster exit. RPA measurements for this condition show a single peak near the plasma potential measured by the emissive probe. This implies that there is no significant ion acceleration in this mode and that it is not suited for high specific impulse thruster operations.

A blue xenon mode, shown in Fig. 10, was achieved with a flow rate of 2.2 sccm and a deposited power of

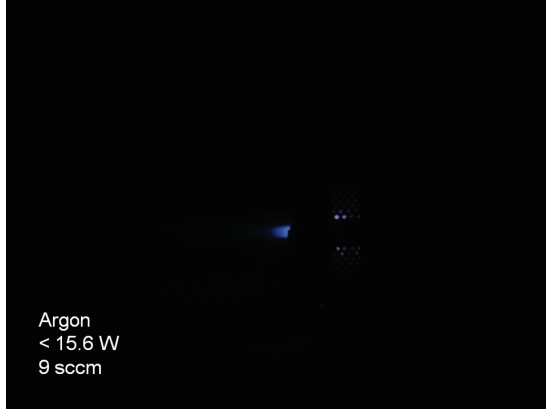


(a) Picture of Argon discharge with operating conditions: $\dot{m} = 25$ sccm, $P_{dep} \leq 19.9$ W, $p = 2.74 \times 10^{-4}$ Torr.

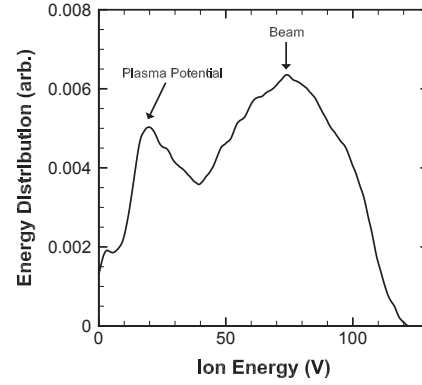


(b) Ion energy distribution ($-dI/dV$). RPA: $V_{REP} = -35$ V, $V_{SE} = -61$ V, $V_{COL} = -45$ V, $V_{IR} = (-25, 150)$ V

Figure 7: Diffuse pink discharge



(a) Picture of Argon discharge with operating conditions: $\dot{m} = 9$ sccm, $P_{dep} \leq 15.6$ W, $p = 1.01 \times 10^{-4}$ Torr



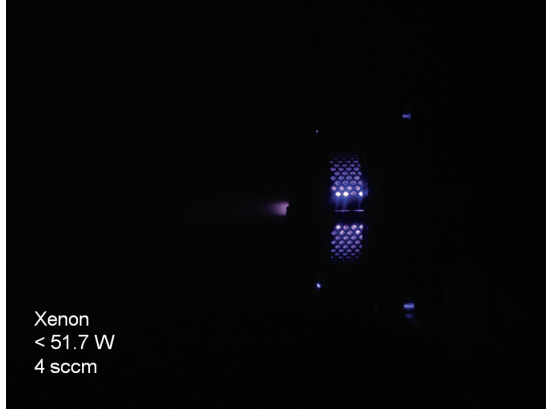
(b) Ion energy distribution ($-dI/dV$) with RPA settings: $V_{REP} = -26$ V, $V_{SE} = -50$ V, $V_{COL} = -30$ V, $V_{IR} = (-25, 150)$ V

Figure 8: Collimated blue discharge

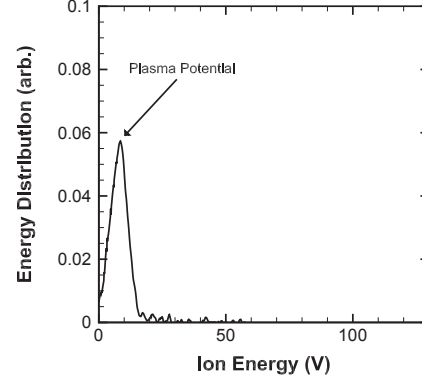
≤ 20.1 W. The background pressure for this operating condition was 3.56×10^{-4} Torr. The emissive probe and the RPA were positioned 30 cm downstream of the thruster exit. The RPA trace for this condition is shown in Fig. 10 and has two distinct peaks. The low energy peak corresponds to the plasma potential, as measured by the emissive probe. The high energy peak was created by beam ions accelerated by the CAT, with energies of ~ 34 eV after correcting for the plasma potential. The presence of beam ions suggests that this operating condition may be suited for thruster operations.

VI. Conclusion

The CubeSat Ambipolar Thruster will enable significant orbit changes for CubeSats to transfer into optimal orbits, deploy mesh networks, or compensate for drag, just to name a few examples. These new mission types will greatly enhance the power of the CubeSat platform and spur further growth in the already rapidly expanding world of nanosatellites. A prototype CAT engine has been fired using argon and xenon as the propellant. Visual inspection shows that there exists an optimal match of power and mass flow rate

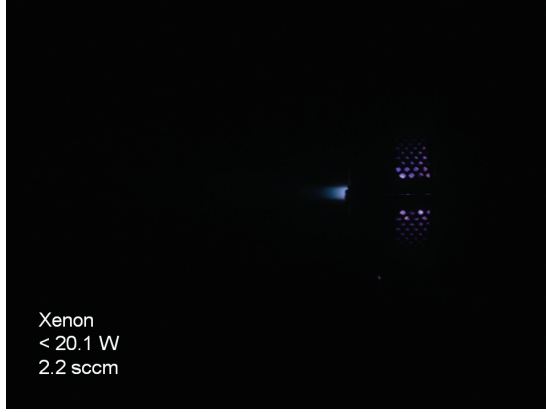


(a) Picture of Xenon discharge with operating conditions: $\dot{m} = 4$ sccm, $P_{dep} \leq 51.7$ W, $p = 3.96 \times 10^{-4}$ Torr

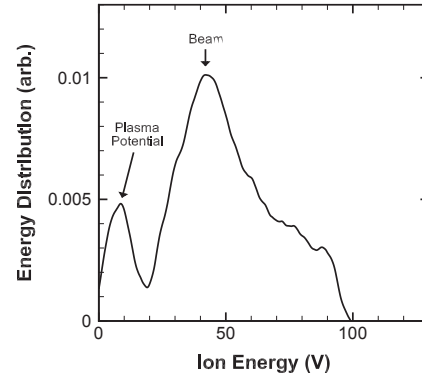


(b) Ion energy distribution ($-dI/dV$). RPA: $V_{REP} = -72$ V, $V_{SE} = -92$ V, $V_{COL} = -78$ V, $V_{IR} = (-25, 60)$ V

Figure 9: Diffuse pink discharge



(a) Picture of Xenon discharge with operating conditions: $\dot{m} = 2.2$ sccm, $P_{dep} \leq 20.1$ W, $p = 3.56 \times 10^{-4}$ Torr



(b) Ion energy distribution ($-dI/dV$) with RPA settings: $V_{REP} = -24$ V, $V_{SE} = -39$ V, $V_{COL} = -30$ V, $V_{IR} = (-25, 130)$ V

Figure 10: Collimated blue discharge

to produce a collimated plasma plume that follows the magnetic nozzle field lines. Flow rates that are too large disrupt this collimation, though it is not yet clear how that is linked to performance.

VII. Future Work

A rigorous testing campaign has begun to measure CAT's performance parameters. A retarding potential analyzer will measure the ion energy distribution function far downstream of the thruster. Electric probes will be used to measure the plasma parameters of the plume. A double probe will measure the 2D distribution of electron densities and temperatures while an emissive probe will be used to measure the plasma potential. These plasma measurements will provide insight into the ion acceleration mechanism in the thruster and quantify the RF signal that escapes from the thruster.

Thrust measurements are critically important for determining CAT's capabilities and a torsion balance thrust stand is in development. Using a proportional-integral-derivative controller to provide a counterbalancing force from a solenoid the thruster position is maintained while it is fired. Once the thrust stand is

operational, the range of CAT operating parameters can be explored to investigate the effects of mass flow rate, power, propellant, etc. on thrust and specific impulse.

Once the prototype is well diagnosed engineering and flight hardware will be developed for the Plasma Ambipolar Thruster for Responsive In Orbit Transfers (PATRIOT) mission, a technical demonstration of CAT. Partnering with the Michigan Exploration Laboratory (MXL) a 3U CubeSat will be designed and flown to demonstrate CAT's ability to perform orbit changing maneuvers.

VIII. Acknowledgments

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