Thrust Characterization and Plasma Diagnostics for an Adamantane Thruster

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This paper presents the current development status of a diagnostic suite for the characterization of a solid-fuel adamantane plasma thruster. The progress towards developing a torsional pendulum thrust stand and a double Langmuir probe is described. Passive thrust measurements have been performed, providing a preliminary thrust estimate on the order of 40 μN. Improvements are planned for the thrust stand to utilize active control and eliminate electrostatic interference during testing. Developments are also being implemented on the double Langmuir probe, and this paper discusses the unique challenges faced when utilizing a probe to analyze data from the solid-propellant thruster.

I. Introduction

The University of Southern California's Advanced Spacecraft Propulsion and Energy (ASPEN) Laboratory has been developing a solid-fuel electric propulsion thruster utilizing adamantane ($C_{10}H_{16}$) to eventually integrate into a CubeSat. Adamantane offers several advantages over traditional propellants, including simplified solid phase storage requirements, sublimation at vacuum, and high density while maintaining comparable mass and ionization rates to typical gaseous propellants. ASPEN is characterizing thrust and plasma properties using in-house diagnostic equipment to determine the optimal internal thruster geometry. This paper aims to summarize the current development and testing of these devices as they are used to analyze thruster iterations and delineate a path for further development.

Previously, ASPEN built a single Langmuir probe and used it to characterize the plasma plume of an early iteration of an adamantane thruster. This probe consisted of a moldable design for adaptability, connected to nickel-chromium wire, and a planar probe tip [1]. Measurements from this probe indicated an electron density of 4.17×10^{17} m^{-3}, an electron temperature of 2.9 eV, a plasma potential of 12.63 V, and a floating potential of 9.9 V.

A double Langmuir probe was constructed to improve upon the plasma diagnostics equipment previously developed by the ASPEN laboratory. In theory, a double Langmuir probe offers significant advantages over a single Langmuir probe, including less disturbance of the plasma environment around the probe tips and more precise measurements of data [2]. However, it should be noted that the current collected with a double probe is typically around 20 times less than that of a single probe, which in turn necessitates higher precision when collecting data. The probe we designed and tested was inspired by the design in Ref. [3], chosen due to its simplicity in construction, low cost, and ease of obtaining the necessary materials. Improvements made to the design to fit our vacuum chamber's needs include a more modular design with a D-sub connection and a stand to mount the thruster and probe a set distance of 7 mm apart. Future work will be conducted to standardize the double Langmuir probe design to minimize noisy data and maximize resolution in order to successfully compare the plasma plumes from different iterations of the adamantane-fueled thruster.

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A torsional thrust stand design was selected as the optimal configuration for the thrust stand. Given the vacuum chamber dimensions and the expected thrust values, the torsional design allowed for the highest thrust resolution compared to other thrust stand designs. The thrust stand follows standard electric propulsion measurement techniques described by Ref. [4].

With the double Langmuir probe and the thrust stand, ASPEN intends to characterize different thruster geometries. By varying the ionization chamber and orifice shapes, as shown in Fig. 1, the lab intends to determine the ideal configuration for CubeSat integration.

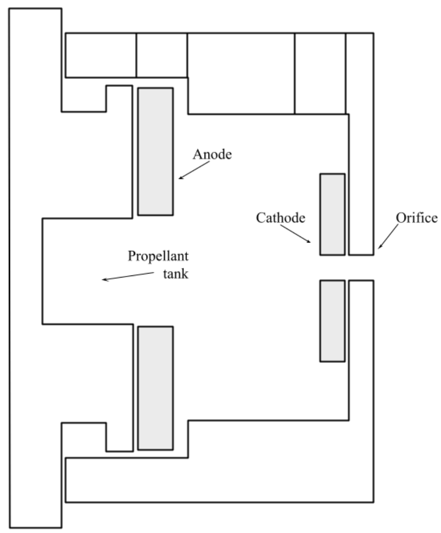

Fig. 1 Base thruster design.

II. Methods

While the development of the thrust stand and the double Langmuir probe is ongoing, both devices were tested in their current configurations to obtain preliminary thrust measurements and plasma data. Each device's current state is described below.

A. Thrust Stand Setup

1. Physical Stand Design

When attempting to characterize electric thrusters, common load cells are not capable of resolving the low thrust produced by the ejected ions. As a result, specialized thrust stands are used, which use displacement around an axis to characterize the thrust. Typical designs include inverted pendulums, hanging pendulums, and torsional pendulums.

The ASPEN thrust stand is a torsional stand selected to maximize the use of space in the lab's vacuum chamber. It consists of an arm that rotates about flex pivots placed at the center of its length. In its current passive configuration, the thruster is mounted at one end of the arm, and a linear variable differential transformer (LVDT) is placed at the opposite end. When the thruster is fired, the arm rotates around the pivots, and the LVDT measures the displacement. A schematic of the ASPEN torsional thrust stand is shown in Fig. 2.

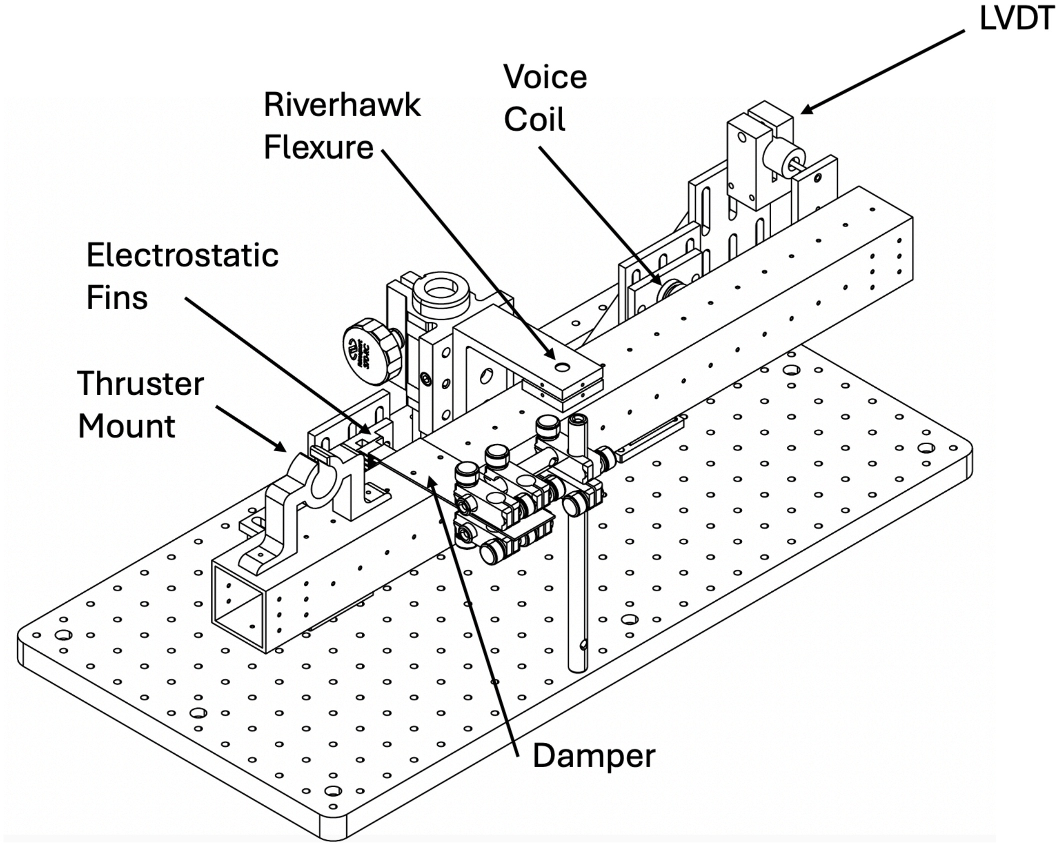

Fig. 2 All active and passive components are shown; currently, ASPEN is only using the passive LVDT measurements.

The thrust balance arm is a 2-foot-long hollow 6061 Aluminum bar. The arm's length enhances the thrust stand's sensitivity by extending the thrust moment arm while ensuring the thruster remains distanced from the chamber wall. The flexures used at the center of the arm are two Riverhawk 5012-600 pivot flexures with a spring constant of 0.311 $\frac{N \cdot m}{rad}$. The pivot flexures are designed to provide around 3 micrometers of deflection for the expected 29 micronewtons of thrust generated by the thruster [5].

The thruster sits in a 3D-printed resin mount 1.5 inches above the balance arm. Rotational oscillations are damped with a 2-inch by 5-inch piece of aluminum held between 4 magnets. For the thrust stand to receive power, a DB-9 feedthrough was mounted to the chamber, and we ensured that both the thrust stand and the chamber were grounded throughout testing. The complete setup inside the chamber is shown in Fig. 3 below.

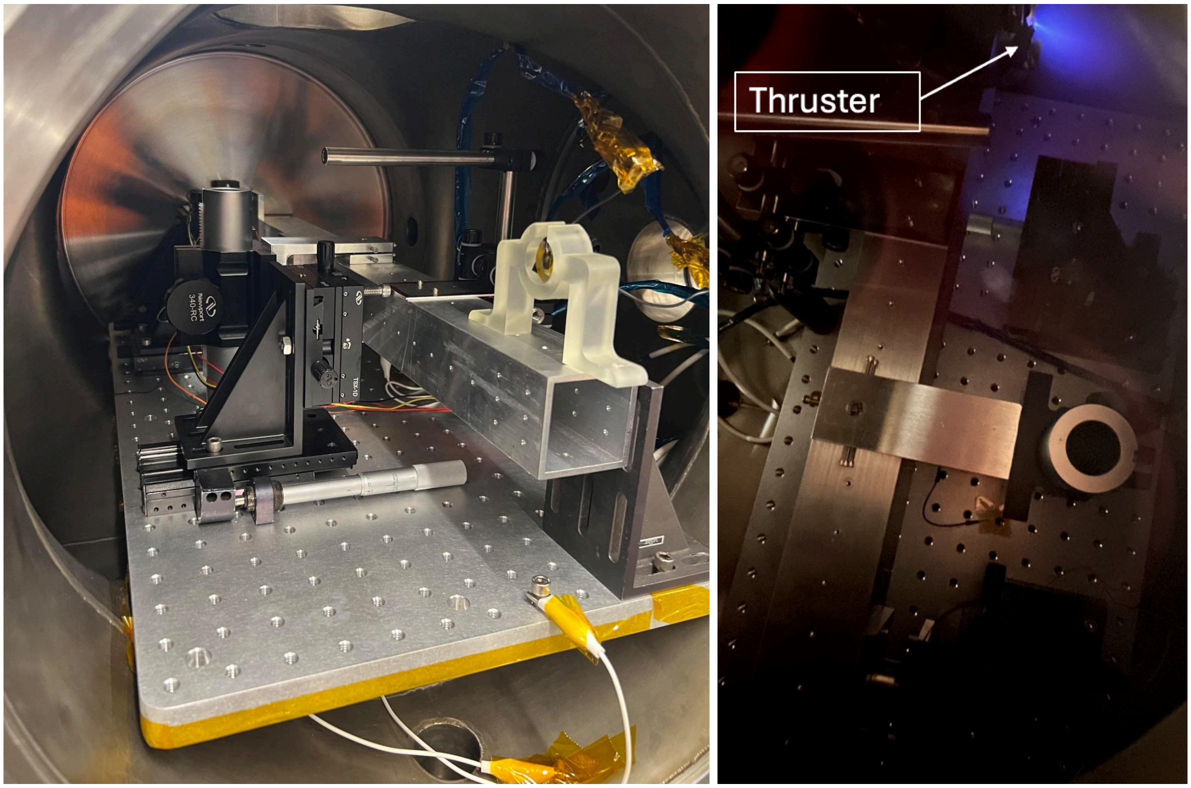

Fig. 3 Thrust stand setup inside the chamber prior to and during testing. Plasma is clearly visible during the test.

Going forward, a few key changes will be made to improve the measurement quality of the thrust stand. Active control will be implemented using a voice coil actuator to balance the stand at a null position. Additionally, electrostatic fins will be integrated to calibrate the stand precisely. A waterfall wiring setup using high-voltage coaxial cable will also be implemented to reduce external interference on the thrust measurement from wiring within the chamber.

2. Thrust Stand Data Collection Method

The thruster was placed in the resin mount and turned on to measure thrust when a pressure of 15.9 millitorrs was achieved in the vacuum chamber. A potential of 1000 volts was applied to the thruster, creating a plasma plume at the thruster orifice.

The LVDT voltage reading V was converted to beam displacement δ in meters using the conversion factor displayed in Eq. (1).

$$\delta = 0.000125 * V \tag{1}$$

The conversion factor was determined by relating the maximum nominal voltage range (±10V) and displacement range (±1.25mm) of the LVDT. The thrust F_t was then calculated with a force balance using δthe spring constant k and the moment arm between the thruster and the pivot point L with Eq. (2).

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

The resulting thrust profiles were analyzed to understand the performance of the thrust stand and the thruster.

B. Double Langmuir Probe Setup

1. Physical Probe Design

The double Langmuir probe (Fig. 4) consists of two 0.51-millimeter diameter tungsten wires encased in alumina tubing, spaced 1.0 millimeters apart and protruding from a double-bore ceramic tube by 5 millimeters. This alumina tube is shielded by concentric layers of copper tubing and glass to insulate the wires from any plasma interferences, as done in Ref. [3]. The glass sleeve was bonded to the copper using a thermally conductive casting epoxy adhesive with high heat, which was black alumina loaded (Thermo-Bond 90). The probe is placed within the plasma plume of the thruster, centered at the thruster orifice, while inside the vacuum chamber. The tungsten wires are attached to wires which are soldered to a D-subminiature connector. This connector runs through a D-sub vacuum port, and the wires then run to a data analysis circuit described in the next section. All wires and exposed insulation were covered in Kapton tape to reduce electrostatic buildup. During testing, arcing was observed on the plate holding the thruster and probe, which was subsequently covered in Kapton tape to eliminate arcing and provide insulation. The testing was completed under vacuum conditions of less than 50 millitorrs with a plasma thruster receiving an input voltage of approximately 1 kilovolt.

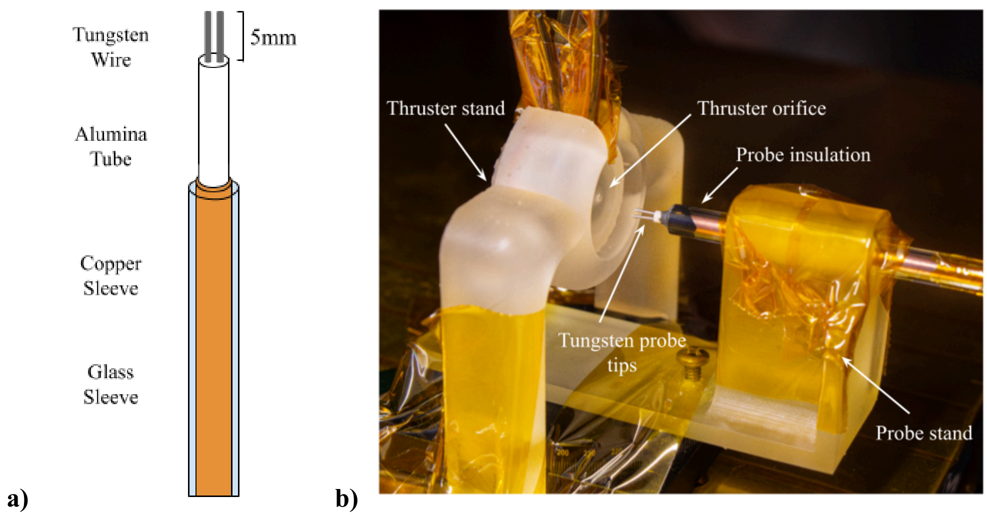

Fig. 4 a) Probe design with components. b) Probe fully integrated to test the thruster.

2. Data Collection Method

Double Langmuir probes work by biasing one probe tip against the other. The probe tips are placed in the plasma to operate under the same conditions while avoiding arcing between wires. One probe tip is connected to the ground of a variable power supply, and the other end of the probe is biased to the voltage set by the power supply. Current data are collected along the positive probe tip as the plasma acts, in essence, as a resistor to complete the circuit.

To collect data, a voltage was swept from about -28 volts to 28 volts utilizing a waveform generator and an op-amp with a gain of 3.55. The power supply setup included two power supplies linked to the circuit, a 100 MHz digital oscilloscope (Rigol DHO802), and a waveform generator producing a sawtooth wave. The waveform generator was set to 10 Hz with a voltage peak-to-peak of 16 volts. The voltage across the 100 kΩ resistor, V, is recorded in Volts in an analog I/O DAQ device (NI USB-6211) connected to LabView. The voltage was then converted to current, I, through the relationship $\frac{V}{R} = I$. The circuit used for data acquisition (Fig. 5a) was developed to be manufactured on a printable circuit board, which can be seen in Fig. 5b.

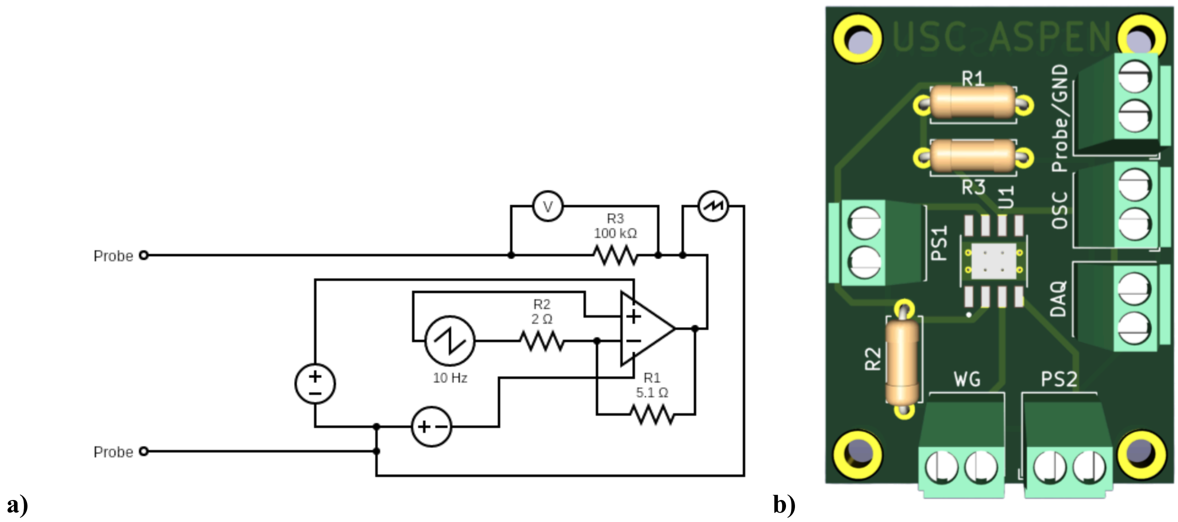

Fig. 5 Circuit for Langmuir probe data acquisition. a) Electrical circuit diagram. b) 3D model of PCB.

Extensive care was taken to ensure the circuit was correctly assembled, functioned as expected, and was floating, with no ground shared with the vacuum chamber or thruster. Had the experiments yielded valid results, the data would have been separated into individual sweeps of 0.1 seconds to discern the I-V curve generated by the probe and, consequently, the derived plasma characteristics.

III. Results

A. Thrust Stand Results

A thrust profile for a 2-minute thruster firing is displayed in Figure 6 below. Plasma was generated using a 1000-volt potential difference, generating an estimated thrust of 40 micronetwons.

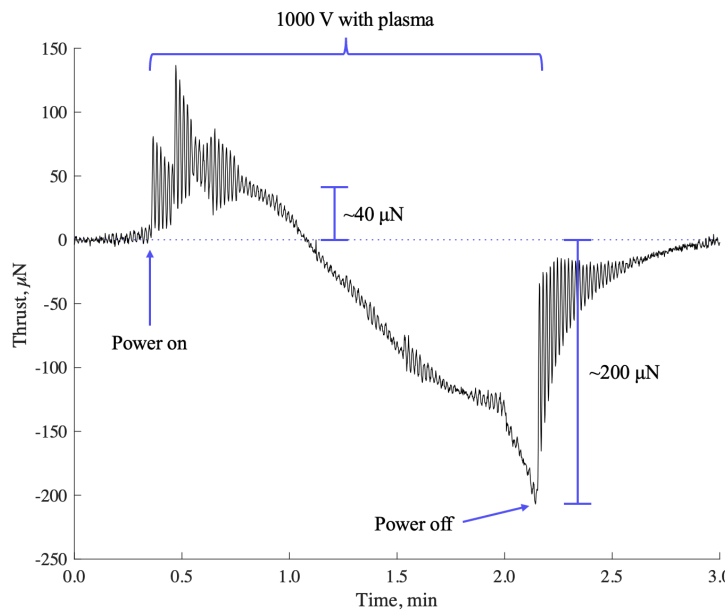

Fig. 6 Thrust profile at a potential difference of 1000V. Thrust on the order of 40 μN was measured; however, this thrust was overshadowed by the electrostatic attraction between the wires powering the thruster.

During testing, thrust was clearly generated, shown by the initial positive spike in the thrust profile. However, the spike was quickly reversed, indicating a pull on the arm in the opposite direction of thrust. This negative pull was attributed to the force on the stand from the electrostatic attraction between the wires powering the thruster. Because the wires were connected directly to the thruster, they could torque the arm, offsetting and masking thrust.

A test was performed to characterize this electrostatic attraction. A 1000-volt potential was applied to a thruster without propellant, generating no plasma. The thrust profile of this test is displayed in Fig. 7.

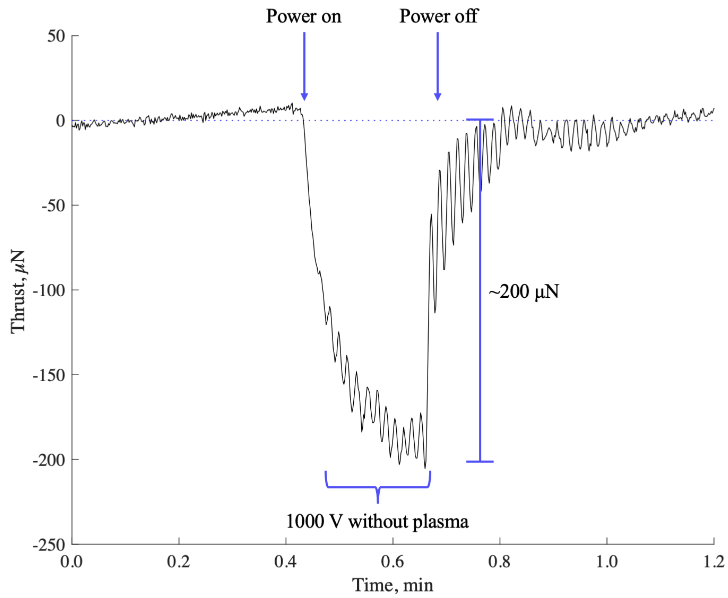

Fig. 7 Thrust profile due to electrostatic attraction without adamantane plasma.

This test produced a negative thrust profile consistent with the initial test's negative profile. It confirmed that the electrostatic attraction between wiring impacted the thrust profile. Additionally, it confirmed that plasma thrust was measured from the positive spike in the initial test, as that positive spike was not present in the second test.

B. Double Probe Results

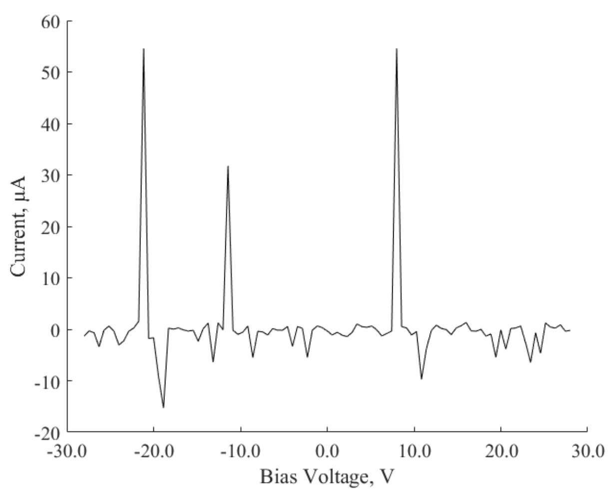

Fig. 8 Current data over the course of a single function generator sweep with noise observed.

Initial testing with a double probe demonstrated that the data collected by the NI DAQ via LabView portrayed extensive noise found within the system while the thruster produced a plasma plume. This was seen before any data processing. During testing, a few different patterns were observed. Early on, periodic noise was observed to occur at a rate of 150 Hz. The spikes in these data indicate it was aliased. To some success, the vacuum chamber was pumped down to around 30 millitorrs to reduce this periodic noise. An example of the data generated during testing at a lower pressure is pictured in Fig. 8, where it can be seen that although there is no periodic noise, there are significant spikes in voltage data, with minor fluctuations in the data centered around 0 μA of current.

What was expected during testing was a smooth I-V curve that intersects the origin of a Current vs. Voltage graph, as seen in Figure 9. Instead, because the data collected exhibit abnormal behavior vastly different than what is expected, at this time, the data collected are not sufficient to characterize the plasma.

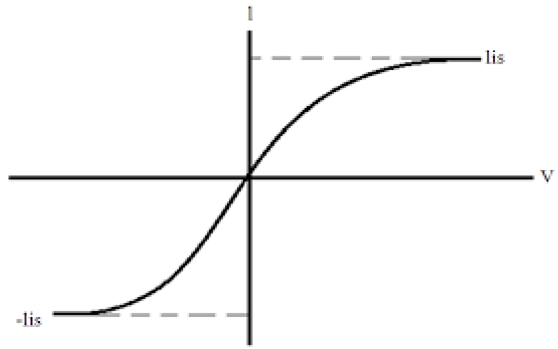

Fig. 9 A typical Double Probe I-V Curve [6].

IV. Discussion

In the previous year, we relied on indirect thrust measurements by observing the deflection of a hanging inverted pendulum caused by the plume. Whereas this method provided a rough estimate of the amount of thrust provided by the thruster, the torsional pendulum has the potential to obtain more reliable data. The thrust stand approach eliminates many assumptions required in indirect measurement and improves precision, repeatability, and overall confidence in the results.

The thrust stand was able to measure thrust, but it was also limited in its current configuration. With no active balancing from the voice coil actuator or precise calibration from the electrostatic calibration fins, the measurements relied solely on the LVDT and nominal spring constant values. Additionally, interference from electrostatic attraction between the wires in the chamber severely impacted the data for most trials. Going forward, steps will be taken to introduce active control and accurate calibration and to reduce interference from external forces within the chamber.

Several factors in relation to the thruster could explain the results observed with the double Langmuir probe. Post-test inspections of the thruster revealed carbon buildup on the cathode, along with other deposits on the interior walls. It is possible that the collection area of the probe is being compromised by an accumulation of these materials on the probe, reducing the measured current levels to a magnitude below a resolution that the detection instruments can support [7]. Multiple steps will be taken to solve this problem. First, the thruster will be constructed out of a material that does not outgas under vacuum. Currently, the thruster iterations are 3D printed with resin to enable rapid testing and easy modification to the thruster design. It is likely, however, that the resin used to manufacture this thruster outgasses and perhaps reacts with adamantane fragments to produce excessive buildup. Furthermore, the thruster will be run with air plasma to ensure the adamantane fuel is the source of the contamination occurring. Altering the thruster design to minimize deposits is key not only to collecting clean diagnostic data but also to creating a robust system that will reliably operate in space.

Another possible cause is extreme fluctuations and unstable plasma. During testing, the plasma plume emitted from the thruster was observed to flicker over time and gradually weaken as its fuel was consumed. Transient plasma behavior could destabilize the sheath surrounding the probe tips, leading to inconsistent current readings [8]. Plasma instability can also contribute to the extreme noise that is seen. If the amplitude of the fluctuations exceeded the magnitude of the collected data, it could be drowned out to an indiscernible degree. Small fluctuations is observed during data collection with a single Langmuir probe [1], but a double Langmuir probe's reduced current collection capabilities magnify the noise concern observed in our plasma diagnostics. The thruster tested in this work visually produces much less plasma than observed in Ref. [1], which could lead to smaller magnitudes of current collected along the probe. To minimize noise, the thruster will be run with a turbo pump to reduce the ability of arcing to occur between probe tips.

Equipped with the knowledge gained through extensive testing and troubleshooting, ASPEN's diagnostics team will continue to improve the design of the double Langmuir probe to reduce noise in data through the ways described above. The data collected by the double probe will be used to validate data previously gathered with a single Langmuir probe, as well as offer critical insight into the density and temperature of plasma generated by an adamantane-fueled thruster.

V. Conclusion

This work is important for the continued development of a solid-fuel thruster by the University of Southern California's ASPEN Lab. The detailed equipment will be used to compare various thruster geometries to identify the ideal chamber architecture. Continued experimentation will be conducted to verify this result and find an ideal chamber geometry. The diagnostic capabilities of the ASPEN Lab will continue to grow, including a further investigation into the causes of the noise and problems with data collection. Testing conducted in support of this work indicated the need to reduce deposits on the thruster and diagnostics tools as a result of the thruster operation. Additionally, data collected from the thrust stand and plasma diagnostics are essential to validate and improve numerical simulations to optimize thruster geometry. The goal is to utilize data from the equipment described in this work to fully characterize ASPEN's solid-fuel thruster and support its eventual implementation in space for the deorbiting of CubeSats.

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$$\delta = 0.000125 * V$$