Progress and Developments of Ultra-Compact 10 Watt Class Adamantane Fueled Hall Thrusters for Picosatellites

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Low-temperature sublimating molecular propellants are an attractive alternative to conventional fuels for traditionally gas-fed electric propulsion such as Hall thrusters. Adamantane has been identified for its potential to allow for extreme miniaturization of conventional Hall thruster systems, while allowing for safer handling and significantly wider material compatibility over well explored alternatives such as Iodine. In this paper, developments of ultra-compact, tightly integrated Hall thrusters are discussed, ranging in compatibility from 1U Cubesats down to 3P PocketQubes. These developments are the first reported instances of Hall thrusters operating on Adamantane fuel, including ignition with a novel low-power glow discharge cathode, development of the first PocketQube-class Hall thruster system, and the smallest reported full Hall thruster systems to date.

I. Nomenclature

1U	=	single base unit standard for Cubesats (10 cm x 10 cm x 10 cm)
1P	=	single base unit standard for PocketQubes (5 cm x 5 cm x 5 cm)
kV	=	kilo-Volt

II. Introduction

While significant work over the years has been put into the miniaturization of the Hall thruster head, with reported discharge channels only a few mm or less in width [1-4], relatively less emphasis has been put on scaling the entire Hall thruster system to sizes significantly smaller than 1U in volume. Much of the difficulties in extreme miniaturization can be attributed to the auxiliaries for Hall thrusters rather than the thruster head itself – fuel tanks, fuel management, neutralizers, and electronics. While Hall thruster heads have been demonstrated at very small scales, full Hall thruster systems still remain too large for the smallest class of nanosatellites and picosatellites ranging from around 3P class PocketQubes to 1U-class Cubesats.

Solid fuels represent an attractive alternative in particular to conventional electric propulsion systems such as Hall, gridded ion, and RF plasma. Iodine has been studied extensively as one of the most dominant alternatives in the field. Despite its number of advantages, Iodine has several drawbacks, including its highly corrosive nature, as well as toxicity in handling, requiring special material compatibility challenges for thruster development and considerations for corrosion prepared pumping infrastructure for testing. Other solid metallic fuels that have been tested with Hall thrusters prior, including bismuth, magnesium, and zinc require high power levels and heat for delivery of the metal propellants, far in excess that can be managed at the picosat level [5-7]. Metals with low vaporizing points and low ionization thresholds such as Mercury and Cesium pose significant toxicity hazards for handling, as well as pose significant environmental concerns.

Although there are a limited number of suitable low-temperature, low-toxicity sublimating materials suitable for use in propulsion, several from the diamandoid hydrocarbon family have emerged as potential candidates to fit this role. Of particular interest and significance is the lightest substance of this family, Adamantane ($C_{10}H_{16}$), which shares

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many similar physical properties to that of Iodine, without the same issues of corrosiveness and toxicity. Adamantane is a unique diamandoid hydrocarbon that exhibits many similar properties to Iodine – solid fuel storage, direct sublimation at very low temperatures in vacuum, high molecular mass, and large ionization cross-section. While density is four times less than that of Iodine, and has several observed ionization inefficiencies, Adamantane is neither toxic to handle nor corrosive, eliminating material compatibility issues or special handling concerns.

While a few tests have been conducted using Adamantane in low and high-power RF gridded ion thrusters [8-11], very low power operation has not been sufficiently explored, and to date no tests have been conducted using Adamantane with Hall thrusters. Despite its interesting properties as a direct sublimation fuel for electric propulsion, Adamantane still remains virtually unknown in the field. Over the past year, AIS has been working extensively on the use of Adamantane as an alternative molecular fuel with the specific goal to achieve extreme full-system miniaturization of conventional Hall thruster systems through its ADAMANT Series initiative. AIS proposes that Adamantane can allow for radical full-system miniaturization and cost reduction of conventional Hall thruster technology, allowing for unprecedented scaling while being safer and easier to handle than Iodine. In the past year, AIS has reported the first ever operation of a Hall thruster using sublimated Adamantane fuel across several highly compact, low-power Hall thrusters and a unique hollow cathode. These prototype Hall thrusters range from 0.33U down to 0.125U (or 1P in PocketQube standards) in size for the entire assembly including Hall thruster, cathode, fuel management and delivery system, and electronics, and are some of the smallest full system Hall thrusters yet to be developed in the field.

III. Properties of Adamantane and Iodine as Molecular Propellants

The most common solid sublimating alternative fuel currently explored in electric propulsion is Iodine, which has been studied extensively in prior literature for a wide variety of propulsion systems. Adamantane, while relatively unknown in the field, shares many of the advantages of Iodine which lends for its attractiveness as a propellant. Table 1 shows some of the basic physical properties of Adamantane and Iodine, while Table 2 refers to some practical considerations for use of each in electric propulsion.

Table 1 Physical Properties [8]

Properties	Adamantane	Iodine
AMU	136.2	126.9
1st Ionization Energy (eV)	9.23	9.3
Boiling Point (K)	543.18 (sublimation)	457.6
Density (g/cm3)	1.07	4.93

Table 2 Practical Considerations for Propellant Use [8]

Properties	Adamantane	Iodine
Storage	solid	solid
Delivery	sublimation	sublimation
Toxicity	low	high
Cost	$1/g	$0.06/g
Other Considerations	Amorphous carbon buildup	corrosive

For any propellant selection, there are a number of trade-offs to consider. While Adamantane has been demonstrated as advantageous for this development due to its significantly lower toxicity and lack of material compatibility issues, Adamantane is significantly less dense than Iodine, allowing for much less total fuel capacity in the same volume. In addition, under certain discharge characteristics, like those inside a hollow cathode, amorphous carbon deposits and buildup presents a significant challenge for overcoming for long-term operation. Finally, because Adamantane is a highly complex hydrocarbon, rather than a purely elemental fuel, the resulting plasma and ion species are extremely complex and difficult to analyze, and issues with high electronegative affinity and fragmentation of the fuel during ionization, larger ionization losses occur. Nevertheless, the ease of sublimation at very low temperatures and overall simplicity of handling lends itself better to simplified and low-cost fuel delivery systems with very low power budgets and tight payload volume budgets.

IV. Preliminary Low-Power Sublimation and Ionization Tests

Prior to Hall thruster design and prototyping, preliminary work was done to first determine the feasibility of sublimation and ionization of Adamantane at low temperature and total power. A simple sublimation and discharge test cell was constructed for this purpose. To create the test cell, two circuit boards from a prior thruster development project were used to create the heater surface. A 25 mm diameter, 19 watt ceramic-metal heater element was sandwiched between two boards as a heat source for sublimation. To hold the Adamantane fuel on the topmost heated board, a 3D printed housing was used with a slit in the top for feeding in raw Adamantane, and to allow for sublimated vapors to escape into the discharge cell mounted directly above. To create the discharge cell, a 3 cm length of borosilicate glass tubing was epoxied to two thin stainless steel plates on the top and bottom using Hysol-1C. The bottom plate used a 1.4 mm diameter hole for gas feed, and the top plate used a 1 mm diameter hole for exhaust. Prior to final assembly, both the 3D printed housing and the epoxied test cell were baked and degassed in vacuum for several hours to mitigate any extraneous and unwanted gas loads during testing.

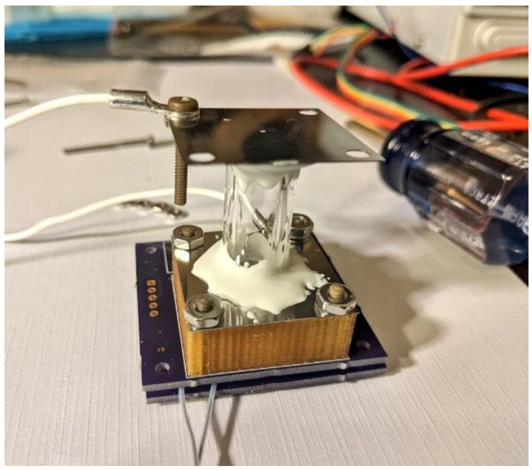

Fig. 1 Low power sublimation and ionization test cell for preliminary Adamantane studies.

Four tests were conducted, operating the sublimation and discharge cell under various configurations of applied discharge voltages, polarities, and heater power. Sublimation was demonstrated passively from ambient chamber temperatures as low as 11 C, and actively with heater sublimation power up to 3.5 watts at several tens of degrees C. Stable discharge was achieved from power levels as low as 0.75 watts up to 3 watts, with applied voltages ranging from 1.5 kV up to 3.5 kV. This stable discharge was demonstrated on both passive and active sublimation, with higher applied voltage allowing for discharge initiation at very low sublimation rates at ambient temperatures. During the tests, basic discharge was demonstrated, as well as extraction of both positive and negative charge depending on plate polarity, and operation of the test cell as a simulated glow-discharge cold hollow cathode, where a stable neutralizer plume was extracted. In particular, the max total input power of any test was 6.7 watts, where 3.2 watts was used to sustain the neutralizer plume and discharge, and the remaining 3.5 watts for sublimation heater power.

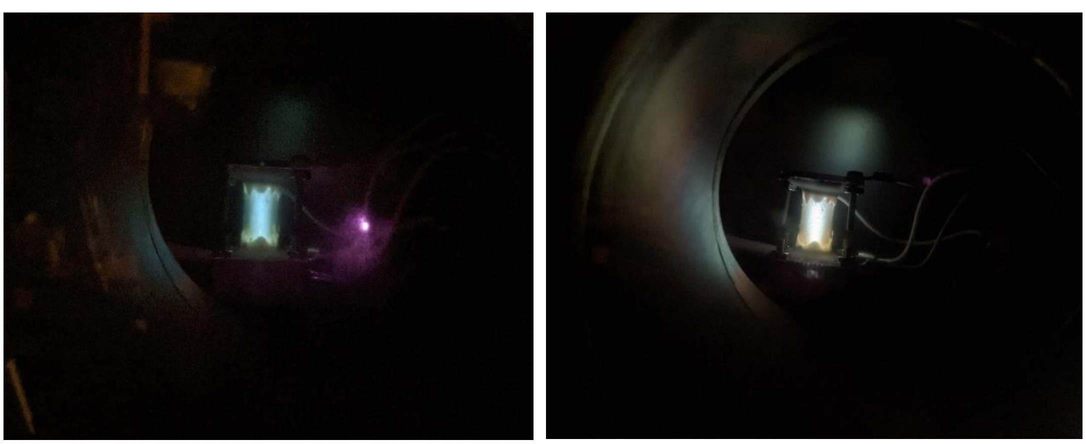

Fig. 2 1 watt Adamantane discharge (left), 2 watt Adamantane discharge (right).

Fig. 3 Low power Adamantane beam extraction (left), 3 watt Adamantane neutralizer plume extraction (right).

V. Testing and Development of the AIS-GDN1 2W Glow Discharge Hollow Cathode

One key subsystem identified as having complexity in extreme scaling for conventional Hall thrusters is the cathode, especially with unconventional, non-inert fuels. While cathodes are typically only a fraction of volume and power for standard Hall thruster systems, at the very low power scale at several tens of watts and less, and total system volume less than 1U, it becomes increasingly difficult to reduce cathode size and power in relation to the Hall thruster head. Low power miniature dispenser inserts and materials are readily available off the shelf, however typical materials such as Barium impregnated cathodes or LaB6 dispenser cathode would become rapidly poisoned and damaged if used with non-inert complex molecular fuels such as Adamantane. As a result, these cathodes, of both heated and heater-less types, represents a challenge for use with Adamantane. Alternatively, RF cathodes have been demonstrated for use with a wide range of both inert and non-inert fuels, however both size and power scaling becomes a challenge at the extreme miniature end, and for extremely small and low-power RF cathodes, RF power in the GHz range is required, adding additional cost and significant complexity to the overall electronics.

Based on the preliminary sublimation and glow discharge tests, particularly with simulation of a glow-discharge neutralizer plume at low total power, a novel low-power cathode alternative was developed specifically for use at extremely low power levels with complex non-inert fuels such as Adamantane, though any fuel can be used as well, and can be scaled up arbitrarily in power. The first prototype cathode, the AIS-GDN1, leverages glow-discharge cold hollow cathode technology used in the particle physics and experimental manufacturing fields. Unlike typical hollow cathodes in Hall thrusters, the GDN1 operates in a cold-cathode glow-discharge mode, relying on a direct high voltage, low current discharge, eliminating heaters, inserts, or RF. While this style of cathode has not enjoyed use in electric propulsion systems, such cathodes have been studied extensively as high current e-beam sources in other experimental fields for decades, demonstrated at power scaling from less than 1 watt to megawatt class systems for the largest pulsed sources, and can range from sub-mm to tens of cm in diameter [12-21]. Due to their simple and robust design, they can be manufactured at an extremely low cost with common materials and are compatible with virtually any gas. These properties allow for operation of the GDN1 at only a few watts of input power and allows for extreme miniaturization of conventional hollow-cathode technology while being incredibly simple and low-cost to manufacture.

To construct this cathode, 3D printing was leveraged to allow for low cost fabrication while incorporating a number of complex geometries into the design and relying on commonly available materials. The housing of the GDN1 is made from Somos PerFORM ceramic-embedded SLA resin. This resin is a high-performance SLA material which boasts high dielectric strength, high heat capacity, and high dimensional tolerances. Although vacuum outgassing data is not available for this material, over the numerous tests to date with a wide variety of propulsion systems at AIS, Somos PerFORM has not exhibited any noticeable outgassing, even under high heat loads and for use has high voltage enclosures exposed to direct plasma bombardment. Despite being a high performance SLA material, Somos PerFORM is readily available and offered at a low-cost from 3D printing manufacturing service providers, allowing for substantial reduction in cost compared to if the housing were made from custom machined ceramics or sintered ceramic. The ability to 3D print the housing also has allowed to keep the design incredibly compact, and include features like the integrated fuel feed channel directly into the structure itself.

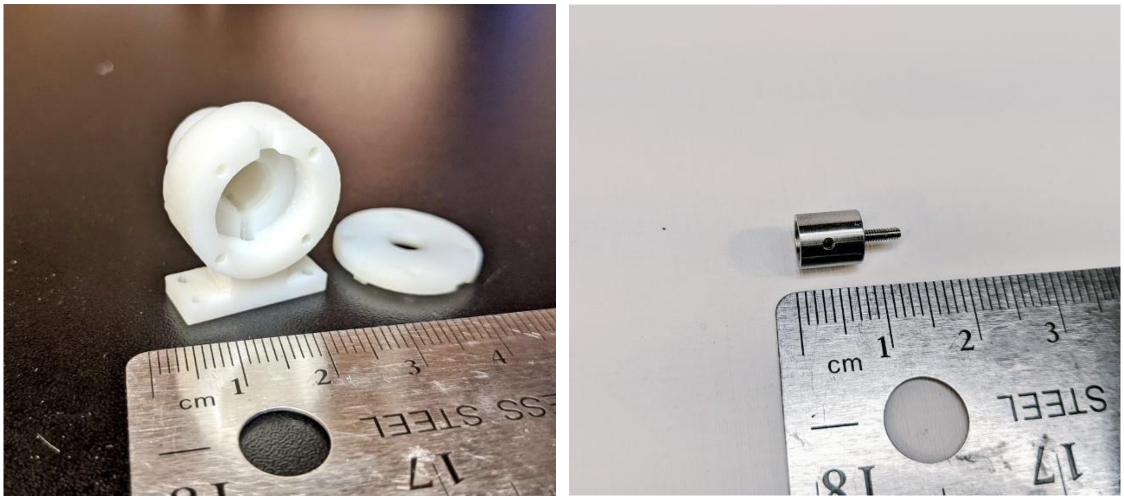

Fig. 4 GDN1 housing made from Somos PerFORM (left), stainless steel hollow cathode (right).

The entire cathode assembly measures 20 mm x 20 mm x 24 mm in total volume. Taking advantage of the ability for 3D printed structures to embed complex internal geometries and passages, direct fuel feed channels were incorporated into the 3D printed housing. The GDN1 also uses a three-electrode configuration for glow-discharge hollow cathode electron sources: a negatively biased hollow cathode, a grounded anode with an aperture, and a third extractor electrode with a positive bias for plume extraction. The hollow cathode itself is a simple stainless steel cup measuring 7 mm in length with an internal diameter of 4.5 mm. The anode and extractor electrodes are made with thin laser-cut stainless steel sheet, and the internal insulators consist of off-the-shelf ceramic washers. A small feedhole on the side of the cathode lines up internally with the gas feed channel in the housing, allowing for direct gas flow into the cathode, helping to eliminate external feedlines. A threaded stud is machined directly onto the cathode insert to provide the high voltage electrical connection for the discharge power.

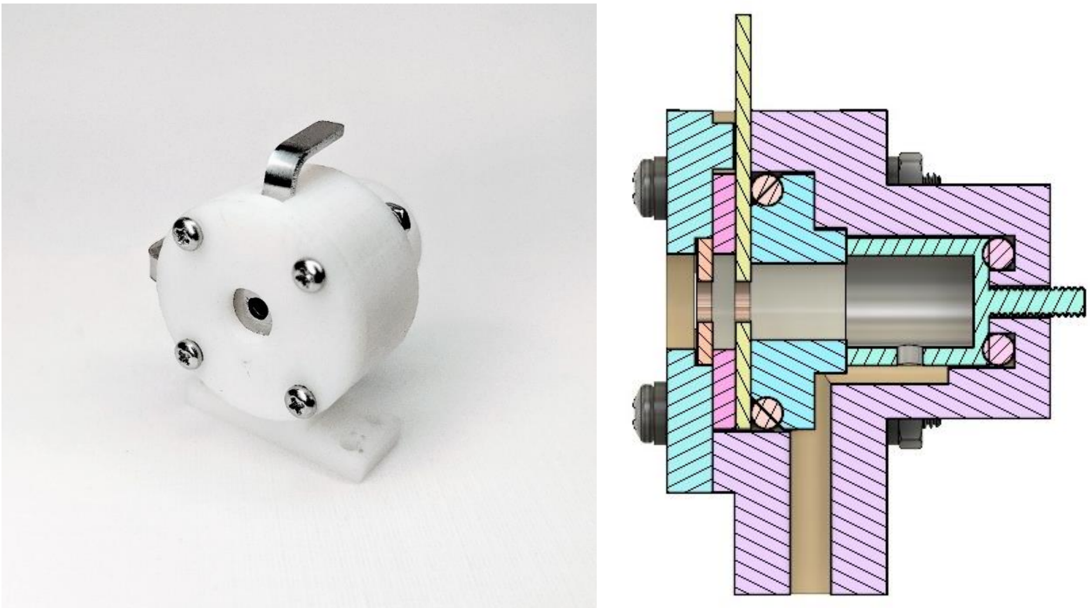

Fig. 5 Full assembly of the GDN1 neutralizer cathode (left), cross sectional model of the GDN1 (right).

Initial testing of the GDN1 was conducted in a self-sustaining discharge mode without operation with a Hall thruster or external biased anode collector. Due to the use of a three electrode configuration, plume extraction could be achieved by adjusting both the negative cathode bias and positive extractor bias. The cathode was mounted to the prototype AIS-EHT1 End Hall Thruster, which was used only to provide Adamantane fuel directly from the sublimation fuel deliver system to the cathode, and operated without the Hall thruster head on.

At a very low voltage of only a couple hundred volts on the cathode, a glow was visible from the hollow cathode. As extractor power was turned on and increased, the glow from the cathode intensified. Eventually, a bright plume could be seen emanating from the cathode as a successful neutralizer plume was established. As extractor power was then raised to maximum power, with the discharge supply operated at minimal voltage, the output plume grew larger. The neutralizer plume was operated until evidence of fuel depletion, indicated by flickering of the neutralizer plume and eventual decrease in output. Max power during peak operation of the cathode was 2 watts total.

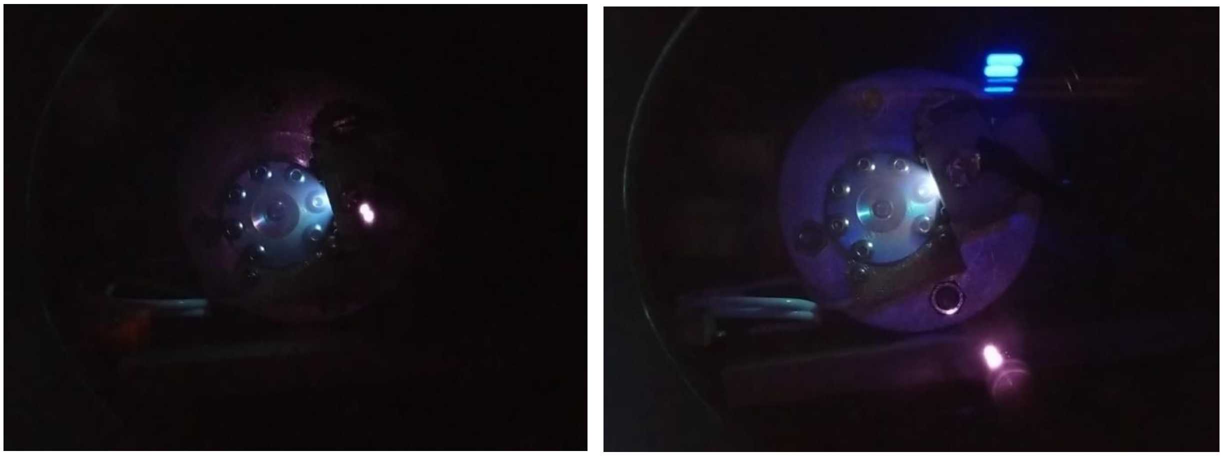

Fig. 6 Initial self-sustained ignition of the GDN1 at low power (left), full power neutralizer plume output at 2 watts (right).

After the ignition test, the cathode was disassembled for inspection. It was found that during the short run, significant buildup of amorphous carbon occurred inside the cathode and around the inner face of both apertures on the anode and extractor. This represents one of the key challenges using Adamantane in cathodes, especially with small orifices. Although Adamantane does not have any corrosive properties, the buildup of amorphous carbon in the cathode and output apertures can cause issues, primarily clogging of the feed hole in the cathode and output orifice of both the anode and extractor plates, leading to decreased performance and lifetime.

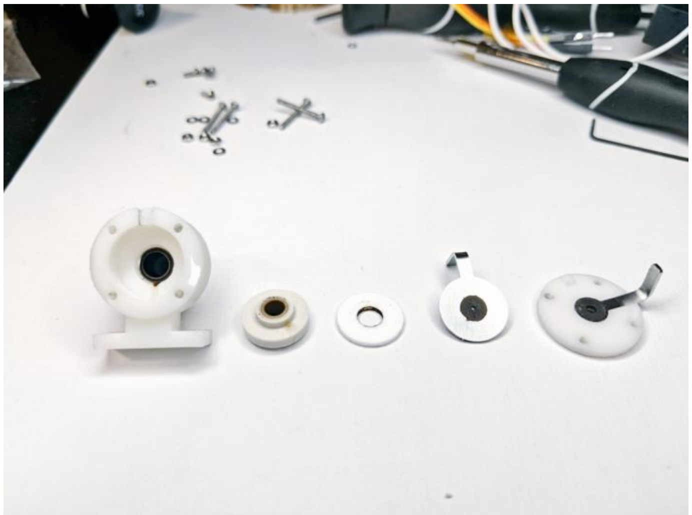

Fig. 7 Post-test inspection of the GDN1. Significant amorphous carbon buildup can be seen deposited along all exposed internal surfaces.

VI. Testing and Development of the AIS-EHT1 Micro End-Hall Thruster

The first generation design of micro Hall thrusters at AIS relied on inspiration from industrial Hall ion sources [22] used for surface processing to simplify manufacturing and construction to make miniaturization easier. The full Hall thruster design consists of three major parts: the sublimation fuel delivery system (SFDS), the Hall thruster head, and the cathode. All of these elements were designed to be tightly integrated and directly interfaced together, eliminating any external propellant feedlines and allowing for the full assembly to be highly compact.

A. Sublimation Fuel Delivery System (SFDS)

Since Adamantane is a direct sublimating fuel, it can be stored unpressurized as a solid. Because of this, the fuel tank could be designed for direct feeding into the Hall thruster head without the need for pressurized design considerations. The first generation SFDS utilized a simple stainless steel heater cartridge, fit into a 3D printed housing, which allowed for a low-power ceramic metal heater to directly heat the fuel cartridge for sublimation. To keep the Adamantane pressed against the heated face of the cartridge, a presser plate with holes drilled in to allow for vapors to escape was used. A conical spring is located between the presser plate and the upper seal plate for minimal space under max compression. As Adamantane is depleted, the presser plate evenly compresses the remaining fuel into the heated face as vapors rise up through the distribution holes in the plates. In order to reduce the size of the full system as much as possible and simplify initial testing, no external valving of fuel feed lines were used, however it is recognized that a final system must include valving to prevent passive sublimation of Adamantane from the fuel tank when in orbit. The Hall thruster head was also specifically designed to integrate directly on top of the SFDS, allowing Adamantane vapors to flow directly into the Hall thruster, keeping the entire fuel delivery and Hall thruster system tightly integrated as one block.

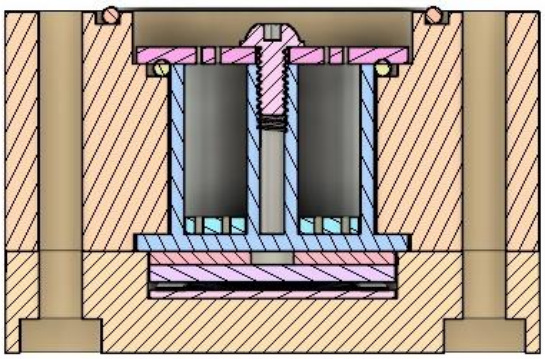

Fig. 8 Cross section of the SFDS with outer housing, fuel heater cartridge, ceramic heater, spring loaded presser plate, and upper distribution plate.

Prior to final assembly, the thruster must be first fueled with Adamantane. Adamantane has the consistency of coarse table salt, which is poured directly into the fuel heater cartridge and packed down. The presser plate is placed over the fuel charge, followed by the conical compression spring, providing continuous contact with the bottom heated portion of the cartridge, which is heated by a ceramic-metal heater in direct contact with it underneath. The cartridge is then fit into the 3D printed housing from the bottom, and locked into place from the top with the upper plate, simultaneously securing the cartridge while compressing the spring for fuel feed. Several Viton o-rings provide sealing from vapors escaping between the heater cartridge and the housing, and the housing to the Hall thruster adapter plate.

Fig. 9 Heater cartridge filled with Adamantane (top left), cartridge and presser plate with spring inserted into housing (top right), sealed fuel tank (bottom left), complete depletion of fuel post-test (bottom right).

B. AIS-EHT1 Micro End Hall Thruster Head Design

In order to minimize costs and simplify manufacturing, the EHT1 thruster head design was based around general industrial end Hall ion sources, specifically using off-the-shelf standard ceramic washers as insulators and machining the internal components around these washers. While most Hall thrusters in the field are stationary layer or anode layer, it was decided to first experiment with an end Hall style for this first system. Although discharge current to beam current conversion efficiency is significantly lower compared to stationary layer and anode layer designs, with larger beam divergence and overall poorer performance, end Hall sources can be made much simpler and lower cost, which was a major driving point of the initial development. End Hall sources are also very robust, and are often run with a wide range of inert, non-inert, and corrosive gases in industry.

In order to accomplish tight integration and direct adapting of the Hall thruster head, cathode feed, and fuel delivery, the EHT1 thruster head was directly machined into the adapter flange which allows it to be directly bolted to the fuel delivery system, eliminating any fuel lines. In addition, the adapter flange has mounting holes and a fuel feed port for the GDN1, located right next to the thruster head. This allows simultaneous feeding of both the thruster head and hollow cathode from a single fuel vapor source, further eliminating the need for additional feed lines, and keeps the total system volume highly compact. The proportion of fuel flow between the thruster head and the cathode is adjusted via physical dimensions of the fuel feed holes for each. In the event the hollow cathode is not used (as in the case of operation with a filament neutralizer), the cathode feed port can be blanked off, redirecting all fuel flow to the Hall thruster head. The adapter flange measures only 50 mm in diameter, with the thruster head offset to one side, measuring only 20 mm in diameter and 10 mm in height fully assembled. Due to its size, permanent magnets were selected as the magnetic field source for the thruster. Around the periphery of the Hall thruster outer casing are milled holes to accept stacks of small cylindrical Samarium Cobalt (SmCo) magnets. The entire thruster head and adapter plate was machined from 1018 steel, allowing for housing to be a part of the magnetic circuit while still machined from a single block to adapt to the SFDS.

The thruster internal components consists of an anode, which is powered through a machined port on the side of the cylindrical housing, a plasma baffle used to protect the inner central magnet while simultaneously distributing gas through the thruster head, insulators made from off-the-shelf alumina washers, and an upper pole piece. A wave disc spring is inserted under the plasma baffle, and the upper pole piece compresses and secures the entire assembly together between the insulating washers when bolted to the top of the casing. The adapter plate also includes mounting holes for the anode feed adapter, which uses a 3D printed housing for insulation and clamping of the feed wire. Gas feeds into the thruster head through a series of small drilled holes located radially around the center magnet, directly under the plasma baffle.

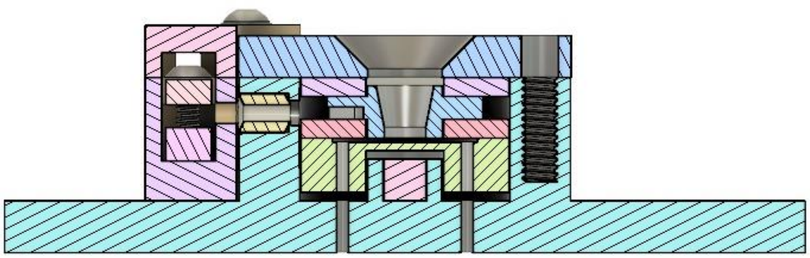

Fig. 10   Cross section of the EHT1 End Hall Thruster head.

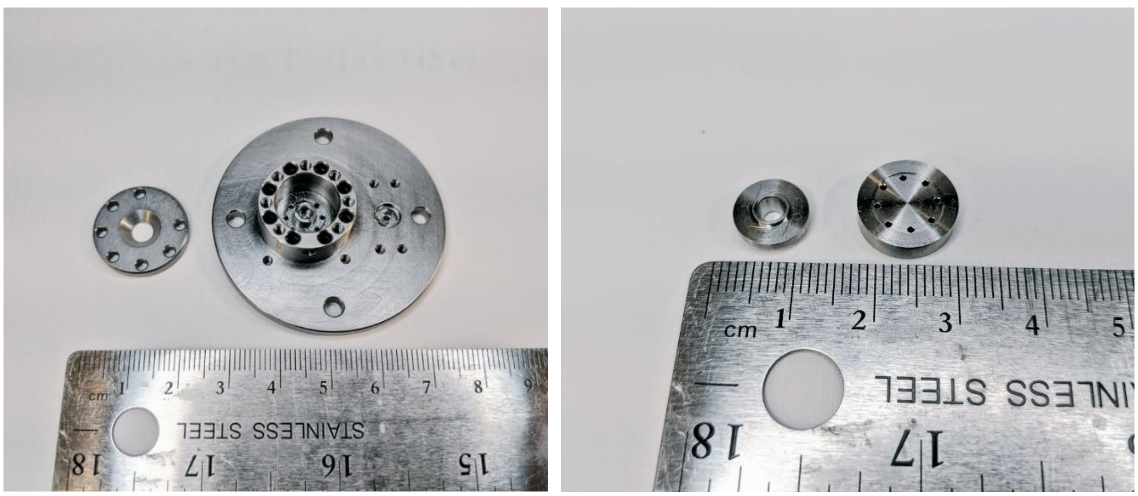

Fig. 11   1018 steel upper pole piece and outer casing (left), 304 stainless steel anode and plasma baffle (right).

Fig. 12   Fully assembled EHT1 Hall thruster head.

C. EHT1 Testing with Tungsten Filament Neutralizer

For the first ignition test of the EHT1, a simple Tungsten filament neutralizer configuration was used to first validate operation of the sublimation fuel delivery system and Hall thruster head. Because the EHT1 was designed with inspiration from industrial sources, it can be easily reconfigured to operate with a standard filament across the head, or using the side mounted cathode. The anode was connected to a 2 watts, 3.5 kV Pico Electronics power supply for the discharge power. The filament was connected to an external 30 volt, 10 amp DC power supply.

Fig. 13 Fully assembled EHT1 Hall thruster system with SFDS, configured for operation with a Tungsten filament neutralizer.

The HV discharge supply was first brought up to 2 kV to verify no breakdown would occur in the thruster. After, the sublimation heater was turned on to 3.5 watts of power. After a minute or two, the vacuum pressure began to rise, indicating successful controlled sublimation and fuel delivery with the SFDS. Filament power was then slowly turned on, starting at a few watts of power. As filament power was slowly increased, discharge voltage started to drop, which was an indication that loading on the supply was occurring due to current flow from ionization. At 50 watts of filament power, discharge voltage began to rapidly drop, and eventually stabilized at 500-600 volts, indicating actual sustained ionization and discharge. At this point, beam current was measured at 120 uA on the Faraday cup, indicating ignition and as a result, an accelerated exhaust plume of ions. Due to the brightness of the filament, it was impossible to directly observe any discharge or ionization glow during operation. The test was run until depletion of the fuel, indicated by system readouts, and later confirmed after disassembly, with 100% utilization of the fuel charge and no residual condensation.

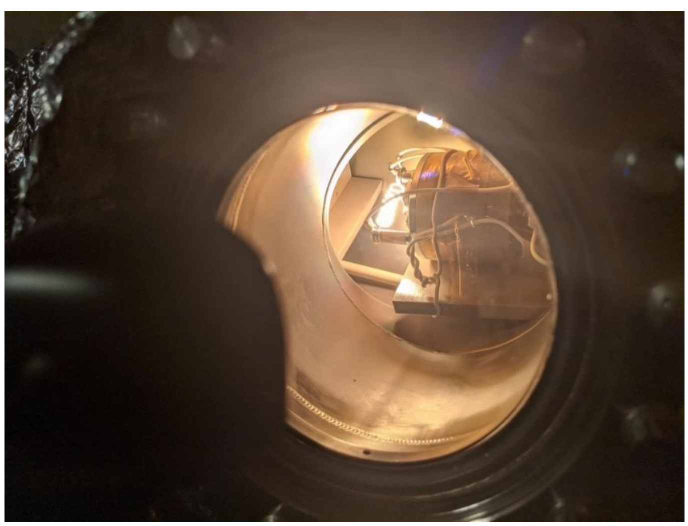

Fig. 14 Ignition testing of the EHT1 with Tungsten filament neutralizer.

D. EHT1 Testing with the GDN1 Neutralizer Cathode

After successful operation of the EHT1 with a filament, the GDN1 cathode was installed onto the thruster adapter baseplate and run on its own to verify ignition. Because of the tightly integrated design, no external feedline is needed to connect either the Hall thruster head or the cathode to the fuel tank. Instead, both the Hall thruster and cathode are simultaneously fed from the same tank through the adapter plate.

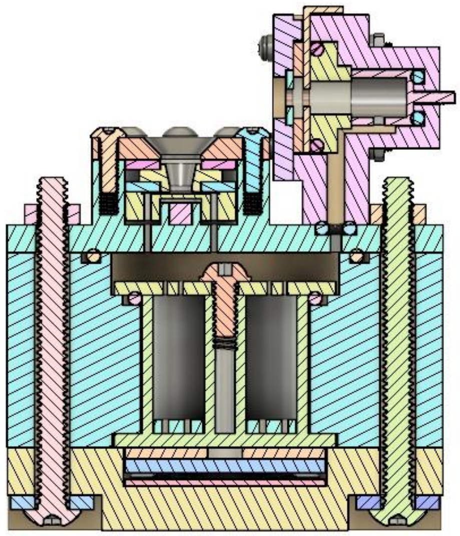

Fig. 15 Cross section of the full EHT1 assembly with fuel tank, Hall thruster, and cathode. The flow path can be seen from the tank to both the thruster head and cathode, as sublimated vapors are directly fed into each through drilled ports on the integrated mounting flange.

Fig. 16 Fully assembled EHT1 thruster head with 3D printed anode power adapter and GDN1 cathode.

After ignition was established with just the cathode operating in a self-sustaining discharge mode with Adamantane fuel, several tests were conducted to establish ignition of the Hall thruster with the cathode using sublimated Adamantane fuel. For the new full system tests, the original 2 watt anode power supply used for ignition with the tungsten filament was swapped out with a 9 watt, 1 kV Pico Electronics supply, and a dedicated driver was built for the cathode with two additional Pico supplies for the cathode and extractor bias. The power electronics for the anode discharge supply and cathode supply were directly mounted to a custom aluminum bracket, which bolts directly to threaded inserts at the bottom of the fuel tank. The total volume of the system with electronics is 0.33U, which allows for compatibility even in 1U Cubesats, particularly if extra tuna-can volume allowances are made.

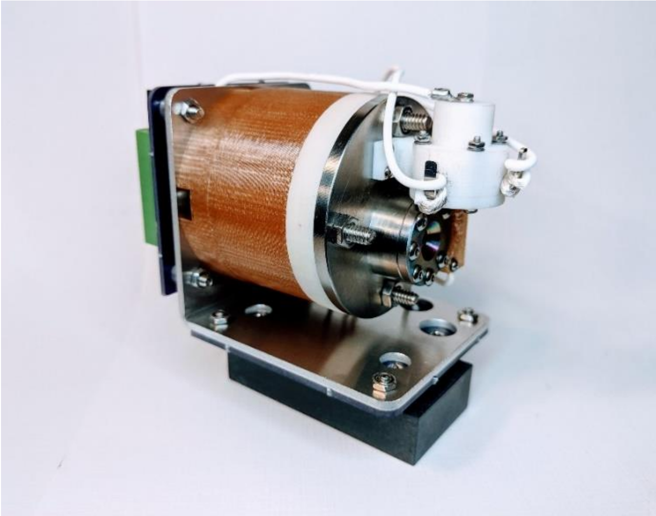

Fig. 17 Complete assembly of the EHT1 Micro End Hall Thruster System with Hall thruster, GDN1 cathode, SFDS fuel tank, and power electronics on mounting bracket.

During the first ignition attempt, plasma bridging between the anode and cathode was successfully established. However, no exhaust plume was observed, and no beam current was read on the Faraday cup.

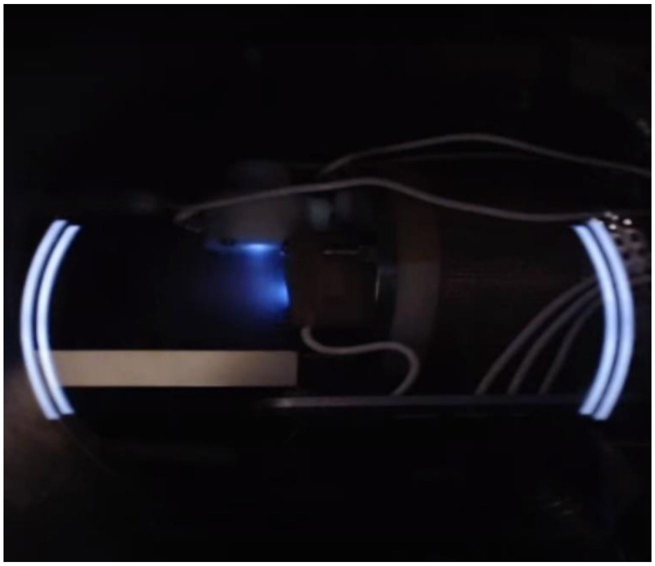

Fig. 18 Initial plasma bridging during first full system ignition attempt with Adamantane fuel.

For the second ignition test, the cathode discharge power supply was reconfigured to run at higher voltages using the original prototype setup for the earlier self-sustained discharge test with the GDN1. During this test, significantly brighter plasma bridging was observed between the Hall thruster head and the cathode. Despite the plasma bridging remaining stable, no beam current was again observed on the Faraday cup, indicating a lack of proper ignition.

Fig. 19 More intense plasma bridging after modifications for the second ignition attempt with Adamantane fuel.

Towards the end of the test, the plasma began to flicker and was eventually extinguished, earlier than anticipated based on prior testing with the amount of Adamantane fuel present. All readouts indicated no electronics failure as well. Upon disassembly of the thruster for inspection, it was found that at this increased output, the extractor aperture became completely clogged with amorphous carbon deposits. However, the inside of the Hall thruster head itself remained relatively clean, although some discoloration can be seen due to the hydrocarbon plasma discharge.

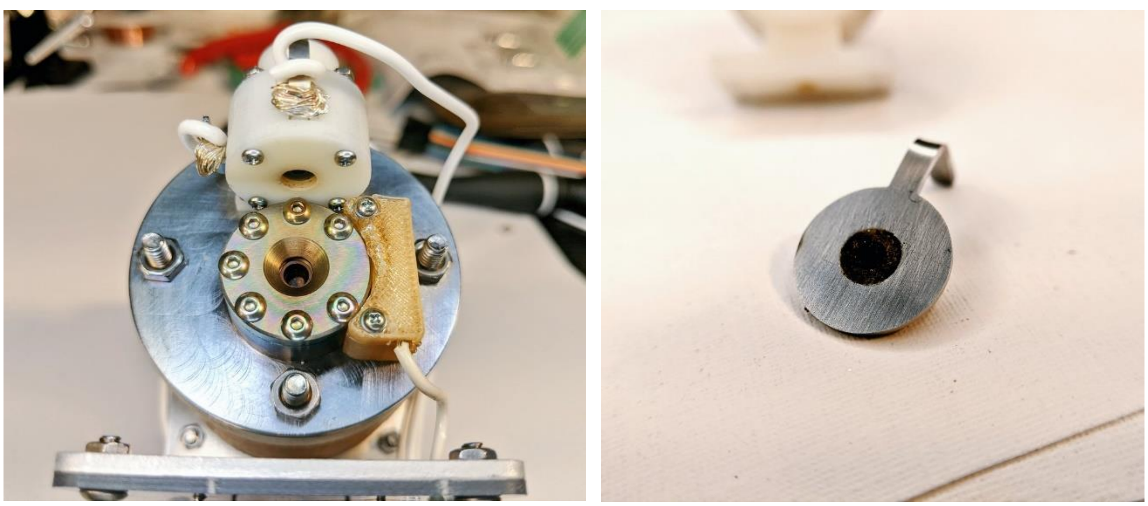

Fig. 20 Discoloration on the thruster due to the hydrocarbon plume (left), amorphous carbon clogging of the neutralizer extractor aperture (right).

For the third test, magnetic field strength was increased by using additional permanent magnets in the steel thruster housing. Both the anode and extractor aperture diameters in the GDN1 cathode were also increased to prevent clogging from carbon buildup. This time, after bringing up anode and cathode power with sufficient fuel flow, successful bridging was established, and with full anode power, a transition could be seen from bridging to exhaust plume formation, where stable beam current was read from the Faraday cup, indicating successful ignition of the EHT1 using the GDN1 cathode. The total max thruster input power was 26 watts, with 15 watts for the anode discharge, 2 watts for the cathode, and 9 watts for the sublimation heater. After full power ignition was achieved, anode power was cycled from full power to 50% power, where beam current was still read on the Faraday cup and the exhaust plume was still stable.

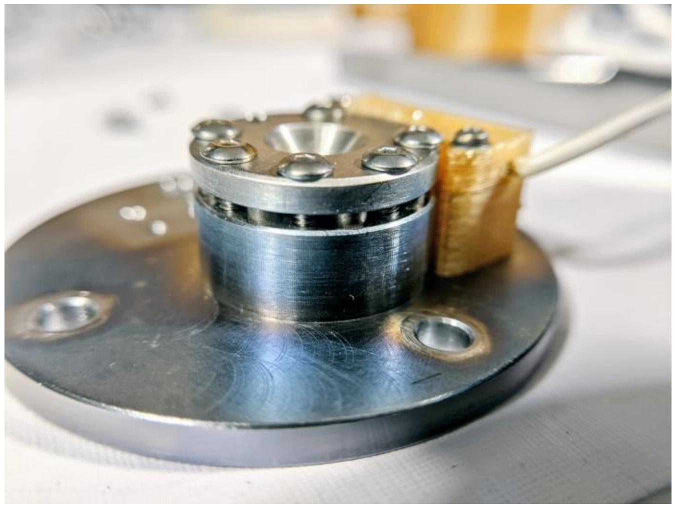

Fig. 21 Modification to the EHT1 with additional SmCo magnets to increase magnetic field strength.

Fig. 22 Initial plasma bridging at low discharge power (left), successful ignition with fully expanded plume at full discharge power (right).

The thruster was operated stably at full ignition until chamber pressure rose to excessive levels, forcing the test to end earlier than planned. After the test, the thruster was removed for inspection. It could be immediately observed that full discharge power and ignition caused significant discoloration and thermal stress fractures in the Somos PerFORM cathode housing. Significant buildup of amorphous carbon was observed inside the cathode, however the larger aperture diameters helped prevent clogging, at the cost of running the sublimation heater at higher levels than anticipated to compensate for increased fuel flow needed for ignition. Despite the thermal stresses on the relatively small cathode, the thruster was able to perform without issue, although redesign of the GDN1 is required to better manage thermal stresses at increased power levels for sustained operation in the future.

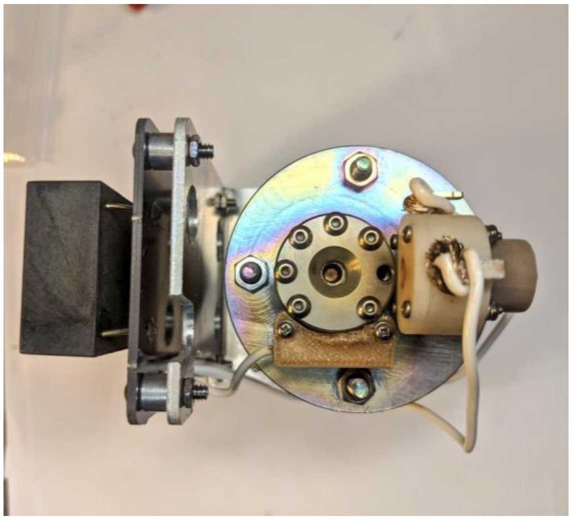

Fig. 23   Discoloration around the thruster head due to the hydrocarbon plasma exhaust.

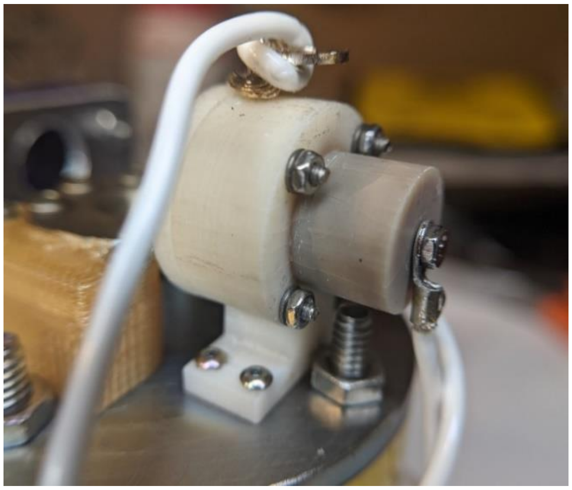

Fig. 24   Discoloration and thermal stress fractures in the GDN1 Somos PerFORM housing.

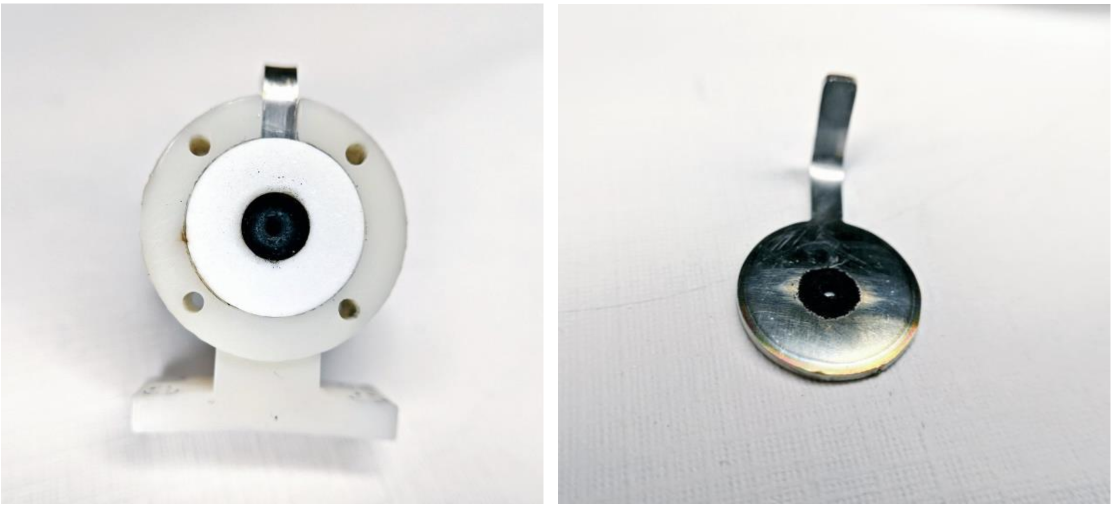

Fig. 25   Examples of amorphous carbon buildup on one of the ceramic insulating washers in the GDN1 (left), amorphous carbon buildup around the anode aperture (right).

VII. Testing and Development of the AIS-AHT1-PQ Pico Anode Layer Hall Thruster

Taking lessons learned from the prior developments and tests, a new Hall thruster system was developed to push the limits of full system miniaturization for Hall thrusters. The AIS-AHT1-PQ was designed with an enhanced sublimation fuel delivery system to significantly increase onboard fuel capacity in a smaller total package than the original EHT1 fuel system, while incorporating a new micro fuel valve to better control fuel delivery and management. In order to further reduce total system size, neutralizer-less operation was explored, as well as initial testing with a Tungsten filament neutralizer. The thruster head design was also switched from end Hall to anode layer to further improve overall thruster efficiency of the system and to more easily allow for experiments in a neutralizer-less configuration.

A. Enhanced Sublimation Fuel Deliver System (SFDS)

The AHT1-PQ sublimation fuel delivery system design was inspired by the initial work done on the first gen EHT1 SFDS, with significant changes to improve total fuel capacity and flow control. Instead of a small heated metal cartridge inside a 3D printed housing, the entire fuel tank consists of a custom machined solid aluminum tank which integrates sealing, mounting, wire routing channels, and slots for an integrated micro-valve and larger ceramic heater underneath. The fuel capacity was increased from 3 to 18 grams, while keeping the overall tank volume smaller than the original EHT1 tank. Due to the thermal design and larger integrated heater, the entire fuel tank and exposed surfaces to Adamantane fuel flow operate at high enough temperatures to prevent re-condensation of the fuel. It was also found that the micro fuel valve operates warm under nominal conditions, helping prevent clogging in the valve. The fuel tank also shares the same presser plate concept with the same conical compression spring to keep the Adamantane fuel even compressed against the heated bottom portion of the tank. Routed channels in the bottom of the tank and upper tank cover direct the Adamantane vapors into the Hall thruster head, which is mounted to the top of the tank as one integrated unit. Viton o-ring seals provide sealing around the flow channels to prevent Adamantane vapors from escaping.

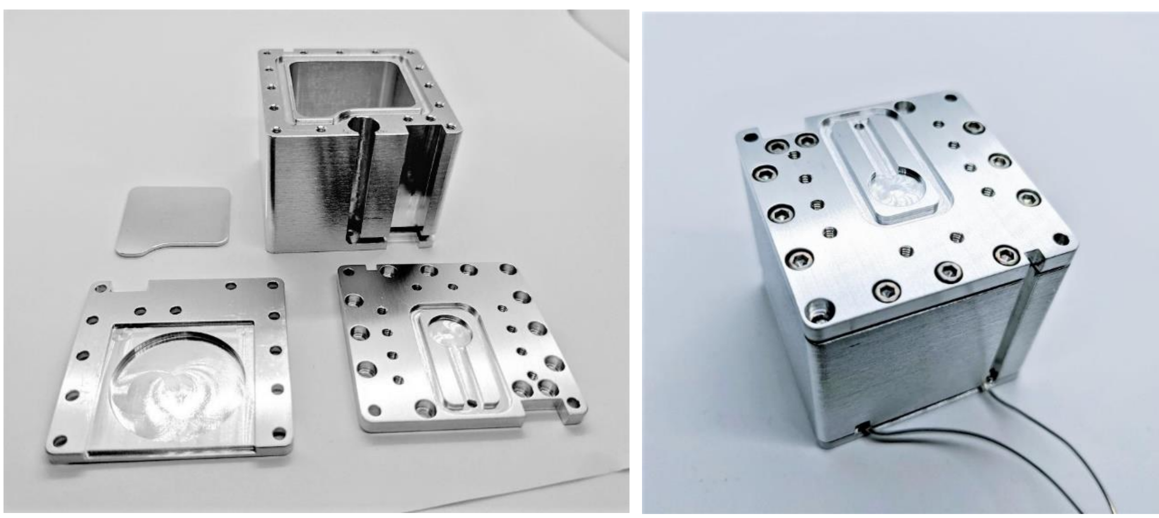

Fig. 26 Components of the enhanced sublimation fuel delivery system including solid aluminum tank, lower heater plate, upper tank cover, and presser plate (left). Fully assembled sublimation fuel delivery system with tank cover mounted (right).

Filling and sealing of the AHT1-PQ sublimation tank is identical to the EHT1 design, with Adamantane being poured directly into the tank and tightly packed down. A precision cut presser plate is then installed, followed by the conical compression spring, and the tank lid. However, unlike the EHT1 design, where Adamantane vapors directly rise up through the presser plate and lid, the vapors first travel downwards through the bottom of the tank, through a routed channel next to the ceramic heater, then back up through the micro fuel valve on the side, and through a routed channel across the top of the tank lid, rising directly into the Hall thruster head. Like the prior EHT1 SFDS, the new enhanced SFDS has exhibited 100% fuel utilization capability, with no issues of re-condensation, and extremely uniform sublimation and depletion of the fuel charge during operation.

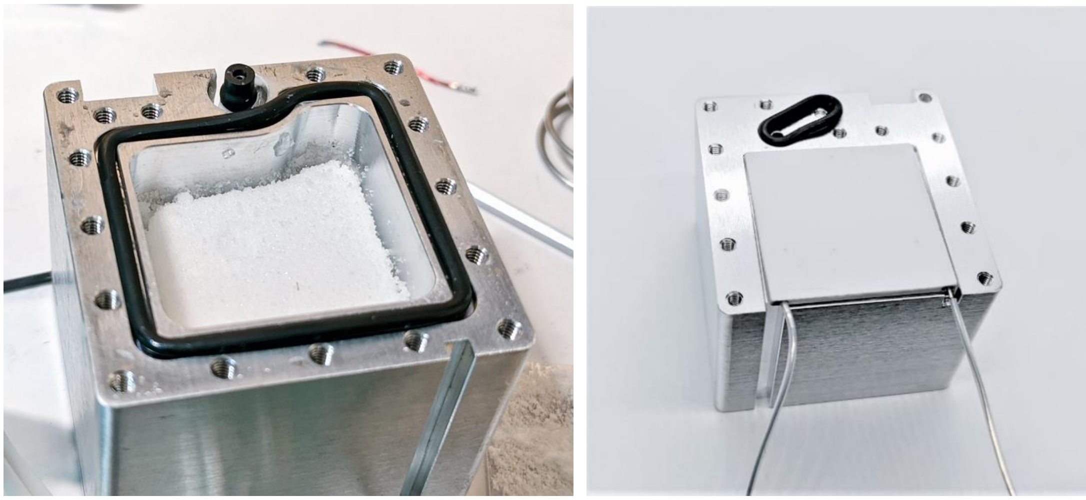

Fig. 27 Filling the fuel tank with Adamantane fuel (left). Bottom view of the tank with low-power ceramic heater in the routed heater channel (right).

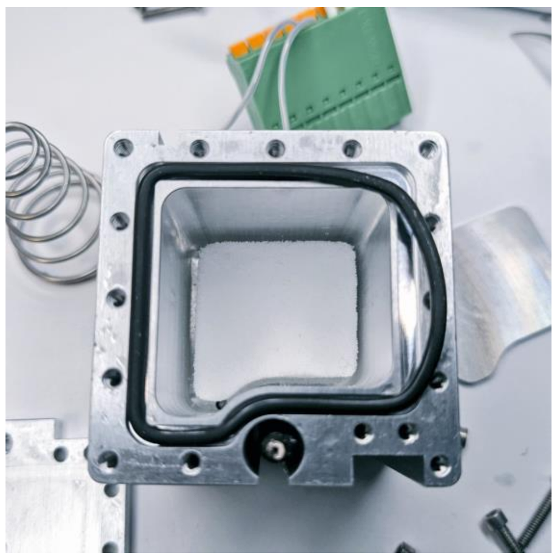

Fig. 28 Remaining Adamantane fuel charge prior to complete depletion. Evidence of extremely uniform sublimation during operation.

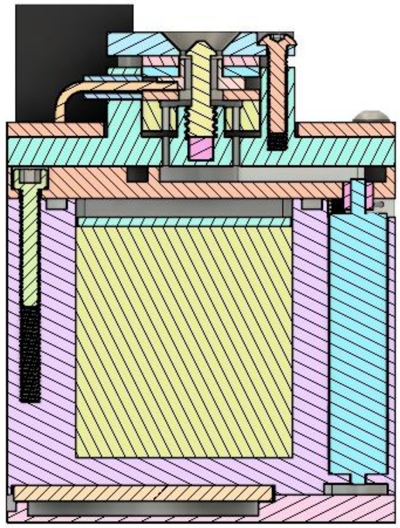

Fig. 29 Cross section of the full AHT1-PQ system assembly with fuel tank, integrated micro valve, and full Hall thruster head assembly.

B. Design of the AHT1-PQ Hall Thruster Head

The AHT1-PQ Hall thruster head has undergone several major design changes and iterations over the course of development. The initial concept leveraged the basic topology of the EHT1, revolving around the outer housing being machined directly into the fuel adapter plate. For this system, it was decided to switch from end Hall to anode layer to significantly increase beam current to discharge current conversion efficiency. In addition, industrial anode layer ion sources are often run in a neutralizer-less self-discharge mode, where discharge is initiated through significantly higher voltages than typically seen in conventional Hall thrusters, relying on secondary electron emission through ion bombardment of the housing. It was decided to first pursue neutralizer-less operation to simplify the electronics and reduce the total package volume even further without the need of an external cathode.

Fig. 30 1018 steel thruster housing machined into the adapter flange baseplate (left). Stainless steel plasma baffle, steel upper pole piece, and steel center pole piece (right.)

The first design had a similar layout to the EHT1. The Hall thruster cylindrical outer housing followed the same dimensions, however the anode, plasma baffle, and upper pole piece were modified for an anode layer topology. In addition, the central inner magnet of the original design was replaced with a permanent magnet under the central pole piece. The housing and anode design was also designed to accept the same off the shelf ceramic insulating washers, and used the same concept of a wave spring under the plasma baffle to allow for compression locking of the entire internal structure when the upper pole piece was bolted to the top of the housing.

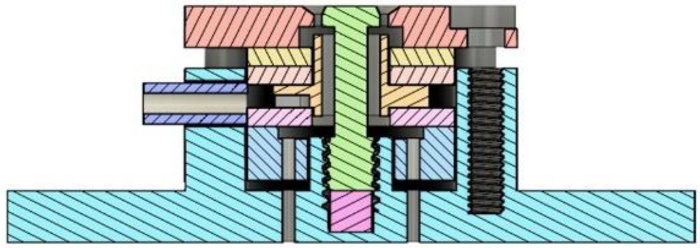

Fig. 31   Cross section of the V1 design for the AHT1-PQ.

In order to keep the system as compact as possible, both the high voltage supply for the main discharge, and the fuel valve control electronics were mounted on a board that fits on the top of the Hall thruster flange baseplate, with a central cutout to allow for the thruster head to portrude out, allowing for direct connection from the anode power feedthrough to the discharge supply.

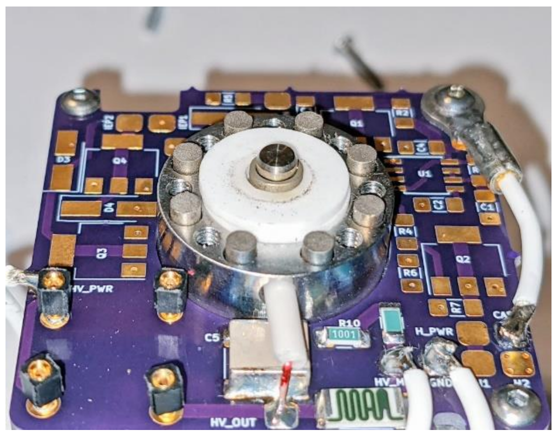

Fig. 32   Exposed thruster head interior with SmCo magnets around the sides, and the ceramic washer, anode, and central pole piece in the thruster head. The prototype PCB can be seen with anode power connection.

Testing of this design however failed to yield stable operation. During the first several tests, no plasma could be initiated from the Hall thruster head, despite operating the anode at excessive voltages of over 2 kV. Inspection of the thruster revealed that discharge was occurring internally between the bore of the anode and the central pole piece. As a result, the design was modified to focus the discharge towards the top of the anode. The entire internal structure was replaced with a single 3D printed Somos PerFORM component, which served as an insulator, anode mount, and fuel flow channel. The anode was also changed to a thinner ring design.

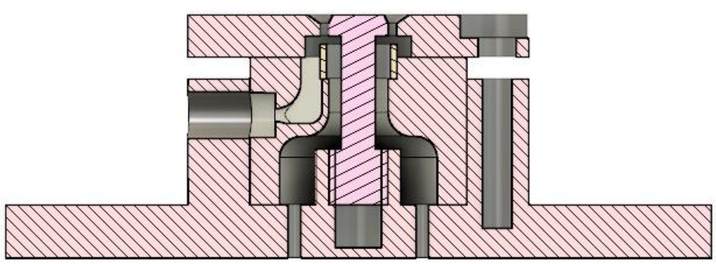

Fig. 33   Cross section of the revised V2 AHT1-PQ thruster head assembly. The internal plasma baffle and insulating washers were replaced with a single 3D printed Somos PerFORM component, which holds a thin ring-anode.

Two variations of thin ring anodes were tested in this configuration. The first, made of thin stainless steel tubing, produced extremely unstable discharges. The second anode was constructed from thin copper fingerstock, forming a segmented crown shape. While this produced marginally better results, discharge was concentrated at only certain points due to the enhanced field at the sharp edges of the segments and uneveness of the anode alignment and construction, still resulting in a highly unstable discharge, as well as uneven distribution of plasma around the discharge channel.

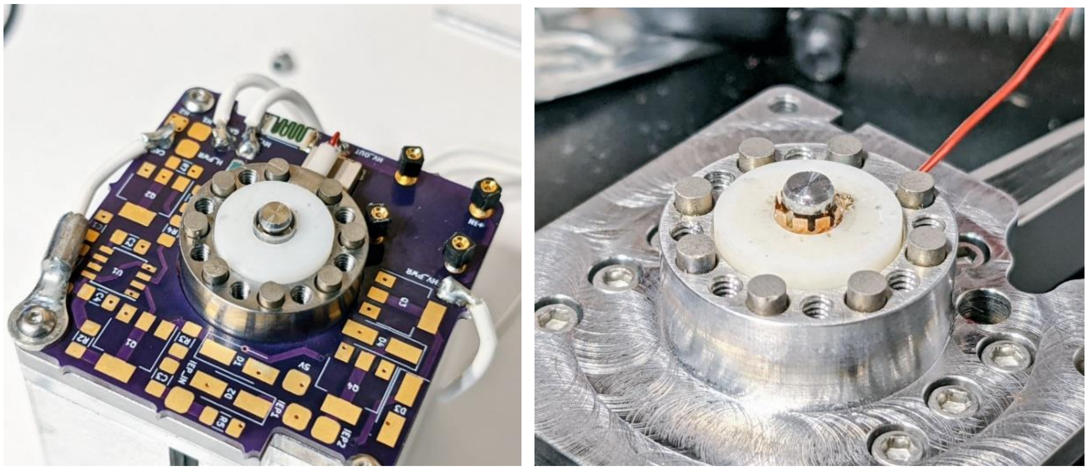

Fig. 34 Exposed thruster head interior with the Somos PerFORM insulator and stainless steel ring anode (left), and segmented copper crown anode (right).

For the next configuration, the anode was reverted back to a thin stainless steel ring, however the upper pole cap bore diameter was enlarged to increase the discharge channel width. Like prior testing, this produced unsatisfactory results, failing to achieve any form of stable discharge or plasma ignition.

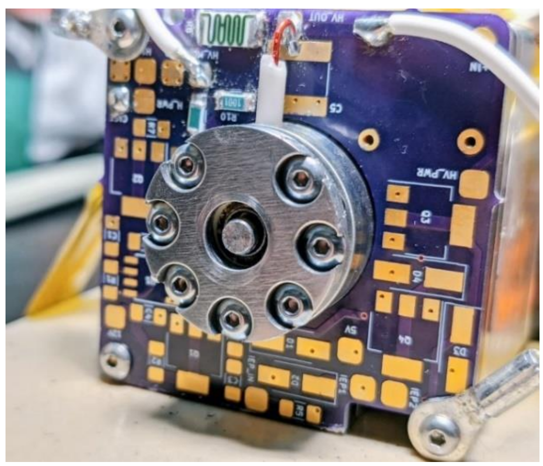

Fig. 35 Modified upper pole piece with enlarged bore.

Finally, the entire geometry of the Hall thruster was completely redesigned, significantly expanding the width and depth of the discharge channel, increasing the width of the anode, modifying the pole pieces, and providing better isolation between the anode and inner pole piece while improving the fuel flow path with a new Somos PerFORM insulator insert.

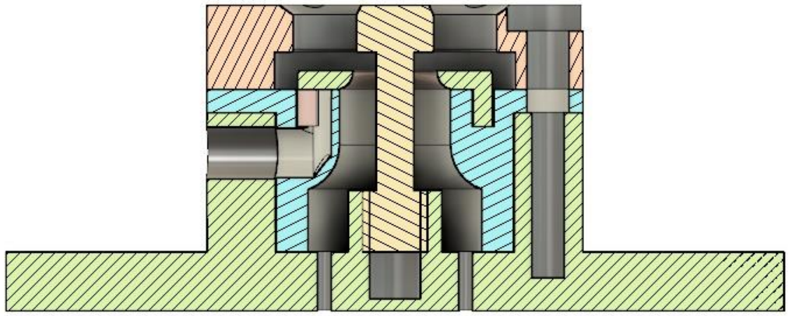

Fig. 36 Cross section of the V3 design for the AHT1-PQ with improve Somos PerFORM insulator, wider surface copper anode, wide-bore upper pole piece, and new inner pole piece.


Fig. 37 Steel upper pole piece, copper anode, and steel inner pole piece (left). Somos PerFORM insulator insert (right).

Over the numerous prior tests, it was also found that magnetic field strength was far too strong with the original magnet configuration. While the EHT1 benefited from increased magnetic field strength, the AHT1-PQ required as minimal magnetic field as possible to prevent sputtering and pulsed instability of the discharge. As a result, only two of the eight permanent magnet channels were filled around the housing, located at opposite side of the head.

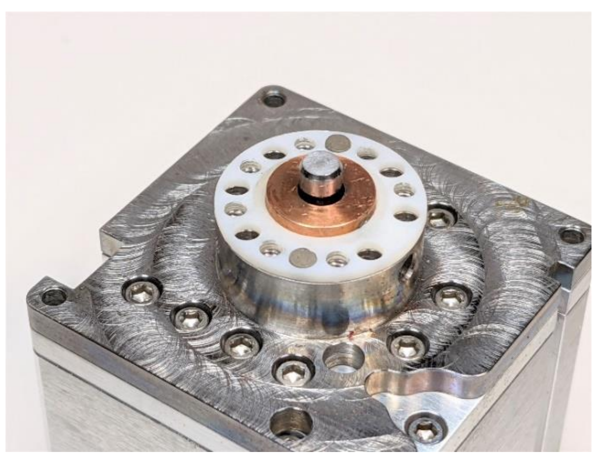

Fig. 38 Exposed thruster head interior of the V3 design with improved anode, inner pole piece, and insulator insert design. Only two sets of magnets can be seen in this configuration, as prior tests indicated the full set of magnets was far too high for stable discharge to be sustained.

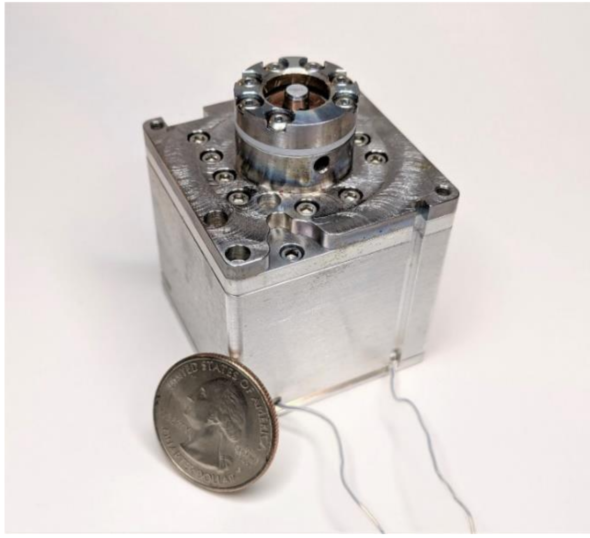

Fig. 39   Complete assembly of the AHT1-PQ Pico Hall Thruster, with integrated fuel sublimation tank and Hall thruster head.

C. Ignition Testing of the AHT1-PQ

Each iteration of the V1 and V2 AHT1-PQ Hall thruster head design underwent a number of tests, however all prior efforts failed to yield any stable ignition in a neutralizer-less mode of operation. This was due to improper discharge channel dimensions, constricted fuel flow path, excessive magnetic field strength, and poor selection of anode geometry and overall design considerations. For the final V3 iteration, in addition to the adjusted magnetic field with the wider surface copper anode and larger upper pole aperture, stable neutralizer-less ignition was finally achieved at a discharge power up to 15 watts. However, thruster voltages had to be run at extreme levels in excess of 2 kV, and fuel flow rates ended up being substantially higher than anticipated. Although a plume was ignited, the combination of excessive voltage and flow rate outweighed the benefit of reduced size and complexity operating without an external cathode. As a result, it was decided to modify the design to revert back to testing with cathodes, and develop a new low-power cathode solution for the AHT1-PQ.

Fig. 40   Exhaust plume during ignition of the V3 iteration of the AHT1-PQ Hall thruster head design with Adamantane fuel at up to 15 watts discharge power.

In order to verify operation of the AHT1-PQ with an external neutralizer source, a simple Tungsten filament neutralizer identical to the first test of the EHT1 was set up. Like the EHT1 test, at filament power levels of 50 watts, beam was detected on the Faraday cup readout. Higher beam current was achieved than with the EHT1, however the discharge was not as stable. Anode discharge power was 15 watts during ignition.

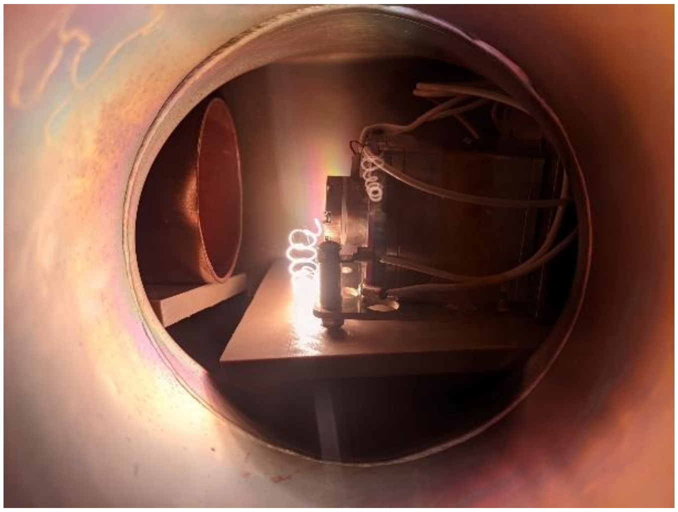

Fig. 41 Testing of the AHT1-PQ Hall thruster using a 50 watt tungsten filament neutralizer.

After extensive research into available alternatives, and looking at the objectives for keeping total power and size of the system at a minimal level, it was decided to utilize a low-power off-the-shelf carbon nanotube (CNT) cathode for the next iteration. Although CNT cathodes have been significantly less explored for Hall thrusters, they have been successfully demonstrated in relevant plasma environments [23-25]. The current design has been modified to extend the current Somos PerFORM internal insulator to also hold this new external cathode. The anode has also been modified to be brought right to the surface for a wall-less discharge configuration. End Hall configurations will also be re-explored as well, due to the simplicity and stability of the discharge at low power, which was already prior demonstrated with the EHT1 design. Electronics for the anode and cathode power would be fit on a board around the Hall thruster head like the prior iteration, while fuel valve control would be mounted on a single board at the bottom of the fuel tank, keeping the total cross section compatible with PocketQube class satellites, and extending the total volume to around 1.5P. Anode discharge power is anticipated to be 2 watts, with cathode power up to 5 watts, and total expected power with discharge, cathode, heater, and valve control at 10 to 15 Watts.

Fig. 42 Conceptual CAD render of the AHT1-PQ Hall Thruster with Wall-less Discharge and CNT Cathode.

VIII. Conclusion

The first operation of Hall thrusters on Adamantane fuel has been reported, with both end Hall and anode layer types, using a combination of Tungsten filament neutralizers, a novel micro-glow discharge hollow cathode, and neutralizer-less operation. Operation of the low-power cathode based on cold glow discharge hollow cathode technology has been demonstrated at 2 watts cathode power with purely sublimated Adamantane fuel, sufficient enough for ignition of the smallest scale Hall thrusters.

Both fuel delivery and ionization have also been demonstrated at very low power levels, with sublimation being observed at temperatures as low as 11 C in ambient conditions, as well as active sublimation at several tens of degrees C, at heater power levels up to 10 watts. Ionization has also been demonstrated at high voltages at power levels as low as 0.75 watts, with thruster ignition ranging from 2 to 15 watts of discharge power. While operation has proven a challenge at low power levels, fuel delivery via direct low-power sublimation has proven extremely effective and simple to accomplish, with complete fuel utilization demonstrated in several tank designs over numerous test, with little issues with re-condensation or clogging during fuel delivery. By leveraging the low sublimating temperatures of Adamantane and a simple sublimation fuel delivery system, extremely tight integration of the Hall thruster, cathode, and fuel system has been demonstrated, paving the way for unprecedented miniaturization of full Hall thruster systems, allowing for scaling of full Hall thruster systems down to PocketQube class satellites.

Moving forward, several key challenges need to be addressed. First, the effects of amorphous carbon buildup inside glow-discharge cathodes needs to be further studied to help mitigate these effects, particularly for longer operating times. Amorphous carbon buildup represents one of the biggest challenges for Adamantane fuel in gas-fed cathodes. However, there is significantly less deposits present in the Hall thruster head itself, presenting less issue for long term operation with the thruster head. To help mitigate these issues with cathode lifetime, carbon nanotube cathodes will be tested with both end Hall and wall-less discharge Hall thrusters to demonstrate the viability of these cathodes with low-power Hall thrusters and non-inert fuels. Cathode output must be sufficient at low enough powers for ignition of the Hall thruster at low discharge power, and operated with higher than typical discharge voltages to keep fuel flow rates, and therefore heater power, down to minimal levels to achieve total system power of around 10W while keeping the system tightly integrated. Finally, the extremely tight integration demonstrated with the EHT1 and AHT1-PQ Hall thruster systems will be scaled up to assess scaling of these techniques for larger and higher power class thrusters, and explored for other types of electric propulsion.

Acknowledgments

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