Applied Ion Systems

AIS-TR-026

AIS-EHT1 Micro End-Hall Thruster

Preliminary Ignition Test 1 - 02/13/2021

Testing Report and Summary

Michael Bretti – 07/24/2021

I. BACKGROUND

The AIS ADAMANT Series thrusters leverages Adamantane, a diamandoid hydrocarbon which exhibits many unique properties allowing for the potential of extreme power and size miniaturization of conventional gas-fed electric propulsion systems, with significantly reduced toxicity and no known corrosion issues like its similar and highly explored cousin Iodine. Currently, the ADAMANT Series is focusing on the development of highly integrated and modular micro-Hall thrusters run purely on sublimated Adamantane fuel. Total system power depending on the thruster is currently aimed from 5W up to 20W for the smallest class systems, with the ability to scale up to more conventional 50W class systems. Despite its unique potential as an alternative molecular propellant for conventional gas-fed EP, little work has been done on Adamantane for use as a fuel in the field.

While Adamantane has been tested a couple of times in literature, this has only been done at much higher power levels in larger gridded ion thrusters at hundreds of watts to kW class systems. Despite successful operation at higher power levels, with performance similar to Xenon, Krypton, and Iodine, Adamantane has been largely dismissed in literature without custom modifications to the chemical composition to overcome some of the inefficiencies inherent to the fuel, and overall testing in the field has been practically non-existent otherwise. Due to its many attractive properties however, such as solid storage, ease of sublimation, high ionization cross-section, high molecular weight, low cost, non-corrosiveness, and low-toxicity, Adamantane has been identified as a key technical enabler in meeting the unique challenges being addressed and inherent limitations in funding and infrastructure at AIS, and fully embraced as the central focus of new development efforts at AIS through the ADAMANT Series, which leveraging the unique properties of Adamantane to overcome conventional scaling limitations in EP technology such as Hall thrusters.

Looking at currently available limited data, and drawing extrapolations from these test results and basic principles of related EP systems and other alternative fuels, AIS proposes that Adamantane can allow for unprecedented scaling of conventional gas-fed EP technologies, allowing for low-power operation and unpressurized feed for the smallest class of satellites in the field. With significantly less toxicity, and no corrosion issues like Iodine, Adamantane has further potential for much greater total system cost reduction using conventional materials in the design of the Hall thruster, neutralizer, and propellant feed system. AIS is also taking a radically unconventional approach towards cathode design to leverage these advantages to create the smallest fully integrated Hall thruster systems ever developed in the field. AIS is currently the leading developer of Adamantane research for micro-EP, and the first and only company in the world to exclusively develop Adamantane for use with micro ion and plasma thrusters.

II. OVERVIEW

This first test of the EHT1 aimed to establish beam and ignition of the thruster utilizing a simple heated tungsten filament neutralizer. The purpose of this test was to attempt to run the EHT1 in the simplest mode possible, verifying the initial design before moving on to an individual hollow-cathode neutralizer test, followed by both systems run together. This would also be the first time the fuel system would be used with the thruster to provide sublimated Adamantane fuel for operation, in addition to the first time the prototype discharge supply was tested with the thruster. This test builds off of the prior four preliminary ionization and sublimation tests performed using Adamantane fuel and a simple test cell in vacuum (*see AIS-TR-22, AIS-TR-23, AIS-TR-24, and AIS-TR-25 for further details.)*

Throughout the first four preliminary tests, AIS demonstrated the ability of Adamantane to be sublimated at extremely low background temperatures in vacuum, as low as 11C. Adamantane was also successfully sublimated with very low heater power of 3.5W and less for these tests. In addition, the first instances of ultra-low power ionization of Adamantane for propulsion use was demonstrated, with successful glow-discharge ionization of both passively and actively sublimated fuel from less than 1W to 2W. In these ionization tests, the ionization test cell was configured and successfully operated for a variety of conditions, including general ionization, operation as a glow-discharge hollow-cathode plasma source, as well as both positive and negative charge extraction from the same plasma.

End-hall sources are widely used in ion beam processing due to wide beam divergence, low beam energy, simplicity, and robustness. While wide beam divergence and low beam energy is undesirable for propulsion systems, the simplicity and robustness of end-hall sources makes for an ideal low-cost test platform. The EHT1 design leverages design elements from industrial end-Hall ion sources, allowing for simplified construction, and relying on only off-the-shelf ceramics. Typically, industrial sources are often run with tungsten filament neutralizers, though hollow cathode can also be employed. As such, operating the EHT1 as a simple end-hall source with a tungsten filament with Adamantane fuel would help verify the potential to move forward on the design. Because of this, the thruster was specifically designed to be able to accommodate a tungsten filament mounting assembly for simplified testing and operation as a generic industrial end-Hall source.

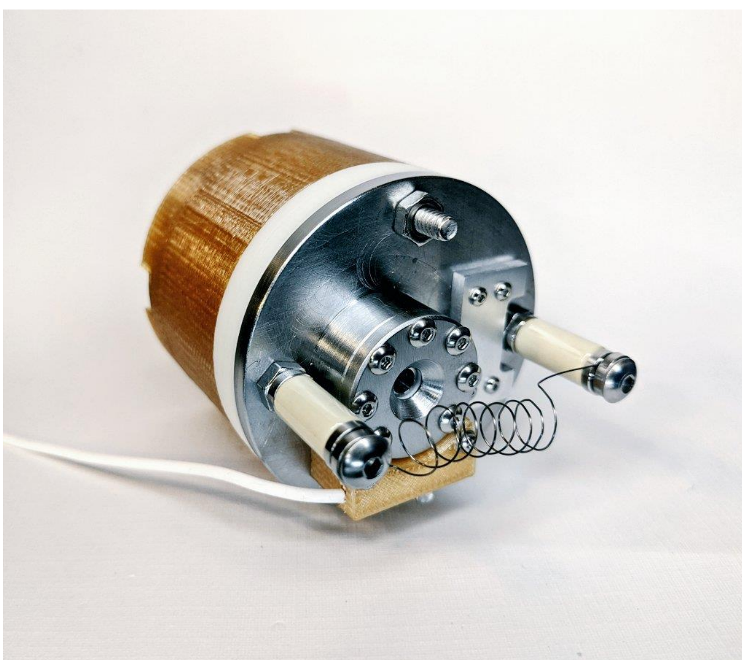

FIGURE 1: *Fully assembled EHT1 with tungsten filament neutralizer modification*

III. PRELIMINARY TEST SETUP

The EHT1 thruster head itself is 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 and a fuel feed port for the GDN1 Glow Discharge Hollow Cathode Neutralizer, 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 this test), the cathode feed port can be blanked off. The adapter flange measures only 50mm in diameter, with the thruster head offset to one side, measuring only 20mm in diameter and 10mm in height fully assembled.

FIGURE 2: *Fully assembled EHT1 thruster head.*

The SFDS, or Sublimation Fuel Delivery System, consists of an outer housing, currently made from 3D printed Ultem 1010, an inner heated fuel cartridge, and a heater assembly located under the heater cartridge. The fuel tank measures the same outer diameter as the EHT1 adapter flange at 50mm, allowing it to be directly mounted under the thruster and provide sublimated Adamantane vapors to both the Hall thruster and neutralizer simultaneously.

FIGURE 3: *Assembled SFDS with heater cartridge mounted inside the housing.*

The full EHT1 assembly consists of three major subsystems tightly integrated together as one unit – the sublimation fuel delivery system (SFDS), fuel valve, and Hall thruster head assembly. Currently, valve development is still underway, and as such, only the valve housing is used without a valve, meaning fuel is continuously sublimated from the start to the end of the test. Rate of flow however is still controlled via sublimation heater.

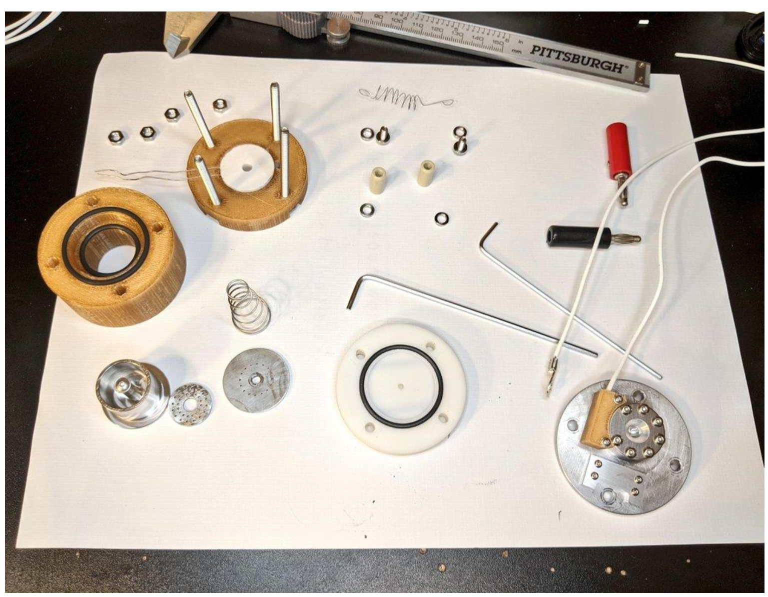

FIGURE 4: *Complete parts for assembly. Left: fuel system, Center: valve housing, Right: Hall thruster head assembly*

Prior to final assembly, the thruster must be fueled with Adamantane. Adamantane has the consistency of coarse table salt, which is poured directly into the fuel heater cartridge and packed down. A presser plate is placed over the fuel charge, preventing fuel from escaping, while allowing vapors to rise up from sublimation through holes drilled around the plate.

FIGURE 5: *Fueling of the fuel heater cartidge with Adamantane.*

After filling the heater cartridge with about 3 grams of Adamantane, the cartridge is inserted into the 3D printed Ultem housing. A conical spring presses the plate into the Adamantane, providing continuous contact with the bottom heated portion of the cartridge, which is heated by a ceramic-metal heater in direct contact with it. A top fuel plate completes the assembly, locking the cartridge into the fuel tank housing and compressing the spring into the fuel presser plate.

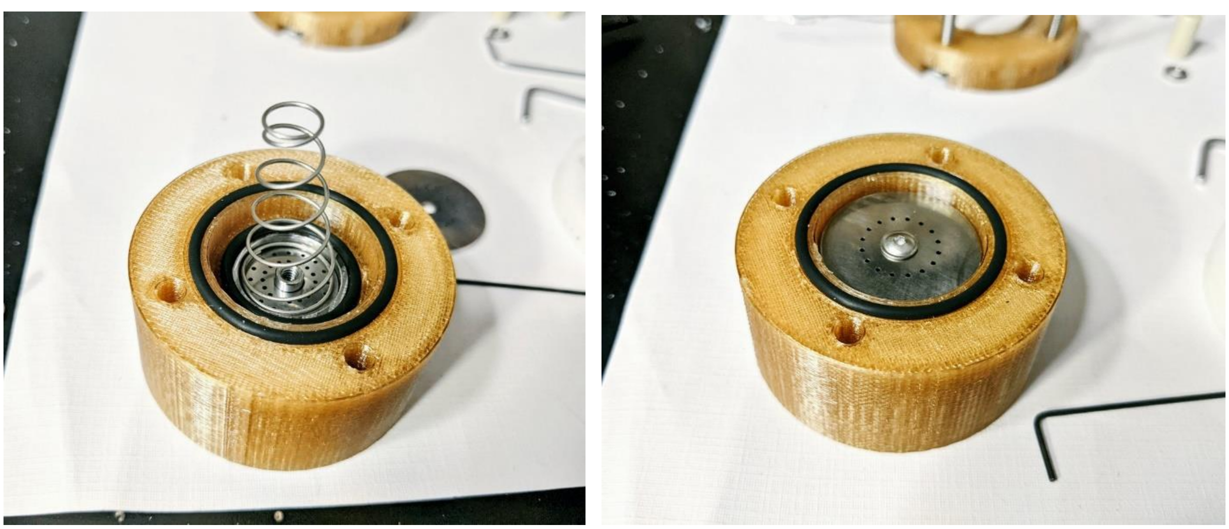

FIGURE 6: *Assembly and sealing of the fuel cartirdge inside the fuel system housing.*

The thruster was then assembled with the fully loaded fuel tank, in addition to the blank off plate over the neutralizer feed port on the Hall thruster adapter plate, and insulator posts for the tungsten filament mount.

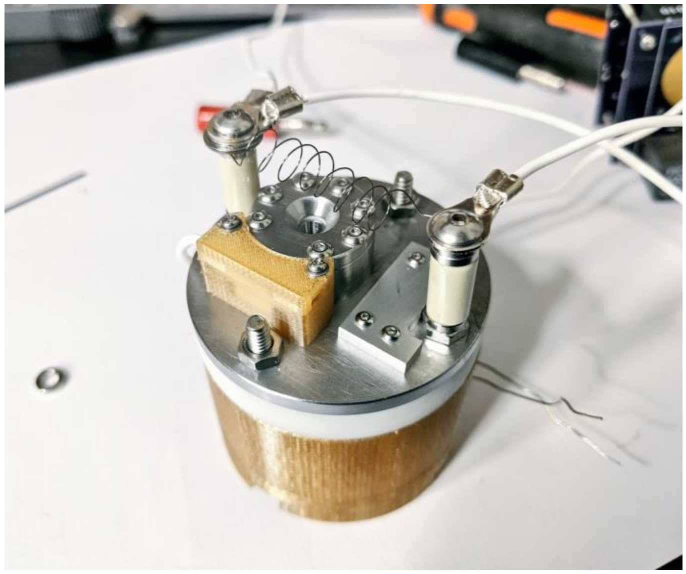

FIGURE 7: *Completely assembled and wired EHT1 with tungsten filament adapter.*

The thruster was wired to a makeshift power supply using a 2W, +3.5kV Pico power supply for the discharge power. The filament would be wired to an external 30V, 10A DC power supply.

IV. TESTING

After assembly, the thruster was loaded into the chamber. To keep the thruster aligned with the copper Faraday cup, the thruster was taped to a PEEK baseplate using Kapton tape, which also helped to secure wires in place and prevent them from moving during loading into the chamber and alignment.

FIGURE 8: *EHT1 mounted in high vacuum chamber.*

After pumpdown, ignition was attempted. The HV discharge supply was first brought up to 2kV to verify no breakdown would occur in the thruster. After, the sublimation heater was turned on to 3.5W of power. After a minute or two, the vacuum pressure began to rise, eventually settling at the mid 10^-4 Torr range, indicating successful controlled sublimation and fuel delivery with the SFDS. Filament power was then slowly turned on, starting at a few watts of power. Monitoring the HV discharge supply readout however, there was no indication of a discharge. Waiting for several minutes, the HV supply was brought up to an overdriven max voltage of 5kV. The sublimation heater supply was increased to its maximum output as well to further increase fuel feed rate, However, no indication of discharge or beam was observed. Since the benchtop supply was maxed out for the heater, and the HV discharge supply was also maxed out, the last option was to increase filament power, with the hope that more electrons would allow for ionization of the gas.

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 50W of filament power, discharge voltage began to rapidly drop, and eventually stabilized at 500-600V, indicating actual sustained ionization and discharge. At this point, beam current was measured at 120uA, 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.

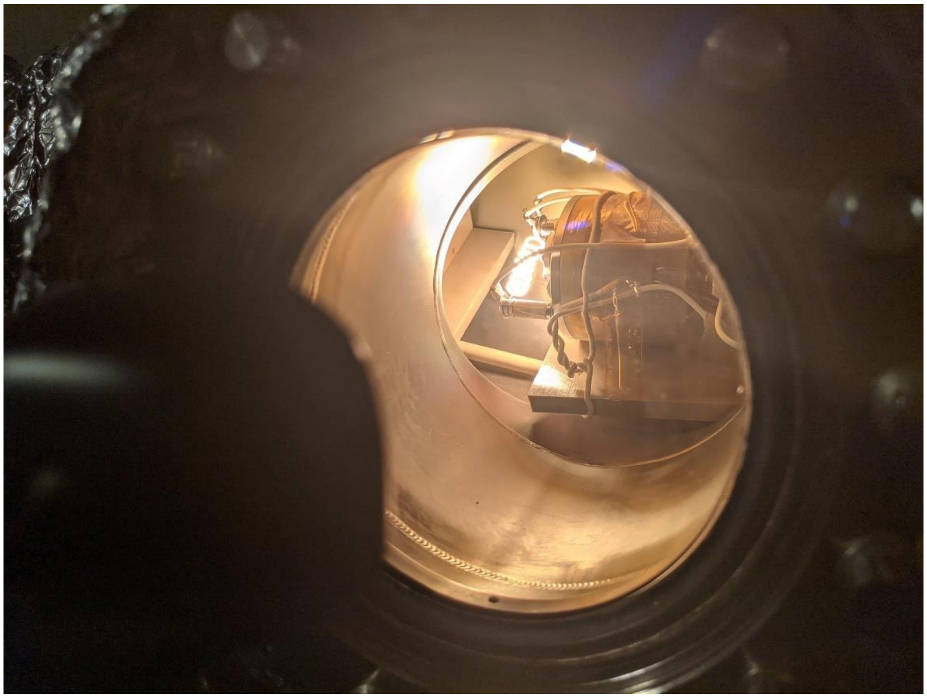

FIGURE 9: *Operation of the EHT1 in vacuum with 50W filament neutralizer power and 2W discharge power.*

The thruster was run until depletion of the fuel, indicated by dropping beam current, which eventually terminated, and discharge voltage rose again.

V. POST TEST ANALYSIS

After the test, the thruster was removed from the chamber and inspected. Clear evidence of sputtering from the tungsten filament was present, as well as discoloration as a result of the ionized hydrocarbon gas. In addition, a black dot in the center of the plasma and fuel baffle was clearly visible inside the thruster, evidence of electron bombardment which resulted in ionization of the gas, and with high enough emission, beam formation.

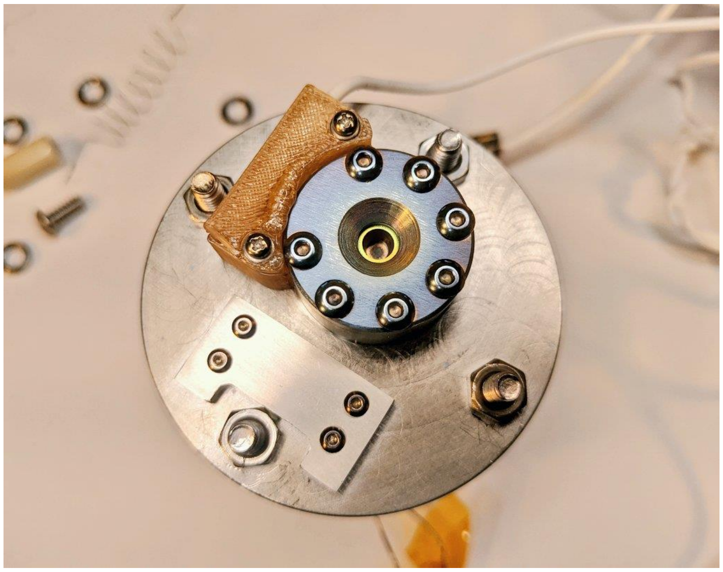

FIGURE 10: *Post-test inspection of the EHT1. Tungsten sputtering and hydrocarbon discoloration is visible on the hall thruster head, and evidence of discharge can be seen in the center of the fuel baffle inside the thruster.*

Upon further disassembly of the system, it was confirmed that no Adamantane remained in the fuel tank, and that complete sublimation was achieved with full fuel utilization. In addition, evidence of fuel buildup, condensation, charring, or any detrimental effects from fuel heating and sublimation were present within the system.

FIGURE 11: *Evidence of complete fuel sublimation after the test.*

-VI. CONCLUSION

The first ignition test of the EHT1 was successfully completed using a simple heated tungsten filament neutralizer. During the test, ignition was confirmed by the rapid drop in discharge voltage, increase in discharge power, and measured beam current on the Faraday cup. Filament power of at least 50W was required in order to sustain discharge and beam current. Lowering the filament voltage after ignition caused beam to cut out, and bringing it back up to full power restored beam. Ignition was also demonstrated using only 2W of discharge power, although this required very high filament power to boil off enough electrons to ionize the gas for ignition. The system was run on pure Adamantane fuel, sublimated from the SFDS for first time. After the test, complete sublimation of the fuel was confirmed. As far as the author is aware, this is the first time beam has been demonstrated and reported in a Hall thruster using Adamantane fuel.

Now that the base EHT1 and SFDS designs have been vetted and run in the simplest mode possible, the next test phase will focus on stand-alone operation of the new GDN1 Glow-Discharge Hollow-Cathode Neutralizer, a 2W miniature cold hollow-cathode. Once ignition and operation of the GDN1 has been confirmed, then both the EHT1 and GDN1 will be run together for full system ignition tests.