Applied Ion Systems

AIS-TR-007

AIS-gPPT3-1C Gridded Pulsed Plasma Thruster

Phase II – Impulse Bit Testing - 09/12/2019

Testing Report

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I. TEST PARAMETERS

- **System:** AIS-gPPT3-1C Integrated Propulsion Module V1
- **Main Bank Capacitor:** 0.2uF X7R ceramic capacitor
- **Main Bank Charging Voltage:** 944V
- **Shot Energy:** 0.09J
- **Pulse Repetition Rate:** 0.30 Hz
- **Total Number of Shots:** 80
- **Maximum Chamber Pressure During Testing:** 1 x 10^-5 Torr
- **Test Stand:** Micro Pendulum Impulse Bit Stand with Kapton Flapper
- **Testing Status:** COMPLETE

II. TEST OVERVIEW

This test represents Phase II of testing and development for the AIS-gPPT3-1C Integrated Propulsion Module V1. The purpose of the test was to quantify impulse bit measurements of the thruster using a micro-pendulum test stand, capable of measurements in the single uN-s impulse-bit range. This test represents the first successful impulse bit measurements of a fully integrated pulsed plasma thruster system produced at Applied Ion Systems. Data obtained from this and subsequent tests will be used to expand research information and work on a unique and relatively unexplored class of sub-Joule micro pulsed plasma thrusters for PocketQube-class satellites.

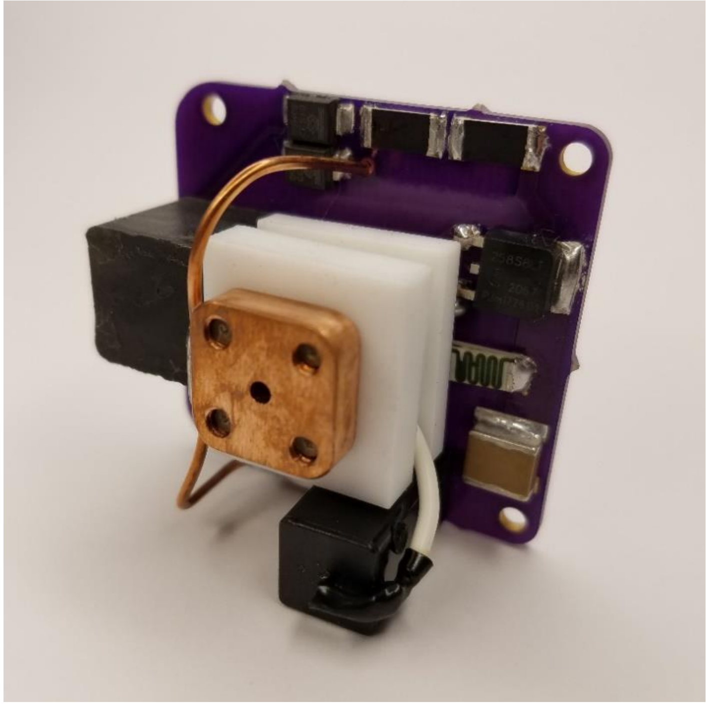

FIGURE 1: *Completed AIS-gPPT2-1C Integrated Propulsion Module V1.*

Testing was performed in the Micro Propulsion Testing Chamber using the Integrated High Vacuum Test Stand. Pumpdown conditioning of the system was achieved from roughing levels due to prior ignition testing. Ignition testing vacuum levels were first verified at 1 x 10^-5 Torr maximum before attempting ignition.

III. MICRO PENDULUM TEST STAND

In order to quantify impulse-bit measurements in the single uN-s range in a very limited chamber space, a simple micro pendulum stand was constructed. The stand is made from 0.0625” thick sheets of Teflon cut in a circular profile to fit the ID of standard 6” conflat tees. A central Teflon frame is supported on either side by additional Teflon frames, and bolted together with 316 stainless steel hardware. The support frames were cut away on the viewing side so that pendulum movement as well as any potential arc faults in the thruster connections could be observed.

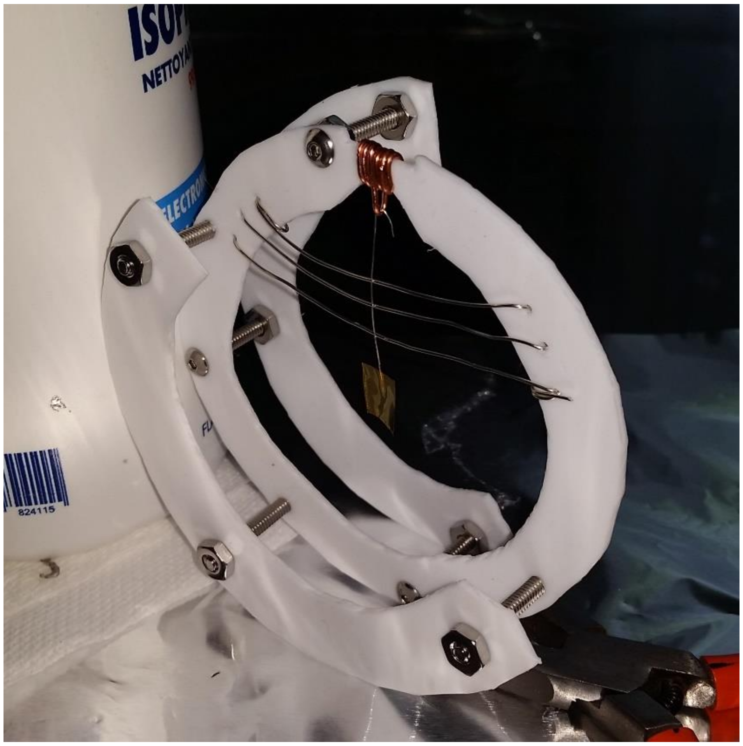

FIGURE 2: *Completed micro-pendulum test stand.*

The pendulum itself consists of a 30 AWG tin-coated copper wire with a 0.43” x 0.40” (1.082 cm x 1.015 cm) square flapper made from two pieces of 1 mil Kapton tape. The pendulum wire extends down to the center of the Kapton flapper by 0.20” (0.5 cm). The pendulum is supported at a fulcrum made from 18 gauge copper wire, wire-wrapped on the frame to create a loop centered at the top of the middle Teflon support. The length of the pendulum is selected so that the center of the pendulum flapper is aligned with the center of the output bore of the thruster. This length corresponds to 1.38” (3.5 cm).

In addition, pendulum stop-bars made of three lengths of tin-coated copper wire are used to prevent the ultra-light Kapton flap from sticking to the thruster at close distances due to residual static charge. This forces the pendulum to always start from the same position consistently for each shot. In addition, using three thin-gauge stop-bars as opposed to one thicker one helps distribute the force of the returning pendulum across the pendulum wire, preventing deformation of the thin wire string as it returns to the start position.

The frame is slid into the chamber through the port opposite of the thruster mounting feedthrough, and rotated so that the center of the pendulum flapper is aligned in all axis with the center of the thruster output bore. Alignment is first confirmed through the side viewport to set the distance, then looking down into the chamber for rotational alignment.

__FIGURE 3:__ Micro-pendulum test stand and AIS-gPPT3-1C mounted into test chamber.

In order to take measurements of displacement, the frame was aligned so the pendulum rested vertically and centered at the thruster output. A camera phone was centered and aligned outside the 6” conflat viewport and used to record video of the test. After testing, the video was slowed down to 0.5x speed, and manually stepped to find the point of maximum displacement of the pendulum during each thruster shot recorded. The angle was then estimated by overlaying lines on the captured video frame and noting the approximate angle. The resulting angle was then used to calculate displacement based on the distance from the fulcrum to the center of the pendulum. This displacement was used to calculate impulse-bit.

IV. IMPULSE BIT MEASUREMENTS

By knowing parameters of the pendulum used, as well as displacement of the pendulum during each shot, impulse bit can be estimated through very simple, low-tech, and low-cost means for pulsed thrusters. The following equation is used to calculate impulse bit, as described in a paper by Aheieva, Toyoda, and Cho for developments on vacuum arc thrusters for micro and nanoatellites[1], who also used a similar Kapton pendulum system in a larger chamber:

Eq.1

$$\boldsymbol{I_{bit} = m\sqrt{2 * g * (L - \sqrt{L^2 - x^2})}}$$

Where

$I_{bit} = Impulse\ Bit\ (Ns)$

$m = mass\ of\ pendulum\ (kg)$

$g = acceleration\ due\ to\ gravity\ (m/s^2)$

$L = length\ of\ pendulum\ (m)$
$x = displacement\ of\ pendulum\ (m)$

Due to current equipment restrictions, mass of the pendulum was estimated based of measurements of the flapper and average density of the flapper material rather than directly weighed. The calculation is simplified by only taking into account the mass of the flapper and neglecting the mass of the string. However, the mass of the string is non-negligible compared to the flapper, and the impulse bit estimates as a result will be lower than actual, representing lower-bound impulse bit for each shot.

The Kapton flapper was measured with digital calipers to be 1.082cm x 1.015cm x 0.005cm. With an average density of Kapton at 1.42 g/cm^3, this correlates to a mass of 0.0084 grams. The 30 AWG copper wire extends 0.5cm into the Kapton flapper, with a diameter of 0.025 cm. With an average density of copper at 8.96 g/cm^3, the resulting mass of the wire insert is estimated to be 0.0011 grams. Therefore, the estimated total mass of the flapper is estimated at around 0.0095 grams.

With the length of the pendulum from the fulcrum to the center of the flapper at 3.5cm for L in *Equation 1*, and the constant g = 9.807 m/s^2, impulse bit can be estimated based on displacement of the pendulum at the center point of the flapper from the initial position to final position. Angles for each shot were measured and recorded from the video, and knowing the length of the pendulum, displacement can be determined.

During the test, a total of 80 shots were recorded and measured. Capacitor energy per shot was set to around 0.09J, fired at a repetition rate of 0.3Hz based on charging times between shots.

V. RESULTS AND DISCUSSION

Over the course of the test, 80 shots were recorded from the thruster onto the Kapton pendulum before failure of the main bank occurred. Capturing and measuring the angles of displacement manually for each shot, displacement angles varied around 6-7 degrees per shot, resulting in an I-bit between 0.58-0.68 uN-s, for an average of about 0.65 uN-s. An example of shot analysis can be seen below in *Figure 4*.

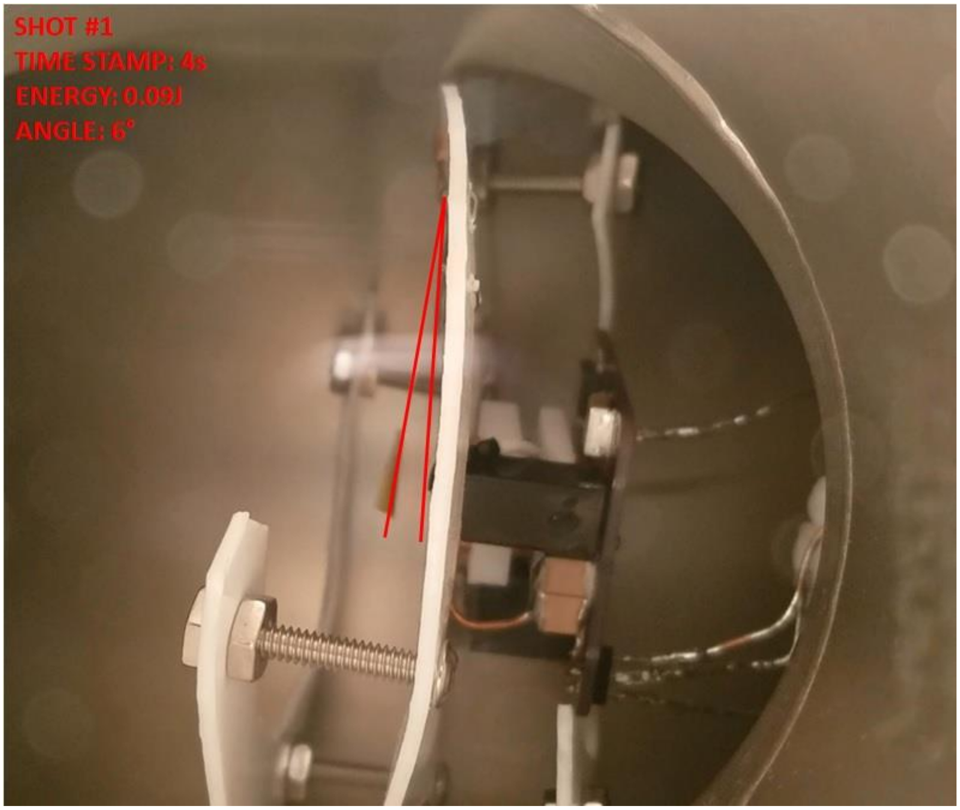

FIGURE 4: *Impulse bit measurement via angle analysis of micro pendulum displacement.*

Based on the prior AIS-gPPT2-1C impulse bit testing, empirical scaling predicted an average I-bit of ~0.76 uN-s for 0.09J energy. Due to the simplicity of the setup, and error involved in measurements, this prediction is within reasonable bounds of expected performance of the AIS-gPPT3-1C impulse bit of 0.65 uN-s. At the nominal rate of 0.3 Hz, this equates to an average thrust level of around 0.22 uN.

VII. PLASMA PLUME INTERACTION WITH PENDULUM

For the thruster to move the Kapton pendulum, the plasma plume exhaust must interact with the flapper head, ideally with minimal losses due to deflection or rotation. During the test, it was observed that the pendulum was maintained mostly centered to the exhaust, where the plume fires into the center of the flapper. Since the plasma exhaust is neutral, charging of the pendulum does not occur. During video analysis, a clear delay between firing, plume evolution, interaction with the pendulum, and resulting force exerted on the pendulum can be seen. An example of the plume interacting with the pendulum can be seen below in *Figure 5*. Unlike prior tests operated at higher thruster power levels, no evidence of erosion or ejected particles from the thruster electrodes was observed.

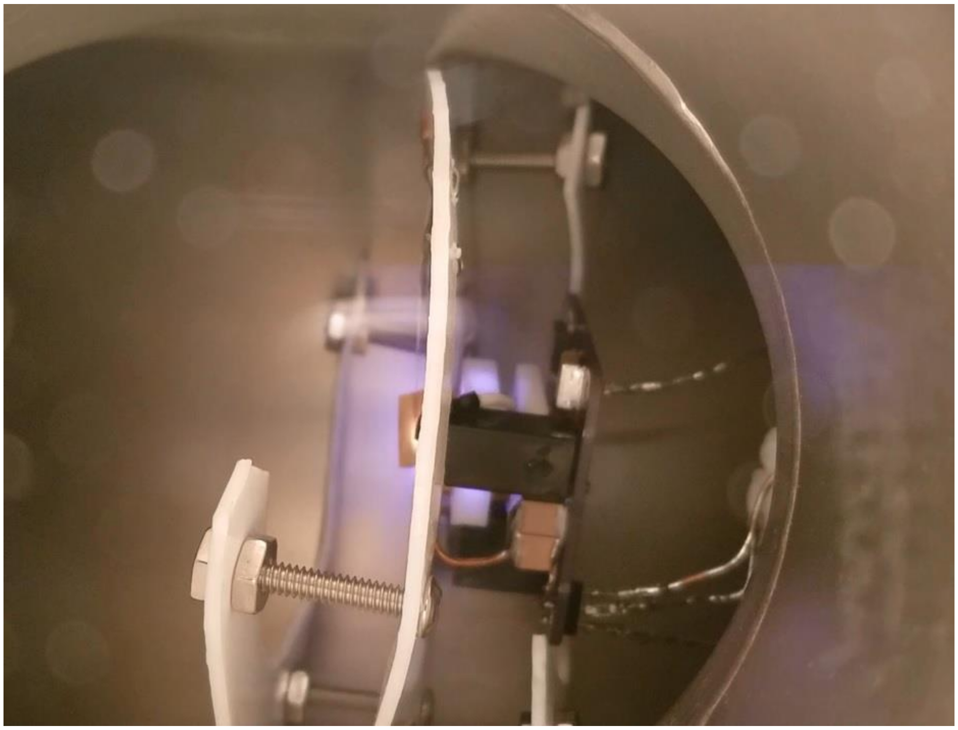

FIGURE 5: *Captured plasma plume interacting with the micro pendulum Kapton flapper.*

VIII. PERFORMANCE COMPARISON TO LITERATURE

While there is still relatively little work on sub-joule pulsed plasma thrusters in literature, there are a few systems that have been reported on. One particular example that falls in the same power and performance class as the AIS-gPPT3-1C for direct comparison can be seen with STRaND-1 3U CubeSat pulsed plasma thruster system from the University of Surrey[2]. The system utilizes a total of 8 pulsed plasma thrusters for attitude control for the CubeSat. Each of the pulsed plasma thrusters are individually controlled, and individually are at similar power and energy levels of the AIS-gPPT3-1C. *Table 1* below compares resulting thruster parameters and performance.

Sub-Joule Micro Pulsed Plasma Thruster Comparison							
Thruster	**Vin**	**Power (W)**	**Charge Time (S)**	**Energy (J)**	**Impulse Bit (uN-s)**	**Thrust (uN)**	**Specific Impulse (s)**
STRaND-1	5	1.5	6	0.19	0.56	0.09	321.8
AIS-gPPT3-1C	3.3	0.5	3	0.09	0.66	0.22	<300*

TABLE 1: Specs and performance comparison between the STRaND-1 and AIS-gPPT3-1C

As can be seen from the table, despite operating at significantly less input power with bank energy half that of the STRaND-1 PPTs, performance of the AIS-gPPT3-1C is significantly more optimized for its size and energy class, with higher impulse bit, thrust, and faster firing rate. Although ISP has not been measured, based on energy scaling trends in literature, it is expected that the ISP of the AIS-gPPT3-1C will be below 300s.

IX. CONCLUSION AND FUTURE RECOMMENDATIONS

Impulse bit measurement results have been presented for the AIS-gPPT3-1C Integrated Propulsion System, a sub-joule micro pulsed plasma thruster for nanosatellites. Based on testing results and observations, several recommendations can be made going forward in regards to both thruster testing, as well as design optimization.

Thrust and impulse bit are found to be within the expected range based on prior study analysis as well as data presented in literature. In addition, performance has shown to be comparable to, and even exceed performance of a directly similar sub-Joule micro-PPT in literature, with greatly simplified design, manufacturing, and cost. This exemplifies one of the key advantages of the Applied Ion Systems approach, in openly designing advanced propulsion systems at extreme cost reduction with minimal tooling and infrastructure that is available to the average maker at home, making propulsion more accessible beyond typical work done in conventional academic literature.

During post-test analysis of the thruster, no evidence of charring, erosion, or change in Teflon fuel bore diameter was observed. The AIS-gPPT3-1C currently operates at 0.09J, with starting bore surface area of 0.239 cm^2. In this case, energy density is only 0.38 J/cm^2 max. Prior testing on the AIS-gPPT2-1C at much higher energy densities have resulted in charring and burning of the Teflon, resulting in shorting and failure of the thruster. After 130 shots, no sign of charring or wear was noticed for the AIS-gPPT3-1C, and is not considered a bottleneck to performance like in the older gPPT2. Should electronics reliability be solved, it is expected that the fuel bore could provide tens of thousands of shots and higher at the very low operating energy levels of the main pulse bank.

A major and critical bottleneck going forward however is main pulse capacitor bank. Between this test and the prior ignition testing, the thruster only lasted a total of 130 shots before the capacitor shorted. Despite having proper voltage rating and being under-driven, the capacitors used, normal HV SMT X7R capacitors, are not adequate for the high stresses see during operation in a vacuum environment. New high current pulse rated capacitors are needed. A viable capacitor in a similar form factor and voltage rating may be C0G dielectric capacitors, which have higher stability and overall better performance ratings. Going forward, the AIS-gPPT3-1C electronics board will need to be modified to accommodate for these higher performance capacitors.

X. REFERENCES

1. Aheieva, K., Toyoda, K., Mengu, C. “Vacuum Arc Thruster Development and Testing for Micro- and Nanosatellites”, IEPC-2015-425p/ISTS-2015-b-425p, July 2015.
2. Shaw, Peter. “Pulsed Plasma Thrusters for Small Satellites”, Surrey Space Center, University of Surrey, June 2011.