Applied Ion Systems
AIS-TR-004
AIS-gPPT2-1C Gridded Pulsed Plasma Thruster
Phase II – Impulse Bit Testing - 06/02/2019
Testing Report
Michael Bretti – 06/19/2019

I. TEST PARAMETERS

- **Main Bank Capacitor:** 1uF polypropylene film capacitor
- **Main Bank Charging Voltage:** 890-1300V
- **Energy:** 0.40-0.84J
- **Ignition Circuit:** hydrogen thyratron pulser
- **Ignition Capacitor:** 0.01uF plastic capacitor
- **Ignition Voltage:** 4kV
- **Maximum Chamber Pressure During Testing:** 1 x 10^-5 Torr
- **Test Stand:** Micro Pendulum Impulse Bit Stand with Kapton Flapper
- **Testing Status:** SUCCESFUL

II. TEST OVERVIEW

This test represents Phase II of testing and development for the AIS-gPPT2-1C Single-Channel Gridded Pulsed Plasma Thruster. 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 thruster produced at Applied Ion Systems, and will allow for qualification and optimization of thrusters. 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.

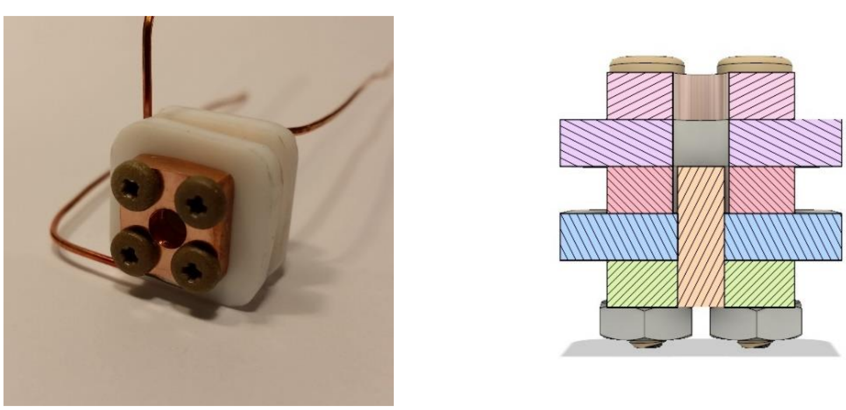


FIGURE 1: *Completed AIS-gPPT2-1C thruster (left), cross-sectional CAD view (right).*

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. Ignition voltage was set to 4kV, while the main bank voltage was set to a maximum value of 1.3kV. Depending on the repetition rate, and hence time to charge the capacitor between shots, this corresponds to a stored energy of 0.40J to 0.84J for the 1uF capacitor. The chamber was grounded during testing. Impulse bit was measured using a newly constructed micro-pendulum test stand, allowing for small impulse bit measurements in the limited chamber space.

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.

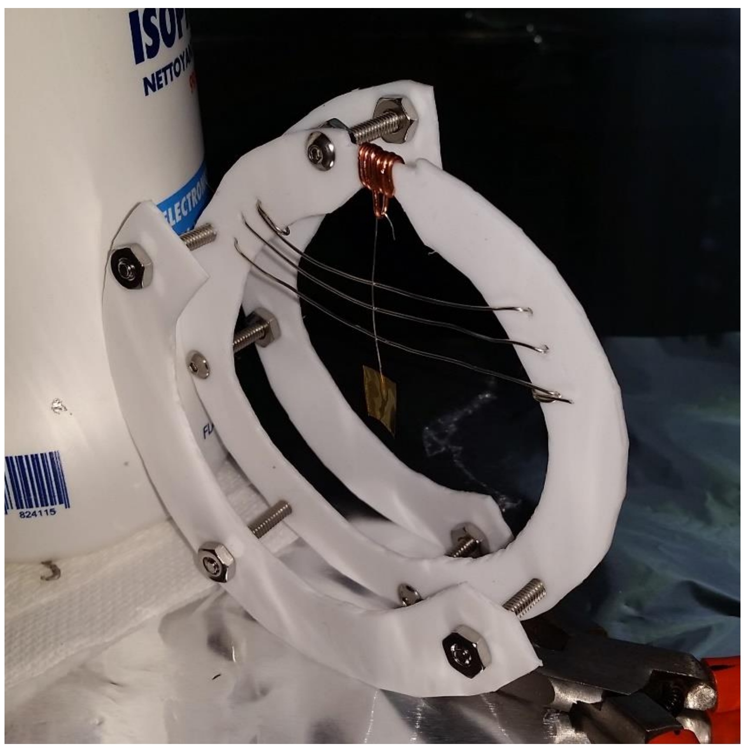


FIGURE 2: *Completed micro-pendulum test stand.*

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.

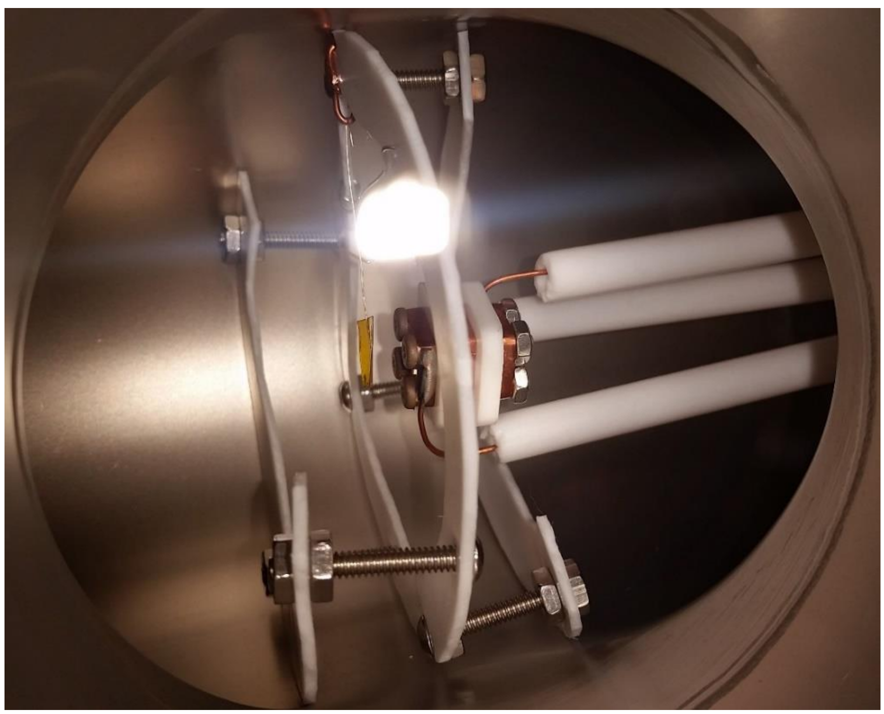


FIGURE 3: *Micro-pendulum test stand and AIS-gPPT2-1C mounted into test chamber.*

FIGURE 4: *Alignment of the micro pendulum Kapton flapper center to the center of the thruster output.*

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.

FIGURE 5: *Vertical alignment of the pendulum to the thruster, as well as the initial starting distance and captured frame using an external camera for recording.*

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 22 shots were recorded and measured. Capacitor energy varied from 0.40J to 0.84J based on charging times between shots. Capacitor voltage, and subsequent stored energy for each shot, was estimated based on calculating the charging time of the capacitor for the power supply providing 1300V at 1.5mA. Shots and overlaid angles can be seen in *Figure 6* below:

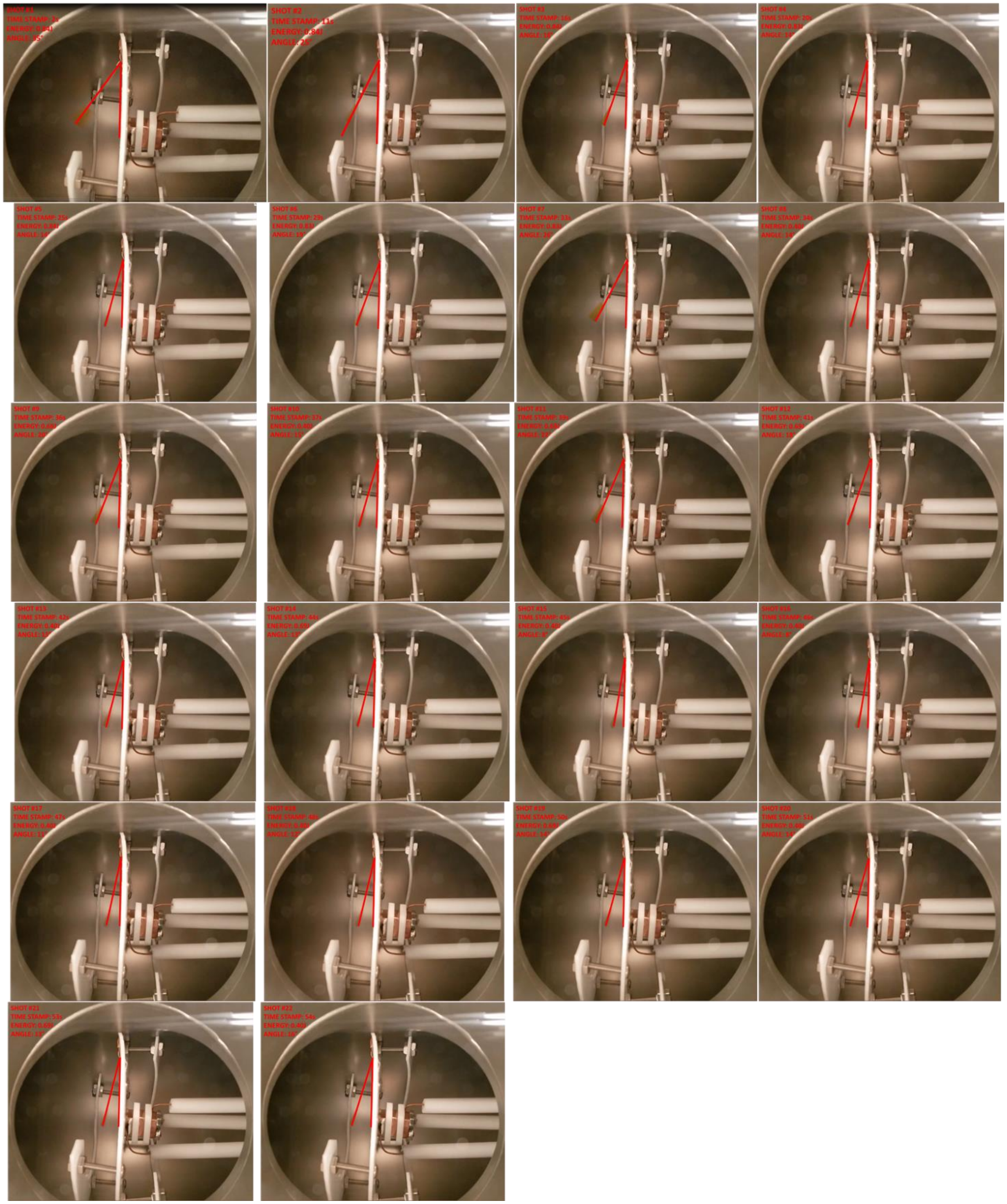


FIGURE 6: *Captured angles for each of the 22 recorded shots for impulse bit measurements.*

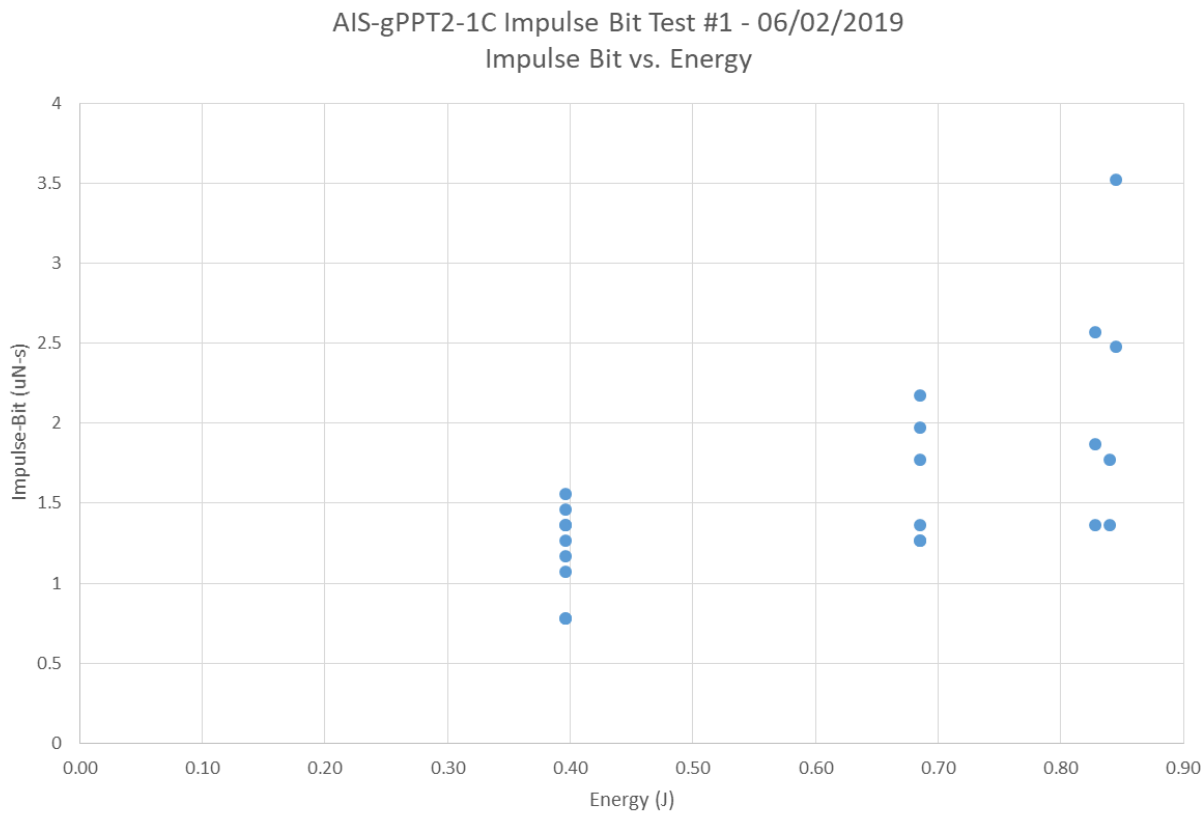
V. RESULTS AND DISCUSSION

For each shot, the time stamp in the video, as well as charging time between shots were noted. With a 1uF main capacitor, and a charging current of 1.5mA max at a peak voltage of 1.3kV DC, capacitor voltage and energy were estimated for each shot. Shot angles were recorded, and by knowing the pendulum length from the fulcrum to the center of the flapper to be 3.5cm, displacement was calculated. Using displacement, and other known parameters, impulse bit was calculated from *Equation 1*.

AIS-gPPT2-1C Impulse Bit Measurements - Test Data							
Shot #	Time Stamp (s)	Charge Time (s)	Voltage (V)	Energy (J)	Angle (Degrees)	Displacement (cm)	I-Bit (uN-s)
1	2	10	1300	0.84	35	2.10	3.52
2	11	9	1300	0.84	25	1.52	2.48
3	16	5	1296	0.84	18	1.10	1.77
4	20	4	1287	0.83	14	0.85	1.36
5	25	5	1296	0.84	14	0.85	1.36
6	29	4	1287	0.83	19	1.16	1.87
7	33	4	1287	0.83	26	1.57	2.57
8	34	1	890	0.40	14	0.85	1.36
9	36	2	1171	0.69	20	1.22	1.97
10	37	1	890	0.40	15	0.91	1.46
11	39	2	1171	0.69	22	1.34	2.17
12	41	2	1171	0.69	18	1.10	1.77
13	42	1	890	0.40	13	0.79	1.26
14	44	2	1171	0.69	13	0.79	1.26
15	45	1	890	0.40	8	0.49	0.78
16	46	1	890	0.40	8	0.49	0.78
17	47	1	890	0.40	11	0.67	1.07
18	48	1	890	0.40	12	0.73	1.17
19	50	2	1171	0.69	14	0.85	1.36
20	51	1	890	0.40	14	0.85	1.36
21	53	2	1171	0.69	13	0.79	1.26
22	54	1	890	0.40	16	0.97	1.56

TABLE 1: *Impulse bit measurement data.*

Graphing the impulse bit vs energy data in *Graph 1* below, an interesting trend can be observed in the shot-to-shot distribution for impulse bit consistency. As stored energy is increased, shot-to-shot variation also increases for the thruster as well.

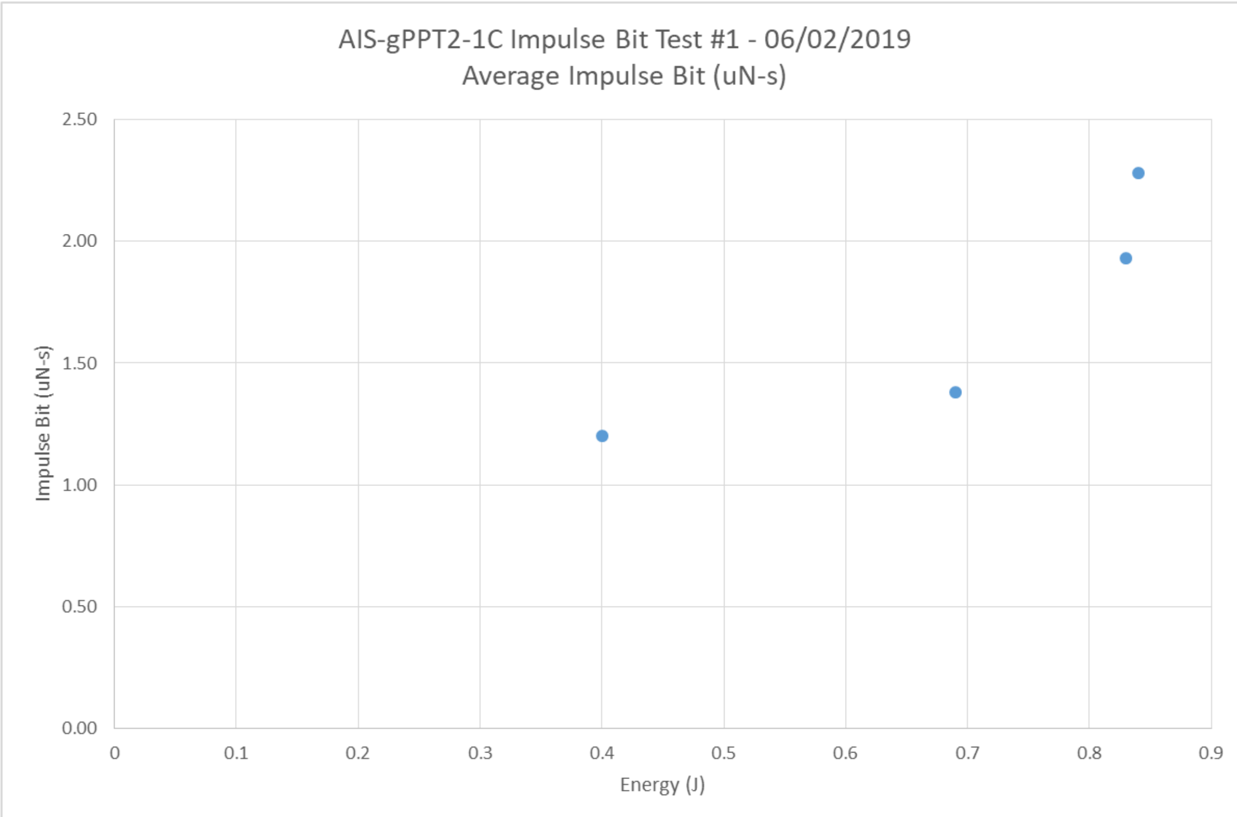


GRAPH 1: *Impulse bit vs energy measurements for all 22 recorded shots.*

Based on the results, average impulse bit for each shot energy was determined. The average data is used to correlate a line of best fit for additional performance predictions in the following sections. *Table 2* and *Graph 2* below depict the resulting data.

AIS-gPPT2-1C Average Impulse Bit		
Number of Shots	**Energy (J)**	**Avg Impulse Bit (uN-s)**
9	0.4	1.20
6	0.69	1.38
3	0.83	1.93
4	0.84	2.28

TABLE 2: *Average impulse bit vs. energy*



GRAPH 2: *Average impulse bit vs. energy.*

As can be seen, while shot to shot variation increased for increasing capacitor energy for the thruster during this test, the average impulse bit value increased as well. However, only a low number of shots were recorded for each energy during the test, and future efforts will be made to collect more shot data.

VI. PERFORMANCE PROJECTIONS

Based on test data and average impulse bit for each shot energy, a trend line was found to predict performance of the current thruster configuration with various charging voltages, limited to 1W max power for the charging supply. At present, the supply selected for the electronics development of the gPPT thruster series is based around the EMCO AG series power supplies, which consist of small, surface mount linear supplies with a max power rating of 1W. These supplies can be purchased for a wide variety of output voltages, in both positive and negative polarity from 100V up to 6000V. These supplies were selected due to their incredibly compact size, low power requirements, high efficiency, and ability to generate a wide range of voltages, only requiring power, ground, and a control voltage signal up to the rail voltage of 5V. It is anticipated that standard PocketQube-class satellites will have a propulsion power budget of no more than 1W max, though larger stacked units will have additional power available.

The charging voltages selected for this study were based around realistic expected capacitor bank voltages, based on current testing data, as well as literature. Realistically, charging power will be slightly less than max available from the supply since a portion of that power will be utilized for the ignition circuitry as well. Power supplies and current specs can be found in *Table 3* below:

AIS-gPPT2-1C Estimated Operational Parameters Selected EMCO AG Series Supplies for Performance Projection Study			
Supply	**Voltage (kV)**	**Current (mA)**	**Power (W)**
AG10P-5	1	1	1
AG12P-5	1.2	0.83	1
AG15P-5	1.5	0.66	1
AG20P-5	2	0.5	1

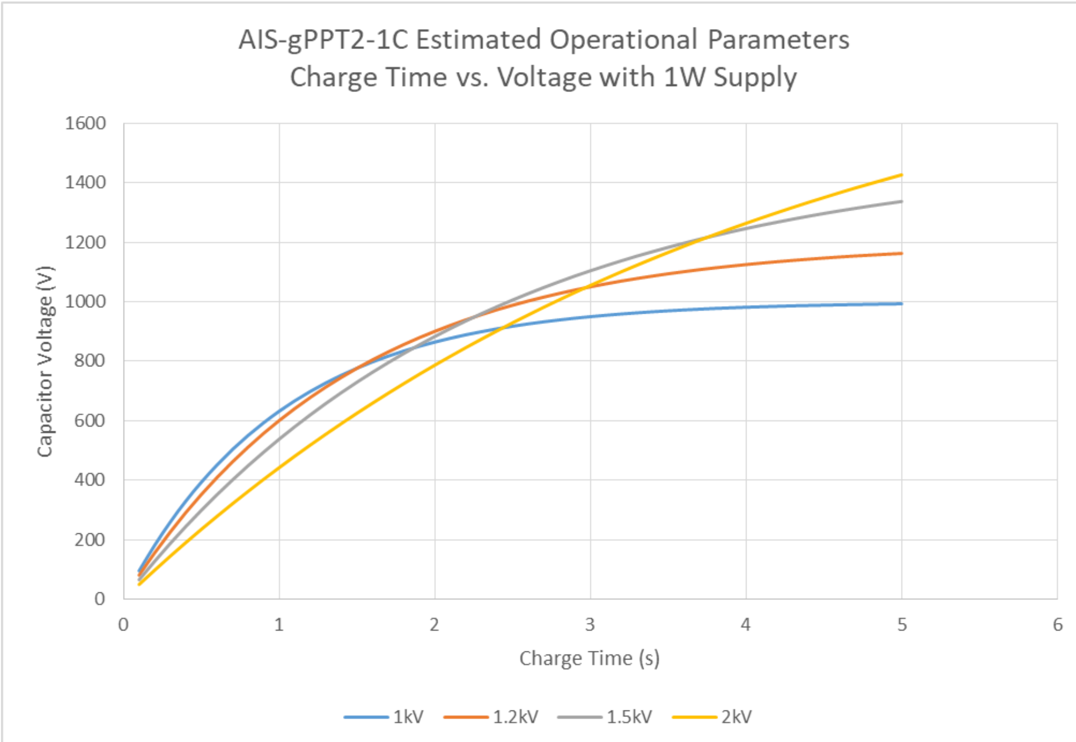
TABLE 3: *Selected EMCO AG series high voltage power supply specs for thruster electronics implementation and performance projection study.*

Based on the scaling trend line relating average impulse bit to energy depicted in *Graph 2*,

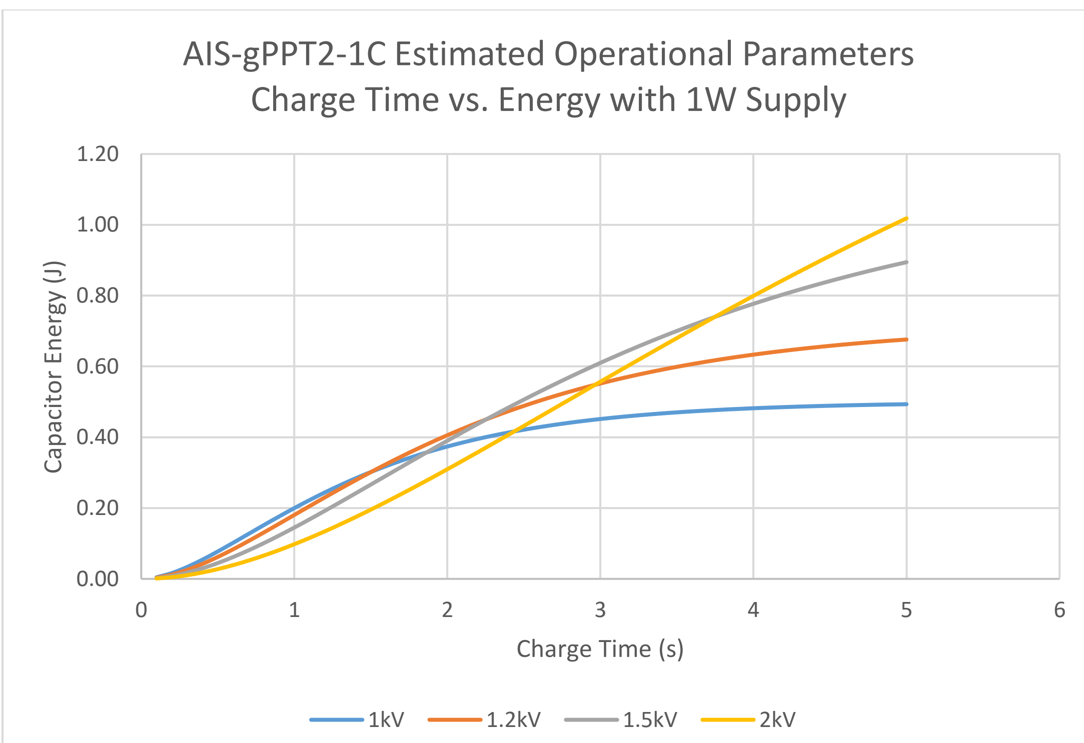
Eq.2 $$\boldsymbol{y = 0.6744e^{1.2923x}}$$

where:
y = impulse bit
x = energy

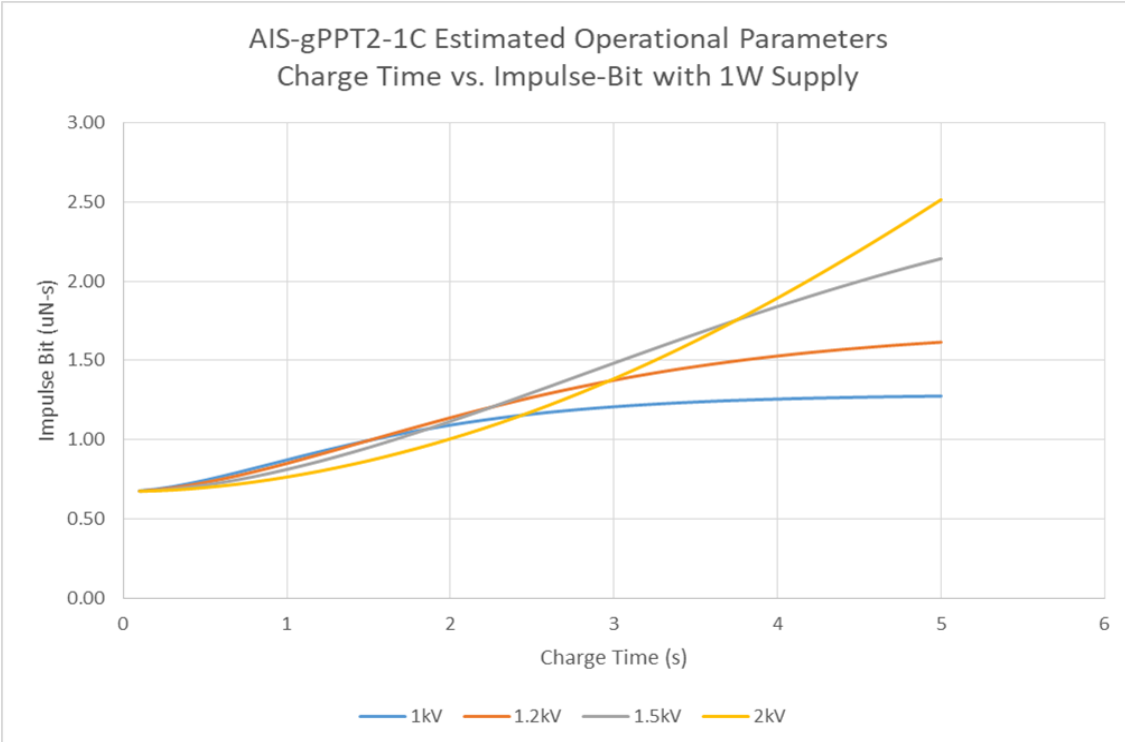
projections on thruster performance for impulse bit for a given estimated charging voltage based on total available power with various high voltage supplies are presented. Four areas were looked at in relation to charging time: capacitor voltage, capacitor energy, impulse-bit, and thrust. *Graphs 3*, *4*, *5*, and *6* depict voltage, energy, impulse-bit, and thrust in relationship to charging time, respectively:



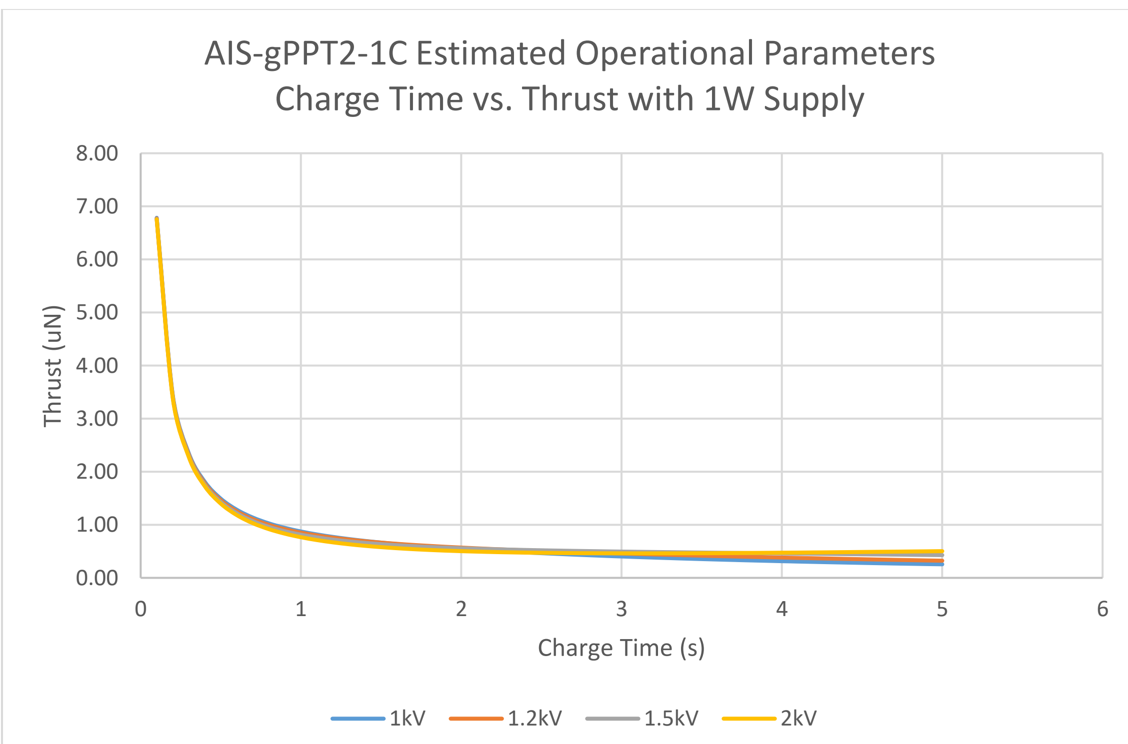
GRAPH 3: *Projected charge time vs voltage performance with various 1W EMCO power supplies for a 1uF main bank capacitor.*



GRAPH 4: *Projected charge time vs capacitor energy with various 1W EMCO power supplies for a 1uF main bank capacitor.*



GRAPH 5: *Projected charge time vs impulse bit with various 1W EMCO power supplies for a 1uF main bank capacitor.*



GRAPH 6: *Projected charge time vs thrust performance with various 1W EMCO power supplies for a 1uF main bank capacitor.*

Based on projected data and trend lines, assuming scaling follows average projections reported above, as well as ideal charging scenarios using maximum power available from the charging supply, the following conclusions are presented:

- In the previous ignition test, the thruster was successfully fired down to a main capacitor voltage of 680V at a repetition rate of 2Hz, corresponding to a discharge energy of 0.23J. Based on current projections for a 1W limited supply, the 1kV EMCO supply has a slight advantage in charging time over the other three supplies, corresponding to a maximum repetition rate of a little under 1Hz for this minimum tested energy level. This falls into the general region where from 0 seconds to 1.5 seconds, the 1kV supply has the advantage in terms of minimum charging time to establish maximum capacitor energy, about 0.3J at 1.5 seconds, in the corresponding charging time, resulting in slightly higher impulse bit and thrust.

- From about 1.5 seconds to 2.3 seconds charging time, the 1.2kV supply has an advantage for impulse bit and thrust, with a maximum impulse bit of 1.22 uN-s at 2.3 seconds.

- From 2.3 seconds to 3.7 seconds, the 1.5kV supply takes the advantage for impulse bit in the given charging time, with a maximum impulse bit of 1.74 uN-s in the stated time frame.

- Finally, for charging times of 3.7 seconds and greater, the 2kV supply has the advantage for charging time to impulse bit.

From this analysis, it can be seen that based on mission specifications and thruster parameters, there can be an optimal charging supply for a limited power range. Depending on mission requirements for objectives such as station keeping or attitude control, based on the required repetition rate, impulse bit, and thrust needed, the proper supply can be selected to optimize performance in the required range.

One thing of particular interest is the rate of change differences between energy vs. impulse bit, and energy vs. thrust, seen in *Graphs 5* and *6* respectively. Based on current data for this particular thruster and impulse bit test over the projected realistic charging range, for charging times greater than 1 second, corresponding to a repetition rate of 1Hz or less, impulse bit increases by a little less than 2 uN-s, while thrust decreases by about 0.5 uN. However, for charging times under 1 second, particularly in the region of less than 0.5 seconds, although energy impulse bit is significantly lower at less than 0.2J and between 0.7-0.8 uN-s respectively, thrust radically increases from 1.5 uN at 0.5s charging time to up to 6.75 uN at 0.1s charging time, corresponding to repetition rates from 2Hz to 10Hz. So far, the thruster has been successfully fired in prior tests at a minimum voltage of 680V at 0.23J, 2Hz. If the thruster was able to fire at much lower voltages, but significantly higher frequency, large gains in thrust can be realized, assuming scaling and performance remains as predicted. Therefore another balance in performance optimization based on mission parameters can be made. If higher specific impulse is required, a lower rep-rate, higher energy capacitor charge would be desirable. However, if very small impulse bit, but larger thrust is required, it may be optimal to run the thruster at as low charging voltage and as high repetition rate as possible, under 0.5 seconds charging time for a power supply limit of 1W.

VII. PLASMA PLUME INTERACTION WITH PENDULUM

During recording and analysis of the video in looking at displacement measurements of the pendulum, several frames were captured showing the plasma plume as it interacted with the pendulum prior to the movement of the pendulum. In shots *#2* and *#16* of *Figure 7* below, clear evidence can be seen of electrode erosion from the deflection of copper particles off the pendulum, which resulted in particle deflection to the lower left corner. Each case represents both the highest and lowest energy shot recorded during the test, and seems to show that similar levels of electrode erosion is occurring across the entire operational range of stored energy during firing of the thruster. From the slowed video analysis, there is also a clear and noticeable delay between plasma plume formation and movement of the pendulum.

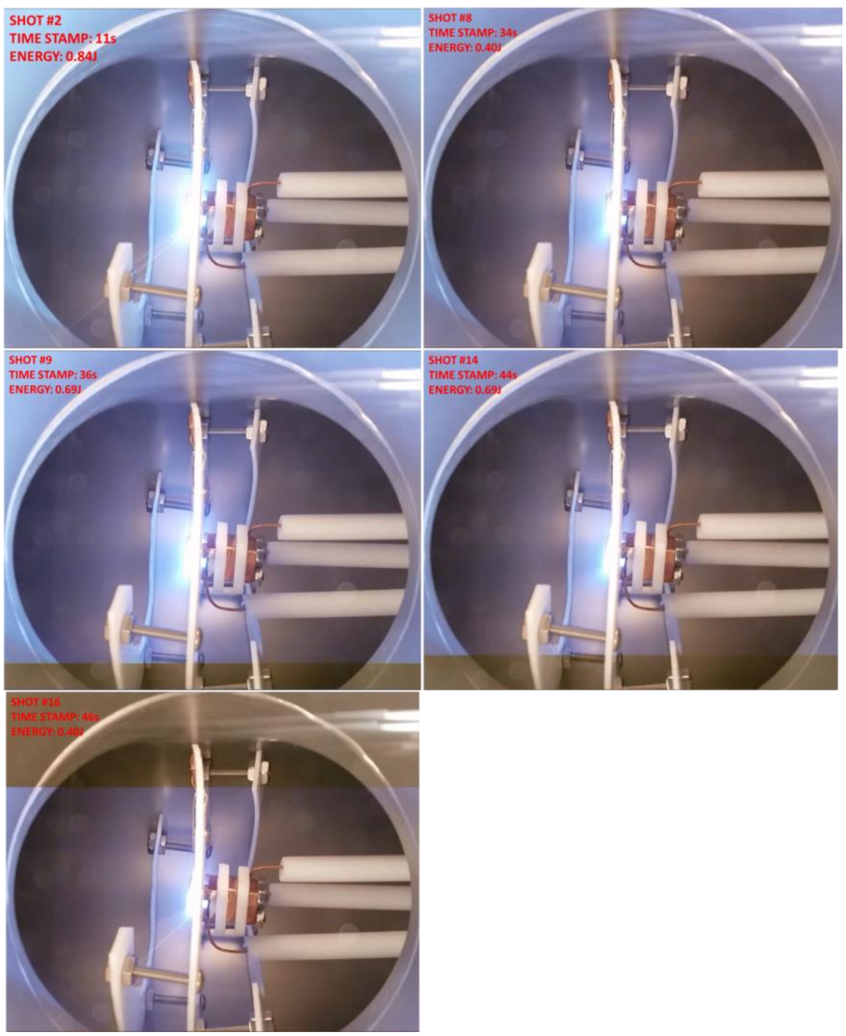


FIGURE 7: *Captured plasma plume interacting with the micro pendulum Kapton flapper. Shots #2 and #16 capture evidence of electrode erosion from ejected copper particles deflecting off the pendulum to lower-diagonal left direction.*

VIII. CONCLUSION AND FUTURE RECOMMENDATIONS

Impulse bit measurements have been presented for the AIS-gPPT2-1C Single-Channel Gridded Pulsed Plasma Thruster, in addition to performance predictions based on thruster power supply selection and current measured results. Several recommendations can be made going forward in regards to both thruster testing, as well as design optimization.

For future testing, the primary objective will be obtaining a larger dataset of pulse measurements, and stepping up through a wider range of capacitor energy to establish better trends for empirical scaling analysis. Longer term testing to look at overall lifetime performance and subsequent degradation over time will be implemented as well. In addition, effort will be made to start designing and utilizing a power supply more representative of what would be actually deployed in the final package, limiting total available power for both the main bank circuitry as well as the ignition circuitry to 1W max, on a miniaturized and integrated PCB. This greatly simplifies testing connections and feedthrough requirements, and allows for low-voltage feedthroughs to be used, since the power supply would only require 5V, ground, and trigger pulse. This reduces the need for the large thrytron pulser currently in use, and will significantly reduce test equipment interference. This also greatly reduces the risk of external arc faults damaging sensitive electronics, as the high voltage will be contained on the PCB, mounted directly to the thruster. Finally, it allows for a more realistic representation of thruster operation as deployed.

For design optimization, several key areas need to be further explored going forward. For coaxial based electrothermal PPTs, it has been shown that an output nozzle can increase thruster performance. Therefore, the next iteration will utilize an output nozzle machined in the output electrode. In addition, work done on pulsed vacuum arc thrusters have also shown that electrode erosion can be reduced, and performance can be increased, utilizing an external magnetic field to concentrate the plasma plume. Both permanent magnets as well as electromagnets have been employed. Due to the extreme power limitations imposed on a 1P PocketQube-class thruster, permanent magnets would be ideal from the power perspective. It is therefore recommended to explore the use of miniature, high strength permanent magnets integrated with the output nozzle on the output electrode to see if gains in impulse bit can be further realized like with testing done on VATs.

Another major design issue that must be addressed and overcome is the issue with thruster lifetime. While electrode erosion is present, and has been visually confirmed during testing, the primary limit to thruster lifetime for such small-scale micro-PPTs is the extremely limited available fuel mass due to the small size of the thruster necessary for integration with the smallest class of standard satellite frames. While Teflon fuel has been long verified and regarded as the ideal choice for PPTs, the extremely small amounts of fuel present in the micro-thruster presents lifetime limitations. Currently, with the AIS-gPPT2-1C thruster, a total of less than 400 shots for the single channel has shown noticeable decrease in thruster output and performance. As a result, new and novel methods of improving lifetime for such small sub-Joule thusters must be explored for a practical solution to be realized. One method to explore would be the use of multiple channels, as proposed in the original first-generation AIS-gPPT1thruster. Such multi-channel operation has been proposed in literature, although with more conventional longer-length coaxial PPTs. However, to effectively control fuel usage, erosion, and performance, each individual channel must be triggered and controlled independently, rather than relying on random statistical breakdown, which was the initial method considered. This has the benefit of multiplying the maximum lifetime of a single channel by the total number of channels, and allows for much more controlled operation of thruster performance as fuel is used up in each channel. However, this presents a major technical challenge in triggering each channel, as the available space for the power supply, including the thruster, for a PocketQube is extremely limited.

The second method to be explored in conjunction with multi-channel operation proposed above is to increase the available fuel mass in the small working area. This is most readily achieved by both reducing the diameter of the Teflon fuel channel, as well as increasing the channel length. Currently, the thruster fuel channel is 0.15" diameter, 0.125" long. The next generation of the gPPT series will look to reducing this diameter to 0.125" or less, as well as increasing the channel length up to 0.25". However, for increased channel length, operation of the thruster at lower voltages may be more difficult, and potentially pose limitations for repetition rate as well as a result.

Current efforts are also underway in exploring the use of metal fuels with small, sub-Joule PPTs. Normally, metal fuels have been reserved for higher energy pulsed plasma thrusters, as well as vacuum arc thrusters. Common metals include aluminum, titanium, and nickel. In order to overcome the higher ablation energy and/or currents often needed for these metals, lower melting point metals and eutectic alloys are being explored. This can include a wide range of fuel selections, such as Bismuth, Indium, Bismuth-Tin, or Bismuth-Tin-Indium mixes such as Field's Metal. For the sake of keeping fuels non-toxic, alloys with Antimony, Cadmium, and Lead will not be considered.

In addition to the metal fuel solution proposed above, internal cavity geometries will be explored to optimize performance, taking advantage of the predominantly electrothermal mechanism of plasma acceleration in this thruster configuration. This may include implementing a converging insulator channel, leading to a diverging output nozzle, with additional magnetic enhancement on the output.

Advantages of metal fuels is improved shot to shot consistency over Teflon, which is currently another shortcoming of the current thruster configuration. Lower melting point metal fuels may allow for such improved shot consistency of Teflon, while increasing overall thruster lifetime due to less fuel ablation per pulse, but having still higher ablation than more common higher temperature metals. This may ultimately allow for a single channel thruster to be used, relaxing the complexity needed if multiple channels were to be employed with a Teflon fuel solution for the gPPT thruster series. Finally, higher repetition rates can be realized with metal fuel thrusters. A major concern that needs to be tested is the effect of metal sputtering on internal insulators, leading to premature failure of the thruster due to shorting. Ceramics are the first choice of selection for the insulator, however other insulators such as PEEK and ULTEM are being considered as well.

Finally, work is underway to develop the first generation of PCBs for the integrated high voltage charging and trigger circuitry, which must be small enough for practical use with down to 1P

PocketQubes and have a total power draw of no more than 1W max. The supply must provide a main charging voltage of up to 2kV, with a trigger voltage of at least 4kV. The thruster assembly will be directly mounted to the PCB to minimize space, and must have a total low enough profile that other electronics and modules can be reasonably used with a 1P class PocketQube. In addition for such small satellites to reasonably take advantage of the benefits of onboard propulsion, methods of attitude control must be employed and developed at a miniaturized scale in order for propulsion to be used effectively.

IX. 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.