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Development of a Fiber-Fed Pulsed Plasma Thruster for Small Satellites

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ABSTRACT

CU Aerospace has developed a fiber-fed pulsed plasma thruster (FPPT) which consumes PTFE (Teflon) propellant in spooled form, fed with extrusion 3D printer technology. The thruster uses a parallel energy storage unit (ESU) design, assembling >300 COTS capacitors into discrete 10 J modules while maintaining low per-cap current levels. The discharge is initiated by a pulsed regenerative carbon igniter located in the thruster cathode. Thruster performance varies with pulse energy and fuel feed rate, with measured impulse bits ranging from 0.057 – 0.241 mN-s and 960 – 2400 s specific impulse. The highest specific impulse measured is 2423 s for 40 J pulse energy. A 1U 20 J ESU flight design with 331 g PTFE fuel provides 5500 N-s total impulse. Accelerated subsystem life testing has demonstrated > 600 million capacitor charge / discharge cycles with nearly identical per-cap current waveforms.

INTRODUCTION

Classic PPT technology is mature, and has historically been limited by specific mass and propellant load to precision pointing and small delta-V applications.[1,2] A recent CUA thruster advancement, Monofilament Vaporization Propulsion (MVP), successfully adapted extrusion 3D printing technology to feed polymer propellant fiber to a resistojet thrust chamber.[3] The Fiber-Fed Pulsed Plasma Thruster (FPPT) leverages this advancement by controlling the feed of PTFE fiber to its discharge region, accommodating versatile propellant storage and enabling high PTFE throughput and variable ablated fuel mass. An innovative, modular >300 unit ceramic capacitor bank dramatically lowers system specific mass to 10-15 g/W. FPPT is inherently safe; its non-pressurized, non-toxic, inert propellant and construction materials minimize range safety concerns. The thruster has accumulated more than 1 million pulses, with thrust-stand measured I_{bits} ranging from 0.057 – 0.241 mN-s and 960 – 2400 s specific impulse. A 1U FPPT will provide 2200 – 5500 N-s total impulse from 331 g of propellant, with a ΔV of 0.6 – 1.1 km/s for a 5 kg CubeSat. A 1U design variation with 590 g of propellant enables as much as 10,000 N-s and a ΔV of 2 km/s for a 5 kg CubeSat. Extending the design to a 2U form factor increases propellant mass to 1.4 kg and ΔV to 9.2 km/s for an 8 kg CubeSat. CUA anticipates a flight-like > 2,500 N-s 1U integrated system life-tested by mid-2020.

TECHNOLOGY DESCRIPTION

FPPT development has comprised three main efforts: the fiber feed mechanism, the energy storage unit (ESU), and the ignition system. A schematic of the FPPT, **Figure 1**, depicts a typical layout of the system including these three subsystems and **Figure 2** shows a two-module (20 J) assembled FPPT breadboard. **Figure 3** shows the FPPT in operation, and **Figures 4 and 5** show FPPT during and before operation for different feed rate conditions (slower and faster).

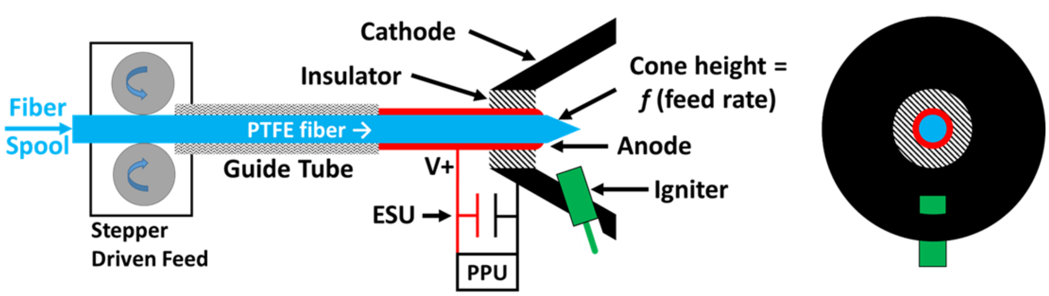

Figure 1: FPPT Schematic Cross-Section (left) and End View (right)

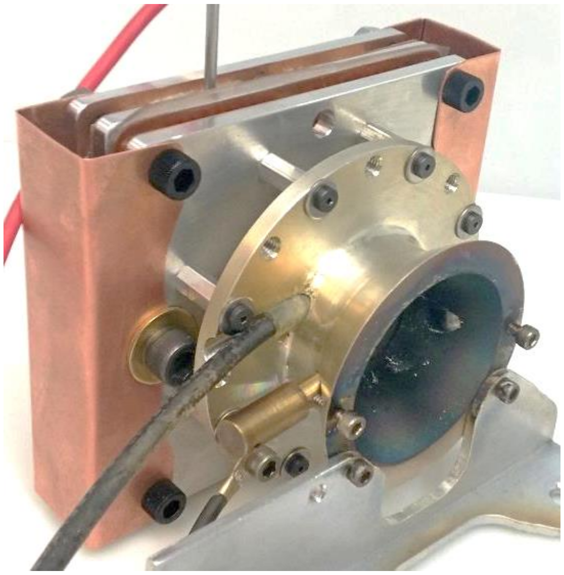

Figure 2: FPPT Assembly with Two 10 J Capacitor Modules (20 J total ESU)

Fiber Feed

The FPPT feed system adapts the feed system from the Monofilament Vapor Propulsion system, and employs COTS 3D printer mechanical drive components well described and tested by Woodruff, *et al*.[3] Spooled PTFE fiber is fed into the thrust chamber through a tubular anode, using a stepper motor to control feed rate. The capacitive ESU is charged and a current pulse is initiated by the pulsed igniter discharge. Fuel is vaporized and electromagnetically and electrothermally accelerated out of the cathode volume, which then returns to a vacuum state, and the cycle repeats.

ESU

The FPPT capacitive energy storage unit contains >300 parallel 100 mm^3 ceramic capacitors assembled into discrete higher-capacitance 10 J ESU modules (or "cap banks"), which are then parallel-connected to store 10 – 40 J. This approach enables scaling of stored energy and facilitates mitigation of ESU failures through subscale testing. **Figure 6** depicts the volume savings of this approach by comparing ~10 J capacitor assemblies for mica and ceramic technologies.

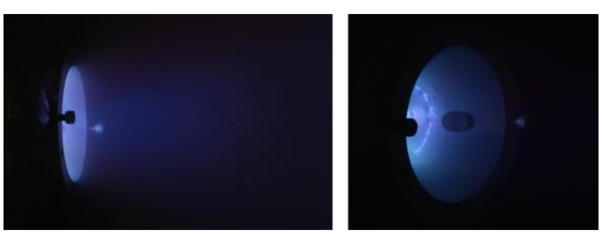

Figure 3: FPPT During Operation

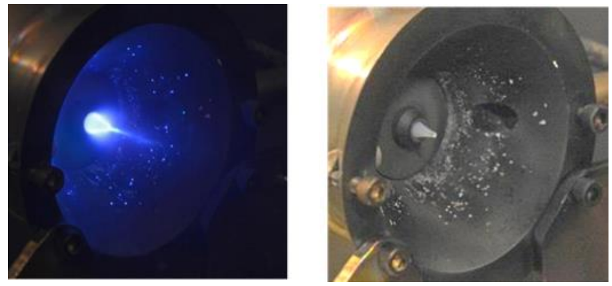

Figure 4: FPPT During (left) and Before (right) Pulsed Operation with Slower Feed Rate

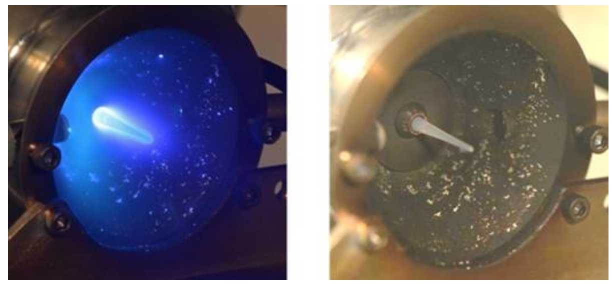

Figure 5: FPPT During (left) and Before (right) Pulsed Operation with Faster Feed Rate

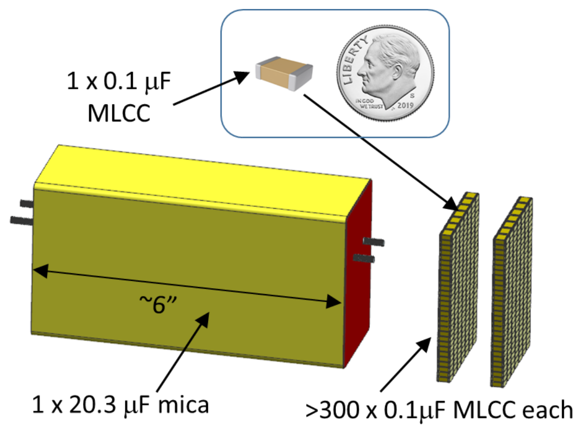

Figure 6: 25 J Mica Cap (1540 g) vs. Twin 10 J ESU Modules (280 g)

Subscale capacitor life testing at representative per-cap current levels into surrogate loads has achieved failure-free discharge life in excess of >600 million pulses. **Figure 7** shows current traces during thrust testing of a FPPT two-module ESU and during accelerated life testing of a subscale ESU test rig at high pulse rate. Accelerated life testing of the ESU modules follows the first failure, with an expected voltage exponent n between 3 and 7 in the form of Equation 1:[4,5]

$$L_1 = \left[\frac{V_2}{V_1}\right]^n \times 2^{(T_2 - T_1)/\theta} \times L_2 \quad (1)$$

where L_1 = expected life at V_1 and T_1, and V_2 and T_2 are accelerated test conditions yielding accelerated life L_2, V is voltage, T is temperature, *n* is the voltage constant, and θ is a thermal constant.

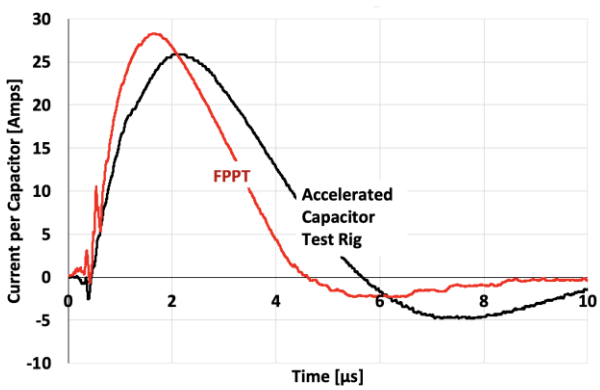

Figure 7: Measured Per-Cap Current Waveforms for Actual FPPT and Accelerated ESU Test Rig

Ignition

Regenerative carbon igniters (RCI) (**Figures 8 and 9**) were designed and developed for the FPPT. Coaxial in construction, they rely on a high resistance carbon layer located between electrodes that is regenerated by carbon plating during thruster operation.

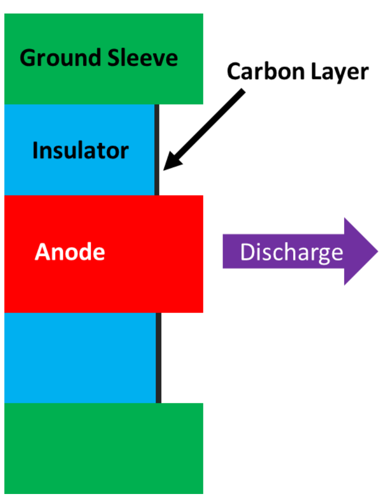

Figure 8: Regenerative Carbon Igniter Concept

Figure 9: Regenerative Carbon Igniter

The system uses an array of four igniters in the cathode fired in order. Igniter operation and discharge ignition has been maintained throughout the test program, and two igniters have demonstrated > 1 million pulses collectively.

PPU

Development bench testing has been performed with laboratory electronics. ESU charging in the bench tests has been accomplished by a Lumina CCPF capacitor charging supply. Discharge ignition has been triggered via LabVIEW serial communication, adaptive electronics, and a 0.5 J Unison Industries Ignition Exciter box powered by benchtop DC power supplies.

Flight electronics, including ESU charging and discharge initiation, are in the later stages of development.

PERFORMANCE

FPPT performance has been mapped across a variety of parameters – fuel feed, ESU capacitance, ESU energy, pulse rate, and total power. Incremental improvements through the development program have yielded a handful of targeted operating conditions, listed below in **Tables 1-4**.

A unique trait of the FPPT system is that for a given input power, the thruster head has been demonstrated, to operate stably over a range of fuel feed rates. This gives rise to a range of operating conditions with differing steady-state exposed fuel shapes and their associated performance points.

Table 1: 10 J, 33 μF FPPT Performance

ṁ [μg/pulse]	I_{bit} [mN-s]	I_{sp} [s]	Thrust @ 66 W [mN]
5.16	0.057	1126	0.51

Table 2: 20 J, 66 μF FPPT Performance

ṁ [μg/pulse]	I_{bit} [mN-s]	I_{sp} [s]	Thrust @ 66 W [mN]
5.16	0.088	1738	0.38
7.74	0.105	1383	0.46
12.38	0.122	1005	0.53

Table 3: 20J, 132 μF FPPT Performance

ṁ [μg/pulse]	I_{bit} [mN-s]	I_{sp} [s]	Thrust @ 66 W [mN]
7.74	0.133	1752	0.42

Table 4: 40 J, 132 μF FPPT Performance

ṁ [μg/pulse]	I_{bit} [mN-s]	I_{sp} [s]	Thrust @ 66 W [mN]
7.74	0.184	2423	0.37
15.5	0.241	1585	0.48

Steady-operation FPPT thrust measurements are shown in **Figure 10** as a function of power input and operating conditions. Each set of data represents the same operating conditions at different pulse rates showing that thrust is directly proportional to pulse rate and correspondingly total power input. For the data shown in **Figure 10** the lowest pulse rate was 2 Hz and the highest was 8 Hz. Each of the 4 unique operating conditions shown was fired for a minimum of 10,000 pulses before taking the thrust measurement to ensure a properly formed propellant cone, thereby ensuring an accurate I_{sp} calculation. **Figure 10** contains 44 unique thrust measurements (for clarity, only a sampling of the total number taken is shown), each of which is an average of the turn-on and turn-off thrust level with a ±5% shot-to-shot repeatability.

Figure 11 shows specific thrust (μN/W) as a function of the specific impulse for different capacitor banks and energies per pulse. In each case, higher I_{sp} is the result of lower mass per pulse, and higher thrust arises from increased mass per pulse. The original FPPT goal of 1200 s was significantly exceeded, with peak performance surpassing 2400 s. This particular point was measured six times, three at 4 Hz and 2 Hz pulse rates respectively, and as always were preceded by over 10,000 firings to ensure an accurate feed rate determination.

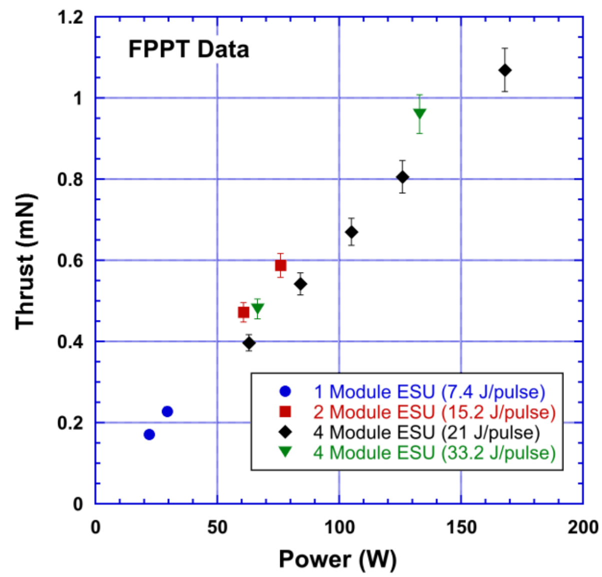

Figure 10: Total thrust versus power as a function of different capacitor (ESU) banks/modules and different pulsed operating conditions. (Shot-to-shot repeatability of ± 5%.)

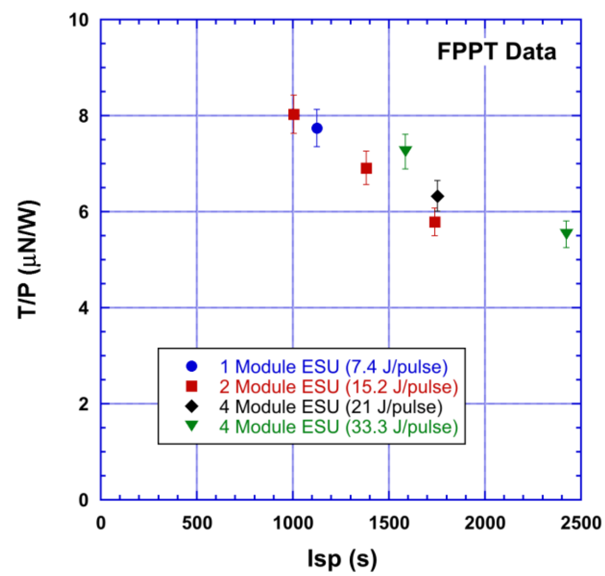

Figure 11: Specific thrust vs. specific impulse. (Error bars are ± 5%.)

Figure 12 shows thruster efficiency as a function of specific impulse. The 2400 s condition is the most electrically efficient case at over 6.5%, but results in reduced specific thrust (**Figure 11**). Heritage PPT-11 data showed efficiencies exceeding 10% are possible, and ongoing Phase II SBIR development is expected to yield efficiencies exceeding this 10% mark. Thruster efficiency is computed by dividing the thrust power ($T*U_e/2$) by supply power. The capacitor charging power supply input is monitored, and its rated efficiency is applied to the measured supply wall power draw when calculating the power into the thruster capacitors. To date, efficiency increases have been modest with higher discharge energy and more significant with higher I_{sp} (via feeding less propellant per Joule). As a result, operating at high efficiency provides a corresponding lower thrust, and requires more thruster firings to consume a given propellant load. Conversely, high thrust operation is less efficient, but requires fewer thruster firings. The ongoing NASA R&D program at CUA is examining increases in efficiency via optimizations of propellant diameter, anode geometry, cathode geometry, and discharge impedance matching.

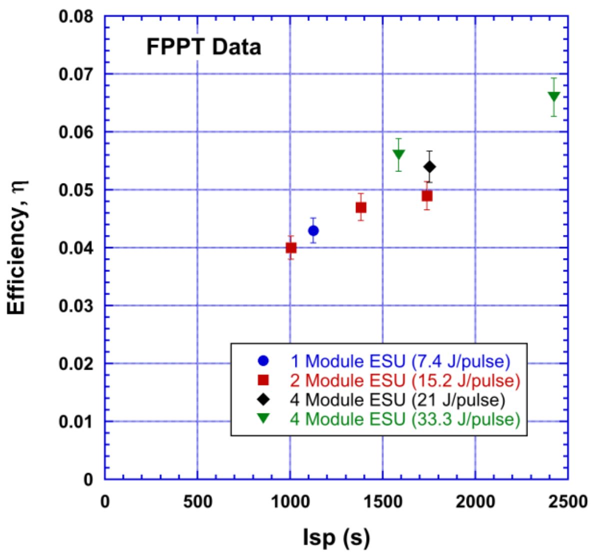

Figure 12: Thrust efficiency vs. specific impulse. (Error bars are ± 5%.)

Discussion

ESU layout, assembly, and integration has represented the most difficult challenge in FPPT development. CUA began testing at the single-module 10 J level and progressed with 2 and 4 module configurations to the 40 J level. As expected, peak current and specific impulse increased with pulse energy.

By varying fuel feed rate, a T vs. I_{sp} performance envelope was established.

Anode erosion in FPPT is low at values between immeasurable and approximately 0.20 µg / pulse depending on operating conditions. These erosion rates compare to fuel ablation rates of 5-10 µg / pulse for nominal 20 J operating conditions. Anode erosion minimized with lower fuel feed for all pulse energies, corresponding to high I_{sp} / low thrust operation.

PRESENT STATUS

A 1-U flight design is nearly complete, **Figure 13**. Flight electronics and ESU modules are likewise nearing completion. This unit features a 2-module 20 J ESU and >300 g PTFE fiber along with the feed motor, storage spool, multiple igniters, and ESU charging / motor controller / discharge ignition circuits. The estimated performance of the 1U FPPT system illustrated in **Figure 13** is listed in **Table 5**.

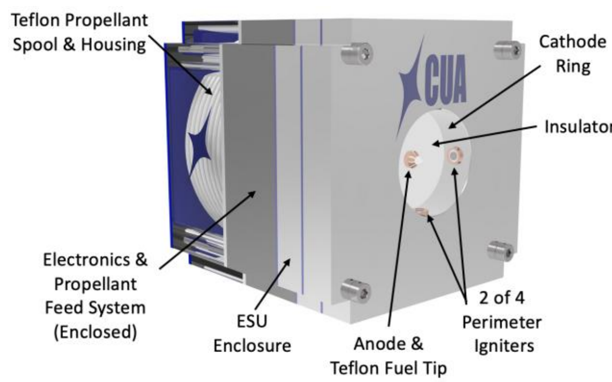

Figure 13 – Illustration of FPPT propulsion system contained within a 1U envelope.

Table 5: Estimated Performance of a 1U FPPT with 20 J ESU

PARAMETER	FPPT
Thruster System Package Volume	1,000 cm^3
Available Tank Volume	150 cm^3
Propellant	Teflon Fiber
Propellant Mass	331 g
Dry Mass	1,209 g
Wet Mass	1,540 g
Nominal Power Draw	48 W
Pulse Rate	2.7 Hz
Specific Impulse	900 – 1,700 s
Mass Flow Rate	0.04 – 0.014 mg/s
Thrust	0.38 – 0.24 mN
Total Impulse	2,900 – 5,500 N-s
Vol. Impulse (tot. impulse / sys. vol.)	2,900 – 5,500 N-s/L
Delta-V Capability (for a **5 kg S/C Wet Mass**)	600 – 1,140 m/s
TRL	5

CONCLUDING REMARKS

CUA has successfully developed the FPPT from concept to 1-U flight design. Over 1 million pulses have been executed on the breadboard FPPT system, and over 600 million pulses have been executed on a subscale life-test ESU.

A regenerative carbon igniter has been fabricated and used successfully for discharge initiation. Due to its regenerative nature, igniter erosion has not been found to be life-limiting.

The FPPT performance envelope can be broadened by varying the fuel feed rate. Fuel feed is user selectable to vary thrust and specific impulse. Additionally, FPPT is inherently a 0 – 100% throttleable system.

FPPT thrusters are expected to provide a compact, light-weight, non-hazardous propulsion technology solution, available in a family of sizes. FPPT requires no safety equipment for storage, transportation, integration, and testing, and places no demanding requirements on the launch provider, making it an attractive low-cost solution for DOD industry, research, and academic CubeSat and small-satellite missions.

ACKNOWLEDGEMENTS

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