Qualification of a Pulsed, Millinewton Class Metal Plasma Thruster for Broad Mission Applications

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Abstract: In the field of low power (<100W) electric propulsion, all thruster options demand significant trade-offs between operating parameters, reliability and scalable cost. With many systems on the market there are concerns with reliability, the need for extra considerations such as electron neutralizers for pure ion plumes, and the cost or craft compatibility of propellants. The Metal Plasma Thruster (MPT) is a new type of electric propulsion technology intended for low power applications. The system imparts momentum using inert, solid metal pucks as a propellant by using pulsed power to convert the metal into high velocity (~17km/s for Mo) jets of quasi-neutral plasma. The MPT technology does not require gas or liquid propellants, neutralizers, standby heaters, high voltage electronics, high electric or magnetic fields to operate. This comparatively simple pulsed operation is amenable to closed loop control, which provides for fine thrust control and S/C directed impulse on demand. Furthermore, the technology can use any metal as propellant, opening up unique opportunities for In-Situ Resource Utilization (ISRU) as well as customizability of performance for meeting specific mission needs. This paper describes implementation and direct measurement of this closed loop control mode as well as impulse measurement of multiple metals consistent with the aim of ISRU at NASA Glenn Research Center (GRC).

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I. Introduction

This paper presents measurements of impulse bits and thrust from a metal plasma thruster dubbed Xantus. The measurements were made at the NASA/GRC VF-3 vacuum facility using a sensitive torsional thrust stand[1].

The Xantus MPT, shown in Figure 1, is a pulsed, electric propulsion thruster that ejects small bursts of highly ionized plasma from solid metal propellant to provide impulsive thrust with no moving parts, no gases or liquids or valves and operates using a simple, 45V Power Processor Unit (PPU).

This paper is organized as follows: **section II** describes the operation of the Xantus MPT and the torsional thrust stand. The descriptions are brief as these have been described in detail in earlier publications[2,3]. **Sections III and IV** present the impulse bit and thrust measurement campaigns conducted at NASA GRC. The first campaign tested a Xantus MPT consisting of four identical, square "pucks" of Molybdenum (see unit -005 in Figure 1). The second campaign tested a Xantus thruster (see unit -001 of Figure 1) with three different pucks: Molybdenum, Copper and Stainless Steel. The Mo and Cu pucks were made of solid metal (identical in shape to the four pucks in Figure 1), but the stainless-steel puck was comprised of a sandwich of thin sheets of stainless steel identical to the steel used in upper stages of rockets that have been discarded in orbit and pose a potential collision hazard to the increasing number of smaller satellites that now occupy LEO. The small satellite numbers are growing rapidly. It will become critically important to remove the large, useless rocket bodies in LEO before one of them collides with other satellites and, in the worst case, provokes the Kessler syndrome.

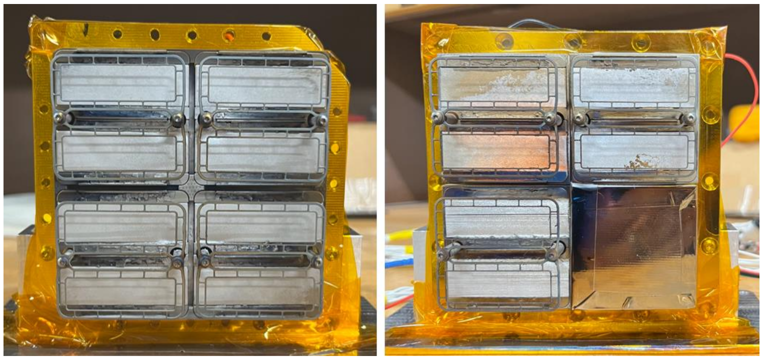

Figure 1. Xantus MPT, unit -005 (left) and -001 (right).

II. XANTUS MPT AND TORSIONAL THRUST STAND

A. METAL PLASMA THRUSTER OPERATION

The Xantus MPT uses pulsed cathodic arcs to generate very tiny impulse bits. By firing the thruster repetitively (at rates of 1Hz – 10Hz), these impulse bits cumulatively provide useful impulse to affect the orientation or orbital radius of satellites in a broad mass range from Cubesats to ESPA Class satellites in LEO, MEO and GEO[**]. The cathodic arc discharge of the Xantus MPT erodes and ionizes the metal propellant from tiny spots (~1µm in size) on the puck surface into a plasma cone that expands into the vacuum at speeds of 6.8 km/s – 30.6 km/s, depending upon the metal propellant that is used[4]. The typical spot lasts for <1µs: hence during a typical 2ms duration arc discharge, there are thousands of such spots that wink on and off across the puck surface. The spots are randomly distributed and over millions of pulses cover most of the available surface. The erosion rate of refractory metals such as Molybdenum (Mo) and Niobium (Nb) is ~35 µg/C[4]. For an arc of 0.3 Coulomb total charge, the mass eroded is ≈10 µg/pulse. At a speed of 17.4 km/s (Mo target), the ideal impulse-bit created by each pulse is 0.174 mNs. This ideal impulse bit is reduced by three deleterious factors: the hot plasma expands into a "supersonic" cone of $\pm 20^0$ about the axis. The radial component of momentum reduces the thrust to 85% of the purely axial maximum; the plasma is not fully ionized. Refractory metals such as Mo are found to be doubly ionized in such arcs but nevertheless the ion fraction is only about 95%; lastly, the anode (see Figure 1) is not 100% transparent. The anode's transparency varies from shot to shot depending upon where the cathode spots are created and how they propagate across the puck during the ~2ms arc period. The central part of the anode is 100% transparent (Figure 1) while the corners at the edges are as low as 33% in transparency. For a typical anode transparency of 80%, the product of these three deleterious corrections is 95% x 85% x 80% = 65%. The ideal impulse bit of 0.174mNs is reduced to 0.113mNs. At a pulse repetition rate of 9 Hz, the ideal thrust produced is approximately 1 mN. Erosion creates a deepening well in the puck that eventually ejects most of the available metal into space, leading to end-of-life of the puck. Each square Mo puck in Figure 1 begins with a mass of 120g. If 90% of the puck mass or 110g are eroded, this mass would generate ~1250Ns of total

[**] benchmarkspacesystems.com

(useful) impulse. The four pairs of pucks would give a total mission impulse up to 5kNs, from a thruster volume of 98mm x 98mm x 60mm, or ~0.6U.

B. VACUUM FACILITY

The Torsional Thrust Stand was housed in a vacuum chamber 1.5 m in diameter and 4.5 m long and evacuated by either four oil diffusion pumps (ODPs) or one turbomolecular pump, backed by a roughing pump. The pumping speed of the ODPs is 80,000 liter/sec at 0.05 mPa. Facility pressure was measured with two Granville-Phillips micro ion gauges, both located on the facility wall. One gauge was within 1 meter of the thruster and the other was located at the opposite end of the facility; both gauges were monitored and recorded during testing. Typical background pressure during MPT testing was 0.1 mPa.

1. THRUST STAND

Figure 2. MPT5.0-005 Mounted to Thrust Stand in VF-3 at NASA/GRC (View from Front).

Figure 2 shows the Xantus unit mounted on the torsional thrust stand at NASA/ GRC's VF-3 facility. A torsional type thrust stand was used to measure impulse bits from the MPT. A review of the development and operation

of the thrust stand can be found in the work by Haag[1]. The impulse-bit was determined as a function of thrust stand deflection, spring stiffness, and natural frequency. Thrust stand deflection was measured using a linear-variable differential transformer (LVDT) and natural frequency was measured by allowing the stand to oscillate under a near un-damped condition. In-situ calibration weights were used to apply a known force to determine the deflection of the thrust stand.

Figure 4 demonstrates a calibration cycle in which the LVDT signal is monitored during the application and removal of two known calibration loads. Figure 3 demonstrates a near un-damped oscillation of the thrust stand used to measure the stand natural frequency.

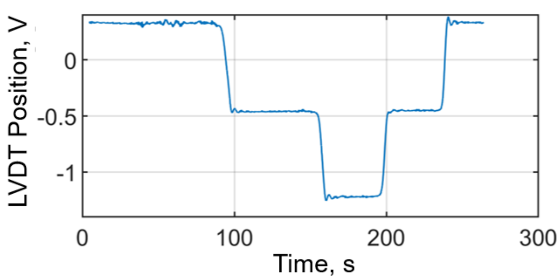

Figure 4. Sample Calibration Cycle to Determine Calibration k (mN/V).

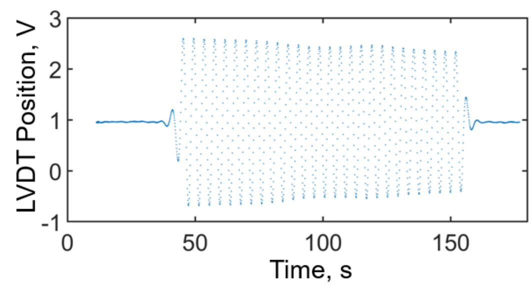

Figure 3. Sample Natural Frequency Cycle to Determine Calibration ω_n (rad/s).

The thrust stand was equipped with a damping actuator capable of operating in a near un-damped state or a near critically damped state. The actuator was enabled or disabled external to the facility to allow measurement of calibration weights, natural frequency oscillations, or thruster impulse bits as needed. The stand was also equipped with a two-axis inclinometer and set of piezoelectric actuators to ensure consistent inclination of the thrust stand during calibration and thruster measurement. The measurement uncertainty in the impulse-bit was estimated to be ±2%.

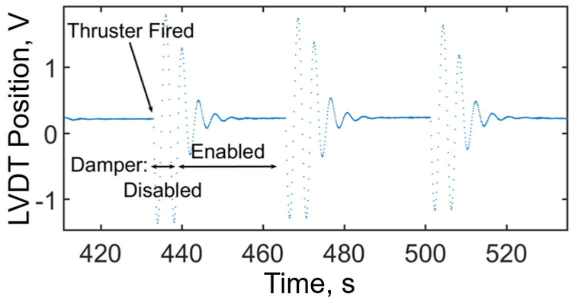

Figure 5. Sample Impulse Bits.

Figure 5 demonstrates three impulse bit events from the thruster. The annotations on the bottom of the figure demonstrate the durations during which the damper actuator was enabled and disabled. The annotations also denote the time of the thruster firing, and the response can be observed in the LVDT signal. Using the peak-to-peak amplitude of the LVDT after an impulse bit event, along with the calibration data and the natural frequency values, the total impulse imparted to the stand can be calculated. Example calculations of impulse bit measured on a torsional thrust stand can be found in reference[3].

III. IMPULSE MEASUREMENTS AND ESTIMATES: TWO CAMPAIGNS

C. FIRST CAMPAIGN: MOLYBDENUM TARGET

This paper presents results from two test campaigns carried out at the VF-3 vacuum facility at NASA/GRC. The first campaign in August tested a Xantus MPT with four identical pucks of Mo while the second campaign tested a version of the Xantus with three pucks: Mo, Cu and stainless-steel (see Figure 1).

Table 1 shows how the impulse bit is calculated for a single shot from Puck 1. There are four Mo pucks (see Figure 1), but the calculations are shown only for Puck 1.

Table 1. Measured and Estimated Impulse Bits: First Campaign.

Puck	V_initial, V	V_final, V	Charge into arc, C	calculated impulse bit, mNs	measured impulse bit, mNs	Anode Transmission
1	45	28.7	0.359	0.218	0.160	91%

The capacitor initial charge voltage, V_initial, is 45V. After the discharge of ~2ms duration, the voltage has dropped to V_final of 28.7V on this shot (column 3 of Table 1). The voltage difference and the 22-mF capacitance give the charge into the arc as 0.359 C (column 4). This *single measured parameter suffices* to estimate the ideal impulse bit.

The textbook by Anders[4] contains comprehensive data on cathodic arcs that have been studied for several decades. Key parameters such as erosion rate, ion speed and degree of ionization have been measured or estimated for dozens of metal elements. Table 2 shows relevant data for Mo, Cu and Fe (as a substitute for stainless steel) that have been culled from Anders[4] and from published data on the Plasma Applications Group of Lawrence Berkeley National Laboratory (PAG/LBNL) website[††].

Table 2. Key Parameters for Cathodic Arcs of Mo, Cu and Fe[4,††]

cathode material	cohesive energy (eV/atom)	arc burning voltage (V)	ion kinetic energy (eV)	Ion speed, m/s	Ionization Fraction, %	Erosion rate, μg/C
Fe	4.28	22.7	46	12677	78%	32
Cu	3.49	23.4	57	13229	72%	35
Mo	6.82	29.3	149	17408	95%	35

The Cohesive Energy Rule for vacuum arcs postulated by Anders[4] describes an empirical relationship between the cathode material and the arc burning voltage, namely, that the burning voltage (column 3) depends approximately linearly on the cohesive energy (column 2). The ion kinetic energy (column 4) gives the ion speed (column 5). Anders and several others have made detailed measurements of the ionization fraction and erosion rates in cathodic arcs. The currents and pulse durations of these measurements are very similar to those of the Xantus thruster, so we will assume the values given in Table 2.

The Mo erosion rate (Table 2) is ≈35 μg/C. The product of 0.36C charge and erosion rate gives the mass ejected from the puck surface as 12.6μg. The measured ion speed[4] is 17,408 m/s. Hence the (ideal) impulse bit on this shot is 0.218 mNs (column 5). The metal plasma thruster is unique among all electric propulsion thrusters in that its impulse (thrust) may be estimated so easily using a single measured electrical parameter. This ideal impulse bit must be

[††] LBNL Website

corrected for real-world inefficiencies as mentioned earlier. We assume that the beam divergence correction is 85% and that the ionization fraction is 95%. This leaves the (variable) anode transmission as a free parameter, that is calculated to be 91% for this shot.

Table 3. Thruster Parameters for Xantus with a Mo Puck.

	V_initial, V	V_final, V	measured impulse bit, mNs	Energy into arc, J	Thrust energy, J	Thrust Efficiency, %	Thrust/Power, mN/kW
1	45	28.7	0.160	13.2	1.39	10.5%	12.1

Table 3 shows how we use the measured impulse bit and speed to calculate other thruster parameters.

The measured final voltage of 28.7V gives the energy delivered to the arc as 13.2J. The thrust energy is given by the ejected mass Δm (12.6μg) and ion speed (17,408m/s) as 1.39J. The thrust efficiency is calculated from:

$$\eta_{thrust} = \frac{\frac{1}{2} I_{bit} u}{\Delta E} = \frac{\frac{1}{2}\Delta m\, u^2}{\frac{1}{2} C\left(V_i^2 - V_f^2\right)} \quad (1)$$

where V_i is the initial charge voltage of the PPU capacitors, V_f the burning voltage of the arc (at which the arc current cuts off), I_{bit} is the measured impulse bit and C is the capacitance. ΔE is the energy dissipated by the thruster/pulse, calculated from the measured voltage on the capacitor at the start and at the end of the pulse. This method of estimating the efficiency takes into account all the losses in the driver circuit as well as the thruster inefficiency. Hence the thrust efficiency is 10.5% for this shot and lastly, the thrust/power ratio (T/P) is calculated to be 12.1mN/kW. For perspective, this 12mN/kW value implies that an 40W Xantus thruster (operating on a 30kg – 50kg satellite) would provide a thrust of ≈0.5mN. In VLEO for example, this thrust would combat atmospheric drag for such a satellite making excursions from 300km down to 200km in elliptical orbits (to sample the ionosphere or take optical and infrared images) for 115 days, assuming the full impulse of 5kNs.

Table 4. Calculated and Measured Impulse Bits: Mo Pucks 1 and 2 at 45V Charge (Campaign 1).

Puck	V_initial, V	V_final, V	Charge into arc, C	calculated impulse bit, mNs	measured impulse bit, mNs	Anode Transmission
1	45	30.9	0.310	0.189	0.117	77%
1	45	35.4	0.211	0.129	0.074	71%
1	45	30.6	0.317	0.193	0.121	78%
1	45	28.4	0.365	0.223	0.139	77%
1	45	28.6	0.361	0.220	0.154	87%
1	45	35.5	0.209	0.127	0.089	87%
1	45	28.7	0.359	0.218	0.145	82%
1	45	29.6	0.339	0.206	0.144	86%
1	45	28.6	0.361	0.220	0.152	86%
1	45	28.3	0.367	0.224	0.161	89%
1	45	33.2	0.260	0.158	0.105	82%
1	45	28.7	0.359	0.218	0.158	90%
1	45	29.3	0.345	0.210	0.146	86%
1	45	29.9	0.332	0.202	0.136	83%
1	45	28.7	0.359	0.218	0.160	91%
2	45	33.4	0.255	0.155	0.109	87%
2	45	29.6	0.339	0.206	0.170	102%
2	45	37.8	0.158	0.097	0.065	83%
2	45	33.7	0.249	0.151	0.100	82%
2	45	29.2	0.348	0.212	0.158	92%

With this background, we next present data from more shots during the August campaign, in Table 4 and 5. Table 4 shows impulse bits measured from pucks 1 and 2 of the Xantus MPT with the PPU charged to 45 V. The data are sorted by puck number in column 1. Columns 2 and 3 show the measured capacitor voltages in the PPU. Column 4 shows the calculated charge into the arc for a 22mF capacitor. Column 5 shows the calculated ideal impulse bit, using only the eroded mass (from the charge and erosion rate (see Table 2) while assuming no impulse loss due to beam divergence, 100% ionization and 100% anode transmission. Colum 6 shows the impulse bits measured using the thrust stand as described in **section II**. The anode transmission for each shot is calculated from the measured impulse bit, assuming 95% ionization and 15% beam divergence loss. It is observed that the transmission varies from a low of 71% up to 102%. The 102% is not real and reflects the error in such estimates. Merely increasing the divergence correction to 86% or the erosion rate to 36μg/C would reduce the maximum anode transmission to 100%. A glance at Figure 1 shows that when the spots are all located under the central portion of the anode, the transmission would be 100%.

Table 5. Calculated and Measured Impulse Bits: Mo Pucks 3 and 4 at 45V Charge (Campaign 1).

Puck	V_initial, V	V_final, V	Charge into arc, C	calculated impulse bit, mNs	measured impulse bit, mNs	Anode Transmission
3	45	29.4	0.343	0.221	0.143	80%
3	45	31.7	0.293	0.188	0.116	76%
3	45	35.2	0.216	0.139	0.050	45%
3	45	29.8	0.334	0.215	0.142	82%
3	45	29.6	0.339	0.218	0.140	79%
3	45	29.7	0.337	0.217	0.143	82%
3	45	29.5	0.341	0.220	0.147	83%
3	45	29.3	0.345	0.222	0.140	78%
3	45	28.8	0.356	0.230	0.155	84%
3	45	30.5	0.319	0.205	0.142	86%
4	45	36.80	0.180	0.116	0.090	96%
4	45	38.00	0.154	0.099	0.059	74%
4	45	30.00	0.330	0.213	0.169	98%
4	45	29.20	0.348	0.224	0.177	98%
4	45	34.70	0.227	0.146	0.110	93%
4	45	28.00	0.374	0.241	0.185	95%
4	45	29.80	0.334	0.215	0.171	98%
4	45	32.2	0.282	0.181	0.128	87%
4	45	29.9	0.332	0.214	0.158	91%
4	45	32.6	0.273	0.176	0.127	90%
4	45	30.3	0.323	0.208	0.148	88%
4	45	31.4	0.299	0.193	0.142	91%
4	45	31.8	0.290	0.187	0.132	87%
4	45	27.9	0.376	0.242	0.165	84%
4	45	29.8	0.334	0.215	0.167	96%
4	45	28.9	0.354	0.228	0.180	98%
4	45	28.9	0.354	0.228	0.182	99%
4	45	28.3	0.367	0.237	0.181	95%

Table 5 shows impulse bits measured from pucks 3 and 4 of the Xantus MPT with the PPU charged to 45 V. The calculated anode transmission is mostly >80% with the exception of one shot that shows 45% transmission. It is evident that the cathode spots on this shot clustered close to the edge of the pucks where the anode is less transmissive. Such a behavior is atypical, with most shots showing 80% - 100% transmission. However, this pathological behavior is influenced by contaminants on the puck surface and plays a role in explaining why the second campaign produced poorer results, as described in **section IV**.

Although the spots always begin near the edges of the puck (where the trigger plasma is most intense), they migrate away from that edge as new spots seek fresh cathode material to erode. Since the typical spot lifetime is ~1µs and since each spot carries ~20A (see Anders[4]), there are ~10 spots at any given time carrying the 200A discharge current. These groups of spots wink on and off during the ~2ms arc current event. An extinguished spot at one location reappears at an adjacent location, to maintain current continuity. The spots do not physically move but disappear and reappear at new locations. The "phase" velocity of such migration is ~5 – 10m/s[4]. 10m/s for 2ms is a distance of 2cm. Thus the spots are expected to migrate and cover the entire puck surface eventually.

Table 6 shows how we use the measured impulse bit and speed to calculate other thruster parameters. As discussed earlier for Table 3, we calculate the energy into the arc, thrust energy, thrust efficiency and thrust/power (T/P) ratio (shown in the last column). The average T/P for pucks 1 and 2 is 11mN/kW.

Table 7 shows similar calculations for pucks 3 and 4. The average T/P ratio for these pucks is 12mN/kW, similar to that for the single shot shown in Table 1. The third row of this table shows the one drop-out at 5.8mN/kW that corresponds to the poor anode transmission of 45% (see Table 5). Since some of the mass is deposited onto or reflected from the anode, the thrust is lower.

To summarize campaign 1, four Mo pucks were tested at 45V PPU capacitor charge. The measured impulse bits were used to deduce the effective anode transmission, assuming fixed values for the ionization fraction and beam divergence correction. For the most part, the anode transmission was found to vary from around 80% to 100%, with a few exceptions. One particularly poor shot from puck 3 showed 45% anode transmission. This suggested that for that particular shot, the cathode spots had not migrated away from the edge to occupy the central region opposite the open part of the anode. While this was a rare occurrence during campaign 1, it became a problem during campaign 2, as discussed next.

Table 6. Thruster Parameters for Mo Pucks 1 and 2 (Campaign 1).

Puck	V_initial, V	V_final, V	measured impulse bit, mNs	Energy into arc, J	Thrust energy, J	Thrust Efficiency, %	Thrust/Power, mN/kW
1	45	30.9	0.117	11.8	1.02	8.7%	9.9
1	45	35.4	0.074	8.5	0.64	7.6%	8.7
1	45	30.6	0.121	12.0	1.05	8.8%	10.1
1	45	28.4	0.139	13.4	1.21	9.0%	10.4
1	45	28.6	0.154	13.3	1.34	10.1%	11.6
1	45	35.5	0.089	8.4	0.77	9.2%	10.6
1	45	28.7	0.145	13.2	1.26	9.6%	11.0
1	45	29.6	0.144	12.6	1.25	9.9%	11.4
1	45	28.6	0.152	13.3	1.32	10.0%	11.4
1	45	28.3	0.161	13.5	1.40	10.4%	12.0
1	45	33.2	0.105	10.2	0.91	9.0%	10.3
1	45	28.7	0.158	13.2	1.38	10.4%	12.0
1	45	29.3	0.146	12.8	1.27	9.9%	11.4
1	45	29.9	0.136	12.4	1.18	9.5%	10.9
1	45	28.7	0.160	13.2	1.39	10.5%	12.1
2	45	33.4	0.109	10.0	0.95	9.5%	10.9
2	45	29.6	0.170	12.6	1.48	11.7%	13.5
2	45	37.8	0.065	6.6	0.57	8.6%	9.9
2	45	33.7	0.100	9.8	0.87	8.9%	10.2
2	45	29.2	0.158	12.9	1.38	10.7%	12.3

Table 7. Thruster Parameters for Mo Pucks 3 and 4 (Campaign 1).

Puck	V_initial, V	V_final, V	measured impulse bit, mNs	Energy into arc, J	Thrust energy, J	Thrust Efficiency, %	Thrust/Power, mN/kW
3	45	29.4	0.143	12.8	1.24	9.7%	11.2
3	45	31.7	0.116	11.2	1.01	9.0%	10.3
3	45	35.2	0.050	8.6	0.44	5.0%	5.8
3	45	29.8	0.142	12.5	1.24	9.9%	11.4
3	45	29.6	0.140	12.6	1.22	9.6%	11.1
3	45	29.7	0.143	12.6	1.24	9.9%	11.4
3	45	29.5	0.147	12.7	1.28	10.1%	11.6
3	45	29.3	0.140	12.8	1.22	9.5%	10.9
3	45	28.8	0.155	13.2	1.35	10.3%	11.8
3	45	30.5	0.142	12.0	1.24	10.3%	11.8
4	45	36.80	0.090	7.4	0.78	10.6%	12.2
4	45	38.00	0.059	6.4	0.51	8.0%	9.2
4	45	30.00	0.169	12.4	1.47	11.9%	13.7
4	45	29.20	0.177	12.9	1.54	11.9%	13.7
4	45	34.70	0.110	9.0	0.96	10.6%	12.2
4	45	28.00	0.185	13.7	1.61	11.8%	13.6
4	45	29.80	0.171	12.5	1.49	11.9%	13.7
4	45	32.2	0.128	10.9	1.11	10.2%	11.8
4	45	29.9	0.158	12.4	1.38	11.1%	12.7
4	45	32.6	0.127	10.6	1.11	10.4%	12.0
4	45	30.3	0.148	12.2	1.29	10.6%	12.2
4	45	31.4	0.142	11.4	1.24	10.8%	12.4
4	45	31.8	0.132	11.2	1.15	10.3%	11.8
4	45	27.9	0.165	13.7	1.44	10.5%	12.0
4	45	29.8	0.167	12.5	1.45	11.6%	13.4
4	45	28.9	0.180	13.1	1.57	12.0%	13.8
4	45	28.9	0.182	13.1	1.58	12.1%	13.9
4	45	28.3	0.181	13.5	1.58	11.7%	13.4

D. SECOND CAMPAIGN: Mo, Cu AND STAINLESS-STEEL TARGETS

Campaign 2 occurred in November 2023. We first repeated the campaign 1 tests with MPT5.0-005 (all four Mo pucks), next we tested the multi-material unit MPT5.0-001 (see Figure 1). This unit was a testbed to gather thrust data for two metals other than Mo (the current standard), Copper and Stainless Steel. Copper is a viable candidate for a back-up option as it's still quite dense (meaning good propellant storage) but should perform quite well based on previous cathodic arc studies. Stainless Steel, specifically 0.015" thick sheet stock of 304 Stainless Steel is an interesting candidate because that is the exact kind of metal found in the balloon tanks of the Centaur rocket upper stage, many of which are currently locked in orbit as debris. This would demonstrate our ability to use on-orbit debris as a source for propulsion. A robot would rendezvous with the target debris, slice the shell into thin (0.015" strips) of stainless steel and pack those into the empty puck slots in several bare Xantus thruster heads. The docked vehicle would then turn on the Xantus MPTs, burn up the stainless-steel fuel, and reload the spent heads with debris mass until sufficient impulse is generated to maneuver the object into VLEO for atmospheric burn-up. Maneuver to graveyard orbits is another possibility.

Table 8. Measured Impulse bits and Thruster Parameters for Mo Pucks 1-4 (Campaign 2).

Puck	V_initial, V	V_final, V	Charge into arc, C	calculated impulse bit, mNs	measured impulse bit, mNs	Anode Transmission	Thrust/Power, mN/kW
1	45.2	39.1	0.134	0.070	0.021	38%	3.8
1	45.2	39.3	0.130	0.068	0.018	33%	3.2
1	45.2	28.9	0.359	0.187	0.089	59%	6.7
1	45.2	30.4	0.326	0.170	0.080	58%	6.5
1	45.2	32.2	0.286	0.149	0.076	63%	6.9
1	45.2	33.1	0.267	0.139	0.034	30%	3.3
1	45.2	39.3	0.130	0.068	0.016	29%	2.9
1	45.2	32.6	0.277	0.144	0.038	33%	3.5
1	45.2	37.0	0.180	0.094	0.029	38%	3.9
1	45.2	29.8	0.339	0.177	0.051	36%	4.0
1	45.2	31.7	0.297	0.155	0.048	38%	4.2
1	45.2	38.4	0.150	0.078	0.040	63%	6.4
1	45.2	38.9	0.139	0.072	0.041	70%	7.0
1	45.2	30.9	0.315	0.164	0.086	65%	7.2
1	45.2	35.5	0.213	0.111	0.037	41%	4.3
1	45.2	32	0.290	0.152	0.082	67%	7.3
1	45.2	35.8	0.207	0.108	0.063	72%	7.5
1	45.2	34.5	0.235	0.123	0.070	71%	7.5
2	45.2	29.4	0.348	0.182	0.074	51%	5.7
2	45.2	34.6	0.233	0.122	0.036	36%	3.8
2	45.2	37.7	0.165	0.086	0.029	42%	4.2
3	45.2	39.7	0.121	0.063	0.022	42%	4.2
3	45.2	29.6	0.343	0.179	0.090	62%	7.0
3	45.2	29.6	0.343	0.179	0.092	64%	7.2
3	45.2	29.4	0.348	0.182	0.097	66%	7.5
3	45.2	28.3	0.372	0.194	0.095	61%	7.0
3	45.2	28.2	0.374	0.195	0.093	59%	6.8
3	45.2	37.7	0.165	0.086	0.039	56%	5.7
3	45.2	28.0	0.378	0.198	0.091	57%	6.6
3	45.2	29.1	0.354	0.185	0.089	60%	6.8
3	45.2	28.8	0.361	0.188	0.095	62%	7.1
3	45.2	29.7	0.341	0.178	0.089	62%	7.0
3	45.2	34.0	0.246	0.129	0.089	86%	9.1
3	45.2	27.9	0.381	0.199	0.095	59%	6.8
3	45.2	28.1	0.376	0.196	0.089	56%	6.5
4	45.2	34.8	0.229	0.119	0.040	42%	4.4
4	45.2	33.8	0.251	0.131	0.025	24%	2.6
4	45.2	29.3	0.350	0.183	0.091	62%	7.0

Table 8 shows the measured impulse bits, deduced anode transmission values and T/P ratio for all four pucks. The logic proceeds as already described earlier. We turn directly to the startling observation that the anode transmissions are so much lower in this campaign than in campaign 1. The values ranged from 24% to 86%, with most shots below 65%. It was no surprise that the T/P ratios were also low, ranging from 2.6mN/kW up to 9.1mN/kW. Inspection of the pucks after removal from vacuum showed discoloration at the corners, leading to the suspicion of contamination of the puck surfaces.

Before we address this contamination issue, we present data from the Cu and stainless-steel pucks.

Table 9 shows the Cu data. While the deduced anode transmission values are higher than for the contaminated Mo pucks (Table 8), they are nevertheless mostly below 60%, whereas the campaign 1 Mo data showed 80% - 99% transmission (see Table 5). It is apparent that the Cu puck was also contaminated, though to a lesser degree than the Mo pucks.

The deduced average T/P ratio for the Cu puck is about 5mN/kW. Since the average anode transmission is only 63%, if one assumes that a clean puck would achieve 100% transmission then the projected T/P ratio would be

≈8mN/kW. This is to be contrasted with the average values of 11mN/kW to 12mN/kW for Mo. The 25% lower T/P ratio is consistent with the 25% lower ion speed of Cu (13,229m/s v. 17,408m/s for Mo).

Table 10 shows the results obtained from the stainless-steel puck #3. The deduced anode transmission values for this puck are higher than for both the Cu and the Mo, yet the average of 85% is lower than the maximum possible 100% for a clean puck whose spots cluster below the open face of the anode. The average T/P ratio for stainless-steel is 6.2mN/kW, which would increase to 7.3mN/kW for a clean (uncontaminated) puck.

Table 9. Measured Impulse Bits and Thruster Parameters for Cu Puck 2 (Campaign 2).

Puck	V_i	V_f	charge, C	ideal impulse bit, mNs	measured impulse bit, mNs	Anode Transmission	Thrust/Power, mN/kW
2	45.2	30.2	0.330	0.153	0.053	57%	4.3
2	45.2	28.6	0.365	0.169	0.066	64%	4.9
2	45.2	28.6	0.365	0.169	0.067	65%	5.0
2	45.2	24.6	0.453	0.210	0.087	68%	5.5
2	45.2	23.2	0.484	0.224	0.095	69%	5.7
2	45.2	23.9	0.469	0.217	0.1	75%	6.2
2	45.2	25	0.444	0.206	0.091	72%	5.8
2	45.2	22.6	0.497	0.230	0.1	71%	5.9
2	45.2	31.5	0.301	0.140	0.055	64%	4.8
2	45.2	25.4	0.436	0.202	0.089	72%	5.8
2	45.2	25.5	0.433	0.201	0.061	50%	4.0
2	45.2	29.7	0.341	0.158	0.047	49%	3.7
2	45.2	29.9	0.337	0.156	0.054	57%	4.3
2	45.2	30.5	0.323	0.150	0.054	59%	4.4
2	45.2	25	0.444	0.206	0.078	62%	5.0
2	45.2	29.6	0.343	0.159	0.062	64%	4.8
2	45.2	28.6	0.365	0.169	0.047	45%	3.5
2	45.2	27.9	0.381	0.176	0.071	66%	5.1
2	45.2	26.7	0.407	0.188	0.076	66%	5.2
2	45.2	23.1	0.486	0.225	0.096	70%	5.8

Table 10. Measured Impulse Bits and Thruster Parameters for Stainless-Steel Puck 3 (Campaign 2).

Puck	V_i	V_f	charge, C	ideal impulse bit, mNs	measured impulse bit, mNs	Anode Transmission	Thrust/Power, mN/kW
3	45.2	30.9	0.315	0.128	0.069	82%	5.8
3	45.2	33.6	0.255	0.104	0.06	87%	6.0
3	45.2	30.1	0.332	0.135	0.067	75%	5.4
3	45.2	26.8	0.405	0.164	0.095	87%	6.5
3	45.2	36.5	0.191	0.078	0.038	74%	4.9
3	45.2	25.9	0.425	0.172	0.104	91%	6.9
3	45.2	26.2	0.418	0.170	0.106	94%	7.1
3	45.2	23.9	0.469	0.190	0.111	88%	6.9
3	45.2	28.9	0.359	0.145	0.081	84%	6.1
3	45.2	29.9	0.337	0.137	0.068	75%	5.4
3	45.2	22.4	0.502	0.203	0.119	88%	7.0
3	45.2	27.0	0.400	0.162	0.094	87%	6.5
3	45.2	33.3	0.262	0.106	0.068	97%	6.6
3	45.2	28.9	0.359	0.145	0.074	77%	5.6

To summarize, the T/P ratios are: Mo, 11mN/kW to 12mN/kW; Cu, 5mN/kW (possibly increasing to 8mN/kW for a clean puck); stainless-steel, 6.2mN/kW possibly up to 7.3mN/kW for a clean puck.

E. CONTINUOUS FIRE THRUST MEASUREMEMNTS

Before we address the contamination issue with campaign 2, we present measurements of thrust measured directly on the pendulum thrust stand, by firing the Xantus MPT (Mo pucks) in "continuous fire" mode.

By varying the pulse repetition rate from 0.5Hz up to 5Hz, the average power input to the MPT was varied from 5W up to 48W.

Figure 6 (blue triangles) shows the measured T/P ratio from these runs. The T/P ratio varies from 6.2mN/kW up to 7.7mN/kW. These numbers are similar to the values in Table 8 deduced from the single shot impulse measurements. Recall that we have speculated that the values are low because contamination has forced the spots to cluster in a less transparent region of the anode, leading to mass and thrust loss.

Figure 6 shows red diamonds with the legend defining these as "adaptive runs". What are these?

While there is rather tight control on the energy available for each shot of the MPT (22mF capacitor charged to +45V), the amount of energy that any given shot will use does vary quite a bit. While a burned-in MPT will consistently bring the capacitor charge down towards +30V, any given shot can vary anywhere in the range of the max cap charge (+45V) voltage down to that +30V value. And while when averaged over thousands of shots the total impulse is quite reproducible, the total power going into the unit can vary significantly depending on from what post-arc voltage the capacitor needs to be recharged.

This behavior is better illustrated below in Figure 7 that shows a simplified example of two heads firing in alternation, where Head 1 consistently drains the capacitor from +45V down to +30V while Head 2 is only draining down to +35V. The MPT currently functions in one of two modes, the first being "constant firing rate" mode, meaning an arc is triggered every X milliseconds, in this case every 1000 milliseconds. For this example, this means that Head 1 is operating at about 24.8W and Head 2 at 17.6W for an average of 21.2W.

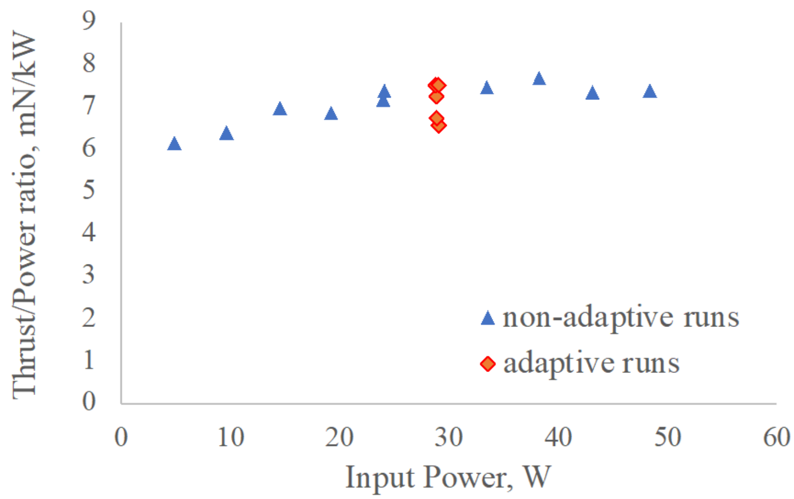

Figure 6. Measured Continuous Fire Thrust/Power ratio.

This variable power could be less than desirable for a few reasons. Firstly, it creates a bit of a trial-and-error operation for the spacecraft where the controller must try different rates to figure out a power budget to operate the MPT. Secondly, as the MPT burns through its fuel the physical length of the arc grows and the total plasma resistance can also increase, meaning a constant rate that previously operated at a certain average power/impulse would then change. Thirdly, there does seem to be a variation in performance from head-to-head which means there could be further differences depending on the shot pattern.

To improve upon this challenge, we implemented closed loop control, allowing the MPT to operate in the second mode, "adaptive firing rate" mode which adjusts the rate of firing on the fly depending on the desired output power which is set by the spacecraft. The method relies on our onboard post-shot capacitor voltage measurement. Instead of simply printing it out for telemetry tracking, the MPT uses this capacitor voltage reading to evaluate the total charge (and hence impulse) of the last shot and adjusts the next shot's timing accordingly. By implementing an adaptive recharge rate (akin to an adaptive firing rate) and a set desired power of 25W (for example), the MPT would be able to quickly sense the previous shot's total charge and then adjust the recharge time to ensure each shot lands on 25W average. Figure 7 shows a simplified example of how this works, with the same simulated performance between Head 1 and Head 2 as mentioned above. However, in this case the onboard controller adapts the timing of the following shot to achieve a constant power output of 25W.

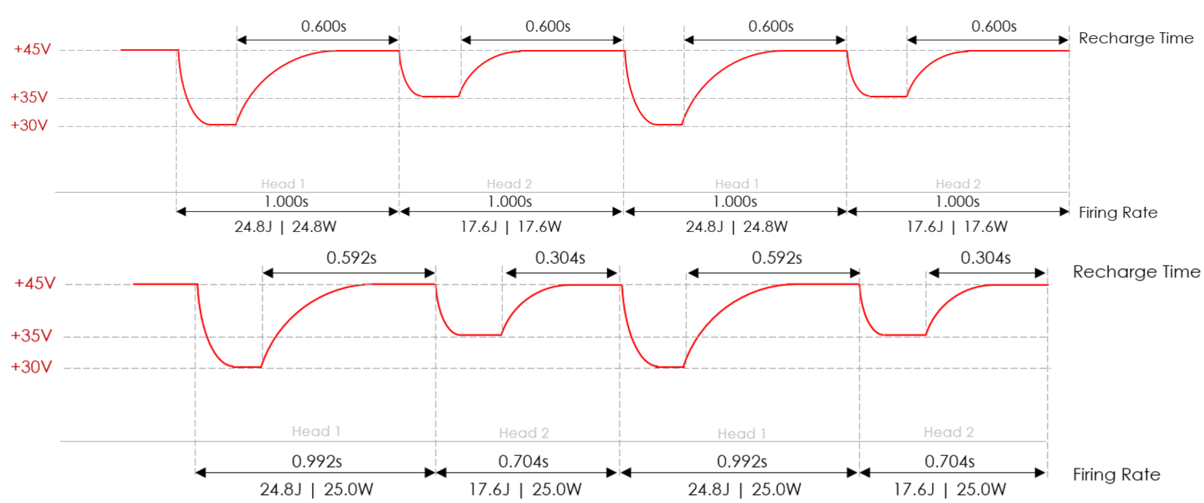

Figure 7. Constant Firing Rate Mode (top) Versus Adaptive Firing Rate Mode (bottom).

Going back to Figure 6, the red diamonds are T/P measurements from adaptive runs at a set power of 30W. It turns out that the actual power was closer to 29W. The T/P ratios are similar to those deduced for the non-adaptive runs.

The tests of different pucks showed that the MPT is flexible in its choice of propellant. Any conducting metal may be used. The tradeoff is ion speed, erosion rate and puck density. The results showed that Cu and stainless steel are viable alternatives to Mo. Earlier tests had shown that Nb and Al were also viable. Despite contamination of the pucks in campaign 2, the results demonstrate the versatility of the MPT, operable with many types of propellant, with a simple, adaptive control algorithm that enables operation at a constant power (hence a constant thrust) despite shot-shot fluctuations in impulse bits.

IV. UNDERSTANDING THE CONTAMINATION ISSUE

Between campaign 1 and campaign 2, what had changed at the VF-3 facility? The chillers of the Oil Diffusion Pumps had been turned off. It was speculated that even though the ODPs were off during the campaign, residual pump oil in the ODP wells might have back streamed into the chamber and coated the pucks. Figure 8 shows the view of the VF-3 chamber as seen by the MPT when mounted onto the thrust stand whereby the MPT can be seen located directly in front of the ODP well. Due to shadowing of the puck surface by the anode, the zones near the edges and particularly near the corners might have been spared the contamination. Then it is possible that the cathode spots formed in these zones and stayed there, as conditions were not favorable for cathode spot formation elsewhere.

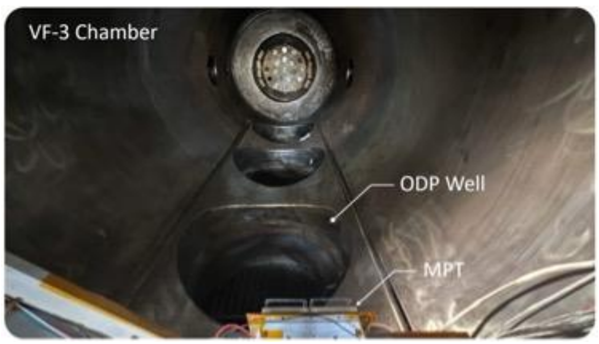

Figure 8. MPT View of ODP Wells in VF-3 Chamber.

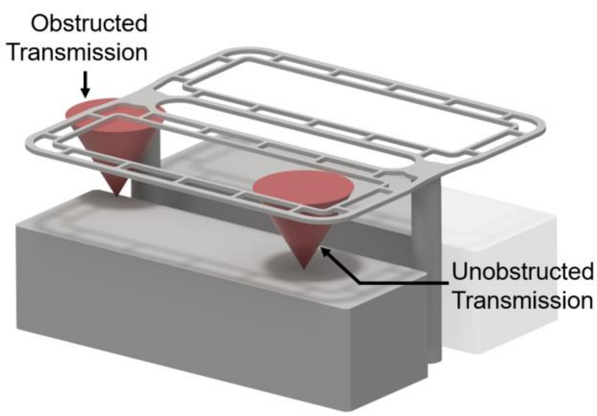

Figure 9. Simplified CAD of MPT Puck Showing Example Arc Plumes.

Figure 9 shows the concept of such shadowing and localization of the spots. The figure shows two arc plasma plumes: one is centered across the puck width, and the Mo plasma, based on the plume geometry, is 100% transmitted by the anode. The second arc plume is located near the anode post and under the thickest part of the anode grid. Here the transmission can be as low as 50% depending upon the size of the plume. Since a given arc creates cathode spots in different locations, but usually clustered together in a local zone on any given shot, it is estimated that the anode transmission can vary between 50% and 100% on any given shot. Usually the plumes do not cluster close to the anode post and hence the average transmission is closer to 90%, but there can be pathological cases where the transmission is lower. We have observed that when there are surface contaminants these contaminants can drive arc emission to regions devoid of contaminants until the contaminants are cleaned up by successive arcs. The pucks are cleaned with alcohol before tests begin, but if there are contaminants (such as pump oil vapor or outgassing from volatiles in the vacuum system) then this can create a temporary drop in anode transmission.

Figure 10 shows a high-speed camera still of an arc from a single shot that appears to be centered across the puck width and hence shows 100% anode transmission.

Figure 11 shows high-speed camera still of a shot where the arc plume is close to the anode post and hence will have a much lower anode transmission. Calculation of the open area of the anode in that location shows that the effective transmission can vary from 75% down to 50% depending upon the diameter of the plasma plume at that location. A worst-case scenario could be a small plume that also impinges upon the anode post, with loss of plasma to that post. The net transmission would then be even lower. An important fact to consider is that such arc plume

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behavior is not the norm for Xantus. Under clean conditions, as demonstrated over >50M pulses in vacuum, there is no evidence of such a strong variation in anode transmission.

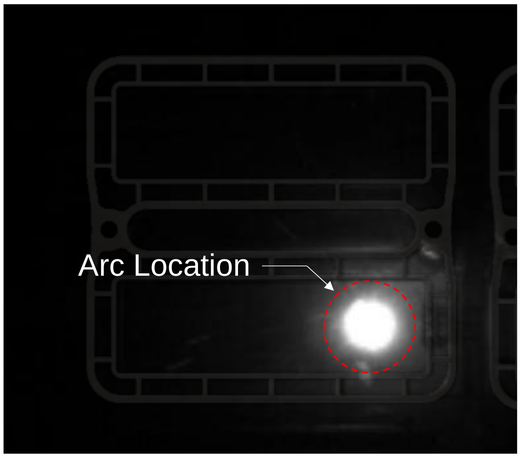

Figure 10. High-Speed Camera Still of Puck Centered Arc, ~100% Transmission.

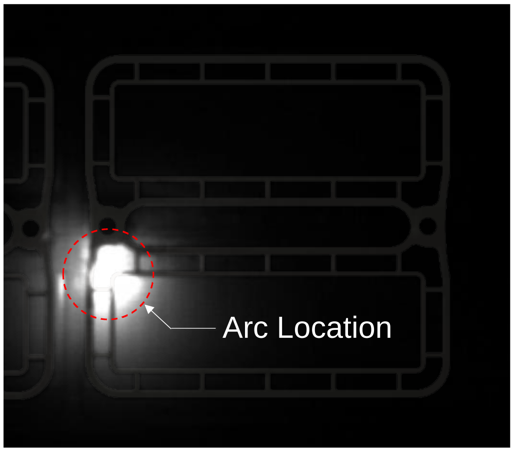

Figure 11. High-Speed Camera Still of Corner Arc, ~50% Transmission.

To test this hypothesis, covers were placed over the ODP wells, and new impulse measurements were made. The results are summarized in Table 11.

Table 11. Measured Impulse Bits and Thruster Parameters for Mo Puck #1 with the Oil Diffusion Pump Wells Covered (Campaign 2).

Puck	V_initial, V	V_final, V	Charge into arc, C	calculated impulse bit, mNs	measured impulse bit, mNs	Anode Transmission	Thrust/Power, mN/kW
1	45.2	32.6	0.277	0.145	0.085	73%	7.9
1	45.2	32.6	0.277	0.145	0.083	71%	7.7
1	45.2	32	0.290	0.152	0.091	74%	8.1
1	45.2	31.4	0.304	0.159	0.095	74%	8.2
1	45.2	36.3	0.196	0.102	0.064	78%	8.0

The deduced anode transmissions are now higher than with the ODP covers off (see Table 8) but still lower than the 80% - 100% observed during campaign 1. The 73% to 78% values in this case might be because the pucks were not fully cleaned by arcs to remove all residual traces of oil residue.

V. CONCLUSIONS

This paper has presented measurements of impulse bits and thrust from a metal plasma thruster, dubbed the Xantus MPT. Xantus has no moving parts, no liquids or gases or valves and uses a relatively simple 45V PPU. The tests described here demonstrate that Xantus may be operated with any conducting metal across the periodic table, which gives the mission planner options. Operation with Molybdenum pucks show thrust/power ratio of around 11mN/kW up to 12mN/kW. Hence this is a ~1mN class thruster for small satellites with mass in the 50kg range. The basic unit cell thruster measures 98mm x 98mm x 60mm or a volume of 0.6U. The four pucks in such a volume with a total mass of 1.2kg give a maximum impulse of 5kNs. The thruster is scalable. For NASA's Artemis mission, we have configured four such unit cells as a 4.8kg/2U package that should give a total of 20kNs. That impulse would be adequate to drive a cis-lunar trajectory and maintain a 12U or 16U satellite in lunar orbit for many months. Larger satellites would use larger arrays. The limitation is thermal management. The thrust efficiency of the Xantus is only ~10%. Even accounting for radiative loss from the hot plasma plume, up to 75% - 80% of the input power has to be conducted from the thruster and radiated into space from the satellite structure. One version of Xantus has been launched into LEO on March 4, 2024, and is expected to gain flight heritage in a month or two.

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