METAL PLASMA THRUSTER (MPT) : FROM GARAGE TO ORBIT IN 4 YEARS

GLASGOW, SCOTLAND | 20 – 23 MAY 2024

Kent Frankovich[(1)], Mahadevan Krishnan[(2)]

[(1)] *Benchmark Space Systems, Pleasanton, California, USA, kfrankovich@benchmark-space.com:*
[(2)] *AASC, Oakland, California, USA, krish@aasc.space*:

KEYWORDS: propulsion, electric propulsion, metal plasma thruster, ISRU

ABSTRACT:

In the field of low power (<100W) electric propulsion, there are few options that don't come with significant trade-offs when it comes to operating parameters, reliability or cost. With many existing systems on the market there are concerns with reliability, the need for extra considerations like neutralizing ion plumes and the cost or craft compatibility of propellants.

The Metal Plasma Thruster (MPT) is a new class 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 metal mass into high velocity (~17km/s) jets of quasi-neutral plasma. The MPT technology does not require gas or liquid propellants, neutralizers, heaters, high voltage electronics, high electric or magnetic fields to operate. Furthermore, the design itself needs no special manufacturing or high precision components, making it more easily scaled for higher production volumes.

The concept of an MPT has been a subject of research for more than two decades[1][2]. More recently, using NASA SBIR funding starting in 2018, the proof-of-concept TRL-4 thruster has rapidly evolved to a TRL-7, flight-ready system through a combination of low-cost prototyping and test-to-fail, iterative, in-vacuum testing.

To maintain a rapid pace at minimum development cost, the design approach has been both additive and iterative, with significant test gates after each iteration to tease out and address failure modes. Starting with the SBIR Phase I in 2018 with the most basic version of the thruster heads themselves being driven directly by external benchtop supplies and verifying the thrust on a NASA/GRC thrust stand[3], the next iteration involved making the system self-contained, creating onboard controls, telemetry and a basic PPU. The SBIR Phase II led to the design of a 1.5U package with more emphasis on qualifying for flight and operating in orbit. The PhI / PhII projects [80NSSC18P2214 / *80NSSC19C0223*] were followed by a Phase II Sequential [*80NSSC21C0615*], whose focus has been on design for a larger market, changing the PPU architecture to operate in higher radiation environments, while reducing dependency on a more volatile EE supply chain and redesigning around a 1U form factor while tailoring for mass production.

1. NASA SBIR PHASE I - PROOF OF CONCEPT

While the physics behind the MPT has been studied for more than two decades, beginning in 2018 the push to productize the technology was made with a NASA SBIR Phase I grant aimed at exploring a proof of concept (POC) thruster module that could feasibly fit onto a space craft.

The overall approach to this design task was to focus on low cost, rapid iteration supported by an existing vacuum chamber setup (at the time residing in a personal garage) which allowed for quick test-to-fail campaigns.

1.1. Metal Plasma Thruster (MPT) Technology

The basics of the Metal Plasma Thruster (MPT) revolves around imparting momentum to a spacecraft by ejecting high energy jets of quasi-neutral metal plasma. This is done through pulsed discharges of stored electrical energy as a cathodic arc, essentially ablating the surface a of a metal fuel, in this case Molybdenum. See Fig. 1 for a simplified diagram of operation.

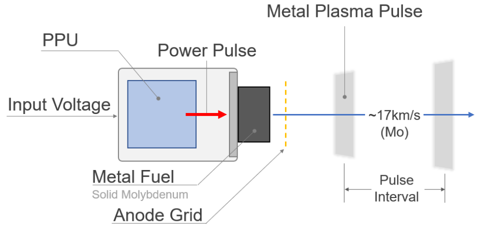

Figure 1. Simplified MPT Diagram

There are a number of benefits to this technology, including the inertness of the fuel (safe, unable to leak), the simplicity of the technology (no heaters, neutralizers or high voltage electronics) and the pulsed operation, allowing for incredibly precise maneuvering or pointing.

1.2. MPT Version 1.0

For a first prototype, version 1.0, the quickest path was determined to be designing a rather simple power and control electronics stack attached to a legacy head design which was arrayed into four separate thrusters. This was done based on the CubeSat standard dimension of 10cm as that would open a thruster module to the broadest potential applications.

A render of this first design can be seen in Fig. 2 which highlights the standard sizing of 10cm per side and a total depth of around 6cm.

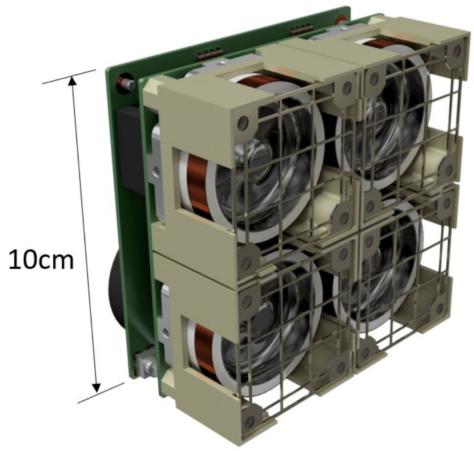

Figure 2. MPT1.0 Render

Initial testing in vacuum (see Fig. 3) revealed the design's limitations. While the ability to charge and create arcs was proven successful in such a small form factor, the unit was plagued by onboard electronics issues such as controller resets and component failures.

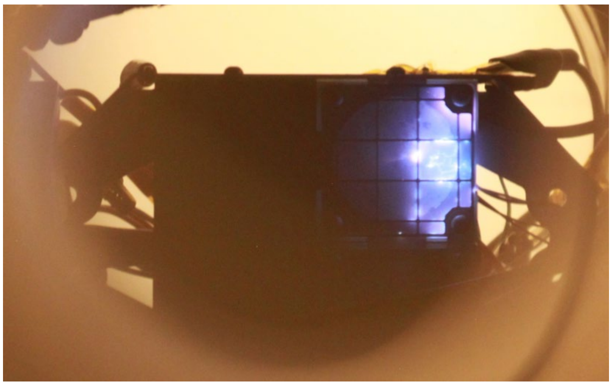

Figure 3. MPT1.0 Firing in Vacuum

Data gathered during in-vacuum operation supported the root cause of these electrical issues were likely due to internally generated EMI as a result of the very high dI/dt during the main cathodic arc event.

1.3. MPT Version 2.0

The electrical noise issues proved challenging to address through the more standard approaches (isolation, noise suppression, filtering, current return paths, etc.). It was deemed prudent to separate the MPT into two distinct parts to help keep the development process moving at pace. The first half consisted of the fully contained electronics package, called the Power Processing Unit (PPU) and the second half consisted of the head assembly, which contained the Molybdenum fuel pucks and supporting circuitry.

While the PPU was at mid redesign, a test bed for the heads was created, MPT V2.0 (see Fig. 4). In alignment with the previous unit, this design also took advantage of low cost, rapid iteration such as a simple sheet metal body and rapid turn PCBAs.

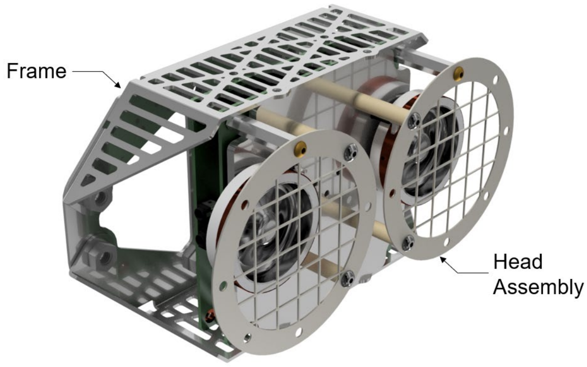

Figure 4. MPT2.0 Render

Along with being used to form initial understanding of how the puck erosion evolves during longer duration testing, this unit was also taken to NASA Glenn Research Center (GRC) to gather direct impulse measurements on the thrust stand in the VF-3 facility.

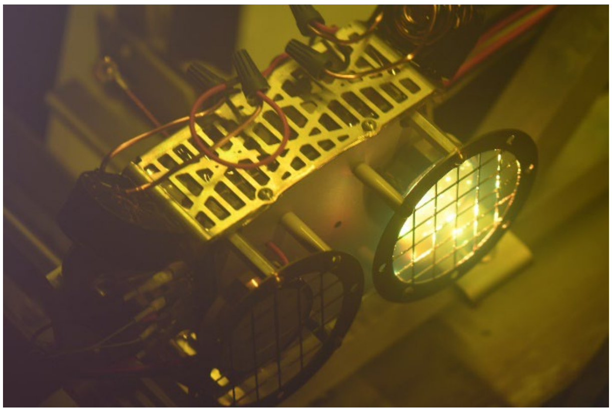

Figure 5. MPT2.0 Firing in VF-3 at NASA GRC

This platform also allowed for further characterization of the electrical noise challenges and ultimately helped support development of the first electrical architecture change that seemed to address it.

1.4. MPT Version 3.0

Armed with measured data validating the impulse and an approach to compartmentalize the electrical noise enabling onboard embedded control, the next step was to create the 3rd design iteration shown in Fig. 6.

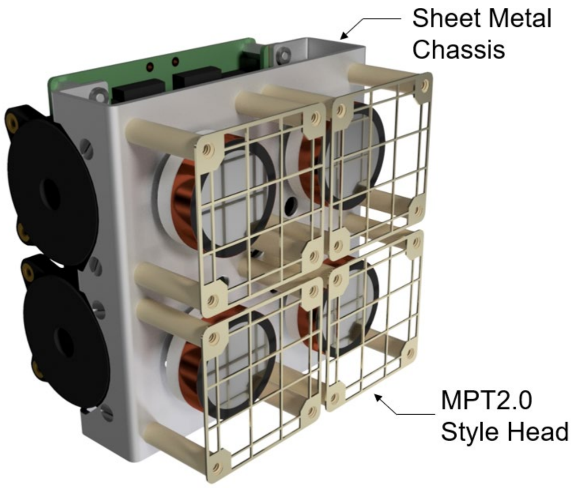

Figure 6. MPT3.0 Render

This design incorporated many of the functional aspects of the previous two iterations, such as the head architecture and sheet metal chassis but began to test out improvements such as adding in UART based interface, temperature telemetry and simplifying the power electronics.

By this point, approximately one year into the project, a number of milestones had been reached; successfully gathering actual impulse data from NASA GRC, demonstrating the technology could be packaged into a fully contained module and laying the groundwork for command and control using a single interface. The NASA Phase I grant had more than met its milestones and proof-of-concept had been demonstrated.

2. NASA SBIR PHASE II – DESIGN FOR FLIGHT

Where the NASA SBIR Phase I work centered around proving that the technology could feasibly work as a thruster module, the NASA SBIR Phase II aimed to prove the technology could become a design qualified to actually fly and operate in space.

2.1. MPT Version 4.1

Work on the next version of the MPT kicked off late in 2019. This version was derived on an interim version 4.0 (not shown) to expand to offer six total thrusters (15cm in length) in order to meet a desired total impulse of around 5.4kNs for the full unit (see Fig. 7).

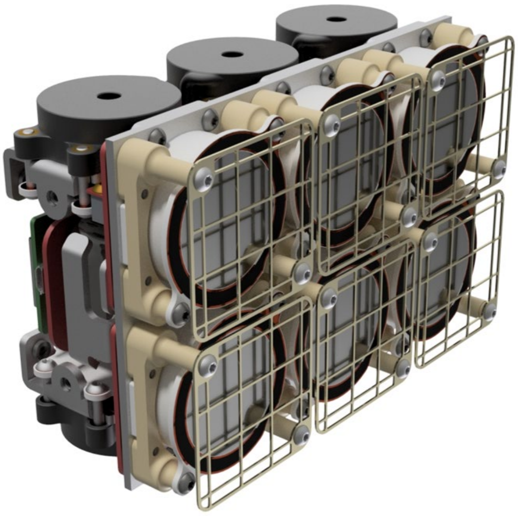

Figure 7. MPT4.1 Render

Designing for flight was a key part of this version and caused some significant departures from the previous three versions.

Ensuring the design could survive launch vibration drove a series of mechanical architecture changes such as replacing ceramics used as both electrical isolation and structural elements with more elastic materials, completely overhauling the chassis structure and redesigning many solder joints into bolted connections, to name a few.

The MPT, similar to other electric propulsion systems, creates a significant amount of heat while operating which has to be conducted out of the unit. To aid in this process multiple heat-sinking design elements were added which help to move any heat generated directly to the mounting interface for better heat rejection.

Testing of this unit in the vacuum chamber proved informative, with a number of potential failure modes being identified, including an unfortunate return of the controller resets which, while happening more sporadically, would still appear during longer arcing events.

2.2. MPT Version 4.2

Again, by leveraging more modern tools for rapid prototyping, two quick follow-on design iterations to the main circuit boards were built, tested and repeated, dubbed MPT4.1’ and MPT4.1’’, finally culminating in a new version closely related to the previous, MPT4.2, shown in Fig. 8.

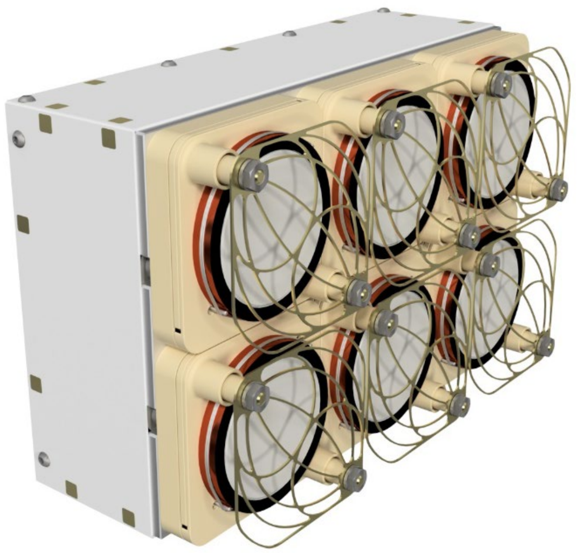

Figure 8. MPT4.2 Render

Along with further refining the controller circuitry to be immune to the firing noise, including a new full EMI shield enclosing the PPU, the unit was also constructed around the ability to measure its own shot-to-shot performance to be used for relaying telemetry during operation and laying the groundwork for future closed-loop control.

Now armed with a functional, fully integrated model with six individually addressable thrusters, the next step was to put the unit through its paces. An example of what the cathodic arcs look like during operation in vacuum can be seen in Fig. 9 where all six heads are being fired in successive pulses, captured on a single long exposure photo.

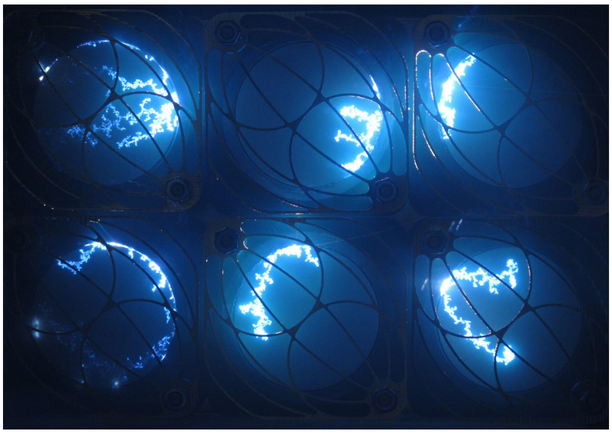

Figure 9. Exposure Photo of MPT4.2 in Operation

Following a successful demonstration in vacuum this prototype was then put through a first vibe test per NASA GEVs, shown in Fig. 10, in order to tease out any weaknesses in the design to be addressed for the next version.

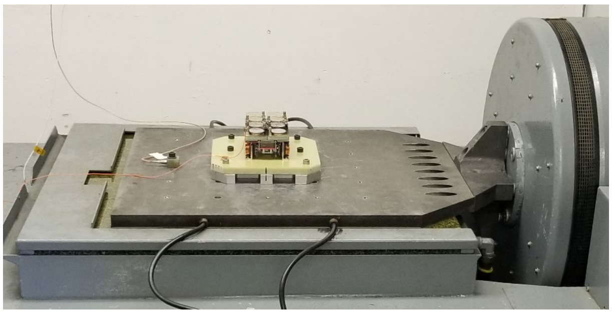

Figure 10. MPT4.2 on Vibe Table

The design proved largely robust aside for a few minor internal failed electrical joints that were subsequently addressed.

2.3. MPT Version 4.3 – Delivery for Flight

Compared to the level of redesign happening during the NASA SBIR Phase I versions, at this point the iterations were much smaller tweaks made with the goal of achieving a first functional and flight capable design.

And this drive was well motivated, in parallel with the above developments, as of August 2020 the MPT was selected by OSS/USSF to be integrated into the Orion Space 12U EWS/RROCI mission for a proposed 2022 launch, helping drive refinements for this next version, MPT4.3.

This revision included fixes based on learnings from the previous vibe tests with MPT4.2, a refinement of the output telemetry to better interface with a spacecraft's systems including a standard JSON format, onboard monitoring of performance data and automatic shutoffs etc.

Three units of this design were constructed, the first destined for a long life-test campaign to gather the first proof of design robustness (or identify the weakness thereof), accumulating over 12M total shots over the course of more than 3 months of continuous firing in vacuum, worth noting at this point in the vacuum chamber still located in a personal garage. A photograph of this unit's eroded Molybdenum puck can be seen in Fig. 11.

Figure 11. MPT4.3-001 Puck Post Campaign

The second unit, MPT4.3-002, considered the "qual" unit, was subjected to vibe and then put into the chamber for functional testing to validate the fixes to the issues found in the previous test. The unit showed full functionality both prior to and post vibe, see Fig. 12 for a photo of this unit on the vibe table.

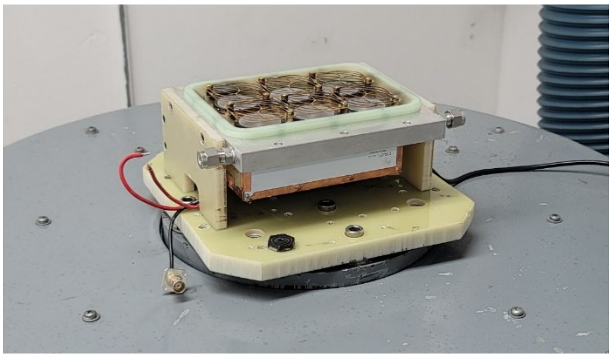

Figure 12. MPT4.3-002 on Vibe Table

The third unit, MPT4.3-003 was then delivered for integration into the EWS/RROCI spacecraft in April of 2021, three years from the start of the MPT development.

3. NASA SBIR PHASE II SEQUENTIAL – DESIGN FOR PRODUCTION

Whereas the NASA SBIR Phase II work centered around qualifying the technology and creating an initial design capable of operating in space, it would be fair to call the final prototypes "one-off", with minimal optimization for production or test and largely hand-built in parallel while figuring out the build process itself.

The NASA SBIR Phase II Sequential grant through the Artemis program was aimed at further refining this design, targeting the ability to mass-produce thrusters with repeatable quality and reliability as well as increasing the capability of the thruster.

3.1. MPT Version 5.0

The first pass at this process involved a number of improvements in parallel. Probably the most noticeable is the complete redesign of the pucks themselves, moving from the circular shape that had been the basis for each previous prototype to the proposed rectangular shape. Erosion depth of the metal propellant is the default limiter to the life of the unit, increasing the total area of the fuel metal also increases the total impulse available for the unit.

Fig. 13 shows a comparison of the two designs, with the total impulse available for each head being proportional to their exposed area, in this case switching to rectangular pucks would increase the total impulse by 47% (892mm² vs. 1,314mm²).

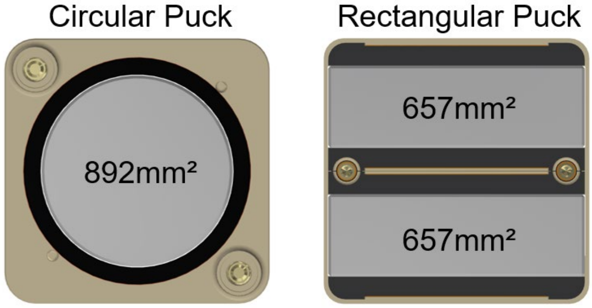

Figure 13. Puck Area Comparison, Circle vs. Rectangle

Total impulse wasn't the only improvement made in going this direction, baked into this design change were several improvements to the head assembly which removed any need for hand soldering or special assembly procedures. Turning every aspect into a part that could be purchased directly from standard suppliers and getting closer to turnkey.

To help speed up the development process this next prototype followed the previous method of splitting the thruster into two distinct parts for faster testing and results. The new head architecture change was constructed and adapted to be used with the already proven MPT4.3 PPU as a testing platform, allowing for a quick return to in-vacuum testing. Fig. 14 shows a render of this assembled testing platform, dubbed MPT4.3s as it's based on the 4.3 PPU but includes a test of the "square" heads.

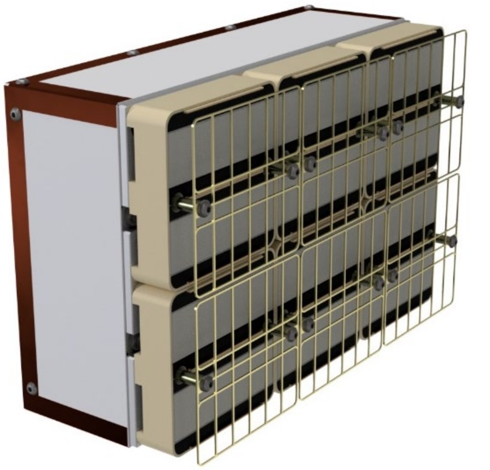

Figure 14. MPT4.3s Render

However, this six head design was not the goal of this design improvement towards production. While that form factor was ideal for the first launch through the Phase II grant, the best fit for potential market adoption would be through a return to the 1U form factor design. This was further enabled by this change to a rectangular puck architecture, where previously MPT version 4.3 was able to carry 5.4kNs of fuel using six heads, the new design would be able to carry 5kNs in only a four head design.

Therefore, in parallel with the architecture change of the heads, a similar redesign of the PPU architecture was initiated. This included among other things, designing for survival in the cis lunar and lunar orbit environments (per the Artemis requirements), designing for manufacturing and production assembly.

Since design for scale was the goal, simply going with all rad-hard components for the PPU was not an option as it would quickly become prohibitively expensive. The design approach taken was a blend of first attempting to change circuit architectures to be less susceptible to radiation by design, adding redundancy and recovery where possible, using COTS components with radiation survival data if available and finally, finding true rad-tolerant components where they were critical. Included in this design revision was a pass at removing any single-source electronic components given the more recent volatility in the global supply chain.

The first full prototype was ready for test in 2022, now compacted to a 98mm x98mm x 60mm form factor with only ~0.6U of volume, complete with a rad-tolerant and fully voltage isolated PPU, onboard control, adaptable to a wide range of spacecraft bus input voltages. See Fig. 15 for a CAD render.

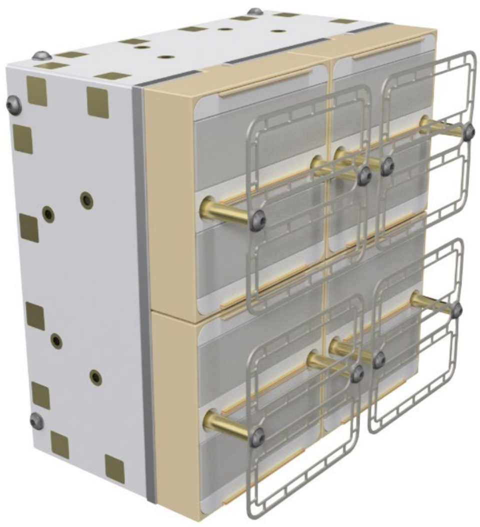

Figure 15. MPT5.0 Render

4. BENCHMARK ACQUISITION – BUILD AT SCALE

Starting in late 2022, Benchmark Space Systems acquired rights to the MPT thruster and offered to assist with marketing and sales to a larger market that was already being addressed by Benchmark's Chemical thrusters. AASC agreed to partner with Benchmark Space Systems to help leverage further development resources, production capability and construction of a team capable of delivering on a reliable electric propulsion system.

With the growth of the team working on the MPT and the new capability to scale production there was a push towards a final design ready for delivery.

This current stage involves a major scale-up in capability to build, test and qualify the MPT design, now called Xantus (see Fig. 16). Including a PPU overhaul, a total of over 10,000 hrs of in-vacuum unit testing, further measurements of both thrust and impulse at NASA GRC, vibe and TVAC qual just to name a few.

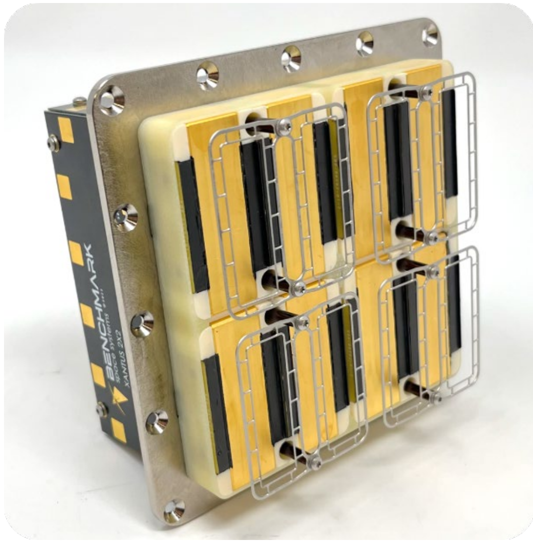

Figure 16. Xantus X4 Metal Plasma Thruster

The unit parameters for the Xantus X4 can be seen in Tab. 1, highlighting the compact, simple operation and versatile input power range.

Table 1. Xantus X4 Unit Parameters

Parameter	Value
Wet Mass	1.2kg
Volume	94mm x 94mm x 60mm
Thrust/Power	10μN/W
Total Impulse	5kNs
Turn-On Delay	Instant Cold Start
Power Rating	1W to 100W
Interface	UART over RS-422

Benchmark has also been critical in helping drive a number of improvements aimed at increasing customer experience such as off-the-shelf software and load-sim style development units available to help with MPT onboarding, revising the communication protocol allow for arraying units and standardizing to a short list of mechanical interfaces, leading to a current backlog of dozens of Xantus units ready for delivery in 2024 alone.

CONCLUSION:

Supported by NASA SBIR grants, and with the aim of rapidly achieving a mature design ready for commercialization, design development and flight qualification were driven in parallel through the NASA SBIR Phase I, Phase II and Phase II

Sequential programs. Our process of rapid iteration coupled with an aggressive test-to-fail approach to development was able to take the technology from initial proof-of-concept to a first flight unit delivery and launch into LEO (OSS/USSF EWS RROCI mission) in only 3 years.

The first launch of the MPT on an Orion Space RROCI mission for the USSF was in January 2023. The MPT technically made it to orbit but was not separated from the upper stage due to a deployer malfunction. The satellite burned up on upper stage re-entry. A second launch took place in March 2024, with successful separation and orbit insertion. At last, we may claim that the MPT has gone from garage to orbit.

Since then, the technology has continued to mature at Benchmark Space Systems and drive towards scalability, with an emphasis on reliability, including direct impulse and thrust measurements of multiple metal propellants at NASA GRC (AIAA/JPP published) and over 10,000hrs of in-vacuum operation.

5. REFERENCES

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