34th Space Symposium, Technical Track, Colorado Springs, Colorado, USA
Presented on April 16, 2018

Updated Performance Measurements of the Phase Four RF Thruster

M Umair Siddiqui, PhD
Chief Scientist, Phase Four, umair@phasefour.io

ABSTRACT

We present the latest performance measurements of The Phase Four RF Thruster (RFT) from testing performed at The Aerospace Corporation. The RFT is a scalable thruster for Cube Satellites to large 500+ kg satellites, which uses RF power to heat xenon plasma propellant, and accelerate it in a radially diverging magnetic plume. The resultant thrust and specific impulse performance is related in context of electric propulsion development efforts for upcoming large volume satellite constellations. Measurements demonstrate that The RFT is making significant progress toward higher values of specific impulse and thrust necessary to service such spacecraft.

INTRODUCTION

Several thousands of satellites are projected to be launched and deployed into large constellations over the next 5 to 10 years [1] [2] [3]. Such constellations are imparting new challenges and opportunities on the supporting technologies and supply chains as they will be required to deliver spaceflight-quality systems and services at orders of magnitude higher volume and lower cost than ever previously achieved [4]. Key among these technologies are electric propulsion engines that will propel the satellites into their orbital locations and maintain their position and pointing requirements.

No engine has publicly demonstrated an ability to meet the performance and the production needs for the upcoming constellations. In this paper we present the Phase Four Radio Frequency Thruster (RFT), an electric propulsion engine designed with performance, volume manufacturability and scalability from the outset. Measurements were previously disclosed that demonstrated that the proof-of-concept “RFT-0” generated a 5x improvement in specific impulse per Watt than every other RF thruster ever directly tested on a thrust stand, at less than 10% the mass and volume of the other systems [5]. Here we present direct thrust performance measurements from the next generation “RFT-2”. The measurements represent the highest performing electrode-free RF engine data ever directly measured, and a performance scaling that extrapolates to meet the needs of the upcoming major constellations.

In the next section we describe The RFT in context of the existing state of the art small satellite electric propulsion engines. Subsequently, we describe the test campaign at Phase Four and The Aerospace Corporation and analyze the results. Finally, we describe the upcoming developments and tests, as they pertain to the needs of upcoming satellite constellations.

THE PHASE FOUR RADIO FREQUENCY THRUSTER

The Phase Four RFT is an electrodeless RF propulsion engine that scales from the mass, volume and power budget of Cube Satellites up to larger satellite applications. Figure 1 shows a diagram of the core components of The RFT and Figure 2 shows an image of The RFT-2 unit firing in the Phase Four laboratory. Propellant (nominally xenon gas) is injected into a “plasma liner” at a fixed mass flow rate, which is wrapped in an RF antenna with a proprietary geometry. The liner-antenna assembly is housed inside a series of permanent magnets that generate a fixed magnetic field inside the liner and out of the liner’s exit orifice. A high frequency radio signal is applied to the antenna and the “near field” radiation under the antenna inside the liner ignites the gas into a plasma, and subsequently heats the plasma propellant. The hot xenon plasma then expands rapidly in all directions inside the liner. Similar to how a chemical rocket engine nozzle directs the hot propellant, the magnetic field inside the liner and in the near-region of the liner exit is designed to direct the hot plasma out of the exit orifice, generating thrust. The physical processes of this RF plasma thermal expansion are detailed elsewhere [5] [6].

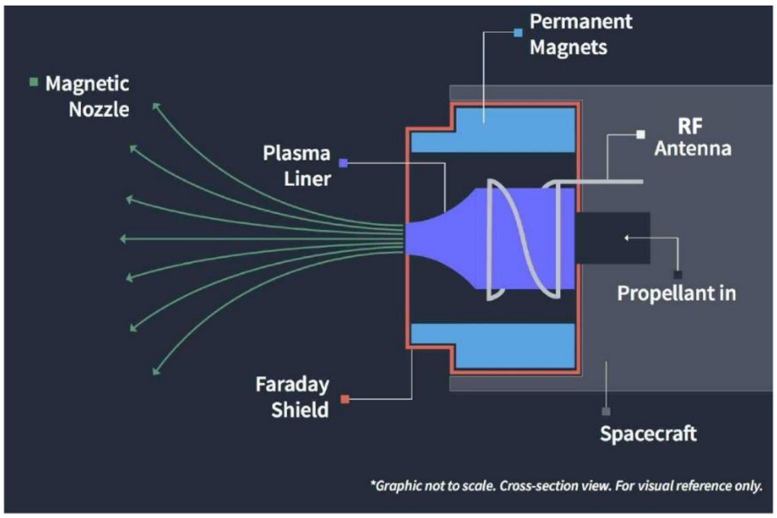

Figure 1: A diagram of the Phase Four RFT and critical internal components (not to scale).

The implications of this technology are significant in the field of electric propulsion for three reasons:

1. The technology does not require an anode or cathode
2. The system does not require high voltage electronics
3. The thruster geometry and subcomponents are simply manufactured.

Most electric propulsion systems used today, such as Gridded Ion Engines (GIEs) and Hall Effect Thrusters (HETs) require an anode and cathode, across which hundreds to thousands of volts are applied to accelerate the plasma propellant [7]. This process, while effective, causes plasma particles to bombard the anode and cathode surfaces, eroding them over time. The erosion causes the thruster performance to decay and eventually induces the thruster to fail [8]

[9]. GIEs and HETs also require high voltage electronics to boost the spacecraft batteries up to 100's and 1,000's of volts, to power the anode and cathode. These systems, often referred to as Power Processing Units (PPUs), can be large, heavy, and difficult to miniaturize while maintaining high efficiency. Finally, GIE and HET geometries can be difficult to fabricate at scale, especially small thrusters that are optimal for use on upcoming small satellite mega constellations [10].

Because radio frequency thrusters in general are simple, electrodeless, and low voltage, there has been considerable interest in their development for many years [11]. To date, no radio frequency thruster has been able to demonstrate performance scaling on track or comparable to existing state of the art GIEs and HETs [12] [13] [14]. The Phase Four RFT differentiating approach is the realization that RF thrusters must be miniaturized to achieve maximal RF power density in the plasma and optimal effects of the plasma heating. Furthermore, Phase Four has put significant effort into understanding and optimizing an antenna geometry to couple power to the propellent in small plasma systems. Finally, by beginning with a small geometry engine from the outset, Phase Four leverages advances in wireless power electronics miniaturization to effectively decrease the size of the PPU and avoid high voltage electronics everywhere in the engine.

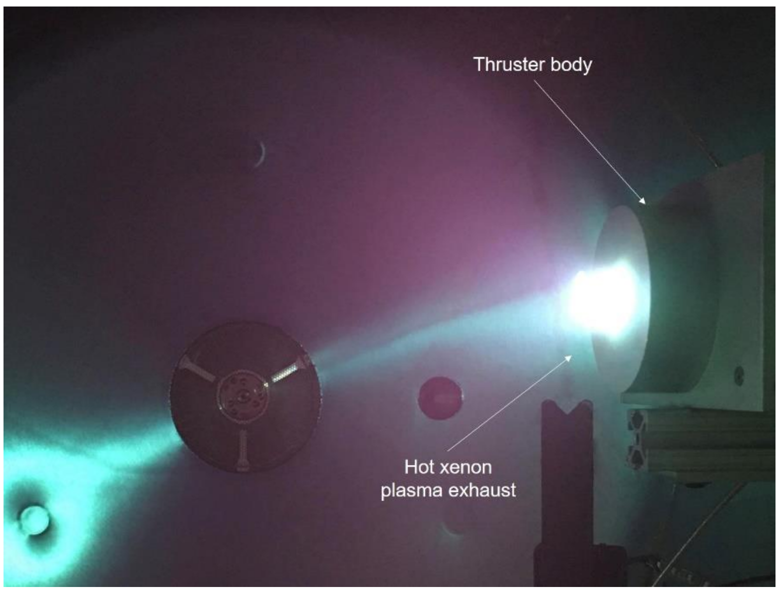

Figure 2: An image of the RFT-2 firing in the Phase Four laboratory.

TESTING RESULTS AND DISCUSSION

Testing electric propulsion systems is a careful process as the thrust forces being measured are comparable to the weight of heavy pieces of paper. Furthermore, as the engines are designed to operate in space, the tests must be performed in a laboratory vacuum facility that replicates the vacuum of space. The measurements presented here were performed at The Aerospace Corporation in a 2.4 m diameter, 3.7 m long vacuum facility pumped by a 30,000 l/s cryogenic pump. For these measurements the base pressure of the system was in the 10^{-8} Torr range. To measure the output of a low thrust engine, the thruster is balanced on a torsional pendulum thrust stand. A thrust stand is a diagnostic that displaces in position when the device under test generates a thrusting force. The displacement is correlated to a thrust force after the thrust stand is calibrated. For a given thrust measurement with a known thruster propellant flow rate, the specific impulse of the engine is calculated by

$$I_{sp} = \frac{F_t}{dm * g_0}$$

where F_t is the thrust force in Newtons, dm is the propellant flow rate in kg/sec and g_0 is the acceleration rate on the surface of the Earth (9.8 m/sec^2). The specific impulse is a measure of the efficiency of the engine with respect to propellant usage, like miles per gallon for cars. Details of the thrust measurement apparatus and procedure are provided elsewhere [5] [15].

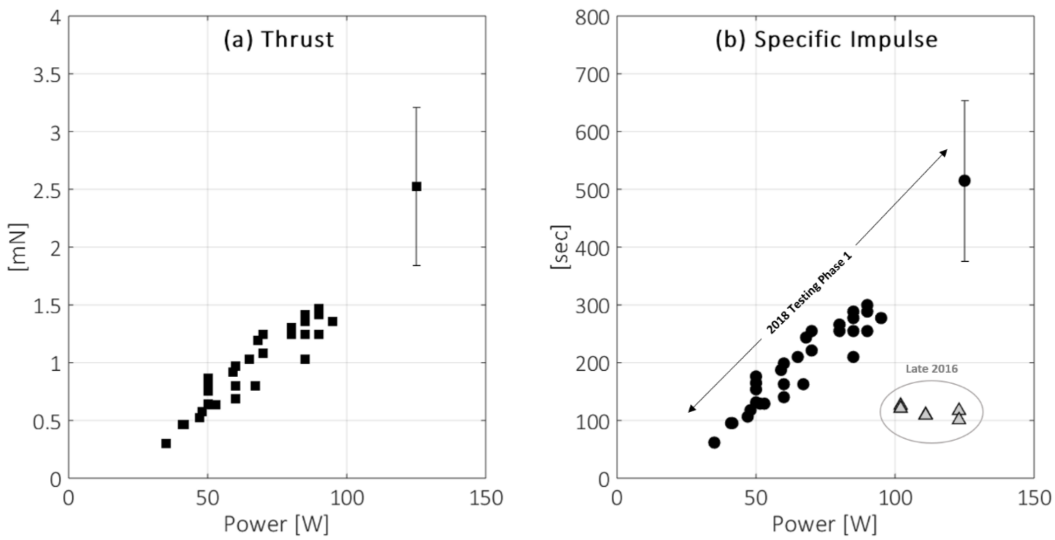

Figure 3: (a) The RFT-2 thrust measurements versus power and (b) measured specific impulse versus RF power between 40 W and 125 W at 0.5 mg/sec xenon mass flow rate. Data in gray show the previously presented results of The RFT-0 proof-of-concept system [5].

Figure 3 shows thrust and specific impulse measurements performed on The RFT-2 at The Aerospace Corporation between 40 W and 125 W of input power at 0.5 mg/sec xenon propellant flow rate. Each measurement consisted of engine hot firings between 15 seconds and 240 seconds long. The measurements constituted Phase 1 of RFT-2 performance testing. Panel (a) shows that across this range, the thrust increases approximately linearly with power. As specific impulse is directly proportional to thrust for a fixed propellant flow rate, it also increases linearly within this regime. The thrust and specific impulse measured ranged from 0.35 ± 0.005 mN to approximately 2.5 ± 0.55 mN, and 65 ± 1 seconds and 510 ± 130 seconds respectively, between 40 W and 125 W. For powers between 40 W and 100 W, the uncertainty of the measurements was smaller than the size of the plot points. The scatter in the data at any given power setting is attributed to a myriad of perturbations to the diagnostic, including thrust stand heating, power and gas line heating and pressurization, and thruster heating. For the purposes of Phase 1 testing these perturbations, while noted, were not actively controlled.

After performance measurements up to 100 W, a series of measurements at 125 W was attempted. The measurement point at 125 W is an average of 5 thrust measurements, ranging in duration between 30 seconds and 4 minutes. The average result is represented by the single data point, and the range in measured values including uncertainty is represented by the wide error bars in the top right hand corner of both panels. The cause for the jump in input power was to investigate the differences in thrust performance after the propellant gas became fully ionized. In The RFT-2, it is estimated that at 0.5 mg/sec of xenon flow, a majority of the propellant would be ionized after 100 W of input power, based off of calculations made of ionization rates in other plasma propulsion systems [16] [17] [18]. Given the fact that The RFT's plasma heating and thrust generation mechanism is novel for directly-tested thrusters, it was of significant priority to investigate the performance scaling at large power steps above 100 W. However, at such power levels the variance in the thrust stand measurement became large as the system was strongly perturbed by power and feed line heating. Also, at higher powers, an additional perturbation of water desorption from internal thruster surfaces generating false signals of thrust, contributed further uncertainty. The high power operation water desorption also prevented further higher power measurements until long duration thruster operations could be possible on the thrust stand, such that all the internal adsorbed water in the thruster could be desorbed. The thrust stand was not intended for long duration measurements of a high power system, preventing higher power measurements in Phase 1.[1]

For direct comparison, the previously presented RFT-0 results are shown as the gray triangles in the lower right corner of Figure 3(b). Those measurements constituted a 2x to 5x improvement over every RF thruster directly measured on a thrust stand in specific impulse per Watt of input power [5]. The recent RFT-2 results (black squares and circles) exhibit a 4x to 6x improvement over the RFT-0 results, demonstrating significant progress in the development of RF thrusters. Furthermore, a linear best fit of the performance results per input power suggest that the thruster specific impulse scales between 3.5 seconds per Watt to 6.5 seconds per Watt. Such scaling is typical of small Gridded Ion Engines and Hall Effect Thrusters that operate in similar power regimes [8] [9] [19]. While those existing GIEs and HETs were tested at higher propellant mass flow rates and thus generated more thrust, and those systems operated at powers greater than 200 W, the demonstration of this level of performance scaling is a first for any electrode-free radio frequency thruster.

UPCOMING RFT-2 TEST CAMPAIGN

Assuming the thrust continues to scale linearly with input power implies that The RFT should be able to achieve between 1,400 seconds and 2,600 seconds of specific impulse, at 6 mN to 10 mN of thrust at 0.5 mg/sec of xenon propellant flow and 400 W of input power. It is unclear if the performance scales linearly, accelerates with input power, or slows down with input power. Furthermore, it is unknown how the thruster responds at propellant flow settings closer to 1 mg/sec of xenon, like GIEs and HETs in the same power and size class. To answer these questions Phase 2 of RFT-2 testing consists of a series of measurements designed to

[1] As an additional note, the thruster was able to maintain and couple to primarily water plasmas as the water from internal feed lines desorbed and was ionized and heated by the RF near field. Water plasma is a significant propellant of interest for future deep-space propulsion systems.

fully eliminate internal water inside the thruster, and to measure the thrust at higher powers and longer durations on a thrust stand designed for high power testing. The RFT-2 will be tested at high powers and at higher propellant flow rates, comparable to GIEs and HETs in the same mass and power class. Furthermore, The RFT-2 will be tested for long durations (> 100 hours, with a goal of 1,000's of hours) and many on-off cycles (> 100, with a goal of > 1,000 cycles). The performance changes over time will be measured, as well as wall erosion rates, to estimate the total lifetime of the thruster. These results will be presented at upcoming meetings and conferences.

SUMMARY

The Phase Four RFT is a radio frequency thruster that is applicable from Cube Satellites to larger spacecraft. The RFT has no anode or cathode, uses no high voltage electronics, and is easily manufacturable at scale. While radio frequency thrusters have been studied in research laboratories for several decades, to date no RF thruster has demonstrated performance scaling comparable to the existing state of the art small Gridded Ion Engines and Hall Effect Thrusters. The Phase Four RFT has recently completed the first half of a performance testing campaign at The Aerospace Corporation, which focused on low power and low propellant flow rate operations. The data demonstrate a performance scaling of approximately 3.5 to 6.5 seconds per Watt, which is comparable to low power GIE and HET performance scaling. The second phase of performance testing will focus on higher power measurements, higher propellant flow rates, and at longer duration firing operations. Specifically, the second phase will determine how the thruster performance scales up to 400 W of input power at approximately 1 mg/sec of xenon propellant flow. Furthermore, the testing will investigate the performance changes over time over the course of 100's to 1,000's of hours of run time. In summary, The Phase Four RFT is the first RF thruster that has achieved meaningful performance scaling while eliminating the major electric propulsion problems of electrodes, complex electronics, and complex fabrication procedures.

REFERENCES

[1] SpaceWorks, "Nano/Microsatellite Market Forecast, 8th Edition," SpaceWorks Enterprises, Inc., 2018.

[2] C. Henry, "1,400 Satellites Projected to Launch Over Next Decade," 26 August 2015. [Online]. Available: https://www.satellitetoday.com/innovation/2015/08/26/1400-satellites-projected-to-launch-over-next-decade/. [Accessed 29 March 2018].

[3] C. Henry, "OneWeb asks FCC to authorize 1,200 more satellites," 20 March 2018. [Online]. Available: http://spacenews.com/oneweb-asks-fcc-to-authorize-1200-more-satellites/. [Accessed 29 March 2018].

[4] P. d. Selding, "OneWeb's Powerful Partners in Their Own Words," 26 June 2015. [Online]. Available: http://spacenews.com/onewebs-partners-in-their-own-words/. [Accessed 29 March 2018].

[5] M. U. Siddiqui, C. Cretel, J. Synowiec, A. Hsu, J. Young and R. Spektor, "First Performance Measurements of the Phase Four RF Thruster," in *International Electric Propulsion Conference*, Atlanta, 2017.

[6] X. Zhang, E. Aguirre, D. Thompson, J. McKee, M. Henriquez and E. Scime, "Pressure dependence of an ion beam accelerating structure in an expanding helicon plasma," *Physics of Plasmas,* vol. 25, p. 023503, 2018.

[7] D. Goebel and I. Katz, Fundamentals of Electric Propulsion, Hoboken: Wiley, 2008.

[8] W. Tighe, K.-R. Chien and R. Spears, "XIPS Ion Thrusters for Small Satellite Applications," in *21st Annual AIAA/USU Conference on Small Satellites*, 2007.

[9] R. Conversano, D. Goebel, R. Hofer and I. Mikellides, "Performance Analysis of a Low-Power Magnetically Shielded," *Journal of Propulsion and Power,* vol. 33, no. 4, p. 975, 2017.

[10] V. Khayms and M. Martinez-Sanchez, "Design of a miniaturized Hall thruster for microsatellites," in *Joint Propulsion Conference*, Buena Vista, FL, 1996.

[11] R. Jahn, Physics of Electric Propulsion, Minneola, New York: Dover, 1968.

[12] K. Takahashi, T. Lafleur, C. Charles, P. Alexander, R. Boswell, M. Perren, R. Laine, S. Pottinger, V. Lappas, T. Harle and D. Lamprou, "Direct thrust measurement of a permanent magnet helicon," *Applied Physics Letters,* vol. 98, p. 141503, 2011.

[13] A. Shabshelowitz and A. Gallimore, "Performance and Probe Measurements of a Radio-Frequency Plasma Thruster," *Journal of Propulsion and Power,* vol. 29, no. 4, p. 919, 2013.

[14] L. Williams and M. Walker, "Thrust Measurements of a Radio Frequency Plasma Source," *Journal of Propulsion and Power,* vol. 29, no. 3, p. 520, 2013.

[15] A. Hsu, E. Beiting and T. Curtiss, "Performance of a Torsional Thrust Stand with 1 uN Sensitivity," in *Joint Conference of the 30th International Symposium on Space Technology and Science and 34th International Electric Propulsion Conference and 6th Nano-satellite Symposium*, 2015.

[16] K. Hara, M. Sekerak, I. Boyd and A. Gallimore, "Perturbation analysis of ionization oscillations in Hall effect thrusters," *Physics of Plasmas,* vol. 21, p. 122103, 2014.

[17] E. Bering, M. Brukardt, J. Squire, T. Glover, V. Jacobson and G. McCaskill, "Recent Improvements In Ionization Costs And Ion Cyclotron Heating Efficiency in The VASIMR Engine," in *44th AIAA Aerospace Sciences Meeting and Exhibit*, Reno, NV, 2006.

[18] J. Sheehan, T. Collard, B. Longmier and I. Goglio, "New Low-Power Plasma Thruster for Nanosatellites," in *Propulsion and Energy Forum*, Cleveland, OH, 2014.

[19] J. Frieman, T. Liu, M. Walker, J. Makela, A. Mathers and P. Peterson, "Performance Evaluation of the T-40 Low-Power Hall Current Thruster," in *AIAA Propulsion and Energy Forum*, Salt Lake City, UT, 2016.

