Miniature Ion Thrusters: A Review of Modern Technologies and Mission Capabilities

IEPC-2015-275／ISTS-2015-b-275

Presented at Joint Conference of 30th International Symposium on Space Technology and Science 34th International Electric Propulsion Conference and 6th Nano-satellite Symposium, Hyogo-Kobe, Japan July 4 – 10, 2015

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Abstract: There are inherent challenges to ion thruster miniaturization, but many current thrusters exhibit desirable performance. Depending on mission requirements, modern ion thrusters provide thruster capabilities that are attractive for missions for both large and small spacecraft. In addition to providing (1) high specific impulse, I_{sp}, (~1000 – 3000 s), these thrusters can provide (2) very precise thrust and impulse bits, (3) low disturbance thrust, and (4) low contamination and spacecraft interaction potential. These capabilities are attractive for high ΔV exploration and orbit/inclination change missions, precision orbit maintenance, formation flying, or precision pointing/control. Many thruster options exist that employ RF, microwave, and DC ring cusp discharges. These thrusters use low contamination propellants such as xenon, but may also use highly-storable propellants such as iodine.

Nomenclature

α	=	thrust correction factor
ε_B	=	energy required to make a beam ion
η_E	=	electrical efficiency
η_m	=	mass utilization efficiency
η_{ud}	=	discharge utilization efficiency
F_T	=	beam divergence correction factor
J_B	=	beam current
m_i	=	ion mass
$\dot{m}_b$	=	beam mass flow rate
$\dot{m}_d$	=	discharge mass flow rate
$\dot{m}_n$	=	neutralizer mass flow rate
$\dot{m}_p$	=	propellant mass flow rate
P_A	=	ancillary power
P_B	=	beam power
P_D	=	discharge power
P_{in}	=	input power
P_N	=	neutralizer power
V_B	=	beam voltage

I. Introduction

MINIATURE or "micro" ion thrusters, diameter ≤ ~3 cm, offer an important and unique capability for mission and spacecraft designers since they are capable of delivering desirable thrust levels (up to ~1-2 mN), thrust control, propellant efficiency (Isp ~1000 – 3000 s), and mission ΔV. Recent and continued improvements in miniature spacecraft technologies and approaches have increased the capabilities and science return that can be delivered by microsatellites. Most notably, improved solar power collection and processing can provide the power necessary to achieve challenging and desirable mission objectives for both Earth and near-Earth missions.[1] Miniature ion thrusters are also desirable for the primary or secondary propulsion for distributed formations of small and larger spacecraft.[2,3,4]

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The objective of this paper is to review modern ion thruster technology and mission capabilities. The paper begins with a brief description of ion thruster operation and important considerations at the miniature scale. This is followed by a review of early development efforts towards miniature ion thrusters that use modern propellants, and then a discussion of the status, and path forward, for these technologies. Finally, the paper concludes with a discussion of the mission types that are enabled by this unique electric propulsion technology, which is complemented by a brief comparison to other EP micropropulsion options for certain missions.

II. Miniature Ion Thruster Performance

To understand the unique challenges, and advantages, of ion thrusters at the miniature scale, we first describe ion thruster operation and performance metrics. We then discuss ion thruster discharge and neutralization options.

A. Ion Thruster Operation

Ion thruster operation can be thought of as three processes. Following Figure 1, a plasma is first created in a discharge chamber (here shown as a dc ring cusp), the ions are accelerated through two (possibly three) ion optics grids, and then a neutralizer emits electrons to provide system charge neutralization.

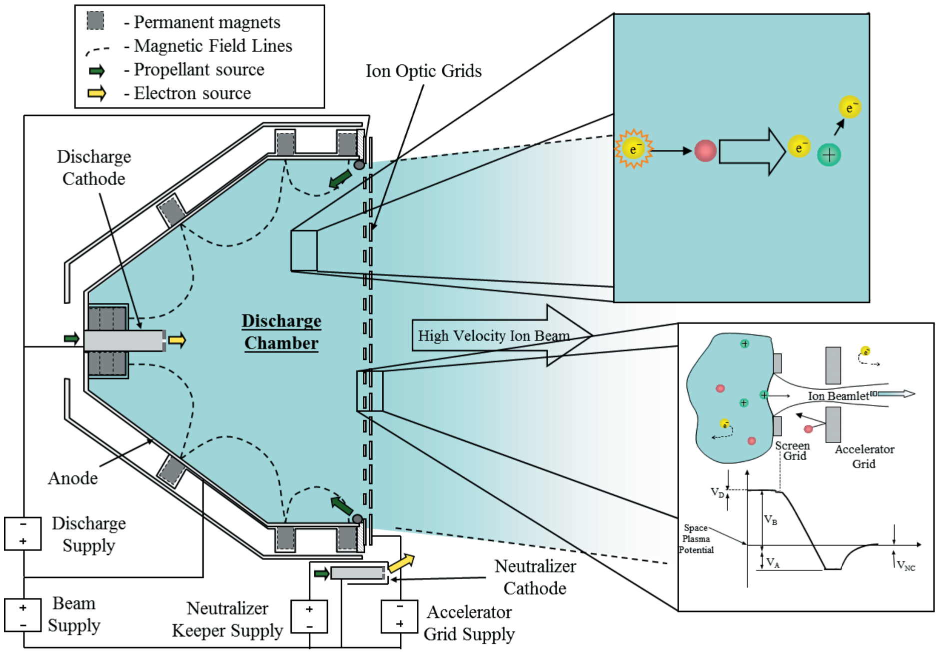


Figure 1. Ion thruster schematic and processes

The total efficiency of an ion thruster can be expressed as the product of the electrical efficiency, η_E, and the mass utilization efficiency, η_m, and the square of the product of losses due to beam divergence and multiplied charged ions.[5]

$$\eta_t = \eta_E \eta_m (\alpha F_T)^2$$

These loss terms are small in miniature ion thrusters,[6] such that the total efficiency can be thought of as nearly the product of the electrical and discharge utilization efficiencies.

$$\eta_E = \frac{P_B}{P_{in}} = \frac{V_B J_B}{V_B J_B + P_N + P_A + P_D} = \frac{1}{1 + l_N + l_A + \varepsilon_B / V_B}$$

For ion thrusters, the electrical efficiency is typically dominated by discharge losses, $\varepsilon_B = P_D / J_B$, (thought of as the amount of discharge power needed to create a beam ions in units [W/A] or equivalently [eV/ion]) such that the quality of the ion thruster discharge is a strong indicator of overall efficiency of the design. At the miniature scale, regardless of discharge type, these losses are considerable compared to larger thrusters. For DC discharges, the power dedicated to the discharge must take into account if any additional power is needed to operate the cathode; while RF and microwave discharge must account for DC-RF losses and reflected power.

Another consideration that is of increasing importance at miniature scales is the normalized losses associated with the neutralizer power, $l_N \equiv P_N/P_B$, and ancillary power requirements, $l_A \equiv P_A/P_B$, such as propellant heating, etc. In particular, neutralizer technologies have not yet been optimized at the miniature scale and associated losses can become significant without careful design considerations. Some discussion and approaches to this issue are discussed later.

The mass utilization efficiency, η_m, is a measure of the propellant flow that is used as beam ions. For miniature ion thrusters, where the beam is predominantly single ions, this can be approximated by

$$\eta_m = \frac{\dot{m}_b}{\dot{m}_p} \approx \frac{J_B}{\dot{m}_p(e/m_i)}$$

Since the mass flow rate of propellant is the sum of the discharge and neutralizer flow, i.e. $\dot{m}_p = \dot{m}_d + \dot{m}_n$, it is important to minimize or eliminate the neutralizer. Another metric to measure the discharge performance is via the discharge utilization efficiency, η_{ud}. Again, assuming only singly charged beam ions, the discharge utilization can be approximated by

$$\eta_{ud} = \frac{\dot{m}_b}{\dot{m}_d} \approx \frac{J_B}{\dot{m}_d(e/m_i)}$$

This efficiency can be interpreted as a measure of the discharge to utilize the discharge propellant as beam ions, and can also be considered as a measure of the grids ability to contain the unionized neutrals, while allowing the ions to pass. On the latter perspective, and as will be discussed later, one can find that the relatively smaller area of grids to allow for more aggressive grid designs that better serve this function.

Using η_{ud} and ε_B, the discharge efficiency of ion thrusters is commonly plotted along discharge performance curves as shown schematically in Figure 2, where the most desirable performance is typically found at the knee of the curve. The superior performance of large ion thrusters are commonly found on curves that knee closer to the bottom right of the curve, while miniature ion thrusters usually exhibit performance at higher discharge losses overall. For a given discharge, the losses will increase as the propellant efficiency increases since comparatively more of the discharge power is lost to inelastic collisions with ions, than in the generation of ions from the neutral background.

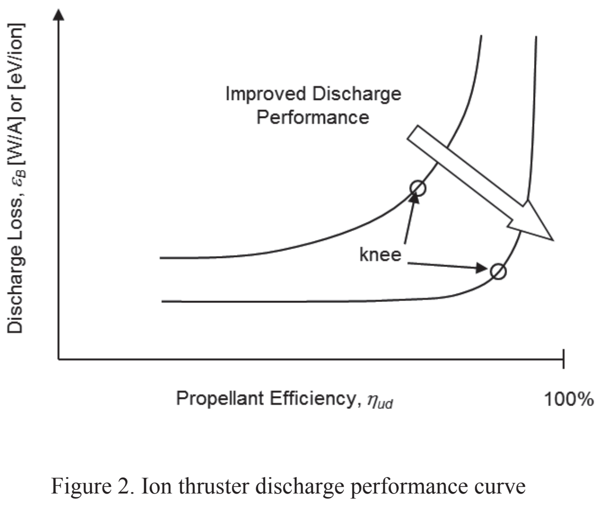


Figure 2. Ion thruster discharge performance curve

B. Discharge Types

Historically successful ion thruster discharges can generally be differentiated between those generated by direct current (DC) electron bombardment (i.e., Kaufman and ring cusp) and those generated by electromagnetic fields, i.e., radio frequency (RF) or microwave. DC discharge typically employ a hollow cathode to create a DC-electron discharge. For conventionally sized ion thrusters, the most efficient discharges and thrusters have typically been achieved using the ring cusp approach, due primarily to lower discharge losses, ε_B; though, several successful thrusters and missions have been achieved with Kaufman, RF, and microwave which can exhibit other important advantages. For example, electromagnetic discharges, such as RF, can be designed such that the antenna is not in contact with plasma, which can avoid potential issues with discharge cathode life. Many of the ion thrusters indicated as using "microwave" discharge can be described as electron cyclotron resonance (ECR) discharges since a permanent magnet is usually used to more efficiently couple to microwave power to the plasma; this paper will use the term microwave to be in keeping with the ion thruster literature.

III. Modern Miniature Ion Thrusters

This section overviews the development and status of "modern" miniature ion thrusters (i.e., ion thruster that use modern propellants). First, early thrusters that used cesium and mercury are described, followed by the development of modern ion thrusters decades later. The modern ion thrusters are differentiated by their discharge type, namely: DC ring cusp, microwave, and RF. Some discussion is then given to ongoing efforts to improve ion thruster performance.

A. Early Miniature to Small Ion Thrusters

The earliest laboratory tests of miniature ion thrusters were reported in 1967 using cesium propellant at only 1.2 cm and 3 cm scales, as part of a multi-scale development effort using Kaufman-type discharges by Sohl, et al.[7] At larger scales, ion thrusters of 5 cm and 4 cm were tested using mercury propellant around the same time. For example, 5 cm mercury ion thrusters with Kaufman discharge were tested from about 1966 through 1973 by several researchers and institutions.[8,9,10,11] Testing results of a 4 cm RF mercury thruster were reported in 1972 by Trojan, et al.,[12] thus demonstrating the first use of and electromagnetic discharge at smaller scales. These ion thruster miniaturization developments were not pursued for the following decades in favor of larger thrusters with more desirable performance.

B. Modern Miniature Ion Thrusters

Since cesium and mercury propellants were eventually abandoned by the ion thruster community, there was a need to develop a miniature ion thruster that could exhibit desirable performance on "modern" noble gas propellants, and meet the needs of electric propulsion mission possibilities in the mN to sub-mN range. This was considered a challenging task due to the inherent discharge inefficiencies at the miniature scale and inherently lower ionization potential for noble gas options in comparison to cesium and mercury. Development of miniature noble gas ion thrusters has been primarily conducted in the United States, Germany, and Japan.

The first successful noble gas miniature ion thruster was reported by Wirz, et al. starting in 2001 using a permanent magnet DC discharge.[13,14,15,2,6,16] This thruster, which came to be known as the Miniature Xenon Ion (MiXI) thruster, uses a ring cusp DC discharge and advanced ion optics to achieve desirable total efficiency, up to 56%, very high propellant efficiency, up to 82%, and thrust levels over 1.5 mN. As shown in Figure 3, more recent efforts using miniaturized hollow cathodes showed that a self-heated cathode discharge could be achieved with similar performance[17]. The MiXI thruster was run in pulsed width modulated (PWM) mode and was able to consistently achieve an impulse bit of only 1 μN•s.[18]

Figure 3. MiXI Thruster, miniature hollow cathode, and MiXI operating with miniature hollow cathode.

Efforts at several institutions in Japan have led to the development of microwave discharge designs that yield desirable performance and relatively low overall power consumption.[19] For example, the μ1 ion thruster shown in Figure 4 employs a 2 cm discharge chamber with a typical thruster performance of approximately 0.3 mN, 1100 s I_{sp}, and 15.1 W of total power consumption.[20]

Figure 4. Microwave 2 cm discharge μ1 thruster.

Over the past decade, miniature RF ion thruster has become quite popular in Europe and the United States. Giessen University scaled down the successful 10 cm RIT-10 RF ion engine and continue the earlier RIT-4 work mentioned above, culminating in the demonstration of a 4 cm RIT-4[21] in 2005 and then the 2.5 cm diameter μNRIT-2.5[22] in 2009 by Feili, et al. The μNRIT-2.5 thruster provides up to approximately 0.5 mN, with power efficiency over 40%, propellant efficiency near 50%, but high ion production costs of over 2400 eV/ion. Similar efforts were also taken by Mistoco, et al. starting in 2004[23,24] and Trudel, et al.[25] in 2009 for a 1 cm RF discharge.

Figure 5. 2.5 cm RF discharge uNRIT-2.5 thruster

Researchers at Airbus have developed a RIT-μX miniature ion thruster, where a single discharge design is used while two different grid sizes can be used to achieve thrust ranges of 0.05 – 1.3 mN and 0.084 – 2.5 mN, respectively.[26] Recently, researchers at Busek have demonstrated the use of iodine propellant in their BIT-3 RF ion thruster which allows a 3x storage density over pressurized xenon.[27,28] In Figure 1, the thruster is shown operating on an iodine discharge with a neutralizer cathode operating with xenon.

Figure 6. BIT-3 RF ion thruster operating on iodine.

A comparison of some of the thruster performance values reported in the literature are shown in Table 1. Note that many of these efficiencies do not include full system efficiencies and don't consider losses such as those attributed to the neutralizer. Nonetheless, as can be seen from this table, an impressive range of thruster capabilities are available with miniature ion thrusters.

Table 1. Comparison of some miniature ion thrusters. (The 30 cm NSTAR thruster is includuded for reference.)

Thruster	Institution	Discharge Type	Diameter (cm)	I_{sp} (s)	Thrust (mN)	η_t (%)	η_{ud} (%)	η_E (%)	Ref
MiXI	Caltech/JPL UCLA	Ring-Cusp	3	1764-3184	0.1-1.553	31-56	48-82	>40	14
μNRIT-2.5	University of Giessen	RF	2.5	363-2861	0.05-0.6	≤ 24.4	15-52	4-47	22 & 29
μ1	ISASJAXA	ECR	2.0	1410	0.297	–	46	–	20
MRIT	Penn State	RF	1	5480	0.059	12.8	<80	15.2	25
MMIT	Penn State	ECR	2	5500	0.25	32	32	50	30
NSTAR	JPL	Ring-Cusp	30	3127	92.7	61.9	91	–	5

One performance challenge with miniature ion thrusters is beam neutralization. Several solutions have been considered, each with their own merit and challenges. The first is to use an external thermionic hollow cathode, or a designated neutralizer RF or microwave discharge for neutralization, as is done with larger thrusters. This is a robust option, but has the drawback of requiring some power and propellant to operate the cathode. Another option is to use a propellant-less field emission cathode, such as the flight-qualified carbon nanotube field emission (CNTFE) cathode from Busek.[31] This option is attractive due to the lack of need for propellant to operate the cathode, but the extractable electron current density is limited. Most recently, researchers at the university of Tokyo and JAXA/ISAS have explored the use of bipolar operation, by alternating the ion and electron extraction responsibilities between two identical thrusters.[20] This process is shown schematically in Figure 7. In this figure, the unipolar mode is the condition where there is a designated neutralizer discharge, while the bipolar mode, though less efficient, could be considered for a mission where commonality is desired of performance.

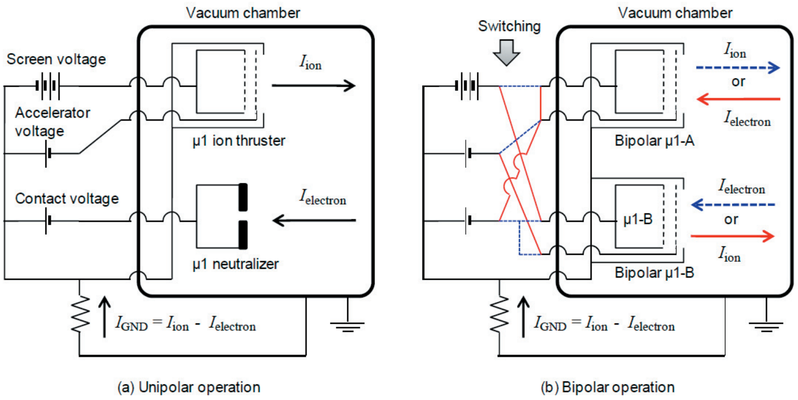


Figure 7. Electrical connections and circuits for the μ1 ion thruster in unipolar and bipolar operation.

IV. Missions Capabilities

This section overviews some of the many mission enabling capabilities for miniature ion thruster. First of all, a qualitative correlation of capabilities to mission type is made. Secondly, miniature ion thrusters are compared to other EP micropropulsion concepts. Finally some mission examples are given.

A. Thruster Features and Mission Capabilities

Miniature ion thrusters have several performance features that make them attractive for a wide range of missions as summarized in Table 2. Similar to larger ion thruster, the most obvious advantage of miniature ion thrusters is their ability to achieve <u>high specific impulse, I_{sp}</u>, (~1000 – 3000 s). Some of the less obvious and less advertised advantages include <u>very precise thrust and impulse bits</u> due to highly controllable electric thrust that is simply proportional to $\sqrt{V_B}$, <u>low disturbance thrust</u> through the use of amplitude modulated thrust in the mN to sub-mN range, and <u>low</u>

contamination and spacecraft interaction potential due to the potential to use of inert, non-condensable noble gas propellants, quiet electrical operation, and inherently low beam divergence half-angle (~5 - 15°). From these performance features it is clear why many mission designers have incorporated miniature ion thrusters for a wide range of mission classes and for many spacecraft.

Table 2. Mission Classes for Miniature Ion Thrusters

Mission Class	Nanospacecraft (1 – 10 kg)	Microspacecraft (10 – 100 kg)	Small spacecraft (100 – 1000 kg)	Large spacecraft (>1000 kg)
Exploration	X	X		
Orbit/Inclination Change	X	X		
Precision Orbit Maintenance	X	X	X	X
Formation Flying	X	X	X	X
Precision Control/Pointing		X	X	X

X – applicable to mission

For an exploration mission, i.e., beyond GEO, miniature ion thrusters can provide attractive ΔV for microspacecraft to targets such as asteroids.[32] The PROCYON asteroid mission, Figure 8, flew a 70 kg spacecraft using the μ1-derived miniature ion thruster unit (ITU) as part of the I-COUPS (Ion thruster and Cold-gas thruster Unified Propulsion System) thruster combination that shares a common propellant supply.[33] To date, the ion thruster was able to operate for 223 hours with an average thrust of 346 μN, thus being the first micropropulsion system on a small spacecraft of less than 100 kg to operate in deep space.[34] At the time of this writing the ion thruster has experienced a grid short that has not been cleared.[35]

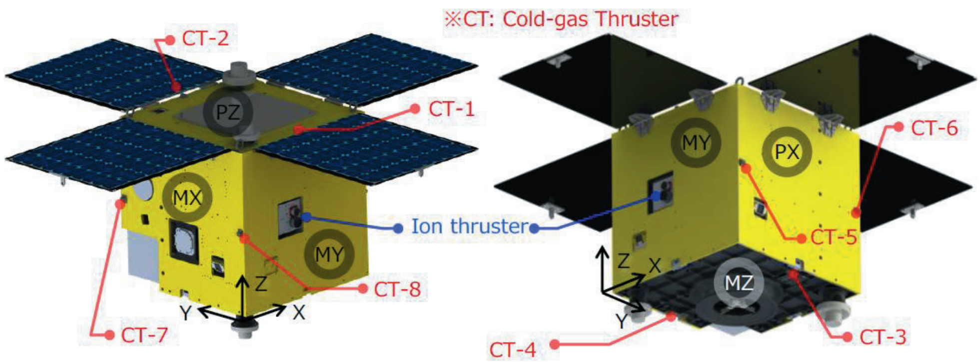


Figure 8. I-COUPS Thruster configuration on the PROCYON spacecraft [refPROCYON].

A recent mission study using a MiXI thruster baseline showed that a nanospacecraft could be consider for a lunar missions, or beyond.[1] This same ΔV could be used for large orbit and inclination change or maintenance for a nanospacecraft, as shown in Figure 9. A similar mission architecture was use for a 6U "LunarCube" that uses the BIT-3 RF ion thruster as shown in Figure 10.[36] This architecture is designed to provide 3.2 km/s of Delta-V and a total impulse of 37 kN-s.

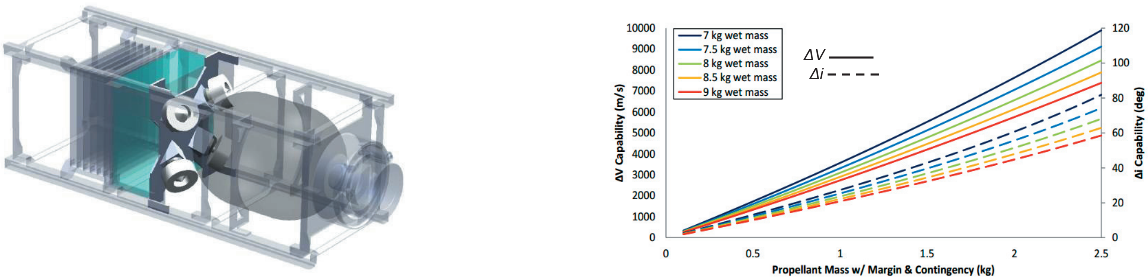


Figure 9. Internal configuration and mission capabilities for a high ΔV 3U CubeSat employing the MiXI Thruster.[1]

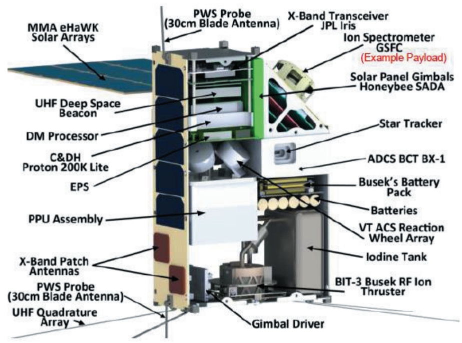
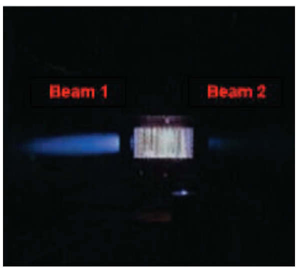


Figure 10. 6U LunarCube with BIT-3 RF Ion Thruster.[36]

Of recent interest are missions that provide the next generation of Earth observation using precision orbit maintenance for small to large spacecraft. Depending on orbit altitude and spacecraft size, miniature ion thrusters can provide mN to sub-mN level thrust that can maintain constellation type spacecraft architectures using either drag-free or "loose" formation control.[3] A particular example is the Next Generation Gravity Mission (NGGM), which follows in the footsteps of the the highly successful GRACE (Gravity Recovery and Climate Experiment) and GOCE (Gravity and Steady State Ocean Circulation Explorer) gravity missions. Similar to GOCE, this mission is considering the use of the precision thrust that can be provided by ion thrusters, but in this case the desired thrust range is 50 – 500 μN. Parallel efforts at Giessen University on the μN-RIT and at Qinetiq on the "MiDGIT" double-ended miniature RF ion thruster have been undertaken to address the needs of this mission class.[37]



Double-ended MiDGIT

B. Comparison to Other Micropropulsion Options

When comparing miniature ion thrusters to other micropropulsion options, one must consider many factors. In general, the requirements of mN to sub-mN thrust level is enough to make miniature ion thrusters a strong candidate. In the table below, we compare the attractiveness of different propulsion options for a representative formation flying mission such as the Terrestrial Planet Finder – Interferometer (TPF-I). As discussed in reference 2, these 1000 kg spacecraft require mN to sub-mN, low-disturbance thrust levels that must performance formation flying maneuvers for many years, thus the need for high specific impulse. For this particular mission, the spacecraft are flying in close formation and the interferometric observation employs very sensitive optics at cryogenic temperatures. As a result, contamination potential for candidate thruster options must be extremely low. For this mission, and others with similar requirements, miniature ion thruster may prove to be very well-suited.

Thruster Technology	Thrust Range (mN)	Primary Thrust Control	Isp (sec)	Plume Divergence Half-Angle (°)	Propellant	Contamination Potential
Formation Flying Mission Targets	*0.01 - 1.1*	*Amplitude Modulated (AM)*	*> 1,000*	*< 20*	-	*Low*
Mini Ion	0.02 - 1.5 (0.001 – 0.1)	AM (also PWM)	2,500 - 3,500	5-15	Xenon	Low
Hall	4-17 (0.05 – 4)	AM (also PWM)	1,200 - 1,600	60-75	Xenon	Low (except for beam divergence)
Teflon PPT	~ 1 @ 1 Hz	Pulse Width Modulated (PWM)	650-1400	30-45	Teflon	High
Cold Gas	4.5 - 1000	PWM	65	45	Nitrogen	Low
Colloid	0.001-0.1	AM	100 - 500	18	Ionic Liquids	High
Cs- FEEP	0.1 – 1.4	AM	6,000 - 12,000	30-45	Cesium	Very High
In-FEEP	0.001 - 0.1	AM	4,000 - 12,000	30-45	Indium	High

V. Conclusion

Miniature ion thrusters enable a wide range of attractive missions near Earth and beyond. Significant advancements in miniature ion thruster technology and hardware have been made since the turn of the century, and additional advancements are sure to come in the forthcoming years.

The author has made an effort to accurately represent the history and state-of-the-art in miniature ion thruster technology. Due to the copious work in the area, it is likely that I have missed some research or made some misrepresentations that should be addressed in the peer-reviewed journal version of this paper. If you are aware of such content, please do not hesitate to contact the author at your earliest convenience.

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