

# Initial Thrust Measurements of Marshall's Ion-ion Thruster

Natalie R.S. Caruso<sup>1</sup>, Tyler Scogin<sup>2</sup>, Thomas M. Liu<sup>3</sup>, and Mitchell L.R. Walker<sup>4</sup>  
*Georgia Institute of Technology, Atlanta, GA 30332*

Kurt A. Polzin<sup>5</sup> and John W. Dankanich<sup>6</sup>  
*NASA George C. Marshall Space Flight Center, Huntsville, AL 35811*

Electronegative ion thrusters are a variation of traditional gridded ion thruster technology differentiated by the production and acceleration of both positive and negative ions. Benefits of electronegative ion thrusters include the elimination of lifetime-limiting cathodes from the thruster architecture and the ability to generate appreciable thrust from both charge species. While much progress has been made in the development of electronegative ion thruster technology, direct thrust measurements are required to unambiguously demonstrate the efficacy of the concept and support continued development. In the present work, direct thrust measurements of the thrust produced by the MINT (Marshall's Ion-ion Thruster) are performed using an inverted-pendulum thrust stand in the High-Power Electric Propulsion Laboratory's Vacuum Test Facility-1 at the Georgia Institute of Technology with operating pressures ranging from  $4.8 \times 10^{-5}$  and  $5.7 \times 10^{-5}$  torr. Thrust is recorded while operating with a propellant volumetric mixture ratio of 5:1 argon to nitrogen with total volumetric flow rates of 6, 12, and 24 sccm (0.17, 0.34, and 0.68 mg/s). Plasma is generated using a helical antenna at 13.56 MHz and radio frequency (RF) power levels of 150 and 350 W. The acceleration grid assembly is operated using both sinusoidal and square waveform biases of  $\pm 350$  V at frequencies of 4, 10, 25, 125, and 225 kHz. Thrust is recorded for two separate thruster configurations: with and without the magnetic filter. No thrust is discernable during thruster operation without the magnetic filter for any volumetric flow rate, RF forward Power level, or acceleration grid biasing scheme. For the full thruster configuration, with the magnetic filter installed, a brief burst of thrust of approximately  $3.75 \text{ mN} \pm 3 \text{ mN}$  of error is observed at the start of grid operation for a volumetric flow rate of 24 sccm at 350 W RF power using a sinusoidal waveform grid bias at 125 kHz and  $\pm 350$  V. Similar bursts in thrust are observed using a square waveform grid bias at 10 kHz and  $\pm 350$  V for volumetric flow rates of 6, 10, and 12 sccm at 150, 350, and 350 W respectively. The only operating condition that exhibits repeated thrust spikes throughout thruster operation is the 24 sccm condition with a 5:1 mixture ratio at 150 W RF power using the 10 kHz square waveform acceleration grid bias. Thrust spikes for this condition measure 3 mN with an error of  $\pm 2.5 \text{ mN}$ . There are no operating conditions tested that show continuous thrust production.

## Nomenclature

$\gamma$	= Thrust Correction Factor
$J_{ions}$	= Ion Current Density
$P_{in}$	= Total Power Input
$RF$	= Radio Frequency
$sccm$	= Standard Cubic Centimeters per Minute
$T_{MAX}$	= Maximum Thrust

---

<sup>1</sup> Graduate Student Researcher, School of Aerospace Engineering, nschloeder3@gatech.edu, Student Member AIAA

<sup>2</sup> Graduate Student Researcher, School of Aerospace Engineering, tscogin@gatech.edu, Student Member AIAA

<sup>3</sup> Research Engineer, School of Aerospace Engineering, thomas.liu@ae.gatech.edu, Member AIAA

<sup>4</sup> Associate Professor, School of Aerospace Engineering, mitchell.walker@ae.gatech.edu, Associate Fellow AIAA

<sup>5</sup> Propulsion Research Engineer, Propulsion Research and Technology Applications Branch, Propulsion Systems Department, kurt.a.polzin@nasa.gov, Associate Fellow AIAA

<sup>6</sup> Program Manager, Technology Development and Transfer Office, john.dankanich@nasa.gov, Associate Fellow AIAA

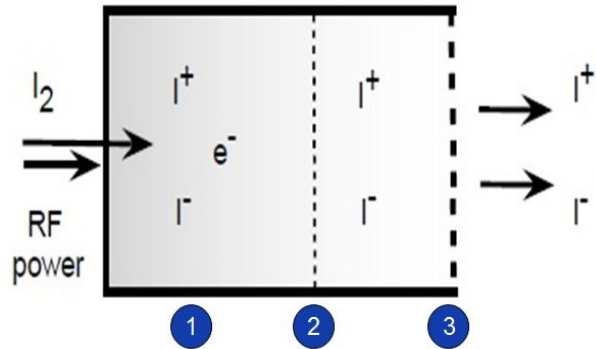
$T_{opt}$  = Optical Transparency of the Grid Assembly  
 $V_a, V_b, V_s$  = Acceleration, Beam, and Screen Voltage

## I. Introduction to Electronegative Ion Thrusters

CLASSICAL gridded ion thrusters ionize propellant generating positive ions that accelerate through negatively biased grids to generate thrust, and electrons that are collected at an internal anode and released external to the thruster body using a cathode to neutralize the exhaust plume.<sup>1</sup> The use of acceleration grids and neutralizing cathodes in classical gridded ion thrusters enables thrust production at the expense of decreased thruster life expectancy. The electronegative ion thruster concept proposes a method of thrust production that eliminates the neutralizing cathode by generating and accelerating positive and negative ions that result in a quasineutral plume.<sup>2-4</sup> Cathodes often require additional support structures, power sources, and propellant feed lines that contribute to the mass of the spacecraft as well as needing high-purity propellant gases that increase both development and mission costs. The quasineutral plume eliminates the need for a neutralizing cathode and associated cost penalties in addition to eliminating a lifetime-limiting component of the traditional thruster assembly.<sup>2-4</sup>

As shown in Figure 1, electronegative ion thrusters are characterized by three distinct operational stages. The first stage (1) is the ionization region where positive ions and electrons are generated. This is often achieved by broadcasting RF power into the neutral propellant located in the source region of the discharge chamber resulting in the formation of positive ions and electrons. The second stage (2) is the electron filtering region where the temperature of the electrons is lowered, trapping them in the source region thereby enabling the electrons to attach onto neutral atoms to form negative ions.<sup>5</sup> In the previous electronegative thruster designs, this phenomenon is achieved with a magnetic filter generated by either permanent magnets or solenoid coils. The third and final stage (3) is the acceleration region where positive and negative ions are expelled from the thruster body to produce thrust. Two previous designs of the acceleration region come from the Plasma Propulsion with Electronegative GASES (PEGASES) thrusters. The first acceleration method used two separate grid assemblies located at opposite ends of the thruster body, with each grid assembly biased with an electric field intended to accelerate positive ions using a negative applied grid voltage or negative ions using a positive applied grid voltage.<sup>4</sup> The second PEGASES thruster used a single grid assembly with an alternating potential bias to expel both charge species in a time-dependent manner.<sup>2</sup> Evaluation of the effectiveness of these acceleration schemes is required to move the study of electronegative ion thrusters forward.

General development in the field of electronegative ion thrusters has focused on the diagnostics required to characterize the quasineutral plume. Currently, thrust values have been theorized, but no direct measurements have been recorded for the Marshall's Ion-ion Thruster (MINT) or any of its predecessors. In this paper we seek to fill this void in thruster performance characterization data, which are required before the concept will merit significant future investigations. In this work, direct thrust measurements of the MINT operating while immersed in a high vacuum environment with operating pressures of approximately  $4.8 \times 10^{-5}$  and  $5.7 \times 10^{-5}$  torr are performed. A 5:1 volumetric propellant mixture of argon to nitrogen at total volumetric flow rates of 6, 12, and 24 standard cubic centimeters per minute (sccm) is used during thruster operation. Nitrogen was chosen as a potential electronegative propellant due to its 3.04 rating on the Pauling Electronegativity Scale. The choice to use nitrogen is made more attractive due to its low cost and relative safety compared to other high ranking electronegative elements in the halogen family. Radio frequency (RF) source operation is performed at 13.56 MHz and power levels of 150 and 350 W. The acceleration grid assembly is operated using both sinusoidal and square waveform biases that alternate between -350 to +350 V at frequencies of 4, 10, 25, 125, and 225 kHz. Should nitrogen form negative ions and an electronegative plasma is created and produces thrust, a steady thrust level of 1.2 mN is expected. Should only positive ions form, thrust may be recorded as occurring in short bursts corresponding to a negative grid bias capable of accelerating the positive ions while the electrons remain trapped upstream of the magnetic filter until recombination with a positive ion occurs in the source region and neutral propellant exits the thruster.



**Figure 1. Conceptual regions within an electronegative ion thruster.<sup>3</sup>**

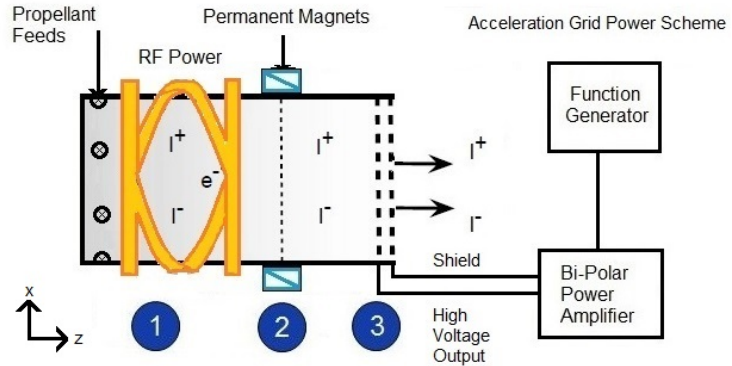
## II. Experimental Apparatus

### A. Marshall's Ion-ion Thruster: Design and Calculated Performance

A schematic of Marshall's Ion-ion Thruster (MINT) is shown in Figure 2. The first stage (1), the source region, incorporates a six-port propellant feed design and a double-helix, half-turn Nagoya antenna for RF operation at 13.56 MHz to enable propellant ionization. To ensure an even distribution of neutral propellant, the propellant feed lines are located every 60 degrees along the circumference of the discharge chamber upstream of the RF antenna.

Electron filtering in the second stage (2) is achieved using a magnetic filter generated between two permanent neodymium magnets across the x-y thruster plane. The magnetic filter has a magnetic field strength of 250 Gauss at the thruster centerline.<sup>6</sup> This magnetic filter is used to decrease electron temperature as the electrons travel in the positive z-direction along an increasing magnetic field gradient, thereby producing more desirable conditions for attachment to neutrals and subsequent negative ion formation. The heavier positive and negative ions pass through the magnetic filter towards the acceleration stage unimpeded.

The final stage (3) of the MINT accelerates positive and negative ions through a set of molybdenum grid optics. An Agilent 33220A 20MHz Function/Arbitrary Waveform Generator sends a sinusoidal or square waveform at a frequency of 4, 10, 25, 125, or 225 kHz to a Trek Model PZD350A M/S bi-polar power amplifier with a current limit of 400 mA that biases the upstream screen grid ( $\pm 350$  V) relative to the downstream acceleration grid. The alternating potential bias allows for alternating acceleration of both positive and negative ions in the third stage. Table 1. lists the values used to calculate the maximum thrust for the MINT estimated to be approximately 1.2 mN given the acceleration grid aperture sizes and the modified ion current calculated using the Child-Langmuir Law for round apertures with a physical grid transparency of 0.65 and a maximum grid bias of 350 V. These calculations were performed using methods previously used for classical gridded ion thrusters with an assumed thrust correction factor of 0.958.<sup>1, 6</sup>



**Figure 2. Top down view of MINT schematic with electronegative ion thruster stages labeled.**

**Table 1. MINT performance estimates calculated from the Child-Langmuir Law for round apertures and classical grid design.<sup>6</sup>**

Property	Value	Units	Description
$\gamma$	0.958	-	Thrust Correction Factor <sup>1</sup>
$V_s$	350	V	Screen Grid Bias
$V_a$	0	V	Accel Grid Bias
$V_b$	315	V	Beam Voltage
$P_{in}$	700	W	Total Input Power
$T_{opt}$	0.65	-	Physical Grid Transparency
$J_{ions}$	~1.5	mA/cm <sup>2</sup>	Ion Current Density
$T_{MAX}$	~1.2	mN	Maximum Possible Thrust

### B. Operating Conditions

Thrust measurements are recorded for two separate thruster configurations. The first configuration (C1) included all three stages of the electronegative ion thruster concept. The second configuration (C2) excludes the magnetic filter in order to determine the MINT's ability to operate like a traditional ion engine in the absence of a cathode while still using the same grid biasing schemes for an electronegative ion. For operation in both configurations, a propellant mixture of argon and nitrogen is used at a fixed volumetric mixture ratio of 5:1 for total volumetric flow

rates of 6, 12, and 24 sccm. In cases where potential thrust behavior is observed, thrust measurements are repeated in the absence of nitrogen to quantify its contribution to the overall thrust produced and to determine if negative ions are formed.

At each flow rate, two RF power conditions are used to ionize propellant in the source region. The first power condition uses 150 W, and the second uses 350 W forward RF power. Previous experience showed that operating at or above 400 W forward RF power led to current shorting in the grids exceeding the 400 mA current limit of the bipolar amplifier resulting in a breakdown of the waveform grid bias. All RF testing is performed at a frequency of 13.56 MHz and matching was adjusted to maintain a standing wave ratio (SWR) less than 1.05.

For each RF power condition, eight different grid biasing schemes are implemented and detailed in Table 2. Each scheme is differentiated by a waveform and frequency supplied by the function generator to the bipolar amplifier that increases the voltage 100 times before sending it to the grid assembly. All grid bias waveforms alternated between  $\pm 350$  V when applied to the grid assembly, the highest peak-to-peak voltage supported by the bipolar amplifier. These schemes are chosen based on PIC simulations conducted in Refs. 7 and 8 where acceleration of both positive and negative ions was considered.

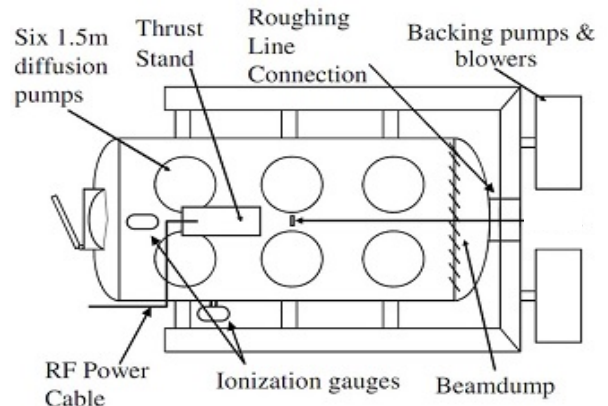
**Table 2. Biasing schemes applied to acceleration grids during operation of both thruster configurations.**

<u>Grid Biasing Scheme</u>	<u>Waveform</u>	<u>Frequency (kHz)</u>
1	Sinusoidal	25
2	Sinusoidal	125
3	Sinusoidal	225
4	Square	4
5	Square	10
6	Square	25
7	Square	125
8	Square	225

### III. Experimental Equipment

#### A. Vacuum Test Facility

The MINT is tested inside of the 4-m diameter, 7-m long Vacuum Test Facility-1 (VTF-1) at the Georgia Institute of Technology's High-Power Electric Propulsion Laboratory (HPEPL). The stainless steel vacuum chamber shown schematically in Fig. 3, uses two 3800-CFM blowers and two 495-CRM rotary vane pumps to drop the pressure to approximately 30 mtorr. Then, six 1.5-m diffusion pumps with chilled, optical baffles on the inlets are used to bring the chamber down to a base pressure of  $2.4 \times 10^{-5}$  torr measured with a BA-571 ion gauge. VTF-1 has a pumping speed of 600,000 L/s for diatomic nitrogen and a published effective pumping speed of 125,000 L/s for argon.<sup>9</sup> During operation, the MINT is mounted on top of the thrust stand exhausting towards the beamdump. The operating pressures for these tests ranged from  $4.8 \times 10^{-5}$  to  $5.7 \times 10^{-5}$  over the full range of flowrates used.



**Figure 3. Schematic of Vacuum Test Facility-1.**

#### B. Thrust Stand

The thrust stand used is a null-type inverted pendulum thrust stand installed along the centerline of VTF-1.<sup>10</sup> The MINT is mounted on top of two parallel plates connected by four flexures that deflect when thrust is produced. A linear variable differential transformer (LVDT) measures the position of the upper plate while two electromagnetic actuators control the motion of the assembly. The first actuator (damper coil) compensates for vibrations while the second actuator (null coil) keeps the upper plate in a fixed position. The actuators are controlled using two proportional-integral-derivative control circuits that react according to the position of the upper plate as reported by the LVDT. The null coil current is directly correlated to the force required to maintain the position of the upper plate

and is a measure of the thrust produced. The null coil current is calibrated using a series of known weights to determine the relationship of the null coil current output to thrust exerted on the flexures.

Thrust is determined by comparing the magnitude of the increase in current required by the null coil to keep the thruster stationary during firing and the current corresponding to the known calibration weights previously loaded on the thrust stand. Error for these measurements is determined to be half the value of the noise in the recorded current exhibited by the null coil while the thruster operates and while the thruster is off.

#### IV. Results and Discussion

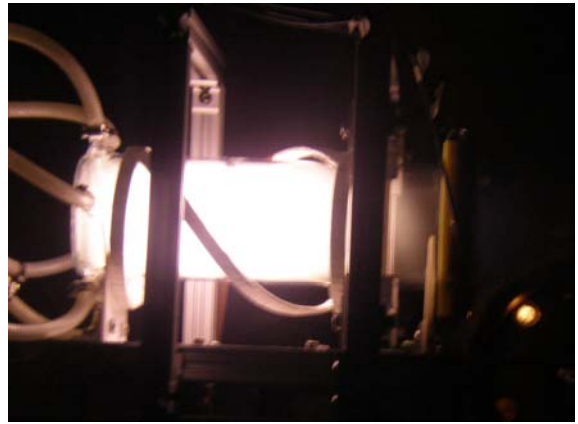
##### A. Thrust Measurements in Configuration 1 (Electron Filter Present)

Thrust measurements in the presence of the magnetic filter (configuration C1) show that none of the grid biasing schemes using a sinusoidal waveform (schemes 1-3) exhibit thrust production above the thrust stand noise floor with the exception of the 350 W, 24 sccm case using grid biasing scheme number 2. In this instance we observe an initial thrust spike of  $3.75 \text{ mN} \pm 3 \text{ mN}$  that then immediately drops below the noise floor. For all other sinusoidal waveform biases, thrust stand behavior did not change from nominal during plasma source operation regardless of the grid bias scheme, RF forward power, or volumetric flow rate. Thrust measurements recorded during square waveform grid biasing however, exhibit potential thrust for the 10 kHz biasing scheme (number 5) for multiple flow rates, RF powers, and volumetric mixture ratios consistent with the results of Ref. 7 which showed square waveforms to be the most promising grid bias waveform for thrust generation in an electronegative ion thruster. Thrust behavior for grid biasing scheme number 5 shown in Table 3. is characterized as brief thrust spikes that occur at the start of grid operation and then disappear with the exception of the 150 W, 24 sccm case which showed repeated thrust spikes above the noise floor on the order of 3 mN with an error of  $\pm 2.5 \text{ mN}$  throughout firing. To confirm the thrust spikes observed are not a result of thermal or electrical loading acting on the thrust stand by the grid assembly power lines, thrust data are recorded in the absence of plasma while turning the grids on and off; no thrust spikes are observed. RF ignition occurs before activating the grids and also does not result in an immediate spike in thrust.

**Table 3. Recorded thrust data for successful grid biasing schemes in Configuration C1.**

<u>Grid Bias Scheme</u>	<u>Total Volumetric Flow Rate</u>	<u>Ar:N Ratio</u>	<u>RF Power</u>	<u>Potential Thrust</u>	<u>Thrust Error</u>	<u>Description of Thrust Behavior</u>
2	24 sccm	5:1	350 W	~3.75 mN	$\pm 3 \text{ mN}$	Single spike
5	6 sccm	5:1	150 W	~4.5 mN	$\pm 3 \text{ mN}$	Single spike at grid start up
5	10 sccm	5:0	350 W	~3 mN	$\pm 1.75 \text{ mN}$	Single spike at grid start up
5	12 sccm	5:1	350 W	~4.25 mN	$\pm 3.75 \text{ mN}$	Single spike at grid start up
5	24 sccm	5:1	150 W	~3 mN	$\pm 2.5 \text{ mN}$	Repeated spikes

Additional observations of the plasma behavior in the source region revealed the tendency of the thruster to self-extinguish at the 6 sccm flow rate operating condition despite constant, matched forward RF power for the 150 W operating condition. The 6 sccm volumetric flow rate was the original intended operating flow rate for this thruster design but it does not appear sustainable at 150 W forward RF power during high vacuum operation. Due to the instability of 6 sccm operation, an increase in volumetric flow rate is required to maintain plasma in the source at low powers. Unfortunately, this will lead to a decrease in anticipated specific impulse and propellant utilization. Determination of the minimum required volumetric flow rate at low RF power for high vacuum thruster operation is outside the scope of this paper. It is also observed during operation of the MINT that a minimum argon flow rate of 30 sccm and RF forward power levels above 300 W during high vacuum operation is required to instigate plasma formation in the source region. Other complications with thruster



**Figure 4. MINT operating on the thrust stand at Georgia Tech.**

operation included a degradation of the grid biasing waveforms at high frequencies. For grid schemes using a frequency of 125 or 225 kHz (schemes 2, 3, 7, and 8), both the sinusoidal and square waveforms are seen to transform into triangle waveforms after going through the bipolar amplifier despite adjustments made to the amplifier's damping circuit. This may affect the grid assembly's ability to successfully generate thrust and is independent of thruster configuration.

Overall, continuous thrust is not observed for any of the grid biasing schemes tested in thruster Configuration 1. A lack of continuous thrust may indicate that nitrogen has failed to produce negative ions. A better electronegative propellant, such as sulfur hexafluoride or iodine, may be required to realize the full capability of the electronegative ion thruster and permit performance measurements that will demonstrate successful operation. The most promising grid biasing scheme tested in this work is scheme 5 which yields thrust spikes at varying operating parameters.

## **B. Thrust Measurements in Configuration 2 (Electron Filter Absent)**

To determine the applicability of the MINT to function as a traditional ion thruster without a lifetime-limiting neutralizer cathode, thrust measurements are repeated for the same volumetric flow rates, RF forward power levels, and grid biasing schemes with the magnetic filter removed from the thruster architecture. In configuration C2, electrons may be permitted to exit the thruster during a positive grid bias but they will not generate any statistically-significant thrust due to their low mass. The same grid biasing schemes for configuration C1 are also used.

Without the magnetic filter to confine the electrons in the area of influence of the RF antenna, ignition of the source region was not possible at the operating pressure of about  $6.3 \times 10^{-5}$  torr using argon volumetric flowrates as high as 40 sccm and over 1000 W of forward RF power. Background argon gas is added to the chamber to raise the operating pressure to  $1.3 \times 10^{-4}$  torr before plasma ignition was achieved, thus discounting this configuration's use as an alternative to classical gridded ion engines for high-vacuum applications.

Once the plasma is ignited, all previous operating scenarios were retested at an operating pressure range of  $4.8 \times 10^{-5}$  to  $5.7 \times 10^{-5}$  torr. No combination of operating conditions yield discernible, sustained thrust. Some conditions may have produced brief spikes in thrust on the order of 1 mN, but these spikes were not repeated and remained close to the noise level ( $\pm 1$  mN) of the recorded null coil current. In the absence of the magnetic filter, the grid biasing schemes discussed are not suitable replacements for the cathode structure required in classical gridded ion engines.

Regarding plasma behavior, the 125 and 225 kHz biasing schemes for both sinusoidal and square waveforms, at a total volumetric flow rate of 6 sccm, showed a depletion of visible plasma in the discharge chamber directly upstream of the grid assembly. This behavior was not observed when the magnetic filter was present due to the increased plasma confinement provided by the permanent magnets' magnetic field. This reduction in plasma directly upstream of the acceleration grid assembly further reinforces the assertion that the electronegative ion thruster could not operate in the capacity of a traditional gridded ion engine without the associated cathode.

## **V. Conclusions**

The electronegative ion thruster concept holds the promise of eliminating the lifetime-limiting cathode structure from traditional gridded ion engines by generating positive and negative ions that are then alternately accelerated to produce thrust while still maintaining overall charge-neutrality within the thruster. In this paper we discussed initial attempts to show the efficacy of the electronegative ion thruster concept by performing the first direct thrust measurements on the MINT device.

In this work, nitrogen was employed as a potential electronegative propellant gas. Nitrogen has a 3.04 rating on the Pauling Electronegativity Scale and it was thought this might be high enough to support negative ion production. However, the lack of any measurable continuous thrust production indicates that it is unlikely that negative ions were formed using nitrogen gas. This leads us to believe that only halogen gases will properly permit the formation of the negative ions needed for thrust production in the electronegative thruster concept.

For this paper, two thruster configurations were evaluated using the same operating conditions of volumetric flow rate, volumetric propellant mixture ratio, forward RF power, and acceleration grid biasing. For the full electronegative thruster configuration, only two grid biasing schemes produced thrust above the noise floor of the thrust stand. The most notable of these schemes was the 10 kHz square waveform grid biasing scheme which showed repeated thrust spikes over thruster operation for the 24 sccm case.

The second configuration entailed operation in the absence of the magnetic filter to evaluate the ability of the MINT to function as a traditional ion thruster in the absence of the cathode assembly. In this configuration, ignition of the source plasma was not possible during high vacuum operation due to the lack of plasma confinement which had previously been provided by the permanent magnets of the electron filter. Also, plasma was observed to

extinguish directly upstream of the acceleration grids for the 150 W, 6 sccm volumetric flow rate at grid bias frequencies of 125 and 225 kHz. Configuration C2 failed to produce thrust for any of the operating conditions tested.

Moving forward, the opportunity for the MINT to generate thrust in an electronegative ion thruster configuration appears to require the use of a halogen propellant and a grid biasing scheme similar to scheme 5. Thrust predictions are also expected to increase if higher peak-to-peak voltages can be applied to the grids.

### Acknowledgements

The authors would like to thank Dr. Ane Aanesland of École Polytechnique for her input regarding electronegative ion thrusters. The authors also want to thank Jason Frieman and Nathan Brown for their assistance in experimental set-up and thrust stand operation.

### References

- <sup>1</sup>Goebel, Dan M., and Katz, Ira, *Fundamentals of Electric Propulsion: Ion and Hall Thrusters*, John Wiley & Sons, Inc., New Jersey, 2008, Chaps. 2, 5.
- <sup>2</sup>Aanesland1, A., Rafalskyi, D., Bredin, J., Grondein, P., Oudini2, N., & Chabert, P. (2013, October 6-10). The PEGASES gridded ion-ion thruster performance and predictions. *Presented at the 33rd International Electric Propulsion Conference, The George Washington University, Washington, D.C., USA IEPC-2013-259*
- <sup>3</sup>Aanesland, A., Meige, A., & Chabert, P. (2009). Electric propulsion using ion-ion plasmas. *Journal of Physics: Conference Series* 162 doi:10.1088/1742-6596/162/1/012009
- <sup>4</sup>Aanesland, A., Leray, G., & Chabert, P. (2008, July 21-23). PEGASES – Plasma Propulsion with Electronegative GASES. *Presented at 44th AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit, Hartford, CT, USA AIAA 2008-5198*
- <sup>5</sup>Aanesland, A., Bredin, J., Chabert, P., & Godyak, V. (2012). Electron energy distribution function and plasma parameters across magnetic filters. *American Institute of Physics: Appl. Phys. Lett.* 100, 044102. doi: 10.1063/1.3680088
- <sup>6</sup>Natalie Schloeder, Thomas Liu, Kurt Polzin, John Dankanich, Anne Aanesland, Mitchell Walker, “Design and Preliminary Performance Testing of Electronegative Gas Plasma Thruster,” 50th Joint Propulsion Conference and Exhibit, Cleveland, OH, July 28-30, 2014.
- <sup>7</sup>Oudini, N., Raimbault, J.-L., Chabert, P., Meige, A., & Aanesland, A. (2013). Particle-in-cell simulation of an electronegative plasma under direct current bias studied in a large range of electronegativity. *Physics of Plasmas (1994-present)* 20, 043501 doi: 10.1063/1.4798501
- <sup>8</sup>Lafleur, T., Rafalskyi, D., & Aanesland, A., “Alternate extraction and acceleration of positive and negative ions from a gridded plasma source,” *Plasma Sources Sci. Technol.* 24 (2015) doi:10.1088/0963-0252/24/1/015005
- <sup>9</sup>Williams, L., “Ion Acceleration Mechanisms of Helicon Thrusters,” Ph.D. Dissertation, Aerospace Engineering Dept., Georgia Institute of Technology, Atlanta, Ga, 2013.
- <sup>10</sup>Xu, K., Walker, M. L. R., “High-Power, Null-Type, Inverted Pendulum Thrust Stand,” *Review of Scientific Instruments*, Volume 80, Number 5, May 2009, pp. 055103 1-6.