Development of a Micro ECR Ion Thruster for Space Propulsion

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Abstract: **In this study, we are aiming to develop an electric propulsion system suitable for miniature satellites especially CubeSats. Electron Cyclotron Resonance Ion Thruster (ECR Ion Thruster), combining the advantages of high density plasma jet and high specific impulse, could be the promising candidate for satellite's propulsion subsystem. In the phase of preliminary design, SIMION software was used to define the configuration of ion thruster depending on the simulation results of ion behaviors and ion optics. Currently, the prototype system is capable to produce nearly 0.9 milli-newtons thrust and around 1025~3076s specific impulse with the calculation of plasma diagnostics.**

Nomenclature

A	=	cross section area
A_0	=	cross section area of screen grid
A'	=	cross section area of 1st acceleration grid
e	=	elementary charge
F	=	force
η	=	ion transparency
g	=	gravitational acceleration (g_E)
I	=	current
I_b	=	beam current
m_e	=	electron mass
$\dot{m}_{pro}$	=	propellant flow rate
N_0	=	ion density on screen grid
N'	=	ion density on 1st acceleration grid
n	=	ion density
φ	=	potential
$r_{pinhole}$	=	pinhole radius
T	=	thrust
V	=	voltage
V_b	=	beam voltage
V_e	=	exhaust velocity
v	=	velocity
W_{beam}	=	beam width

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I. Introduction

Ion thruster is a form of electric propulsion by generating thrust from ion acceleration. Unlike chemical propulsion, electric propulsion, especially ion thruster, has the strength of higher specific impulse (I_{SP}), which means higher propulsion efficiency. Accordingly, it can meet the requirement of deep space exploration mission. The propulsion system, the crux of the entire spacecraft, is by far the most sophisticated among the other subsystems. In addition, it has diverse applications, for instance, breaking through the atmosphere, Hohmann transfer, orbit maintenance maneuver and attitude control, which is highly correlated to the mission life of spacecraft, satellites and space probes.

CubeSats (abbreviation of Cube Satellites) and microsatellites are rising stars in this century due to their advantages on manufacturing, standardization, and cost.[1] Besides, Elon Musk plans to launch a constellation of 4,000 satellites around the globe (also 500-750 miles up) to beam a Wi-Fi signal to the most remote regions, in doing so turning his company into a global communications provider. As a way to reconciling the two facts, budget limitation on science, and curiosity of planetary and deep space explorations, it is foreseen a growing trend towards tiny and lightweight satellites (or a constellation) with correspondingly low power thrusters implemented for orbit maneuver. Therefore, the top priority is to develop a simple, reliable and valuable propulsion system, especially for CubeSats. Although the evidence shows that Pulse Plasma Thruster is the better choice for CubeSats in between VLEO (Very Low Earth Orbit) and LEO (Low Earth Orbit), ion thruster still provides an alternative choice to extend the mission range up to deep space and assist microsatellites to operate a long lifetime independently or coordinate with other space probes. Ion thrusters have been operated for many space missions, such as Deep Space 1 in 1998 from NASA [2-4], Artemis in 2001 from ESA[5], Hayabusa 2 in 2014 from JAXA[6-8] etc. Consequently, a microscale ECR Ion thruster has designed for future applications of miniature satellites in this study.

A micro ion thruster with 80 mm in inner diameter and 94 mm in length adapted to the CubeSat specifications is undertaken. Electron Cyclotron Resonance (ECR) Plasma is generated under 875 G background magnetic field supplied by a solenoid. Ions are initially extracted from plasma generation region to the pre-acceleration region, and further accelerated to the high speed in main acceleration region. The Coulomb acceleration force is provided by a parallel electric field supplied by a sequence of metal grids. In this study, ion gyro-radius is 0.13 cm and testing temperature is closed to ambient temperature.

To enhance the thruster efficiency, ion transparency should be much higher than neutral particle (fuel) transparency in the pre-acceleration region, while ions should be accelerated to higher initial speed before entering main acceleration region. To investigate the combined effects of electric and magnetic fields on ion motion in this region, single particle motion simulation is performed by SIMION software. Ion lensing effect, which reduces ion pitch angle effect and increases the ion transparency, can be raised by increasing thruster boundary potential. Then the optimum pre-acceleration length can be determined to be the same as ion lensing focal length. Furthermore, the solenoid also provides a wall voltage to help increasing ion extraction efficiency. Since there are plasma inside the chamber, cyclotron motion will initiate the chain reaction to enhance plasma density by collision effects between neutral particles and electrons. Thus, electron cyclotron resonance will do the job to accelerate electrons to make a high-density ion source.

II. Plasma Simulation of Single Particle Motion

A. SIMION Numerical Simulation

SIMION, a "leap-frog method" charged particles simulation software, shows the mutual time differential relations between electric field, magnetic field, particle position, and particle speed in a time-domain calculation to simulate how charged particles move inside the ion thruster. SIMION program using direct methods such as finite-difference which is straightforward to apply and capable to optimize and extend makes it suitable for a wide variety of real-world systems.[9-11]

SIMION uses a highly modified fourth-order Runge-Kutta method orientated to fixed distance step integration. And the interpolation inside each style box of array points is to integrate each fixed distance step by solving Laplace's equation shown in Fig 1. The methods are interactive to promote understanding, allowing us to adjust parameters during the simulation and immediately visualize the resultant fields and trajectories.

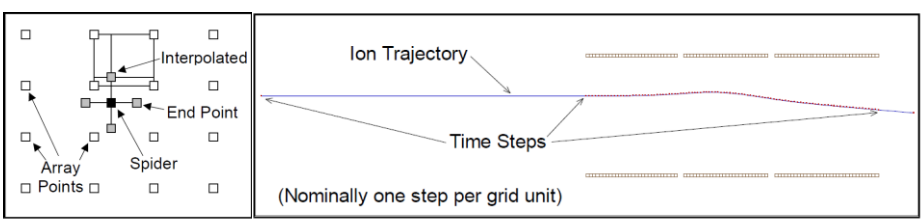


Figure 1. Obtaining field gradients and numerical integration.[9]

B. Model Background

In the model setting and definition of micro ECR ion thruster, this ion thruster is divided into three parts: plasma generation region, pre-acceleration region, and ion optics region. In "plasma generation region", it exists the interaction between neutral particles, free electrons, and charged particles which including the sequence from the neutral gas injection, gaseous ambipolar diffusion, ionization to the ion extraction on screen grid. It's quite complicated to simulate the whole phenomenon in this software in view of SIMION software targeting the field of charged particle trajectories and motions.

To enhance thruster efficiency, ion transparency should be much higher than neutral particle (fuel) transparency in the "pre-acceleration" region, while ions should be accelerated to higher initial speed before entering the main acceleration region (ion optics section). Under investigating the combined effects of electric and magnetic fields on ion motion in this region, single particle motion simulation is performed by SIMION software and the results will act a protagonist to tell us how particles collide and interact with each other among "pre-acceleration" region and "ion optics" region, which is same as the whole region between screen grid, 1st acceleration grid, and 2nd acceleration grid simplified shown in Fig 2. It is assumed to generate plasma before screen grid and extract the ions from generation region to pre-acceleration region. However, pre-acceleration is the intermediate zone to separate neutral particles and ions. And ion optics will be discussed after 1st acceleration grid.

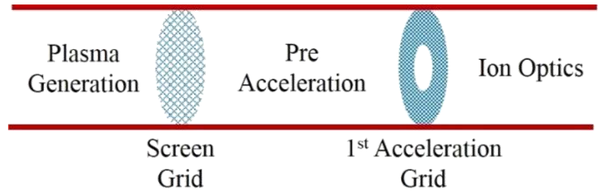


Figure 2. Schematic diagram of three reaction regions.

At the beginning of drawing the potential array, it is very critical to verify the background magnetic field of 875 Gauss provided by the solenoid. In order to simulate a uniform background magnetic field, the geometry size of the magnetic field is set as ten times larger than the geometry size of the static electric field. Here it is assumed to have a full background uniform magnetic field in simulation before manufacturing the whole system. However, it could only be considered as uniform inside the thruster and will diffuse after the last grid in reality. In the end, particle setting is the necessary part of SIMION simulation. Some key parameters can be enumerated for particles definition including number of particles, mass of particles, charge of each particle, the source position of particles, velocity format, direction of particles injection, speed value of particles, time of birth (TOB), charge weighting factor (CWF), and choosing color in case there are couple groups of particle being injected.

C. Configuration of thrusters

In this research, there are two types of micro ECR ion thruster where type1 is four-grids-ion-engine (GIE4), and type2 is a three-grids-ion-engine (GIE3) shown in Table 1 and Table 2, respectively. Type1 includes four grids, and its simulation zone's diameter and length equal to 22 millimeters and 60 millimeters. In comparison, type2 has only three grids, but its simulation zone's diameter and length enlarge to 80 millimeters and 60 millimeters.

Table 1. Configuration of type1 GIE4 thruster.

Total length (mm)	60
— Pre-acceleration section (mm)	10
— Ion optics section 1 (mm)	19
— Ion optics section 2 (mm)	29
Inner diameter (mm)	22
Screen voltage (V)	+5
1st acceleration grid voltage (V)	-100
2nd acceleration grid voltage (V)	-500
3rd acceleration grid voltage (V)	-1000
Wall voltage (V)	+75
Neutralizer (V)	0

Table 2. The Specification of type2 GIE3 thruster.

Total length (mm)	80
— Pre-acceleration section (mm)	25
— Ion optics section (mm)	34
Inner diameter (mm)	60
Screen voltage (V)	+5
1st acceleration grid voltage (V)	-100
2nd acceleration grid voltage (V)	-1000
Wall voltage (V)	+100
Neutralizer (V)	0
Microwave frequency (GHz)	2.45
Microwave (W)	10~30

D. Model Setting

In the definition of initial particle parameters, it is determined to feed group argon particles first which the mass is 40 amu and the charge value is 1e as argon ions. The "source position" determined the injection form of particles, and "single vector" was chosen first for discussing the simulation results of ion pitch angle effect. Then, "line distribution" has been used for calculating the ion transparency and ion extraction efficiency. The velocity format was defined as "direction + speed", "single vector direction" and a "Gaussian distribution speed" which contains mean velocity, standard deviation, and full width at half maximum (FWHM) with the unit of millimeter over microseconds. Furthermore, the micro ECR ion thruster is a continuous system, the thrust created by plasma plume will maintain continuously since electron cyclotron resonance effect initiated. For the purpose of maintaining original system condition, the time of birth (TOB) sets zero, charge weighting factor (CWF) remains one.

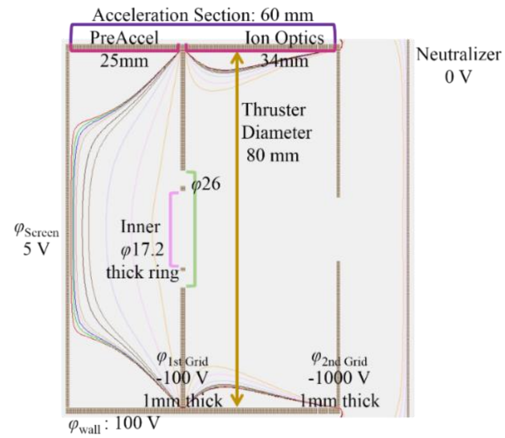


Figure 3. Configuration and potential contour of Type 2 GIE3 thruster.

Electron Cyclotron Resonance Plasma has been chosen as the ion source to avoid the efficiency decay caused by electrode erosion effect. With the goal of having a high ion transparency and to conserve fuel, first, should focus on the ion extraction in the "Pre-Acceleration" region between screen grid and 1st acceleration grid in order to create an ion beam for ion optics, and the "ion pitch angle effect" is the crux. Hence, the procedure of figuring out the key parameters of 1st acceleration grid coupling with ion pitch angle effects starts from setting initial Pre-Acceleration region length "h" to simulate the ion pitch angle transparency of offset on radial Y-direction. By definition, "Ion Transparency" in the Pre-Acceleration Zone is $\eta = N'/N_0$.

Then, optimizing Pre-Acceleration region length "h_{opt}" to simulate the ion pitch angle transparency accompany with a wall voltage, φ_{wall}, providing by solenoid will concentrate the beam width (w). Results showed that decreasing h will reduce the opportunity of ion hitting the wall; however increasing φ_{wall} may cause the ion reflection. It is a contradiction when applying a wall potential higher than both screen grid and 1st acceleration grid, the ion trajectories of line distribution will be confined from nearly columnar to obvious conical, but few lower energy ions will be forced to reflect and bombard the screen grid at the same time. Finally, figure out the "$\varphi_{wall,opt}$" and Ion Extraction Efficiency, of which the ion pitch angle transparency simulated by different φ_{wall} with h_{opt}. Thus, the key parameters of 1st acceleration grid: mesh shape, mesh hole dimension, grid thickness, and its alignment etc. can be confirmed as well.

$$\text{Ion Extraction Efficiency} = \frac{\eta_{ion}}{\eta_{neutral}} = \frac{N'/N_0}{A'/A_0} = \frac{N'_{1st\ acceleration\ grid}/N_{screen\ grid}}{A_{pinhole}/A_{thruster\ cross\ section}}. \quad (1)$$

In this formula, screen grid (density N_0 and cross section area A_0) is a mesh grid for the purpose of segmenting plasma generation region and pre-acceleration region; and the 1st acceleration grid (density N' and cross section area A') is a pinhole grid to extract an ion beam.

In summary, five conclusions are listed between ion pitch angle effect and ion transparency for the phenomenon and results in the pre-acceleration region. First, ion pitch angle effect can be deducted under small offsets. While using line distribution (transparency in real case) to simulate particle motion, ion pitch angle is not the dominant factor. And, ion transparency will increase accompany with the length (h) of pre-acceleration region decreases. Moreover, when applying wall voltage to concentrate the beam width will help increasing ion transparency and decreasing neutral particles transparency simultaneously. Finally, ion extraction efficiency is the dominant point to create an ion beam successfully which also can define the grid's pinhole radius.

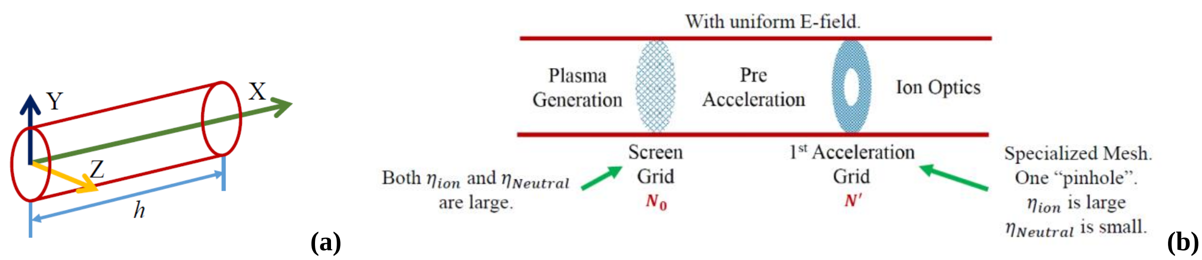


Figure 4. Schematic diagram of a) coordinate system in SIMION, and b) the definition of ion transparency.

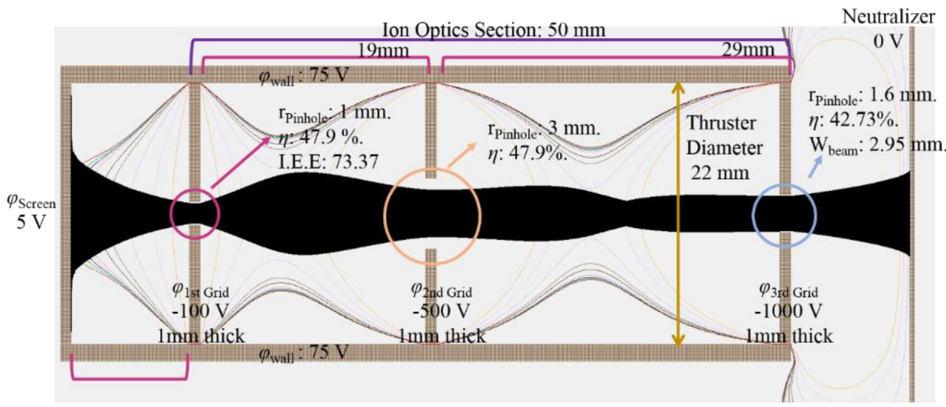


Figure 5. Simulation results of ion optics of GIE4 ion thruster.

3D SIMION simulation results show that the ion transparency is higher than 90% at all pitch angles when the position offset of incident ion is less than 3mm from thruster's axial line. For offset higher than 5mm, ion transparency is zero for all positive pitch angles and less than 30% for negative pitch angles. Ion lensing effect, which reduces ion pitch angle effect and increases ion transparency, can be raised by increasing thruster boundary potential. Then the optimum pre-acceleration length can be determined to be the same as ion lensing focal length. After that, different voltages on several acceleration grids were applied in order to create a potential gradient to implement ion optics between electrically biased grids. Thus, all the GIE4 ion thruster's manufacturing parameters are illustrated shown in Fig.5 above.

The comparison of ion density with thruster diameter, an obvious difference is that when the author tried best to concentrate and accelerate all the ions generated from the pre-acceleration region, there is an innate disadvantage that the phenomenon of ion hitting the wall and ion reflection will decrease the efficiency from the initial condition.

Based on applying wall potential to extract and concentrate the ion beam similar to the mechanism of ion ejection of an accelerator, it will lead to the consequence of existing a ratio in between ion extraction area and initial thruster cross-section area. Evidence shows that Type 1 GIE4 ion thruster will nearly be extracted 10 percent (= $0.5^2/3^2$) ions while Type 2 GIE3 ion thruster can nearly be extracted 40 percent (= $2.5^2/4^2$) ions relative to different thruster's diameter.

In conclusion, the Type 2 "GIE3 ion thruster" shown in the Fig.6 is much better for creating higher thrust density, and also suitable for the specification of CubeSat.

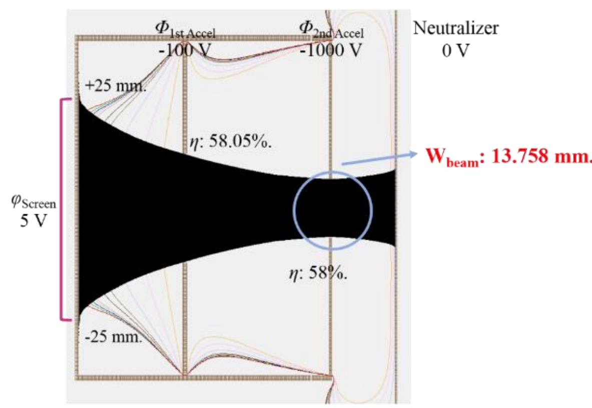


Figure 6. Simulation results of ion optics of GIE3 ion thruster.

III. Results and Discussion

This ECR ion thruster prototype system can be divided into four parts: ion source, acceleration grids, neutralizer and the solenoid. The ECR ion source and acceleration grids are the main components of the thruster. And the neutralizer stands an important status to provide the free thermal electrons emission, to guide the ejected ion beam, and to neutralize it simultaneously. With the flowchart of experiments, there are several experiments in this study: (1) vacuum test, (2) neutralizer test with Molybdenum filament, (3) neutralizer test with Tungsten filament, (4) ion bombardment experiment, (5) experiment of free electron received with magnetic field, (6) searching the direct parameters for ECR effect, (7) potential gradient experiments of biased grids, (8) experiment of ECR ion thruster, and (9) plasma diagnostics.

A. Electron Bombardment Ion Thruster

After pumping down the vacuum chamber for hours, the chamber pressure is detected by ion gauge showing 10^{-4} Torr. Usually, the mass flow rate of argon gas is operated under the range between 3 SCCM to 6 SCCM according to the calculation and several paper references. Since the chamber pressure is checked nearly around 1.5×10^{-4} Torr under experiments, the neutralizer should be checked as the top priority. Neutralizer not only guides the ion beam but also creates the free electron emission as the kindling origin to help ionize neutral argon gas. When it came up to have ion bombardment, the screen grid was applied as a high voltage potential reaching kilo-voltages.

Since there existed some very low ionized rate plasma came from ion bombardment, it is necessary to realize what happened, to observe its stability and continuity, and calculating the ion density. Fig. 7 shows the example that the measurement system was received 500 mA (saturated because of the limitation of the power supply) when neutralizer applied 1.8 Ampere while screen grid was working around kilo-Voltages. The obvious purple light shows the argon plasma plume with around 500 mA. Thus, the "plasma density" of electron bombardment can be calculated by the formulas in below.

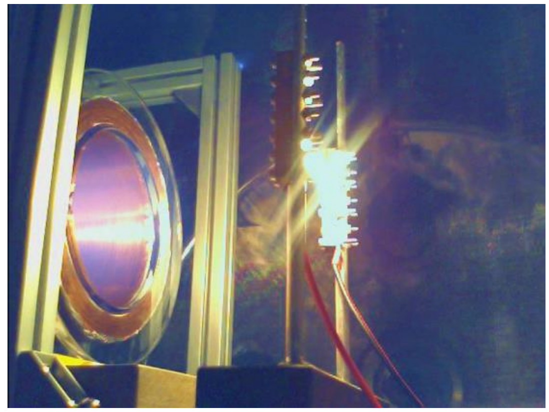


Figure 7. Electron bombardment ion thruster.

The energy equation is:

$$E = \frac{1}{2} m_e v^2. \tag{2}$$

However, the current can be described as:

$$I = eAnv = eAn\sqrt{\frac{2eV}{m_e}}. \tag{3}$$

Hence, the ion density can be calculated as:

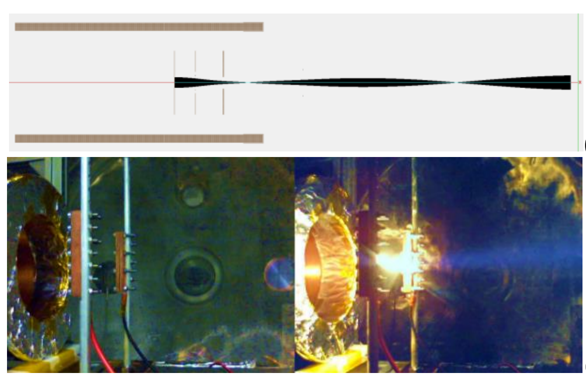
$$n = \frac{I}{eA}\sqrt{\frac{m_e}{2eV}} \cong 7.55 \times 10^7 cm^{-3}. \tag{4}$$

As the value of ion density was known, the thrust force for a singly charged propellant can be calculated as 12.9 milli-newtons. It is quite large for an ion thruster which its thrust was generated by ion bombardment effect. However, the value of thrust, 12.9 milli-newtons, is the summation in all directions. It would be better to apply a magnetic field and concentrate the ion beam in the next experiments for the reasons of fuel saving and preventing the bombardment erosion of screen grid. This ion bombardment phenomenon is similar to turn on the afterburner of aircraft fighters. It can create a highly instantaneous thrust but also waste the fuel a lot. If the free thermal electrons didn't collide the neutral particles to generate ions, the neutral charge argon propellant would be wasted.

Consequently, propellant consumption is the crux of efficiency which affects the mission lifetime. The plasma density of ion bombardment was not quite enough because of two reasons. The first one is the limitation of the power supply can only provide maximum 1000 V and 0.5 mA. If sensor received the display data as 0.5 mA, it actually was under saturation. So the expected plasma density should be higher. Secondly, general ECR plasma has the density from 10^8 to 10^{12} per cubic centimeter. That is the reason why developing ECR ion thruster, not the electron bombardment thruster. Thus, applying magnetic field into the system is necessary. It is no doubt that magnetic field will help concentrate the ion beam but reduce the ion density due to some electron repel phenomenon.

B. Micro ECR Ion Thruster

In the Fig. 8 (a) of SIMION simulation, this was used to check all the assumption including decoupling the thruster's outer wall and solenoid's inner wall, and assuming the plasma only generated in the middle of screen grid where free electrons came from downstream and hit the screen grid causing screen grid quenched after experiments. In fact, the assuming plasma extraction area on the screen grid is closed to the impact area which is almost the same size as second acceleration grid's pinhole. Thankfully, an ECR ion thruster has been initiated and under stable operation as shown in Fig. 8 (b). In the near future, increasing the ion extraction area on screen grid will be the top issue.



(a)

(b)

Figure 8. a) SIMION simulation for ECR ion thruster and b) Initiating an ECR ion thruster.

C. Thrust and Specific Impulse

Thrust is the force supplied by the engine to the spacecraft. Since the spacecraft mass changes with time due to the propellant consumption, the thrust is given by the time rate of change of the momentum. For ion and Hall thrusters, ions are accelerated to high exhaust velocity using an electrical power source. The velocity of the ions greatly exceeds that of any unionized propellant that may escape from the thruster. With several substitution and derivation, the thrust for a singly charged propellant (q = e) is

$$T = \sqrt{\frac{2M}{e}} I_b \sqrt{V_b} \text{ [Newton]} \tag{5}$$

where beam current I_b is in amperes and beam voltage V_b is in volts.[12]

The thrust is proportional to the beam current times the square root of the acceleration voltage. There are three key parameters in this equation: atomic mass, beam current, and beam voltage. Respectively, the thrust can be increased by changing Argon to Xenon (three times atomic mass), increasing beam current from plasma generation, and enlarging beam difference between biased grids. In the case of ion thrusters, there is a spread in beam energies produced in the thruster, and beam voltage represents the effective or average beam voltage. This equation is the basic thrust equation that applies for a unidirectional, singly ionized, mono-energetic beam of ions. The equation must be modified to account for the divergence of the ion beam and the presence of multiply charged ions commonly observed in electric thrusters. The assumption of a mono-energetic ion beam is generally valid for ion thrusters. It is recorded that the sensor on the power supply of screen grid received 40 mA ion beam current.

The thrust of designing ECR ion thruster is: [12]

$$T = \sqrt{\frac{2 \cdot 40 \cdot m_p}{e}} \cdot 0.04 \cdot \sqrt{600} = 895.4 \mu N. \tag{6}$$

Specific impulse, termed I_{sp}, is a measure of thrust efficiency and is defined as the ratio of the thrust to the rate of propellant consumption. Specific impulse for constant thrust and propellant flow rate is: [12]

$$I_{sp} = T / \dot{m_{pro}} g \tag{7}$$

where g is the acceleration of gravity, 9.79 m/s^2 in Taiwan. For an argon ECR ion thruster, the specific impulse is 1025.37 to 3076.11 sec.

For the thrust calculation of argon cold gas flow, the mean speed of argon particles is 8.59 m/s. Hence, the thrust of 1 SCCM argon cold gas flow can be calculated as: [12]

$$F = \dot{m_{pro}} V_e = 2.55 \times 10^{-7} N. \tag{8}$$

During the experiments, the author tried to tune the mass flow rate from 1 SCCM to 3 SCCM which the thrust of argon cold gas flow was in the range of 0.255 μN to 0.766 μN by assuming the gas injection fully filling the plasma generation region. However, it seems no significant difference on thrust calculated by plasma diagnostics between 1 SCCM to 3 SCCM. It could be saturated or the value of ionization rate was very low. It should be studied and solved in the future. In a sentence, according to the thrust from 3 SCCM argon cold gas flow is 0.766 μN which is much smaller than 0.9mN, it can be confirmed that this ECR ion thruster is effective.

IV. Conclusion

It has been successfully developed an ECR ion thruster for space propulsion. Plasma diagnostics of Langmuir probe array, Faraday cup array, and retarding field analyzer will establish to set up an integrated diagnostics of the ion beam. This is the first ECR ion thruster in Taiwan trying to fulfill an electric propulsion thruster for deep space exploration. Furthermore, SIMION simulation used to define the configuration of the thruster and to estimate the ion behaviors, similarly match the experimental observation of ion beam. The achievement of developing an ECR ion thruster for space propulsion with 0.9 mN thrust and 1025 to 3076 seconds specific impulse is a significant breakthrough. Owing to the power utilization and weight punishment from the solenoid, providing a magnetic field for ECR effect, future work will decouple the magnetic field and electric field by replacing the solenoid with cusp magnets and copper foil tape.

Acknowledgments

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