Development of Metallic Ion Thruster using Magnetron Electron-beam Bombardment

IEPC-2019- A-382

Presented at the 36th International Electric Propulsion Conference
University of Vienna • Vienna, Austria
September 15-20, 2019

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Abstract: Metallic Ion Thruster using Magnetron Electron-beam Bombardment (MIT-MEB) is a new type of electric thrusters we are developing. Instead of using inert gas, it uses a solid metal as the propellant. I apply electron-beam evaporation technology and electron impact ionization to the electric thruster. It can use any conductors as propellants. Our metallic ion thruster can be used on deep space exploration because it is possible to collect metallic propellants from asteroids, planets, star dusts, etc. Solid propellants do not need huge gas cylinders. It can also be fitted in a CubeSat. We built a prototype with a size of ~ 5×5×5 cm^3, and a weight less than 500 g. The MIT-MEB concept is never used in any electric thruster and is very competitive internationally. MIT-MEB provides high specific impulse (I_{sp}) like any conventional ion thrusters. Comparing to conventional ion thrusters where inert gas is used as the propellant, the metallic propellant is in solid state, high density, easy to be stored and cheap. Different from the inert gas used in conventional plasma thrusters, the metallic target is in the solid state, high density, easy to be stored and cheap. The design is divided into three parts: a metallic evaporator and an ion accelerator and a neutralizer. The principle of electron-beam (E-beam) evaporation, where a metal target is evaporated and ionized by thermal-emitted electrons, is used. The working condition is independent of the vacuum condition so that it works in the ultra-high vacuum space. A focusing magnet with a magnetic field about 0.2~0.3 T between the target surface and the filament is used to guide electrons toward the center of the target so that the metal is evaporated and ionized. A prototype has been built and tested. The metallic targets were heated to more than 415 °C by electron bombardment. A mass flow rate of $(2.2\pm0.4)\times10^{-4}$ (g/s) and $(1.8\pm0.3)\times10^{-5}$ (g/s) using Zn at 5 kV/3 mA and 1 kV/ 15mA E-beam current was measured. An ionization rate of 0.030±0.008 % and 1.0±0.3 % using Zn at 5 kV and 1 kV E-beam current was measured. Therefore, the estimated thrust is 0.8±0.4 μN and 1.0±0.4 μN with a power of about 25 W. The Estimated I_{sp} is 12,300 s and 5,500 s respectively. Considering the contribution of vapors, the total thrust is 84±20 μN and 8.0±1.4 μN respectively.

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Nomenclature

A	=	heated area
α_e	=	a constant depending on the material
β	=	ionization rate
esbe.V	=	electric potential
e_const	=	elementary charge
E_k	=	kinetic energy
F	=	force (Newton)
F_{th}	=	thrust contributed by vapor
F_{ion}	=	thrust contributed by ion
g	=	gram
HV	=	high voltage
I_e	=	E-beam current
I_f	=	E-gun filament current
I_n	=	neutralizing electrons current
I_{nf}	=	neutralizing filament current
I_{sp}	=	specific impulse
k_B	=	Boltzmann constant
M	=	the atomic mass of the material
m_i	=	atomic mass of ions
$\dot{m}$	=	mass flow rate
$\dot{m}_{metal}$	=	mass flow of metal vapor
$\dot{m}_{ion}$	=	mass flow of metal ions
$\dot{m}_g$	=	gravitational acceleration
me_const	=	electron mass
mf.normB	=	magnetic field strength
P_v	=	vapor pressure of metal
P_h	=	background pressure
q	=	charge
r_g	=	gyroradius
s	=	time in second
T	=	temperature in Kelvin
V_{ev}	=	exhaust velocity
V_{th}	=	thermal velocity
V_{ion}	=	ion velocity
V_f	=	E-gun filament voltage
V_{nf}	=	neutralizing filament voltage

I.Introduction

The principle of an ion thruster is to ionize the gas first then use the electric force to accelerate ions. Therefore, spacecrafts are pushed by reaction forces from ejecting ions. The thrust can be adjusted by changing the electric field strength. Exhausted ions can reach a very high speed so that it is very efficient. This is the most efficient way in rocket technologies that has been put into practical use. Since the specific impulse (I_{sp}), a measure of how efficient propellant is used, is much larger than other existing propulsion technologies, only a small amount of propulsion is required. The total weight can be reduced so that a smaller and economical launch vehicle can be used and the fuel saved is significant.

We invented a new type of ion thruster, that uses a metal target as a propellant. We named it Metallic Ion Thruster using Magnetron Electron-beam Bombardment (MIT-MEB). MIT-MEB and traditional ion propulsions is that we use solid metal targets as propellants. So, first step I have to find a way to make the target change its phase to vapor and must also be able to operate in ultra-high vacuum. The second step is to change the vapor to a plasma. Combining two conditions above, I chose electron-beam (E-beam) evaporation to generate ions. It is because using electrons as working particles can work in ultra-high vacuum and can ionize vapor through electron impact ionization effect.

Electron-beam (E-beam) evaporation uses accelerated electrons bombarding the coating material. The kinetic energy of the electrons is converted into heat and evaporate. Since electron beam heating provides extremely high energy density, materials can be heated to temperatures up to 3000~6000 °C. Therefore, refractory metals or compounds can still be evaporated. However, the E-beam can be deflected by Lawrence force from a magnetic field. Therefore, we can control the bombardment location of E-beam. since that working particles are electrons and come from thermal-emission electrons. They circulate in the loop and can operate in ultra-high vacuum. This means that I don't need to worry about the source of working particles in outer space. Second, electron beam bombardments will ionize the material through the electron impact ionization. Third, electron beam induced secondary electrons and backscattered electrons can further increase the ionization rate. These three advantages make us choose an E-beam evaporation to vaporize the propellant.

II.Physical picture of MIT-MEB

A. Physical picture of MIT-MEB

As shown in Fig. 1, magnetic field lines that pass through the filament are shown. The hot filament is used as the electron source. When the electrons emit from the filament to the anode, they have an electrostatic repulsion tendency to diverge from each other. Since the electrons leave the filament, they feel a huge magnetic field strength. Electrons will be magnetized and follow magnetic field lines. When these magnetic field lines converge to a point on the target, the electrons can be focused on the surface of the target. With the information of electric fields, magnetic fields, gyroradius, ionization we can construct a clear physical picture of MIT-MEB:

(1) The filament as the electron source emits free electrons. (2) Electrons are magnetized by the magnetic field and follow magnetic field lines. (3) Electrons are accelerated by the electric field obtaining kinetic energy and move toward the metallic target along magnetic field lines. (4) Energetic electrons bombard the metallic target and convert their kinetic energy into heat. (5) The target is heated until it becomes vapor. (6) The metallic vapor is ionized through electron impact ionizations when it pass through the region between the filament and the target. (7) The metallic ions are accelerated by the accelerating grid. (8) Ions are neutralized by the neutralizer. (9) Ions as well as electrons leave the thruster with high exhausted speed and provide the thrust.

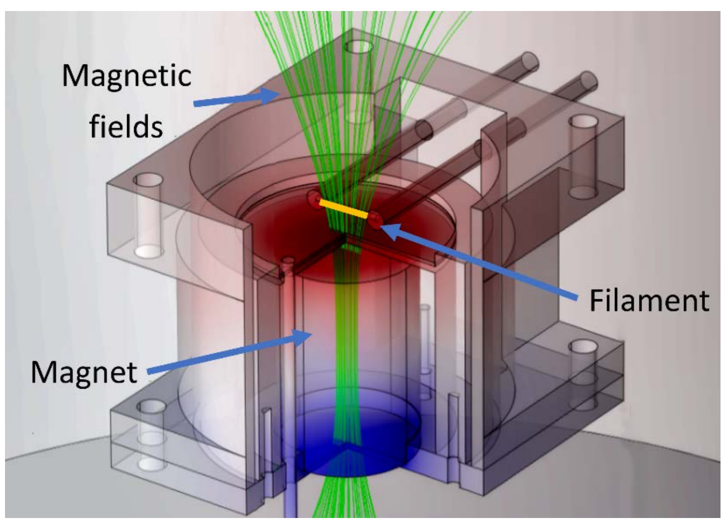

Figure 1. The magnetic field lines pass through the electrons source of MIT-MEB.

B. Prototype of MIT-MEB

The design of MIT-MEB is shown in Fig. 2. The design is divided into three parts: a metallic ion source, an ion accelerator, and a neutralizer.

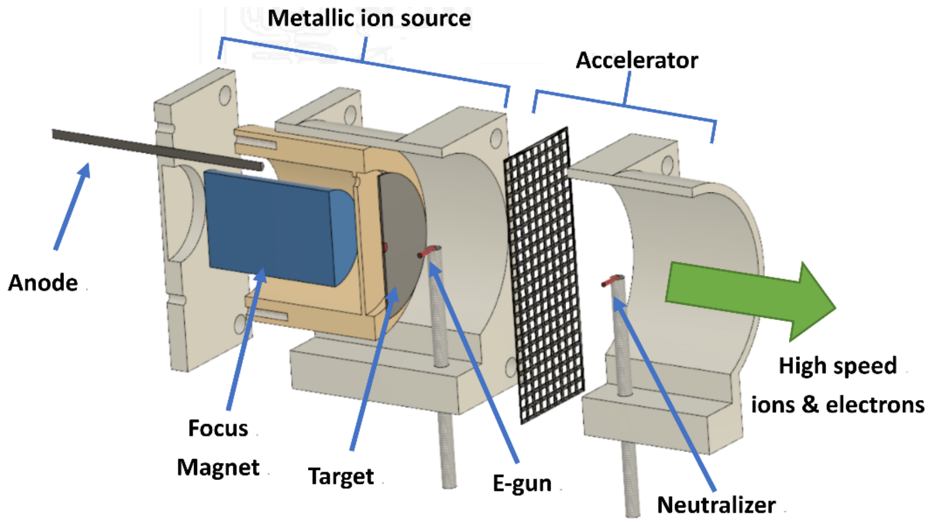

Figure 2. Structural design blueprint of MIT-MEB.

I built two types of prototypes of MIT-MEB with a size of ~ 5×5×5 cm^3, and a weight less than 500 g. Due to the need for high temperature and insulation, I use either quartz or sapphire ceramics as materials for the body of the thrusters. It is because the melting points of quartz and ceramics are 1650 ° C and 2054 ° C, respectively. The density of quartz is 2.65 g/cm^3 and the density of ceramics is 3.97 g/cm^3. Quartz is crystal brittle but transparent So that it is easier for observation. Sapphire ceramic is strong and durable. Both have irreplaceable advantages so I used both to build four prototypes according to different needs. Fig. 3. Shows prototypes of MIT-MEB: (a) is the structure of MIT-MEB (b) is made of sapphire ceramic (c) is made of quartz.

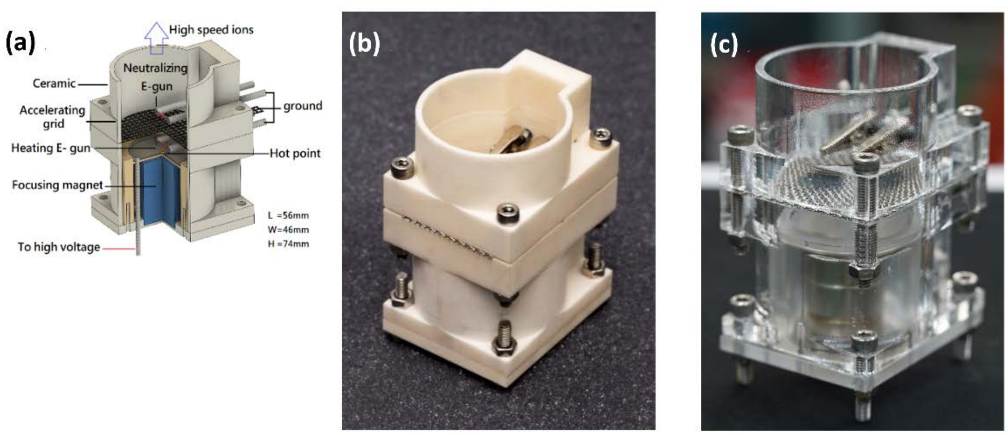

Figure 3. (a) prototype of MIT-MEB (b) is sapphire ceramic (c) is Quartz.

III.Thruster parameter

A. Ion mass flow rate:

The ion generator provides ions needed for the ion thruster. A tungsten filament is placed on top of the metallic target. The tungsten filament will be joule heated to 1000°C ~ 1500°C so that it emits free electrons. We can use Richardson's law to describe the relationship between the emitted current density and the filament temperature. The emitted electrons will be accelerated by high voltage and bombard the solid metal target. Therefore, electrons with high energy transfer their kinetic energy into thermal energy of metallic target. To increase the efficiency of heating the target, electrons will be guided by magnetic field provided by the focusing magnet behind the target. We can control electrons so that they heat a small region on the metallic target and create a high-density electrons cloud on the metal surface. Note that electrons not only come from the hot filament but also from the backscattered and secondary electrons from the metal surface when energetic electrons hit the target. When the metal is evaporated, its vapor will pass through the electron cloud and be ionized by electron impact. As a result, metallic ions are generated. The easier the material is evaporated, the better it is for our ion thruster. How easily the material is evaporated depends on its vapor pressure. If the vapor pressure of the material A is higher than that of the material B at the same temperature, material A is easier to become a vapor than the material B. In other words, the temperature required for the material A will be lower than that of the material B to reach the same vapor pressure. The formula for thermal evaporation is given by:

$$\dot{m}_{metal}\left(\frac{g}{s}\right) = A\times\alpha_e\, 5.84\times10^{-2}\sqrt{\frac{M}{T}}\,(P_v\text{-}P_h), \qquad (1)$$

where $\dot{m}_{metal}$ is the vaporizing mass flow rate, A is the heated area, α_e is a constant depending on the material, M is the atomic mass of the material, T is the heated temperature, P_v is the vapor pressure of the material at temperature T and P_h is the background pressure. Assuming that the heating conditions are the same, the larger the P_v, the larger the mass flow rate of the vapor can be obtained. An alternative way to see this is the lower the temperature to reach the same P_v, the easier to vaporize the material leading to a higher mass flow rate. We use the look-up table to select metals with high vapor pressure as targets. Vapor pressure P_v of common metals is listed in Table 1. It shows that zinc and lead the metal are with the highest vapor pressure at the same temperature and are obtained easily. According to the formula (1) for calculating thrusts, lead can provide us with high thrust because of its high atomic mass. However, it is highly toxic. Therefore, in practical considerations, we chose zinc as the material for experiments. Note that materials with lower melting points does not mean they are evaporated easier. For example, the melting point of tin is only 231.9 °C while zinc needs 419.5 °C to be melted. However, when the tin reaches the vapor pressure of 10^{-3} Torr, its temperature must reach 1315 °C while zinc only needs 565 °C. In other words, zinc is easier to be vaporized. This is another reason that we pick zinc as the propellant.

Material \ T (K) \ PE (torr)	10^{-3}	10^{-2}	10^{-1}	10^{0}	10^{1}	10^{2}
Al ($M = 27.0$ amu)	1162	1269	1396	1552	1760	2022
Fe ($M = 55.8$ amu)	1583	1720	1875	2056	2312	2633
Cu ($M = 63.5$ amu)	1414	1546	1705	1901	2152	2480
Zn ($M = 65.4$ amu)	565	616	678	760	866	1009
Ag ($M = 107.9$ amu)	1209	1320	1457	1626	1848	2138
Sn ($M = 118.7$ amu)	1315	1462	1646	1882	1976	2241
Au ($M = 197.0$ amu)	1589	1738	1919	2140	2427	2794
Pb ($M = 207.2$ amu)	898	991	1105	1248	1440	1690

Table 1. Temperature T in kelvin for different PE in Torr for different metallic materials

Assume that ions leave are all singly charged, i.e., Z = +1, the electron flux equals to the ion flux. Therefore, we can define the ionization rate:

$$\beta \equiv \frac{\dot{m}_{ion}}{\dot{m}_{metal}} \qquad (2)$$

where β is the ionization rate, and $\dot{m}_{ion}$ is the ion mass flow rate. The ionization rate is the ratio between the number of ions to that of the neutral gas so the value of β is between 0 and 1. Therefore, we have total mass flow rate of ions:

$$\dot{m}_{ion}\left(\frac{g}{s}\right) = \beta\times A\times\alpha_e\, 5.84\times10^{-2}\sqrt{\frac{M}{T}}\,(P_v\text{-}P_h) \qquad (3)$$

B. Thrust

The propellant is accelerated and exhausted from the thruster. The thrust is provided by reaction force from the exhausted propellant. Assuming the propellant is accelerated to a specific kinetic energy E_k before being exhausted, the thrust F is given by:

$$F = \frac{d}{dt}(mv_{ex}) = \frac{dm}{dt} v_{ex} = \dot{m} \times \sqrt{\frac{2E_k}{m_i}} \quad (4)$$

where $\dot{m}$ is the ion mass flow rate of the propellant, v_{ex} is the ion exhaust velocity, m_i is atom mass of ions and E_k is the kinetic energy of ions obtained by passing through the accelerating grid. Since ions that are accelerated in the ion thrusters are the main source of thrusts, only ions are considered when calculating the thrust. The thrust F is written as:

$$F = \dot{m}_{ion} \times v_{ion} \quad (5)$$

where $\dot{m}_{ion}$ is Ion mass flow rate, v_{ion} is exhausted ions velocity.

C. Specific impulse (I_{sp})

Specific impulse is a parameter that measures the thrust efficiency. The unit of I_{sp} is in seconds, meaning the time that an 1 kg propellant lasts while keeping 9.8 N of thrust. Specific impulse is only related to exhaust speed of the propellant. It is defined as:

$$I_{sp} \equiv \frac{F}{\dot{m}_g} = \frac{v_{ion}}{9.8} \text{ (sec)} \quad (6)$$

where g is the gravitational acceleration. When the propellant is exhausted with high speed, the I_{sp} is larger meaning higher efficiency. A spacecraft has a higher final speed using a thruster with a higher I_{sp}.

IV.Simulation result of Magnetron E-beam

A. Simulation of the magnetic fields and electric fields

Gyromotion occurs when electrons enter a region with a magnetic field. The gyroradius is proportional to the speed of the electron and inversely proportional to the strength of the magnetic field. If gyroradius is much smaller than the system size, we call the electrons being magnetized by the magnetic field. When the electron is magnetized, it moves along the magnetic field line. I use this principle to control the bombarding region of the E-beam. In order to simulate the distribution of the magnetic field, I need to know the magnetic field of magnets. Therefore, I used a Gauss meter to measure the magnetic field of the magnet. Shown in Fig .4, the Gauss meter was used to measure the magnetic fields of the magnet in the Z-directions. The sensor measures the magnetic field moves in the X-direction. We measured magnetic field strength at 0.92 mm, 1.42 mm, 1.92 mm, and 2.42 mm above the magnet's top surface of Z-direction. The size of each step of the stage is 0.5 mm. Since the magnet is cylindrically symmetrical, we mirror the measurement results to obtain the magnetic field distribution of the entire magnet. The magnet we used is a 1 cm thick neodymium magnet with a diameter of 2 cm. The magnetic field measurement results are shown in Fig. 5.

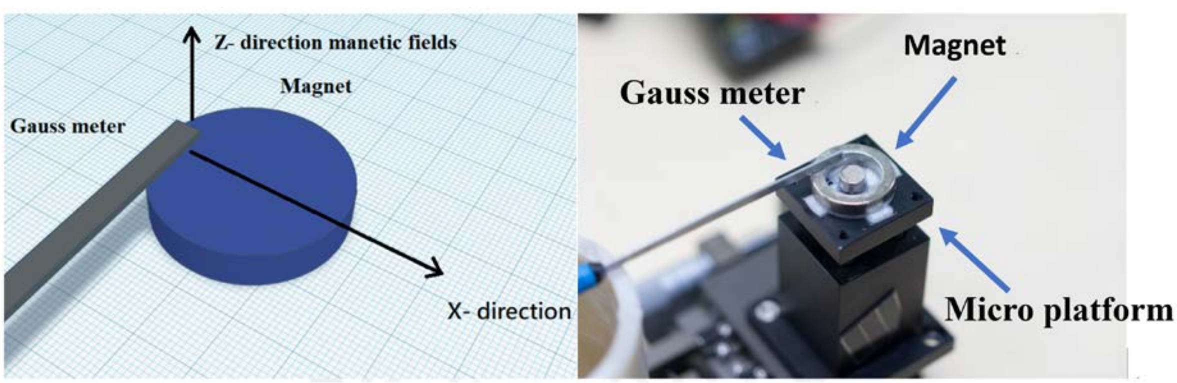

Figure 4. Gauss meter is used to measure the magnetic fields of the magnet in the Z direction.

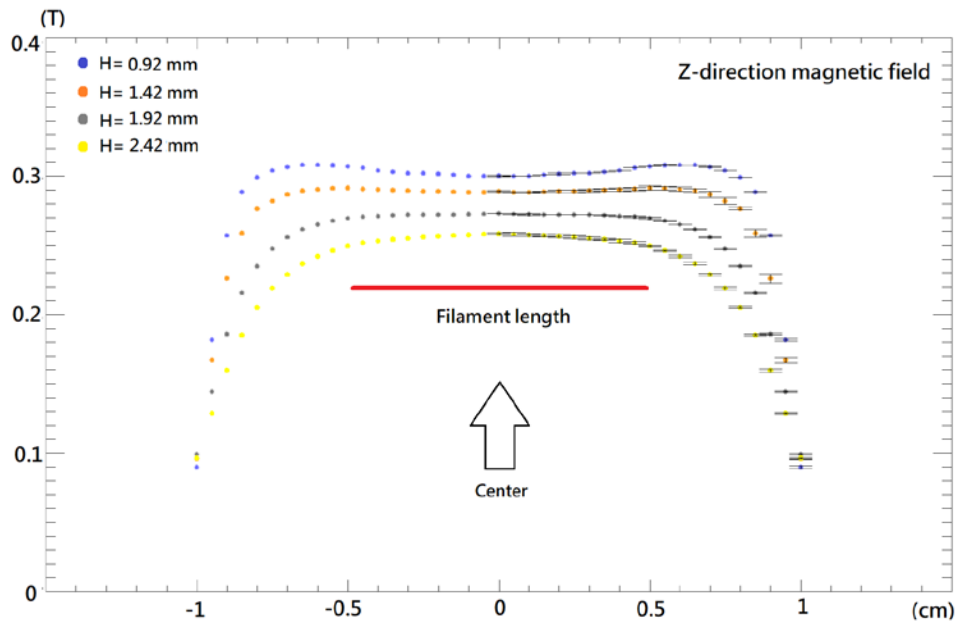

Figure 5. Magnetic fields distribution of Z-direction of the focusing magnet.

I only measured the magnetic field at some important locations which are between the filament and the target. Since the magnetic field of a magnet is only determined by the shape of the magnet and its magnetization, I constructed a magnet in Comsol with the same dimensions to that of the actual one and adjust the magnetization of the magnet to 1050,000 [Ampere/m] to fit the experimental data. Thus, I can construct the profile of the magnetic field in the space. Since we only care about the gyroradius of the electrons in the radial direction, we only simulate the magnetic field in the Z-direction. The comparison between simulations and experiments of the Z-direction magnetic field is shown in Fig. 6 where magnetization 1.05×10^{6} Ampere/m is used in the simulation. Solid lines are from the simulations and points are from the measurements. You can see that both the simulated and measured magnetic fields at the center of the magnet are not the highest meaning simulations catch the same feature of the actual field.

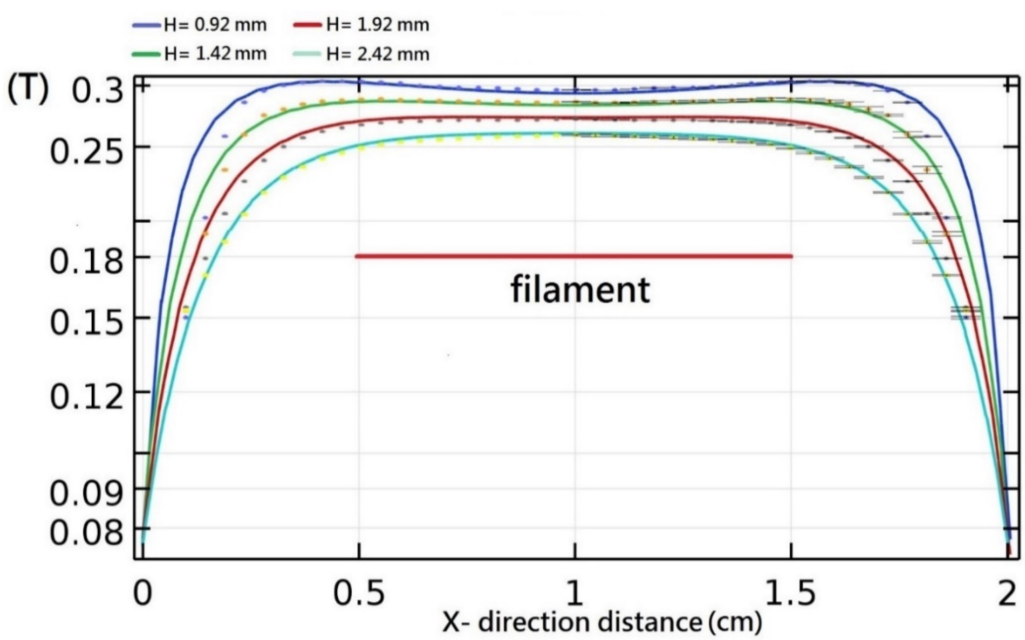

Figure 6. Curve fitting with magnet fields of focus magnet.

The profile of the electric field is obtained by using Comsol to solve the Poisson equation. The metallic target is connected to positive high voltage in order to attract electrons for bombardments. The filament is at ground and the target is at the positive high voltage. The electric field distribution can be easily obtained by taking the negative gradient of the potential. The simulation result of the electric field is shown in Fig. 7. You can expect that electrons move away from the filament and follow the electric fields if there is no magnetic field.

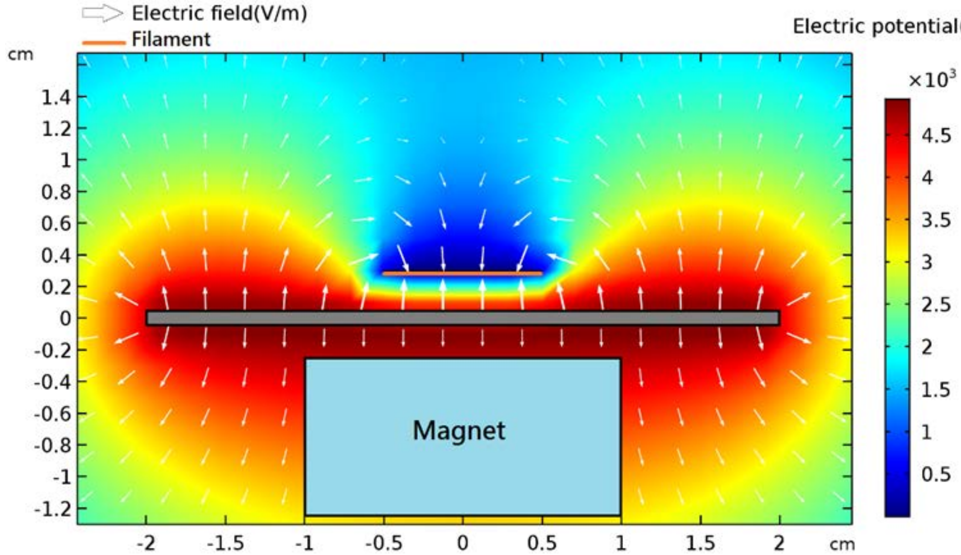

Figure 7. Simulation result of electric field.

B. Calculations of gyroradius

When we get the profiles of electric and magnetic fields, we can obtain the kinetic energy of electrons and the magnetic field strength at any locations. Fig. 8 shows the simulated electric and magnetic fields.

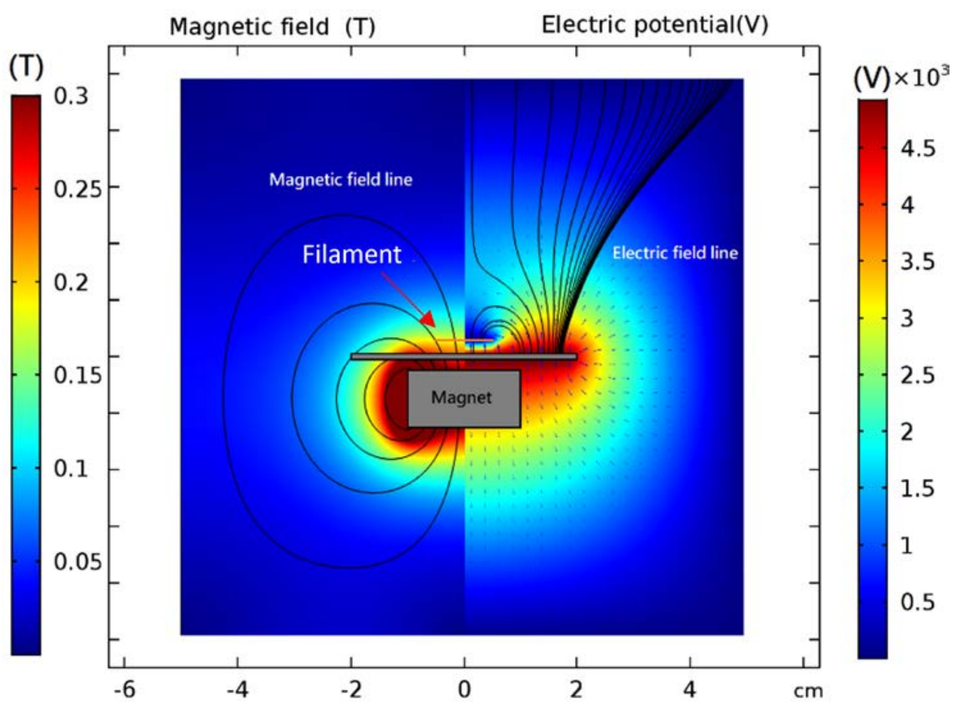

Figure 8. Electric field and magnetic field profile.

Through these two pieces of information, we can calculate the gyroradius when electrons move from the filament to different positions. The potential of the filament is 0 and we know the distribution of the potential. Therefore, the kinetic energy of the electron equals to the potential at the location of the electron, i.e. E_k=e*V. We can then substitute the kinetic energy of the electron into the equation to get the gyroradius. The formula of gyroradius written in Comsol is

$$r_g= ((me\_const)*((2*esbe.V*e\_const)/(me\_const))^{0.5})/((e\_const)*(mf.normB)), \quad (7)$$

where me_const is the electron mass, esbe.V is the electric potential, e_const is the elementary charge, mf.normB is the magnetic field strength. Simulated gyroradius is shown in Fig. 9. You can see that gyroradius is only 0.02-0.1 cm between the filament and the target. The value is much smaller than the scale of the target, 5 cm in diameter. Therefore, electrons are magnetized and move along magnetic field lines.

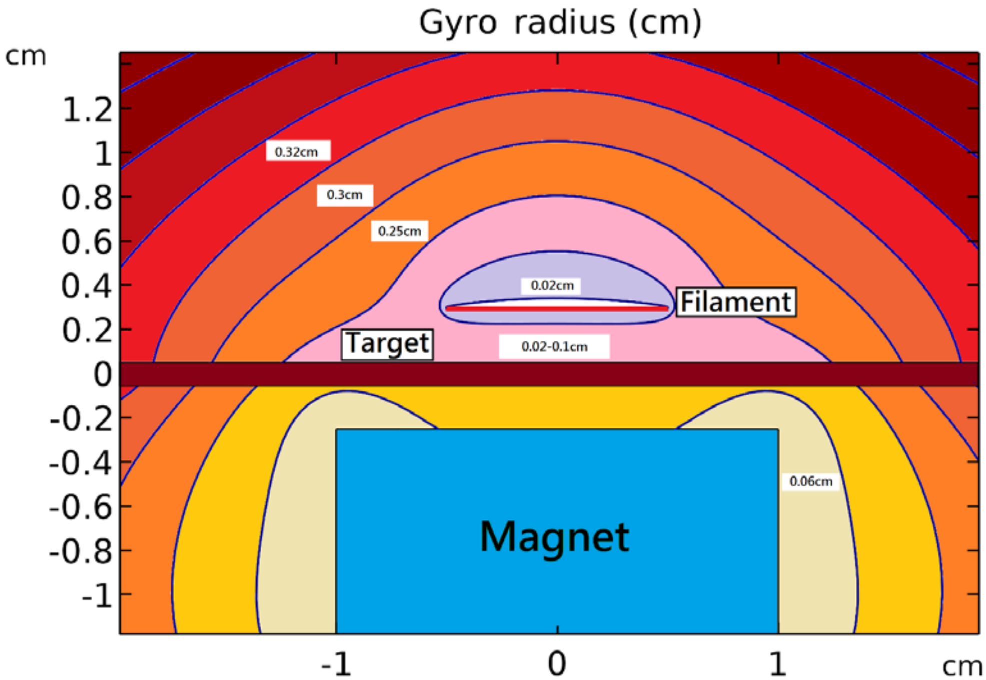

Figure 9. Simulation result of gyroradius profile.

V.Measurement methods

A. Parameter measurements

As shown in Fig. 10, it is the circuit of MIT-MEB. We have measure high voltage (HV), E-beam current (I_e), E-gun filament voltage (V_f), E-gun filament current (I_f), neutralizing filament voltage (V_{nf}), and neutralizing filament current (I_{nf}) and neutralizing electrons current (I_n). Below I will explain the physical meaning of the seven data. (1) HV: the voltage between the E-gun/grid and the metallic target. It is used to accelerate thermal electrons to hit the metallic target and accelerate the ions leaving the thruster. Therefore, HV corresponds to the kinetic energy and speed of electrons and ions. (2) I_e: the current of the high voltage power supply. It should equal to the sum of the electron beam current and the ion beam current. The value of I_e is actually determined by the ability of releasing free electrons of the E-gun filament. The product of HV and I_e is the thrust power consumption of MIT-MEB. (3) V_f: the voltage of the power used to heat the E-gun filament. (4) I_f: the current of the power used to heat the E-gun filament. It is used to control the filament temperature and thus the emitted electron current from the filament. Therefore, by adjusting If, we can control the E-beam current I_e. The product of V_f and If is the total power consumption of the E-gun filament. (5) V_{nf}: the voltage of power used to heat the neutralizer filament. V_{nf} is determined by Inf and the resistance of the neutralizer filament. It is normally ~ 2.45 V. (6) I_{nf}: the current of the power used to heat the neutralizer filament. The product of V_{nf} and Inf is the total power consumption of the neutralizer filament. (7) I_n: It is a current between neutralizer filament and the whole ion source. Since the neutralizer filament will release free electrons, they will follow the ions and leave the thruster. Therefore, theoretically, I_n equals the ion current. However, ions may attract some electrons from the E-gun filament. Therefore, I_n should be less than or equal to the ion current, i.e., the lower bond of the ion current. I use an ammeter to measure I_n in the circuit.

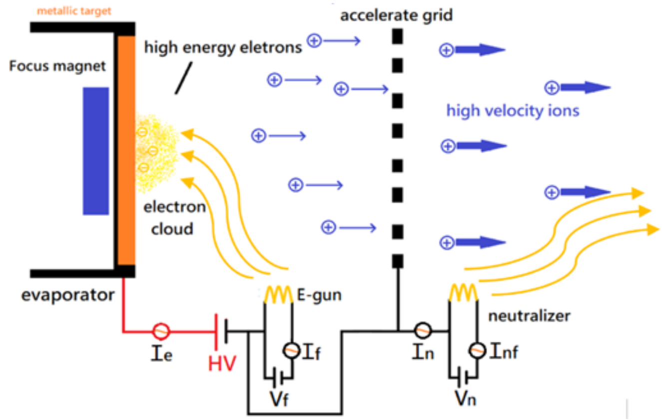

Figure 10. The circuit of MIT-MEB.

B. Evaporation rates

The evaporation rate $\dot{m}_{metal} = \frac{m_i - m_f}{\Delta t}$. In the measurement, by measuring the mass difference of the targets before and after the experiments and the experimental time, we can obtain the evaporation rate. After several tries, we found that the mass difference is 0.1 to 0.001 g after each experiment. Therefore, the precision of the scale must be 0.0001 g. The model of the scale we used is Sartorius TE124S. In order to reduce the error, we measured the target and the evaporator together.

C. Ionization rates

The equation for ionization rate is $\beta = \frac{I_n}{q} \times (\frac{\dot{m}_{Metal}}{M_{Atom}})^{-1}$. Therefore, by measuring I_n and evaporation rate $\dot{m}_{metal}$, we can calculate ionization rate β.

VI.Results

A. Targets after being bombarded by E-beams

When the metallic target is bombarded by electrons, the center of the target is melted significantly as shown in Fig. 11. This proves our simulation results that the magnetic field can well confine the electrons forming an E-beams and guide them to the center of the target. This greatly increases the evaporation efficiency. We can see that the degree of melting from 5 kV accelerating voltage and 3 mA E-beam current (5 kV/3 mA) is higher than that from 1 kV accelerating voltage and 15 mA E-beam current (1 kV/15 mA). We conclude that the higher the accelerating voltage under the same power, the kinetic energy of the electrons can be converted into the thermal energy of the target more efficiently.

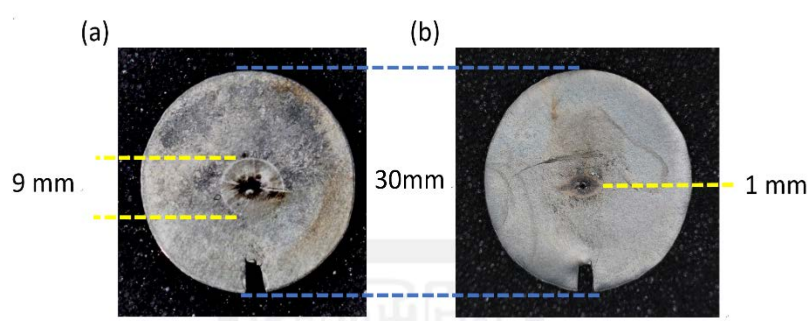

Figure 11. The zinc target is heated by electrons and melted (a) in 5 kV/3 mA/5 min, (b). in 1 kV/15 mA/5 min.

However, if you look closer at the result of 1 kV/15 mA as shown in Fig. 11, you will find that the target is burned out forming a hole with diameter about 1 mm. It seems like it sublimated directly from the solid-state into a gaseous state rather than melting first then evaporating into a gaseous state. This shows that 1-keV E-beam heating effect is better than 5-keV E-beam. It is possible that the smaller the energy of electrons in the same magnetic field, the smaller the gyroradius. So that, the heat was more concentrated.

B. Results of MIT-MEB of 5 kV/3 mA and 1kV/15mA E-beam

In this section I will show the results of MIT-MEB using a 5 kV/1kV accelerating voltage with 3 mA/15 mA E-beam current. All results are averages of 5 sets of experiments and 5 minute. The experimental prototype is shown in Fig. 12.

C. E-beam current with 5 kV/1 kV accelerate voltage

As shown in Fig. 13. The average E-beam current (I_e) with 5 kV is 3±0.1 mA. The average E-beam current (I_e) of 1 kV is 15.7±0.4 mA. Therefore, the power of the electron beam is about 15 W.

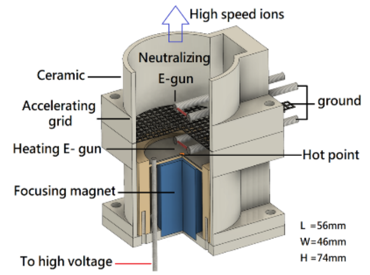

Figure 12. The experimental prototype

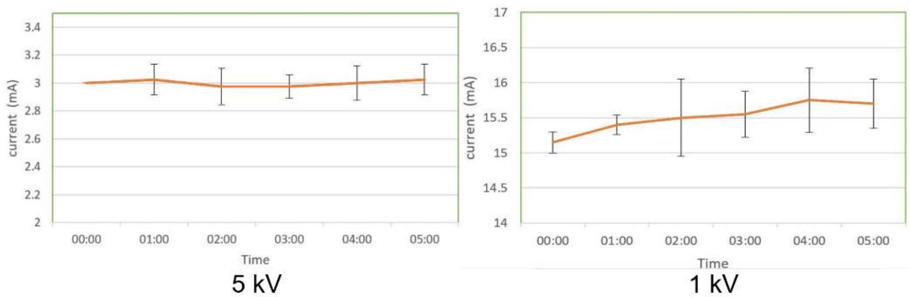

Figure 13. The current curve of the E-beam of MIT-MEB at 5 kV/1 kV.

D. Evaporation rates

At 5 kV/3 mA, the mass different of the target is $(7.0\pm0.8)\times10^{-2}$ (g). The evaporation rate is $(2.2\pm0.4)\times10^{-4}$ (g/s). At 1 kV/ 15 mA, the mass different of the target is $(5.6\pm1.1)\times10^{-3}$ (g). The evaporation rate is $(1.8\pm0.3)\times10^{-5}$ (g/s). As shown in Fig. 14.

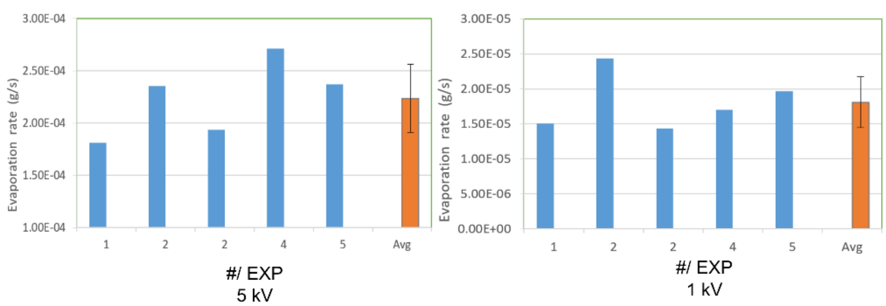

Figure 14. The evaporation rate of the E-beam of MIT-MEB at 5 kV/1 kV.

D. Ionization rates

The current curve of the neutralizer of MIT-MEB is shown in Fig. 15. The maximum 0.11±0.01 mA and 0.27±0.03 mA occurs at the fifth minute. Since In gradually become saturated, we choose the maximum value to calculate. According to formula (2), the ionization rate is

$$\beta = \frac{(0.27\pm0.03)\times10^{-3}}{1.6\times10^{-19}} \div \frac{(1.8\pm0.3)\times10^{-5}}{65\times1.67\times10^{-24}} = 1.0\pm0.3\ \% \qquad (1\ kV)$$

$$\beta = \frac{(0.11\pm0.01)\times10^{-3}}{1.6\times10^{-19}} \div \frac{(2.2\pm0.4)\times10^{-4}}{65\times1.67\times10^{-24}} = 0.030\pm0.008\ \% \qquad (5\ kV)$$

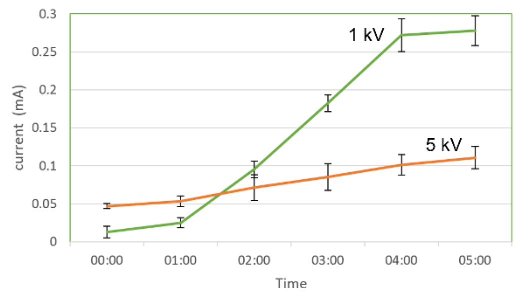

Figure 15. The ionization rate of MIT-MEB at 5 kV/1 kV.

E. Expected thrusts

According to formula (4), the evaporation rate of (2.2±0.4)×10^{-4}(g/s) and the ionization rate of 0.030±0.008%, the theoretical thrust of 5 kV T(μN):

$$F_{ion} = (0.030\pm0.008\ \%)(2.2\pm0.4\times10^{-4}) \times \sqrt{\frac{2\times5000V\times1.6\times10^{-19}}{65\times1.67\times10^{-27}}} = 0.8\pm0.4\mu N.$$

The evaporation rate of (1.8±0.3)×10^{-5} (g/s) and the ionization rate of 1±0.27 %, the theoretical thrust of 1 kV T(μN):

$$F_{ion} = (1\pm0.27\ \%)(1.8\pm0.3)\times10^{-5} \times \sqrt{\frac{2\times1000V\times1.6\times10^{-19}}{65\times1.67\times10^{-27}}} = 1.0\pm0.4\ \mu N.$$

F. Expected I_{sp}

According to formula (6), we can calculate the specific impulse I_{sp} (sec):

$$I_{sp} = \frac{1}{9.8} \times \sqrt{\frac{2\times5000V\times1.6\times10^{-19}}{65\times1.67\times10^{-27}}} = 12{,}300\ sec\ (5\ kV).$$

$$I_{sp} = \frac{1}{9.8} \times \sqrt{\frac{2\times1000V\times1.6\times10^{-19}}{65\times1.67\times10^{-27}}} = 5{,}500\ sec\ (1\ kV).$$

G. Comparison

Comparison of propulsion parameters of MIT-MEB under experimental conditions of 1 kV and 5 kV accelerating voltage is shown in Table. 2. Although the evaporation rate of 5 using kV is 10 times higher than that of using 1 kV, the ionization rate is 30 times lower than that of using 1 kV. This shows that although 5 kV has better evaporation capability, the ability of ionizing gas is lower. This eventually lead to two thrusts almost. I will discuss this phenomenon in the next chapter which seems to be related to the number of electrons and the cross section of different energy electrons.

Condition	*Power*	*Evaporation rate*	*Ionization rate*	*Thrust*	I_{sp}
5 kV/3 mA	25±1 W	(2.2±0.4)×10^{-4} (g/s)	0.030±0.008 %	0.8±0.4 μN	12,300 s
1 kV/15 mA	26.2±0.7 W	(1.8±0.3)×10^{-5} (g/s)	1.0±0.3%	1.0±0.4 μN	5,500 s

Table 2. Comparison of thruster parameters of 1 kV and 5 kV of MIT-MEB under same E-beam power.

VII. Discussion

The experimental results show that the electron impact ionization efficiency with the energy of 1 keV is much higher than that of 5 keV at the same electron beam power (15 W). Although the number of electrons of E-beam at 1 kV accelerating voltage is only five times than that of 5 kV, the ionization rate of using 1 kV accelerating voltage is 30 times more than that of using 5 kV. This shows that other mechanisms cause a huge gap difference in ionization rate between 1 kV and 5 kV. This may be related to the cross section of electron impact ionization for zinc, the number of secondary and backscattered electrons.

A. Cross section of electron impact ionization for zinc

The first ionization energy of zinc is 9.4 eV. This means that the energy of the electrons must be at least 9.4 eV to ionize the zinc atom. When energetic electrons (5 keV is used) collide with the zinc target, about 30 % of them collide with the solid target elastically and are backscattered with the energy of $E_{BSE} \approx 0.51E_0 = 2.55$ keV [5]. Rest electrons collide with the target inelastically and create true secondary electrons, those originally in the solid and are ejected by energies delivered by incoming-energetic electrons, with energies typically less than 15 eV [7, 8]. The true secondary electron yield which defined as the ratio between the secondary electrons to the incoming electrons is more than unity for most materials for incoming electrons with energy in the order of 1 keV or less. The yield goes down to ~ 0.1 when the energy of incoming electrons is in the order of 5 keV or higher [7, 9]. In any cases, secondary electrons, including backscattered and true secondary electrons, are confined by the electric potential and the magnetic field in a small region forming an electron cloud on top of the target surface. Shown in Fig. 16 is the cross section of electron impact ionization for zinc [10]. The cross section peaks at ~ 50 eV according to Tawara and Kato's measurements [11]. Comparing energies of the accelerated and backscattered electrons to the first ionization energy of 9.4 eV for zinc [12] and the energy with the largest ionization cross section, the energy of electrons in the cloud is more than sufficient to ionize atoms. Therefore, it can be seen that the lower the acceleration voltage the better. Not only can the cross section be maximized but also the number of electrons can be increased with the same power. According to the above theory, the ideal E-beam accelerating voltage may fall around 100 V.

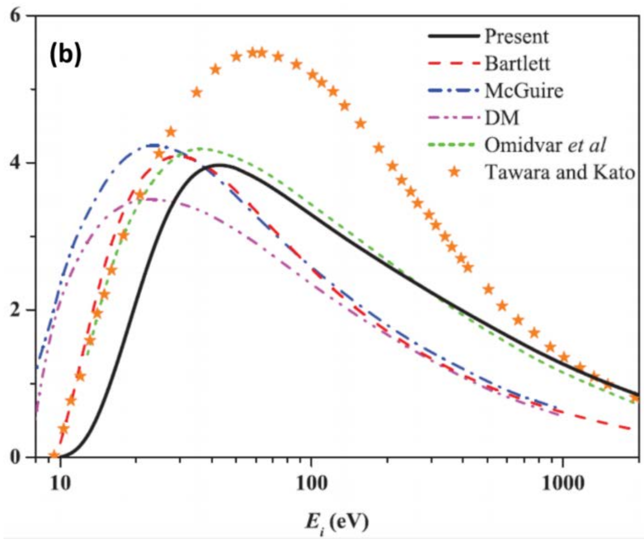

Figure 16. Cross section of electron impact ionization for zinc [10].

B. The contribution of thrust from vapor

The experimental results show that the ionization rate is very low. This shows that more than 99 % of the gas particles are not accelerated by the electric field but are moving at the thermal speed. Therefore, considering the contribution of thermal velocity. $F_{total} = F_{th} + F_{ion}$, we can rewrite Eq. (4) as

$$F_{total} = \dot{m}_{th} \times V_{th} + \dot{m}_{ion} \times V_{ion} ,$$

$$F_{total} = [(1-\beta)\times \dot{m}_{Metal} \times \sqrt{\frac{2k_BT}{m}}] + [\beta\times \dot{m}_{Metal} \times \sqrt{\frac{2E_k}{m}}]$$

where V_{th} is thermal velocity, k_B is the Boltzmann constant, T is the temperature in Kelvin, and m is the mass of a particle. We assume that the temperature of zinc vapor is 300 ˚C because the vapor pressure of Zn is about 0.01 Torr at this temperature. The thermal velocity of 300 ˚C vapor is 381m/s, the corresponding I_{sp} is 38.8 sec. We calculate the thrust of thermal vapor based on experimental data of 5 kV and 1 kV:

$$F_{th} \text{ of 5 kV} = [(99.07\pm0.008\ \%)\times(2.2\pm0.4)\times10^{-4}\times381] = 83\pm20\ \mu\text{N} ,$$

$$F_{th} \text{ of 1 kV} = [(99\pm0.3\ \%)\times(1.8\pm0.3)\times10^{-5}\times381] = 7\pm1\ \mu\text{N} ,$$

and the total thrust is

$$F_{total} \text{ of 5 kV} = (83\pm20)+(0.8\pm0.4)= 84\pm20\ \mu\text{N} ,$$

$$F_{total} \text{ of } 1 \text{ kV} = (7\pm1)+(1.0\pm0.4)= 8.0\pm1.4 \, \mu \text{N} .$$

It can be seen that at the acceleration voltage of 5 kV, the thrust contributed from the vapor is dominant. At an acceleration voltage of 1 kV, the thrust contributed by the steam is similar to the thrust contributed by the ion.

C. Comparisons with other ion thrusters

In Table 3, comparisons between MIT-MEB with some well-known ion thrusters are given [13]. Note that we only calculate the thrust contributed by the ion current. Our thruster is smaller in diameter compared to other ion thrusters but the thrust is comparable to any other ion thrusters with a much higher specific impulse if it is linearly scaled up. The thrusts and the I_{sp} can be increased by simply adding an extra accelerator. It provides the possibilities to explore deeper space such as Moon or Mars missions using CubeSats.

Name	*Propellant*	*Diameter*	*Power (W)*	*I_{sp} (sec)*	*$M_{propellant}$(kg/s)*	*β (%)*	*Thrust (mN)*
MIT-MEB[a] 5 kV	Zn	~ 5	24.8	12,300[i]	2.2×10^{-7}	0.03	0.8×10^{-3}
MIT-MEB 1 kV	Zn	~5	26.1	5500[i]	1.8×10^{-8}	1	1×10^{-3}
13-cm XIPS[b]	Xenon	13	421	2507	7.0×10^{-7}	78	17.2
25-cm XIPS[c]	Xenon	25	4300	3550	4.8×10^{-6}	87	166
NSTAR[d]	Xenon	28.6	577 - 2567	1979 – 3127	N/A	N/A	20.7 - 92.7
T5 Kaufman[e]	Xenon	10	476	3200	5.7×10^{-7}	78	18
RIT-10 RF[f]	Xenon	10	459	3400	4.5×10^{-7}	71	15
μ10 ECR[g]	Xenon	10	340	3090	2.7×10^{-7}	70	8.1
ETS-8 Kaufmanh	Xenon	12	541 – 611	2402 - 2665	8.9×10^{-7}	74	20.9 - 23.2

Table 3. Comparisons between our design to current ion thrusters [13].

[a]Metallic ion thruster using magnetron e-beam bombardments.
[b]Huges 13-cm Xenon Ion Propulsion System (XIPS)
[c]Huges 25-cm Xenon Ion Propulsion System (XIPS)
[d]NASA Evolutionary Xenon Thruster
[e]by Qinetiq in England
[f]Radio-frequency Ion Thruster Assembly
[g]by Japan Aerospace Exploration Agency (JAXA)
[h]Mitsubishi Electric Corporation on the Engineering Test Satellite VIII
[i]The I_{sp} of MIT-MEB only calculate the contribution of ions

VIII.Future work

According to the results of our experiments, the prototype of MIT-MEB has a very low ionization rate. In order to achieve practical purposes, we must increase the ionization rate. We believe that the reason for the low ionization rate is due to the fact that electrons cannot be confined between the target and the grid for a long time. We went through designs of gridded ion thrusters and the Hall thrusters and found that both of them confine electrons for a long time. This is to increase probability of the collision between electrons and vapors. According to the structure of MIT-MEB, I design the corresponding magnetic field trap to confine the electrons. As shown in Fig. 17, I add a ring magnet to confine electrons. Shown in Fig. 18 is the simulated magnetic field where a ring magnet is added above the grid that separates the ion source region and the accelerator region. When electrons propagate toward the target, they may be reflected due to the magnetic mirror effect. For those electrons penetrate through the magnetic mirror point, they will collide and heat the target. Further, for electrons reflected from the magnetic mirror point and backscattered from the target, they first move upward but are reflected back down by the electric potential between the filament and the target.

Furthermore, electrons are confined radially by the magnetic field. As a result, electrons are confined in the triangle region in Fig. 18. The ionization fraction supposes to be increased.

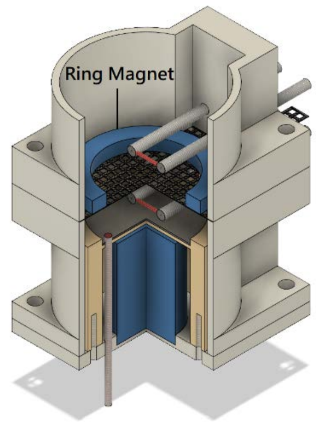

Figure 17. Add a ring magnet to confined the electrons.

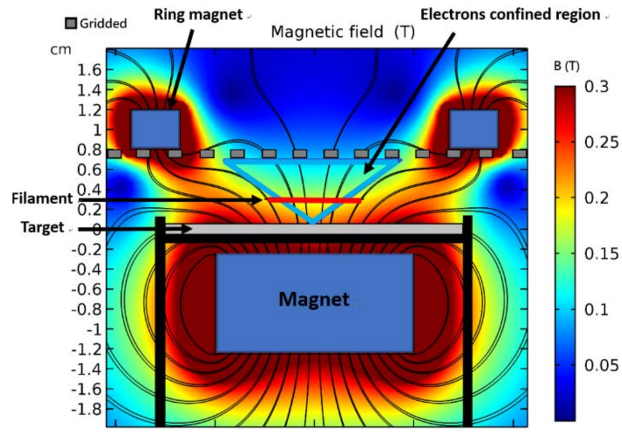

Figure 18. Concept of confining electrons in the gray triangle region using a ring magnet.

IX.Conclusion

It is a new idea of making an ion thruster that is much smaller in size but with comparable performance to any ion thrusters to date. Metallic Ion Thruster using Magnetron E-beam Bombardment uses a metallic target as the propellant. Different from the inert gas used in conventional plasma thrusters, the metal target is in the solid state, high density, easy to be stored and cheap. The design is divided into three parts: a metal evaporator and an ion accelerator and a neutralizer. The principle of E-beam evaporation, where a metallic target is evaporated and ionized by E-beam, is used. A focusing magnet with a magnetic field about 0.2~0.3 T between the target surface and the filament is used to guide electrons toward the center of the target so that the metal is evaporated and ionized. A prototype has been built and tested. The metallic targets were heated to more than 415 °C by electron bombardment. A mass flow rate of $(2.2\pm0.4)\times10^{-4}$ (g/s) and $(1.8\pm0.3)\times10^{-5}$ (g/s) using Zn at 5 kV/3 mA and 1 kV/ 15 mA E-beam current was measured. An ionization rate of 0.030±0.008 % and 1.0±0.3 % using Zn at 5 kV and 1 kV E-beam current was measured. Therefore, the estimated thrust of ions is 0.8±0.4 μN and 1.0±0.4 μN corresponding to 5 kV/3 mA and 1 kV/15 mA E-beam current, respectively, with a power of about 25 W. The Estimated I_{sp} of ions is 12,300 s and 5,500 s, respectively. Considering the contribution of vapors, the total thrust is 84±20 μN and 8±1 μN respectively.

In the future, we have two goals to improve the performance of the MIT-MEB. First, due to the low ionization rate of the prototype of MIT-MEB, we plan to add a ring magnet to confine electrons. Looking forward to increasing the chance of collision between electrons and vapor. Second, we want to use an energy-free electron source to further reduce power consumption and suitable for CubeSat.

Acknowledgments

The work is supported by the Ministry of Science and Technology (MOST),
Taiwan under Award Number 107-2628-E-006-006-MY2.

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