Development of a Microwave Discharge Ion Engine using Multi-Monopole Antenna

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Abstract

On 9/5/2003, the planet probe " HAYABUSA " as MUSES-C project was launched by The Institute of Space and Astronautical Science. "HAYABUSA " has microwave discharge ion engines and these engines are characterized by their high efficiency and specific impulse in comparison with chemical engine. A large ion engine can be used as a planet explorer, while a small ion engine can be used as attitude control of small satellite. We have been developing a high thrust density microwave discharge ion engine using " Multi-Monopole Antenna " .

The performance of this engine are: ion cost of 344W/A, propellant utilization efficiency of 52% and thrust density of 0.055mN/cm^2 for Kr gas flow rate of 2.5sccm, microwave(2.45GHz) power of 32W and acceleration voltage of 1.4kV.

Background

In recent years, many ion engine have been developed and used for the artifical satelite on a geostationary orbit or planetary exploration[1]. The Institute of Space and Astronautical Science (ISAS) developed an electron cyclotron resonance (ECR) discharge ion engine (Fig.1) as an asteroid exploration spacecraft. The thruster utilizes no cathodes for plasma production, so it is relieved from the cathode heater failure that results from the degradation of the cathodes. In addition, the thruster unit consists of one microwave power source, with which quick ignition without any preheating sequence is possible.

These features as well as very simplified power supply units will assure longer lifetime and higher reliability as compared to conventional DC dischage thrusters with cathodes such as hollow ones[2].

Microwave discharge ion engine /HAYABUSA

Microwave discharge ion engine of ISAS has electron cyclotron resonance (ECR) layer that was located near the dischage chamber. Plasma is produced in the ECR layer, then this engine will produce non uniform plasma distribution and predicting the lifetime of this engine's grid is very difficult.

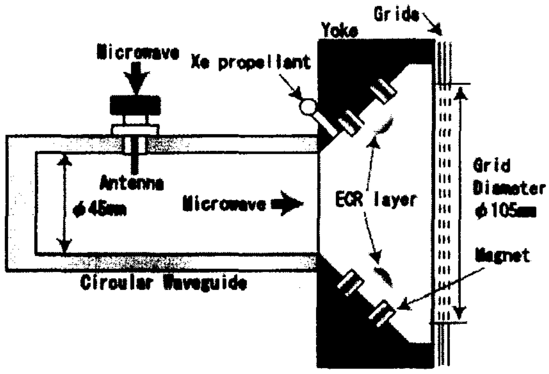

Figure 1: Microwave Discharge Ion Engin of ISAS

One of solutions of this problem is uniform plasma production by extending the ECR layer. However the method of microwave introduction for this engine prevents the microwave from spreading effectively to all over the extended ECR layer. To improve the microwave introduction system is necessary for increasing the thrust density by producing uniform and high density plasma.

Multi-Monopole Antenna

Multi-Monopole Antenna system considenced here is shown in Figs.2 and 3. The antennas are set on the ECR layer. Microwave launched by the monopole antenna is transferred to receiver pins in the divider, and each receiver pin works as a monopole antenna[3]. Thus, microwave can be introduced at any points by Multi-Monopole antenna. The following are characteristics of this antenna.

1. Non contact microwave transfer.
2. Small loss of microwave power in the transfer.
3. Effective distribution of the microwave power among many monopole antennas.

Experiments

Experimental setup

Fig.4 shows an experimental setup adopted here.

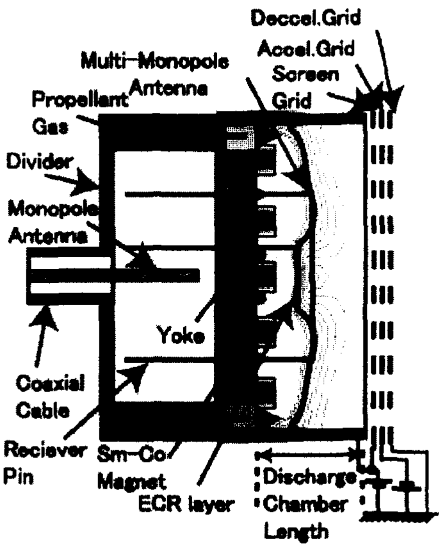

Figure 2: Cross section of Multi-Monopole type Ion Engine

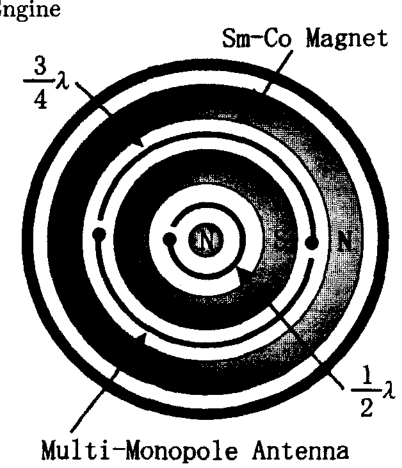

Figure 3: Front view of Multi-Monopole type Ion Engine

The experimental apparatus consists of cylindrical vaccum chamber (inner diameter of 60cm and length of 100cm), 2.45GHz microwave power source, microwave dischage ion engine, and vaccum pumps. The apparatus is run with Ar or Kr gas as propellant. Microwave power is supplied from the power source through a coaxial line to the thruster. An ECR layer in the discharge chamber is genarated by using Sm-Co permanent magnets(Fig.5). Microwave discharge plasma is generated and confined in a magnetic cusp produced by the permanent magnets. Ions in the plasma are extracted and accelerated by electrostatically biased grids (Table 1). The Screen Grid is biased to 1.5kV towards the grounded Acceleration Grid and Deccleration Grid.

The vaccum chamber is evacuated below 5.7×10^{-7} Torr by combination of a turbo molecular pump ($300l$/s) and a cryo pump ($2000l$/s) for the operations of the discharge chamber. When Ar gas flow rate is 2.5sccm, this chamber is evacuated to 2.2×10^{-5} Torr, and when Kr gas flow rate is 2.5sccm, 2.8×10^{-5} Torr is attained in the same condition.

By varying the microwave input power, mass flow rate, grid voltage, and discharge chamber length, we measured the ion beam current and also estimated ion production cost, fuel utilization efficiency and thrust density.

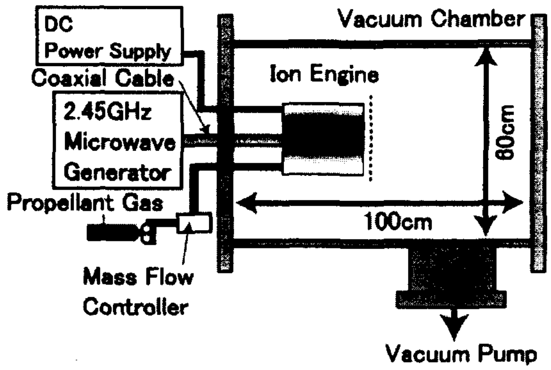

Figure 4: Experimental setup

Table 1: Grid parameter

Material	C/C
Diameter	105mm
Distance between girds	0.5mm
Open ratio	
Screen Grid	67 %
Accel. Grid	24 %
Deccel. Grid	67 %

Configuration of Magnet field

Fig.5 shows magnetic field in the discharge chamber. By varying the discharge chamber length, we have adjusted the distance (important parameter) between the ECR layer and grid.

Ion production cost and propellant utilization efficiency are estimated to examine performance of the ion engine by measuring ion currents through grids with ampere meter of DC power source. Ion Production Cost ϵ_c and Propellant Utilization Efficiency η_c are given as

$$\epsilon_c(\mathrm{W/A}) = \frac{\text{Microwave Power (W)}}{\text{Ion Beam Current (A)}}, \quad (1)$$

$$\eta_c(\%) = \frac{\text{Ion Beam Current (A)} \times 100}{\text{Equivalent Current of Propellant Gas(A)}}. \quad (2)$$

The performance tests between 20mm and 25mm of discharge chamber length are shown in Fig.6. Here $\dot{m}$ is the mass flow rate, V is the grid voltage, and l is the discharge chamber length. Performance of this engine was better with l=25mm than with 20mm. We founded no improvement by increasing the length from 25 to 30mm. Threfore we take up 25mm of discharge chamber length for further study.

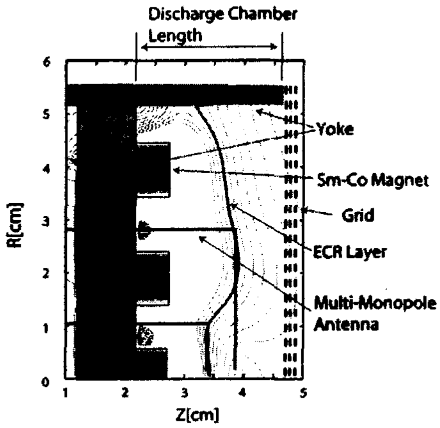

Figure 5: Magnetic field in the discharge chamber

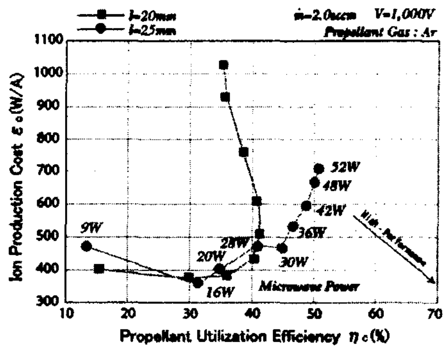

Figure 6: Comparison of thrust performance between discharge chamber length l=20 and 25mm

Probe measurements

The measurement result of plasma density was shown in Fig.7. Here the ions were not accelerated, l is 25mm and propellant gas is Ar. Langmuir probe was set near the grid, because ion was extracted by the grid. At a part of grid area, plasma density attained was over the cut-off density (n_c= $7.5\times10^{10}cm^3$).

Using Kr and Ar as propellant

Thrust performances between propelant gases is compared in Fig.8. With Kr gas, ion engine was more efficient than with Ar gas. Threfore, to use more efficient propellant gas can improve the performance.

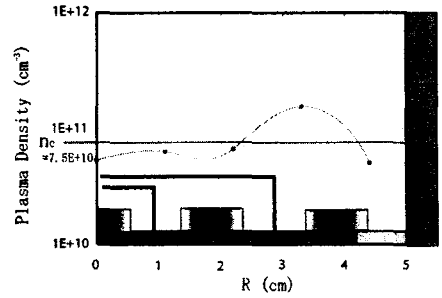

Figure 7: Radial distribution of plasma density

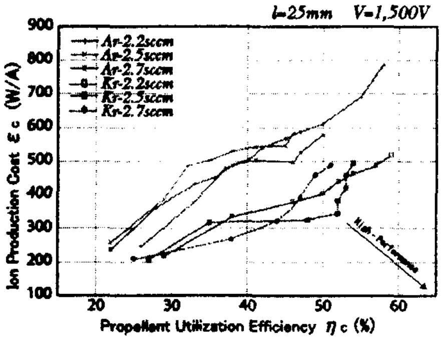

Figure 8: Comparison of thrust performance between Ar and Kr propellant gases

Discussion

As for the discharge chamber length, an adequate value was considered as 25mm. This result was obtained by appropriate plasma production area. For small production area (l=20mm), enough prasma can not be created in this engine, while for large area (l=30mm), plasma loss by the interior of dischage chamber is larger.

As for the plasma density, the highest density area has a density over the cut-off one. The reason is that the electric field of microwave propagates in the plasma by the skin effect. The skin depth d is expressed as

$$d = 1/k_0\sqrt{(\omega_p/\omega)^2 - 1}. \qquad (3)$$

Here k_0 is the wave number of microwave, and it is 8.2 m^{-1} at 2.45GHz. ω_p is the plasma angular frequency, and ω is the frequency of microwave. The skin depth is calculated as 3.3cm for $1.0 \times 10^{11}cm^{-3}$ of plasma density. Consequently the electric field of microwave can be propagated to the measurement position. Radial distribution of density was nearly uniform in comparision with ISAS engine, because the ratio between the highest density to lowest one was improved from 10^2

Table 2: Performance test result of Ion Engine

Propellant Gas	Ar	Kr
Microwave Power(W)	30	32
Gas Flow Rate(sccm)	2.2	2.5
Ion Beam Current(mA)	76.4	93.1
Ion Production Cost(W/A)	393	344
Propellant Utilization Efficiency(%)	48	52
Thrust Density(mN/cm^2)	0.029	0.055

(ISAS) to 2 (Multi - Monopole Antenna).

As for the ion engine performance, using Kr as propellant gas has higher perfomance than using Ar. Discharge ion current was influenced by the ionization energy: Kr (14.00eV) and Ar (15.76eV). The best performance are: ion cost of 344W/A, propellant utilization efficiency of 52% and thrust density of $0.055 mN/cm^2$ for Kr gas flow rate of 2.5sccm, microwave(2.45GHz) power of 32W and acceleration voltage of 1.4kV(Table 2). Here the thrust density is expressed as F/A; the thrust F is given as

$$F = I_b \sqrt{2MV/e}. \quad (4)$$

Here I_b is the ion beam current, M is the ion mass, V is the ion extraction voltage, and e is the elementary charge. Here again, A is the grid area.

Conclusion

In order to create uniform plasma and increase thrust density, Multi-Monopole Antenna was taken up here for Microwave Discharge Ion Engine.

For this engine, radial distribution of plasma density was more uniform than ISAS one, and a part of discharege chamber has a density over the cut-off density. The best performance was thrust density of $0.055 mN/cm^2$, when discharge chamber length is 25mm and propellant gas is Kr.

Further Study

In the future, we will estimate Microwave Discharge Ion Engine using Multi-Monopole Anttena at another conditions as follows.

1. To change the configuration of the Multi-Monopole Antenna.
2. To use Xe gas as lower ionization enegy propellant gas.

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