Feasibility Study on Performance Enhancement Options for the ECR Ion Thruster μ10

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In order to adapt to a wide variety of the space flights, such as small geosynchronous satellites and deep space explorers, feasibility study of performance enhancement options for the microwave discharge ion thruster μ10 is underway. Authors are considering the following five options: 1. Lower insertion loss DC blocks; 2. Direct monopole antenna insertion to the discharge chamber without using a circular waveguide part; 3. Optimization of gas injector layout which was originally located deep in the waveguide; 4. Additional magnet rings aiming ion loss reduction to the side wall of the discharge chamber; 5. New ion optics consists of a thinner screen grid and a smaller-hole accelerator grid. Not all but most of them have already been tested and reported in this article. The original models for Hayabusa asteroid explorer generated 8 mN at maximum. Larger thrust generation was impossible even if propellant flow rates and microwave powers were increased. It turned out to be feasible to increase the maximum thrust to a range of 10 – 11 mN with above mentioned options by supplying more flow rates and/or more microwave powers.

\textbf{Key Words:} Electron Cyclotron Resonance, Ion Thruster

1. Introduction

Japan’s Hayabusa asteroid explorer, launched on May 9, 2003, has executed the orbit maneuver using ECR discharge ion engines “μ10,” which have electro-static grids of effective diameter 105 mm and established 30,500 hours the total numbers of space operational time to generate accumulated total impulse of 0.79 MN·s by the end of 2007\textsuperscript{1}. In order to adapt to a wide variety of the space flights, such as small geosynchronous satellites (1 – 1.5 tons in GEO) and deep space explorers (Hayabusa-2), feasibility study of performance enhancement options for the μ10 is underway.

The essential part of the thruster design of original μ10 for Hayabusa was frozen in 1997. The ion source showed beam current saturation to the excessive supply of propellant and microwaves. To overcome the saturation and extend the thrust range, authors are considering the following five options: 1. Lower insertion loss DC blocks with improved mechanical strength.
2. Direct monopole antenna insertion to the discharge chamber without using a circular waveguide part.
3. Optimization of gas injector layout which was originally located deep in the waveguide and might prevent high thrust operation at higher microwave powers and xenon flow rates.
4. Additional magnet rings aiming reduction of ion loss to the side wall of the discharge chamber.
5. New ion optics consists of a thinner screen grid and a smaller-hole accelerator grid.

The first four options have already been experimentally evaluated. Fig. 1 shows the original and the new (laboratory model) DC blocks. The new one has an insertion loss of 0.2 dB which is 0.3 dB smaller than the original one. This will slightly improve electrical efficiency of the thruster only if the beam current is lineally increased as a function of microwave power input, though the original μ10's tendency was not so.

Options No. 2 and 3 are breakthroughs in the μ10 development history and thrust range has been extended over 10 mN. Improvement by the option No. 4 turned out very small, so the result will not be reported here. The option No. 5 were partly evaluated using only the new accelerator grid. The thinner screen grid have already fabricated and will soon be tested to increase extracted ion current fraction.

In this paper several small design changes will be proposed for thrust enhancement which may extend the application of μ10 from just station keeping of small satellites to orbit raising, broaden launch windows of deep space missions and increase number of reachable target minor bodies. The design changes should be as minor as possible to avoid repetition of cost and time consuming additional qualification process.
2. Experimental Apparatus

Table 1 shows the specifications of the Hayabusa μ10. The upper half of Fig. 2 and Fig. 3 show cross sectional views of the waveguide-type μ10 used in this work. 8 gas injectors were added to the original Hayabusa μ10, which had only one injector deep in the circular waveguide. These new injectors were made by tapping M3 threads to the aluminum magnet spacer. Inside of the spacer works as a gas manifold and there is only one inlet for all these new injectors outside the side wall of the discharge chamber. The injectors can be equipped with gas deflector attachments to survey the effect of gas injection direction on thruster performance as illustrated in the figure. They can be plugged with setscrews, if necessary. Injection direction and number of injectors were experimental parameters. Flow rates to the original injector and new injectors were individually changed using two mass flow controllers. The lower half of Fig. 3 shows the new microwave launching design using a quarter wavelength monopole antenna directly inserted into the discharge chamber. This compact ion source has 16 gas ports around the antenna and flow directions are along the diverging chamber wall surfaces.

Original accelerator grid of the μ10 has apertures whose diameters are 1.8 mm as summarized in Table 1. In order to increase the mass utilization efficiency, a new grid with smaller apertures was designed and fabricated. Its aperture diameter was as small as 1.5 mm but severe direct impingement of ion beams were not expected based on the more challenging attempt on the ion thruster μ20 with much smaller accelerator apertures whose diameters are 0.9 – 1.3 mm\(^3\). Open area fractions of the original large hole accelerator grid (LHAG) and the new small hole accelerator grid (SHAG) are 24% and 17%, respectively. Neutral atoms leakage from the discharge chamber will decrease to 69% of the original. For example, if the mass utilization of the LHAG configuration is 70%, then application of the SHAG may recover it to 77%.

Thruster performances were obtained after at least 30 minutes continuous firing for warming up. Background pressure was \(5 \times 10^{-4} – 2 \times 10^{-3}\) Pa depending on the total xenon flow rates. Microwave powers in the following experimental results were calibrated and defined at the antenna input point.

![Fig. 2. Front view of the waveguide-type discharge chamber that illustrates the gas ports locations in azimuthal direction for gas distribution experiments.](image)

![Fig. 3. Cross sectional side views of waveguide-type (upper) and monopole-type (lower) μ10 that illustrate gas injector and microwave launcher configurations. The original model of μ10 has the only injector at a) position. Deflectors were attached onto the threaded injectors a) to change the flow direction such as b) – e). Monopole-type has 16 gas distributors f) around the antenna.](image)

Table 1. Specifications of the Hayabusa μ10.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tbody>
<tr>
<td>Beam diameter (mm)</td>
<td>105</td>
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<tr>
<td>Microwave frequency (GHz)</td>
<td>4.25</td>
</tr>
<tr>
<td>Microwave power (W)</td>
<td>32</td>
</tr>
<tr>
<td>Screen voltage (V)</td>
<td>1470, 1530</td>
</tr>
<tr>
<td>Accelerator voltage (V)</td>
<td>~330</td>
</tr>
<tr>
<td>Decelerator and neutralizer voltage (V)</td>
<td>~30 (Constant current operation)</td>
</tr>
<tr>
<td>Nominal xenon flow rate (sccm)</td>
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<tr>
<td>Nominal beam current (mA)</td>
<td>130 – 150</td>
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<tr>
<td>Nominal thrust (mN)</td>
<td>8</td>
</tr>
<tr>
<td>Specific impulse (s)</td>
<td>3100</td>
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<tr>
<td>Mass utilization efficiency</td>
<td>0.85 (Ion source only)</td>
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<tr>
<td>Screen grid thickness (mm)</td>
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<tr>
<td>Accel. grid thickness (mm)</td>
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<tr>
<td>Decel. grid thickness (mm)</td>
<td>1.0</td>
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<tr>
<td>Number of apertures</td>
<td>855</td>
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<td>Screen aperture diam. (mm)</td>
<td>3.05</td>
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<tr>
<td>Accel. aperture diam. (mm)</td>
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<td>Decel. aperture diam. (mm)</td>
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<td>67%</td>
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<tr>
<td>Accel. open area fraction</td>
<td>24%</td>
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<tr>
<td>Decel. open area fraction</td>
<td>48%</td>
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3. Results and Discussion

3.1. Baseline performance of the original model

Fig. 4 shows the baseline performance of the original μ10. The flow rate of 2.2 sccm is the optimum that maximize ion beam current at any given microwave powers. At the optimum flow rate, increasing microwave power higher than 30 W is almost worthless because the ion beam current shows saturation behavior. In deep space missions, it is important and essential capability for the electric propulsion system to change the power consumption as a function of solar distance and resulting solar power generation. For example, Hayabusa's μ10 was throttled down from 8 mN(350W) to 6 mN(250W) according to the solar distances from 0.8AU to 1.7AU, by changing xenon flow rate with keeping microwave power of 32 W. The problem is that the beam current jumps in the flow rate range between 1.9 and 2.1 sccm as shown in Fig. 6. In this range thrust fluctuation induced by bang-bang pressure regulation of the propellant management unit is the largest. The fluctuation of the ion engine system power makes it difficult to make full use of available spacecraft power in deep space missions.

3.1. Compact ion source with a center monopole antenna

This new configuration as shown in the lower half of Fig. 3 had excellent microwave matching capability. The reflection was always less than 2 W even during idling mode in which beam acceleration is stopped and plasma discharge is maintained. With the original thruster the reflection in such condition exceeds 6 W. Smaller reflection reduces heat dissipation of the microwave feed lines and increases system reliability. Fig. 5 indicates that the beam current increases as the microwave power increases and no saturation was observed. The optimum flow rate was 2.6 sccm. When the microwave power of 41 W was supplied, the maximum thrust of 10 mN (170 mA) was obtained. Ion beam current as a function of xenon flow rate is almost linear as shown in Fig. 6, which is another advantage to the original design.

Fig. 4. Beam current as a function of microwave power for the original μ10 with a waveguide.

Fig. 5. Beam current as a function of microwave power for the compact μ10 with a center monopole antenna.

Fig. 6. Flow rate throttling of the original and the monopole thrusters at a microwave power of 30 W.

Practically, switch to the monopole design is impossible because the antenna inserted in the discharge chamber requires endurance test. However, this experiment was very informative and suggest that the extreme saturation characteristics of the original design are inherent in the μ10's waveguide.

3.2. Flow rate distribution between a waveguide gas port and an inter-magnet gas port

Another configuration with additional gas ports as shown in Fig. 2 was tested. Flow rate ratio of the waveguide gas port to one of the inter-magnet gas ports in the same azimuthal angle ($\theta = 0$) was changed as 1:0, 1:2 and 0:1. For each distribution ratio there is an optimum total flow rate that maximize ion beam current. The optimum flow rate increases as the flow...
rate fraction of the inter-magnet gas port increases. At the microwave of 30 W the largest beam current of 168 mA was obtained when the flow rate ratio was 0:1. At the power of 37 W the champion data of 178 mA was recorded when the flow rate ratio was 0:1 and the total flow rate was 3.4 sccm. Generally, mass utilization efficiency at the beam current peak is higher when the flow rate fraction of the waveguide port is higher. Thus we should determine the optimum flow rate distribution depending on the maximum ion beam current required. If intermediate ratio other than 1:0 and 0:1 is demanded, flow divider that can adjust the distribution ratio has to be developed.

Fig. 7. Flow rate throttling curves for different flow rate distributions of a waveguide gas port and one of inter-magnet gas ports ($\theta = 0$) at a microwave power of 30 W. The flow rate ratios in the figure are “waveguide” : “inter-magnet.”

3.3. Number of injectors along with the azimuthal direction

In the next experiment some of 8 gas injectors (Type “a” of Fig. 3) between magnets were used. Number of active injectors was changed by plugging unnecessary ports with setscrews. Number of injectors and azimuthal locations of selected injectors had a small effect on the performance. Two gas ports at the azimuthal angles 0 and 180 degree showed best throttling curve.

Figures 9 and 10 show plasma luminosities taken with the same camera settings. The pink luminosity at the center region is the feature of the waveguide injection and was not clearly observed in the inter-magnet-only gas injection cases below the critical flow rate that maximize the beam current. It seems that the ignition of the pink center plasma prevents the further beam generation at larger flow rates.

Fig. 8. Flow rate throttling curves for different combinations of inter-magnet gas injectors (Type a) at a microwave power of 30 W.

Fig. 9. Plasma luminosities of the waveguide-only gas injection (left) and inter-magnet-only gas injection (right) at the same beam current of 135 mA. Operating conditions are 30 W, 2.2 sccm and 30 W, 3.3 sccm, respectively.

Fig. 10. Plasma luminosity of the inter-magnet-only gas injection at peak beam current operations. Operating conditions were 168 mA, 30 W, 3.47 sccm and 187 mA, 44 W, 3.47 sccm, respectively. A bright spot on the inter-magnet gas port ($\theta = 0$ deg.) was obvious.
3.4. Small hole accelerator grid

The small hole accelerator grid improves neutral atoms confinement in the discharge chamber and reduces required propellant flow rate. Fig. 11 shows such improvement by the employment of the SHAG. Accelerator drain currents were almost the same as the original large hole accelerator grid. So the beam ions do not seem to impinge the grid directly. Because the inter-magnet gas injection shows lower propellant utilization efficiency, combination with the SHAG is promising.

Fig. 11. Flow rate throttling curves for three different gas injection methods with a large hole (1.8 mm) accelerator grid and with a small hole (1.5 mm) accelerator grid at a microwave power of 30 W.

3.5. Injector directions

Effects of the injector directions were investigated as shown in Fig. 12. Dummy deflectors were attached to evaluate the plasma loss effect by the immersed deflectors in the case of waveguide-only injections. The types b) – e) had deflectors immersed into the plasma as depicted in the upper half of Fig. 3. Considering that these losses will reduce 10 mA of ion beam current, injectors directly formed onto the magnet spacer for a), b) and c) directions so that no plasma loss happens would result in similar performances as in the Fig. 12 a). Injections to the downstream directions like types d) and e) were the worst.

3.6. More microwave powers

Throttling curves shown in Figures 7, 8, 11 and 12 have inefficient gentle slope portions. These can be eliminated by increasing microwave powers as shown in Fig. 13. In order to recover the mass utilization loss in the high thrust operations by the new gas injection methods, discharge power should be increased. The largest beam current so far demonstrated is 187 mA corresponding to the thrust of 11.1 mN.

Fig. 12. Flow rate throttling curves for different gas injection directions.

Fig. 13. Flow rate throttling curves for different microwave powers using the original large hole accelerator grid (LHAG).

4. Conclusion

The original well-tuned μ10 ion thruster can generate 8 mN at a specific impulse (including neutralizer flow) of 3100 s with consuming 30 W of microwaves and 2.2 sccm of xenon flow. Design change of gas injector layout has the large impact on thrust enhancement. The highest thrust of 10 mN can be generated when all the xenon flow of 3.47 sccm was injected from two 3-mm diameter gas ports in the direction normal to the local chamber wall surface. Mass utilization efficiencies are decreased from the original μ10’s value of 86% down to 68% (Isp = 2550 s) if the microwave power is limited to 30W. The mass utilization efficiency can be improved by 3 – 5% by using a small hole accelerator grid.
whose aperture diameter was decreased from 1.8 to 1.5 mm. If microwave power is increased to 44 W, the maximum thrust of 11.1 mN so far demonstrated can be generated at the same flow rate with a mass utilization efficiency of 75% (Isp = 2840 s).

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References