Thrust Measurement of an Ion Engine System

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A thrust measuring device using the gas bearing method was designed and constructed. Direct thrust measurement of an ion engine, using argon as a propellant, was carried out in a vacuum chamber. The thruster components were placed on a floating turntable supported axially and radially by a gas bearing for friction-free rotation. The measured thrust was 83% of the value calculated from the beam current and the accelerating potential.

Nomenclature

E	= output voltage of thrust detector
E_c	= supply voltage to power supply unit
F	= thrust of the ion engine
f	= actually detected force using differential transformer
h_0	= floated gap
J_B	= beam current
J_B^*	= equivalent beam current
L	= arm length of z axis torque
l_1, l_2	= moment arm length for rotation
ΔM_0	= increment of angular momentum at pitch axis wheel without beam ejection
ΔM_1	= increment of angular momentum at pitch axis wheel during beam ejection
m_i	= mass of propellant
P_0, P_1, P_x	= lubricant gas pressure
P_2	= pressure of the vacuum chamber
P_s	= supplied lubricant gas pressure
Q, Q_1, Q_2, Q_3	= lubricant gas flow rate
R_0, R_1, R_2	= radius
R_x	= distance from gas supply hole
S	= pumping speed
Δt	= beam ejection time
V_n	= net accelerating voltage or screen voltage
V_n^*	= equivalent screen voltage
W	= load
α	= sensitivity of thrust detector
μ	= gas viscosity
η	= efficiency of power supply unit

Introduction

AN ELECTRON bombardment ion engine was studied for an attitude or a position control device for artificial satellites. In September of 1982, a 5 cm diam. ion engine in the Japanese Engineering Test Satellite-III was launched in a 1000 km high circular orbit. Tests using this engine started from November 1982.

The thrust force of the ion engine can be calculated theoretically by production of an accelerating potential and a beam current. However, double-charged ions and the divergence of the ion beam cannot be neglected in evaluating the actual thrust. These effects reduce the value of the theoretically calculated thrust force. Measurement of the thrust on the ground may be rather difficult. In space, ion thrust can be obtained by measuring variations of the revolutional speed of a momentum wheel on the ETS-III satellite.

This paper presents the results of direct thrust measurement on the ground using a thrust stand and a small, lightweight power supply unit. The ground test data are compared with the space data.

Components of the System

Ion Engine

The ion engine used for the thrust measurements was originally designated for the performance evaluation of a 5 cm diam. mercury propellant ion engine with hollow cathodes. The engine was modified by replacing the hollow cathodes with filament ones for simplicity. This reduced the number of power supply units necessary. As a propellant, argon was selected instead of mercury. It was stored in a tank with 1 atom. pressure. When a flow rate of 1×10^{-2} Pa.m^3/s was set during a one-h experiment, 10% of the stored propellant was consumed. The flow rate was adjusted before the experiment and the flow was controlled by a solenoid valve.

Power Supply Unit

The following five power units were required for operating the ion engine:

1) A filament heater unit for emitting thermal electrons.
2) A discharge unit for bombarding neutral particles and changing them to charged particles.
3) A screen unit for accelerating positive ions.
4) A neutralizer filament heater unit for electron emission.
5) An accelerating unit for preventing electrons emitted by the neutralizer from going to the thruster.

A power supply unit for providing these potentials was designed and constructed (Ref. 1). The power source was a silver-zinc secondary battery. The battery cells were contained in a pressure vessel. The power supply unit was a DC-DC converter type. It changed primary DC power to required potentials with high efficiency. Sufficient consideration was given to the possibility of a high voltage breakdown due to outgas from the power supply unit under vacuum.

Figure 1 is an electronic circuit diagram with its specifications. The left portion of the diagram is the self-oscillating driver, the central portion is the power amplification stage, and the right is the rectification portion. T_1 and T_2 are driver and power transformers. E_c is a supply voltage to the unit from the secondary battery. Five outputs were delivered to each terminal of the thruster. The power supply unit was box-shaped. Its dimensions were 15 cm wide,

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10 cm long, and 8.5 cm high. The case was coated with black epoxy resin. The weight of the power supply unit was 1.2 kg.

The output waveform of the screen voltage and its ripple are shown in Fig. 2. The data were obtained by connecting a dummy load instead of the thruster. The ripple was $2V_{pp}$ at the nominal beam current ($J_B^* = 30mA$). Since the beam current was modulated by the ripple of the screen voltage, the ripple should be minimized. Variation in the output potential and efficiency when the output current is changed is shown in Fig. 3. Here, V_n^* decreases with an increase of J_B^*. A feedback loop for controlling is not added. Therefore, monitoring of the screen voltage and the beam current is necessary for calculating electrical thrust. The output of the heater power unit was not rectified because the voltage drop of the diode was great and the power loss at the diode was not neglected. Figure 4 shows the efficiency of the power supply unit (PSU) when the supply voltage was changed. This measurement was made in order to investigate the changes which occur in the output voltage of the secondary battery. A constant efficiency was obtained for a range of ±10% of the nominal value.

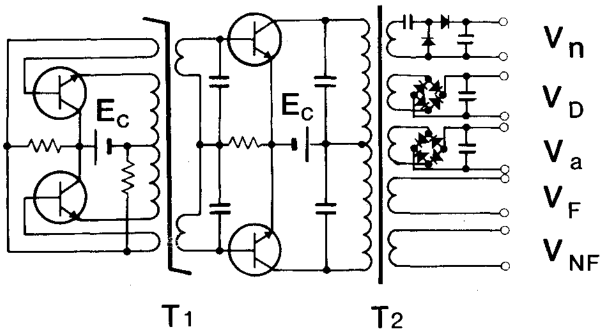

Fig. 1 Circuit diagram of power supply unit; V_n screen unit (1200 V, 30 mA); V_D discharge unit (60 V, 0.5 A); V_a accelerating grid unit (450 V, 1 mA); V_F filament heater unit (10 V, 5 A); V_{NF} neutralizer filament heater unit (10 V, 6 A).

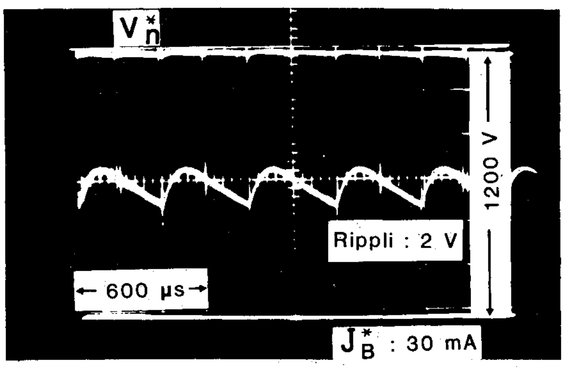

Fig. 2 Output waveform of screen unit.

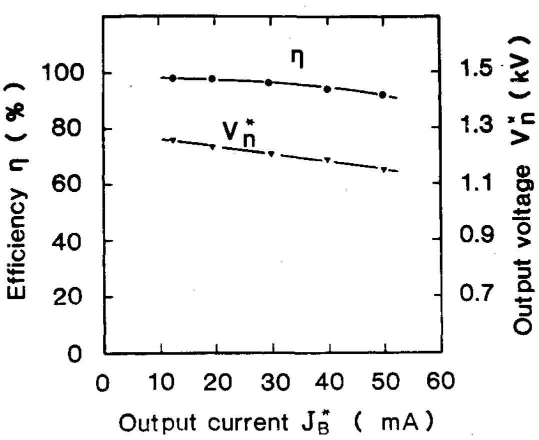

Fig. 3 Characteristics of screen unit.

Thrust Stand

Direct thrust measurement was attempted using a gas bearing device. In order to achieve a friction-free condition, the thruster system with the necessary power supply units must be isolated from the measuring devices. The requirements for an ion thrust measuring device have been given previously (Refs. 2 and 3)

1) to measure a small thrust of 0.01-0.1 g,
2) to sustain a system weight of about 20 kg, and
3) to not harm the ion engine operation.

A preliminary test of the thrust measuring device was made. Figure 5 shows a sketch of a thrust bearing for the test. The test was carried out in a vacuum chamber. In this figure, lubricant gas is introduced from a gas inlet and ejected through a central hole of the thrust bearing. It floats the inner cylinder. The gas is pumped through a groove which runs concentrically along the surface of the bearing before it passes into the vacuum chamber. The pressure distribution of the thrust bearing was monitored by six pressure transducers, as shown in Fig. 6. The capability of the thrust bearing was investigated by changing the number of dummy weights. In this figure, the lubricant gas is introduced at R_0 with a pressure of P_s while the gas is pumped at R_1. If it is assumed that the gas flow is isothermally viscous, and that pressure drops linearly, the amount of escaped gas Q_2 and the load

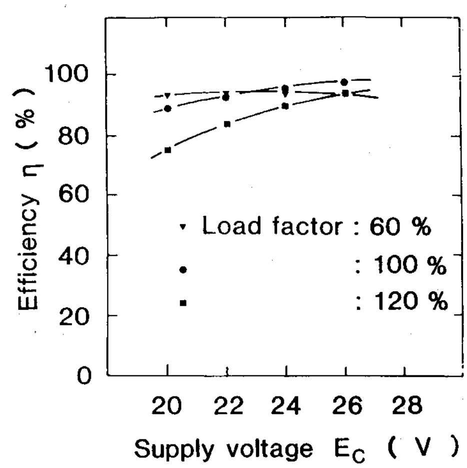

Fig. 4 Characteristics of power supply unit.

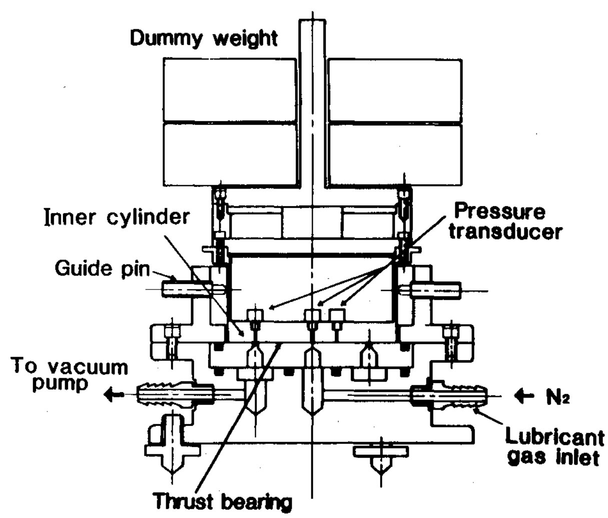

Fig. 5 Preliminary thrust stand.

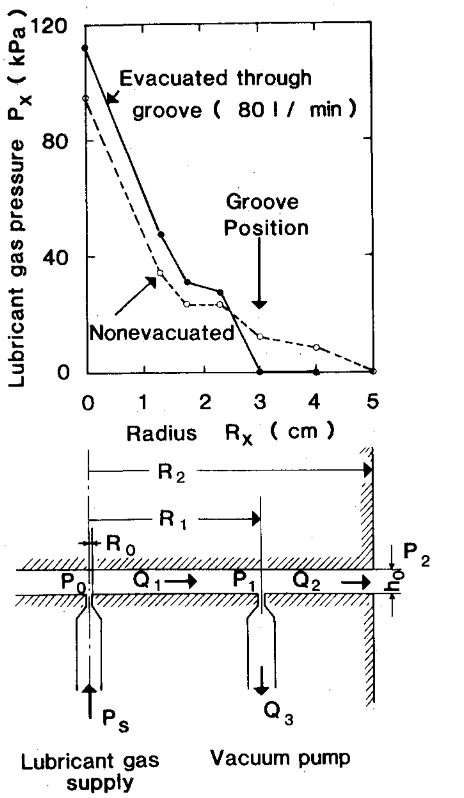

Fig. 6 Actual pressure profile with a detailed sketch of the thrust bearing.

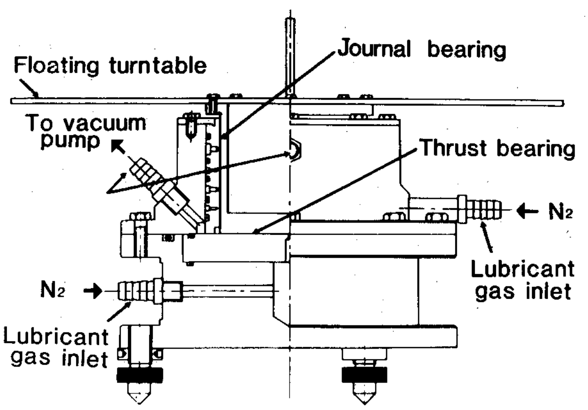

Fig. 7 Thrust stand.

capability of the bearing can be estimated as follows

$$Q_1 = h_0^3 (P_0^2 - P_1^2) / 12\mu \ln(R_1/R_2) \tag{1}$$

$$Q_2 = h_0^3 (P_1^2 - P_2^2) / 12\mu \ln(R_2 R_0) \tag{2}$$

$$Q_3 = P_1 S \tag{3}$$

$$Q_1 = Q_2 + Q_3 \tag{4}$$

$$W = \pi (R_1^2 P_0 + R_1 R_2 P_1) / 3 \tag{5}$$

During the test, the pressure in the groove decreased greatly, as shown in this figure. This prevented the gas from flowing into the vacuum chamber. A similar effect was expected for a journal bearing.

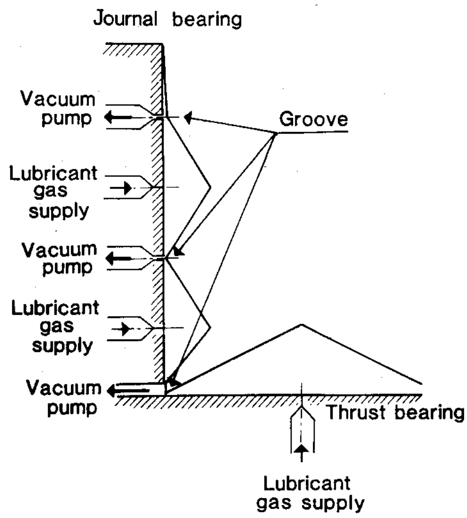

Fig. 8 Imaginary inner pressure profile.

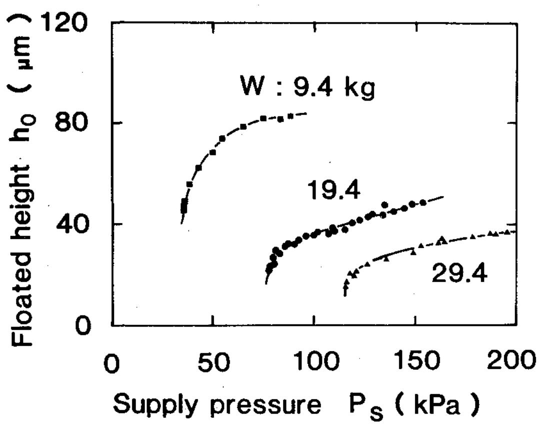

Fig. 9 Load capability of thrust stand.

Figure 7 shows the thrust stand, the design of which was based on the preliminary test. A turntable was fixed on a rotational cylinder.

Figure 8 shows the inner pressure distribution of the thrust stand. It is easy to understand the function of the thrust and journal bearings. The former floats the ion engine system and the latter supports it horizontally under friction free conditions. Figure 9 shows the load capability of the thrust bearing. A weight of 29.4 kg can be handled by this bearing with a supply pressure of 150 kPa. Figure 10 shows how gas which entered into the vacuum chamber was trapped by the grooves. Only 0.1% of the gas actually entered the chamber.

Thrust was detected by differential transformer, using the null method. Calibration was carried out at atmospheric conditons before the transformer was placed inside the chamber. The disturbances torque of the bearing resulted in a rough surface finish or bad boring of orifices was not generated.

Telemetry and Command

The beam current and accelerating voltage of the operating system was transmitted by the frequency modulated technique. Other telemetry data was not monitored, since only two FM channels were provided. Operation of the system was controlled by turning a light on and off. A photodiode received the light and drove a relay for the PSU and a valve for the propellant feed tank.

Integration

Power could not come from outside the thrust stand, since the external rotational force and feeder friction distorted the

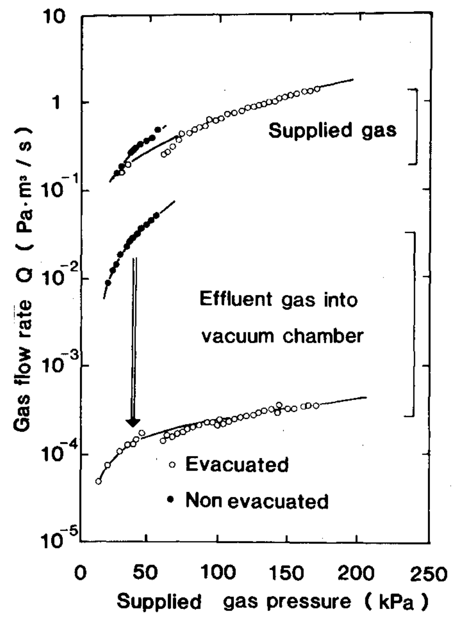

Fig. 10 Effect of evacuation through grooves.

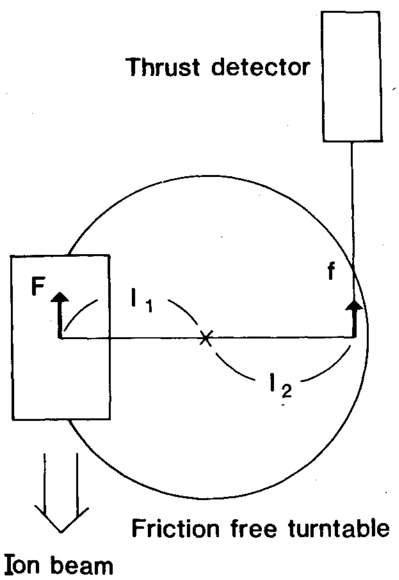

Fig. 11 Principle of thrust measurement.

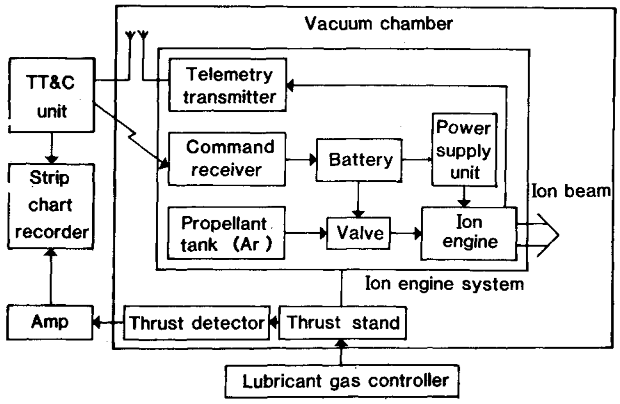

Fig. 12 Block diagram of thrust measurement.

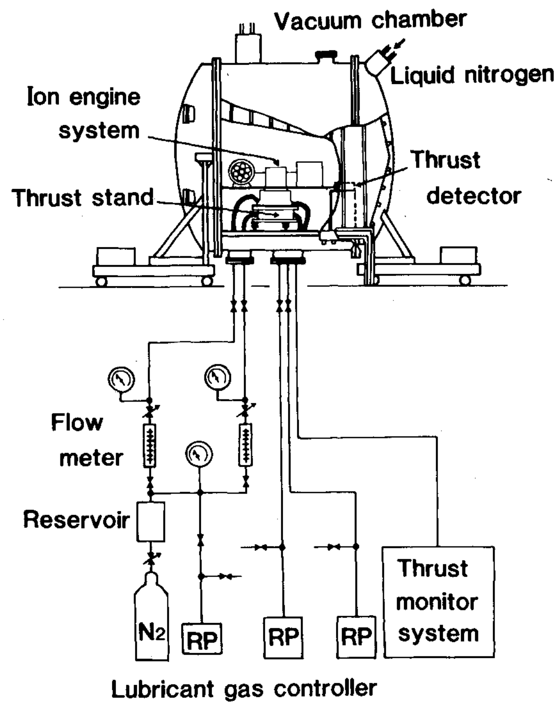

Fig. 13 Schematic diagram of equipment for lubricant gas control.

measurements. Thus, the ion engine, power conditioner, battery, telemetry transmitter, which communicated the performance data of the system, and a command receiver were carefully placed on the table to keep the rotor against the thrust stand. The layout of the subsystem was determined by balance considerations. Output cables from the power supply unit were connected to the engine. When a photodiode received light, the PSU was switched on. Since a fine wire drawn from the center table was connected to a facility ground, the beam current returned to the power supply.

The total weight, including the rotor and the turntable, was 20 kg. The weight breakdown of the ion engine system was:

Ion engine	1.35 kg
Power supply unit	1.2 kg
Battery	6.32 kg

The ion thrust was measured by torque detection (Fig. 11). The ion beam was ejected toward the tangential direction of the table. Let the distance from the center of the table to the ion engine be l_1 and the distance to the torque detector be l_2. Then the thrust force is:

$$F=fl_1/l_2 \tag{6}$$

$$f=\alpha E \tag{7}$$

$$F=\alpha El_1/l_2 \tag{8}$$

The theoretical thrust of the ion engine obtained from the net accelerating voltage V_n and the beam current J_B is:

$$F=2m_i/eV_nJ_B \tag{9}$$

Figure 12 shows the test block diagram. Figure 13 shows the lubricant gas controller with the vacuum chamber. The flow rate of lubricant gas was adjusted by a flow meter and the gas was introduced into the thrust stand installed in the vacuum chamber. The gas floated the engine system and it was evacuated by rotary pumps (RP). The chamber itself was evacuated by a 32 in. diam. oil diffusion pump with an effective pumping speed for nitrogen of 5000 l/s.

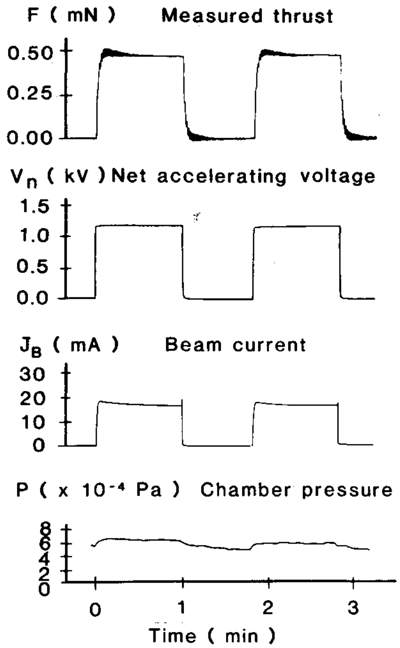

Fig. 14 Test results.

Results and Discussion

The ion thruster was operated by a lightweight power supply unit on a floating turntable. The pressure inside the vacuum chamber was maintained below 1×10^{-3} Pa. The telemetry data on the beam current J_B and screen voltage V_n which was obtained are shown in Fig. 14, with the real thrust F. It was found that the ion engine responded immediately after the command light was turned on. The measured thrust was 55 mg, which was 83% of the calculated value. Tests were repeated 15 times and no significant difference in the thrust level values was observed. The difference between the measured thrust value and the calculated one is considered to result from beam divergence, double-charged ions, and measurement error. There are many reports about double-charged ions and beam divergence (Refs. 4, 5, 6, and 7). However, it is not easy to evaluate such errors numerically and such an analysis is beyond the scope of this paper. Since the space test of the engine on the ETS-III has been carried out, the ground test data obtained can be used in comparison. ETS-III is a satellite with a three-axis stabilized device. A change in satellite attitude from ion beam ejection is obtained by a variation in the revolution speed of a momentum wheel. The thrust generated by the ion engine is calculated by the change. When one of the thrusters is operated, the angular momentum is stored on a pitch axis wheel. When the ion thruster is not operated, the varation of the angular momentum at the pitch axis wheel is considered to be slight, since the contribution of other disturbances is negligible. The thrust is obtained by the following equation

$$F = (\Delta M_l - \Delta M_0)/L\Delta t \tag{10}$$

The ratio of thrust force obtained from the ETS-III data compared with the calculated one is 0.93, which was higher than 0.83 in this case. Although the thrust parameters $J_B = 20$ mA, $V_n = 1200$ V for the argon thruster are similar to those obtained for the mercury thruster on the ETS-III ($J_B = 30$ mA, $V_n = 1000$ V), the former thrust level is much smaller than the latter because of the different propellant used. The effect of double-charged ions is considered to be significant because high discharge voltage (60 V) and the small thrust force seems to contribute much to error. They will be reduced when a larger thruster is installed on the device.

Conclusion

A thrust measuring device and a power supply unit were developed in order to investigate the performance of an ion engine. Since the lubricant gas was evacuated before it entered the vacuum chamber, the vacuum pressure inside the chamber was maintained below 1×10^{-3} Pa during ion beam ejection. The thrust force was successfully measured by the thrust stand. A comparison of the theoretically obtained value and the measured one was made and a good result was obtained.

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