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A Fundamental Experiment of Microwave Beaming Propulsion

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Abstract

Experiments on a pulsed microwave thruster were conducted using a 1 MW gyrotron developed by the Japan Atomic Energy Research Institute. The pulsed microwave, whose duration is 0.2~1msec, was focused by a parabolic mirror/nozzle and air-breakdown was induced. Precise optical alignment was not necessary to produce plasma using an ignition rod. Thrust impulse is measured using a load cell force transducer. As a result, the maximum momentum coupling coefficient, C_m was 28 N/MW at 0.2msec pulse width. C_m varied inversely with the pulse width.

INTRODUCTION

The concept of energy beaming propulsion for launcher is explained as follows: When a high-power pulsed beam transmitted from the ground is focused in the atmospheric air, breakdown occurs near the focus and plasma is formed. The plasma absorbs the following part of the pulsed beam and expands outward with generating shock waves. The shock waves propagate outward and reflect on a nozzle surface of a thruster. As a result, impulsive thrust is imparted on the thruster. Since the energy is provided to a spacecraft from the outside and the atmospheric air is utilized as a propellant, it is not necessary to load an energy source or a propellant on board in an air-breathing mode. For this reason, this type of propulsion will be able to achieve a high payload ratio at remarkably low launch cost.

Energy can be transmitted either by a laser beam or a microwave beam to a spacecraft. Many experimental and analytical researches have been carried out on laser beaming propulsion. (For example, references [1-3]) On the other hand, quite few number of studies have been conducted about a microwave beaming propulsion mainly because of its poor directionality. However it is not the case when the transmission distance is less than 100km. Furthermore, microwave system has following advantages: Efficiency of energy conversion from electricity to microwave can be more than 90% and development cost of microwave generators would be much lower than that of laser oscillators. In addition, microwave phased array technology enables us to realize a single large-diameter beam that is not only high-power but also coherent [4].

The purpose of this study is to evaluate the performance of microwave beaming propulsion through the thrust impulse measurements.

EXPERINENTAL EQUIPMENTS AND METHODS

A high-power gyrotron developed by JAERI (Japan Atomic Energy Research Institute) was used to generate microwave.[5] A picture of the gyrotron is shown in Fig 1. It's microwave power reaches up to about 1 MW. The specifications of gyrotron are shown in Table 1. This high-power facility is originally constructed as a RF heating device for fusion reactor researches.

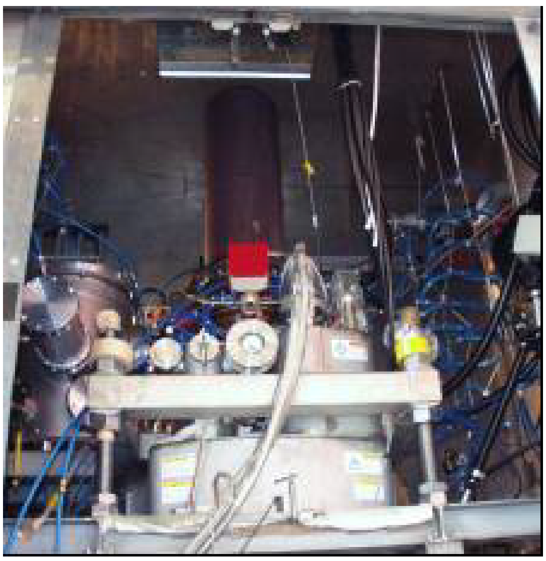

Fig. 1 The gyrotron developed at the Japan Atomic Energy Research Institute.

Table 1 Specifications of the JAERI gyrotron

Frequency	170GHz
Maximum output	1MW
Duration	< 1 sec
Transverse mode	Gaussian
Transmission mode	HE11

The electrical efficiency is about 50%. A diamond plate is utilized for the output window of such high power microwave. The microwave is leaded from the gyrotron to the thruster using a metal tube wave-guide. The distance between the output window of wave-guide and the thruster was 30cm.

A thruster with a parabolic mirror was fabricated for the impulse measurement. Diameter of the nozzle was 90mm at the exit plane, and the focal length of parabola was 15mm. The body was made of duralumin and the surface is coated with cupper. The weight was about 2kg. A picture of the thruster is shown in Fig 2.

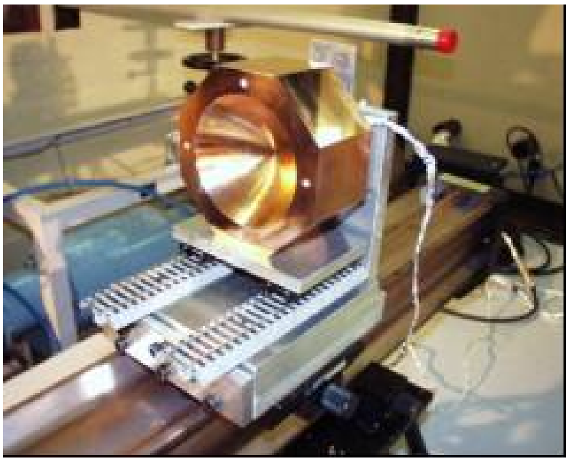

Fig. 2 A picture of microwave thruster on a thrust stand.

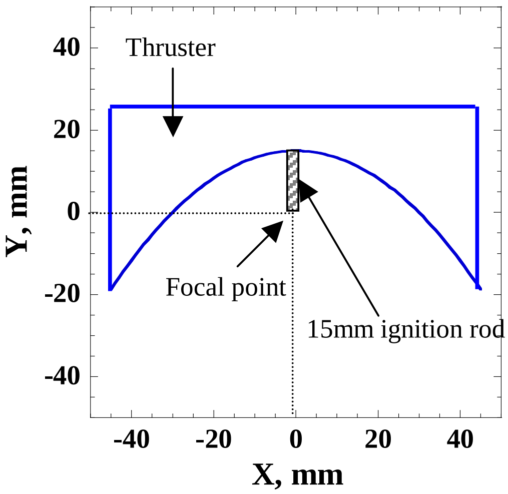

Fig. 3 Cross sectional view of the thruster with an ignition rod.

Since ignition probability was found quite sensitive to the alignment between the wave-guide and thruster, an ignition rod, which was made of brass, was used to assist ignition. Figure 3 is a cross section view of the thruster with the ignition rod. The length of rod was about 15mm, which is the same as the focal length. The diameter of rod was 3mm.

In the experiment, the luminescence of plasma was measured with a semiconductor photo detector. It has a rise time of 20nsec. A distance between the focus of the parabola and the detector was about 10cm. A top view of the measurement system is illustrated in Fig 4.

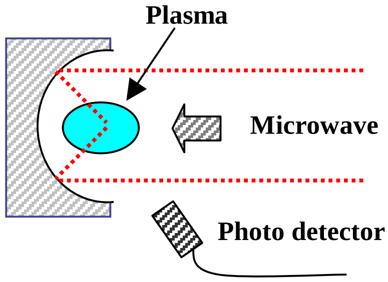

Fig. 4 A system for plasma luminescence measurement.

The thruster was mounted on wheels and rails. Then it was force-free in the thrust direction. Thrust was measured with a load cell force transducer (LM-1KA, Kyowa Dengyo, Inc.) The characteristic frequency of this measurement system is 80Hz, which is relatively slow comparing with actual thrusting speed because of the mass of thruster. Therefore, integrated thrust impulse has been estimated from the peak force recorded by the transducer. Calibration was conducted using an impulse hammer. The calibration system is illustrated in Fig. 5.

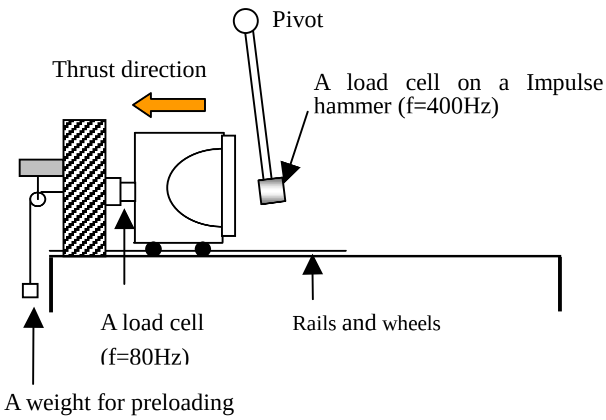

Fig. 5 Calibration for thrust measurement.

Imitational impulse wes given much slower than actual one. Figure 6 shows the relationship between the peak of transducer signal and the impulse given by the impulse hummer. The relationship was very linear.

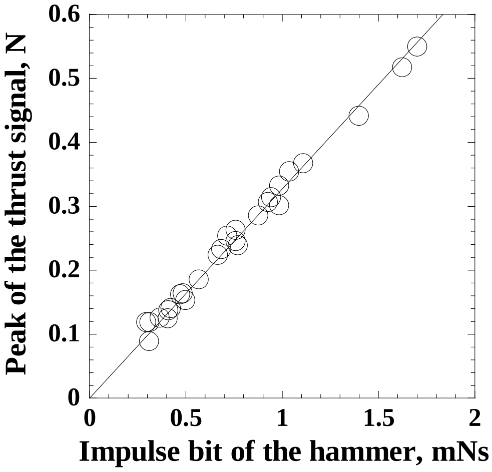

Fig. 6 A calibration diagram.

RESULT AND DISCUSSION

Production of plasma

Figure 7 shows a photograph of the thruster and the plasma generated by focusing microwave. Using the ignition rod, ignition probability reached at almost 100% even when the alignment was not taken carefully. The measured thrust with the ignition rod was almost the same as the one without it.

Fig. 7 A photograph of the thruster and the plasma produced by focusing microwave.

The luminescence of plasma

Microwave power, P and pulse width, τ were variable in this experiment. Histories of plasma luminescence intensity and microwave power are shown in Fig 8. Here, t is the elapsed time from ignition. Plasma production started simultaneously with microwave irradiation. The luminescence intensity was increased sharply until t<0.03msec and decreased when microwave was ceased.

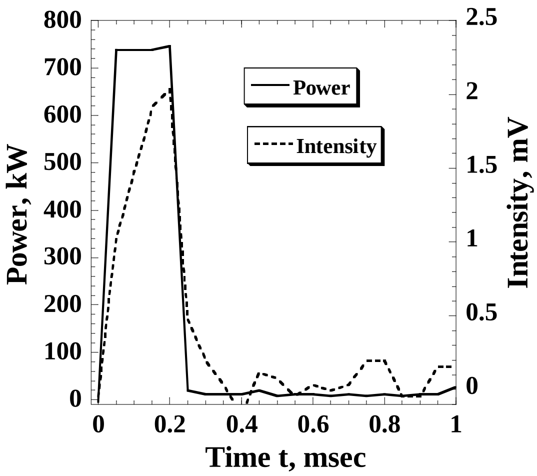

Fig. 8 Histories of plasma luminescence intensity and microwave power. *P*=746kW and τ = 0.2msec.

The dependency on pulse width is shown in Fig. 9. Duration of illumination was almost same as the pulse width, while the intensity was increased with the pulse width,

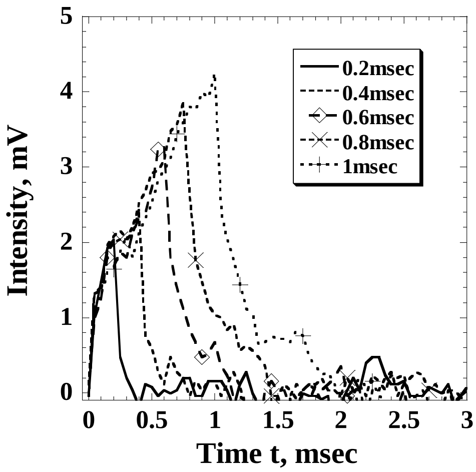

Fig. 9 Plasma luminescence variation for various pulse width of microwave irradiation. *P*=746kW.

Thrust measurements

Figures 11 shows the relationship between the measured thrust impulse and the pulse width for microwave power. The relationship was obviously not proportional. Although the impulse bit was increased monotonically with the pulse width, the increments were very small at $\tau > 0.4$msec. This suggests that there would be a transition from an efficient thrusting mode to an inefficient mode.

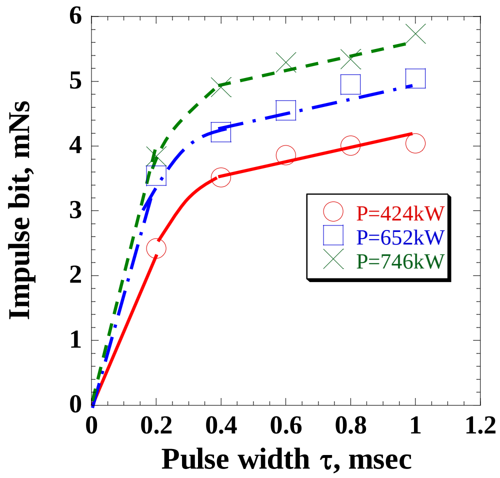

Fig. 10 Measured impulse bit for various pulse width

Figure 11 shows the thrust impulse together with the history of plasma luminescence at P=746kW t=1msec. According to the variation of these quantities, the heating process can be divided into three regimes:

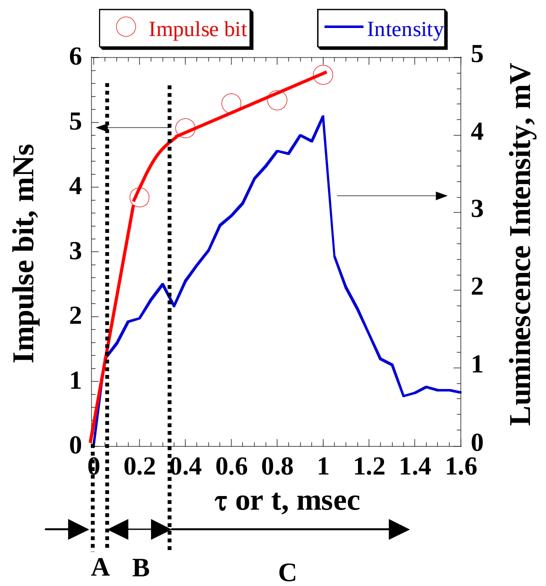

Fig. 11 Measured impulse bit and luminescence history for τ=1msec. *P*=746kW.

In Regime A ($0<t<0.03$msec), both the luminescence intensity of plasma and the thrust impulse were increased (or expected to be increased) sharply. In this regime, a Microwave Supported Detonation wave is thought to be a possible efficient heating mechanism [6]. Since the size of plasma is still small in this regime, most of supplied microwave energy is absorbed in the front layer of plasma, enhancing the detonation wave itself as illustrated in Fig. 12.

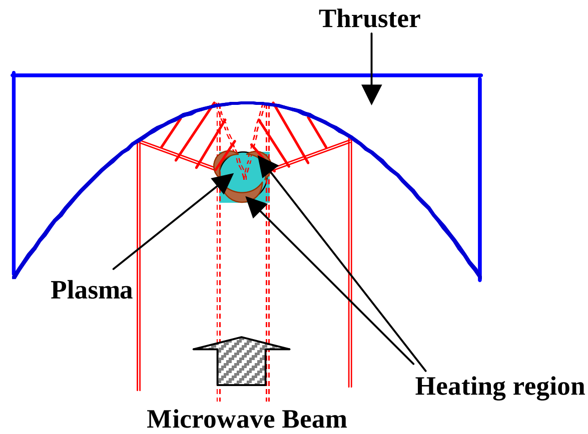

Fig. 12 The heatingpattern in Regime A

In Regime B ($0.03<t<0.4$msec), the increments of thrust impulse and luminescence intensity slowed down gradually as seen Fig. 11. In this time range, plasma is expected to have expanded to a certain scale. As illustrated in Fig. 13, the front heating region (upper side in the picture) is becoming smaller and rear heating region (lower side in the picture) is getting larger instead.

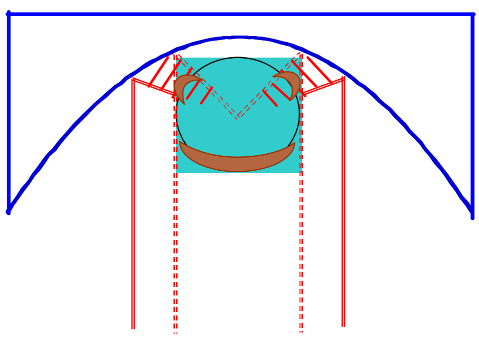

Fig. 13 Heating Regime B

In Regime C, the luminescence intensity was increased linearly with the elapsed time, while the thrust impulse was almost unchanged. This would indicate that the plasma continued to expand further, and the heating mechanism was shifted from MSD heating (isometric heating) to isobaric heating, resulting in small pressure increase. As illustrated in

Fig. 14, the plasma is expected already bigger than microwave beam diameter in this regime.

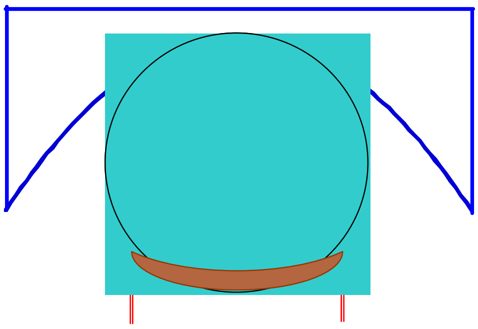

Fig. 14 Heating Regime C

The momentum coupling coefficient, C_m was estimated from the measured impulse bit as,

$$C_m = \frac{I}{P\tau} \quad (1)$$

Here, *I* is the measured thrust impulse. C_m is plotted in Fig. 15. It is increased inversely with pulse width. The maximum C_m was 28N/MW at τ =0.2msec which was the shortest pulse width possible in this experiment.

Although this C_m is one order of magnitude lower than those of laser beamed propulsion, shortening the pulse width or enlarging the parabola size would improve it in the future.

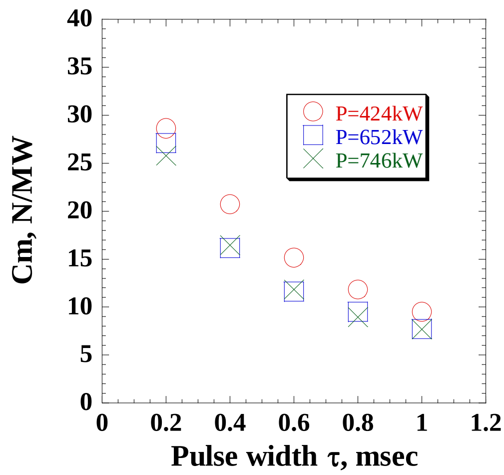

Fig. 15 C_m vs. pulse width

SUMMARY

1. Using an ignition rod, ignition probability was reached to almost 100% even though precise alignment was not taken.
2. Thrust impulse was measured by a load cell force transducer and the momentum coupling coefficient, C_m was estimated.
3. The maximum C_m was 28N/MW at 0.2msec pulse width.
4. C_m varied inversely with the pulse width, so that it would be improved by shortening pulse width.

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