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Thrust generation experiments on microwave rocket with a beam concentrator for long distance wireless power feeding

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ABSTRACT

Experiments using a 1 MW-class gyrotron were conducted to examine a beamed energy propulsion rocket, a microwave rocket with a beam concentrator for long-distance wireless power feeding. The incident beam is transmitted from a beam transmission mirror system. The beam transmission mirror system expands the incident beam diameter to 240 mm to extend the Rayleigh length. The beam concentrator receives the beam and guides it into a 56-mm-diameter cylindrical thruster tube. Plasma ignition and ionization front propagation in the thruster were observed through an acrylic window using a fast-framing camera. Atmospheric air was used as a propellant. Thrust generation was achieved with the beam concentrator. The maximum thrust impulse was estimated as 71 mN s/pulse from a pressure history at the thrust wall at the input energy of 638 J/pulse. The corresponding momentum coupling coefficient, C_m was inferred as 204 N/MW.

1. Introduction

Beamed energy propulsion (BEP) is a means of drastically decreasing the huge costs of transporting mass to space using chemical rockets. In this concept, a spacecraft acquires propulsive energy from electromagnetic beams such as laser or microwave beams irradiated from a remote location. Many experiments and analytical studies have been conducted to assess BEP since 1970. That number is increasing quickly with the development of high-power beam sources [1–9].

A microwave rocket is a BEP rocket using microwave beams of the millimeter-wave band: 100 GHz. A microwave rocket can use ambient air as a propellant. No on-board propellant is required during its atmospheric flight, resulting in a high payload ratio. The pressure in the thruster of the microwave rocket is compressed through a pulse detonation cycle, similarly to pulse detonation engines [10,11], with no complex device such as a turbo pump. Consequently, the structure is simpler than that of a conventional chemical rocket engine, offering lower manufacturing cost.

The thruster is a cylindrical tube with a closed end as shown in Fig. 1. The closed end is called a thrust wall. A focusing reflector is mounted at the thrust wall as an initiator of the millimeter wave discharge. In the engine cycle, microwave beams are injected into the thruster from the open end. The incident beams are then focused by the focusing reflector; plasma is ignited at the focal point. The ionization front of the plasma propagates toward the incident microwave beam, absorbing the beam power. A shock wave is then driven. High pressure behind the shock wave imparts a thrust impulse.

A powerful microwave beam generator, a gyrotron, is a promising beam source. In the field of nuclear fusion, 1-MW-class gyrotrons have been developed as plasma heating devices [12–16]. According to feasibility studies [17,18], extremely high manufacturing costs are necessary for beam facilities, but that cost can be amortized over many repeated uses.

In 2004, Nakagawa et al. [19] conducted launch experiments with single-pulse operation and evaluated the thrust performance in terms of the momentum coupling coefficient, C_m, which is defined as the ratio of the propulsive impulse to the incident beam energy. As a result, they achieved large C_m of 395 N/MW, which is comparable to that of air-breathing laser BEPs. Oda et al. [20] measured the thrust performance under multi-pulse operation. Results show that steady repetitive impulses were achieved under multi-pulse operation with a forced-breathing system. The measured thrust impulse was estimated as 60 mN at a 50 Hz

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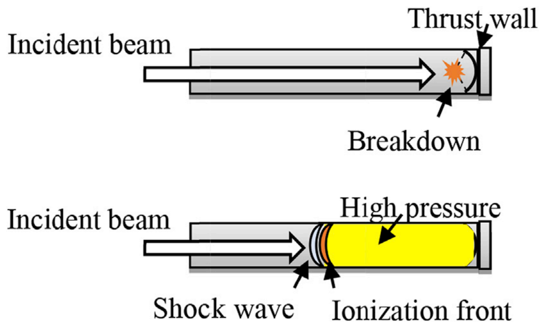

Fig. 1. Schematic image of the thrust generation process.

repetition frequency. Oda et al. [21–26] also reported that the ionization front propagation velocity increased with the incident beam power density.

Long-distance beam transfer is a key benefit of BEP launchers. However, the transmission distance was limited in these experiments [19–26] because of diffraction. The millimeter wave was irradiated from a 2.5 inch corrugated waveguide through a sapphire window. The beam waist was estimated as 20.4 mm; the Rayleigh length was, accordingly, 0.7 m. Consequently, the beam power density decreased after propagating longer than 0.7 m.

Yamaguchi et al. [27] developed a long-distance beam transmission system with a transmission mirror system and a receiving mirror system. The transmission mirror system expands the beam diameter from 40.8 mm to 240 mm and thereby extend the Rayleigh length from 0.7 m to 20.4 m. The receiving mirror system that comprised a convex parabolic mirror and a concave parabolic mirror was mounted on the thruster to compress the beam and guide it into the thruster. The receiving mirror system was necessary to increase the beam power density at the thruster sufficiently high to drive the detonation. However, the exhaust stream from the thruster strikes the convex parabolic mirror directly, thereby decreasing the thrust performance. Moreover, the receiving mirror system is heavier than the thruster. It changes the center of gravity, making it different from the thruster center axis.

This study employed a millimeter-wave beam concentrator: a symmetric tapered-tube to receive the expanded beam. The negative influences of the exhaust stream are not strong with the beam concentrator compared with the receiving mirror system. The size and mass can be reduced with the beam concentrator compared with the receiving mirror system. A quasi-optical design of the beam concentrator to avoid the backward reflection of the incident beam was proposed in Ref. [28]. The transition beam power of a concentrator designed by the proposed design was measured at an incident beam power of 3.09 mW.

The purposes of the study are measurement of the plasma ignition and evaluation of the thrust performance with the beam concentrator using the 1-MW-class gyrotron as a beam source. Plasma ignited in the thruster was observed using a fast-framing camera. Pressure in the thruster was also measured. The impulsive thrust was inferred from pressure histories at the thrust wall. In addition, abnormal ignition in the beam concentrator occurred under multi-pulse condition was observed.

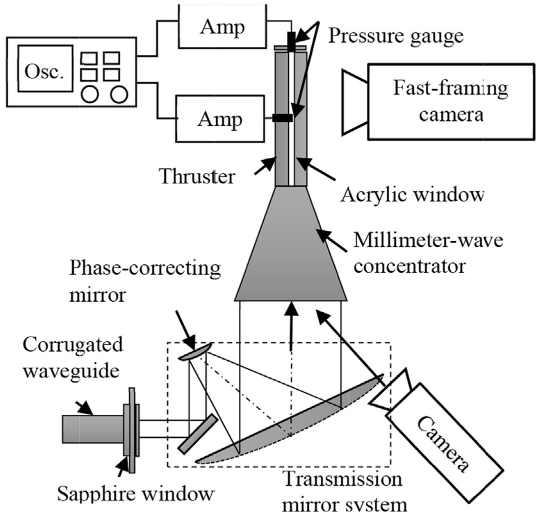

Fig. 2. Experimental setup for plasma observation and pressure measurement. The transmission mirror system is identical to Ref. [27].

2. Experimental apparatus

Fig. 2 portrays a schematic diagram of the experimental setup. The transmission mirror system is identical to Ref. [27]. The transmission mirror system includes a convex parabolic mirror, a concave parabolic mirror, and a flat mirror. Incident millimeter-wave beams are irradiated from an outlet of the oversized corrugated waveguide through a sapphire window. The beam waist (radius) of incident beams is 20.4 mm. The flat mirror turns the incident beam direction to the convex parabolic mirror. The convex parabolic mirror is a phase-correcting mirror that modifies the beam shape to a spherical wave. The focal point of the spherical wave is formed by the concave parabolic mirror. The incident beam therefore becomes a beam that is parallel at the concave parabolic mirror. The beam diameter is eventually expanded from 40.8 mm to 240 mm.

The beam concentrator is connected directly to the thruster, the diameters and length of which are, respectively, 250 mm, 54 mm, and 470 mm.

The diameters and length of the thruster are 500 mm and 56 mm, respectively. A screw is installed at the focal point of the focusing reflector to support the ignition. Atmospheric air was used as a propellant. The thruster has an acrylic window that facilitates observation of the ignited plasma inside the thruster with a fast-framing camera. Two pressure gauges are installed at the thrust wall and at the mid-point of the thruster. Impulsive thrust and shock wave propagation velocity are deduced from the pressure histories. A commercial camera is used to observe emissions from the plasma inside the beam concentrator.

A 1-MW-class gyrotron developed at the National Institutes for Quantum and Radiological Science and Technology for the ITER project was used as a beam source [14–16]. The incident millimeter-wave beam frequency was 170 GHz. The incident beam power was measured at 638 kW using a dummy load.

3. Results and discussion

3.1. Plasma ignition and ionization front propagation

The plasma ignition was successfully obtained with the beam concentrator. Fig. 3 presents framing photographs of ionization front propagation in the thruster observed through the acrylic window with

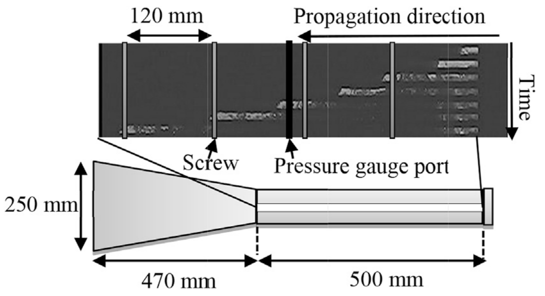

Fig. 3. Framing photograph of the ionization front propagation in the thruster. The pulse irradiation time is 0.8 ms. The time interval of each frame is 0.1 ms.