44th AIAA Aerospace Sciences Meeting and Exhibit
9-12 January 2006, Reno, Nevada

AIAA 2006-765

An Experimental Study on a Thrust Generation Model for Microwave Beamed Energy Propulsion

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In a microwave beaming thruster with a cylindrical tube, a plasma front propagates in the tube absorbing microwave power in a supersonic speed accompanying a shock wave. Therefore, the pulse detonation engine model is expected useful. In this study, pressure histories in the thruster were measured using pressure gauges and compared to pulse detonation engine (PDE) model. As a result, the propagation velocities of the shock wave and plasma front were found identical. Measured pressure at the thruster wall showed a similar history to that from the PDE model. These result shows that thrust generation model based on the PDE model would be applicable to the microwave beaming thruster.

I. Introduction

Air-breathing beamed energy propulsion is expected to realize a low cost launch vehicle with a high-payload ratio. Because propulsive energy is provided to the vehicle by beamed energy transmitted from the ground instead of loading a heavy energy source on itself and atmospheric air is utilized for propellant while the air-breathing mode. Recently, researches on BEP are held by many groups.[1,2]

In BEP, once an energy beam station is built, it can be used for multiple launch counts. The development cost for a high power beam generator is predominant when the launch count is small. The development cost for microwave generators is expected two orders of magnitude lower than that of laser, because a GW-class beam generator would be achievable by clustering existing high-power oscillators using phased array technology. Then, microwave beaming propulsion is expected to achieve the lower launch cost with fewer launch counts than laser beaming propulsion.[3] However, there was a problem in use of a microwave beam, owing to its poor directionality compared with a laser beam. For example, if a 2.45GHz microwave beam is used, the beam transmitter diameter becomes several hundreds meters for 100km transmission. However, necessary diameter can be reduced using short wavelength microwaves such as a millimeter wave. In these years, gyrotrons have been successfully developed as a high power millimeter wave sources and have achieved MW-class output.[4,5]

We studied on a repetitive pulsed microwave beaming thruster, which is similar to a repetitive pulsed laser thruster. Our concept is explained as follows: When a high power pulsed microwave beam is provided into a focusing reflector, atmospheric discharge arises. The induced plasma absorbs the following part of the microwave pulse and expands outwards while generating a shock wave. The shock wave drives impulsive force to the reflector. Then repetitive microwave pulses produce propulsive thrust. This operation mode is called a pulsejet mode, which is followed by ramjet and rocket modes to reach an orbit.

In 2003, our research group conducted a single pulse experiment using a conceptual thruster model with a parabolic reflector. The measured momentum coupling coefficient C_m, defined as a ratio of propulsive impulse to input power, was over 400N/MW. In the research, vertical flight experiment was also conducted and we achieved 2-

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m altitude flight demonstration.[6] As a next step, we conducted a multi-pulsed experiment using conical thruster models in 2004. The thruster also gained thrust successfully at each pulse. [7]

In microwave beaming propulsion, both plasma and shock waves play an important role in thrust generation process. Thus, the observation of plasma and shockwave is necessary. In early 1980s, Brodskii *et al.* observed atmospheric millimeter-wave plasma using a 85GHz gyrotron. According to Brodskii et al., plasma front propagates towards radiation source in 10-100m/sec. In the power density condition S>3kW/cm^2, increase in propagation velocity U is quadratic to S. This result shows that plasma front propagates far faster than the classical theory by Raizer.[8,9] They proposed a propagation model with non-equilibrium plasma. Zorin pointed out that in the power density condition S>12kW/cm^2, plasma propagates in supersonic.[10] The observation on the relation of a plasma front and a shock wave was conducted using a parabola thruster model. The velocities of ionization front of plasma and shock wave propagation were measured. As a result, plasma and shockwave propagated in the same order of supersonic velocity. This result suggested that plasma and shockwave have some interaction to each other in their propagation process.[11]

The dependence of thrust performance on plasma behavior was also observed. In ref. 12, thrust measurement of the thruster models with 1-dimensionla cylindrical nozzle was conducted in 660kW and 400kW. Figure 1 shows dependence of momentum coupling coefficient C_m on normalized plasma propagation distance $U\tau/L$ where U is the observed plasma propagation velocity and τ is the pulse duration. As shown in Fig. 1, optimum plasma propagation distance was nearly equal to the length of thruster nozzle. [12]

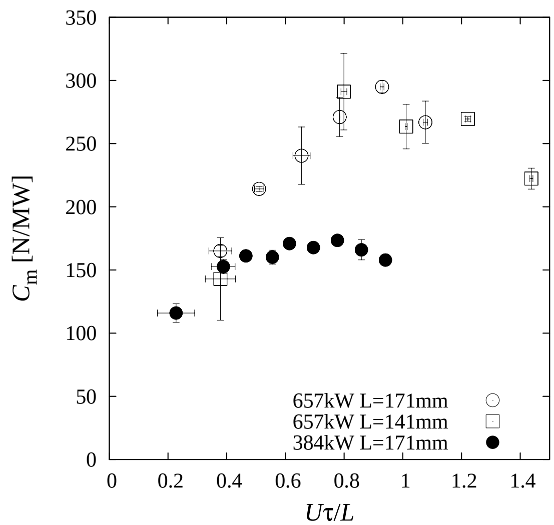

Figure 1. Dependence of C_m on thruster scale parameter. [12]

To optimize the thruster design, a thrust generation model is necessary. For the thruster with a 1D tube used in ref.12, the thrust generation model is expected to have an analogy to the model of pulse detonation engine (PDE), because plasma and shock wave propagate in the nozzle like detonation wave propagation in PDE. In PDE model, pressure history in the engine is described to the detonation wave propagation process. Then, in microwave beaming thruster, pressure history in the thruster would be also related with microwave plasma and shock wave propagation process.

In this study, an observation of plasma and shock wave in 1D thruster models was conducted. Pressure history of the thruster models was measured using a pressure gauge and it was compared to the PDE model.

II. Thrust Generation Model

The thrust generation model of a microwave beaming thruster with a 1D nozzle is explained in an analogy of the PDE model. Figure 2 shows the schematics of the model. In the PDE model, a detonation wave starts from the engine wall and propagates towards the nozzle exit in the 1D nozzle. The detonation wave makes sharp pressure increment from p_1 to p_2. The pressure ratio at the detonation wave and a flow velocity behind the detonation wave are described as following equations. They are based on the Chapman-Jouget detonation model, which assumes the flow velocity behind the detonation to be a local sonic velocity.

$$\frac{p_2}{p_1} = \frac{U^2 + (\gamma_1 - 1)c_{v1}T_1}{(\gamma_2 + 1)(\gamma_1 - 1)c_{v1}T_1} \tag{1}$$

$$a_2 = v_2 = \frac{\gamma_2\left[U^2 + (\gamma_1 - 1)c_{v1}T_1\right]}{(\gamma_2 + 1)U^2}U \tag{2}$$

U, c_{v1}, T_1, γ_n, v_2, and a_2, are a velocity of the detonation wave relative to thruster wall, atmospheric specific heat, atmospheric temperature, ratio of specific heat at each region n, a flow velocity at the region behind detonation wave relative to detonation wave surface, and local sonic speed at the region behind the detonation wave, respectively. [13]

The rarefaction wave follows the detonation wave and pressure decreases to p_3. The pressure at the region from the tail of the rarefaction wave to the engine wall keeps constant until the termination of the detonation wave.

$$\frac{p_3}{p_2} = \left[1 - \frac{\gamma_2 - 1}{2} M_{2c}\right]^{\frac{2\gamma_2}{\gamma_2 - 1}} \tag{3}$$

$$M_{2c} = \frac{U - v_2}{a_2} \tag{4}$$

Here, M_{2c} is Mach number behind the detonation wave relative to thruster wall.

After the termination of the detonation wave, an expansion wave propagates from the nozzle exit towards the engine wall at the velocity $U_{\text{expansion}}$, which is equal to sonic speed at the constant pressure region, and pressurized driving gas in the nozzle is exhausted and the pressure in the nozzle decreases to atmospheric pressure. [14,15,16]

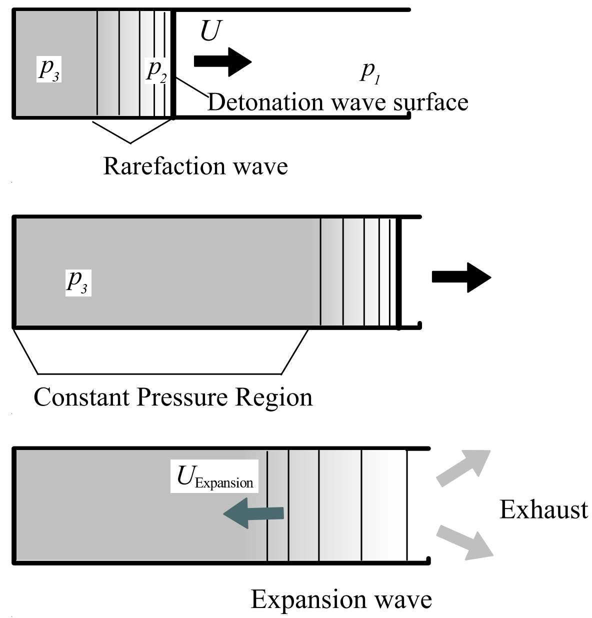

Figure 2.Schematics of detonation engine cycle.

$$U_{\text{expansion}} = a_3 = a_2\left(1 - \frac{\gamma_2 - 1}{2} M_{2\text{c}}\right) \tag{5}$$

Total impulsive thrust force I gained through one cycle operation is calculated by integrating pressure history at the engine wall. As pressure at the thruster wall is constant during propagation of the detonation wave and the expansion wave in the nozzle, the total impulse is described as the product of constant pressure p_3, area of the engine wall A, and duration time of constant pressure T_{plato}.

$$I = \int (p - p_1) A dt = (p_3 - p_1) A T_{\text{plato}} \tag{6}$$

$$T_{\text{plato}} = \frac{L_{\text{thruster}}}{U} + \frac{L_{\text{thruster}}}{U_{\text{expansion}}} \tag{7}$$

Using above equations, some characteristic parameters were calculated. Its result is listed in Table 1.

In microwave beaming thruster, ionization front of plasma with a shock wave converts microwave energy to the driving gas instead of detonation wave.

Table 1. Result of PDE model calculation.

U [m/sec]	p_2 [bar]	p_3 [bar]	$U_{\text{expansion}}(=a_3)$ [m/sec]	T_{plato}(*) [msec]	I (**) [Nsec]
900	4.4	2.0	515	0.55	0.067
800	3.6	1.7	473	0.61	0.052
700	2.8	1.4	434	0.67	0.038
600	2.2	1.2	398	0.75	0.024
500	1.7	1.1	367	0.85	0.011

(*) Case for L_{thruster} = 180mm

(**) Case for circular thruster wall with 40mm diameter

III. Experimental Setup

A. Microwave Generator

As a microwave beam generator, we used a high power millimeter wave gyrotron developed in Japan Atomic Energy Agency (JAEA) as a microwave power source for electron cyclotron heating and electron cyclotron current drive (ECH/ECCD) system of International Thermonuclear Experimental Reactor (ITER). Figure 3 shows a photograph of gyrotron, 3m height and 800kg weight. Its frequency is 170GHz, and the maximum output power is up to 1MW. Microwave pulse duration is variable from 0.1msec to 10sec at 1MW power condition and its power is almost constant during the pulse duration.[17]

The microwave beam is transmitted through the corrugated waveguide to the experiment site. The output microwave beam was 0th Gaussian beam with 40mm waist. Microwave power at the waveguide end was measured using a dummy load before the measurement.

Figure 3. Photograph of gyrotron.

B. Pressure Measurement Apparatus

A conceptual thruster model with conical thruster wall and cylindrical nozzle was used for plasma and shockwave measurement, as shown in Fig.4. The microwave beam is inputted from cylindrical nozzle exit and the conical thruster wall ignites plasma. Plasma and shock wave propagate through the cylindrical nozzle absorbing microwave beam during the microwave pulse. This thruster model has the same nozzle shape used in ref.6 and 12.

As a cylindrical body was made of acrylic plastic, plasma development in the thruster was visible and observed using a high speed framing camera to deduce the velocity of plasma propagation.

The pressure in the thruster was measured using a high speed pressure gauge (Kistler's 603B). The signal of pressure gauge was processed using a charge amplifier (Kistler's 5011B) and the processed signal was recorded using a digital oscilloscope.

The pressure history at thruster wall was measured, in the setup shown in Fig.4(a). Pressure gauge was settled perpendicular to the microwave beam axis at the conical thruster wall. Thruster length L was 180mm. The diameter

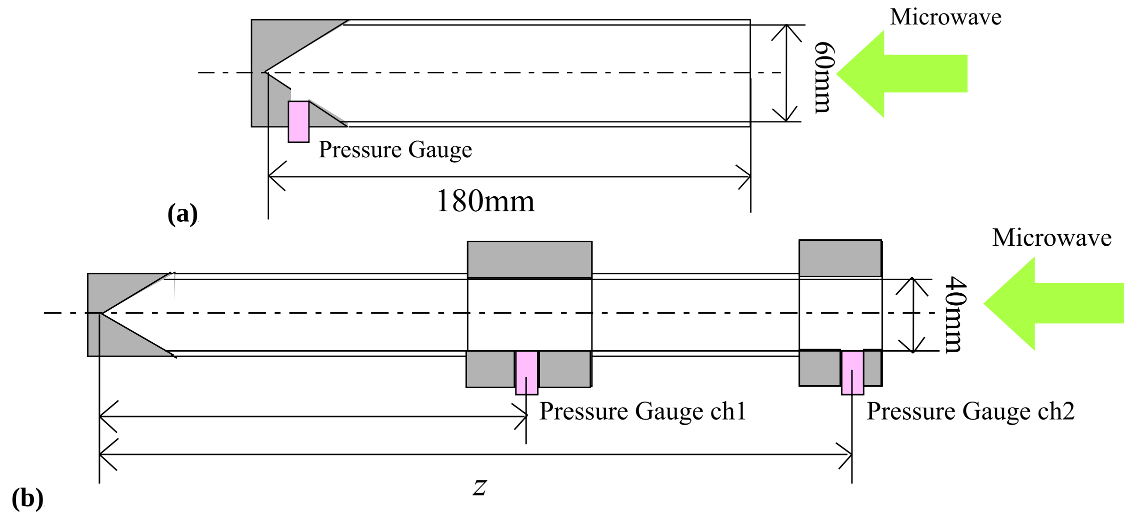

Figure 4. Schematics of pressure measurement setup.

of cylindrical nozzle was 60mm.

Next, to deduce the velocity of the shock wave, pressure gauges were settled at cylindrical nozzle part, as shown in Fig.4(b). Two gauges were used and pressure histories at the different position were recorded at the same time. The measured position of the gauge z was varied 320, 370, 420, and 480mm, from conical top of the thruster wall. In this setup, the diameter of cylindrical nozzle was 40mm.

IV. Experimental Result and Discussion

A. Measurement Result of Pressure History

Figure 5 shows the typical pressure history at the thruster wall. The duration of microwave pulse was settled 0.4msec, then length of plasma propagation was nearly equal to cylindrical nozzle length. Firstly, sharp and large pressure increment occurred and decreased quickly. Then pressure was constant during the pulse duration and started to decrease when expansion wave arrived at the thruster wall. This history was very similar to that of the PDE thrust generation model.

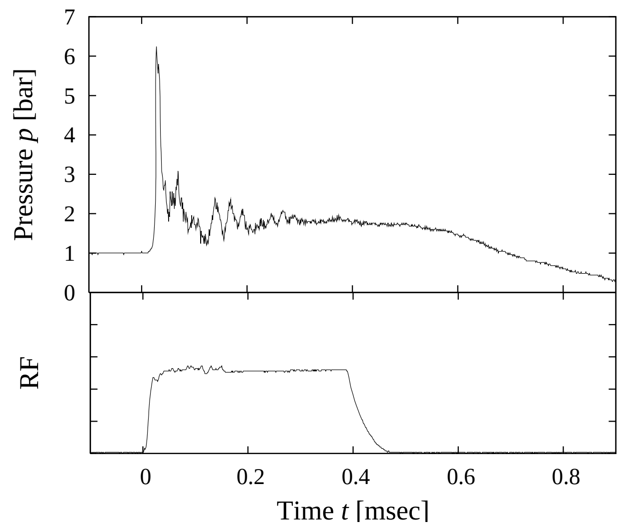

Figure 5. Typical record of pressure gauge at thruster wall. *P*=850kW

Next, the pressure history at the cylindrical part is shown in Fig.6. In Fig.6, records of the pressure gauges set at z = 320mm, z = 370mm and z = 420mm from the conical top are shown. Sharp increment of pressure detects arrival time of shock wave at the measured point. Each record of the pressure gauge revealed constant pressure epoch as same to the record at the thruster wall and arrival time of an expansion wave was also found at time of pressure decrease.

The arrival time of the shock wave and the expansion wave at each position was plotted in Fig.7. The arrival time and gauge location shows good linearity and the propagation velocities of the shock wave and the expansion wave were deduced. In P=850kW condition, the velocities of the shock wave and the expansion wave were 820m/sec and 470m/sec, respectively. Each propagation velocity shows good agreement to the calculated result listed in Table 1.

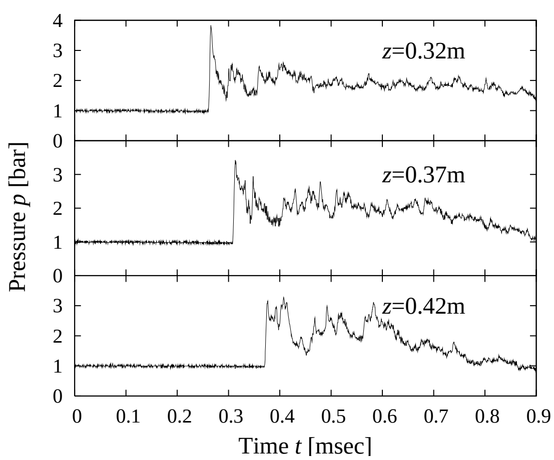

Figure 6. Typical record of pressure gauge at cylindrical part. *P*=850kW condition.

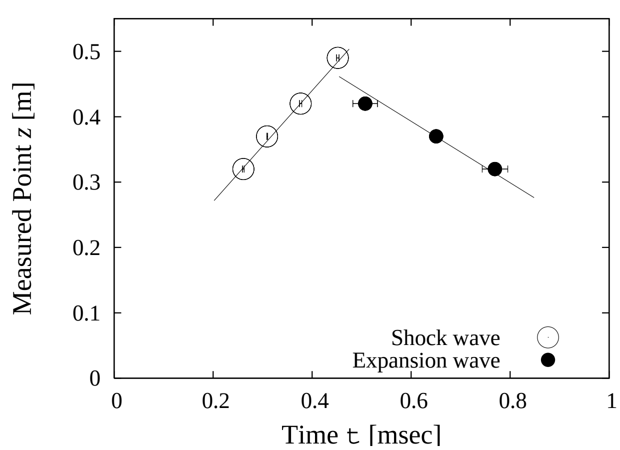

Figure 7. Relation of position of pressure gauge and arrival time. *P*=850kW condition.

B. Dependence of Plasma and Shock Wave Propagation Velocity on Power Condition

At the same time, velocity of plasma propagation was deduced using a high-framing speed camera. Frame interval was settled about 55μsec. Photographs of plasma behavior are shown in Fig.8. In the cylindrical nozzle, the velocity of plasma propagation was also nearly constant.

In Fig.9, the velocities of the shock wave and plasma propagation were plotted to the peak power density of the Gaussian beam. The velocities were increased with power density. As shown, both plasma and the shock wave propagated in the same velocity of supersonic at each power density condition.

This indicates that during microwave pulse input, microwave energy absorbed at plasma front drives shock wave at constant velocity in the thruster. So then, as long as plasma propagates in the thruster, microwave energy can be converted to the shock wave and can impart thrust force, as same to pulse detonation engine.

Figure 10 shows pressure behind the rarefaction wave, which was deduced from the constant pressure region of the pressure history measured at the thruster end wall, dependence on the velocity of shock wave. Although the velocity was increased, measured pressure was not increased much. This is very different point to PDE model.

In PDE model, pressure increases with the velocity increment of the shock wave as shown in Fig.10. This indicates that C-J detonation which is energy conversion process in the PDE model is not able to apply for microwave plasma and shock wave propagation process.

Although the microwave energy absorbing process is different to C-J detonation process in PDE model, gas dynamics in the region behind the shock wave and thrust imparting process of PDE model are still good for microwave beaming thruster.

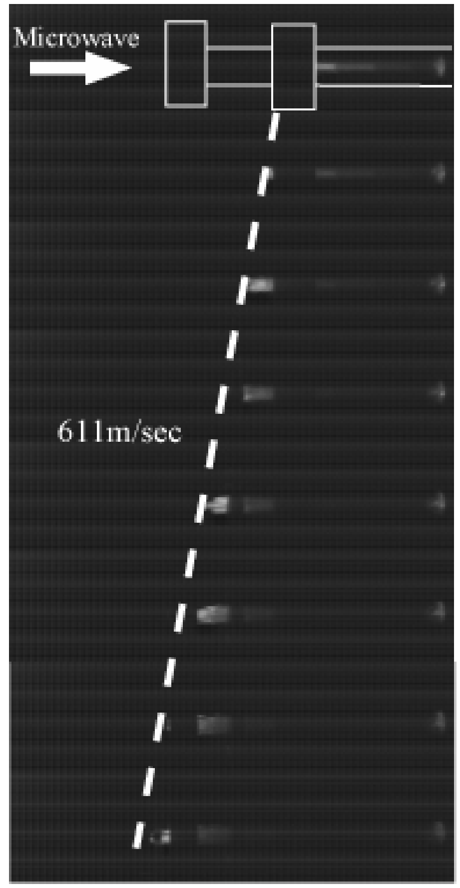

Figure 8.Pphotographs of plasma propagation by a high speed framing camera. *P*=630kW condition. 18000FPS

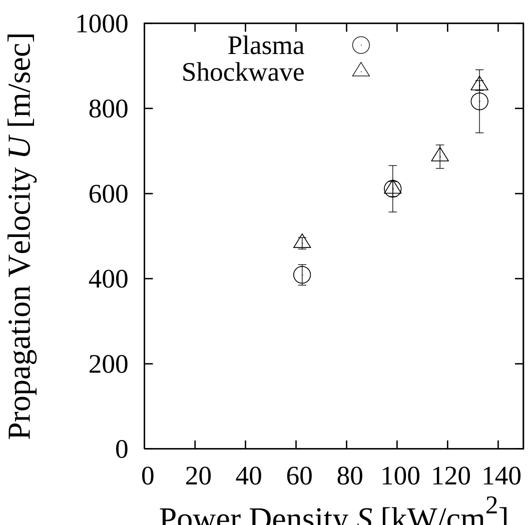

Figure 9. Relation of plasma and shock wave propagation velocity.

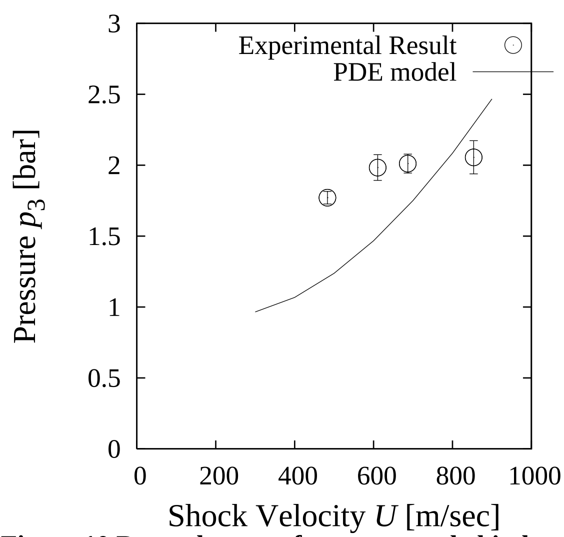

Figure 10.Dependence of pressure behind of rarefaction wave on shock wave propagation velocity.

V. Conclusion

Measurement of the pressure history in the microwave beaming thruster with a 1D cylindrical nozzle was conducted. Pressure histories at the thruster wall and the nozzle wall were measured. At the same time, the propagation velocity of plasma in the nozzle was measured.

Measured pressure at the thruster wall was similar to that of the PDE thrust generation model. Especially, constant pressure was revealed while plasma and an expansion wave propagate in the nozzle. With the result of pressure measurement at 4 positions at the cylindrical nozzle, the propagation velocities of the shock wave and the expansion wave were deduced. Both were propagated in nearly constant velocity through the nozzle. The velocity of the shock wave was compared to the plasma propagation velocity. As a result, the shock wave and plasma propagated in the same velocity.

Above result indicates that the thrust producing model based on the PDE model is useful for the microwave beaming propulsion.

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