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Quasi-steady Operation of Repetitively-pulsed Laser Thruster

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Summary: An experimental study of quasi-steady operation of repetitively-pulsed laser thruster was conducted by using Kr-F laser of 100 pps (pulse per second). The measured impulse coupling coefficient is comparable to the result previously reported and the theoretical value predicted by the transparent vapor model. The thrust level in a quasi-steady operation can be estimated as the impulse coupling coefficient multiplied by the average power of the laser beam, since the time in which the recoil momentum is delivered by each shot of laser beam is satisfactorily smaller than the laser pulse interval. The specific impulse is also measured. It is larger than the theoretical value predicted from the transparent vapor model. During a few thousand shots of laser, there was not much reduction in the impulse coupling coefficient at the present laser power of a few watts. The new configuration in which the thrust vector is anti-parallel to the laser beam is proposed and is demonstrated.

1. INTRODUCTION

The laser thruster is an advanced thruster having a characteristics of high specific impulse and a medium thrust density. In this propulsion, a remotely transmitted laser energy couples with an absorbing medium which is ejected from the absorption chamber and produces a thrust. It attracts much attention as an advanced thruster suitable to an orbital transfer vehicle (OTV) [*1*]. We have proposed a system experiment of the laser propulsion system onbord a Space Flyer Unit [*2*].

The laser thruster is classified into two types according to the type of the laser generator employed; the one is the repetitively-pulsed (RP) type and another is the continuous type (CW)[1] (see Fig. 1). Much experimental works have been done about the RP type [*1, 3*]. In those experiments, a laser generator of a various oscillation wave length were used and the impulse coupling induced by the irradiation of a single-shot of a laser beam was measured. In order to operate the RP type thruster quasi-steadily, the pulsed laser generator of high repetition rate is necessary. The recent development in laser technology makes this type of laser generator possible. Although there are a various kinds of such generator, the gas laser is promising in a view point of high power. The TEA CO_2 laser and excimer laser are candidates for such purpose. At current technology status, the excimer laser is advanced in comparison to the TEA CO_2 laser in a view point of high repetition rate. The excimer laser of 50 W level is commercially available. In a near future, the excimer laser of kilo-watts level will be available. In the present paper, we studied the characteristics of the quasi-steady operation of the RP type laser thruster by using the eximer laser. In the quasi-steady operation, there are much problem unresolved; 1) what kind of coupling occurs between each impulse due to each laser shot? 2) how is the variation in the impulse coupling coefficient during the quasi-steady operation. We report a preliminary result for these problems.

In the current RP type laser thruster, the thrust vector is parallel to the beam direction as shown in Fig. 1. This severely limits the mission which can be executed by a vehicle equipped with the RP laser thruster. In this paper we propose and demonstrate the new configuration of RP laser thruster in which the thrust vector can be anti-parallel to the laser beam. This configuration is similar to the CW type configuration and can execute a wide variety of mission.

2. Coupling between laser and medium

The excimer laser oscillates at ultra-violet region and, hence, has a better coupling with a solid medium. A various kind of metals were employed as a thrust medium. The thrust induced by a laser irradiation was measured. Before going to the experimental result, we briefly review a theoretical aspect.

We assume that a spot size D of the laser beam is so large that it satisfies the following relation;

$$D \ll \sqrt{\kappa \Delta t}$$

where κ is the heat conductivity and Δt is the irradiation time. It guarantees that the one-dimentional model is applicable; i.e., the physical quantities are uniform in the plane perpendicular to the laser beam direction. At first, the medium is heated up by

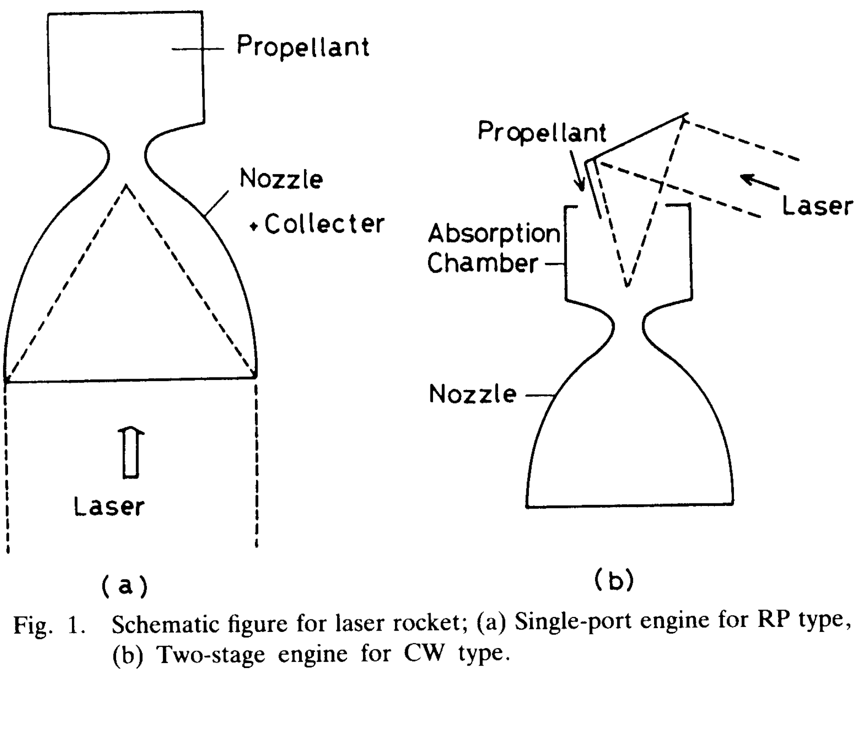

Fig. 1. Schematic figure for laser rocket; (a) Single-port engine for RP type, (b) Two-stage engine for CW type.

the irradiation, it melts and begins to evaporate. The vapor run away from the surface and it takes out not only the mass but also the energy transferred from the irradiation. Hence, at the steady state, the following relation is satisfied;

$$I=\dot{\mu}E$$
$$\dot{\mu}=P_v(T)\left(\frac{m}{2\pi kT}\right)^{1/2},$$
$$E=L_v+L_f+C(T-T_0)$$

where I is the laser intensity per unit area, $\dot{\mu}$ the mass evaporation rate, E the internal energy of the vapor. Here $P_v(T)$ is the evaporation pressure, m the atomic mass, T the temperature, T_0 the room temperature, C the heat capacity and the L_v and L_f is the heat of vaporaization and fusion, respectively. The recoil momentum induced by the vapor pressure is

$$\frac{1}{2}P_v(T)\pi D^2\Delta t.$$

The normalized impulse coupling coefficient β is given as

$$\beta=P_v(T)/I$$
$$=\frac{(2\pi kT/m)^{1/2}}{L_f+L_v+C(T-T_0)}.$$

The form of this equation suggests that there exists the maximum coupling coefficient at some temperature. Since the temperature is a monotonically increasing function of the laser intensity, it suggest that the coupling coefficient becomes maximum at some laser intensity. In the consideration above, we assume that the vapor is transparent to the incident laser. In this view point, we call this theoretical model as the transparent vapor model. When the laser intensity increases, this assumption breaks down and the vapor is ionized by absorbing the laser energy. The absorption of laser causes the further acceleration of the vapor.

3. Experiment

Experimental set-up

The experimental set-up is shown schematically at Fig. 2. The laser generator employed is Kr-F laser (0.242 μm). The output energy per pulse is about 0.05 J. The pulse duration time is 20 nano second. The laser generator can be externally triggered and is used nominally at the repetition rate of 100 pps (pulse pe second). The laser beam is focused through the focusing lens of 130 mm focal length on the target. The length between the lens and target is controllable so that the laser intensity per unit area on the target surface can be controlled.

The recoil momentum given to the target is measured by the apparatus shown in Fig. 3. The target and the target holder are suspended by strings. The horizontal

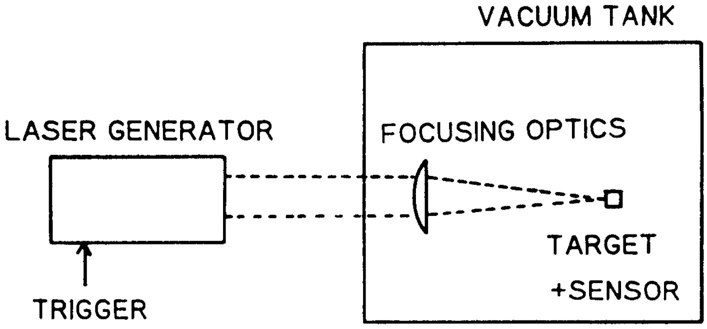

Fig. 2. Schematic figure for an experimental set-up.

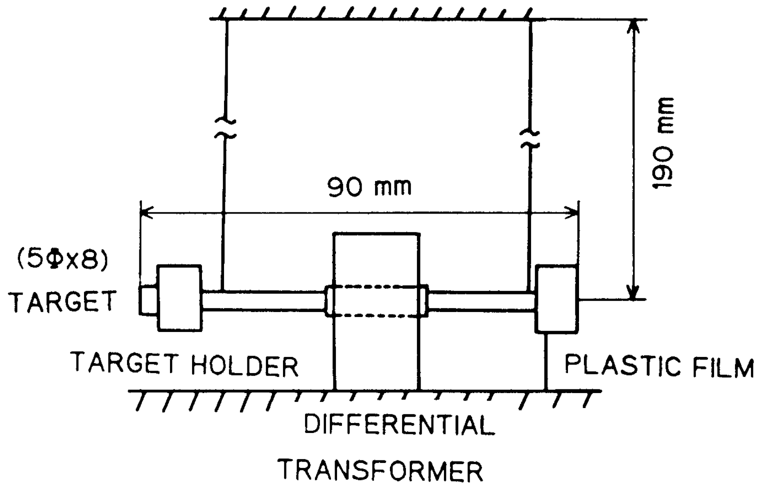

Fig. 3. Schematic figure for an apparatus measuring a recoil momentum of a target.

Table 1. Impulse coupling coefficient and specific impulse

Target	$\beta_a^{a)}$ (dyne/W)	$I_{sp,a}^{b)}$ (sec)	$\beta_v^{c)}$ (dyne/W)	$I_{sp,v}^{d)}$ (sec)
Zn	2.8	1.46×10^3	1.1	$4.7\times10^2(3.4\times10^3)$
C	3.3	3.9×10^3	0.64	1.4×10^3
Ti (alloy)	3.8	4.5×10^3	0.71	5.6×10^2
Al	3.0	7.8×10^3	0.66	7.9×10^2
Ti			0.54	

a) Impluse coupling coefficient in an atmospheric pressure.
b) Specific impulse in an atmospheric pressure.
c) Impulse coupling coefficient in vacuum.
d) Specific impulse in vacuum.
e) Specific impulse estimated from transparent vapor model.

motion is regulated by a spring of the plastic film. The displacement of the target is measured by a differential transformer. This apparatus and the focusing lens are set in a tank which can be evacuated.

Single shot and quasi-steady operation

A single shot of laser beam generates an impulse on a target. After the impulse, the target executes an oscillation with dumping. Figure 4 is the typical differential transformer output for Aluminum target under an atmospheric pressure. On the other hand, the laser irradiation of 100 pps rate makes a quai-static force on the target since the oscillation period of the target motion is satisfactorily larger than the time interval of the laser pulses. Figure 5 is the typical output for the same target by the laser irradiation of 100 pps rate and 1 second duration. We can obtain the recoil momentum due to the single shot of laser from the sensor output shown in Fig. 4 by using the period of the target motion and the static calibration of the sensor. The quasi-static force during the quasi-steady operation can be obtained directly from the sensor output shown in Fig. 5. The recoil momentum and the static force are normalized by the laser energy per pulse and the average power, respectively. They give the impulse coupling coefficient β. The both impulse coupling coefficients in dynes/W are 2.4 and 3.25, respectively. They are almost equivalent. It means that the plenomenon due to each pulsed laser irradiation is independent each other. That is, the time t_f in which the heated vapor flows out is much smaller than the time interval Δt between the laser pulses. In fact the time t_f is about 10^{-5} sec as estimated from the measurement of the specific impulse. Hence the condition $\Delta t \gg t_f$ is satisfied.

Influence of the background gas

Figure 6 shows the impulse coupling coefficient under the environment of air of various pressure. The target is Zinc. Although the impulse coupling coefficient under 10 torr is almost the same, it is much larger under an atmospheric pressure. When the gas around the target exists, the laser irradiation causes the gas break-down along the target surface. The plasma induced by the break-down can absorb laser energy further. As a result, the laser energy is absorbed at the gas around the target surface. This energy causes a blast wave which generate the high pressure on the target surface and induces an impulse on the target. In Fig. 6, the theoretical value estimated from

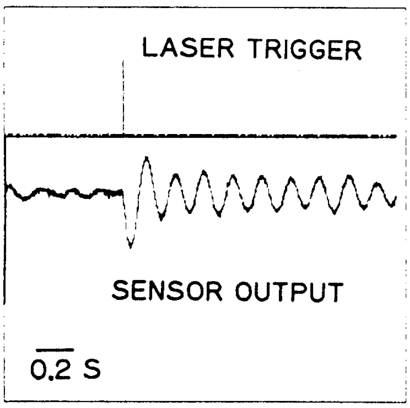

Fig. 4. Sensor out-put for a single shot of laser under an atmospheric pressure. The target is Aluminum.

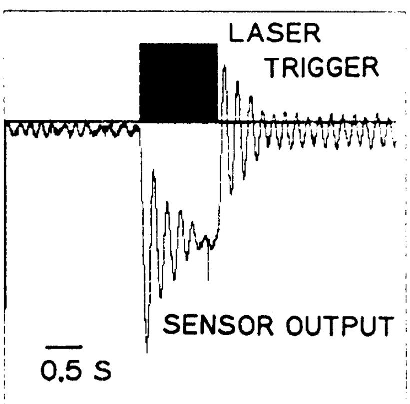

Fig. 5. Sensor output for a repetitively-pulsed laser of 100 pps under an atmospheric pressure. The duration time is 1 second.

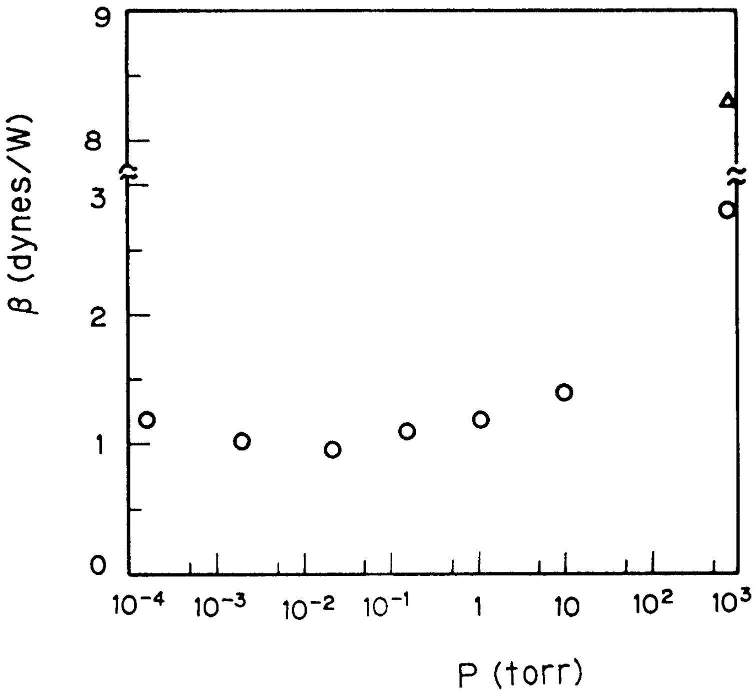

Fig. 6. Impulse coupling coefficient for Zn target. The symbol ○ is the present result and △ is the result estimated from the blast wave theory.

the blast wave model is plotted. As can be seen from the observation of the target surface, a part of laser energy evaporates the target and generate the impulse by the target vapor in addition to the blast induced in the surrounding gas.

Comparison with other result

Rosen *et al.*[3] have conducted the similar experiment by using the Aluminum target. The impulse coupling coefficient is obtained by using a Xe-F laser of 0.35 μm wave length, pulse duration $\simeq 5\times10^{-7}$ second and energy per pulse $\simeq$3 jule. Figure 7 shows Rosen's result and the theoretical value based on the transparent vapor model. The present result at the laser intensity $\simeq 10^9$ W/cm^2 is almost equivalent to Rosen's result and the theoretical value. In Fig. 8, the impulse coupling coefficient for Zinc target is shown. The present result for Zinc target also is comparable to the theoretical value.

Influence of quasi-steady operation

In the quasi-steady operation, the supply of a medium is quite important. In the present experiment, we examine a characteristics of the medium under the quasi-steady operation. In Fig. 8, the impulse coupling coefficients in every 1000 shots are shown. Although much reduction in the impulse coupling coefficient does not occur even after 10^4 shots, the target surface sustains damage; it is scooped in a shape of crater (see Fig. 9). For a longer operation, this crater becomes deeper and the defocusing of the laser beam might occur at the bottom of the crater. As a result, the reduction of the impulse coupling coefficient occurs. This means that the active supply of the medium is necessary under the condition of the operation of much longer time

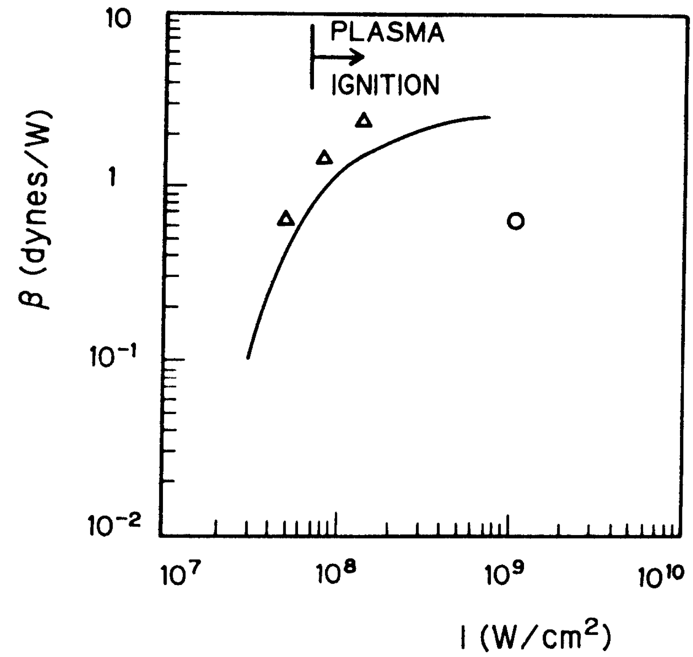

Fig. 7. Impulse coupling coefficient for Al target in vacuum. The symbol △ represent the Rosen's result, the full line the result estimated from the transparent vapor model (the absorption coefficient of 0.25 is assumed), the symbol ○ the present result.

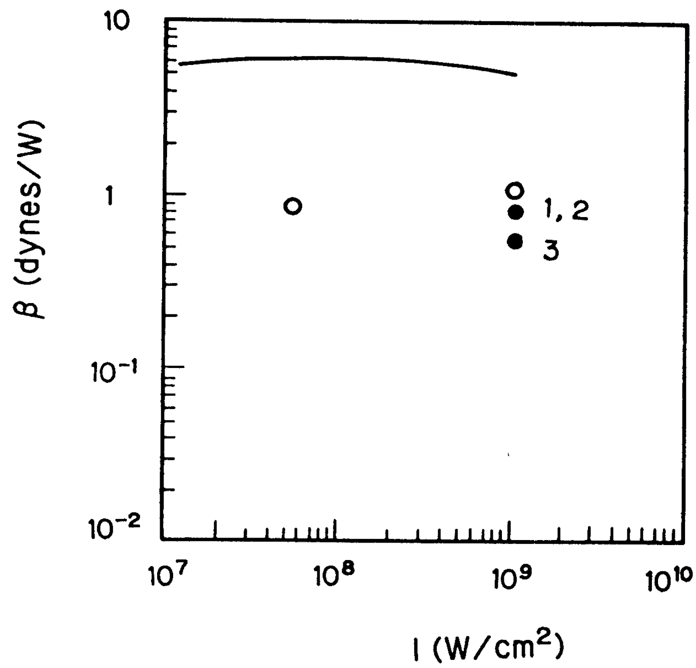

Fig. 8. Impulse coupling coefficient for Zn target in vacuum. The number next to the symbol indicates the value obtained after every 1000 shots of laser.

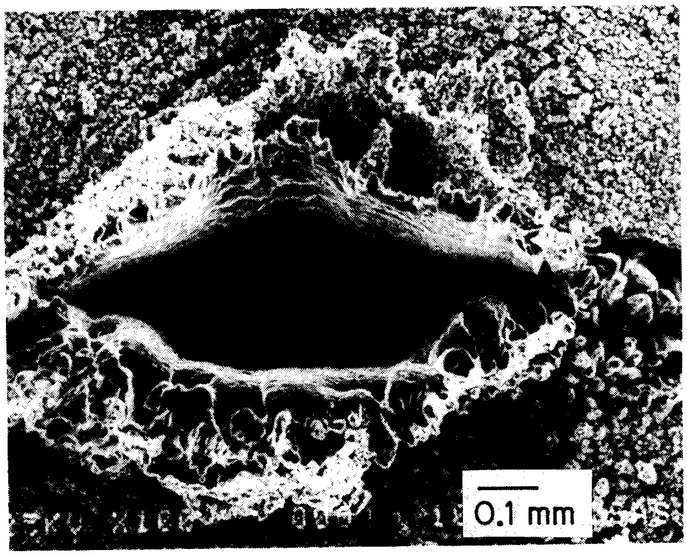

Fig. 9. Photograph of the Aluminum target after 10^4 shots.

or the operation by using much higher average power laser.

Specific impulse

The specific impulse induced by the laser irradiation can be defined by

$$R/(\Delta m \times g),$$

where R is the impulse, Δm is mass defect per pulse, g the gravity constant. Since the mass defect per pulse is much smaller, we obtain it by averaging the mass defect induced by 10^4 shots. This corresponds to the quasi-steady operation of 10 second. During the operation, the impulse coupling at the final stage is reduced by 10~20% in comparison to the one at the initial stage. In Table 1, the specific impulse for various targets is shown. These values are larger than the theoretical estimate by the transparent vapour model. The theoretical value is estimated as $\sqrt{kT/m}/g$. It implies that an additional acceleration of the target vapor is induced, which can be attained by the laser energy absorption at the vapor.

Anti-parallel RP laser thruster

In the usual RP laser thruster, the thrust is generated in parallel to the laser beam direction. Hence, as is shown in Fig.1, it is proposed that the nozzle inner surface is utilized as a focusing facility. However, this idea has a severe defect in that the direction of the thrust is limited in relation to the laser beam direction. On the other hand, the anti-parallel thrust vector is obtained in the CW type. In this type, a wide variety of thrust vector direction can be attained by changing the beam direction before introducing it into an absorption chamber. To generate the anti-parallel thrust in the RP type thruster, we propose the configuration shown in Fig. 10. In this configuration, the laser beam is introduced through the window. The target on which the laser beam is focused is set near the window surface. The target vapor which

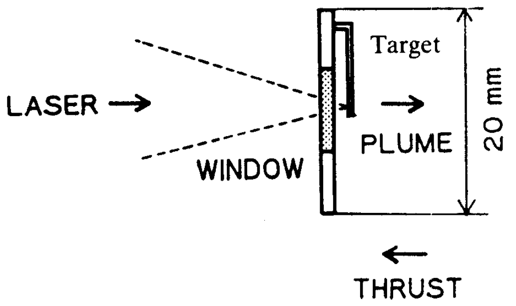

Fig. 10. Configuration of RP laser thruster generating an antiparallel thrust vector to the laser beam direction.

evaporates from the target surface is reflected at the window surface and gives it a recoil momentum. The impulse coupling coefficient of 0.9 dynes/W for this configuration of Zinc target was attained under an atmospheric pressure. Although this is smaller than the one for the parallel thrust vector configuration, much higher impulse coupling coefficient can be expected by reducing the space between the target and the window. However the contamination of the window by the vapor may increase. This may cause the break down of the window due to an increase in an absorption of the laser energy at the window. The protection of the window is a future problem for the configuration of this type of RP laser thruster.

4. Summary

The characteristics of the quasi-steady operation of RP laser thruster are investigated for a variety of target by using Kr-F (0.242 μm) laser irradiation of 100 pps. Also the new configuration of RP laser thruster in which the thrust vector is anti-parallel to the laser beam direction is proposed and demonstrated. The followings are summaries;

1) The impulse coupling coefficient is comparable to the result previously reported and the theoretical value predicted by the transparent vapor model.
2) The impulse in an atmospheric pressure is greater than the one in vacuum condition. The blast wave theory can explain the increment of the impulse in an atmospheric pressure. The vapor which evaporates from the target surface also contributes to the impulse.
3) The thrust produced in a quasi-steady operation can be estimated to be almost the impulse coupling coefficient multiplied by the average power of the laser radiation. It means that the time in which the recoil momentum is delivered by the laser shot is sufficiently small in comparison with the time interval of the RP laser beam. The coupling between the pulses may appear at the operation by the laser beam having a high repetition rate of more than about 10^5 pps.
4) The reduction of the impulse coupling during the quasi-steady operation is not severe at the present experiment. However it is expected that the reduction becomes severe for the operation of much longer time or the operation by the

laser beam of much higher average power.

5) The specific impulse is measured for a variety of target. The value is rather greater than the one expected from the transparent vapor model. It means that the absorption of the laser inside the vapor occurs.
6) The new configuration of RP laser thruster in which the thrust vector is anti-parallel to the laser beam direction is proposed and demonstrated. The protection of the window from the target vapor is a future problem.

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