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ドーナツモードレーザー打ち上げシステムのインパルスに関する実験的研究

Experimental Study of the Impulse Generation generated by Donut-mode Beam Launch System

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Abstract（概要）

The impulse on the spherical target induced by laser irradiation in the nanosecond regime at the wavelength of 1.064 μm is experimental studied. The donut-mode beam generated by an optics system irradiates the target surface in order to improve the stabilization performance. The laser fluence, based on the different spot diameter and the thickness of donut-mode beam, is varied from 3.5 J/cm^2 to 53.6 J/cm^2. The impulse measured by a load cell system shows its dependence on laser fluence and the strong relation with the shock wave expansion in presence of ambient air.

Nomenclature

E_L	:Laser pulse energy (J)
E_{dn}	:Energy of donut-mode beam (J)
I_m	:Impulse (Nm)
C_m	:Momentum coupling coefficient (N/MW),
ϕ	:Laser fluence (J/cm^2)
p_a	:Ambient pressure in test chamber (Pa)
R_0	:Radius of spherical target (mm)
r_{in}	:Inner radius of Donut-mode beam (mm)
t_{dn}	:Thickness of donut-mode (mm)
I_L	:Laser power density (W/cm^2)
τ_L	:Laser pulse width (ns)
λ	:Laser wavelength (μm)
R_{disk}	:The radius of the disk (mm)

1. Introduction

The laser propulsion system has been developed since the initial concepts of Kantrowitz's theory in 1972.[1] As estimated, for launching a nanosatellite with a mass of the order of kilograms into low earth orbit using laser propulsion system gave a lower cost than that using a chemical rocket propulsion. Currently, a Megajoule-level pulse energy has been achieved at the National Ignition Facility,[2] that satisfies the energy requirement in laser propulsion system.

Myrabo et al. designed the first laser-powered vehicle, called Light craft, and as demonstrated, the Light craft achieved the highest attitude of 71 meters from the ground in 1999.[3] By analysis method from Takahashi,[4] the Light craft might loss the altitude stability during the flight. The real data flight[3] shows that the Light craft deviated from riding-beam after three seconds. Hence, the stabilization of the target during the launch by the laser propulsion system has been a challenge. A new approach of the laser propulsion system was proposed that operates based on the combination between a spherical target and a donut-mode laser beam, as shown in Fig. 1.[5] A spherical target is launched along the donut-beam which has a ring shape with a low intensity in the center. Several generation methods for obtaining the donut-mode beam has reported.[6,7] These donut-mode beams were generated using a Mach-Zehnder interferometer or using a conical Brewster optical element. These methods require the complex and costly system and the donut-mode beam size is of the order of nanometer-size and micrometer-size. In our previous work,[8] the donut-mode beam was generated using an optical system equipped with donut-mode in order to eliminate the energy of the center beam. However, the laser energy was not conserved and the laser fluence was low and not enable to change.

Moreover, for the laser propulsion system, precise quantitative experimental data of impulse and the observation of shock wave are necessary for a precise feasibility study. C_m defined as the ratio of I_m to E_L for an aluminum spherical target was found determined as a function of the dimensionless blast radius, R_{disk}/R_{bw}, where R_{disk} is the radius of the disk and $R_{bw}=(E_L/p_a)^{1/3}$.[9] However, the study was conducted under low laser fluence, which decreases C_m. On the other hand, during the laser ablation, shock wave expands and interacts with each other. The study about the shock-shock interaction has been limited for the laser propulsion. The aim of the present study is to investigate the impulse generation and shock-shock interaction on the target irradiated by the donut-mode laser beam in the wide range of ambient pressure. The donut-mode beam is generated using an optics system without the energy loss. The shock-shock interaction is visualized using a Schlieren system.

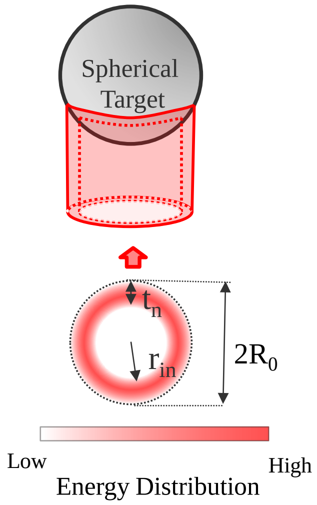


Fig.1 The donut-mode laser beam concept.

2. Experimental setup

Figure 2 shows the schematics of the experimental setup. All experiments were conducted in the vacuum chamber whose pressure was controlled by using a rotary and a turbo-molecule pumps. The ambient pressure, p_a, was changed in the wide range from 10 Pa to 100 kPa. A Nd:YAG laser (Surelite, Ex, Continuum Ld.,) was used as the laser source for all experiments. The shot-to-shot energy was examined by a Multi-Function Optical Meter, the variation of E_L was 5%.

For impulse measurement, a spherical target whose diameter is 10 mm is mounted on a pendulum system. The movement of the target during irradiation was recorded by a digital video recorded FDR-AX40 (Sony Ltd.) that provides avi file of 29 frames per second. The distance between the target at the rest and highest position is used to calculate the impulse.

For Schlieren visualization, a high-speed camera Ultra (NAC Co. Ltd) and a short arc power flash (Nissin Electronic Co., Ltd) are used. The short arc power flash can supply high intensity of light during the experiment. In this study, the Schlieren images of plume and shock expansion are recorded at 10^6 frames per second. The camera exposure time is 100 ns.

The donut optics system consists of a concave lens, several convex lenses, and an axicon lens, as shown in Fig. 3. The fluence is varied by changing the spot area on the target surface.

For plasma generation, the fluence should exceed a threshold value, typically of the order of several J/cm^2 for ns laser pulse.[10) The threshold fluence, ϕ_0 is given by[11)

$$\phi_0 = \rho L_V \beta^{1/2} \tau_L^{1/2} \qquad (1)$$

where ρ is the target density (2.7 g/cm^2), L_V is the latent heat of vaporization (10800 J/g), β is the thermal diffusivity (0.9849 cm^2/s), and τ_L is the laser pulse width (5×10^{-9} s). Thus, ϕ_0 equals 2.04 J/cm^2 in the present study. Three cases with the different dimension of the donut mode beam are used, whose inner diameter, r_{in}, varies from 4.55 mm to 3.74 mm, t_n varies from 0.60 to 0.04, respectively, as shown in Table 1. ϕ was kept approximately 22 J/cm^2, which exceed the above-mentioned threshold value.

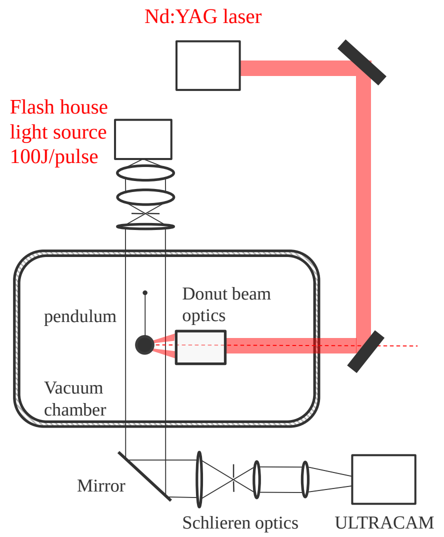


Fig. 2 The schematic of experimental setup

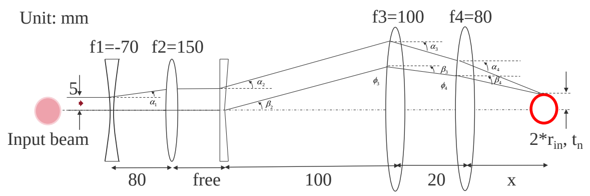


Fig. 3 The donut-mode beam optics system

Table 2. The experimental case of the donut-mode beam

Case	r_{in} [mm]	t_n [mm]	Fluence [J/cm2]
1	3.63	0.12	21.75
2	2.75	0.15	21.93
3	2.46	0.17	21.78

3. Results

3.1 Donut-mode beam pattern

To confirm the actual pattern of the donut-mode beam, the thermal paper was placed at several positions that have the different distance from the third convex lens to the target center, x. The laser energy was kept at lower-level of E_L=0.2 J to avoid the damage of the paper. The axicon angle is 5 degrees. As shown in figure 4, it is found that the beam has a donut-mode shape with the no energy in the center of the spot. From the viewpoint of the practical use for laser propulsion experiment, the present optics system is suitable to generate the various donut-mode size with different laser fluence.

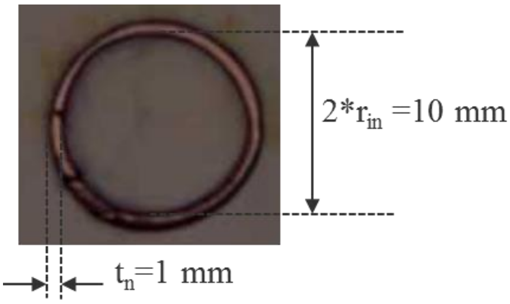


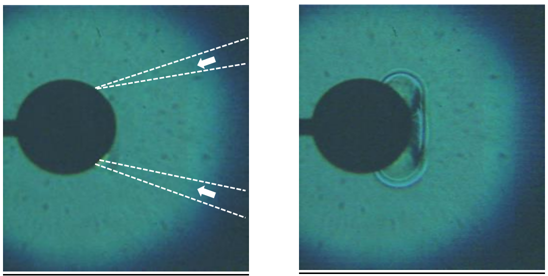
Fig.4 The donut-mode beam pattern before the target

3.2 Visualization of the shock-shock interaction

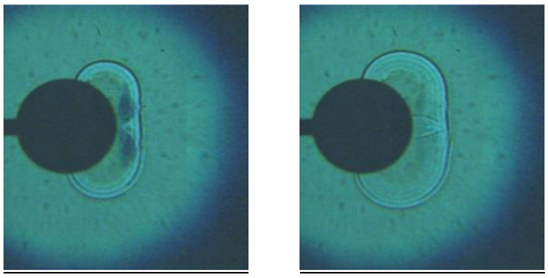
Schlieren pictures are shown in Fig. 5. The laser pulse started to irradiate at t=0 μs from the right-hand side. For the first case, figure 5a, the r_{in} and t_n of the donut beam were kept at 3.63 mm and 0.12 mm corresponding to Φ=22 J/cm^2. As shown in Fig. 5a, the toroidal shock wave expands, part of waves interacts along the symmetry axis. The shock interacts and creates a locally high-pressure region in the early stage of expansion, and then reflects in the center line, as shown at t=6050 ns. The generation of jet flow is not visible.

For the second case, figure 5b, the dimension of the donut was adjusted smaller than case 1, corresponding to r_{in} =2.75 mm, t_n=0.15 mm. The jet flow which is visible should be originated from the shock focusing,[12,13] and Mach reflection phenomenon.[14] At later timing, the jet flow products the protrusion.

For the third case, the phenomenon is the same as the second case. It should be noted that the jet flow might be stronger and more visible for the smaller radius of the donut-mode beam. That can be explained by the increasing of Mach number of shock wave before the interaction due to the short distance of the expansion.

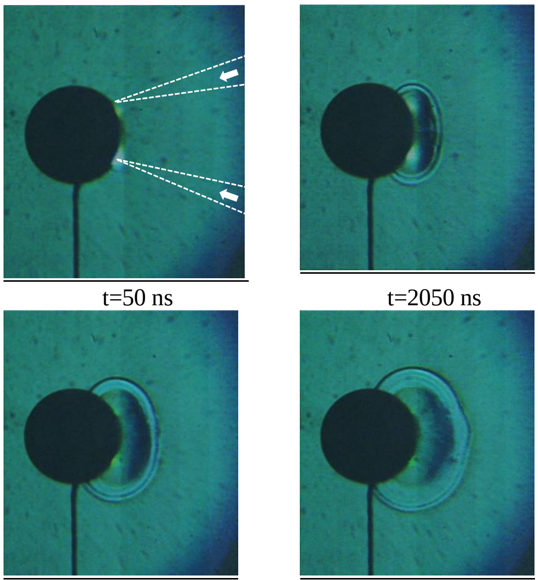


t=50 ns t=2050 ns



t=4050 ns t=6050 ns

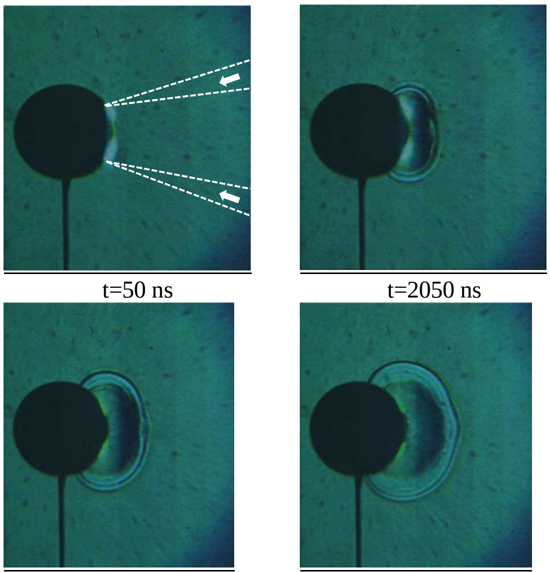
(a) Case 1: R_{in}=3.63 mm, t_n=0.12 mm



t=50 ns t=2050 ns

t=4050 ns t=6050 ns

(b) Case 2: R_{in}=2.75 mm, t_n=0.15 mm



t=50 ns t=2050 ns

t=4050 ns t=6050 ns

(c) Case 3: R_{in}=2.46 mm, t_n=0.17 mm

Fig. 5 Schlieren figures around the sphere after laser irradiation in the different dimension of donut-mode beam, laser fluence Φ≈21 J/cm^2

3.3 Impulse performance

In Fig.6, the value of C_m varying in the wide range of p_a from 10 Pa to 100 kPa is shown. The red points are the impulse results that were measured in our previous study in the case of the single spot beam.[15] Using the theory of the pendulum system, we can express C_m as

$$C_m = (1/EI)\sqrt{2mgIl_c}\sqrt{1-\cos(D/l_c)} \qquad (2)$$

where l, r, m, l_c, I, P, L, D are moment arm, radius of target, mass of the target, distance from the pivot to the center of mass, moment of inertia of pendulum, momentum, angular momentum, and oscillation amplitude, respectively. In the low-pressure condition, p_a < 100 Pa, C_m is found having the approximately same value in three cases. The impulse was generated from the ablation jet. C_m is a function of $I\lambda\sqrt{\tau}$ which consistent with the Phipps's theory in the vacuum, where I, λ, τ are the laser intensity, wavelength, and pulse width of the laser beam, respectively.[16] For p_a > 100 Pa, C_m increases monotonically with p_a. Especially for p_a > 10 kPa, the impulse generation is dominated by the expansion of the blast wave above the surface of the sphere. As shown in Fig.5, the toroidal shock wave has better performance in generating impulse than the spherical shock wave created by the single spot beam. The interaction of shock keeps the high local pressure domain on the target's surface that makes the increase of the impulse. As a result, the donut-mode beam shows a better performance of impulse than single spot beam due to the generation of the jet flow, especially when p_a > 10 kPa.

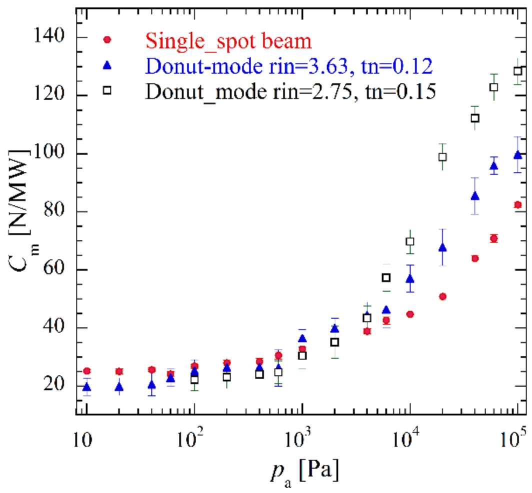


Fig. 6 The momentum coupling coefficient Cm in the wide range of ambient pressure, p_a, from 10 Pa to 100 kPa, laser fluence $\Phi \approx 21$ J/cm^2

4. Conclusion

In this study, the propulsive performance of laser propulsion to the spherical target irradiated by the donut-mode beam was primarily investigated in a wide range of ambient pressure. The shock propagation captured by Schlieren method indicates that shock-shock interaction resulting in the jet flow affects directly to the impulse generation. Furthermore, the propulsive performance of donut-mode laser beam was confirmed and the trend of variation of C_m was found to have a higher value for the donut-mode beam's case than that in the conventional single spot beam's case.

Acknowledgement

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