PRAMANA — journal of physics

Vol. 62, No. 4
April 2004
pp. 923–932

Impulse coupling in laser-driven microtargets

P BHARGAVA, M KUMAR, H KUMAR, P PANDIT, R PANDEY and A K NATH*
Industrial CO_2 Laser Section, Centre for Advanced Technology, Indore 452 013, India
*Corresponding Author
E-mail: aknath@cat.ernet.in

MS received 15 May 2003; revised 23 October 2003; accepted 12 December 2003

Abstract. We have studied about the thrust imparted to targets of different materials by pulsed TEA CO_2 laser and chopped CW CO_2 laser in air and its dependence on different parameters such as laser intensity and pulse duration. We estimated the impulse-coupling coefficient and compared it with the published results. The mechanism of generation of thrust by laser incident on targets in air is, in effect, combination of those involved in laser ablation in vacuum and laser-induced air detonation.

Keywords. Laser propulsion; CO_2 lasers; microtargets; impulse coupling.

PACS Nos 79.20.Ds; 52.38.Mf; 52.50.Jm; 42.55.Lt

1. Introduction

In recent times the launching of spacecrafts by imparting thrust with an intense laser beam has attracted worldwide attention because of the possibility of reduction in launching cost of payloads into low earth orbit (LEO) with conventional (chemical) rockets [1–7]. The mechanism of generating thrust by either detonating air plasma or evaporating/ablating solid or liquid by laser energy is being seen as a potential alternative to chemical propulsion for space vehicles. The novelty in this concept is the fact that no or very minimal fuel is carried on board, and the specific impulse is infinite. Key advantages of this concept includes launching relatively many small payloads under high thrust, good specific impulse, simplicity and reliability of mechanism, simple propellant energy system, reduced order of magnitude or production cost or launch cost of satellites.

The idea of laser propulsion was first mooted by Marx [8] in 1966 to propel interstellar vehicle by terrestrial laser beam. Phipps and Michaelis [2] have provided a detailed review on laser propulsion including its history and prospects. There are three different modes through which a light craft can be propelled by the laser beam.

One of the modes is to deflect the light craft with radiation pressure exerted by an intense laser beam [8]. Laser beam of power P made incident on a rear end of the target from where it is totally reflected back, exerts a force of magnitude $2P/c$ on the surface, where c is the velocity of light. Recently, Myrabo *et al* [6] carried out propulsion experiment under vacuum conditions at 7.9–13.9 kW CO_2 laser power and measured force of $3.3–6.7 \times 10^{-3}$ N/MW exerted by the laser beam. This propulsion mechanism is much less efficient in producing thrust than other two mechanisms of propulsion, namely, laser ablation and air detonation. However, this is capable of achieving relativistic speeds [8] in vacuum condition and can be useful to deflect the light craft to small inclination for the correction of orbit orientation.

In 1972, Kantrowitz [9] suggested the laser ablation propulsion wherein a remote laser heated a target propellant to produce an ablation plasma jet for thrust. When a laser pulse is incident on a target, the mechanical impulse imparted by the laser beam depends on several factors, and many phenomena such as absorption of laser radiation by the target, vaporization, plasma formation, energy coupling in plasma and subsequent transfer to the target, pressure exerted by the escaping vapor etc are involved. The impulse-coupling coefficient $C_{\rm m}$ defined as the ratio of target momentum to incident laser energy during laser ablation is commonly used as the figure of merit for this interaction. Thus, $C_{\rm m}$ among other factors depend on the characteristics of target material, laser wavelength λ, laser intensity I and laser pulse duration τ. Based on a large number of published experimental data of laser impulse coupling with targets in vacuum and their own results, Phipps *et al* [10] established that $C_{\rm m}$ scaled as $(I\lambda\sqrt{\tau})^{-0.3}$. The impulse-coupling coefficient lies in the 1–100 N·s/MJ range for the wide variation in laser intensity ranging from 3 $\rm MW/cm^2$ to 70 $\rm TW/cm^2$, laser wavelength from 248 nm–10.6 micron and pulse duration from 1.5 ms to 500 ps. This mode of propulsion is attractive at heights beyond a few kilometers from the Earth where the air density is very low.

In a more recent experiment, Yabe *et al* [7] demonstrated similar propulsion to drive microplanes made of paper by a 590 mJ, 5 ns pulse Nd:YAG laser. They used different types of target materials such as aluminum foil, water droplets attached to aluminum foil and layered target (called exotic target) the top layer being transparent to laser light. In their experiment, impulse-coupling coefficient of the laser energy to produce thrust on targets of different materials by laser ablation was of the order of 10^2–10^3 N·s/MJ.

The above scheme requires some suitable fuel to be carried on board that can be ablated by the ground-based laser beam. In the third mode of propulsion no fuel is required on board. Instead, a high-energy laser pulse is focused by on-board mirrors and used to heat air flowing through the engine inlet. The high-energy laser pulse produces an intense detonation wave which exerts thrust on the light craft. This is also called as air-breathing mode of propulsion. Use of atmospheric air as the working fuel results in infinite specific impulse which is defined proportional to momentum gained by the craft per unit mass loss due to burning of on-board fuel. Myrabo *et al* [3] reported the impulse-coupling coefficient in the range between 100 and 143 N·s/MJ. Schall *et al* [5] reported a maximum value of 333 N·s/MJ. Using this scheme Myrabo *et al* [3] as well as Bohn [11] have actually flown small light craft devices to altitudes of 10–30 m using tens of kilowatts CO_2 lasers.

It is obvious from the various experimental results that $C_{\rm m}$ depends on the mode of propulsion, target materials and laser parameters. Phipps *et al* [10] have presented exhaustive results of $C_{\rm m}$ for laser ablation in vacuum. If the process is taking place in air the optical breakdown of air introduces further complication and this is expected to influence the thrust produced by the laser. Yabe *et al* have estimated the value of C_m in air for different targets driven by ns duration Nd : YAG laser. The objective of the present study is to estimate the amount of thrust that can be imparted by the high power CW and pulsed TEA CO_2 lasers to the targets in air and to understand the basic phenomena involved in laser propulsion. CO_2 laser is one of the most versatile ones among the various lasers considered for laser propulsion, in terms of mode of operation (continuous wave, pulsed, modulated), power capability, and high efficiency. Phipps *et al* [12] compared three possible laser wavelengths : 530 nm (2nd harmonic of Nd : glass laser), 1.32 micron (the oxygen–iodine laser) and 11.1 micron (the isotopic CO_2 laser), the wavelength which penetrates the atmosphere well. Considering the available laser power and possible problems associated with the atmospheric turbulence, adaptive optics and mirror steering for various wavelengths, they concluded that the CO_2 laser is the best choice. Our experimental results show that the impulse-coupling coefficient in air is higher than that reported in vacuum [10]. In fact it was closer to the value reported in air-breathing mode of propulsion [11]. Moreover, the laser pulse duration did not influence C_m as strongly as reported in vacuum condition. We have attempted to explain these observations.

2. Experiment and results

The indigenously developed 3.5 kW CW CO_2 lasers and high repetition rate TEA (transversely excited atmospheric pressure) pulsed CO_2 laser of 500 Hz and 500 W average power rating [13] were used in the present study of impulse coupling with targets made of wood, wood wrapped with aluminum foil, nylon, teflon and plexiglass. Lightweight targets of different materials were made conical shaped and weighed approximately 0.2–0.4 g.

The initial velocity imparted to the target by the laser pulse was estimated by the pendulum method as used by others [6,11]. The experimental set up to measure the pendulum deflection is schematically shown in figure 1. The travel time of the laser-driven target from its rest position was measured by monitoring the time interval, when the laser beam struck the target and at the instant when target intercepted a He–Ne laser beam placed at a known distance. A relation expressing the initial velocity U imparted to the target by the laser beam can be easily derived in terms of the time of flight t, the vertical height gained by the pendulum h and the angle from vertical at which the pendulum intercepted the He–Ne laser beam θ:

$$U = [(2h/t)^2 \mathrm{cosec}^2\theta + 2gh]^{1/2},$$

where g is the acceleration due to gravity.

The first set of experiments involved thrust imparted by the rapid vaporization of target using high peak power pulses from the TEA CO_2 laser. The pulse peak power was about 2 MW. Experiments were done with laser pulses having initial spike of about 150 ns without and with a tail of about 6 μs duration, which was controlled by varying the laser gas mixture. Figure 2a shows a typical laser pulse with a long tail ($\sim$5 μs duration) in a laser gas mixture, $CO_2 : N_2 : He = 5 : 7 : 68$

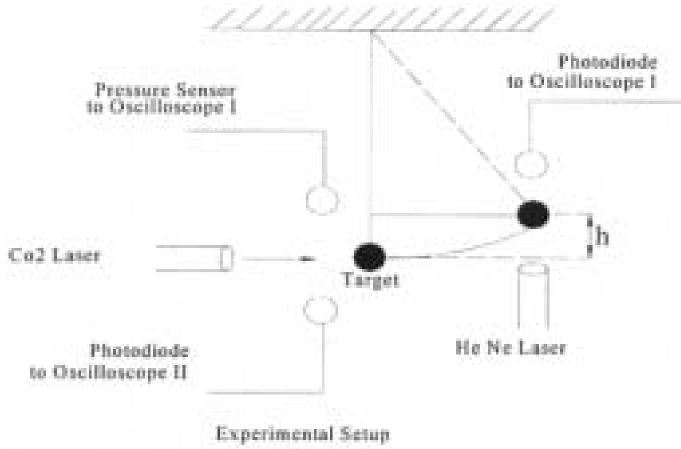

Figure 1. Experimental set up of pendulum to measure deflection of target by laser thrust.

and figure 2b shows a laser pulse with a short tail (1 μs duration) in a gas mixture, $CO_2 : N_2 : He = 7:1:32$. The laser pulse energy was varied in the range from 300 mJ to 700 mJ per pulse by varying the laser excitation voltage. The second set of experiments was done with the CW CO_2 laser. The CW beam was chopped by controlling the electrical excitation current. The duration of chopped pulse was about 100 ms and the power was 1.2 kW. The TEA CO_2 laser/chopped CW laser beam was focused on the target with the help of a 150 mm focal length ZnSe lens. The laser intensity incident on the target was varied by changing either the laser power or the spot size of the beam on the target.

The impulse-coupling coefficient C_{m} is calculated as the ratio of the target momentum (mU) produced to the incident laser pulse energy W:

$$C_{\mathrm{m}} = mU/W \text{ dyne·s/J } (10^{-5} \text{ N·s/J}).$$

The dependence of the momentum-coupling coefficient C_{m} on the laser intensity was studied on cone-shaped wooden target for lightweight. Wooden targets were getting damaged with a few pulses of the laser beam incident on them and due to this there was large shot-to-shot variation in the deflection. Therefore, a small piece of thin aluminum foil was stuck on the plane surface of the target on which laser beam was striking. This reduced the shot-to-shot variation and yielded consistent results. The dependence of C_{m} on the laser intensity is shown in figure 3. It was found that C_{m} increased with the laser intensity to a maximum value of about 200 N·s/MJ at about 0.5 TW/m^2 laser intensity and beyond this it dropped down sharply and again rose gradually with further increase of the laser intensity. The initial velocity of the target produced by the laser pulse varied in the range of 15 cm/s–45 cm/s in our experimental range of laser intensity. The experiment was carried out with laser pulses of two different shapes and time durations as shown in figures 2a and 2b, maintaining the laser pulse energy constant. Contrary to the expectation of C_{m} scaling as $(I\lambda\sqrt{\tau})^{-0.3}$ it was observed that there was no significant difference in C_{m} for these two types of pulses.

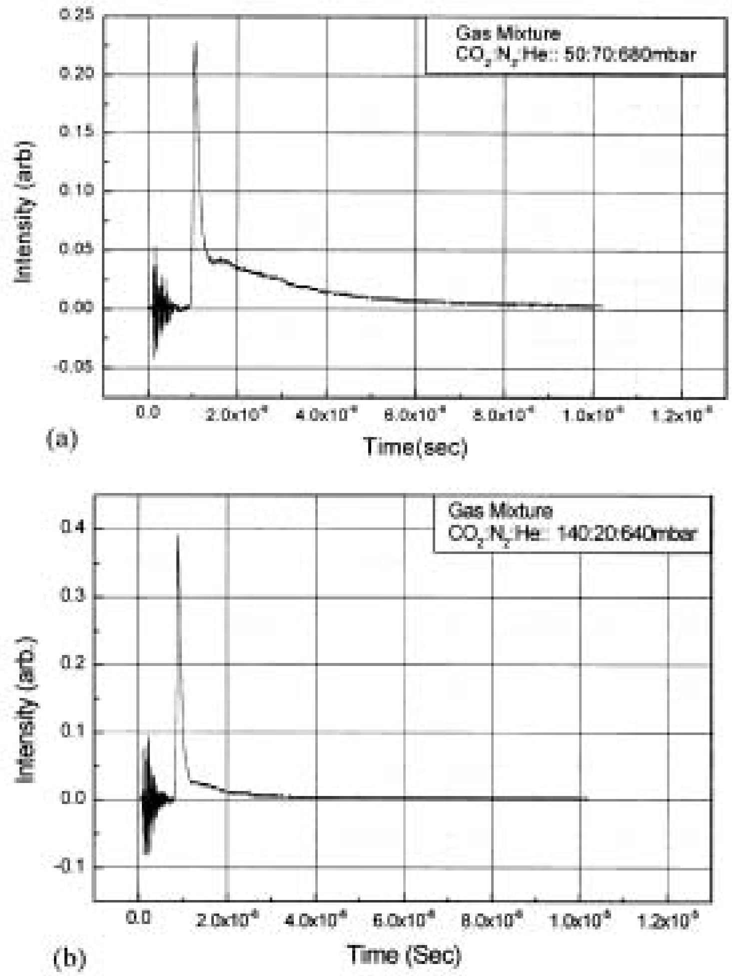

Figure 2. TEA CO_2 laser pulses for two different laser gas mixtures.

The impulse-coupling coefficient was measured for targets of different materials, namely, wood without aluminum foil, plexiglass, nylon and teflon. Results are presented in figure 4. The magnitude of C_{m} for these materials fell in the range of 100–240 N·s/MJ. In all experiments including wood with aluminum foil, the laser pulse incident on the target produced a tiny luminous plume at the target surface. At higher intensities it formed intense plasma. Plasma produced by the laser pulse was detected with a fast photo-detector. Figure 5 shows the plasma luminosity at $\sim$1 TW/m^2 laser intensity for different target materials. With the scatter of the data no consistent trend of variation in C_{m} values for different materials studied over the present range of power density could be established. However, some correlations between the value of C_{m} and plasma luminosity could be observed. At about 1 TW/m^2 laser intensity, in some cases such as in plexiglass, nylon and teflon, C_{m} value was relatively less for materials in which plasma intensity was more.

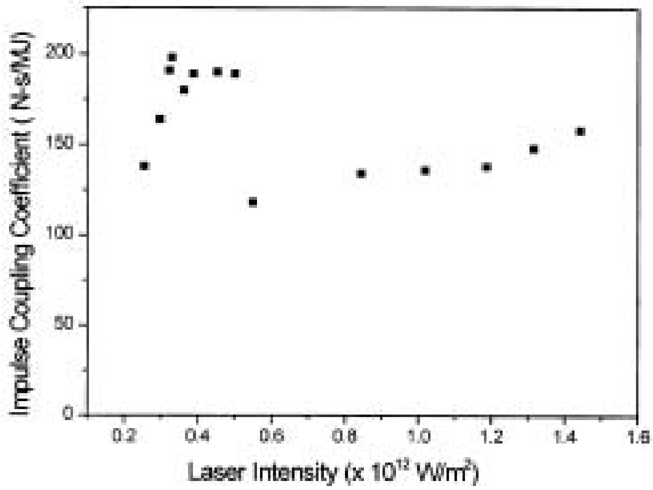

Figure 3. Variation of $C_{\rm m}$ with laser intensity. Target: Aluminum foil fixed on wooden cone.

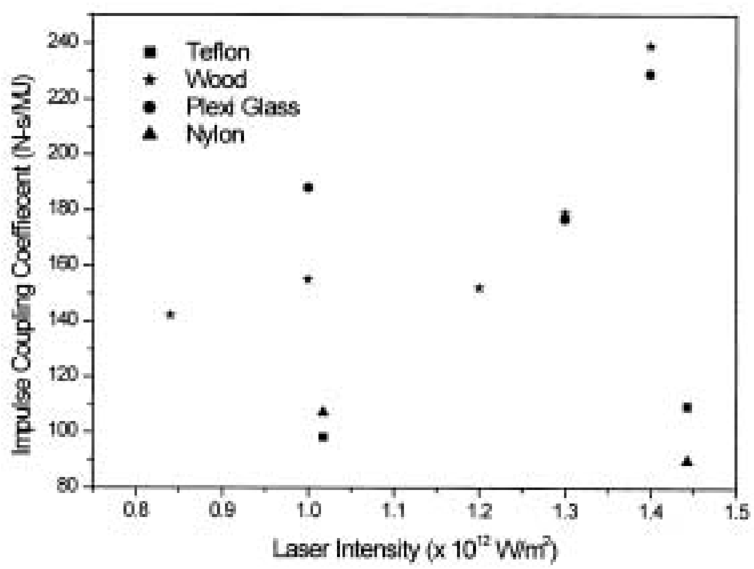

Figure 4. $C_{\rm m}$ for different target materials.

In order to study the effect of continuous wave (CW) CO_2 laser in kW power range the pendulum experiment was done with the wooden target and chopped laser pulse of 100 ms duration and 1.2 kW power. It produced initial velocity of 45 ± 3 cm/s in a 1.07 g target. The impulse-coupling coefficient was about 4 N·s/MJ, much smaller than that produced by high peak power TEA laser pulses. Various experimental parameters and estimated initial velocity and impulse-coupling coef-

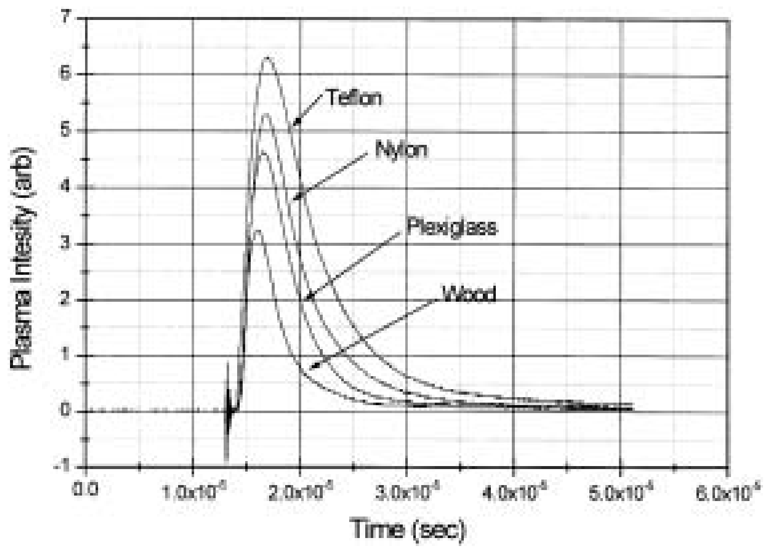

Figure 5. Plasma-plume luminosity for different target materials.

ficient for chopped CW and high peak power laser pulse are presented in table 1 for comparison. This shows that though the relatively low power chopped laser beam could impart high initial velocity and momentum to the target than those produced by high peak power laser pulses, the impulse-coupling coefficient was much lower.

3. Discussion

Our measured values of $C_{\rm m}$ in different materials lie in 100–240 N·s/MJ range. Yabe *et al* [7] had estimated $C_{\rm m} = 237$ N·s/MJ in their experiment on exotic targets in air with a few ns duration Nd:YAG laser. These values are on the higher side of the values reported by Phipps *et al* [10] for different targets in vacuum with lasers of different wavelengths and laser pulse durations. However, our values are closer to those reported by Bohn [11] measured in the air breathing or air plasma detonation mode. Phipps *et al* [10] have shown that $C_{\rm m}$ scaled with $(I \cdot \lambda \cdot \sqrt{\tau})^{-0.3}$ under vacuum condition and for aluminum alloy and C–H target materials it was

Table 1. Comparison of experimental parameters and laser impulse coupling for chopped CW and pulse TEA lasers.

Mass of target (g)	Laser power (W)	Laser intensity (MW/cm^2)	Laser energy (J)	Laser pulse duration (s)	Initial velocity (cm/s)	Momentum gained (N·s)	$C_{\rm m}$ (N·s/MJ)
1.1	1.2×10^3	0.15	120	100×10^{-3}	45	4.6×10^{-4}	4
0.3	1.2×10^6	1×10^2	0.5	160×10^{-9}	30	0.8×10^{-4}	190

in the range of 1–100 N·s/MJ for $(I \cdot \lambda \cdot \sqrt{\tau})$ varying from 0.1 to 10^7 W·cm·$\sqrt{s}$. For our case the magnitude of $(I \cdot \lambda \cdot \sqrt{\tau})$ is about 40 W·cm·$\sqrt{s}$ and corresponding to this $C_{\rm m}$ should be about 30 N·s/MJ. Such a large deviation of our results obtained with the target in air from the values in vacuum and more closer match with those obtained in air breathing mode indicate that the air plasma formed close to the target surface plays an important role in producing the impulse.

We observed that with the increase of incident laser intensity, $C_{\rm m}$ first rose rapidly to a peak value then decayed sharply for further increase of laser intensity and again increased gradually (figure 3). This behavior is also in variance with that reported in vacuum [10] where $C_{\rm m}$ after reaching a maximum decreases gradually and monotonically.

The different trend of variation of $C_{\rm m}$ with laser intensity for targets in atmosphere vis-à-vis in vacuum could be attributed to different contributions of the thrust producing mechanisms. Intense laser pulse incident on the target vaporizes or ablates a small amount of material from the surface. At laser intensities below the magnitude $I_{\max}$ for the maximum $C_{\rm m}$, the reaction pressure of the laser ablated or blow-off vapor produces the thrust on the target in air as well as in vacuum. Air at the surface may act like a second tamping surface which could contribute to higher value of $C_{\rm m}$ in air compared to that in vacuum. The initial rapid rise of $C_{\rm m}$ is attributed to the reduction of heat loss due to thermal diffusion [14]. At laser intensities above a threshold $I_{\max} \sim 1$ TW/m^2 [10,15] plasma is formed at the target surface. Electrons emitted from the target surface initiate breakdown in atmosphere and create air plasma through the avalanche ionization process [14]. Air-plasma launches a laser-supported detonation (LSD) wave under certain conditions of laser intensity and ambient pressure which produces a shock pressure on the target [15]. This makes a significant contribution to the thrust generated on to the target. In the absence of any ambient gas in vacuum, the ablated material or vapor forms plasma at the surface and the recoil pressure of blow-off material only creates the thrust [10]. The plasma absorbs further laser energy by inverse Bremsstrahlung process and shields the target from rest of the laser pulse. The sharp decay of $C_{\rm m}$ for laser intensity beyond $I_{\max}$ is attributed to the formation of the dense plasma. The reasons for higher value of $C_{\rm m}$ in air than in vacuum can be attributed to the following:

i. Air at the surface may act like a second tamping surface.
ii. In atmosphere very little material is ablated from the target [16]. Laser pulse produces plasma in air initiated by electrons emitted from the target surface, whereas in vacuum a part of laser energy is spent in heating the target material, vaporizing it to form plasma.
iii. For the same laser intensity the pressure generated by air plasma and its build-up rate are higher than those of laser ablated plasma in vacuum [15].

The reason for the gradual increase of $C_{\rm m}$ after the sharp decay with the increase of laser intensity above $I_{\max}$ can be attributed to the following: We observed that the number of lasing modes and higher-order mode intensity increased when the laser power was increased by increasing the excitation voltage. This would produce non-uniform spatial intensity distribution on the target. It has been reported that LSD is initiated at local surface defect sites and imperfections [15]. This in conjunction with non-uniform intensity distribution could produce several tiny plasmas on the target surface instead of one single uniform plasma plume, which may not be able to block the entire spatially distributed laser beam. Hettche *et al* [16] reported that the major contribution to the total impulse resulted from in-air irradiation of aluminum by a pulsed CO_2 laser was associated with the plasma pressure during the initial stages of the plasma–surface interaction and the corresponding impulse coupling coefficient should increase linearly with beam intensity. This corroborates with our experimental results.

Another observation which is similar to that reported by Hettche *et al* [16] but at variance with that reported by Phipps *et al* [10] for impulse in vacuum and also with that of Schall *et al* [5] for air breathing mode is that C_{m} did not change significantly in our experiment when the laser pulse was changed from a 160 ns spike with about a microsecond tail to a similar spike with about 5 microsecond tail keeping the laser pulse energy constant. While Phipps *et al* reported gradual reduction in C_{m} with the increase of $I \cdot \sqrt{\tau}$ for laser intensity beyond the threshold of vapor–plasma transition in vacuum. Schall *et al* observed increase in C_{m} with the increase of I and reduction in τ. In our experimental condition the dependence of C_{m} on I and τ seems to be influenced by the effects of both laser ablation in vacuum and laser air detonation, and is dependent on laser energy rather than on I and τ independently.

Among the different target materials experimented, the magnitude of C_{m} in some of them was relatively small for which the plasma was more intense. Higher plasma intensity indicates that more laser power is spent in increasing the plasma temperature and less in ablation of target material which directly produces the thrust. Besides the physical and thermal properties and ionization potential of the target materials, the optical reflectivity of the target surface could also influence the plasma formation. While the higher reflectivity will result in lower C_{m}, the interference of the incident and reflected laser beams near the surface could produce higher laser intensity which would facilitate formation of more intense plasma close to the surface.

The reason for very low value of C_{m} in case of chopped laser pulse is that the laser power density is too low for fast ablation of material and a large fraction of laser energy is lost via thermal diffusion due to long pulse duration.

4. Conclusion

High impulse-coupling coefficient has been measured in laser propulsion of objects in air with pulsed TEA CO_2 laser. The laser thrust generation on target in air has contribution of both laser ablation and laser air-breakdown. The magnitude of C_{m} was relatively small in materials for which the air-plasma intensity was more. For the chopped laser pulse of 10's ms duration C_{m} was very small due to high energy loss via thermal diffusion.

Acknowledgement

Sincere and dedicated work of all ICL Section members in developing high power CO_2 lasers is duly acknowledged.

References

[1] C R Phipps, J P Reilly and J W Campbell, *Laser and particle beams* **18(4)**, 661 (2000)
[2] C R Phipps and M M Michaelis, *Laser and particle beams* **12(1)**, 23 (1994)
[3] L N Myrabo, D G Messitt and F B Mead Jr., *AIAA Report*, 98-1001, Aerospace Science Meeting, Reno NV, Jan. 12–16 (1998)
[4] Y Tsujikawa, K Imasaki, M Nino, Y Minami and Y Hatsuda, *Proc. High Power Laser Ablation III* edited by C R Phipps (Washington, SPIE 2000) vol. 4065, p. 54
[5] W O Schall, W L Bohn, W Mayerhofer, W Riede and E Zeyfang, *Proc. High Power Laser Ablation III* edited by C R Phipps (Washington, SPIE 2000) vol. 4065, p. 472
[6] L N Myrabo, T R Knowles, J O Bagford and D B Seibert, *Proc. High Power Laser Ablation III* edited by C R Phipps, (Washington, SPIE 2000) vol. 4065, p. 521
[7] T Yabe, C Phipps, M Yamaguchi, R Nakagawa, K Aoki, H Mine, Y Ogata, C Baasandash, M Nakagawa, E Fujiwara, K Yoshida, A Nishiguchi and I Kajiwara, *Appl. Phys. Lett.* **80(23)**, 4318 (2002)
[8] G Marx, *Nature* **211**, 22 (1966)
[9] A Kantrowitz, *Astronautics and Aeronautics* **10(5)**, 74 (1972)
[10] C R Phipps Jr., T P Turner, R F Harrisson, G W York, W Z Osborne, G K Anderson, X F Corils, L C Haynes, H S Steele and K C Spicochi, *J. Appl. Phys.* **64(3)**, 1083 (1988)
[11] W L Bohn, *Proc. High Power Laser Ablation II* edited by C R Phipps and M Nilino (Washington, SPIE 2000) vol. 3885, p.48
[12] C R Phipps, J P Reilly and J W Campbell, *Proc. Gas Flow and Chemical Lasers* edited by A Lapucci and M Clofini (Washington, SPIE 2001) vol. 4184, p.571
[13] A K Nath, *Nuclear India* **36(3-4)**, 3 (2002)
[14] J F Ready, *Effects of high-power laser radiation* (Academic Press Inc., Orlando, 1971)
[15] R E Beverly III and C T Walters, *J. Appl. Phys.* **47(8)**, 3485 (1976)
[16] L R Hettche, J T Schriempf and R L Stegman, *J. Appl. Phys.* **44(9)**, 4079 (1973)