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Effects of Confined Laser Ablation on Laser Plasma Propulsion *

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We investigate the effects of confined laser ablation on laser plasma propulsion. Compared with planar ablation, the cavity ablation provides an effective way to obtain a large target momentum and a high coupling coefficient. When laser pulses are focused into a cavity with 1 mm diameter and 2 mm depth, a high coupling coefficient is obtained. By using a glass layer to cover the cavity, the coupling coefficient is enhanced by 10 times. Meanwhile, it is found that with the increase of the target surface size, the target momentum presents a linear increase.

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When a high-power laser pulse is focused onto a solid target, absorption of the laser pulse energy is followed by a supersonic expansion of the created plasma from the ablated target surface. Because of the momentum conservation, this ablation exerts an impulse on the target in the direction opposite to the expansion. In order to reach a large momentum transfer and a high coupling coefficient, many experiments are focused on the confined ablation, where the plasma expansion is confined by a transparent layer covering the target surface.[1−4] Through the confinement, the coupling coefficient is greatly enhanced. The enhancement of the coupling coefficient using such a transparent layer is, however, only possible for a large focal-spot size and a low laser intensity. It is our wish to enhance the momentum transfer and the coupling coefficient by focusing intense laser pulses into a cavity in the targets. In this experiment, the dependence of the target momentum and the coupling coefficient on the cavity size is measured. A transparent glass layer is also employed to cover the cavity target. Different from other experiments in vacuum, our experiments are carried out in air, where the coupling coefficient can be enhanced by the laser-supported detonation (LSD) wave.[5] Based on the cylindrical shock wave model, the dependence of the target momentum on the target surface sizes is also discussed.

The schematic setup is illustrated in Fig. 1. A pendulum is used to measure the target momentum and the coupling coefficient. Here 7 ns laser pulses at 532 nm are focused perpendicularly on the target surface, and the maximum laser energy on the target surface is approximately 900 mJ at 10 Hz. A He–Ne laser beam is focused onto the target edge. A photodiode is placed in the other side of the target to monitor the target movement. The time for the swing target crossing the He–Ne laser beam is recorded by an oscilloscope. Through the target thickness and the crossing time, target velocity can be deduced. Then the target momentum can be easily calculated from the target velocity and the target mass. Targets used in the experiment are aluminum. There are three types of target. The first are planar targets. Laser pulses are directly focused on the target surface. The second types are cavity targets, with a cavity on target surface. The laser beam is focused into the cavity. Cavities have the same depth of 2 mm but with different diameters. As the third type, the cavity targets are covered with a transparent glass layer. The laser beam is focused into the cavity through the glass layer as shown in the inset in Fig. 1. The glass layer is fixed by a holder and the cavity target is placed against on it. After irradiation a laser pulse, the glass layer does not move together with the target. The experimental results given in the following are averaged for many times. In the measurements of the dependence of the target momentum on the target surface size, the targets are the first-type targets.

When a target is irradiated by a laser beam in air, blow-off of target material and breakdown of the air in front of the target surface occur. Supersonic expansion of the ionized plasma from the target surface and the formation of the LSD wave can both transfer impulse to the target. Figure 2(a) shows the dependence of the target momentum on laser energy for planar targets and the targets with 1-mm and 2-mm diameter cavities, respectively. It is clearly seen from Fig. 2(a) that the target momentum is enhanced by the cavity targets. Compared with the planar targets, the target momentum is nearly doubled for ablation of 1 mm diameter cavity targets. This indicates that the confinement of the plasma expansion can efficiently enhance the target momentum. For the target with a cavity of 2 mm diameter, the enhanced target momentum can be observed only for high laser energy because of the large volume of plasma. For low laser

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energy, the target momentum is roughly equal to that of planar ablation. This is attributed to the plasma volume being so small that the confinement effect of such a cavity on the plasma expansion is negligible.

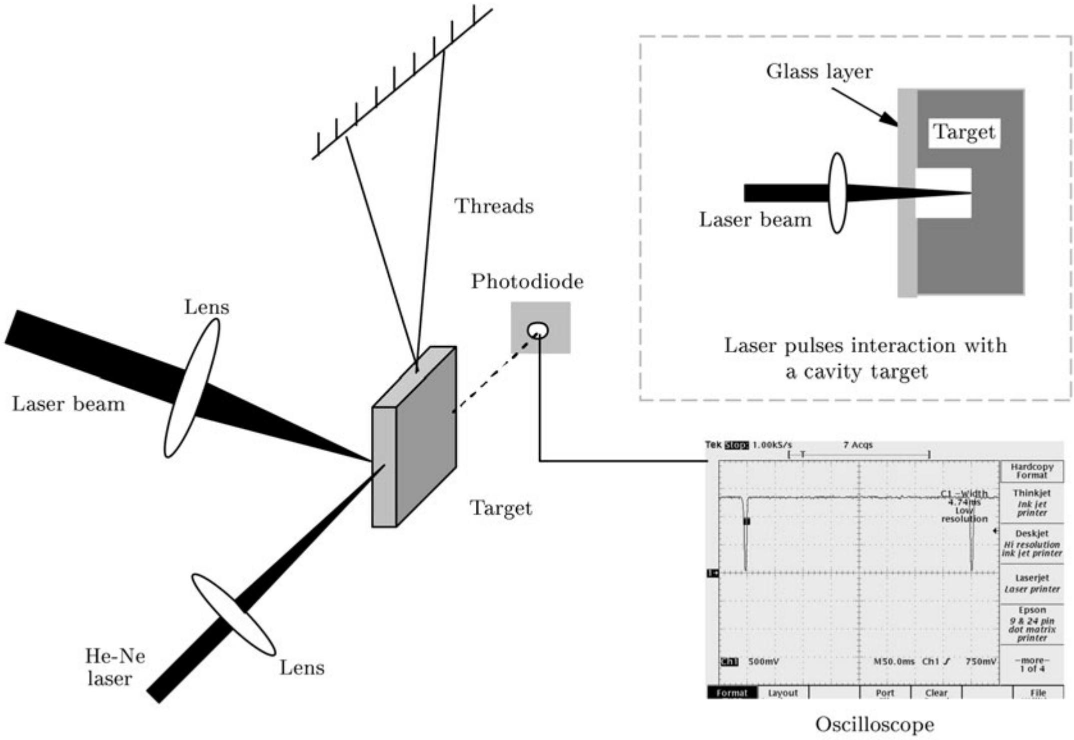

Fig. 1. Schematic of the experimental setup. The inset shows the laser-pulse ablation of a cavity target covered with a 2-mm thickness glass layer, in which the laser beam is directly focused into the cavity through the glass layer.

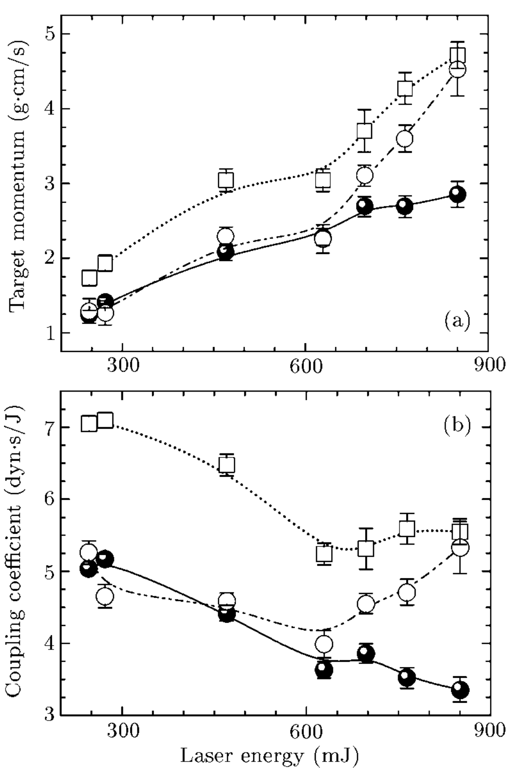

Fig. 2. Dependence of the target momentum (a) and the coupling coefficient (b) on the laser energy for the 1-mm diameter cavity (open squares), 2 mm diameter cavity (open circles) and planar target (closed circles).

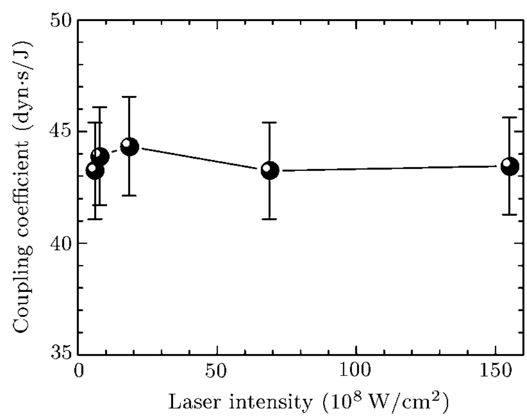

Fig. 3. Dependence of the coupling coefficient on the laser intensity for ablation of a cavity target covered with a 2-mm thickness glass layer. The cavity is 3 mm diameter and 2 mm depth.

From the dependence of the coupling coefficient on the laser energy for two cavities and planar target shown in Fig. 2(b), we can see that the smaller cavity generates higher coupling coefficient. This is also in agreement with the results shown in Fig. 2(a). It is known that at relatively low laser intensity, laser energy absorption is dominated by the inverse Bremsstrahlung absorption. As the plasma is initiated in the cavity, the lateral expansion is confined. The cavity acts as a trap in which light energy of the trailing edge of the laser pulses can be efficiently absorbed by the confined plasma.[6,7] The laser pulses can fully interact with the plasma. This results in a high plasma density and plasma temperature in the cavity. Meanwhile, a large amount of reflected laser beam is absorbed by the cavity wall, which further enhances the energy coupling between the laser pulses and the target. Therefore, more laser energy is converted into the plasma for ablation of a small cavity target.

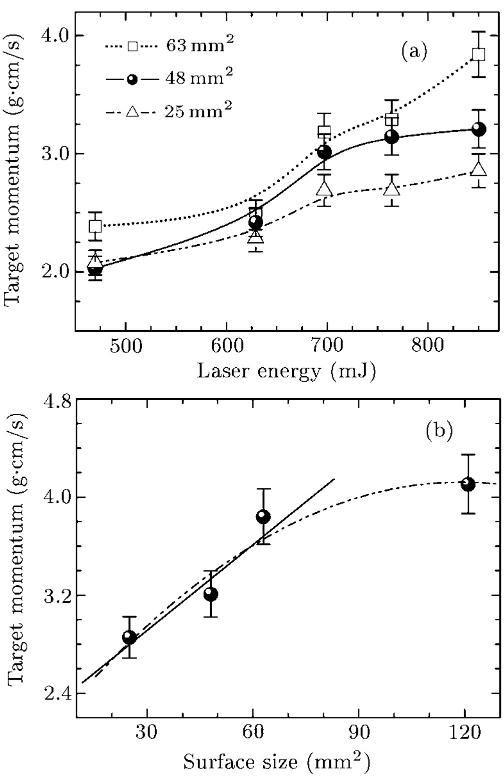

Fig. 4. Dependence of the target momentum on the laser energy for ablation of targets with different surface sizes. The target surface is planar and without glass layer covered it. (a) The target momentum as a function of the laser energy. (b) Target momentum as a function of target surface sizes, the circles represent the experimental data and the solid line is the fit.

In the investigation of the coupling coefficient dependence on the cavity sizes, it is found that the coupling coefficient decreases rapidly with the increase of the cavity diameters. As the cavity diameter is over 3 mm, the coupling efficient is close to that of the planar ablation. It is known that when a laser pulse is focused on the target surface, the maximum expansion of ablated matter is in the normal direction to the surface and the distribution can be described with a simple function,[8,9]

$$E(\theta) = E_0 \cos^n(\theta), \tag{1}$$

where θ is the angle of expansion with respect to the surface normal, E is the energy or density of the ablated matter, n varies with ablation conditions from 4–8. From Eq. (1), we can see that in the cavity lateral direction, the ablated matter is distributed in a very narrow spatial size. As the plasma is generated in a larger cavity, the distribution in the lateral direction is widened. However, when the cavity size is larger than the lateral distribution size, the cavity has no effect on the enhancing the coupling coefficient.

In order to further enhance the coupling coefficient, a transparent glass layer is used to cover the cavity. It is found that the coupling coefficient is enhanced by 10 times. The maximum coupling coefficient is about 44.34 dyn·s/J. This indicates that the coupling coefficient in the normal direction is enhanced more efficiently than that in the lateral direction. Meanwhile, under our experimental conditions, the coupling coefficient is not strongly varied with the laser intensity as shown in Fig. 3.

The above results clearly show the enhanced coupling coefficient and target momentum by using the cavity ablation. If the ablation is performed in a special configuration such as a hollow target, higher coupling efficient can be predicted.

Apart from the target configuration, target surface size also determines the target momentum. Figure 4 shows the target momentum as a function of the laser energy for different surface sizes. It can be seen that larger target surface size generates a high target momentum as shown in Fig. 4(a) and the target momentum shows a linear increase with the increase of the target surface size shown in Fig. 4(b). In the investigation of the relationship between the momentum transfer with the target surface size, typically two models are proposed. One is the spherical blast wave model[10] and the other is the cylindrical shock wave model.[11] For the target momentum dependence on the target surface size, these models present the same tendency and agree with our experimental results, although these two models are suitable for different laser pulse width. As the matter of fact, the blast waves play the same role of exerting the impulse to the target in both models. When the blast wave expands off the target surface, the delivery process ends accordingly. There, we take the cylindrical blast wave model as a sample to analyse the process. The impulse is written as[11]

$$I_{ip}^{\propto} \int [p(t)R(t)^2]dt, \tag{2}$$

where p is the pressure generation on the target surface, R is the shock wave radius. For a small target surface,

$$P \propto A_T(A_0)^{1/2}(I)^{1/3}, \tag{3}$$

where P is the target momentum, A_T is the target surface area, A_0 is the laser beam focal-spot size and I is the laser intensity. It can be seen from Eq. (3) that, for a fixed laser focal-spot size and laser intensity, the target momentum is proportional to the target surface area. This tendency agrees with our results in Fig. 4(b). Meanwhile, because the blast wave attenuates very fast in air, the target momentum can not infinitely increase with the increase of the target surface size. When the target surface is much larger than the laser focal spot, the target momentum approaches a constant.

In conclusion, our results show that a confined ablation can generate a high target momentum and a high coupling coefficient. Compared with ablation of planar targets, the target momentum is significantly increased for cavity targets. Using a transparent glass layer to cover the cavity, the coupling coefficient can be enhanced by 10 times. This indicates that a higher coupling coefficient is obtained for a tightly confined ablation, especially the confinement in the target normal direction. From the measurement of lifetime of the plasma fluorescence,[12] it is found that the cover layer prolongs the interaction time of laser pulses with targets, which enhances the laser energy absorption and results in a high coupling coefficient. Meanwhile, the target momentum and coupling coefficient is related to the target surface size. This is consistent with the predictions of the cylindrical and spherical blast wave models.

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