Application of laser plasma in propulsion

Zhi-Yuan Zheng\textsuperscript{1,2}, Yi Zhang\textsuperscript{1}, Peng-Fei Zhu\textsuperscript{1}, Feng Liu\textsuperscript{1}, Xin Lu\textsuperscript{1}, Yu-Tong Li\textsuperscript{1*}, Jie Zhang\textsuperscript{1,3*}

\textsuperscript{1} Beijing National Laboratory for Condensed Matter Physics, Institute of Physics, Chinese Academy of Sciences, Beijing 100080, China
\textsuperscript{2} School of materials Science and Technology, China University of Geosciences, Beijing 100083, China
\textsuperscript{3} Department of Physics, Shanghai Jiao Tong University, Shanghai 200240, China

*E-mail: jzhang@aphy.iphy.ac.cn, ytli@aphy.iphy.ac.cn

Abstract. In laser plasma propulsion, laser interaction with multilayer target is investigated. The first layer of the target of fluid water, rigid glass, flexible polyimide as well as polyimide are tested. It is found that the coupling coefficient of water confinement is higher and it is enhanced two orders compared with direct ablation. Through calculation the ablation pressure, higher coupling coefficient is attribute to the plasma confinement and impedance mismatch. Furthermore, the images of the polymers after ablation are observed.

1. Introduction
Laser plasma propulsion is a new concept developing in recent years. Due to its high coupling coefficient and high specific impulse as well as generating very small thrust force, it attracts much attention in launching spacecraft, clear space debris, precisely positioning macro-satellites [1,2]. Until now, many experiments are performed to enhance the coupling coefficient between the laser beam and the target. Yabe obtained high coupling coefficient by attaching a thin water film on the target surface [3]. Fabbro placed a transparent layer in front of the target surface to enhance the coupling coefficient [4]. In our previous experiments, the coupling coefficient was enhanced more than 10 times by cover the target surface with a glass layer [5,6]. These experiments confirm that laser pulse interaction with a multilayer targets can efficiently enhance the coupling coefficient. However, what is the main mechanism resulting in such a high efficiency in laser plasma propulsion is discussed from many aspects. In this paper, base on an impedance mismatch technology and a confinement ablation model, the mechanism of the higher coupling coefficient is analyzed. The first layer of the target consisting of fluid water and rigid glass are investigated. Finally, the images of the polymers after ablation are observed.

2. Impedance mismatch technology and confinement ablation
In laser ablation solid target in air, the ablation pressure can be written as [4],

\[ P \text{ (GPa)} = 3.22 \left( \frac{\alpha}{2 \alpha + 3} \right)^{2/3} \rho_0^{1/3} (g / \text{cm}^3) \times I^{2/3} (GW / \text{cm}^2) \]  

(1)
where \( I \) is the laser intensity, \( \rho_0 \) is the air density, \( \alpha \) is the fraction of internal energy devoted to thermal energy. If the target is consisting of multiplayer and laser is focused on the first layer, pressure generated in the first layer will propagate to the second layer. Then, impedance mismatch should be considered. Impedance mismatch method provides a very simple means to enhance the shock pressure at the interface of the two materials. It can cause ablation pressure jump, when a shock launched from the low impedance layer reaches the interface. The pressure increase depends on the shock impedance mismatch of the layers.

On the other hand, for a multiplayer target, if the laser pulses transmit the first layer and direct focus on the second layer, plasma is induced in the interface between the two layers. The plasma expansion can be confined and the ablation pressure can be enhanced. A confinement ablation model was previously developed for prediction of laser-induced pressures in the interface. The maximum pressure is given by the following relation [7-9],

\[
P(GPa) = 0.01 \sqrt{\frac{\alpha}{\alpha + 3}} \times \sqrt{Z(g \cdot cm^{-2} \cdot s^{-1})} \times \sqrt{I(GW/cm^2)}
\]

where \( \alpha \) is the fraction of internal energy devoted to thermal energy, \( I \) the incident power intensity. \( Z \) is the shock impedance between two layers, which is defined as,

\[
\frac{2}{Z} = \frac{1}{Z_1} + \frac{1}{Z_2}
\]

where \( Z_1 \) and \( Z_2 \) are the shock impedances of the first and second layer of the target material.

3. Results and discussion

Fig.1 shows the comparison of the ablation pressure generation in water-aluminum, glass-aluminum and direct aluminum ablation. In direction ablation, the air is also considered as a confined ablation. Considering the laser wavelength of 532 nm, the \( \alpha \) is 0.4 in equation (2) (typically \( \alpha = 0.25 \)). It is found that with increase of the laser intensity, the ablation pressure increases. The pressures generation with water and glass layers are much higher than for direct ablation. Over ten times of ablation pressure is observed by water.

Compared the shock impedance of water and glass, the water is lower and both of them are lower than that of aluminum. This indicates that laser pulses incident from a low impedance layer to a high impedance layer, the ablation pressure can be enhanced. And a higher mismatch results in a higher pressure.

In order to comparison with experimental results, the target momentum is calculated from the ablation pressure. It is written as,

\[
M = P \times \tau \times A
\]

\( M \) is the target momentum, \( \tau \) the interaction time and \( A \) the laser focal area. Since the interaction time is prolonged by 2-3 times by the first layer, it is assumed 21 ns in this calculation for laser width of 7 ns.

Fig. 2 (a) and (b) show comparison the calculation results with experimental results in water-aluminum and glass-aluminum targets. Target momentum is measured by a

Fig. 1 Ablation pressure generation in multiplayer targets of water-aluminium (a), glass-aluminium (b) and direct aluminum ablation (c).
pendulum. It is found that both of the calculation values agree with experiment results. But at higher laser intensity, they present different behaviors.

For water layer, the target momentum at high laser intensity is slightly higher in experiment than in calculation. It is known that the water confined ablation usually involves the formation of shock wave accompanying with the plasma, particulates, vapor bubbles and other effects. In addition to the shock wave, vapor bubbles and particulates also influence on the coupling efficiency. The target momentum measured in experiment is the total effect of them. The calculation results in Fig. 2(a) are only deduced from the ablation pressure, so it is smaller than that of experimental results. However, with a glass layer Fig. 2(b), the target momentum is slightly lower in experiment than in calculation at high laser intensity. This is due to the ionization of the glass surface, which will shield more energy impinging on the target surface.

For laser pulse interaction with a multilayer target, the impedance mismatch and confinement ablation both contribute to the ablation pressure. If laser pulses transmit the first layer and induce plasma in the second layer, the first laser only serves as a confinement medium to confine the plasma expansion. Under this case, the confinement ablation plays a dominant role. The interaction time and the coupling coefficient are both enhanced. On the other hand, if plasma is induced on the interface of two layers, impedance mismatch and confinement both occur in ablation process. Which one plays a dominant role is determined by the characteristics of the target layers such as density, impedance, and ionization threshold et al. For another case, plasma is only induced on the first layer. The shock pressure transmits from the first layer to the second layer. Only the impedance mismatch determines the ablation pressure.

For the first layer, it is usually transparent and very thin. With plasma induced on the second layer, plasmas on the rear and front surface of the first layer are also observed. This indicates that impedance mismatch and confinement ablation both contribute to the process. Which one plays a dominant role is determined by the experimental conditions. For a fixed target material, the ablation can be enhanced by the layer thickness, which is equal to enhance the confinement effect.

On the other hand, for the polymer, it is often used as the first layer in laser plasma microthrust because the metal conductivity was too high to permit achievement of the temperatures necessary for efficient propulsion and minimally acceptable specific impulse [10]. Thus, the images of the polymers after ablation are observed. It can be seen from Fig. 3 that polythene (PE) and polyimide present different surface ablation.
After ablation of 5 shots, solid products redeposit on the surface are serious with laser intensity increase. Especially for the PE, a cavity and solid products are obviously seen after ablation. A suitable polymer should have high ablation threshold and no ablation products back streaming onto the optics. Comparison with two materials, it indicates that the polyimide is relatively suitable.

4. Conclusion
Laser pulses interaction with multilayer targets are investigated base on an impedance mismatch technology and confinement ablation. Results show that two mechanisms both enhance the coupling efficiency. Which one plays a dominant role is determined by the experimental conditions. For the target layer, larger impedance mismatch and higher confinement will results in a higher coupling efficiency. For the polymer, the polyimide is better than PE with less solid products.

Acknowledgments
This program is support by the National Nature Science Foundation of China (Grant Nos. 10575129, 10675164, 10390161 and 60321003 ), and National Basic Research Program of China (973 Program) (Grant No.2007CB815102 ).

References
[1] C. R. Phipps, J. R. Luke, G. G. Mcduff, T. Lippert, 2003, Appl. Phys. A, 7, 193
[2] C. R. Phipps, J. R. Luke, T. Lippert, M. Hauer, A. Wokaun, 2004, Appl. Phys. A, 79, 1385
[3] T. Yabe, C. Phipps, M. Yamaguchi et al., 2002, Appl. Phys. Lett., 80, 4318
[4] R. Fabbro, J. Fournier, P. Ballard et al., 1990, J. Appl. Phys., 68, 775
[5] Z. Y. Zheng, J. Zhang, X. Lu et al., 2005, Chin. Phys. Lett., 22, 1725
[6] Z. Y. Zheng, J. Zhang, Z. Q. Hao et al., 2006, Chin. Phys., 15, 580
[7] H. C. pant, M. Shukla, H. D. Pandey et al., 2006, Laser and Particle beams, 24, 169
[8] L. Berthe, R. Fabbro, P. Peyre and E. Bartncki, 1999, J. Appl. Phys., 85, 7552
[9] P. Peyre, L. Berthe, R. Fabbro, A. Sollier, 2004, J. Phys. D: Appl. Phys., 37, 1132
[10] T. Lippert, C. David, M. Hauer et al., 2002, App. Surf. Sci., 186, 14