Paper airplane propelled by laser plasma channels generated by femtosecond laser pulses in air

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Abstract: A long plasma channel, formed due to the dynamic balance between the nonlinear self-focusing and the plasma defocusing in the propagation of intense femtosecond laser pulses in air, is demonstrated to be able to continuously propel a paper airplane without complicated focusing optics. The maximum coupling coefficient generated by the plasma channel is found to be more than 8.5 dyne/W. In the plasma channel, the detonation wave generation with the air ionization is found to be the propulsive source.

OCIS codes: (320.7090) Ultrafast laser; (350.5400) Plasma; (999.9999) Ablative laser propulsion; (350.3390) Laser material processing

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#9335 - $15.00 USD Received 7 November 2005; revised 15 December 2005; accepted 15 December 2005

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1. Introduction

Research in resent years on the laser plasma propulsion has gained much attention due to many advantages over other conventional methods of producing thrust [1-7]. Laser plasma propulsion has two main operating modes: "rocketing mode" and "air-breathing mode". The difference between them is that the craft has to dissipate its propellants for the rocketing mode and whereas there is no mass dissipation for the air-breathing mode. For the latter, laser pulses are directly focused in air and the air is served as the propellant. The propulsive source comes from a laser supported-detonation wave generated with the air ionization [3]. Due to these unique advantages, the air-breathing mode can significantly increase the effective weight ratio of payload. Up to date, in all experiments for the air-breathing mode, the configuration of the craft has to be specifically designed for continuously focusing the laser beam [5,6]. The focal position of the laser beam has to be adjusted accordingly with the movement of the craft. In this paper, we propose a new scheme of "laser plasma channel propulsion", in which a long plasma channel generated by intense femtosecond laser pulses in air is served as a propulsive power. Preliminary experiments demonstrate that the plasma channel can continuously propel a paper airplane in a long distance without complicated optical focus. The coupling coefficient generation with the plasma channel propagation is measured, and the propulsive source of the plasma channel is investigated by measurement the dissipation of the target mass.

2. Experimental setup

The experiments are carried out using a homemade Ti:sapphire chirped-pulse amplification system (XL-II) , which can provide an energy up to 640 mJ in 30 fs pulses at a wavelength of 800 nm. The repetition rate is 10 Hz. In experiments, the laser pulses are launched in air and focused by a positive lens. The coupling coefficient (the ratio of the target momentum to the incident laser energy) along the plasma channel is measured by a pendulum as shown in Fig. 1. A He-Ne laser beam is focused along the target surface into a photodiode placed on the other side of the aluminum target. After irradiation of a laser pulse, the target crosses the He-Ne laser beam. The crossing time is recorded by a digital oscilloscope. Through the target edge width and the crossing time, target velocity can be calculated. The target momentum can then be easily obtained from the target velocity and the target mass. Meanwhile, the evolution of the plasma channel is determined by an acoustic diagnoise [8,9], in which the sound signal is detected by a microphone and recorded by a digital oscilloscope.

The self-guiding of femtosecond laser pulses and forming of a long plasma channel in air are well known phenomena nowadays. Femtosecond laser pulses will self-focus, caused by the kerr response of air, if the laser power exceeds several GW, leading sharp increase of the laser intensity. This creates a plasma by photoionization of air molecules. The dynamic balance between the self-focusing and the ionization induced defocusing effects leads to a long plasma channel over several hundred meters [10,11]. A typical image of a portion of a laser plasma channel is given in Fig. 2(a). It is demonstrated that such a plasma channel can continuously propel a light paper airplane without complicated focusing optics as shown in Fig. 2(b). The paper airplane is located on an air-cushion track and sustained by the airflow from an air-compressor. For 36 mJ laser energy, a paper airplane with 1.32 gram can be accelerated to 2.05 cm/s^2.

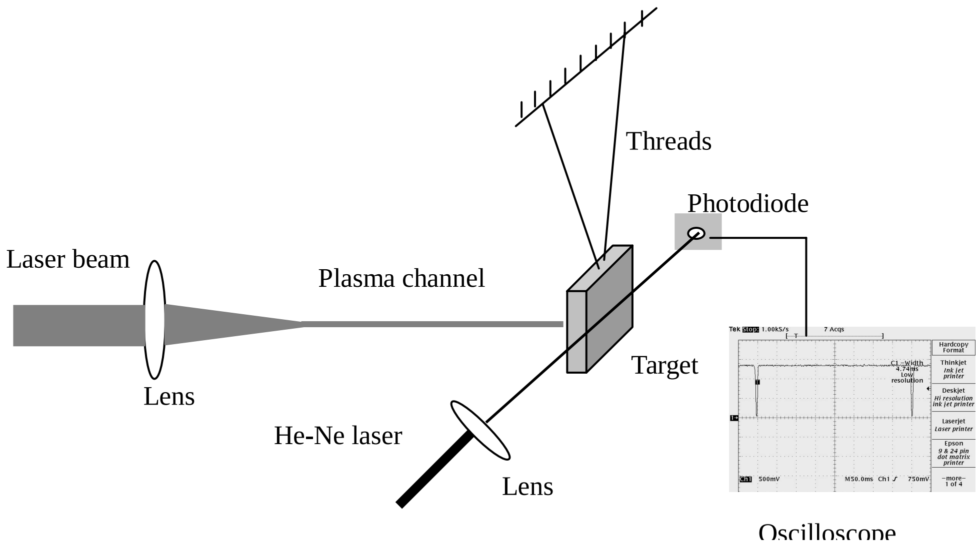

Fig. 1 Schematic of the setup for measurement the coupling coefficient along the plasma channel propagation.

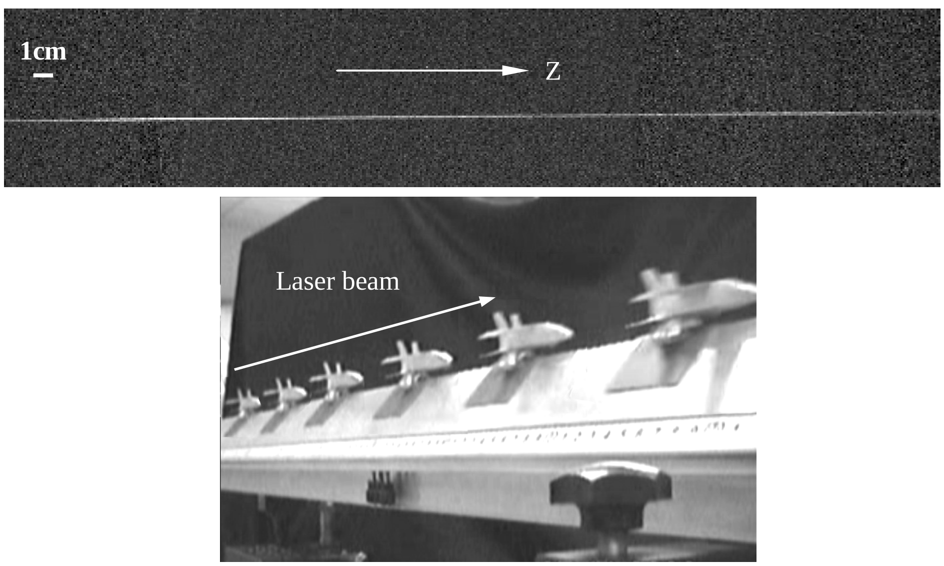

Fig. 2. (a) A typical image of a portion of a laser plasma channel recorded by a charge-coupled device (CCD). (b) Flight trajectories of the paper airplane on the air-cushion track.

3. Results and discussions

The length of the plasma channel varies with the laser energy, pulse width and the focal length of the lens. With 50 fs, 36 mJ laser pulses focused by a focal lens with f=4 m, the evolution and the coupling coefficient of the plasma channel are shown in Fig. 3. The jump on the sound signal around 340 cm indicates the starting of the plasma channel, and the rapid decrease of the sound signal around 480 cm indicates its ending [9]. This allows us to determine the length of the plasma channel to be about 140 cm as indicated by the arrows. On

#9335 - $15.00 USD Received 7 November 2005; revised 15 December 2005; accepted 15 December 2005

the other hand, the coupling coefficient sharply jumps to 6 dyne/W at around 330 cm and drops down at around 450 cm. Within a length of 120 cm, the coupling coefficient does not vary much. We can define this length as a “propulsive length”. It is mostly consistence with the starting and ending of the plasma channel.

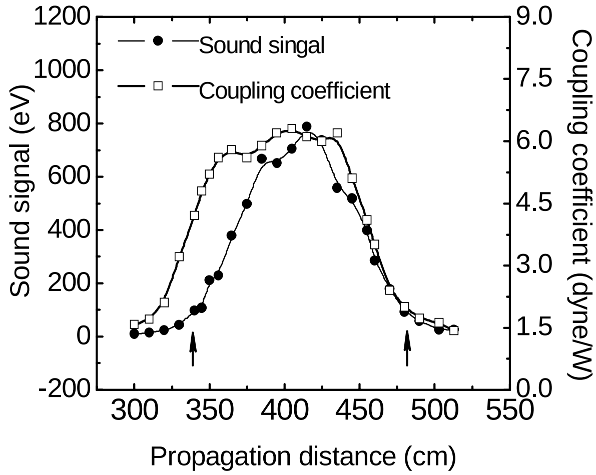

Fig. 3 The sound signal (solid circle) and the coupling coefficient (open square) as a function of the plasma channel propagation for a focal lens f=4 m.

For the propulsive length, it tightly relates with the plasma channel length, but its starting and ending also differ from that of the plasma channel. Before the start of the plasma channel, if the laser intensity is high, the target can still be propelled. At the end of the plasma channel, due to a few filaments appearance within the channel and the energy locked in the filaments [12], the plasma channel is not powerful enough to propel the target. Comparing the plasma channel length with the propulsive length, generally speaking, the plasma channel is much longer than the propulsive length. This phenomenon is evident for a long plasma channel. With 36 mJ laser pulses focused by a lens of f=8 m, the plasma channel is about 5.65 m, but the propulsive length is only 3.05 m as shown in Fig. 4.

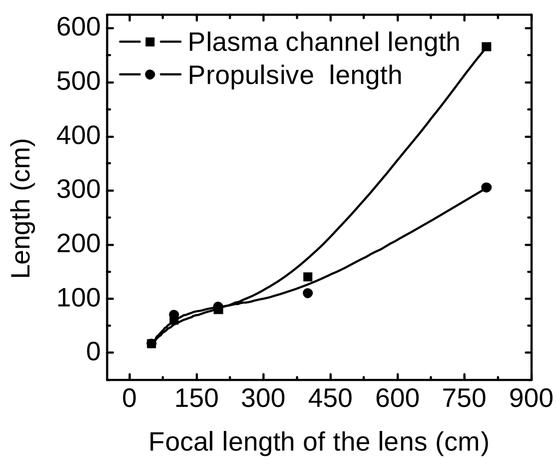

Fig. 4 Comparison the propulsive length with the plasma channel length with 36 mJ laser energy.

#9335 - $15.00 USD Received 7 November 2005; revised 15 December 2005; accepted 15 December 2005

In the plasma channel, the energy loss is relatively small compared with the total laser energy. The energy approximately decays linearly with the propagation distance [13]:

$$E(z) \approx E(0)(1-\beta z) \tag{1}$$

Where β is the laser energy decay coefficient per Rayleigh length and $E(0)$ is the initial laser energy. Because β is small, the main energy loss is due to the ionization in the propagation process. In the plasma channel, laser intensity almost keeps a constant [14]. This leads to a nearly constant coupling coefficient over a distance until the laser energy can not sustain the plasma channel. When the laser intensity is lower than the threshold of the air ionization, the plasma channel then collapses and the coupling coefficient also sharply decreases. From this point, it can be understood that under the same laser energy, a longer plasma channel, a smaller coupling coefficient is presented. As shown in Fig. 5 with 36 mJ laser energy, for a plasma channel of 17 cm, the averaged coupling coefficient is about 8.5 dyne/W, but it decreases to 5.1 dyne/W for a plasma channel of 5.65 m. On the other hand, the length and the coupling coefficient of the plasma channel can be adjusted by the laser focus conditions. With a focal lens of 30 m and 85 mJ laser energy, a long plasma channel over 200 m is observed. But propagation for such a long distance, the divergence angle of the laser beam is so large that it is not convenient to measure the coupling coefficient. On the other hand, due to the energy loss in the plasma formation and the generation of the continuum emission, the plasma channel is not powerful enough to propel the target.

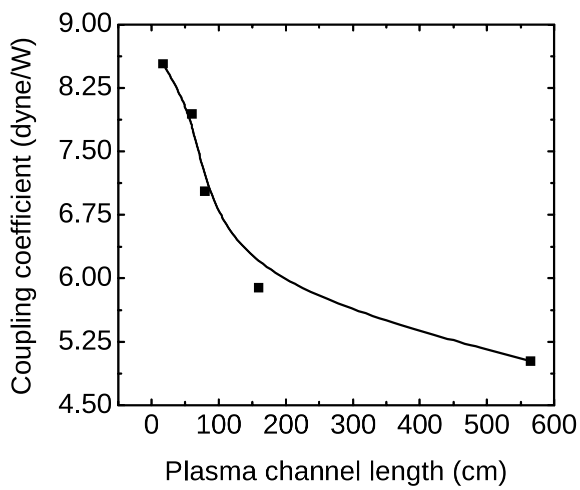

Fig. 5 The averaged coupling coefficient in the "propulsive length" as a function of the plasma channel length.

One advantage of the plasma channels to propel a craft is that within a long distance the craft can be steadily propelled without complicated focusing optics. Whereas for nanosecond or microsecond laser pulses, propulsion only occurs near the geometry focal point of the lens. Over the focal point, the coupling coefficient dramatically decreases due to the defocus of the laser beam. In order to realize a continuous propulsion, the tail of the craft has to be specially designed. Another advantage of the plasma channel propulsion is that in the plasma channel the air is served as the propellant. This can be indicated from measurement of the ablation mass as discussed in follow.

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The mass-removal rate along a plasma channel of 3.65 m is measured. At every measurement position, the target is fired thousands of shots. By weighing the target mass before and after the ablation, the mass dissipation can be determined. It is noted that after thousands of shots, the aluminum target shows a mass increase rather than a decrease. This is may be caused by the oxidation of the target surface in air. However, if the laser plasma completely comes from the target material, target surface oxidation does not compensate the mass loss after thousands of shots with a mass-removal rate of 0.2 μg/pulse [15]. This demonstrates that the laser plasma comes from the air not from the target material. Under this case, the propulsive source only comes from the detonation wave generated with the air ionization. In our previous experiments using the nanosecond laser pulses to ablate targets, the propulsive source also mainly comes from the detonation wave but not from the target ablation [16].

For microsecond or nanosecond laser pulses ablation target in air, a detonation wave can be induced with high laser intensity. But due to a long laser width, the target dissipation can not be ruled out [15]. This makes the coupling coefficient strongly dependent on the target properties. But for femtosecond laser propagation in air, due to the detonation wave generation accompanying with the plasma channel, the coupling coefficient is less dependent on the target properties.

In conclusion, in this paper, we propose a new concept of “laser plasma channel propulsion”. With femtosecond laser propagation in air, a long plasma channel is induced due to the dynamic balance between the nonlinear self-focusing and the plasma defocusing. It is demonstrated that the plasma channel can continuously propel a light paper airplane without complicated focusing optics. It is found that in the plasma channel, air serves as the propellant and the propulsive source comes from the detonation wave. From this point of view, the plasma channel is a very useful source to realize a long propulsion in atmosphere. With development of the laser technology and further research in the laser propagation, a very long distance propulsion with high coupling coefficient could be expected.

Acknowledgments

We acknowledge financial support from the National Natural Science Foundation of China (grants 10374116, 60321003, 10390161) and National High-tech ICF program of China.