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Design and test of a laser assisted pulsed plasma thruster prototype

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Abstract. Pulsed plasma thruster (PPT) is widely used in space propulsion due to its high reliability, specific impulse and systematic simpleness, but its improvement has been troubled for years by its low efficiency. In this paper, a novel laser assisted pulsed plasma thruster (LAPPT) prototype is designed, in which the traditional spark ignitor is replaced by 532nm laser. With a series of experimental test on LAPPT, the enhancement of impulse bit, specific impulse, impulse coupling coefficient is confirmed. This study introduces a novel method to improve PPT's performance and set a solid foundation for further research.

1. Introduction

Pulsed plasma thruster (PPT) [1] is a kind of electromagnetic propulsion. Traditionally, a spark plug is charged to ablated propellant, producing a small amount of plasma which subsequently causes intense discharge current, then the magnetic field generated accelerated the plasma and produce thrust. Although its detailed physical procedure is still not revealed, PPT has been applicated in a lot of space mission since 1960s due to it stable reliability [2], high specific impulse and simple structure. Nevertheless, the efficiency of PPT has been quite low for years despite the effort of researchers. Many research have pointed out the low efficiency of PPT is mainly caused by the 'delay ablation' effect: In the beginning of discharge, the acceleration by electromagnetic field is strong but the charged particles are rare, and in the late time of discharge, much neutral particles are produced by heat but cannot be accelerated by electromagnetic field. In short words, the ablation procedure and the discharge procedure are not efficiently coupled [3] [4]. Hou Dali [5] of Shanghai Jiao Tong University shows that the spark plug structure has an important influence on the ignition performance of PPT. Increasing the incident electron velocity is conducive to improving the ignition performance and achieving higher propulsion performance [6] [7].

Laser ablation [8] is widely used in plasma engineering, the energy of high power energy is so focused and intense that it can ablated the target area and generated much plasma in a very short time. If laser ablation is used to replace spark plug for PPT, it should generate more plasma in a shorter time, which helps the coupling of ablation and discharge [9]

Motivated by the idea above, a laser assisted pulsed plasma thruster (LAPPT) is designed in which the ignition is laser ablation instead of spark plug. The test bed for LAPPT is also established and the propulsion performance of LAPPT were experimentally tested.

2. DeSign of LAPPT

As is shown in Fig 1, the LAPPT consists of three subsystems. Power supply provides discharge energy and laser provides the initial plasma for the thruster, the thruster coupling the laser plasma and discharge energy to generate thrust

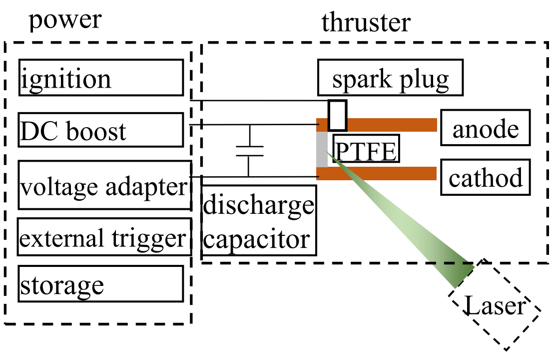

Figure 1. Schematic of LAPPT

Thruster consists of a $2\mu f$ capacitor for store electric energy from the power supply, it is directly fixed on the pedestal because it's quite heavy. The discharge current cause's strong electromagnetic field, in order to weaken electromagnetic interference, the discharge electrodes are vertically and the terminals of capacitor are horizontally set. PTFE bulk is chosen to be the propellant, it is very common in traditional PPT and it is easy to ionize by laser. The electrodes clamp the propellant to form a semi open discharge chamber and the size of discharge room can be adjusted by changing the height of PTFE bulk and the laser beam can enter the discharge room from open side and hit target surface. Some parameters of thruster are listed in Table 1. All components are constrained tight so that impulse can be directly transported from discharge room to pedestal. This prototype satisfies the need of impulse test and geometrically adjust for LAPPT.

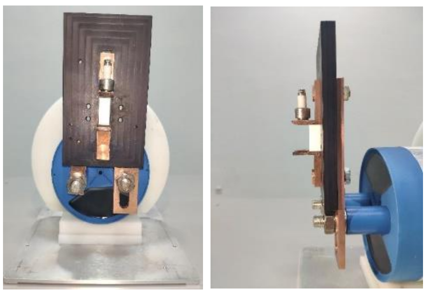

Figure 2. LAPPT thruster.

Table 1. Parameters of thruster

component	item	value
eletrode	length	30mm
	width	12mm
	thickness	3mm
	material	copper
propellant	height(gap of eletrodes)	26mm
capacitor	capacity	2μf
	esr	10mω
	weight	1.62kg

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The power supply is an integrated circuit, it has a common ground, a DC output to charge capacitor, the adjust range is from 1200V to 2000V.it also has a DC output to ignites spark plug so it can also work in PPT mode to compare with the LAPPT mode. The power supply could work with its internal clock and the pulse rater can vary from 1Hz to 1.3Hz, it can also triggered by external clock so it could work with other devices synchronously.

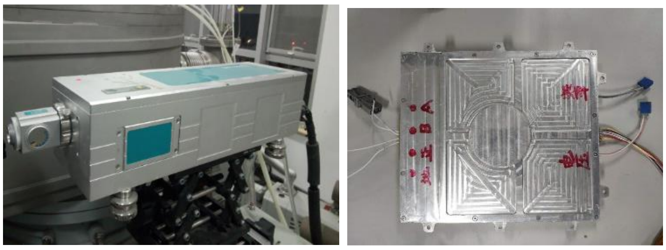

Figure 3. Power supply and laser supply

The pulse laser is Nd: YaG in 532nm, the pulse width is 8ns, and the pulse energy could be adjusted by altering control voltage varying from 0mJ to 210mJ. This laser is easy to handle but too large for aerospace applications, in further research, the structure should be more compact.

3. Setup of testbed

To evaluate the performance of LAPPT prototype, a testbed is established to measure the impulse and other propulsion parameters of LAPPT and PPT.

As is shown in Fig 4, the thruster is fixed on one end of a torsion pendulum and a counter weight is on the other end. When the impulse generated, the torsion pendulum would rotate around the pivot and the rotate angle θ could be measured by a displacement sensor.

$$\theta_{max} = \frac{d_{max}}{L} \tag{1}$$

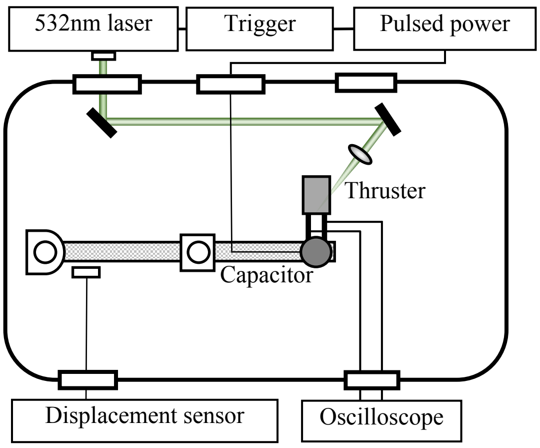

Figure 4. Schematic of test bed

With the method introduced in literature [] [], it the impulse *I* could be calculated by eq. [] [].

$$\theta_{max} = \frac{Id_{max}}{J\omega_d} \tag{2}$$

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Where L is the arm length of torsion arm, d_{max} is the displacement by impulse. ω_d Is the torsion's frequency, J is the moment of inertia.

The laser beam is introduced by a set of light path system, and the incidence angle is about 60°, this angle would reduce the contamination to the optic components by the jet plume.

The torsion pendulum and thruster are in a vacuum tank, and the pressure could be set as low as 1×10^{-3}Pa. Laser and power share common external trigger DG645, so that the laser and electric output are synchronous.

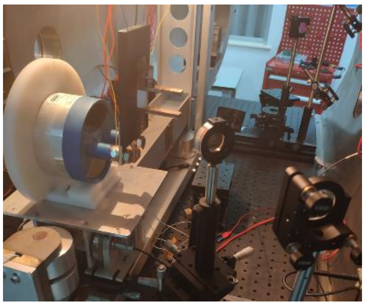

Figure 5. Test bed

By weighing the mass of propellant bulk before and after experiment, the ablated mass m_s could be obtained. The ablated mass for one pulse is estimated to be approximately $10\mu g$, but the resolution of balance is $10\mu g$, the accumulated ablated mass could be weighed only after more than 20 times of ablation. In our test, the number of ablation is 200.

$$m_s = \frac{m_1 - m_2}{n} \tag{3}$$

Figure 6. Balance for weighing propellant

According to the impulse bit, energy supplied and the mass ablated, the coupling efficient, specific impulse and efficiency could be obtained.

$$I_{sp} = \frac{I}{m_s} \tag{4}$$

$$C_m = \frac{I}{E} \tag{5}$$

$$\eta = \frac{\frac{1}{2} m_s v^2}{E} = \frac{1}{2} g_0 \cdot C_m \cdot I_{sp} \tag{6}$$

4. Results and discussions

Firstly, the propulsion characteristics of traditional PPT with spark plug is measured and is shown in Fig 7.it can be clearly seen that the impulse bit , ablated mass, specific impulse increase as the discharge energy grow larger. The best parameters are obtained when discharge energy reaches 4J. In the following test, the propulsion parameter of PPT in 4J discharge energy (expressed as PPT-4J) are used as reference for LAPPT.

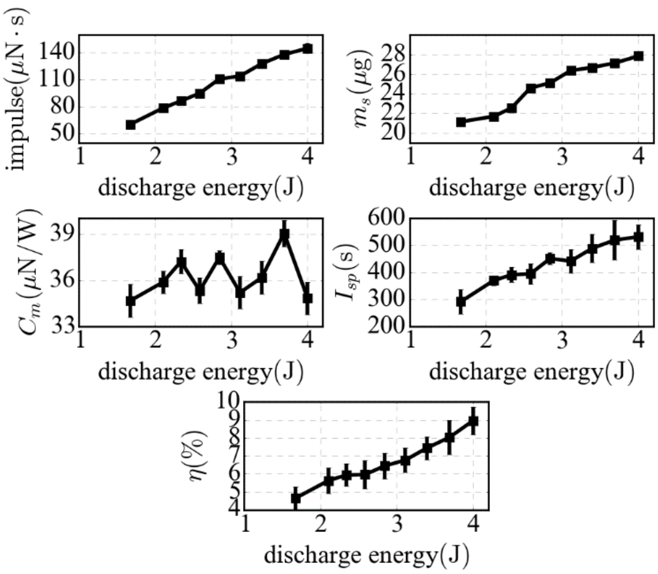

Figure 7. PPT propulsion test results

Fig 8 shows the results of variation of impulse bit with laser. With the increase of laser energy, the impulse of LAT increases gradually. When the laser energy is less than 42.3 mJ, the impulse is too weak to be measured, which indicates that the ablation threshold of LAT should be more than 42.3mJ. The impulse bit of LAPPT is always better than that of PPT-4J+LAT which means LAPPT is a better way to coupling laser energy and electric energy than use PPT or LAT separately; with the increase of laser energy, the impulse bit of LAPPT increases at first and then decreases, reaching the maximum value when the laser energy is about 86.4mJ. This may be due to the excessive expansion of the generated plasma and the short residence time in the discharge chamber, resulting in insufficient discharge of the plate. In addition, when the laser energy is less than 61.2mJ, LAPPT can still ignite successfully, which indicates that the application of electric field also changes the ablation process of LAT and reduces its ablation threshold.

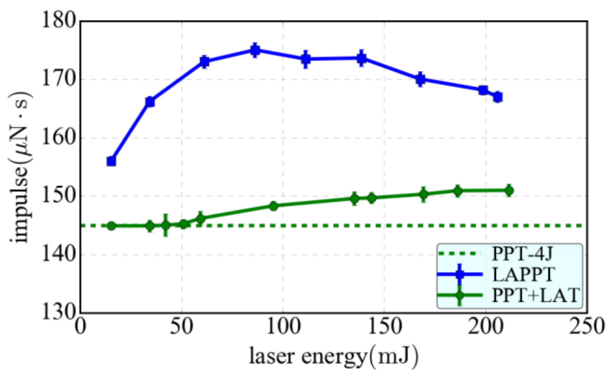

Figure 8. Variation of impulse bit with laser

As the Fig 9 shows, the impulse coupling coefficient of LAT increases at first and then decreases with the increase of laser energy. When the laser energy reaches 95.2mJ, the impulse coupling coefficient reaches its maximum, which is equal to the impulse coupling coefficient of PPT, and is smaller than that of PPT under other laser energy conditions. The impulse coupling coefficient of LAPPT increases at first and then decreases with the increase of laser energy, and the variation range is small and always higher than that of PPT. Coupling coefficient. This shows that the impulse effect is better than that of PPT and LAPPT due to the coupling of laser ablation ignition and plate discharge.

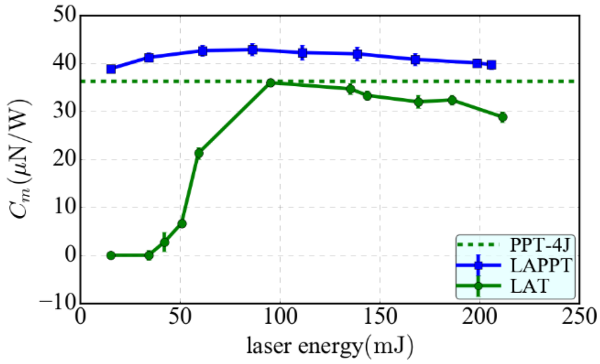

Figure 9. Variation of impulse coupling coefficient with laser

Fig 10 shows that, with the increase of laser energy, the specific impulse of LAT increases first and then decreases, and is always significantly lower than that of PPT-4J. When the laser energy reaches 190mJ, the specific impulse reaches the maximum value of 68.9 s. The specific impulse of LAPPT increases first and then decreases, and is always higher than that of PPT. When the laser energy reaches 86.4mJ, the specific impulse reaches the maximum value of 671.6 s.

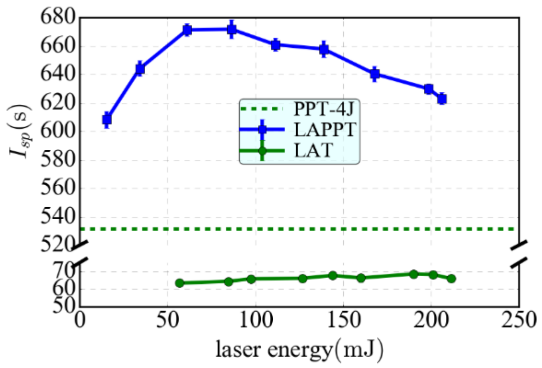

Figure 10. Variation of specific impulse with laser

Fig 11with the increase of laser energy, the propulsion efficiency of LAPPT increases first and then decreases, and is always greater than that of PPT-4J mode. When the laser energy reaches 86.4mJ, the maximum propulsion efficiency of LAPPT reaches 13.58%. It can be seen that although the propulsion efficiency of the LAT mode itself is low, the laser ablation ignition has a significant enhancement on the electric propulsion efficiency of the pulsed plasma.

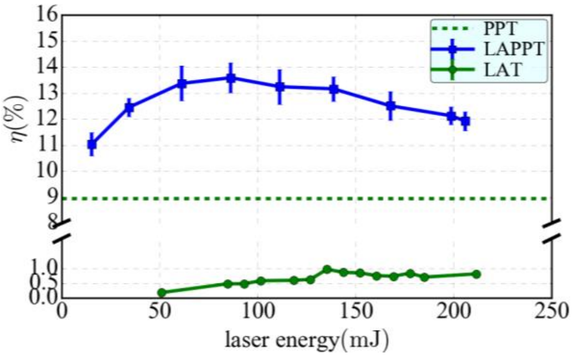

Figure 11. Variation of efficiency with laser

5. Conclusion

Generally speaking, the LAPPT mode, due to the effect of laser ablation ignition, has a remarkable increase in the impulse of element compared with PPT under the same discharge energy, and a slight decrease in the ablation amount, resulting in a significant improvement in the propulsion efficiency. The maximum laser energy is only 200mJ, which is much less than the discharge energy of 4J. However, from the experimental results, the change of laser energy has a certain impact on the propulsion performance of LAPPT, and its impulse is slightly reduced. The momentum, impulse coupling coefficient, specific impulse and propulsion efficiency all increase at first and then decrease with the increase of laser energy. The maximum value is obtained near the laser energy which makes the maximum impulse coupling coefficient of LAT. It is worth mentioning that in the experiment, the LAT propulsion efficiency is very low and the propulsion performance is not good. This is mainly due to the poor impulse coupling between PTFE and laser. For laser ablation propulsion, PTFE is not a propellant.

Acknowledgements

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