A novel pulsed plasma thruster design based on special capillary cavity structure
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Abstract: Pulsed plasma thruster has many advantages for the small satellite application, such as the simple structure, high reliability and low cost, etc. However, the limited performance impedes its further development and application. In this paper, a novel pulsed plasma thruster is developed. It combines the advantages of the electrothermal and electromagnetic thruster. It features with the inner accelerating rod type anode and capillary cavity. The design concept and general analysis has been conducted. And based on the experiment platform, the discharge characteristic and plume emission characteristic has been studied. the results showed that the new designed thruster had some different features in current and voltage waveform compared with the typical pulsed plasma thrusters and the general velocity of the plume was estimated to be 7.81km/s. More experiment will be conducted to verify the function of the rod type anode in accelerating particles electromagnetically.

Nomenclature

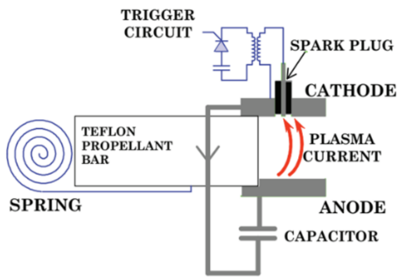
I_b	=	impulse bit
mi	=	the velocity of the specie *i*
v_i	=	the velocity of the specie *i*
η	=	the overall efficiency of the thruster
m	=	the ablation mass of one shot
E	=	the charging energy of the capacitor
S	=	the distance between the two PMT arrangement position
t_1	=	the moment of the first PMT output
t_2	=	the moment of the second PMT output
v	=	general velocity of plasma bulk

I.Introduction

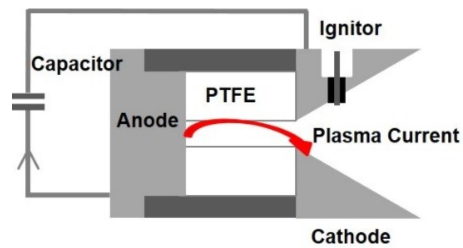
With the development of micro-satellite technology, more and more complex space mission can be accomplished by micro-satellites formation flying and coordination. The micro electric propulsion system with power levels below 100 W is widely used in the small satellite and it shows a bright future. Its optimization requires much more research [1].

Pulsed plasma thruster (PPT) first appeared in 1960s and has been applied to many space missions. PPT is very suitable for the micro-satellite application for its robustness, compactness and low cost. It is capable of fulfilling the task need, such as attitude control; drag compensation, etc. Many famous satellites are featured with PPTs, such as Zond-2, LES-6, EO-1. After several decades' development, however, the performance of the PPT still needs to be improved. Many researches have been done to increase its efficiency, higher thrust to power ratio and other parameters [2]. PPT can be divided into 2 types based on its major acceleration mechanism: electrothermal(ET) PPT and electromagnetic(EM) PPT. Both type have their own advantage and weakness. The EM PPT accelerates the charged particles with Lorentz force. It features with high impulse and low impulse bit. While in the case of ET PPT, the particles thrust out under the gradient of pressure in the small cavity. The impulse bit can be adjusted by changing charging voltage, capacitor capacitance and discharge cavity dimension. According to the literature, most of energy would be consume by ohmic heating in a low energy level PPT [3-4]. So, the electrothermal PPT has advantage in overall efficiency. However, due to the electrothermal acceleration, the ET PPT suffers from low specific impulse. More attention should be paid to the overall characteristic improvement.

In this paper, a novel structure PPT was described. It was designed at aim of combining strength of EM and ET acceleration mechanism to improve PPT performance. A theoretical analysis is conducted to verify the design concept. By the preliminary experiment, the typical voltage and current waveform was acquired and it showed some different feature.



(a) electromagnetic PPT



(b) electrothermal PPT

Figure 1 Different PPT type schematic

II. Structure Design of the PPT

It showed that many PPTs operate with a majority of neutral particles with low velocity. It has been recognized that these low velocity parts contribute little to the thrust and cause the overall inefficiency consequently. Many researches have been carried out to try to reduce the neutral particle fraction, such as setting additional capacitors and switches to induce double discharge [5], using additional parallel rail to accelerate the late ablation vapor [6], etc. These works do have achieved improvement of the performance to some extent, however, they suffer a lot from the loss of compactness and simplicity. In this paper, we propose a solution from the view of increasing the heavy particles velocity which would directly increase the thrust.

A. Theoretical analysis

The impulse bit of a thruster can be calculated with equation (1). It is the sum of the momentum of all the particles. And the equation (2) shows the overall efficiency.

$$I_b = \sum m_i v_i \tag{1}$$

$$\eta = {I_b}^2 / 2mE \tag{2}$$

With the same shot mass, the overall efficiency increases with the impulse bit. More specifically, the average velocity of the particles determines the impulse bit and final overall efficiency.

Table 1 shows the characteristic of fast part and slow part of plume species of the benchmark thruster-LES8/9[1].

Table 1 Characteristic of the different part of the thruster LES8/9

Parameters	*Fast part*	*Slow part*
Mass(μg) –*m*	6.0	22.5
Thrust(μN) –*T*	234	66
Kinetic energy(J) –${I_b}^2/2m$	4.6	0.1
Formation energy(J) –*E*	0.7	2.6

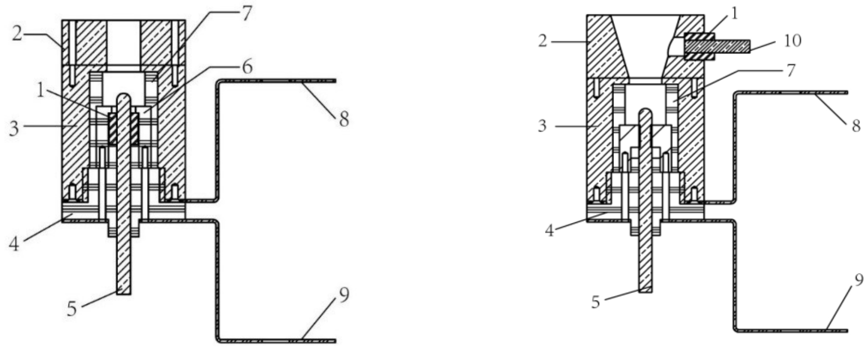
It can be easily seen that the slow part consumes large amount of formation energy but small amount of kinetic energy. It is believed that the late time ablation causes the inefficiency of the thruster. Most of the slow part particles generate after the discharge process. In result, the charged particles could not be accelerated in a weak magnetic field and the neutral particles could not be electromagnetically accelerated. Based on the data, it can be calculated that the average velocity of fast part can be 1.1 km/s, while the slow part is only 90 m/s. Many effort has been paid to reduce the amount of the neutral part, such as increasing the ionization rate, reducing the shot mass and additional accelerating rail to inducing second discharge.

Actually, from the table 1, we can conclude that there are two methods to improve the efficiency: a) reduce the slow part and its formation energy; b) increase the slow part kinetic energy with the other accelerating mechanism, such as electrothermal acceleration. The ablation PPT is based on passive feeding mechanism and it is hard to control the ablation amount in each shot. Moreover, in traditional PPT structure, the parallel rail provides limited utilization of the ohomic heating which dissipates during the operation process and causes energy loss.

Researchers in Japan and Germany did lots of work on low energy level electrothermal PPT [7-11]. Compared with the electromagnetic PPT, it has higher overall efficiency, larger impulse bit and lower specific impulse. It convinced that the electrothermal acceleration mechanism has good effect in this low energy level. Thus, a new design concept raised which combined the advantage of the electrothermal and electromagnetic acceleration.

B. Structure of the thruster

In the theoretical analysis part, it is shown that the combination of the electrothermal and electromagnetical acceleration mechanism could provide a solution for the inefficiency problem.



a) trigger in the rear b) trigger in the front

Figure 2 The side view of the new design PPT

The new design PPT consists following parts: 1. SiC semiconductor igniter; 2. Brass cathode; 3. Enclosure; 4. Fixed terminal; 5. Trigger rod; 6. Inner electrode; 7. teflon material; 8, 9. Transmission line.

The igniter consists of tungsten trigger rod and SiC semiconducting material with high performance. It produces electrons when applied a high voltage pulse and initiates the flashover in the capillary cavity. The initial plasma produced by capillary discharge will be accelerated by Lorentz force and produces a thrust.

Based on the previous analysis results, a novel structure PPT was designed. It mainly consisted two parts: the first part was a capillary cavity made of polytetrafluoroethylene (PTFE). In capillary cavity, the surface flashover was initiated by the outcome electrons and ions produced by self-made spark plug. After formation of the arc, PTFE ablated, dissolved and supplied to the plasma channel. In this stage, the plasma was mainly accelerated gas-dynamically [3]. Due to the tight space of capillary cavity, the gas-dynamic force can effectively accelerate either the charged or neutral particles. The second part was coaxial electrode. It was used to accelerated the plasma produced by the capillary discharge. In this stage the charged particles would be further accelerated electromagnetically; the neutral parts may be ionized and gain electromagnetic force. With the double acceleration process, the charged particles would reach a higher exhaust velocity.

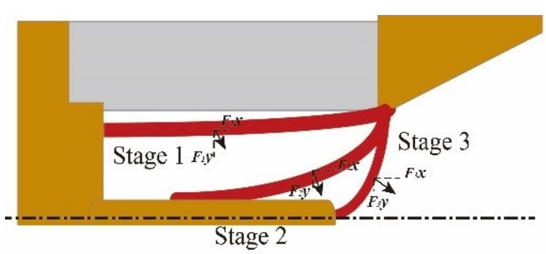


Figure 3 The concept of the new design PPT working process

The structure of novel PPT was designed elaborately. In order to maximize the transfer efficiency, a low inductance design was adopted. The main capacitor was selected; transmission line was designed. The circuit parameters were estimated which showed well fit with the experiment results.

The design concept includes the following advantages:

1. the small cavity of the pulsed plasma thruster could increase the utilization of the ohmic heating. The temperature and pressure gradient provides the electrothermal acceleration effect;
2. the inner electrode on the anode induce the plasma channel move from the bottom of the rod to the tip. With the change of the plasma position, the plasma channel acquires the electromagnetic force. The axial force

component accelerates the plasma channel thrust out and the radical force component make the plasma pinch inside the cavity and decrease the ablation mass per shot.

III.Experiment result

A. Experimental platform

In order to investigate the characteristic of the thruster, experiment platform was established. It includes the discharge characteristic experiment platform, plume characteristic platform and a thrust stand.

1) the discharge characteristic

Figure 4 is the schematic of the discharge characteristic platform. The typical voltage and current waveform of the main capacitor and trigger capacitor was acquired. Based on that, the deposited energy, equivalent circuit parameter and transfer efficiency was studied. Moreover, the trigger characteristic was studied, which was useful for the practical application.

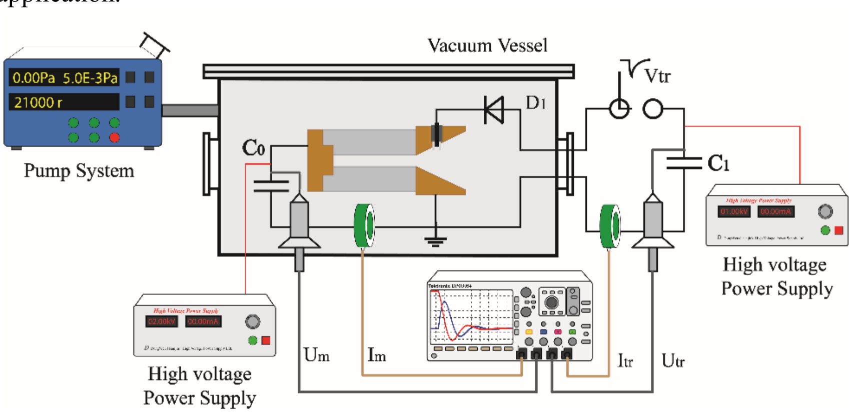


Figure 4 The schematic of the discharge characteristic study platform

2) the plume characteristic

Figure 5 shows the plume characteristic platform. With the PMT and spectrometer, the emission characteristic was studied.

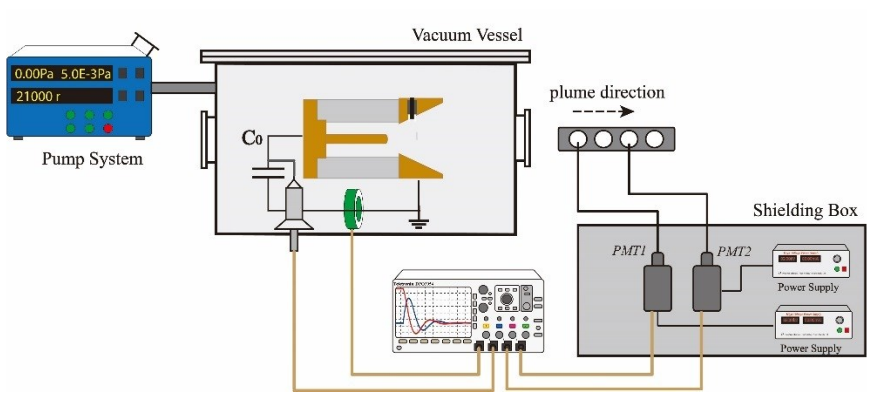


Figure 5 The schematic of the plume characteristic study platform

PMT is widely used in the discharge detection. In this study, two PMTs were used to measure the plume general velocity [12]. They were arranged along the axial of the cathode nozzle. The PMTs were connected with optical fibers and away from the thruster system to remove the influence of electromagnetic noise arising from the PPT operation with a high discharge current on the profiles detected with the photodiode. The optical fibers were mounted on a holder; 10mm ,30mm downstream the nozzle. The diameter of the fiber is 2500μm. Each luminescence from the plume was transported through the optical fibers and was detected by the respective PMT module.

In order to eliminate the influence of PMT response difference on the measurement, a comparison was conducted. Based on the PMT response signal, the general velocity of the particles was estimated.

3) the thrust force measurement

Torsional-type thrust stand exhibits a balance of high thrust measurement sensitivity and low environmental noise sensitive. A torsional balance was developed to study the characteristic of the pulsed plasma thruster. The torsional balance was calibrated with a novel structure printed circuit board electrostatic comb. However, due to some reason, the work on the impulse measurement of the pulsed plasma thruster has not finished yet. More attention will be paid to the analysis and improvement.

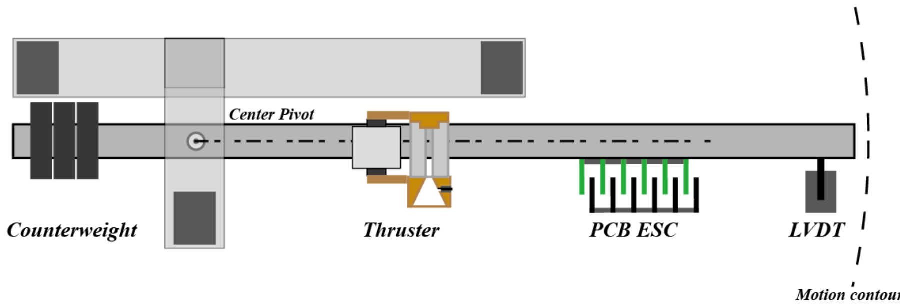


Figure 6 The schematic of the thrust stand

B. Experiment results

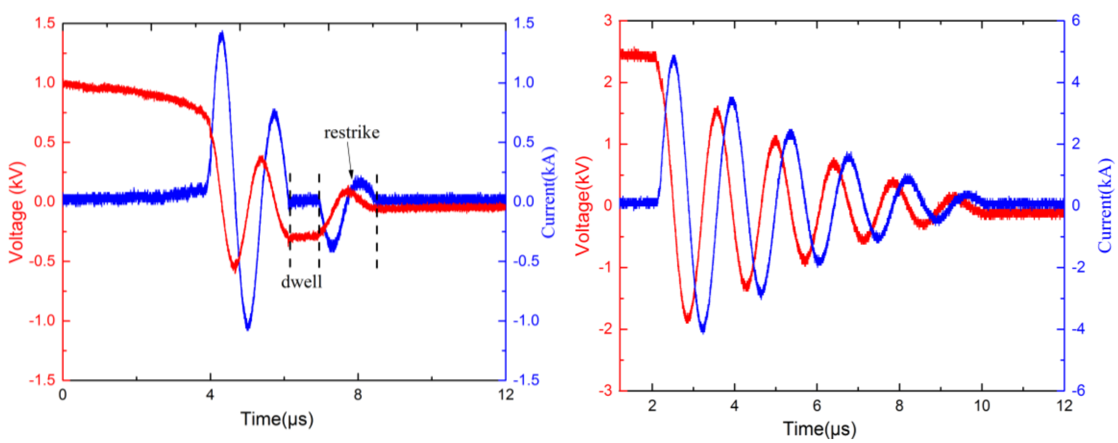
1) The discharge characteristic

The influence of charging voltage, cavity dimension and rod anode length have been studied. The typical voltage and current waveform has been acquired.

a) Typical discharge waveform

Two typical discharge types were recognized in the experiment. The main feature in type A was the dwell and restrike. And the type B was a typical damped sinusoidal oscillation. Type A occurred with a low charging voltage and a larger cavity. In figure 4, a) is corresponding to a charging voltage of 1kV and the cavity is 10mm in length and 8mm in diameter. The rod anode is 10mm in length and 3mm in diameter.

The dwell phenomena may prove the accelerating effect of the rod anode. According to the analysis of transition process, the arc channel would move from the end of anode to the tip along the rod. It would result in the decrease of the PTFE wall ablation. The arc could not sustain without the ablation supply and it distinct. The temperature of the PTFE surface keeps in a high level and it continued to melt and dissolve. The existed charging particles in the capillary collided with the gas and the restrike occurred.



(a) Type A: The waveform with “restrike” (b) Type B: the waveform without strike

Figure 7 The typical discharge waveform

b) The influence of charging voltage

Figure 8 shows the influence of the charging voltage on the discharge waveform. With the increase of the charging voltage, discharge current increases. The resistance of the plasma decreases with the charging voltage. Higher voltage would raise the ionization ratio. Higher current results in a higher ablation rate and increase the plasma temperature. More charged particles flow into the discharge channel to raise plasma channel conductance.

With the increase of the applied voltage, more energy transfers to the capillary and the deposited energy in plasma increases. The transfer efficiency, however, decreases with the increasing voltage.

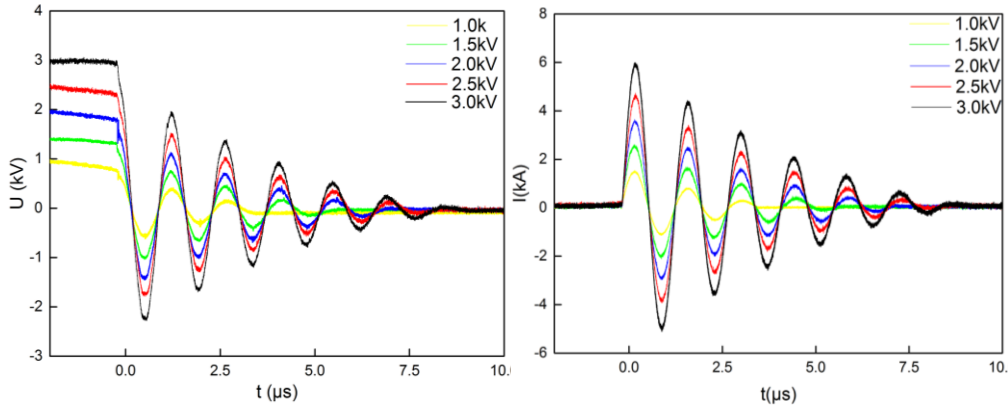


Figure 8 The influence of the charging voltage on the discharge waveform

c) The influence of capillary dimension

The figure 9 shows the influence of the cavity length on the discharge waveform. And figure 10 shows the influence of the cavity diameter on the discharge waveform.

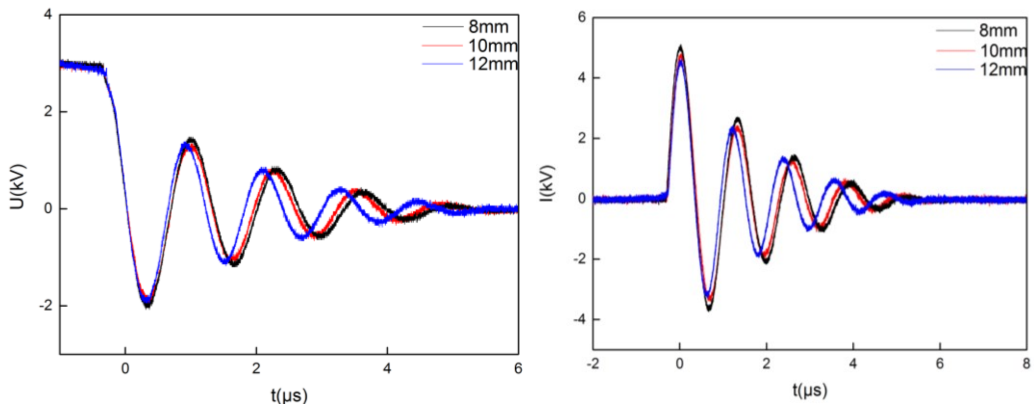


Figure 9 The influence of the cavity length on the discharge waveform

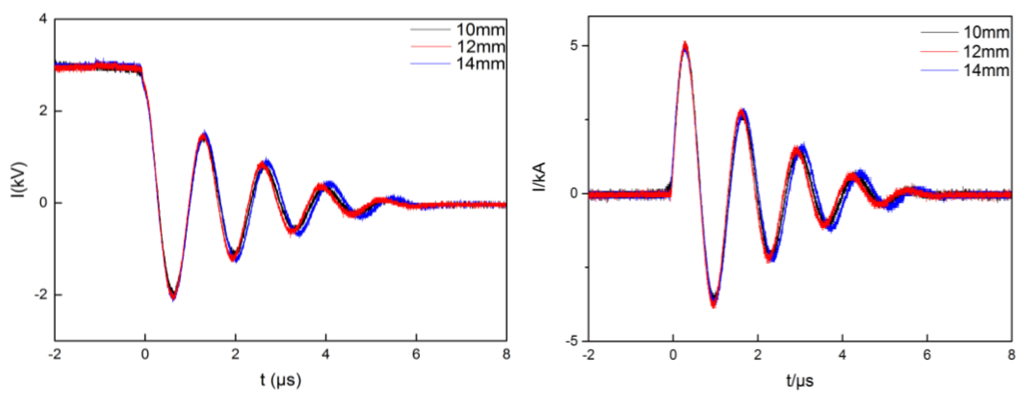


Figure 10 The influence of the cavity diameter on the discharge waveform

With the increase of the cavity length, the discharge current decreases. The duration of the discharge currentincreases with the cavity length. with the increase of diameter, the plasma inductance and resistance decrease. As a result, the discharge current waveform has a shorter period time and larger current amplitude.

d) the influence of the length of rod anode

Figure 11 shows the influence of the length of the rod anode on the discharge waveform. The length of the rod anode has a influence on the equivalent circuit parameters. However, based on the voltage and current waveform, the acceleration effect of the rod anode could not be verified.

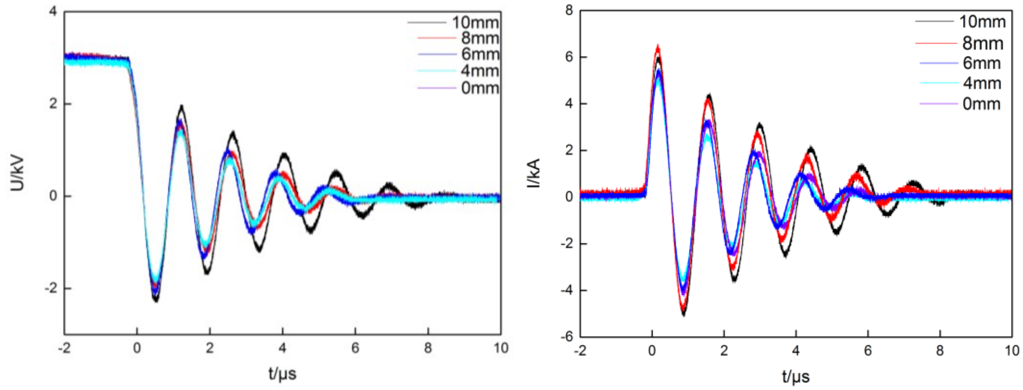


Figure 11 The influence of the length of the rod anode on the discharge waveform

2) the light emission characteristic of the pulsed plasma thruster

The emission intensity waveform was acquired. Figure 12 shows the emission intensity waveform. It showed that the emission intensity had a similar tendency with the current waveform. There were several peaks in the emission intensity waveform which were corresponding to the current. The emission lasted for 6μs, more than the current period which was the effect of the late time ablation.

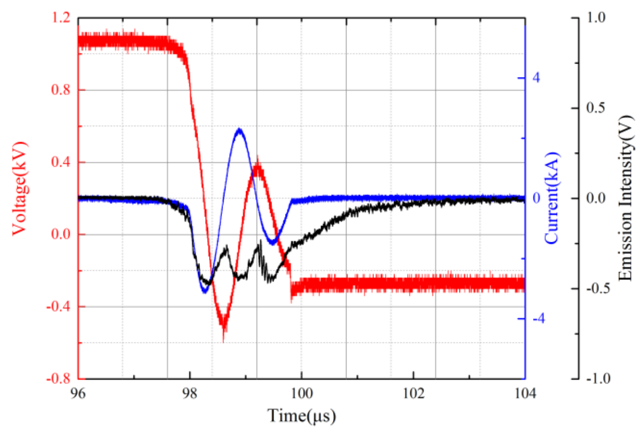


Fig12 The emission intensity, discharge current and voltage waveform

The Figure 13 shows the output signal of the two PMTs. The distance of the PMT is 2cm. Based on the Time of flight(TOF) method, the velocity of the plume was estimated. The result showed that the plume velocity could reach 15.6km/s.

$$V = \frac{\triangle S}{t_2 - t_1} \tag{3}$$

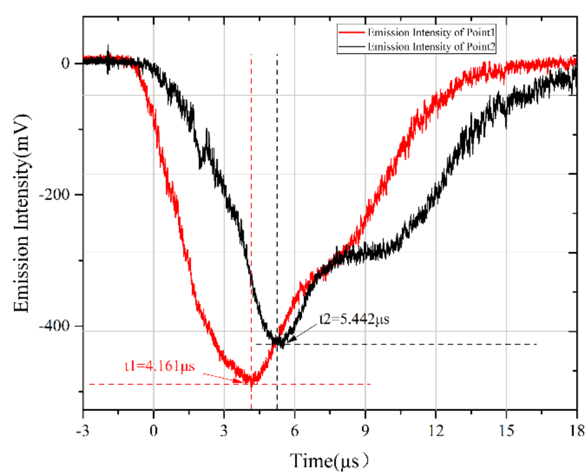


Figure 13 The output waveform of the two PMT

IV.Conclusion

In this paper, a novel pulsed plasma thruster design was shown. In order to increase the overall efficiency, the analysis of the particles distribution was conducted. Based on the analysis, it showed that increasing the velocity of the neutral part could have a good effect. The thruster is featured with a narrow cavity and rod like anode which may combine the advantage of electrothermal and electromagnetic acceleration.

In order to test the new design thruster's performance, the experimental platform was established. The typical discharge voltage waveform and current waveform was acquired. It showed some different features with the typical pulsed plasma thrusters. The influence of charging voltage, cavity dimension and rod anode length on the discharge characteristic were studied. With PMTs, the general velocity of the plasma bulk was estimated, which could be 7.91km/s, much faster than the typical electrothermal thruster. It could be an evidence of the existence of the electromagnetic force produced by the rod like anode. Unfortunately, the thrust stand does not finish yet and more experiment verification will be done in near future.

References

[1]R. L. Burton, P.J. Turch "Pulsed Plasma Thruster," Journal of Propulsion and Power, vol. 14, no. 5, pp.716 - 735, Feb. 1998.

[2] Wright W P, Ferrer P. "Electric micropropulsion systems," Progress in Aerospace Sciences, 2015, vol.74, pp:48-61.

[3] Yung-An Chan, Christoph Montag, and Georg Herdrich, Tony Schönherr "Review of Thermal Pulsed Plasma Thruster - Design, Characterization, and Application," in Proc. Joint Conference of 30th International Symposium on Space Technology and Science 34th International Electric Propulsion Conference and 6th Nano-satellite Symposium, Hyogo-Kobe, Japan, July 4–10, 2015, IEPC-2015-20/ISTS-2015-b-20, pp:1-12

[4] Laperriere, D. D., Gatsonis, N. A., and Demetriou, M. A., "Electromechanical Modeling of Applied Field Micro Pulsed PlasmaThrusters," 41st AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit, AIAA-2005-4077, Arizona, USA, 2005.

[5] Okawa Y, Tachibana T. "Double Discharge Operation for a Pulsed Plasma Thruster", Japan Society of Aeronautical Space Sciences, 2003, Vol.51, No.590 (2003), pp. 114-118.

[6] Marques R I. "A mechanism to accelerate the late ablation in pulsed plasma thrusters" University of Southampton Proceedings, University of Southampton, 2009.

[7] Toshiaki Edamitsu and Hirokazu Tahara, "Performance Measurement and Flow field Calculation of an Electrothermal Pulsed Plasma Thruster with a Propellant Feeding Mechanism," in Proc. 29th International Electric Propulsion Conference, Princeton University, October 31 – November 4, 2005, IEPC-2005-105, pp:1-14.

[8] Matthias Lau, Georg Herdrich, Stefanos Fasoulas and Hans-Peter Roser, "A Thermal Pulsed Plasma Truster for Microsatellite Propulsion", in Proc.32nd International Electric Propulsion Conference, Wiesbaden, Germany, September 11–15, 2011, IEPC-2011-140

[9] Junji Uezu and Junpei Iio, Yukiya Kamishima and Haruki Takegahara, "Study on Pulsed Plasma Thruster Configuration to Expand Impulse Bit Range," in Proc. 29th International Electric Propulsion Conference, Princeton University, October 31 – November 4, 2005, IEPC-2005-234, pp:1-12

[10] Ishii Y, Yamamotu T, Yamada M, et al. "Development of Electrothermal Pulsed Plasma Thrusters for Osaka - Institute - of - Technology Electric - Rocket - Engine onboard Small Space Ship" in Proc. AIP Conference, 2009,vol 1084, pp: 918

[11] Fujita R, Tahara H. "Development of Electrothermal Pulsed Plasma Thruster Systems onboard Osaka Institute of Technology PROITERES Nano-Satellites" in Proc. 33rd International Electric Propulsion Conference, The George Washington University, Washington, D.C., USA, October 6–10, 2013, IEPC-2013-97

[12] Miyasaka T, Kobayashi A, Asato K. Optical Measurements of Exhaust Process of an Electrothermal Pulsed Plasma Thruster. Transactions of Jwri, 2012, 41:37-44.