Electrostatic Probe Measurements in a 4 J Pulsed Plasma Thruster

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Zun Zhang,[1] Haibin Tang,[2] Yuan Yang,[3] and Mingxin Li.[4]
Beijing University of Aeronautics and Astronautics, Beijing, Zip 100191, China

Abstract: The discharge current and voltage curves of the 4 J laboratory model Teflon pulsed plasma thruster were measured, allowing determination of the circuit parameters. Triple Langmuir probe were used to measure electron temperature and density at the location of 15 cm from the Teflon surface, and at the angular position of 10 degrees in the plane parallel to the thruster electrodes. Time of flight (TOF) probes were used to investigate the velocity of the plasma at the positions of 8 cm, 13 cm and 18 cm. The discharge curves show that the discharge time of the 4 J PPT is 4 μs, the initial charge voltage is 2000 V and the peak value of the discharge current is 19.2 kA. The electron temperature is 8.377×10^{4} K and the electron density is 2.71×10^{20} m^{-3} at the 15 cm, 10 degrees position. The velocity of the plasma V_{rise} is 60-120 km/s，V_{peak} is 80 km/s and V_{down} is 40 km/s。

Nomenclature

A	=	area of probe
C	=	capacitance of the main capacitor
e	=	charge of electron
I_1	=	first positive peak value of the discharge current
I_2	=	first negative peak value of the discharge current
I_3	=	measured ion current of the negative probe
k	=	Boltzmann constant
L	=	total inductance of the circuit
m_i	=	mass of ion
N_e	=	electron density
R	=	total resistance of the circuit
s	=	distance of time of flight (TOF) probes
t	=	time delay of TOF probe signals
t_{rise}	=	arrival time of the probe signals
t_{peak}	=	time of peak probe signals
t_{down}	=	decrease time of the probe signals
T	=	period of the discharge current
T_e	=	electron temperature
v_{rise}	=	corresponding velocity of the t_{rise}
v_{peak}	=	corresponding velocity of the t_{peak}

[1] Graduate Student, School of Astronautics, zhangzun@sa.buaa.edu.cn.
[2] Professor, School of Astronautics, thb@buaa.edu.cn.
[3] Graduate Student, School of Astronautics, andrew85141696@126.com.
[4] Graduate Student, School of Astronautics, limingxingbd@163.com.

v_{down} = corresponding velocity of the t_{down}
V_{d2} = measured voltage difference between the positive probe and the floating probe
V_{d3} = fixed voltage between the positive and negative probes
V_n = voltage of probe n
β = constant indicating variation of ion current with probe potential
χ_{dn} = non-dimensional potential of V_n
η = non-dimensional form of β

I. Introduction

Pulsed plasma thruster is one of electromagnetic propulsion system that relies on the Lorentz force generated by an arc passing from anode to cathode and the self-induced magnetic fields to accelerate the propellant to produce the thrust.[1] Pulsed Plasma Thrusters are widely utilized due to their low power requirements, simplicity, reliability and the ability of supplying small and accurate thrust.[2]

The characterization of plume properties of the PPT is important because the plume of the PPT consists of a series of plasma blobs including neutral and charged particles from the Teflon propellant and eroded particles from the thruster electrodes and other parts[3]. The plume of the PPT may cause communication and electromagnetic interference to the spacecraft. Successful combination of PPT on spacecrafts requires the comprehensive investigation of the plume characters. Additionally, plume properties could are important in improving thruster performance and optimization of design.[1]

Electrostatic probes (Langmuir probes) were the first diagnostics developed to take measurements inside the plasma. Triple Langmuir Probe theory was first introduced and implemented by Chen and Sekiguchi in 1965, which was a new and simple method to derive the electron temperature and density within the plasma over time at the specific locations. [4]

Triple probe method has been successfully used in MPD plum measurement by Dennis L. Tilley, Arnold J. Kelly and Robert G. Jahn.[5] This method has also been used in a 1 kW Arcjet thruster measurement by S. A. Bufton, R. L. Burton, and H. Krier.[6] Endeavors to apply triple Langmuir probes in the PPT plume test have been underway for several years. Two sets of single Langmuir probes were used by Robert Eckman to get the velocity of ions. From the analysis, two ion populations were identified with a slow one traveling at about 30 km/s and a faster one traveling at approximately 60 km/s.[7,8] Double Langmuir probe was used by W. J. Guman and M. Begun to study the electron temperature and density variations of the exhaust plum of a PPT at different locations.[9] Triple Langmuir probe was used by Lawrence T. Byrne et al. to derive the average maximum electron temperature and density at different positions.

The discharge current and voltage of a 4 J laboratory PPT were measured leading to the investigation of the discharge process and the circuit parameters.

Single Langmuir probe was used to measure the velocity of the plasma at some specific locations. And the Triple Langmuir probe was used to simultaneously measure electron temperatures and electron densities in the plume of a 4 J laboratory PPT.

II. Experiment Apparatus

A. Test Facility

All the experiments were taken in a DVS-3200 vacuum system, shown in Fig. 1, which including the vacuum chamber, pumps, control system and other assistant systems. The vacuum chamber is 0.8 m in diameter and 1 m in length. The base pressure in the vacuum chamber can maintain at 1.3×10^{-3} Pa during the experiment.

A stepper motor driven translation system was used to move the probes axially along the centerline of the PPT thruster, allowing a range of measurements at a set of positions.

Figure 1. Vacuum system.

The translation system includes a moving stand and a control stand, the moving stand was set inside the vacuum chamber and the control stand outside the vacuum chamber allowing for reposition of the Langmuir probes during testing. This system is able to reposition the probes from the exit plane of the thruster to 15 cm from the surface of the Teflon.

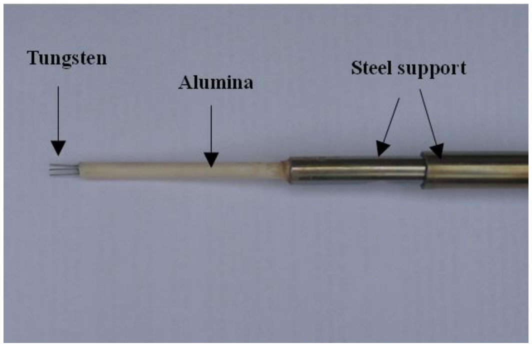


Figure 2. The head of the triple probe.

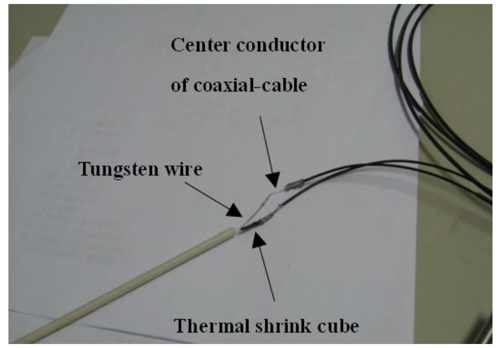


Figure 3. The connection of the Tungsten and cables.

The triple probe consists of three exposed wires which were 0.3 mm diameter tungsten and were fed through four bore alumina tubing with a diameter of 3.5 mm, shown in Fig. 2. These wires are about 10 cm long, with 9 mm exposed at the tip of the probe. The alumina tubing serves to hold the wires at a fixed separation of about 2 mm and insulate the wires from the probe support. After the tungsten wires pass through the tubing, they were welded to the center conductor of three coaxial cables and were insulated with heat shrink tubing shown in Fig. 3. Then the cables pass through the vacuum chamber and lead to the measurement circuit and the oscilloscope.

The thruster was mounted horizontally inside the vacuum chamber and the translation system was mounted axially with the center line of the thruster. The setup of the test Facilities such as PPT, triple probes, moving stand and the vacuum chamber were shown in Fig. 4.

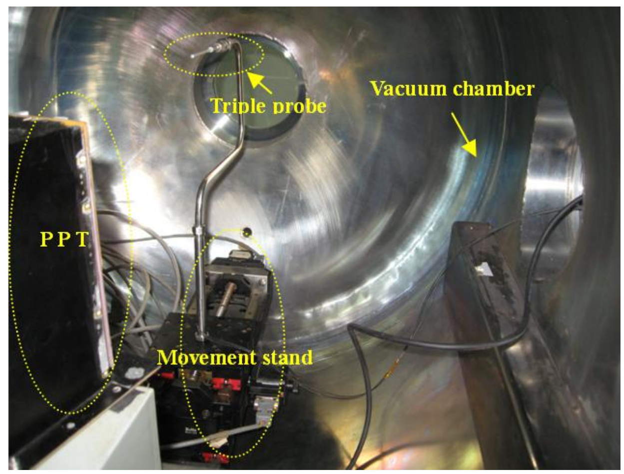


Figure 4. Apparatus setup in the vacuum chamber.

Table 1. 4 J laboratory model PPT general performances

Propellant profile, mm^2	25×10
Energy per discharge, J	4
Total energy consumption, W	5
Capacitance of main capacitor, μF	2±5%
Charge voltage to main capacitor, kV	2±1%
Charge voltage to ignition capacitor, V	500

B. Thruster

The thruster used in this experiment has a parallel electrode configuration which uses solid Teflon as propellant. A 2±5% μF capacitor capable of storing approximately 4 J is used before discharge. A solid bar of Teflon propellant with a cross section of 1.0 cm×2.5 cm is spring fed to the electrodes. The general performances of the 4J laboratory model PPT are shown in table 1.

The power conditioner for the laboratory model PPT mainly includes the adjustable main discharge circuit, the 500 V trigger circuit and the trigger control circuit. The block diagram of the power conditioner is shown in Fig. 5.

The power conditioner accepts a commonly used AC 220

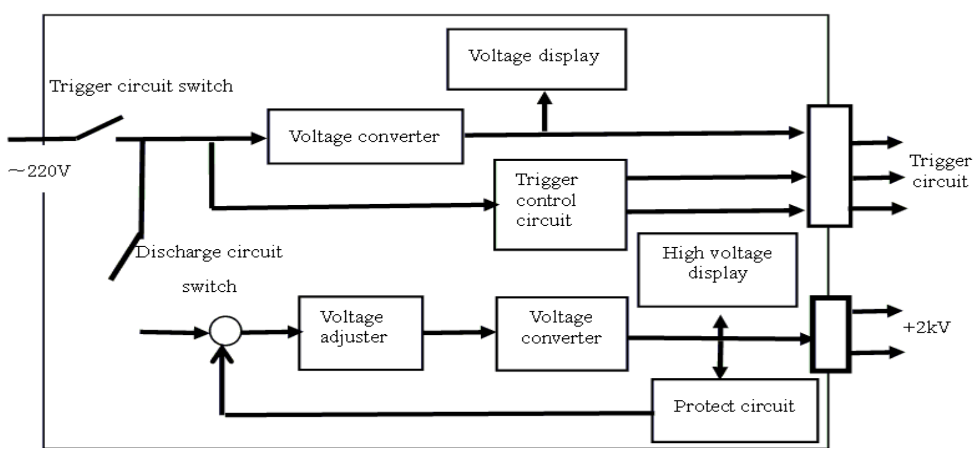


Figure 5. The power unit for PPT.

V 50 Hz voltage and converts it to a 0-3 kV adjustable DC for main discharge and 500 V DC needed by the ignite spark. At the same time the power conditioner also provides a controlling pulse for the ignition subsystem so that the thruster works successfully.

III. Data analysis and discussion

A. Measurement of the Discharge Voltage and Current of the PPT

During the thruster operation, the discharge current was measured with a Rogowsky coil with the calibration constant of 5000 A/V. The voltage was measured outside the vacuum chamber across the positive and the negative poles of the main discharge power unit (that is across the capacitor of the thruster) with a standard Tektronix voltage probe (Tektronix P5100, attenuation factor ×100, 2.5 kV peak, with an accuracy of +l%).

Both probes were connected to a Tektronix 100 MHz DPO3014 oscilloscope. The discharge current and the voltage of the thruster are shown in Fig. 6.

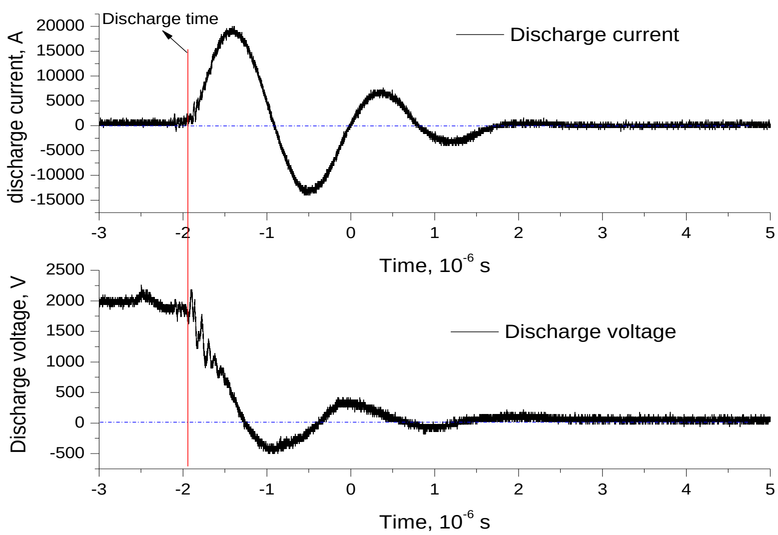


Figure 6. The discharge current and voltage of the 4 J PPT.

From Fig. 6, when the initial charge voltage to the thruster is 2 kV, the peak value of the discharge current is 19.2 kA and the discharge time of the PPT is about 4 μ s.

Measuring the discharge current and the voltage allows the investigation of the discharge process of the thruster itself and the parameters of the circuit such as its own resistance *R* and inductance *L*.

The total circuit inductance and resistance were calculated with equation (1) and (2). [10,11]

$$L = \frac{T^2}{4\pi^2} \cdot \frac{1}{C} \tag{1}$$

$$R = \frac{2 \cdot L}{T} \cdot \ln\left(\frac{I_1}{I_2}\right) \tag{2}$$

In the equations, T (s) is the period of the discharge current, C (pF) is the capacitance of the main capacitor, L (nH) is the total inductance of the circuit, R (mΩ) is the total resistance of the circuit, I_1 is the first positive peak value of the discharge current and I_2 is the first negative peak value of the discharge current.

Depending on the discharge curves and the equations, the discharge parameters of the PPT circuit are summarized in table 2.

Table 2. The discharge parameters of the PPT

Discharge energy	Capacitance（μ F）	Period (μ s)	I_1/I_2 (kA/kA)	L（nH）	R(mΩ)
4 J	2	2	19.2/13.2=1.45	51	18.95

B. Measurement of the Langmuir probe

Triple Langmuir probe was first derived and implemented by Chen and Sekiguchi in 1965,[12] and further developed by Byrne, Gatsonis, Eckmann and Scharlemann.[13,14,15,16] . This method is convenient because it does not need a large amount of data to form a V-I curve at a short pulse time around 5-15 microseconds. This character leads to the instantaneous measurement of electron temperature T_e and density N_e.

The triple probe consists of three exposed wires. A fixed voltage V_{d3} is applied between two of those wires, when the plasma comes, generating a current I_3 in that circuit, which is measured. The voltage difference V_{d2} between the positive wire and the third wire, which is electrically floating, is also measured, as shown in Fig. 7.

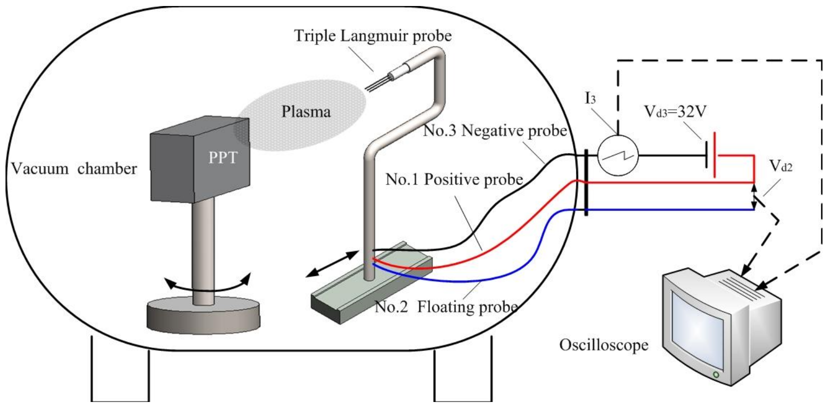


Figure 7. The measurement diagram of Langmuir triple probe.

Using the methods described above, these two values allow for the evaluation of the electron temperature T_e, and subsequently the electron density N_e.

The electron temperature T_e can be derived from the V_{d2} measurement using the equation (3) and electron density N_e can be derived from the equation (4).

$$\frac{1}{2}=\frac{1-\frac{1}{2}([1-\beta V_{d2}]^{1/2}+[1+\beta(V_{d3}-V_{d2})]^{1/2})\exp(-\chi_{d2})}{1-\exp(-\chi_{d3})} \tag{3}$$

$$n_e=\frac{\exp(\frac{1}{2})\frac{I_3}{A}(1-\eta(\chi_f-\frac{1}{2}))^{1/2}}{e(\frac{kT_e}{m_i})^{1/2}([1+\eta(\chi_{d3}-\chi_{d2})]^{1/2}-\exp(-(\chi_{d3}-\chi_{d2})))} \tag{4}$$

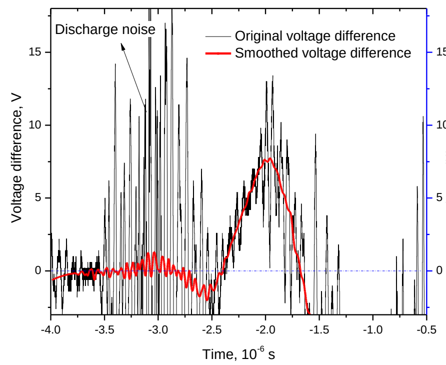
In the equations, V_{d2} and I_3 are the measured voltage and current. V_{d3} is the fixed voltage applied between the positive and negative probes. β is a constant indicating variation of ion current with probe potential. $\chi_{dn}=\frac{e\cdot|V_n-V_p|}{k\cdot T_e}$ is the non-dimensional potential of the electrode V_n with respect to the plasma potential V_p. k is the Boltzmann constant and e is the unit charge of an electron. A is the area of probe. m_i is the mass of ion. η is the non-dimensional form of β.

The voltage difference V_{d2} is measured with a Tektronix P5205 100 MHz high voltage differential probe and the current I_3 is measured with a Tektronix TCP 0150 50 MHz Hall current probe. The two measurements lead to the oscilloscope and saved for data analysis.

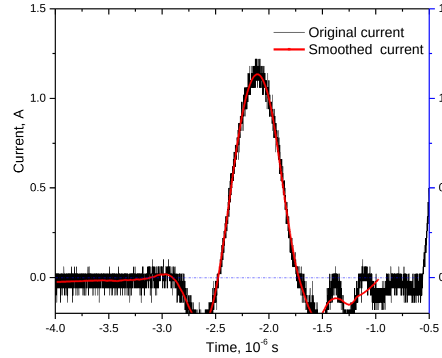
A typical set of voltage and current traces, at the location of 15 cm axial downstream from the Teflon surface and 10 degrees off the centerline of the PPT in the parallel plane with the electrodes, is shown in Fig. 8 (a) and (b).

There are a lot of noises in the measurement of V_{d2} compared with the measurement of I_3. The noises manifest themselves in two aspects. At the start of the pulse, the spark plug breaks down the gap and initiates a burst of electromagnetic noise. During the pulse, the noise maybe comes from the connection of the voltage probe and the coaxial cables, and also the vibration of the environment.

So the measurement of V_{d2} and I_3 were smoothed using the method of weighted average Adjacent-Averaging in the software of OrigionPro 8. The data curves of V_{d2} and I_3 after smoothing are shown in Fig. 8.



(a). V_{d2} before and after smoothing



(b). I_3 before and after smoothing

Figure 8 V_{d2} and I_3 before and after smoothing at 15 cm 10 degrees downstream

The electron temperature T_e will be derived from the smoothed V_{d2} depending on the function (3). And the electron density N_e will be derived from the smoothed I_3 using the function (4). Three repeated measurements of electron temperature T_e and electron density N_e at the location of 15 cm downstream and 10 degrees off the centerline are shown in Fig. 9 (a), (b), and (c).

The maximum T_e and N_e in the three tests, and the average values are summarized in table 3.

Table 3. The maximum and the average T_e and N_e in the three repeat measurements

Max T_e-1	Max T_e-2	Max T_e-3	Max T_e-Average
94100	67460	89752	83770
Max N_e-1	Max N_e-2	Max N_e-3	Max N_e-Average
3.1E20	2.36E20	2.67E20	2.71E20

From table 3, the average maximum electron temperature is 83770 K that is about 7.2 eV; and the average maximum electron density is 2.71×10^{20} m^{-3} at the location of 15 cm from Teflon and 10 degrees off center line for the 4 J Teflon PPT.

C. Measurement of the Time of Flight probe

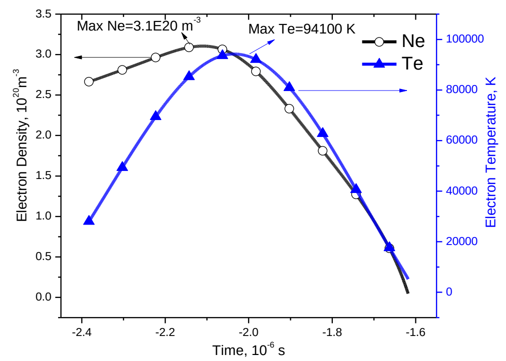
Single Langmuir probe was used as time of flight (TOF) probe, which was placed apart at the positions of 8 cm, 13 cm and 18 cm. The voltage signals of the probe were collected to identify the time delay t during the distance s. The velocity of the plasma v will be derived from equation (5).

$$v = \frac{s}{t} \tag{5}$$

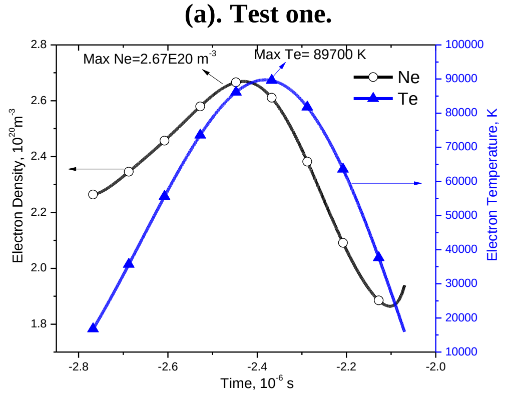
The voltage curves of the probe at different locations are shown in Fig. 10.

The voltage of the probe at different positions also indicates the characters of the charged particles in the plasma, they all go sharply down to 200~600V at the beginning of the curves, then goes upwards mildly to zero and oscillates several times. The first negative peak value and the first positive peak value decrease with further distance because the density and velocity of electrons are decreased.

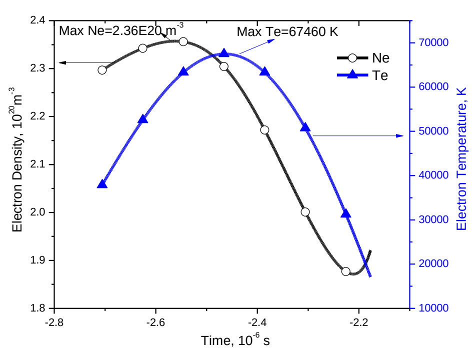
The voltage variations of probe can be explained as following: When the electrons and ions are accelerated at the surface of Teflon, the electrons with comparatively low mass



(a). Test one.



(b). Test two.



(c). Test three

Figure 9. T_e and N_e at 15 cm 10 degrees

will obtain much higher velocity than the ions with high mass. At the time of electrons and ions are travelling to the probe, they could affect each other and their relative velocity will decrease.

But the electrons still arrive at the probe a little earlier than the ions, which is the reason why the voltage of the probe firstly goes sharply down. This high negative electric field will repel electrons and attract ions to balance the electric field. Then the voltage of the probe goes upward to zero. It is interesting that the voltage of the probe goes up and down afterward, this is maybe because the different populations of electrons and ions, with different velocities, arrive at the probe at different times.

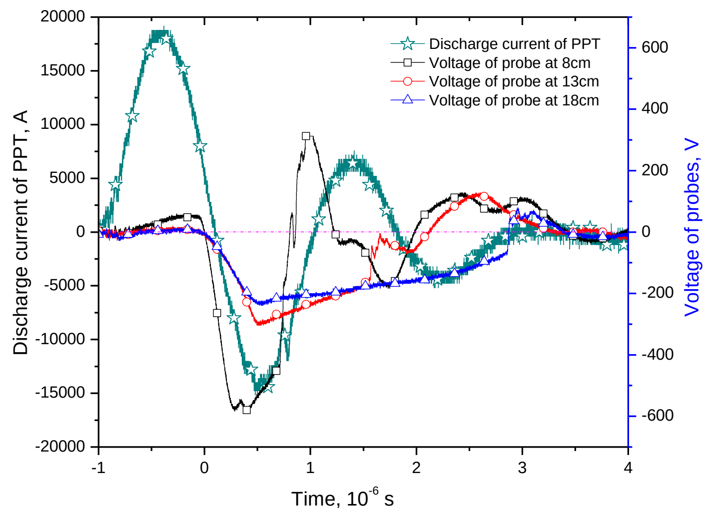


Figure 10. The voltage curves of TOF probe at 8, 13 and 18 cm .

The arrival time of the probe signals are labeled as t_{rise}, the time of peak probe signals labeled as t_{peak}, and decrease time of the probe signals labeled as t_{down}. The velocities with the corresponding time are respectively marked as v_{rise}, v_{peak} and v_{down}. These data at the different positions are shown in table 4.

Table 4. The corresponding time and velocity from the TOF probe at different locations

	8 cm	13 cm	18 cm	Average
t_{rise}（μ s）	0.909	0.933	1.002	—
t_{peak}（μ s）	1.25	1.46	1.605	—
t_{down}（μ s）	2.174	3.112	3.84	—
v_{rise}（km/s）	88	139	179	135
v_{peak}（km/s）	64	89	112	88
v_{down}（km/s）	37	42	47	42

The values of v_{rise} at different locations are scattering in the range of 80-180 km/s, the values of v_{peak} are scattering in the range of 60-120 km/s and the values of v_{down} are approximately 40 km/s.

IV. Conclusions and future work

The discharge current and the voltage of the 4 J PPT have been measured. From the discharge curves, the discharge process of the thruster itself and the parameters of the circuit such as its own resistance *R* and inductance *L* have been investigated and calculated.

Triple Langmuir probes and the circuit for the probe measurements have been designed and used in this experiment. The averaged maximum electron temperature and averaged maximum electron density at the location of 15 cm 10 degrees have been calculated.

The velocity of the plasma has been measured depending on the theory of the TOF probe at the different locations of 8 cm, 13 cm and 18 cm. The average velocity with the arrive time of the probe signals is 135 km/s, the average velocity with the time of peak probe signals is 88 km/s and the average velocity with the decrease time of the probe signals is 42 km/s.

The shock pressure measurement of the plasma for the thruster is our research work in the future. The pressure probe will give more information such as the total pressure of the plume, the velocity of the plasma, and also the thrust of the thruster.

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References

[1] R. M. Myers, L. A. Arrington, E. J. Pencil, J. Carter, J. Heminger, and N. Gatsonis, “Pulsed Plasma Thruster Contamination,” *32th AIAA/ASME/SAE/ASEE Joint Propulsion Conference*, USA, 1996 .

[2] Han-Ji Wu, and Xue-Zhang Feng, “Experimental Research of 20 joule PPT,” *AIAA/DGLR/JSASS 18th International Electric Propulsion Conference,* USA, 1985.

[3] Robert Francis Eckman, “Langmuir Probe Measurements in the Plume of a Pulsed Plasma Thruster,” Science Master Degree Dissertation, Worcester polytechnic institute, Mechanical Engineering, 1999.

[4] Sin-Li Chen, and T. Sekiguchi, “Instantaneous Direct-Display System of Plasma Parameters by Means of Triple Probe,” *Journal of Applied Physics*, Vol. 26, No. 8, 1965, pp. 2363–2375.

[5] Dennis L. Tilley, Arnold J. Kelly, and Robert G. Jahn, “The Application of the Triple Probe Method to MPD Thruster Plumes,” AIAA/DGLR/JSASS *21th International Electric Propulsion Conference,* USA, 1990.

[6] S. A. Bufton, R. L. Burton, and H. Krier, “Measured Plasma Properties at the Exit Plane of a 1 kWArcjet,” *31st AIAA/ASME/SAE/ASEE Joint Propulsion Conference,* USA, 1995.

[7] Robert Eckman, “Pulsed plasma thruster plume diagnostics,” *AIAA* 98-0004.

[8] Robert Eckman, Lawrence Byrne, Edward Cameron, Nikos A. Gatsonis, and Erik J. Pencil, “Triple Langmuir Probe Measurements in the Plume of a Pulsed Plasma Thruster,” *AIAA* 98-3806, 1998.

[9] W. J. Guman, and M. Begun, “Exhaust plume studies of a pulsed plasma thruster,” *AIAA/DGLR 13th International Electric Propulsion Conference,* USA, 1978.

[10] Carsten A. Scharlemann, and Thomas M. York, “Investigation of a PPT Utilizing Water as Component Propellant,” *IEPC* 2003.

[11] Carsten A. Scharlemann, and Thomas M. York, “Pulsed Plasma Thruster Using Water Propellant, Part Ⅰ:Investigation of Thrust Behavior and Mechanism,” *39st AIAA/ASME/SAE/ASEE Joint Propulsion Conference*, USA, 2003.

[12] Sin-Li Chen, and T. Sekiguchi, “Instantaneous Direct-Display System of Plasma Parameters by Means of Triple Probe,” *Journal of Applied Physics*, Vol. 26, No. 8, 1965, pp. 2363–2375.

[13] L. Byrne, “Langmuir Probe Measurement in the Plume of a Pulsed Plasma Thruster,” Master Degree Dissertation, Worcester Polytechnic Institute, 2002.

[14] Nikolaos A. Gatsonis, Jurg Zwahlen, Adrian Wheelock, Erik J. Pencil, and Hani Kamhawi, “Pulsed Plasma Thruster Plume Investigation Using a Current-Mode Quadrupole Probe Method,” *Journal of Propulsion and Power*. Vol. 20, No. 2, 2004, pp. 243–254.

[15] Robert Eckman, Lawrence Byrne, Nikolaos A. Gatsonis, and Eric J. Pencil, “Triple Langmuir Probe Measurements in the Plume of a Pulsed Plasma Thruster,” Journal of Propulsion and Power. Vol. 17, No. 4, 2001, pp. 762–771.

[16] C. Scharlemann, “Investigation of Thrust Mechanisms in a Water fed Pulsed Plasma Thruster,” Ph.D. Degree Dissertation, Ohio State University, 1999.