Investigations on the Flowing Pulsed Plasma of a 20J Pulsed Plasma Thruster

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Abstract: Investigations on the flowing pulsed plasma of a 20 J Teflon pulsed plasma thruster (PPT) have been carried out by the triple Langmuir probe and Time of Flight probe. The temporal and special profiles of electron temperature and density could be obtained by the triple Langmuir probe. And the velocity of the plasma could be obtained by the Time of Flight probe. The discharge current and voltage show that there are several half cycles in one discharge of PPT, which indicates that there are multiple micro-discharges in each discharge. This phenomenon can also be seen in the temporal electron temperature and density profiles showing 3-4 peeks in the profiles. The special distribution of electron temperature shows that the electron temperature remains very high about 12 eV to 16 eV at a nearer distance from the thruster, and it drops to 6 eV when the distance goes further. The maximum electron density is around 4.5×10^{20} m^{-3}, and it decreases with the increased axial distances.

Nomenclature

A	=	Probe area
e	=	charge of electron
I_3	=	measured probe current
k	=	Boltzmann constant
m_i	=	mass of ion
n_e	=	electron density
T_e	=	electron temperature
V_{d2}	=	measured probe voltage
V_{d3}	=	fixed probe voltage
V_n	=	Probe potential of No. n
V_p	=	Plasma potential
β	=	constant indicating variation of ion current with probe potential
η	=	non-dimensional of β

I. Introduction

A PPT is an attractive propulsion option for small power-limited satellites due to its low power requirements, simplicity, and robustness[1]. Generally, the PPT operates at low power levels (<100 W) by charging the energy-storage capacitor at a long time scale (～1 s), and then discharging it at a short time scale (～10 μ s) with high

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instantaneous power. The simplicity and robustness of the PPT are achieved through the application of a solid propellant (typically Teflon), which can overcome the problems of complexity and dry mass of the storage system associated with liquid or gaseous propellants[2]. Based on the advantages above, the PPT (on the Zond 2 spacecraft launched on November 30, 1964) becomes the first application of electric propulsion system applied in the spacecraft. The PPT is also successfully used in various missions around the world such as attitude control, orbit maintenance, precise positioning, orbit insertion and deorbit[3, 4].

However, the flowing pulse plume plasma of PPT may cause communication and electromagnetic interference to the spacecraft. Successful combination of PPT on spacecrafts requires the comprehensive investigations on the plume characters. Additionally, plume properties are important for the thruster improvement and optimization design.[5]

Electrostatic probes (Langmuir probes) were the first diagnostics developed to take measurements inside the plasma. Both single and double Langmuir probe methods require an I-V curve which is formed by sweeping the voltage applied to the probes and measuring the current collected at one specific location. This I-V curve is used to determine the electron temperatures and densities of the plasma[6,7,8]. This curve needs a lot of data and complex data processing. To overcome these drawbacks, a new and simple method, the triple Langmuir probe method, was introduced and implemented by Chen and Sekiguchi in 1965 to derive the instantaneous electron temperature and density within the plasma over time at the specific locations[9, 10,11,12,13].

Langmuir probes experiments in the flowing pulsed plasma were performed by Eckman et al. for the PPT with 5 J, 20 J and 40 J energy levels. The voltage-mode method was used to determine the instantaneous electron temperature and density at radial distances within 20 cm from thruster surface and at the off-centerline angles within 30 degrees in the parallel plane and 45 degrees in the perpendicular plane. The results showed the spatial and temporal variation of the plume. Maximum electron density near the exit of the thruster is 1.6×10^{20} m^{-3}, 1.6×10^{21} m^{-3}, and 1.8×10^{21} m^{-3} respectively for the 5, 20 and 40 J energy levels. The maximum electron temperature ranged from 3.75 to 4.0 eV near the exit of the thruster. Measurements showed a large angular variation in the perpendicular plane and very little in the parallel plane.[14] The current-mode triple Langmuir probes and double probes were used by Byrne et al to measure electron temperature and density of the plume in the PPT. Results showed the presence of hot electrons of approximately 5 to 10 eV at the beginning of the pulse. The maximum electron density were $6.6\times10^{19}\pm1.3\times10^{19}$ m^{-3} for the 5 J PPT, $7.2\times10^{20}\pm1.4\times10^{20}$ m^{-3} for the 20 J PPT, and $1.2\times10^{21}\pm2.7\times10^{20}$ m^{-3} for the 40 J PPT. The result from the double Langmuir probe showed good agreement with the triple probe method. [15]

PPTs have been investigated in China since 1970s, and took its first space test in China on Dec 7, 1981[16], which is the first space test of China's electric propulsion systems. In the early studies, the scholars investigated the main PPT parameters and their relationship between the electrical and geometric parameters. They have obtained the thruster efficiency (2%), averaged impulse bit (6.5 mg·s) and specific impulse (280 s) [17]. And they have shown that the thruster performance is significantly affected by the factor of electrode spacing-to-width ratio[18]. Unfortunately, further investigations were paused for tens of years. After the stagnancy, research works on PPT have been restarted recent years.

In our work, a Langmuir probe diagnostics system is constructed to get the flowing pulsed plasma properties. The rest of the paper is organized as follows: Section Ⅱ introduces the experimental apparatus including the thruster, vacuum system, and Langmuir probe. In Section Ⅲ are shown the experimental profiles of the electron temperature and density. Section Ⅳ discusses the multiple micro-discharges phenomenon in one PPT discharge and concludes the major results of our research.

II. Experiment Apparatus

A. Thruster and the vacuum chamber

A 20 J laboratory model Teflon PPT with a parallel electrode configuration was used in this experiment. The solid bar of Teflon propellant with a cross section of 1.3 cm×2.5 cm is spring fed to the electrodes. A spark plug is located at the base of the cathode controlled by the power conditioner to initiate the discharge. The power conditioner accepts a commonly used AC 220 V 50 Hz voltage and converts it to a 0-3 kV adjustable DC for the main discharge capacitor and 500 V DC needed by the spark plug. At the same time the power conditioner also provides controlling pulses with different frequencies for the ignition subsystem so that the thruster works successfully.

The Langmuir probe experiments were performed in a cryogenic vacuum system, as shown in Fig. 1, which includes a vacuum chamber (0.8 m in diameter and 1 m in length), dry vacuum pump, cryogenic pump, control system and other assistant devices. The background pressure can maintain to be 1.3×10^{-3} Pa during the experiment.

Figure 1. Cryogenic vacuum system.

B. Langmuir probe

Triple Langmuir probes consist of three identical probes placed in the plasma, which was used in the experiment to gain the electron temperature T_e and the electron density n_e. A fixed voltage V_{d3} (32 V batteries) is applied between two of those wires, when the plasma comes, generating a current I_3, which was measured. The voltage difference V_{d2} between the positive wire and the third wire is also measured.

The electron temperature T_e can be derived from the V_{d2} measurement using the equation (1) and electron density n_e can be derived from the equation (2) [22,19].

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

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

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. $\chi_{dn}=\left(e\cdot\left|V_n-V_p\right|\right)/\left(k\cdot T_e\right)$ 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.

Step-motor-driven translation equipment was used to position and reposition the Langmuir probe. It consists of a movement mechanism inside the vacuum chamber used to move the Langmuir probe, and a servo control system outside the vacuum chamber. Movements of up to 150 mm are possible when the repositioning precision is less than 5 μ m and the maximum velocity is 20 mm/s.

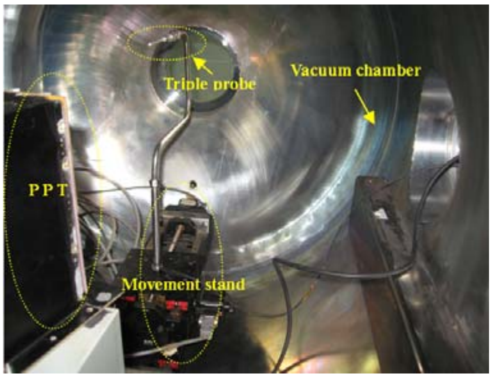

Figure 2. Langmuir Probe in the vacuum chamber.

Figure 3. Langmuir probe design.

III. Experimental Results

A. Discharge voltage and current

In order to supervise the discharge process of the thruster, the discharge voltage and current of the thruster were collected by a high voltage probe (Tek P5100) and a Rogowsky coil. The discharge voltage and current results are shown in Fig 4.

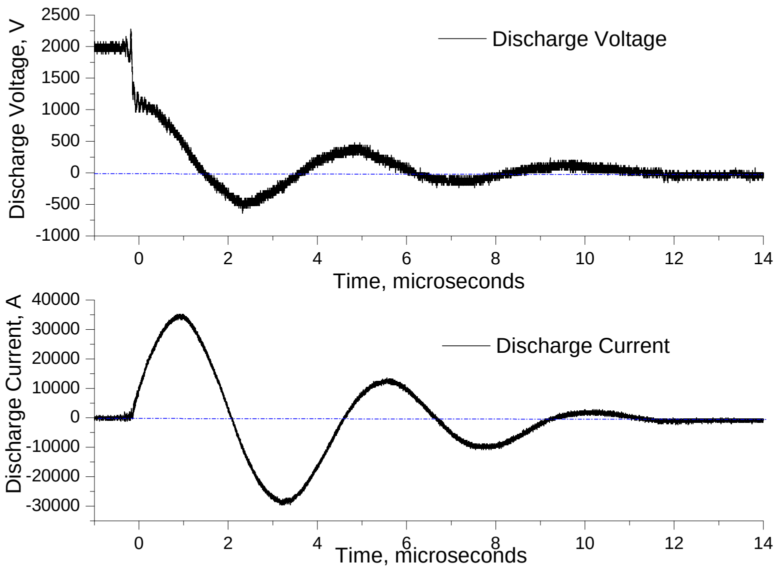

Figure 4. The discharge current and voltage of the 20 J PPT.

The discharge current oscillates in the manner of a damped sine wave, and lasts for about 12 μ s. This period can be obviously divided into four half-cycles (about 2.5 μ s period each), with four peak values indicating not only the "re-strike" [20] but also the "quadruple-strike" phenomena.

B. Electron temperature and density profiles

Triple Langmuir probe measurements were taken in the locations of 3 cm, 5 cm, 7 cm, 8cm, 10 cm and 15 cm from the Teflon surface at the centerline of the thruster. At least 3 tests were carried out at each location, and these 3 original profiles are averaged. A typical set of averaged voltage and current profiles (in black line) from the triple Langmuir probe at the location of 5 cm are shown in Figs. 5 and 6. However, there is lots of high frequency noise present in the profiles. In order to decrease these noises, a FFT filter method was used to allow the low frequency signal to pass and prevent the high frequency noise. The FFT filter used a 5×10^5 Hz low pass filter for the pass of discharge voltage and current signals. In this way, the high frequency noise was deleted and the main signal trends were shown.

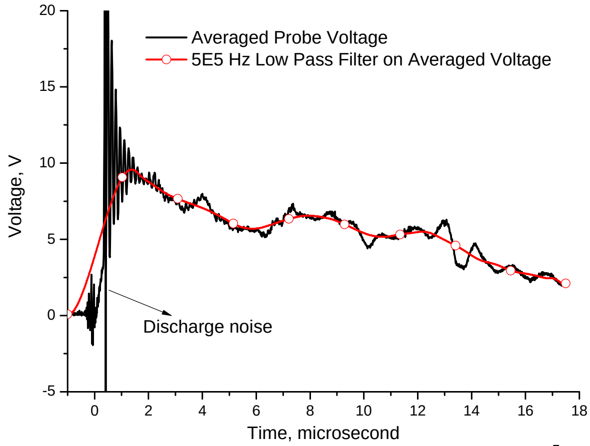

Figure 5. Probe voltage before and after the 5 ×10^5 Hz FFT filter.

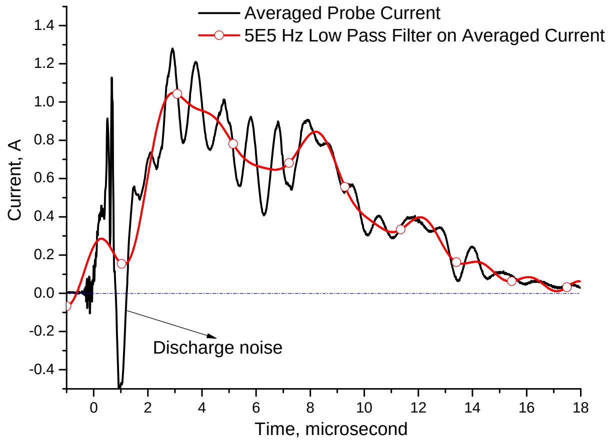

Figure 6. Probe current before and after the 5 ×10^5 Hz FFT filter.

The data after the FFT filter were used to calculate the electron temperature depending on the equation (1) and electron density depending on the equation (2). The calculated electron temperature and density profiles with time at an axial distance of 5 cm are shown in Fig. 7.

It is interesting to see that there are three peeks in the electron temperature and density profiles. This phenomenon is related to the discharge process of the thruster. At the beginning of the pulses, some very hot electrons present themselves at the beginning with the electron temperature around 15 eV. The second peaks of the electron temperatures drop to about 9 eV after 8 microseconds. The third peaks of the electron temperature drop down to 7 eV after 12 microseconds. The first peak electron density is around 4.5×10^{20} m^{-3} and drop to about 3×10^{20} m^{-3} after 8 microseconds. After 12 microseconds the electron densities drop to 1.0×10^{20} m^{-3}.

The Spatial variation of the maximum electron temperature and densities of the pulsed plume plasma at the different locations along centerline is shown in Fig.8.

Generally, the maximum electron temperature and density decrease with further distance. The maximum electron temperatures at 3cm, 5 cm, 8cm and 10cm remain very high about 12 eV to 16 eV. It drops to 6 eV at the further distance of 15 cm. The maximum electron densities at 3cm, 5 cm and 8cm are around 4.5×10^{20} m^{-3}. When the distance gets further, the maximum electron densities drop down to 2.8×10^{20} m^{-3} at 10 cm and 1.6×10^{20} m^{-3} at 15 cm.

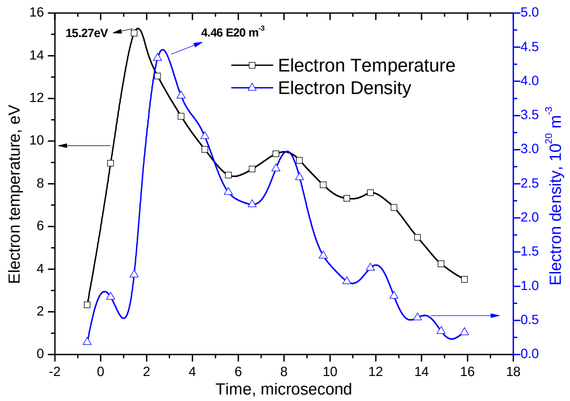

Figure 7. Electron temperature and density with time.

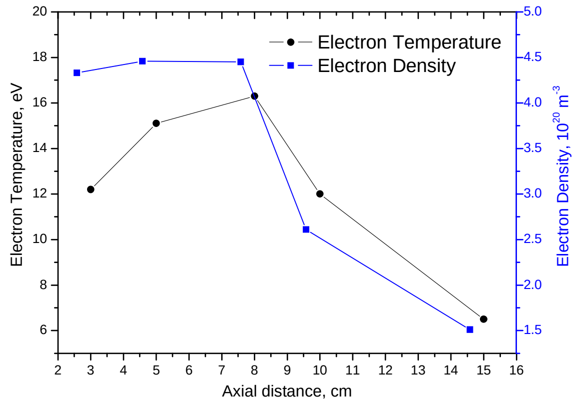

Figure 8. Spatial variation of Electron temperature and density.

C. Time of flight probe profiles

Double Langmuir probe was used as the Time of Flight probe to get the velocity of the flowing plasma. The probe was set in the axial distances of 3 cm, 5 cm, 8 cm, 10 cm and 15 cm from the Teflon surface, and the current traces from the probe are shown in Fig. 9. The velocity of the plasma will be derived from the fixed distances and the time delay between the different current traces as in Fig. 9. The calculated average velocity of the flowing pulsed plasma is around 30 (km/s).

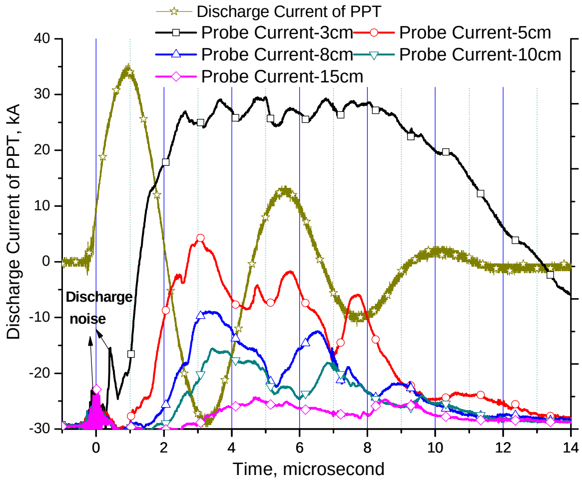

Figure 9. Time of Flight probe profiles.

IV. Conclusion

Triple Langmuir probe and Time of flight probe were successfully used in studying the properties of the flowing pulsed plasma of a 20J PPT. The temporal electron temperature and density profiles show that there are three oscillation peeks. This phenomenon depends heavily on the discharge properties of the main capacitor. The discharge current profile also shows four current half cycles indicating there are four micro-discharges in one PPT discharge. The fourth micro-discharge in the main discharge has little energy that it cannot ablate enough Teflon propellant and so did not show itself in the temporal electron temperature and density profiles.

With the help of the Step-motor-driven translation equipment, the special electron temperature and density profiles were obtained. The special profiles show that the maximum electron temperature and density decrease with increased axial distance, generally.

The average velocity of the flowing pulsed plasma is obtained using the Time of Flight probe.

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