Experiment Study on the Plasma Parameters Measurement in Backflow Region of Ion Thruster

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***Abstract*—**The charge-exchange xenon (CEX) ion generated by ion thruster can backflow to the surface of spacecraft and threaten to the safety of spacecraft operation. In order to evaluate the effects of the induced plasma environment in backflow regions on the spacecraft, we designed a spherical single Langmuir probe of 5.8cm in diameter for measuring low-density plasma parameters in backflow region of ion thruster. In practice, the tests are performed in a two-dimensional array (40cm×60cm) composed of 20 sites. The experiment results illustrate that the electron temperature ranges from 3.71eV to 3.96eV, with the mean value of 3.82eV and the standard deviation of 0.064eV. The electron density ranges from $8.30\times10^{12}/\mathrm{m}^3$ to$1.66\times10^{13}/\mathrm{m}^3$, with the mean value of $1.30\times10^{13}/\mathrm{m}^3$ and the standard deviation of $2.15\times10^{12}/\mathrm{m}^3$. All data is analyzed according to the "ideal" plasma conditions of Maxwellian distributions.

***Keywords*—**Langmuir Probe; Plasma parameters; Ion thruster; Backflow region.

I. INTRODUCTION

ION propulsion based on electrostatic acceleration of ions are high-efficiency, high-specific impulse propulsion systems that will be widely used in spacecraft attitude control and orbit transfer. During the operation of ion propulsion, besides the high-velocity plume ions (main xenon ions) generated by ion thruster plume and the electrons generated by neutralizer, the interaction between the fast xenon ion and the slow xenon atom in plume generates the fast neutral xenon atom and slow xenon ions, which are called charge-exchange xenon (CEX) ion. Some of the CEX ions can backflow to the surface around spacecraft leading to deposition contamination that can affect thermal control surfaces, optical sensors, solar arrays, science instrumentation, and communications. The typical damages include the electrostatic discharge, parasitic current losses, ion sputtering, increased levels of EMI and so on [1],[2],[3]. In severe case, these effects result in the failure of spacecraft missions. In order to understand the interactions between thruster plume and spacecraft, the backflow plasma parameters induced by the plume of ion propulsion, such as electron temperature (T_e) and density (n_e), must be investigate. In this paper, we have referred to the plasma measurement scheme in ISS [4], and developed a gold plated spherical Langmuir probe of 5.8centimeter to measure the electron temperature (1eV to 5eV) and density ($10^{10}/\mathrm{m}^3$to$10^{14}/\mathrm{m}^3$).

II. PLASMA MEASURING PRINCIPLE

A. Langmuir Probe Theory

Of all plasma diagnostic methods, the Langmuir probe technique is the simplest and widely used in the low density plasma measurement. The Langmuir probe is an electrode immersed in a plasma with a bias voltage applied to it, which was invented by Irving Langmuir in the early 20th century and used for measuring electron temperature, electron density and localized floating potential of plasma diagnostics[5],[6]. The principle of the measurement technique is to vary the bias voltage and to measure the collected current to acquire the current-voltage (I–V) characteristic of the probe. For the spherical Langmuir probe, the collected currents in the saturation regions are strongly influenced by the probe geometry, the sheath size, and the velocity of the probe relative to the surrounding plasma. In general, the sheath size is defined as the non-neutral space charge region adjacent to a biased probe. For the flat probe, the sheath area would not change with probe bias, resulting a obvious electron saturation, however, for the cylindrical and spherical probe, if the sheath size is much smaller than the probe radius, all the current crossing the sheath boundary is collected and the electron saturation current is easy determined, however, if the sheath size is comparable or larger than the probe radius (i.e. thick sheath), not all particles entering the sheath are collected for Orbital Motion Limited (OML) theory. So, the probe collected currents don't appear saturation. The theory for explaining the I-V characteristic is considerable complex, however, approximate theories can be used under 'ideal' plasma conditions, which must be satisfy the basic electrostatic probe theory. It is namely that (1) the plasma densities and pressures must be low so that there must be no collisions within the sheath and the mean-free path must be large compared with the sheath thickness. (2) the probe dimensions must be sufficiently small compared to the mean free path for collisions of the ions and electrons, so that its insertion in the plasma does not change the characteristics of

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the plasma, further, the space charge sheath thickness around the probe is much smaller than the probe dimension. (3) there must be no production of electrons by impact, the photoelectrons, secondary emission. (4) the effects of the magnetic field are not considered. Under conditions, the plasma electron temperature, the plasma potential, the floating potential and the electron density can be obtained from analyzing the I–V characteristic curve. A typical I-V characteristic contains three main regions of the ion saturation region, the electron retardation region and the electron saturation region, as shown in Fig. 1.

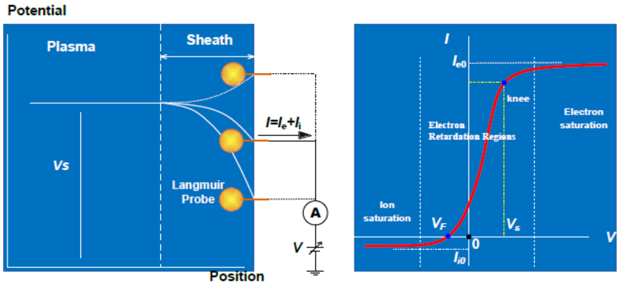

Fig. 1 Measuring principle and I-V characteristic curve of Langmuir Probe

Let the plasma potential (space potential) be V_s, and the potential applied to the probe relative to the plasma be V. V_s is the potential outside the sheath where no electric fields exist between the probe surface and the surrounding quasi-neutral plasma (n_e=n_i). When $V>>V_s$, this region is called the electron saturation region where the probe collects an electron current and repels ions. When $V<<V_s$, this region is called the ion saturation region where the probe collects ions current and repels electrons from the ambient plasma. When $V=V_s$, namely, the probe surface is as same potential as the surrounding plasma, the charged particles hitting the probe with the random velocity of $\overline{v_e}$ or $\overline{v_i}$ forms the probe random thermal current I_{eth} or I_{ith}。 For electrons,

$$I_{eth} = 0.25 n_0 eS\overline{v_e} = n_0 eS[(kT_e)/(2\pi m_e)]^{1/2}. \tag{1}$$

where e is the fundamental electron charge, and n_0, S, kT_e, m_e are respectively the quasi-neutral plasma density, the probe surface area, the electron temperature and the electron mass. Correspondingly, the saturation ion current I_{ith} is

$$I_{ith} = 0.25 n_0 eS\overline{v_i} = n_0 eS[(kT_i)/(2\pi m_i)]^{1/2}. \tag{2}$$

Where, kT_i , m_i are respectively the ion temperature and the ion mass. Since m_e<<m_i, and in general $kT_e > kT_i$, I_{eth} is much larger than I_{ith}, and the latter can be neglected.

When the total current collected by the probe sums to zero, the potential of V relative to V_s is defined as the floating potential V_f. $V_f = V_{I=0}$-V_s. The region between $V_f = V_{I=0}$-V_s is called the electron retardation region. In this region, the electrons are partially repelled by the negative potential $V-V_s$ and the electron current I_e increases exponentially with the probe potential V .The total currents collected by probe is given by

$$I = I_{es}\exp[e(V - V_s)/(kT_e)] - I_{is}. \tag{3}$$

where, I_{es}, I_{is} are respectively the electron saturation current and the ion saturation current. For an isolated probe at steady state, the currents to the probe surface must be zero, thus

$$I_{is} = I_{es}\exp[e(V_{I=0} - V_s)/(kT_e)]. \tag{4}$$

So,

$$-eV_f = kT_e\ln(I_{es}/I_{is}). \tag{5}$$

The plasma electron temperature (T_e) and density (n_e) are derived from (5) and (1):

$$kT_e = -eV_f/[\ln(I_{es}/I_{is})], \tag{6}$$

and

$$\begin{aligned} n_e &= I_{es}[(2\pi m_e)/(kT_e)]^{1/2}/(eS) \\ &\approx 3.73\times 10^{13} I_{es}/[S(kT_e)^{1/2}]. \end{aligned} \tag{7}$$

B. LP Sensor Design

All tables and figures you insert in your document are only to help you gauge the size of your paper, for the convenience of the referees, and to make it easy for you to distribute preprints. In this study, the plasma density ranges from 10^{10}/m^{3}to10^{14}/m^3 and the electron temperature ranges from 0.1eV to 5eV. According to the classical electrostatic probe theory [7],

$$\lambda_D << r_p << \lambda_f. \tag{8}$$

where , r_p is the radius of the spherical probe**,** and λ_D,λ_f are is respectively the Debye length and collision mean free path. The relationship of λ_D to electron number density and temperature[8] is

$$\lambda_D = 743[(kT_e)/n_e]^{1/2}. \tag{9}$$

where, λ_D is in cm, kT_e is in eV, N_e is in /cm^3. To avoid disturbing the plasma, the probe should be as small as possible. In order to collect the lower density plasma in the backflow region plasma, the Langmuir probe was designed as a hollow spherical structure with a diameter of 5.8cm. The probe is built in Titanium and coated with gold film of 500nn to 800nm, which is mainly considered that the gold coating can provide a good uniformity of the probe's material work-function to restrain the photoelectron emitting. The spherical probe is insulated with a thin ceramic tube. The probe sensor is connected to electric control unit (ECU) using a shielded coaxial cable. ECU consist the sweep circuit, the power module, the signal conditioning circuit, the control module and the host computer. The sweep power circuit can generates the sweep bias to the probe varied from –20V to 80V relative to the ground，and the step is 200mV. The probe collected currents is amplified and modulated in the signal conditioning circuit and converted the digital measuring signal through the analog-to-digital. The control module implements the power supply on-off, the data storage, and communication.

III. EXPERIMENTAL

A. Description of the System

The ground-simulating testing for the backflow region plasma of ion thruster is carried out in vacuum chamber of 2m in diameter, 2.5m in length. The cryogenic pump can provide an ultimate vacuum pressure of 1.0×10^{-4}Pa. The Xe plasma source creates a low-energy charge-exchange ion environment in the backflow region behind the plasma beam, where the electron temperature ranges from 1eV to 5eV and the electron density ranges from $10^{11}/m^3$ to $10^{14}/m^3$.The spherical Langmuir probe is mounted on a 3-dimensional movable metal fixture controlled by the computer outside the vacuum chamber. In practice, we keep the z-motion invariability, and only move the x-motion and the y-motion from A1 to A5, B5 to B1, C1 to C5, and D5 to D1, then, the plasma parameter in different position in the backflow region can be obtained. In order to conveniently compare measured data, we choose 20 testing points in the region of 40cm×60cm behind the ion thruster, and the distance adjacent testing point is 20cm behind the thruster. The Scheme of the backflow region plasma parameter measurement is shown in Fig. 2.

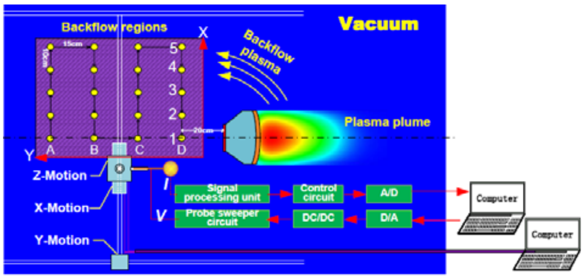

Fig. 2 Scheme of plasma testing in backflow region

B. Langmuir Probe Measurements

The Langmuir probe is connected with ECU in vacuum chamber, and the shell structure of ECU must be grounded. When the vacuum pressure reaches 6.0×10^{-4}Pa and the plasma beam keeps steady state, ECU begin to apply the sweep voltage to the Langmuir probe and acquire the collected current data. The sweep mode refers to the method of the Wide-Sweep Langmuir Probe (WLP) deployed on the International Space Station (ISS)[5]. In region of -20V to -10V, the variety of the ion current is very small, so the step voltage is 200mV, in region of -10V to 30V, the plasma potential need to be ascertained, so the step voltage is 100mV, and in region of 20V to 80V, the step voltage is 200mV. The testing data packets generated by ECU are transferred to the host computer outside the vacuum chamber, and converted to the voltage and current.

C. Data Analysis

The plasma environment in vacuum chamber is more complex than ideal plasma environment. Especially, the secondary electrons generated by Xe+ hitting the chamber wall will impact on the plasma current collection. But in this paper, we consider the plasma follows a Maxwellian distribution, and the effects of the photoelectrons, of secondary emission and of the magnetic field are neglected. The main analyzing steps consist:

1. Plot the *I*-*V* curve with the experimental data from the data acquisition system using the OriginPro software.

2. Make the d*I*/d*V*-*V* curve and identify the point of highest maximum of the first derivative of the electron current. V_s and the electron saturation current can be determined. The ion saturation current can be determined by the same method as the electron current.

3. Identify the floating potential by $V_f = V_{I=0}-V_s$ where V_f is determined by 2order polynomial fit of data in near the point of the current equivalent to zero.

4. Calculate the electron temperature and density by using (6) and (7) respectively.

In this study, we have only illustrated the typical *I*-V curve at site A1. In Fig. 3 (a), the bias voltage and the current are on a linear scale, and in Fig. 3(b), the bias voltage is on a linear scale, however, the current is on a logarithm scale. Fig. 3(c) is the d*I*/d*V*-*V* curve corresponding to Fig. 3 (a).

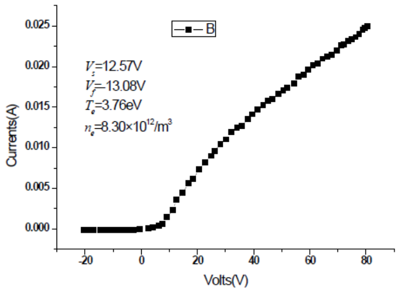

Fig. 3(a) The linear scale *I*-*V* characteristic at site A1

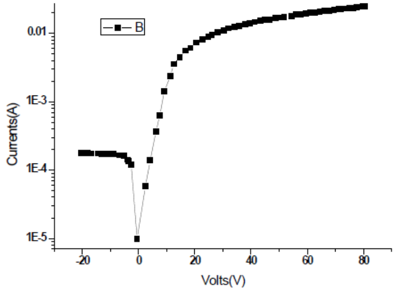

Fig. 3 (b) The semi-log I-V characteristic curve at site A1

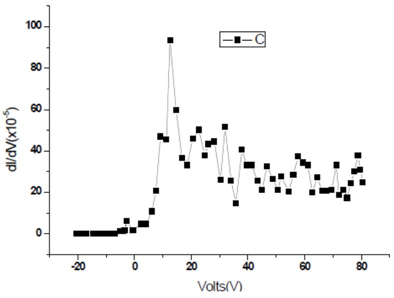

Fig. 3 (c) The dI/dV-V curve on linear scale at site A1

As can be seen from Fig. 3(a), the "knee" of the *I*-V curve is not so indistinct. In this case, the space potential V_s and the electron saturation current are determined by drawing the d*I*/d*V* curve. From the plots, the space potential V_s 12.57 V, and the calculated floating potential V_f is -13.08V. The electron temperature and density calculated by using (6) and (7) are 3.76eV and $8.30\times10^{12}/m^3$respectively.

D. Results and Discussions

The parameters of the electron temperature and density at all 20 sites are shown in Fig. 4.

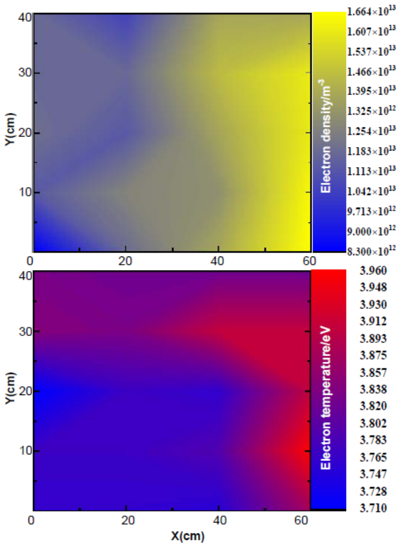

Fig. 4 The distributions of electron temperature and density at 20 sites in backflow region

As can be seen from Fig. 4, in the backflow regions of 40cm ×60cm behind the ion thruster, there is an approximate uniform distribution for the electron temperature and density. The electron temperature ranges from 3.71eV to 3.96eV, with the mean value of 3.82eV and the standard deviation of 0.064eV. The maximum and the minimum value of electron temperatures occur at site D2 and A3. The electron density ranges from $8.30\times10^{12}/m^3$ to$1.66\times10^{13}/m^3$, with the mean value of $1.30\times10^{13}/m^3$ and the standard deviation of $2.15\times10^{12}/m^3$. The maximum and the minimum value of electron densities occur at A1 and D1. Due to the Orbital Motion Limited (OML) theory being ignored, the measured results of the plasma densities are slightly greater than the real values. Affected by the acceleration field of ion thruster grid, the electrons with energy of 3.87eV to 3.96eV and density of $1.60\times10^{13}/m^3$ to$1.66\times10^{13}/m^3$ focus on the location near the ion thrust. These results are consistent with the simulated result in backflow region of SPT 100 by I.G. Mikellides et al.[9].

IV. CONCLUSION

The spherical single Langmuir probe may be applied to the plasma diagnose in backflow of ion thruster. The test shows that the plasma in backflow region of ion thruster is characterized by the electron density of 8.30×10^{12}/m3 to$1.66\times10^{13}/m^3$ (mean value is $1.30\times10^{13}/m^3$ and standard deviation is $2.15\times10^{12}/m^3$)and the electron temperatures of 3.71eV to 3.96eV (mean value is 3.82eV and standard deviation is 0.064eV). The plasma potentials for the all sites range between 11.30V to 12.99V.

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