Steady and oscillatory plasma properties in the near-field plume of a hollow cathode

Zun ZHANG (张尊), Kan XIE (谢侃), Jiting OUYANG (欧阳吉庭), Ning GUO (郭宁), Yu QIN (秦宇), Qimeng XIA (夏启蒙), Song BAI (白松), Xianming WU (吴先明) and Zengjie GU (谷增杰)

1 School of Physics, Beijing Institute of Technology, Beijing 100081, People’s Republic of China
2 School of Astronautics, Beijing Institute of Technology, Beijing 100081, People’s Republic of China
3 Lanzhou Institute of Physics, CAST, Lanzhou 730000, People’s Republic of China

E-mail: xiekan@bit.edu.cn

Received 20 July 2017, revised 24 November 2017
Accepted for publication 24 November 2017
Published 21 December 2017

Abstract
Hollow cathodes serve as electron sources in Hall thrusters, ion thrusters and other electric propulsion systems. One of the vital problems in their application is the cathode erosion. However, the basic erosion mechanism and the source of high-energy ions cause of erosion are not fully understood. In this paper, both potential measurements and simulation analyses were performed to explain the formation of high-energy ions. A high-speed camera, a single Langmuir probe and a floating emissive probe were used to determine the steady and oscillatory plasma properties in the near-field plume of a hollow cathode. The temporal structure, electron temperature, electron density, and both static and oscillation of plasma potentials of the plume have been obtained by the diagnostics mentioned above. The experimental results show that there exists a potential hill (about 30 V) and also severe potential oscillations in the near-plume region. Moreover, a simple 2D particle-in-cell model was used to analyze the energy transition between the potential hill and/or its oscillations and the ions. The simulation results show that the energy of ions gained from the static potential background is about 20 eV, but it could reach to 60 eV when the plasma oscillates.

Keywords: hollow cathode, plasma potential oscillation, Langmuir probe, emissive probe, PIC simulation

(Some figures may appear in colour only in the online journal)

1. Introduction
Hollow cathodes are a common component employed as electron sources or neutralizers for many electric propulsion systems, such as ion thrusters [1, 2], Hall thrusters [3–5], electrodynamic tethers [6, 7], and micro-thrusters [8, 9]. One of the life limiting factors of the propulsion systems is the cathode erosion. The fundamental mechanism of the cathode erosion is still not fully understood, particularly for the problem of the origin of the high-energy ions in the cathode plume. The measured energy of these ions can reach as high as 100 eV [10] and cause the erosion of the keeper electrode. This energy of ions far exceed that gained by acceleration potential through the discharge voltage on order of 30 V. The mechanism of ion acceleration, therefore, cannot be explained with traditional models.

Cathode erosion has been intensively studied. The research is mainly focused on experimental measurements of high energy ions and theoretical investigation of the mechanisms of their formation. Several such mechanisms have been suggested including potential hills [11, 12], multiple collisions of ions with the cathode orifice [13], plasma potential oscillations [14–16], charge exchange collisions between ions and neutrals [17, 18], double ionization [16], and ion acoustic turbulence [19, 20].The plasma properties in the near-plume region (or near-keeper region) has been found to be of high importance as it could be directly associated with the high-energy ions.
In the framework of our research, the spatial and temporal profiles of the plasma properties in the near-plume region have been obtained by the measurements of a high-speed camera, a Langmuir probe, and an emissive probe for establishing a clear hypothesis on the generation mechanism of high-energy ions. A paper recently published by Yu Qin et al showed the experimental phenomenon of high amplitude of potential oscillations near the hollow cathode [21]. Based on this foundation, here we try to understand the energy transition mechanism from the potential oscillations to the high-energy ions. Therefore, the frequency characteristics of the potential oscillations have been analyzed, and a 2D PIC model was used to predict where and how the high-energy ions come from. The experimental results show that both the plasma potential hill and potential oscillations phenomena exist in the near-plume region of the hollow cathode, and the simulation results predict that the plasma potential oscillations could effectively enhance the energy of ions.

2. Experimental apparatus

2.1. Hollow cathode and experimental facility

The hollow cathode used in the experiment is a 6 mm diameter tungsten tube capped with a protective plate with a 0.6 mm diameter orifice in the center. An insert of tantalum is set inside the cathode tube. To induce the electron emission, the cathode is heated by a resistive coil insulated by a multi-layer tantalum-foil radiation shield. The keeper is positioned 1 mm downstream the cathode and has an orifice (2.4 mm diameter) in the center. We used a hollow cylindrical anode with a diameter of 200 mm and length of 200 mm. The gap between the keeper exit and the ring section is 5 mm.

Figure 1 shows the schematic of the experimental apparatus. Experiments were carried out in a 1.8 m × 4 m cylindrical vacuum chamber. The neutral background pressure in the vacuum chamber, monitored by two ionization gauges, was maintained at $(1.6-4.7) \times 10^{-3}$ Pa during the experiments with xenon flow rates in the range of 1–15 sccm.

2.2. Diagnostics and error analysis

2.2.1. High-speed camera. A high-speed camera (Photron Fastcam SA1.1) was used to record the temporal pictures of the plume plasma of the cathode. The camera is an advanced CMOS sensor with one mega pixel resolution for high light sensitivity. The key features of this camera are 1024 × 1024 resolution to 5 400 fps, 675 000 fps at reduced resolution, 20 micron pixels, and 12 bit monochrome or 36 bit color sensor. It can be controlled by a PC via a gigabit Ethernet connection [22].

2.2.2. Single Langmuir probe. The Langmuir probe is a fundamental diagnostic instrument that measures the electron temperature $T_e$, electron density $n_e$, ion density $n_i$, floating potential $V_f$, plasma potential $V_s$, and electron energy distribution functions from a plotted current–voltage ($I$–$V$) characteristic [23, 24].

We used a single Langmuir probe of a cylindrical type, with a tip diameter of 0.4 mm and a length of 10 mm. The probe is isolated by a ceramic ring leaving only the tip as the ion collecting area within the plasma. The probe tip is made of tungsten in order to reduce the thermal load and second
2.2.3. Floating emissive probe. A floating emissive probe was used to measure the plasma potential and potential oscillation of the near-plume plasma. The emitting part of the probe was a filament made of 0.1 mm diameter tungsten wire. The theory of the floating emissive probe is well established and relatively straightforward to implement. Normally, a conducting electrode placed in plasma will float at a potential below the true plasma potential due to the higher flux of electrons relative to more massive ions. In an emissive probe, a filament is heated to a point where it will emit electrons and neutralize the surrounding plasma sheath. When hot enough, the probe will float near the true plasma potential. A floating emissive probe provides a direct measure of plasma potential without the requirement of a voltage sweep or data reduction operations, as it is in the case of the standard emissive or the Langmuir probes [27, 28].

The uncertainty in the plasma potential is estimated to be in the range of $\pm 5 \text{ V}$ for the data presented in this study (based on a 4 V drop across the filament and measured electron temperatures of up to 8 eV).

2.3. Data acquisition

Probe positioning was achieved by two orthogonal axis translation mechanism powered by two step-motors separately. The translation mechanism consists of two movement stands inside the vacuum chamber, and a servo control windows outside of it. Movement of up to 300 mm is possible with each movement stand.

A data acquisition system with 16 isolated channels is used to measure simultaneously applied voltage and the corresponding probe current for all the probes. The sampling rate of the signals is 1 kHz during all experiments.

3. Experiment results

3.1. Structure of plasma plume

The high-speed camera was used to capture both the steady and oscillation plume plasma phenomena. Figure 2 shows the background plasma structure of the hollow cathode plume in the camera working condition of 500 frames per second (2000 $\mu$ s of exposure), from which we can clearly see that the plume plasma is symmetric with respect to the cathode centerline. It allowed us to use the axial symmetry approximation. Moreover, from figure 2 we can observe a very bright area in the plume just behind the keeper. Based on the comparison with the plasma potential profiles as shown in section 3.2, this area corresponded to the potential hill and plasma oscillations region.

In order to examine the luminous area more clearly, we enlarged it and applied a much higher time-resolution (180 000 frames per second, that is 5.5 $\mu$ s of exposure) mode of the high speed camera. The enlarged area is plotted in figure 2. The temporal oscillation results in a half oscillation period are shown in figure 3. The time interval between camera shots is about 11 $\mu$ s.

3.2. Steady plasma properties

Figure 4 plots a typical $I-V$ characteristics of the single Langmuir probe. This plot illustrates the methodology of obtaining the floating potential $V_f$, the plasma potential $V_p$, and the ion saturation current $I_{\text{sat}}$. The floating potential $V_f$ refers to the zero of the net current. The plasma potential $V_p$ corresponds to the maximum of $I-V$ characteristic derivative. The ion saturation current $I_{\text{sat}}$ was obtained by extrapolating the linear fit of ion current until its intersection with floating potential $V_f$.

In Maxwellian approximation for electrons the transition region of the semi-logarithmic $I-V$ characteristic (Logarithm of discharge current versus voltage applied to the probe $V_p$) should be linear. The inverse slope of the linear part of this $\ln(I) - V$ characteristic is the electron temperature in eV, as shown in equation (1). The electron number density was calculated by equation (2). Figure 5 demonstrates how the electron temperature $T_e$ is determined.

$$\frac{1}{T_e} = \frac{\ln(I_{\text{total}})}{V_p}, \quad (1)$$

$$I_{\text{sat}} = I_{\text{Bohm}} = \alpha n_e e A_p \frac{kT_e}{m_i}, \quad (2)$$

where, $I_{\text{total}}$ is the total probe current, $V_p$ is the probe voltage, $T_e$ is the electron temperature in eV, $I_{\text{sat}}$ is the ion saturation current, $I_{\text{Bohm}}$ is the Bohm current to the probe, $\alpha$ represents the density at the sheath edge relative to the density in the main plasma, the theoretical value of $\alpha$ equals to 0.61, $n_e$ is the electron density, $e$ is the electron charge, $A_p$ is the probe...
collecting area, \( k \) is the Boltzmann constant, \( T_e \) is the electron temperature in K, and \( m_i \) is the ion mass.

Figure 6 depicts the contour plots of plasma electron density, electron temperature, and plasma potential obtained by the single Langmuir probe under different working conditions. Figures 6(a)–(c) are electron density, electron temperature, and plasma potential contours respectively under the working condition of 3 A discharge current and 2.5 sccm mass flow rate (\( J_D = 3 \text{ A}, m = 2.5 \text{ sccm} \)). While, figures 6(d)–(f) are electron density, electron temperature, and plasma potential contours respectively with a discharge current of 9 A, and a mass flow rate of 7.5 sccm (\( J_D = 9 \text{ A}, m = 7.5 \text{ sccm} \)).

It can be seen from these contour plots that the overall shape of the plasma properties curves is similar but the amplitude differs a lot under different working conditions. The electron density gets its maximum at the centerline near the cathode and decreases with both increasing radial and axial position. The electron temperature reaches its maximum near the anode ring due to the potential acceleration between the anode and cathode. The plasma potential contour clearly
Figure 6. Contour plot of plasma properties measured by single Langmuir probe. (a), (d) Electron density; (b), (e) electron temperature; (c), (f) plasma potential.
shows a potential hill about 30 V just downstream of the cathode.

3.3. Oscillatory plasma properties

Figure 7 shows the time-domain (a) and frequency-domain (b) profiles of plasma oscillations under the working condition of a 9 A discharge current and 7.5 sccm mass flow rate. In these figures, we can see the potential fluctuations with different axial distances from the keeper at the centerline of the hollow cathode.

In order to understand the oscillation profiles more clearly, we defined the average plasma potential, amplitude of plasma potential, frequency, and amplitude of frequency, as shown in figures 8 and 9. Therefore, figures 10(a) and (b) shows the spatial distribution of the average plasma potential and amplitude of its oscillation respectively. Figures 10(c) and (d) shows the spatial distribution of the frequency properties and amplitude of its oscillation respectively. We can see that the plasma potential, frequency and their amplitude reach their maximum at the centerline just downstream of the cathode. It is worth noticing that the potential profile is very similar to the plume image that the high-speed camera has captured.
4. Simulation

In order to understand the energy transition mechanism between the plasma potential hill and/or its oscillation and the high-energy ions, we employed a simplified PIC model to calculate the ion energy distribution after they pass through the static potential hill and/or its oscillation [18]. Here, we applied the measured plasma-potential maps of the cathode as the potential background to calculate the spatial electric field. Then determine initial conditions for a simulation ions and calculate the ion energy based on the initial conditions. The simulation was made to verify whether the ions could gain energy after they pass through this kind of potential field.

4.1. Model description

Figure 11 shows the flow chart of the model. In addition, a detailed model description is shown as following:

4.1.1. Generate computational grids. The simulation area is a 2D configuration symmetric with respect to the centerline of the cathode. The maximum radial distance is 45 mm, and the maximum axial distance is 90 mm for the hollow cylindrical type anode. The rectangular simulation area has four boundaries. Only the axial centerline boundary is a reflecting boundary, all other boundaries are absorbing.

4.1.2. Enter initial parameters. Initial parameters consist of physical parameters, calculation coefficients and constants, and parameters characterizing the potential distributions. Potential distribution parameters are very important for our research as they are tightly related to the ion energy distribution. The average potential, amplitude of potential oscillation, frequency and amplitude of frequency were obtained from the experimental tests.

4.1.3. Input ions. The position of the maximum potential was determined by the experimental data. Ions are added at
the position where the plasma potential reaches its maximum and flow to arbitrary directions. At the same time, ions are supposed to have a constant initial energy equal to 2 eV, and have an arbitrary velocity component:

\[ v_{\text{imid}} = \sqrt{\frac{3kT_i}{m}}, \]  

\[ v_{iz} = v_{\text{imid}} \cos(2\pi R_1) \sin(2\pi R_2), \]  

\[ v_{ir} = v_{\text{imid}} \cos(2\pi R_1) \cos(2\pi R_2), \]  

\[ v_{i\theta} = v_{\text{imid}} \sin(2\pi R_1), \]

where, \( v_{\text{imid}} \) is the initial velocity of ion, \( k \) is the Boltzmann constant, \( 1.38 \times 10^{-23} \text{ JK}^{-1} \), \( T_i \) is the ion temperature, \( v_{iz} \) is the axial velocity of ion, \( v_{ir} \) is the radial velocity of ion, \( v_{i\theta} \) is the angular velocity of ion, and both \( R_1 \) and \( R_2 \) are random numbers between 0 and 1.

4.1.4. Calculate plasma potential and electric field. As long as the average plasma potential \( \phi_0 \), the amplitude of the potential oscillation \( A \), and the period of the potential oscillation \( T \) are determined by the experiment, the plasma potential \( \phi \) (equals to electric field \( E \)) is calculated by:

\[ \phi = \phi_0 + A \sin \left( \frac{2\pi}{T} t \right). \]  

where, potential oscillation comes from the simulated sine function. As the simulation grids are much smaller than the experiment test points, \( \phi_0, A, \) and \( T \) are obtained from the linear interpolation of the experimental data.

4.1.5. Acceleration caused by the electric field. The basic momentum equations of ions used in the simulation are described as following:

\[ \frac{d}{dt} mv = q(E + v \times B), \]  

\[ \frac{d}{dt} x = v, \]

where, \( m \) is ion mass, \( v \) is velocity vector of ions, \( q \) is electricity quantity of ions, \( E \) is electric field vector, \( B \) is magnetic field vector, and \( x \) is position vector.

For simplification, we assume that: (1) only singly charged ions are present, as double ionized ions contribution is about 10% [29, 30]; (2) neutrals and electrons are neglected; (3) self-magnetic field is not considered. Therefore, the magnetic field \( B = 0 \).

4.1.6. Renew ion speed and position. Renew the speed and position of ions after they passed through the electric field.

4.1.7. Output the ion energy distribution. Output the number and energy of ions when the number of ions remains constant in one simulation case.

4.2. Results

Figure 12 shows the simulation results at the cathode working condition of 5 A discharge current and 2.5 sccm mass flow rate. The pink line with leftward triangles represents the ion energy distribution calculated with only the average plasma potential added as the potential background. The maximum ion energy reached is about 20 eV. The black line with squares shows the ion energy distribution with both the average potential and its oscillations added. Notably, the maximum ion energy enhanced to 60 eV. This means that the plasma potential oscillation plays an important role in increasing the ion energy, which could help to identify the origin of the high-energy ions in the hollow cathode plume. Moreover, the role of amplitude and frequency of potential oscillations has also been examined in our simulations. As

![Figure 11. Flowchart of the PIC model.](image-url)

![Figure 12. Ion energy distribution from simulation results.](image-url)
shown in figure 12, the red with circles and the green with upward triangles lines present the ion energy distributions simulated with double and triple amplitude of the potential oscillations respectively. The results show that the maximum ion energy increases with an enlarged amplitude of potential oscillations. The dark blue with downward triangles and the light blue with diamonds curves present the ion energy distributions simulated with the 10 and 100-times-value frequency of the potential oscillation respectively. The maximum ion energy increases with an increasing frequency of potential oscillations. The maximum ion energy rises above 100 eV after the oscillation frequency is enlarged to 100 times. These results indicate that both the amplitude and frequency properties of the plasma potential oscillation have a big influence on the formation of high-energy ions.

5. Conclusions

Both experimental and simulation works have been done to evaluate plasma properties in the near-field plume of a hollow cathode. The experimental data shows that the plasma plume of the cathode is symmetric with respect to its centerline. Two phenomena were observed: a potential hill of about 30 V at the centerline just downstream the cathode and severe potential oscillations (∼80 eV) in the near plume region. Both factors could cause a formation of high-energy ions.

The simulation results show that the plasma oscillation could effectively enhance the average energy of ions. Moreover, both the amplitude and frequency of the potential oscillation have a certain influence on the ion energy distribution. The results show that the maximum ion energy could reach 60 eV with potential oscillations added in the simulation. Whereas, the maximum ion energy of 20 eV was received when only the background average plasma potential was considered. The ion energy could even exceed 100 eV with certain values of oscillation frequency.

Therefore, we believe that both the potential hill and potential oscillation (amplitude and frequency) mechanisms make an effect on the formation of high-energy ions.

Acknowledgments

The authors would like to acknowledge financial support from National Natural Science Foundation of China under Grant Nos. 11402025 and 11475019, and also from China Academy of Space Technology under Grant Nos. YJJ0701 and ZWK1608.

References