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To cite this article: Jianwu HE et al 2018 Plasma Sci. Technol. 20 025403

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Plasma Sci. Technol. 20 (2018) 025403 (6pp)

https://doi.org/10.1088/2058-6272/aa89e1

Study of electron-extraction characteristics of an inductively coupled radio-frequency plasma neutralizer

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Received 13 July 2017, revised 1 September 2017 Accepted for publication 1 September 2017 Published 4 January 2018



Abstract

Inductively coupled radio-frequency (RF) plasma neutralizer (RPN) is an insert-free device that can be employed as an electron source in electric propulsion applications. Electron-extraction characteristics of the RPN are related to the bulk plasma parameters and the device's geometry. Therefore, the effects of different electron-extraction apertures and operational parameters upon the electron-extraction characteristics are investigated according to the global nonambipolar flow and sheath model. Moreover, these models can also be used to explain why the electron-extraction characteristics of the RPN strongly depend upon the formation of the anode spot. During the experimental study, two types of anode spots are observed. Each of them has unique characteristics of electron extraction. Moreover, the hysteresis of an anode spot is observed by changing the xenon volume-flow rates or the bias voltages. In addition, the rapid ignited method, gas-utilization factor, electron-extraction cost and other factors that need to be considered in the design of the RPN are also discussed.

Keywords: electron source, plasma cathode, RF neutralizer, RF plasma, anode spot

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

1. Introduction

For many electric propulsion applications, the neutralization of ion-beam current is necessary. As the remaining opposite charge leads to a charging up of the spacecraft when positively charged particles are ejected from an ion thruster, the spacecraft should be kept nearly at ground potential to maintain the normal operation of electronic equipment and ion thrusters. Thus, extra electrons must be removed by a neutralizer, which is generally a hollow cathode [1]. However, hollow cathodes are well known to be very sensitive to certain reactive gases and to have a limited lifetime due to evaporation of the insert material. Additionally, the insert material must be preheated to a high temperature before operation. As a result, an electric-propulsion system with a hollow cathode cannot be quickly ignited and must be carefully operated [2]. To overcome these application constraints, insert-free plasma cathodes have been introduced in recent years, such as capacitively [3] and inductively [1, 2, 4–10] coupled RF plasma cathodes (CCPCs and ICPCs, respectively), electron-cyclotron-resonance cathodes (ECRCs) [11, 12], and helicon cathodes [13, 14]. The efficiency of an ICPC is better than that of a CCPC or an ECRC under low source power and low volume-flow rate, and the helicon cathode needs a strong magnetic field and high-RF power. Thus, ICPCs are considered to be one of the best choices for neutralization of an ion thruster [9].

Due to the advantages of ICPCs, several research groups have theoretically investigated inductively coupled radiofrequency plasma neutralizers (RPNs) and conducted a series of experimental studies. All experimental results [1, 4–7, 10] show that the electron-beam current suddenly jumps to a larger value when the bulk plasma is applied with a sufficiently high bias voltage, and a luminous secondary plasma, which is known as an anode spot, is formed at the orifice of the discharge chamber [9]. Formation of an anode spot is the most important feature of RPNs because larger electron beams can be extracted from an RPN after this formation takes place. However, there has been no specific research on the relationship between electron-extraction characteristics and anode-spot formation in an RPN.

In this study, the relationship between electron-extraction characteristics and anode-spot formation in an RPN are described based on the experimental results and theoretical analysis of Baalrud *et al* [15–17] for electron-bombarded plasma. Then, we develop a mini-RPN for application to electric micro-propulsion, especially to an RF ion micro-thruster developed in our laboratory.

2. Global nonambipolar flow and sheath models

Anode-spot formation mainly depends upon the operational parameters and design of the electron-extraction structure. Baalrud *et al* [15–17] studied anode-spot formation near at an anode plate inserted into the electron-bombarded plasma. They considered an unmagnetized, low-temperature, weakly collisional case with collisionless sheaths and all ions being singly ionized [16]. There are three possible sheath types near the anode plate, namely ion sheaths, double-layer sheaths, and electron sheaths. The type of sheaths is determined by the following conditions [15]:

$$\frac{A_{\rm E}}{A_{\rm W}} \ge \left[\frac{0.6}{\mu} - 1\right]^{-1} \quad \text{ion sheath} \\
\mu < \frac{A_{\rm E}}{A_{\rm W}} < \left[\frac{0.6}{\mu} - 1\right]^{-1} \quad \text{double layer} \quad (1) \\
\frac{A_{\rm E}}{A_{\rm W}} \le \mu \quad \text{electron sheath.}$$

Here, $m_{\rm e}$ is the electron mass, $M_{\rm i}$ is the positive-ion mass, $A_{\rm E}$ is the surface area of the anode plate placed in the bulk plasma, and $A_{\rm W}$ is the wall area of the discharge chamber. In this case, $\mu = \sqrt{2.26m_{\rm e}/M_{\rm i}} \approx 0.003$ for xenon, and $[0.6/\mu - 1]^{-1} \approx 1.7 \mu$.

Reference [16] defines the global nonambipolar flow as the case where electrons and ions are lost separately on different boundaries. A simple example is for two boundaries: one collecting only electrons and one collecting only ions. In this case, there may be an anode glow or spot formed near at the electron-collecting boundary and a double-layer sheath formed between the anode spot and the bulk plasma. Longmier [13] and Baalrud [15] found that an anode glow or spot may form when $A_E/A_W < \mu$. This means that the global nonambipolar flow can be established as long as this condition is satisfied and a sufficiently positive bias is applied to the anode plate.

If this condition also applies to RPNs, then A_E is the area of electron-extraction aperture and A_W is the effective area for ion loss at the discharge chamber. The potential distribution of the electron sheath, anode glow, and anode spot formed in the RPN should be consistent with the results of [15], as shown in figure 1. When the electron sheath is formed near



Figure 1. Schematic of the anode-spot (AS), anode-glow, and electron-sheath (ES) potential profiles [15].

the orifice, the potential drops from the anode-plate potential, $V_{\rm E}$, to the plasma potential, $V_{\rm P}$, in a few Debye lengths, $\lambda_{\rm D}$, and $V_{\rm P}$ is hardly affected by $V_{\rm E}$, i.e., the electron sheath acts as a potential shield. This length will be extended to approximately 10 Debye lengths after an anode glow forms, and the plasma potential will increase with the influence of the electron temperature in the glow region. Once the anode spot is formed, its potential, $V_{\rm AS}$ satisfies $V_{\rm E} > V_{\rm AS} > V_{\rm P}$ and $\Delta \phi_{\rm i} = V_{\rm AS} - V_{\rm P} \approx E_{\rm i}/e$. Here, $E_{\rm i}$ is the first ionization energy of the working gas. Therefore, the bulk plasma potential will be locked with $V_{\rm E}$. Thus, a suspension probe can be used to determine the transition from an electron sheath to an anode glow and an anode spot by detecting its potential.

3. Experimental setup

Based on the sheath classification introduced above and the experience of researchers at Giessen university studying RF ion micro-thrusters [18], a small RPN is designed by taking into account the actual requirements of an RF ion micro-thruster which requires a large adjustment range and the maximum electron-extraction current of approximately 100 mA. The diameter of the discharge chamber is 10 mm and the length is 15 mm. Four types of electron-extraction orifice are designed. The specifications are shown in table 1. The main purpose of this design is to verify whether the formation conditions of the anode spot in the RPN are consistent with [14].

For the RPN system shown in figure 2, the RF power supply consists of an RF signal source, power amplifier, and directional power meter, which can provide a 0.1–150 MHz RF signal and a 1–200 W RF power output. A semi-automatic matching network is used to match the impedance of the RF coil. It is mainly composed of two capacitors, one of which is connected in parallel to the RF coil to produce an oscillating circuit to sustain the RF plasma. The other capacitor is connected in series to the oscillating circuit to reduce the reflected RF power.

Table 1. Dimensions of different orifices for the study of anode-spot formation.

No.	Orifice (mm)	$A_{\rm E}/A_{\rm W}$	Expected sheath type
#1	$D_{\rm o} = 1, L_{\rm o} = 2$	0.0012	Electron sheath
#2	$D_{\rm o} = 1.6, L_{\rm o} = 2$	0.0032	Double layer
#3	$D_{\rm o} = 2, L_{\rm o} = 2$	0.005	Double layer
#4	$D_{\rm o} = 2.5, L_{\rm o} = 2$	0.0078	Ion sheath



Figure 2. Schematic illustration of the RPN experimental system.

In this experiment, xenon gas is used as a working gas and the micro-flow controller has a volume-flow adjustment range of 0–1 sccm (standard-state cubic centimeters per minute) with an increment of 0.001 sccm. To obtain the rapid ignition of the RPN neutralizer at lower RF power and small volume-flow rate, a suspension probe connected to a highvoltage power supply is inserted in the discharge chamber. Rapid ignition can be achieved by high-voltage breakdown between the probe and the ion collector. Additionally, sheath transitions also can be detected by the suspension probe, which connects to a multimeter through a double-pole switch. Then, an electrode is placed at the front of the RPN with about 1 cm spacing so as to extract electrons from the discharge chamber, and a DC power supply is used to provide the required bias voltages for the formation of anode spots.

The RPN neutralizer is placed in an ultra-high vacuum chamber with a cubic main tank with three molecular pumps and a small cylindrical tank for rapid operation. During the working of the neutralizer, the pressure within the vacuum chamber can be maintained on the order of 10^{-4} Pa at a pumping speed of 5600 L s⁻¹, fully meeting experimental requirements.

4. Experimental results and discussion

4.1. Working-gas volume-flow rate

The ignition of the inductively coupled RF plasma source is supported by the high-voltage power supply of the RF ion micro-thruster. This power supply is connected to the



Figure 3. Extracted electron current at 10 W RF power, 40 V bias voltage, various orifice diameters, and various volume-flow rates ('Ie +' represents the rising mode of the volume-flow rate, 'Ie-' represents the opposite).

suspension probe through a double-pole switch, and the distance between the probe and the ion collector is set to 1.5 mm. The breakdown voltage is related to the internal pressure of the discharge chamber, meaning that the greater the workinggas volume-flow rate, Q_m , the smaller the breakdown voltage. When the Q_m is greater than 0.2 sccm, the breakdown voltage is approximately 500 V for the #3 orifice. In the event of a breakdown, a large number of electrons will be instantly produced and driven by RF energy to create an RF-plasma self-sustaining discharge. Additionally, it is suggested that an RF of around 8 MHz should be used in the chamber with a diameter of 10 mm [18]. In this study, we also verify that the discharge performance is better when the RF is approximately 8 MHz than when it is 6.5 or 9 MHz.

The electron currents, I_{EEC} , extracted from orifices #1-#4 at a constant RF power of 10 W, a bias voltage of 40 V, and various volume-flow rates are shown in figure 3. It is apparent that, by increasing the Q_m to a critical value, the electron current extracted from orifices #1-#3 will jump to a large value. This is because the anode spot is formed near the orifice such that causes a jump in the I_{EEC} [9]. When the bulk-plasma density no longer increases with the Q_m , the I_{EEC} reaches its saturation value. Then, the I_{EEC} also decreases with the decline of Q_m and jumps back to a small value when the Q_m is much smaller than the critical volume-flow rate. This is called hysteresis of the I-Q characteristic, and appears only when meeting the formation conditions of the electron sheath or double sheath, as shown by inequality (1).

Here the I_{EEC} of RPN with orifice #1 has a large adjustment range, thus, making it highly suitable as a neutralizer for the RF-ion micro-thruster, which needs an adjustable electron-extraction current to neutralize the ion-beam current. Anode spot can also be formed when the double sheath condition (#2 and #3) is satisfied, but the adjustable range of the I_{EEC} is small and only applies to the thrust-fixed ion beam neutralization tasks.



Figure 4. I-V characteristics of RPN with various orifices at 15 W RF power and 0.2 sccm volume-flow rate.

4.2. Bias voltage and RF power

The current-voltage characteristics of the RPN with various orifices are presented in the figure 4. The hysteresis of orifice #1 is similar to that obtained by previous research on RF cathodes [9–11] or anode spots [14–16, 19]. Baalrud *et al* [15] have explained the hysteresis behavior of an anode spot, suggesting that such spots will form when there are equal densities of ions and electrons in a Debye cube near the orifice. On the voltage upswing, the only source of ions in the double sheath is within the thin anode glow upstream of the aperture plasma. Once the anode spot is established, it acts an ion source and can thus be maintained at lower voltages [7].

However, the hysteresis is not obvious when the aperture diameter is 1.6 or 2 mm, but the electron-extraction performance of the RPN with an aperture diameter of 2 mm is much higher than the others, and the maximum I_{EEC} reaches 380 mA. This is because the large aperture causes an increase in the surface area of the anode spot. Therefore, more electrons in the bulk plasma enter the anode-spot region, such that a better electron-extraction performance is achieved.

After the formation of the anode spot for the orifices #1-#3, the I_{EEC} will increase along with the bias voltage, before finally reaching the saturation state. This is because the plasma density is limited by the RF power or the neutral-gas density such that the electrons entering the anode-spot region reach saturation. At this point, increasing the $Q_{\rm m}$ and RF power obviously improves the electron density, resulting in a larger beam of electrons. For orifice #4 with an aperture diameter of 2.5 mm, there was no jump for the I_{EEC} by increasing the bias voltage, V_{Bias} . This means that no anode spot formed under this condition, and so a larger electron current could not be extracted.

The effects of RF power and $Q_{\rm m}$ upon *I*–*V* characteristics are shown in figure 5. The figure shows the I-V characteristics of orifice #2 at three constant RF powers and $Q_{\rm m}$. The critical bias voltage of the anode-spot formation is shown to be inversely proportional to the $Q_{\rm m}$ at smaller volume-flow rates.



Figure 5. Effects of RF power (10, 15 and 20 W) and volume-flow rate (0.1, 0.15 and 0.2) upon the I-V characteristics of orifice #2 at various bias voltages.

This is because increasing the $Q_{\rm m}$ leads to more ionization near the orifice, such that the anode spot is set to smaller bias voltages [15]. At higher gas pressures, the critical bias voltage varies weakly with $Q_{\rm m}$. It is possible that the applied electric field is partially shielded by the orifice in the case of a small aperture [7]. In addition, the penetration of an electric field into the bulk plasma is also limited by the orifice. Thus, the V_{Bias} required to maintain the anode spot should be higher than that for larger aperture sizes, as observed in our experiments.

Additionally, the higher the RF power, the higher the critical voltage and the lower the critical volume-flow rate of the anode-spot formation. This is because the electron temperature increases with the absorption of more RF power, causing the plasma potential to increase, thus necessitating a higher bias voltage. Another result is that the saturated electron current is proportional to the RF power at a constant $Q_{\rm m}$ of 0.15 sccm. Lastly, the hysteresis in the I-V diagram is more pronounced when the $Q_{\rm m}$ or the RF power are low.

4.3. Plasma potential and anode-spot shape

During the transition of the sheath near the anode plate, the plasma potential that meets the formation conditions of the electron sheath is depicted in figure 1. This also applies to RPNs, but in this case, the anode spot is far from the anode plate and formed upstream of the orifice. Thus, there will be some differences in the plasma-potential description. Here, the sectional area of orifice acts as the actual anode surface, $A_{\rm E}$, the potential of which is less than the $V_{\rm Bias}$ applied to the anode plate. However, this does not change the effects of the sheath transition upon the plasma potential. The potential of the suspension probe can be used to determine the type of sheath, and the measurement results are shown in figure 6.

When a suspension probe is inserted into the plasma, a pre-sheath and an ion sheath will be formed near its surface, making the average ion and electron fluxes equal at this surface. This is known as ambipolar loss [16]. The plasma



Figure 6. Suspension-probe-potential analysis with different orifice diameters at 15 W RF power and 0.2 sccm volume-flow rate.

potential can be expressed as

$$V_{\rm P} \approx \frac{T_{\rm e}}{e} \ln\left(\mu\right) + V_{\rm Probe},$$
 (2)

where $T_{\rm e}$ is the electron temperature in electron volts and $V_{\rm Probe}$ is the potential of the suspension probe. For xenon, $V_{\rm P} \approx 5.8T_{\rm e}/e + V_{\rm Probe}$, and electron temperature usually ranges from 2 to 5 eV [20]. Thus, it is possible to determine the type of sheath by estimating the plasma potential and comparing it with figure 1.

The suspension-probe potential for orifice #1 that satisfies $A_{\rm E}/A_{\rm W} < \mu$ changes very little with increased $V_{\rm Bias}$. This result indicates that there should be an electron sheath near the orifice after the formation of the anode spot such that the bias potential drops rapidly to the potential of the anode spot. A double-sheath structure should be formed between the anode spot and the main plasma, making the potential distribution similar to that shown in figure 1. Meanwhile, the probe potential before the anode-spot formation is a negative value of about -0.2 V, becoming positive afterward as the $V_{\rm Bias}$ increases to a critical value about 40 V. In this case, the anode spot looks like a spherical fireball also observed by other researchers [9–11]. The surface area of the spherical fireball is much larger than the aperture area, meaning the electron current becomes more than ten times its original value.

For orifices #2 and #3 satisfying $\mu < A_E/A_W < 1.7 \mu$, an anode spot may also be formed. However, the glow plasma extending from the orifice was experimentally observed to have a significant inclination, and the anode spot was also tilted toward the collector in the discharge chamber. This shows that the shape of the anode spot is a cylindrical fire rod, rather than a spherical fireball, matching the descriptions in [15]. The surface area of the cylindrical fire rod is smaller than that of the spherical fireball formed in front of the orifice. Therefore, after the formation of the cylindrical anode spot, the amplification coefficient of the electron-extraction current, η_e , is only 3–5, much smaller than the η_e of the sphericalanode spot. In addition, the potential of the suspension probe is also polarized after the formation of the anode spot, and finally locks with the V_{Bias} . This is the second feature of the double-sheath structure, consistent with the analysis in section 2.

Orifice #4 also satisfies $A_E/A_W > 1.7 \mu$, i.e., the formation condition of an ion sheath. There is no jump in the I_{EEC} as the V_{Bias} increases. However, the potential of the suspension probe also experiences a polarity change and increases with the V_{Bias} until it becomes locked. However, this potential distribution is not the same as the ion-sheathpotential distribution described in [16]. This suggests that an anode-glow plasma exists at the aperture, as in [7]. If the sheath thickness near the orifice is small relative to the aperture diameter, the electron current extracted from the bulk plasma can be expressed as

$$I_{\rm ECC} = \frac{e n_{\rm ag} v_{\rm d} (V_{\rm Bias} - V_{\rm P}) A_{\rm E}}{l N_{\rm g}},\tag{3}$$

where n_{ag} is the electron density in the anode spot, v_d is the electron-drift velocity, l is the distance between the anode plate and the orifice, and N_g is the neutral-gas density [7]. It can be seen from the above formula that V_p and V_{Bias} have the same rate of growth when the electron current is saturated. The experimental results are consistent with this model.

4.4. Gas-utilization factor and electron-extraction cost

Propellant and power are limited resources in space, so the neutralizer's gas-utilization factor and total power consumption are key parameters for evaluating its performance. The gas-utilization factor refers to the average number of ionizations and recombinations of Xe atoms in the discharge chamber and the equivalent current of 1 sccm in xenon is about 71.4 mA. Thus, for xenon, the gas-utilization factor can be expressed as

$$\eta_{\rm m} = \frac{I_{\rm e}[{\rm mA}]}{71.4[{\rm mA/sccm}] \cdot Q[{\rm sccm}]}.$$
(4)

The electron-extraction cost is defined as the ratio of the total power (including RF power and the power loss in bias DC supply) to I_{EEC} . The cost can be written as

$$\eta_{\rm EEC} = V_{\rm Bias} + \frac{P_{\rm RF}}{I_{\rm EEC}}.$$
(5)

The $\eta_{\rm m}$ and $\eta_{\rm EEC}$ of the RPN with an aperture diameter of 2 mm are presented in figure 7 due to this aperture's optimal performance. The $\eta_{\rm m}$ is inversely proportional to the $\eta_{\rm EEC}$ before the electron current reaches saturation. In addition, the greater the $Q_{\rm m}$, the smaller the $\eta_{\rm m}$ and $\eta_{\rm EEC}$. While the RF power is greater, the $\eta_{\rm m}$ and electron-emission power increase. Therefore, if a constant $I_{\rm EEC}$ is required, we must select the appropriate $Q_{\rm m}$ and RF power. Selecting a $Q_{\rm m}$ of 0.2 sccm and an RF power 15 W, the electron current of 343 mA is obtained when the $V_{\rm Bias}$ rises to 60 V (shown in figure 4). The $\eta_{\rm EEC}$ is 104 W A⁻¹ and the $\eta_{\rm m}$ is about 24 (shown in figure 7).



Figure 7. Gas-utilization factor and electron-extraction cost with orifice #3 at various volume-flow rates and RF powers.

5. Conclusions

A smaller RPN with four types of orifice is manufactured to investigate the relationship between electron-extraction performance and anode-spot formation. The effect of operational parameters on the gas-utilization factor, electron-extraction cost and I_{EEC} are investigated by an experimental study. The experimental results show that, at a constant RF power, the I_{EEC} is improved by increasing the $Q_{\rm m}$ and $V_{\rm Bias}$ before finally reaching a saturation level at higher volume-flow rates or saturated V_{Bias} . Moreover, when the RF power is increased, the I_{EEC} increases. We also verify that the electron-extraction aperture's dimensions can be optimized to achieve a specific electron current. For the orifice #4 which satisfies the condition of $A_{\rm E}/A_{\rm W} > 1.7 \,\mu$, an anode-glow plasma will be formed near the orifice. However, no anode spot will be formed, so a large electron current cannot be provided under this condition. Moreover, the orifice #4 also requires a larger volume flow to sustain the RF plasma discharge. For the orifice #2 and #3 (satisfied $\mu < A_{\rm E}/A_{\rm W} < 1.7 \mu$), a cylindrical-anode spot formed upstream of the orifice. In this case, larger orifice diameters increase the I_{EEC} at the saturation volume-flow rate and bias voltage. Such orifices also perform optimally in terms of their gas-utilization factor and electronextraction cost. However, there is a small adjustable range of I_{EEC} in this case. For the orifice #1 (satisfied $A_{\text{E}}/A_{\text{W}} < \mu$), a spherical-anode spot can be formed, and the hysteresis is more pronounced than other orifice dimensions. In this case, although the electron-extraction performance is not the optimal, the I_{EEC} can be continuously adjusted over a large range.

Acknowledgments

This work is supported by the Strategic Priority Research Program of the Chinese Academy of Sciences (Grant No. XDB23030100). The authors would like to thank Enago (www.enago.cn) for the English language review.

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