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# Theoretical Investigation and Modeling of Current Extraction from a Radio-Frequency Cathode

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**Plasma cathodes are electron sources which use a plasma discharge in order to extract electrons. Plasma discharge of these cathodes is produced by various methods. The device takes its name from the method of plasma generation. After plasma generation, an extraction set up is used in order to obtain electron current from the bulk plasma. Extraction of electrons from a plasma cathode device is related to the bulk plasma parameters as well as the extraction apparatus geometry. So, the theory of radio frequency cathode consist of two parts: first, modeling a quasineutral inductively coupled plasma and second, modeling of plasma sheath and effects of applying a bias voltage on the plasma. Theory of quasineutral inductively coupled plasma has been developed widely and some zero-dimensional and multi-dimensional models have been introduced by numerous scientists. In contrast, theory of applying a positive potential and electron current extraction from a bulk plasma is considered in recent years. For this reason, there are limited models that can be used in this field. In this study, a novel 0-D model is proposed for numerical investigation of the current extraction mechanism of plasma cathode device. Also, a DC circuit is developed which models the electron current traveling from the grounded electrode to the positive electrode of the DC power source.**

## Nomenclature

| | |
|---|---|
| $m$ | Mass |
| $v$ | Velocity |
| $V$ | Electric potential |
| $n$ | Number density |
| $A$ | Area |
| $\nu$ | Collision frequency |
| $\forall$ | Volume |
| $I$ | Electric Current |
| $\Gamma$ | Particle flux |
| $k_B$ | Boltzmann's constant |
| $T$ | Temperature |
| $P$ | Power |

*Subscript*

| | |
|---|---|
| $i$ | Ion species |
| $e$ | Electron species |
| $g$ | Neutral species |
| $iz$ | Ionization |
| $exc$ | Excitation |
| $DC$ | Direct current |
| $RF$ | Radio frequency |

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# I. Introduction

Hollow cathodes have been commonly used as electron sources in electric propulsion application. These types of cathodes provide high electron current density by using low electric power and gas consumption. However, they have certain disadvantages:

1. Hollow cathode's lifetime is limited by the evaporation of the insert material. For long duration space missions where electric thrusters such as ion engines are being considered to be used, there is a need for neutralizer devices that would work for 6 to 10 years. Also, oxygen and water impurities in the propellant can dramatically increase the work function of the insert material and thus limiting the operational lifetime.

2. The insert works at relatively high temperature and thus must be heated before starting the neutralizer operation. This uses considerable power and also prevents the neutralizer from switching on or off fast.[1,2]

In order to overcome these problems, plasma cathode devices have been introduced in recent years. Plasma cathodes are insert free devices that use a bulk plasma inside a chamber in order to extract electrons. Various methods have been used for bulk plasma generation in the plasma cathodes. Examples are capacitively[1] or inductively coupled[3,4] plasma sources, which operate without magnetic fields. Other examples are electron cyclotron resonance (ECR)[5,6] and helicon[2] sources that use magnetic fields.

Helicon sources are mostly used in the discharge chamber of ion thrusters in order to create plasma. This is because they can produce the highest plasma densities for a given RF power. But, they need strong magnetic fields and high RF powers. ECR and capacitive sources do not operate efficiently in the low-power and low-mass-flow-rates that is typical for the operation of a cathode.[2]

Inductively coupled plasma source is considered as one of the preferred choices for the plasma cathode device. Inductively coupled plasma cathode (ICPC) can reach to significant plasma densities ($10^{16}$ to $10^{18}$ $m^{-3}$) and have high total electron extraction current. Because of the beneficial aspects of inductively coupled plasma cathodes, several research groups have fabricated and done experimental research about these types of cathodes.

Experiments[3,7] show that applying a sufficiently high bias voltage to the source (or bulk) plasma will create a secondary structure inside the cathode which is known as ***anode spot*** or ***fireball*** . Formation of anode spot is the most important feature of the plasma cathode device. Anode spot formation affects the current extraction considerably and should be taken into account in the modeling of plasma cathode device performance. In this study, a novel 0-D model is proposed for numerical investigation of current extraction mechanism of plasma cathode device which considers the formation of anode spot, and also its effect on the bulk plasma and current extraction.

# II. Theory of plasma cathode

Plasma cathodes are devices that employ a primary plasma discharge which is generated inside a chamber in order to extract electron current. Various methods have been used in the plasma generation part of these devices. The device takes its name from the method of plasma generation. After plasma is formed, an extraction setup, which consists of two electrodes (one of them grounded and the other biased positively with respect to the ground) and a DC power source, is employed in order to extract electrons from the plasma. The grounded electrode is placed inside the chamber of the device and the positively biased electrode is placed outside of it, near the orifice of the chamber. So, by applying a potential difference between these two electrodes, an electron current will flow from the grounded electrode to the positively biased electrode. A schematic of a basic plasma cathode device is shown in Figure 1.

Electron current extraction from plasma cathode depends on both plasma generation part and electron extraction part of it.[8] So, in order to model the operation of radio-frequency cathode (or any other plasma cathode device), both of these parts and also their interaction should be taken to account.

Theory of quasineutral inductively coupled plasma has been developed widely and some zero-dimensional and multi-dimensional models have been introduced by numerous scientists.[9] Each of these theories consider ICP from a specific point of view, for example, fluid model, electromagnetic model, electrodynamic model, etc. Also, plasma-wall interaction and sheath have been investigated and numerous models have been introduced. But, the theory of applying a positive bias voltage to a bulk plasma in order extract electrons has not been developed completely and there are many difficulties in terms of explaining the exact processes and phenomena that are observed during electron current extraction. So, this remains as an unsolved problem in the field of plasma physics science.

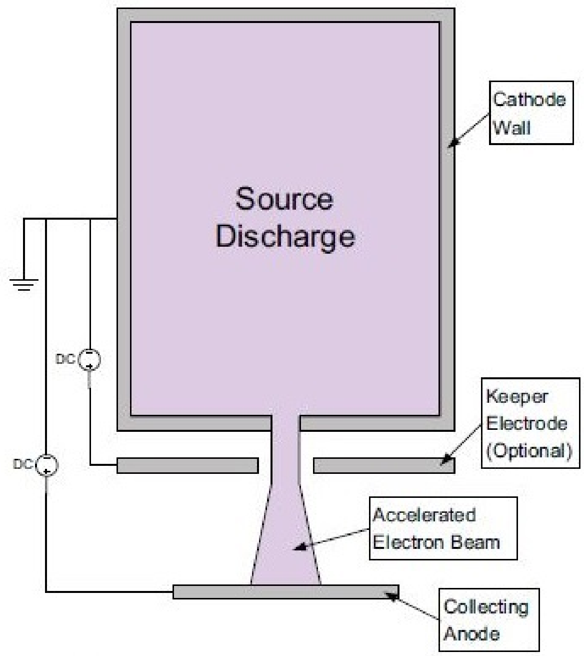


**Figure 1. Schematic of a basic plasma cathode[8]**

The experimental investigations show that the source plasma and extraction mechanisms do not work separately and interact with each other. Application of a bias voltage and extraction of electrons from source plasma not only perturbs the plasma potential, but also affects the bulk plasma density and electron temperature. Also, when the applied bias voltage reaches a critical value, new plasma structures form inside the plasma chamber that are very important for the operational characteristics of the plasma cathode device.

Applying a potential difference between the electrodes of plasma cathode in order to extract electron from primarily generated plasma inside the chamber of the device, and immersing a positively biased electrode inside a bulk plasma are two types of the same problem. So, the experimental and theoretical studies regarding one of these two cases can be used for the investigation of the other. Actually, both of these cases are part of a more general problem known as double layers in the plasma physics science. Despite the lack of theoretical models for current extraction from a source plasma, numerous experimental studies[10,11,12] have been conducted.

Plasma potential profile near a positively biased surface which works in the electron sheath regime decreases monotonically with a positive curvature with respect to the bulk plasma potential. But, actually it is true only for low bias voltages. The applied power by a biased surface is mostly spent to accelerate electrons towards the surface and hence increasing the electron energy. These high energy electrons have much higher ionization reaction rate and cause more ionization near the biased surface. This leads to phenomena like anode glow and anode spot.[12]

By increasing the bias voltage, electron energy due to acceleration towards the bias surface increases to a value that is equal to ionization energy of neutral particles. The newly born ions are warded off from the biased surface and newly born electrons are attracted towards the bias surface. But, the electrons are attracted with much higher speed ($v_e = \sqrt{\frac{m_i}{m_e}} v_i$). It leaves a region that has positive space charge near the biased surface and results in formation of a double layer.[10] In this way, anode glow and double layer sheath are created. Anode glow is a thin (on the order of tens of Debye lengths) and shiny region near the positively biased surface.[12]

Increasing the bias voltage to a greater value increases the ion density in the positive region in front of the bias surface. When the ion density and electron density inside a Debye cube near the bias surface become equal, a quasineutral plasma will be formed. In order for the ions to be lost from this quasineutral plasma to the bulk plasma, they should reach the Bohm speed. The region where the ions are accelerated to the Bohm speed should be quasineutral too and should have a potential drop near $T_e/e$, where $T_e$ is the local electron temperature. In order for this to occur, the electron sheath has to expand to a length of hundreds of Debye lengths. So, when the ion density becomes equal to the electron density in the anode glow, it will be abruptly transitioned to a new structure. This large quasineutral, spherical and luminous region in front of positively biased electrode is named "anode spot". The critical bias voltage which the rapid transitions from anode glow to anode spot happens is inversely proportional to the neutral gas pressure ($\Delta\phi \propto \frac{1}{n_g}$). This is because by increasing the neutral density more ionization occurs near the biased surface and quasineutrality is set at lesser bias voltages.[12]

Images of the generation of an anode spot in the orifice of an RF plasma cathode, obtained by LCIF measurements[7] is shown in Figure 2. This figure shows that by applying a potential difference outside the orifice of the RF plasma (and extracting electron current from it), an anode spot forms near the orifice of the cathode, and increasing the applied bias potential increases the size of it. This size becomes maximum when bias voltage is increased to a critical value, and from that point on increasing the bias voltage does not increase the size of the anode spot.[7]

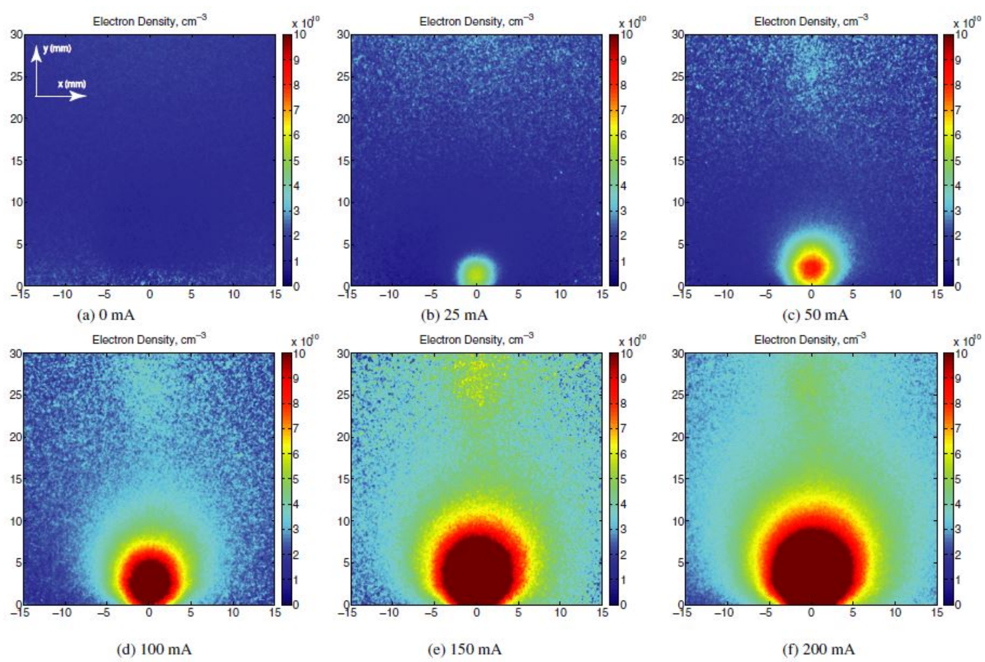


**Figure 2. Plasma density inside an RF plasma cathode for different extracted currents**[7]

Before establishing the anode spot, the extracted electron current by positively bias electrode is not considerable. By establishing an anode spot near the biased surface, a jump in the extracted current occurs.

The current jump has been observed in all plasma cathode studies.[3,8,13] When an anode spot is created in front of the biased surface (or orifice of a plasma cathode), the electron extraction area becomes the surface area of the anode spot. So, the extraction area suddenly becomes much larger and there will be a jump in the extracted electron current. The I-V characteristic for a positively biased surface immersed in a plasma is shown in Figure 3. It is obvious that before establishing the anode spot, the extracted current is very small and establishing an anode spot causes a jump in extracted electron current. So, formation of the anode spot is thought to be the main reason for the transition of electron extraction from the low current mode the high current mode.[10] It is obvious that considering a Maxwellian energy distribution for the electrons and calculating the saturation current through the orifice area in order to obtain the extracted current will be deceiving. When the anode spot reaches its maximum size by increasing the bias voltage, the extracted current reaches its maximum value too and no more current can be extracted by increasing the bias voltage further.[7] Another phenomenon that can be seen in Figure 3 is the hysteresis in the I-V characteristic. It means that after the anode spot is formed, by decreasing the bias voltage, the anode spot will continue to exist to much lower bias voltages than the critical bias voltage.[12]



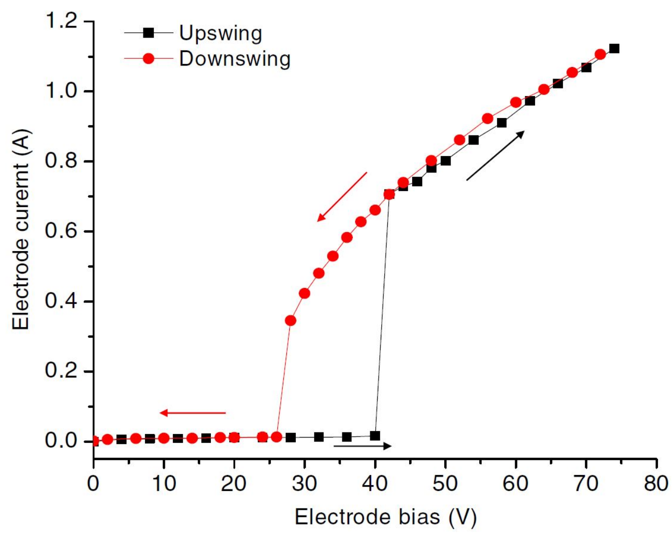


**Figure 3. I-V characteristics for a positively biased surface immersed in a bulk plasma[12]**

Also, the formation of anode spot leads to considerable changes in the bulk plasma. The most important effects of the anode spot formation in the bulk plasma are:

1. By formation of an anode spot, the bulk plasma potential locks to the bias potential, which is called the *plasma potential locking*. At the anode glow regime, plasma potential is not affected much by the bias potential. But, by formation of an anode spot, plasma potential jumps and locks to the bias potential by a nearly constant value. This constant value, which is the difference between bulk plasma potential and bias voltage, is the neutral gas ionization potential plus a few electron-volts.

2. Formation of an anode spot also affects the bulk plasma density and electron temperature. By applying a bias voltage and forming an electron sheath, the electron temperature of the bulk plasma increases. Then, by the formation of an anode spot, electron temperature experiences a sudden increase.[12]

In order to model the plasma cathode device operation and electron current characteristics, it is necessary to take into account the anode spot formation and its effects on the extracted current and the bulk plasma. A novel 0-D model is proposed in the next section to accomplish these goals.

## III. 0-D model of plasma cathode device

As described in the previous section, plasma cathode device operation is considerably affected by the creation of the anode spot at the orifice exit of the device. So, any modeling effort that does not account for the presence of the anode spot will not give reliable results. In this section a 0-D model for the operation of the plasma cathode device is introduced. This model describes the additional effects of applying a biased voltage to a bulk plasma. The aim the proposed 0-D model is to capture the I-V characteristics of the plasma cathode device in the presence of anode spot.

Figure 4 shows the potential distribution for the bulk plasma and anode spot in the presence of an anode spot. In this figure, three regions are indicated: I) bulk plasma, II) double layer and III) anode spot. $V_{p,bulk}$ shows the potential difference between the grounded ion collector electrode and the bulk plasma. $E_{iz}$ is the potential difference between bulk plasma and anode spot or the potential difference between two sides of the double layer. $T_{e,as}$ is the anode spot electron temperature. In the presence of anode spot, the bulk plasma is locked to the bias voltage, by a value of $E_{iz} + T_{e,as}$. So, for plasma potential we can write:

$$V_{p,bulk} = V_{bias} - (E_{iz} + T_{e,as}) \tag{1}$$

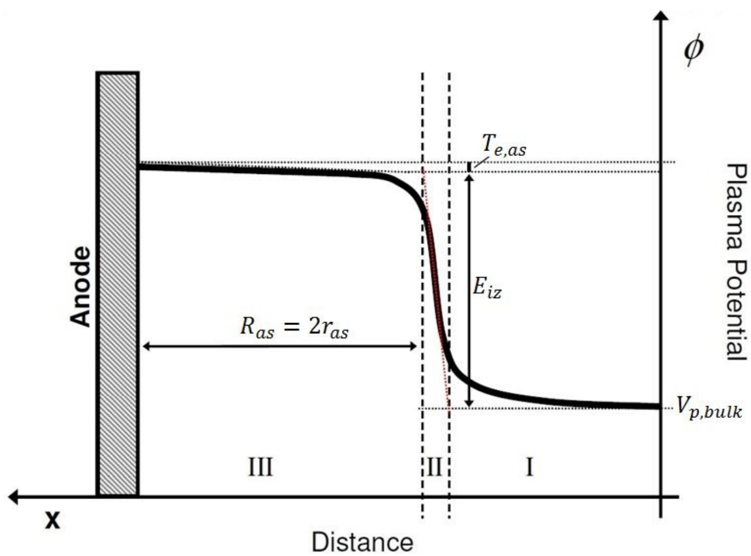


**Figure 4. Bulk plasma and anode spot potential distribution**[13]

If we consider the basic operation and goal of plasma cathode device, we can find out that the device is a DC circuit such that its aim is to deliver DC current from one electrode (grounded electrode) to the other electrode (positively biased electrode). So, to model the operation of the device, the DC current circuit should be added. The importance of the circuit models in theoretical investigations of potential structures is known widely in cosmic plasma science.[14] Figure 5 shows the proposed DC current circuit model of the plasma cathode device in the presence of an anode spot inside it. In this circuit, bulk plasma and anode spot are modeled as two resistors where the DC power is deposited. $I_{e,extracted}$ is the extracted current from the plasma cathode. $V_{p,bulk}$ is the potential difference between grounded wall and bulk plasma, in other words, it is the bulk plasma potential. $I_{thermal,bulk}$ is the electron thermal current that is lost from the bulk plasma through the anode spot surface. Also, the ion current that is generated in the anode spot and lost to the bulk plasma is considered as an electron current from bulk plasma to the anode spot. Only a portion (represented by the factor of $\gamma$) of the accelerated electrons that pass thought the anode spot participate in the ionization reactions inside the anode spot, and the others are lost directly through the cathode orifice. The $\gamma$ factor will be derived later. The directly lost electrons, fall through a potential of $E_{iz} + T_{e,as}$. As described in the previous section, the potential drop through the double layer of anode spot is equal to the neutral gas ionization energy ($E_{iz}$). The electrons that participate in the reactions inside the anode spot (which have been accelerated through a potential of $E_{iz}$ in the double layer), will generate an electron current which is represented by $I_{gen,as}$. Finally, the extracted electron current from the plasma cathode device will be the summation of current that is lost directly from the bulk plasma,$(1-\gamma)I_{thermal,bulk}$, and the thermal current that is lost from anode spot quasineutral plasma through the orifice of the plasma cathode, $I_{thermal,as}$. Using the proposed DC circuit for the plasma cathode, we can obtain the applied DC power to the bulk plasma and anode spot:

$$P_{DC,bulk} = V_{p,bulk}\ I_{e,extracted} \tag{2}$$

$$P_{DC,as} = \gamma E_{iz} I_{thermal,bulk} + E_{iz} I_{gen,as} \tag{3}$$

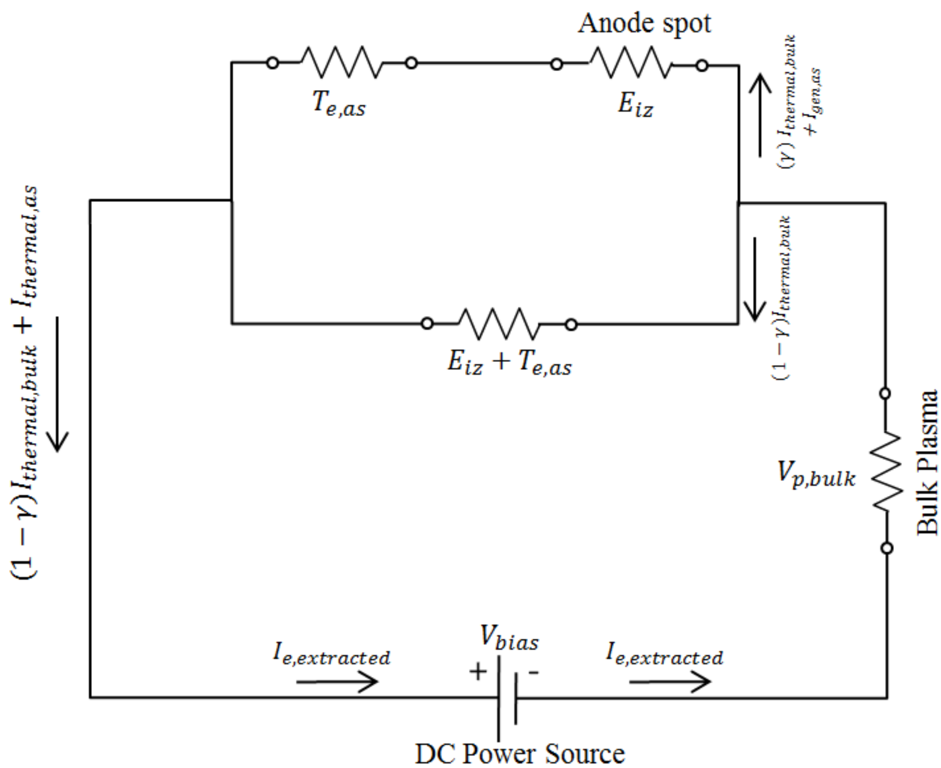


**Figure 5. Schematic of the DC current circuit of the plasma cathode device**

## A. Particle balance for bulk plasma

It can be considered that all ions generated inside the plasma cathode are lost to the walls. It is equivalent to the assumption that no ion is lost through the orifice of the plasma cathode device. Because of the high potential difference between the bulk plasma and biased surface, this assumption seems to be appropriate. Applying this assumption, the particle balance for the bulk plasma will be:

$$n_{e,bulk}\ n_g\ K_{iz,bulk}\ \forall_{bulk} + I_{gen,as}/e = n_s\ u_B\ A_{wall} \tag{4}$$

where $n_{e,bulk}$ is the electron density in the bulk plasma, $n_g$ is the neutral gas density, $K_{iz,bulk}$ is the ionization reaction rate for bulk plasma, $\forall_{bulk}$ is bulk plasma volume and $u_B = \sqrt{\frac{k_B T_{e,bulk}}{M_i}}$ is the Bohm velocity. $n_s$ is plasma density at the sheath edge, which can be assumed to be $n_s = 0.5 n_{e,bulk}$.[15] $I_{ion,as}/e$ is the value of the number of generated ions per second inside the anode spot and will be described later.

## B. Power balance for bulk plasma

In plasma cathode device, power is deposited to the bulk plasma by two mechanisms: RF power (or other mechanisms that the device is designed to work) and DC power. The DC power deposition in bulk plasma is presented in equation (2). So, for the absorbed power for the bulk plasma we will have

$$P_{abs,bulk} = P_{DC,bulk} + P_{RF} = V_{p,bulk}\, I_{e,extracted} + P_{RF} \tag{5}$$

Assuming cold ions, the energy loss mechanisms from the bulk plasma are the electron current which flows to the anode spot and collisions inside the bulk plasma. Electron flux through the bulk plasma is the electron thermal flux, $\Gamma_{thermal,bulk} = n_{e,bulk}\ v_{thermal,bulk}/4$, where $v_{th,bulk} = \left(\frac{8k_B T_{e,bulk}}{\pi m_e}\right)^{1/2}$ is the mean electron thermal velocity in the bulk plasma. So, the electron current exiting the bulk plasma through the anode spot surface can be found as:

$$I_{thermal,bulk} = e\Gamma_{thermal,bulk}\ A_{as} \tag{6}$$

where $A_{as}$ is the anode spot area. In this model, the anode spot is assumed to be as a sphere. The electrons that leave the bulk plasma have an average thermal energy of $3/2k_B\ T_{e,bulk}$. So, for the energy, that electron flux is taking out of the bulk plasma through the anode spot surface area, we can write

$$P_{loss,thermal,bulk} = \Gamma_{thermal,bulk}\ E_{thermal,bulk} A_{as} = \frac{1}{4}\ n_{e,bulk}\ v_{thermal,bulk} \frac{3}{2}\ k_B\ T_{e,bulk} A_{as} \tag{7}$$

The second mechanism of power loss is through collisions inside the bulk plasma, which can be expressed by

$$P_{loss,coll,bulk} = n_{e,bulk}\ n_g \left[K_{iz,bulk}\ \epsilon_{iz} + K_{exc,bulk}\epsilon_{exc}\right] \forall_{bulk} \tag{8}$$

where $\epsilon_{iz}$ and $\epsilon_{exc}$ are ionization and excitation energy for the neutral gas and $K_{exc,bulk}$ is the excitation reaction rate for the bulk plasma.

Equating the absorbed and lost energies, we can obtain the power balance equation for the bulk plasma:

$$P_{DC,bulk} + P_{RF} = P_{loss,coll,bulk} + P_{loss,thermal,bulk} \tag{9}$$

### C. Particle balance for anode spot

Because of the strong electric field inside the anode spot, all generated ions are lost to the bulk plasma. Since the anode spot is a quasineutral region, the ions that are lost to bulk plasma satisfy the Bohm criterion. So, the ion current will be

$$I_{i,as} = n_{i,as}\ u_{B,as}\ A_{as}\ e \tag{10}$$

where $n_{i,as}$ is the ion density in the anode spot and $u_{B,as} = \sqrt{eT_{e,as}/M_i}$ is the Bohm speed for the anode spot plasma. The generated ions inside the anode spot have a current

$$I_{i,gen,as} = n_{e,drifted}\ n_g\ K_{iz,as}\ \forall_{as}\ e \tag{11}$$

where $n_{e,drifted}$ is the drifted electron density in the anode spot which is equal to the ion density because of the quasineutrality. Equating equations (10) and (11) we obtain

$$\forall_{as}/A_{as} = r_{as}/3 = \frac{1}{K_{iz,as}\ n_g}\sqrt{eT_{e,as}/M_i} \tag{12}$$

In the anode spot, electrons are not in the equilibrium state and have a drift velocity. So, conventional reaction rates derived for Maxwellian distribution cannot be used to obtain the ionization rate for the drifted electron flux in the anode spot. Conde et. al.[16] have derived an expression for ionization reaction rate of drifted electrons which are fallen from a potential of $E_{iz}$ and have thermal velocity of $v_{thermal,bulk}$:

$$K_{iz,as} = \sigma_o v_{thermal,bulk} E_{iz} \left[\frac{3+10{u_o}^2}{8{u_o}^3}\ \mathrm{erf}(2u_o) + \frac{2+{u_o}^2}{{u_o}^2\sqrt{\pi}} + \frac{e^{-4{u_o}^2}}{2{u_o}^2\sqrt{\pi}}\right] \tag{13}$$

where $\sigma_o = (d\sigma/dE)_{E=E_{iz}}$ and $u_o = \sqrt{E_{iz}/(k_B T_{e,bulk})}$.

As was expressed earlier, electron flux entering from the bulk plasma to the low potential side of the double layer is $n_{e,bulk} v_{thermal,bulk}/4$. At the higher potential side of the double layer, where the electrons are accelerated by a potential difference of $E_{iz}$, the electron drift velocity is $\sqrt{2eE_{iz}/m_e}$, drifted electron flux is $\Gamma_{e,drifted} = n_{e,drifted} \sqrt{2eE_{iz}/m_e}$. Electron fluxes at low potential and high potential side of the double layer are equal, so we can write

$$n_{e,bulk}\ v_{thermal,bulk}/4 = n_{e,drifted}\ \sqrt{2eE_{iz}/m_e} \tag{14}$$

From this equation, we can obtain

$$n_{e,drifted} = \frac{n_{e,bulk}\ v_{thermal,bulk}}{4\sqrt{2eE_{iz}/m_e}} \tag{15}$$

In order to obtain the density of electrons that are generated inside the anode spot, $n_{e,gen,as}$, we need an extra equation. This equation can be the current conservation for the anode spot, which shows that the thermal electron current which is lost trough the orifice of the plasma cathode is equal to the generated electron current inside the anode spot plus the portion of drifted electron current which is thermalized by participating in the ionization reactions inside the anode spot:

$$I_{thermal,as} = \Gamma_{thermal,as}\ A_{orifice}\ e = \frac{1}{4}\ n_{e,gen,as}\ v_{thermal,as}\ A_{orifice}\ e = \gamma\ I_{thermal,bulk} + I_{i,gen,as} \tag{16}$$

### D. Power balance for anode spot

Power is brought to the anode spot by the drifted electrons. Drifted electrons that enter the anode spot has two types of energy: one is the electron thermal energy that they have obtained from the bulk plasma, calculated in equation (7), and the other is the drifted energy that is modeled in Figure 5 and equation (3) as $P_{DC,as}$. So, the absorbed energy for the anode spot is

$$P_{absorbed,as} = P_{DC,as} + \gamma\ P_{loss,thermal,bulk} \tag{17}$$

As stated earlier, only a portion of the electrons that are ejected from the bulk plasma and drifted to the anode spot participate in the inelastic reactions inside the anode spot and are thermalized. The other electrons exit the anode spot without any reaction and energy loss. The applied DC power to the anode spot has been derived in equation (3). In this equation, $\gamma$ is a coefficient that shows the fraction of drifted electrons that have participated in the reactions inside the anode spot. We know that the ionization collision frequency is $\nu_{iz,as} = K_{iz,as}\ n_g$. Also, the rate of number of electrons entering the anode spot through the double layer is $\dot{N}_{drifted} = I_{drifted}/e = I_{thermal,bulk}/e$. So, we can find $\gamma$ as

$$\gamma = \frac{\nu_{iz,as}}{\dot{N}_{drifted}} = \frac{K_{iz,as}\ n_g\ e}{I_{e,drifted}} = \frac{K_{iz,as}\ n_g\ e}{I_{thermal,bulk}} \tag{18}$$

Energy loss mechanisms from the anode spot are the collisions reactions inside it and the energy of electrons that escape from the anode spot. The power loss via collision can be written as

$$P_{loss,coll,as} = n_{e,drifted}\ n_g\ [K_{iz,as}\ \epsilon_{iz} + K_{exc,as}\epsilon_{exc}]\ \forall_{as} \tag{19}$$

where $K_{exc,as}$ is the excitation reaction rate for anode spot and is a function of $T_{e,as}$.

The energy of thermal electrons escaping through the orifice of the plasma cathode device can be expressed as

$$P_{loss,thermal,as} = \Gamma_{e,thermal,as}\ E_{thermal,as} = \frac{1}{4}\ n_{e,gen,as}\ v_{thermal,as}\ \frac{3}{2}k_B\ T_{e,as}A_{orifice} \tag{20}$$

where $A_{orifice}$ is the orifice area of the plasma cathode.

By equating the absorbed and lost energies for the anode spot, we can write the energy balance for the anode spot

$$P_{DC,as} + \gamma\ P_{loss,thermal,bulk} = P_{loss,thermal,as} + P_{loss,coll,as} \tag{21}$$

### E. Extracted current saturation mechanism

From experimental observations, we know that extracted current from the plasma cathode device reaches a maximum value in a fixed inner pressure (mass flow rate) and RF power. The most probable reason for the current saturation is that the anode spot cannot grow further, by increasing the bias voltage.[7] When this occurs, anode spot cannot collect more electrons from the bulk plasma. So, the electron current to the biased surface will saturate. Also, by the saturation of the extracted current, the bulk plasma potential cannot lock to the bias voltage, and the bulk plasma potential, electron density and electron temperature will not increase by increasing the bias voltage.

Now, the question is what makes the anode spot reach its maximum size and prevents it from growing more. It is considered that the answer to this question lays in the $\gamma$ value. By increasing the bias voltage, the electron current from the bulk plasma to the anode spot increases, but more of the electrons participate in the ionization inside the anode spot. So, increasing the bias voltage increases $\gamma$. When $\gamma$ becomes one, all of the electrons entering the anode spot participate in the ionization process inside it. So, by increasing the bias voltage more, $K_{iz,as}$ will increase, and it will become greater than the number of electrons entering the anode spot from bulk plasma. So, no more electrons can pass the anode spot and the extracted current will saturate. So, the criterion for the extracted current saturation for the plasma cathode device is

$$\gamma = 1 \tag{22}$$

## IV. Conclusion

In the presented study, plasma cathode devices, and their operation and current extraction mechanism are described. Using previous theoretical and experimental studies, it is shown that the formation of a double layer structure, which is known as anode spot, is the most important factor in the plasma cathode device operation. So, any attempt to model the operation of these devices should consider the formation of the double layer structures and their effects on the current extraction characteristics of the device.

In this study a novel electrical circuit representation is proposed to model the DC current which flows from the grounded electrode of the DC power supply to its positively biased electrode. It is considered that applying a biased voltage in order to extract electrons from a bulk plasma actually deposits DC power to the plasma. Before the formation of the anode spot, the plasma resistance is very high that only a very low current can pass through it. But, by the formation of anode spot, plasma behaves as a conductor for the DC current can flow through it. Also, energized electrons in the DC electric field gain very high drift speeds. This increases the ionization rates and high electron densities inside the bulk plasma and anode spot dramatically. The applied DC power and consequent high ionization rates are considered as the reasons for the high extracted currents in the presence of the anode spot. The reason for saturation of extracted current is considered to be the participation of all electrons falling from the double layer in the ionization reactions inside the anode spot, so that no more electron can pass through the anode spot and no more ionization is occurred inside it.

The next step for this study is to solve the proposed equations and compare the obtained results with the experimental findings. Also, parametric studies in terms of geometric and operational parameters are going to be conducted.

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# References

[1]Weis, S., Schartner, K. H., Löb, H., and Feili, D., "Development of a capacitively coupled insert-free RF-neutralizer," *29th International Electric Propulsion Conference, Princeton University, USA*, 2005, IEPC-2005-086.

[2]Longmier, B. W. and Hershkowitz, N., "Electrodeless Plasma Cathode for Neutralization of Ion Thrusters," *41st Joint Propulsion Conference, Tucson, USA*, 2005, AIAA-2005-3856.

[3]Hatakeyama, T., Irie, M., Watanabe, H., Okutsu, A., Aoyagi, J., and Takegahara, H., "Preliminary Study on Radio Frequency Neutralizer for Ion Engine," *30th International Electric Propulsion Conference, Florence, Italy*, 2007, IEPC-2007-226.

[4]Godyak, V., Raitses, Y., and Fisch, N. J., "RF plasma cathode-neutralizer for space applications," *30th International Electric Propulsion Conference, Florence, Italy*, 2007, IEPC-2007-266.

[5]Hidaka, Y., Foster, J., Getty, W., Gilgenbach, R., and Lau, Y., "Performance and analysis of an electron cyclotron resonance plasma cathode," *Journal of Vacuum Science and Technology A*, Vol. 25, No. 4, 2007, pp. 781–790.

[6]Weatherford, B., Foster, J., and Kamhawi, H., "Electron current extraction from a permanent magnet waveguide plasma cathode," *Review of Scientific Instruments*, Vol. 82, No. 9, 2011, pp. 093507.

[7]Weatherford, B., Barnat, E., and Foster, J., "Two-dimensional laser collision-induced fluorescence measurements of plasma properties near an RF plasma cathode extraction aperture," *Plasma Sources Science and Technology*, Vol. 21, No. 5, 2012, pp. 055030.

[8]Weatherford, B. R., *Development and Study of an Electron Cyclotron Resonance Waveguide Plasma Cathode for Electric Propulsion Applications*, Ph.D. thesis, University of Michigan, 2011.

[9]Chabert, P., Braithwaite, N., and Braithwaite, N. S. J., *Physics of Radio-Frequency Plasmas*, Cambridge University Press, 2011.

[10]Song, B., d'Angelo, N., and Merlino, R., "On anode spots, double layers and plasma contactors," *Journal of Physics D: Applied Physics*, Vol. 24, No. 10, 1991, pp. 1789.

[11]Sanduloviciu, M., Borcia, C., and Leu, G., "Self-organization phenomena in current carrying plasmas related to the non-linearity of the current versus voltage characteristic," *Physics Letters A*, Vol. 208, No. 1, 1995, pp. 136–142.

[12]Baalrud, S., Longmier, B., and Hershkowitz, N., "Equilibrium states of anodic double layers," *Plasma Sources Science and Technology*, Vol. 18, No. 3, 2009, pp. 035002.

[13]Longmier, B. W., *Plasma Sheath Behavior in a Total Nonambipolar Radio Frequency Generated Plasma Electron Source*, Ph.D. thesis, University of Wisconsin-Madison, 2007.

[14]Alfvén, H., "Double layers and circuits in astrophysics," *IEEE Transactions on Plasma Science*, Vol. 14, No. 6, 1986, pp. 779–793.

[15]Goebel, D. M., "Analytical discharge model for RF ion thrusters," *IEEE Transactions on Plasma Science*, Vol. 36, No. 5, 2008, pp. 2111–2121.

[16]Conde, L., Ibanez, L., and Ferro-Fontan, C., "Electron impact ionization by drifting electrons in weakly ionized plasmas," *Physical Review E*, Vol. 64, No. 4, 2001, pp. 046402.