Experimental Investigation of Operational Parameters of A Prototype Radio Frequency Plasma Cathode

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***Abstract*—Plasma cathodes have attracted much attention in recent years, and various types of such cathodes have been developed and tested by different research groups. In these types of electron sources, a bulk plasma is generated inside a vessel, which has an orifice at its front plate. Then, by applying a positive potential outside the vessel, electrons of the bulk plasma are extracted from this orifice. Various plasma sources, such as helicon, electron cyclotron resonance (ECR), microwave and radio frequency (RF) are used for the bulk plasma generation of the plasma cathode devices. Compact geometry, easy generation, and high density and efficiency of the RF plasma make it preferable for the plasma cathode applications. In this study, the operation procedures and characteristics of a prototype RF cathode device are described. In addition, some experimental results from the testing of the prototype RF cathode are presented.**

Keywords— electric propulsion, plasma cathode, RF cathode.

I. INTRODUCTION

Electron sources (cathodes) play an important role in electric propulsion applications. Some electric thrusters, such as Kaufman type ion thrusters, need an electron source to provide the electrons for the plasma generation inside the thruster. Also, the neutralization of the ions that are accelerated out from the thruster is a very important and essential task. The most important reasons for the neutralization of the ion plume outside of the thruster are: 1) By throwing ions out from the thruster, a net negative charge is left in the spacecraft. This negative charge would create an electric potential that could harm the spacecraft and its components. 2) Because of the negative charge on the spacecraft, the ions would tent towards diverge to the spacecraft surfaces. Because of the high energy of the ions, it could be harmful for the spacecraft surfaces. In addition, when the ions are divergent, the thrust and the efficiency of the thruster are reduced considerably. 3) The unneutralized ion plume outside the thruster creates an electric field which prevents the forthcoming ions to be ejected from the thruster, and this reduces the efficiency of the device [1][2].

Considering these facts about the importance of the electron sources, numerous concepts have been developed. The first ion thrusters developed in 1960s (electron-bombardment ion thrusters), employed directly heated tungsten filaments as a source of electrons in the neutralization process. But, tungsten has a high work function, so the filaments had to be heated to a temperature as high as 2600 K to emit electron current densities on the order of 1 A/cm^2. To reach this temperature, it needs a high heater power, nearly the power that is needed to create the plasma itself. This will reduce the efficiency of the thruster considerably. Also, filament's lifetime is limited by rapid evaporation of its material at the high temperature and by erosion of the tungsten surface which is bombarded by ions. This type of cathode has a lifetime of hundred hours or less [3].

To solve these problems, hollow cathodes were introduced. Hollow cathodes include a hollow tube and an orifice plate on the downstream end of it. Inside the tube, there is a cylindrical insert that is pushed towards the orifice plate. This insert is an active electron emitter. The insert is chosen between materials that have a low work function, in order to have better electron emission. The cathode tube is covered with a heater that heats insert in order to start discharge. The electrons that are emitted from the insert have collisions with the gas injected from the cathode tube, and this forms plasma inside tube. This plasma is used to extract electrons through the orifice [3].

Hollow cathodes provide high electron current density by using low electric power and gas. However, they have some disadvantages. The evaporation of the insert material is a lifetime limit for the hollow cathode. Also, impurities such as oxygen and water in the propellant can dramatically increase the erosion of the insert. In addition, the insert needs very high temperature in order to start emitting electrons. So, the cathode tube must be heated before startup of the cathode. The heating process needs high power. It also takes a significant time and prevents the cathode from switching on or off fast.

Plasma cathode devices, as a solution for the disadvantages of the hollow cathode, have been introduced in recent years. These devices are insert free. Plasma cathodes use a bulk plasma, which is generated inside their vessel, in order to extract electrons. This bulk plasma could be chosen among various types of the plasmas. The device takes its name from the method of the plasma generation. For example, capacitively coupled plasma (CCP) [4], inductively coupled plasma (ICP) [5][6], electron cyclotron resonance (ECR) plasma [7][8] and helicon plasma [9] have been used as the plasma generation method in plasma cathode devices.

Because of its compact geometry, and efficient operation, even in low applied power and gas flow rates, the RF plasma source is considered as one the best choices for the plasma cathode device. In this study, components and design parameters of an RF plasma cathode are described. In addition, some experimental results about the ICP generation and electron extraction from the prototype RF plasma cathode are presented.

II. RF PLASMA CATHODE

A prototype RF plasma cathode is designed and manufactured in order to investigate the basic operational characteristics of the device. A 3D technical drawing and a picture of this prototype RF plasma cathode is shown in Fig.1. This design concept is taken from Hatakeyama et al.'s study [5]. The vessel of the prototype RF plasma cathode is made of pyrex. The vessel is 4 cm in diameter and 5 cm in length. The RF coil is made of 4 mm diameter copper tube and has 5 turns. 0.5 mm thick molybdenum plate is used as the ion collector electrode inside the vessel of the RF cathode. The vessel has an orifice in the center of its end surface. The diameter of this orifice is 2 mm. The gas inlet is a long pyrex tube and is also integrated with the vessel. There is a thin hole on the backside of the vessel which allows the connection of the ion collector to the ground using a thin wire. The RF cathode vessel and RF coil are mounted on a backplate thorough the holes on the backplate. First, a fiber board (used for construction purposes) was chosen to be used as the backplate. But, because of the outgassing problem of this material, it was not possible to reduce the pressure inside the vacuum chamber. So, a teflon plate was used as the backplate, instead of fiber plate.

III. EXPERIMENTAL SETUP

The RF plasma cathode experiments have been conducted at the vacuum chamber facility of the Bogazici University Space Technologies Laboratory (BUSTLab). This vacuum chamber is a 1.5 m diameter 2.7 m long cylindrical tank. By using a mechanical pump and two cryogenic pumps, the pressure inside the vacuum chamber is maintained on the order of 1.2×10^{-5} Torr for 10sccm argon flow rate. In order to conduct the experiments, various setups such as gas feed, DC power and RF power are used together. In this section, the DC and RF setups, as the most important ones, are described.

Fig. 1. Schematic and manufactured RF plasma cathode

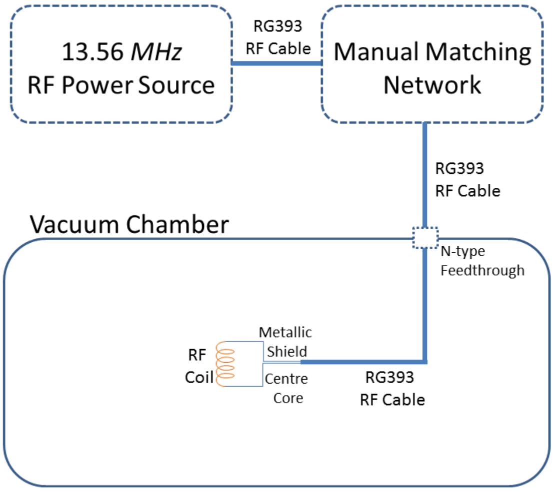

Fig. 2. Schematic of the radio-frequency setup of the RF plasma cathode experiments

A. *RF Power Source, Matching Network and RF Setup*

A schematic of the RF setup is shown in Fig.2. In this setup, RF power is carried through RG393 coaxial cables. The RF power is brought from the RF power source to the matching network. The output of the matching network is connected to an N-type connector. The RF power is carried from the outside to the inside of the vacuum chamber by an N-type feedthrough. Both sides of this feedthrough have female N-type connectors and the male N-type connectors on the end of the cables are attached to the feedthrough. On the vacuum side, a third RG393 cable is used to carry the RF power. This RG393 cable is open-ended, and the metallic shield layer of it is attached to one end of an RF coil and the center core of the cable is attached to the other end of this RF coil. Using this configuration, the RF power is supplied to RF coil (and plasma) efficiently.

B. *DC power source configuration*

The DC power setup of the RF plasma cathode is shown in Fig.3. The DC power supply is a 1.5 kW device which could provide a maximum DC voltage of 1250 V and maximum DC current of 1.2 A. The electron current of the DC circuit could be read and recorded on a computer by connecting the DC power supply to the computer, using an USB connection. So, the I-V characteristics of the RF cathode could be obtained using this power supply.

The DC power is carried through a DC feedthrough into the vacuum chamber. Inside the vacuum chamber, the positive contact is connected to the biased electrode, and the negative contact is connected to the ion collecting electrode inside the RF cathode. The bias voltage is increased gradually and the current is read from the device.

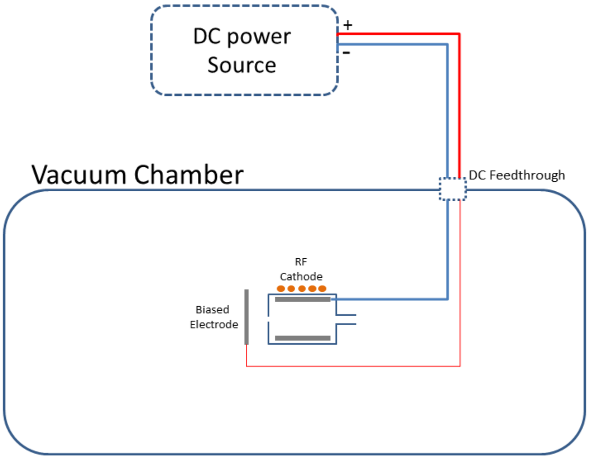

Fig. 3. Schematic of DC the power setup of the RF plasma cathode experiments

IV. EXPERIMENTAL RESULTS AND DISCUSSION

Plasma cathode device operation consists of two parts: 1) plasma generation, 2) electron extraction. In the experimental study of the prototype RF cathode both of these parts are investigated. The experiments are conducted to deduce the main operational characteristics of the RF plasma cathode.

A. *Plasma Generation*

Previous studies on the inductively coupled plasma (ICP) have shown that by applying the RF power to the coil, first a capacitively coupled plasma (CCP) forms at low RF powers. Then, by applying more RF power, a sudden change from CCP mode to ICP mode occurs, and the ICP plasma is generated. This abrupt change is known as E-H mode transition [10]. The E-H mode transition is also observed in RF plasma cathode. Fig.4 shows the lowest value of the forward RF power, which ignites CCP plasma, for various argon mass flow rates. For mass flow rates lower than 3 sccm, no CCP plasma was observed and ICP plasma was ignited directly. Fig.4 shows that by increasing the mass flow rate to 6 sccm, the power needed for CCP ignition becomes less, and for mass flow rates higher than 6 sccm, a constant power is needed to ignite the CCP plasma.

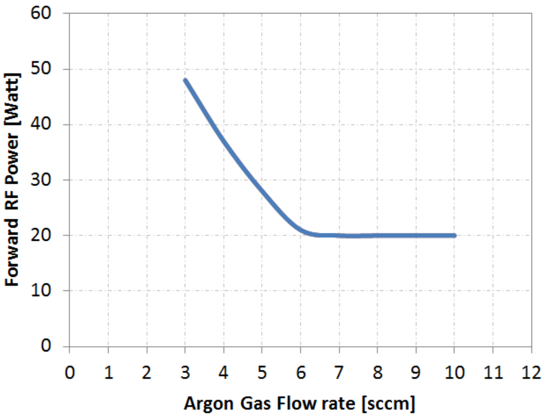

Fig. 4. Lowest forward RF power needed for CCP generation inside the RF plasma cathode for various argon mass flow rates

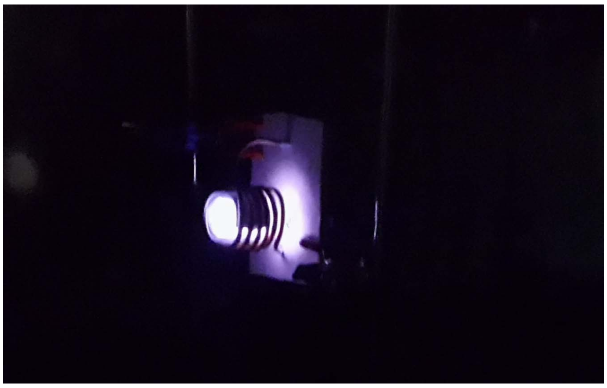

Fig. 5. RF plasma cathode operating at the ICP mode

CCP plasma is very dim and is generated only in a small part of the cathode vessel. By increasing the RF power, the CCP plasma becomes more luminous and it encompasses a larger part of the vessel. At a certain value of the RF power, an abrupt transition from CCP to ICP occurs and the plasma becomes very luminous, like a fluorescent lamp. At this point, the ICP plasma is generated. The photograph of the RF plasma cathode operating at the ICP mode is shown in Fig.5.

Fig.6 shows the lowest forward RF power for ICP generation in the RF plasma cathode, for various argon mass flow rates. Similar to the CCP plasma, the forward power needed for the ICP generation decreases by increasing the mass flow rate from 0.5 to 6 sccm. For mass flow rates higher than 6 sccm a constant power is needed to ignite the ICP plasma inside the RF plasma cathode.

After the ICP plasma generated, it could be sustained at lower values of the RF power. So, first the ICP plasma could be generated by higher RF powers, and after that it could be sustained at very low RF powers. This phenomenon is known as "hysteresis" and is an important characteristic of the ICP plasma [10]. The RF power values which could sustain the ICP plasma for various argon mass flow rates are shown in Fig.7. It can be seen from this figure that by increasing the mass flow rate, the lowest RF power needed to sustain the ICP plasma decreases. At 10 sccm of argon mass flow rate, an RF power as low as 9 Watts is needed to sustain the ICP plasma, after it is generated.

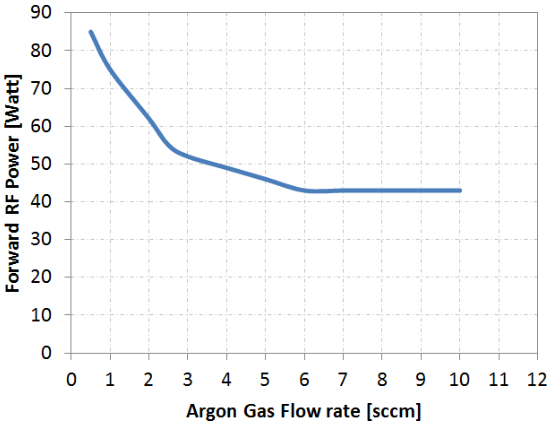

Fig. 6. Lowest forward RF power needed for E-H mode tarnsition and ICP generation inside the RF plasma cathode for various argon mass flow rates

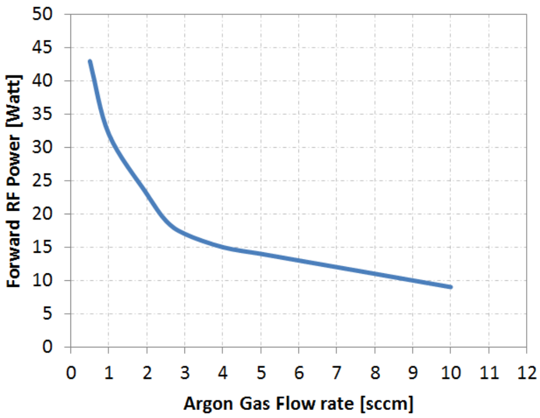

Fig. 7. Lowest forward RF power which could sustain the ICP plasma inside the RF plasma cathode, after the ICP plasma is generated, for various argon mass flow rates

B. Electron Extraction

In order to investigate the electron emission characteristics of the RF plasma cathode, a metallic plate was placed at a 1.5 cm distance from the frontplate of the cathode. As described in section III, the positive electrode of the DC power supply is connected to this plate, and the bias voltage is applied to the RF plasma cathode through it. The I-V characteristics of the RF plasma cathode for 3 and 4 sccm argon mass flow rates are shown in Fig.8 and Fig.9. It was observed that before the ignition of the ICP plasma, no current could be extracted from the RF plasma cathode, even by bias voltages as high as 200 V. So, in order to extract current from the cathode, the ICP plasma should be ignited first. At a certain flow rate, in order to extract electrons at the RF powers lower than the value needed for ICP ignition, first, the ICP is ignited by applying the minimum power, and then the power is reduced to the desired value. For example, in order to obtain the I-V characteristics of the device at 3 sccm argon mass flow rate and 25 W RF power, first 52 W (as the minimum power for ICP ignition at 3 sccm mass flow rate) is applied to the cathode, then the RF power is reduced to 25 W.

I-V characteristics of the plasma cathode in Fig.8 and Fig.9 show that at low bias voltages, the collected current is nearly zero. At a certain bias voltage, a jump in the extracted current is observed and secondary plasma, which is more luminous, is generated at the orifice of the cathode. This secondary plasma is known as anode spot and is the reason of the sudden increase of the extracted current [11]. From this point on, by increasing the bias voltage, the extracted current increases to a maximum value. When the bias voltage is increased to higher values, the plasma becomes unstable and the extracted current drops. When the bias voltage is increased to a certain value, the bias voltage effect extinguishes the ICP plasma and the extracted current becomes zero.

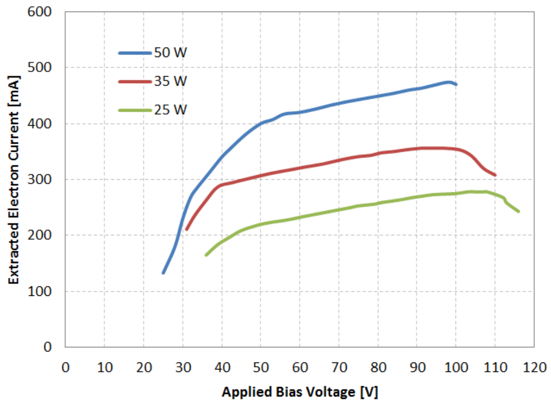

Fig. 8. I-V characteristics of the RF plasma cathode for 4 sccm argon gas flow rate and variuos RF power values

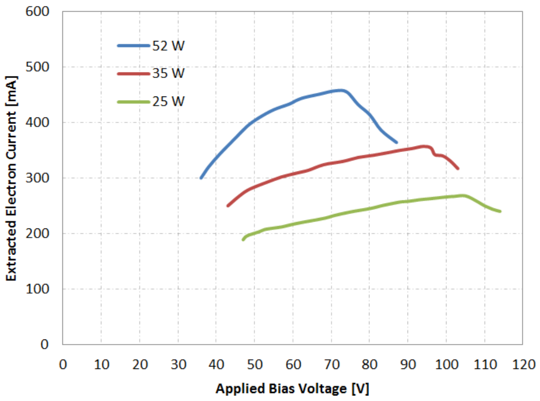

Fig. 9. I-V characteristics of the RF plasma cathode for 3 sccm argon gas flow rate and variuos RF power values

Fig.8 and Fig.9 show that at a constant mass flow rate, for higher RF powers, the current jump occurs at lower bias potentials. For example, at 3 sccm mass flow rate, the current jump occurs at 36 V for 52 W, and at 47 V for 25 W. Also, by increasing the RF power, the extracted current increases. It is observed that the extinguishing of the ICP plasma due to high bias voltage occurs at higher voltages for lower value of the RF power. It means that at lower RF powers, the ICP plasma could be sustained at higher values of the bias voltage.

In order to investigate the effect of the mass flow rate on the extracted current, the I-V characteristics of the cathode at 3 and 4 sccm of argon mass flow rates, and 40 W of RF power are compared. As shown in Fig.10, by increasing the mass flow rate, the jump in the extracted current occurs at lower bias voltages. Also, at a certain bias voltage, the extracted current is higher for higher mass flow rates.

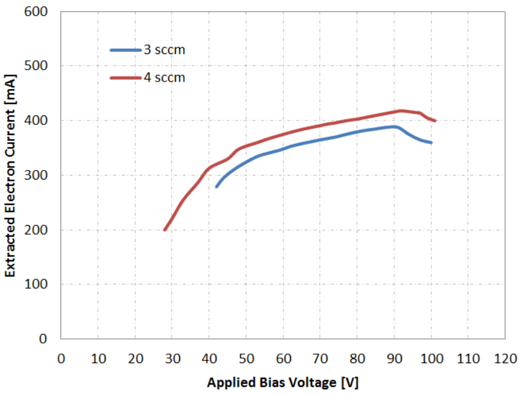

Fig. 10. I-V characteristics of the RF plasma cathode for 3 and 4 sccm argon gas flow rate and 40 W RF power

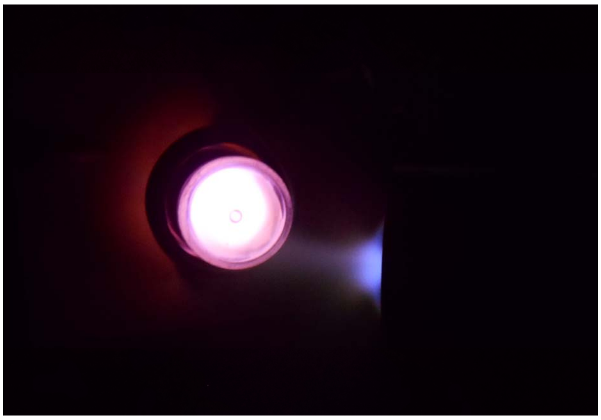

Fig. 11. Cusped field Hall thruster operating with the RF plasma cathode

C. Operation of the RF cathode with cusped field Hall thruster

The plasma cathode was used as the electron source and neutralizer of a home-built 40 mm diameter cusped field Hall thruster (CFHT-40) at the BUSTLab. As expected, the RF cathode operating at the ICP mode was capable of instantaneous initiation, and was able to sustain the thruster operation. It could provide currents as high as 1.2 A, which is the current limit of the DC power source used. A photograph of the CFHT-40 thruster operating with the RF plasma cathode is shown in Fig.11. However, at the CCP mode, the cathode was not able to initiate the plasma of the thruster.

V. CONCLUSION

A prototype RF plasma cathode was manufactured and tested in order to capture the main characteristics and operational procedures of the device. It was observed that before the generation of the ICP plasma inside the cathode, no electron current could be extracted from it. Also, the device starts to emit electrons at a certain value of the bias voltage. By increasing the bias voltage, the extracted current increases to a maximum and after that, increasing the bias voltage extinguishes the ICP plasma, and the extracted current becomes zero. Higher RF power and higher mass flow rate provide more electron current. Considering these results, it is concluded that a good procedure for the operation of the cathode could be the easy ignition of the ICP plasma at higher mass flow rates and RF powers, and reducing them to provide the desired electron current after the ignition of the of the ICP plasma.

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References

[1] Reader, P. D., White, D. P., and Isaacson, G. C., "Argon plasma bridge neutralizer operation with a 10-cm-beam-diameter ion etching source," Journal of Vacuum Science and Technology, Vol. 15, No. 3, 1978, pp. 1093-01095.

[2] Othmer, C., Glassmeier, K.-H., Motschmann, U., and Richter, I., "Numerical parameter studies of ion-thruster-beam neutralization," Journal of Propulsion and Power, Vol. 19, No. 5, 2003, pp. 953-963.

[3] Goebel, D. M. and Katz, I., Fundamentals of electric propulsion: ion and Hall thrusters, Wiley, 2008.

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

[5] 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.

[6] 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.

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

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

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

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

[11] Jahanbakhsh, S. and Celik, M., "Theoretical Investigation and Modeling of Current Extraction from a Radio-Frequency Cathode," 50th Joint Propulsion Conference (JPC), Cleveland, OH, July 2014, also AIAA-2014-3402.