Experimental Study of the Effects of Different Design Parameters on the Plasma Characteristics and the Extracted Current of a Prototype Radio-Frequency Plasma Cathode

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As an alternative to hollow cathode, plasma cathodes are being considered to be used in electric propulsion applications as electron sources. Plasma cathodes are types of electron sources where a bulk plasma, generated inside a chamber, is used to extract electrons through an orifice. This is done by applying a positive potential in front of the orifice of the device, or the electron extraction is achieved as a result of the higher potential of the thruster ion beam. Various methods, such as helicon, electron cyclotron resonance (ECR), microwave and radio frequency (RF), have been employed for the plasma generation inside the plasma cathode devices. The device takes its name from the method of the plasma generation. The advantages of the RF plasma such as compact geometry, easy generation, and high density and efficiency, make it preferable for the plasma cathode applications. The aim of the present study is to investigate the basic operational principles of the RF plasma cathode, and the effect of different parameters on its operation. It is shown that the electron extraction is only possible when the RF plasma cathode operates in the ICP mode. Also, the effect of different operational parameters, such as RF power, argon mass flow rate and the positive voltage of the biased electrode, on the electron extraction of the RF plasma cathode are presented.

I. Introduction

Tungsten filaments were the first electron sources used in early electric propulsion applications such as electron-bombardment ion thrusters, which were developed in 1960s. To obtain electron current, the filament should be heated. But, tungsten has a high work function, so the filaments should be heated to a high temperature to emit the desired electron current. To reach this temperature, a high heater power is needed. In addition, heating up the tungsten filament results in its evaporation, and the surface of the filament is subjected to the ion bombardment. These effects limit the lifetime of the tungsten filament. So, this type of cathode has a lifetime of a hundred hours or less.[1]

Hollow cathodes were introduced in 1960s, as a result of the problems encountered in using the tungsten filaments. Hollow cathode has a cylindrical hollow tube as the plasma vessel. This hollow tube has an orifice plate at one of its end surfaces. Inside the tube, there is a cylindrical insert, which is an electron emitter, that is pushed towards the orifice plate. The materials that are used as the insert have low work function, in order to have better thermionic electron emission. The hollow tube is surrounded by a heater, which heats the insert to reach necessary temperatures for the initiation of sufficient thermionic emission from the insert

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surface. The electrons that are emitted from the insert have collisions with the gas that is supplied to the cathode, and this process results in the formation of a plasma inside the tube. This plasma is used to extract electrons through the orifice.[1]

Although hollow cathodes operate efficiently and provide high electron current density by using low electric power and propellant, they have some disadvantages. Even though it is much less that that of the tungsten filaments, the evaporation of the insert material is a lifetime-limiting factor. Also, presence of any impurities such as oxygen and water vapor in the propellant or in the test environment, may lead to chemical alternation of the surface of the insert material, and thus resulting in a significant decrease in its thermionic emission capabilities. In addition, due to high temperatures needed for its operation to begin, the initial heating process of the insert material can take a significant amount of time and power, and thus preventing the cathode from being switched on immediately.

As an alternative for the hollow cathode, plasma cathode devices have been introduced in recent years. These devices do not employ an insert material. In plasma cathode, a bulk plasma is generated inside a vessel. This bulk plasma is used to extract electrons. Similar to hollow cathode, the electrons are extracted through an orifice. The method of bulk plasma generation could be chosen among various methods which are employed to generate plasmas. The device takes its name from the method of the plasma generation. For example, capacitively coupled plasma (CCP),[2] inductively coupled plasma (ICP),[3,4] electron cyclotron resonance (ECR) plasma[5,6] and helicon plasma[7] have been used as the plasma generation method in plasma cathode devices.

Inductively coupled plasma generation could be achieved in compact geometries, and it could operate efficiently, even for low applied power and for low gas flow rates. Because of these advantages, the ICP is considered as one the best choices for the plasma cathode device. In this study, two different designs are presented for the radio frequency cathode device. The advantages and problems of the both designs are described. Also, some experimental results about the ICP generation and electron extraction from the prototype RF plasma cathode are presented.

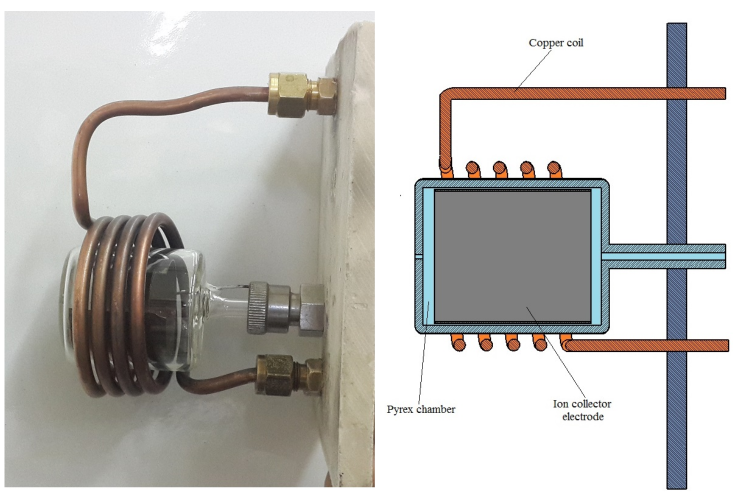

Figure 1. 2D drawing and the picture of the manufactured prototype RF plasma cathode

II. RF Plasma Cathode Designs

In order to understand the basic operational behavior of the RF plasma cathode, a prototype version of this device was designed and manufactured. Figure 1 shows a 2D drawing and picture of the prototype RF plasma cathode. The concept of this design is taken from Hatakeyama et al.'s study.[3] The prototype RF plasma cathode has three main parts: pyrex chamber, copper coil and ion collector electrode. As can be seen from the picture, the chamber, front plate and gas inlet of the prototype RF plasma cathode are manufactured as one component. This integrated component is made of pyrex. The chamber 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 chamber of the RF cathode. The chamber has an orifice in the center of its front surface. The diameter of this orifice is 2 mm. There is a thin hole on the backside of the chamber which allows the connection of the ion collector to the ground using a thin wire. This hole is sealed using a ceramic glue. The RF cathode chamber and RF coil are mounted on a backplate through appropriately machined holes on the backplate. The backplate is made of teflon.

Although the described prototype RF plasma cathode is easy to manufacture and easy to use, some design parameters such as the orifice length and diameter could not be controlled properly when manufacturing the cathode chamber. Also, after manufacturing the cathode, the inside of the chamber is unreachable. So, it is not possible to change the ion collector electrode and clean the inside of the chamber, when it is needed. To solve these problems, an advanced version of the RF plasma cathode device was designed and manufactured. The 2D drawing and a picture of this design of the RF plasma cathode is shown in Figure 2. In this design, the chamber is also maid of pyrex. But, the front plate is not integrated with the chamber. Instead, the chamber is extended out to the sides at its end, so that an o-ring between the extended part and the front plate is used achieve sealing. The extended part of the chamber is pressed towards the orifice plate with the help of 8 threaded rods that are bolted to the back plate.

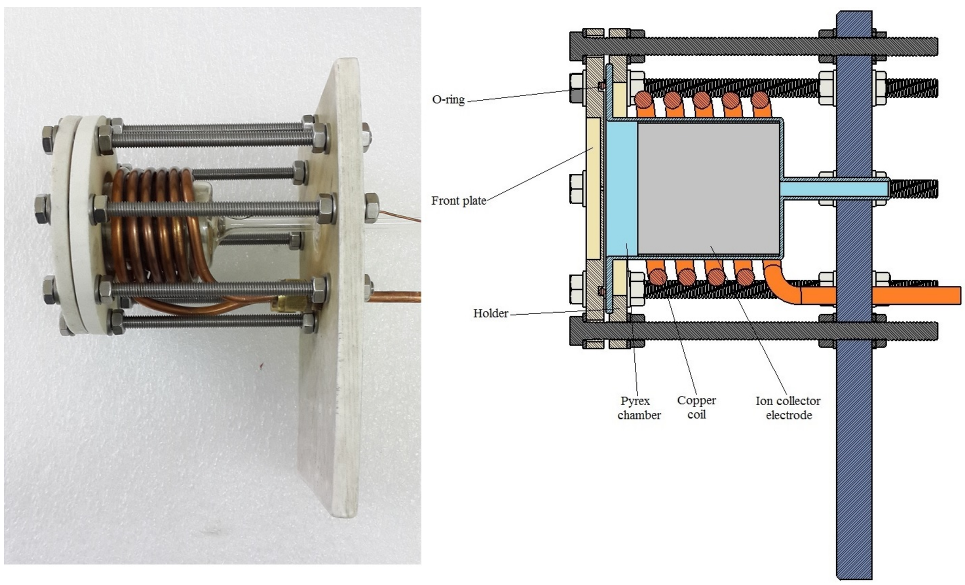

Figure 2. 2D drawing and picture of the new prototype RF plasma cathode

III. Experimental Setup

The RF plasma cathode experiments have been conducted inside 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. The chamber is rough pumped with a rotary vane pump with roots blower with a pumping capacity of 253 m^3/h. The chamber is then pumped with two 12-inch cryogenic pumps each with 3100 liters per second argon pumping capacity. With these two cryogenic pumps, the pressure inside the vacuum chamber is maintained on the order of 3.2×10^{-5} Torr for 10 sccm argon flow rate.

Schematic of the radio frequency power setup is shown in Figure 3. In this setup, coaxial RG393 cables with N-type connectors are used to carry the RF power. The output of the matching network is connected to an N-type connector. A double-sided N-type feedthrough, with female N-type connectors on both sides, is used for carrying the RF power from outside to inside of the vacuum chamber. Inside the vacuum chamber, one end of the coaxial cable is left open. The center core of the cable is connected to one end of the copper

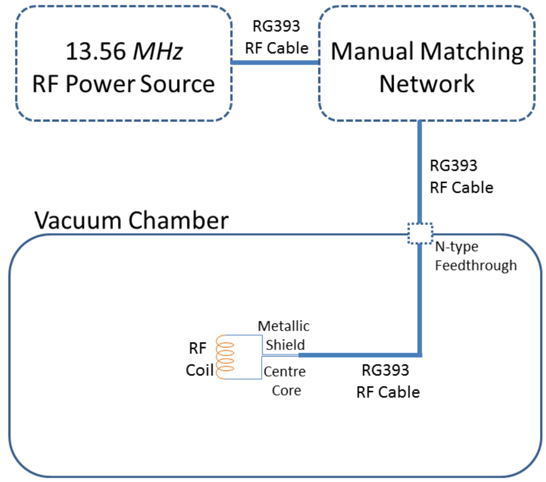

Figure 3. Radio frequency power setup of the RF plasma cathode experiments

coil, and the metallic shield of the coaxial cable is connected to the other end. Using this setup, the RF power is applied to the copper coil, antenna, to generate the plasma.

In order to extract electrons from the cathode, an electrode is placed in front of it. This electrode is connected to the positive side of a DC power supply, and the ion collector and negative side of the power supply are connected to the common ground. 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 a USB connection. So, the current versus voltage 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.

IV. Experimental Results and Discussions

A picture of the more advanced design of the RF plasma cathode placed inside the vacuum chamber for testing and a picture during its operation inside the chamber are shown in 4. After the more advanced design of the RF plasma cathode was manufactured and tested, some problems were observed on the ICP generation of the device. So, the experimental results presented in this study belong to the prototype RF plasma cathode shown in Figure 1.

Plasma cathode device operation consists of two parts: i) plasma generation, ii) 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

Applying radio frequency power to coil antenna leads to the generation of two types of plasma: capacitively coupled plasma (CCP) and inductively coupled plasma (ICP). Capacitively coupled plasma forms at low RF powers. After the generation of the CCP plasma, increasing the RF power leads to an abrupt transition from CCP to ICP. This abrupt change is known as E-H mode transition.[8] The E-H mode transition is also observed in RF plasma cathode.

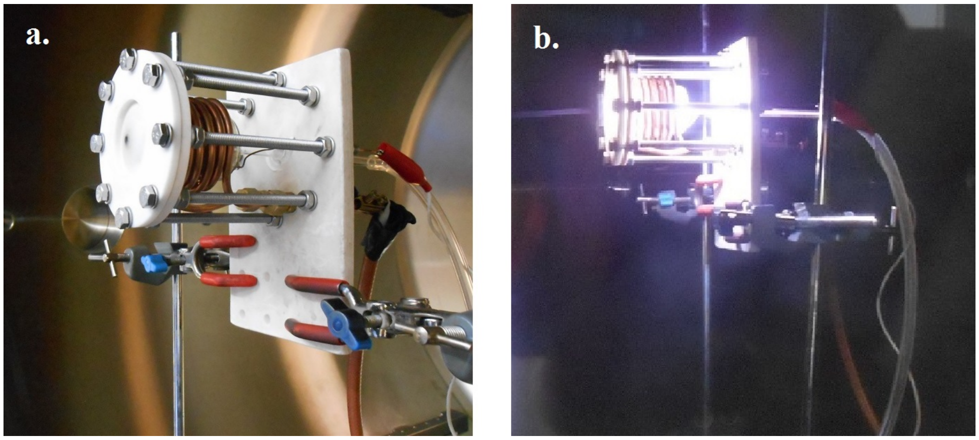

Figure 4. Pictures of the RF cathode test setup a) inside the vaccum chamber and b) during its operation

The minimum values of the RF power needed for CCP plasma generation, ICP plasma generation and sustaining the ICP plasma inside the RF plasma cathode are shown in Table 1. Regarding the CCP generation inside the cathode, for mass flow rates lower than 3 sccm, no CCP plasma was observed and ICP plasma was ignited directly. This table shows that as the mass flow rate is increased to 6 sccm, the power needed for CCP ignition drops, and for mass flow rates higher than 6 sccm, a constant power is needed to ignite the CCP plasma.

The most obvious feature of the CCP plasma inside the RF cathode is that this plasma is very dim, especially at low RF powers. At low RF powers, the CCP plasma encompasses only a small part of the cathode chamber. By increasing the RF power, the CCP plasma grows in size and becomes more luminous. When the RF power reaches to a certain value, an abrupt change occurs and plasma becomes very luminous. This abrupt change is the E-H mode transition, which is described above.

The lowest values of the applied RF power which could generate the ICP plasma inside the RF plasma cathode at various argon mass flow rates are presented in Table 1. From this table it can be seen that by increasing the argon mass flow rate from 0.5 sccm to 6 sccm, the RF power needed for the ICP generation decreases, and for argon mass flow rates higher than 6 sccm, a constant power is needed for the ICP generation.

Table 1. Minimum RF power needed for CCP generation, ICP generation and sustaining the ICP plasma inside the RF plasma cathode for various argon mass flow rates

Argon Mass Flow Rate [sccm]	0.5	1	2	2.5	3	4	5	6	7	8	9	10
Minimum RF Power for CCP Generation [W]					48	37	28	21	20	20	20	20
Minimum RF Power for ICP Generation [W]	87	81	80	63	55	53	50	46	46	46	46	46
Minimum RF Power for Sustaining ICP [W]	43	32	23	19	17	15	14	13	12	11	10	9

An important property of the ICP plasma is that the plasma could be sustained at lower RF powers, after it is generated. This behavior of the ICP plasma is known as "hysteresis".[8] Regarding the RF plasma cathode operation, the ICP plasma could be generated by applying high RF powers, and the device could operate on ICP mode, even by decreasing the RF power. The lowest values of the RF power that could sustain the ICP plasma inside the RF plasma cathode, for various argon mass flow rates, are shown in Table 1. The results presented in this table show that by increasing the mass flow rate, the RF needed to sustain the ICP plasma decreases.

B. Electron Extraction

To extract electrons from the RF plasma cathode, a metallic plate is placed in front of the orifice of the device and it is biased positively relative to the grounded ion collector inside the cathode. During the RF plasma cathode experiments, it was observed that before the ICP generation, it is impossible to extract electron current from the device. So, the CCP plasma could not provide any electron current, even in bias potentials as high as 200 V. So, referring the problems of ICP plasma generation inside the advanced design of the RF plasma cathode, it was not possible to examine its electron extraction characteristics.

In prototype RF plasma cathode experiments, the positively biased metallic plate was placed at a distance of 1.5 cm from the frontplate of the cathode. Figure 5 shows the extracted electron current versus the applied bias potential for 3 and 4 sccm of argon mass flow rate. When examining the I-V characteristics of the RF plasma cathode, the hysteresis phenomenon is used widely. In order to obtain the I-V characteristics of the device for RF power values lower than the minimum power needed for ICP generation, first the minimum value of RF power is applied and ICP is generated, and then the RF power is reduced to the desired values. For example, in order to obtain the I-V characteristics of the device at 3 sccm argon flow rate and 25 W of 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.

The results of the electron extraction experiments presented in Figure 5 show that at low bias voltages no electron current could be extracted from the device. Increasing the bias voltage to a certain value leads to generation of a secondary plasma. Generation of this plasma causes a jump in the extracted electron current from the device. This secondary plasma is known as *anode spot*.[9] By increasing the bias voltage to higher value, the extracted current increases to a maximum value. Increasing the bias voltage to higher values causes instabilities in the ICP plasma and the extracted electron current drops due to these instabilities. At a certain value of the bias voltage, the instabilities inside the cathode extinguishes the ICP plasma. So, the plasma inside the cathode returns to the CCP mode, and the extracted current becomes zero.

Figure 5 shows that at a constant mass flow rate, for higher RF powers, the current jump occurs at lower bias potentials. For example, at 3 sccm argon 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 values of the RF power. It means that at lower RF powers, the ICP plasma could be sustained at higher values of the bias voltage.

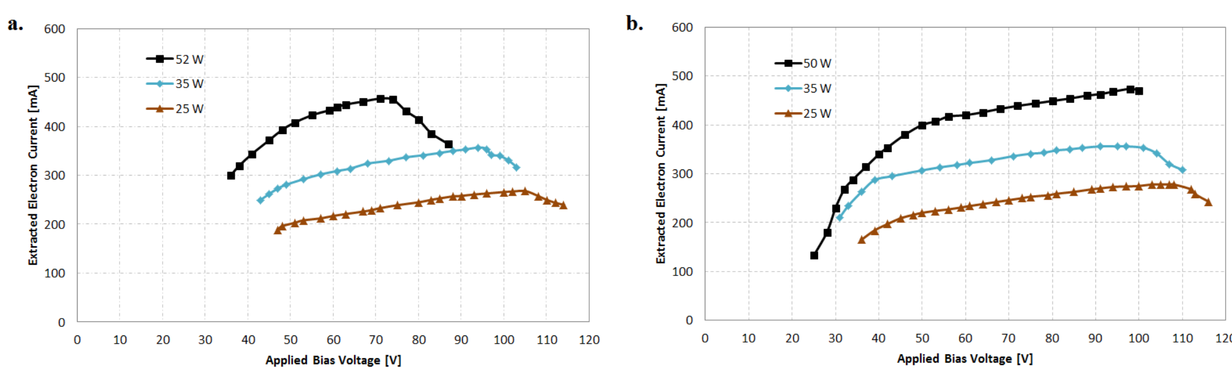

Figure 5. I-V characteristics of the RF plasma cathode for a) 3sccm and b) 4sccm of argon gas flow rates at various RF power values

Figure 6 shows the I-V characteristics of the RF plasma cathode device for 40 W of RF power and 3 sccm and 4 sccm of argon mass flow rates. The results of this figure show that at a constant value of the RF power, more electron current is extracted at higher mass flow rates. Also, it is observed that the current jump and anode spot generation occurred at lower bias voltages for the higher mass flow rate case.

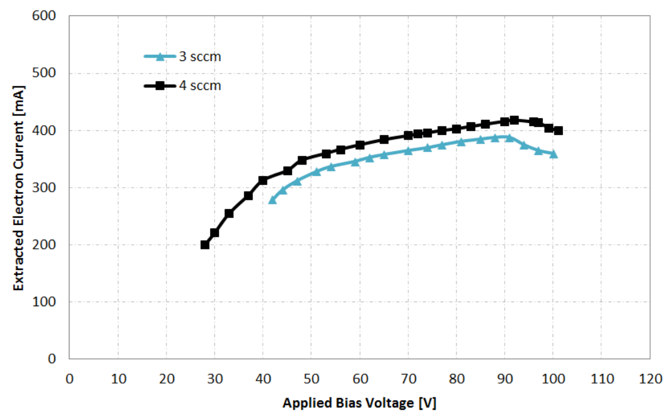

Figure 6. I-V characteristics of the RF plasma cathode for 3 sccm and 4 sccm argon gas flow rates at 40 W RF power

C. Operation of the RF cathode with Cusped Field Hall Thruster

A 40 mm diameter cusped field Hall thruster (CFHT-40) was desigend and manufactured at the BUSTLab. The prototype RF plasma cathode was used as the neutralizer and electron source of this thruster. When operating in the ICP mode, the RF plasma cathode was able to instantaneously ignite the plasma of the thruster and sustain its operation. It is observed that the cathode was able to provide electron current of 1.2 A, which is the maximum current limit of the DC power supply used in these thruster experiments. Similar to the current extraction experiments, the RF cathode operating at the CCP mode could not provide electrons for the thruster and the device was not able to ignite the plasma at the CCP mode.

V. Conclusion

Two different RF plasma cathode designs were presented. Both of these designs was manufactures and tested. Experimental studies have shown that in order to extract electrons from the RF plasma cathode, the plasma inside the cathode should be at the ICP mode. Due to some problems observed regarding the ICP generation inside the advanced design of the cathode, the experimental results generated in this study belong to the prototype RF plasma cathode only.

The electron extraction experiments show that the I-V characteristics of the device is not continuous and the cathode does not emit electrons at lower values of the bias potential. At a certain value of bias voltage, a certain jump in the extracted current is observed. By increasing the bias voltage, the extracted current increases to a maximum, and after that, increasing the voltage reduces the current, and extinguishes the ICP plasma at a certain value of the bias potential. It is observed that by applying higher RF power and higher mass flow rates, the extracted electron current is increased.

Acknowledgments

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