A Parametric Study of Electron Extraction from a Low Frequency Inductively Coupled RF-Plasma Source

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Abstract: The electron extraction from a low-frequency (2 MHz) inductively-coupled rf-plasma cathode is characterized in the presence of the gas flow. The extracting electrode is movable and biased with respect to the rf-cathode. The variable parameters include extracting voltage, inter-electrode distance between the extracting electrode and rf-plasma source, rf-power and xenon gas flow. The results demonstrate that the electron supply from the rf-cathode can be controlled in a broad range of the extraction current.

I. Introduction

PLASMA hollow cathodes with thermionic emitters made from low work function materials are extensively used in plasma propulsion to sustain the dc discharges and to provide charge and current neutralization of the ion flow from ion and Hall thrusters.[1-5] The critical issues of the thermionic hollow cathodes are possible failures of emitter and heater, lifetime limitation, high sensitivity of emission properties to various contaminations, a time consuming start-up, noise and oscillatory disturbances affecting the generation of random EMI. Alternative cathode-neutralizer configurations such as dc arcjet[6] were proposed and studied to overcome some of these issues. The operation of the arc jet cathode-neutralizer is based on the electron extraction from the arc plasma. At low pressures, the arcjet operation requires electron emission from its cathode to maintain the arc discharge. Consider instead a non-emitting plasma cathode in which the plasma is produced by rf-waves. Like in the arcjet neutralizer, the electron extraction in this cathode is also from the plasma. However, in the absence of the electron emission from the walls, the dc electric circuit of the rf-cathode is closed only by the ion current to the cathode chamber wall. The extraction of electrons from the rf-plasma cathode can be implemented through the opening in the cathode chamber. If the electron saturation current through this opening is larger than the ion saturation current to the chamber wall, then the maximum electron extraction current is limited by the ion Bohm current.[7] This limiting current is determined by the plasma density in the cathode chamber, the ion Bohm velocity at the sheath edge and the surface area of the chamber.

In contrast to thermionic plasma cathodes, the operation of the non-emitting rf-plasma cathode does not require heating or large electric fields. In addition to potentially favorable lifetime and operational characteristics, including smaller ion-induced sputtering, weaker sensitivity to wall contamination and a faster ignition procedure as compared to thermionic hollow cathodes, the electron extraction current from the rf-plasma cathode can be varied and controlled by changing the gas flow, rf-power, or ion collecting surface. A better controllability of the rf-plasma cathode could facilitate a more efficient implementation of non-self-sustained operation of low power Hall thrusters.[8-11] In this new operating regime, conventional annular and non-conventional cylindrical Hall thrusters demonstrated significantly higher performance than in the normal self-sustained regime.[8,10,11] With the thermionic hollow cathodes, the non-self-sustained thruster operation was implemented by running the auxiliary cathode discharge between the intermediate keeper electrode and the cathode emitter.[10,11] For example, for the cylindrical

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Hall thrusters, 30% plume narrowing (Fig. 1), 20% thrust increase and up to 50-60% increase of the thruster anode efficiency were achieved when the keeper current was 3-4 times larger than the main (thruster) discharge current (~0.5-0.7 A).[8-11] However such unusual operation of the hollow cathode requires additional power consumption (up to 50 W) for the keeper discharge, which reduces the total thruster efficiency.[8,10] Moreover, the operation of the hollow cathode with a high keeper current may shorten the cathode lifetime. In this respect, if the non-emitting plasma cathode was able to maintain a similar high performance operation of the Hall thruster, it could be a preferable option even with comparable power consumption.

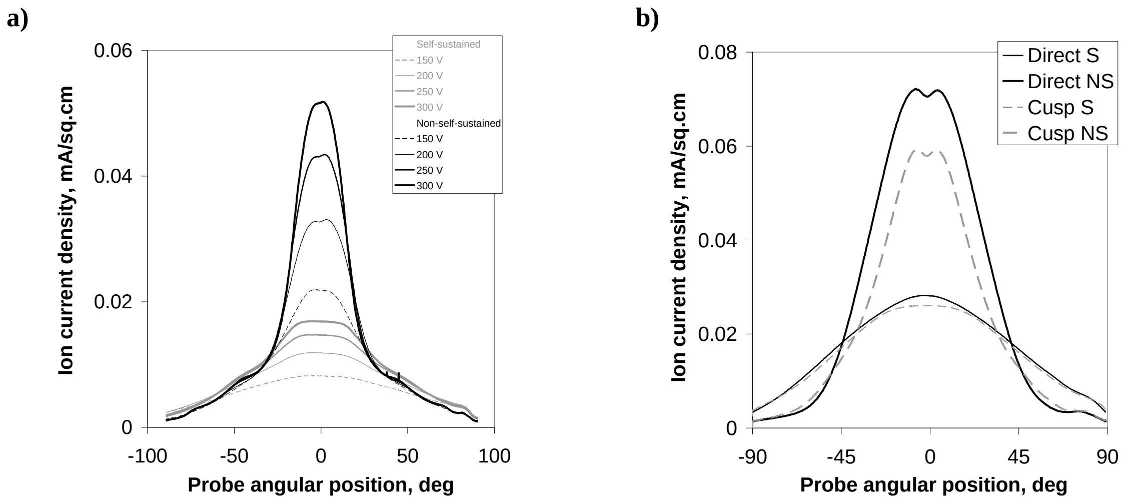

Figure 1. Plume narrowing effect for different low power Hall thrusters of differential geometry and magnetic field configurations (from Ref. 11). The non-self-sustained operation is referred to the thruster operation with the auxiliary cathode-keeper discharge, while the self-sustained operation is when the hollow cathode operates in the normal self-heated regime. The ion angular current distribution measured in the far-field plume (70 cm from the thruster) by the planar probe with a guarding sleeve.
a) For the conventional annular Hall thruster at different discharge voltages and the flow rate of 3.4 sccm; (b) For the cylindrical Hall thruster with direct and cusp magnetic field configurations at the discharge voltage of 250 V and xenon gas flow rate of 4 sccm.

Several rf-plasma cathode configurations were developed and tested for thruster applications, including helicon-based rf-plasma cathode,[7] resonant cavity microwave cathode,[12] ECR discharge cathode[13] and an inductively-coupled plasma (ICP) cathode.[14] For microwave and ECR cathodes, the use of high frequency is associated with low efficiency of rf converters leading to additional weight for thermal management of these converters. Moreover, magnetic field circuits required for helicon and ECR cathodes are also are associated with higher cost, weight and complexity.

In Ref. 14, we described a plasma cathode, which is based on a new inductively coupled plasma (ICP) source developed by Godyak. This ICP source uses an efficient internal antenna operated at the relatively low frequency of 2 MHz. The cathode was shown to operate in a wide range of gas pressure and electron emission current. The cathode demonstrated a very efficient power to plasma conversion. The last assures a high efficiency of the plasma cathode (Ampere/Watt). This cathode demonstrated the maximal partial cathode efficiency (extracted current-to-the rf-power)of 25 mA/W=(40 V)$^{-1}$.[14] In this paper, we continue parametric studies of the electron extraction from this cathode with focus on the effect of the cathode operating parameters and the extracting bias voltage on the extracted electron current from this plasma cathode. As compared to previous experiments, these experiments were conducted in a larger vacuum chamber and at lower background pressure in the downstream region of the vacuum chamber where the electron collecting electrode is placed.

II. Experimental Setup

Fig. 2 shows the rf-cathode and the experimental setup. The plasma cathode consists of a cylindrical stainless steel chamber 7.5 cm ID and 10 cm length. A cylindrical rf-antenna encapsulated into glass shell of 2.5 cm OD. The extracting opening is 1.5 cm diam. Thus, the ratio of the ion collecting area to the electron extracting area is much less than $(M_{ion}/2\pi m_e)^{0.5}$, where M_{ion} and m_e are the ion mass and the electron mass, respectively. Under such conditions, the maximum electron extraction current through the opening is limited by the ion Bohm current to the wall of the rf-cathode.[7]

The gas inlet tube, the high voltage electrode or filament used for ignition of the rf-discharge and Langmuir probes are fixed at the top part of the chamber. The cathode was connected to the 12" diameter six-way stainless steel vacuum chamber through the 2-3/4" diameter ceramic vacuum breaker. The chamber was pumped with a turbo pump backed with a mechanical pump. In the described experiments, the background pressure did not exceed 0.3 mtorr at the xenon gas flow rate of 10 sccm.

The rf-antenna was energized at 2 MHz with an rf-power source via resonant matching network. The transmitted to the matching network rf power was measured with rf-power meter. In previous experiments,[9] additional direct measurements of the rf-current, voltage and phase shift between them were used to determine the power losses in the antenna and matching network were evaluated and the power transfer efficiency (the ratio of the power absorbed by plasma to that delivered to the matching network).[14]

The extracted electron current was collected by a 2.5 cm diameter movable electrode, which was biased positive with respect to the floating cathode. All measurements were performed with xenon gas. The gas flow was measured with a FC-260 model Millipore flow controller.

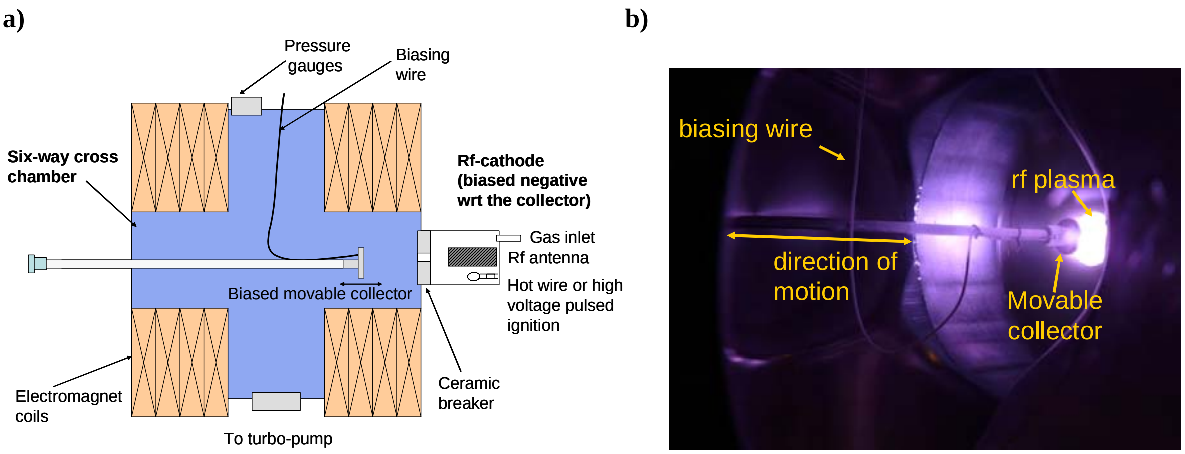

Figure 2. Experimental setup for tests of rf- plasma cathode at the PPPL: a) schematic b) during the cathode operation with xenon gas.

III. Experimental Results

The effects of the collector bias voltage (or the extracting voltage) and the distance between the collector (or the extracting electrode) and the rf-plasma cathode on the electron extraction from the cathode plasma are shown in Fig. 3. The extracted current saturates with the bias voltage due to the saturation of the ion current to the chamber wall of the rf-cathode (Fig. 3a). The saturation current almost does not change with the distance between the extracting electrode and the rf-cathode. However, a large voltage over longer inter-electrode distance is needed to maintain this current. Note that the bias voltage threshold at which the extracted current saturates increases almost linear with the inter-electrode distance. If the voltage drops in the anode and cathode sheaths are not affected by changing the inter-electrode distance, this result could be explained by employing Ohm law - for constant background pressure and rf-plasma conditions, the same electric field is needed to maintain the same current at different inter-electrode distances.

The operation of the plasma cathode can be analyzed in terms of the partial (rf) and total cathode efficiencies (Figs. 3b and 4). The partial efficiency is defined as the ratio of the extracted current to the rf-power (i.e. for the saturation current, this efficiency is equal to the inverse ion cost in the rf- discharge). In the present experiments, this efficiency reaches 25-30 mA/W (i.e. ~ $(33\text{-}40\ V)^{-1}$). In Ref. 14, we reported similar results for the same cathode operated in a different setup at high background pressures.

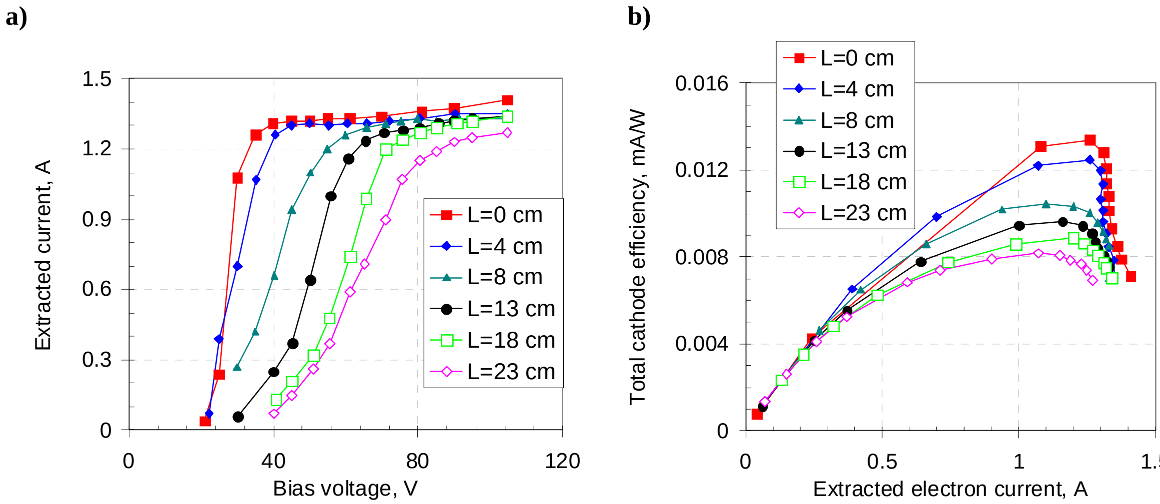

Figure 3. The effects of the bias voltage of the collector with respect to the cathode and the inter-electrode distance between the collector electrode and the rf-plasma cathode: a) the extracted current collected by the collector electrode as a function of the collector bias and b) the total cathode efficiency as a function of the extracted current at different inter-electrode distances and bias voltages (from figure on the left). The total cathode efficiency is defined as the ratio of the extracted current to the total power, including rf-power and dc extracting power. Note, that the maximum partial cathode efficiency (rf-power only) is 30 mA/W = (33 V)$^{-1}$.

The total cathode efficiency is the ratio of the extracted electron current to the total power, including rf power and the dc power associated with the electron extraction. Fig. 3b shows that a closer proximity of the extracting electrode leads to high efficiencies. The total efficiency drops as the extracting (bias) voltage increases above the voltage threshold. For larger gas flow rates, the maximum total efficiency is higher (Fig. 4) that is likely due to lower electron temperatures, which are required to maintain balance between the ionization and the wall losses. For low pressure weakly ionized discharges, the increase of the power leads to the increase of the plasma density. This is probably what can explain the increase of the electron extracted current with the rf-power (Fig. 4).

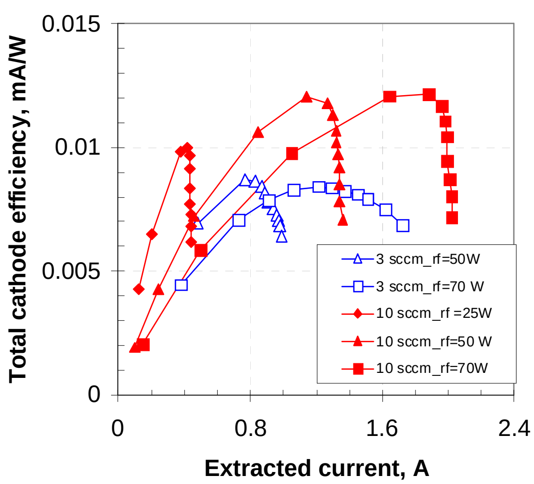

Figure 4. Total cathode efficiency for different xenon gas flow rates and rf power obtained for the inter-electrode distance of 5 cm. Note, that the maximum partial cathode efficiency (rf-power only) is 30 mA/W = (33 V)$^{-1}$

IV. Concluding Remarks

We continued parametric studies of the electron extraction from the non-emitting rf-plasma cathode, which is based on a new inductively-coupled plasma source with an efficient internal antenna operated at the relatively low frequency of 2 MHz. The obtained results generally confirmed results of previous studies, which were conducted in a smaller vacuum chamber at relatively higher background pressures in the downstream region of the electron collector. The demonstrated maximum partial (rf power) cathode efficiency is ~ 30 mA/W, while the maximum total cathode efficiency, which takes into account rf-power and the dc extracting power is ~ 12-13 mA/W. It is shown that the electron current from rf-plasma cathode can be controlled by varying the rf-power (Fig. 4). This feature of the rf-cathode can be useful for implementation of high performance non-self-sustained regimes of low power Hall thrusters.[8-12]

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