RF Plasma Cathode-Neutralizer for Space Applications

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Abstract: A new plasma cathode-neutralizer based on electron extraction from inductively coupled plasma (ICP) with an internal antenna operated at low frequency has been characterized in a wide range of rf power and gas pressure. The extracted electron current and ICP electrical and plasma parameters were measured as functions of rf power, downstream gas pressure and extracting voltage. Found in our experiment the maximal electron emission efficiency of 25 mA/W = (40 V)$^{-1}$ is found to exceed those described in the literature for microwave and helicon plasma cathodes.

I. Introduction

EXISTING cathode technologies for space applications are based on fundamental phenomena of electron emission from solids, including field emission and thermionic emission. Plasma hollow cathodes with thermionic emitters made from low work function materials (e.g LaB6) or composites (e.g. porous tungsten impregnated with the low-work-function composite of barium oxide, calcium oxide, and aluminum oxide) are extensively used in plasma propulsion due to their large generated current densities and low cathode-fall voltages.[1] For these cathodes, the dominant surface emission process is field-enhanced, thermionic emission.

The critical issues associated with the thermionic hollow cathodes are possible failures of emitter and heater, lifetime limitation due to depletion of low work function impregnated materials, localized heating and plasma-induced erosion of the emitter, high sensitivity of emission properties to various contaminations, a time consuming procedure for the cathode start-up. Consider instead a plasma cathode, which uses electron extraction from plasma, where the electric circuit is closed mainly by ion current to the cathode chamber surface. In contrast to thermionic plasma cathodes, the operation of this non-emissive cathode does not require heating or large electric fields. Several non-emissive plasma cathode configurations were developed and tested for thruster applications, including resonant cavity microwave cathode,[2,3] helicon-based rf plasma cathode[4,5] and ECR discharge cathode.[6-8] For these cathodes, the use of high frequency is associated with low efficiency of rf converters leading to additional weight for thermal management of these converters. In addition, magnetic field circuits required for helicon and ECR cathodes are also are associated with higher cost, weight and structural complexity.

In the present work, we describe a new plasma cathode, which is based on inductively coupled plasma (ICP) with an efficient internal antenna operated at the relatively low frequency of 2 MHz. It is able to operate in a wide range of gas pressure and electron emission current, and differs from known plasma cathodes by a very efficient power to plasma conversion. The last assures a high efficiency of the plasma cathode (Ampere/Watt). It has performance superior to those reported in the literature. It does not require magnetic field (unlike helicon and ECR sources) or a microwave frequency (resonant cavity and ECR cathodes, > 1 GHz).

II. Experimental Setup

The plasma cathode shown in Fig. 1 consists of a cylindrical stainless steel chamber 75 mm ID and 100 mm length having two openings on the top and the bottom. A cylindrical rf antenna encapsulated into glass shell 25 mm OD was inserted in the top opening while the extraction tube 15 mm ID, 38 mm long with NW16 connector was welded to the bottom opening. The gas inlet tube, the starting filament cathode and Langmuir probes were fixed at the top part of the chamber.

The extruded in the chamber length of the antenna was 55 mm. 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 P was measured with rf power meter. By additional direct measurements of the rf current, voltage and phase shift between them, 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) was found [9].

The electron current was drawn through the extracting tube to the NW-16 elbow connector that was insulated from the grounded tube and being positively biased served as an electron collector. The other end of the elbow connector was connected to a pumped vacuum chamber where downstream gas pressure was measured. The measurements were performed in xenon gas.

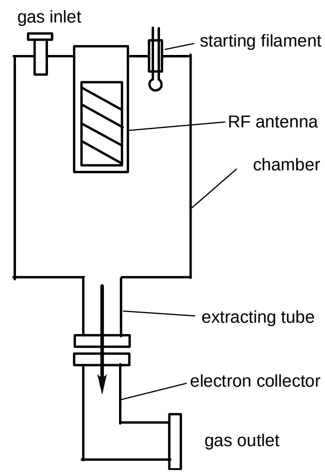

Figure 1. Schematic diagram of the plasma cathode.

III. Experimental Results

The measured power transfer efficiency of the new plasma cathode is shown in Figs. 2 and 3. It was found through measurement of the total transmitted power and power losses in the antenna and matching network. Fig. 2 shows the power transfer efficiency as a function of the total rf power at the fixed values of downstream xenon pressure p = 0.5 mTorr and extracting voltage V_{ex} = 30 V. An unusually high efficiency reaching over 97% in the power range between 75 and 200 W suggests negligible power losses in the antenna and matching network (less than 3%). Such large efficiency is due to a strong antenna to plasma coupling provided by the immersed in the plasma antenna.

Pressure dependence of the power transfer efficiency is shown in Fig. 3 for the fixed total rf power P = 50 W. In xenon pressure range between 0.1 and 10 mTorr, the power transfer efficiency is slowly growing with gas pressure and lies between 0.94 and 0.98%. Found here power and gas pressure dependence is typical for any ICP source and is associated with plasma conductivity dependence on power and gas pressure [10,11].

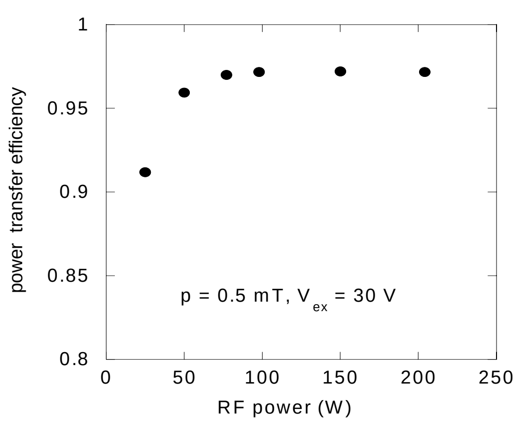

Figure 2. Power transfer efficiency versus RF power.

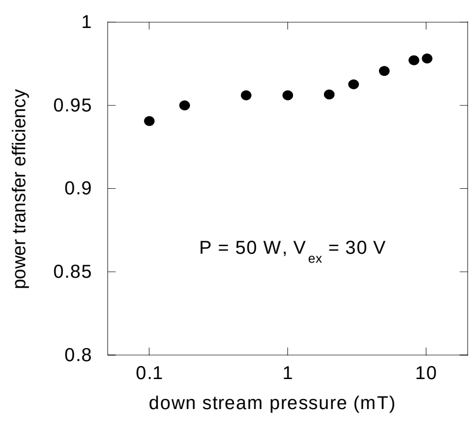

Figure 3. Power transfer efficiency versus downstream pressure.

Electron energy probability functions (EEPF) measured at different down stream pressures and rf power 100 W are shown in Fig. 4 and corresponding values of the plasma density and the electron temperature, calculated as corresponding integrals of the measured EEPF, are shown in Fig. 5. Note that due to pumping through a narrow extraction tube, gas pressure in the discharge chamber is considerably higher than the measured downstream pressure; the difference could be an order of magnitude. Also, the plasma density maximum is not between the antenna and side wall where it was measured, but somewhere in the middle between the antenna end and the bottom opening, on the chamber axis. Depending on gas pressure the plasma density here is a few times larger than in the point of measurement. In Figs. 4 and 5, the trends in EEPF and basic plasma parameters are typical for the low pressure ICP.[11]

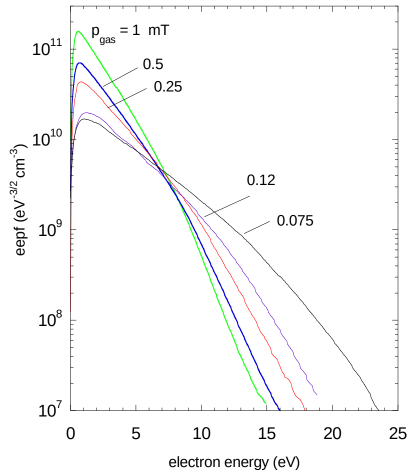

Figure 4. Electron energy probability functions for different downstream pressure, P = 100 W.

The extracted current to the elbow electron collector as a function of the extracting collector voltage reference to the grounded chamber and extracting tube is shown in Fig. 6. As seen in Fig. 6, the electron extraction through the extraction tube is starting at 10 V and reaching saturation at the collector voltage around 30 V. Increase in the extracted electron current leads to increase in the negative voltage across the wall sheath that is close to the plasma space potential shown in Fig. 7 as a function of extracted current. The increase in negative wall sheath voltage from floating (8.44 V) to the current biased (13.9 V) corresponds to cut off of the electron current to the wall. The maximal wall sheath voltage (13.9 V) corresponding to the electron saturation current appears to be small enough for any appreciable wall sputtering due to ion bombardment.

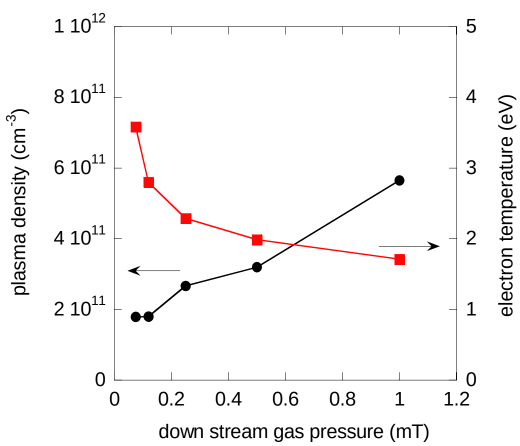

Figure 5. Plasma density and electron temperature versus downstream pressure.

The attempt to increase the extracted current by biasing the collector with dc power source operating in the current source mode caused the discharge extinguish. This is due to the saturation of the ion current to the chamber wall and a sharp rise in the wall sheath voltage with the ion current that is equal to the electron extracted current. Thus, the plasma cathode likely has some internal blocking mechanism, preventing an excessive wall sheath voltage, which causes erosion of the chamber wall.

Also in Fig. 7, the effect of the extracted electron current on plasma density is shown. The extracted electron current adds to the main rf discharge current induced by the antenna, and thus increases the plasma density by factor 1.68 at the maximal extracted current of 1 A. At the same time, the shape of the EEPF and the electron temperature was found practically unchanged with extracted current.

The extraction current dependence on the rf power at the down stream gas pressure 0.5 mTorr and the extracting voltage 30 V is shown in Fig. 8. The extracted current is nearly proportional to the rf power. At high rf power (200 W), there is a trend to saturation, probably associated with gas rarefaction caused by its heating. At p = 0.5 mTorr, in the power range between 20 and 200 W, the plasma cathode efficiency is about 20 mA/W, corresponding to 50 eV per an extracted electron.

It is known that there is an optimal product of gas pressure on characteristic size of the bounded plasma that provide maximal number of ionization per discharge power.[12] The extracted current dependence on the down stream gas pressure (Fig. 9) indicates its optimal value around 2-3 mTorr. This value corresponds to the pressure inside the chamber around 10 mTorr. At this optimal pressure, the plasma cathode efficiency is about 25 mA/W, it is essentially larger than that in the microwave (14 mA/W at 60 V extraction voltage [2]), and in the helicon (11-12.5 mA/W at 80 V extraction voltage [4,5]) plasma cathodes. In the both cases, the dc extraction voltage was at list twice larger than in our experiment and thus contributed to the rf discharge power in a larger extend than in our plasma cathode.

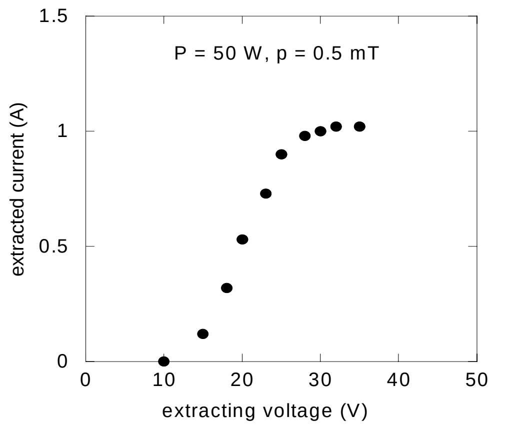

Figure 6. Extracted electron current versus extracting voltage.

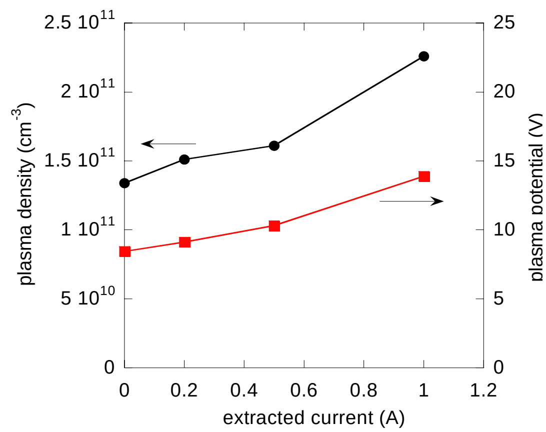

Figure 7. Plasma density and plasma potential versus extracted current.

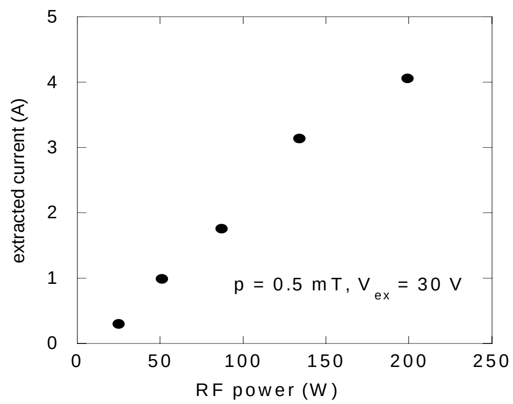

Figure 8. Extracted current versus RF power.

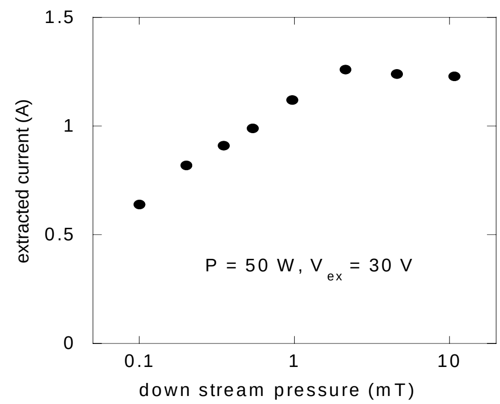

Figure 9. Extracted current versus downstream pressure.

IV. Conclusion

We described a new plasma cathode, which is based on ICP with an efficient internal antenna operated at the relatively low frequency of 2 MHz. This plasma cathode is able to operate in a wide range of gas pressure and electron emission current. It differs from known plasma cathodes by a very efficient power to plasma conversion, assuring a high efficiency of the plasma cathode. The cathode has a superior performance comparing to those reported in the literature. It operates at much lower frequency and therefore, required rf power source is more efficient and cheaper than microwave and high frequency power sources. Utilization of an internal antenna prevents electromagnetic radiation out of metal chamber. The new plasma cathode is simpler, has ridged construction and a smaller weight that those described in the literature. In future works, the rf-plasma cathode will be used to study high performance overrun-current regimes of the cylindrical Hall thrusters.[13]

Acknowledgment

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