Ferromagnetic Enhanced Inductively Coupled Plasma Cathode for Thruster Ion Neutralization

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Abstract. Plasma cathodes can be used as electron sources in electric propulsion applications. Unlike hollow cathodes where a low work function insert material that needs to be heated to elevated temperatures is utilized for the electron emission, plasma cathodes do not need to be preheated, and could be switched on instantaneously. Recently, at Bogazici University Space Technologies Laboratory (BUSTLab), radio frequency (RF) plasma cathode devices for use as electron sources of plasma thrusters have been studied, manufactured and successfully tested. Introduction of a ferromagnetic core enhances the power transfer efficiency of the inductively coupled plasma (ICP). In this paper, we present the design, manufacture and tests of two prototype radio-frequency cathodes, one with a standard coil antenna and the other with Mn-Zn ferrite core, for use in space propulsion applications as an electron source. The extracted electron current, electron extraction cost and gas utilization factor for the developed plasma cathodes have been studied.

INTRODUCTION

For spacecraft electric propulsion applications, hollow cathodes where a low work function emitter material is used for the thermionic emission of electrons are typically used[1, 2]. However, there is a growing interest in using plasma cathode devices as alternatives to hollow cathodes. In plasma cathode devices, plasma is generated in a small chamber and electrons are extracted out of this plasma chamber through an orifice opening on one of the chamber walls[3]. Plasma cathodes can be switched on in a much shorter time when compared with hollow cathodes where the emitter material needs to be preheated to elevated temperatures [4]. In plasma cathode devices, for the generation of the plasma, different plasma generation methods such as radio frequency capacitively coupled plasma (CCP)[5] or inductively coupled plasma (ICP)[6], microwave [7, 8] and helicon[9] have been employed.

At Bogazici University Space Technologies Laboratory (BUSTLab), two different designs of radio frequency (RF) plasma cathode devices for use as electron sources of plasma thrusters had been studied, designed, manufactured and successfully tested[10]. The concept of these earlier plasma cathodes developed at BUSTLab had been taken from Hatakeyama et al.'s study[6]. In a plasma cathode device, there are two major processes: plasma generation and electron extraction. It is proposed that by adding a ferrite core in the antenna, the matching of the RF power to the plasma can be increased considerably, and the power efficiency for plasma generation can be improved significantly [11, 12, 13].

As part of this study, two RF plasma cathodes, one with a standard five turn coil antenna, similar to an earlier work[10], and the other with a single turn ferrite core antenna have been designed, manufactured and experimentally studied, with Argon propellant, in order to understand the effects of ferrite core in improving the RF power coupling to the plasma and increasing the mass utilization efficiency of the device.

DESIGN AND EXPERIMENTAL RESULTS

Drawings of the built RF plasma cathode devices are shown in Figure 1. Figure 1a shows the cathode with a coil antenna, whereas in Figure 1b, the cathode with an antenna where a novel design of ferrite materials in desired orientations (as shown in Figure 1c) is shown.

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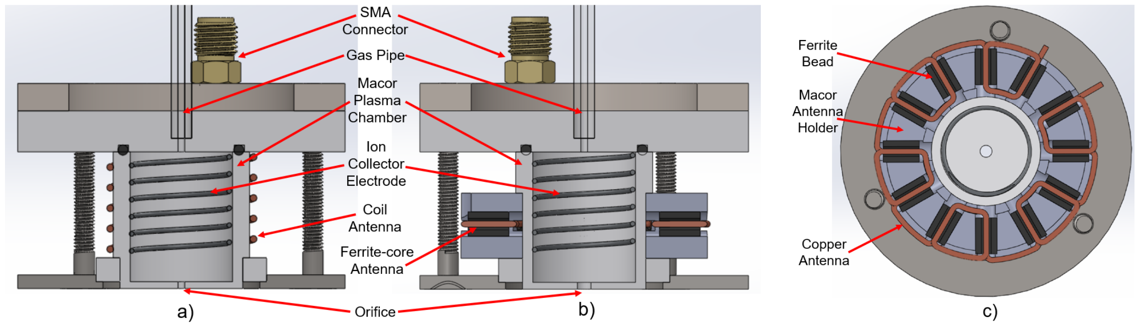

FIGURE 1. Cross-sectional drawing of the a) RF plasma cathode with a standard coil antenna b) RF plasma cathode with a ferrite core antenna, c) structure of the ferrite core antenna

The manufactured RF plasma cathodes have cup shaped macor chambers with inner diameter of 15 mm and length of 19 mm. The chamber has a 1.2 mm diameter orifice on the front wall. This macor chamber is placed on a macor back plate with a 1/8 inch gas inlet, and a groove for an o-ring of 16 mm diameter at 1.5 mm thickness. The chamber is secured on the back plate with the help of a set of stainless steel rings bolted to each other with the help of three long M3 screws. A coil shaped 0.7 mm thick molybdenum wire is placed on the inside wall of the chamber as the ion collector electrode. There is a small hole on the backplate aligned with the inside wall of the chamber to allow the connection of this ion collector coil to ground using a thin wire. This hole is sealed using epoxy glue. The RF antenna is attached to an SMA connector placed at the backplate. For the experiments, the area of the coil shaped ion collector is estimated to be 5.8 cm^2.

For the cathode with a standard coil antenna, a helical 5 turn copper wire of 1 mm diameter is used. For the cathode with ferrite core antenna, copper wire of 0.7 mm in diameter is wound around a specially machined macor piece where 12 Mn-Zn ferrite tubes of 1.75 mm inner diameter, 3.5 mm outer diameter and 6 mm of length are placed in radial directions as shown in Figure 1c.

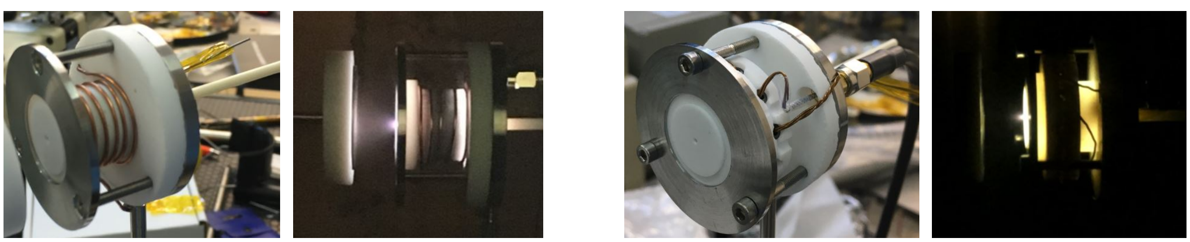

FIGURE 2. Pictures of the plasma cathodes with 5 turn coil antenna (left two images) and with ferrite core antenna (right two images)

The experimental measurements have been conducted inside the BUSTLab vacuum chamber which is 1.5m in diameter and 2.7m in length. During the tests, the vacuum level of the chamber has been kept on the order of 1.7×10^{-5} Torr for 4 sccm argon flow rate. Coaxial RG393 cables with N-type connectors are used to carry the 13.56 MHz RF power from the power supply to the vacuum feedthrough through a manual matching network. For the extraction of the electron current from the cathode, a 4 cm diameter stainless steel electrode is placed 12 mm in front of the orifice region. This electrode is connected to a DC power supply.

As expressed above, operation of a RF plasma cathode device consists of two parts: plasma generation and electron extraction. During the experimental studies, the matching network was used to find the best matching capacitor and inductor settings for the given antenna and plasma conditions. During the experiments the argon mass flow rate is set to a constant value, and an ICP plasma is generated inside the chamber. After this, a positive potential is applied to the electrode in front of the orifice and the extracted electron current values are recorded for varying propellant flow rate, RF power to the antenna and electrode potential values.

The measured values are compared with similar studies form the literature as presented in Table 1. The electron extraction cost is defined as the power required for the plasma production and the extraction of 1 A of electron current.

The gas utilization factor indicates the average number of times that an atom repeats ionization/recombination while it stays inside the discharge chamber [6].

TABLE 1. Comparison of the performance parameters for the plasma cathodes with and without ferrite core

Device	Propellant	Volume Flow Rate [sccm]	Extracted Current [mA]	Electron Extraction Cost [W/A]	Gas Utilization Factor
RF cathode with single turn ferrite core antenna	Argon	9	1420	216	2.21
RF cathode with five turn coil antenna	Argon	4	780	182	2.73
RF cathode by Hatekeyama[6]	Xenon	2.0	1500	93	10.6
RF cathode by Longmier[9]	Argon	15	3500	186	3.8
RF cathode by Weis[5]	Xenon	1.5	100	510	0.37

CONCLUSION

Two different RF plasma cathodes are manufactured, and tests were conducted to investigate the effect of a ferrite core on the performance of these RF plasma cathode devices. Based on the experimental results observed for the presented novel single turn ferrite core antenna design, it is expected that when an increased number of turns are used the power coupling to the plasma would increase, thus reducing the electron extraction cost beyond what is achieved with standard multiple turn coil antenna.

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