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Modelling of a radio frequency plasma bridge neutralizer (RFPBN)

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Abstract

A performance model of a radio frequency plasma bridge neutralizer was developed to calculate the electrical parameters and optimize the neutralizer design. Minimization of power losses and gas consumption, and a maximization of the neutralizer lifetime and the reliability of the system are requirements of all electric propulsion concepts and strongly determine their future application. The requirements of the neutralizer depend on mission profiles.

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Keywords: spacecraft; low thrust propulsion; control laws: Earth-Moon system, libration point, shaded areas.

1. Introduction

All electric propulsion concepts require electron sources for neutralization of the positive charge generated by the emitted ion current. Most of them operate with help of hollow cathodes with the well-known disadvantage - the sensitivity of the inserts against oxygen and vibrations, which leads to malfunctions of the neutralizer as in the case of the “Artemis”-mission electric propulsion system.

A cathode-less plasma bridge neutralizer should avoid these problems and was therefore developed and tested in the form of an inductively coupled radio frequency (RF) plasma excitation neutralizer at IOM [1,2,3].

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2. Design

The design of the radio frequency plasma bridge neutralizer (RFPBN) was developed at IOM based on a breadboard model [1,2]. The RFPBN consists of a plasma chamber with a hole (orifice) for the electron extraction, the matching network for minimizing the reflected RF power, the gas inlet and the electrical interface (Fig. 1**Ошибка! Источник ссылки не найден.**).

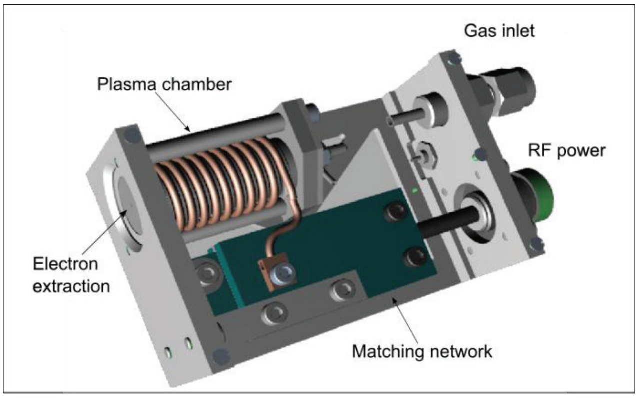

Fig. 1. Design of the RFPBN

The plasma chamber is cylindrical in shape and surrounded by a copper coil. This coil induces an electromagnetic field into the plasma chamber and generates an inductively coupled plasma (ICP). The electrons in the plasma will be extracted through the orifice at the front of the plasma chamber by generating a plasma bridge.

The matching network is especially designed for the neutralizer requirements. It consists of a stack of copper plates, which are internally connected to obtain two shielded capacitors. The capacitors must be thermally stable. This is a challenging task, because the capacitors are mounted close to the plasma chamber and, therefore, will experience a considerable thermal load by heat radiation.

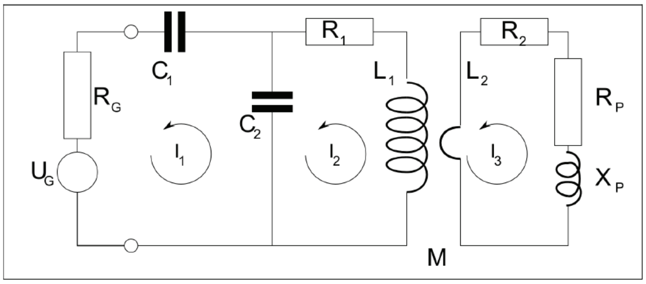

Fig. 2. Equivalent circuit diagram of the RFPBN with matching network

Fig. 1 shows the equivalent circuit diagram of the RFPBN with the matching network. The capacitor C2 of the matching network and the coil L1 of the neutralizer build a resonant parallel circuit. The other capacitor C1 is in series to the resonant circuit for compensating the imaginary part of the complex impedance value.

The gas inlet is integrated at the centre of the back side of the plasma chamber such that the gas flows is centred into the plasma chamber. To dissipate positive charges of the ionized gas ions, an ion collector is integrated on the inner side of the plasma chamber. This collector is slotted to minimize the leakage currents. The ion collector can be biased by a negative voltage to support the plasma bridge generation.

3. Performance model

The performance model calculations comprise two parts, the energy balance equation (Lieberman model, [4,5]) to calculate the plasma parameters and the transformer model [6] to estimate the reflected and power losses in the RFPBN system. A set of input parameters (Table 1) are necessary to run the simulation. All steps in the performance model loop (Fig. 3) are carried out at least once before the loop can be terminated.

First, the energy balance equation will be solved for a given RF power. The result is a set of plasma parameters (Table 2), which are thereafter used as input parameters for calculating the absorbed RF power in the plasma. This value is used in into the energy balance equation for the next loop run. The change of plasma density n between two runs is the criterion for the termination of the performance model calculation.

Table 1. List of input parameters for the performance model calculations.

Geometrical parameters	Electrical parameters	Gas parameters	Environmental parameter
Plasma chamber: Radius, length, extraction hole diameter Coil: Radius, length, number of turns	RF power, RF frequency, RFG impedance, matching network capacitance	Gas type, gas flow rate, gas temperature	Chamber pressure

3.1. Energy balance equation

The energy balance equation is used for the simulation of plasma parameters in inductively coupled, cylindrically shaped plasmas. The absorbed RF power P_{abs} is equal to the total power loss (Equation 1). E_T includes contributions by excitation, ionisation and elastic collision processes between ions and neutrals, and the losses by interaction with the chamber wall.

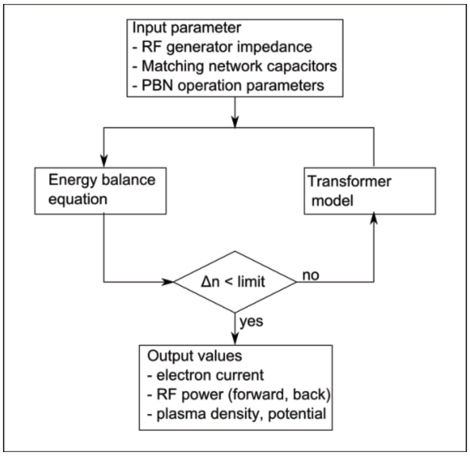

Fig. 3. Flow chart of the performance model

$$P_{abs} = en_0 u_B A_{eff} E_T \tag{1}$$

The effective loss area A_{eff} is calculated from the neutralizer geometry (length, diameter) and the screening length in the plasma volume. The Bohm velocity u_B depends on the electron temperature arising from the rate coefficient of ionisation and excitation processes. The plasma density n_0 can be calculated with this procedure. Gas specific parameters such as ionisation and excitation cross sections must be known to run the simulation.

Table 2. Output parameters of the performance modelling (selection).

Plasma parameters	Electrical parameters
• Electron density in the volume and sheath • Electron temperature • Average electron and gas particle velocity • Gas temperature • Wall potential • Resistance • Inductance • Debye length • Neutral density • Effective loss area for recombination processes • Bohm velocity	• Reflected RF power • Impedance of the system with and without plasma • Extracted electron current with and without plasma bridge • Absorbed RF power

3.2. Transformer model

The transformer model [6] describes the inductively coupled plasma system as a transformer with a primary and a secondary side. The secondary side consist of the plasma resistance R_p and the plasma inductance L_P in series. The plasma will be approximated by a coil with a winding number $N = 1$. The resistance R_p can be calculated using the Lieberman model results. The primary side is defined by the geometry (diameter, length, number of turns) of the RFPBN.

On the basis of the equivalent circuit (Fig. 2), the voltages and currents inside the plasma and in the matching network can be calculated using the Kirchhoff law for meshes by Equation (2).

$$\begin{aligned} U_g &= (R_g + X_{C1} + X_{C2})I_1 - X_{C2}I_2 \\ 0 &= -X_{C2}I_1 + (X_{C2} + R_1 + X_{L1} + X_M)I_2 - X_M I_3 \\ 0 &= -X_M I_2 + (R_2 + X_{L2} + R_p + X_p)I_3 \end{aligned} \tag{2}$$

X_C and X_L are the impedances of the capacitors and inductances, respectively, and M the mutual impedance of the transformer.

The performance model was written using the numerical computational package and high-level, numerically oriented programming language Scilab with a graphic unit interface [7]. The software is designed as a modular concept, which allows expanding it to include other working gases and excitation processes as described above.

Table 3. Input parameter values for the performance model calculations.

Parameter	Unit	Value
Radius / length of plasma chamber	[mm]	6 / 40
Extraction hole diameter	[mm]	0.2, 0.5, 1.0
Radius / length of coil	[mm]	8 / 32
Number of turns of coil		12
RF power / frequency	[W/MHz]	0 … 100
RFG impedance	[Ω]	50
Capacitance C_1 / C_2	[pF]	64 /150
Gas type / flow rate	[-/sccm]	Xe / 0 … 5
Gas temperature	[°C]	300
Chamber pressure	[mbar]	8 x 10^{-5}

4. Results

Performance model calculations were carried out in order to optimize the design of the RFPBN. In the following, selected results are presented. The calculations were done using the parameters given in **Ошибка! Источник ссылки не найден.**. We studied the influence of the gas flow rate, RF power and orifice diameter on the performance parameters. Fig. 4 shows calculation results for the extracted electron current vs. xenon flow rate for three orifice diameters.

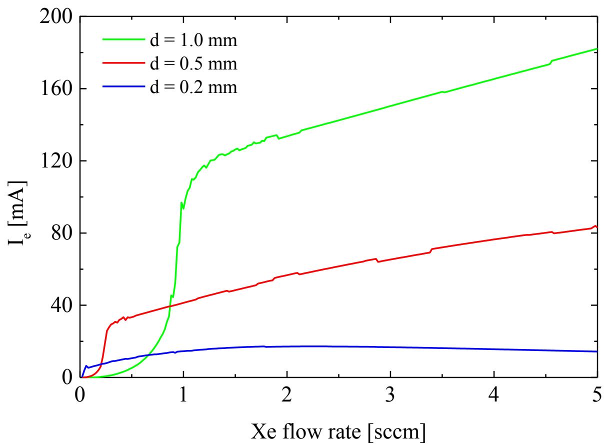

Fig. 4. Extracted electron current as function of xenon flow rate for various extraction orifice diameters and an RF power of 10 W

Apart from the case of an orifice diameter of 0.2 mm, the extracted electron current increases with increasing xenon flow rate as well as with increasing orifice diameter. In case of an orifice diameter of 0.2 mm, the electron current reaches a maximum at 2.0 sccm xenon flow rate because the induced RF power will be shielded by the plasma itself and is dominated by the skin effect.

In Fig. 5 the extracted electron current as a function of the RF power for the three different orifice diameters at fixed xenon flow rate is plotted. The current increases nonlinearly with the RF power because ohmic losses occur in the wires and the coil.

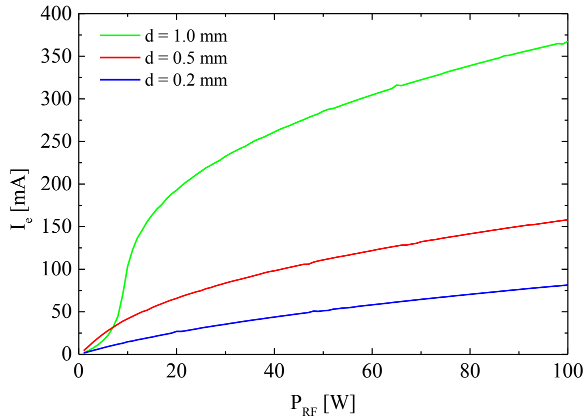

Fig. 5. Extracted electron current as function of RF power for various extraction orifice diameters and a xenon flow rate of 1.0 sccm

4.1. Wall potential

Fig. 6 summarizes calculation results of the plasma potential vs. xenon flow rate for the three orifice diameters at a fixed RF power.

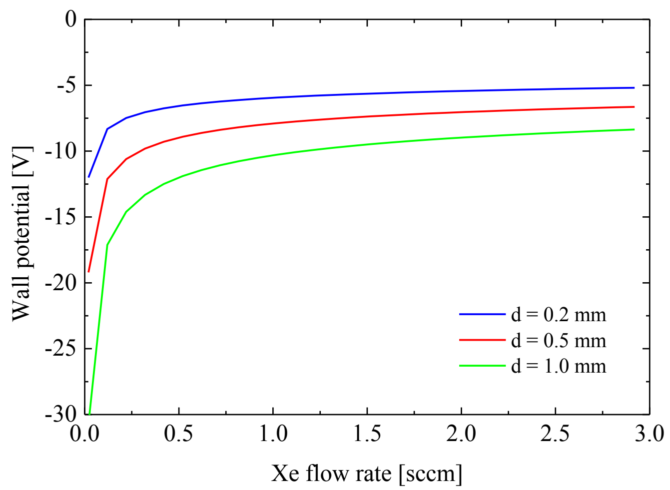

Fig. 6. Wall potential as function of xenon flow rate for various extraction orifice diameters and an RF power of 10 W

The wall potential is a measure for the energy of the ions in the plasma. With this energy, the ions can impinge on the wall of the plasma chamber, the orifice hole and the ion collector. These processes can influence the lifetime of RFPBN, because impingement of energetic particles leads to sputtering, i.e. erosion:

1. The extraction hole in the orifice could be eroded, i.e. the orifice diameter increases with time and, as consequence of that, the pressure inside the plasma chamber will decrease, which results in a smaller plasma density and, thus, a smaller extracted electron current. Thereby, the gas flow or the RF must be increased in order to keep the extracted

electron current constant.

2. The plasma chamber could be eroded with the risk that a short circuit between the coil windings and the housing of the neutralizer is created. This scenario is rather unlikely because the wall chamber thickness is greater than 1 mm.
3. The integrated ion collector could be eroded and the eroded material could be deposited on the inner wall of the plasma chamber. Then the ion collector material would form a conductive layer that would shield the electromagnetic field due to the skin effect. Thus, the plasma density and the extracted electron current would decrease. This could only be compensated by increasing the RF power.

In order to avoid or minimize erosion, it is necessary to minimize the plasma wall potential. It must be kept lower than the sputter threshold energy of the interacting material.

The sputter threshold energy does not only depend on the material but also on the ion species. Exemplary, selected threshold energies for Ar, Kr and Xe ion bombardment are given in **Ошибка! Источник ссылки не найден.**.

Table 4. Sputter threshold energy Eth in units of eV of selected materials for bombardment with Ar, Kr and Xe ions [8]..

Material	Ar	Kr	Xe
Mo	26.5	36.7	49.1
Cu	15.8	24.5	34.2
Ni	20.8	32.9	46.4
Ti	25.4	41.8	59.1

Following the data in **Ошибка! Источник ссылки не найден.**, it is clear that it is favourable to use xenon gas because all materials have the highest sputter threshold energy for xenon ion bombardment. However, the data in **Ошибка! Источник ссылки не найден.** show that argon and krypton might be used too.

4.2. Plasma impedance

Fig. 7-8 show calculation results of the real and imaginary part of the plasma impedance as function of the RF power (Fig. 7) and flow rate (Fig. 8), respectively.

Both the real and the imaginary part decrease with increasing RF power. However, increasing the xenon flow rate leads to an increase of the real part but to a decrease of the imaginary part. For a fixed matching network, it is important that the neutralizer working point is in a region with a small impedance change.

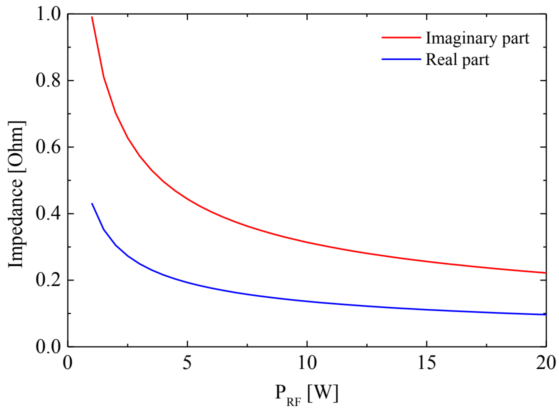

Fig. 7. Real (red line) and imaginary part (green line) of the plasma impedance as function of RF power at a xenon flow rate of 1.0 sccm

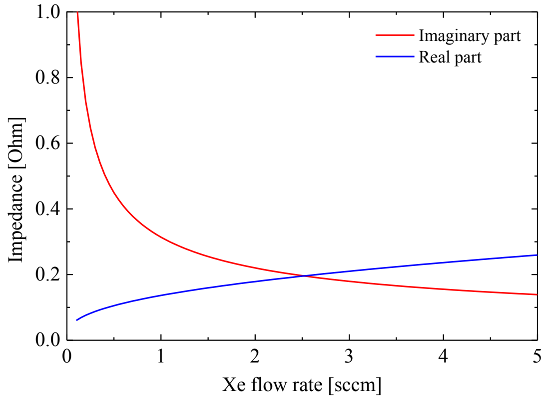

Fig. 8. Real (red line) and imaginary part (green line) of the plasma impedance as function of xenon flow rate at an RF power of 10 W

4.3. Electron temperature

Fig. 9. summarizes calculated electron temperature data vs. xenon flow rate. It is found that the electron temperature decreases with increasing xenon flow rate because the increased neutral density leads to a greater interaction between neutrals and electrons (thermalization). The electron temperature is independent of the RF power for a fixed gas flow (not shown here).

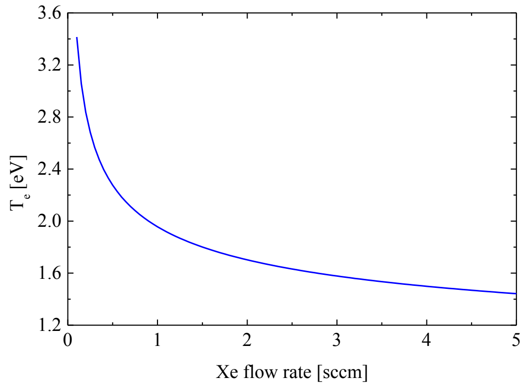

Fig. 9. Electron temperature as function of xenon flow rate (RF power 10 W)

4.4. Plasma density

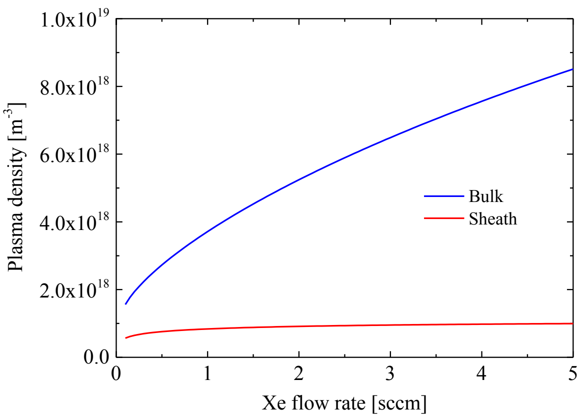

Fig. 10. Plasma density in the bulk (blue line) and in the sheath (red line) as function of xenon flow rate for an RF power of 10 W

The calculated plasma density data in the bulk and in the sheath vs. xenon flow rate are plotted in Fig. 10. It is noticed, as expected, that both plasma densities increase with increasing xenon flow rate. Similarly, the plasma density increases with increasing RF power (not shown here). The best neutralizer working point can be selected by either the gas flow rate variation or RF power variation.

5. Conclusion

We have performed performance model calculations based on the energy balance equation (Lieberman model, [4,5]) and the transformer model [6]. The influence of a geometrical parameter (orifice diameter), RF power and gas flow rate (with Xe gas) on the extractable electron current has been investigated. Furthermore, the plasma wall potential, the complex plasma impedance, the electron temperature and the plasma density have been calculated. Based on the calculation results, the design of the RFPBN can be optimized to specific needs.

Furthermore, the optimization of the RFPBN design with respect to mechanical and thermal stability is in progress. These activities are done in collaboration with our project partner Sgenia Soluciones s.l. (Madrid, Spain). Experimental verification of the calculation results will be one of the next steps after finalizing the designs and the manufacturing of the RFPBN.

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