Design and Performance Test of a RF Plasma Bridge Neutralizer

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Most electric propulsion concepts require electron sources for neutralization of the positive space charge generated by the emitted ion beam. As an alternative to, for example, hollow cathode systems, a radio-frequency plasma bridge neutralizer (RFPBN) employing an inductive-coupled plasma excitation was designed and tested at the Leibniz Institute of Surface Engineering (IOM). The RFPBN concept device consists of a cylindrical plasma chamber and an integrated matching network for a fixed frequency of 13.56 MHz and is adapted for applications which require electron currents between 2 and 100 mA. The neutralizer performance as the relation between extracted electron current and supplied DC and RF power shows that the presented concept is a viable alternative to conventional electron sources for ion beam neutralization. The RFPBN device was also successfully tested to withstand the mechanical stress with regard to vibration and shock imposed by a typical space mission. Furthermore, the RFPBN successfully passed a 900 hour endurance test and an 100 hour neutralization verification test using a RIT10 EVO gridded ion thruster from ArianeGroup.

Nomenclature

I_e	= extracted electron current
PE	= power efficiency
P_{RF}	= radio-frequency power
U_e	= emission voltage
U_{SSG}	= secondary star ground

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I. Introduction

Most electric propulsion concepts require electron sources for the neutralization of the positive space charge generated by the ion beam emitted from the thruster. Hollow cathode systems were often used for electric propulsion with the well-known disadvantage, i.e. the sensitivity of the inserts against oxygen and vibrations which can lead to malfunctions of the neutralizer. These problems can be avoided by employing an inductive-coupled plasma excitation. Therefore, a radio-frequency plasma bridge neutralizer (RFPBN) based on this concept has been developed and tested at IOM.[1–3] A performance model of the radio-frequency plasma bridge neutralizer was developed to calculate the electrical parameters and optimize the neutralizer design.[4] The neutralizer performance as the relation between extracted electron current and supplied DC and RF power shows that the presented concept is a viable alternative to conventional electron sources for ion beam neutralization.

In this paper, the design of the RFPBN, the results of the mechanical vibration and shock as well as thermal tests and the performance data of the electrical operation test are presented. Furthermore, data from the endurance test are shown and the space charge neutralization of a gridded ion thruster beam is demonstrated using the RFPBN.

II. Design of the RFPBN

The design of the radio-frequency plasma bridge neutralizer (RFPBN) developed at IOM bases on a breadboard model.[1,2] The RFPBN consists of a cylindrical plasma chamber with a hole (orifice) for the electron extraction, an integrated matching network for a fixed frequency of 13.56 MHz that minimizes the reflected RF power, a gas inlet and the electrical interface (Fig. 1). The plasma chamber is surrounded by a copper coil that induces an electromagnetic field in the chamber and thus generates an inductive-coupled plasma (ICP). The electrons are extracted from the plasma through the orifice with the help of a plasma bridge. The dedicated matching network consists of a stack of copper plates internally connected to obtain two shielded capacitors.[4] One challenge is to guarantee sufficient thermal stability as the matching network is placed close to the plasma chamber and is therefore subjected to a significant heat load under operation.

The design is adapted for applications which require electron currents between 2 and 100 mA. With respect to previous versions of the RFPBN[4] the mechanical design was recently optimized to withstand the stress due to vibration and shock imposed by a typical space mission.

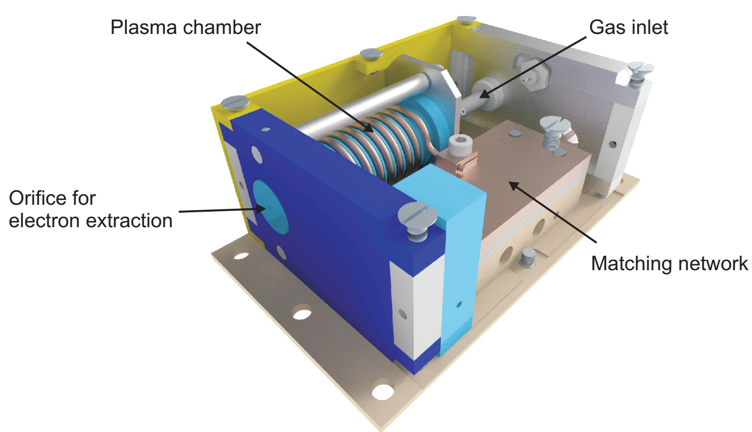

Figure 1. CAD representation of the RFPBN design.

III. Performance of the RFPBN

The performance test of the RFPBN was conducted in the IOM vacuum chamber Rez2000 (diameter: 1.2 m, length: 2.5 m) with a base pressure of $4 \cdot 10^{-7}$ mbar. The operation parameters RF power, Xe flow rate and emission voltage were varied to study the extracted electron current. In all measurements a hysteresis was observed in the dependency between the extracted electron current I_e and the emission voltage U_e (not shown). Upon increasing U_e, the current I_e rises abruptly by at least one order of magnitude at a specific voltage value that strongly depends on the RF power, the xenon flow rate and the back pressure in the vacuum chamber. At this voltage value, the plasma sheath inside the neutralizer's extraction orifice has broken down and a plasma bridge has formed due to the electric field created by the neutralizer's electron emission voltage U_e and the space charge of the thruster's ion beam (or the potential of an electron collector plate when no thruster is present). When decreasing U_e again, the current I_e drops less abruptly and the plasma bridge will break down at an U_e value lower than the one required for plasma bridge formation.

Figure 2 shows I_e as a function of U_e for different Xe flow rates (the curves are recorded while lowering U_e from 60 V to 0 V). As can be seen, the RFPBN meets the requirement to provide electron currents in the range from 2 to 100 mA. No plasma bridge formation could be observed with a xenon flow rate less than 0.4 sccm for emission voltages up to 60 V.

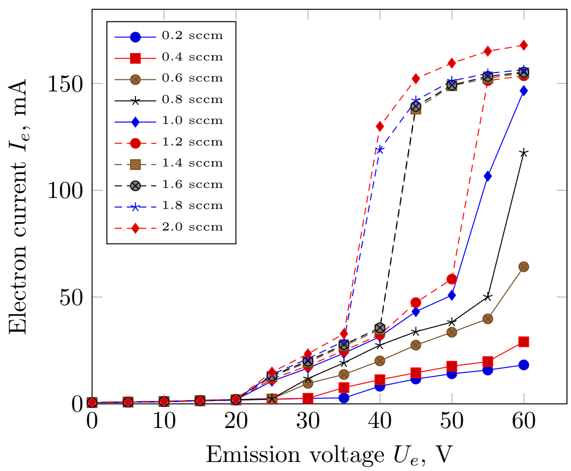

Figure 2. Extracted electron current I_e as function of the applied emission voltage U_e for different Xe flow rates and an RF power of $P_{RF} = 10$ W.

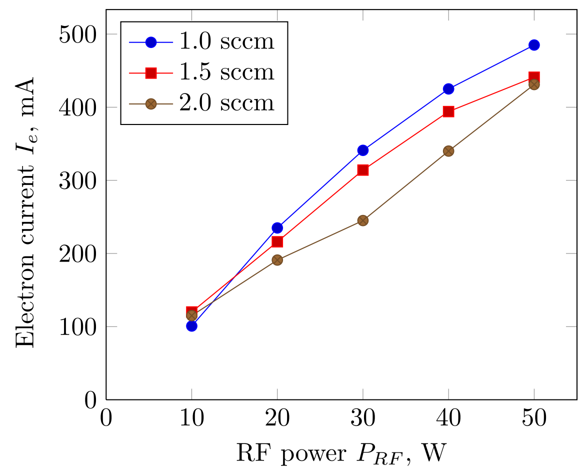

Figure 3. Extracted electron current I_e as function of the RF power of P_{RF} for different Xe flow rates and an emission voltage of $U_e = 60$ V.

Figure 3 shows the dependency of I_e on the RF power for different Xe flow rates. In order to extract an electron current of 100 mA an RF power of 10 W is sufficient. Upon increasing the RF power, electron currents well in excess of 100 mA can be achieved.

A measure for the efficiency of the RFPBN is the power efficiency PE calculated as the extracted current divided by the sum of forward RF power and DC extraction power (equation 1).

$$PE = \frac{I_e}{P_{RF} + I_e \cdot U_e} \tag{1}$$

The power efficiency is much smaller than 1 mA/W when no plasma bridge is formed. After plasma bridge formation, the values are between 2 and 10 mA/W with the highest efficiencies achieved at the lowest RF power.

IV. Mechanical and thermal tests

In order to check the mechanical and thermal robustness, the RFPBN was subjected to mechanical vibration and shock as well as thermal cycling tests. All tests were performed by Sgenia Industrial (Madrid, Spain). The specifications of the mechanical tests are based on the requirements for the Proba-3 mission and can be found in tables 1 and 2. The vibration tests were performed for all three axes that coincided with the principal axes of the RFPBN device. At the beginning and at the end of the vibration test sequence for each axis, a resonance search was conducted to monitor any changes in the mechanical integrity of the RFPBN. Furthermore, the RFPBN was inspected visually. The lowest natural frequency observed was around 500 Hz, significantly larger than 140 Hz as required by the specifications.

The shock tests were performed for all six corresponding directions in space and the RFPBN inspected visually after each axis.

Frequency, Hz	Level	Sweep rate or duration
Resonance search		
5 to 2000	0.5 g	2 octaves/min
Sinusoidal test		
5 to 20	11 mm (0 to peak)	2 octaves/min
20 to 100	20 g amplitude	2 octaves/min
Random vibration test		
20 to 60	+9 dB / octave	120 seconds
60 to 400	0.5 g^2 / Hz	120 seconds
400 to 2000	-6 dB / octave	120 seconds

Table 1. Specifications of the mechanical vibration test performed for all three axes (x, y, z).

Duration, ms	Acceleration, g
0.1	100
1.0	100
2.0	100

Table 2. Specifications of the mechanical shock test performed for all six perpendicular directions of space ($-x, x, -y, y, -z, z$).

After the mechanical tests, the RFPBN was subjected to thermal cycling tests as specified in table 3. At the end of the four cycles, the device was inspected visually.

Temperature cycling	$-40 \ldots 50°$C
Number of cycles	4
Dwell time (hot and cold)	2 hours
Temperature rate of change	1 K / min
Stabilization criterion	$<$ 1 K / min

Table 3. Specifications of the thermal cycling test.

The RFPBN passed all tests without any noticable damage. An operation test conducted afterwards showed that the RFPBN was still fully functional and within error margins had the same performance as before.

V. Endurance test

After the mechanical and thermal tests, an endurance test over a period of 900 hours was performed with the RFPBN in the IOM vacuum test facility Rez600 of 0.6 m diameter and length, interrupted every 300 hours for visual inspection. The whole test was performed with the following parameters: $I_e = 100$ mA, 0.6 sccm Xe flow rate, RF power $P_{RF} = (12 \pm 1)$ W and the emission voltage U_e adjusted manually to keep I_e within 5% of the preset value. As the resolution or smallest increment of the RF generator employed is 1 W, the RF power may have changed by ± 1 W during the test. All relevant data were logged continuously during the whole test.

The wiring of the components for the endurance test is shown in Fig. 4. The extracted electron current I_e was collected with a graphite plate on ground potential placed ≈ 3 cm in front of the orifice. Figure 5 shows exemplarily the extracted electron current, the emission voltage and the RF power for the last 300 hours of the endurance test. The small changes made to the emission voltage U_e during test when the electron

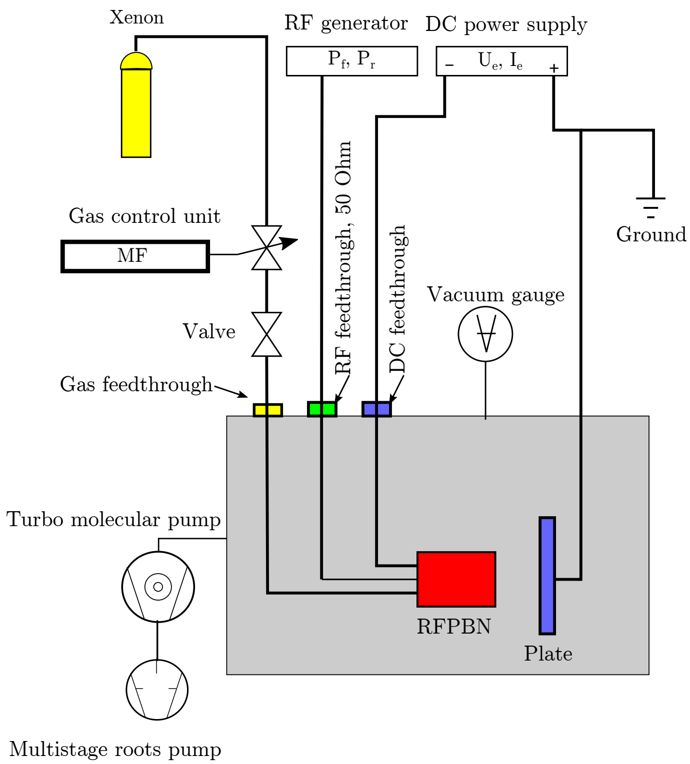

Figure 4. Schematic setup used for the endurance test of the RFPBN.

current deviated more than 5 mA from the preset value of I_e = 100 mA can be discerned. Especially at the beginning of each test period, when the RFPBN had not yet been thermally stable, it was necessary to readjust the emission voltage in order to keep the electron emission current constant. Thermal stability was achieved after ≈ 2 h of operation. Apart from this, the RFPBN demonstrated a stable operation without failure throughout the endurance test.

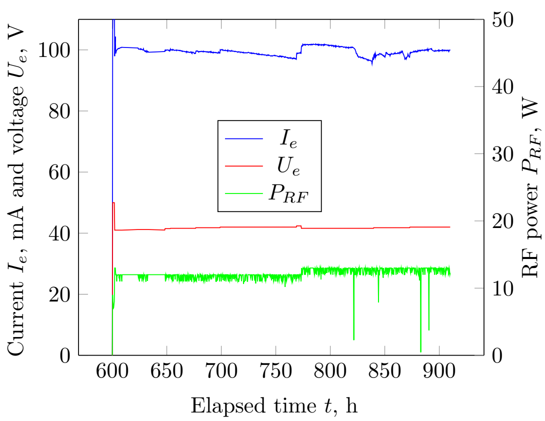

Figure 5. Electron current I_e, emission voltage U_e and RF power P_{RF} as a function of time during the last 300 hours of the endurance test.

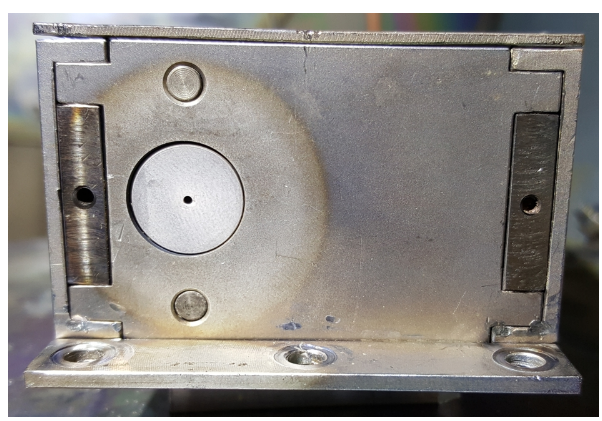

Figure 6. Optical image of the front side of the RFPBN after the endurance test. The discoloration around the orifice is clearly visible.

Figure 6 shows a picture of the electron extraction orifice of the RFPBN after 900 hours of endurance test. No measurable change in the diameter of the orifice aperture could be observed during the test. There is only a discoloration of the area around the extraction hole which increases over time. This change may be due to the presence of the electron collector only a few centimeters in front of the hole or from Xe ions that are present in the plasma bridge and are accelerated towards the RFPBN (the ion collector close behind the front face of the plasma chamber is negatively biased with U_e with respect to the collector plate), continuously bombarding the area around the orifice.

VI. Neutralization verification test

After the endurance test, a neutralization verification test was performed in the IOM vacuum test facility Rez2000 together with a gridded ion thruster RIT10 EVO from ArianeGroup. The wiring of the components for the neutralization test is shown in Fig. 7. Thruster and RFPBN are fixed on a isolated mounting plate so that both components have the same reference potential (SSG, secondary star ground) with respect to the ground of the vacuum chamber. The RFPBN is mounted at the same position as the conventional neutralizer used on the thruster and injects the electrons perpendicularly to the ion beam direction.

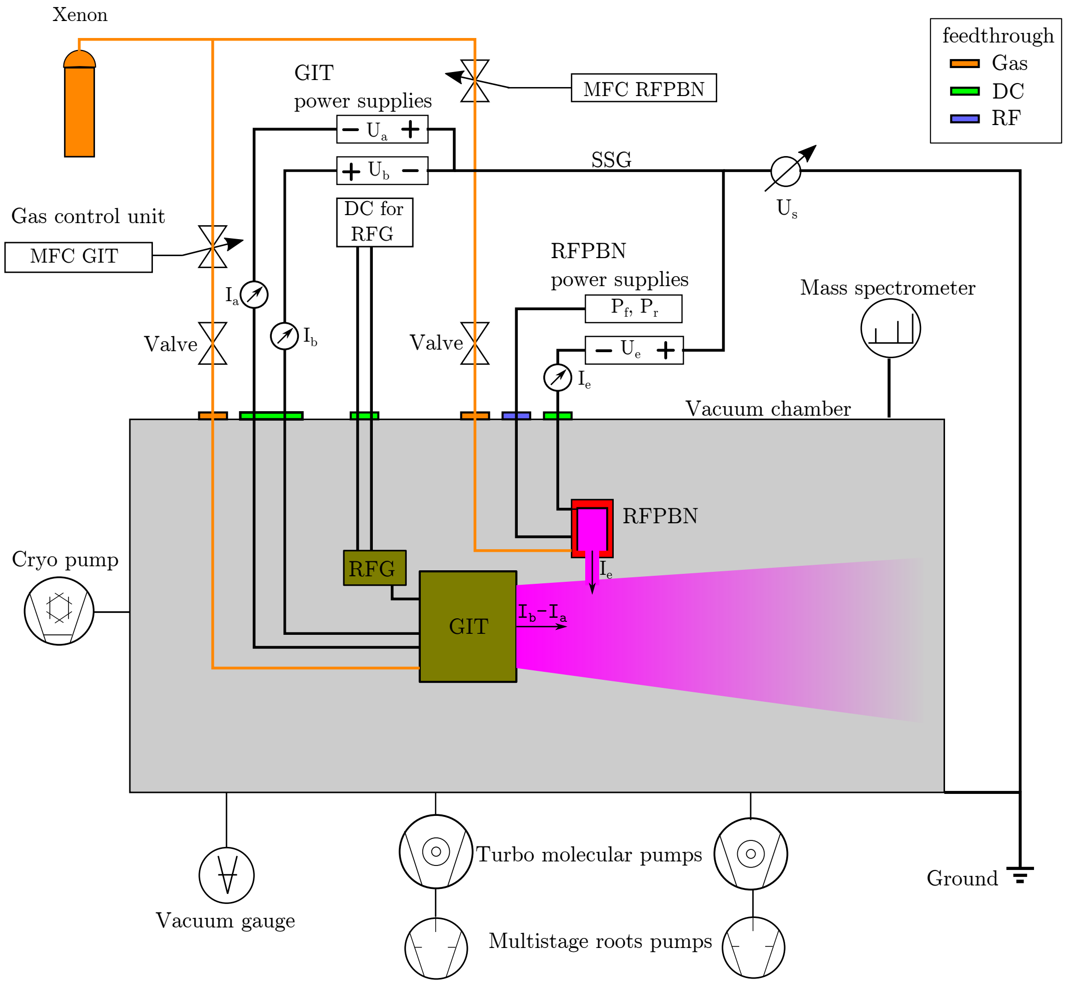

Figure 7. Schematic setup used for the neutralization verification test of the RFPBN.

The neutralization test was performed over a period of 100 hours and the extracted electron current I_e, the ion current of the thruster and the SSG potential U_{SSG} continuously recorded as function of time. The RFPBN parameter set was identical to the endurance test, again the emission voltage U_e has been adjusted manually to keep I_e within 5% of 100 mA, here to values lower than in the endurance test, because the space charge potential of the ion beam is more positive than the potential of the electron collector plate in the endurance test. The thruster was operated with a beam voltage of 900 V and emitted a Xe ion beam of 100 mA current.

Figure 8 shows the extracted electron current, the secondary star ground and the emission voltage as function of time for the period from 900 to 1000 h (calculated from the beginning of the endurance test). The small dip in the values around $t = 992$ h was caused by a short failure of the thruster which could be restarted immediately. The SSG potential U_{SSG} varies slightly between 6 and 9 V in the test period. The positive value of the SSG potential shows that the space charge of the ion beam is overcompensated, even when the beam current of the thruster and the extracted electron current from the RFPBN are identical. This can occur, because secondary electrons are generated by the ion bombardment of, e.g. the walls of the vacuum chamber, and compensate the space charge in addition to the electrons from the neutralizer.

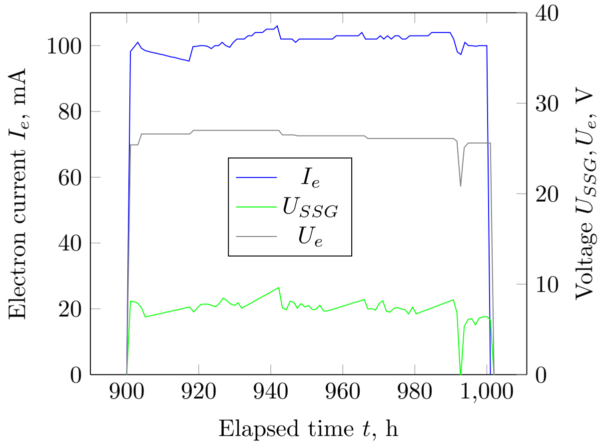

Figure 8. Extracted electron current I_e, Secondary Star Ground (SSG) U_{SSG} and emission voltage U_e during the neutralization test. At $t = 992$ h the thruster stopped operation causing U_{SSG} and U_e to drop until the thruster was re-ignited.

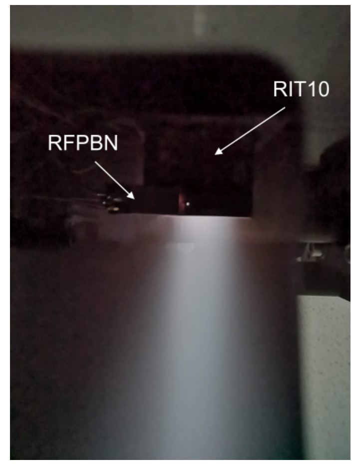

Figure 9. Optical image of the RIT10 thruster and RFPBN in operation (top view).

The figure 9 shows the thruster and the neutralizer with the extracted ion beam. The plume of the neutralizer is not visible, because it is covered by the engine housing of the RIT10 EVO. During the test, it was observed that a small change (a few mA) in the difference between the ion current from the thruster and the electron current from the neutralizer leads to a change in the SSG potential, i.e. that the beam of the ion thruster is coupled with the electrons of the RFPBN.

VII. Conclusion

A radio-frequency plasma bridge neutralizer was designed and tested at IOM that can provide electron currents in a wide range between a few mA up to several hundred mA. The RFPBN proved to be robust to mechanical and thermal stress and performed over 1000 h without any problems in the device operation, continuously extracting 100 mA of electrons in the endurance and neutralization test. The fact, that the RFPBN input power was constant over the hole test period without the need to be increased for constant I_e is an indication that there were no noticeable deposits on the inside of the discharge chamber of the RFPBN which would otherwise have resulted in an absorption of RF power. Due to these promising results, the RFPBN concept may prove to be an attractive alternative to conventional neutralizers in future electric propulsion applications.

Acknowledgments

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