Investigation of a modified RIT-μX operating as an electron source

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Abstract: The work has as its major goal the modification and operation of the miniaturized thruster RIT-μX thruster as an electron source and with this prove the concept of using a system with this architecture for the neutralization of ion beams of other thrusters. If proven to be feasible, a radio-frequency neutralizer would allow the reduction of the number of power sources in the final spacecraft configuration, since it would possible to reuse sources from the thruster itself. In the first section the general concepts about electric propulsion are presented and the central problem of the work is formally stated and a brief review is performed showing what was done in the context of the electron sources of this type. In the third section the processes of dimensioning and computation of operational parameters is presented, including a brief theoretical consideration. In the fourth section the experimental methodology is presented showing the process that will be used in the operation of the system, which consist of three experimental configurations: thruster mode, electron gun mode, and plasma bridge mode. Lastly, in the sixth chapter it is presented the obtained results and a brief discussion about the data.

I. Introduction

In the context of flight electric propulsion systems, one of the most critical components is the electron source either for beam neutralization or generation of the main discharge. Up to now, most of the commercial and scientific missions have relied on hollow cathodes due to their high reliability and performance. On the other hand, the complex manufacturing and handling process makes their development and usage expensive[1] and motivates the continuous search for alternative cathode concepts.

In order to have simpler and more robust systems, several research groups started to investigate alternative principles, specially with independent plasma generation and extraction, the so-called plasma cathodes.[2–5] These types of cathodes uses electrons from the plasma itself to generate the necessary current, and closes the circuit collecting the ions at an internal electrode. Despite not being as efficient as the traditional cathodes, the absence of sensible materials and the fact that they work at close-to-ambient temperature levels make them far less prone to fail during a given mission time. The Hayabusa mission inaugurated this new trend being the first to fly a plasma cathode in 2005.[6]

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These cathodes are usually classified by its plasma generation mechanism. The most common methods are the electron-cyclotron resonance (ECR),[6] capacitively coupled plasma (CCP),[2] inductively coupled plasma (ICP),[3] helicon discharge[5] and resonant cavity.[7] Particularly, the ICP cathode, first presented in 2005 by researchers of the Tokyo Metropolitan University,[8] uses relatively low frequency magnetic field generated by a coil in order to induce internal eddy currents to heat the plasma. The generated electrons are extracted through an orifice placed at the end of the cathode body, while the ions close the circuit being collected and neutralized at an internal electrode called the "ion collector".[3]

In parallel, the Justus-Liebig University of Gießen in cooperation with Airbus Safran Launchers (ASL, formerly known as EADS) have been working since the 1960's on the technology of radio-frequency ion thrusters (RIT's) that, similarly to the described cathode, uses ICP discharges to generate the plasma. In the context of this development, ASL recently developed a miniaturized thruster called the RIT-μX.

With the objective of finding novel concepts of cathodes that can decrease of the number of power supplies needed in a RIT propulsion system, the main objective of this work is to study the possibility of using a modified version of the RIT-μX to serve as an electron source for beam neutralization of larger thrusters, working in a similar way to an ICP cathode. If feasible, this new concept would decrease the cost of development campaigns of new thrusters and allow the conceiving of novel propulsion system architectures. Since one the major goals of the project is to maximize the reuse of existing systems in order to decrease the overall cost of the project, the RIT-μX was chosen as the basis for the neutralizer design with minor modifications, namely the inclusion of the internal electrode and the modification of the orifice configuration on the grids.

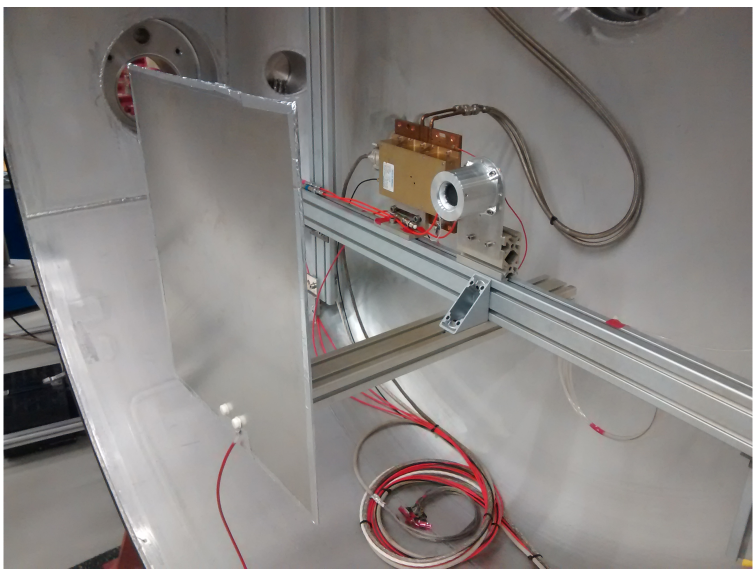


Figure 1: Setup of the experiment, showing the anode plate, the radio-frequency generator and the converted ion thruster.

The article will consist on the description and discussion about the test campaign of the modified version of the thruster (figure 1 shows the experimental setup used). In the first part it will be presented an introduction, review and the central problem of the work. In the second part it will be shown the mechanical design modifications done to the thruster and all the technical aspects considered to apply them. In the third part, the test procedure will be presented, together with an explanation about the laboratory installations and the physical setup of the tests. In the last part, the results of the experimental investigation will be presented along with a broad discussion showing the main conclusions related to the data acquired.

II. Design of the electron source

A. Theoretical considerations

In designing an ICP electron source, the two major areas that must be considered for its general analysis, the plasma generation mechanism and the electron extraction physics.

The mechanism for generation of an inductively coupled plasma in a cylindrical geometry it is widely known in the literature.[9,10] Even though the mechanical configuration used in the experiments was not cylindrical, the equations cited before are considered here as an approximate solution for the prediction and analysis of the performance measurements conducted. As described by Lieberman and Lichtenberg[9] the general expression for the power absorbed by a plasma in a cylindrical region of radius r_0 and height l, by induction, is given by,

$$P_{abs} = \frac{\pi}{l\omega\varepsilon_0}\mathrm{Re}\left[\frac{jkr_0 J_1(kr_0)}{\varepsilon_p J_0(kr_0)}\right] N^2 I_b^2 \tag{1}$$

Where ω, ε_0, ε_p, j, $k = k_0\sqrt{\varepsilon_p}$, $J_{0,1}$, N and I_b are the external current frequency, vacuum permittivity, plasma permittivity, the imaginary number, the modified wavenumber, Bessel functions of the first kind, number of turns in the induction coil, and the coil current magnitude, respectively. Equating expression 1 to the power loss, in the form,

$$P_{abs} = en_0 u_B A_{\mathrm{eff}} \epsilon_T \tag{2}$$

It is possible to solve this equation numerically in order to obtain different plasma parameters needed to estimate the basic characteristics of the plasma discharge within the system. If considered $A_{\mathrm{eff}} \approx 2\pi r_0^2 h_l + 2\pi r_0 l h_r$ as suggested by Lieberman,[9] it is possible to calculate the approximate solution for an ideal cylindrical plasma. Considering the extraction of electrons, the collected current can be approximated by,

$$I_e = \frac{1}{4} en_0 \sqrt{\frac{8k_B T_e}{\pi m_e}} \exp\left[\frac{e(\phi_e - \phi_p)}{k_B T_e}\right] \tag{3}$$

Where ϕ_p is the plasma potential, it is interesting to note that as the electrical potential gets close to the plasma potential, I_e approaches a saturation current. Another important aspect is that, as shown by Longmier[5] the main condition for the flow to achieve the non-ambipolar condition is that,

$$\frac{A_i}{A_e} \approx \sqrt{\frac{2m_i}{\pi m_e}} \tag{4}$$

Which guarantees the maximum efficiency in electron current extraction, diminishing the several losses generally present in cathodes of this type.

B. Mechanical configuration

One of the major goals of the project is to maximize the reuse of existing systems in order to decrease the overall cost of the project, thus it was chosen to use the thruster RIT-µX as the basis for neutralizer.

The major issue be addressed to convert the thruster to an electron source, is to increase the internal area of ion collection and optimize the orifices areas and disposition. In order to increase this collection area, a metallic wall, made of molybdenum, was installed on the surface of the ionizer cavity, and connected to the first grid. In order to avoid a shield of the plasma, the metallic wall was constructed with vertical slots, thus allowing the magnetic field to penetrate. The figure 2 shows the construction of the system.

As said, another major question is the design of the orifices. In order to decrease the mass flow consumption it is interesting to decrease the total area of the orifices. Two designs were selected initially to be tested, a plate with a single orifice with diameter of 1.5 mm, and a second one which is the same grid of the LISA Pathfinder model of the thruster, with 12 orifices of 1.5 mm of diameter.

In this work we only report the tests conducted with the multi-orifice configuration, that allow it to be re-utilized as a common thruster, in dual operation mode. Despite being more optimized, the single orifice configuration will be tested on a future campaign to asses the operational differences between both configurations.

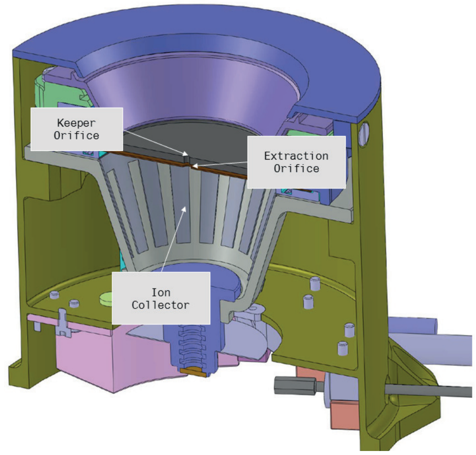


Figure 2: Section view of the modified thruster.

III. Experimental investigation

A. Test procedure

The execution of the experimental campaign was divided in three main phases as described below. Each of the parts was characterized by a different test arrangement aiming to provide a clear assessment of the main operational parameters of the system.

1. Thruster mode

In the first part of the experimental campaign, the system was operated as a thruster with the common two-grid configuration extracting ion current and thus generating thrust. The main objective of this part was to provide a comprehensive base for comparison with previous tests of the RIT-μX in order to assess the effects on the performance caused by the inclusion of the metallic ion collector in the ionization cavity. This evaluation is closely related to the plasma discharge performance itself rather than to the extraction characteristics, being almost completely valid for most of the other operation modes. Figure 8c shows the diagram of the experiment.

The operation of the system in this part was only aimed in reproducing curves of RF-power versus mass flow rate, for constant ion beam current values. The current values selected were 1.4 and 2.22 mA, while the mass flow rate was swept between the values of 0.028 and 0.085 sccm of Xenon. The major limitation in this test was the maximum RF-power capable of being delivered by the RFG without overheating, which was approximately 35 W. The first and second grid were maintained with constant voltage values of 1550 and −300 V, respectively, the RFG frequency was maintained with a frequency of 2.55 MHz.

The recorded data in this part was the voltage and current values in the first and second grid, the voltage and current of the RFG, mass flow rate, input signal frequency and vacuum chamber pressure.

2. Electron gun mode

In this part, the system was still operated using the two-grid configuration, but now with a different voltage profile applied to them in order to extract electron current instead of the common ion current.

The objective in this case was to prove that it is possible to convert the thruster in an electron source by simply modifying the applied voltage levels to favor electron current extraction. With this conversion, the system would have the potential of having a dual functionality, working either to provide thrust or electron current simply by changing its potential profile. The first experiment of this section was to compute the electron current levels for different combinations of voltage values in the first and second grid, for a constant voltage value on the anode plate. The second experiment of this part aimed again to reproduce again curves of RF-power versus mass flow rate, but in this case for constant electron current. Figure 8b shows the diagram of the experiment.

In the first investigation the voltage in the first grid/ion collector was varied from −700 to −100 V, with 100 V steps. At each of these values, the difference between the first and second grid was varied from 150 to 550 V, with 25 V steps. The mass flow rate was maintained constant at 0.06 sccm, frequency at 2.55 MHz, and anode voltage at 12 V. The second investigation held constant the electron current value at 60 and 130 mA, sweeping the mass flow rate from 0.014 to 0.1 sccm again with the limitation of maximum RF-power. In this part the first grid was set to −300 V, second to −50 V and the anode was kept with 12 V. In the electron gun mode, the anode plate was kept 10 cm away from the thruster.

3. Plasma bridge mode

In the third section of experiments, the system was operated using a configuration with just one grid, corresponding to the first grid in the previous tests plus the internal ion collector.

The major objective in this case was to operate the system as a plasma bridge, without active acceleration of the electrons by the grids. In contrast with the previous case, here the first grid is maintained in ground potential and the extraction is controlled only by the potential applied to the anode plate. In the first part of the investigation the RF-power was maintained constant and the extracted current was computed as the anode voltage was varied. In the second part, similarly to the previous ones, the extracted current was maintained constant, while the power was computed and the mass flow rate was varied. In the last part, the current was again maintained constant but at this time the power was registered for different anode voltage, in order to account the influence of this parameter. Figure 8a shows the diagram of the experiment.

In the first part the voltage is varied in the range from 0 to 1000 V, RF-power is maintained in 18.7, 21.6 and 24 W, with mass flow rate of 0.3 sccm. In the second series of experiments the current was maintained constant at 40, 80, and 120 mA, mass flow was varied between 0.1 and 0.75 sccm, anode voltage was kept at 12 V, and RF-power was computed. In the last experiment the extracted current was maintained constant at 80 mA, the anode voltage was set to 7, 12 and 15 V, the mass flow rate was varied between 0.1 and 0.75 sccm, and again the RF-power was computed. In the plasma bridge mode, the anode plate was kept 5 cm away from the thruster.

B. Facilities and test setup

All experiments were conducted at the Electric Propulsion Laboratory of the Justus-Liebig Gießen University. All test of this work were conducted at the "Big-Mac" vacuum chamber, which consists of a cylindrical vessel with a diameter of 1600 mm and depth of 1200 mm, with a total volume of 2.1 m^3. The pumping unit of consists of one turbo molecular pump and a cryogenic system with two panels. The total pumping capacity for Xenon is over 25000 l/s, maintaining an average pressure of 10^{-7} mbar in idle mode and about 10^{-6} mbar for the mass flow rates considered in this work.

As shown in figure 1, the test setup inside the vacuum chamber consisted of the electron source, a test qualified radio-frequency generator (RFG) and the anode plate. The anode plate was a rectangular graphite plate of 500 by 400 mm and it was connected through an insulating PTFE interface in order to be polarized and avoid any electrical arcs to the chamber. In the figure, the plate is shown in an unrealistic position, since all tests were performed with an effective distance equal or less than 100 mm.

The team of the electric propulsion laboratory of JLU supplied all electrical power supplies, data acquisition systems, and other test equipment, and further information about these equipment can be obtained by direct contact with the responsible.

IV. Results

A. Thruster mode

The data collected in the mapping on the thruster mode is shown in figure 3. The trend that appeared in the measurements shows a close resemblance to previous tests, with a power increase of approximately 10% in the same operational points, as shown by internal documents about the thruster's performance. It is not straightforward to point out the root cause of this systematic performance depletion, but one of the most probable causes is the presence of the metallic ion collector within the ionizer cavity, which couples to the RF, dissipating power, and impedes an effective RF coupling to the plasma.

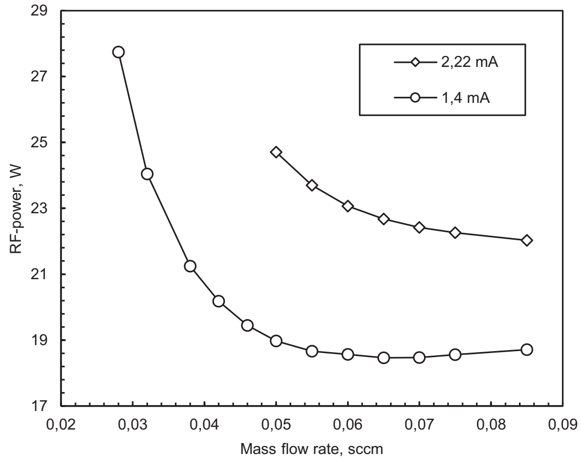
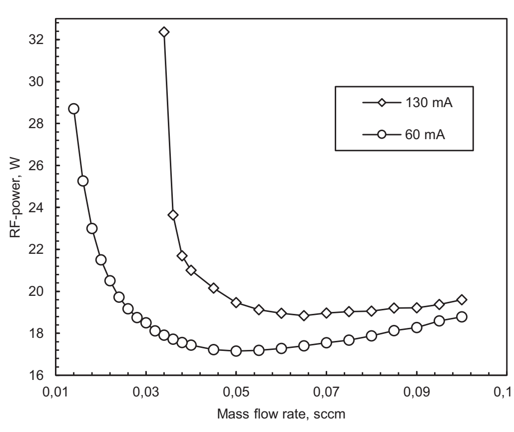


Figure 3: Constant ion current curves for the thruster mode.

Even with the observed performance depletion, it is seen in the data trend that, if desired, it would be possible to use the system as a thruster and that the ion collector does not cause major perturbations in its operation. This observation opens the possibility to use the system as a neutralizer and a thruster, depending only in the voltage profile applied to the grids. One possible application to this would be the usage of two thrusters with different angular positions, one performing actual thrust and the other performing neutralization. When desired to apply a force in the other direction the thrusters could interchange the functions. This combined mode could eliminate the need for a traditional hollow cathode.

B. Electron gun mode

The electron gun mode used the same configuration as the thruster operation, but with a different voltage profile, as described in section 2. Figure 4a show the result from the measurements of constant extracted current. It is possible to observe the data observed presents the same behavior as a thruster with a region of minimum RF-power for the same available current and an exponential-like increase in power for lower mass flow rate values. Comparing the current levels present in this case and the one present in the thruster mode, it is clear to see the contrasting behaviors of both operational modes.



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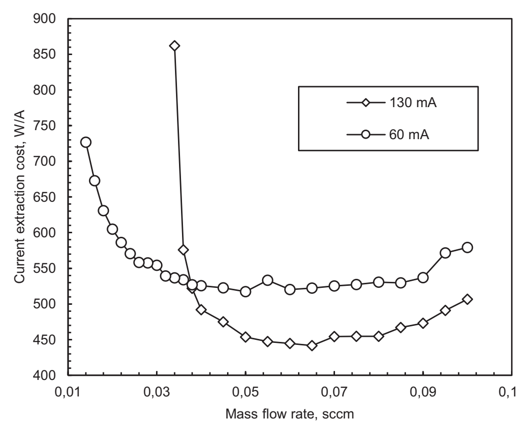
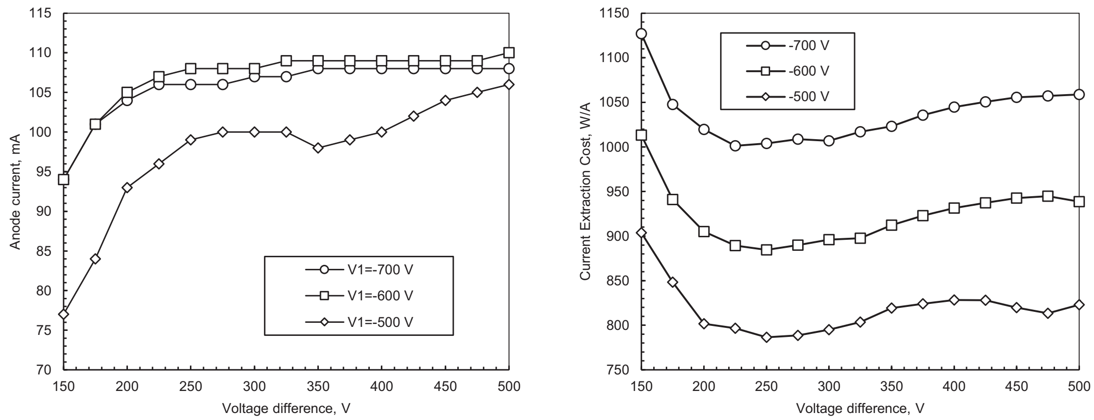


(b)

Figure 4: Constant current curve computing power consumption (a) and current extraction cost (b).



(a) (b)

Figure 5: Anode current (a) and current extraction cost (b) for different values of voltage in the first grid and ion collector (V1) and second grid (voltage difference).

A current extraction cost can be defined as P_T/I_a, where P_T is the total power consumed by the system (including coil power, grids power, and anode power), and Ia is the electron current collected by the anode plate. Figure 4b shows the behavior of this cost in both curves.

C. Plasma bridge mode

The plasma bridge operation used only the screen grid plus the ion collector, both in the ground potential. The acceleration grid was removed and its contact ring was kept also in the same voltage level.

Figure 6 shows the variation of the anode current depending on the voltage applied to the anode plate with constant power (left) and the resulting current extraction cost (right). In the current plot, it is possible to observe that the trend has an exponential behavior until a maximum point between 15 and 20 V, where there is a steep decreasing in the current followed by a milder increase. It is important to note that the most interesting region for ion beam neutralization applications is bellow the 25 V threshold where the behavior of the current shows a predictable monotonic trend and continuous decrease of current extraction cost. The current extraction cost is given by,

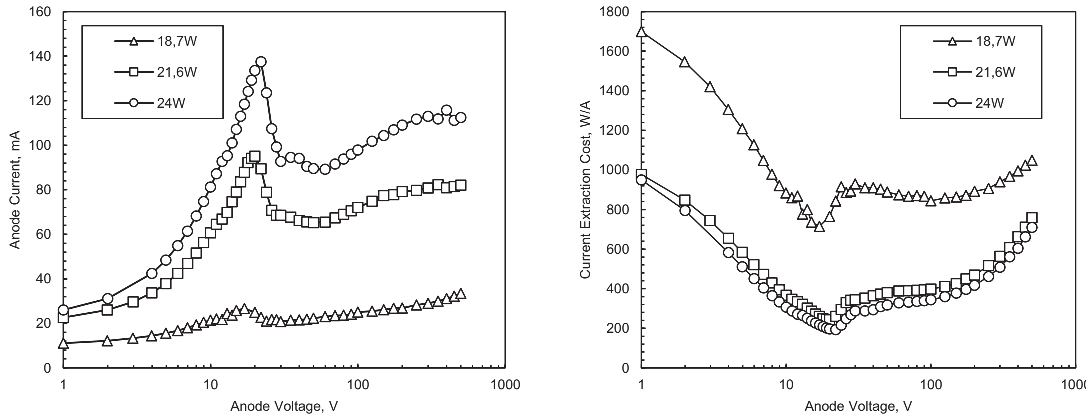
$$C_e = \frac{P_T}{I_a} = \frac{P_{RF}}{I_a} + V_a \tag{5}$$

Figure 9 also shows the current extraction cost in function of the gas utilization factor for the constant-power experiment. It is observed that in the inflexion point, present in figure 6, the data also diverges from the relation between the factors. If gas utilization factor is defined as $F = I_a/k\dot{m}$, where k is the equivalent number of charges in the Xenon flow, the relation between both parameters can be written as,

$$C_e = \frac{1}{k\dot{m}}\frac{P_T}{F} \tag{6}$$

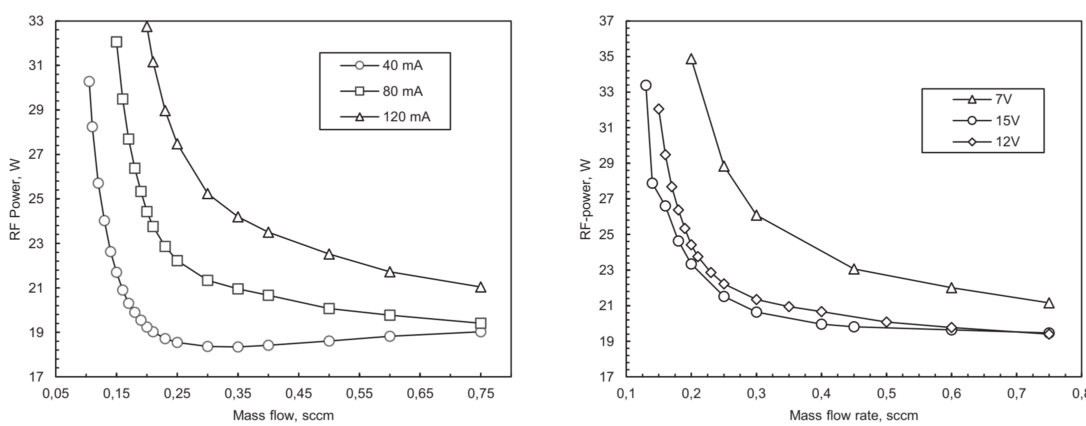
Observing the plot of this relation it becomes clear that the break point arises from the non-linear, non-monotonic behavior found in the voltage-current relation around 15-20V. There is still no clear understanding on the behavior of the measured curves, but non-linear VI relations are common on electrical elements, as diodes, and traditional hollow cathodes present similar behavior.

In the second part, the constant current curves were investigated. Figure 7 shows the data for three different current values (left), and the data for constant current but different anode voltage values (right). The curve follows the general trend for radio-frequency discharges and have a similar behavior to the thruster and electron-gun operation, for different values of internal pressure that follows the different mass flow input values.



(a) (b)

Figure 6: Anode current (a) and current extraction cost (b) depending on anode voltage for different values of constant power.



(a) (b)

Figure 7: Constant current curves for different values of anode current (a) and different values of anode voltage (b).

V. Conclusion and discussion

This project had as its main goal to prove the concept of using a modified version of the RIT-μX as a RF electron source. In order to explore all possibilities the system was tested in three different modes, the first one as a thruster, the second one accelerating electrons maintaining two grids, and the third as a plasma bridge, without the second grid.

The point of highest performance occurred in plasma bridge mode, producing 140 mA, while consuming 24 W of power, using 0.3 sccm, having approximately 190 W/A of current extraction cost. This value when compared to the literature is 2 times higher than the most efficient system operated, in.[11] This discrepancy in the result can be justified by the fact that the other tests in the literature are conducted in much higher power levels (62 W in the case of[11]) thus decreasing the current extraction cost, as shown by the measured trend.

Considering the performance achieved and all the data gathered about the system in all the three modes it is possible to explore some application cases for a future system based on these architectures. The most straightforward application would be for the neutralization of ion beams of gridded ion thrusters. Taking into consideration just the thrusters produced by Airbus DS it is possible to see that the only thruster that this system would be capable of neutralizing would be another RIT-μX, which produced current levels in the order of 10 mA. Other thrusters as the RIT-10 and the RIT-2X, produces current levels in the order of 500 mA and 1000 mA respectively. Beyond that, since the system was capable to produce up to 140 mA of current, becomes evident that it is possible to neutralize not just one unity of the RIT-μX, but a cluster (up to 14).

From the application cited before it is also possible to consider the usage of the system with a dual functionality: as a thruster and as neutralizer. In this way, it would be possible, for example, to apply two thrusters of the same type in different positions, and while one is performing thrust the other one is producing an electron beam for neutralization, and vice versa. This opens the possibility to eliminate systems (hollow cathodes) and simplify propulsion systems using several thrusters.

VI. Acknowledgements

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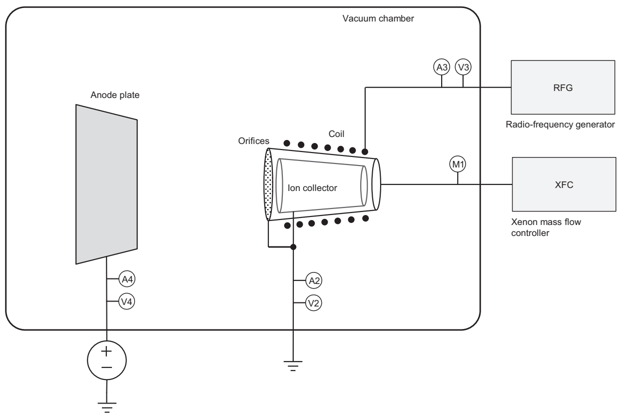

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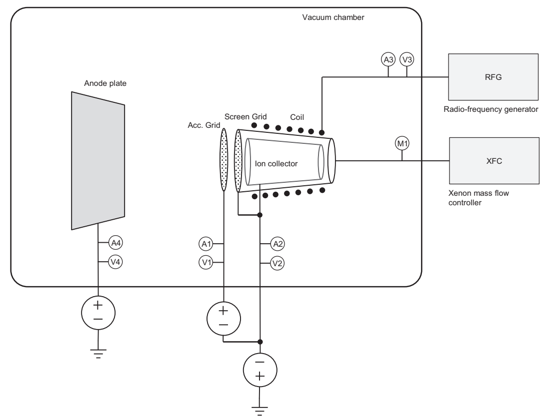

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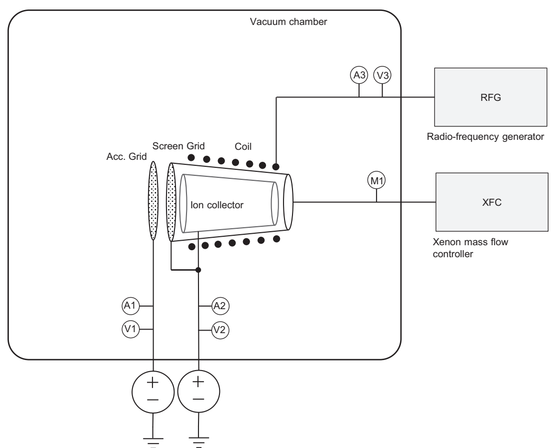
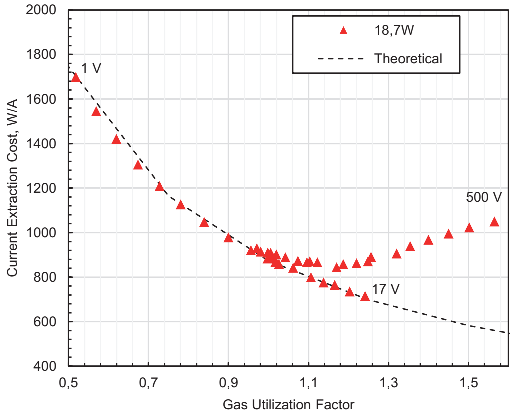


(c)

Figure 8: The experimental setup considered: (a) thruster mode, (b) electron gun mode and (c) plasma bridge mode.



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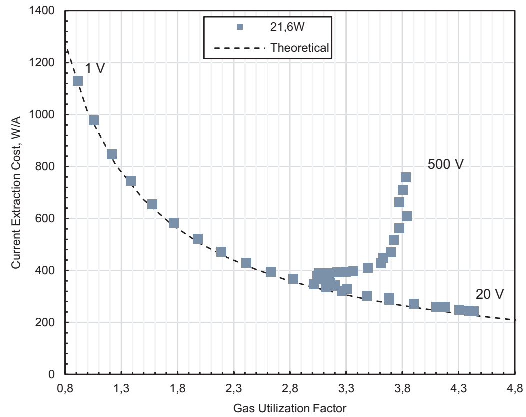

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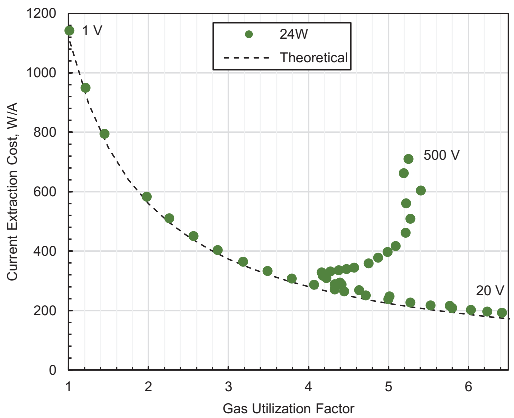

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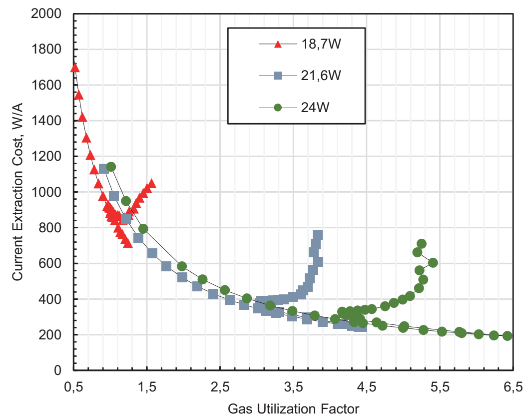

(d)

Figure 9: Comparison between theoretical and experimental curve of the extraction cost versus the gas utilization factor for 18.7W (a), 21.6W (b), 24W(c) and the three together for comparison.