RF Power - Plasma Coupling Experimental Results in a Helicon Plasma Thruster Prototype

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In this research, the plasma response of the Helicon Plasma Thruster experimental prototype is characterized for different operational parameters (P_{RF},$\dot{m}$,B). The system sensitivity against variation of these parameters is monitored as part of the closed loop control design for the HPT Engineering Model (EM). The plasma impedance at each working point is then identified with a simplified mathematical plasma model, in order to set the final electronics components selection of the HPT EM. Furthermore, the experimental characterization of the system electronics response is compared against the component based model prediction to validate that model. In this way we obtain the cost-effective analysis tool of the system response.

Nomenclature

α	= attenuation factor
β	= propagation constant
B	= magnetic flux density
$\dot{m}$	= propellant mass flow
P_{RF}	= radio-frequency power
$s_{ij}, \boldsymbol{S}$	= scattering parameters
SWR	= standing wave ratio
Z_c	= circuit impedance
$z_{ij}, \boldsymbol{Z}$	= z-parameters
Z_m	= measured impedance
Z_p	= plasma impedance
Z_t	= total impedance (combined plasma and circuit impedance)

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I. Introduction

As part of the detailed design of the Helicon Plasma Thruster (HPT) for its evolution towards in-space applications from an experimental prototype to an advanced engineering model (EM)[6], one of the key tasks is to model the dynamic electronic response of the thruster unit when varying the functional parameters. This model helps on setting the correct closed loop control strategy and to size the RF power subsystem components to ensure the maximum power transmission efficiency at the whole operational envelope, which should enable a dual mode operation (high specific impulse/high thrust).

In order to tackle with such task, this experimental research aims at understanding the electronics response of the HPT covering the following objectives:

- Identify the sensitivity of the thruster when varying the control parameters that define the system performance. This step is necessary in the design of the closed loop control of the HPT EM system (sensitivity analysis).

- Characterize the plasma impedance response against several working points. This step covers the dimensioning of the whole RF power subsystem, in particular it would provide remarkable information to size the circuitry that would adapt the thruster impedance to the RF generator output one, in order to maximize the power transmitted to the plasma beam.

- Experimentally validate the HPT electronics model, which is the design tool that predicts the whole system response during operation based only in the circuit components values. This goal would enable a cost-effective solution for future design tasks, which would not require the exhaustive methodology that has been followed during the experimental test campaign object of this paper.

The paper is structured as follows: section I covers this introduction; the experimental test platform and the methodology followed to reach the research goals are presented in section II; then the electronics models and corrections required to retrieve the plasma information are presented in section III. Finally, the experimental results are presented and discussed in section IV. The summary conclusions and future work are presented in section V.

II. Experimental platform and methodology

In the scope of this research, the experimental plasma impedance characterization test is based on the modified HPT prototype design up to 1kW, the HPT5M, jointly developed by UC3M and SENER[2,3,5] to explore and advance this technology for its commercial application. This experimental platform consists of two separated subsystems, the so called thruster unit (TU), and the radio-frequency generator and power unit (RFGPU).

A. Thruster Unit (TU)

The Helicon Plasma Thruster is based on a helicon plasma source which is modified to its application for Electric Space Propulsion. It consist of an RF antenna in charge of exciting a neutral gas to generate a plasma that is accelerated producing thrust. The neutral gas and the generated plasma are confined in a cylindrical dielectric chamber with an injection mechanism, surrounded by a magnetic generator coil in charge of creating the desired magnetic topology for efficient energy transmission to the plasma, plasma confinement and ion beam acceleration.

For the experiments carried out, the plasma chamber is a quartz glass tube of 125mm length which is wrapped by an helical antenna of 75mm placed in the centre of the tube and that is directly connected to a custom feeding line. Just after the antenna, the magnetic coil is positioned to generate a convergent-divergent magnetic topology or magnetic nozzle, to accelerate the generated plasma beam.

B. Radiofrequency Generator and Power Unit (RFGPU)

The RFGPU is the electronic assembly that generates, conditions, controls and matches the RF power to the antenna within the HPT05M.

The breadboard model (BBM) of the RFGPU has been designed for plasma research purposes, with the a main goal of finding an optimal thruster operation point to fully design a fixed RFGPU. Due to the plasma impedance uncertainty as well as the optimum operation point, the BBM is designed with a variable matching network (VMN) and a custom length feed line. These elements together are known as the matching network subsystem in the BBM design (Figure 1).

The power amplifier (PA) for these tests is a COTS unit that generates the RF power (<1KW) which may be delivered to the load/antenna. It also measures the forward and backward power, detects the SWR and includes protections for its own electronics. In addition a bidirectional coupler is used to continuously monitor the forward and backward power as well as the impedance seen at the MN subsystem input Z_m. In order to simplify the elements of the whole matching block, the VMN has been implemented by means of two air capacitors in L-Match configuration.

The most critical part of the VMN design is the selection of the capacitors range value. Due to the plasma impedance uncertainty, some assumptions are needed. The first one is that plasma shall be ignited just radiating to the antenna impedance. After this point, the change of impedance may be noticed due to plasma and may be corrected. If the range is not suitable it can be extended by adding more capacitance in the VMN or increasing/decreasing the coax feed line length. That is why the feed line length is considered part of the MN subsystem. Figure 2b shows the impedance range of the VMN. There is a combination of capacitance value for each impedance inside the red zone. By rotating these impedance values in the chart according to the length of the feeder line, the resulting impedance matches the total impedance Z_t (antenna plus plasma impedance).
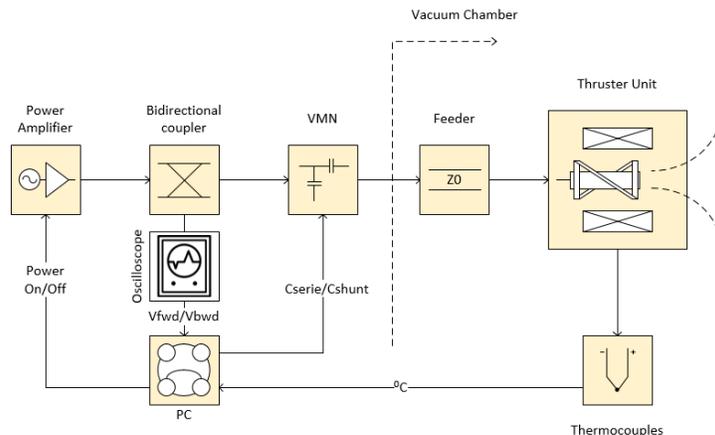

Figure 1: HPT Experimental set-up schematic.

C.   Methodology

To determine the plasma impedance response and the thruster sensitivity at different working regimes , several operational test on the HPT05M are carried out, each of them exploring the TU impedance response against the variation of its operational parameters: the supplied RF power (P_{RF}, measured at the PA output), the operating propellant mass flow ($\dot{m}$), and the magnetic flux density (B) while maintaining a constant position of the variable control capacitors.

During each experiment, the forward and reflected power are monitored by means of a bidirectional coupler. The information of the relative power ratios and their phase provide the measured impedance at that point of the line and the SWR, which is used to characterize the impedance matching to the system beyond the VMN.

Based on the electronics models detailed in section III and the measured impedance, an estimation of the total thruster unit and the plasma impedances can be processed. This preliminary estimation is then refined by a dedicated thermal drift experiment around the reference point. The outcome of this test is a correction factor to compensate the observed thermal drift in the circuit during operation.
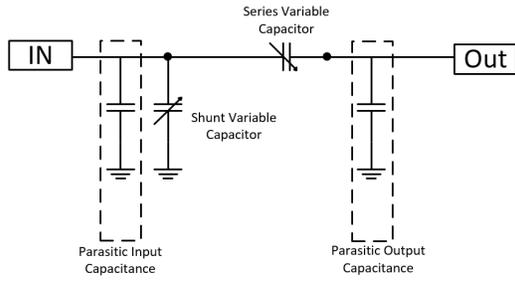
(a) Electrical model.
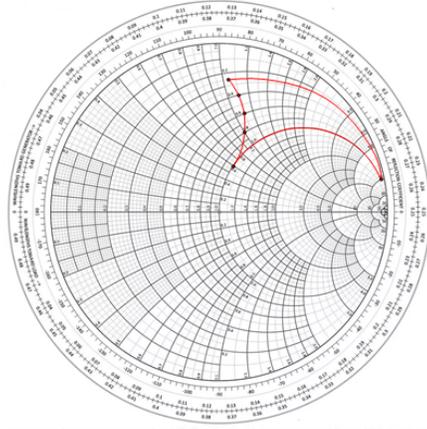
(b) Adaptable range.

Figure 2: VMN electrical model and adaption region map.

Besides, the processed SWR provides the power transmission variation, which is an indicator of the sensitivity around the operational reference point against each of the system parameters.

III.   Electronics Characterization Model

A.   Electronics component model

This subsection introduces and explains the model based on the components/parts values. This is the model to be validated with the experimental campaign (one of the goals of the activity). The first element is the MN model. The impedance measured with the directional coupler at the MN input (Z_{in}) is converted to the MN Z_{out} with the circuit model outlined in Figure 2a.

Two main parasitic capacitances are identified: the capacitance between the input and the box chassis and the capacitance between the output and the chassis. This parasitic capacitances are different for each capacitance value of the variable capacitors, but are easy to characterize by measuring with a VNA. When the input is in short circuit, the capacitance value is independent from shunt capacitor position (in the range 40-360 pF), and the measure shows an offset, which is the parasitic between the output and chassis (Figure 3a). But when the output is short-circuited, the parasitic input capacitance depends on both shunt and series capacitance value as shown in Figure 3b.

With the estimated output matching impedance, Z_{out}, taking into account the parasitics previously described, the impedance at the antenna input port is straight forward with the widely known transmission line equations, taking into account the feed line length (l):

$$Z_{ap} = Z_0 \cdot (Z_{MNout} + Z_0 * \tanh(\alpha + j\beta) * (-l))/(Z_0 + Z_{MNout} * \tanh(\alpha + j\beta) * (-l)) \tag{1}$$

Z_{ap} is the impedance of the antenna when coupled with the plasma, so if the antenna impedance is well characterized, the difference between both admittances must be the plasma admittance.

B.   Experimental characterization model

The experimental characterization model consist of three parts: the external circuit part, consisting of the bidirectional coupler, the VMN and the feeder line, the thruster impedance model, and the plasma impedance model.

For the external circuit part, the experimental model is characterized based on direct measurement of the scattering parameters s_{ij} of the two ports network going from the bidirectional coupler to the RF feeder output connector. For each position of the VMN capacitors being tested, there is a matrix of scattering parameters s_{ij}, which are directly measured with a vector network analyser (VNA) at the system operating
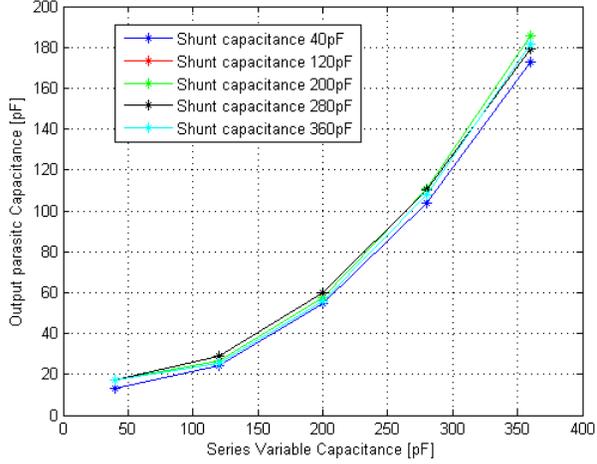
(a) VMN Output parasitic capacitance.
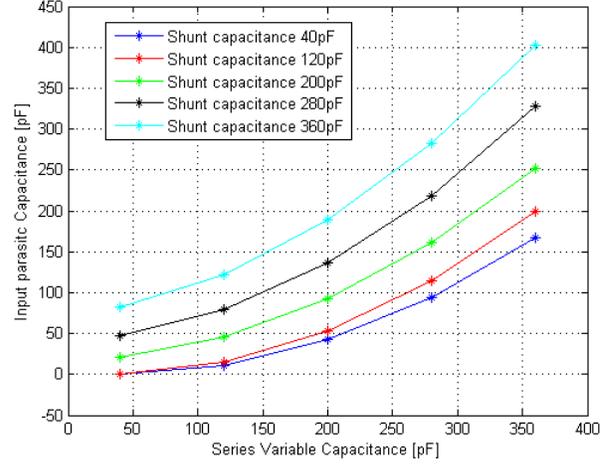
(b) VMN input parasitic capacitance.

Figure 3: VMN Parasitic capacitance model

frequency of 13.56Mhz. The thruster impedance model is also empirical, obtained by measuring with the VNA the thruster impedance without plasma Z_c. Finally, the plasma model is obtained based on the previous models together with the measurement of the whole system impedance derived from the power readings during operation Z_m, under certain coupling model assumptions. For the scope of this research, a simplified parallel impedance coupling scheme, assuming the plasma impedance is in parallel with the circuit impedance. Defined in this way, the numerical model is easier to implement and characterize.

From the scattering parameters, the z-parameters, z_{ij}, of the two ports circuit can be derived considering the reference impedance for the transformation $Z_0 = 50\Omega$ (internal VNA impedance) with the relation given by Eq. 2. With them, the plasma impedance, under the assumption of parallel connection, can be estimated in complex form as per Eq. 3.

$$\boldsymbol{Z} = (I - \boldsymbol{S})^{-1} \cdot (I + \boldsymbol{S}) \cdot Z_0 \tag{2}$$

$$Z_p = \frac{Z_{c+p} \cdot Z_c}{Z_c - Zc + p} = \frac{Z_c \cdot \left(-z_{22} - \frac{z_{12} \cdot z_{21}}{Z_m - z_{11}}\right)}{Z_c + z_{22} + \frac{z_{12} \cdot z_{21}}{Z_m - z_{11}}} \tag{3}$$

It shall be remarked that this complete model relays on measuring each s_{ij} matrix for each control capacitors combination, which implies a considerable effort when exploring several envelope points.

C. Thermal compensation model

During the HPT05M experiments, the electronics behaviour evolves throughout time due to the thermal response of the system. In order to compensate that effect, the thermal evolution of the total impedance is tracked at reference operational point. With that information, and assuming the plasma impedance remains constant (it should depend only on the operational parameters that are fixed: mass flow, magnetic flux and power level), the evolution of the external and the thruster circuits model can be tracked. Since determining the evolution of the external circuit part is difficult during operation, it is going to be assumed that only the thruster impedance Z_c varies. With that correction factor it is possible to modify the raw experimental values of Z_t obtained during the experimental campaign to get a more precise plasma impedance model for design purposes.

IV. Experimental results

For the scope of this paper, three experiments have been carried out with the set-up and methodology described in section II. Based on a reference operating point defined by $(P_{RF}, \dot{m}, B) = (450W, 10 sccm of Xe, 625G)$, the parameters have been varied within a limited range to analyse the system response. For each of the control parameters, several sweeps have been run, in order to ensure data consistency amongst each run.

A. Control parameters system sensitivity response

The relative variation of the SWR when varying the system parameters has been monitored. This gives an indicator of the sensitivity of the HPT against each of them, which is an important result when designing the HPT closed loop control. The results obtained are reported in Figure 4.

The results reflect that the variation of the magnetic field has a higher impact on the transferred power to the system when compared to the mass flow and power results.

In view of the results for the mass flow and for the power level, two behaviours are derived: one for larger values of the control parameters $(P_{RF}, \dot{m}, B)$ and other for lower values. Comparing both, it is observed that reducing the mass flow and the power below the reference point has a bigger impact on the system response, with a more abrupt slope of the SWR curve.
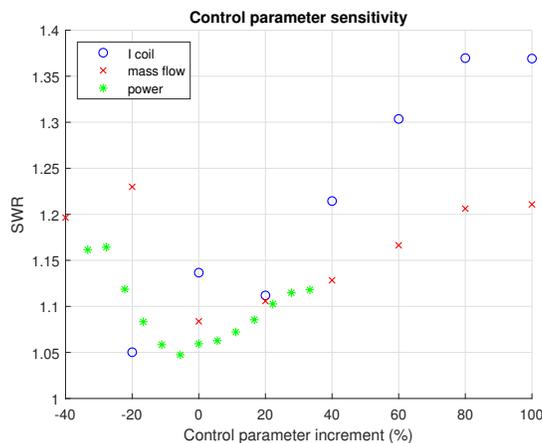

Figure 4: HPT system sensitivity analysis results.

B. Plasma impedance estimation

With the measured impedance Z_m for each of the experimental conditions, together with the experimental model data retrieved for each case, the total impedance Z_t and the plasma impedance Z_p are derived. The evolution with each of the control parameters is displayed in Figure 5, considering the mean values for all the sweeps performed with each functional parameter.

Attending to the power variation analysis, it is observed that for higher power values the plasma impedance becomes more resistive whereas its inductance reduces. This implies that when increasing the power level the thruster delivers more power to the plasma when maintaining the other two parameters.

Concerning the magnetic field variation, the opposite behaviour is observed, meaning that for larger magnetic field values the power consumed by the plasma is lower when maintaining the mass flow and the power level.

For the mass flow range explored, the behaviour of the impedance is slightly different. It can be seen that there is a big difference between low mass flow values and higher mass flow values. This could be related to a plasma mode change when decreasing the mass flow. When the mass flow is increased, the plasma resistance also increases until a saturation point, where changing the mass flow does not affect to the impedance significantly.
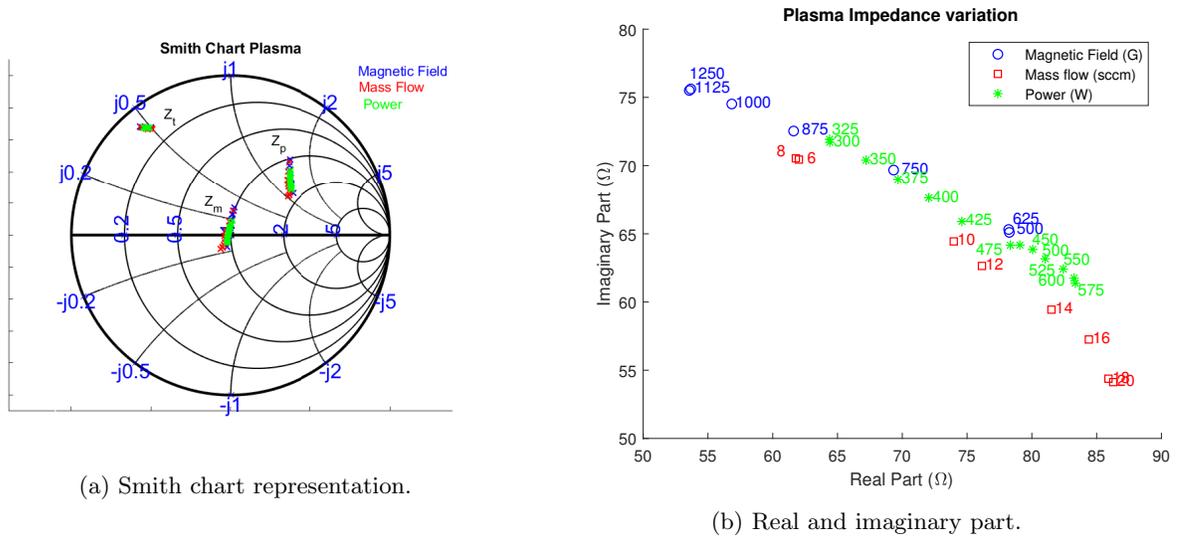
(a) Smith chart representation.

(b) Real and imaginary part.

Figure 5: HPT system impedance analysis results.

C. Electronics component model validation

With the experimental results obtained, both component based model and the empirical model based on direct VNA measurements can be compared in order to check the accuracy of the first one on estimating the results based on forward and backward power measurements at the bidirectional coupler. In Figure 6, the impedance estimation for both methods is shown in the Smith Chart for the plasma variation with the propellant mass flow $\dot{m}$. Bearing in mind those results, it can be considered that the component based estimation provides accurate results when compared to the measurement model but for minor deviations that can be neglected due to the observed variation of the measurements. This validates this model for future extensive test campaigns to fully characterize the detailed thruster operational envelope, avoiding the experimental approach that requires characterizing the external circuit part, with its associated s_{ij} matrix, for each of the VMN control capacitors positions.
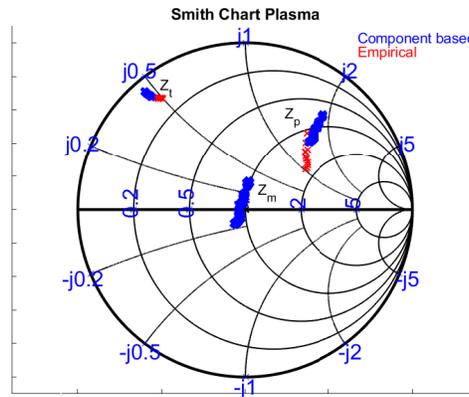

Figure 6: Electronics component model validation results.

V.   Conclusion and further work

The work performed has shown the electronic behaviour of the HPT05M around a reference operational point when varying the functional parameters $(P_{RF}, \dot{m}, B)$. The obtained results have been processed to get the HPT thruster electronic sensitivity and the impedance variation related to those parameters. Both a component based electronic model and the experimental model employed for impedance estimation have been compared demonstrating good agreement on the estimation. This validates the former component model for future extensive research experiments to characterize the HPT electronics response.

Further research will be carried out at different reference points in order to check the consistency of the observed behaviour departing from different baseline electronic overall response (different VMN capacitors values). This also will cover the system response when simultaneously increase/reduce different parameters with respect to the analysed reference point.

Acknowledgments

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