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# Simulating the electromagnetic behaviour of a vacuum chamber in the presence of a thruster's plume: comparison with experimental measurements

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**Abstract:** In this paper, we show the influence of the plasma plume of the ID-HALL thruster on the electromagnetic behaviour of a vacuum chamber in the undermoded regime by studying the magnitude of the reflection coefficient. We have compared experimental and numerical results obtained by simulating a metallic cylindrical cavity with and without plasma in the Ansys HFSS electromagnetic software. We have obtained the same trend in the experimental and numerical results.

## I. Context

With the advent of New Space, opening up the space sector to private players, new scientific challenges have emerged, leading to the development of innovative technologies. A major challenge is the miniaturisation of satellites to reduce production and launch costs, leading to the creation of CubeSats and NanoSats. However, this technological progress brings new problems, in particular electromagnetic compatibility (EMC) issues between the thruster plasma plume and communications systems. A significant source of interference is the electromagnetic radiation from the thruster. Space thrusters generate plasma plumes that exhibit various instabilities in the frequency range from kHz to GHz<sup>1</sup>, causing unwanted electromagnetic radiation.

To measure the plasma self-emission, the thruster must be placed in a metallic vacuum chamber, which acts as a reverberant cavity. When an electromagnetic wave is emitted into the chamber, it is reflected of the metal wall, interfering with plasma self-emission measurements. To carry out EMC measurements of thrusters without the interference caused by these reflections, various approaches have been explored in the literature. The first solution to eliminate these reflections is to build a vacuum chamber from radio-transparent materials (DASA/MBB<sup>2</sup> Fig.1), such as plastic or glass, which are transparent to electromagnetic waves. This chamber is placed in an anechoic chamber at atmospheric pressure where the antenna is located. The vacuum required for optimum operation of an electric thruster cannot be achieved in this type of installation. To overcome this problem, special facilities have been developed by Aerospazio in Italy, the Aerospace Corporation in

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the United States, the University of Giessen in Germany and RIAME in Russia<sup>1</sup>. These facilities combine a metallic vacuum chamber with an electromagnetic anechoic chamber, as shown Fig.1. The vacuum chamber in these facilities is unique. It has a dielectric section that fits inside the anechoic chamber. The thruster is placed in this part of the vacuum chamber, while the antenna is placed inside the anechoic chamber as before. These installations limit the impact of the vacuum chamber on wave behavior. However, they are very expensive to install and the measurements are complex to analyse.

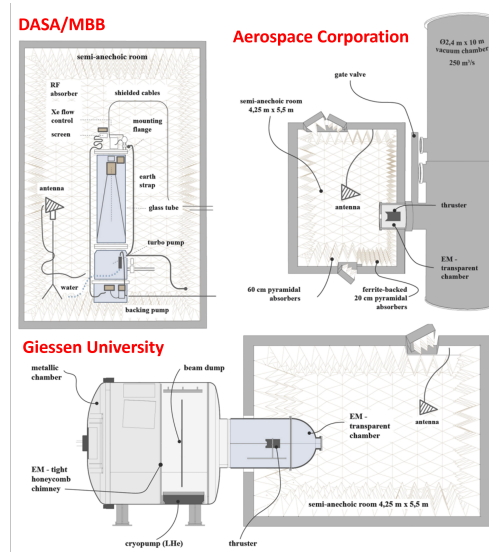


Figure 1: Test facilities for EMC studies<sup>1</sup>

Another solution is to cover the chamber wall with radio-absorbent materials and perform measurements in a vacuum, as shown in Fig.2 and Fig.3. This solution allows measurements to be made directly in an anechoic vacuum chamber over a narrow frequency range. However, it is difficult to obtain anechoic behaviour over the entire frequency range under investigation because of the lack of broadband absorbing coatings and their unstable properties in a vacuum due to outgassing.

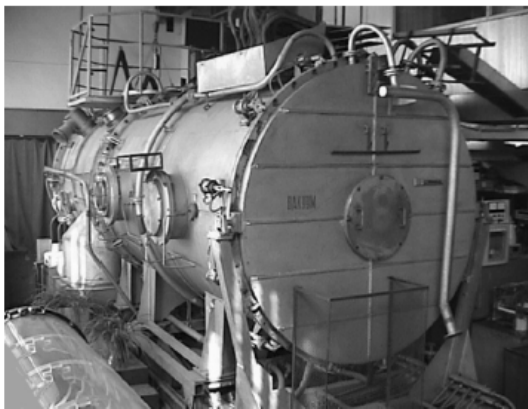


Figure 2: Experimental set-up<sup>3</sup>

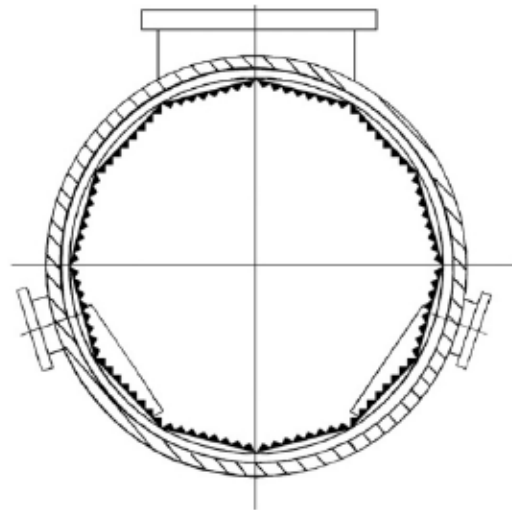


Figure 3: Cross-section of the vacuum chamber.<sup>3</sup>

In order to continue using existing installations, studies have been carried out in metal vacuum chambers with the aim of reducing the influence of reflections on the walls present in these structures. There are two main lines of research: one carried out in vacuum chambers without any modification and the other slightly modified, called reverberation chamber (RVC).

Without any modification of the vacuum chamber, the degree of influence of reflections on measurements in metallic vacuum chambers is characterised, according to the theory of anechoic chambers, by an anechoic factor  $K_a$ . This factor, which determines the anechoic quality of the vacuum chamber, is defined as the ratio between the total power of all reflections and the power of the direct wave. To determine it experimentally, the frequency tuning method is used. This method involves studying the variation in the phase shift between the direct signal and the multiple reflections in order to calculate this coefficient<sup>4</sup>. These studies show that it is qualitatively possible to determine the directional characteristics of the plasma thruster radiation. However, each measure requires additional metrological justification.

Another solution consists in using a mode stirrer inside of the vacuum chamber (see Fig.4). These structures are known as reverberation chambers (RVC)<sup>5</sup>. As the stirrer rotates, it changes the boundary conditions of the electromagnetic modes and thus the resonant frequencies. The stirrer consists of three mechanically coupled plates positioned to break the axial symmetry of the vacuum chamber. The nodes and anti-nodes of the standing waves move to create a quasi-uniform electromagnetic field in the region where the thruster is placed. The disadvantage of these structures is that the minimum frequency at which one wishes to work must be three times higher than the cut-off frequency given by their geometry. In addition, this type of method does not provide any information on the 'transient' behaviour of the radiation.

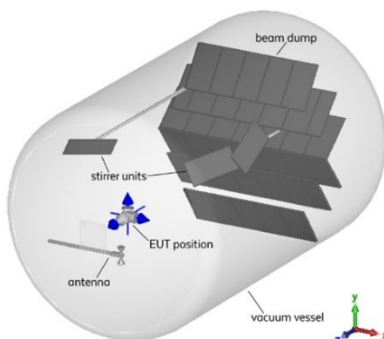


Figure 4: Simplified model of a RVC<sup>5</sup>

In previous work, the self-emission from the ID-HALL 100 W thruster<sup>6</sup> was measured using a monopole-type sensor placed inside the vacuum chamber of the LAPLACE laboratory<sup>7</sup>, as shown in Fig.5 . As explained previously, the signals measured by the sensor inside of this environment are not simply the consequence of direct radiation from the plasma, but also from the multiple echoes resulting from reflections of the metallic wall of the vacuum chamber. To interpret these measurements, it is essential to understand the influence of the plasma on the electromagnetic behaviour of the vacuum chamber. The aim of this paper is to analyze the behavior of the vacuum chamber at the LAPLACE laboratory, where the ID-HALL thruster is located, in a low-frequency range where the modes are spectrally distinct from one another.

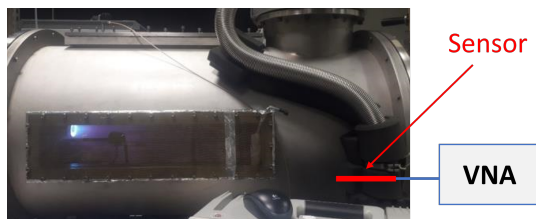


Figure 5: The vacuum chamber of the LAPLACE laboratory with the ID-HALL 100W thruster



## II. Approach

The influence of the plasma on the electromagnetic behaviour of the vacuum chamber was studied experimentally by measuring the norm of the reflection coefficient (the parameter  $S_{11}$ ) of the vacuum chamber in the LAPLACE laboratory (plasma ‘on’ and ‘off’). These were obtained using a coaxial probe placed inside the chamber. A monopole (about 1 cm long) at the end of a coaxial cable was used to couple the sensor to the cavity, as shown in Fig.5 and Fig.6.

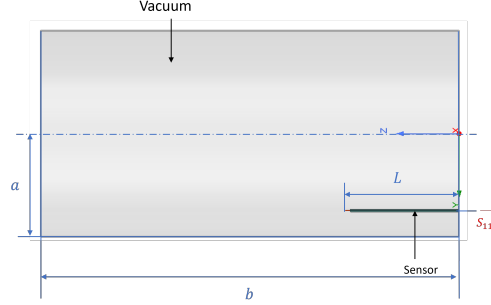


Figure 6: Numerical model of the vacuum chamber.

The metallic vacuum chamber used for the experimental measurements was modelled using the electromagnetic software Ansys HFSS as a cylindrical cavity with a radius of  $a = 23$  cm and a length of  $b = 101.5$  cm, with a monopole inside of length  $L=26$  cm, as shown in Fig.6.

### A. Plasma Model

To model the plasma in Ansys HFSS, an electromagnetic software, we use the Drude model, which gives the local permittivity of the plasma as a function of its local electron density and frequency:

$$\varepsilon_p(\omega) = 1 - \frac{\omega_p^2}{\omega^2 + \nu_m^2} - j \frac{\nu_m}{\omega} \frac{\omega_p^2}{\omega^2 + \nu_m^2} \quad (1)$$

with  $\omega_p = \sqrt{\frac{n_e e^2}{\varepsilon_0 m_e}}$  the plasma pulsation, where  $n_e$  is the plasma electronic density,  $e$  the elementary charge,  $\varepsilon_0$  the permittivity of the vacuum,  $m_e$  the electron mass,  $\omega$  the wave pulsation and  $\nu_m$  the plasma frequency collision (we study a weakly ionised plasma, so we took  $\nu_m/\omega = 0.001$ ). It is important to note that the plasma model is frequency dependent (in other words, the dispersive behaviour of the plasma is included in the model).

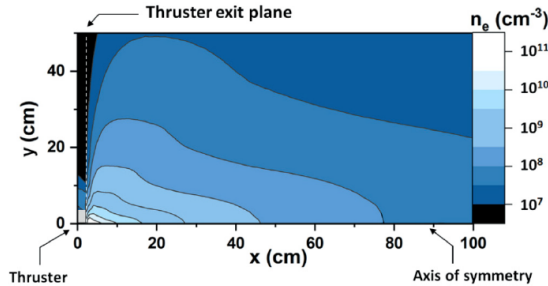


Figure 7: JET2D mapping of electronic density<sup>8</sup>

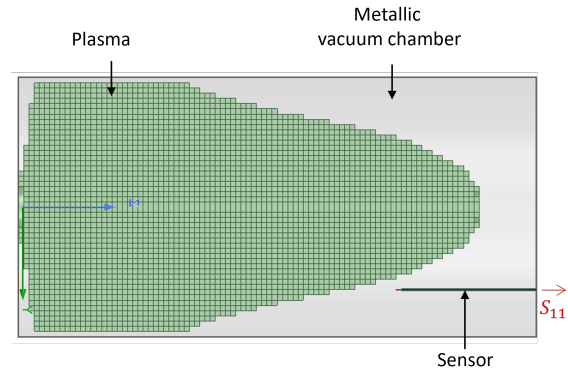


Figure 8: Numerical model of the vacuum chamber with plasma plume.

This electronic density distribution has been obtained for a 100W Hall thruster using the JET2D simulation code<sup>9</sup>, as shown in Fig.7. This simulation does not take into account the reconfiguration of the plasma along the walls of the vacuum chamber. Since it is given in 2D, we have used cylindrical revolution symmetry to model the plasma plume in 3D, as shown in Fig.8, as in the work of De Mejanés and al<sup>8</sup>.

## B. "Microwave Cavity Resonance Spectroscopy" method

To understand the influence of the plasma on the electromagnetic behaviour of the vacuum chamber, we used the Microwave Cavity Resonance Spectroscopy (MCRS) method. This electromagnetic method is widely used to characterise dielectrics and determine their complex permittivities.

Experimentally, an electromagnetic wave is emitted by a vector network analyser (VNA) into a resonator (usually a cylindrical cavity). The wave excites a resonance mode of the cavity and provides information about the behaviour of the resonator. The transmitted or reflected power measured by the VNA can be used to determine the resonance frequency of the mode being probed and the quality factor.

In this technique, a sample is inserted into the resonator. The sample perturbs the field locally and a change in the behaviour of the resonator can be observed. This change is reflected in a change in the resonance frequency (frequency shift) and quality factor (spectral width) as shown in Fig.9 and Fig.10. This information can be used to determine the permittivity of the sample using perturbation theory<sup>10</sup> :

$$\frac{\Delta f_{res}}{f_1} + \frac{1}{2}i\Delta \left( \frac{1}{Q_{res}} \right) = \frac{\iiint_{V_p} (\Delta\varepsilon(r) |E_0(r)|^2) d^3r}{2\varepsilon_0 \iiint_{V_{cav}} |E_0(r)|^2 d^3r} \quad (2)$$

where  $\frac{\Delta f_{res}}{f_1}$  is the frequency shift and  $\Delta \left( \frac{1}{Q_{res}} \right)$  the spectral width,  $\varepsilon_0$  the permittivity of the initial medium,  $\Delta\varepsilon$  the difference in permittivity of the medium before and after perturbation,  $V_p$  the volume of the sample and  $V_{cav}$  that of the cavity.

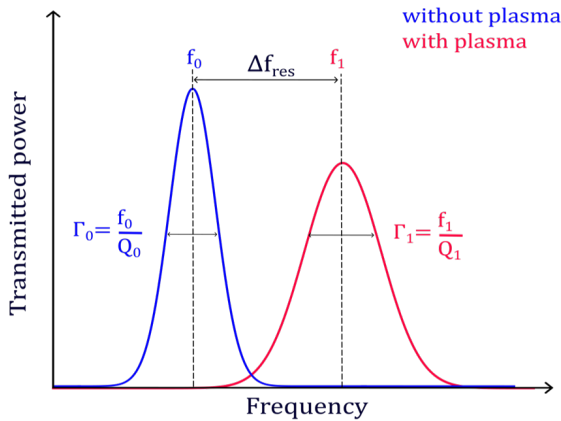


Figure 9: Transmitted power before and after sample insertion

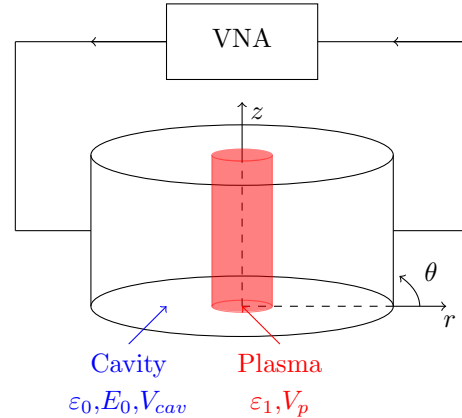


Figure 10: Schematic of the device with sample insertion

The relative permittivity of the plasma is less than 1, so the difference in permittivity will be negative, since  $\Delta\varepsilon = \varepsilon_{rp} - 1$ . This means that the resonant frequency shifts towards higher frequencies, unlike a conventional dielectric whose relative permittivity is greater than 1. The spectral width is proportional to the energy losses that occur in the resonator. The greater the losses, the broader the line. As losses occur in the plasma, the quality factor of the cavity deteriorates and the spectral width increases<sup>11</sup>.

### III. Results and Discussion

During measurements of the reflection coefficient of the vacuum chamber in the LAPLACE laboratory, the first resonance frequency of the vacuum chamber was observed at 262.8 MHz and the second at 691.6 MHz (see Fig.11).

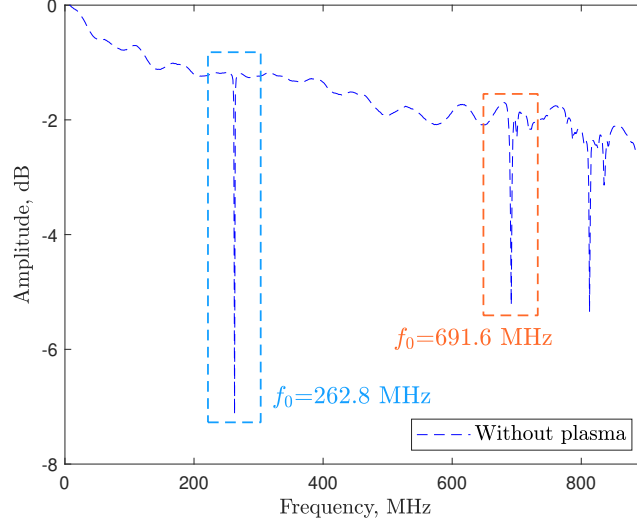


Figure 11: Norm of the reflection coefficient  $|S_{11}|$  of the vacuum chamber measured without plasma.

Considering a canonical geometry, the theoretical resonance frequencies of the fundamental modes  $TE_{111}$   $TM_{010}$ , obtained using the equations (3) and (4), are 382 MHz and 465 MHz respectively, and no cavity resonance mode can exist below these resonance frequencies. It therefore appears that the first observed frequency is not related to a cavity mode. On the other hand, as will be shown later, the second resonance seems to correspond more to the  $TM_{013}$  mode.

$$f_{TE_{111}} = \frac{1}{2\pi\sqrt{\mu\varepsilon}} \sqrt{\left(\frac{x'_{11}}{a}\right)^2 + \left(\frac{\pi}{b}\right)^2} \quad (3)$$

$$f_{TM_{010}} = \frac{1}{2\pi\sqrt{\mu\varepsilon}} \sqrt{\left(\frac{x_{01}}{a}\right)^2} \quad (4)$$

with  $\mu$  the permeability and  $\varepsilon$  the permittivity of the medium,  $a$  the radius of the cavity,  $b$  its length,  $x'_{11} = 1.841$  and  $x_{01} = 2.405$  the first roots of the Bessel functions  $J'_1$  and  $J_1$ .

To study the influence of the plasma on the vacuum chamber, it is important to target a resonant mode of the cavity.

#### A. Study of the nature of resonance modes

We started to numerically study the evolution of the first two resonance frequencies observed as a function of either the radius of the cavity (see Fig.12) or the length of the monopole antenna (see Fig.13) in order to determine the origin of the resonances. The numerical results were compared with the theoretical values for the resonant frequencies of a coaxial cable and the  $TM_{013}$  mode, obtained from the equations (5) and (6) respectively.

$$f_{coax} = \frac{\lambda}{4} = \frac{c}{4L} \quad (5)$$

$$f_{TM_{013}} = \frac{1}{2\pi\sqrt{\mu\epsilon}} \sqrt{\left(\frac{x_{01}}{a}\right)^2 + \left(\frac{3\pi}{b}\right)^2} \quad (6)$$

where  $\lambda$  is the wavelength,  $c$  is the speed of light and  $L$  is the length of the monopole.

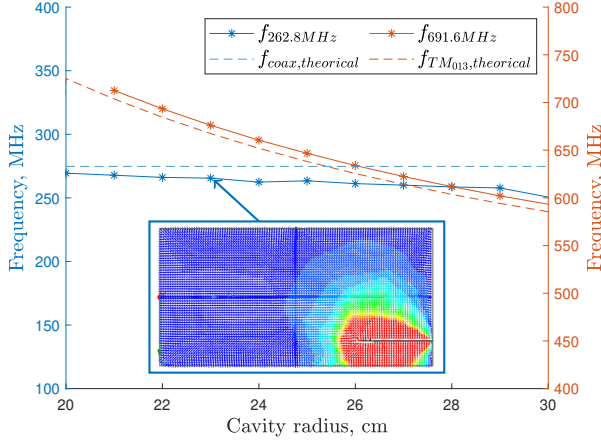


Figure 12: Influence of the cavity radius on the first two resonance frequencies. Inset: Spatial distribution of the electric field norm for a frequency of 258.1 MHz (for a cavity radius of 23 cm).

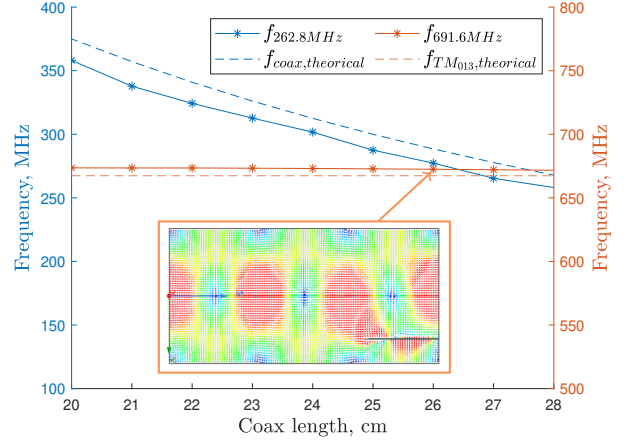


Figure 13: Influence of antenna length on the first two resonance frequencies. Inset: Spatial distribution of the electric field norm for a frequency of 671.7 MHz (for an antenna length of 26 cm).

We note that the first resonance frequency at 258.1 MHz varies only with the length of the antenna, unlike the second resonance frequency at 671.7 MHz, which varies only with the radius of the cavity. These results are in agreement with theoretical results. For example, the spatial distribution of the electric field standard for each of these two frequencies is shown in the insets of Fig.12 and Fig.13. We observe two different types of resonance: the first frequency corresponds to the resonance of the antenna, while the second is due to the  $TM_{013}$  resonance mode of the cavity.

## B. Study of the plasma influence

We will now focus on the study of the  $TM_{013}$  resonance mode of the plasma cavity "off" and "on" (with the plume modelled for a 100 W thruster).

Observing the electric field distributions in the plasma cavity at the second resonance frequency, as shown in Fig.14, we can see that the presence of the plasma affects the electric field distribution. In particular, it is modified by the region of high electronic density, but this perturbation remains local. However, the overall distribution of the electric field still has three maxima (or minima). Therefore it is still possible to consider this as  $TM_{013}$ .

The measurements and numerical results are shown in Fig.15. When the plasma is turned on, we can observe a shift of the resonance frequency ( $\Delta f_{res}/f_{1,exp} = 0.018$ ), as expected by the "Microwave Cavity Resonance Spectroscopy" method. The same trend is obtained in the numerical results, with a slight difference ( $\Delta f_{res}/f_{1,num} = 0.023$ ), which can be explained by the uncertainty in the dimensions of the vacuum chamber.

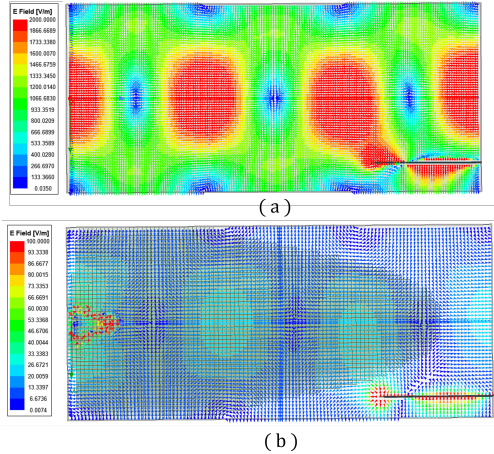


Figure 14: Electric field distribution of the  $TM_{013}$  resonance mode of the cavity without (a) and with plasma (b).

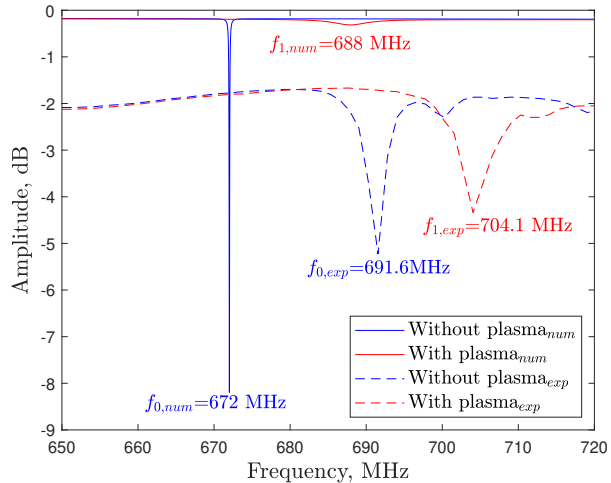


Figure 15: Experimental and numerical reflected coefficient  $|S_{11}|$  of the cavity without and with thruster plasma.

Finally, we observe that the minimum value of the  $|S_{11}|$  standard of the considered mode decreases in the presence of the plasma (in simulation and experiment). However, this decrease is much larger in the simulation than in the experiment. To understand the origin of this behaviour, it will also be necessary to be interested in the spectral width of these modes, as discussed in the conclusion of this paper.

## IV. Conclusion

This work is the first step in our approach to understanding the influence of the plasma on the electromagnetic behaviour of a vacuum chamber.

For this purpose, a numerical method has been implemented to describe the electromagnetic behaviour of the vacuum chamber of the LAPLACE laboratory without and with the plume plasma of the ID-HALL thruster. The numerical results seem to describe the behaviour observed experimentally for the frequency shift induced by the presence of plasma.

The next step is to analyse the influence of the plasma on the spectral width of the "troughs" obtained on the norm of  $S_{11}$  (width affected by the presence of the plasma, as we see in Fig.15). Experimental campaigns coupled with numerical models similar to those presented in this paper are planned to understand the influence of the plasma on this parameter, which takes into account the quality factor of the cavity and the coupling between the antenna and the cavity.

## Acknowledgments

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