ON THE OBSERVATION OF STANDING WAVES IN CYLINDRICAL CAVITIES FILLED BY MICROWAVE DISCHARGE PLASMAS*

L. Celona#, G. Ciavola, S. Gammino, N. Gambino, F. Maimone, D. Mascali, R. Miracoli
INFN-LNS, Via S. Sofia 62, 95123 Catania, Italy

Abstract

A set of measurements has been carried out at INFN-LNS on a plasma reactor used for environmental applications with the aim to characterize it in terms of possible excited resonant modes inside the cavity with and without plasma.

The results have put in evidence that resonant modes are excited inside the cavity and standing waves are formed even in presence of a dense plasma. The measurement of the eigen-frequency shift, which occurs after the plasma ignition, has been carried out, for several values of pressure and power.

The changes in plasma shape, density and electron temperature have been also monitored for different operating conditions by means of a Langmuir Probe.

Such measurements are also relevant for the ECR Ion Sources, as they confirm that the variation of their performances with the frequency can be explained by considering that resonant modes are excited inside the plasma chamber even in presence of a dense plasma.

INTRODUCTION

Many experiments in the last years have shown that significant improvements of ECRIS performances are obtainable by means of a multi-frequency heating of ECR plasmas. On the other hand, it has been demonstrated that a substantial increase of the extracted currents is achieved also by slightly varying the microwave frequency even in the case of single frequency heating [1,2]. This “frequency tuning effect” has been verified experimentally for different ion sources, and in particular some tests carried out on a CAPRICE source at the GSI testbench by sweeping the microwaves in a range of ±40 MHz around 14.5 GHz, have also shown a dependence of the beam intensity distribution from the microwave frequency feeding the plasma chamber [2].

This means that an improvement of the coupling and of the heating phenomena is achieved by properly tuning the frequency of the microwaves. At the same time, from the observations in [2] we can also state that the beam formation process and the beam shape are strongly affected from the frequency variations.

The explanation of these results is strictly linked to the electromagnetic field pattern inside the chamber: in particular, the ECRH and the ionization process change with the electromagnetic field distribution and with its value over the resonance surface. Such distribution cannot be simply determined even supposing the plasma chamber as a cylindrical cavity air filled. In fact, the microwave feeding wavelength is usually much lower with respect to the plasma chamber dimensions; therefore the first resonant frequency of the plasma chamber in vacuum conditions is very far from the operating one (e.g.: for the SERSE source the first resonant frequency is at 1.39 GHz, while the operating frequency is within the 14-18 GHz range). Consequently, the electromagnetic field pattern at the operating frequency is the result of the superposition of the different modes excited in the chamber, each one weighted by its coupling factor.

When the plasma is triggered its presence changes the electromagnetic properties of the whole structure; the previous observations suggest that an electromagnetic modal structure is present in the source even in presence of plasma. In this case, a different electromagnetic field pattern can be produced if the frequency is slightly changed, determining a different efficiency of the plasma heating and of the ionization process [3].

In order to study the evolution of the modes in the plasma chamber when the plasma is created, we exploited a plasma reactor in use at LNS for environmental purposes. This choice has the great advantage with respect to an ECR ion source to have different ports for diagnostics and also to have the possibility to monitor the plasma properties by means of a Langmuir probe (LP).

PLASMA REACTOR DESCRIPTION

The plasma reactor operating at LNS is based on the same physics principles of the Microwave Discharge Ion Sources, that generally are used for industrial applications or as proton sources in nuclear physics. The plasma chamber is a stainless steel cylinder 268.2 mm long, with a radius of 68.5 mm. A magnetic system which consists of three NdFeB permanent magnets rings generates an off-resonance magnetic field along the plasma chamber axis. In the injection side the flanges for the pumping and for the gas injection are located together with a WR284 rectangular waveguide operating in the TE_{10} dominant mode and placed on the cavity axis. In the opposite side DN 40 and DN 25 flanges are used to connect the plasma diagnostics devices such as: mass spectrometer, optical window (to be used for plasma observation and for optical spectroscopy), microwave probes and the Langmuir probe (see figure 1). The microwaves are generated by a Magnetron operating at 2.45 GHz with a 300 W cw of maximum power. A rotative pump is used for vacuum (pressures in the order of a few 10^{-2} mbar are usually obtained).

*Work supported by INFN through the NTA-HPPA strategic project.
#celona@lns.infn.it

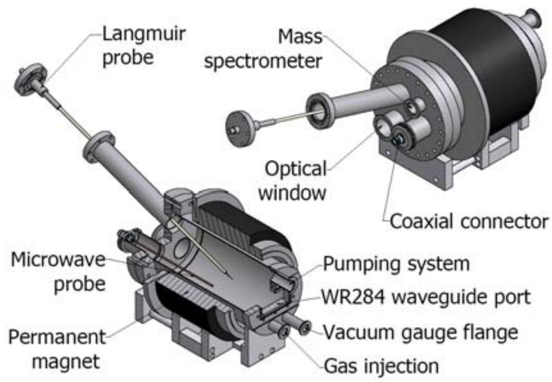

Figure 1: The plasma reactor

The first experiments carried out in the 2007 has permitted a complete characterization of the reactor, in terms of electron density and electron temperature [4]. Optimum operating conditions of microwave power and gas pressure have permitted the n-hexane (C6H14) and cyclo-hexane (C6H16) dissociation [5].
This testbench has been used to investigate the standing wave formation inside the resonant cavity in presence of plasma. Preliminary studies about the coupling between microwave generators and ECRIS have been carried out at INFN-LNS for the SERSE superconducting ion source. Several measurements were performed by means of a Vector Network Analyzer (VNA) able to operate up to 50 GHz, in order to characterize the system including the plasma chamber (in vacuum) and the microwaves line in terms of S matrix [6]. The same VNA has been used for the plasma reactor and the S matrix has been characterized with and without plasma. In our experiment we fixed the microwave frequency feeding the plasma at 2.45 GHz and analysed the plasma properties in terms of the reflection coefficient in the 1-3 GHz frequency range. The experimental set-up is shown in figure 2. A coaxial connector permitted to determine the scattering parameters in presence of the plasma (a series of attenuators were used to reduce the coupled power) and to investigate the best condition of wave-plasma coupling by varying its length.

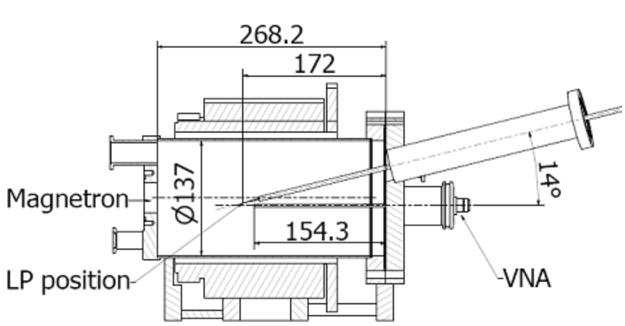

Figure 2: The experimental setup

In order to measure the S_{11} parameters in the different operating conditions the VNA was connected to the coaxial connector while the plasma was ignited through the waveguide. Such not perturbative method allowed to characterize the plasma effect on the resonating modes that exist inside the resonating cavity and also to obtain a reasonable method to evaluate the plasma parameters in terms of electron density. Such calculations are in a reasonable agreement with the plasma parameters measurements carried out with a Langmuir Probe inserted inside the plasma chamber off axis with a slope of 14° as shown in figure 2. Measurements at different positions of the Langmuir probe have been carried out and is was observed that the electron density and temperature increased as the probe penetrated inside the plasma chamber [4]. All the measurements here reported have been carried out by positioning the Langmuir probe tip at z= 17.2 cm inside the cavity, as shown in figure 2, being more stable the plasma and more reliable the data acquired in this position.

EXPERIMENTAL RESULTS

At the beginning we investigated the modes of the cavity in vacuum by measuring the S_{11} seen from the microwave probe and from the WR284 waveguide. The results of the measurement carried out in the 1÷3 GHz frequency range are shown in figure 3: a good agreement has been found with the numerical calculation, as shown in table 1.

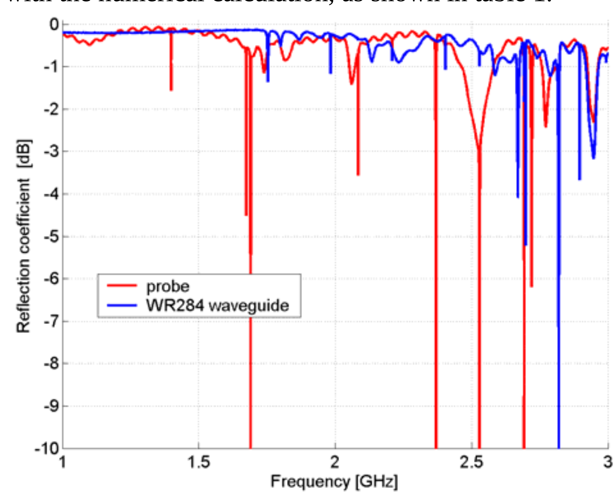

Figure 3: Reflection coefficient measured at the two microwave inputs

By analyzing the reflection coefficient it is possible to characterize the modes that exist inside the plasma chamber. In fact the frequencies for which the minimum values of the S_{11} occur represent the excited modes.

The theoretical calculation of the resonant modes in vacuum has been carried out by solving the eigenvalue equations for the electromagnetic field inside the cylindrical plasma chamber and by using a simplified model of the cavity (it has been considered empty and completely closed).

Table 1: Modes inside the plasma reactor chamber in the 1÷3 GHz frequency range

	Mode	Calculated resonance frequency [GHz]	Measured resonance frequency probe [GHz]	Measured resonance frequency WR284 [GHz]
1	$TE_{1\,1\,1}$	1.39896	1.3978	
2	$TM_{0\,1\,0}$	1.67507	1.6731	
3	$TE_{1\,1\,2}$	1.70123	1.6897	
4	$TM_{0\,1\,1}$	1.76585		1.7534
5	$TM_{0\,1\,2}$	2.01378		1.9822
6	$TE_{1\,1\,3}$	2.11092	2.0838	
7	$TE_{2\,1\,1}$	2.19960	2.2091	2.2089
8	$TM_{0\,1\,3}$	2.37005	2.3687	
9	$TE_{2\,1\,2}$	2.40320		2.4033
10	$TE_{1\,1\,4}$	2.57732	2.5288	2.5287
11	$TM_{1\,1\,0}$	2.66896	2.6925	2.6925
12	$TE_{2\,1\,3}$	2.70872	2.6975	2.6975
13	$TE_{0\,1\,1}$	2.72685	2.7198	
14	$TM_{1\,1\,1}$			
15	$TM_{0\,1\,4}$	2.79351	2.8191	2.8191
16	$TE_{0\,1\,2}$	2.89358	2.8956	2.8956
17	$TM_{1\,1\,2}$			

The equations that determine the allowed frequencies for TM and TE modes are respectively [7]:

$$f_{nml}^{TM\,mode} = \frac{c}{2\pi\sqrt{\mu_r \varepsilon_r}} \sqrt{\left(\frac{p_{nm}}{a}\right)^2 + \left(\frac{l\pi}{d}\right)^2} \quad (1)$$

$$f_{nml}^{TE\,mode} = \frac{c}{2\pi\sqrt{\mu_r \varepsilon_r}} \sqrt{\left(\frac{p'_{nm}}{a}\right)^2 + \left(\frac{l\pi}{d}\right)^2} \quad (2)$$

where: c is the speed of light, ε_r and μ_r are respectively the electrical and magnetic permittivity of the medium filling the cavity (for the air $\varepsilon_r=\mu_r=1$), a and d are the radius and length of the plasma chamber (in our case a=68.5 mm and d=268.2 mm) and finally p_{nm} and p'_{nm} are respectively the zeros of order m of the Bessel functions of order n and its first derivative. Then the three indices n, m, l identify the electromagnetic field pattern of each mode.

The introduction of the LP at z= 17.2 cm, significantly changed the scenario introducing some perturbations which are evident from the measure of the S_{11} parameters at the coaxial probe as shown in fig. 4. Some of the observed modes have resonant frequencies close to ones calculated and measured in vacuum conditions. However, due to the perturbations introduced by the LP we cannot argue if they are TE or TM modes.

When the microwaves are switched on and the plasma is created, for the different operating conditions which have been explored during these measurements, it can be stated that in the 1-3 GHz range a clear electromagnetic modal structure with at least 7 points of minima can be recognized as shown in fig.5.

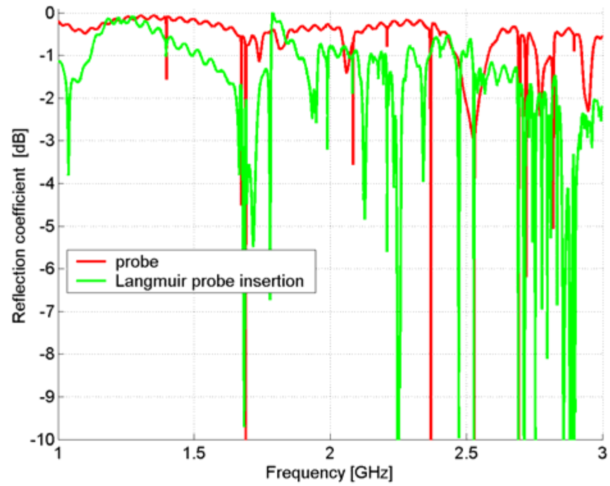

Figure 4: The effect of LP insertion

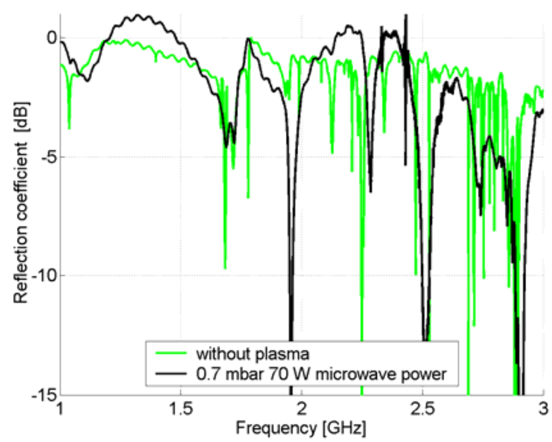

Figure 5: The S_{11} before and after that the plasma is created for a gas pressure of 0.7 mbar and 70 W of microwave power.

It must be pointed out that this analysis do not permit to affirm which modes are really excited inside the plasma chamber, but only that a electromagnetic modal structure is preserved even in presence of plasma.

The excitation of the modes will depend from other parameters such as the chamber dimensions, the location of the waveguide in the injection flange and the waveguide operating mode.

The S_{11} measurements have been carried out with the LP in the position z=17.2 cm at the coaxial input in vacuum conditions; the plasma was created inside the cavity for different operating conditions of gas pressure and microwave power (gas pressure in the range of 0.1-0.9 mbar and microwave power in the range of 40-70 W). It must be remarked that the performed measurements are well reproducible for a given conditions of gas pressure and microwave power.

Figure 6 and 7 report a zoom around the mode at 2.2 GHz. In figure 6 the microwave power was fixed at 70 W and the gas pressure ranged from 0.1 mbar to 0.9 mbar; in figure 7 the gas pressure was fixed at 0.7 mbar and the microwave power was varied from 40 to 70 W. An evident resonating structure can be noticed inside the plasma chamber even in presence of the plasma. The resonances that exist inside the plasma chamber in vacuum shift to higher frequencies decreasing the gas pressure or increasing the microwave power. The origin of the observed effect is the change of plasma density for the different operating conditions.

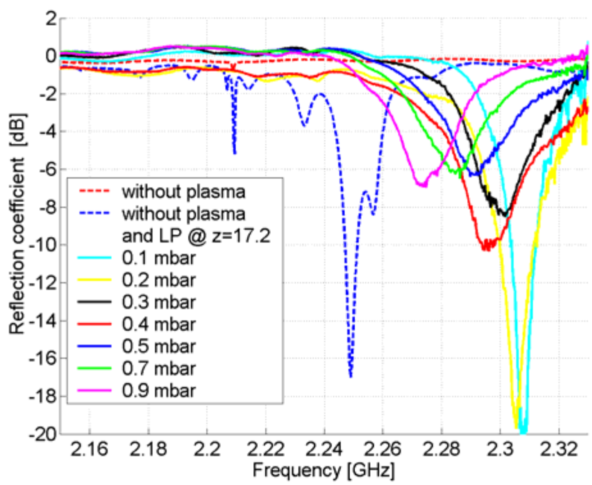

Figure 6: Reflection coefficient without plasma and with plasma vs frequency at different gas pressures and 70 W microwave power

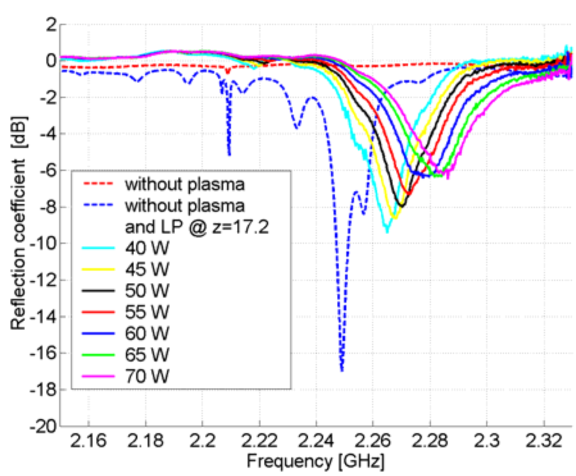

Figure 7: Reflection coefficient without plasma and with plasma vs frequency at different microwave powers and 0.7 mbar gas pressure

In fact, by supposing that the resonance cavity is filled with a homogeneous and un-magnetized plasma, the electrical permittivity in the (1) and (2) is lower than one according to:

$$\varepsilon_r = \left(1 - \frac{\omega_p^2}{\omega^2}\right) \quad (3)$$

where ω is the pulsation generating the plasma (2.45 GHz) and ω_p is the plasma pulsation:

$$\omega_p = \sqrt{\frac{n_e e^2}{m_e \varepsilon_0}} \quad (4)$$

where m_e and e and respectively the electron mass and electron charge, ε_0 is the electrical permittivity in vacuum and n_e is the electron density. Then , under the previous hypothesis, the effect of the plasma on the resonances is a frequency shift due to a decreasing value of the electrical permittivity in (1) and (2). This method can be also used to determine the electron density from the frequency shift. In our case the perturbations due to the LP insertions make difficult to reveal which is the mode that it is shifting to higher frequency when the plasma is ignited. However the LP measurement can be used to identify the mode in vacuum conditions. In particular for 70 W of microwave power and 0.7 mbar of gas pressure an electron density value of $6{\cdot}10^{15}$ m^{-3} is measured with the LP. Inserting such value in (4) and calculating the corresponding electrical permittivity, it is possible to reconstruct that the mode in vacuum conditions should be around 2.21 GHz. At this value in fig. 6 a mode which is present before and after the LP insertion can be observed.
By using the same value of permittivity to the mode at 2.9130 GHz in fig. 5, we obtain that this mode in vacuum conditions should be around 2.8 GHz. In this region of frequency the perturbations due to the LP are stronger with respect to the previous case and different points of minima can be recognized. For our calculations we assumed that the shifting mode is the closer one with frequency of 2.8191 GHz.
If we suppose that the modes which are shifting to higher frequency are the ones above reported we obtain two electron densities curves close one each other and with a reasonable agreement with the values measured with the Langmuir Probe (figure 8).
By applying the same considerations to the measurements performed in fig. 7, the evaluation of electron density has been carried for a gas pressure of 0.7 mbar and for different value of microwave power. Electron density slightly higher than the measured one with the LP have been calculated as shown in fig.9.

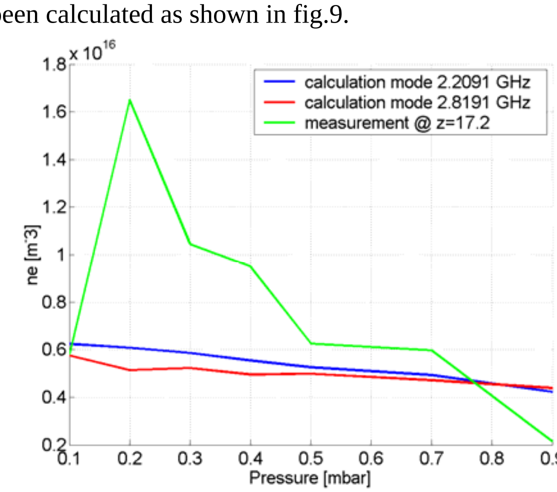

Figure 8: Electron density vs gas pressure for 70 W of microwave power.

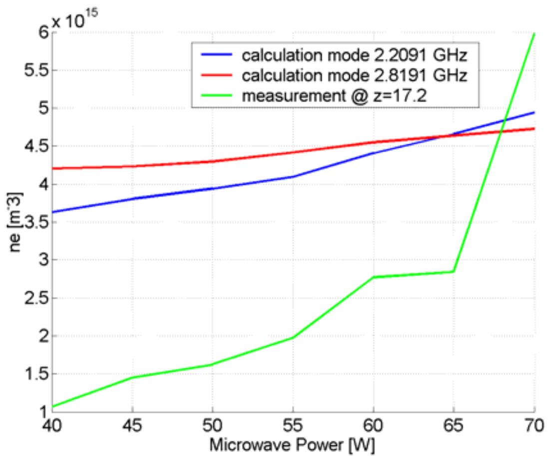

Figure 9: Electron density vs. microwave power for 0.7 mbar of gas pressure.

CONCLUSIONS

The observations above described have permitted to be more confident with the description of the tuning effect given in [2,3,8]. An evident resonating structure have been observed inside the plasma chamber even in presence of the plasma. The resonances present in vacuum conditions shift to higher frequencies when the plasma density increases. The measurement of such shift can be also used to have a rough evaluation of the plasma density. It is evident that the procedure is still not so precise but it is promising as non-perturbing diagnostics. For this reason additional measurements are scheduled for December 2008, with and without the LP in order to have less perturbation on the signals acquired on the VNA. Moreover, theoretical studies will be continued in order to prepare a similar experiment with ECR ion sources.

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