Revista Brasileira de Física, Vol. 17, nº 2, 1987

RF Heating by Cylindrical Plasma Waveguide Modes

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Recebido em 7 de agosto de 1986

Abstract We have experimentally observed in the Mirror Linear Device LISA of the *Universidade Federal Fluminense* the global hybrid mode which has been excited by a microwave power source of 800 W and frequency of 2.45 GHz. The data about the wave (magnetic and electric) fields, the density, and the temperature profiles have been analyzed. These data have shown that there exists a clear absorption of energy by the electrons, due to the electron cyclotron resonance heating, and that the plasma potential drops due to that heating. We have also observed the mode conversion of the microwave into a Langmuir wave at the resonance layer at radial position R = ±3 cm, where R is the inner radius of LISA.

1. INTRODUCTION

In small plasma devices, the shape of the wall, the plasma dielectric constant, and the polarization of the wave at the injectionport establish the modes by which the radio-frequency wave propagates through the plasma. These are the global electromagnetic modes[1,2]. These modes are usually converted into electrostatic modes which, in turn, heat the plasma.

It has been shown by Galvão and Aihara[3,4,5] that during electron cyclotron heating the plasma potential drops. However, for microwaves this still has to be verified and this is one of our goals. Furthermore, we here obtain the heating efficiency as a function of the resonant volume and verify the mode conversion of the microwave into a Langmuir wave.

This work is organized as follows. In section *2* the properties of the hybrid global modes are studied. In section 3 the LISA device is described. In section 4 we present the experimental results. The conclusions are discussed in section 5.

2. HYBRID GLOBAL MODES

The microwave power is injected into the plasma of LISA through a rectangular waveguide. The dominant mode is the TE_{10} and the dominant electric field in the outlet of the waveguide is parallel to the dc magnetic field. To make clear our experimental results, it is worthwhile to make a brief review about wave propagation in a cylindrical waveguide field with a inhomogeneous plasma.

The dielectric tensor in a cylindrical plasma is given by

$$\overleftrightarrow{\varepsilon} = \varepsilon_0 \begin{vmatrix} \varepsilon_{rr} & i\varepsilon_{r\theta} & 0 \\ -i\varepsilon_{\theta r} & \varepsilon_{\theta\theta} & \\ 0 & 0 & \varepsilon_{zz} \end{vmatrix} \qquad (2.1)$$

where

$$\varepsilon_{rr} = \varepsilon_{\theta\theta} = 1 - \frac{\omega_{Pe}^2}{\omega_{ce}^2 - \omega_{RF}^2} , \qquad (2.2)$$

$$\varepsilon_{r\theta} = \varepsilon_{\theta r} = \frac{\omega_{ce}}{\omega_{RF}} \frac{\omega_{Pe}^2}{\omega_{ce}^2 - \omega_{RF}^2} ,$$

$$\varepsilon_{zz} = 1 - \frac{\omega_{Pe}^2}{\omega_{RF}^2} .$$

According to Gore and Lashinsky[6], we can use in our situation the electrostatic approximation instead of the full electromagnetic analysis to describe the plasma waves, because we are interested in plasma guide modes which have a phase velocity much smaller than the speed of light. Thus, the wave fields can be obtained using Poisson's equation, that is

$$\nabla.\overleftrightarrow{\varepsilon}.\nabla\phi = 0 \qquad (2.2)$$

where $\overleftrightarrow{\varepsilon}$ is given by eq.(2.1) and ϕ is the scalar potential.

From eq. (2.2) we have an expression for which is given by

$$\phi = R(r)\, e^{-jn\theta}\, e^{-j\beta Z} \qquad (2.3)$$

where $R(r)$ satisfies the radial differential equation

$$\frac{1}{r}\frac{d}{dr}\left(r\frac{dR}{dr}\right) - \frac{n^2}{r^2}R - \beta^2\frac{\varepsilon_{zz}}{\varepsilon_{rr}}R = 0 \tag{2.4}$$

The relation between the scalar potential ϕ and the electric field is given by

$$\vec{E} = -\nabla\phi \quad . \tag{2.5}$$

From the boundary condition at $r = a$ we have $\phi(a) = 0$ for $J_N(Ta) = 0$, where $Te = P_{n\ell}$ is the ℓ^{th} root of the N^{th}-order Bessel's function of the first kind. To obtain the potential and the electric fields, we use eqs. (2.3), (2.4) and (2.5). The result is

$$\phi = A\,J_N(\mathrm{Tr})\;e^{j(\omega t-N\theta-\beta z)} \quad ,$$

$$E_r = -A\;J_N'(\mathrm{Tr})\;e^{J(\omega t-N\theta-\beta z)} \quad , \tag{2.6}$$

$$E_\theta = jA\,\frac{N}{r}\,J_N(\mathrm{Tr})\;e^{j(\omega t-N\theta-\beta z)} \quad ,$$

and

$$E_z = jA\;\beta\;J_N(\mathrm{Tr})\;e^{j(\omega t-N\theta-\beta z)} \quad ,$$

with

$$T^2 = -\beta^2\frac{\varepsilon_{zz}}{\varepsilon_{rr}} = -\beta^2\frac{(1-\omega_{Pe}^2/\omega_{RF}^2)}{(1+\omega_{Pe}^2/\omega_{ce}^2-\omega_{RF}^2)} \quad , \tag{2.7}$$

and the constant of propagation is

$$\frac{\beta}{T} = \left[\frac{(\omega_{Pe}^2/\omega_{RF}^2)-1}{1+\omega_{Pe}^2/(\omega_{ce}^2-\omega_{RF}^2)}\right]^{1/2} \quad .$$

Since we are interested in the global hybrid modes, that is a mixing between TE_{12} and TM_{03}, it is interesting to describe them.

The components of the electric field for the TE_{12} mode are given from eq. (2.6) by

$$E_r = E_0 J_1'(T_1 r) \tag{2.8}$$

and

$$E_\theta = (1/T_1 r)E_0 J_1(T_1 r) \tag{2.9}$$

where J_1 is Bessel's function of order 1 and T_1 is given by P'_{12}/a, with P'_{12} the second root of the derivative of the Bessel's function $J'_1(z)$, P'_{12} = 5.331, and a is the LISA wall radius. For a = 8.5 cm, we have then T_1 = 0.63 cm^{-1}.

The E_z component of the TM_{03} mode is given by

$$E_z = E_0 J_0(T_2 r) \cos k_z z \quad , \tag{2.10}$$

where T_2 is equal to P_{03}/a, with P_{03} being the third root of the Bessel's function $J_0(z)$, P_{03} = 8.65. With a = 8.5 cm we have T_2 = 1.02 cm^{-1}.

The value of k_z are given by the equation

$$k_z^2 a^2 = \frac{\omega_{RF}^2 a^2}{c^2} - \frac{P_{03}^2}{1 - \dfrac{\omega_{Pe}^2}{(\omega_{RF}^2 - \omega_{ce}^2)}} \tag{2.11}$$

where ω_{RF} is the angular frequency of the microwave and ω_{ce} is the electron cyclotron frequency.

3. DESCRIPTION OF THE LISA MACHINE AND EXPERIMENTAL ANALYSIS

LISA is a linear mirror device which has a total length of 255cm and inner radius 8.5cm. The maximum magnetic field in the uniform region for continuous operations is 10.5 KG; however, in the mirror refiom this field is 13.0 KG. The uniform magnetic field has an extension of 100cm. A region of magnetíc dip was set up disconnecting a certain number of coils, within the original uniform region (fig.1). Two different dip sizes have been created to study the efficiency during the electron cyclotron heating. This efficiency is to be related to the two resonant plasma volumes, namely: small and large resonant plasma volumes.

The gas used is Helium at the pressure of 10^{-5} Torr and the plasma is created by a microwave generator which produces a power of 800 W at a frequency of 2.45 GHz. This power is injected through a rectangular waveguide at the site where there is a dip in the magnetic field.

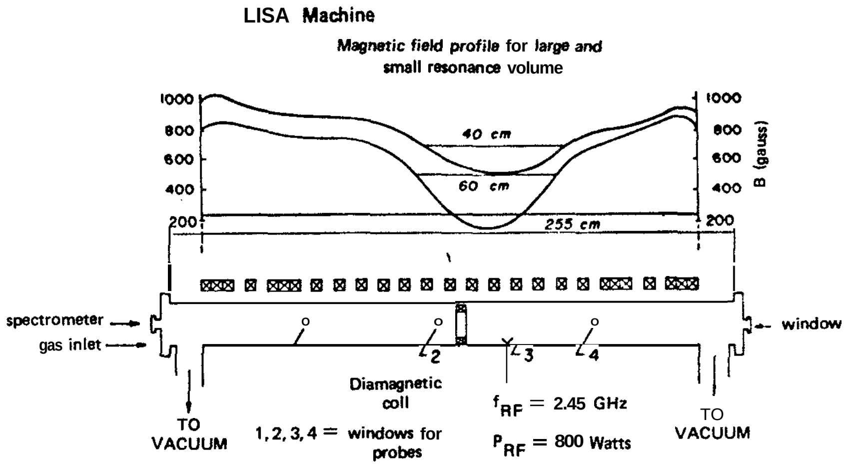


Fig.1 - LISA Machine.

To do the diagnostics we have used plane movable electrostatic probes, Hall probes, magnetic probes, diamagnetic coils, and finally optical spectroscopy.

4. EXPERIMENTAL RESULTS

In this section we describe the measurement which has been carried out in the LISA. The wave generated by the microwave enters in the region of the plasma of LISA and is converted into a hybrid mode[2]. To be specific this hybrid mode resembles a mixture of two cylindrical modes, TE_{12} and TM_{03}. This can be seen from the electric field profiles (figs.3a, 3b, 3c) and from the dispersion relation (eq. 3.7).

Fig. 2 shows the spectrum of the typical values of k_z and λ_z as functions of the magnetic field for the admissible values of 600 to 800 Gauss, for the TM_{03} mode. From this result one can see that it is possible to have a propagation of the TM_{03} mode with the wavelength compatible with the dimensions of the resonant volume.

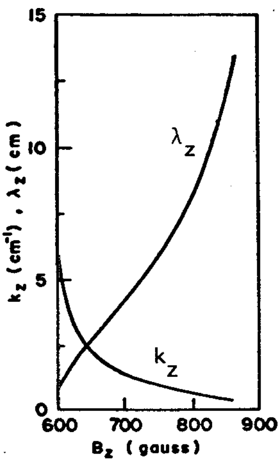


Fig.2 - Admissible wave number k_z and wave length.

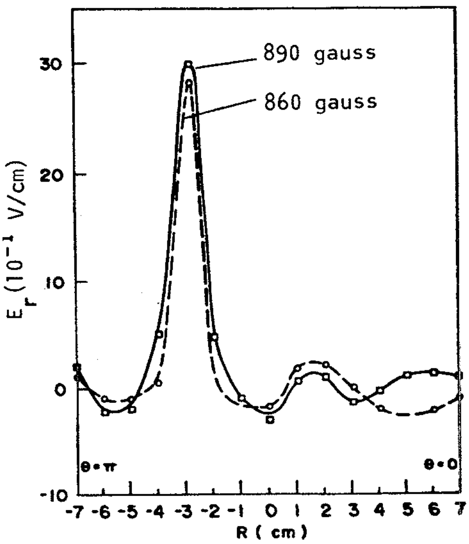
The profiles of the measured electrid field components E_r, E_θ and E_z are shown in figs. 3a, 3b and 3c, respectively. The positive radius refers to the azimuthal angle zero, $0 = 0$, and the negative radius refers to $0 = \pi$. The microwave port is exactly at $0 = p$. These profiles can be identified with the expression given by (2.8) to (2.10), taking into account the resonance and mode conversion, as will be seen in the next section.

4.1 - Electron Temperature Profiles

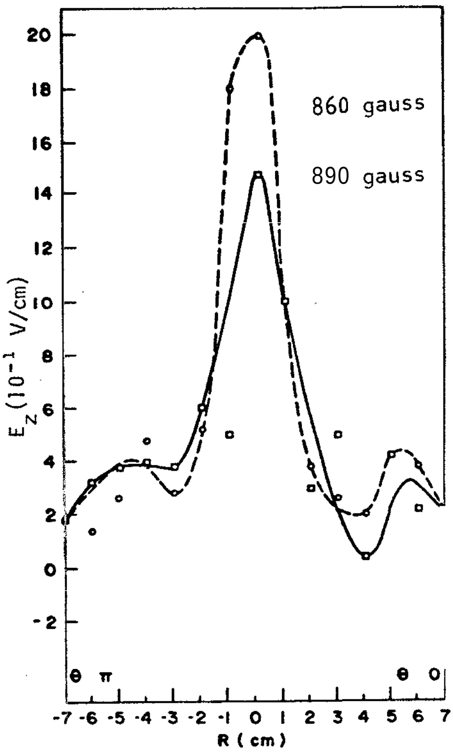
One of the aims of this work is to study the efficiency of the electron cyclotron heating and resonant absorption when the resonant volume size is changed. Figs 4a and 4b show the profiles of the parallel electron temperature, $T_{e\parallel}$, for the two different resonant volume sizes, namely, the large and the small resonant volumes.

One can notice that there is a maximum electron temperature at $r = -3$cm, This is the side in which microwave power is lauchend. This temperature peak is due to both resonant absorption and electron cyclotron resonance heating.

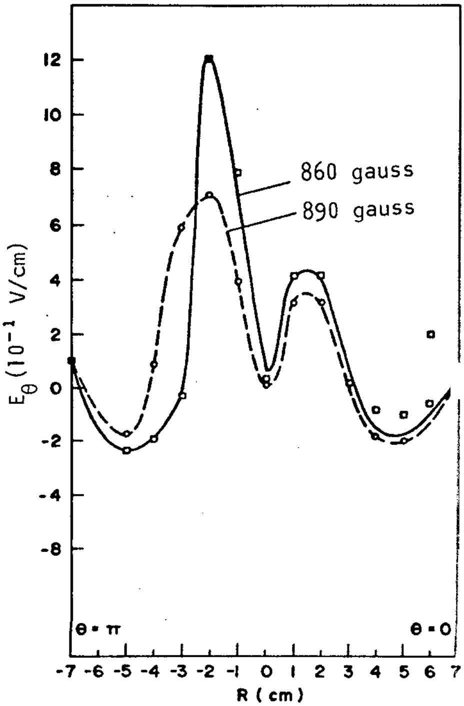
The electric profiles give us an information about the level of absorption and the kind of heating. The peaks which appear in the E_r,



(a)



(c)



(b)

Fig.3a, 3b, 3c - E_r, E_θ and E_z profiles respectively versus radius for different values of magnetic field.

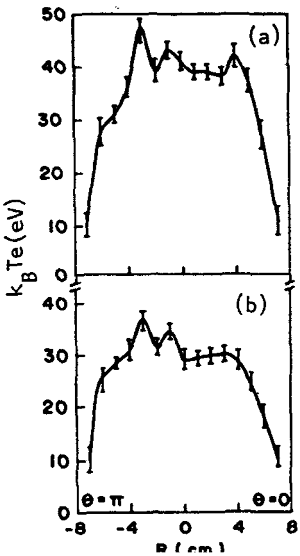


Fig.4 - Temperature profiles for large and small resonant volumes.

E_8 and E fields can be explained as follows: when the microwave is launched, it is predominantly an ordinary mode, that is, the electric field is parallel to the magnetic field. This is checked launching the microwave into the LISA chamber without plasma and measuring the components of the electric field. Now, the wave is launched at an angle of incidence 8 between 0 and 90^o, such that about 70% of the power is carried by the ordinary mode. The remainder power is carried by the extraordinary mode. When the ordinary wave reaches the point r = 3cm, it arrives at the turning point, $\omega_{RF} = \omega_{Pe}$, and is reflected. In this turning point however, there is a linear mode conversion because, even if the wave is reflected, some energy undergoes tunneling and a Langmuir wave is excited[7]. Nevertheless, at this turning point, $\omega^2_{ce}/\omega^2_{RF}$ is slightly larger than one so that the extraordinary wave is not reflected. Thus, for $|r| < 3$cm we have a peak in the electric field E_θ (see fig.3b). Finally, when the extraordinary wave reaches the upper hybrid resonance layer $(x=1-y)$, with $r = \omega^2_{Pe}/\omega^2_{RF}$ and $y = \omega^2_{ce}/\omega^2_{RF}$, we have a linear mode conversion into a Bernstein mode (see fig. 3c) and the dominant absorption is via Landau damping.

At the radial point r = 3.0 cm, the dominant absorption processes responsible for the temperature peak T_e, at r = -3.0 cm, are basically resonant absorption and electron cyclotron absorption.

The absorption power per unit area is given by

$$\frac{P_{abs}}{A} = \frac{\nu}{8\pi} \int |E|^2 \, dr \; ; \quad |E|^2 = E_r^2 + E_\theta^2 \tag{4.1}$$

The resonant absorption contribution is via E_r^2 and the electron cyclotron absorption is via E_θ^2. If one takes the experimental values of E_r and E_θ (figs. 3a and 3b) one comes out with the ratio

$$\frac{P^c_{abs}}{P^r_{abs}} = 0.16 \tag{4.2}$$

where c and r refer respectively to the cyclotron and resonant processes. This result indicates that the dominant process is resonant absorption. The reason why the resonant absorption is dominant might be that the width of the resonant layer L ~ 1.0 cm is larger than that due to the cyclotron resonant zone ΔR ~ 0.14 cm, as follows from the calculation. The resonant zone is given by[e]

$$\Delta R \cong 2R \, k \, v_{th_e}/\omega_{ce}$$

where R is the inner plasma radius, k is the wave vector, and v_{th_e} is the electron thermal velocity.

There are several different types of mechanisms which can increase the absorption in the resonant zone such as inverse Bremsstrahlung, Landau damping, and particle collision. However, it is important to remark that the resonant power absorption is independent of the collision frequency[7]. The power absorbed per unit area is written as follows

$$\frac{P}{A} = \frac{\nu_{eff}}{8\pi} \int |E|^2 \, dr \, , \tag{4.3}$$

where $\nu_{eff} = \sum_i \nu_i$, i = 1,2,3 and the indices refer to Landau damping, inverse Bremsstrahlung, and collisions. However, at the resonant point, r_0, the electric field is given by

$$R = \frac{\sin\theta\, B_z(r_0)}{\frac{r-r_0}{L} - i\,\frac{\nu_{eff}}{\omega_{RF}}} \tag{4.4}$$

where, in the case under consideration, $r_0 \cong -3.0$ cm and ~ 1.0 cm. Introducing the expression (4.4) into eq. (4.3) and taking the limit

$$\lim_{\nu\to 0} \frac{1}{\pi}\int_{-\infty}^{\infty} \frac{\nu}{\alpha^2+\nu^2}\, d\alpha = 1 \,, \tag{4.5}$$

we obtain

$$\frac{P}{A} = L\omega_{Pe}^2 \sin^2\theta \,\frac{|B_z(r_0)|}{8\pi} \quad , \tag{4.6}$$

which is independent of the effective collision frequency ν_{eff}. Thus, the collision frequency drops out of the expression for the power absorbed by the plasma.

4.2 - Heating Efficiency as a Function of the Resonant Volume

From figs. 4a and 4b we can obtain the temperature peak for two cases with different resonant volumes: 47 eV and 37 eV respectively; the first for large volume size and the second for small one.

The average temperature for these two cases are of the order of 40 eV and 30 eV respectively. If we consider that the total microwave power input for both cases is the same, it can be seen that the larger resonant volume is more efficient to absorb energy. However, before this conclusion can be reached, we have to check the energy loss rates for both cases. Let us then consider the energy balance equation

$$\frac{dT_{ej}}{dt} = \alpha_j - \frac{T_{ej}}{\tau_j} \quad , \tag{4.7}$$

where α_j and τ_j are the heating rate and the energy confinement time, respectively, and j = 1,2 indicates the large and small resonant volume cases. In a steady state situation we have

$$T_{ej} = \alpha_j\, \tau_j .$$

The heating rate has been calculated by Barter *et al.*[9] who qudte

$$\alpha = \frac{\pi}{3} B_0 \int n_e \delta(B-B_0)\ dV/n_e dV \tag{4.8}$$

where B_0 is the resonant magnetic field. For our experiment, B_0 = 875 Gauss and $n_e = 7.10^{10}$ cm^{-3}. The resonant volumes are AL_1 and AL, respectively. A is the lengths of the resonant regions. We have L, = 60cm and L_2 = 40cm. Therefore, we can write

$$\alpha_j \sim n_e\ AL_j \tag{4.9}$$

Since we have L, > L„ we conclude that a, > a,.

The energy confinement times τ_1 and τ_2 have been calculated using a 3D particle simulation code, with 5000 particles inthemagnetic field given by the measured values, developed by Raposo *et al.*[10]. For both cases we have the confinement times of the same order of magnitude, τ_1 = 122 µs and τ_2 = 128 µs.

In conclusion, since we have from our experiment the values $T_{e1} > T_{e2}$, and from theory the values τ_1 τ_2, we have confirmed experimentally the relation obtained by Barter *et al.*[9] that is, the heating rate is a function of the resonant volume size.

4.3 - Plasma Potential Drops due to Electron Cyclotron Heating and resonant Absorption

It is known that the plasma potential V_p decreases at the resonant zone when the plasma is heated by electron cyclotron resonance[3,4,5].

This fact is explained as a consequence of the increase of the ratio between the perpendicular and parallel temperature at the electron cyclotron resonance zone, and by effective mirror state[3]. Fig. 5 shows the plasma potential profile for both cases of resonance volume sizes. In both cases we observe a potential drop at the region near r = 3.0 cm. The E_θ component is the responsible for the increase of the perpendicular electron temperature by cyclotron resonance, and E_r for the resonant absorption. Otherwise the dependence of the plasma poten-

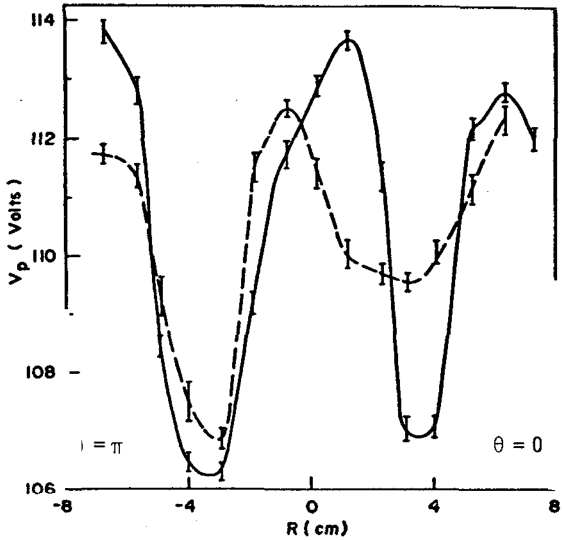


Fig.5 - Plasma potential profile versus radius for large (solid line) and small (dashed line) resonance volume.

tial on the effective collision frequency is given by

$$\nu_{eff} \propto |V_p|^2 .$$

If we consider V_p a Coulomb potential we can write

$$\nu_{ei} \propto |V_p|^2 ,$$

and

$$\nu_{ei} \propto n_e T_e^{-3/2}$$

we conclude that

$$T_e^{-3/2} \propto |V_p|^2 .$$

We can interpret the above result as follows: we have a temperature peak (figs. 4a and 4b), that is: the electrons which are in these regions suffer less collision than the others. Thus, we can conclude that the absorption is via the resonant mode conversion due to the E_r field and due to ECRH via E_θ, rather than collisional absorption. Thus, we have shown that the plasma potential drops even if we have both the electron cyclotron heating and resonant absorption.

5. CONCLUSIONS

It has been experimentally shown that when a microwave is injected into the LISA machine, a hybrid global mode which is a mixture of the modes TE_{11} and TM_{03} is excited. This global mode heats the plasma via the resonant mode conversion and via electron cyclotron resonant heating. To describe analytically the fields of thls hybrid mode an electrostatic approximation has been used which is valid if its phase velocity is smaller than the speed of light.

It has been shown also that, in addition to the resonant absorption, the heating rate due to the electron cyclotron resonance is a function of the resonant volume, confirming Barter's assertion. Finally, we have shown that even if we have both resonant absorption and electron cyclotron resonance heating, the plasma potential drops at the resonant zone.

This work was supported by FINEP, CNPq, CAPES of Brasil. We are thankful to Prof. A.S. Assis, Dr. A. Hasegawa and Dr. M.E. Oakes for useful discussions.

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Resumo

Foi observado experimentalmente na máquina linear do tipo espelho magnético LISA, da Universidade Federal Fluminense, o modo global híbrido que foi excitado pela injeção de micro-ondas com uma potência de 800 W e f_{RF} = 2.45 GHz. Os dados obtidos sobre os campos elétricos e magnéticos desta onda, bem como os perfis de densidade e temperatura foram analisados. Estes dados mostram uma clara existência de uma absorção ciclotrônica pelos elétrons. Além disto, é claramente visível nos gráficos obtidos, a queda do potencial do plasma devido a esta absorção. Foi também observado o modo de conversão ressonante da micro-onda para a onda de Langmuir.