Mode Conversion at the Hybrid Plasma Resonance

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The plasma mode conversion and absorption near the lower hybrid resonance of an inhomogeneous plasma has been studied using Langmuir and rnagnetic probes and also a Faraday cup. The plasma was confined in the mirror linear device LISA, excited by a 28 MHz RF source. It has been shown that the absorption rate and the spatial localization of the mode conversion deperids on the resonant volume created by the externa1 magnetic field. Due to the collisional damping, the quality factor of the machine is comparable to a low-Q cavity resonator.

I. Introduction

An important aspect of many plasmas which occur in laboratory and experimental fusion devices, is the inhomogeneity of one or more of the characteristic parameters such as density, magnetic field and temperature. The inhomogeneity is important in diffusion, instability, reflection and absorption of waves and wave transformation or mode conversion[1]. Lower hybrid excitation and mode conversion in linear devices were originally studied by Briggs and Parker[2] and extensively studied by Simonutti[3]. The main contribution of the present work is the study of the effect of the geometry (small and large resonant volumes) and of the parallel temperature on wave absorption. Especifically, in the case of the lower hybrid wave, several questions on the mode conversion and absorption between fast and slow wave remain unresolved. Among thein are

a) a detailed study of effects of collisional and non-collisional damping;

b) the influence of finite geometry of the device;

c) the importance of the gradients in magnetic field and temperature, compared as those in density;

d) the size and localization of the mode conversion absorption layer which is normally near the resonance point ($\omega_{LH} = \omega_{RF}$).

In this paper we study some of these effects oii the mode conversion and absorption, comparing the numerical solution of the wave equation for the electric field distribution with the experimental data. The spatial localization of the mode conversion region is identified from the electric field measurements.

The experimental data were obtained in the LISA mirror device shown in Fig. 1 and Table 1. The helium plasma was created by a 28 MHz RF source built at UFF tliat excites an helicoidal antenna. The resonant volume profile was changed by disconnecting seven of four coils from the magnetic system, to obtain the large and small resonant volume, respectively (V_ℓ, V_s). This work is organized as follows: in Section II we present the experimental results and analysis; the conclusions are discussed in Section III.

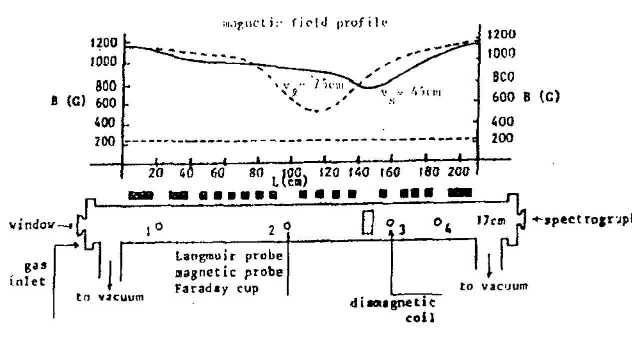

Figure 1: Dimensions of the linear mirror machine LISA and the experimental arrangement plus the axial distribution of the equilibrium magnetic field (V_ℓ) = large resonant volume, V_s = small resonant volume).

Table 1: Summary of the basic LISA and target plasma parameters.

Total length, L	255	cm
Inner radius, r	8.5	cm
Uniform magnetic field, B	10.5	kG
Mirror regon, B	13.0	kG
Extension of the uniform magnetic field	100	cm
Electron density, n_e	10^{10}	cm^{-3}
Electron temperature, T_e	80	eV
Ion temperature, T_i	10	eV

II. Experimental results and analysis

The experiment was carried out on LISA, a linear mirror machine now operating at UFF - Universidade Federal Fluminense[4,5]. For the experiment described here the dc current in the field coils was finely controlled so that the magnetic field varied from 200 Gauss to 1200 Gauss. The diamagnetic effect was not very important because it was only of the order of 1.5 Gauss. Hall probe was used for careful measurements of the field, which were later confirmed by means of a small magnetic probe used with a small ac current superimposed on the main dc current of the field coils. The helium plasma was produced by a RF source of 28 MHz and a 50 W injected power at 10^{-4} Torr filling pressure with a background pressure of 10^{-5} Torr. The antenna used to launch the lower hybrid wave has five loops with inner radius of 5.0 cm and length of 22.0 cm. The experiment was designed so that we were able to have the lower hybrid resonant heating ($\omega_{LH} = \omega_{RF}$). The electron density n_e and the parallel temperature T_E were measured with a small planar Langmuir probe. The value of $T_{0\|}$ has been also measured using a movable energy analyser (Faraday cup) and the results are in good agreement with the data obtained from the Langmuir probe. The electric fields of the wave, E_r, E_θ and E_z were measured by a double floating electrostatic probe.

The experimental data were recently interpreted by Rapozo et al.[5], showing that the lower hybrid layer has been identified experimentally observing the $k_\perp$ value that reaches its maximum at r = ±5.0 cm characterized by a temperature rise. Landau damping and collisional process were responsible for wave dissipation. The wave vector from the cold plasma dispersion relation has its imaginary part increased, with the largest part of dissipation taking place near of $r = \pm 5.0$ cm, the hybrid layer. The operation with seven disconnected coils next to the waveguide port allowed us to get a large resonant volume and a better confinement. To get a small resonant volume, four disconnected coils were used. The peaks in the temperature profile showed that the RF energy was thermalized close to the lower hybrid layer, and there was a dip of the plasma potential localized in the points r = ±5.0 cm for the large and the small resonant volumes, respectively, for the same frequency. At this point, $T_{0\|}$ increased. Completing that study we showed the mode conversion near the resonance layer.

When the resonant lower hybrid layer is reached, which is accesible from the low-density side which requires[6]

$$n_z^2 \geq 1 + \left(\frac{\omega_{pe}^2}{\omega_{ce}^2}\right)\Big|_{\omega=\omega_{LH}}, \tag{1}$$

the E_r, E_θ and E_z profiles are modified by the resonant absorption. The RF frequency condition $f_{RF} = f_{LH}$ has to be satisfied. Figs. 3a, 3b and 3c of ref. [5], show the experimental data of the field profiles in the case of 4.0 < r < 5.0 cm, with E_r and E_z displaying an abrupt drop. Nevertheless, near the column axis the electric field (r < 5.0 cm) has a Bessel's function dependence. The field E_θ has a minimum value in the axis while E_r has a maximum.

An inductive slow wave excited by the helicoidal antenna at r > 5.0 cm traveled inwards to the lower hybrid critical layer, where the slow wave had a resonance. Beyond this layer, it was transmitted into the high density plasma as a fast wave. Fig. 2 shows the favorable density profile[7], in which we were able to obtain the lower hybrid resonance. The fast wave propagated on the high density side of the critical layer and the slow wave propagated on the low density side. It occured because the fast wave was unaccessible at the boundary for perpendicular propagation so that a finite value of the parallel component of the propagation vector, k_z, had to be established.

Stix[1] has shown that a sufficient condition for accessibility is

$$\frac{c^2 k_z^2}{\omega_{pi}^2} > 2 \tag{2}$$

However, in our experiment, it is also necessary to consider a finite k_z because of the finite extension or periodicity of the wave generating structure in the z-direction. The helicoidal antenna has an inner radius of 5.0 cm, a length of $\ell = 22.0$ cm, a number of loops of $N = 5$ and the distance between turns is 4.0 cm. So, from these data we can find $k_z = N\pi/\ell$. Really, there will be a whole spectrum of k_z's because of the impossibility of building a real coil system with only one Fourier component.

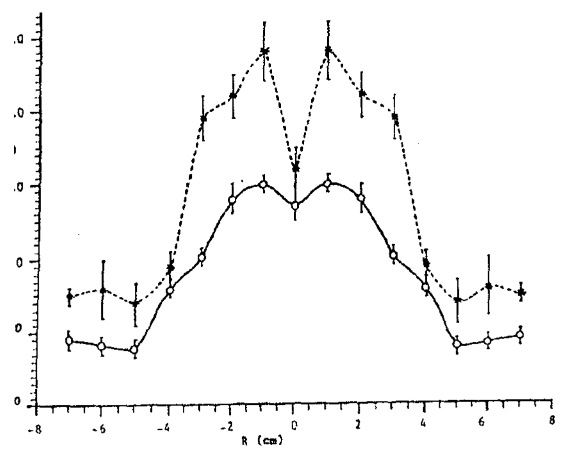

Figure 2: Electron density profile versus radius for large resonant volume (dashed line) and small resonant volume (solid line).

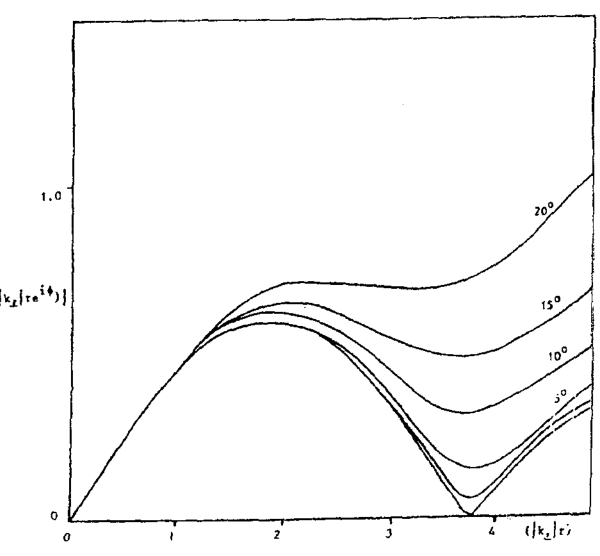

Figure 3: Absolute value of the Bessel's functions J_1 versus $|k_\perp|r$ for different parameters ϕ.

Another iinportant aspect of the inclusion of a finite k_z at the lower hybrid is the effect of collisional and other damping processes on the mode conversion. During the RF heating of plasmas, mode conversion and absorption process are generally important only in a thin layer located about the lower hybrid resonance for the waves. This layer can have a considerable dimension into the plasma, that is the region containing the lower hybrid resonance is broader (3.0 cm < r < 5.0 cm). Theoretically, it has been shown[8] that, for a given point on the density profile, the perpendicular wavelength of the fast mode decreases with the increasing of k, and the wavelength of the slow mode increases with the increasing of temperature. These increasings will shift the low density boundary of the mode conversion - absorption layer to lower densities for a given frequency. In our case, we must also consider the electron-neutral collision frequency, which are responsible for the electron heating over the whole volume[7], so the layer will not be well defined. Then, considering eq.(2), the external k_z and the collisional effects, we have

$$0.71\ cm^{-1} > k_z > 6.0 \times 10\ cm^{-1}. \qquad (3)$$

From the ion saturation current measurements we estimated that the average ion density was about $4.0 \times 10^{10}\ cm^{-3}$, which gave $k_z \sim 10^{-2}\ cm^{-1}$ and $N_{\|} \sim 1.7$.

The lower hybrid layer was identified experimentally observing that the $k_\perp$ value reached its maximum at r < ±15.0 cm, characterized by a temperature rise. Fig. 3 of ref.[5] shows the profiles of the parallel temperature Te as a function of the radius, for two different resonant volume sizes, namely large and small resonant volumes. At the resonant layer (**Ar** $\simeq$ 1.0 cm), the parallel Landau damping on the electrons and the perpendicular Landau damping on the ions were responsible for the wave dissipation. Really we would expect a strong interaction with the ions at the lower hybrid resonance, rather than the electron heating. However, as the plasma is weakly ionized (<< 1%), the collisions are responsible for the RF absorbed over the whole volume. This suggests the idea that the heating via lower hybrid resonance for electrons is global and for ions is local. Furthermore, the electric field E, and the associated wave nurnber k_z are responsible for the electron heating in the center of the plasma column[4,7].

The peaks in the electron temperature profiles show approximately the position of the lower hybrid resonance (tlie static magnetic field had at r = ± 5.0 cm, $B_{dc} = 850$Gauss, which corresponded to $\omega_{LH} = \omega_{RF}$). Close to the resonance layer, the strong electric field E_θ induced by the antenna accelerated the electrons in the perpendicular direction, so $v_\perp/v_\parallel > 1$. The lower hybrid resonance strongly inodified the electric field distribution in tlie plasma, specially at the resonance layer, as shown by Rapozo et al.[5].

The determination of the electric field as a function of time and position, inside and outside the interaction region, lias a paramount importance for the understanding of the mode conversion. Theoretically, the coupled linearized Vlasov-Maxwell system self-consistently determines the structure of amplitude waves propagating within the mode conversion - absorption layer. In order to solve these equations, it is customary to solve the distribution function $f(v)$ in terms of the wave electric field E, and then use this result to find an equivalent dielectric tensor, which may include a differential operator, in our case with respect to r and 0.

Although only the gradient in density perpendicular to the magnetic field is considered, the inclusion of damping effect will give a linear fourth-order mode conversion equation with $k_\perp$ complex[9].

In mode conversion at the lower hybrid, the slow wave travelled inward to the lower hybrid critical layer where it was transmitted into the higher density as a fast wave. In addition to these two propagating solutions, there were two evanescent modes localized on either side of the critical layer. Within the kinetic layer, the applied LH wave resonantly interacted with the particles, yielding a net transfer of power from the wave fields to the plasma, which is governed by a generalized Poynting's theorem, so the complete numerical solution of this problem is very difficult. We simplified such situation, considering a second-order differential equation for $\vec{E}$ with $k_\perp$ complex and $k_z << |k_\perp|$, when $k_\perp$ is larger at tlie hybrid resonant layer as it approaches it from the low density side. As collision can be the mechanism for dissipation of the RF energy, we took the imaginary part of $k_\perp$, increasing with the density profile. So, the best absorption should be at the mode conversion - absorption layer.

Under this simplification we have

$$k_\perp = |k_\perp| e^{i\phi} \tag{4}$$

where

$$|k_\perp| = (k_r^2 + k_i^2)^{1/2} \tag{5}$$

and

$$\phi = \operatorname{arctg}\frac{k_i}{k_r}, \tag{6}$$

with $k_i < k_r$, and also $k_z < k_i$.

The electric field distribution is obtained solving the wave equation, the electric field E_θ is[4],

$$E_\theta = E_0 J_1(|k_\perp| e^{i\phi_r}) \tag{7}$$

where J_1 is a first order Bessel function and E_0 is the maximum value, which we assume that corresponds to the experimental data close to the antenna (0.45 V/cm and 0.35 V/cm, for small and large resonant volumes, respectively).

For tlie numerical calculation of E_θ, E, and E, we estimated the value of $|k_\perp|$ and k_i. From the plasma potential profile, which exhibits maxima and minima as a stationary wave, we chose two points of minimum ($\ell = 10.0$ cm), so $|k_\perp| = 2\pi/10 = 0.68$ cm^{-1}. Another characteristic value was given by $|k_\perp| = \pi/d = 0.18$ cm^{-1}, where d is the LISA diameter[10]. Thus, $0.18 < k_\perp < 0.68$ cm^{-1}. The collisional effects were considered using an estiinate value of k_i between 0.01 and 0.10 cm^{-1}; and we took $|k_\perp| \sim 0.4$ cm^{-1} as an average value.

Figure 3 shows the normalized azimuthal electric field profile versus $|k_\perp|r$ having the angle ϕ as a parameter. We observed that in the range $0 < |k_\perp|r < 2.5$ ($0 < r < 6.0$ cm), the E_θ profile was not modified by the Landau damping and collisional effects near the hybrid layer. This agrees with the experimental data shown by ref. [5], except close to r = 0. We can observe in Figs. 3b and 3c of ref. [5], that the respective electric fields, E, and E,, do not have the typical Bessel function dependence, which is obtained when $k_\perp$ is real.

The drop observed in these profiles, at $2.0 < r < 3.0$ cm is more pronunciated for small resonant volume. A similar behaviour was observed by Rapozo et al. [7] in cavity modes at electron cyclotron and lower hybrid frequency, where it was identified a linear mode conversion.

Figure 4 shows the numerical results of the normalized E,, proportional to $J_0(|k_\perp| e^{i\phi_r})$, which is strongly modified at $2 < |k_\perp|r < 3$, where it would occur the mode conversion. We estimate that the region containing the lower hybrid is approximately 2.0 cm which agrees with the experimental result. However, the experimental E, drops, but it lias a shift to tlie plasma center. Probably, this shift is due to the gradient of the electron density which is shown in Fig. 2. Near r $= 2.0$ cm, $k_\perp$ increases because the wave number $k_\perp$ of the fast wave increases with the increasing $k_\|$ when n_e increases. The same effect can be observed in the E,. profile which is proportional to $J_1'(k_\perp e^{i\phi_r})$, but due to the experimental data, $J_2 \approx 0$ so E,. is also proportional to J_0.

Experimentally it was observed that the electric field for small resonant volume is larger than that for the large resonant one. This means that a good coupling between a RF antenna and plasma does not necessarily lead to a good efficient absorption. The collisional damping in the experiment is global, so we can calculate the quality factor of the machine.

Figures 6a and 6b of ref. [5] show the power deposition profile versus radius for large resonant volume (dashed line) and small resonant volume (solid line) for the cases without and with plasma; these data permit us to obtain the quality factor Q of the LISA cavity. The average values of Q are 4 and 7, respectively. These quantities are proportional to $k_r/2k_i$. Which can be explained as follows: the field amplitudes inside the antenna are proportional to k_r/k_i, so that the stored energy is proportional to (k_r/k_i). During each period á fraction k_i/k_r of the stored energy is absorbed, so the absorbed power becomes proportional to

$$\frac{k_i}{k_r}\left(\frac{k_r}{k_i}\right)^2 = \frac{k_r}{k_i} \tag{8}$$

This quantity is also related to the "Q" of the system following Kramer[11], so we have

$$Q \simeq G_0\frac{k_r}{2k_i}, \tag{9}$$

where G_0 is a factor determined by the geometry. Inserting the experimental values of Q into the eq.(9), we can obtain k_r/k_i with $G_0 \simeq 1$. Thus, as $k_\perp$ is given, we determine k_i and ϕ which agree with the values used in the numerical calculation of the electric field profiles, as was shown in Figs. 3 and 4. This analysis shows an important result about the absorbed power P_w: for a constant applied voltage to the antenna, the absorbed power is inversely proportional to the effective collision frequency in the plasma. In other words as we have the electron-neutral collision frequency v„ $\propto T_e^{1/2}$ and $T_{e\,\|\,LRV} > T_{e\,\|\,SRV}$ we have $P_{WSRV} > P_{WLRV}$.

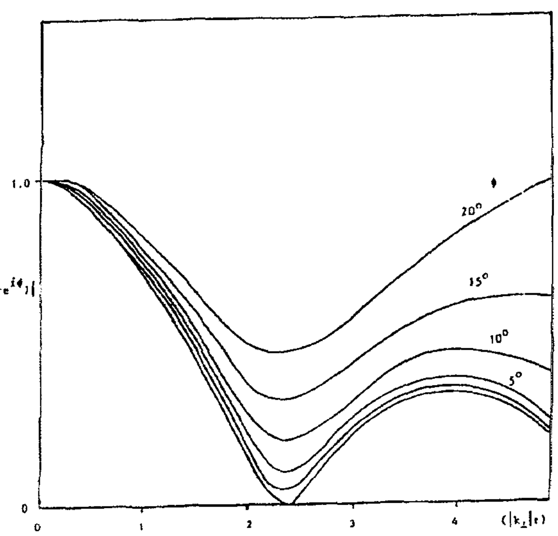

Figure 4: Absolute value of the Bessel's function J_0 versus $|k_\perp|r$ for differcnt parameters ϕ.

III. Conclusions

We have shown that in the LISA machine, the RF wave of 28 MHz is absorbed because of the lower hybrid resonance. The RF energy is thermalized very close to the resonance layer where the parallel temperature is maximum. However, due to the collisional effects the RF energy is transferred to the whole plasma. From the study of the electric field profile we have identified a region where we have mode conversion of a slow wave to a fast wave. As the collisional damping is global, the quality factor Q found in this experiment corresponds to a low-Q cavity.

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