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Plasma heating as a function of the resonant volume and collisions

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Abstract It has been shown analytically and experimentally that the plasma heating rate during electron cyclotron heating is a function of the resonant volume formed by the mirror magnetic field. The target plasma has been produced by radio frequency at the electron cyclotron resonance and the degree of ionization obtained is smaller than 1%. The experiment has been carried out on the linear mirror machine LISA of Universidade Federal Flurninense.

1. Introduction

LISA is a linear magnetic mirror machine designed and constructed at the Max-Planck Institut für Plasmaphysik (Garching, West Germany) which has been reassembled at the Universidade Federal Fluminense (Niterói-RJ). The dimensions of LISA are shown in Figure 1. The main parameters of this device are listed in Table 1. The plasma is weakly ionized (– 1%) and the gas used is helium. This machine has been used at UFF for the investigation of radiofrequency-produced

It has been shown by Galvão and Aihara[2] and later by Rapozo et al.[3] that during electron-cyclotron heating the plasma potential drops. Furthermore, here we obtain the heating efficiency as a function of the resonant volume and collisional heating process. As far as we know no information about the heating efficiency as a function of the resonant volume can be found in the literature, and in this paper we intend to study this problem.

A perturbative treatment is used to calculate the rate of increase of the thermal energy in a plasma contained in a periodically perturbed magnetic field. A sinusoidal perturbation of the magnetic field has been assumed by Berger et al.[4]. In the case where the energy rate increase, it is found that it is proportional to the field modulation factor defined by $\epsilon = \Delta B/B$.

This work is organized as follows: in section **2** the LISA device is described. In section **3** we present the experimental results and analysis. In section **4** we present a study on collisional plasma heating due to magnetic field modulation. The conclusions are presented in section 5.

2. The experiment

The experiment has been carried out on LISA (see figure 1 and table I).

The microwave sources built at UFF use a **2.45 GHz,** 800-watt magnetron. This power is injected through a rectangular waveguide at the site where there is a dip in the static magnetic field. The magnetic field coils are fed by a DC current generator and produce the mirror magnetic field. This field radially confines the RF produced plasma. The mirror coils at the two ends of the device are not used. The magnetic field along the axis is not uniform, since the waveguide port takes up the space of one magnetic coil and consequently a minimum is formed at this location. We use this peculiar feature to have a local mirror-confined plasma and operate with seven disconnected coils next to the waveguide port to get a large resonant volume and a better confinement. To get a small resonant volume four disconnected coils are used. For diagnostics, we use a plane movable Langmuir probe and a diamagnetic coil to measure the plasma density, temperature, and pressure, and a Hall probe to measure the equilibrium magnetic field distribution. The diagnostics arrangement and field distribution are shown in figure 1. The plasma is produced via collisional impact through the electron cyclotron resonance at $\omega_{ce}(B_0) = \omega_{RF}$.

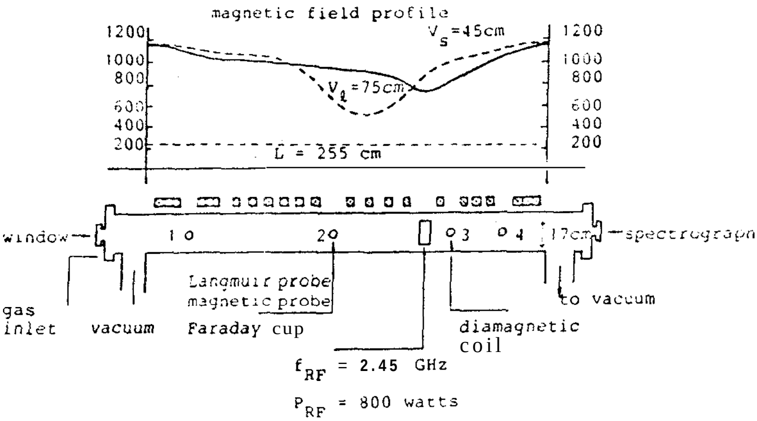

Fig. 1 - Dimensions of the linear mirror machine LISA and the experimental arrangement plus the axial distribution of the equilibrium magnetic field.

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

Total length, L	255 cm
Inner radius, a	8,5 cm
Uniforme magnetic field, B	10.5 Kg
Mirror region, 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	75 cm
Large resonant volume	75 cm
Small resonant volume	45 cm

3. Experimental results and analysis

One of the aims of this work is to study the efficiency of the electron cyclotron heating and collisional heating when the resonant volume size is changed.

Experimental results of plasma pressure, density and temperature are presented in figure 2. The three components of the wave's electric field for large resonant volume and for small resonant volume, measure with floating double probes are shown in figure **3.** The radial oscillations of the electric field reflect the cavity mode nature of LISA plasma under the operated frequency. The qualitative behaviour of the perpendicular power profile versus radius is show in figure 4. The temperature oscillations follow from the RF heating power deposition profile.

From figure 2c we can obtain the parallel temperature peak for two cases with different resonant volumes: 47 eV (large resonant volume - dashed line) and **37** eV (small resonant volume - solid line), respectively.

The average parallel temperatures for the 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 large resonant volume is more efficient to absorb energy. The steady state temperature T_e of the plasma is determined by the energy balance between the gain and loss terms in the energy equation given by[1]

$$\frac{\partial}{\partial t}\left(\frac{3}{2}n_e k T_e\right) + \nabla.\vec{q}_e = (\vec{j}.\vec{E})_{\mathrm{RF}} - \sum_j n_e k(T_e - T_j)\tau_{ej}^{-1} \tag{1}$$

where n_e, T_j and τ_{ej} are respectively the electron plasma density, the temperature of species j, anf the energy equipartition time between electrons and species **j.**

In steady state, the time derivative vanishes. The heat flow term $\vec{q}_e$ represents radial and axial heat losses. The first term on the right stands for RF heating and the second term is heat exchange with other species, primarily neutrals. In principle, we need another energy equation to describe the neutral temperature; however, the neutrals are not confined and they lose energy to the wall so rapidly that the neutral temperature is negligible. The RF heating term is

$$(\vec{j}.\vec{E})_{\mathrm{RF}} = \frac{1}{2}\delta_\perp|\vec{E}_\perp|^2 + \frac{1}{2}\delta_\parallel|\vec{E}_\parallel|^2 = 4\pi\sigma_\perp W_\perp + 4\pi\sigma_\parallel W_\parallel \tag{2}$$

where the factor 1.2 comes frorn the time average of $|\vec{E}|^2$, W is the energy density of the electric field, and

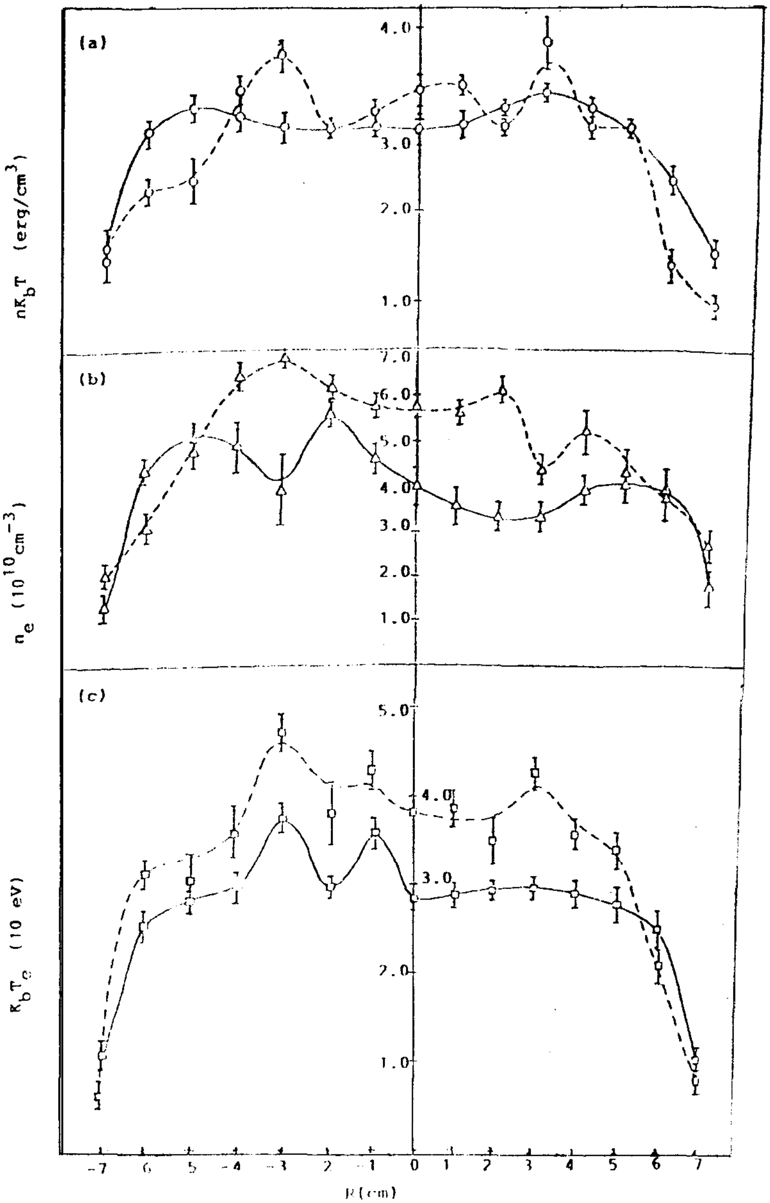

Fig. 2 - Radial distributions of plasma pressure (a), density (b) and temperature (c). - - - large resonant volume. — small resonant plasma.

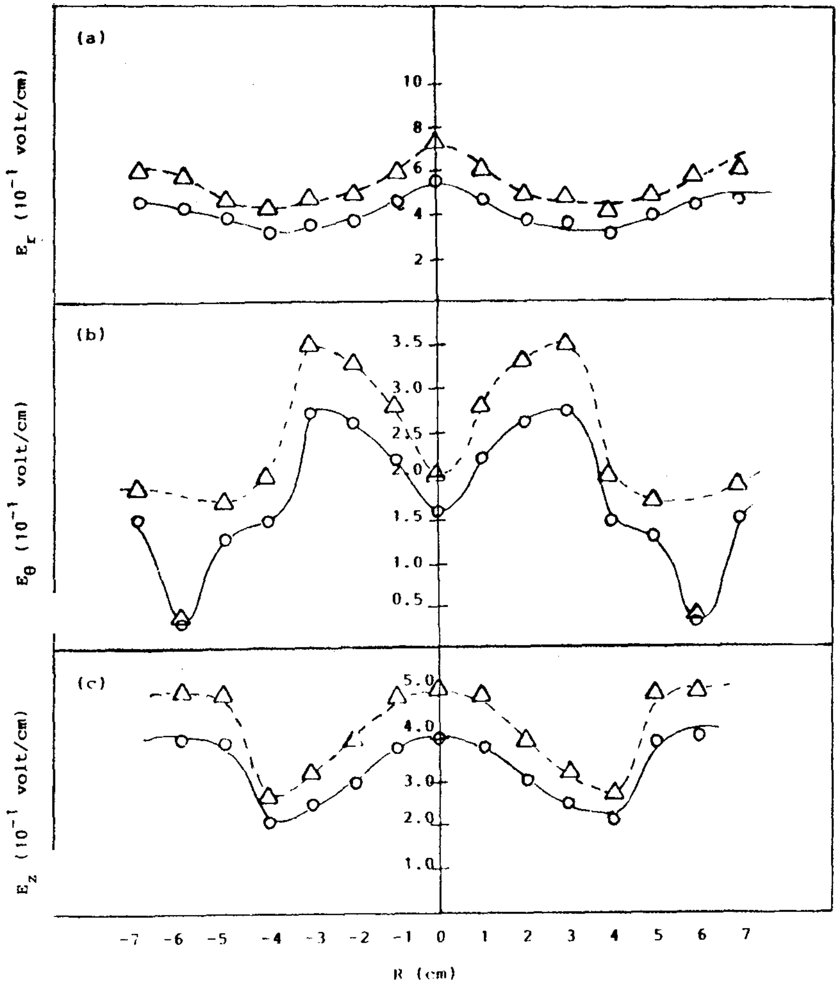

Fig. 3 - Radial distributions of the wave's electric field. Δ large resonant volume. ○ small resonant volume.

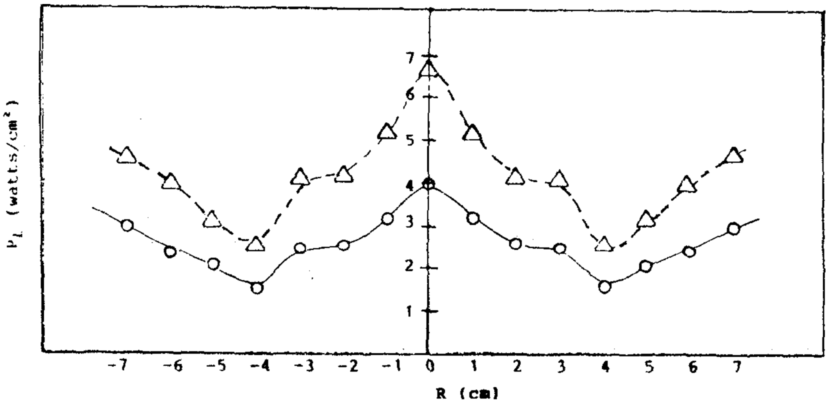

Fig. 4 - Qualitative behaviour of the power profile versus radius. Δ large resonant volume. $\circ$ small resonant volume.

$$\sigma_{\parallel} = \sigma_0 \left(\frac{\nu}{\omega_{\rm RF}}\right)^2$$

$$\sigma_{\perp} = \sigma_0 \frac{\nu^2(\omega_{\rm RF}^2 - \omega_{\rm ce}^2)}{(\omega_{\rm RF}^2 - \omega_{\rm ce}^2)^2 + 4\nu^2\omega_{\rm RF}^2}$$

$$\nu = \nu_{\rm en} = v_{\rm the} Q_{\rm en} n_0$$

$$\sigma_0 = \frac{n_e e^2}{m_e}$$

$$v_{\rm the}^2 = \frac{kT_e}{m_e}$$

$$Q_{\rm en} \cong 2\pi a_0^2$$

where a_0 is the Bohr radius, n_0 is the density of neutral particles, $v_{\rm the}$ is the electron thermal velocity, and Q_{en} is the cross section for collisions between the electron and neutral particles provided by McDaniei[5]. The typical value of $Q_{\rm en}$ given by Book[6] is $5 \times 1-^{-15}$ cm^2 and the value of n_0 for $P = 6 \times 10^{-4}$ torr and for the helium plasma, is $\simeq 2.1 \times 10^{13}$ cm^{-3}. The subscripts $\|$ and $\perp$ refer to parallel and perpendicular directions with respect to the magnetic field.

If we integrate eq. (1) over the plasma volume, the z dependence of the magnetic field leads to a singular contribution to $\sigma_\perp W_\perp$ in the neighbourhood of the resonance, $\omega_{\rm RF} = \omega_{\rm ce}(B_0)$. Here $\hat{z}$ is the cylindrical axis of LISA.

Thus, eq. (1) leads us to

$$\gamma_{\perp} W_{\perp} = \alpha \frac{m_e}{m_i} \nu p_e + \nabla . \vec{q}_e \tag{3}$$

where $\gamma_{\perp}$ is the resonant heating rate[7,8] given by

$$\gamma_{\perp} = 2 \frac{m_e}{m_i} \left(\frac{c}{v_A} \right)^2 \omega_{\mathrm{RF}} \, G \ , \tag{4}$$

$$\tau_{\mathrm{en}}^{-1} = \alpha \frac{m_e}{m_i} \nu \ ,$$

c and v_A are light and Alfvén speeds, G is a dimensionless quantity weighted over plasma density,

$$G = \frac{\pi}{2} B_0 \int n_e \delta(B(z) - B_0) dV . / \int n_e dV \ , \tag{5}$$

and the mass ratio in the expression of τ_{en} is due to energy equipartition[8]. Considering n_e to be uniform, and taking the magnetic field profiles to be parabolic,

$$B(z) = B_{\max} - b \left[1 - \left(\frac{z}{L} \right)^2 \right] \ ,$$

where b $= B_{\max} - B_{\min}$ and L are respectively the depth and width of the magnetic well, z is the axial distance from the minimum of the well, $B_{\min}$. We rewrite eq. (5) after integrating the delta function, as follows

$$G = \frac{\pi}{2} \left(\frac{B_0}{L} \right) \left| \frac{\partial B}{\partial z} \right|_{z_0}^{-1} = \frac{\pi}{2} \left(\frac{B_0}{2b} \right) \left(\frac{z_0}{L} \right)^{-1} \tag{6}$$

$$\left(\frac{z_0}{L} \right)^2 = \frac{B_0 - B_{\min}}{b}$$

The expression of G calculated from the delta function representation is valid only for simple zeros. This requirement is certainly violated at $z_0 = 0$ where $B(z)$ is locally uniform. Under this situation, the ν/ω_{RF} term in $\sigma_{\perp}$ cannot be neglected and the delta functions representation is not valid. In fact, when $\omega_{\mathrm{RF}} = \nu$, $\sigma_{\perp} = \sigma_0/2$ and the heating rate becomes $\gamma_{\perp 0} = 2\pi\alpha_0$ which is the upper limit of eq. (4).

If we consider the experimental value from the small resonant volume $B_{\max} =$ *1160* Gauss and $B_{\min} = 400$ Gauss, for eq. *(6)* we obtain

$$G_2 \simeq 1.2$$

and for the large resonant volume $B_{\max} = 1160$ Gauss and $B_{\min} = 200$ Gauss, therefore

$$G_1 \simeq 0.85$$

(all the parameters for large resonant volume are indicated by the index 1 and for small resonant volume by the index 2, respectively).

We clearly see that

$$G_2 > G_1$$

From the confinement time (τ_{con}), given by Sivukhin[10] for the single mirror machine, we have

$$\tau_{con} = \{[0.785]\ln(R_m)\}/\nu_{en} \tag{7}$$

where ν_{en} is the collision frequency between electron and neutral particles. In our case, where the plasma produced by radiofrequency is weakly ionized, the collisions are predominantly between electron and neutral particles, and $\ln(R_m)$ is the natural logarithm of the mirror ratio. Thus, using the LISA data we find

$$\tau_1 \cong 2.5 \times 10^{-8}\ (s)$$

and

$$\tau_2 \cong 1.3 \times 10^{-8}\ (s)$$

Equation (4) shows that $\gamma_{\perp}$ is proportional to G. This implies that the heating rate for the small resonant volume is slightly larger than that of the large resonant volume, but the confinement time for large resonant volume (τ_1) is not far from twice that of the small resonant one (τ_2), which shows a good agreement with the measured experimental data for the total average electron temperatures (60 eV for the large resonant volume and 47 eV for the small resonant volume). Thus this is simply caused by a larger absorption of the electromagnetic energy in the resonant region of the large resonant volume.

In order to find out the temperature dependence explicitly, we can use the expression given by Rapozo et al.[1]

$$\gamma_{|}W_{\perp} = \alpha\frac{m_e}{m_i}\hat{\nu}\hat{p}_e T_e^{3/2}$$

If we substitute eq. (4) into this expression, we obtain

$$T_e^{3/2} = \left(\frac{c}{v_A}\right)^2 \frac{\omega_{\rm RF} W_|}{\hat{\nu}\hat{p}_e} G \tag{8}$$

where T_e is now in eV units and $\hat{\nu}$ and $\hat{p}_e$ are normalized to a temperature of 1 eV. Using the relevant parameters for large resonant and small resonant volumes, as shown in table 2, we can see that the eq. (8) leads t $< T_e > \cong 78$ eV for large resonant volume and $< T_e > \cong 60$ eV for small resonant volume, which shows a good agreement with the measured average values of 60 eV and 47 eV, respectively.

Table 2 - Relevant parameters for large and small resonant volume.

	large resonant volume	small resonant volume
n_e (cm^{-3})	6×10^{10}	4×10^{10}
$< E >$ (V/cm)	0.82	0.63
$< V_a >$ (cm/s)	0.7×10^9	1.0×10^9
$< W_\| >$ (erg/cm^3)	22×10^{-8}	13×10^{-8}
G	0.85	1.2
$\omega_{\rm RF}$ (s^{-1}	1.54×10^{10}	1.54×10^{10}
$\hat{\nu}$ (s^{-1}	1.67×10^5	1.67×10^5
$\hat{p}_e$ (erg.cm^3)	9.60×10^{-2}	9.60×10^{-2}

4. Collisional plasma heating process using the magnetic field modulation

Here a perturbative treatment has been used to calculate analytically the rate of increase of thermal energy in a plasma contained in a periodically perturbed magnetic field. In the case where the energy rate increases, it has been found to be proportional to the field modulation factor defined by $\epsilon = \Delta B/B$ for a sinusoidal perturbation of the magnetic field, where AB is the magnetic field variation due to the application of an external magnetic perturbation.

Now it may be useful to compare our experimental results with the one of Berger and Barter[8]. To do that we consider the expression given by Berger et a1[4],

$$\frac{dW}{dt} = \frac{\epsilon^2 \nu_{\text{en}} \omega_{\text{RF}}^2}{6\left(\frac{9}{4}\nu_{\text{en}}^2 + \omega_{\text{RF}}^2\right)} W = \gamma_{\perp} W \ . \tag{9}$$

If we consider a slightly collisional plasma, so that $\omega_{\text{RF}} > \nu_{,,,}$ then eq. (9) becomes

$$\frac{dW}{dt} = \frac{\epsilon^2 \nu_{\text{en}}}{6} W \qquad \left[\gamma_{\perp} = \frac{\epsilon^2 \nu_{\text{en}}}{6}\right] \tag{10}$$

From eq. (4) we have

$$\gamma_{\perp 1} \cong 6 \times 10^9 \ \ \mathrm{s}^{-1}) \tag{11}$$

and

$$\gamma_{|2} \cong 3 \times 10^9 \ \ \mathrm{s}^{-1}) \tag{12}$$

where $\gamma_{\perp 1}$ and $\gamma_{\perp 2}$ are the resonant heatings for the large and small resonant volumes, respectively.

Substituting now eqs. (11) and (12) into eq. (10) we find the modulation factor which is given by

$$\epsilon_1 \cong 10$$

and

$$\epsilon_2 \cong 8.0$$

for $\nu_{\text{en1}} \cong 5 \times 10^7\ \mathrm{s}^{-1}$ and $\nu_{\text{en2}} \cong 4.3 \times 10^7\ \mathrm{s}^{-1}$.

Therefore, it can be shown that in order to obtain, using LISA data, the same electron-cyclotron heating efficiency using collisional magnetic pumping it is necessary to have approximately $AB \cong 10$ kG, for a large resonant volume and $AB \cong 8.0$ kG for a small resonant volume.

5. Conclusions

We have shown that the region of large resonant volume is more efficient to absorb energy than the small one, via the calculation of the confinement time. Finally, we have been able to show the consistency between Barter's[8] work and our own experimental results for collisional plasma heating due to the magnetic field modulation.

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Resumo

Foi demonstrado teoricamente e experimentalmente que a razão de aquecimento de um plasma por ondas eletro-ciclotrônicas é uma função do volume ressonante formado pelo espelho magnético. O plasma em estudo foi produzido por radio freqüência na ressonância ciclotrônica dos elétrons, sendo o grau de ionização menor que 1%. O experimento foi realizado na máquina linear tipo espelho LISA da Universidade Federal Fluminense.