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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 Fluminense.

1. INTRODUCTION

LISA is a linear magnetic mirror machine designed and constructed at the Max-Planck Institut für Plasmaphysik (Garching, Germany). The assembly has been made at the Universidade Federal Fluminense (Niterói, RJ) [1]. The dimensions of LISA are shown in Figure 1.

It has been shown by Galvão and Aihara [2] and later by Rapozo et al.[3] that during the electron cyclotron heating the plasma potential drops. Furthermore, we here obtain the heating efficiency as a function of the resonant volume and collisional process.

2. THE EXPERIMENT

The experiment was carried out on LISA [4]. 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 make use of this peculiar feature to have a local mirror confined plasma and operate with seven disconnected coils next to the waveguide port to get a larger mirror

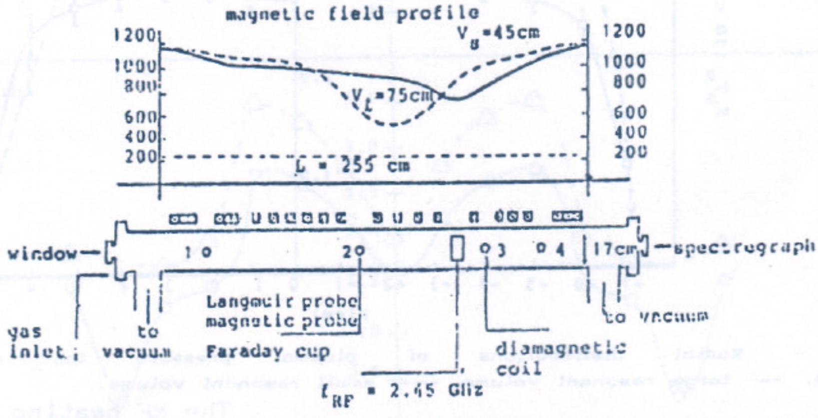

Figure 1 - Dimensions of the linear mirror machine LISA and the experimental arrangement plus the axial distribution of the equilibrium magnetic field.

rate and a better confinement and operate also with four disconnected coils to get a small mirror rate. 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.

3. EXPERIMENTAL RESULTS AND ANALYSIS

Experimental results of plasma pressure, density and temperature are presented in Figure 2. The three components of the wave's electric field for large mirror rate resonance and small mirror rate resonance, measured with floating double probes are shown in Figure 3. The qualitative behaviour power profile versus radius is shown in Figure 4.

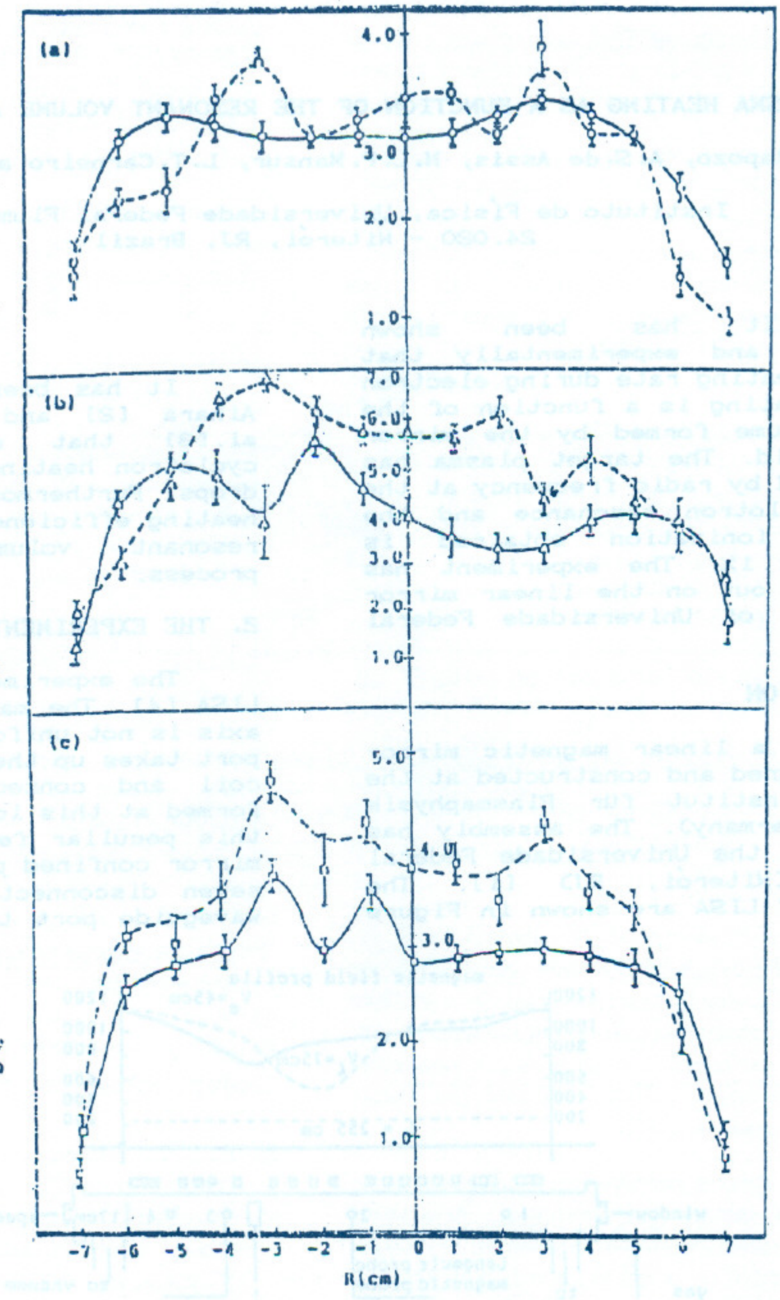

Figure 2 - Radial distributions of plasma pressure (a), density (b), and temperature (c). --- large resonant volume, —— small resonant volume.

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

$$\frac{\partial}{\partial t}\left(\frac{3}{2} n_e k T_e\right) + \nabla\cdot\vec{q}_e = (\vec{J}\cdot\vec{E})_{RF} - \sum_h n_e k (T_e - T_j)\tau_{ej}^{-1} \qquad (1)$$

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

The RF heating form is [1]

$$(\vec{J}\cdot\vec{E})_{RF} = \frac{1}{2}\sigma_\perp |\vec{E}_\perp|^2 + \frac{1}{2}\sigma_{||}|\vec{E}_{||}|^2 = 4\pi\sigma_\perp W_\perp + 4\pi\sigma_{||}W_{||} \qquad (2)$$

where the factor 1/2 comes from the time average of $|\vec{E}|^2$. W is the energy density of the RF electric field.

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

Thus, Eq.(1) leads us to

$$\gamma_\perp W_\perp = \frac{m_e}{m_i}\nu p_e + \nabla\cdot\vec{q}_e \qquad (3)$$

where $\gamma_\perp$ is the resonant heating rate [5,6] given by

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

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

and c and v_A are light and Alfvén speed at B_o and G is a dimensionless quantity weighted over plasma density [6].

The expression derivated for the parameter G made by Rapozo et al. [1] is

$$G = \frac{\pi}{2}\left[\frac{B_0}{L}\right]\left|\frac{\partial B}{\partial z}\right|^{-1}_{z_0} = \frac{\pi}{2}\left[\frac{B_0}{L}\right]\left[\frac{z_0}{L}\right]^{-1},$$

$$\left[\frac{z_0}{L}\right] = \frac{B_0 - B_{min}}{b} \qquad (5)$$

If we consider the experimental value B_{max} = 1160 Gauss - in both situations - , B_{min} = 400 Gauss for the small resonant volume, and B_{min} = 200 Gauss for the large resonant volume, we obtain the parameter G equal to 1.2 and 0.85, respectively.

From the confinement time given by Sivukhin [7] for the single mirror machine, we find $\tau_{con} = 1.3 \times 10^{-8}$s for the small resonant volume and $\tau_{con} = 2.5 \times 10^{-8}$s for the large resonant volume

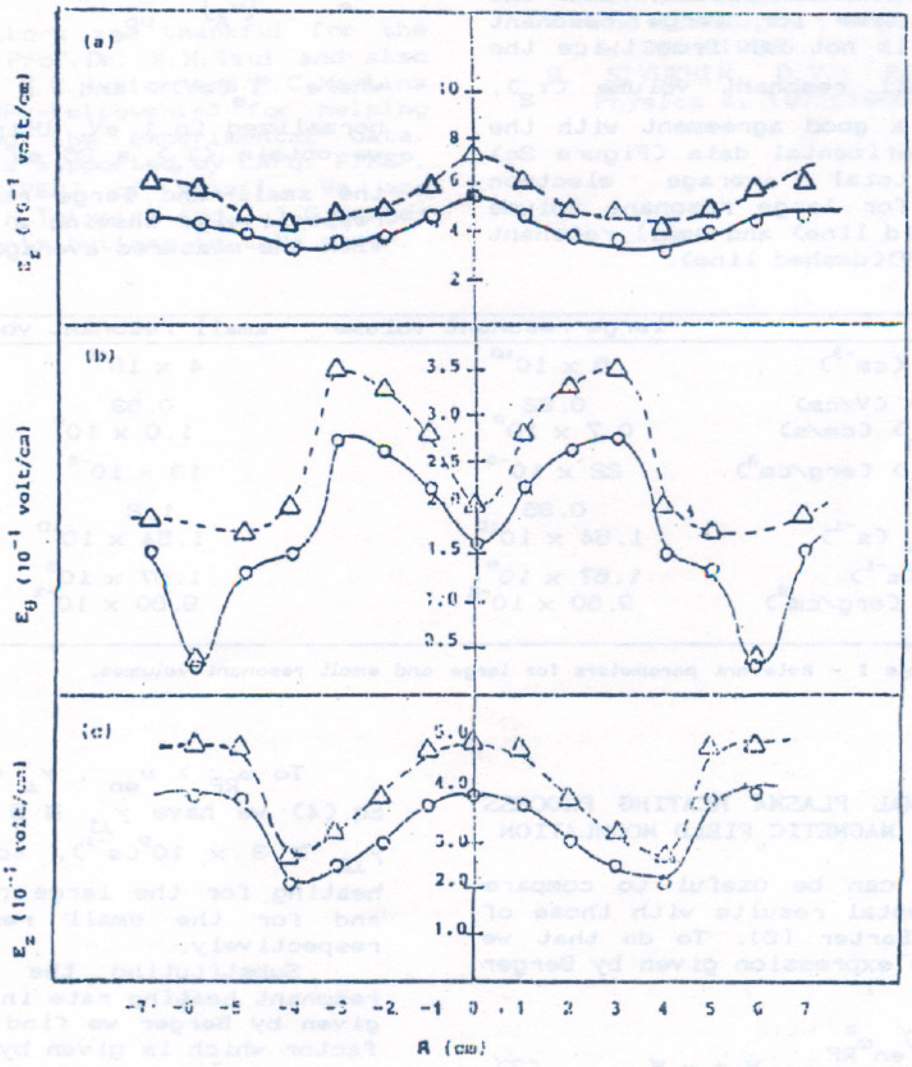

Figure 3 - Radial distribution of the wave's electric field. Δ - large resonant volume, O - small resonant volume.

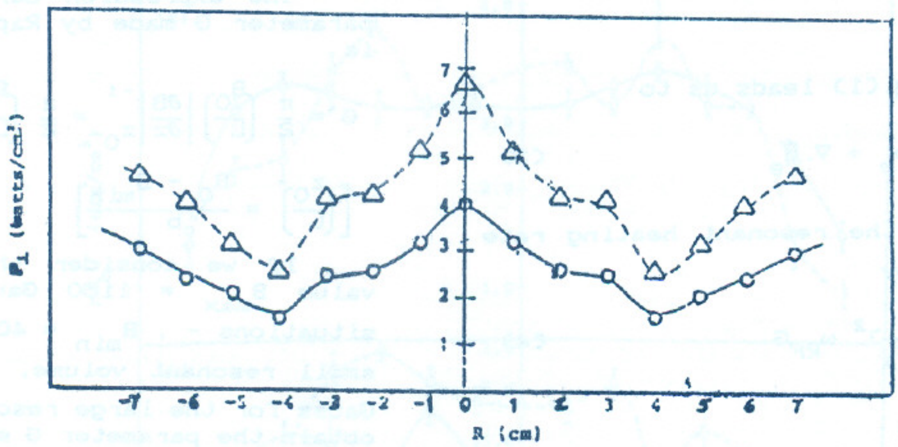

Figure 4 - Qualitative behaviour of the power profile versus radius. Δ - large resonant volume, O - small resonant volume.

The Eq.(4) shows that γ is proportional to G, this implies that the heating rate for small resonant volume is slightly bigger than that of the large resonant volume, but the confinement time for large resonant volume (τ_1) is not far from twice the one for small resonant volume (τ_2), which shows a good agreement with the measured experimental data (Figure 2c) for the total average electron temperature for large resonant volume (40 eV) (solid line) and small resonant volume (30 eV)(dashed line).

The temperature dependence given by Rapozo et al. [1] is

$$T_e^{3/2} = \left(\frac{c}{v_A}\right)^2 \frac{\omega_{RF} W}{\hat{\nu}\hat{p}_e} G \qquad (6)$$

where T_e(eV) and $\hat{\nu}$ and $\hat{p}_e$ are normalized to 1 eV. Using the Table I we obtain $\langle T_e \rangle$ = 26 eV and 47 eV for the small and large resonant volume, respectively, showing a good agreement with the measured average.

	large resonant volume	small resonant volume
n_e (cm^{-3})	6×10^{10}	4×10^{10}
$\langle E \rangle$ (V/cm)	0.82	0.63
$\langle V_a \rangle$ (cm/s)	0.7×10^9	1.0×10^9
$\langle W_1 \rangle$ (erg/cm³)	22×10^{-8}	13×10^{-8}
G	0.85	1.2
ω_{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/cm³)	9.60×10^{-2}	9.60×10^{-2}

Table I - Relevant parameters for large and small resonant volumes.

4. COLLISIONAL PLASMA HEATING PROCESS USING THE MAGNETIC FIELD MODULATION

Now it can be useful to compare our experimental results with those of Berger and Barter [6]. To do that we consider the expression given by Berger et al. [8]

$$\frac{dW}{dt} = \frac{\varepsilon^2 \nu_{en} \omega_{RF}^2}{6(\frac{9}{4}\nu_{en}^2 + \omega_{RF}^2)} W = \gamma_\perp W \qquad (7)$$

To $\omega_{RF} > \nu_{en}$, $\gamma_\perp = \varepsilon^2 \nu_{en}/6$. From Eq.(4) we have $\gamma_{\perp 1} \cong 6 \times 10^9 (s^{-1})$ and $\gamma_{\perp 2} \cong 3 \times 10^9 (s^{-1})$, to the resonant heating for the large resonant volume and for the small resonant volume, respectively.

Substituting the value of the resonant heating rate in the expression given by Berger we find the modulation factor which is given by $\varepsilon_1 \cong 10$ and $\varepsilon_2 \cong 8.0$, for $\nu_{en1} \cong 5 \times 10^7 s^{-1}$ and $\nu_{en2} \cong 4.3 \times 10^7 s^{-1}$.

Therefore, it can be shown that in order to obtain, using LISA data, the same electron-cyclotron heating efficiency than using collisional magnetic, pumping it is necessary to have approximately $\Delta B \cong 10$ kG, for a large resonant volume and $\Delta B \cong 8.0$ 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 work and our own experimental results for collisionsl plasma heating due to the magnetic field modulation.

6. ACKNOWLEDGEMENTS

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