Energy Transport in Mirror Machine Lisa at Electron Cyclotron Resonance

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The energy balance of a weakly ionized radiofrequency produced plasma at electron cyclotron resonance is analyzed both analytically and experimentally for a mirror-confined configuration. It has been shown that the plasma heating rate is a function of the resonant volume and the anisotropic ternperature condition.

I. Introduction

LISA is a linear magnetic rnirror machine donated to the Plasma Physics Laboratory of Universidade Federal Fluminense in 1979 by the MaxPlanck Institut fur Plasmaphysik. We have been using this machine for radio frequency (RF) produced plasma since its arrival. Interaction of a weakly ionized plasma with RF is relevant to, fcr example, RF preionization in tokamaks, RF heating of ionospheric plasmas[1,2], basic nonlinear dynarnics of RF produced laboratory plasma[3,4] and transport properties[5,6].

We are interested in the transport properties of a steady state weakly ionized mirror-confined RF plasma. An RF source of 2.45 GHz and 800 W is used to inject power through the rectangular waveguide to produce the plasma. The magnetic field coils are fed by a DC current generator and produce the rnirror magnetic field. This field radially confines the RF produced plasma.

The rnirror coils at the two extremities are not being 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 field is formed at this location. We make use of this peculiar feature to have a local mirror-confined plasma and operate with seven additional coils next to the waveguide port disconnected to get a larger rnirror ratio and a better confinement. For diagnostics, we use a plane 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. Helium is used as a working gas which is maintained at a background pressure of 6 x 10^{-4} Torr. This gives a neutra1 density of 2×10^{13} cm^{-3}. Plasma is produced via collisional impact through the electron cyclotron resonance at $\omega_{ce}(B_0) =$ w. The diagnostics arrangement, the dimensions of LISA, the field distribution, plasma pressure, density, temperature and the qualitative behavior of the perpendicular power profile versus radius were shown in Figures 1, 2 and 3 of ref.[7]. The three components of the electric field were measured with floating double probes. The radial oscillations of the electric field reflect the nature of a cavity mode of the plasma device under the operating frequency. The temperature oscillations follow from the RF heating power deposition profile. This work is organized as follows: in section II we present the experimental results and analysis and the conclusions are presented in section III.

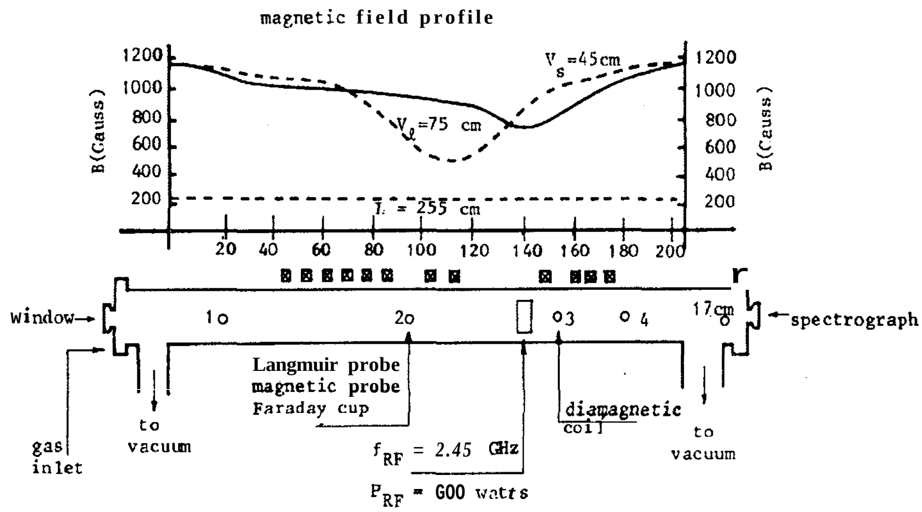

Figure 1: Dimensions of the linear mirror machine LISA and the experimental arrangement plus the axial distribution of the equilibrium magnetic field.

II. Experimental results and analysis

It has been shown by Galvão and Aihara[8] and Rapozo et al.[9] that during the electron cyclotron heating in mirror machines, the plasma potential drops and the ratio of the perpendicular to the parallel temperature of the electrons increases. However, no information about the collisional process are found in these papers. The parallel electron temperature $T_{e\parallel}$ was measured with a small planar Langmuir probe. This value was also measured using a movable energy analyzer (Faraday cup) and the results are in good agreement with the data obtained from the Langmuir probe. The average electron temperature $< T_e >$ was measured spectroscopically and the perpendicular electron temperature was then obtained from $< T_e > = (T_{e\parallel} + 2T_{e\perp})/3$. These values for $T_{e\perp}$ were confirmed by a series of measurements of the electron density and the mirror ratio as a function of the axial position, which allow us to obtain the temperature ratio $T_{e\perp}/T_{e\parallel}$ via a classical relationship for magnetic mirrors. The measurement of $< T_e >$ was carried out using a UV.Q24 spectrograph (Jenoptik Jena GmbH) using the corona method[10], which is based essentially on the ratio of the intensities of two wavelengths of He light (He I 4771 Å) emitted from the helium plasma (singlet, $\lambda = 4713$ Å, and triplet, $\lambda = 4921$ A); the "Helium singlet to triplet method"[11]. With this method we can relate the ratio of the intensities of the two wavelengths (4713 Å/ 4921 Å) to the total electron temperature T_e.

Recently, Rapozo et al.[7] have studied the efficiency of the electron cyclotron heating and collisional heating when the resonant volume is changed. However, in this paper it was not considered the anisotropy of the electron temperature on the energy balance.

The steady state temperature of the plasma was determined by the energy balance between the gain and loss terms (eq. 1 ref.[7]), which leads to,

$$\gamma_\perp W_\perp = \alpha \frac{m_e}{m_i} \nu P_e + \nabla \cdot \vec{q}_e \qquad (1)$$

where $\gamma_\perp$ is the resonant heating rate[5,6,7] given by,

$$\begin{aligned} \gamma_\perp &= 2\frac{m_e}{m_\perp}\left(\frac{c}{v_A}\right)^2 \omega_{RF} G, \qquad (2) \\ \tau_{en}^{-1} &= \alpha \frac{m_e}{m_\perp} \nu \, . \end{aligned}$$

c and v_A are light and Alfvén speeds, G is a dimensionless quantity weighted over plasma density, and the mass ratio on the expression of τ_c is due to energy equipartition. The factor a in this equation must take into account the spatial anisotropy of plasma pressure. To obtain the final expression for T_e, for both cases, large and small resonant volumes, Rapozo et al.[7] have assumed that $a = 2$. In this paper we show that α de-

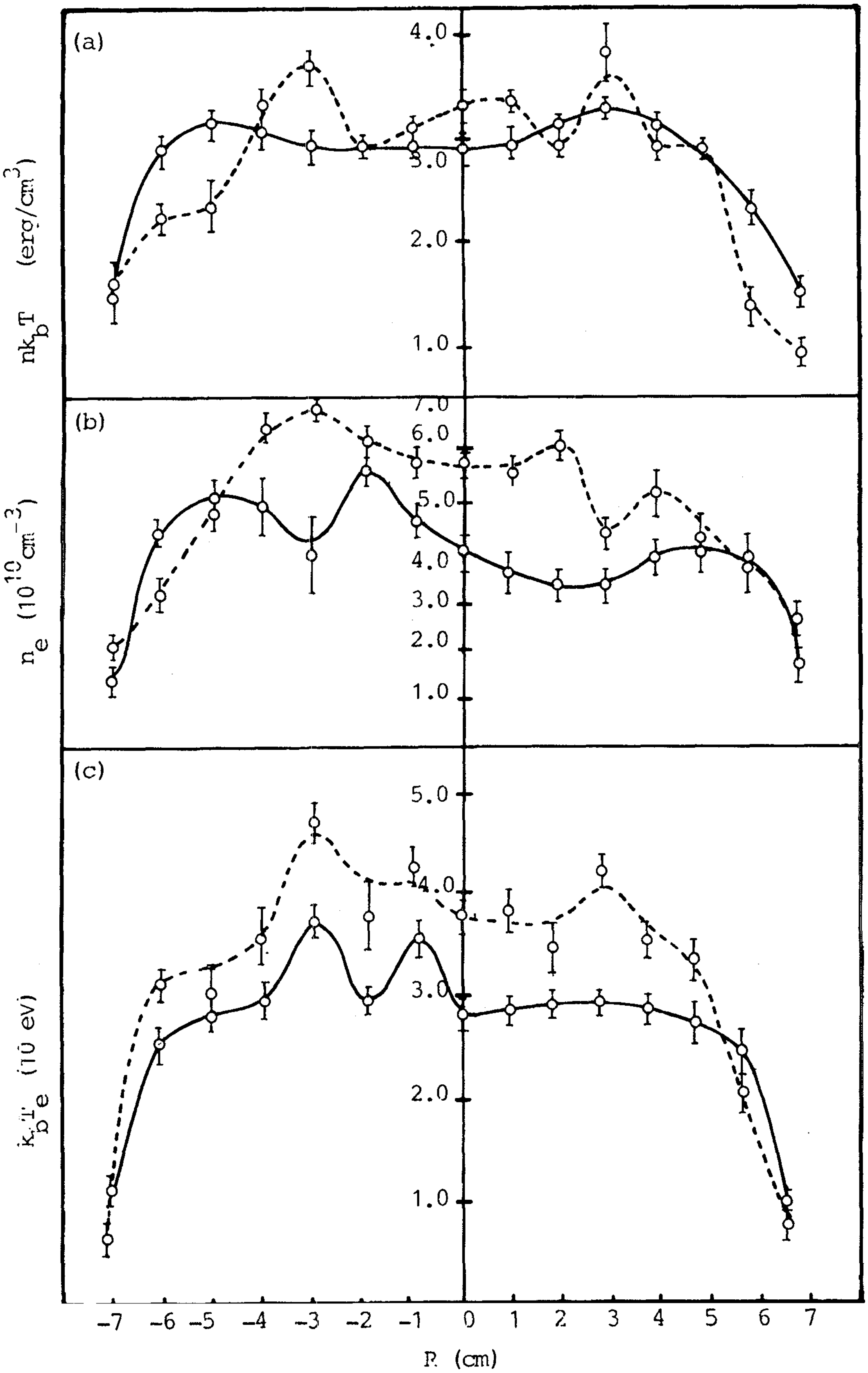

Figure 2: Radial distribution of plasma pressure (a), density (b) and temperature (c). - - - large resonant volume, — small resonant volume.

pends on $0 = T_\perp/T_{||}$, the magnetic field shape and the position of the resonance zone.

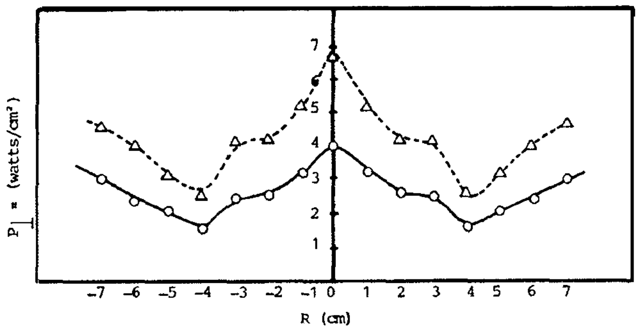

Figure 3: Qualitative behavior of the power profile versus radius. **A** → large resonant volume, o → resonant volume.

Here we consider the energy balance equation as was shown by [12], where the velocity components perpendicular to the magnetic field are heated by the microwave field and the component parallel to the field is heated by electron-electron collisions, because there is a pitch-angle energy diffusion in velocity space.,

The basic equations are

$$n_e k \frac{dT_{e\perp}}{dt} = -\nu_c n_e k(T_{e\perp} - T_{e||}) + (\vec{J}\cdot\vec{E})_\perp - \frac{2T_{e\perp}}{3T_e}(P_{\ell c} + P_{iw}), \quad (3)$$

and

$$n_e k \frac{dT_{e||}}{dt} = \nu_c n_e k(T_{e\perp} - T_{e||}) - \frac{T_{e||}}{3T_e}(P_{\ell c} + P_{\ell w}), \quad (4)$$

where $(\vec{J}\ .\ \vec{E})_\perp$ is the net input power available for plasma heating, $P_{\ell c}$ the power loss due to collisions, $P_{\ell w}$ the power loss due to wall current per unit volume, v, the frequency of Coulomb collision and the factors 1/3 and 2/3 arise from the equipartition of energy into the directions parallel and perpendicular to the magnetic field.

The steady-state solution of eqs. (3) and (4) is $\theta = [1 + (\vec{J}\cdot\vec{E})_\perp/\nu_c n_e k T_e]$, where $T_e = (T_{e||} + 2T_{e\perp})/3$. In the steady state by putting $dT_{e\perp}/dt = dT_{e||}/dt = 0$, $P_{\ell w} < P_{\ell w}$ and $(\vec{J}\cdot\vec{E})_{RF} = \nu_c n_e k T_e$, we set a particular value $\theta = 4/3$, meaning in this case that energy isotropy occurs when the particle confinement time is longer than the relaxation time ν_c^{-1}. However, this value can be compared with the average value obtained from the experimental data 1.4 and 1.5 for large and small resonant volumes, respectively.

However, this condition does not consider the magnetic field profile, the density profile and the position of the resonant layer, where experimentally it was detected that $T_{e\perp}/T_{e||}$ increases[8]. These effects were considered by Sprot[5], obtaining the factor G and recently by Rapozo et al.[7] considering the factors G and a.

Despite the existence of these theories and the abundance of experimental data, detailed quantitative comparisons between these theories and experiment over a range of parameters are lacking. The reason is the difficulty of making accurate temperature measurements and the fact that cooling and loss processes are present[8]. These aspects are related to $\theta = T_{e\perp}/T_{e||}$, so the dimensionless quantity a is not a constant, but it varies according to the experimental condition.

Following Rapozo et al.[7] we integrate eq.(3) over the plasma volume; the z-dependence of the magnetic field leads to a singular contribution to $(\vec{J}\cdot\vec{E})_\perp$ in the neighbourhood of the resonance $\omega_{RF} = \omega_{ce}(B_0)$. Thus, in steady state, we set,

$$\gamma_\perp W_\perp = \alpha F(\theta)\frac{m_e}{m_i}\hat{\nu}\hat{P}_e, \quad (5)$$

where $\gamma_\perp$, G, $\hat{\nu}$ and $\hat{P}_e$ are the usual terms found by Rapozo et al.[7] and others[5,6]. The factor $F(\theta)$ is introduced to allow the anisotropic temperature condition.

Here we are neglecting the power loss due to the wall current and V . $\vec{q}_e$, where the heat flow term $\vec{q}_e$ represents the radial heat losses. The new factor $F(\theta)$ can be derived from eq.(3) by putting $d/dt = 0$ with $T_{e||} = (3/2)[T_e/(\theta + 1/2)]$ and $T_{e\perp} = (3/2)T_e[\theta/(\theta + 1/2)]$, and it is given by,

$$F(\theta) = \frac{5\theta - 3}{2\theta + 1}\ . \quad (6)$$

The isotropic temperature condition $0 = 1$ gives $F(\theta) = 2/3$ and the strong anisotropy $8 \to \infty$ leads to $F(\theta) = 2.5$. Our experiment has a moderate anisotropy because $<\theta_1> \leq 1.4$ and $<\theta_2> \geq 11.5$ (all the parameters for large resonant volume are indicated by the index 1 and for small resonant volume by the index 2).

Rapozo et al.[7] have shown that $G_2 > G_1$ and $\tau_1 > \tau_2$. This implies that the heating rate for small resonant volume is slightly larger than that of the large resonant volume, the confinement time for large resonant volume (τ_1) is twice that of the small resonant volume (τ_2), and the temperature anisotropy for large resonant volume is smaller than that for small resonant one. This shows a good agreement with the experimental data for the total average electron temperature (40 eV and 30 eV for large and small resonant volume, respectively). Thus, this is simply caused by a larger absorption of the electromagnetic energy in the resonant layer of the large resonant volume and consequently a larger temperature relaxation.

In order to find out the temperature explicitly, we substitute $\gamma_\perp$ into the eq.(5) considering that v $\sim T_e^{3/2}$ and $P_e \sim T_e$, we obtain,

$$T_e^{-1/2} = 2\left(\frac{c}{v_A}\right)^2 \frac{\omega_{RF} W_\perp}{\hat{\nu}\hat{P}_e} \frac{G}{\alpha F(\theta)} , \qquad (7)$$

when T_e is now in units of eV and $\hat{\nu}$ and $\hat{P}_e$ are normalized to a temperature of 1 eV. Our results are presented in Table I which show the perpendicular and the parallel temperatures versus the magnetic field, and the relevant parameters for large and small resonant volumes, reproduced of [8,7], respectively.

In eq. (7) a is a factor of order unity whic depends on the geometry of the field and on the density distribution. It is seen from Table I, that at resonance layer (B $\approx$ 1875 Gauss), $F_1(\theta)$ = 0.85, $F_2(\theta)$ = 0.91, therefore choosing α_1 = 2.5 and α_2 = 1.5 we have $< T_{e1} >$= 45.3 for large and $< T_{e2} >$= 34.7 for small resonant volumes, respectively. This shows a good agreement with the measured average value of 45 eV and 37 eV, respectively. However, at the off-resonance regon ($B_{dc} \sim$ 1000 Gauss), with the same values of α_1 and α_2, we have $F_1(8) = F_2(\theta) = 1$, and the calculated temperatures are very differení from the experimental 'lata. A good agreement is obtained by choosing a = 3.0 and α_2 = 2.0. That means that the a parameter is a function of the applied magnetic field profile and the best fit with the experimental data yields $2.5 \leq \alpha_1 \leq 3.0$ and $1.5 \leq \alpha_2 \leq 2.0$ for large and small resonant volume, respectively.

Another important plasma parameter on the LISA machine is the confinement factor,

$$Q_m = 1 - \frac{(R - r_\perp)^2}{\pi R^2}\frac{A}{A+B} , \qquad (8)$$

where R is the LISA inner radius and $r_\perp$ is the Larmor radius for electrons, A and B are respectively the density of electrons confined and not confined by the magnetic mirror. One of the differences between Rapozo's work[13] and this is that we have considered the anisotropic temperature condition $T_\parallel \neq T_\perp$. We have that A is given by,

$$\frac{A}{n_e} = \left(\frac{R_m - 1}{R_m - 1 + \frac{T_{e\perp}}{T_{e\parallel}}}\right)^{1/2} \qquad (9)$$

From Table I we see that, at resonance ($B \approx$ 875 Gauss), the percentage of particles lost (B = n_e − A), in the mirror, is 0.055 for the large resonant volume and 0.1 for the small resonance one. At off-resonance (B $\approx$ 1100 Gauss), this factor increases twice with respect to the value than that at resonance. We can see from eq.(9) that for the small resonant volume, the confinement factor Q_n is larger than that for the large resonant volume, for all values of the ambient magnetic field. This agrees with the average values obtained by [13] for the isotropic temperature condition, where the parallel component of the electric field increases in the case of small resonant volume.

Table I shows that, for small resonant volume, 0 is slightly larger than that for the large resonant one, which confirms the well known fact that the electron confinement is improved with the increase of the ratio $\theta = T_{e\perp}/T_{e\parallel}$.

III. Conclusions

We have shown that a classical transport calculation is adequate to predict the steady state tempera-

Table I - The experimental values of the temperature $T_{e\parallel}$, the magnetic field B and the calculated values of $T_{e\perp}$, the anisotropy $T_{e\perp}/T_{e\parallel}$ and the ratio A/n_e, all for large and small resonant volumes. All temperatures in eV. $T_{e\parallel}$ is obtained using a Langmuir probe. The magnetic field was measured with a Hall probe and also with a magnetic probe with a small ac ripple.

B	$T_{e\parallel}$		$T_{e\perp}$		$T_{e\perp}/T_{e\parallel}$		A/n_e	
(Gauss)	SRV	LRV	SRV	LRV	SRV	LRV	SRV	LRV
11150	27.7	35.5	27.5	34.4	1.00	0.99	0.19	0.090
1100	27.5	35.0	28.0	35.0	1.00	1.00	0.19	0.090
1050	25.0	32.0	28.4	35.5	1.10	1.11	0.17	0.080
1040	24.0	31.0	28.5	35.6	1.18	1.16	0.16	0.077
1030	23.8	30.5	28.6	35.7	1.20	1.16	0.16	0.077
1020	23.4	30.0	29.6	37.0	1.26	1.23	0.15	0.071
1010	23.0	29.5	31.6	39.5	1.40	1.34	0.13	0.062
1000	22.7	29.0	33.6	42.0	1.50	1.45	0.11	0.052
990	22.7	29.0	33.6	42.0	1.50	1.45	0.11	0.052
980	22.7	29.0	33.6	42.0	1.50	1.45	0.11	0.052
970	22.0	28.5	34.8	43.5	1.57	1.52	0.09	0.046
960	22.0	28.5	34.8	43.5	1.58	1.54	0.09	0.044
950	21.8	28.2	35.0	43.8	1.60	1.55	0.09	0.043
940	22.3	28.7	35.5	44.4	1.60	1.55	0.09	0.043
930	22.5	29.0	34.8	43.5	1.55	1.50	0.09	0.048
920	22.0	28.5	35.2	44.0	1.60	1.54	0.09	0.044
910	22.4	28.8	36.8	46.0	1.64	1.60	0.08	0.039
900	22.7	29.0	35.7	44.0	1.56	1.52	0.09	0.046
890	22.5	28.9	31.4	44.2	1.59	1.53	0.09	0.045
880	22.7	29.0	35.0	43.8	1.54	1.51	0.10	0.047
875	27.5	35.0	42.0	50.0	1.52	1.42	0.10	0.055

ture of the RF produced plasma in LISA machine for both large and small resonant volumes.

Temperature anisotropy of the order of 5% to 30% has been found, which is larger for small resonant volume, and the temperature relaxation is larger at large resonant one. This agrees with the fact that we have a Coulomb relaxation ν_c which is proportional to $T_e^{-3/2}$. We also show that the fitting parameter a is larger for large resonant volume that for small resonant one. However, due to the moderate anisotropy found in our experiment, it is not critical to take for α, an average value equal to two, as assumed by [7].

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