Revista Brasileira de Física, Vol. 19, nº 4, 1989

Energy transport of a mirror-confined radio frequency plasma

C. da C. Rapozo, K.H. Tsui and A.S. de Assis
Instituto de Física, Universidade Federal Fluminense, 24020, Niterói, RJ, Brasil

Received February 13, 1989; in final form September 12, 1989

Abstract The energy balance of a weakly ionized radio frequency produced plasma at electron cyclotron resonance is analyzed both analytically and experimentally for a mirror-confined configuration.

1. Radio frequency plasma in LISA

LISA is a linear magnetic mirror machine donated to the Plasma Physics Laboratory at the Universidade Federal Fluminense in 1979 by the Max-Planck Institut fur Plasmaphysik. The dimensions of LISA are shown in figure 1. We have been using this machine for radio frequency (RF) produced plasma studies since its arrival. Interaction of weakly ionized plasma with RF is relevant to, for example, RF pre-ionization in tokamaks, RF heating of ionospheric plasmas[1,2], basic nonlinear dynamics 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 at 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 mirror magnetic field. This field radially confines the RF produced plasma.

The mirror 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 mirror 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. The diagnostic arrangement and field distribution are shown in fig. 1. Helium is used as a working gas which is maintained at a background pressure of 6×10^{-4} Torr. This gives a neutral density of 2×10^{13} cm^{-3}. Plasma is produced via collisional impact through the electron cyclotron resonance at $\Omega_e(B_0) = w$. Experimental results of plasma pressure, density, and temperature are presented in fig. 2. The three components of the electric field of the wave measured with floating double probes are shown in fig. 3. 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.

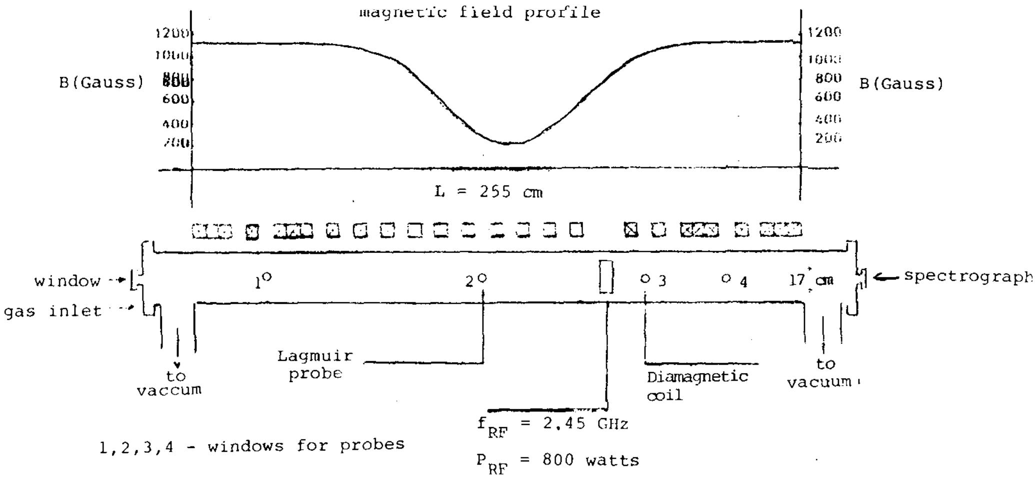

Fig. 1 - Dirnensions of the linear mirror machine LISA and the experimental arrangement plus the axial distribution of the equilibrium magnetic field.

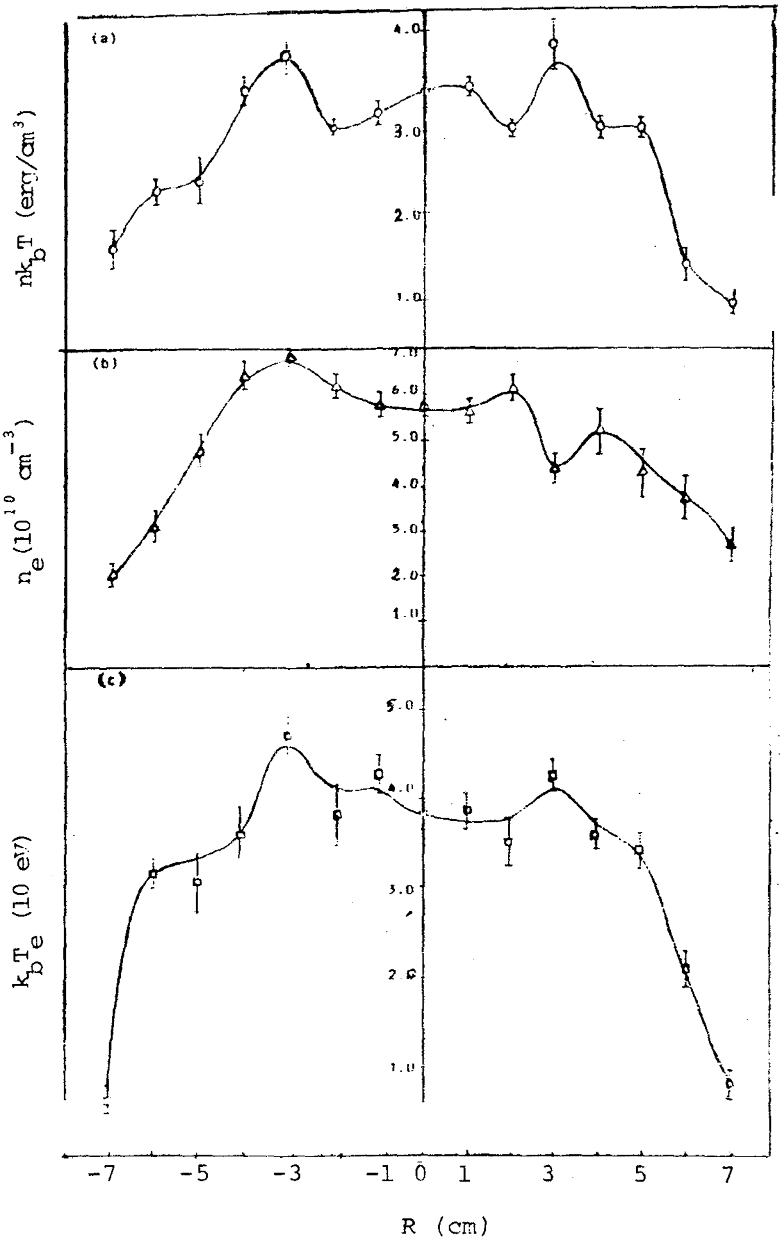

Fig. 2 -Radial distributions of plasma pressure (a), density (b), and temperature (c).

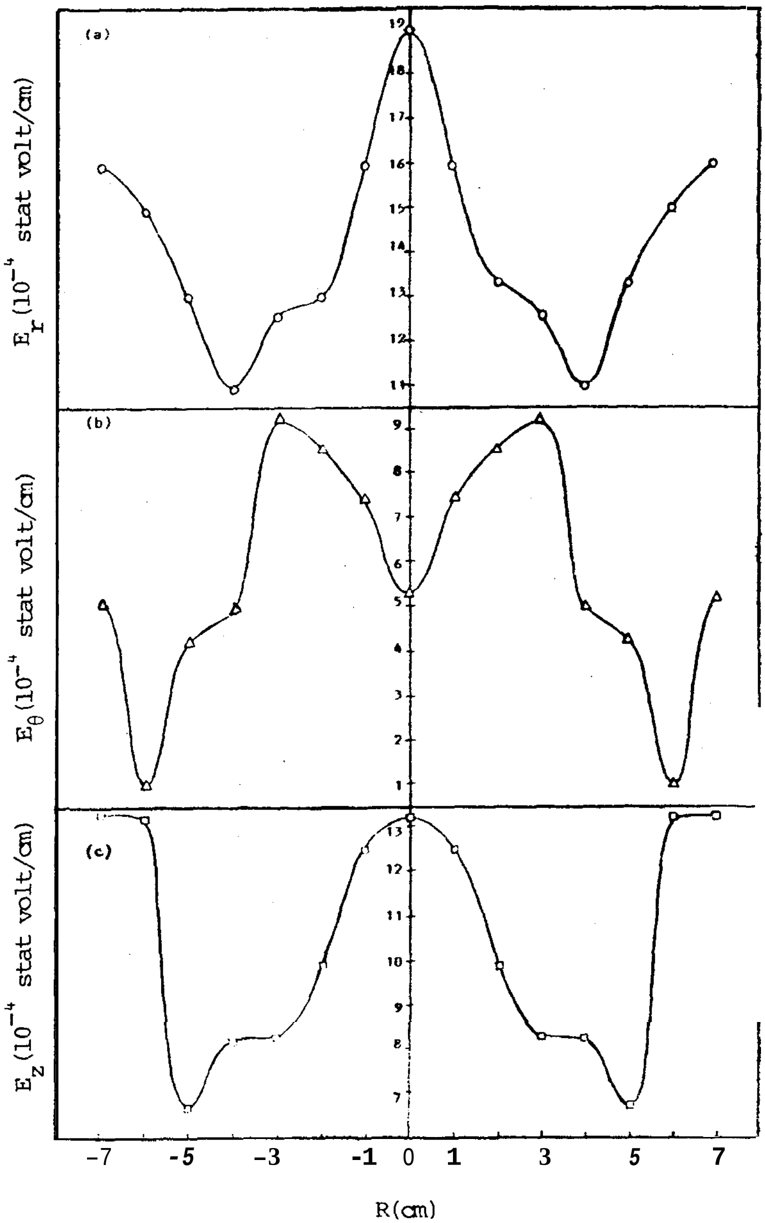

Fig. 3 - Radial distributions of the wave's electnc field.

2. Energy balance

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

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

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

In the steady state, the time derivative vanishes. The heat flow term $\vec{q}_e$ represents radian and axial heat loss. The first term on the right stands for RF heating and the second term is heat exchange with other species, primarily with 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

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

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

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

$$\sigma_\perp = \sigma_0\frac{\nu^2(\omega^2+\Omega_e^2)}{(\omega^2-\Omega_e^2)^2+4\nu^2\omega^2}$$

$$\nu = \nu_{en} = v_{the}\sigma_{en}n_n$$

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

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

$$a_{,,} \cong 2\pi a_0^2$$

where a_0 is the Bohr radius and the value of e_{en} is provided by McDaniel[7]; $\parallel$ and $\perp$ refer to parallel and perpendicular directions with respect to the magnetic field line. Due to the fact that $\nu/\omega \cong 10^{-5}$, $\sigma_\perp$ has a delta function behaviour in the resonant neighbourhood of $\omega = \Omega_e(B_0(z))$ in the limit $\nu/\omega = 0$ [8]. Thus, eq. (1) reads

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

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

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

and

$$\tau_{en}^{-1} = \mathrm{a} \frac{m_e}{m_i} \mathrm{v}$$

and c and v_A are respectively light and Alfvén speed at B_0, and G is a dimensionless quantity weighed over plasma density

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

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

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

where b is the depth of the magnetic well, L is the width, z is measured 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 for 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 term in $\sigma_\perp$ cannot be neglected and the delta function representation is not valid. In fact when $w = \Omega_e$, then

$\sigma_\perp = \sigma_0/2$, and the heating rate becomes $\gamma_{\perp 0} = 2\pi\sigma_0$ which is the upper limit of eq. (4) that corresponds to the resonance of the RF field with a spatially uniform magnetic field B_0.

3. LISA RF plasma

We proceed to calculate the electron temperature using the field amplitudes of fig. 3 to compare with experimental value. To put the temperature dependence explicity, we normalize p,, ν, v_{the}, etc... to 1 eV temperature so that $p_e(T_e) = \hat{p}_e(1$ eV$)T_e$ and so forth. Neglecting the heat from term, eq. (3) now becomes

$$\gamma_\perp W_\perp = \alpha \frac{m_e}{m_i} \hat{\nu} \hat{p}_e T_e^{3/2} \tag{7}$$

where T_e is now in eV units. Using the relevant parameters like $n_e = 6 \times 10^{10}$ cm^{-3}, we have $\nu = 1.67 \times 10^5$ s^{-1}, $\omega_{pe} = 1.38 \times 10^{10}$ s^{-1}, $\hat{v}_{the} = 4.18 \times 10^7$ cm s^{-1}, $v_A = 3.95 \times 10^8$ cm s^{-1}, G = 0.85 which yield $\gamma_{\perp 0} = 5.70 \times 10^{14}$ s^{-1} and $\gamma_\perp = 1.32 \times 10^{14}$ s^{-1}. The energy density of the perpendicular electric field and normalized pressure are $W_\perp = 8.84 \times 10^{-8}$ erg cm^{-3}, p, $= 9.60 \times 10^{-2}$ erg cm^{-3}. Taking a = 2, eq. (7) leads to $T_e \cong 50$ eV which agrees with the measured average value of 40 eV.

To conclude, we have shown that a classical transport calculation is adequate to predict the steady state temperature of the RF produced plasma in LISA. To justify the resonant absorption heating rate $\gamma_\perp$, collisions have to be small, $\nu/\omega \cong 0$. When the resonant absorption takes place and the magnetic field is stationary, the delta function representation of G breaks down and the maximum value of $\gamma_\perp$ is a function of the small but nonzero collision frequency.

The authors are thankful for the opinions of Prof. S. Aihara which have been very constructive in many ways.

This work was supported by Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq) and Financiadora de Estudos e Projetos (FINEP) of Brasil.

References

1. F.W. Perkins, M.V. Goldman, J. Geophys. Res. 86, 600 (1981).
2. L.M. Duncan, R.A. Behnke, Phys. Rev. Lett. 41, 998 (1978).
3. H. Ikegami, S. Aihara, M. Hosokawa, H. Aikawa, Nucl. Fusion 13, 351 (1973).
4. T. Kawamura, H. Momota, C. Namba, Y. Terashima, Nucl. Fusion 11, 339 (1971).
5. J.S. Sprott, Phys. Fluids 14, 1795 (1971).
6. J.D. Barter, J.C. Sprott, K.L. Wong, Phys. Fluids 17, 810 (1974).
7. E.Q. McDaniel, Collision Phenomena in Ionized Gases, John Wiley and Sons, New York (1964).
8. P.M. Morse, H. Feshbach, Methods of Theoretical Physics, Part I, p. 814, McGraw Hill, New York (1953).
9. L. Spitzer Jr., Physics of Fully Ionized Gases, John Wiley and Sons, New York (1962).

Resumo

O balanço de energia de um plasma fracamente ionizado, produzido por radiofreqüência, na ressonância ciclotrônica dos elétrons, é analisado analitica e experimentalmente na máquina linear tipo espelho magnético LISA.