ION KINETICS IN AN ECR PLASMA SOURCE*

César Gutiérrez-Tapia,
Departamento de Física, Instituto Nacional de Investigaciones Nucleares,
Apartado Postal 18-1027, Col. Escandón, México 11801 D. F.

In plasma reactors it is extremely important the study for achieving greater control of critical parameters such as the flux velocities and the energy distribution of ions. These quantities are functions of the reactor physical dimensions, magnetic field profile as well as the kinetic chemical reactions occurring in the discharge. In this work, a model previously reported in [1] is improved. In that model using the drift kinetic equation approach the axial and radial ion fluxes at processing zone of an ECR plasma source are calculated. Now, the ionization rates are calculated from the energy distribution function obtained by a regularization method and using the experimental data of the electric probe measurements. Also, a more exact calculation of the external magnetic field is included.
PACS: 52.50.-b

1.BASIC EQUATIONS

In reactor region of an ECR plasma source, the geometry of the external field $\mathbf{B} = \mathbf{B}(\mathbf{r},t)$ is not uniform. For the case of an ECR plasma source, the magnetic field is strong enough to satisfy

$$\delta = \rho_L / L << 1, \tag{1}$$

where L is the characteristic plasma length and $\rho_L = m_i c v_\perp / ZeB$ is the ion Larmor radius, c is the speed of light in vacuum and Ze is the ion charge. The condition (1) is sufficient to apply the drift kinetic theory [2,3] adopted along the entire work. The approximate version of the drift kinetic equation, reported in [2,3], is assumed appropriate in the small gyroradius limit (1). From condition (1), one can obtain the drift kinetic equations in coordinates $(\mathbf{r}, \mu, U, \gamma, t)$:

$$\frac{\partial \bar{f}_i}{\partial t} + \left(\mathbf{v}_\parallel + \mathbf{v}_D + \mathbf{u}_D\right)\cdot \nabla \bar{f}_i + \left.\frac{d\mu}{dt}\right|_{cg} \frac{\partial \bar{f}_i}{\partial \mu} +$$
$$\left[e\frac{\partial \phi}{\partial t} + \mu \frac{\partial B}{\partial t} - \frac{e}{c}\left(\mathbf{v}_\parallel + \mathbf{v}_D + \mathbf{u}_D\right)\cdot \frac{\partial A}{\partial t}\right] \frac{\partial \bar{f}_i}{\partial U} = C, \tag{2}$$

where $\bar{f}_i = \oint f_i d\gamma$ is the average part of the ion distribution function with respect to the phase γ ; C is the collision operator which includes charge-exchange (cx), elastic collisions (el) and gas ionization by electron impact at the rate $\langle \sigma v \rangle_e$, ϕ is the electrostatic potential, $\mathbf{A}$ is the vector potential, and $\omega_c = ZeB / m_i c$ is the cyclotron frequency. U is the total particle energy, given by

$$U = \frac{m_i v_\parallel^2}{2} + \frac{m_i v_\perp^2}{2} - e\phi . \tag{3}$$

μ is the magnetic moment and $\mathbf{v}_\parallel, \mathbf{v}_D, \mathbf{u}_D$, are the components of the total drift velocity.

In this method the parallel and perpendicular particle fluxes are defined as

$$n\mathbf{V}_\parallel = \int \mathbf{v}_\parallel \bar{f}_i d^3 v,$$
$$n\mathbf{V}_\perp = n\mathbf{V}_D + n\mathbf{U}_D - \nabla \times \left(\frac{\mathbf{B} P_\perp}{m_i \omega_c B} \right), \tag{4}$$

where

$$n\mathbf{V}_D = \int \mathbf{v}_D \bar{f}_i d^3 v; n\mathbf{U}_D = \int u_D \bar{f}_i d^3 v;$$
$$P_\perp = \int \mu B \bar{f}_i d^3 v. \tag{5}$$

The charge-exchange process takes the ions away at a rate $\sigma_{cx} v$ and returns them to the ion distribution at zero velocity. Elastic collisions takes the ions away at a rate $\sigma_{el} v$ and return them isotropically distributed in the center of mass reference frame. Here we will treat the cross sections σ_{cx} and σ_{el} as constants since they are insensitive to the ion energy in the range of energies up to a few eV . In order to solve equation (1) we will assume the following ordering [4]:

$$\omega_{ci} >> n\langle \sigma v \rangle_e >> n(\sigma_{cx} + \sigma_{el}) \sim 1/\tau , \tag{6}$$

where τ is the characteristic discharge time. We also assume that

$$\lambda \equiv \frac{1}{n(\sigma_{cx} + \sigma_{el})} << L. \tag{7}$$

These assumptions allow us to neglect, to lowest order, the time derivatives of $\bar{f}_i$ in equation (1) as well as the charge-exchange and elastic collision terms. As a result, equation (2) reduces to [1]

$$\left[v_\parallel \frac{\mathbf{B}}{B} + \frac{\mu}{m_i \omega_c} \frac{\mathbf{B}\times \nabla B}{B} \right] \cdot \nabla \bar{f}_i = \delta(\mathbf{v}) n_0 n \langle \sigma v \rangle_e, \tag{8}$$

where n_0 and n are the gas and electron densities, respectively Also it has been used the condition of symmetry in magnetic mirror configurations [1]

$$\nabla \times \mathbf{B} \cong 0. \tag{9}$$

2.DISTRIBUTION FUNCTION

The component of equation (8) along the magnetic field line near to the axis can be written as

$$\frac{\partial \bar{f}_i}{\partial z} = \frac{1}{v_\parallel}\delta(\mathbf{v}) n_0 n \langle \sigma v \rangle_e . \tag{10}$$

The integration of the last equation results in

$$\bar{f}_i = \int \frac{\delta(\mathbf{v}) n_0 n \langle \sigma v \rangle_e}{v_\parallel (z', \mu, U)} dz'. \tag{11}$$

3.CALCULATION OF ION FLUXES

From the definitions of the parallel and perpendicular ion fluxes (4) and using the expression for the distribution function, we obtain [1]

$$n\mathbf{V}_\parallel = n_0 n \langle \sigma v \rangle_e z \frac{\mathbf{B}}{B}, \quad n\mathbf{V}_\perp = \frac{v_\parallel n_0 n \langle \sigma v \rangle_e}{2\omega_c B} \mathbf{B} \times \mathbf{e}_z , \tag{12}$$

where $\mathbf{e}_z$ is the unit vector along OZ. The corresponding expressions for the radial and axial components of the ion fluxes are

$$nV_r = n_0 n \langle \sigma v \rangle_e z \frac{B_r}{B}, \quad nV_z = n_0 n \langle \sigma v \rangle_e z \frac{B_z}{B}. \tag{13}$$

4.MAGNETIC FIELD

The magnetic field generated by a current sheet formed by L circular current turns is obtained using the superposition principle, where the magnetic field for one of the turns is used to calculate the magnetic field for the whole current sheet

$$B_r(r,z) = -\sum_{l=1}^{L} \frac{\partial A_{\theta l}}{\partial k_l}\frac{\partial k_l}{\partial z}, \quad B_z(r,z) = \sum_{l=1}^{L}\left(\frac{A_{\theta l}}{2r} + \frac{\partial A_{\theta l}}{\partial k_l}\frac{\partial k_l}{\partial r}\right), \tag{14}$$

where L is the total number of current turns in the sheet, and

$$k_l^2 = \frac{4R_1 r}{(r+R_1)^2 + (z-z_1)^2}, \quad A_{\theta l}(r,z) = \frac{4J}{c}\sqrt{\frac{R_1}{r}} \times \left[\left(\frac{1}{k_l} - \frac{k_l}{2}\right)\mathrm{K}(k_l) - \frac{\mathrm{E}(k_l)}{k_l}\right]. \tag{15}$$

Here $\mathrm{K}(k_l)$ and $\mathrm{E}(k_l)$ are the elliptic integrals of the second and first kind respectively. $z_l = d(l - 1/2)$ is the left-side position of the current sheet on the z axis. Generalizing to the case of N axially aligned magnet coils we obtain

$$B_r(r,z) = -\sum_{n=1}^{N}\sum_{m=1}^{M_n}\sum_{l=1}^{L_n} \frac{\partial A_{\theta lmn}}{\partial k_{lmn}}\frac{\partial k_{lmn}}{\partial z}, \quad B_z(r,z) = \sum_{n=1}^{N}\sum_{m=1}^{M_n}\sum_{l=1}^{L_n}\left(\frac{A_{\theta lmn}}{2r} + \frac{\partial A_{\theta lmn}}{\partial k_{lmn}}\frac{\partial k_{lmn}}{\partial r}\right) \tag{16}$$

where L_n and M_n are the number of loops in each current sheet and the total number of nested sheets in each of the n-th magnet coil respectively. In this case

$$k_{lmn}^2 = \frac{4R_{mn} r}{(r+R_{mn})^2 + (z-z_l)^2}, \quad A_{\theta lmn}(r,z) = \frac{4J_n}{c}\sqrt{\frac{R_{mn}}{r}} \times \left[\left(\frac{1}{k_{lmn}} - \frac{k_{lmn}}{2}\right)\mathrm{K}(k_{lmn}) - \frac{\mathrm{E}(k_{lmn})}{k_{lmn}}\right]. \tag{17}$$

The particular case of three coils is illustrated in Fig.1. The axial distributions of the magnetic field components are plotted in Fig. 2.

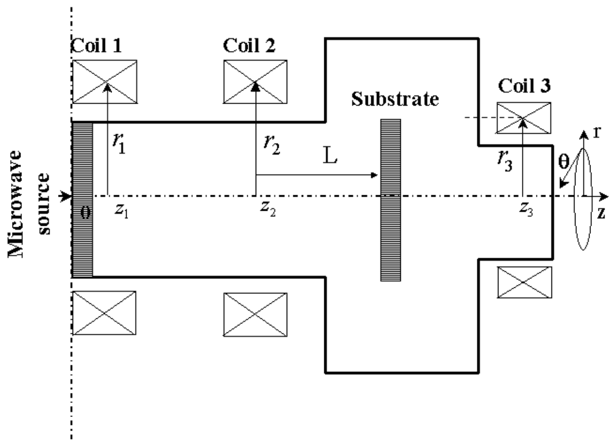

Fig. 1. Schematic representation of an ECR system showing the magnetic system with three coils.

5.DISCUSSION AND CONCLUSIONS

In order to prove agreement of the theoretical results with experimental ones, the same parameters as in [5] are used. These parameters are resumed in Table 1. The argon ions are considered in calculations.

To calculate the ionization rate, it is of great importance to know the energy distribution function. In the case of low ion temperatures ($T_i \leq 2.5$ eV), the maxwellian distribution is a good approximation as can be obtained from the integration of the ion part of the I-V probe characteristic by regularization methods. Using this result, the expression for the ionization rate is calculated.

From expressions (13) it is noticed that the radial and axial ion fluxes are directly proportional to the corresponding magnetic field components.

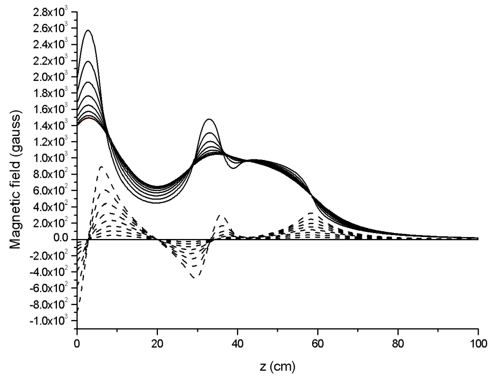

Fig. 2. Axial behavior of the axial (solid) and radial (dashed) components of the magnetic field, for different radii.

Table 1. Parameters reported in [5] and used to validate the theoretical results of the present work.

n_0=5.5E11cm^3	n =4.6E12cm^{-3}	P=10^{-4}torr	T_e=3.5eV
I_i=13.8eV	$\langle \sigma v \rangle_e$ =6.24E-10cm^{-3}/s	T_i=0.5eV	J_1=180A
J_2=90A	J_3=70A	r_1=r_2=10.8cm	r_3=11.4cm
L_1=L_2=14	L_3=46	M_1=M_2=12	M_3=5
Z_1=0.0cm	Z_2=24.6cm	Z_3=74.5	d=0.4cm

In Fig. 3, the axial distribution for both the axial and radial ion fluxes As we can see, the axial ion flux always increases. Otherwise, the radial flux shows a strong irregular behavior.

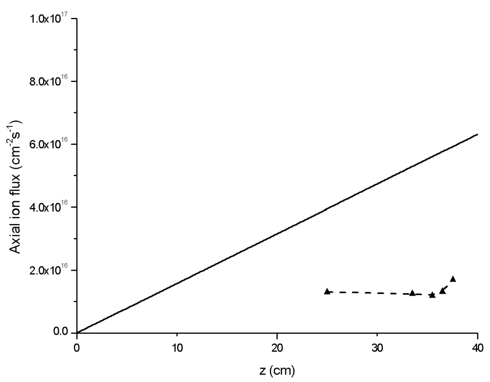

Fig.3. Calculated axial ion flux (solid) and experimental points reported in [5] (dashed) using the parameters resumed in Table 1.

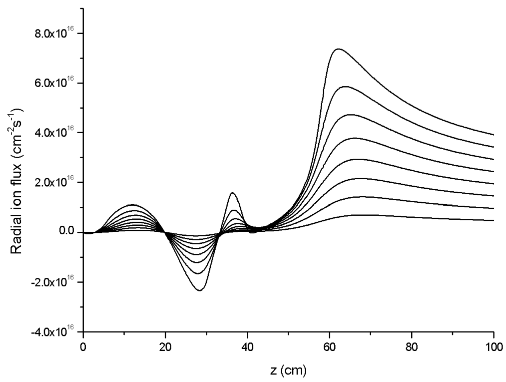

Fig. 4. Axial distribution of the radial ion flux for several radii.

The irregular behavior of the radial ion flux a be the source of the inhomogeneity observed in depositions as is the case of steel nitriding.

REFERENCES

1. J. González-Damián and C. Gutiérrez-Tapia, J.Appl.Phys., **90**, 1124 (2001).
2. R.D. Hazeltine, Plasma Phys., **15**, 77 (1973).
3. F. L. Hinton and R. D. Hazeltine, Rev. Mod. Phys., **48**, 239 (1976).
4. B. N. Breizman and A. V. Arefiev, Phys. Plasmas, **9**, 1015 (2002).
5. N. Sadegui, T. Nakano, D. J. Trevor, and R. A. Gottscho, J. Appl.Phys., **70**, 2552 (1991).

*This work was patially supported by project CONACyT 33873-E