MODELING OF MIRROR CONFINED ECR PLASMAS FOR HIGHLY CHARGED ION PRODUCTION

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1. Introduction

Understanding the physics of ECRIS will make it possible to have a quantitative estimate of the role of the various design parameters of the sources. It is also expected that a good understanding of the physical processes will suggest new developments for further improvements in the domain of cold plasma physics. This article is devoted to the theoretical analysis and numerical developments : the Fokker-Plank code for the electrons is described and its most recent results presented. Some important conclusions can already be drawn from this analysis. Then theoretical results are compared with experiments.

2. 1D Fokker-Planck quasilinear code

The physical processes experienced by the electron population, characterized by its Distribution Function (EDF) can be described by a Fokker-Planck equation :

(i) the collisions with charged particles are described by the Rosenbluth potentials [1],

(ii) the wave-electron interaction is described by quasilinear terms [2],

(iii) the ionization of neutrals (and later ions) is modeled by a source term and is supposed to bring no major modification to the shape of the EDF.

(iv) another source term is added to the equation for the EDF , which describes direct injection of electrons into the plasma (by a first stage for example, or plasma-wall interaction).

2.1. Description of the code

1. In order to simplify the problem we neglect any axial (along the field line) inhomogeneity of the electronic component (square-well assumption for the magnetic field). Equivalently the problem is reduced to a zero-dimensional problem in physical space. The

most convenient variables in that case are the module of the velocity v and the pitch angle μ. Figure 1 shows the loss cone in the case of a positive plasma potential (dotted line). Two domains are considered : the domain (1) where the electrons are electrostatically confined by the plasma potential and the domain (2) where the electrons are trapped in the mirror but some losses are induced at the boundary because of the rf and collisions. These two domains are separated by the velocity v_1 defined as : $v_1 = \sqrt{\frac{2e\Phi}{m_e}}$ where Φ is the plasma potential.

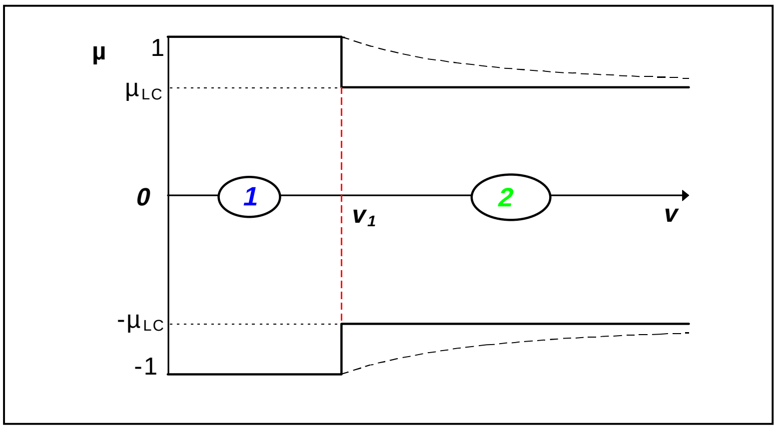

Figure 1. Domain of computation, μ_{LC} is the angle of the loss cone

2. A second approximation is made to simplify the problem : as the collision term is of great complexity, the Rosenbluth potentials are here assumed to be isotropic. This assumption and the modification of the boundary as shown in figure 1 (full line) makes it possible to separate the variables in the collision term so that f can be divided in two parts : $f(v,\mu,t) = F(v,t)H(\mu)$ where H is a solution of a Sturm-Liouville problem and F is only a function of velocity and time. We have therefore two one-dimensional problems to solve instead of one two-dimensional equation.

3. A third approximation is made concerning the quasilinear term : only the most salient features of rf interaction are however taken into account : diffusive heating in velocity, and pitch-angle scattering due to the rf magnetic field.

4. A Dirichlet boundary condition is imposed by the loss cone : f=0 over the boundary. A transmission condition is inserted at $v = v_1$ to ensure flux conservation of particles.

The Sturm-Liouville equation is solved numerically and the equation for F is solved by an implicit finite volume scheme. This separation of the calculation domain is abrupt but it is also possible to divide it in N domains to have a better fit of the loss cone. The results are only slightly modified.

2.2. Numerical results

As expected at low rf power (i.e. at low rf diffusion coefficient) the EDF is close to a maxwellian ; but at large rf power the electrons are pushed to high energies so that the fraction of the electrons below the plasma potential becomes small. The density of the electrons of course increases with the neutral density and with the supplementary injection of electrons. More interesting is the following result (Figure 2) : as the rf diffusion coefficient increases the electron density first increases, saturates and then drops ; the same behavior is observed for the absorbed power (which is easily calculated with the EDF) as can be seen in Figure 3.

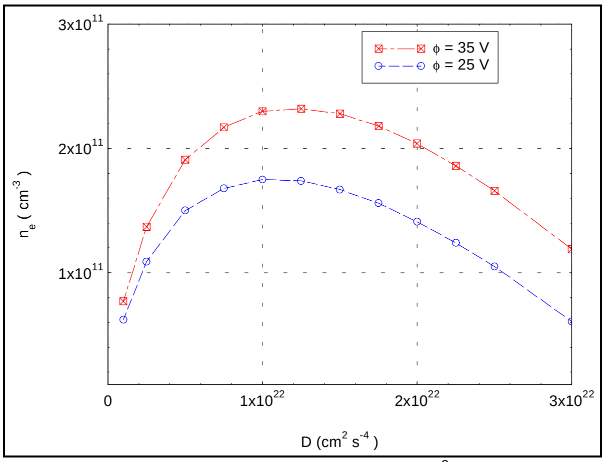

Figure 2. Electron density (in cm^{-3}) versus rf strength for two plasma potentials.

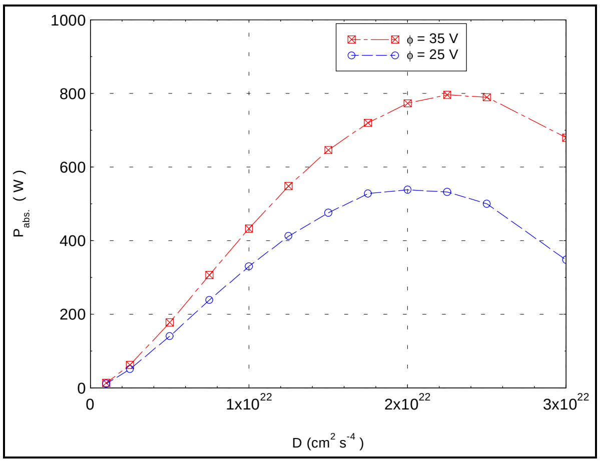

Figure 3. Rf absorbed power versus rf strength for two plasma potentials.

These two results have important consequences : it shows that increasing the rf incident power, or the rf diffusion coefficient, does not necessarily lead to a higher density. It shows also that the rf input power is no longer absorbed when the incident power is increased. This can be understood as follows : as the rf increases the electrons are pushed to higher and higher energies where they experience less and less ionizing collisions ; therefore they do no longer contribute to any increase of density and they are directly pushed out of the plasma by rf pitch-angle scattering. This result explains why the performances of the ECRIS have an optimum operating point with the rf power.

2.3. Comparison with experiments

The electron density is about 3.10^{11} cm^{-3}, it increases very rapidly with the rf power for low values of incident power; but it rapidly saturates and no longer evolves, even for higher neutral pressures. This behavior is not yet well understood but other measurements show that the most significant variation consists in the mean energy of the EDF.

As we are able to measure both the density and the current, it is possible to have an estimate of the transport process, and its magnitude τ_e. The electron lifetime is about 1 ms. It decreases as the pressure increases and as the rf power increases.

Modeling results presented in Figure 4 and Figure 5 have quite the same evolution with power and pressure than experimental results.

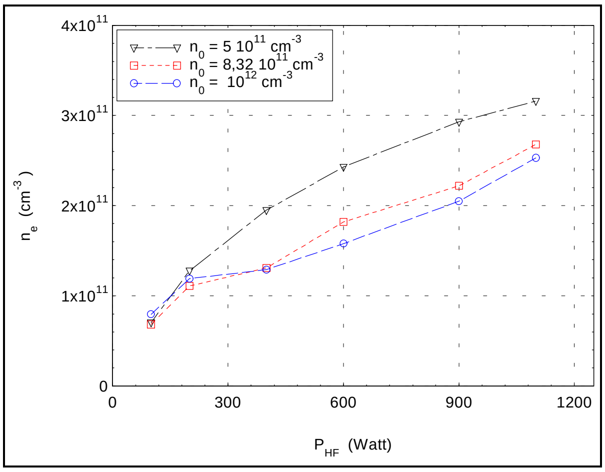

Figure 4. Electron density versus rf power.

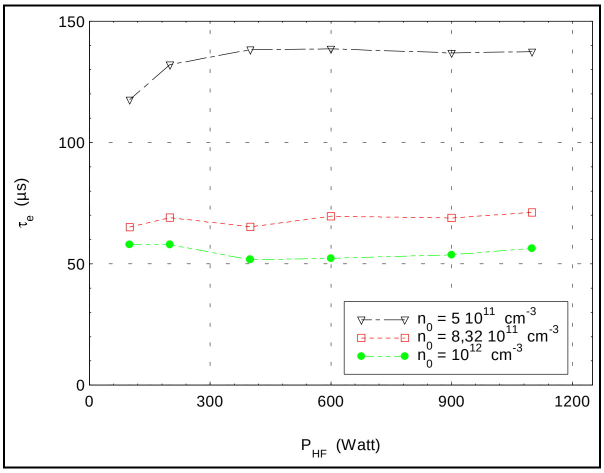

Figure 5. Electron confinement time versus rf power.

3. Conclusion and prospects

Many improvements have been performed in the understanding of ECRIS. It was theoretically proved that the optimum of ECRIS requires a certain amount of rf power - and no more. But these results were obtained with certain approximations which are exaggerated : it is well known that the EDF is anisotropic so that a 2D code is under study. Moreover a coupling between the electrons and the ions is necessary ; therefore we plan to add the dynamics of ions into the 1D code which already gives good qualitative results, before inserting this dynamics into a 2D code.

References

[1] M.N. Rosenbluth, W.M. McDonald, and D.L. Judd: Phys. Rev. **107**, 1 (1957)

[2] C.F. Kennel and F. Engelmann: Phys. Fluids **9**, 2377 (1966)