MONTE CARLO MODEL OF CHARGE-STATE DISTRIBUTIONS FOR ELECTRON CYCLOTRON RESONANCE ION SOURCE PLASMAS*

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Abstract

A computer model for an Electron Cyclotron Resonance Ion Source (ECRIS) plasma is under development that currently incorporates non-Maxwellian distribution functions, multiple atomic species, and ion confinement due to the ambipolar potential that arises from fast electrons. Atomic processes incorporated into the model include multiple ionization and multiple charge-exchange with rate coefficients calculated for non-Maxwellian distributions The electron distribution function is calculated using a Fokker-Planck code with an ECR heating term. The Monte Carlo method is used to calculate the charge-state distribution (CSD) of the ions. The Monte Carlo ion tracking is verified by CSD comparison with a conventional 0-D fluid model, similar to Shirkov's[1]. The Monte Carlo method is chosen for future extension to a 1-D axial model. Axial variations in the plasma parameters could affect confinement, CSD and extraction. The electron Fokker-Planck code is to be extended to 1-D axial by bounce-averaging.

1 INTRODUCTION

The complete understanding and optimization of an ECRIS is complicated with many issues to consider, such as plasma confinement, neutrals, multiple atomic species, and microwave resonances. Optimization for higher charged states and higher current with low emittance is challenging. A typically optimization is by trial and error because there are few suitable numerical tools available, none with a comprehensive modeling capability.

Current ECRIS modeling is typically a 0-D fluid model such as Shirkov's "Classical Model of Ion Confinement and Losses in ECR Ion Sources"[1]. Here the ion charge-state-distribution (CSD) is determined by solving a set of coupled fluid equations. Plasma parameters are assumed to be uniform over the plasma volume and no spatial effects are considered. Confinement is determined from a simple potential and magnetic box/well model. This 0-D fluid modeling has several drawbacks, in particular neglecting the electron distribution function and spatial effects.

1.1 Electron Distribution Function

Due to ECR heating and mirror confinement, the electrons in an ECRIS are expected to be highly non-Maxwellian and non-isotropic. The electrons in most ECRIS models are typically treated as two separate species, cold or warm Maxwellian electrons and hot perfectly confined collisionless electrons whose temperatures need to be input. The electron confinement usually ignores the potential between the plasma and the wall despite evidence that it is comparable to the cold electron energy[2]. Also, the hot electrons are obviously not perfectly confined. Their loss rate must balance the rate at which they are created by ECR heating.

The actual electron distribution, f_e, would be better modeled by a single continuous non-Maxwellian, non-isotropic distribution function. A Fokker-Planck code would allow f_e to be calculated taking into account RF heating and both magnetic and potential confinement. This would also eliminate the electron temperature as a fixed input to the model. Ideally, an ECRIS model should require as input parameters, only experimental knobs such as the magnetic field, gas inlet, rf power etc.

1.2 Spatial Effects

Usually, all effects of spatially varying parameters are ignored in ECRIS models. Confinement is modeled by assuming the magnetic field and potential can be treated as a uniform box/well. Inside the well, all plasma parameters are assumed to be constant. However, an ECRIS can have complex spatially varying asymmetric magnetic fields and potentials. In addition, the plasma parameters are not expected to be uniform. Higher charge-states are expected to be confined deeper in the potential well. The average electron, ion and neutral densities, they interact with, will be different than those seen by lower charge states. In particular, the varying conditions the ions must travel through between the main plasma and the extraction point should be considered.

Due to the high electron mobility, the electron spatial effects can be accounted for by a bounce-averaged Fokker-Planck code. In a typical ECRIS, however, the ion bounce frequency is much smaller than the ion collision frequency and a bounce-averaged treatment is inappropriate. Extending a fluid model axially may also be inappropriate as the plasma near the extraction point will be less dense and thus less collisional than in the center of the plasma and the fluid approximations may not apply. The Monte Carlo method is better suited for determining the ion

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spatial effects. This method can handle both highly collisional and collisionless regimes with smoothly varying and non-symmetric magnetic fields and potentials, resulting in better estimates of the true ion confinement. A Monte Carlo model would also be better suited for the possible future addition of ICRH and the resultant ion distribution anisotropy.

2 GENERIC ECRIS MODEL

In this paper, we present the initial results of the Generic ECRIS Model (GEM) code which attempts to improve ECRIS modeling by using an electron Fokker-Planck code and including Monte-Carlo ion modeling.

Collisional processes incorporated into the model so far include the single, double and triple electron impact ionization cross-sections, σ^I, of Lotz[3],[4] and Müller et. al.[5],[6], along with single, double, triple and quadruple charge-exchange cross-sections, σ^{CX}, from Müller and Salzborn[7]. For simplicity, we will include only single-step collision terms in all of the equations to follow.

2.1 0-D Fluid Model

For comparison, initial modeling results have also been obtained using a 0-D fluid model similar to Shirkov's [1].

Neutral Modeling: The neutral density inside the plasma is determined from the neutral density outside the plasma and the rate at which neutrals are converted into ions inside the plasma volume.

Ambipolarity: Radial transport is assumed to be negligible compared to axial endloss. Thus, the endloss currents must be ambipolar or balance.

$$\frac{n_e}{\tau_e^P} - S_e^{ext} = \sum_j \sum_{q=1}^{A_j} \frac{q n_{j,q}}{\tau_{j,q}^P}$$

where S_e^{ext} is the external electron source.

The confinement time for an ion of atomic species j and charge q, in a confining potential, is given by[8]

$$\tau_{j,q}^P = \left[RL\left(\frac{\pi m_j}{2k_B T_i}\right)^{1/2} + \frac{Gx^2}{\left(x+\frac{1}{2}\right)\left(\nu_{j,q}^o + \nu_{j,q}^i\right)} \right] \exp(x)$$

where

$$x = \frac{qe\varphi_o}{T_i} \quad and \quad G = \frac{\sqrt{\pi}(R+1)\ln(2R+2)}{2R}$$

and φ_o is the ion confining well potential, R is the mirror ratio and L is the length of the core plasma.

Ion Power Balance: The ion temperature is determined by solving the ion power balance

$$\frac{d}{dt}\left(\tfrac{3}{2} T_i \sum_j n_i\right) = \sum_j \left(p_j^o + p_j^{\Delta\phi} + p_j^{ei} + p_j^{CX} + p_j^{loss}\right)$$

where the terms on the right account for, respectively, the initial energy of the ionized neutrals, energy due to ionization inside a potential well, electron collisional heating, energy lost due to charge exchange and energy lost due to the ion endloss. All ion species are assumed to have the same temperature. Model test runs with separate ion temperatures for different atomic species have verified that ion thermal equilibration is fast and all ion species will have nearly identical temperatures.

Ion CSD Modeling: The ion CSD is arguably the most important result desired from an ECRIS model. Traditionally, ECRIS models have determined the CSD by solving a coupled set of fluid equations for multiple atomic species j…

$$\frac{dn_{j,q}}{dt} = \left(n_{j,q-1}\left\langle\sigma_{j,q-1}^I \mathrm{v}_e\right\rangle - n_{j,q}\left\langle\sigma_{j,q\to q}^I \mathrm{v}_e\right\rangle\right) n_e$$

$$+ n_{j,q+1}\sum_{j_2}\left\langle\sigma_{j,q+1\to j_2}^{CX}\mathrm{v}_j\right\rangle n_{j_2,0} - n_{j,q}\sum_{j_2}\left\langle\sigma_{j,q\to j_2}^{CX}\mathrm{v}_j\right\rangle n_{j_2,0} - \frac{n_{j,q}}{\tau_{j,q}}$$

In the above set, there is one equation for each charge-state of each atomic species.

2.2 Fokker-Planck Electron Model

The electron distribution function, $f_e(v,\theta)$, can be determined by solving the Fokker-Planck equation

$$\frac{\partial f_e}{\partial t} + \vec{\mathrm{v}} \bullet \frac{\partial f_e}{\partial \vec{x}} + \frac{\vec{F}}{m_e} \bullet \frac{\partial f_e}{\partial \vec{v}} = \left(\frac{\partial f_e}{\partial}\right)_{coll} + S_e(\mathrm{v},\theta) + S^{rf}(\mathrm{v},\theta)$$

where $(\partial f_e/\partial t)_{coll}$ is the Fokker-Planck collisional operator, S_e is the cold electron source and S^{rf} is the perpendicular diffusion ECRF heating term:

$$S^{rf} = \frac{1}{\mathrm{v}_\perp}\frac{\partial}{\partial \mathrm{v}_\perp}\left(\mathrm{v}_\perp D_{rf}\frac{\partial f_e}{\partial \mathrm{v}_\perp}\right)$$

$$D_{rf} = D_o \exp\left(-\mathrm{v}^2 \big/ 2c^2\right)$$

$$P_{rf} = 2 n_e m_e D_o V_p$$

The nonlinear multispecies code FPPAC94[9] has been incorporated into the model. The Fokker-Planck modeling also determines the e-i collisional energy exchange and the electron confinement.

As the electron distribution function is highly non-Maxwellian and non-isotropic, the reaction-rate coefficient should be calculated explicitly from distribution functions of the two colliding species.

$$\langle\sigma\mathrm{v}\rangle = \frac{1}{n_a n_b}\int d\mathrm{v}\int d\mathrm{v}' f_a(\mathrm{v}) f_b(\mathrm{v}')\sigma\left(|\mathrm{v}\text{-}\mathrm{v}'|\right)|\mathrm{v}\text{-}\mathrm{v}'|$$

The model incorporates a routine[10] to compute the reaction-rates for arbitrarily shaped distribution functions. The routine can employ a non-uniformly spaced velocity-distribution, suitable to an ECRIS, where the electrons, ions and neutrals can have average velocities orders of magnitude apart.

2.3 Monte Carlo Ion Model

As discussed in Section 1.2, a Monte-Carlo model could incorporate the effects of spatially varying parameters on the ion confinement and CSD. A Monte Carlo code has several advantages. The Monte Carlo method is a powerful tool that enables the inclusion of complex geometries, energy distribution functions, and detailed atomic processes. The ion confinement, CSD and distribution function could be calculated axially using axially varying

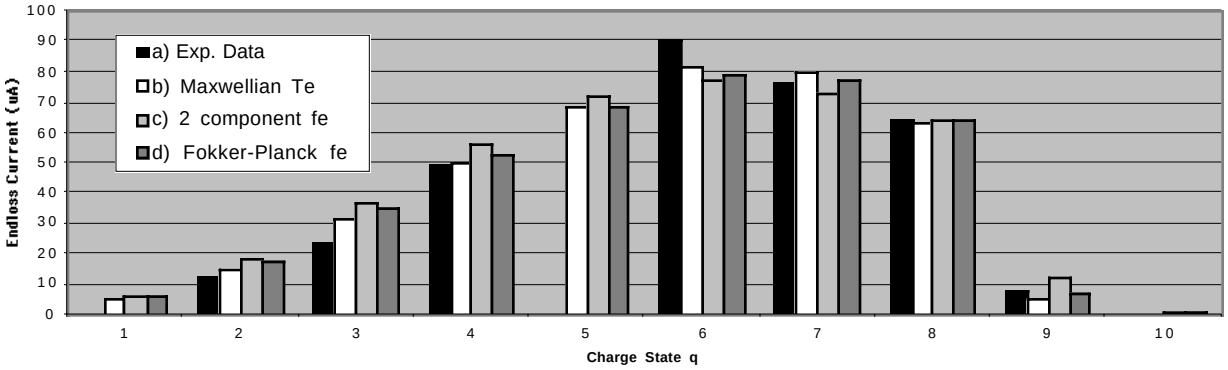

Figure 1: Comparison of Modeling results with ANL ECR-II Faraday cup measurements

plasma parameters such as the potential. A full 1-D axially Monte Carlo ion model is planned for this model.

As a first step, the Monte Carlo method has been incorporated in the code to calculate the 0-D multi-species ion CSD.

3 RESULTS

3.1 Electron Modeling

To investigate the validity of the model, comparisons have been made with Faraday cup measurements from ECR-II at Argonne. Due to an air leak the plasma ions had four major atomic species: He, N, O and Ne ions. The experimental data are shown as plot a in Figure 1.

The need for Fokker-Planck electron modeling is demonstrated by plots b and c in Figure 1. Plot b was produced by a Maxwellian electron distribution (T_e=2 keV) while plot c results from a combining collisionless hot electrons (100keV) with a very small amount (~0.3%) cold electrons (70eV). Clearly, one can match the experimental data using very different assumed electron distributions.

To eliminate this arbitrariness, the electron distribution should be determined by solving the Fokker-Planck equation. The predictions of the Fokker-Planck electron modeling are given as plot d of Figure 1. The Fokker-Planck electron modeling produces a good match to the experimental data with less arbitrariness.

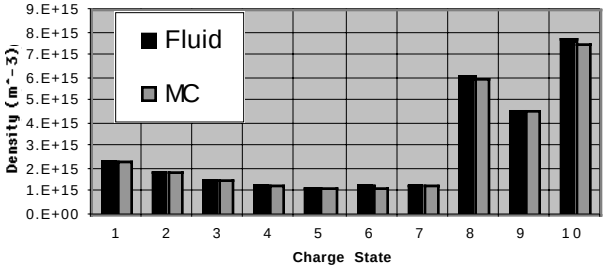

Figure 2: Comparison of Monte Carlo and fluid predictions for the ion densities in a pure Neon plasma

3.2 Ion CSD Modeling

Sample results of the initial CSD Monte Carlo modeling in comparison with the fluid ion modeling are shown in Figure 2 for a pure Neon plasma. They give nearly identical predictions, indicating the Monte Carlo modeling is tracking the ion charge state correctly.

4 DISCUSSION

To be predictive, the model should rely on measured experimental "knobs" only. Even with Fokker-Planck modeling of the electrons, some quantities such as the core plasma length and the electron confining potential still need to be arbitrarily input to the model. By extending the modeling spatially to 1-D axially, one should be able to determine these quantities from the plasma confinement.

The ion Monte-Carlo code must be extended to spatially track the ions and determine their profiles and confinement in addition to their CSD.

The electron Fokker-Planck code should be bounce-average to account for the localization of the ECR resonant surface and also the spatially varying potential and magnetic field. The electron distribution function modeling could also be improved further by including energy losses due to radiation and relativistic effects.

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