KINETIC STUDY OF ELECTRON IMPACT IONIZATION IN A HELIUM DIODE

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1. Introduction

As a next step in the realistic kinetic modeling of collisional bounded plasma systems, we want to study the effects of electron impact ionization (EII) by using an iterative analytic-numerical "trajectory simulation method" [1]-[4] in which kinetic equations are integrated along single-particle trajectories. Being the main mechanism for production of ionic species, EII plays a key role in the plasma production and maintenance of DC glow discharges. In a previous paper [5], we developed a collision integral for EII based on doubly differential cross sections, which we will use here in our simulation program SIMIR. Representative results for a helium planar diode under customary conditions occuring in industrially relevant plasma devices will then be given.

2. Outline of the method

2.1. Model and basic equations

We consider a simplified (1d,2v) plane-diode model, with spatial variations in the z direction. The electrons are emitted by a hot emitter plate (cathode) at $z = 0$, which they leave with half Maxwellian velocity distribution functions. The cold plate (anode) at $z = L$ is a perfectly absorbing electrode. At the present stage, we restrict ourselves to a steady state ($\partial/\partial t = 0$), while a time-dependent simulation is planned for the near future. The velocity distribution function $f_s(\vec{x}, \vec{v}, t)$ of each species s composing the plasma satisfies the kinetic equation

$$\left(\vec{v} \cdot \frac{\partial}{\partial \vec{x}} + \frac{q_s}{m_s}[\vec{E}(\vec{x}, t) + \vec{v} \times \vec{B}(\vec{x}, t)] \cdot \frac{\partial}{\partial \vec{v}}\right) f_s(\vec{x}, \vec{v}, t) = C_s^{EII} \,, \tag{1}$$

where C_s^{EII} is the collision term for EII. The system of equations is completed by Poisson's equation. The expressions for the electron and ion collision terms for EII can be found in [7] and are given by:

$$\begin{aligned} C_e^{EII} &= S\ N(z,t)\ v\ F(v)\ g_1(v)\ f_e(z, v_z, v_n) \qquad (2) \\ &\quad + \frac{m}{I}\ \frac{N(z)}{v^2} \int dv_z' \int dv_n'\ v_n'\ v'^2\ f_e(z, v_z', v_n')\ \widetilde{G}_1(v_z', v_n'; v_z, v_n) \\ &\quad \times \Big(I_1(v_z', v_n'; v_z, v_n) + \widetilde{G}_4(v_z', v_n'; v_z, v_n)\ I_2 v_z', v_n'; v_z, v_n) \Big) \,, \\ C_i^{EII} &= \gamma_i(z)\ \delta(\vec{v}) \,, \qquad (3) \end{aligned}$$

the functions involved being defined in [5] or in [6]. The kinetic equations and Poisson's equation are complemented by appropriate boundary conditions. For neutrals, we assume a full Maxwellian distribution with a temperature of 350K. Since both the electron and ion velocity distribution functions depend only on two velocity coordinates, v_z and v_n, the magnetic field term in the kinetic equations (1) vanishes.

2.2. Basics of the trajectory simulation method

For our goal (the detailed kinetic description of EII), we need a very accurate technique which is able to solve the coupled Boltzmann-Poisson system of equations self-consistently, with realistic boundary conditions and detailed inclusion of collisions, and which yields the velocity distribution functions with great accuracy. The "kinetic trajectory-simulation" method [2] is a method to solve the problem with all the needed features. It is closely related to the method of characteristics [1], and its efficiency has been already demonstrated in several cases [2]-[4]. The discretization of phase space is fundamental for getting accurate numerical results, free of numerical errors and without wasting precious simulation time by using too-fine a grid (Fig 1).

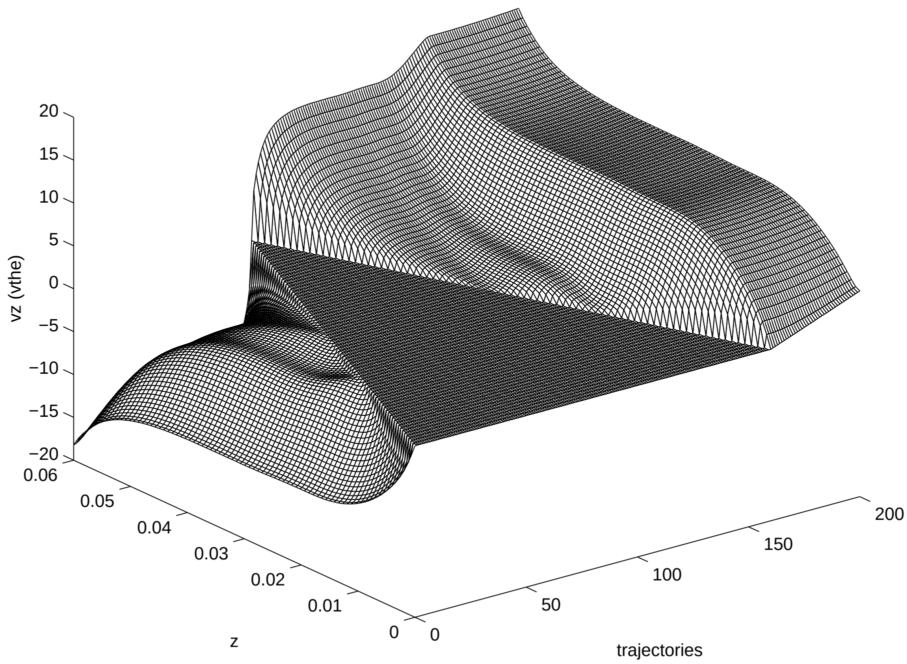

Figure 1. Electron phase-space discretization used by SIMIR for a helium discharge (202x9 mesh for v_z^e and v_n^e).

3. Results and discussion

We now attempt to simulate a helium glow discharge in plane-parallel geometry. The electrons are emitted and accelerated by a monotonically increasing potential distribution obtained with a positive collector bias. The input parameters chosen are $L = 0.06\,m$, $\Phi_e = 0\,V$, $\Phi_c = 60\,V$, $n_e^{(0)} = 1.1\;10^{14}\;m^{-3}$, $n_{bg} = 4.0\;10^{15}\;cm^{-3}$, $T_e = 2100K$, where $n_e^{(0)}$ and n_{bg} are the emission electron density and the background density, respectively, and T_e is the emitter temperature. Running SIMIR with these input parameters, we reach, after about 2800 iterations, a steady state characterized by the plasma potential oscillating between small negative and small positive values and the system's features remaining the same. As representative result, Fig. 2 (a) shows

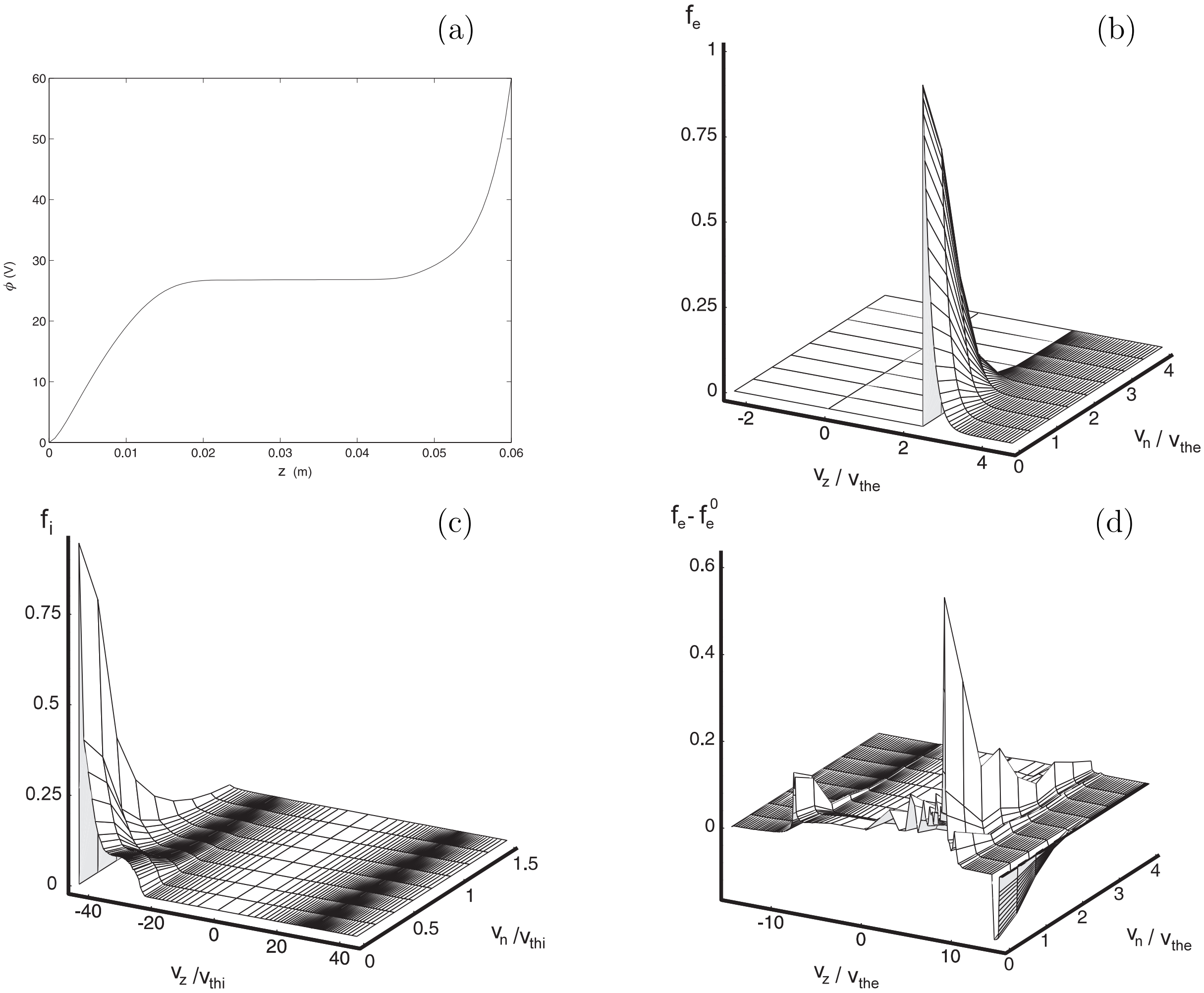

Figure 2. Results from the kinetic simulation program SIMIR. (a) steady-state potential, (b) electron velocity distribution function near the cathode, (c) ion velocity distribution function at $z = 0.006$ m, (f) difference between collisional and collisionless electron velocity distribution function at $z = 0.056$ m.

spatial distributions of the self-consistent electric potential which exhibits a well-developed quasineutral plasma region. Detailed kinetic information on the EII effect can be seen from the microscopic quantities plotted in Figs. 2 (b) and (c), namely normalized electron and ion velocity distribution functions, and the difference electron velocity distribution functions $f^e - f_0^e$ (Fig. 2 (d)), where f_0^e is the collisionless one, which can provide more precise informations on the contribution due to collisions. The electron distribution function remains a cut-off Maxwellian up to about $z \approx 1.6\;cm$ (Fig. 2 (b)). Further into the discharge, more and more collisions occur and the electron collision peak rises. This perfect kinetic picture of the microscopic behavior of our system permits us to distinguish the different electron groups, namely scattered electrons, slow secondary electrons nearly isotropically distributed, some appearing at negative velocities before they are shifted towards positive velocity values, and electrons of the principal peak (emission Maxwellian peak). As we can see, the global effect is the slowing down of electrons. Looking now at the ion velocity distribution functions, we see that rather slow ions are produced near the anode, whereas fast ones constitutes the main ion population near the cathode.

4. Conclusions

We have presented a detailed kinetic study of electron impact ionization (EII) in a helium plasma plane diode. Using our collision term for EII, which takes into account all the angular information available from the doubly differential cross section, in our simulation program SIMIR, we have simulated a realistic plane-parallel ($1d$, $2v$) bounded plasma system. This represents the most detailed kinetic analysis of the EII phenomenon in a bounded plasma system given so far. Inclusion of other collision processes like recombination phenomena has already been performed [6] (results will be presented elsewhere [7]). Furthermore, an analogous time-dependent simulation method should soon be developed which will allow the study of even more interesting systems such as RF discharges used in the micro-electronics industry. Also applications of our method to plasmas near divertor plates in fusion devices are envisaged.

Acknowledgments

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