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Vlasov simulations of plasma-wall interactions in an argon-helium plasma

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Introduction

The plasma-wall transition problem is relevant to most areas of plasma physics. In magnetically confined fusion devices, charged particles in the plasma edge can erode the wall, thus reducing the lifetime of the components facing the plasma. Energetic particles hitting the wall may deteriorate the quality of the plasma confinement, because high-Z impurities are released from the wall and pollute the plasma. In low temperature plasmas, plasma-wall interactions are even more fundamental, because treating a surface is often the very goal to achieve. Most previous experimental and numerical results deal with single-species plasmas, generally argon, which is used in most laboratory experiments. Here, we concentrate on the much less studied case of a two-component plasma (argon and helium), which has attracted some experimental interest in the last few years. Multi-component plasmas are also relevant to tokamak plasmas, which contain hydrogen and deuterium, as well as heavier species as impurities. We present results obtained from kinetic simulations of the interaction between a semi-infinite wall and a weakly collisional argon-helium plasma. The use of a Vlasov code [1, 2] allows us to resolve the various regions of the transition layer with great accuracy.

Model and numerical methods

We consider the interaction between an unmagnetized two-component plasma and an infinite wall. We assume the wall to be perfectly absorbent, i.e. all particles hitting the wall are lost. Due to the planar symmetry, we need only consider variations in the direction x, perpendicular to the surface of the wall. The corresponding phase space is thus two-dimensional: (x,v).

The kinetic model is based on the ion distribution function $f(x,v,t)$, which represents the particle probability density in phase space and can be used to compute macroscopic quantities, such as the particle density $n = \int f dv$ or the average fluid velocity $u = \int f v dv/n$. The evolution of the distribution function is governed by the self-consistent Vlasov-Poisson system, with Maxwell-distributed electrons:

$$\frac{\partial f_j}{\partial t} + v\frac{\partial f_j}{\partial x} - \frac{e}{m}\frac{\partial \phi}{\partial x}\frac{\partial f_j}{\partial v} = \left(\frac{\partial f_j}{\partial t}\right)_{\text{coll}}, \tag{1}$$

$$\frac{\partial^2 \phi}{\partial x^2} = -\frac{e}{\varepsilon_0}[n_i - n_e(\phi)], \qquad n_e(\phi) = n_0 \exp\left(\frac{e\phi}{k_B T_e}\right), \tag{2}$$

where the subscript j denotes the ion species (Ar or He), e is the absolute electron charge, ϕ the self-consistent electric potential, and ε_0 the vacuum dielectric permittivity. The ion density is an admixture of the two species: $n_i = (1-\alpha)n_{\text{Ar}} + \alpha n_{\text{He}}$, where α is the proportion of the light species (helium). The collision operator is a simple relaxation term of the form:

$$\left(\frac{\partial f_j}{\partial t}\right)_{\text{coll}} = -\nu_j(f_j - f_{j0}), \tag{3}$$

where ν_j is the collision rate between ions and their respective neutrals, with equilibrium distribution f_{j0}. We have made the assumption that each ion species only collides with its own neutrals. This is justified by considering the mean free paths for He^+-He collisions ($\lambda = 1.3$cm), Ar^+-Ar collisions ($\lambda = 8$cm), and Ar^+-He collisions ($\lambda =$62cm): the latter are therefore neglected. Ion-ion and ion-electron collisions have mean free paths of the order of 100cm and are also neglected.

The Vlasov equation is solved with an Eulerian code based on a fixed mesh covering the entire phase-space [1]. Unlike in Particle-In-Cell (PIC) codes, the ion distribution function is defined as a smooth function of the phase space variables. The time integration relies on a splitting scheme, which treats each phase space direction separately. This approach has the advantage of reducing the numerical noise compared to PIC simulations. The initial condition corresponds to a plasma at thermodynamic equilibrium, with a Maxwellian distribution at temperature T_0. The results presented in the forthcoming sections always refer to asymptotic steady state configurations, obtained by running the code for a sufficiently long time.

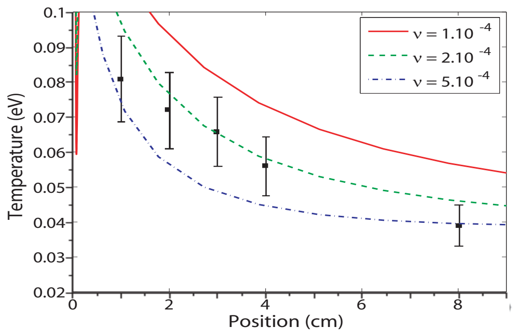

Figure 1: Computed T_i profile for three values of the collision rate (lines), compared to experimental results [3] (dots).

Experimental validation – single-species plasma

Contrarily to previous approaches [1, 2], we consider a case where the mean free path (and not the collision rate) is spatially uniform. The collision rate is equal to $\nu_j = \langle v^2 \rangle^{1/2}/\lambda_j$. The mean square velocity is equal to the thermal speed in the equilibrium plasma, but approaches the mean velocity u when the plasma is strongly accelerated in the Debye sheath. In order to validate our model, we have tried to reproduce the ion temperature profile observed experimentally in a single-species plasma-wall transition [3]. We stress that the temperature is a difficult quantity to reproduce, as it stems from the second moment of the distribution function. The main parameters are as follows: $\tau = T_e/T_i = 25$, $\lambda = 10^4 \lambda_{Di}$, and wall polarisation $\phi_p = -30V$. The result is presented in Fig. 1, for different values of the thermal collision rate $\nu_{th} = V_{th}/\lambda$, measured in units of ω_{pi}. The realistic value $\nu_{th} = 10^{-4}\omega_{pi}$ slightly overestimates the ion temperature, but the result is rather satisfactory for $\nu_{th} = 2 \times 10^{-4}\omega_{pi}$.

Two-species plasma

The profiles of the electron and ion densities are shown in Fig. 2 for a typical two-species plasma-wall transition with $\alpha = 0.3$, $\tau = 25$, and $T_{\mathrm{Ar}} = T_{\mathrm{He}}$. We notice that this proportion is not preserved within the transition, as the argon density decreases faster than the helium density when approaching the wall. Next, we devote some attention to the Bohm criterion in a two-component plasma-wall transition. For a plasma composed of a single ion species, a simple analysis shows that, in order to obtain a monotonic transition, the ions must enter the sheath with a velocity larger than the Bohm speed $c_s = \sqrt{k_B T_e/m_i}$. In a multi-component plasma, the same analysis only provides a global criterion: $\sum_j \frac{n_{j0}}{n_{e0}} \frac{c_j^2}{v_j^2} \leq 1$, where the summation is relative to the ion species; n_{j0} and n_{e0} are the ion and electron densities at the entrance of the sheath, c_j is the Bohm velocity of the j-th species, and v_j is the ion velocity at the sheath entrance. The above criterion can be satisfied in different ways. For instance, each species can enter the sheath with its own Bohm velocity c_j; alternatively, all ion species can enter the sheath with the same velocity – the sound speed of the system, defined by $v_{\mathrm{ph}}^2 = \sum_j (n_{j0}/n_{e0})\, c_j^2$. Recent experiments using argon-helium and argon-xenon plasmas point to the second solution [4].

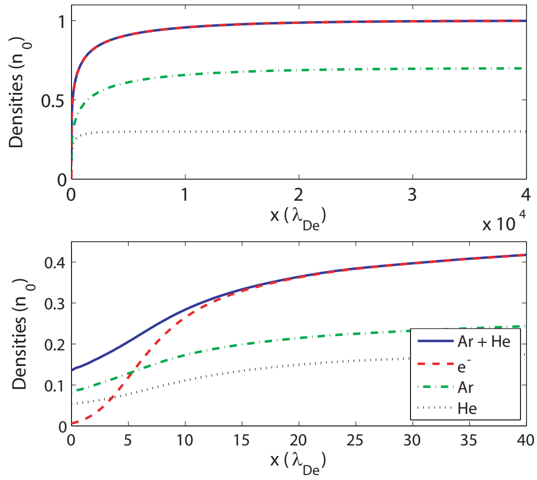

Figure 2: Density profiles in the presheath (top) and Debye sheath (bottom).

In order to clarify this issue, we have performed some simulations with varying concentration of the lighter species, i.e. helium. Figure 3 shows the velocity of each species at the entrance of the Debye sheath as a function of α, together with the system velocity v_{ph}. In contrast to experimental results, the ions enter the sheath with a velocity that is virtually independent on the concentration α. For argon ions, the velocity is close to the sound speed of that species. For

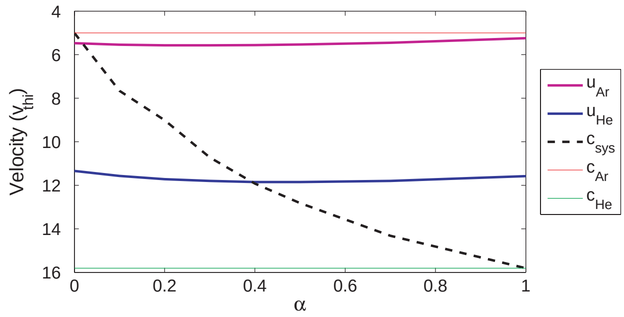

Figure 3: Mean velocities at the entrance of the sheath as a function of the helium concentration α. The dashed line is the sound speed of the system v_{ph}; the straight lines are the individual sound speeds.

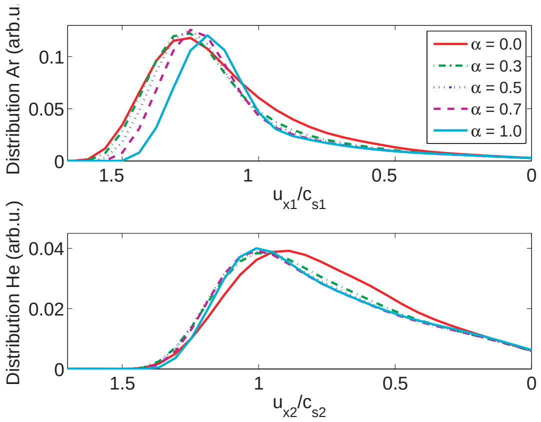

Figure 4: Velocity distributions for argon (top) and helium (bottom) at the entrance of the sheath, for various concentrations.

helium, it is significantly lower (in absolute value) than the sound speed, so that its own Bohm's criterion is not satisfied. This is because the mean-free path of helium is significantly shorter than that of argon.

Indeed, ion-neutral collisions tend to restore the equilibrium Maxwellian, thus dragging the ions towards lower velocities. This is visible in the velocity distribution of helium ions at the sheath entrance (Fig. 4), where a long tail appears at low velocities. The tail is much less pronounced for argon ions. We also notice that the peak of the helium distribution does satisfy Bohm's criterion, although the average velocity does not, due to the presence of the tail.

Further numerical work will be needed to ascertain the origin of the discrepancy with experimental results. A more realistic collision operator might be necessary for a proper description of the two-species problem. Our next step will be to incorporate Ar-He collisions in the model, which would couple the two species in a stronger way (at present the only coupling is provided by the self-consistent electric field).

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