Is the electron kinetics of all plasma surface interactions nonlocal?

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Abstract: For many electron-driven processes at the plasma-surface interface, the electron energy distribution function (EEDF) right at the surface is crucial. The most widely used approximation to find the EEDF is the "local field approximation"; however, can it be valid right next to an electron absorbing wall? Here, we argue that the "nonlocal approximation," commonly associated with very pressures, is the correct model for the EEDF at the surface.

1. Introduction

The EEDF at the plasma-surface interface is deemed crucial for many plasma processes, from semiconductor manufacturing to PFAS (per- and polyfluoroalkyl substances) abatement. However, what is the correct way to determine the EEDF right at the surface? The most common way of determining the EEDF is by solving the Boltzmann equation in the two-term approximation and using the local field approximation (LFA) [1]. However, can the LFA be valid right next to a solid or liquid interface, which is a fully or strongly electron-absorbing medium?

Here, we argue that the nonlocal approximation (NLA) [2] is the correct way to describe the EEDF at the plasma interface and in the plasma sheath in front of it. The NLA is valid if the electron energy relaxation length exceeds the typical system dimensions and is, therefore, typically associated with very low pressures. However, if the "system" is only the plasma sheath with a length of a few Debye lengths, some 10s to 100s of microns, the NLA could also be valid at high pressures, possibly as high as atmospheric pressure.

2. Methods

We developed a hybrid particle-in-cell/Monte Carlo collision code to track the dynamics of electrons in the plasma sheath. The potential profile in the plasma sheath is found from a simple fluid model for collisional sheaths [3]. The EEDF in the bulk plasma is determined with a Monte Carlo simulation, and electrons are injected into the sheath. Electrons are moved with a standard Verlet algorithm, and collisions are treated with a Monte Carlo approach, using the null-collision method for efficiency.

3. Results and Discussion

A distinctive hallmark of the NLA is that the EEDF in the entire system can be described by a single EEDF in terms of total energy, i.e., kinetic plus potential energy. The EEDF of kinetic energy, which determines all collisional and transport properties of electrons, can be found by "cutting off" those low-energy electrons whose total energy is insufficient to overcome the potential barrier to reach a certain position in the system.

Figure 1 shows the EEDF at various positions in the sheath in an argon plasma at 5 Torr. When plotted against total energy, almost all EEDFs collapse onto a single curve, which is clear evidence for the validity of the NLA. Only the EEDF right at the wall lies below those cures, which is caused by the electron-absorbing nature of the interface: electrons that hit the wall do not return to the plasma and are missing from the EEDF.

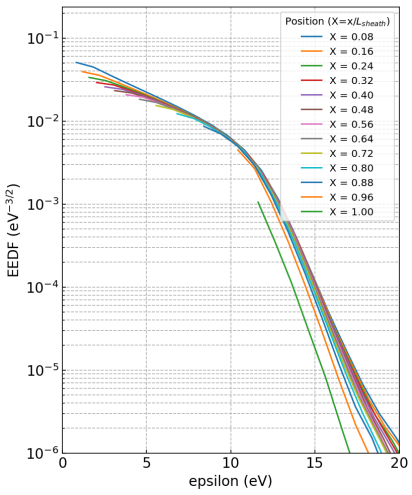

Fig. 1. EEDF in the sheath and at the wall of an argon plasma at 5 Torr (666 Pa) for a plasma density at the sheath boundary of 10^{11}cm^{-3}. The sheath boundary is at $X=0$, the wall at $X=1$, with L_{sheath} denoting the sheath thickness.

One consequence of the nonlocal behavior of the EEDF is that most electron-related properties decrease strongly towards the wall: the mean electron energy drops from 4.5 eV at the sheath boundary to 1.5 eV at the wall, the excitation and ionization rate coefficients drop by more than two orders of magnitude.

4. Conclusion

Correctly describing the EEDF in the plasma sheath is crucial for understanding plasma-surface interactions.

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