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Electrode floating potential in a plasma with additional energetic electrons: theory, simulation and experiment

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1. Introduction

Discharge plasma devices are widely used today in all kinds of plasma processing of materials (etching, ion implantation, thin film deposition, cleaning, etc.) and as negative ion sources for neutral beam heating of fusion plasmas. Discharge plasmas are produced by electron ionisation of neutral gas. Primary electrons are emitted from hot filaments or plate cathodes and then accelerated to ionisation energies by a potential drop between negatively biased cathodes and auxiliary anodes. In this way two-electron population plasma is produced in many laboratory devices [1,2]. In order to further improve the process control and to optimise technological processes for high quality, additional measurements and characterisation as well as theoretical modelling and computer simulations of the discharge plasma are needed.

In the present paper we first theoretically investigate the effect of the two-temperature electron distribution on the collector floating potential. We use the fully kinetic, one dimensional, presheath-sheath model by Schwager and Birdsall [3] in which we introduce a second hot electron Maxwellian population. The hot electron distribution function injected from the plasma source is approximated by a truncated Maxwellian with the maximum velocity corresponding to the discharge voltage in hot cathode discharges. It can be namely expected that no electrons should be found with energies above the accelerating discharge potential. Further, we limit ourselves to lower values of electron temperature ratio (t < 15), which are readily encountered in laboratory plasma devices. The investigation of presheath potential formation in plasma with higher temperature ratios was already presented in an another publication where the formation of a current-less double layer structure was found [4]. We then further complete the theoretical investigation with one-dimensional particle-in-cell computer simulations. The plasma parameters are chosen such that they comply with the laboratory experiment. The measurements were performed in a weakly magnetised argon plasma column produced by hot filament cathode at one end of the machine. All three kinds of results, theoretical, simulation and experimental are compared in conclusions.

2. Model

We use the same model as in our previous investigations [3, 4]. The system, shown in Figure 1, is bounded at x = 0 with a planar plasma source and at x = L by a floating electrode. The plasma, which is injected from the source, consists of ions, cool electrons and additional hot electron component. At the floating collector all ions are absorbed and nearly all electrons are reflected. They are then refluxed in the system in the source region. The electrostatic potential ϕ is assumed to be decreasing from the source toward the collector. We describe the ions by an accelerated half-Maxwellian velocity distribution and the electrons by a truncated full Maxwellian distribution. The hot component is additionally truncated at positive velocity corresponding to the discharge voltage ϕ_D in the plasma source:

$$f_{eh}(\psi, V) = \frac{n_{0eh}}{\mathrm{erf}\left[\sqrt{\frac{\psi_D}{t}}\right]\sqrt{\pi t}} \exp\left[\frac{\psi}{t}\right] \exp\left[\frac{-V^2}{t}\right] \mathrm{H}[V - V_{Me}(\psi)] \mathrm{H}[V - V_D(\psi)] \quad (1)$$

In Eq.1, n_{0eh} is the hot electron density in the plasma source, ψ is the normalised potential $e\phi/kT_{ec}$; V is the normalised electron velocity $v(m_e/2kT_{ec})$; t is the ratio between hot electron temperature T_{eh} and cool electron temperature T_{ec}; and H are the Heaviside step functions with $V_{Me}(\psi) = -(\psi(x) - \psi_C)^{1/2}$ as the normalised velocity of the fastest returned electron and with $V_D(\psi) = (\psi(x) - \psi_D)^{1/2}$ as the normalised cut-off velocity due to the accelerating discharge potential, respectively. We use the same procedure as in [4] to obtain two expressions which

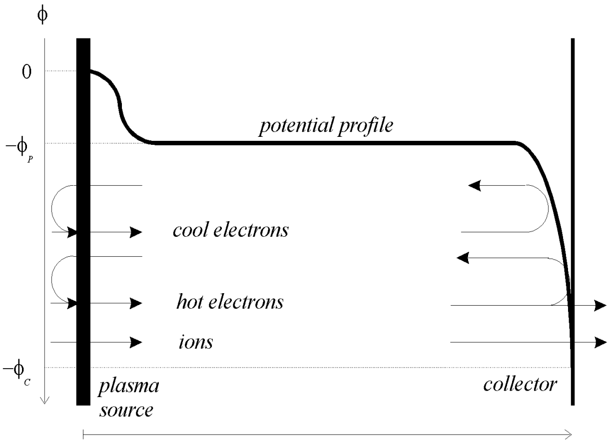

Figure 1. *Model of the plasma system.*

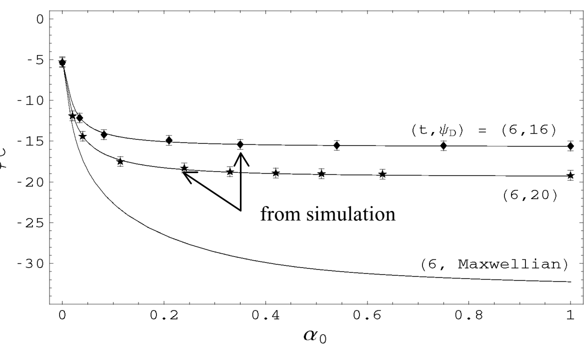

Figure 2. *The normalised electrode floating potential ψ_C as a function of the electron density ratio α_0 for an argon plasma.*

relate the floating potential of the collector ψ_C and the source sheath potential drop ψ_P. From these relations the dependence of the collector floating potential ψ_C on hot electron density ratio α_0 for different values of electron temperature ratio t and discharge cut-off potential values ψ_D was calculated. The calculations were performed for argon plasma ($1/\mu = m_i/m_e = 73440$, $\tau = T_i/T_{0ec} = 0.1$). The results are shown in Figure 2. The floating potential increases very rapidly with increasing electron density ratio from the well-known value of $\psi_C = 5.34$ in single electron component argon plasma and reaches a saturation value, which equals approximately the cut-off potential ψ_D. In pure Maxwellian plasma, the calculation recovers for the maximum value of the floating potential, $\psi_C = 5.34\times t$. The behaviour is well understood by the fact that the floating potential in the plasma is determined mainly by electrons from the high energy tail of the distribution. Already a small value of hot electron current is namely sufficient to compensate the ion saturation current.

3. Simulation

The simulation experiment was performed using the XPDP1 particle-in-cell computer code [5]. The set of fixed and variable parameters were similar to those used in the study of collector and source sheaths of finite ion temperature plasma by Schwager and Birdsall [3]. We added a second hot electron population to the input file and used the mass ratio $\mu = 73440$ for an argon plasma. The plasma system was 5 cm long, which is typicaly equivalent to 100 λ_D in a cool electron plasma or 35 λ_D in a hot electron plasma. The simulations were run in the same way as already described in [4]. All species enter the system at $x = 0$ with a half-

Maxwellian velocity distribution with an ion to cool electron temperature ratio τ = 0.1.The velocity distribution of the hot electeron component is truncated at the velocity which corresponds to the accelerating discharge potential. When the system reaches the steady state, spatial profiles of certain plasma parameters are inspected and analysed. From the potential profiles the electrode floating potential values are obtained. They are plotted in Figure 2 for two sets of parameters t and ψ_D, (t, ψ_D) = (6, 16) and (6, 20), and for several values of α_0. The theoretical and simulation results agree very well. According to the model, the electron density ratio α_0 is calculated from the cool and hot electron density values measured at the source, x = 0. In Figure 3 are shown the velocity distribution functions for cool electrons , f_{ec}, for primary hot electrons, f_{eh}, and for ions, f_i, at the mid position of the simulation region. The ions are already well accelerated in the positive direction because the observation position is well in the presheath of the floating electrode. The cool electrons are all reflected in the sheath of the electrode and their velocity distribution is fully Maxwellian. Of the hot primary electrons only the fastest reach the electrode, the remaining are reppeled. Their velocity distribution is therefore a little bit more depleted in the negative tail, which can be well observed on the logarthimic plot of the distribution function at the lower right in the figure.

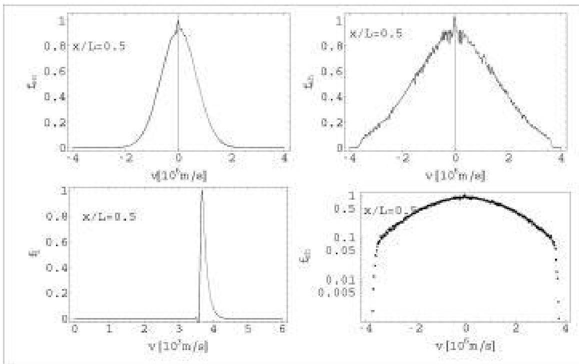

Figure 3. *Velocity distribution functions for cool bulk electrons (f_{ec}), for hot primary electrons (f_{eh}) and for ions (f_i).*

4. Experiment

The floating potential of an electrode was measured in the linear magnetized plasma machine, 1,5 m long and with 18 cm inner diameter. The experimental chamber is first evacuated below 10^{-4} Pa and then argon gas is leaked into the system. In the measurements described in this paper the working pressure was changed between $5{\times}10^{-4}$ Pa and $7{\times}10^{-2}$ Pa. Plasma is produced by a discharge from W/Th filaments, which are heated by direct current. Primary electrons are accelerated by a discharge voltage U_D which was set to 50V and 60V in two sets of measurements. The discharge current was between 200 and 300mA. The magnetic field density in the experimental region was kept at 0.01T. A disc electrode (collector) was mounted into the plasma column perpendicularly to the magnetic field. In this way, the experimental situation could be satisfactorily approximated by onedimensional theoretical and

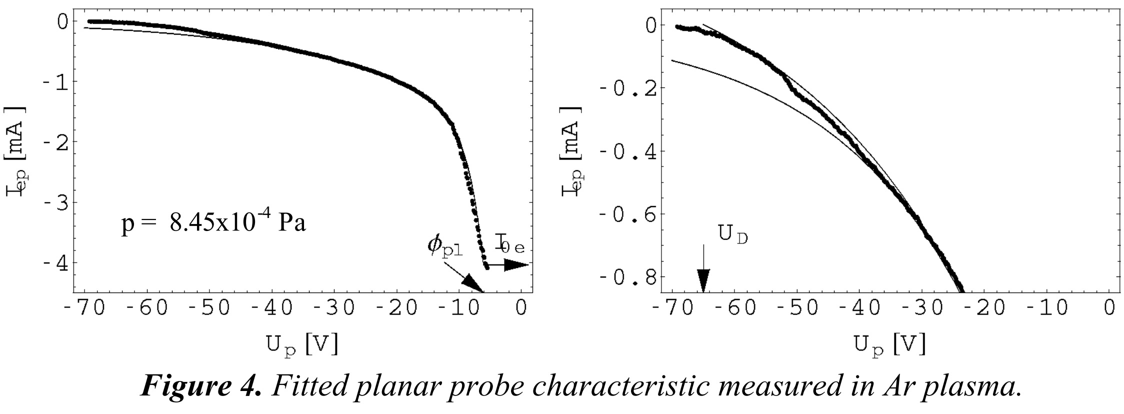

Figure 4. *Fitted planar probe characteristic measured in Ar plasma.*

simulation model. The plasma parameters were obtained from characteristics of a small onesided circular planar Langmuir probe. The overall plasma density is $n = 2$ 6$\times 10^{15}$ m^{-3} and from previous wave propagation experiments the ion temperature is assumed to be smaller then 0.2 eV. After subtracting the ion saturation current obtained by extrapolation of the linear part of the characteristics at the far negative values of the probe potential, a nonlinear fitting procedure was used to determine the hot (T_{eh}) and cool (T_{ec}) electron temperatures, their density ratio α_0 and the plasma potential ϕ_{pl} from the remaining electron part of the characteristics. In Figure 4 typical measured and fitted electron characteristic is shown. It was obtained at lower pressure and the presence of higher energy electron population can be clearly observed. A fitting procedure with two exponential functions indeed indicated that the electron plasma component can be aproximated with two Maxwellian populations with notably different temperatures. It can be also observed from the characteristic that the higher temperature population is depleted around the energy corresponding to the discharge potential, corrected for the heating potential drop on the cathode filaments. By changing the working gas pressure in the system, we were therefore able to control the partial density of hot primary electrons in the plasma. In the presurre range p = 6,5x10^{-2} Pa - 4,5x10^{-4} Pa, temperature ratios $t = 2.2$ up to $t = 7.2$ and, simultaneously, density ratios extending from α_0 = 0,0 up to α_0 = 0,5 were obtained.

5. **Results**

A comparison of theoretical and experimental results for the normalised electrode floating potential is shown in Figure 5. The theoretical values ψ_{Ctheor} were calculated from the relations (2) and (3) using measured values of electron temperature ratio t and electron density ratio α_0 for two sets of working gas pressures at different values of the discharge potential. The agreement between theory and experiment is good. The results from simulations are not shown in Figure 5, but they would agree with theoretical almost perfectly, as already shown in Figure 2. In conclusion, we have successfully applied a theoretical kinetic model to the potential formation in two-electron temperature plasma. Specifically, we have calculated the floating potential and compared the results with results from PIC simulations and from experimental measurements. It was shown that the floating potential depends very sensitively on high energy part of the electron population and thereby on the discharge voltage of the plasma source.

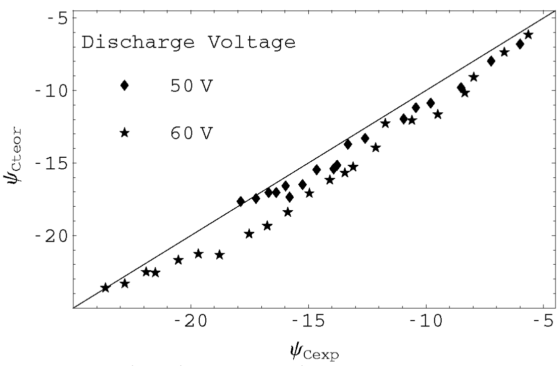

Figure 5. *The theoretical versus experimental floating potential ψ_C in Ar discharge plasma.*

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