COLLISIONLESS ELECTRON HEATING IN MODULATED PLASMA SHEATHS

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1. Introduction

Electron heating in radiofrequency (rf) sheaths is of interest in diverse situations including rf heating of fusion plasmas, communications with spacecraft, and the generation and maintenance of low pressure plasmas used for plasma processing. In capacitively coupled processing discharges, sheath heating can be the most important source of hot electrons so it is essential to understand the heating mechanism in order to devise quantitative models of the discharge.

Our interest in the present work is focused on low pressure capacitive rf plasmas where the applied voltage $V_{rf} \gg kT_e/e$ and the electron mean free path is greater than the sheath width (the interaction is collisionless). Since $\omega_{pi} \ll \omega_{rf} \ll \omega_{pe}$ in these discharges, the ion density is stationary while the electrons move in and out of the sheath region during the rf cycle. Collisionless sheath heating, also known as 'stochastic heating' [1], is modelled as a reflection of the electrons off a moving sheath edge—the so called 'hard wall approximation'—where the final electron velocity is simply $u_f = 2u_s - u_i$ with u_s the instantaneous sheath velocity at the interaction time and u_i the initial velocity.

A convenient and useful model of the sheath structure and of stochastic heating has been given by Lieberman [2,3]. Self-consistent simulations have been used to examine the heating mechanism [3–5]. In this work we examine the scaling of the power loss with applied frequency. In order to make a close comparison to theory, we use a model field $E(x,t)$, not a fully self-consistent simulation. A Monte Carlo approach is used to study the interaction of electrons with the model field and the total power loss is obtained by averaging $j_e \cdot E$ in the sheath region over the rf cycle. A related approach has been used previously by Wendt and Hitchon [6].

2. Theory

The basic assumptions of the theory [2] are consistent with a low pressure plasma driven by a sinusoidal current j_{rf}. An important assumption is that the electron density drops abruptly at the sheath edge, from $n_e = n_i$ on the plasma side to $n_e = 0$ on the wall side. Given the assumptions, one can solve for the ion density $n_i(x)$ and the sheath position $s(t)$. The electric field is given by

$$\begin{aligned} E &= \frac{e}{\varepsilon_0}\int_s^x n_i(\zeta)\,d\zeta \qquad s(t) < x \\ &= 0 \qquad\qquad\qquad\qquad\; s(t) > x. \end{aligned} \tag{1}$$

With the sheath motion specified, the total power loss can be obtained by integrating the power over an rf cycle using the hard wall approximation. The instantaneous power is

$$P(t) = -2m_e \int_{u_s}^{\infty} u_s(u-u_s)^2 \frac{n_s}{n_0} g_0(u-u_0)\,du \tag{2}$$

where u_s is the sheath velocity, $g_0(u-u_0)$ the distribution in the plasma (where the drift velocity u_0 corresponds to j_{rf}), n_0 the plasma density and n_s the density at s. Averaging yields [3]

$$P = \frac{3}{4}\left(\frac{2m_eT_e}{\pi e}\right)^{1/2} \varepsilon_0\omega_{rf}^2 V_s \tag{3}$$

where V_s is the average sheath voltage.

The problem with this approach is that the assumed incident distribution, although giving the correct electron density at the sheath edge, does not satisfy current conservation which instead suggests a drift velocity equal to u_s. Using this in Equation (2) gives a null result for the total power [7]. A relevant result reported by Turner [5] shows that if the sheath edge is eliminated in a self-consistent simulation which preserves the correct density profiles, sheath heating is not significantly affected. This casts some doubt on the efficacy of the basic mechanism (i.e. reflection at a moving sheath edge) proposed for sheath heating.

3. Simulations

The simulations are designed to mimic the theoretical approach as closely as possible. The model field given in Equation (1) is used and the trajectories of individual electrons through the field are integrated using an adaptive step integration algorithm. The electric field is not known explicitly, so to save time we store field values on a position-phase grid and interpolate to the instantaneous electron position. The incident electron velocities are picked randomly from a drifting Maxwellian distribution using a combination of transformation and rejection methods to obtain the correct forward electron flux. The chosen plasma parameters are $n_0 = 10^{10}$ cm^{-3}, $T_e = 3$ eV, $V_s \sim V_{rf} = 200$ V and ω_{rf} is in the range 10-100 MHz.

In comparing the above theory to simulations, it is important to note that the electric field given in Equation (1) does not correctly reproduce the sheath structure. It is not sufficient to take $E = 0$ for $s(t) > 0$ since this would give a flat electron density between the plasma and the sheath edge. In order to force $n_i = n_e$ in this region we add a Boltzmann field derived from $n_i = n_e = n_0 \exp(-e\varphi/kT_e)$ to Equation (1). The extra potential difference is of the order of kT_e/e, much smaller than the sheath voltage. The resulting electron density is shown in Figure 1. For all phases other than $\phi = 0$ some electrons are reflected by the dc Boltzmann field before reaching the sheath edge.

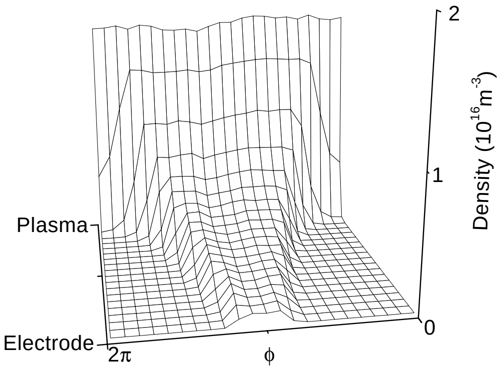

Figure 1: The electron density in the sheath region. The phase $\phi = \omega_{rf} t$.

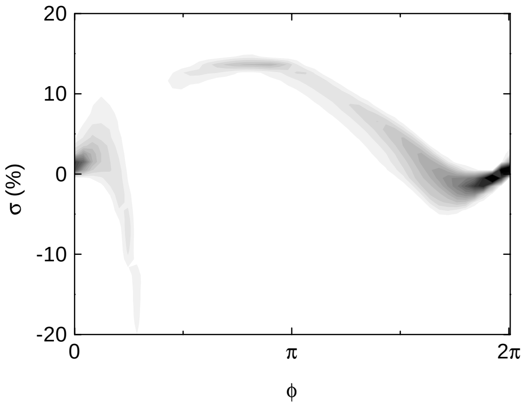

Figure 2: Distribution of errors in the hard wall approximation as a function of phase.

The simulation can be used to test the hard wall approximation directly. As shown in Figure 2, the approximation is reasonable even at 100 MHz. The contour plot shows the distribution of relative errors when the actual exit velocities are compared to the hard wall model. The gap in the Figure corresponds to electrons lost to the wall.

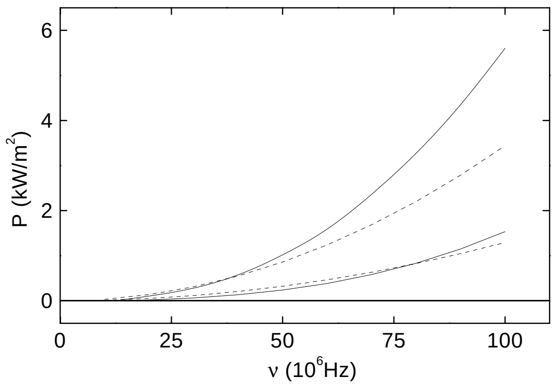

Figure 3: Power loss for $V_{rf} = 200$ V (low) and 500 V (high). Theory is dashed.

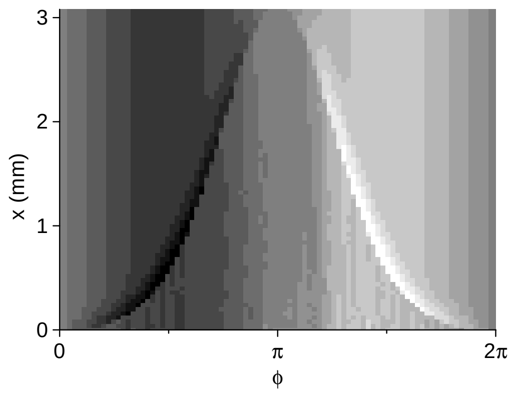

Figure 4: Total current $j_{rf} = j_e + j_D$. Light is positive and dark is negative.

The total power as a function of ω_{rf} is compared to Equation (3) in Figure 3. Heating is obviously present but the higher voltage shows large discrepancies. We note that assuming $u_s \ll u_e$, the thermal velocity, in integrating (2) leads to ω_{rf}^3 scaling [3] but under these conditions the physical basis of the model appears doubtful. Power loss due to electron escape to the wall is neglected in the theory, but it is significant in the simulations only at low frequencies.

It is pertinent to ask whether current is conserved in these simulations. The total current is shown in Figure 4 and it is clear that current conservation is violated at the sheath edge. This is because electrons penetrate into the field beyond $s(t)$ although the model assumes a sharp sheath edge.

4. Conclusion

The simulation highlights the importance of a small field between the plasma and the moving sheath edge. We have assumed a simple Boltzmann form for this field but it is likely that in self-consistent simulations [4,5] this field plays a vital role in sheath heating.

Current conservation is violated in the present simulations because the field is not fully self-consistent and it is possible that this is the source of the observed power loss. Work is in progress in self-consistent simulations using an approach where only the sheath is modelled [4]. This still allows a free choice of incident velocity distributions, an important consideration for comparisons to existing theory.

Acknowledgements.

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References

[1] M.A. Lieberman and V.A. Godyak: Memorandum No. UCB/ERL M97/65 (1997).
[2] M.A. Lieberman: IEEE Trans. Plasma Sci. **16**, 638 (1988).
[3] B.P. Wood et al: IEEE Trans. Plasma Sci. **23**, 89 (1995).
[4] M. Surendra and D. Vender: Appl. Phys. Lett. **65**, 153 (1994).
[5] M.M. Turner: Phys. Rev. Lett. **75**, 1312 (1995).
[6] A.E. Wendt and W.N.G. Hitchon: J. Appl. Phys. **71**, 4718 (1992).
[7] M. Surendra and M. Dalvie: Phys. Rev. E **48**, 3914 (1993).