THEORY OF SHEATHS NEAR POSITIVELY BIASED ELECTRODES

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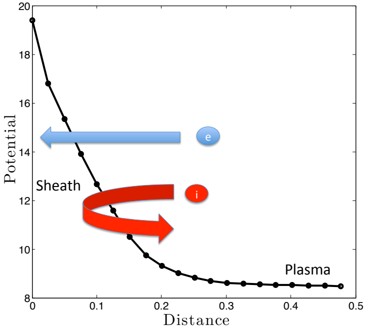
Electron Sheaths - Sheaths that are Electron Rich

- Surround boundaries in a plasma biased above the plasma potential
- Electron-rich
- Global current balance requires that for a monotonic electron sheath $A_E/A_w < \sqrt{2.3m_e/M_i}$ [1]



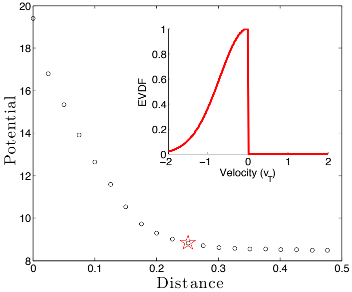
[1] S. D. Baalrud, N. Hershkowitz, and B. Longmier Physics of Plasmas 14, 042109 (2007)

Electron Sheaths are Accompanied by Fast Electron Flows

- Electron sheaths are important for
  - Langmuir probes collecting the electron saturation current
  - tethered space probes and plasma contactors
  - near electrodes used to induce circulation in dusty plasmas
  - sheath prior to the formation of anode spots
- In this work we find that
  - Electron sheaths are accompanied by a presheath
  - The presheath flow velocities approach v_{T_e}
  - Velocity distributions for electrons have a flow shift along with a loss-cone like truncation

Conventional Picture: Electron Sheaths Collect a Random Flux of Electrons

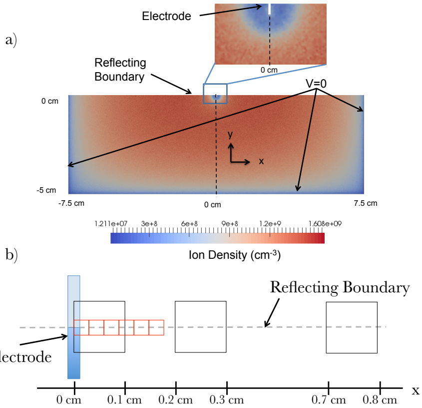
- Flux collected by an electron sheath is the random flux [2,3]
- The electron velocity distribution function (EVDF) is a truncated Maxwellian at the sheath edge [4]
- The electron sheath equivalent of the Bohm criterion is trivially satisfied $\Longrightarrow$ no need for presheath [5,6]



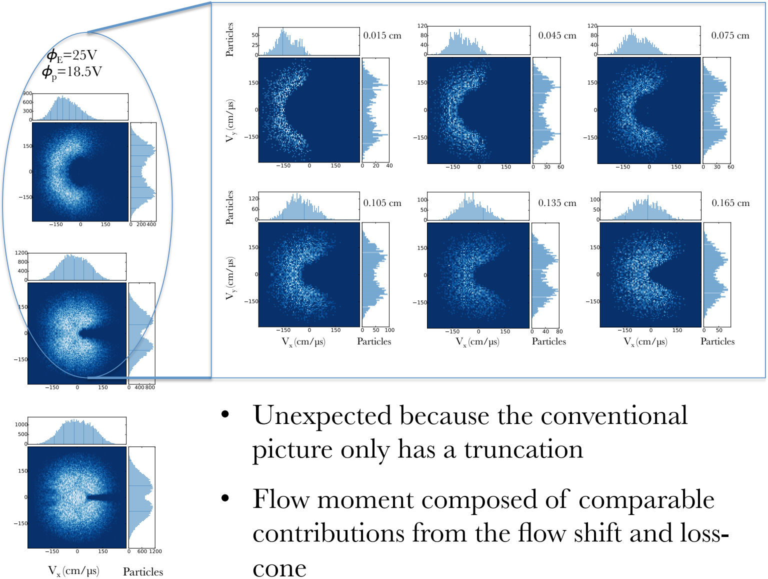
[2] H. M. Mott-Smith and I. Langmuir, Physical Review 28, 727 (1926)
[3] N. Hershkowitz, Physics of Plasmas 12, 055502 (2005)
[4] G. Medicus, Journal of Applied Physics 32, 2512 (1961)
[5] K.-U. Riemann, Journal of Physics D Applied Physics 24, 493(1991)
[6] F. F. Chen, Plasma Sources Science Technology 15, 773 (2006)

Particle-In-Cell Simulations

- Electrostatic PIC code Aleph
- Helium plasma was generated at $10^8 \text{cm}^{-3}\ \mu\text{s}^{-1}$ within the volume
- $\Delta t = 0.5$ ns, 0.02 cm mesh scale, $\lambda_{D_e} = 0.059$ cm, $\omega_{p_e}^{-1} = 0.63ns$
- No collisions with neutrals were included
- Simulations ran for 40μs of physical time
- Will study EVDFs at different locations in front of the electrode

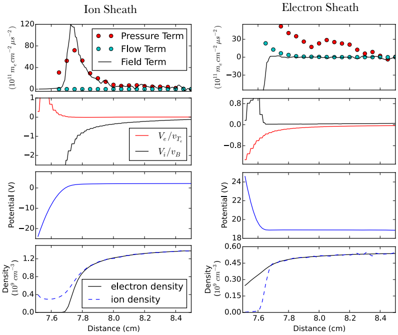


Electron Velocity Distribution Functions Have a Flow Shift and Truncation



- Unexpected because the conventional picture only has a truncation
- Flow moment composed of comparable contributions from the flow shift and loss-cone

Pressure Tensor Gradients Dominates the Presheath Electron Flow



$$\underbrace{m_e n_e \mathbf{V}_e \cdot \nabla \mathbf{V}_e}_{\text{flow term}} = \underbrace{-ne\mathbf{E}}_{\text{field term}} \quad \underbrace{-\nabla \cdot \mathcal{P}_e}_{\text{pressure term}} - \underbrace{\mathbf{R}_e}_{\text{friction}}$$

Why Does the Electron Flow Approach the Electron Thermal Speed?

- **Sheath Criterion**: At the sheath edge $\rho \approx 0$ and $\left| d\rho/d\phi|_{\phi=\phi_0} \right| > 0$ [7]
- This can be rewritten as

$$\sum_s q_s \frac{dn_s}{dz} \leq 0$$

- Using the continuity equation (no source)

$$\sum_s q_s \frac{n_s}{V_s} \frac{dV_s}{dz} \leq 0$$

- The electron presheath has a minimum velocity determined by the momentum equation, approximating this as

$$m_e n_e \mathbf{V}_e \cdot \nabla \mathbf{V}_e = -ne\mathbf{E} - \nabla p_e \hat{z}$$

  the flow velocity is

$$V_e \geq \sqrt{\frac{T_e + T_i}{m_e}} \approx v_{T_e}$$

- Stress moments due to the loss cone will slightly modify this value

[7] K.-U. Riemann, Journal of Physics D Applied Physics 24, 493 (1991)

Pressure Gradient Plays a Larger Role than the Electric Field

- Assume a Boltzmann ion density profile, then quasineutrality implies

$$\frac{dn_e}{dz} = \frac{dn_i}{dz} = -\frac{en_i E}{T_i}$$

- Using $\mathcal{P}_e = p_e \mathcal{I} + \Pi_e$, with $p_e = n_e T_e$ the z component of the momentum equation shows the pressure term is T_e/T_i larger than the electric field term

$$V_e \frac{dV_e}{dz} = -\frac{e}{m_e} E - \underbrace{\frac{T_e}{m_e n_e}\left(-\frac{en_i E}{T_i}\right)}_{\frac{1}{m_e n_e}\nabla p_e} - (\text{stress, friction, other terms})$$

In the electron presheath the electric field causes a density (pressure) gradient. The acceleration of the flow velocity is dominated by the pressure gradient.

Significantly different from ion presheaths

Flow Moment Means Thicker Electron Sheath

- Combining the momentum and continuity equations, ignoring stress and friction terms, and integrating

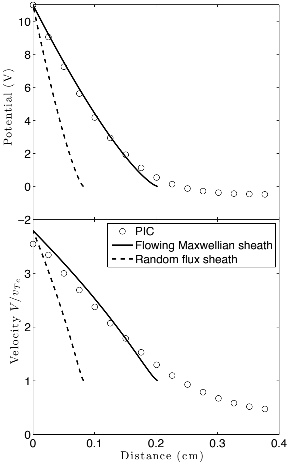
$$\left(\frac{V_e}{v_{Te}}\right)^2 - 2\log\left(\frac{V_e}{v_{Te}}\right) = \frac{2e\phi}{T_e} + 1$$

- Integrating Poisson's equation twice within the sheath:

$$\frac{z}{\lambda_{D_e}} = 0.79\left(\frac{e\Delta\phi}{T_e}\right)^{3/4}$$

- The numerical constant is typically assumed to be 0.32 based on the random flux assumption.

This compares well with previous simulations [8]



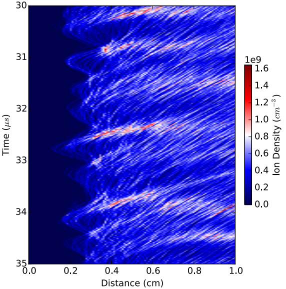
[8] B. Scheiner, S. D. Baalrud, B. T. Yee, M. M. Hopkins, and E. V. Barnat Physics of Plasmas 22, 123520 (2015)

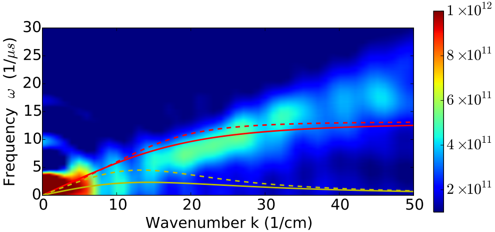
Instabilities

- The dielectric response for a plasma where the electrons are Maxwellian with flow V_e and stationary Maxwellian ions is

$$\epsilon(\mathbf{k},\omega) = 1 - \frac{\omega_{pe}^2}{k^2 v_{T_e}^2} Z'(\xi_e) - \frac{\omega_{pi}^2}{k^2 v_{T_i}^2} Z'(\xi_i) \tag{1}$$

where $\xi_e = \frac{\omega - \mathbf{k}\cdot\mathbf{V_e}}{k v_{T_e}}$ and $\xi_i = \frac{\omega}{k v_{T_i}}$





[8] B. Scheiner, S. D. Baalrud, B. T. Yee, M. M. Hopkins, and E. V. Barnat Physics of Plasmas 22, 123520 (2015)

Summary: Electron Flow in the Electron Presheath is Caused by a Loss-Cone Type Truncation and a Flow Shift

- Electrons flow with a velocity comparable with v_{T_e}
- The flow velocity is composed of two kinetic effects, 1) a loss-cone type truncation and 2) a shift in the maximum value of the EVDF
- The loss-cone truncation is a geometric effect
- This flow is accelerated in a presheath characterized by pressure gradients
- Sheath models with a flow are in better agreement with simulations than the conventional picture