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Locking the Plasma Potential with an Anodic Surface

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Introduction

An electrode biased positive in a plasma contained in a grounded chamber is typically expected to operate in one of two ways:

(1) Probe mode. The anode is very small and expected to have negligible impact on the bulk plasma. Used to collect electrons and measure plasma characteristics, e.g., T_e. Example: Langmuir probes in the electron saturation regime.

(2) Locking mode. The anode is large and the plasma potential increases to be positive with respect to this “wall”. If the anode potential is increased, the bulk plasma potential increases as well. Example: anode in a glow discharge.

We will examine the transition between the two limiting cases to answer:

- How small is small enough?
- How wide is the transition regime?
- How does the plasma description (e.g., fluctuations) vary across the regimes?

Anode Sheath Type Criteria

Reviewing from [1], if we define

A_W = area of grounded walls of chamber,
A_E = area of positively biased electrode, and
$\mu = \sqrt{2.3 m_e / m_i}$,

then balancing ion and electron currents to the two surfaces (under some model assumptions) leads to a plasma potential V_p,

$$V_p = -\frac{T_e}{q_e} \ln\left[\frac{A_W + A_E}{A_W} \mu - \frac{A_E}{A_W} \exp\left(-\frac{q_e \Delta V}{T_e} \right) \right],$$

where $\Delta V = V_p - V_A$, and V_A is the anode voltage. For $V_p >> T_e$, [1] indicates an ion sheath and

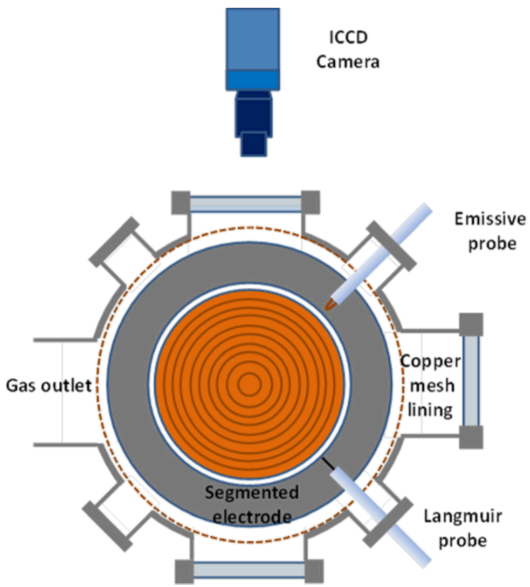
$$\frac{A_E}{A_W} \geq \left(\frac{0.6}{\mu} - 1 \right)^{-1} \approx 1.7\mu \quad \text{(ion sheath).}$$

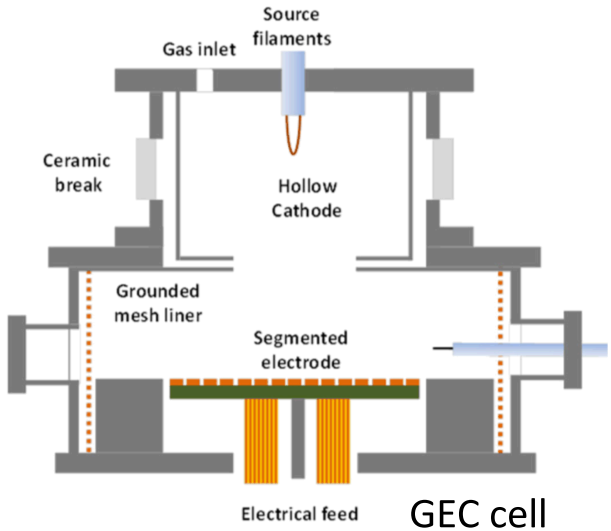
In the other limit, where we assume $T_i << \Delta V$, [1] indicates an electron sheath,

$$\frac{A_E}{A_W} < \mu \quad \text{(electron sheath).}$$

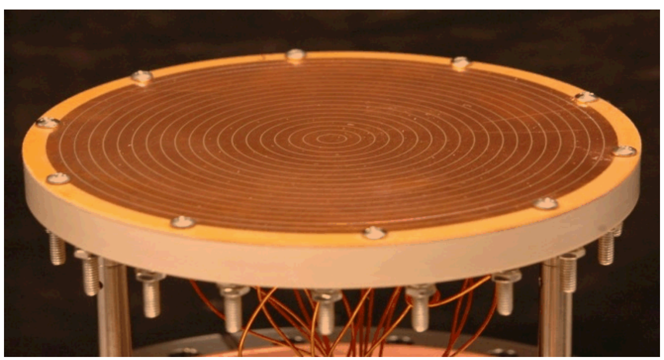
Experimental Results

The full experiment is described in [2].



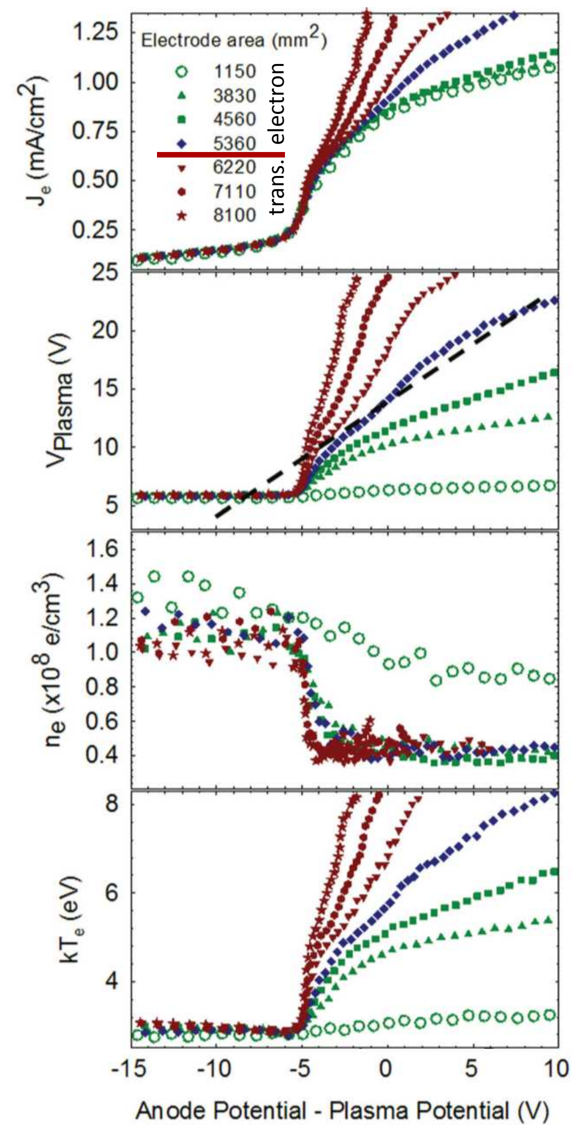


GEC cell

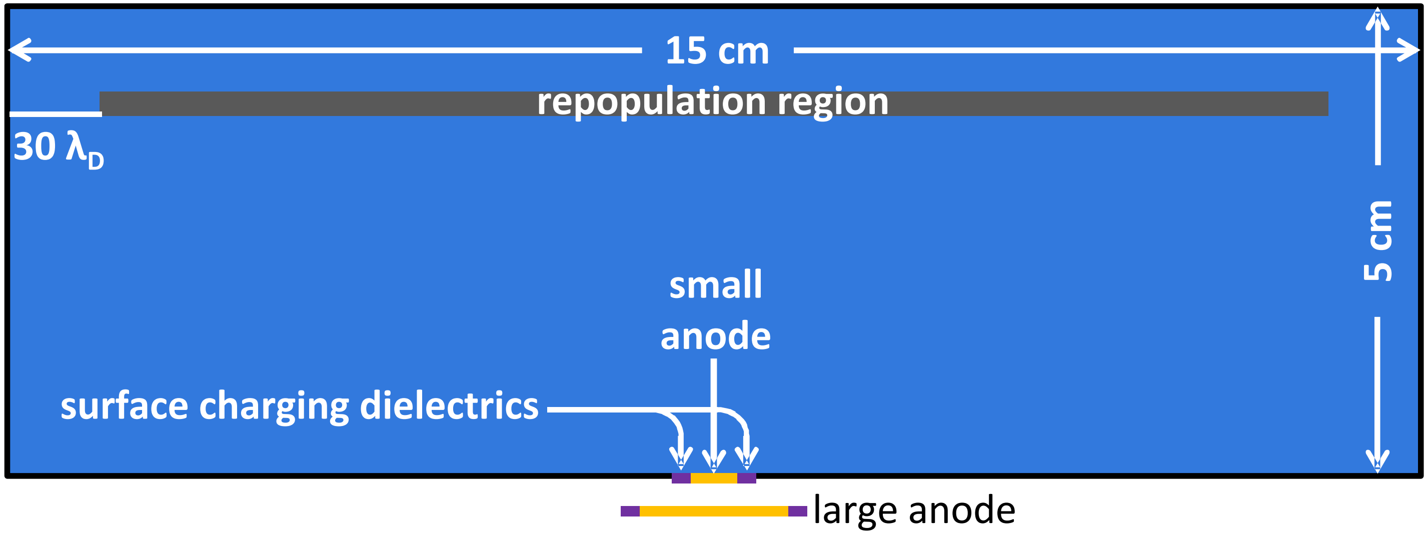


Segmented electrode

20 mTorr He



Computational Model



Neutral He plasma is generated in the repopulation region (T_e = 4 eV, T_i = 0.1 eV) at a rate to approximate experimental densities in the near-anode region (~2 x $10^9/cm^3$ in the repopulation region).

Anode potential is V_A = 20 V. Other walls grounded.

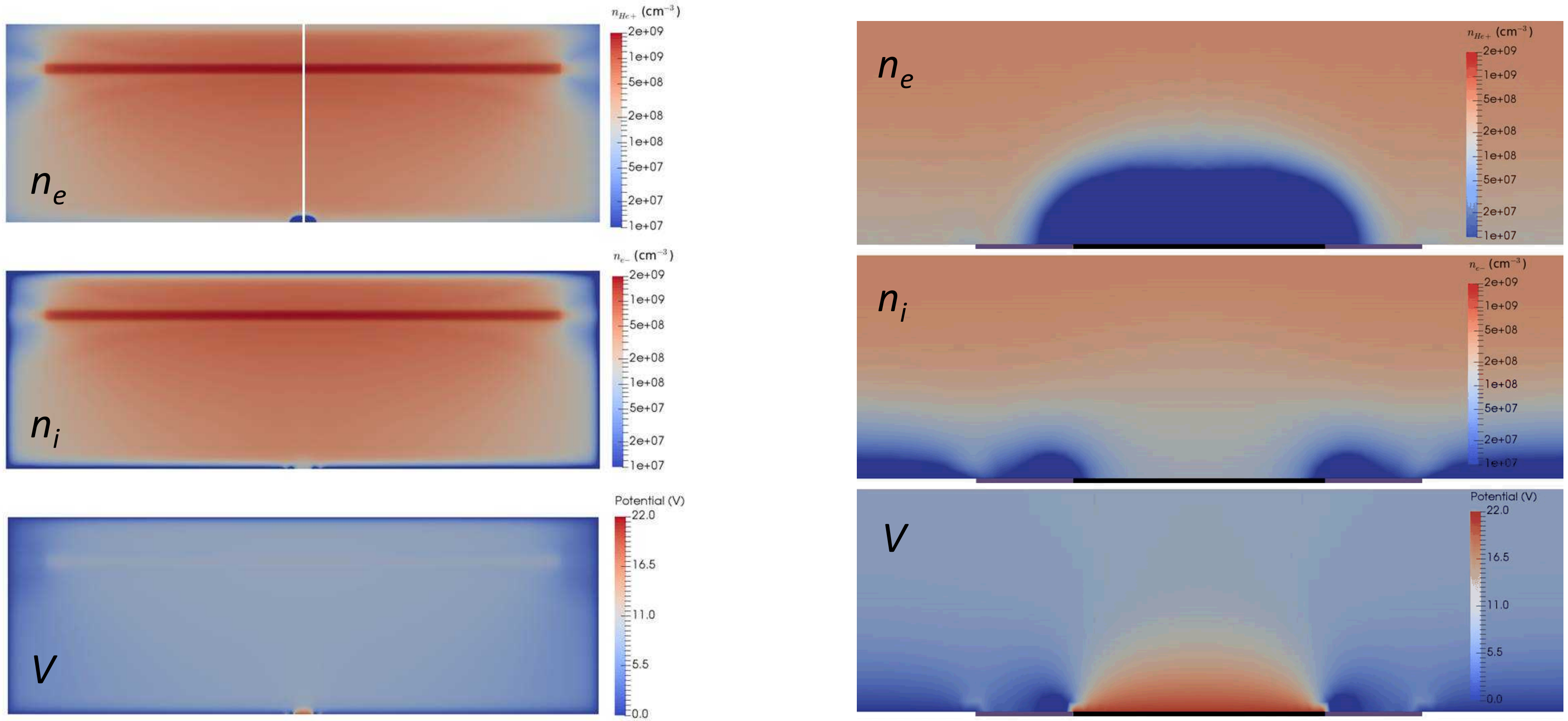
Anode sizes were (0.72, 1.00, 1.35, 1.46, 1.58, 1.70, 1.89, 2.08, 2.25) x μ.

λ_D = 333 μm → Δx = 111 μm
$2/\omega_p$ = 793 ps → Δt = 100 ps

Unstructured triangular mesh has ~161,000 cells (a half-domain was simulated).

Computational Results

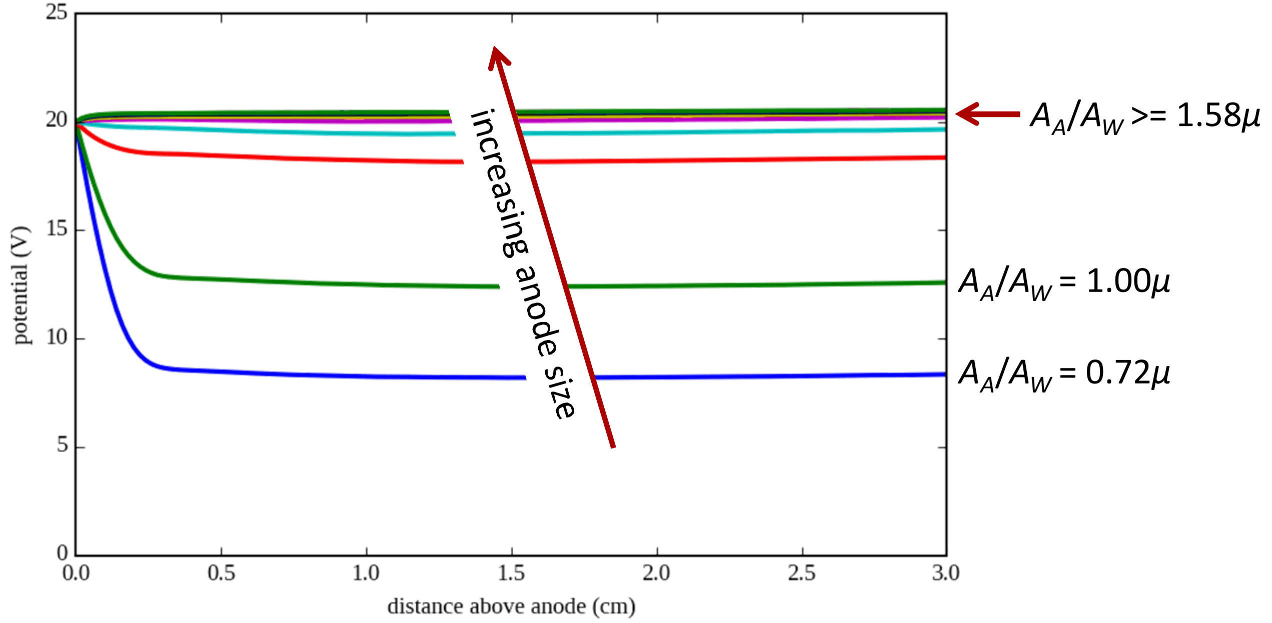
The full study is described in [3].

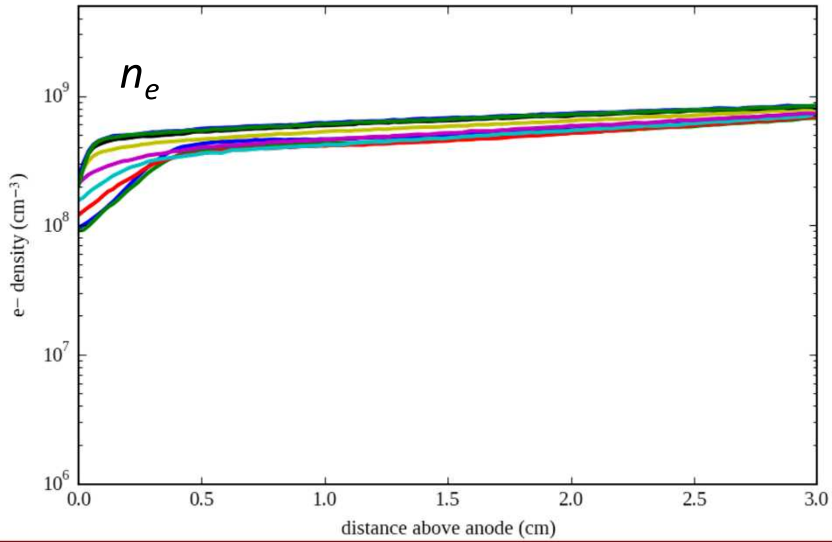


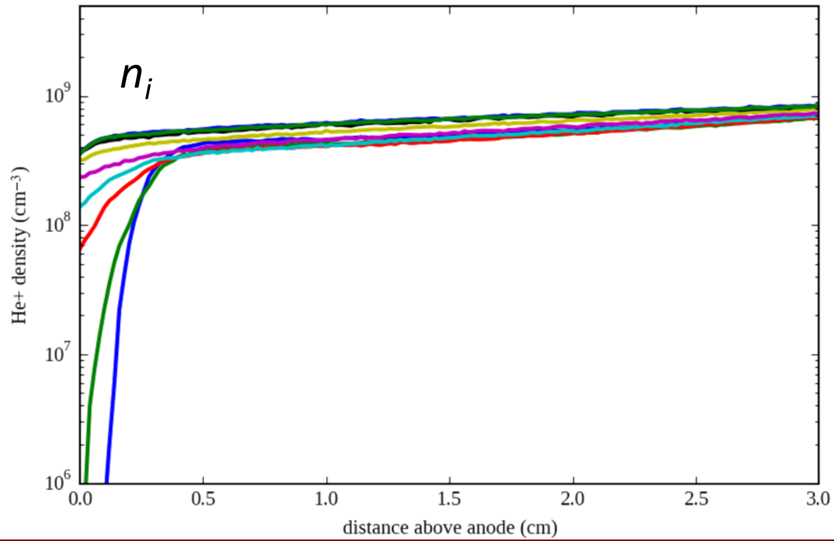
Solutions for $A_A/A_W = 0.72\mu$

The following data is taken along the centerline shown in the top left pane, averaged over 30 µs. Total physical simulation time is 50 µs and steady-state is achieved in ~20 µs. Simulations required ~36 hours on 128 cores.

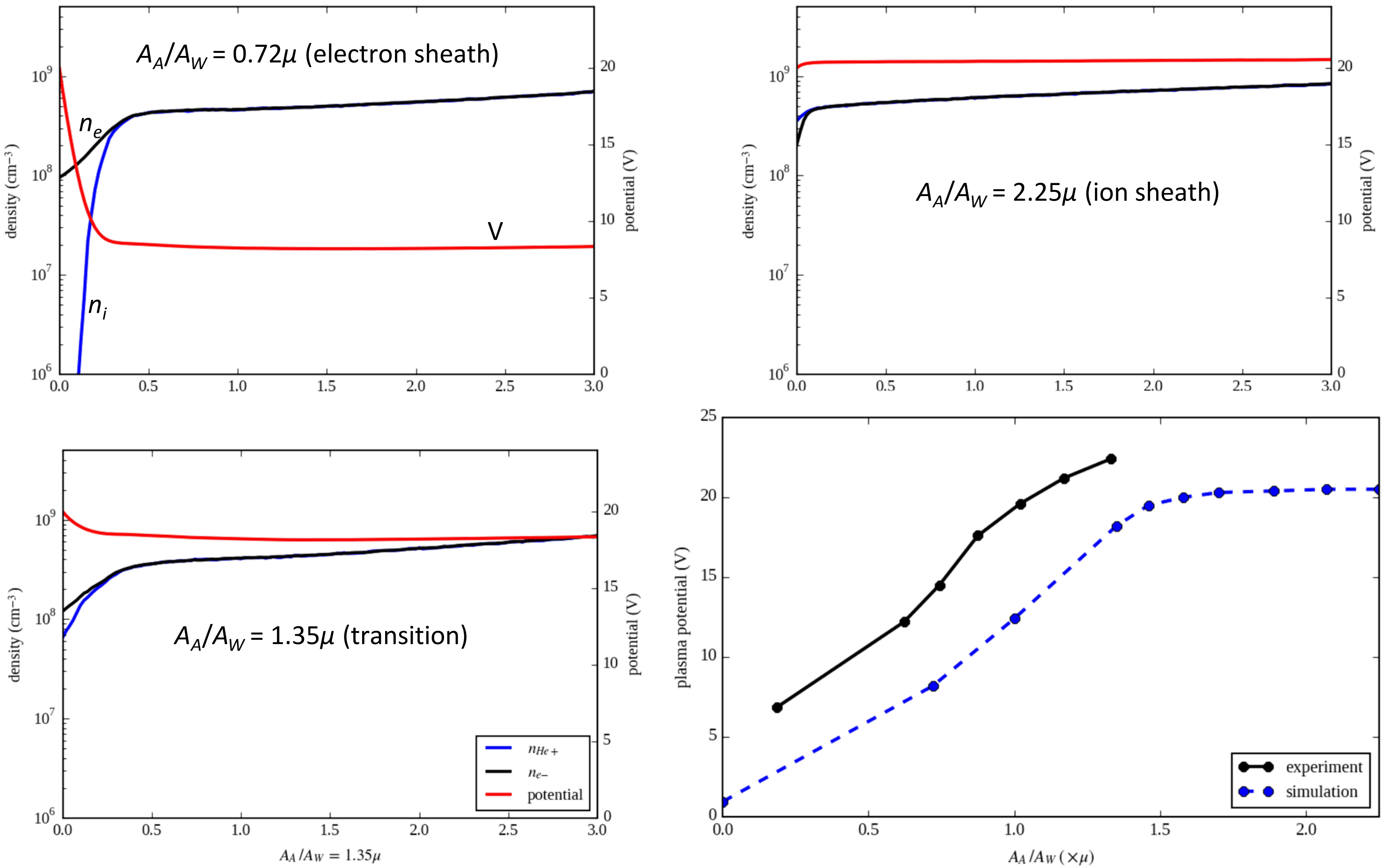
Computational Results





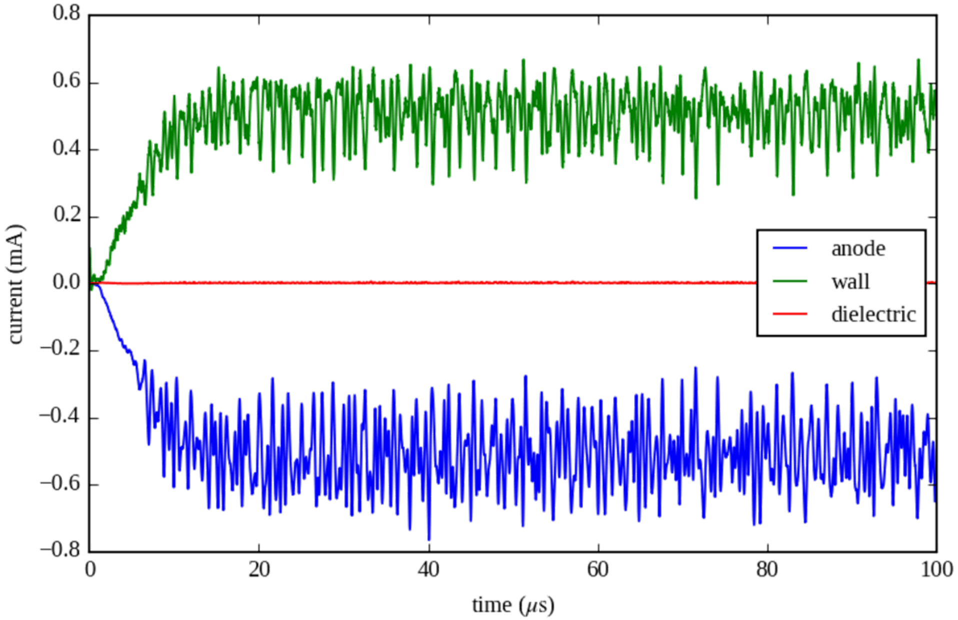


Computational Results

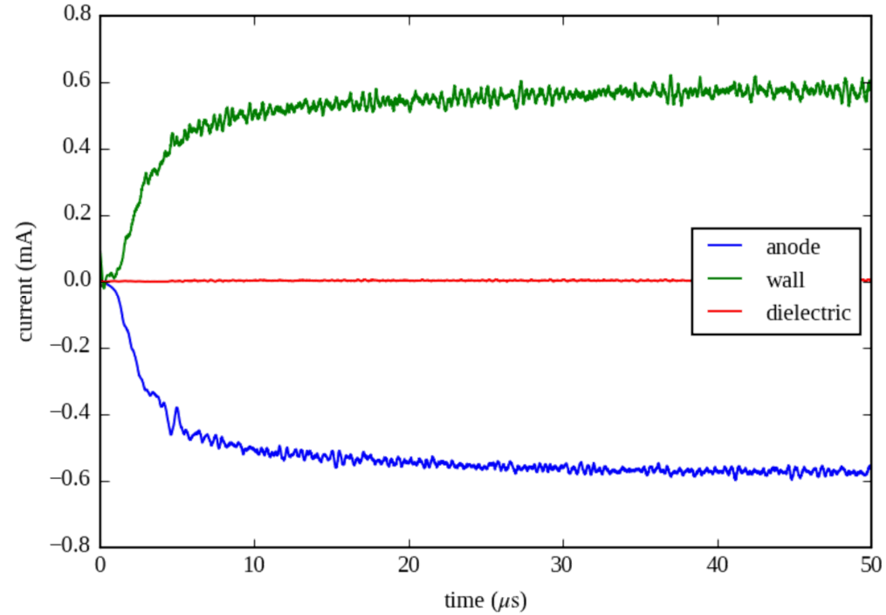


Sheath Stability

Currents for A_A/A_W = 0.72µ



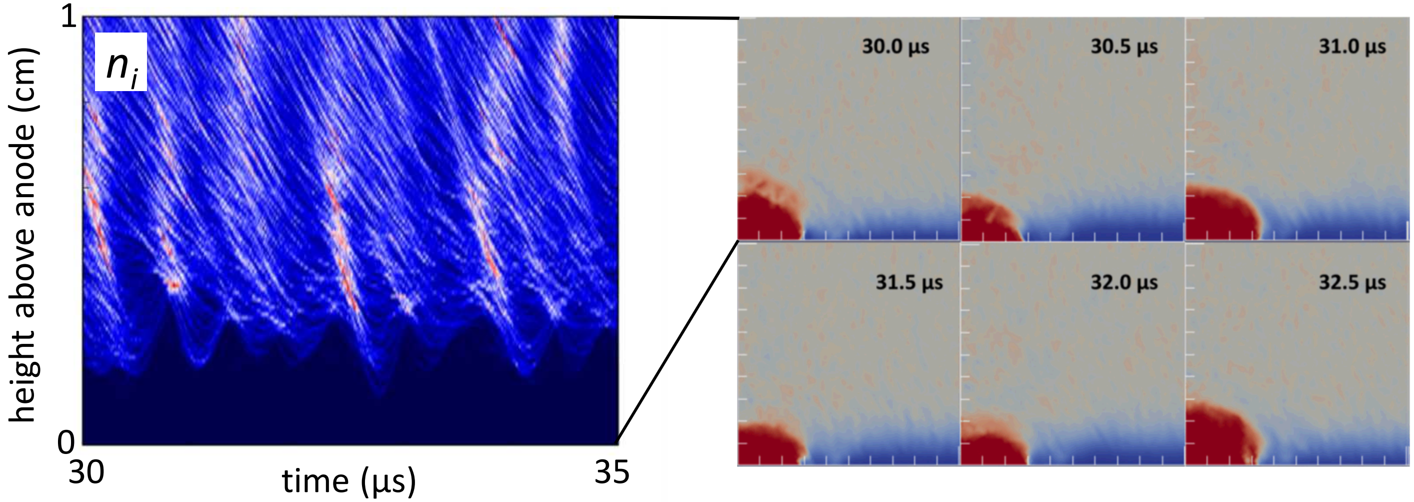
Currents for A_A/A_W = 2.25µ



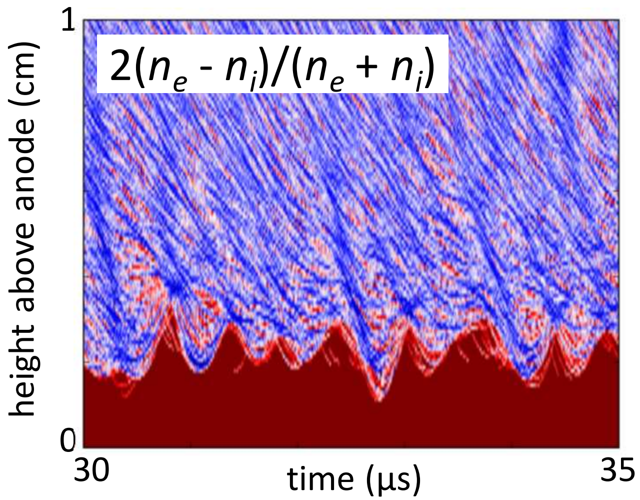
Clearly, the electron sheath is much noisier. We analyzed the fluctuations in terms of ion acoustic wave instabilities caused by differential flow of ions vs. electrons in the presheath region.

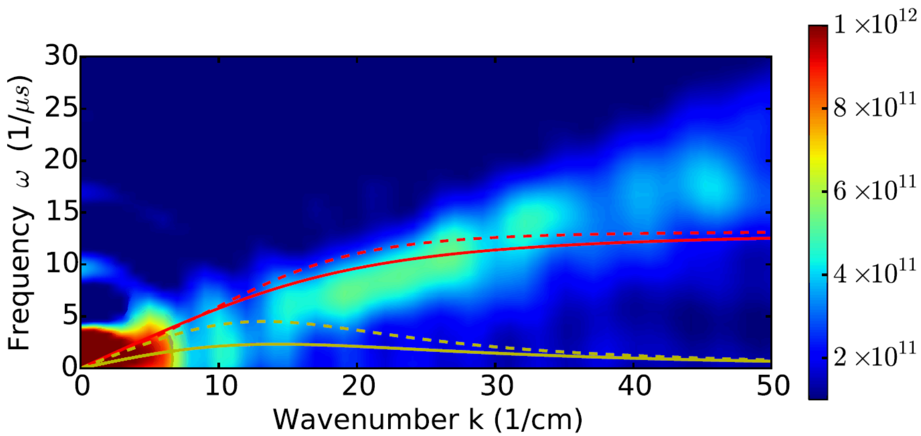
Electron Sheath Location Fluctuations

The full study is described in [4].



charge density above anode (red < 0 < blue)



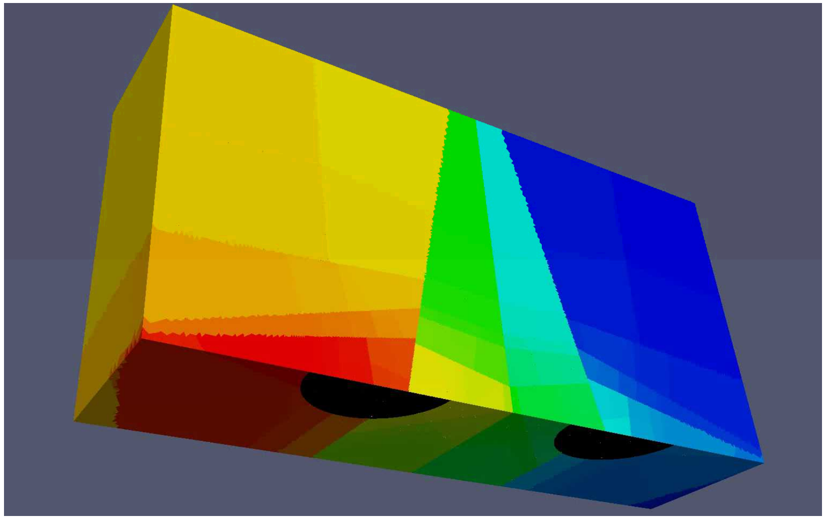


The 2D FFT of the ion density. The solid and dashed red lines corresponds to the real part of the approximate dispersion relation for electron flows of 0.5 and 0.9 x electron Bohm speed.

Conclusions

- Reasonable agreements between all of theory, experiment, and simulation.
- Transition region is narrow:
  - 1.7% of A_W for He (1.8% to 3.5%)
  - 0.44% of A_W for Ar (0.56% to 1%)
- Area of a grounded cylinder inside a GEC cell is ~1.86 x 10^5 mm^2. So positively biased surfaces >= ~10 cm^2 (for Ar) will have significant impact on plasma.
- 1 mm^2 probe size? Grounded chamber area limited to strictly above 180 mm^2 (again for Ar), or ~7.6 mm diameter sphere, to avoid impact (and experimental and computational results imply even larger).
- Electron sheaths exhibit ion acoustic wave instabilities.

Description of Aleph



- 1, 2, or 3D Cartesian
- Unstructured FEM (compatible with CAD)
- Massively parallel
- Hybrid PIC + DSMC (PIC-MCC)
- Electrostatics
- Fixed B field
- Solid conduction
- Advanced surface (electrode) models
- e- approximations (quasi-neutral ambipolar, Boltzmann)
- Collisions, charge exchange, chemistry, excited states, ionization
- Photon transport, photoemission, photoionization
- Advanced particle weighting methods
- Dual mesh (Particle and Electrostatics/Output)
- Dynamic load balancing (tricky)
- Restart (with all particles)
- Agile software infrastructure for extending BCs, post-processed quantities, etc.
- Currently utilizing up to 64K processors (>1B elements, >1B particles)

References

[1] S.D. Baalrud, N. Hershkowitz, B. Longmier, Phys. Plasmas **14** (2007), 042109.

[2] E.V. Barnat, G.R. Laity, S.D. Baalrud, Phys. Plasmas **21** (2014), 103512.

[3] M.M. Hopkins, B.T. Yee, S.D. Baalrud, E.V. Barnat, Phys. Plasmas **23** (2016), 063519.

[4] B. Scheiner, S.D. Baalrud, B.T. Yee, M.M. Hopkins, E.V. Barnat, Phys. Plasmas **22** (2015), 123520.

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