DOUBLE LAYER FORMATION IN A TWO REGION ELECTRONEGATIVE DISCHARGE

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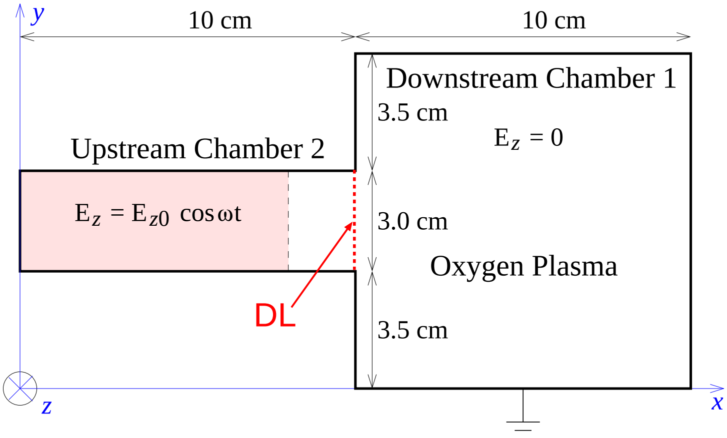
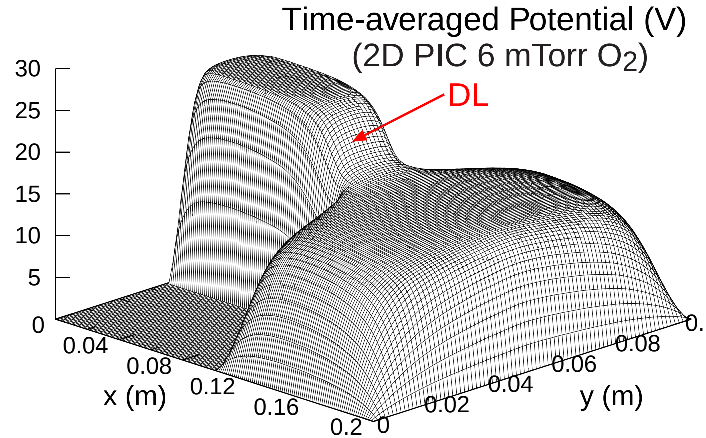
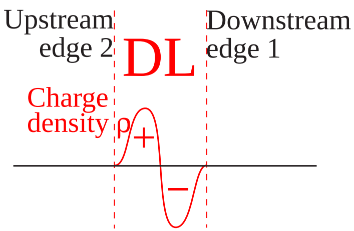
OUTLINE

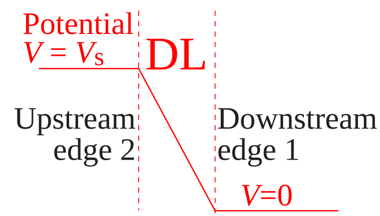
- Introduction
- "Experiments"
  — 2D particle-in-cell (PIC) simulations with rescaled oxygen cross sections
- Theory
  — 1D collisionless model of double layer (DL)
  — Global (volume-averaged) model of upstream and downstream particle and energy balances
- Comparisons
  — Reasonable agreement but also some differences
- Slow and fast wave instabilities
  — The DL has time-varying structure

INTRODUCTION









- Why does a DL form at low pressures?
  - — The particle loss rate is greater upstream than downstream due to the smaller upstream radius
  - — A higher ionization rate (and T_e) is needed upstream than downstream
  - — A DL both "insulates" the low downstream T_e from the high upstream T_e, and it accelerates electrons upstream to increase the ionization rate there

“EXPERIMENTS”

PIC SIMULATION METHOD

- Self-consistent results from first principles with no assumptions about electron and ion velocity distributions
- Upstream heating at 13.56 MHz $\perp$ to the plane of the simulation
- RF field adjusted to keep number of upstream electrons constant
- Stability, speed and accuracy require small plasma reactors with low densities and large Debye lengths:

$$n_e \approx 4 \times 10^{14}\ \mathrm{m}^{-3},\ \lambda_D \approx 0.8\ \mathrm{mm}$$

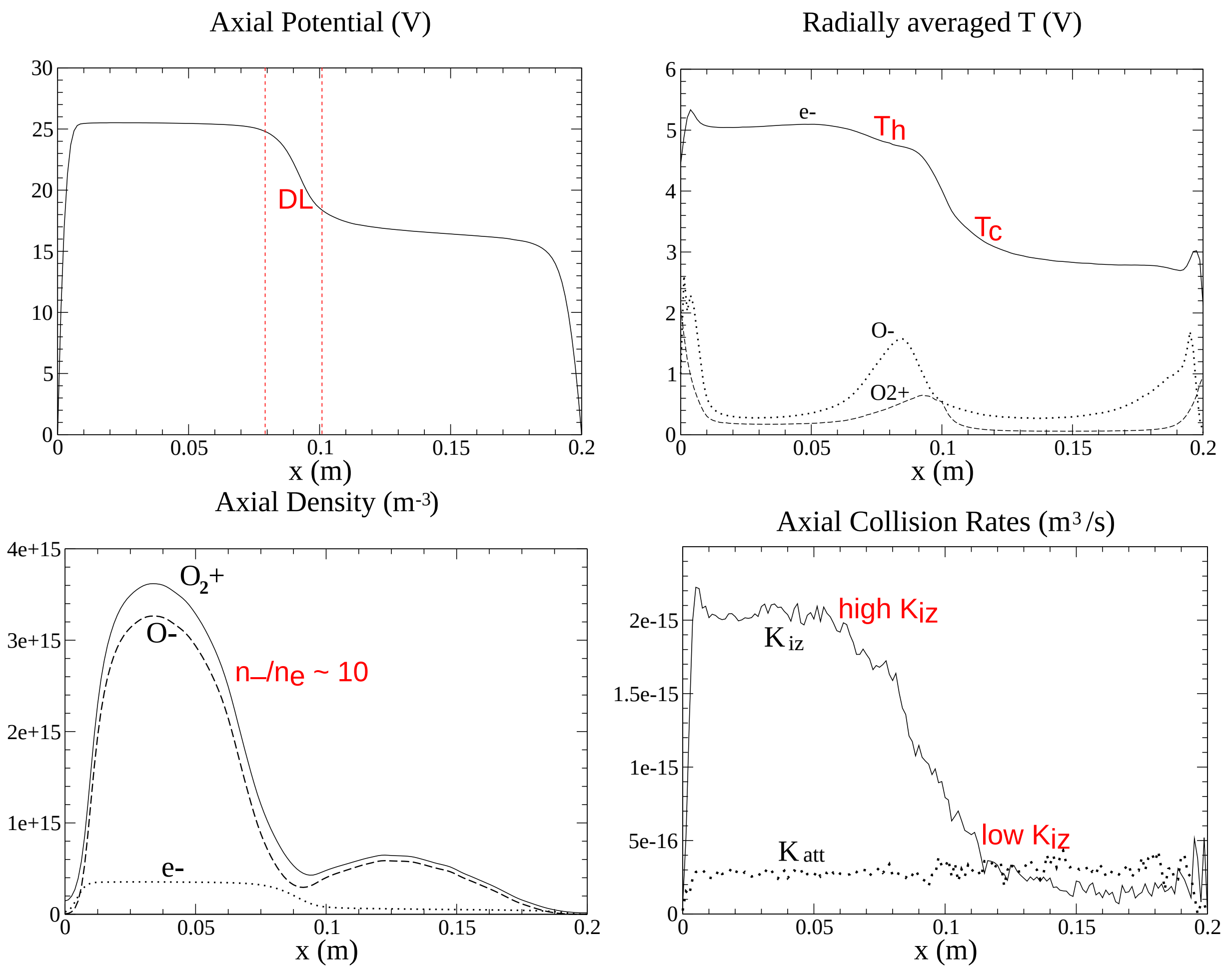
- Due to low densities, rescaled oxygen cross sections were used:

  Positive-negative ion recombination $\uparrow \times 20$

  Dissociative attachment $\uparrow \times 5$

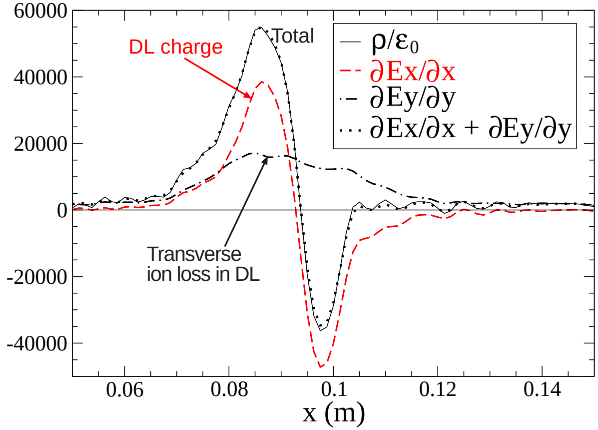
- A typical simulation takes 1–2 weeks
- The pressure range explored is 0.5–24 mTorr
- No DL was observed at 0.5 mTorr

PIC RESULTS FOR 6 mTorr O_2 DISCHARGE

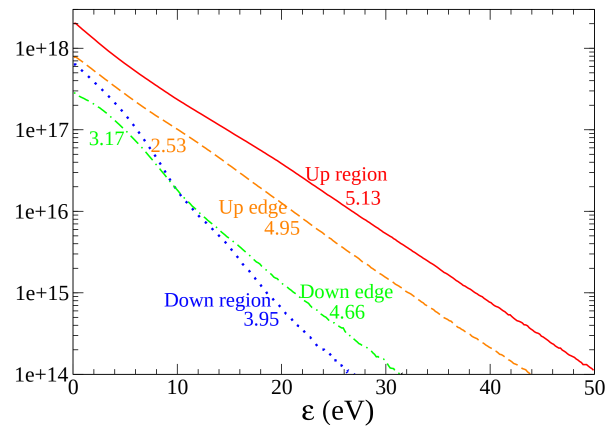


RESULTS FOR 6 mTorr O_2 DISCHARGE (CONT'D)

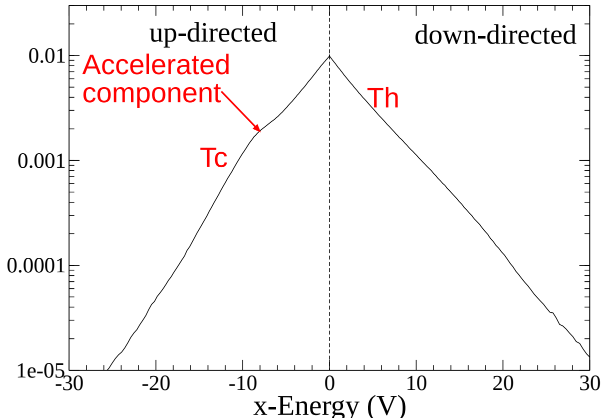
Charge Density Components in DL (V/m^2)



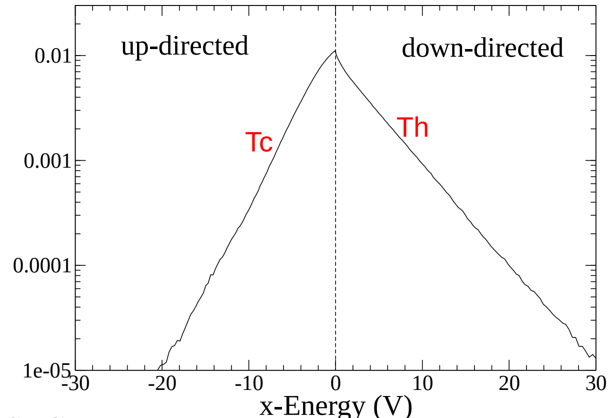
EEPF (a.u.)



Up edge x-component EEDF (a.u.)

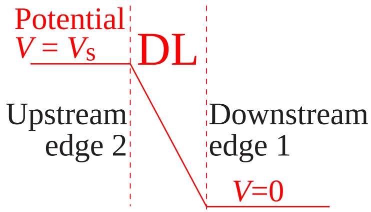


Down-edge x-component EEDF (a.u.)



THEORY

DL MODEL

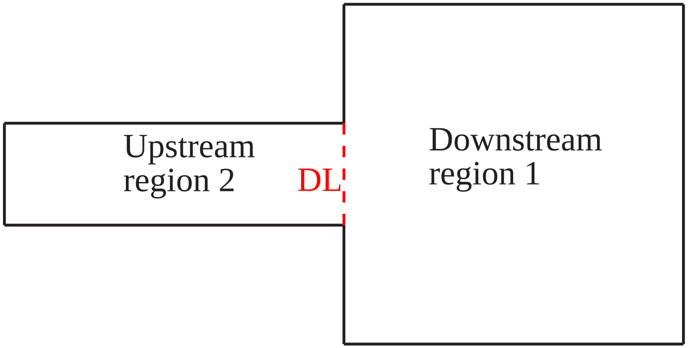


- Charge density ρ and potential V within the DL are found by solving Poisson's equation
- Six types of particles contribute to ρ:
  — thermal positive ions, negative ions, and electrons
  — accelerated positive ions, negative ions, and electrons
- The particle motions are 1D and collisionless
- The boundary conditions are that ρ and $d\rho/dV$ vanish at the DL edges
- An additional condition is that the sum of positive and negative charge in the double layer must vanish; equivalently, the total force acting on the double layer must vanish

$$\int_0^{V_s} \rho(V)\, dV = 0$$

- A final condition that upstream and downstream-directed electron fluxes nearly balance determines the equilibrium value of V_s/T_h.

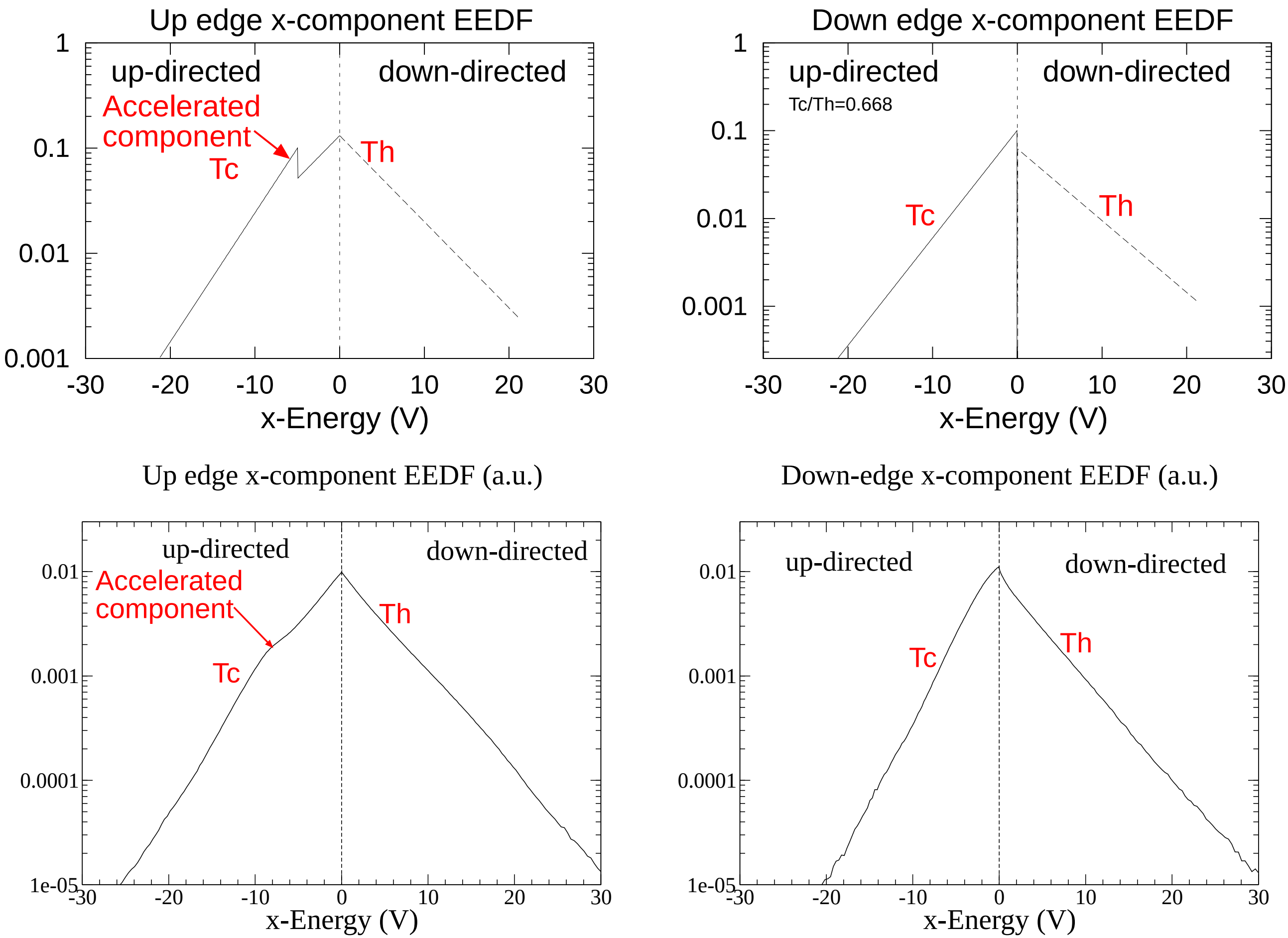
PARTICLE AND ENERGY BALANCES



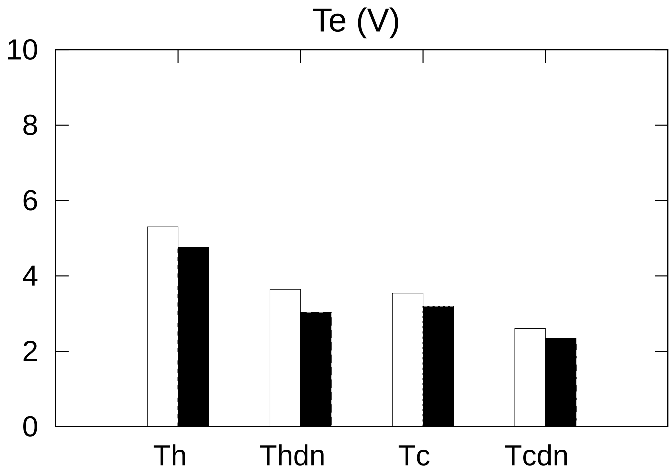
- We use a 2D rectangular geometry
- To determine the equilibrium quantities we use
  — global particle balance upstream
  — global particle balance downstream
  — global energy balance downstream
- Upstream energy balance (which determines the upstream electron density) depends on the input power, and is beyond the scope of this study

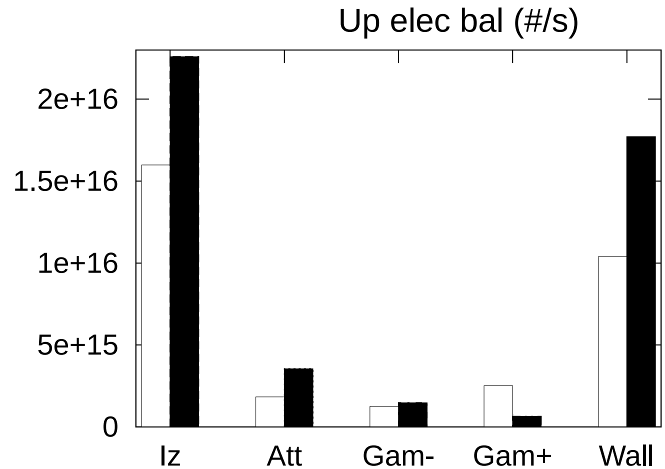
COMPARISONS

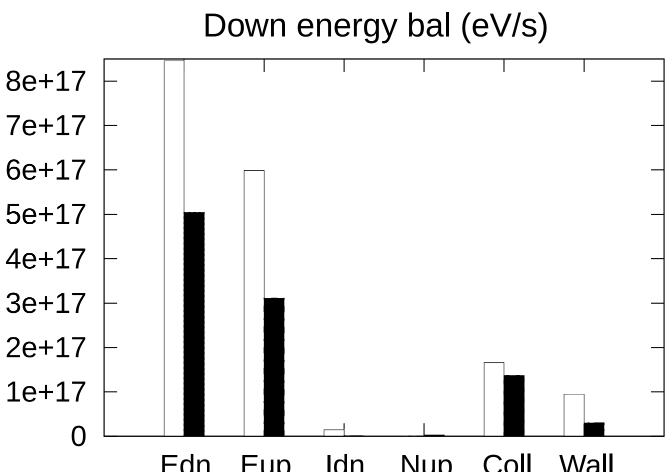
MODEL (TOP) and PIC (BOTTOM) EEDF'S (6 mTorr O_2)

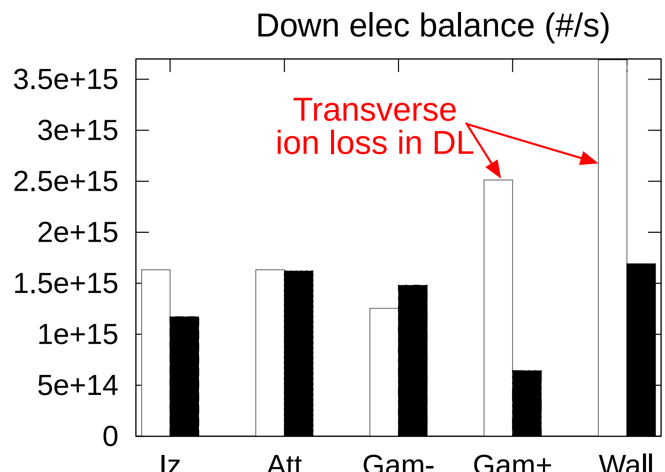


MODEL (WHITE) AND PIC (BLACK) FOR 6 mTorr O_2

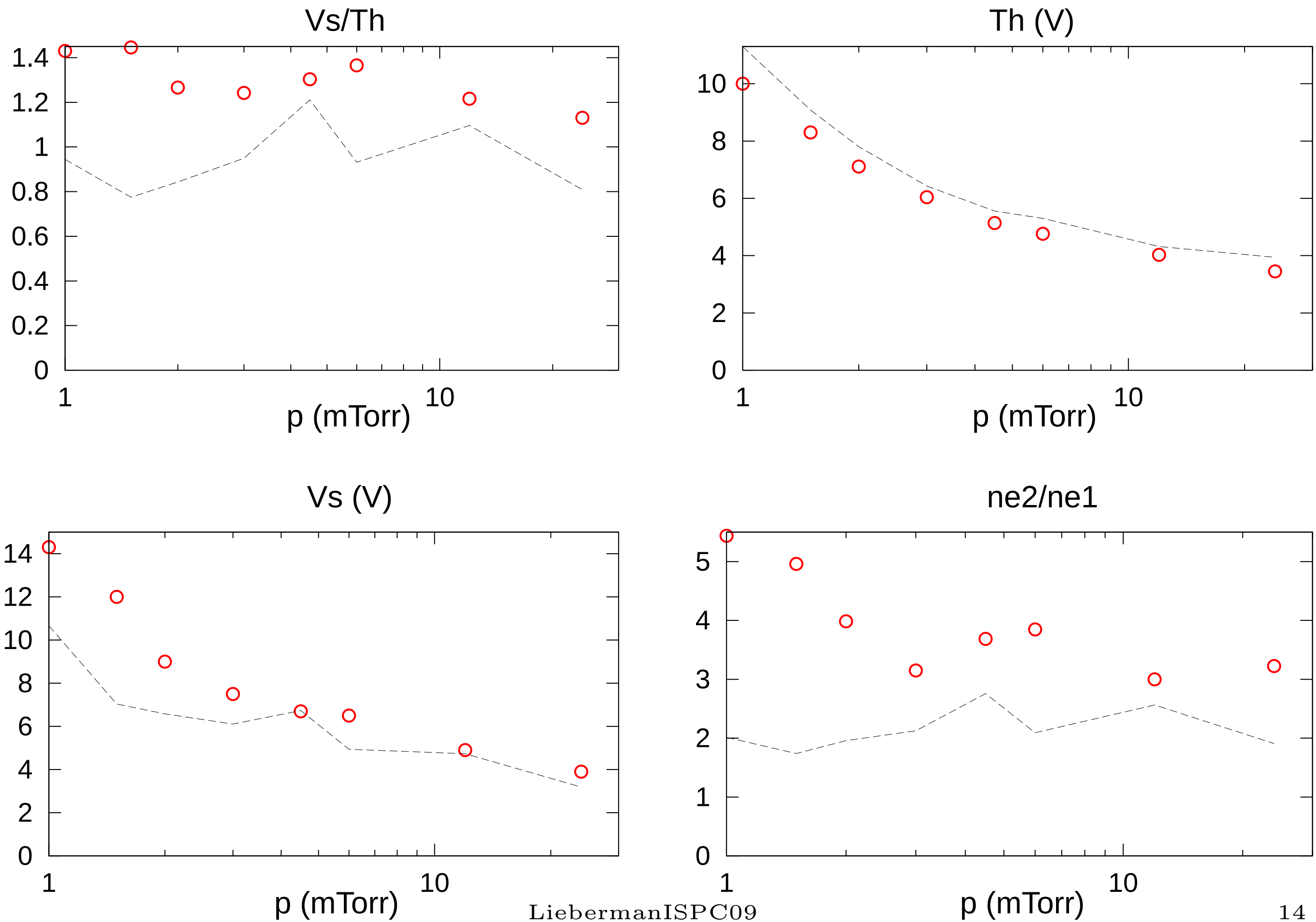






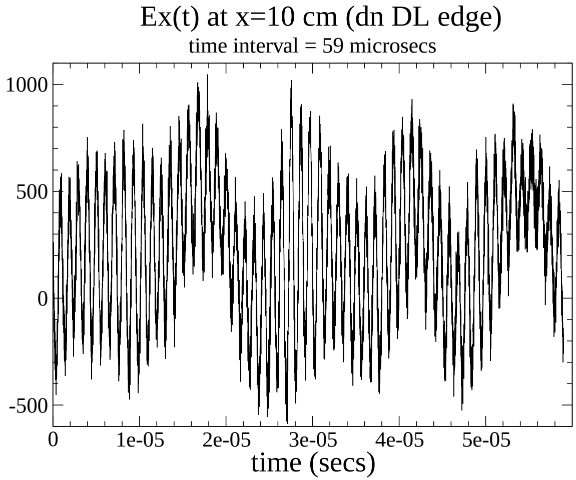


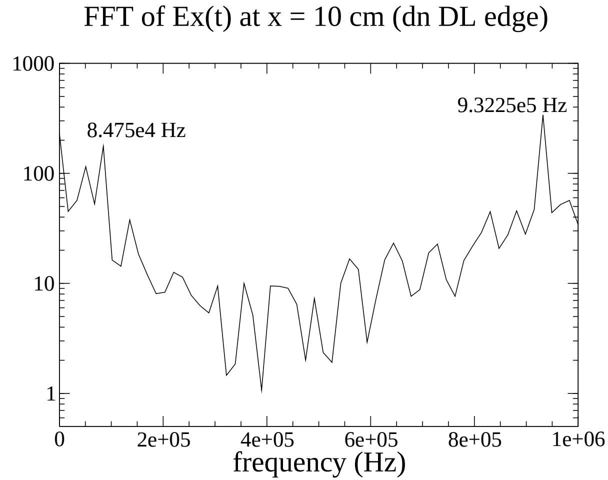
MODEL (DASH) AND PIC (CIRCLES) VS PRESSURE



TIME-VARYING PHENOMENA

SLOW AND FAST WAVE INSTABILITIES (6 mTorr O_2)



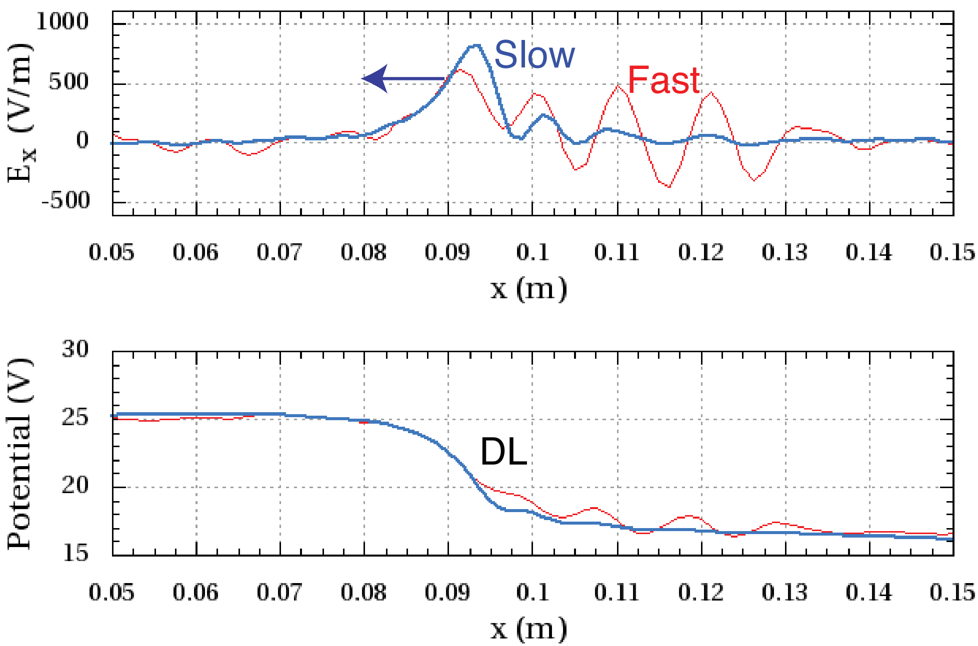


- At 2–12 mTorr, the DL coexists with an unstable slow wave that originates downstream and propagates upstream as it grows
- The wave frequency is 50–100 kHz with a wavelength of order 1 cm
- The wave produces ∼20% oscillations in the double layer potential and ∼0.5 cm oscillations in the DL position
- We believe the wave is driven by counter-streaming flows of positive and negative ions (Tuszewski and Gary, 2003)
- There is an additional unstable fast wave at higher pressures having frequency of order 1 MHz and a wavelength of order 1 cm

MOVIE SHOWING SLOW AND FAST WAVES

Red solid line: fast waves averaged over 0.1475 μs intervals
Blue solid line: slow waves averaged over 1.18 μs intervals

160. Waves in 6 mTorr DL region (23.6 microsecs)



CONCLUSIONS

- 2D PIC simulations can be powerful tools to study the physics of double layer formation
- The simulations provide diagnostics at the edges and inside the DL, which would be very difficult to do in a laboratory experiment
- The simulations show upstream edge Maxwellian electrons along with an accelerated component, and a downstream edge bi-Maxwellian with a hotter tail tied to the upstream temperature
- The simulations show that the DL can coexist with unstable slow and fast wave-driven oscillations
- A 1D analytical DL model coupled with global models of the upstream and downstream particle and energy balance captures the essential physics of DL formation in this two-region system

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