KINETIC EFFECTS
IN PLASMA PROCESSING DISCHARGES

M.A. Lieberman and E. Kawamura

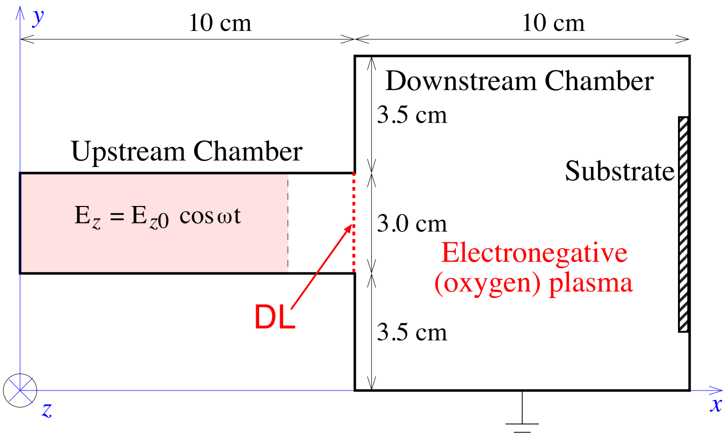
Dept. EECS, UC Berkeley

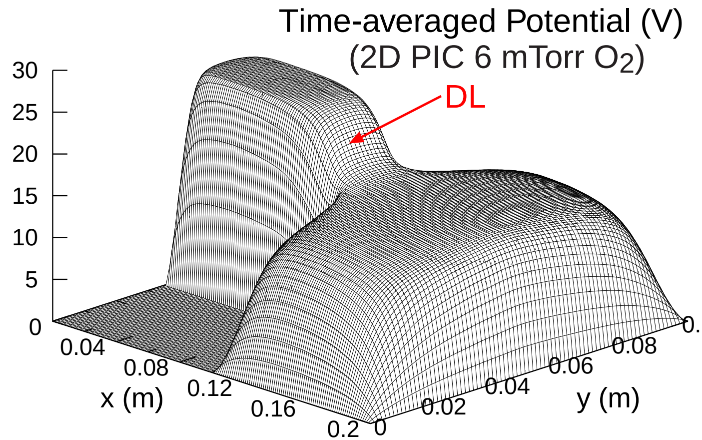
I. 2D PARTICLE-IN-CELL (PIC) SIMULATIONS OF UNSTABLE WAVES EXCITED BY DOUBLE LAYERS

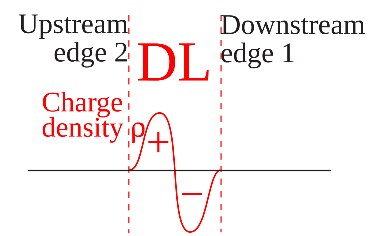
(with A.J. Lichtenberg and J.P. Verboncoeur)

Motivations: remote plasma processing; plasma thrusters

REACTOR CONFIGURATION







- DL's observed over a wide range of pressures (1–24 mTorr) (Kawamura et al, Phys. Fluids, 2009)
- DL's typically have time-varying (wave) structures

ABOUT 2D PIC SIMULATIONS

- Self-consistent results from first principles with no assumptions about electron and ion velocity distributions

- Stability, speed and accuracy require low densities:

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

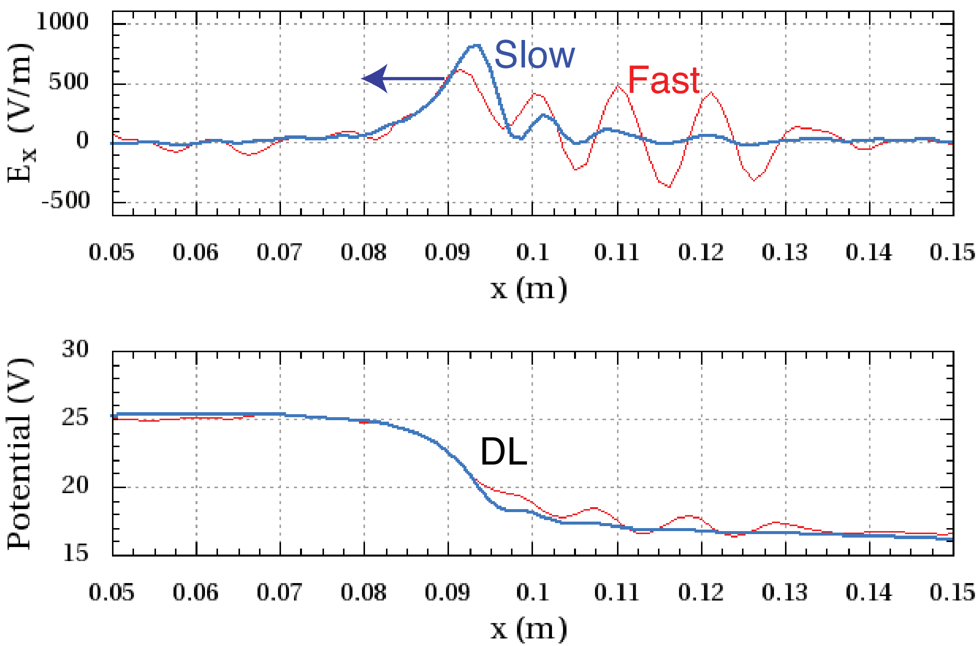
- Rescaled oxygen cross sections are used to simulate higher densities and other chemistries

- A typical simulation takes 1–2 weeks

MOVIE SHOWS SLOW AND FAST WAVES

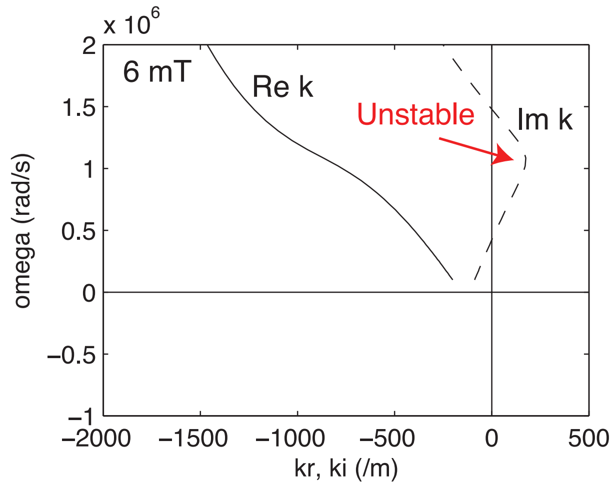
Red: 900 kHz fast waves averaged over 0.1475 μs intervals
Blue: 85 kHz slow waves averaged over 1.18 μs intervals

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



KINETIC THEORY OF UNSTABLE WAVES

- Waves produce 20% oscillations in DL potential and position
- Electron and ion kinetic effects are important



- Most unstable slow wave at $\lambda = 0.7$ cm at 173 kHz (PIC simulation gives $\lambda = 1$ cm at 85 kHz)
- Fast wave weakly damped at $\lambda = 0.7$ cm; excitation from nonuniformities and nonlinearities?

(Kawamura et al, to appear in J. Appl. Phys.)

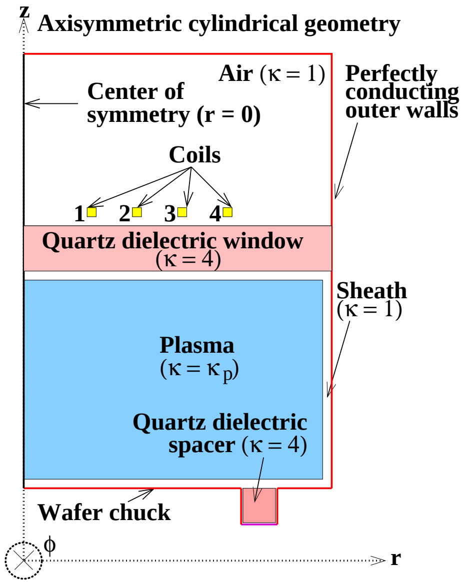
II. BULK-FLUID/ANALYTIC-SHEATH HYBRID SIMULATIONS

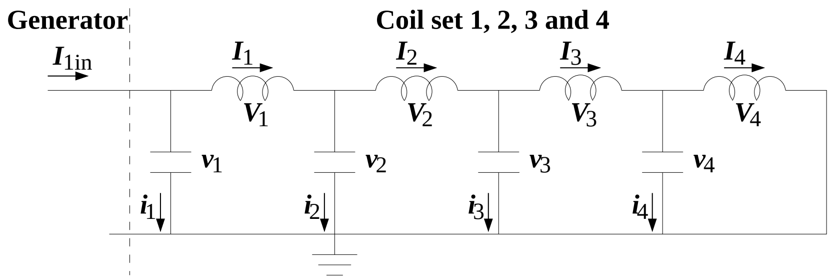
(with D.B. Graves)

Motivation: fast computation of plasma reactor parameters

BULK-FLUID/ANALYTIC-SHEATH MODEL

- Example of inductive reactor (Malyshev and Donnelly, 2000–01)





— Electromagnetic field solve (including wafer chuck rf bias)

— Fluid bulk plasma model

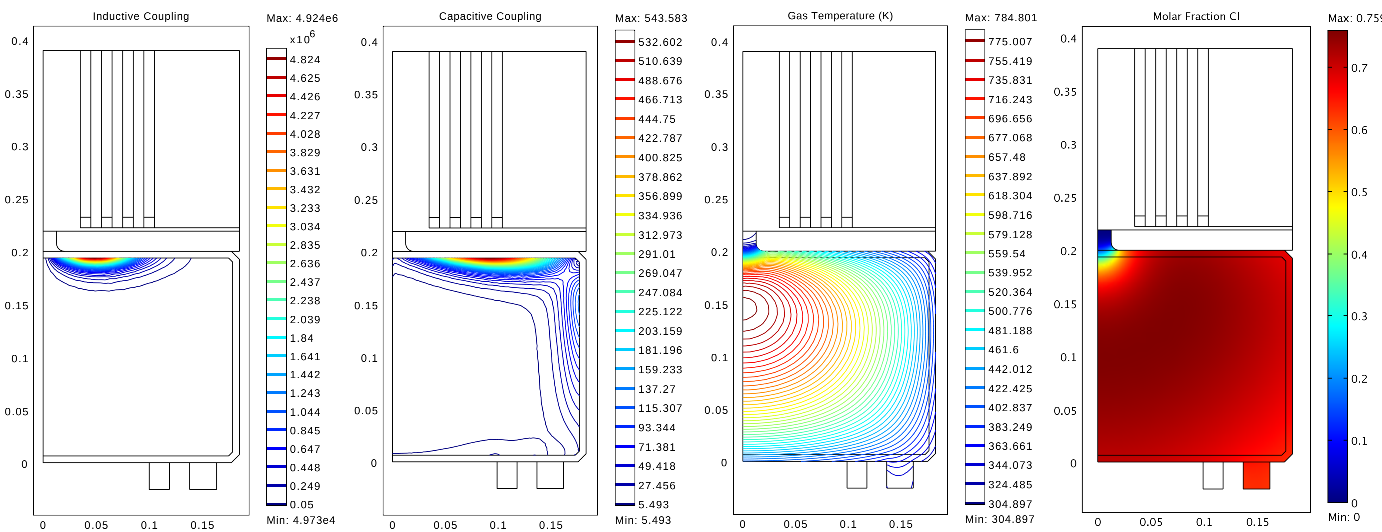
— Analytical sheath model

— Flow model of reactive gas

— Commercial software (COMSOL)

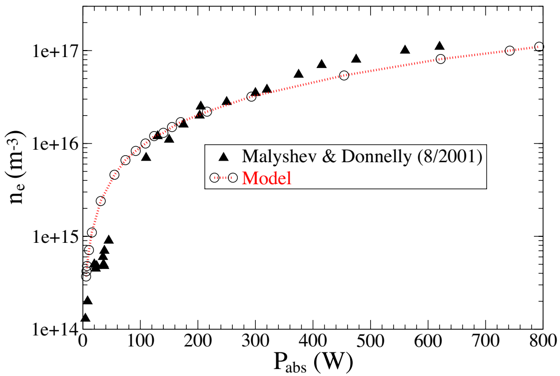
CHLORINE REACTOR SIMULATIONS

- 100 sccm Cl_2 gas flow, 10 mTorr at outlet, 740 W at 13.56 MHz
- Total simulation time ≈ 70 min (2.2 GHz CPU 4GB RAM)
- Inductive >> capacitive power, high gas T, high Cl_2 dissociation

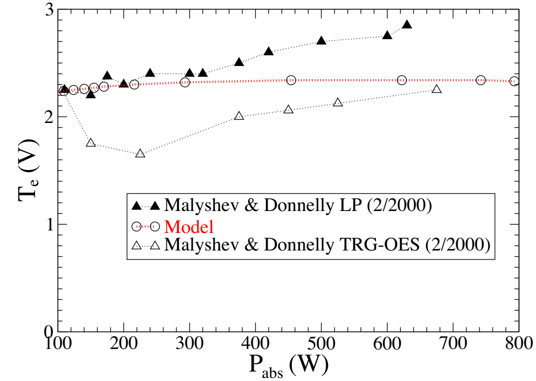


MODEL VERSUS EXPERIMENT

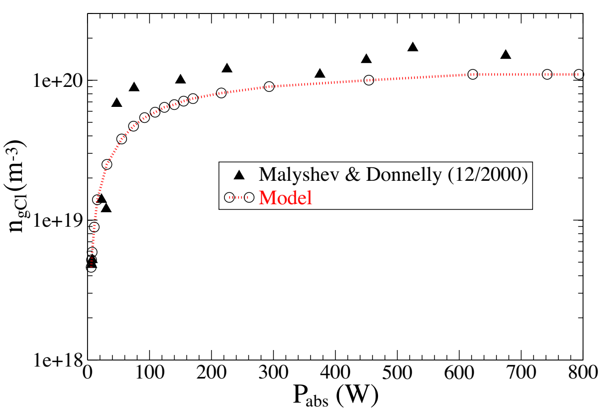
n_e vs. P_{abs} at Discharge Center



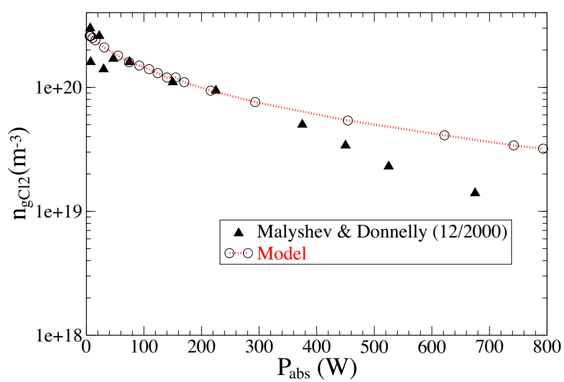
T_e vs. P_{abs} at Discharge Center



n_{gCl} vs. P_{abs} at Discharge Center

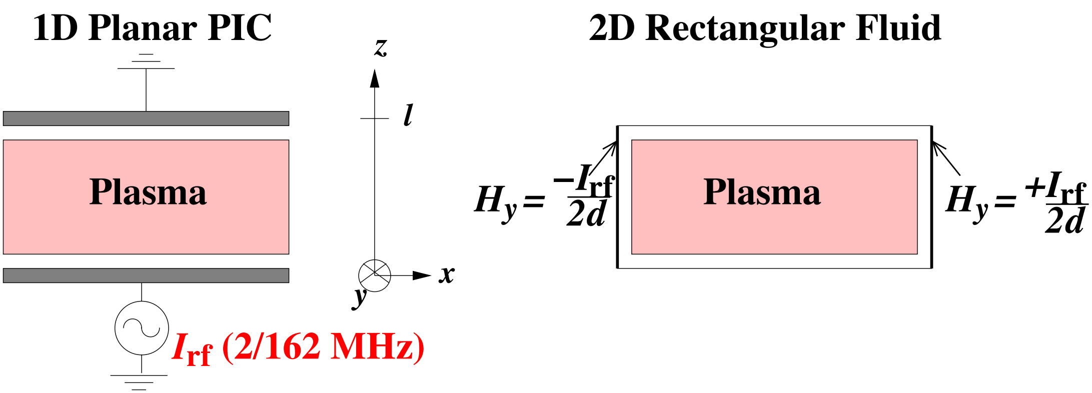


n_{gCl2} vs. P_{abs} at Discharge Center



USING 1D/2D PIC SIMULATIONS

- Benchmark/verify assumptions of hybrid model
- Example of dual frequency excitation



⇒ 1D PIC confirms analytical sheath model

- PIC simulations yield
  — electron energy distribution in bulk plasma
  — ion and fast neutral distributions on the substrate
- Couple PIC to hybrid model

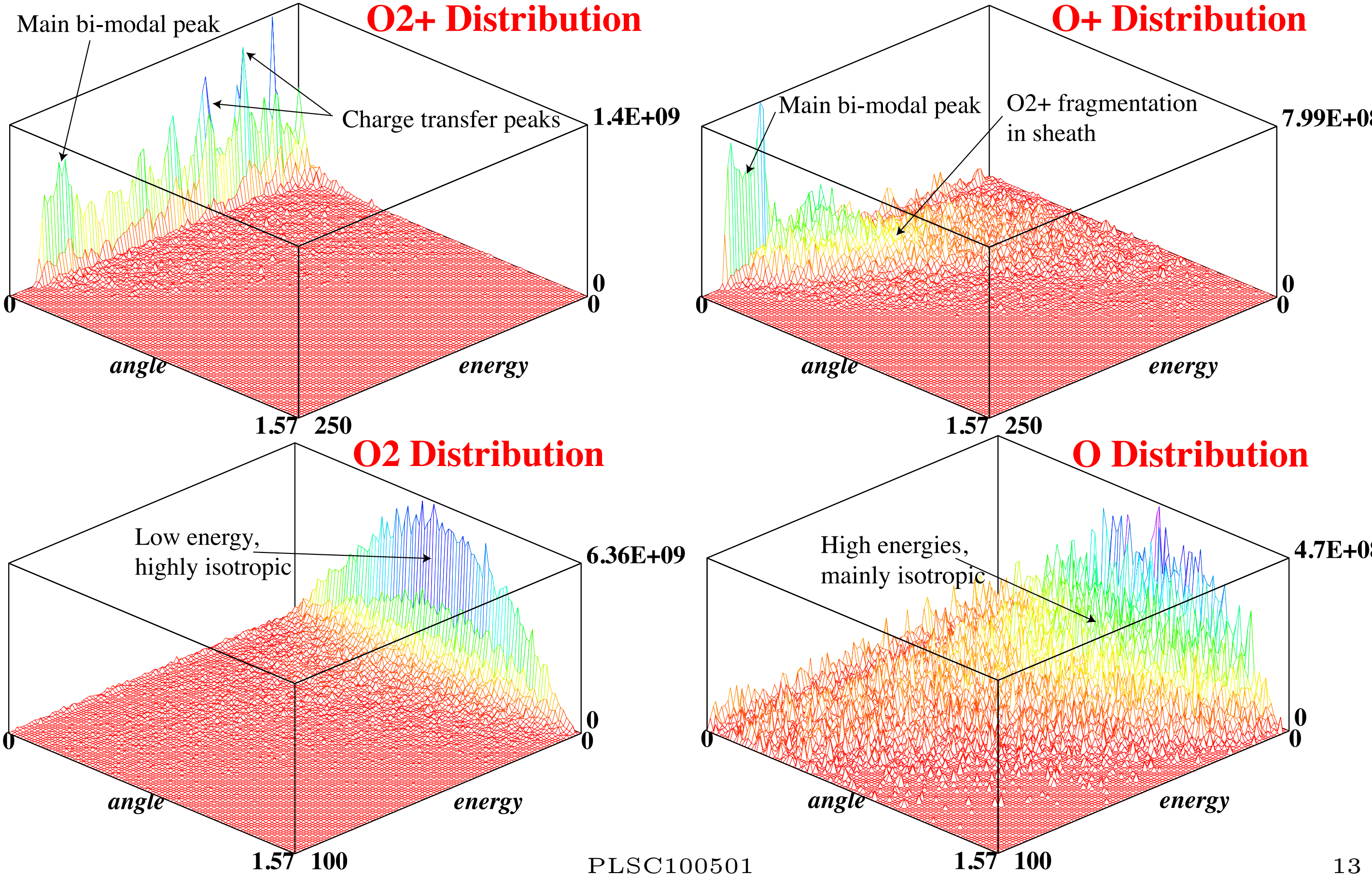
III. OOPD1 — 1D PIC CODE DEVELOPMENT

(with J.P. Verboncoeur, J.T. Gudmundsson and A. Wu)

Motivation: Unified extensible code with easy-to-use interface

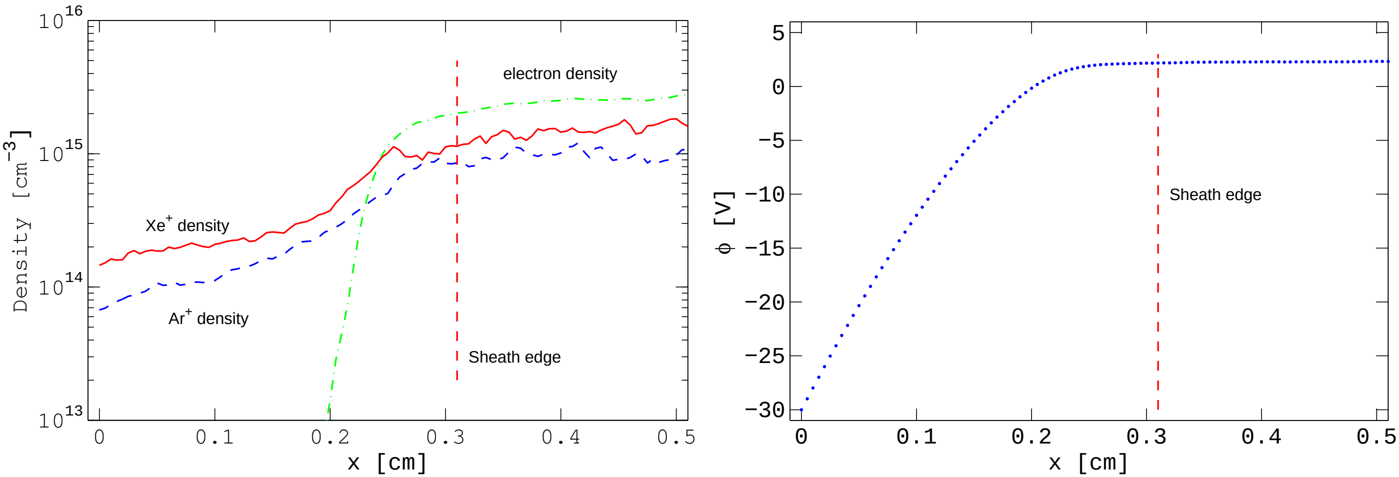
ENERGETIC PARTICLES ON THE SUBSTRATE

(20 mTorr O_2 capacitive discharge: 5 cm gap, 500 V at 13.56 MHz)



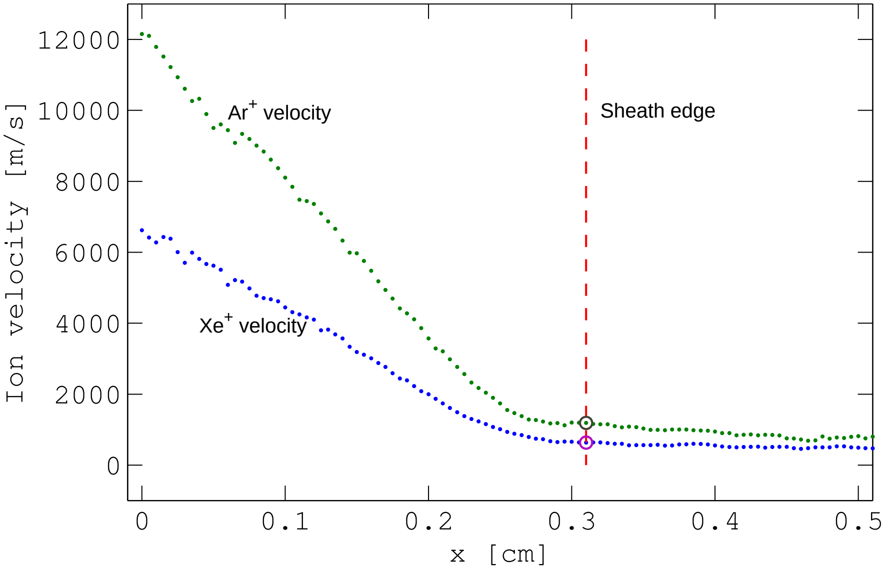
ION LOSS VELOCITIES IN MULTI-ION PLASMAS

- OOPD1 model of an argon/xenon experiment (see Lee, Hershkowitz and Severn 2007)
- Model results:



- Model sheath width = 0.31 cm, experiment = 0.27 cm
- Model $T_e = 0.49$ V, experiment = 0.69 V

ION VELOCITY SIMULATION RESULTS



- Bohm velocities $\sqrt{eT_e/M_i} = 592$ m/s for Xe^+ and 1073 m/s for Ar^+
- Model velocities = 636 m/s for Xe^+ and 1190 m/s for Ar^+
- Experimental velocities = 940 m/s for Xe^+ and 1100 m/s for Ar^+
- This is work in progress