NARROW GAP ELECTRONEGATIVE CAPACITIVE DISCHARGES AND STOCHASTIC HEATING

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Motivation: widely used for thin film etch and deposition

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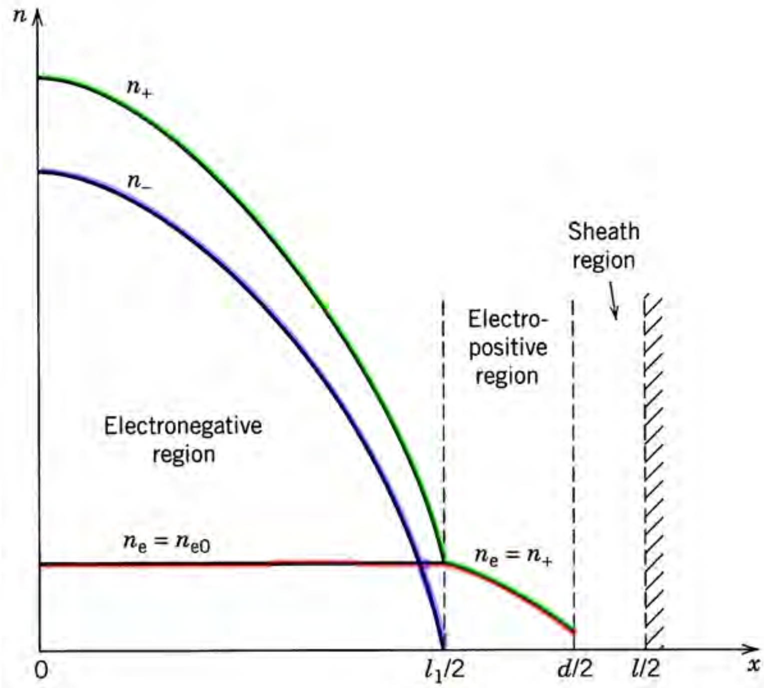
OUTLINE

- Narrow gap oxygen discharges
  — PIC simulations
  — Equilibrium discharge model

- Stochastic (collisionless) heating
  — Narrow gap oxygen
  — Two-step density model with argon
  — Ohmic heating issues
  — Single-step with finite slope

DISCHARGE CONFIGURATION

- Oxygen at 10–100 mTorr, $V_{\rm rf} = 500$–2000 V
- 1D plane-parallel geometry ($\sim$1–10 cm gap length L)
- Usual model is stratified discharge with electronegative (EN) core and electropositive (EP) edge

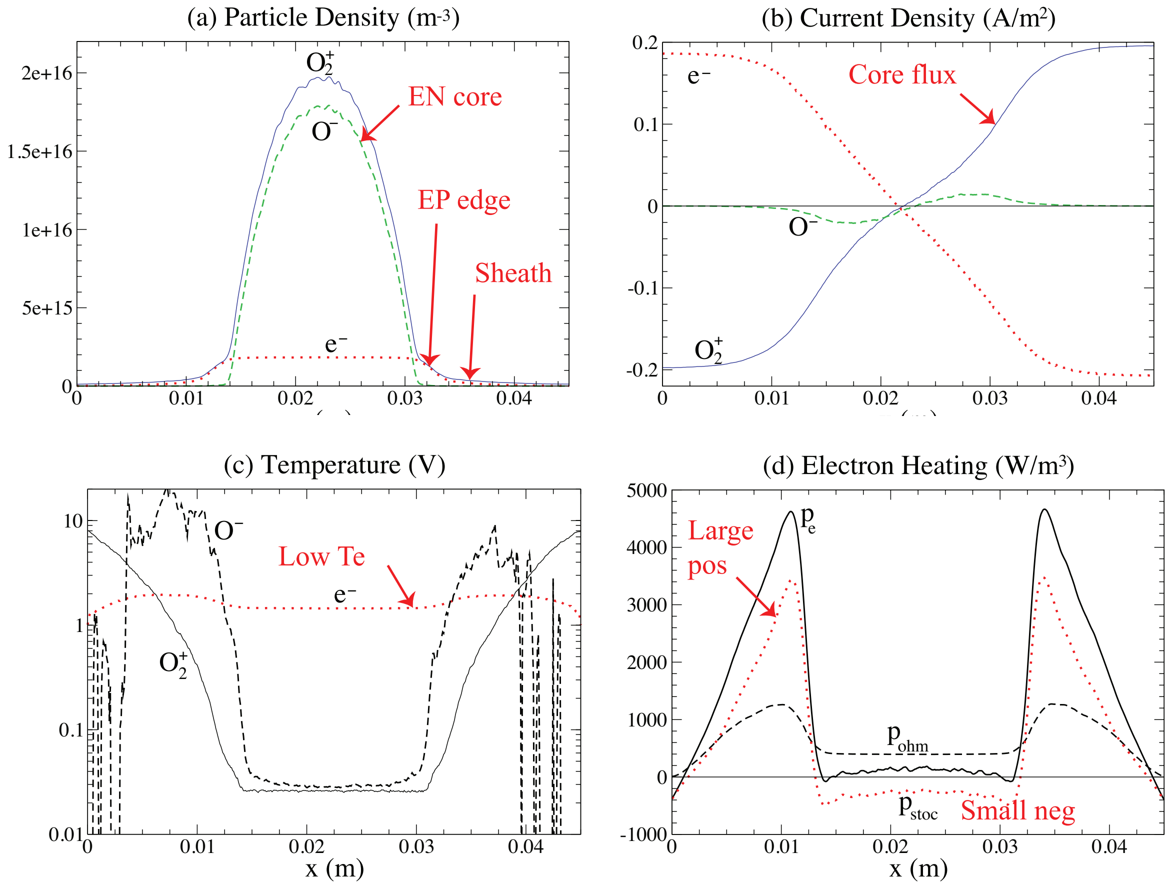


- As L is decreased, the EP edge can disappear and new interesting phenomena are found

PIC SIMULATIONS AND EQUILIBRIUM MODELING

(Vary gap length L at p=50 mTorr, $V_{rf} = 500$ V)

L=4.5 cm (EP EDGE EXISTS)



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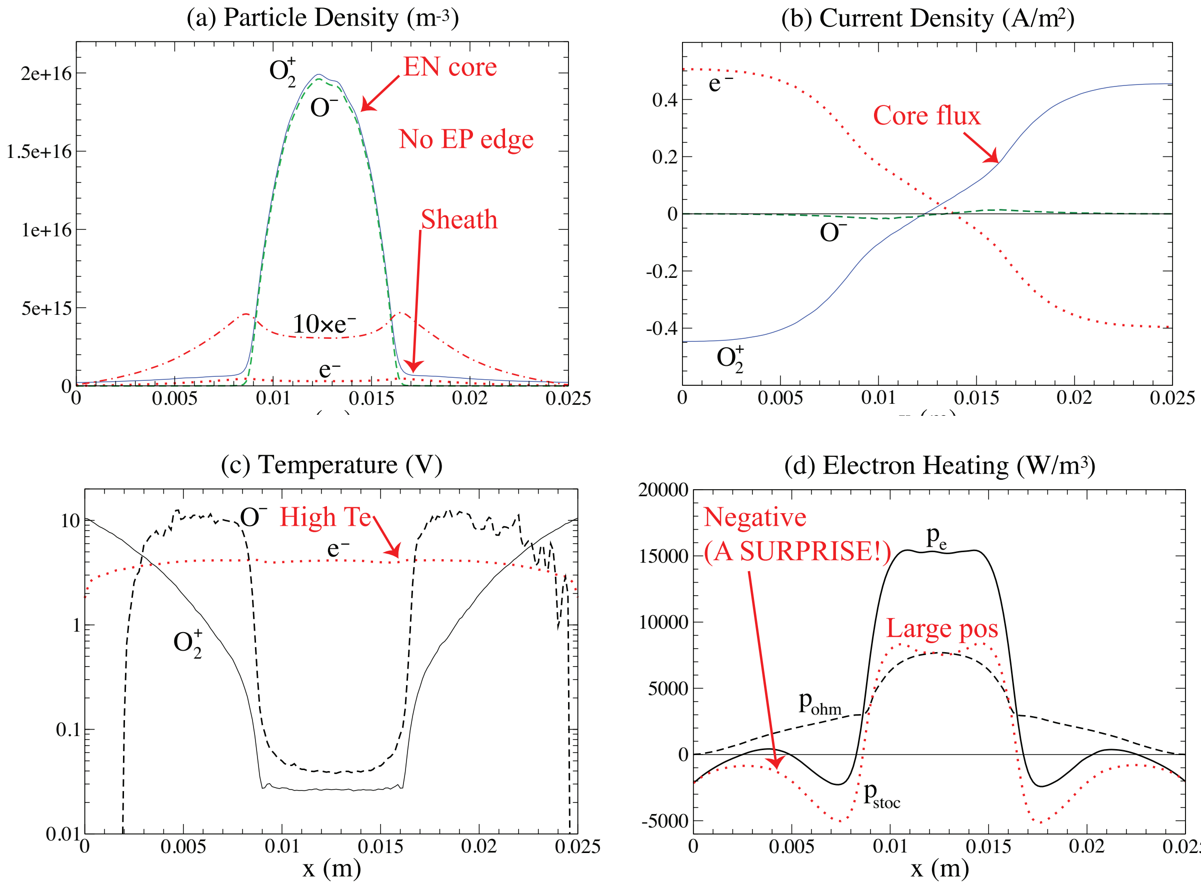
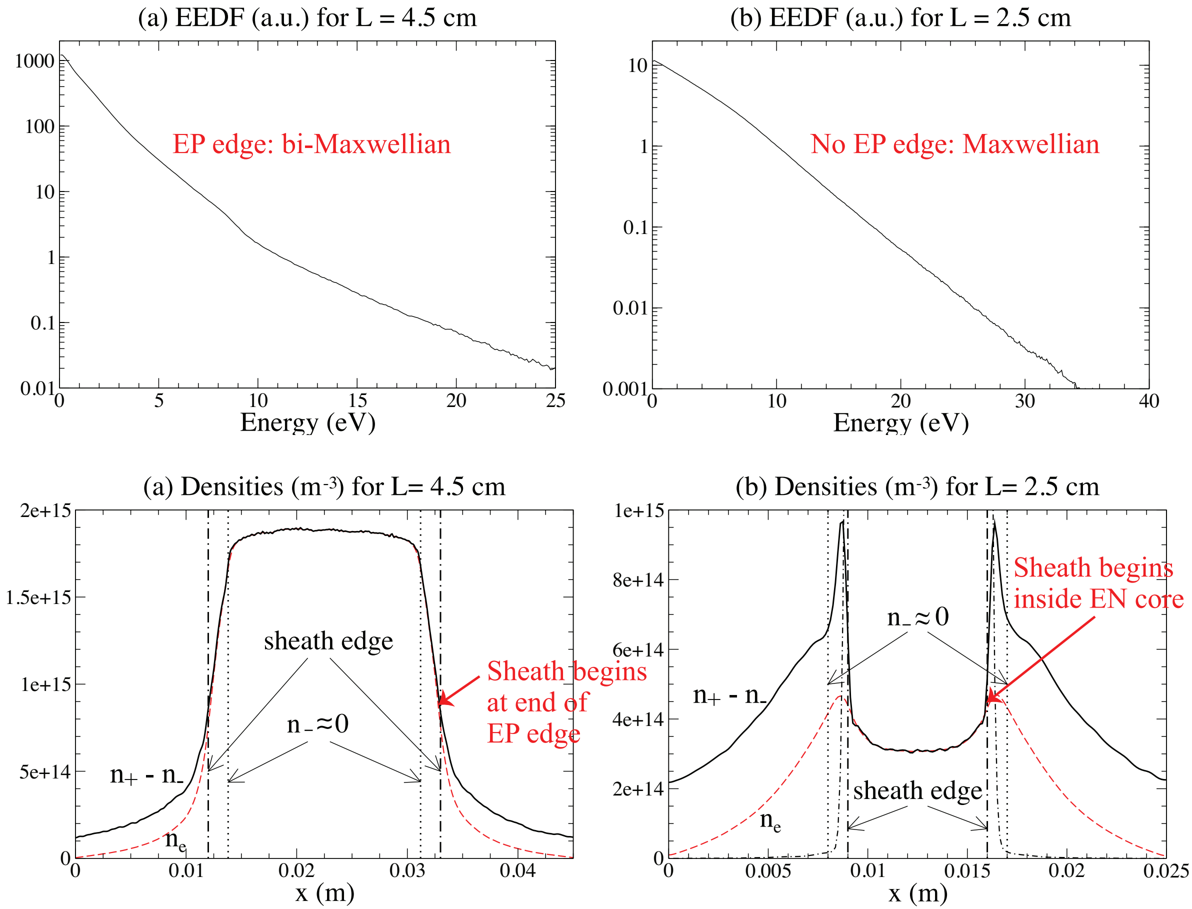
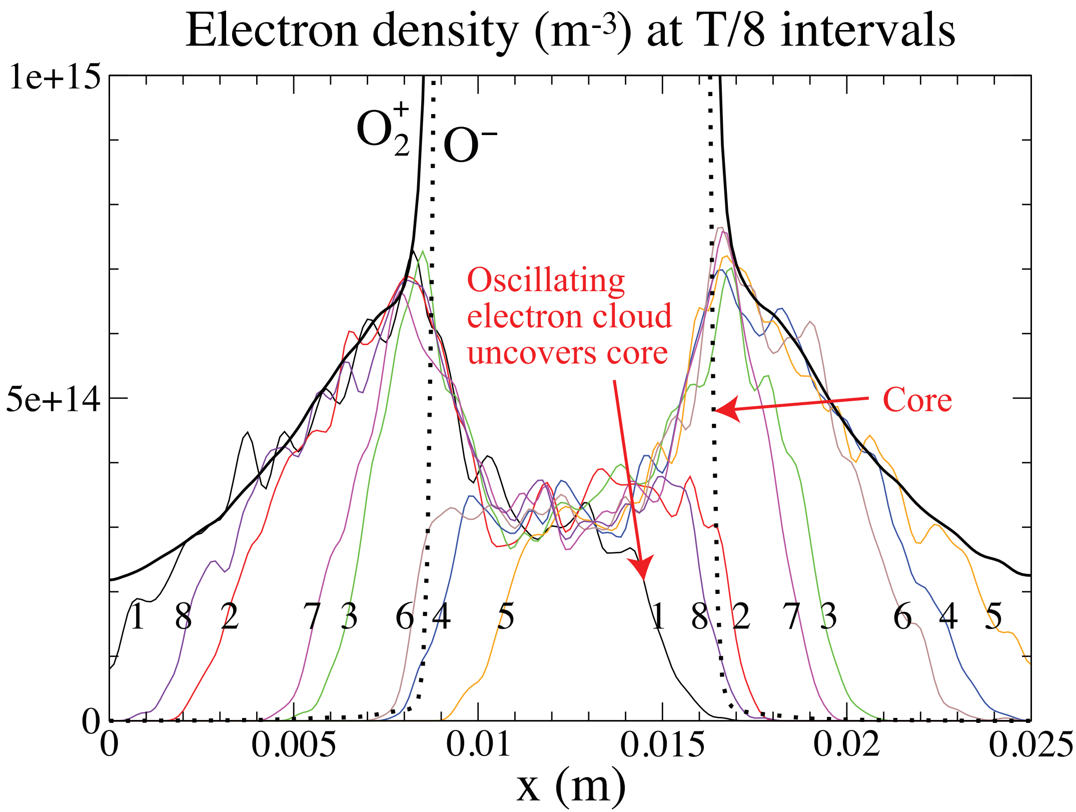
L=2.5 cm (NO EP EDGE)



EEDF'S AND DENSITY DETAILS



TIME-VARYING DENSITY (L=2.5 cm, NO EP EDGE)



MODELING CONSIDERATIONS

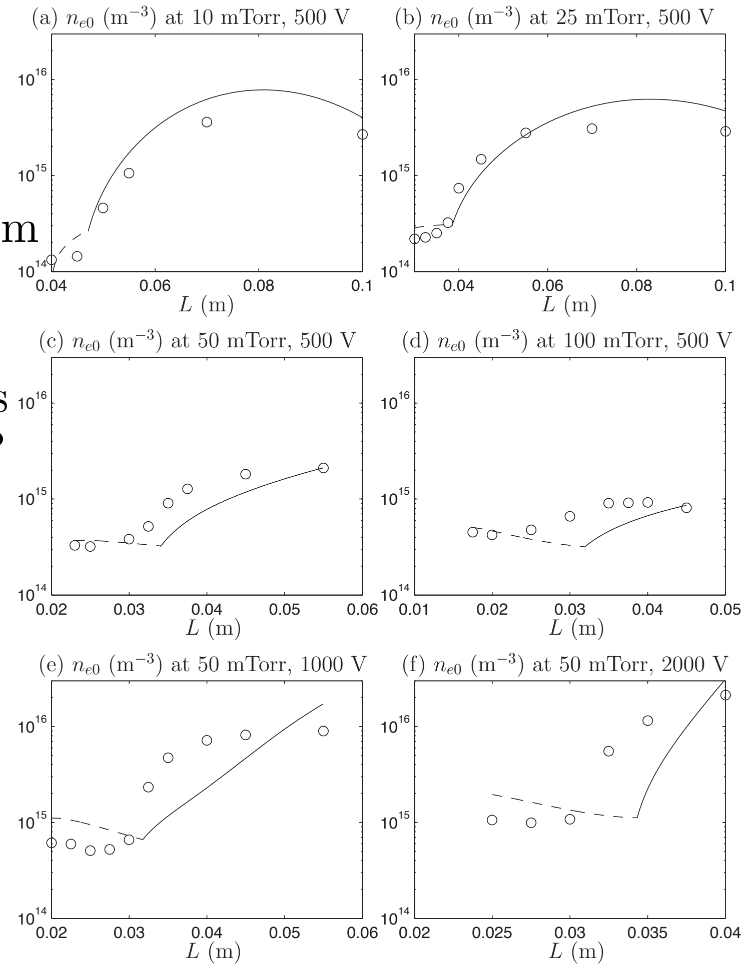
- EP edge exists (larger gap lengths L)
  — Bi-Maxwellian EEDF
  — About half the ion flux generated in sheath/EP edge
  — Usual Child law rf sheath
  — Usual positive collisionless heating in sheath

- No EP edge (smaller gap lengths L)
  — Maxwellian EEDF
  — Over half the ion flux generated in sheath
  — Attachment in sheath is important
  — Unusual rf sheath containing negative ions
  — Negative collisionless heating in sheath, positive in core

- Models developed:
  — model with some inputs from PIC results
  — self-consistent model

MODEL WITH SOME INPUTS FROM PIC

- Rate coefficients and collisional energy losses using PIC EEDF
- Power deposition in core from PIC results
- Solid lines (2-region model with EP edge); Dashed lines (1-region model without EP edge); circles (PIC results)



- Reasonable agreement between model and PIC results (submitted to Physics of Plasmas, 2013)

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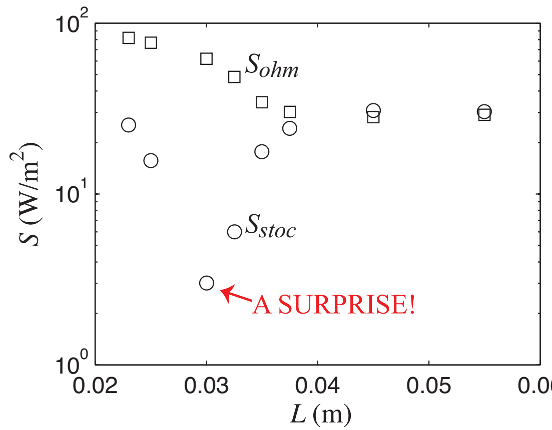
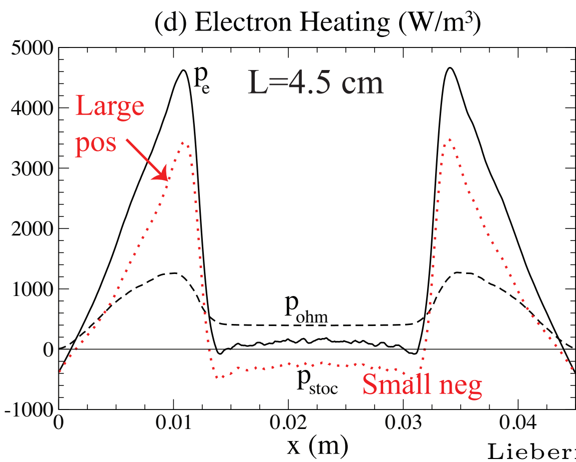
STOCHASTIC (COLLISIONLESS) HEATING

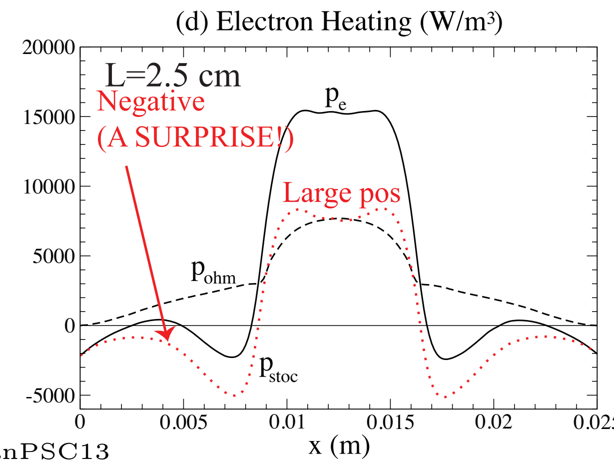
(WORK IN PROGRESS)

PIC RESULTS FOR VARIOUS GAPS L (50 mT, 500 V)

- Stochastic heating small at transition where EP edge disappears
- EP edge exists ⇒ positive heating in sheath, negative in core
- No EP edge ⇒ negative heating in sheath, positive in core

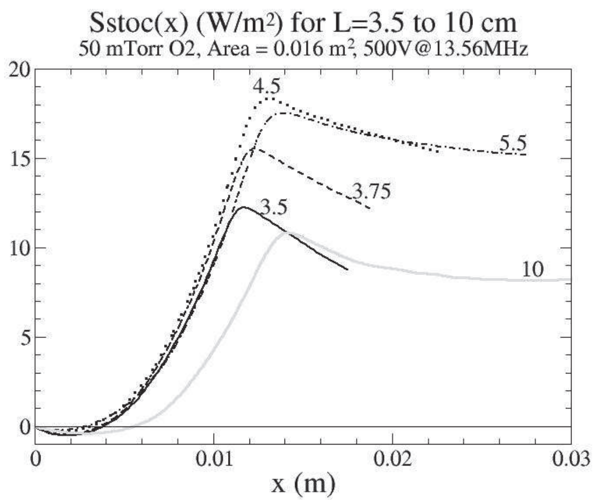


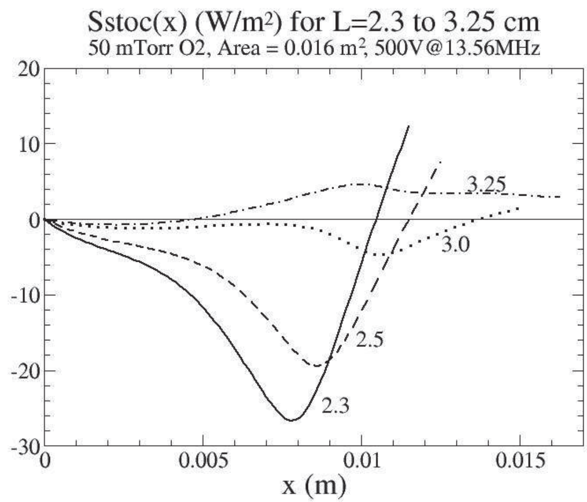




$\mathbf{S_{stoc}(x)}$ FOR VARIOUS GAPS L

- Integrate $p_{\text{stoc}}(x)$ from electrode $(x = 0)$ toward discharge midplane $\Rightarrow S_{\text{stoc}}(x)$





- Large $L \Rightarrow n_e(\text{core}) > n_e(\text{sheath})$
  $\Rightarrow$ positive heating in sheath, negative heating in core
- Small $L \Rightarrow n_e(\text{sheath}) > n_e(\text{core})$
  $\Rightarrow$ negative heating in sheath, positive heating in core

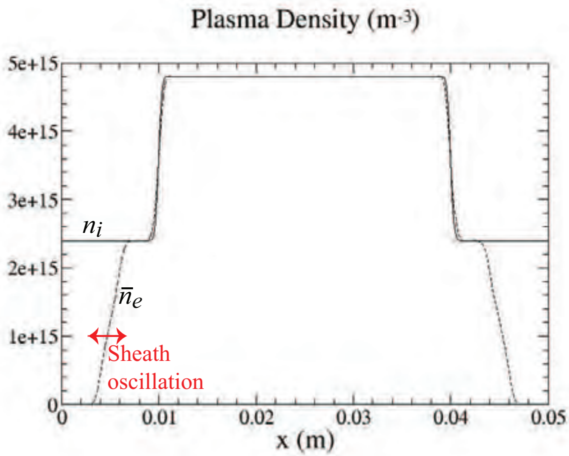
TWO-STEP DENSITY MODEL

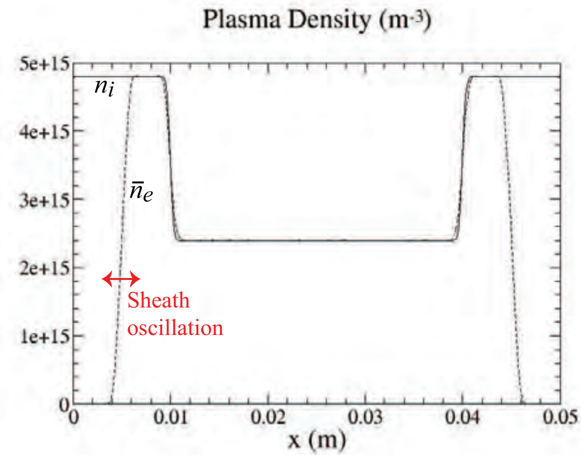
1. I.D. Kaganovich, Phys. Rev. Lett. **89**, 265006 (2002).
2. E. Kawamura, M.A. Lieberman and A.J. Lichtenberg, Phys. Plasmas **13**, 053506 (2006).

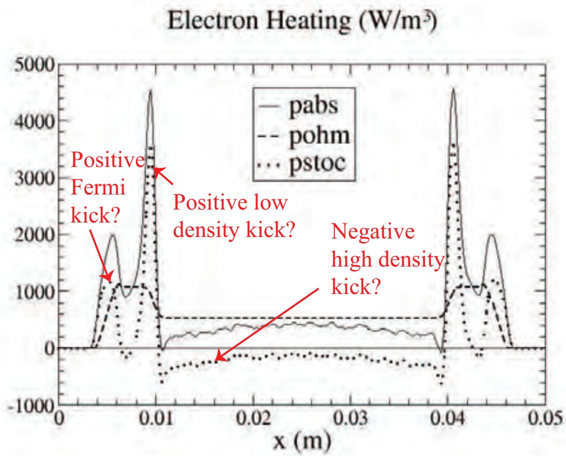
Use to investigate stochastic heating

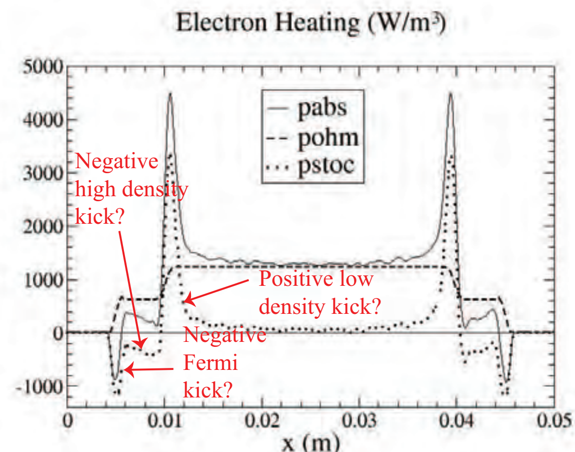
FIXED IONS, PIC ELECTRONS (30 mT Ar, 13.56 MHz)

(Models EN plasma with EP edge) (Models EN plasma with no EP edge)





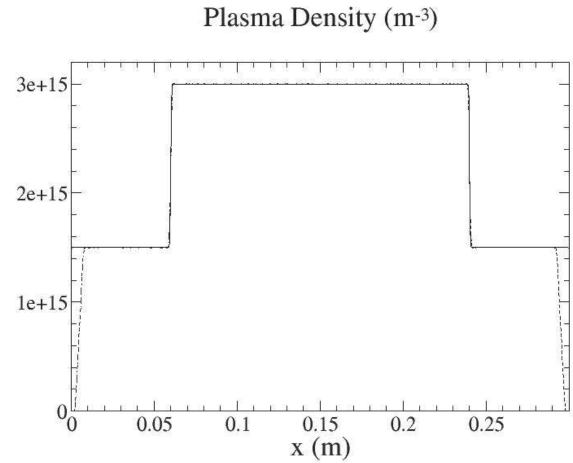


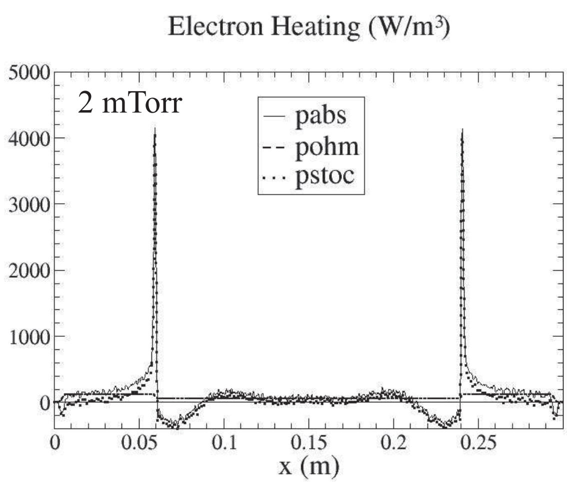


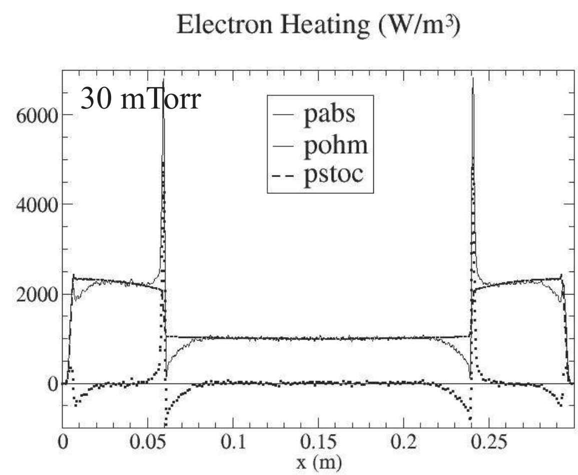
ELECTRON HEATING GAS PRESSURE EFFECTS

- Large device
- 2:1 step at 6 cm
- At 2 mT 66% of heating is ohmic; at 30 mT 96% is ohmic

$\Rightarrow$ error in finding stochastic heating







PIC SIMULATION OHMIC HEATING ISSUES

(see Lister, Li and Godyak, 1996)

- Ohmic power density $p_{\text{ohm}} = \frac{1}{2}|J_{\text{rf}}|^2\text{Re}[1/(\sigma_p + j\omega\epsilon_0)]$, where

$$\sigma_p = -\frac{4\pi}{3}\frac{e^2}{m}\int_0^\infty \frac{v^3 \mathrm{d}v}{j\omega + \nu_m(v)}\frac{\mathrm{d}f_{e0}}{\mathrm{d}v}$$

- The usual simple expression (see Margenau, 1946)

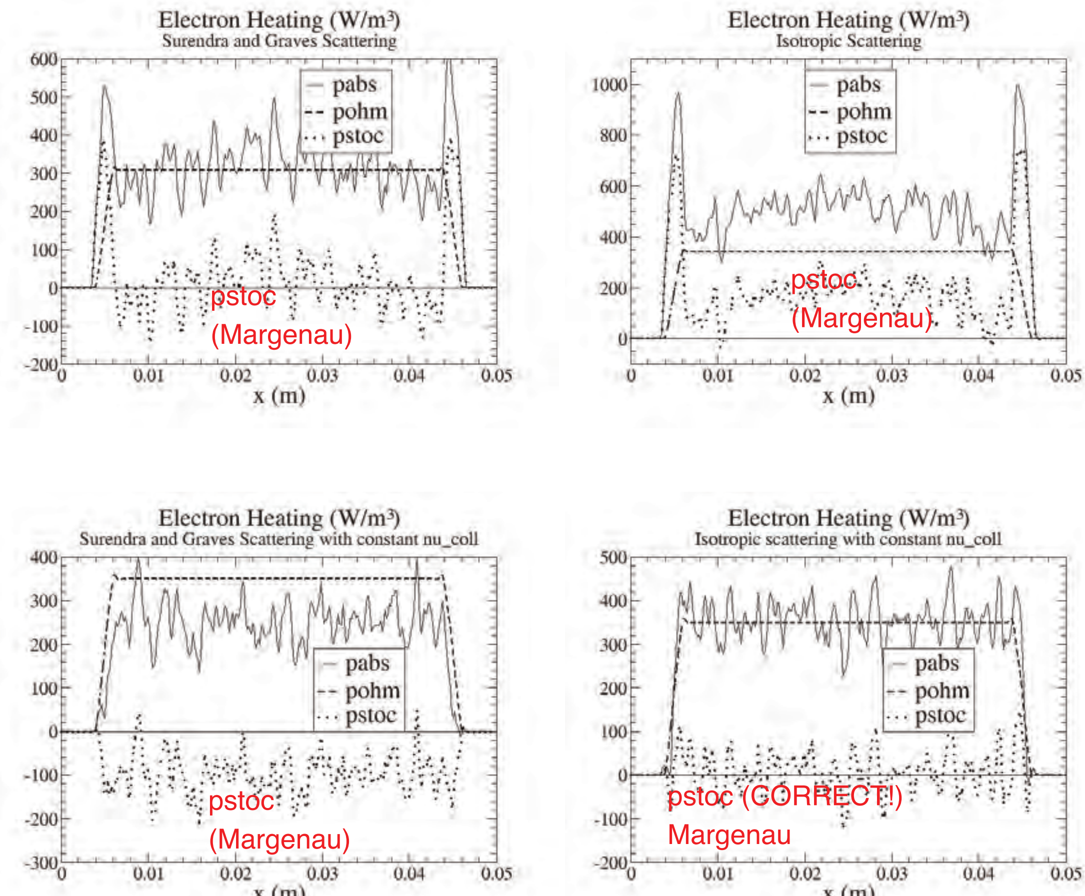
$$\sigma_p = \frac{e^2 n_e}{m(j\omega + \nu_m)}$$

  is not correct unless $\nu_m = \text{const}$

- Argon is a Ramsauer gas with ν_m a function of v
- The momentum transfer frequency ν_m must be distinguished from the "total" collision frequency ν_{coll}
- Large errors in calculating stochastic heating for ohmic heating $\gg$ stochastic heating
- Can use "pseudo-argon" in PIC simulation $\Rightarrow \nu_m = \nu_{\text{coll}} = \text{const}$

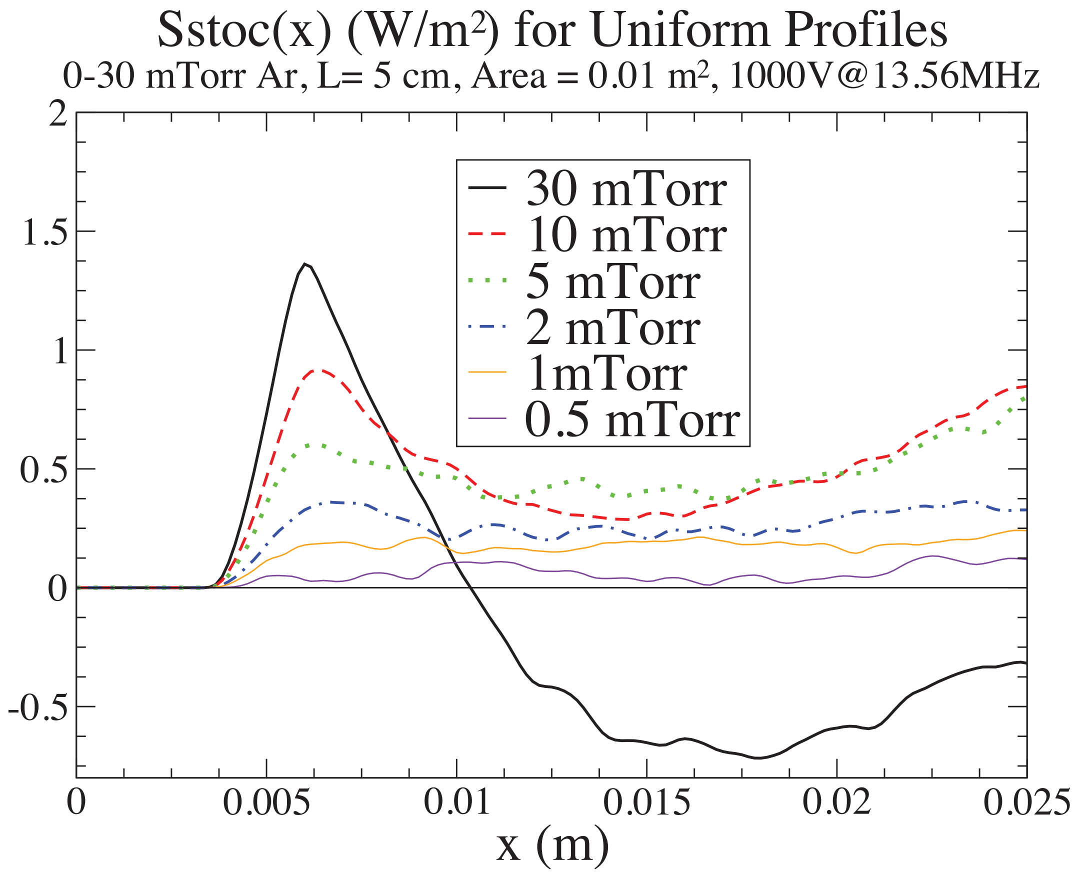
VARIOUS COLLISION MODELS (UNIFORM PLASMA)

Fixed Ion Uniform 5 mTorr Argon with n_b = 4.8e15 m^{-3}
$V_{\rm rf}$=1000 V, f=13.56 MHz, L=0.05 m, Area=0.01 m^2



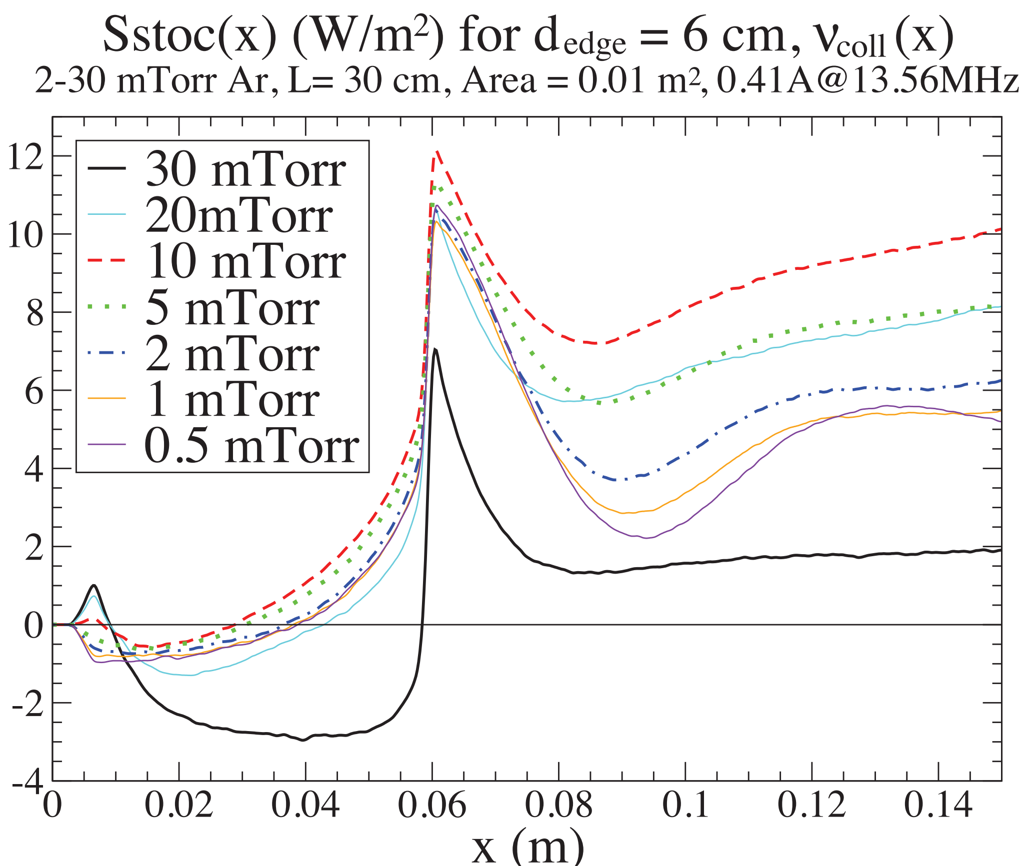
STOCHASTIC HEATING (5 CM UNIFORM PLASMA)

(Ramsauer elastic cross section, non-isotropic scattering)



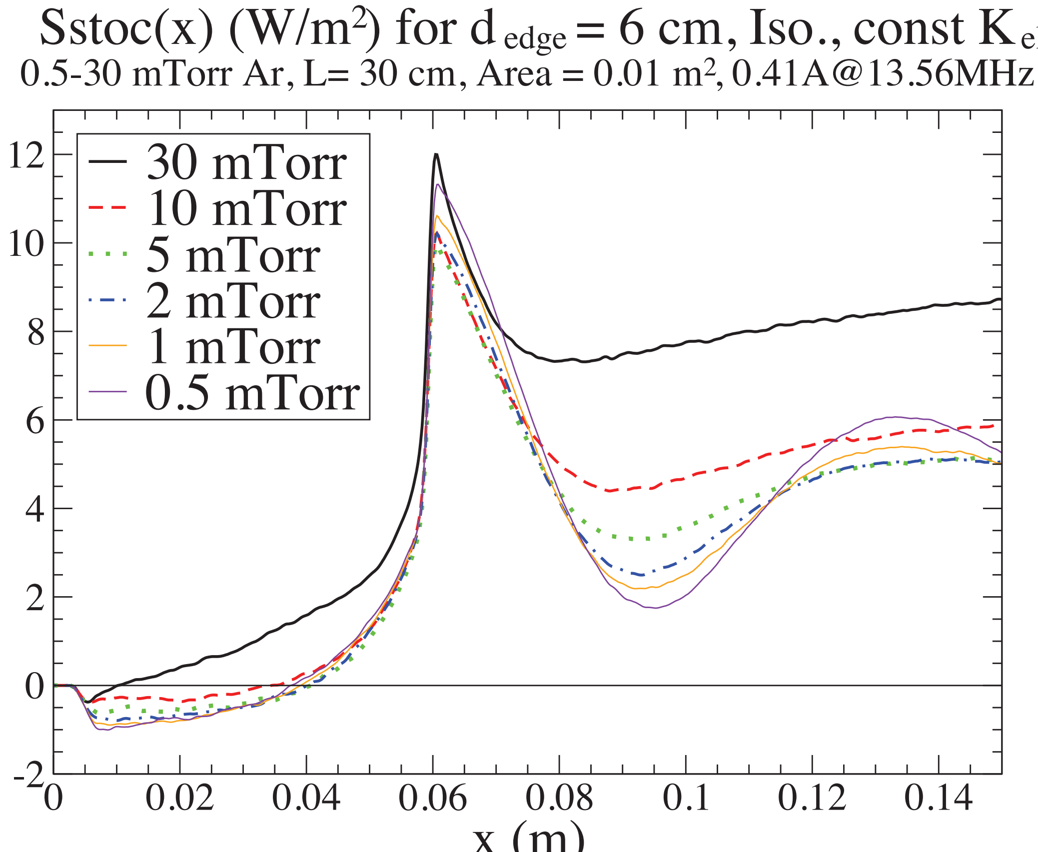
STOCHASTIC HEATING (2:1 STEP, $d_{edge} = 6$ CM)

(Ramsauer elastic cross section, non-isotropic scattering)



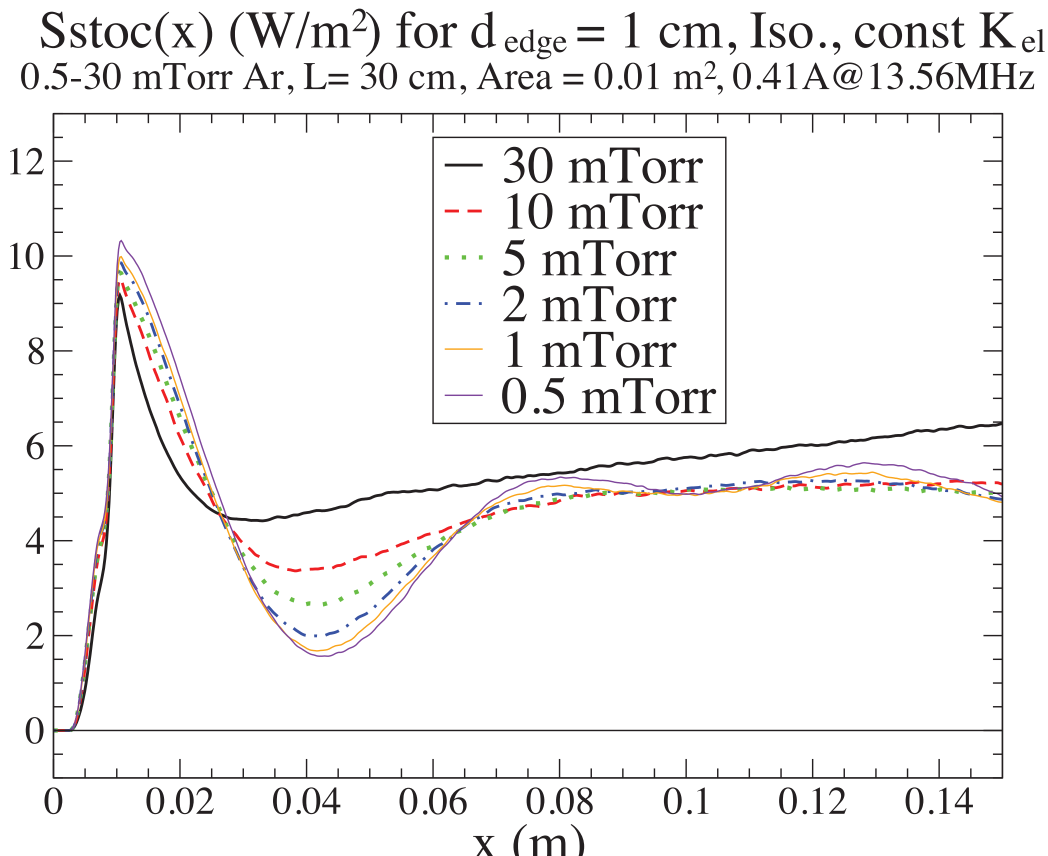
STOCHASTIC HEATING (2:1 STEP, $d_{edge} = 6$ CM)

(Constant collision frequency, isotropic scattering)



STOCHASTIC HEATING (2:1 STEP, $d_{edge} = 1$ CM)

(Constant collision frequency, isotropic scattering)



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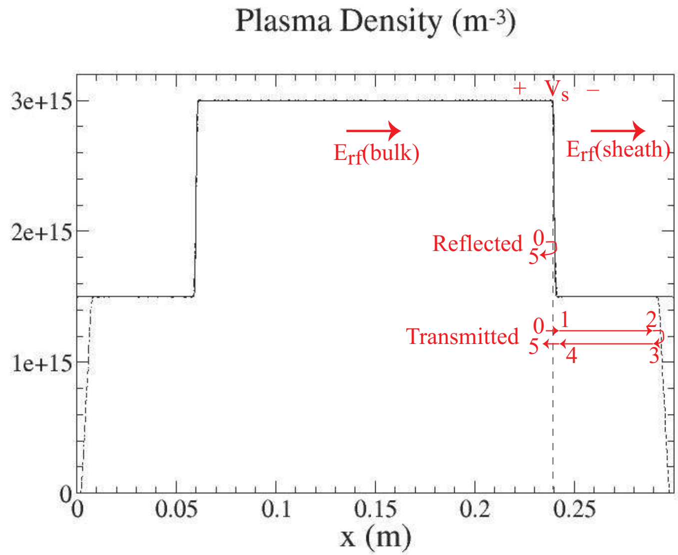
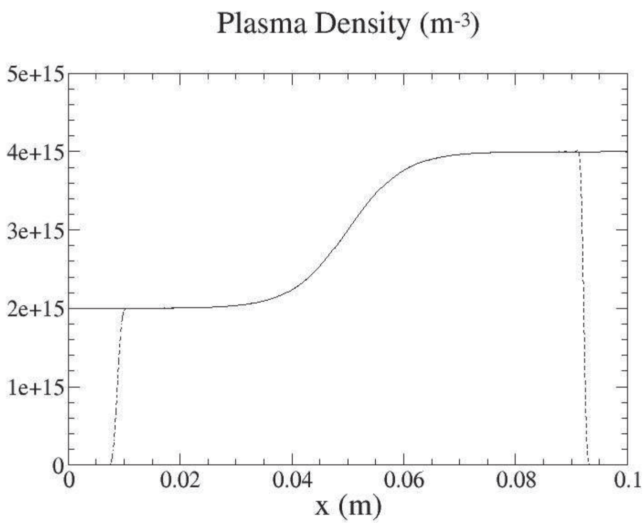
ENERGY KICK FOR TWO-STEP DENSITY



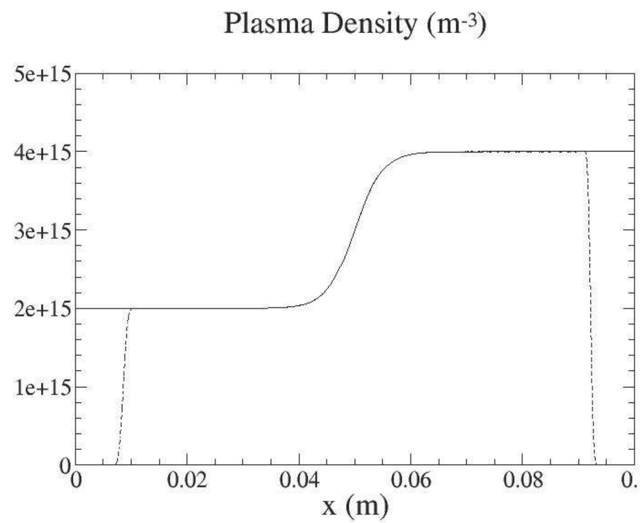
- There is a potential drop $V_s = T_e \ln(n_b/n_s)$ across the step
- There are rf fields $E_{\rm rf}$(bulk) and $E_{\rm rf}$(sheath)
- Calculate the phase-averaged energy kick $\Delta\mathcal{E}$ for transmitted and reflected particles
- There is no contribution to the kick at the oscillating plasma-sheath edge ($2 \rightarrow 3$)

SINGLE STEP WITH VARIABLE SLOPE (PIC)

30 mTorr Argon fixed Ion Tanh profile with a_1=10 to 400, a_2=3, n_l/n_r= 0.5, $I_{\rm rf}$=0.3 A, f=27.12 MHz, L=0.1 m, Area=0.01 m^2, n_l=2e15 m^{-3}



(a) $a_1 = 10$

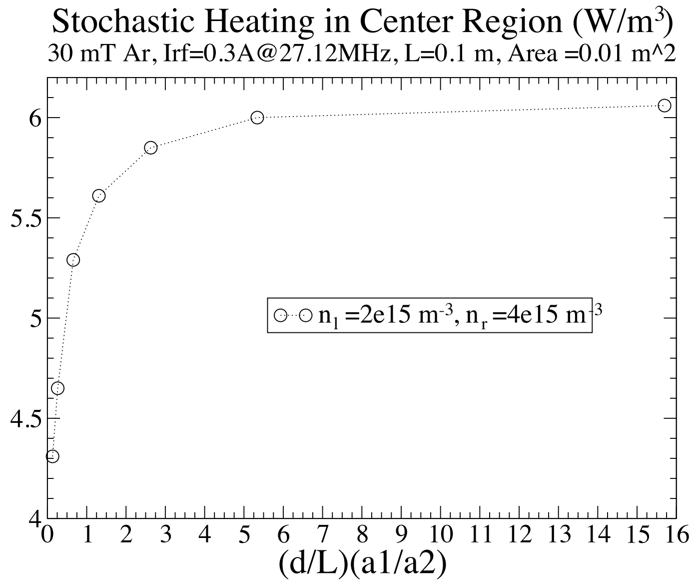


(b) $a_1 = 20$

$$n(x) = \frac{n_0}{2}\left[a_2 + \tanh\left(\frac{a_1}{L}(x - \frac{L}{2})\right)\right]$$

- Vary slope using a_1 in tanh function and find stochastic heating

STOCHASTIC HEATING WITH VARIABLE SLOPE



- $d = v_e/\omega \approx 0.4$ cm = "mixing" length (1 radian phase change) (v_e = electron thermal velocity)
- La_2/a_1 = scale length of step (0.025–3 cm)
- Saturation for small scale length; adiabatic for large scale length
- Electron oscillation amplitude (≈ 0.04 cm) may be significant

SUMMARY

- A transition from a narrow gap EN discharge with an EP edge, to a narrower gap discharge with no EP edge, was investigated with PIC simulations and modeling
- The effects of a bi-Maxwellian EEDF, with an EP edge, and sheath attachment and core uncovering, with no EP edge, need to be taken into account in modeling
- A transition from sheath to internal stochastic heating after the EP edge disappears is observed, and is being studied with fixed ion, two-step and single-step density, PIC simulations
- At the higher pressures, the ohmic heating has to be carefully calculated in order to determine the true stochastic heating in the PIC simulations