CAPACITIVE DISCHARGES DRIVEN BY COMBINED DC/RF SOURCES

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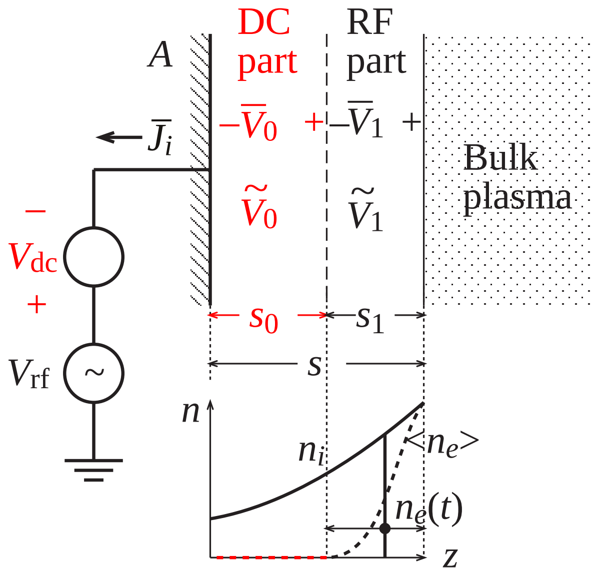
MOTIVATIONS FOR ADDING DC SOURCE

- "Tune" discharge particle and energy balance
  (⇒ $T_e \downarrow$, $n_e \uparrow$, radial uniformity)
- "Tune" secondary electron bombardment of substrate
  (etch selectivities, charging damage)

OUTLINE

- Structure of DC/RF sheaths — theory
- Equal area diode discharges — theory and 1D PIC simulations
- Asymmetric diode discharges — theory and 1D PIC simulations
- Secondary electrons — timescales and energy deposition
- Triode discharges — theory and 2D PIC simulations

STRUCTURE OF A DC/RF SHEATH



DC voltage $\overline{V} = \overline{V}_0 + \overline{V}_1$

RF voltage $\widetilde{V} = \widetilde{V}_0 + \widetilde{V}_1$

- New result for Child law for collisionless ions:

$$\bar{J}_i = \frac{4}{9}\epsilon_0 \left(\frac{2e}{M}\right)^{1/2} \frac{(\overline{V}^{1/2} - \frac{1}{3}\overline{V}_1^{1/2})(\overline{V}^{1/2} + \frac{2}{3}\overline{V}_1^{1/2})^2}{s^2}$$

- New result for Child law for collisional ion sheath also obtained

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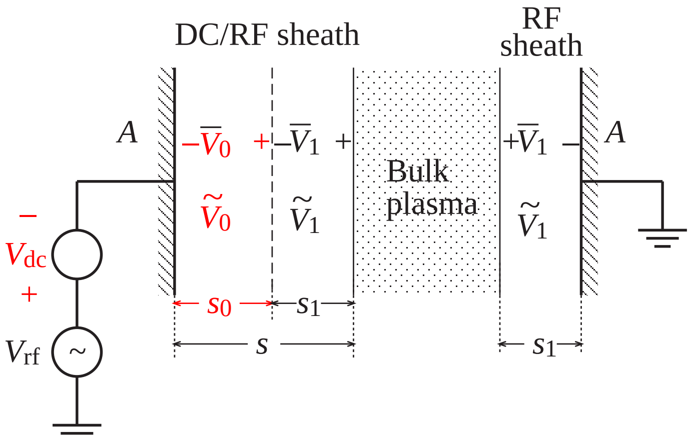
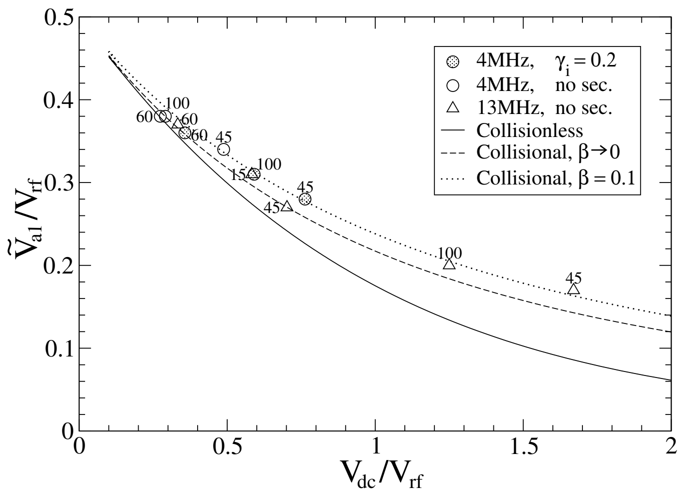
EQUAL AREA DIODE DISCHARGE

- Comparison of theory with 1D particle-in-cell (PIC) simulations



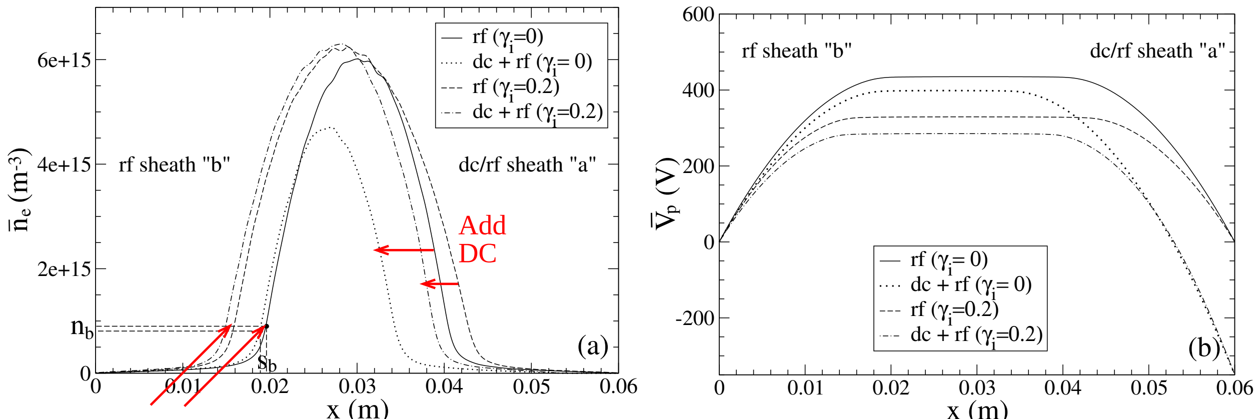


(Symbols: PIC with argon pressure in mTorr; lines: theory; $\beta \propto \lambda_D/\lambda_i$ = collisionality; γ_i = secondary emission coefficient)

- Excellent agreement of PIC with collisional Child law

DENSITY AND VOLTAGE AT CONSTANT P_{rf}

(60 mTorr, 6 cm gap, 4 MHz, 0.017 W/cm^2, $V_{dc} = 350$ V)



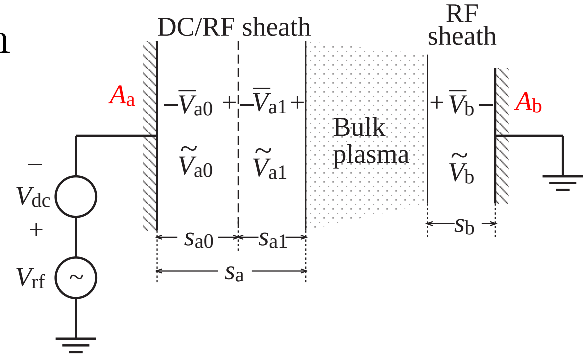
	γ_i	V_{rf} (V)	$\overline{V}_b$ (V)	$\mathcal{E}_{ceff}$ (V)
Rf only	0	1064	436	64
Dc+rf	0	1277	398	60
Rf only	0.2	805	330	53
Dc+rf	0.2	980	283	46

($\overline{V}_b$ = plasma potential; $\mathcal{E}_{ceff}$ =collisional energy loss/electron-ion pair)

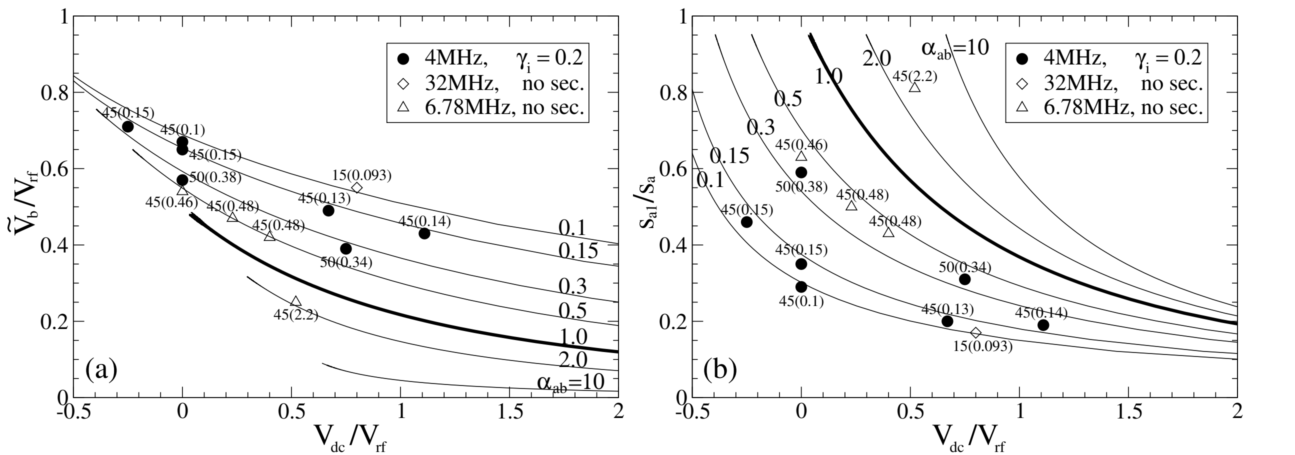
- Plasma potential $\overline{V}_b$ and sheath width s_b independent of V_{dc}
- Secondary electrons increase discharge efficiency
- V_{dc} reduces bulk plasma thickness

ASYMMETRIC DIODE RESULTS

- Excellent agreement between 1D (cylindrical) PIC and collisional CL theory



- Introduce rf voltage asymmetry ratio $\alpha_{ab} = \widetilde{V}_{a1}/\widetilde{V}_b$



Numbers near each symbol: mTorr (α_{ab})

SECONDARY ELECTRON LOSS PROCESSES

- Surface losses to substrate and walls:

  — Transit time across gap $\tau_{\text{fr}} = d/v_h$ at low pressures
  — Diffusion time $\tau_{\text{diff}} = d^2/2D_h$ at higher pressures $(D_h = \lambda_h \bar{v}_h/3)$
  — Trapping time $\tau_{\text{trap}} = \delta/f$ (favorable configuration of rf voltages can trap secondaries for a fraction δ of the rf period $1/f$)

$$\boxed{\tau_{\text{lh}} = (\tau_{\text{fr}}^2 + \tau_{\text{diff}}^2 + \tau_{\text{trap}}^2)^{1/2} = \nu_{\text{lh}}^{-1}}$$

- Volume losses: secondary electrons lose energy and join the thermal population

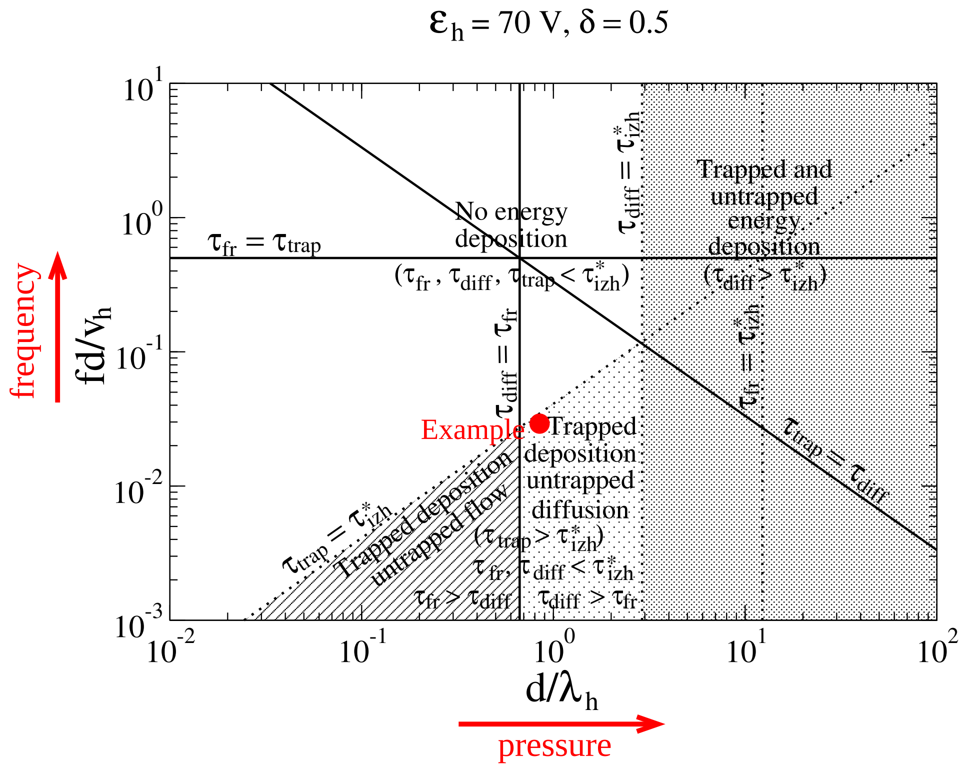
$$\boxed{\tau_{\text{izh}}^* = \frac{\mathcal{E}_{\text{h}}}{\nu_{\text{izh}}\mathcal{E}_{ch}}}$$

($\mathcal{E}_{\text{h}}$, ν_{izh} are secondary energy and ionization frequency;
$\mathcal{E}_{ch} \approx 20$ V is secondary collisional energy loss/e-i pair created)

- Total loss frequency is $\nu_{\text{h}} = \nu_{\text{lh}} + \nu_{\text{izh}}^*$

If $\nu_{\text{izh}}^* \gg \nu_{\text{lh}}$, secondary electrons efficiently produce e-i pairs
If $\nu_{\text{lh}} \gg \nu_{\text{izh}}^*$, secondary electrons efficiently bombard the substrate

ENERGY DEPOSITION REGIONS



- Most interesting regions are where trapped and untrapped electrons behave differently

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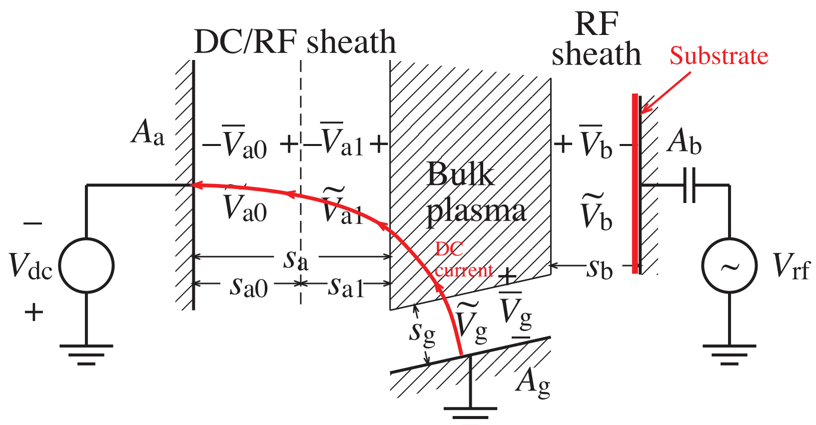
TRIODE DC/RF DISCHARGE

- Substrate can have a dielectric layer which cannot draw dc current

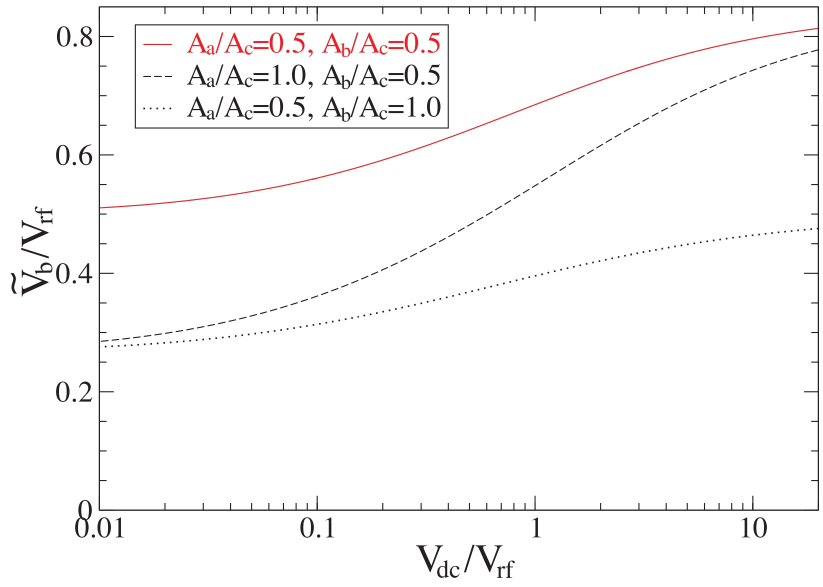
A triode configuration is necessary



- A global model incorporating the collisional dc/rf sheath is used to determine the voltages, currents, and sheath widths

TRIODE RF PLASMA POTENTIAL $\tilde{V}_b$ VERSUS V_{dc}

- Collisional theory results for triode



- Example (red solid line):

  DC electrode area = ground electrode area = $\frac{1}{2}\times$ RF electrode area

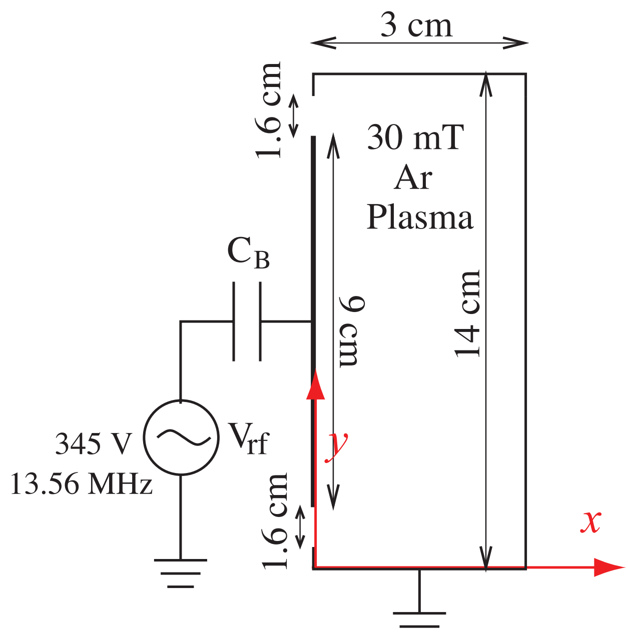
  For $V_{\rm dc} \to 0$, equal area diode and $\widetilde{V}_{\rm b}/V_{\rm rf} = 0.5$

  For $V_{\rm dc} \to \infty$, asymmetric diode and $\widetilde{V}_{\rm b}/V_{\rm rf} = 0.86$.

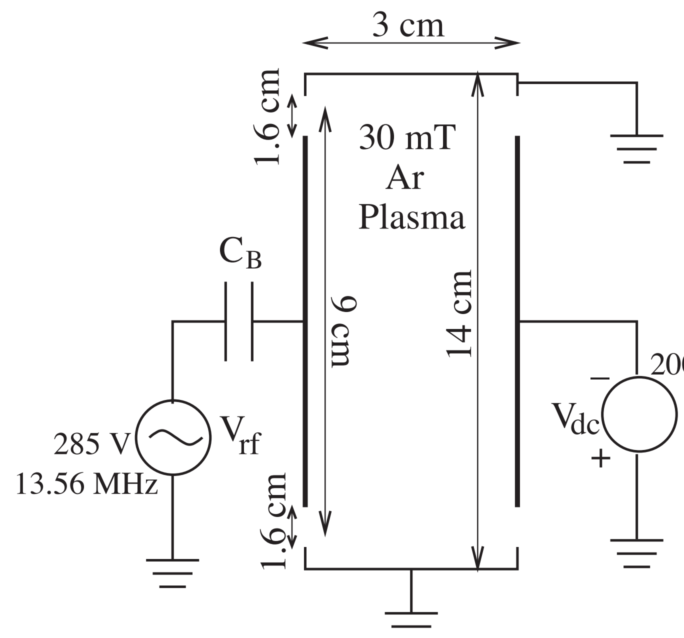
2D PIC SIMULATION BASE CASE

- $p = 30$ mTorr, $P_{\mathrm{rf}} = 2.2$ W, $\gamma_i = 0.2$ at all surfaces
- Secondaries in "trapped deposition, untrapped diffusion" regime

RF only



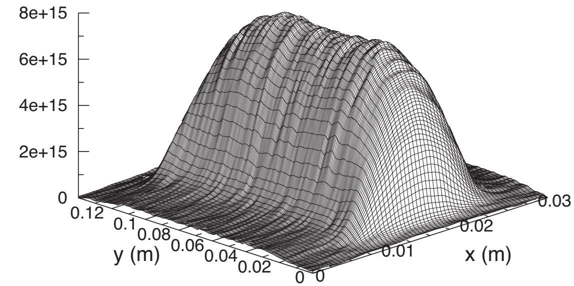
DC/RF triode

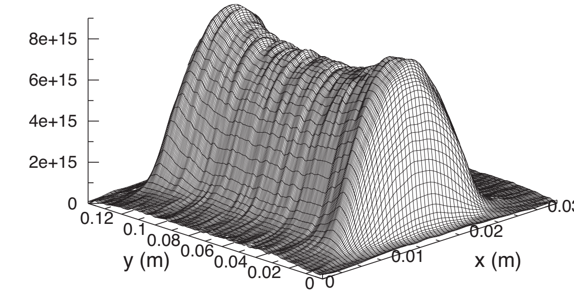


UNIFORMITY IS MODIFIED BY V_{dc}

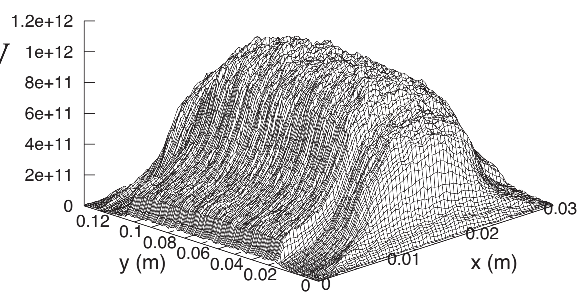
Rf only | Dc/rf

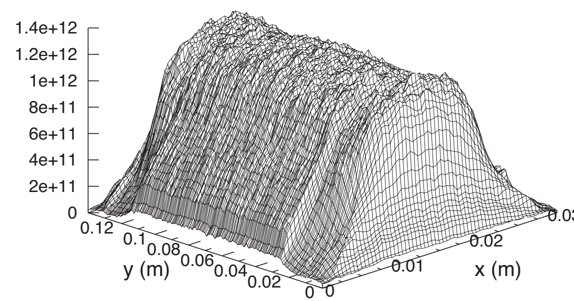
Plasma density (m^{-3})





Secondary density (m^{-3})





- Thinner bulk plasma near midplane ($y = 0.06$ m) for DC/RF case

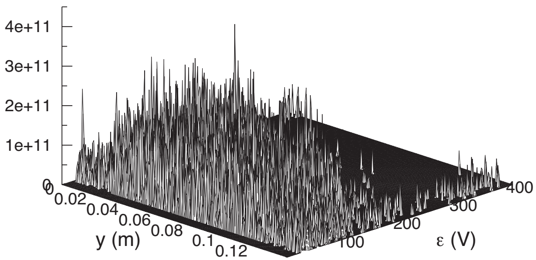
$\Rightarrow$ center-low plasma density profile

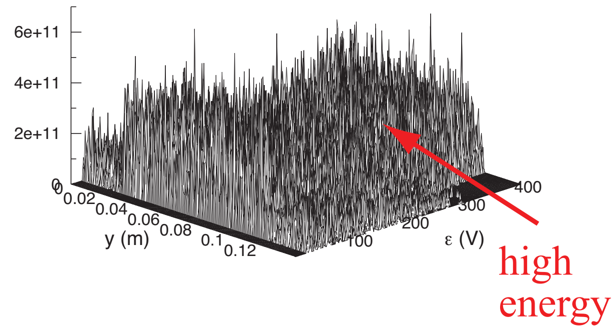
BALLISTIC SECONDARY ELECTRONS CREATED BY V_{dc}

Rf only

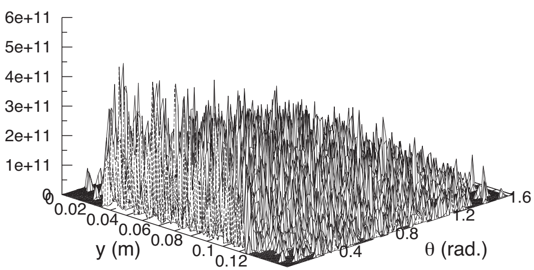
Dc/rf

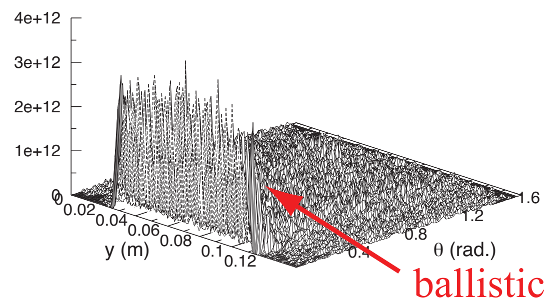
Secondary energy distribution (arb units)





Secondary angular distribution (arb units)





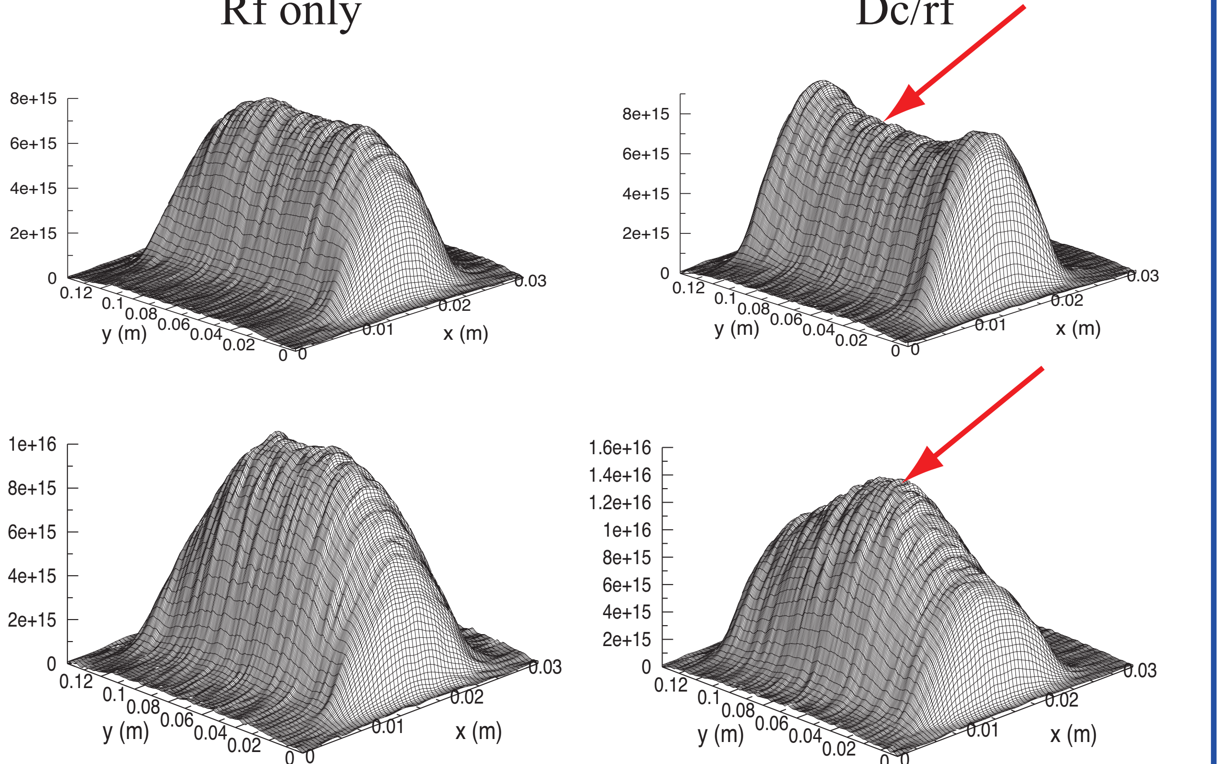
- Secondary electrons are ballistic and have high energies for DC/RF case

PLASMA DENSITY PROFILES VERSUS PRESSURE

Rf only | Dc/rf

30 mTorr

45 mTorr



- Effects of V_{dc} on profile:
  Thinner bulk plasma ⇒ center-low profile
  Increased secondary ionization ⇒ center-high profile

CONCLUSIONS

- Collisionless and collisional DC/RF Child laws determined
- DC voltage can control the discharge asymmetry
- DC voltage increases secondary electron ionization
- DC voltage reduces bulk plasma thickness
- DC voltage promotes the formation of ballistic electrons
- DC voltage modifies the plasma density profile

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Ref: E. Kawamura, M.A. Lieberman, and A.J. Lichtenberg, "Capacitive Discharges Driven by Combined DC/RF Sources", *J. Vac. Sci. Technol. A*, **25,** 1456–74, Sept. 2007