RECENT PROGRESS ON THE PHYSICS OF CAPACITIVE DISCHARGES

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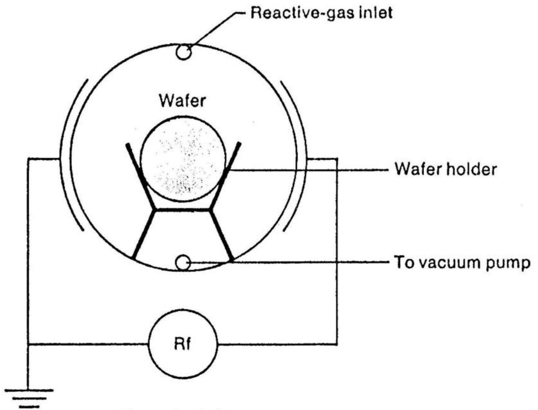
OUTLINE

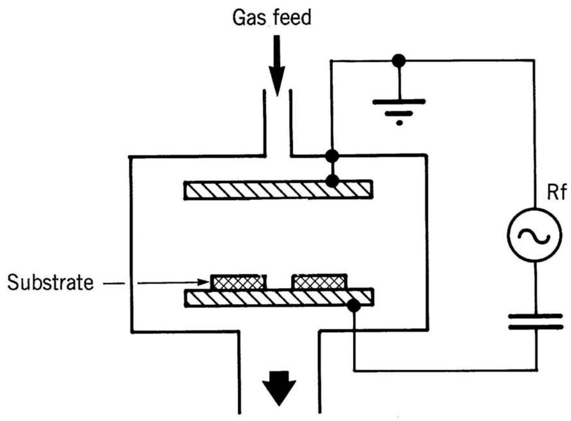
- Why capacitive discharges?
- Dual frequency capacitive discharges
  - — Decoupling conditions
  - — Stochastic heating
- Ion/neutral energy distributions on the substrate sufrace
- Dc/rf discharges
  - — Electron energy distributions at the substrate
- High frequency electromagnetic effects
  - — Standing waves and their control
  - — Skin effects
  - — 2D finite element method solutions
- Nonlinear phenomena

EVOLUTION OF ETCHING DISCHARGES — FIRST AND SECOND GENERATIONS

FIRST GEN-
ERATION

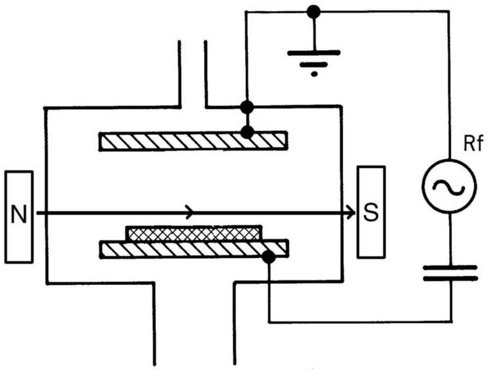


Barrel etcher
(Isotropic etch)

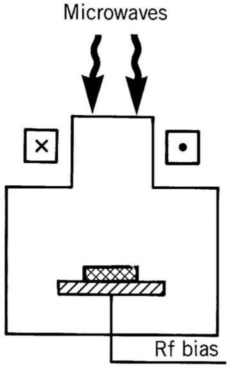


Capacitive
(Anisotropic etch)

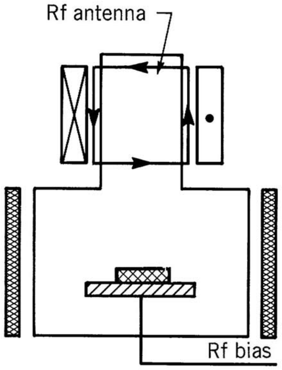
SECOND
GENER-
ATION



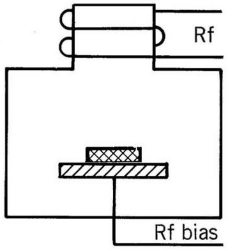
Magnetically enhanced
capacitive discharge



ECR

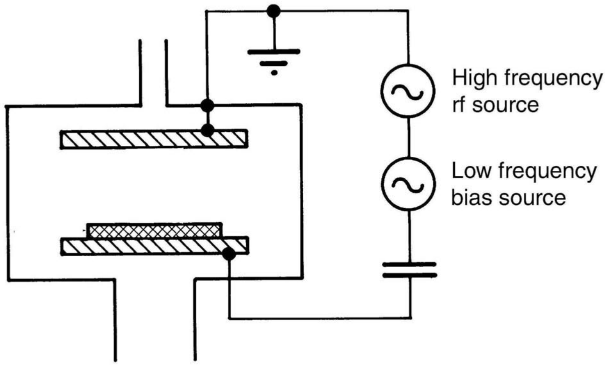


Helicon

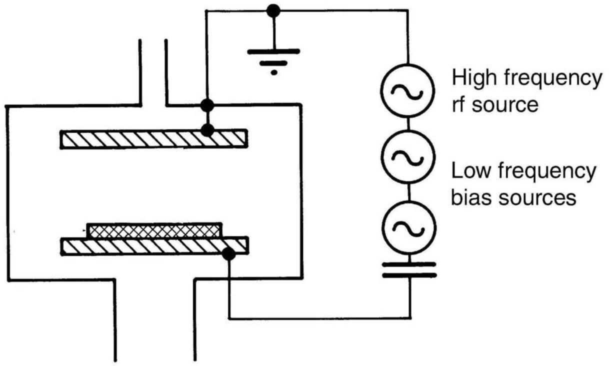


Inductive

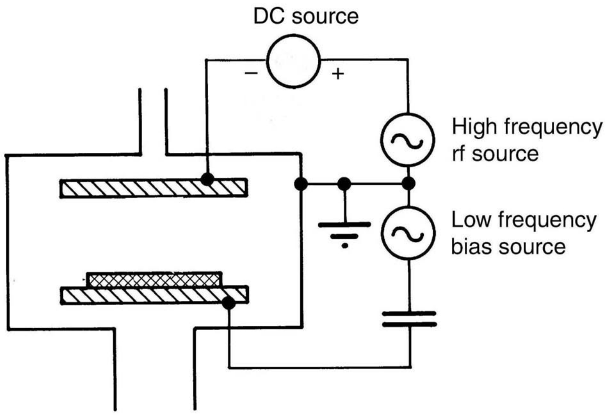
THIRD GENERATION —
INTERCONNECT DIELECTRIC ETCH



Dual frequency capacitive discharge



Triple frequency capacitive discharge



DC/dual frequency capacitive discharge

- In the year 2020
  - — 6nm gate width, 6 billion transistors, 73 GHz on-chip clock
  - — 14–18 wiring levels (dielectric layers)
- Why capacitive discharge?
  - — low surface area seen by plasma (inexpensive)
  - — silicon upper electrode (control of F/CF_x ratio)
  - — robust uniformity over wide pressure range

DUAL FREQUENCY CAPACITIVE DISCHARGES

WHY DUAL FREQUENCY CAPACITIVE DISCHARGES?

- Independent control of ion flux and ion energy

High frequency power P_h controls ion flux
Low frequency voltage V_l controls ion energy

1. H.C. Kim, J.K. Lee, and J.W. Shon, *Phys. Plasmas* **10**, 4545 (2003)
2. M.A. Lieberman, J. Kim, J.P. Booth, J.M. Rax and M.M. Turner, SEMICON Korea Etching Symposium, p. 23 (2003)
3. P.C. Boyle, A.R. Ellingboe, and M.M. Turner, *J. Phys. D: Appl. Phys.* **37**, 697 (2004)

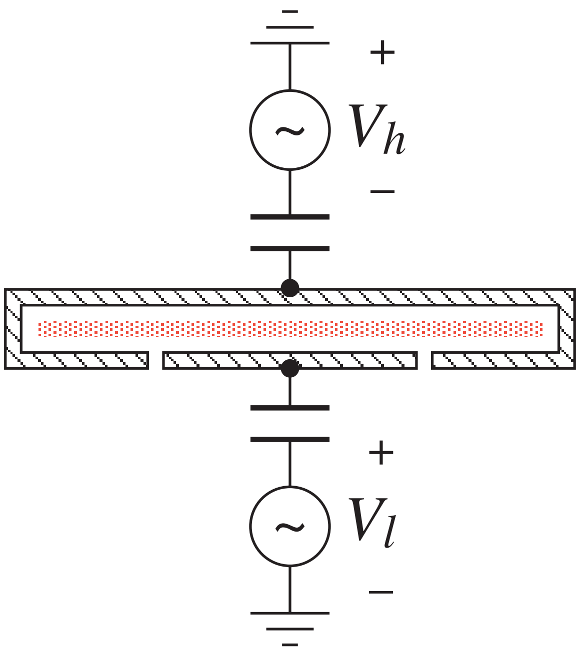
- $R \sim 15$–30 cm, $L \sim 1$–3 cm

$p \sim 30$–300 mTorr, $C_4F_8/O_2/Ar$ feedstock

$f_h \sim 27.1$–160 MHz, $V_h \sim 50$–200 V

$f_l \sim 2$–13.56 MHz, $V_l \sim 500$–1500 V

Absorbed powers $P_h,\ P_l \sim 500$–3000 W



IDEAL DECOUPLING CONDITIONS

- Plasma density $n \ \propto$ electron power P_e

  Total power absorbed:

  $$P_{\text{abs}} = P_e\left(1 + \overbrace{0.4\frac{V_{\text{rf}}}{\mathcal{E}_c + \mathcal{E}_e'}}^{\text{make ion power small}}\right)$$

  $V_{\text{rf}} =$ source voltage, $\mathcal{E}_c + \mathcal{E}_e' =$ electron energy lost/e-i pair created

  — Only high frequency source supplies electron power

  $$\boxed{\omega_h^2 V_h^{1/2} \gg \omega_l^2 V_l^{1/2}}$$

  — High frequency source only supplies electron power

  $$\boxed{V_h \ll 2.5(\mathcal{E}_c + \mathcal{E}_e')}$$

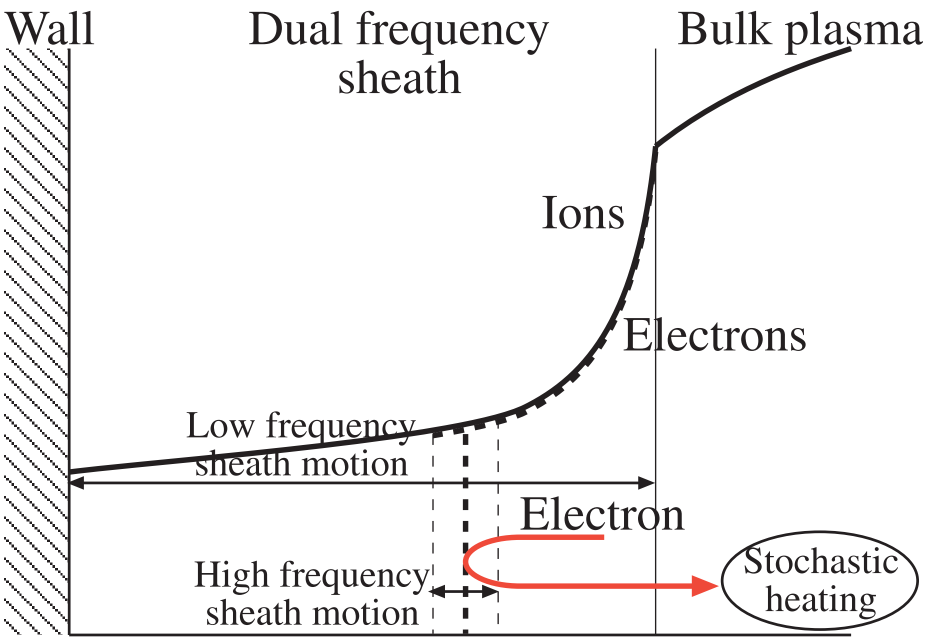
- Dc sheath voltage $\overline{V} \ \propto \ V_h + V_l$ (+ small crossterm)

  — Low frequency source sets sheath voltage

  $$\boxed{V_l \gg V_h}$$

DUAL FREQUENCY STOCHASTIC HEATING

- An important electron heating process below 200 mTorr



- How are electrons heated by the high frequency oscillations?

1. M.M. Turner and P. Chabert, *Phys. Rev. Lett.* **96,** 205001, 2006
2. E. Kawamura, M.A. Lieberman, and A.J. Lichtenberg, *Phys. Plasmas* **13,** 053506, 2006
3. I.D. Kaganovich, O.V. Polomarov, and C.E. Theodosiou, *IEEE Trans. Plasma Sci.* **34,** 696, 2006

STOCHASTIC HEATING POWER

- Hard wall theory in dual frequency regime:

$$\boxed{S_{\text{stoc}} = \underbrace{\frac{1}{2} m \bar{v}_e \frac{J_h^2}{e^2 n_s}} \times \underbrace{\left(1 + \frac{\pi}{4} H_l\right) \left(\frac{H_l}{H_l + 2.2}\right)}}$$

High freq part Low freq part $F(H_l)$

S_{stoc} = stochastic heating power per unit electrode area

m = electron mass

$\bar{v}_e = (8e\mathrm{T}_e/\pi m)^{1/2}$ = mean thermal electron speed

J_h = high frequency current density

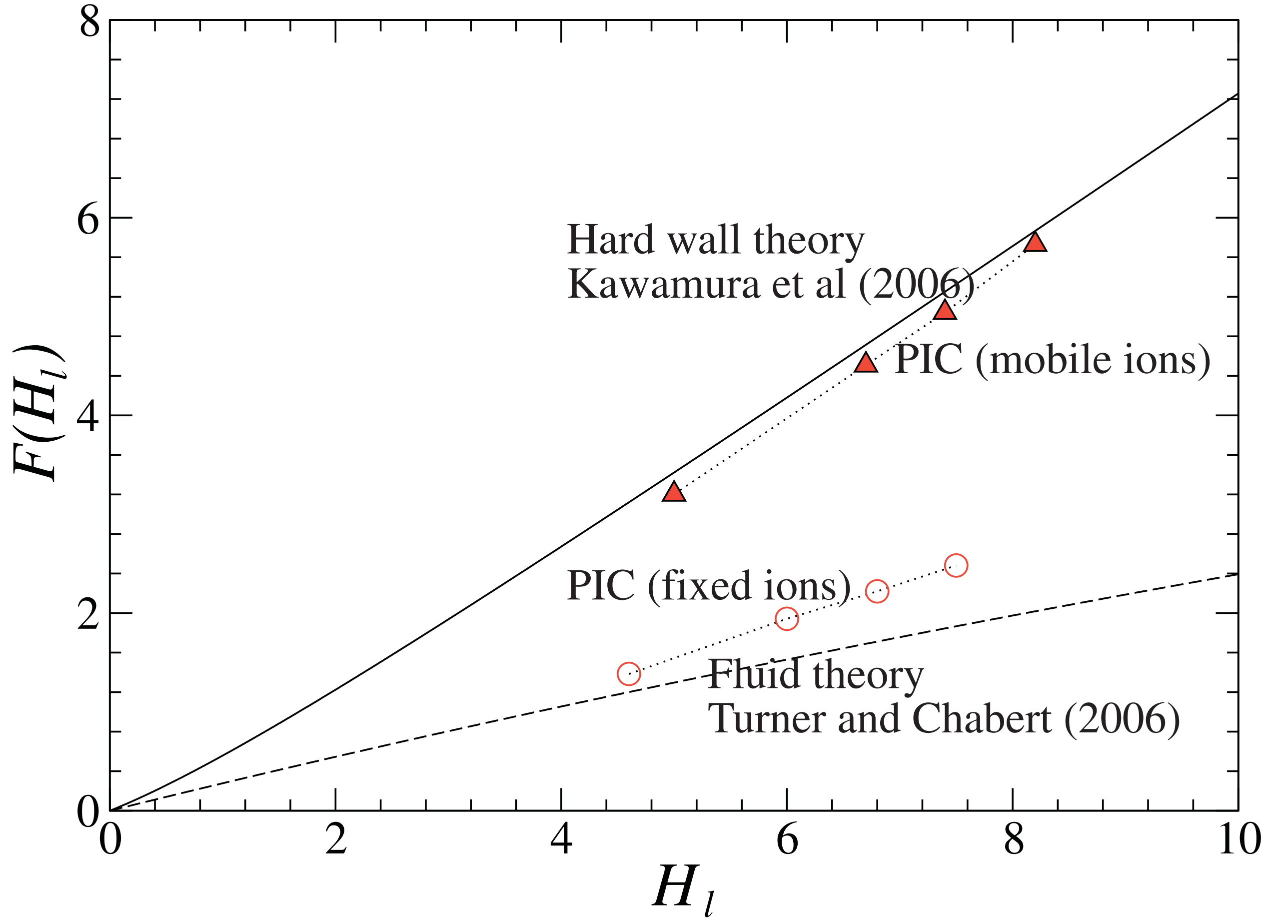
n_s = plasma density at bulk plasma–sheath edge

$H_l = 0.55(V_l/\mathrm{T}_e)^{1/2}$ =low frequency enhancement factor

- Fluid theory gives similar result

PARTICLE-IN-CELL SIMULATIONS

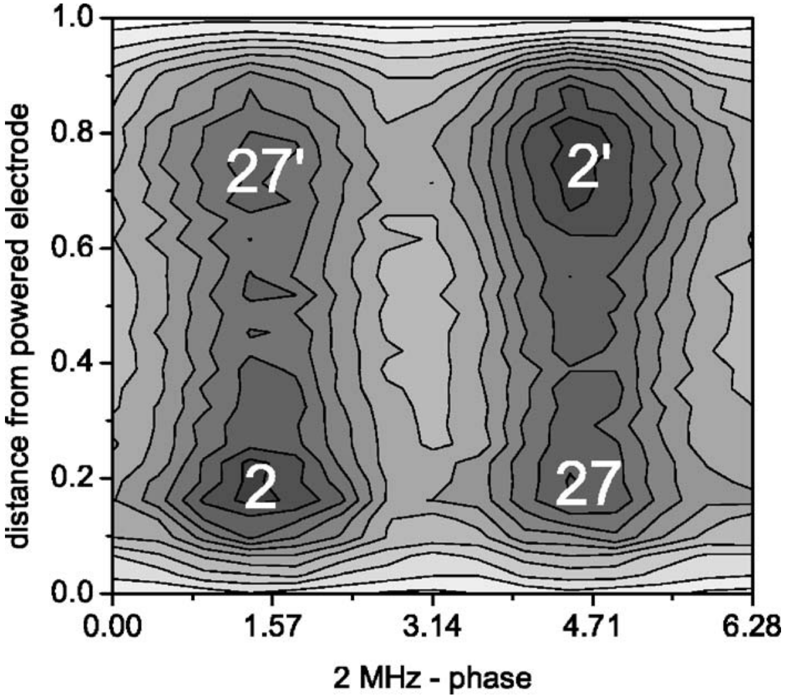
- Dual frequency stochastic heating



- Ohmic heating in the sheath shows similar behavior
(M.M. Turner and P. Chabert, *Appl. Phys. Lett.* **89,** 231502, 2006)

EXPERIMENTS AND SIMULATIONS

- Space- and time-resolved optical emission show coupling



(T. Gans, J. Schulze, D. O'Connell, U. Czarnetski, R. Faulkner, A.R. Ellingboe, and M.M. Turner, *Appl. Phys. Lett.* **89,** 261502, 2006)

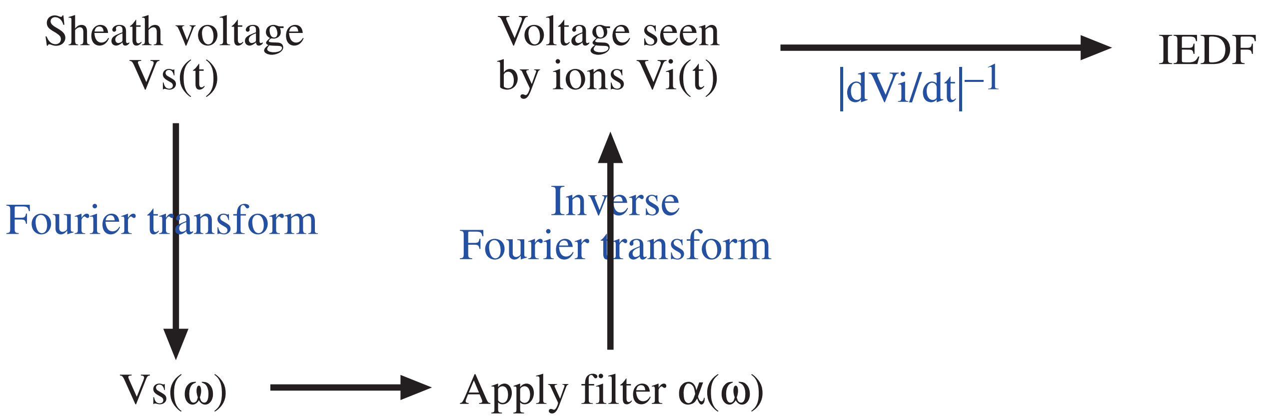
- Energy deposition by "kicked" electrons is complex $\Longrightarrow$ wave-particle interactions, two-stream instabilities (D. O'Connell, T. Gans, D. Vender, U. Czarnetski, and R. Boswell, *Phys. Plasmas* **14,** 034505, 2007)

ION/NEUTRAL ENERGY DISTRIBUTIONS ON THE SUBSTRATE SURFACE

1. T. Panagopoulos and D. Economou, *J. Appl. Phys.* **85,** 3435, 1999
2. S. Shannon, D. Hoffman, J.G. Yang, A. Paterson, and J. Holland, *J. Appl. Phys.* **97,** 103304, 2005
3. A Wu, M.A. Lieberman and J.V. Verboncoeur, *J. Appl. Phys.* **101,** 056105, 2007

ION ENERGY DISTRIBUTION (IED)

- What is energy distribution of ion flux incident on the substrate?
- Collisionless ions with two and three frequencies



Sheath voltage
Vs(t)

Fourier transform

Vs(ω)

Apply filter α(ω)

Inverse
Fourier transform

Voltage seen
by ions Vi(t)

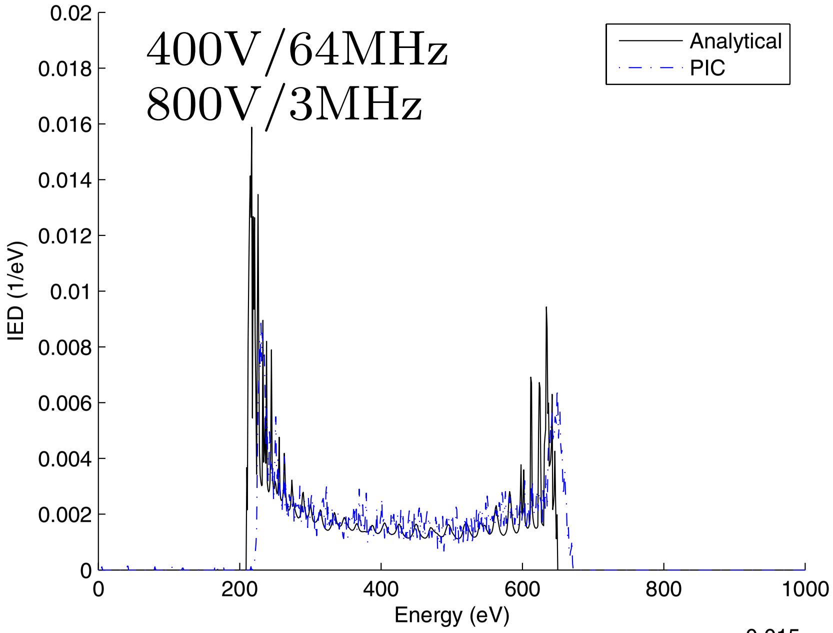
|dVi/dt|$^{-1}$

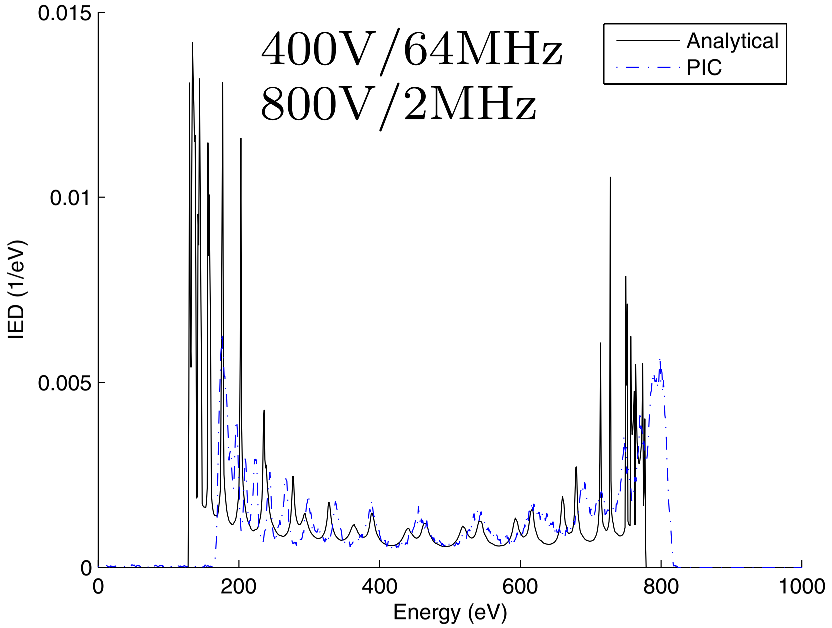
IEDF

- Use filter $\alpha(\omega) = [(c\,\omega\tau_i)^p + 1]^{-1/p}$ with $c = 0.3,\ p = 5$, and
  $\tau_i =$ ion transit time across the sheath $= 3\bar{s}(M/2e\overline{V}_s)^{1/2}$

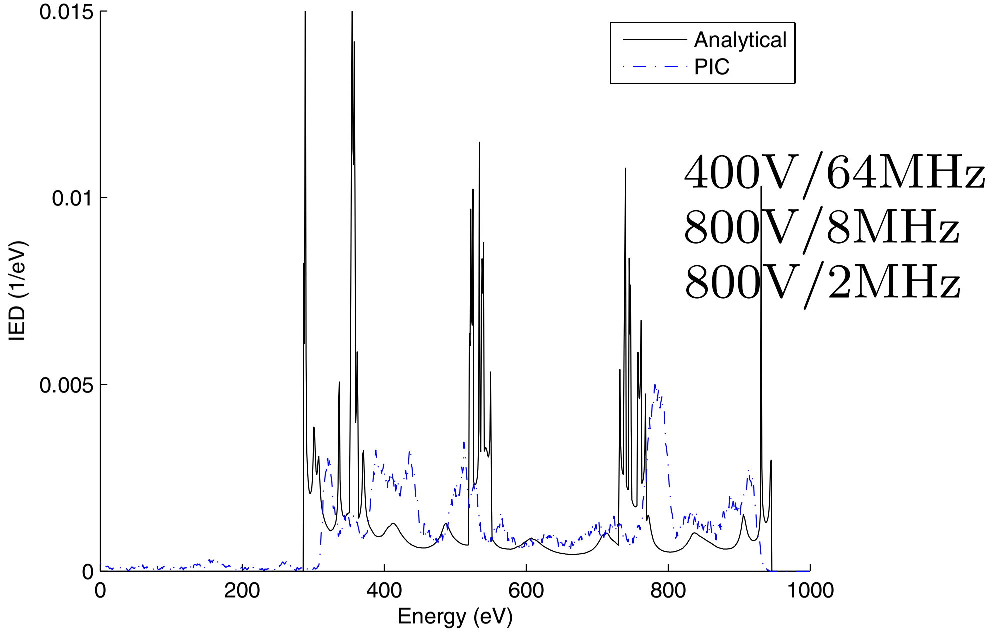
  (P.A. Miller and M.E. Riley, *J. Appl. Phys.* **82,** 3689, 1997
  uses filter with $c = 1,\ p = 2$)

DUAL/TRIPLE FREQUENCY PIC SIMULATIONS

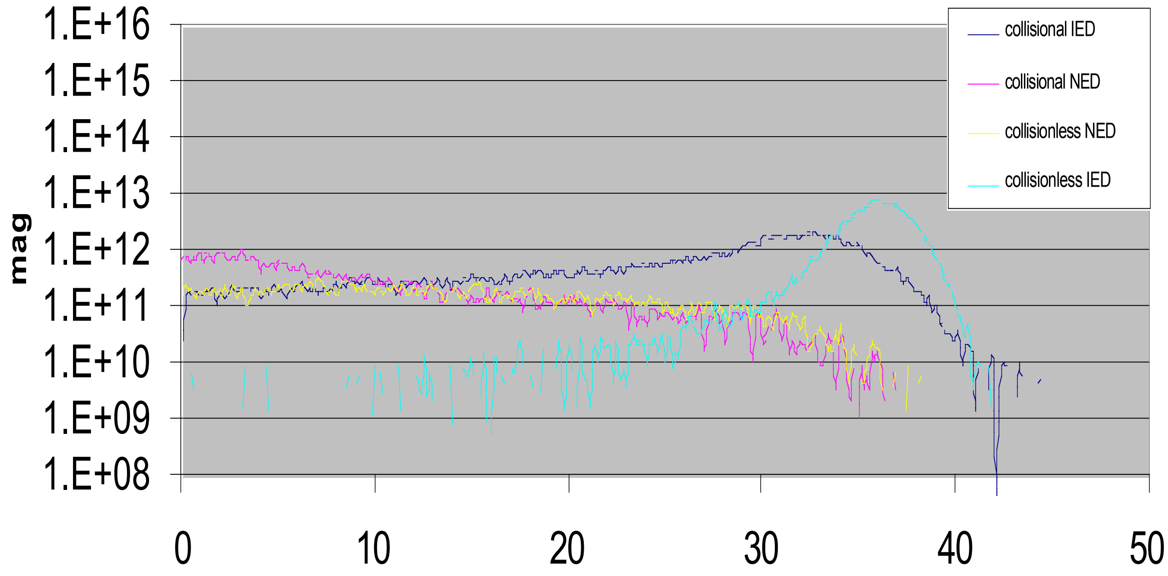




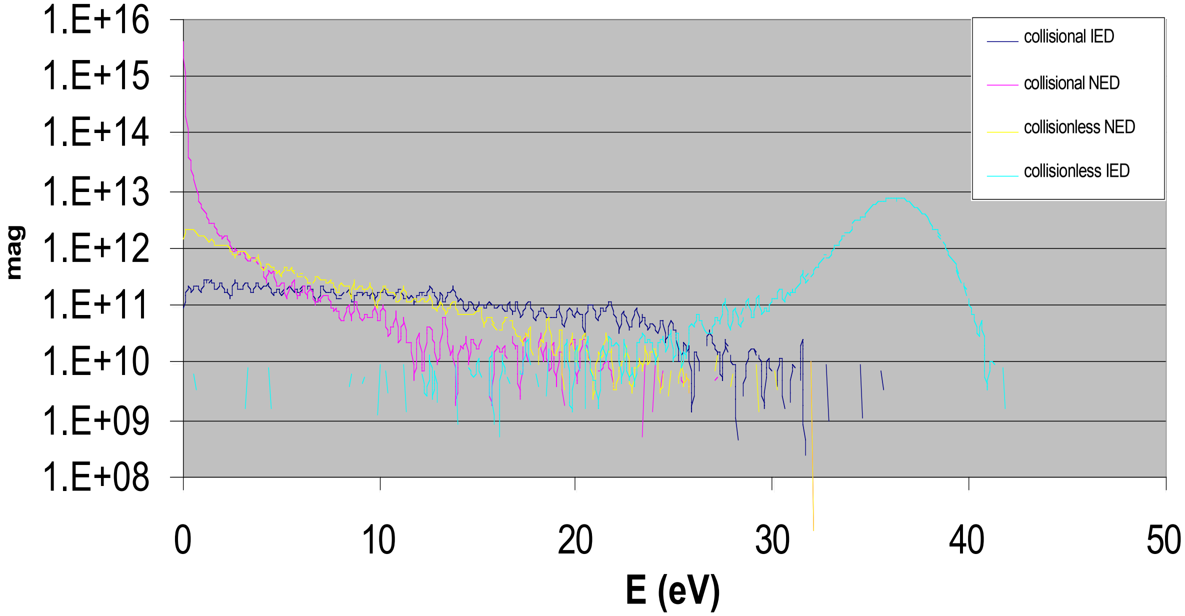
Gap=3 cm
p=30 mTorr
Collisionless ions



COLLISIONS WITH/AMONG NEUTRALS



10 mTorr



80 mTorr

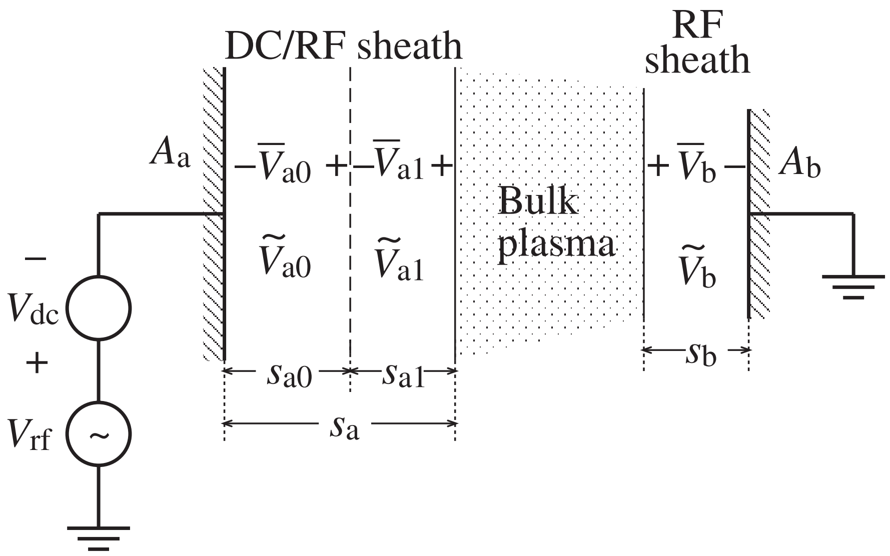
(with A. Wu and J.P. Verboncoeur)

DC/RF DISCHARGES

1. W.T. Lai et al, “Etch Uniformity Control by Gap and DC Superposition at 65nm metal hard-Mask Dual Damescene”, *Proc. Int. Symp. Dry Process*, 2006
2. E. Kawamura, M.A. Lieberman, and A.J. Lichtenberg, “Capacitive Discharges Driven by Combined DC/RF Sources”, submitted to *J. Vac. Sci. Technol. A*, 2007
3. V.A. Godyak and N. Sternberg, *Phys. Rev. A* **42,** 2299, 1990
4. K. Kohler, J.W. Coburn, D.E. Horne, E. Kay, and J.H. Keller, *J. Appl. Phys.* **57,** 59, 1985

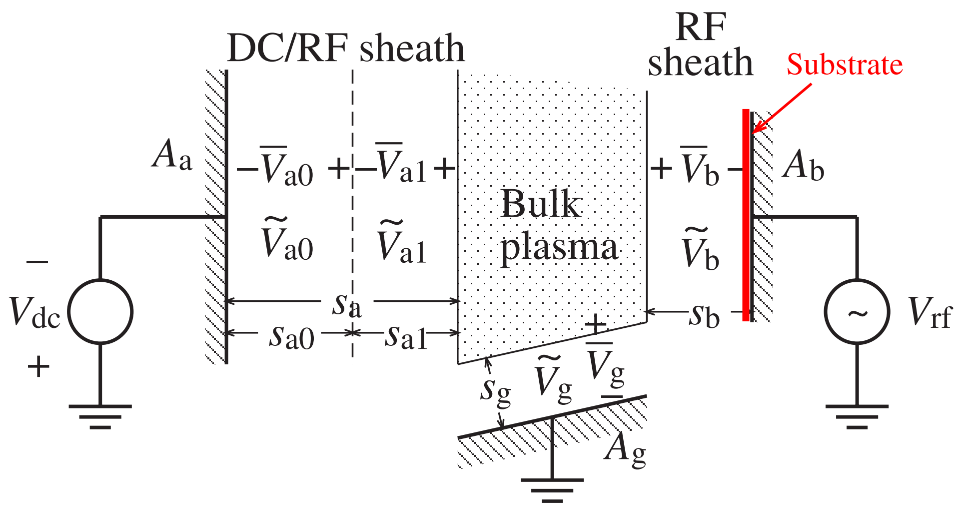
MOTIVATIONS FOR ADDING DC SOURCE

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



DIODE

(for 1D PIC simulations)

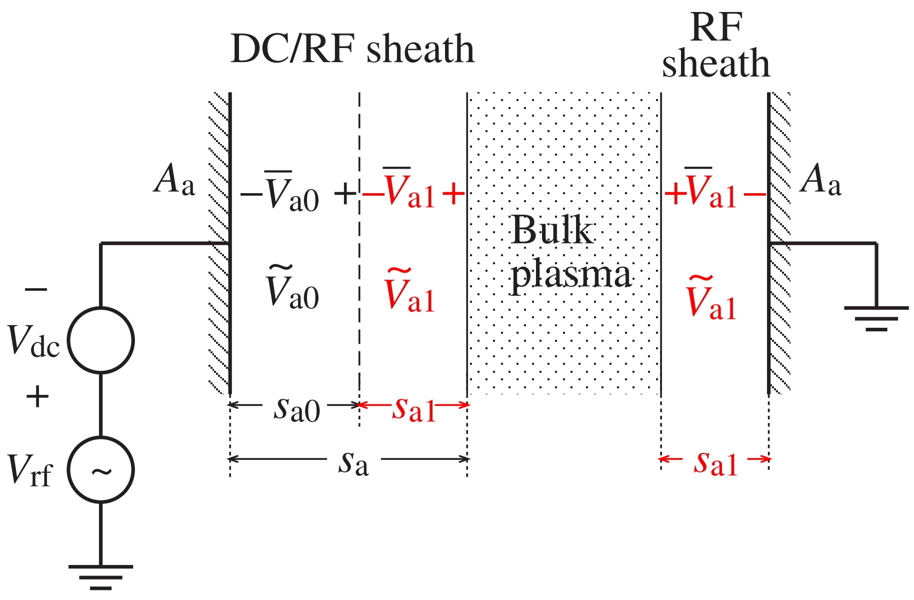


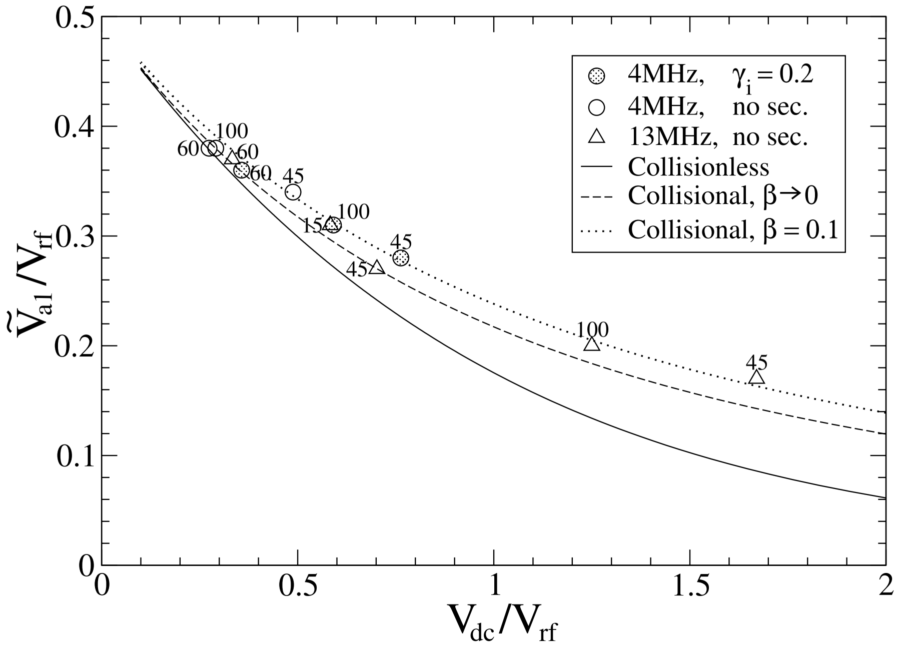
TRIODE

(for industrial use)

COMPARISON TO PIC SIMULATIONS

- Symmetric (1D planar) diode discharges





(Symbols — PIC with pressure in mTorr; lines — theory)

- Asymmetric (1D cylindrical) diode discharges also give good agreement with DC/RF sheath theory

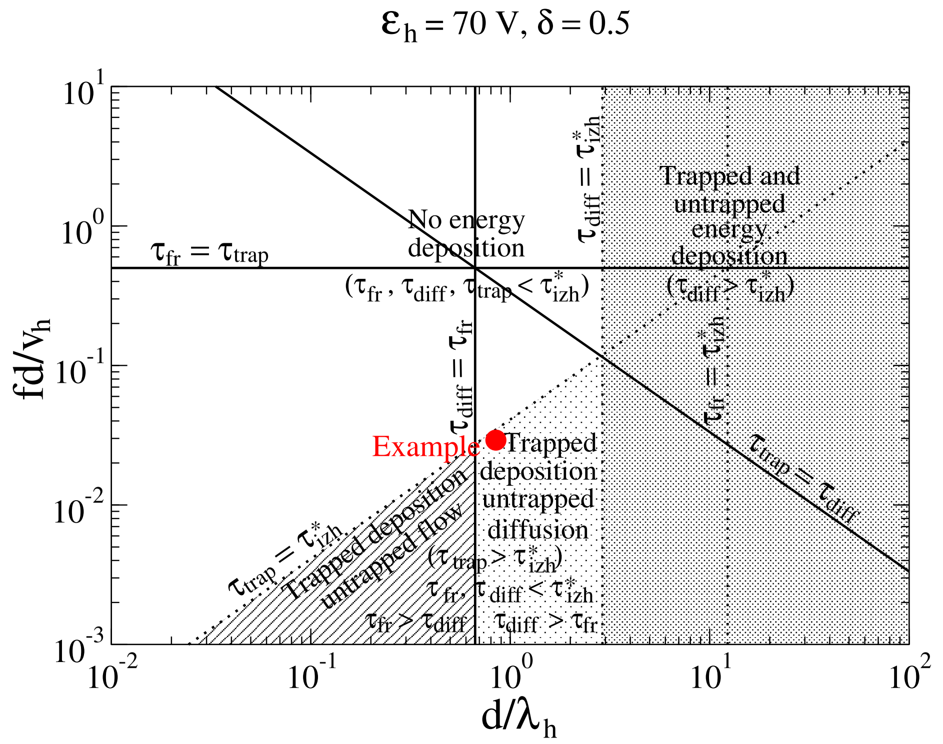
SECONDARY ELECTRON LOSS PROCESSES

— Transit time across gap $\tau_{\rm fr} = d/v_h$ at low pressures

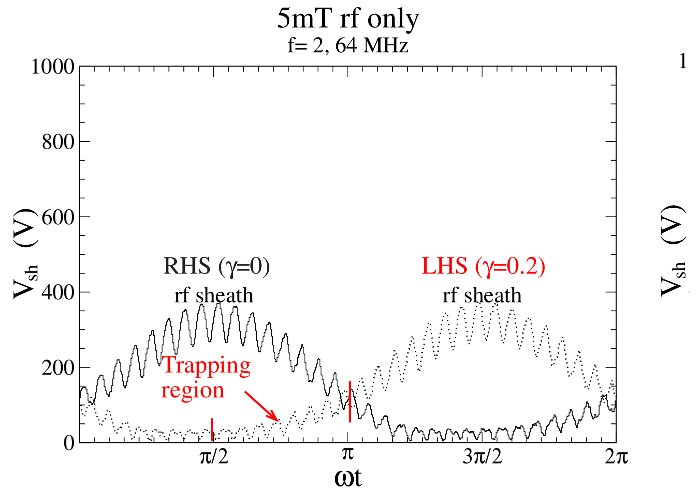
— Diffusion time $\tau_{\rm diff} = d^2/2D_h$ at higher pressures ($D_h = \lambda_h \bar{v}_h/3$)

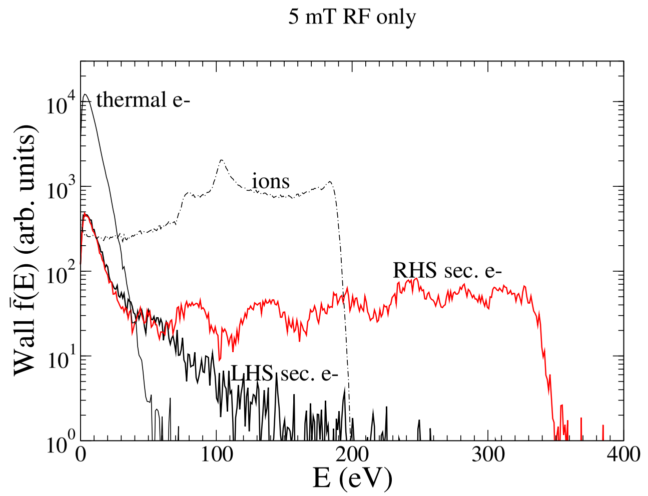
— Trapping time $\tau_{\rm trap} = \delta/f$ (favorable configuration of rf voltages can trap secondaries for a fraction δ of the rf period $1/f$)

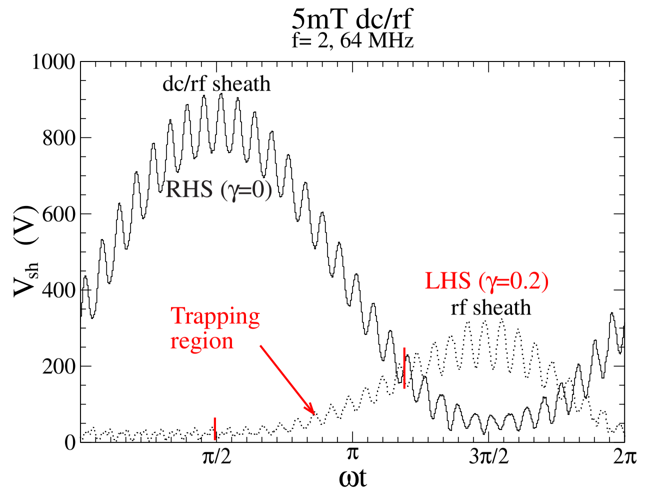
— Collisional energy loss time τ^*_{izh} (secondary electrons lose energy and join the thermal population)

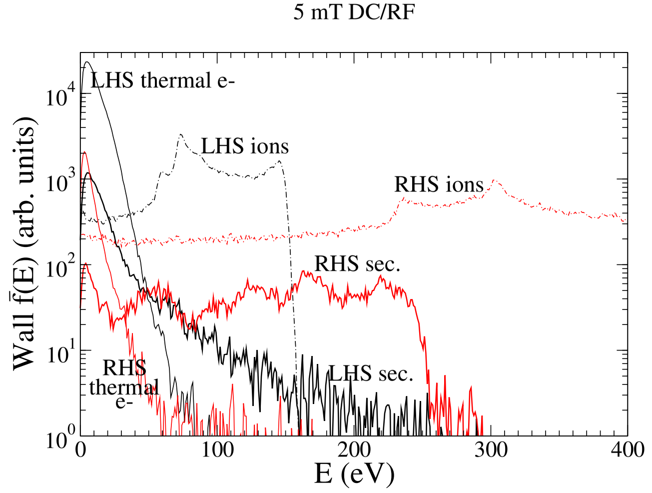


ELECTRON ENERGY DISTRIBUTION ON SUBSTRATE









- DC/RF biasing can control secondary electron characteristics (e.g., increased trapping of secondary electrons)

HIGH FREQUENCY ELECTROMAGNETIC EFFECTS

STANDING WAVES AND SKIN EFFECTS

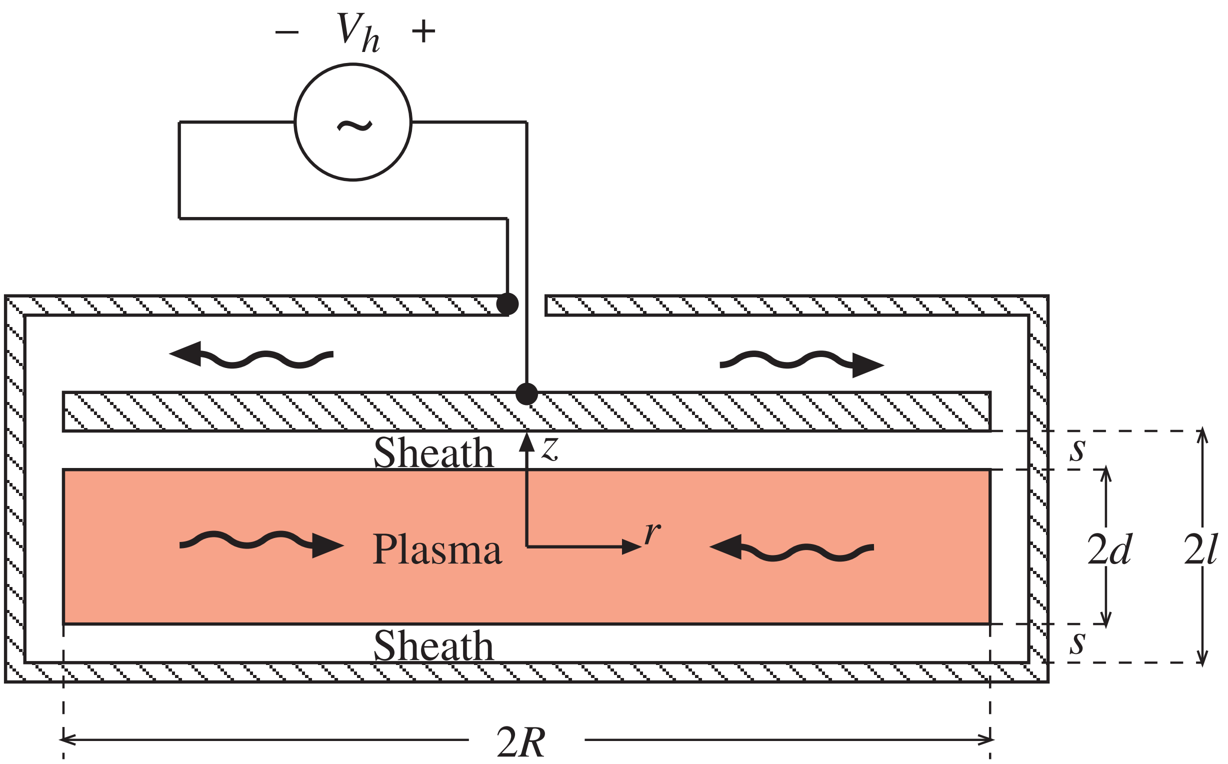
- High frequency and large area ⇒ $\boxed{\text{standing wave effects}}$

- High frequency ⇒ high density ⇒ $\boxed{\text{skin effects}}$

1. M.A. Lieberman, J.P. Booth, P. Chabert, J.M. Rax, and M.M. Turner, *Plasma Sources Sci. Technol.* **11**, 283, 2002
2. P. Chabert, *J. Phys. D: Appl. Phys.* **40**, R63, 2007

CYLINDRICAL CAPACITIVE DISCHARGE

Consider only the high frequency source

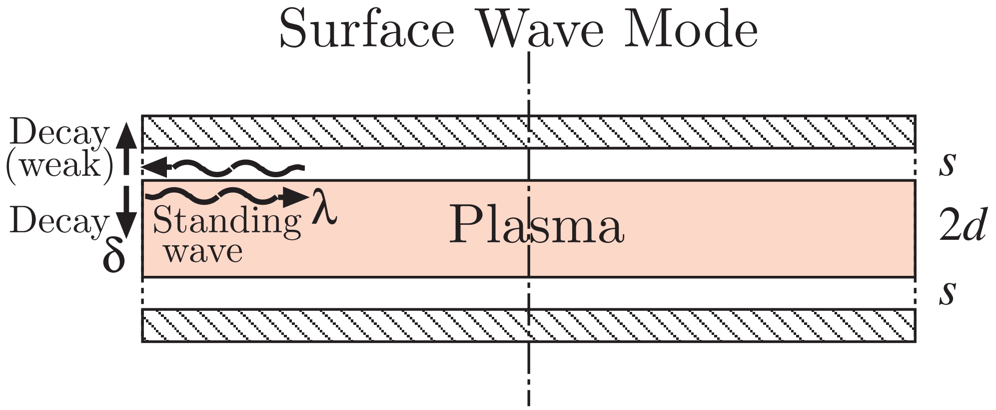


Fields cannot pass through metal plates

(1) V_s excites radially outward wave in top vacuum gap
(2) Outward wave excites radially inward wave in plasma

SURFACE WAVE MODE

- Power enters the plasma via a *surface wave mode:*



- Radial wavelength for surface wave (low density limit):

$$\boxed{\lambda \approx \frac{\lambda_0}{\sqrt{1 + d/s}} \sim \frac{\lambda_0}{3}}$$

with $\lambda_0 = c/f$ the free space wavelength

- Axial skin depth for surface wave:

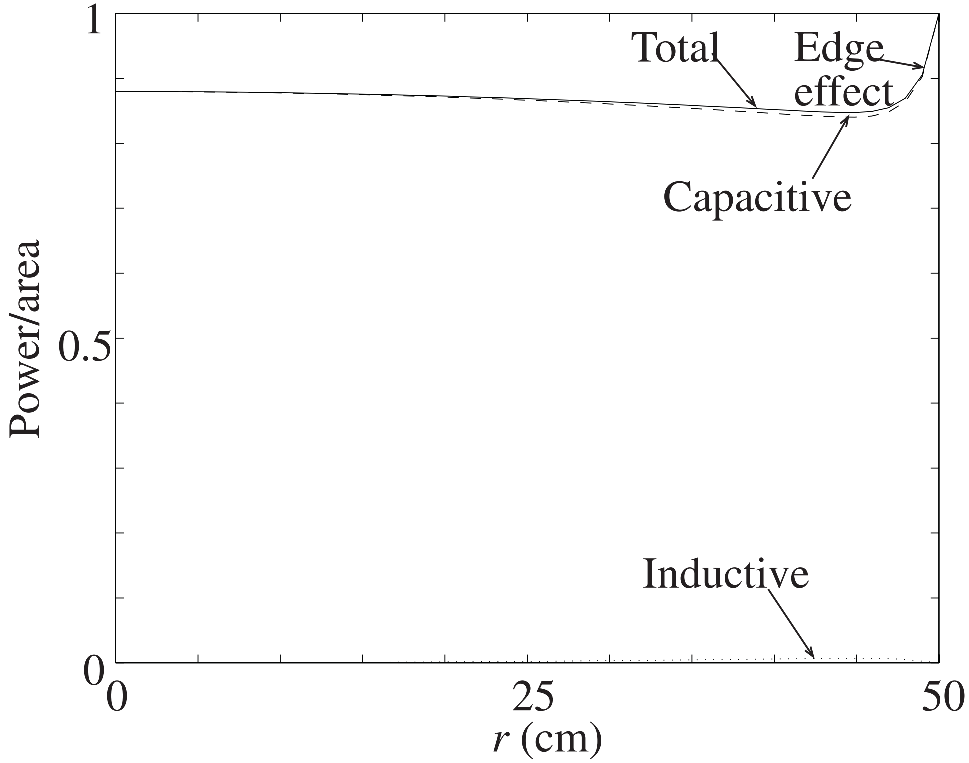
$$\boxed{\delta \sim \frac{c}{\omega_p}}$$

- There are also *evanescent modes* leading to edge effects near $r = R$

STANDING WAVE EFFECT — FIXED $\mathrm{n_e}$ AND s

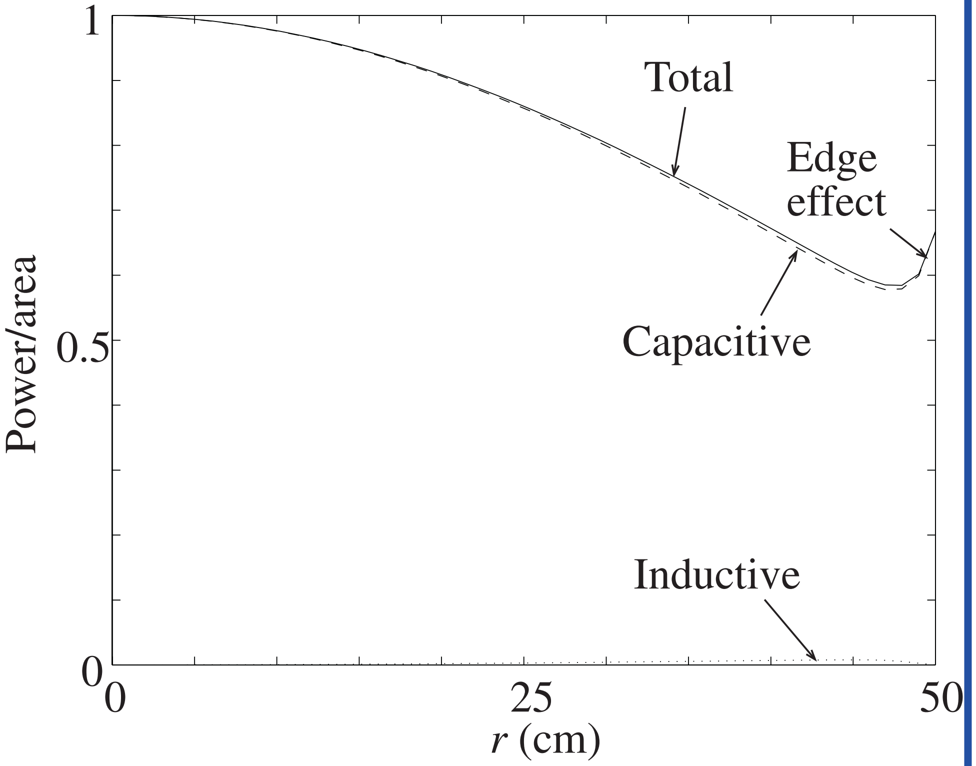
- $R = 50$ cm, $d = 2$ cm, $s = 0.4$ cm, $n_e = 10^9$ cm^{-3}, $\delta \approx 16$ cm
- P_{cap} (dash), P_{ind} (dot) and P_{tot} (solid) as a function of r

13.56 MHz ($\lambda \approx 9$–10 m)



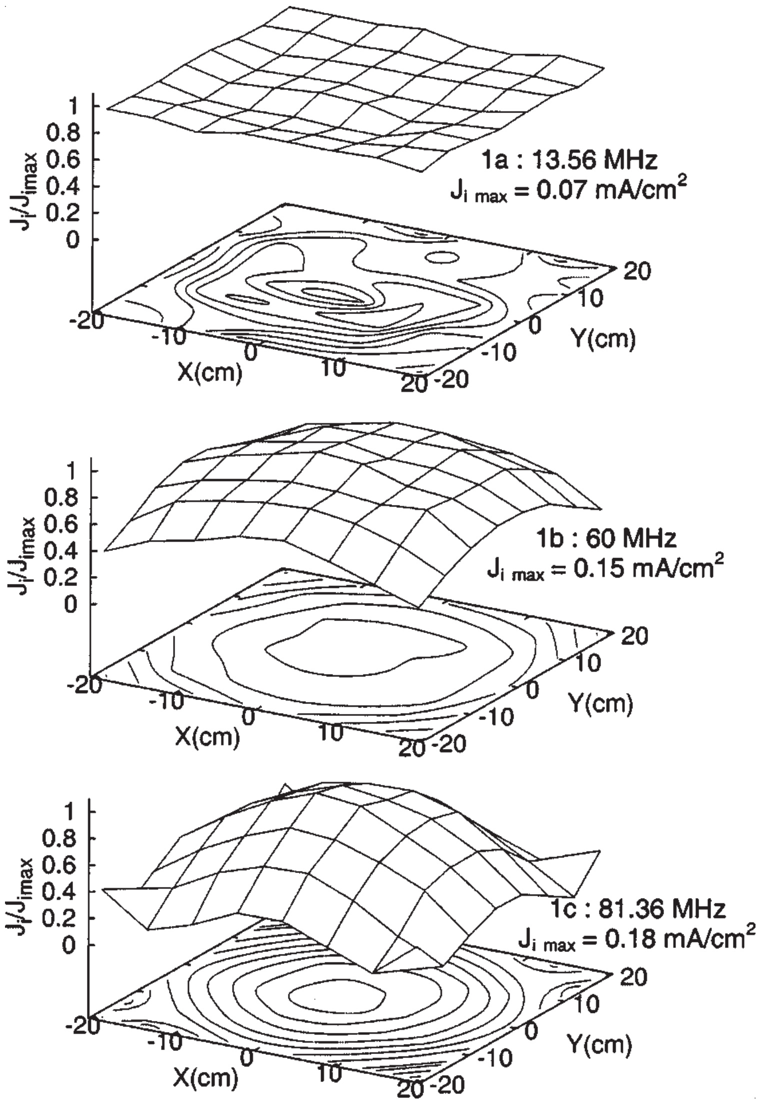
Small standing wave and skin effects

40.7 MHz ($\lambda \approx 3$ m)



Large standing wave effect; center-high profile

EXPERIMENTAL RESULTS FOR STANDING WAVES



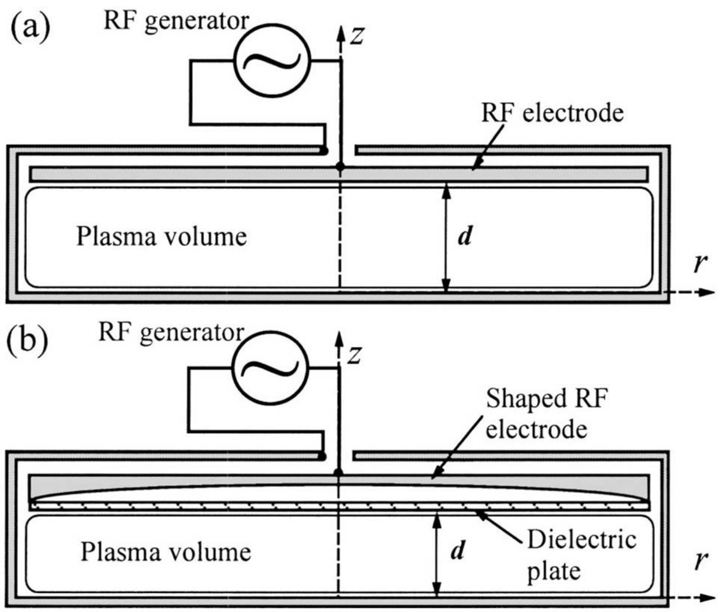
$20{\times}20$ cm discharge
$p = 150$ mTorr
50 W rf power

The standing wave effect is seen at 60 MHz and is more pronounced at 81.36 MHz

(A. Perret, P. Chabert, J-P Booth, J. Jolly, J. Guillon and Ph. Auvray, *Appl. Phys. Lett.* **83**, 243, 2003)

SUPPRESSION OF STANDING WAVE EFFECTS

- Shaped electrode (and diel plate) eliminate standing wave effects



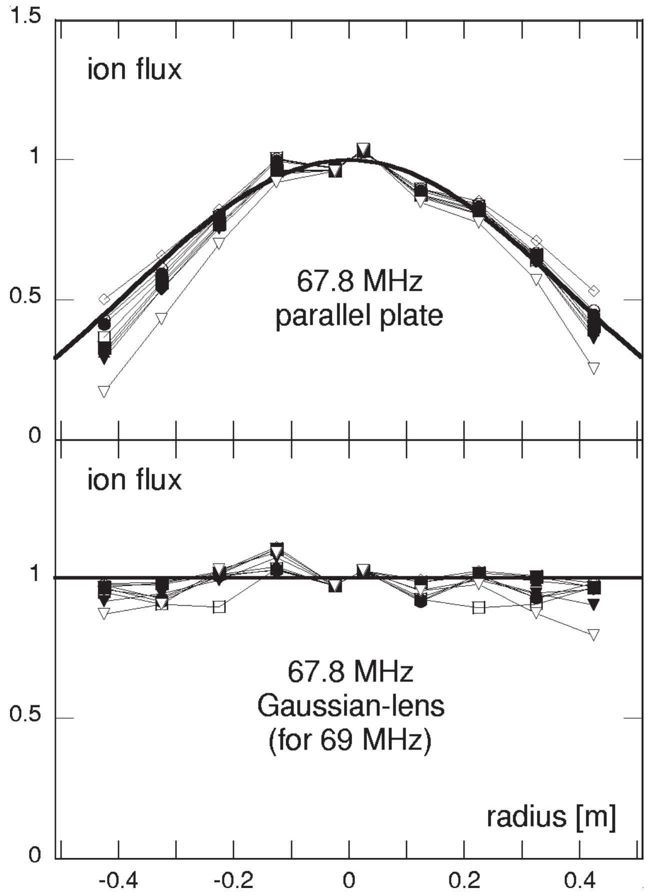
- Increased overall thickness in center compared to edge keeps voltage across discharge section constant
- The electrode shape is a Gaussian, independent of the plasma properties

L. Sansonnens and J. Schmitt, *Appl. Phys. Lett.* **82**, 182 (2003)

P. Chabert, J.L. Raimbault, J.M. Rax, and A. Perret, *Phys. Plasmas* **11**, 4081 (2004)

EXPERIMENTAL CONFIRMATION

- 5–250 mTorr argon, 50–300 W

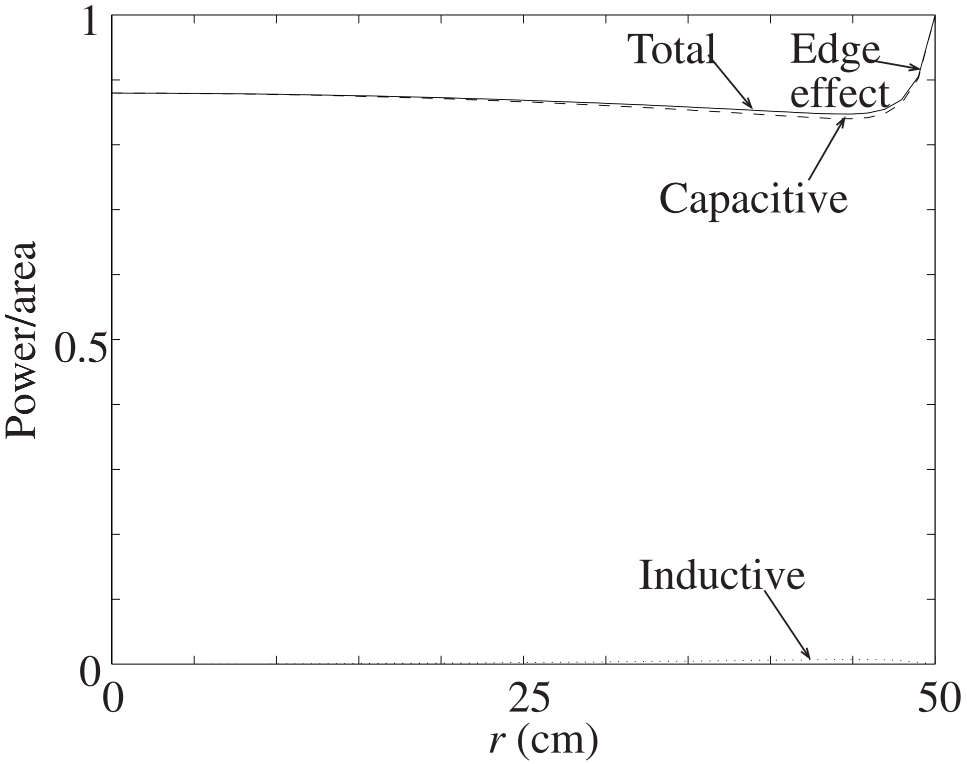


(H. Schmitt, L. Sansonnenns, A.A. Howling, Ch. Hollenstein, M. Elyaakoubi, and J.P.M. Schmitt, *J. Appl. Phys.* **95**, 4559, 2004)

SKIN EFFECTS — FIXED $\mathbf{n_e}$ AND s

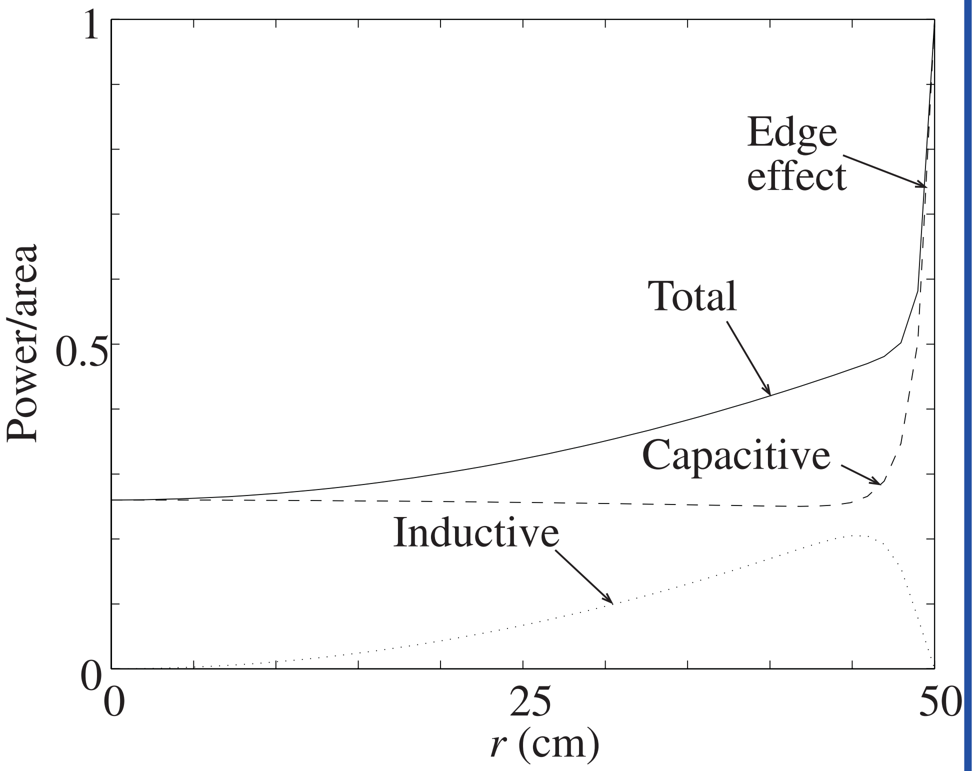
- $R = 50$ cm, $d = 2$ cm, $s = 0.4$ cm, $f = 13.56$ MHz, $\lambda \approx 9$ m
- P_{cap} (dash), P_{ind} (dot) and P_{tot} (solid) as a function of r

$\mathbf{n_e = 10^9\ cm^{-3}}$ $(\delta = 16.7\ \mathrm{cm})$



Small standing wave and skin effects

$\mathbf{n_e = 10^{10}\ cm^{-3}}$ $(\delta = 5.3\ \mathrm{cm})$



Large skin effects; center-low profile

SKIN EFFECTS

- Skin effects $\Longrightarrow$ radial nonuniformities at high densities when

$$\boxed{\delta \lesssim 0.45\,\sqrt{d\,R}}$$

$\delta \propto \dfrac{1}{\sqrt{n}}$ = collisional or collisionless skin depth

d = bulk plasma half-thickness

R = discharge radius

- Use 1D transmission line analysis + global (low pressure) or local (high pressure) power balance

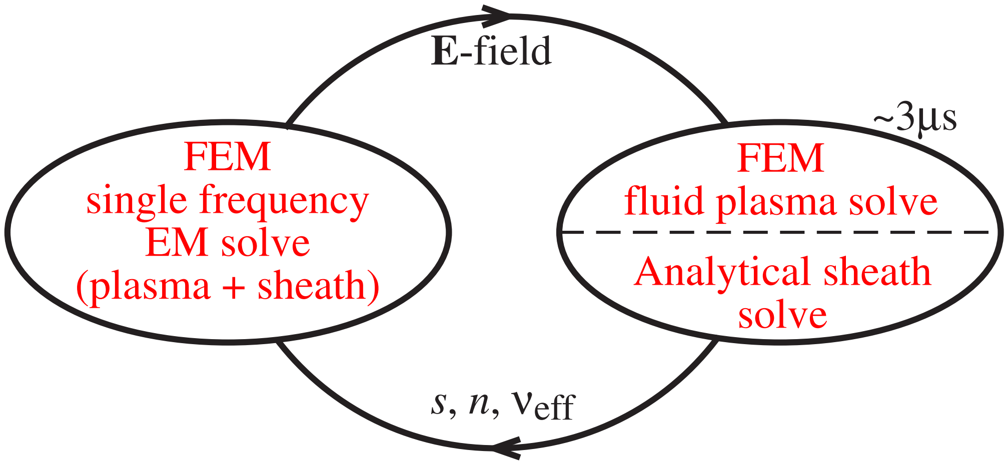
$$\boxed{\Longrightarrow \text{self-consistent standing wave/skin effects}}$$

(P. Chabert, J.L. Raimbault, P. Levif, J.M. Rax, and M.A. Lieberman,
Plasma Sources: Sci. Technol. **15,** S130, 2006)

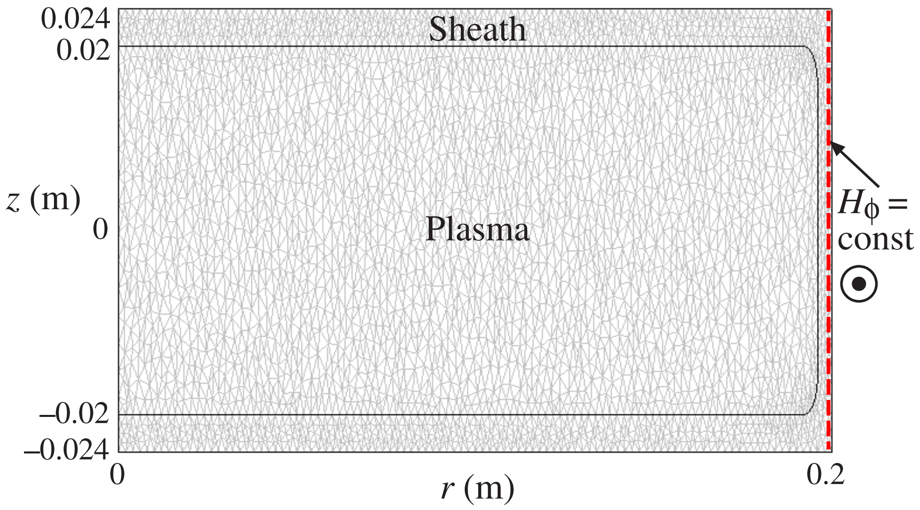
FINITE ELEMENT METHOD (FEM), 2D EM SOLUTIONS

(with Insook Lee and D.B. Graves)

- Arbitrary (asymmetric) discharge geometries and materials
- Transition from global to local power balance
- Distinguish edge effects (electrostatic) versus EM effects
- Series resonance stop band



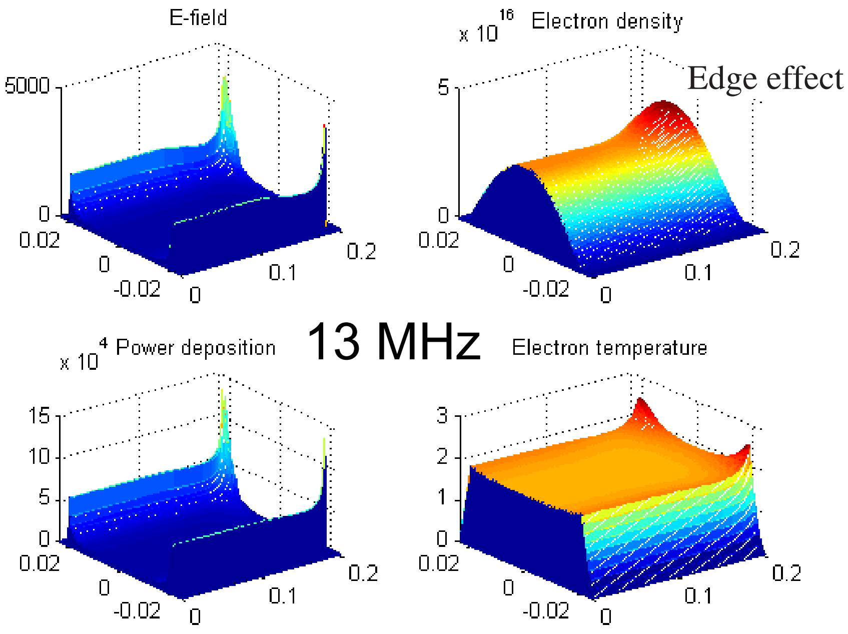
Solution Procedure



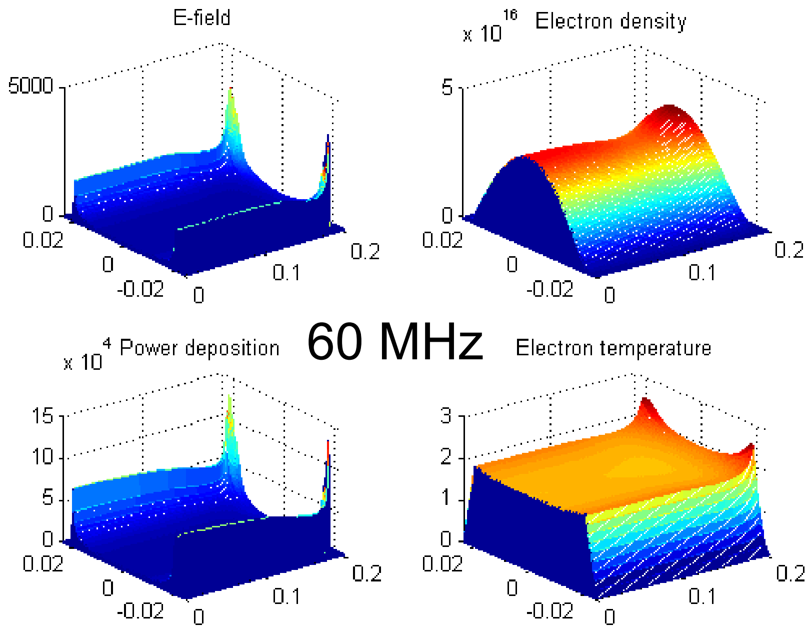
FEM Mesh (6252 elements)

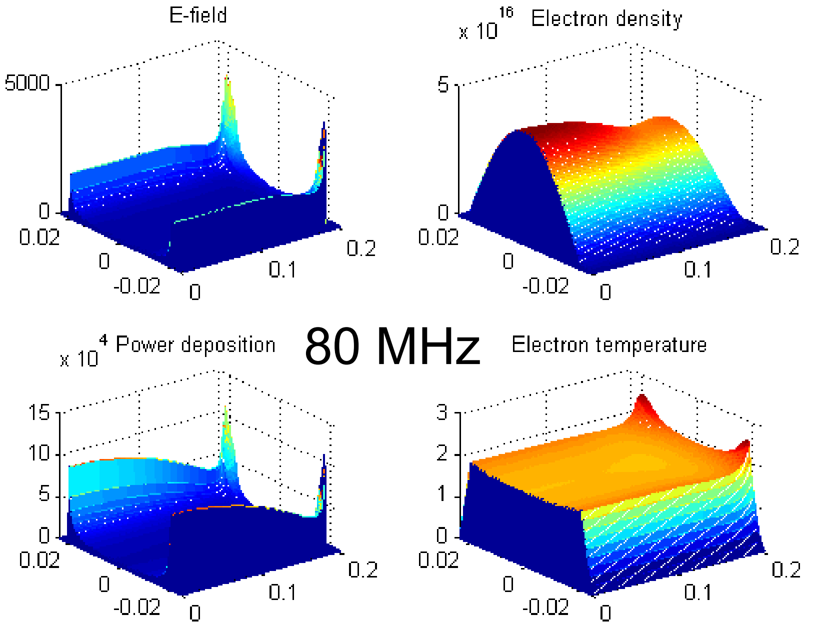
(Analytical model: collisional Child law, variable sheath width, stochastic and ohmic heating in the sheath)

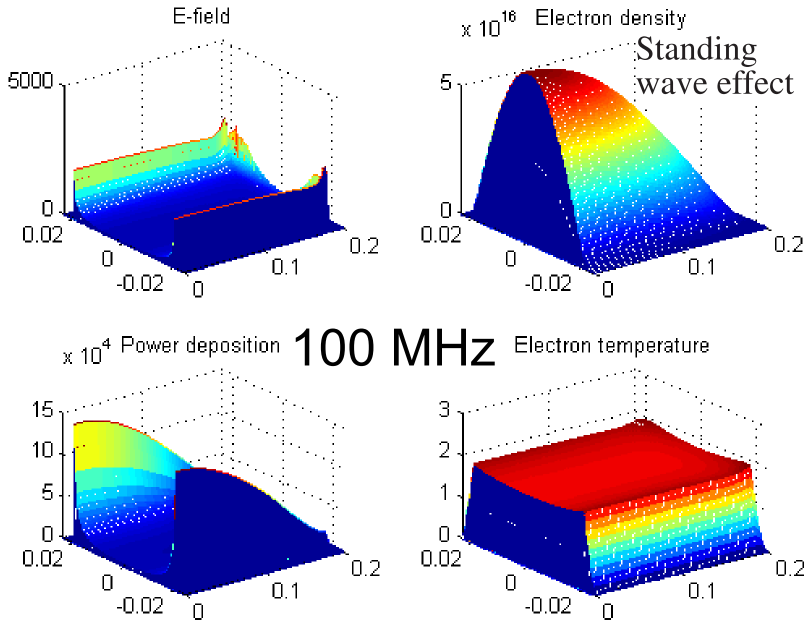
STANDING WAVES — 40 W, 150 mTORR


13 MHz

Edge effect

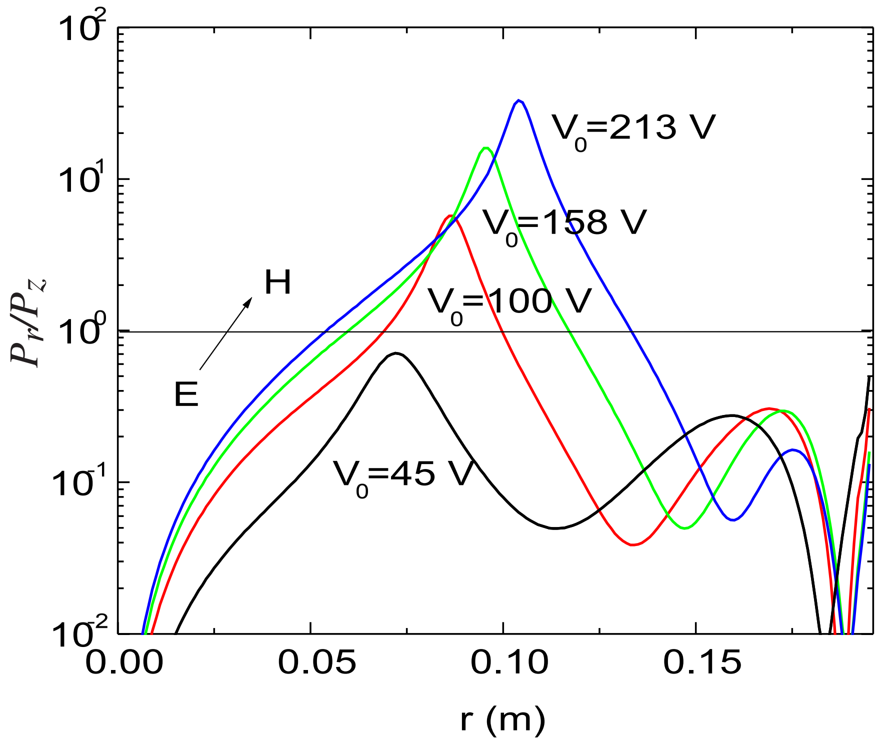

60 MHz


80 MHz

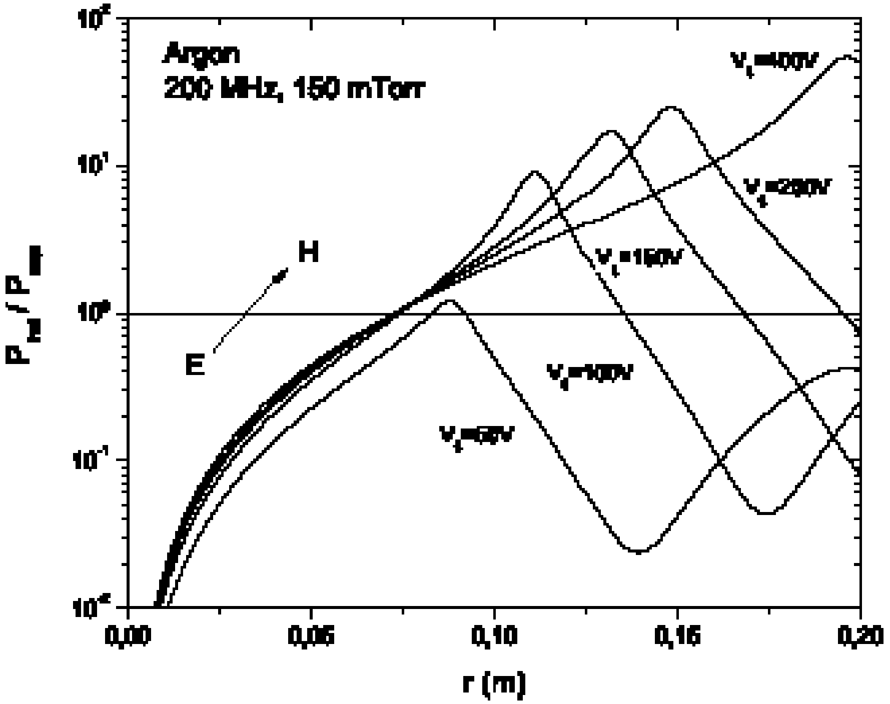

100 MHz

Standing wave effect

SKIN EFFECTS — 150 mTORR



FEM model
(with Insook Lee and D.B. Graves)

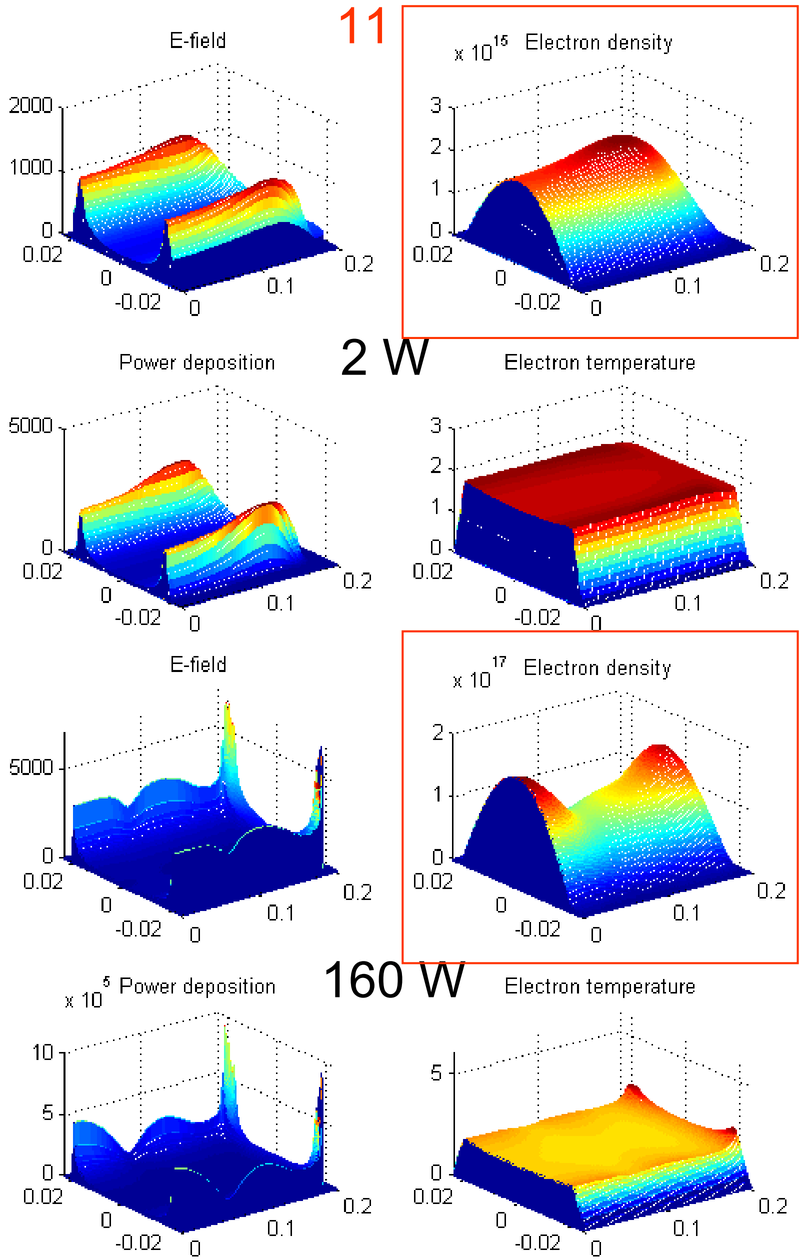


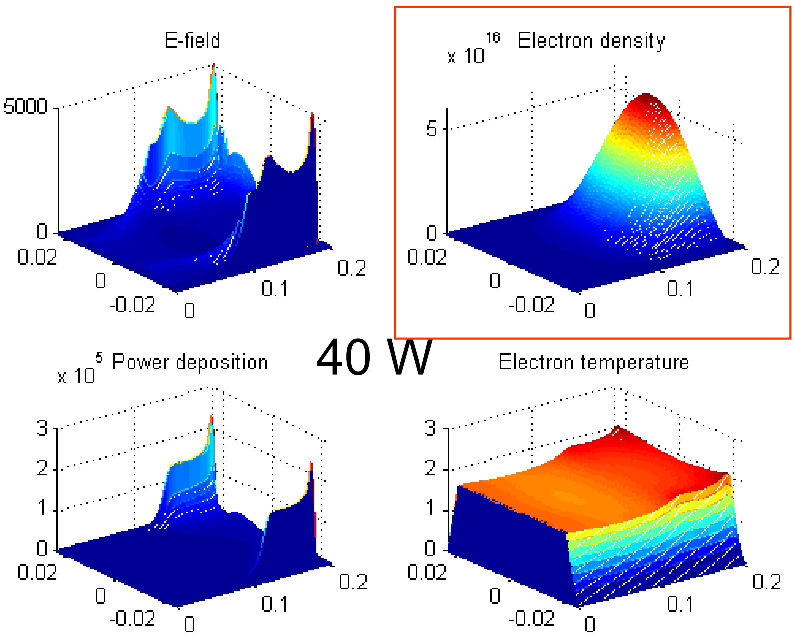
Transmission line model
(P. Chabert et al, *Plasma Sources Sci. Technol.* **15,** S130, 2006)

- Transmission line model: collisionless sheaths, no edge effects, purely local power deposition

In both cases spatial E to H transitions are seen

SERIES RESONANCE — 200 MHz, 150 mTORR





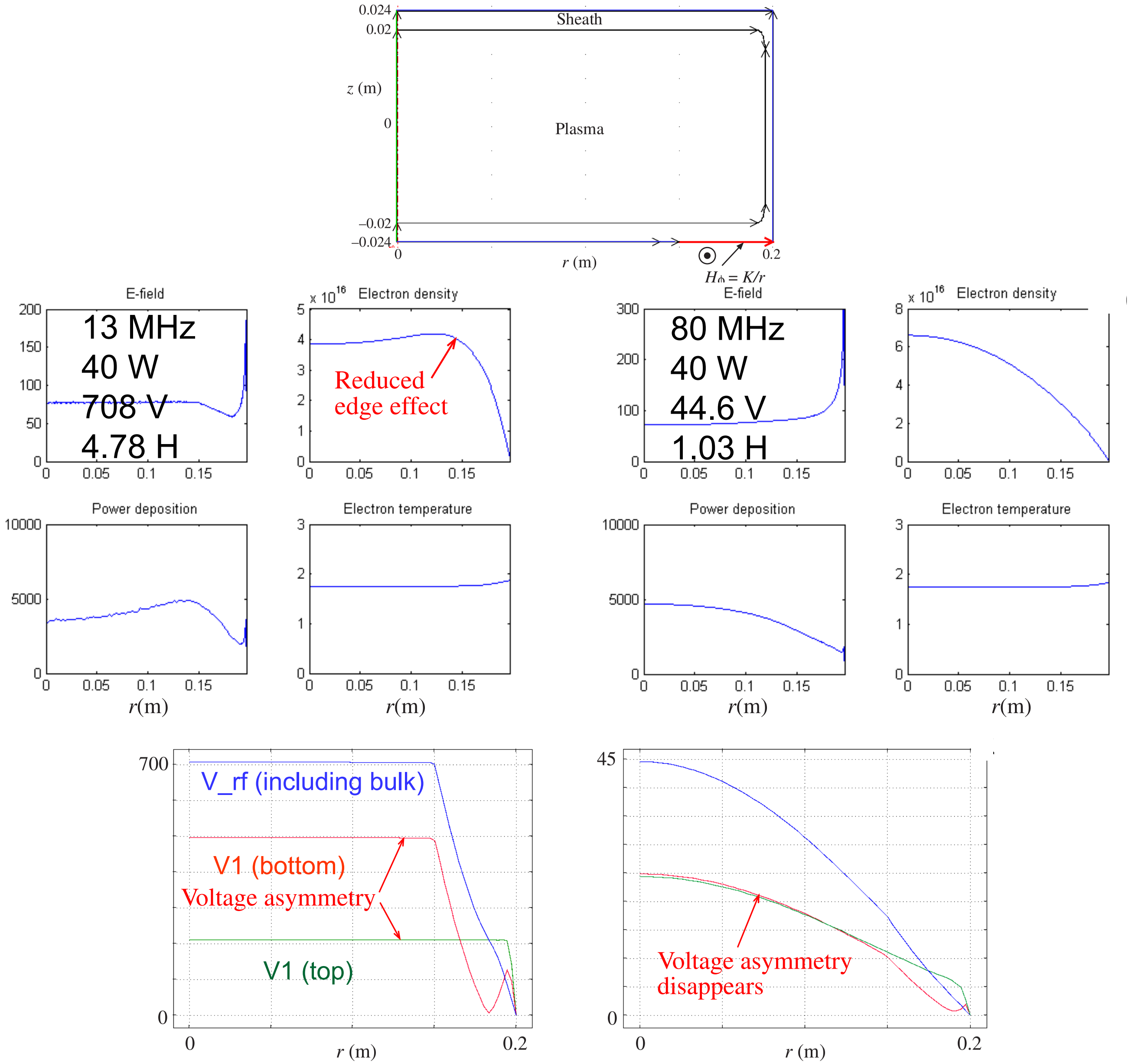
Surface wave does not propagate for

$$\omega_{\rm res} < \omega < \omega_p$$

$\omega_{\rm res}$ = series resonance frequency

ω_p = plasma frequency

ASYMMETRIC (BOTTOM) EXCITATION — 150 mTORR



(see also S. Sansonnens, A.A. Howling, and Ch. Hollenstein, *PSST* **15,** 302, 2006)

NONLINEAR EFFECTS IN CAPACITIVE DISCHARGES

- What I know about nonlinear effects:

PUNT

- So let us enjoy interesting talks on this topic

1. P.A. Miller et al, *Plasma Sources Sci. Technol.* **15**, 889, 2006
2. T. Mussenbrock and R.P. Brinkmann, *Appl. Phys. Lett.* **88**, 151503, 2006
3. T. Mussenbrock, D. Ziegler and R.P. Brinkmann, *Phys. Plasmas* **13**, 083501, 2006

CONCLUSIONS

- CMOS scales to 24-atom gate lengths in 2020
- Third generation capacitive reactors for dielectric etch will dominate the fab
- Capacitive reactor research and development must intensify to meet this need

Download this talk:

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