EDGE EFFECTS IN REACTIVE ION ETCHING: THE WAFER- FOCUS RING GAP*

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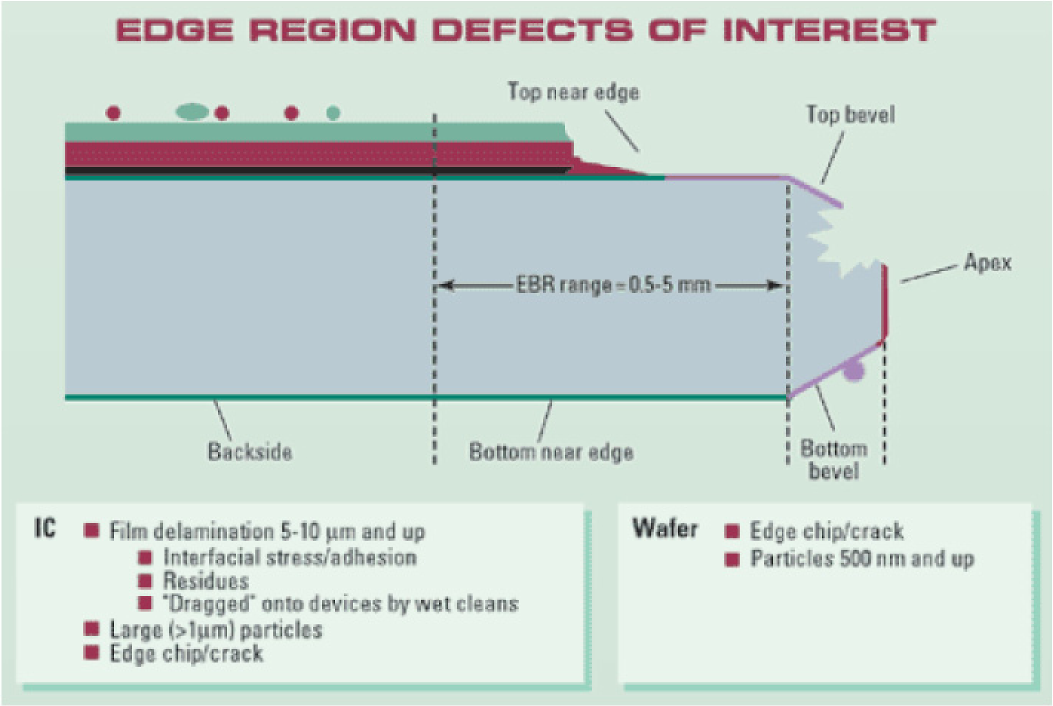
AGENDA

- Wafer edge effects
- Description of the model
- Penetration of plasma into wafer-focus ring gaps in Ar/CF$_4$ CCPs
  - Gap width
  - Focus ring conductivity
  - Focus ring height
- Concluding remarks

WAFER EDGE EFFECTS



IC
- Film delamination 5-10 µm and up
  - Interfacial stress/adhesion
  - Residues
  - "Dragged" onto devices by wet cleans
- Large (>1µm) particles
- Edge chip/crack

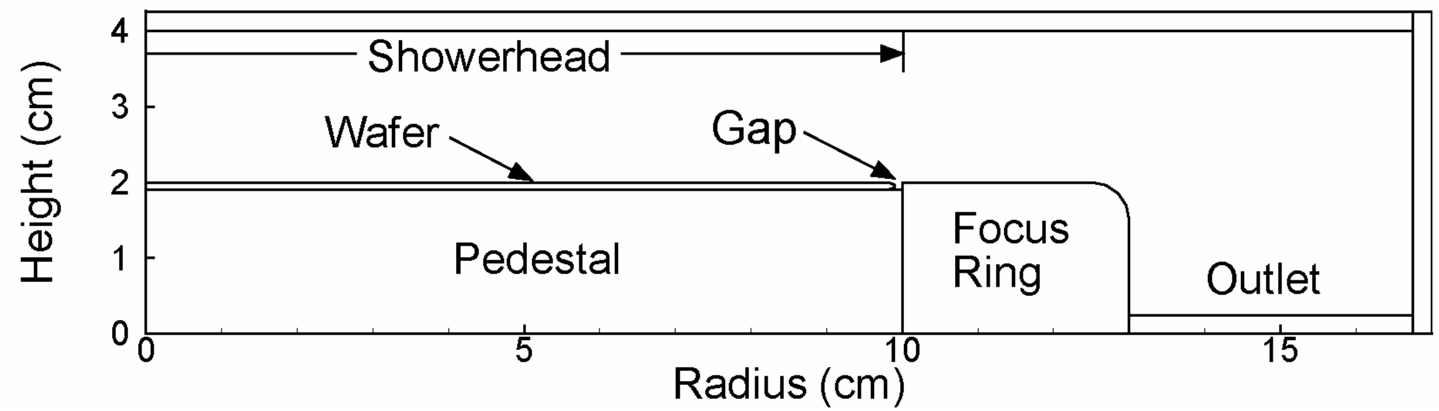
Wafer
- Edge chip/crack
- Particles 500 nm and up

- Gap (< 1 mm) between wafer and focus ring in plasma tools is for mechanical clearance.
- The wafer is often beveled at edge allowing for "under wafer" plasma-surface processes.

- Penetration of plasma into gap can lead to deposition of contaminating films and particles.

PENETRATION OF PLASMA INTO WAFER-FOCUS RING GAP

- Penetration of plasma into wafer-focus ring gap was computationally investigated for a capacitively coupled discharge for polymerizing (Ar/CF_4) conditions.



- 2-dimensional model using an unstructured mesh use used to resolve multiple scale lengths.
- Improvements to algorithms to revolve on momentum into gaps were made.

nonPDPSIM CHARGED PARTICLE TRANSPORT

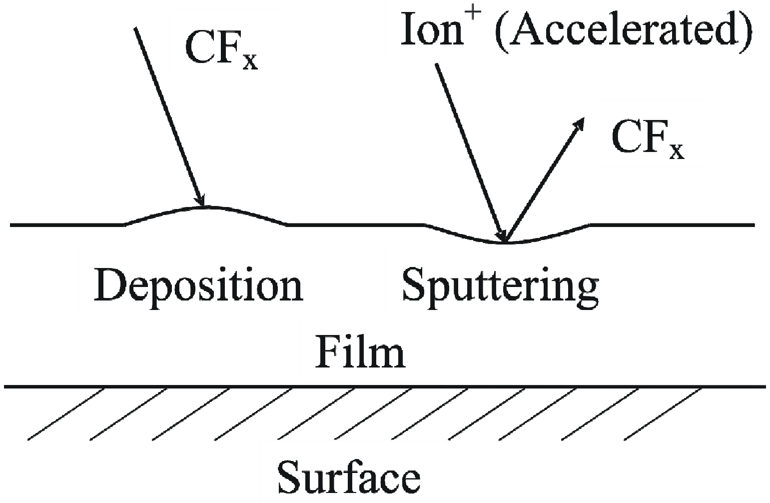
- **Poisson equation: electric potential** $\nabla(\varepsilon \nabla \Phi) = -(\sum_j q_j N_j + \rho)$
- **Transport of charged species *j*** $\frac{\partial N_j}{\partial t} + \nabla \vec{\Gamma} = S$
- **Surface charge balance** $\frac{\partial \rho}{\partial t} = \left[\sum_j q_j \left(-\nabla \vec{\Gamma} + S \right) - \nabla\left(\sigma\left(-\nabla \Phi\right)\right) \right]_{material}$
- **Full momentum for ion fluxes**

$$\frac{\partial \vec{\Gamma}_j}{\partial t} + \nabla\left(\vec{\Gamma}_j \, \vec{v}_j\right) = -\frac{1}{M_j} \nabla P_j + \frac{q_j N_j \vec{E}}{M_j} - \sum_i N_j \nu_{ij} \left(\vec{v}_j - \vec{v}_i\right)$$

- **Transport of secondary electrons from biased substrate is addressed with a Monte Carlo simulation.**
- **Neutral transport addressed with Navier-Stokes equations.**

SURFACE-KINETICS-MODULE (SKM)

- SKM uses fluxes to surface to produce coverage of surface species, sticking coefficients and returning fluxes to the plasma.=
- For demonstration purposes, a simple polymer depositing reaction mechanism.
  - Neutral deposition CF_n on surfaces W producing multiple layers of polymer $Poly_n$
  - Ion sputtering of polymer to generate CF_n



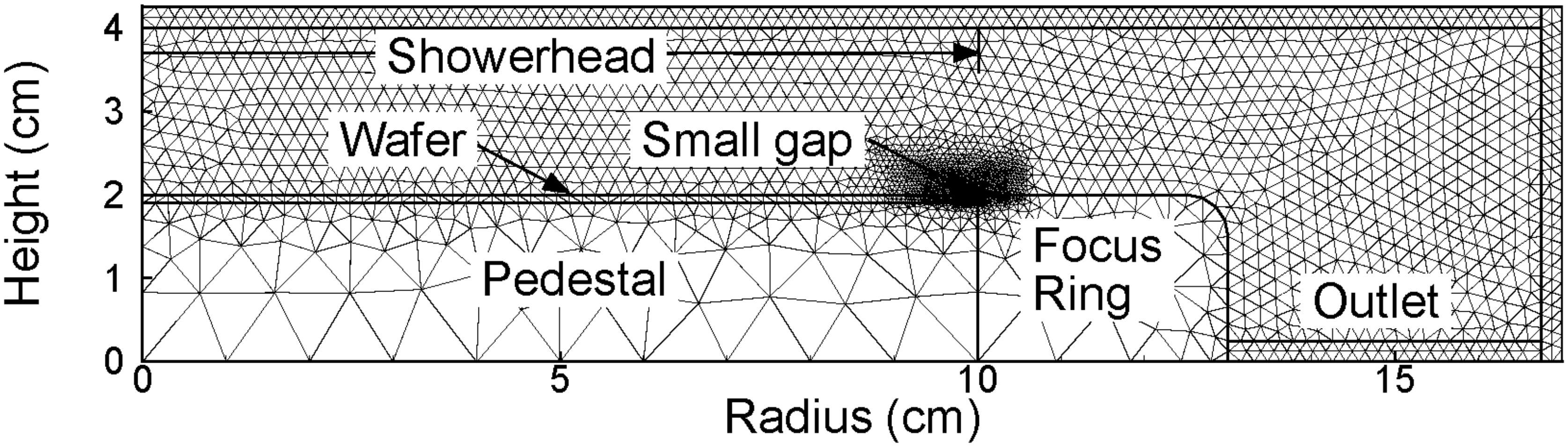
$$CF_n + W \rightarrow Poly_1 + W$$

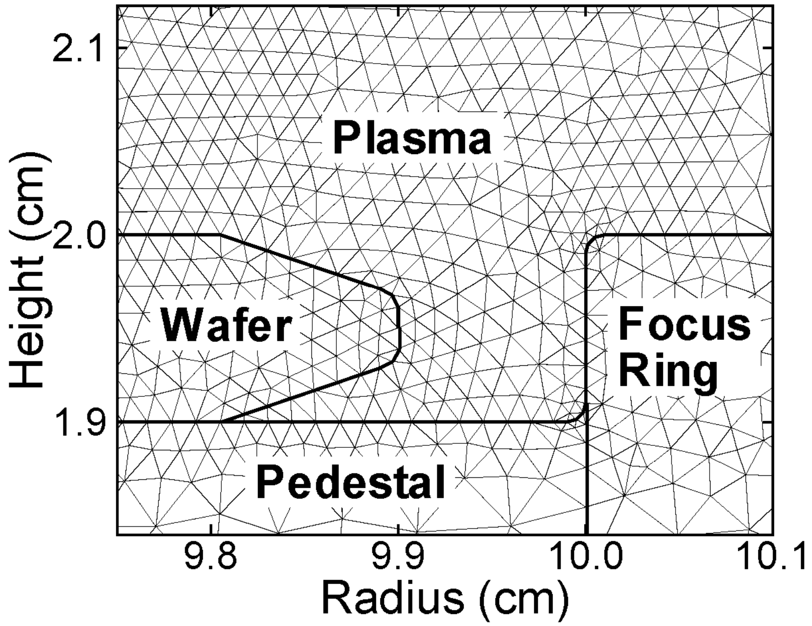
$$CF_n + Poly_m \rightarrow Poly_{m+1}$$

$$M^+ + Poly_1 \rightarrow W + CF_n$$

$$M^+ + Poly_m \rightarrow Poly_{m-1} + CF_n$$

MESHING TO RESOLVE FOCUS RING GAP





- **Unstructured meshes resolve wafer-focus ring gaps of < 1 mm.**

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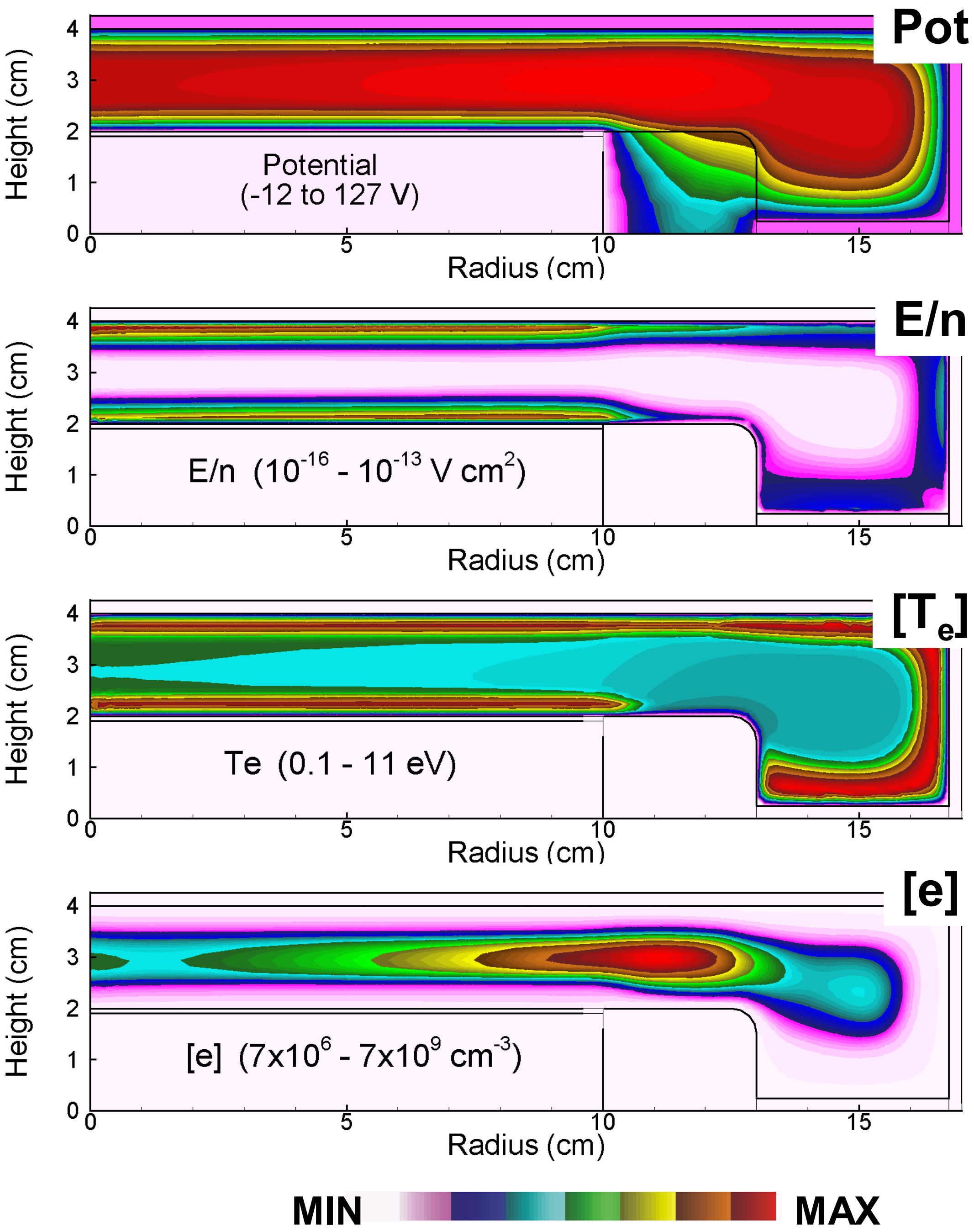

POTENTIAL, E-FIELD, ELECTRONS

- High electric field heats electrons in the sheath regions.
- Off-axis maximum in [e] consequence of focus ring-uncorrelated to gap.
- Ar/CF_4 = 97/03, 10MHz, 90 mTorr, 300 V, 300 sccm

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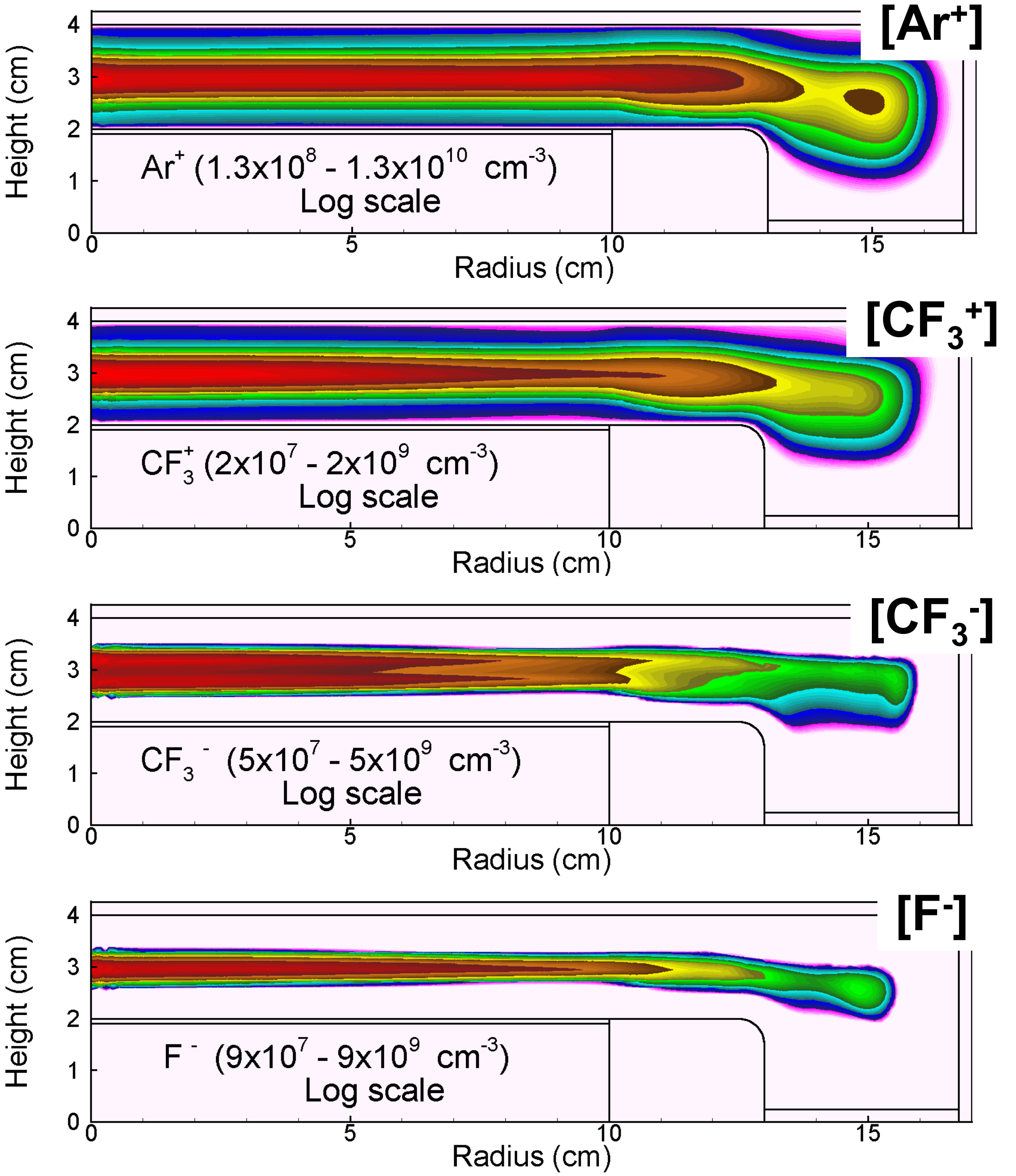
POSITIVE AND NEGATIVE IONS



- Discharge is highly electronegative.
- In spite of non-uniform [e], positive ion fluxes are fairly uniform as [M$^+$] > [e].
- Ar/CF$_4$ = 97/03, 10MHZ, 90 mTorr, 300 V, 300 sccm

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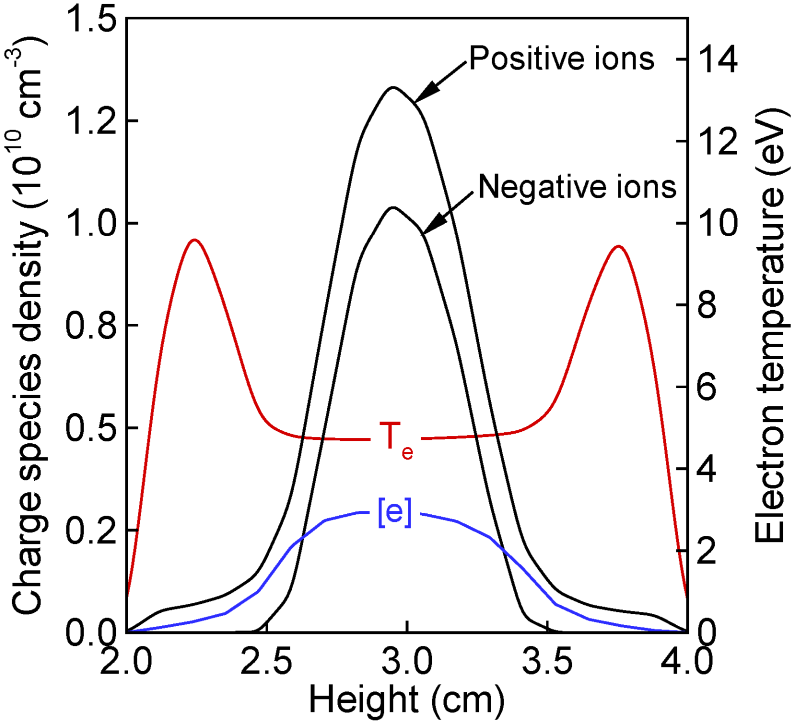
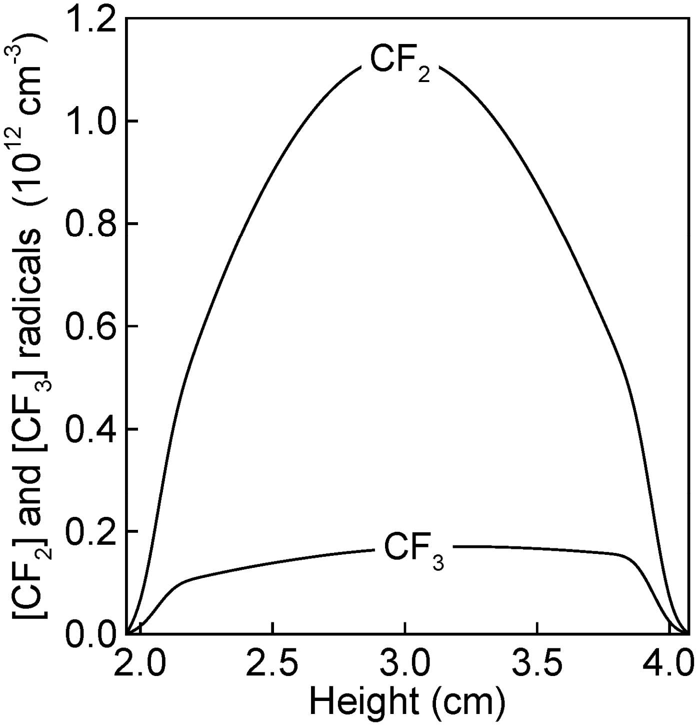
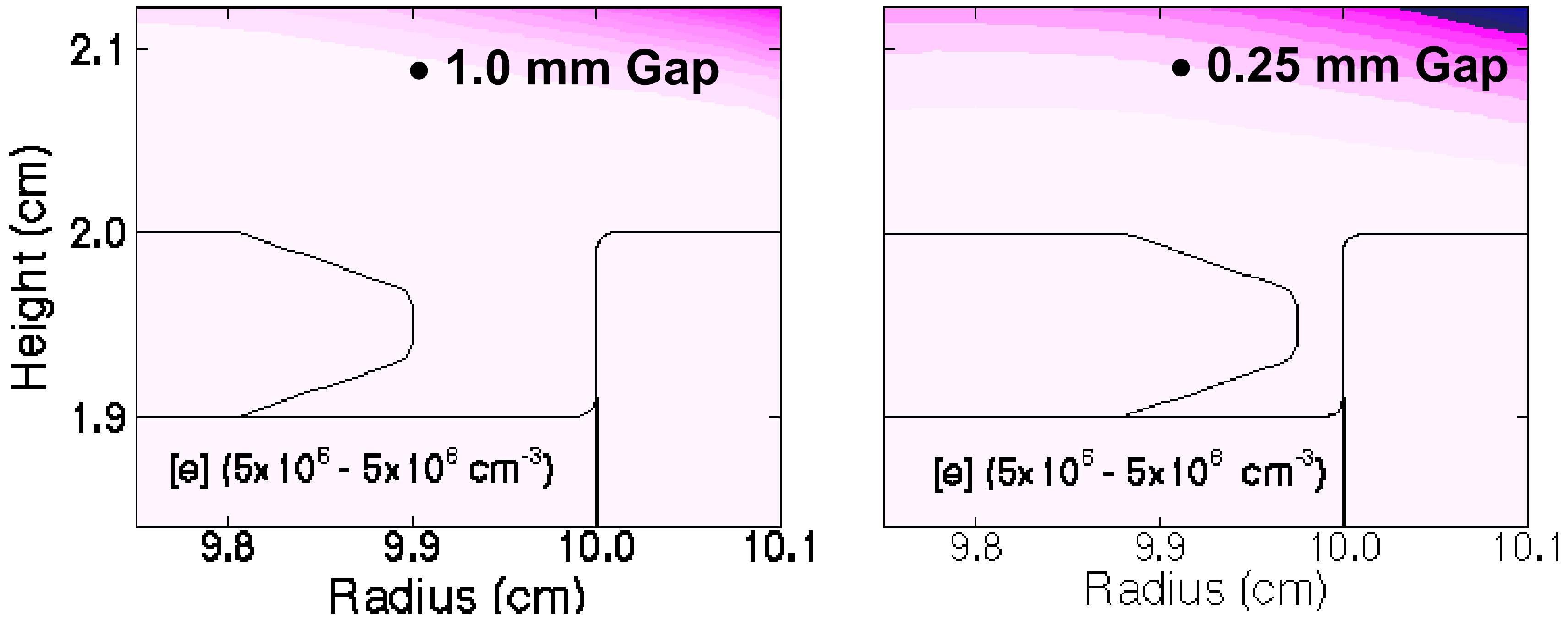
AXIAL DENSITIES





- **Dominant neutral polymerizing radical is CF_2.**
- **Sheaths are many mm thick which is important factor in penetration of plasma into gaps.**
- **Ar/CF_4 = 97/03, 10 MHz, 90 mTorr, 300 V, 300 sccm**

ELECTRON PENETRATION INTO GAP



- **Electron penetration into gaps in anode portion of cycle is nominal due to surface charging and sheath formation.**
- **Ar/CF$_4$ = 97/03, 10 MHz, 90 mTorr, 300 V, 300 sccm**

Animation Slide

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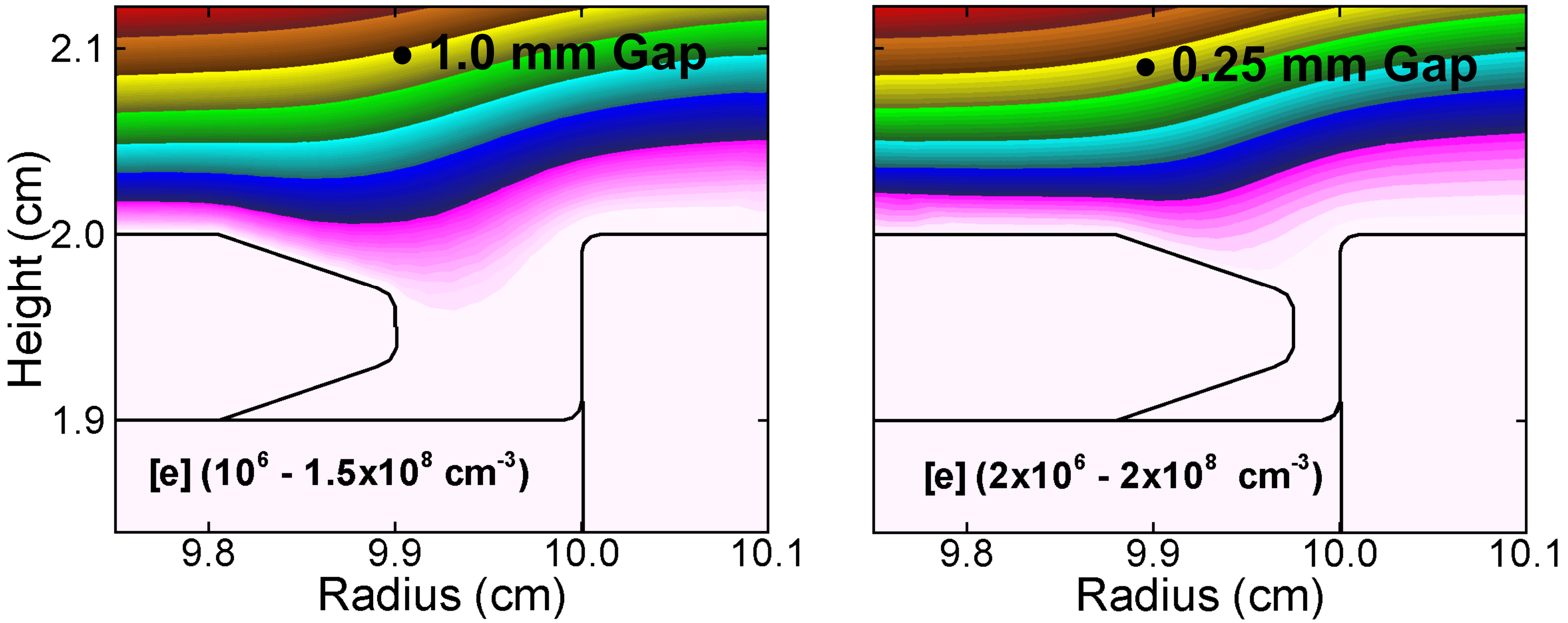

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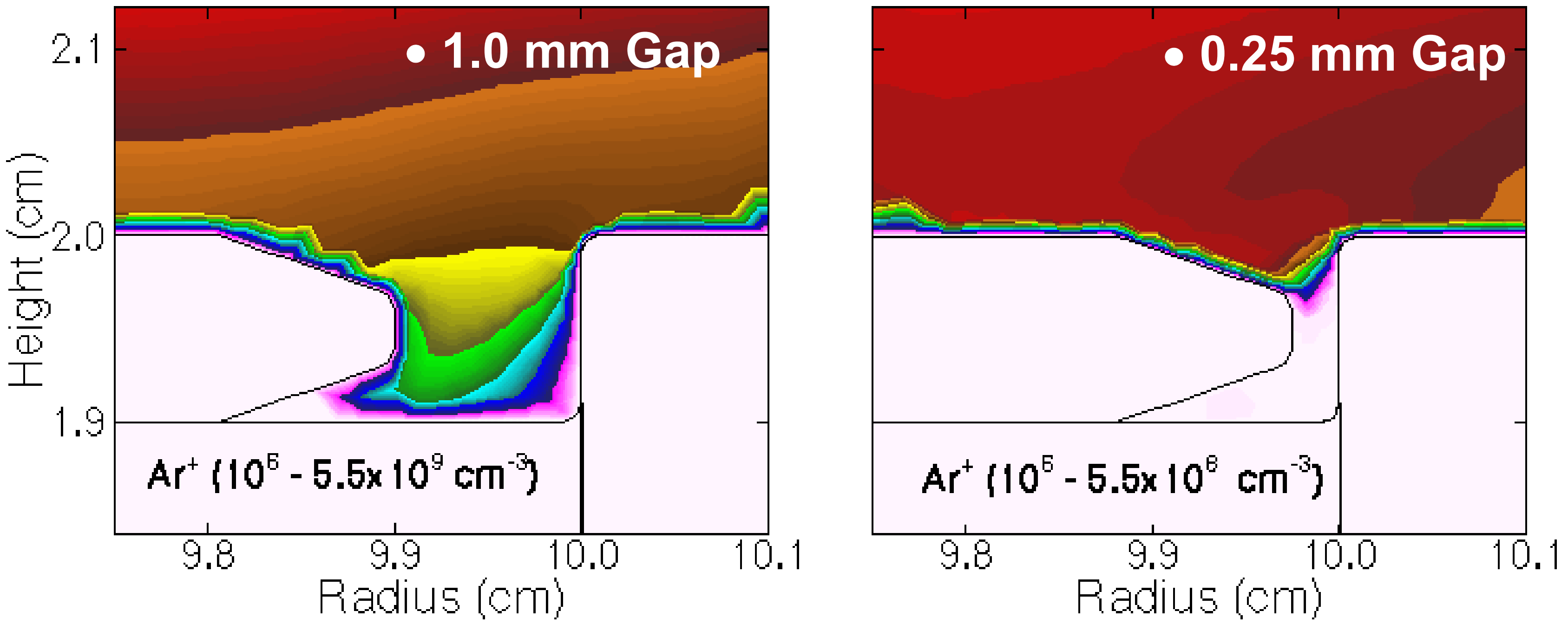
Ar^+ PENETRATION INTO GAP



- **Ions penetrate into larger gap throughout the rf cycle whose size is commensurate with sheath width. Smaller gap receives only nominal flux.**
- **Ar/CF_4 = 97/03, 10 MHz, 90 mTorr, 300 V, 300 sccm**

Animation Slide

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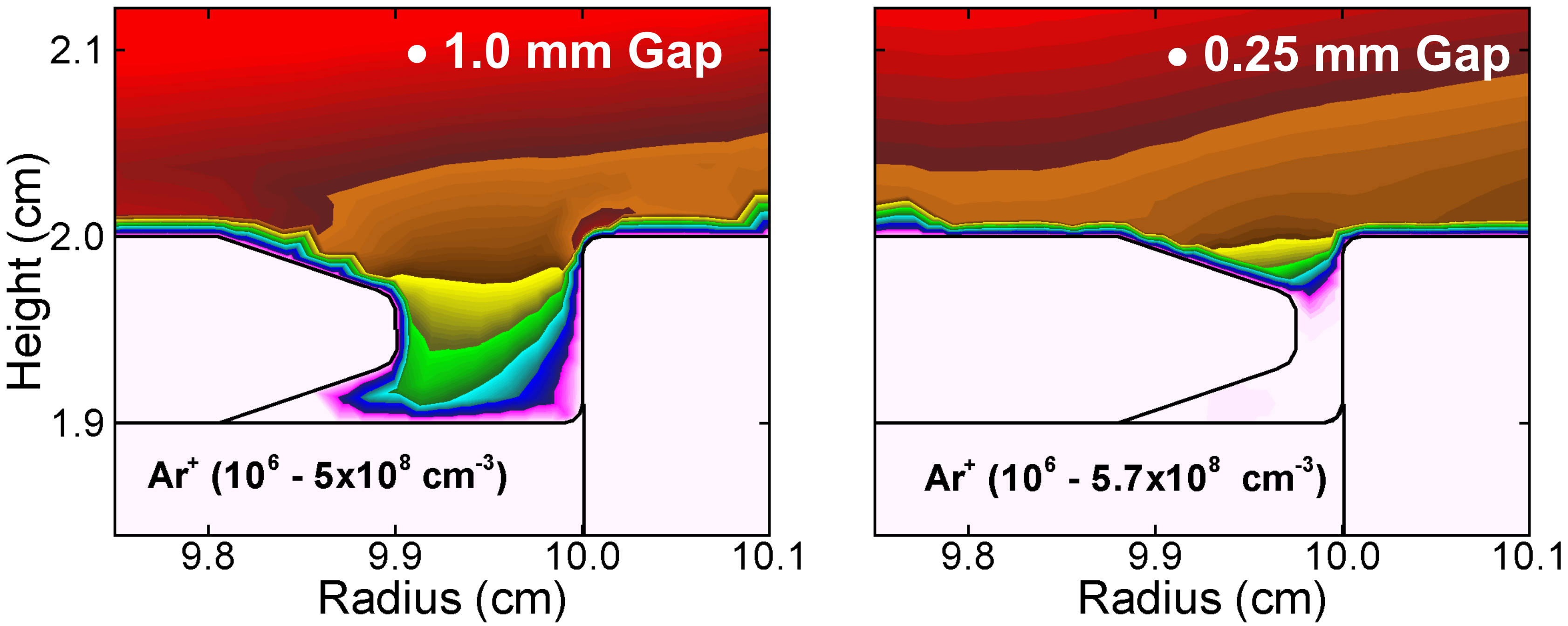

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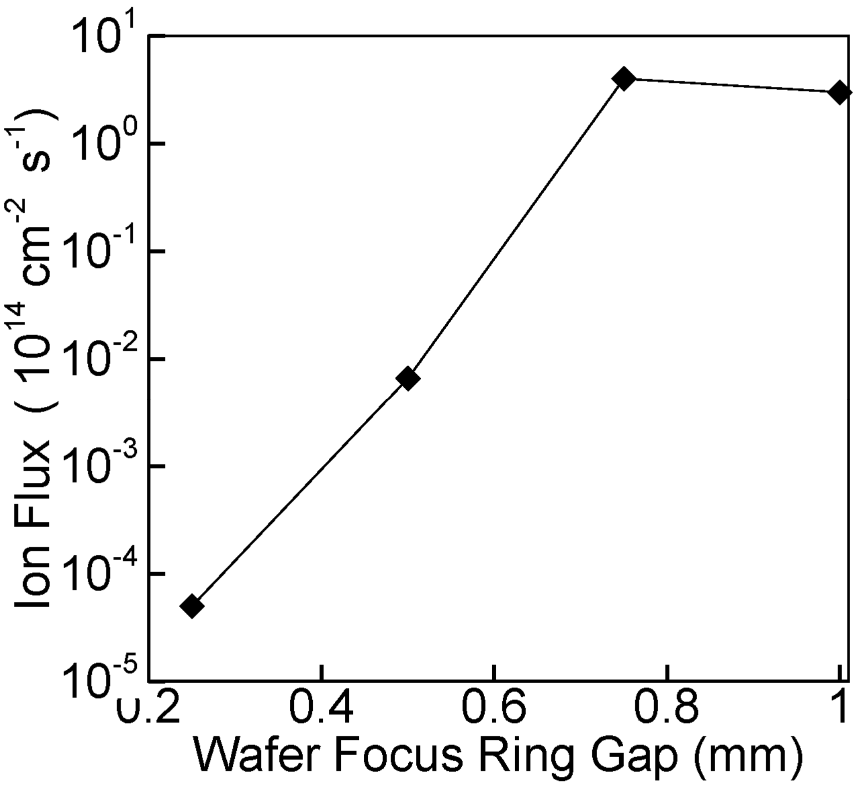
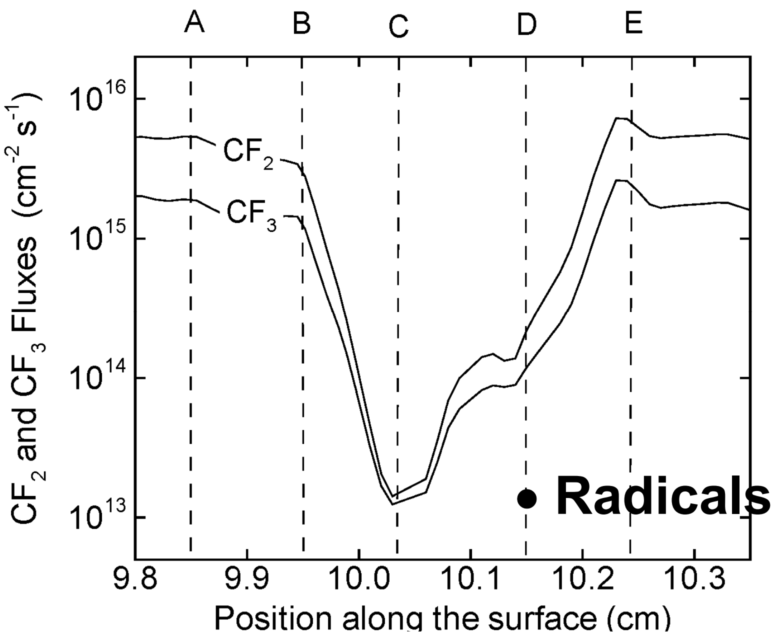
ION PENETRATION vs GAP SIZE

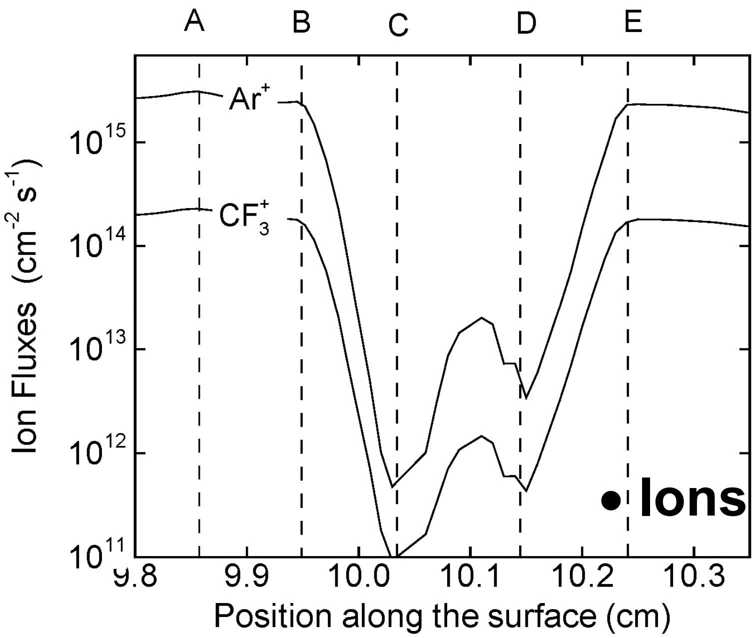


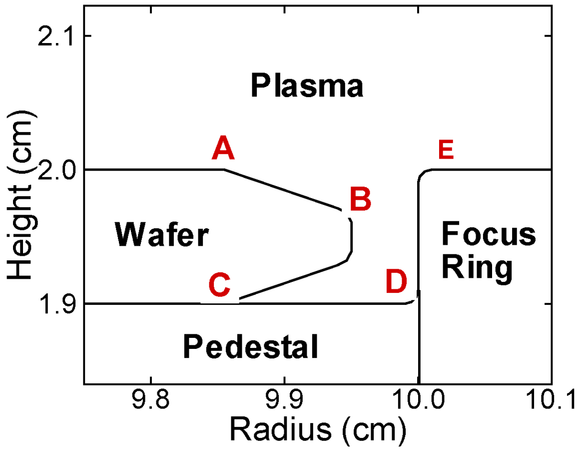
- **Ion penetration into gap critically depends on size relative to sheath.**
- **Gaps ≥ sheath thickness allow penetration.**
- **NOTE! High plasma density tools produce smaller sheaths and more penetration.**
- **Ar/CF_4 = 97/03, 10 MHz, 90 mTorr, 300 V, 300 sccm**

0.5 mm GAP: FLUXES ALONG SURFACES

- **Decrease of ion flux into gap is greater than decrease of neutral radical fluxes.**
- **Negative charging of dielectric focus ring and redirection of ions helps deplete fluxes.**

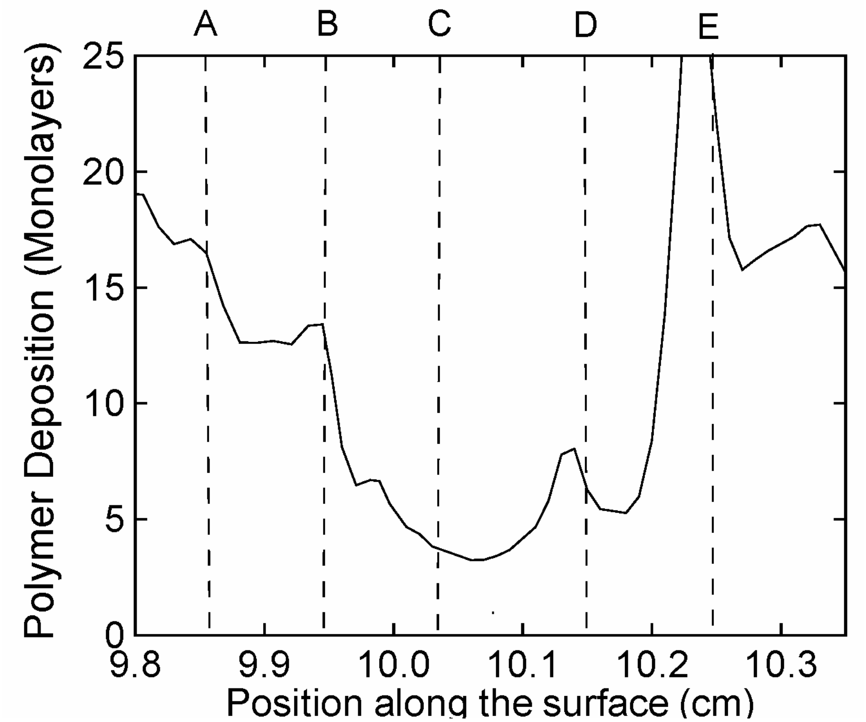


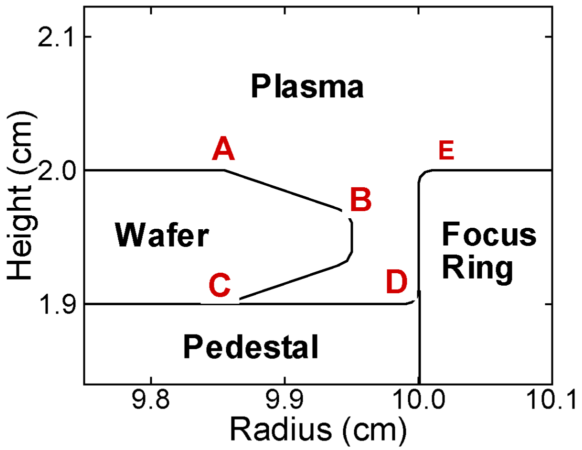




- **Ar/CF_4=97/03, 90 mTorr**

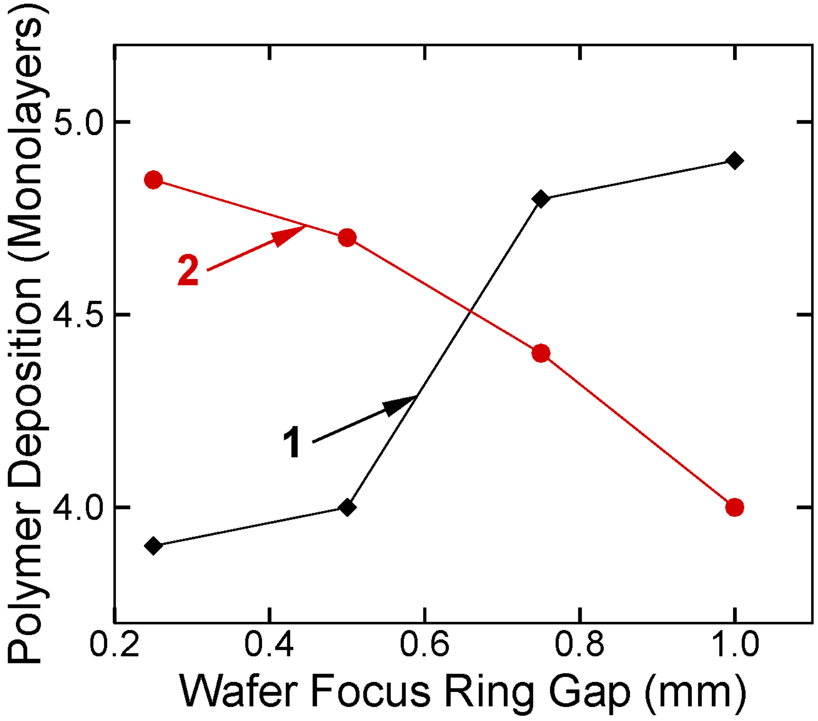
0.5 mm GAP: POLYMER DEPOSITION

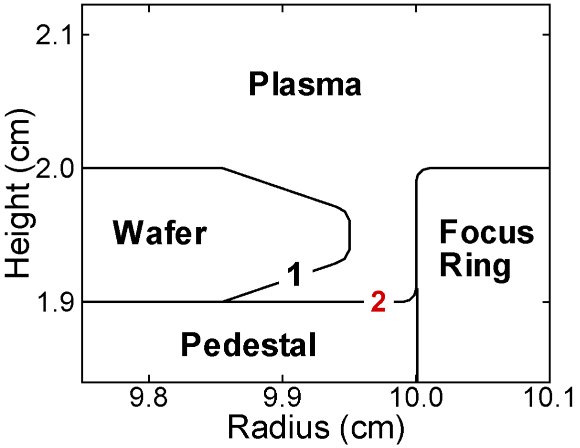




- Lack of ion sputtering of polymer in gap results in disproportionately large deposition.
- 100 decrease in radical flux produces only factor of 5 decrease in polymer.
- Particle formation is likely to be greater.

- Ar/CF_4=97/03, 90 mTorr





POLYMER DEPOSITION vs GAP SIZE

- **When increasing gap size…**

Under bevel:

- **More radical flux penetrates while ion flux is still small.**
- **More deposition**

On pedestal:

- **View angle to plasma enables more ion flux.**

- **Effects are not terribly large over this range of gaps.**

- **Ar/CF_4=97/03, 90 mTorr**

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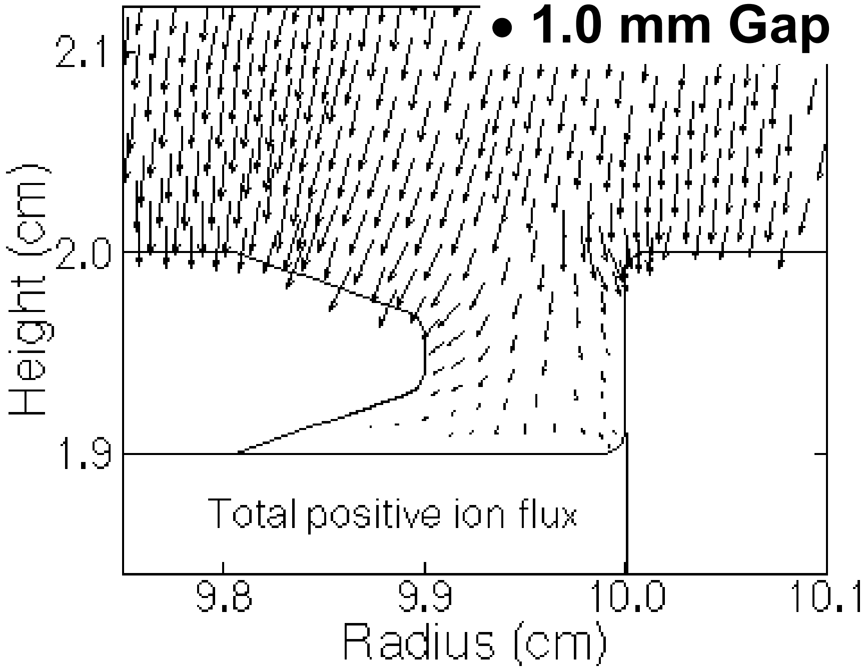
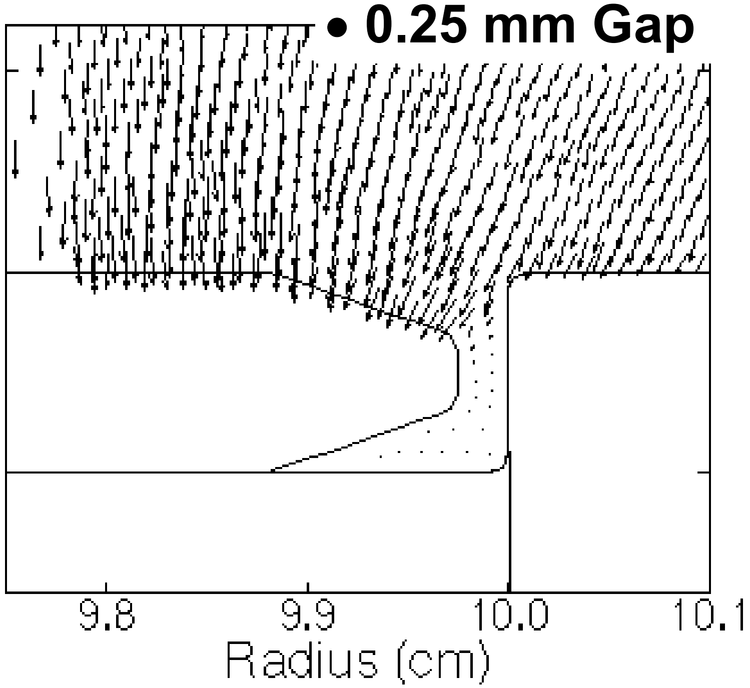
ION FOCUSING



- **1.0 mm Gap**



- **0.25 mm Gap**

- **Ions flux focuses on edges of wafer and focus ring: electric field enhancement and preferential negative charging.**
- **Focusing into bevel of wafer increases with gap size.**
- **Ar/CF$_4$ = 97/03, 10 MHz, 90 mTorr, 300 V, 300 sccm**

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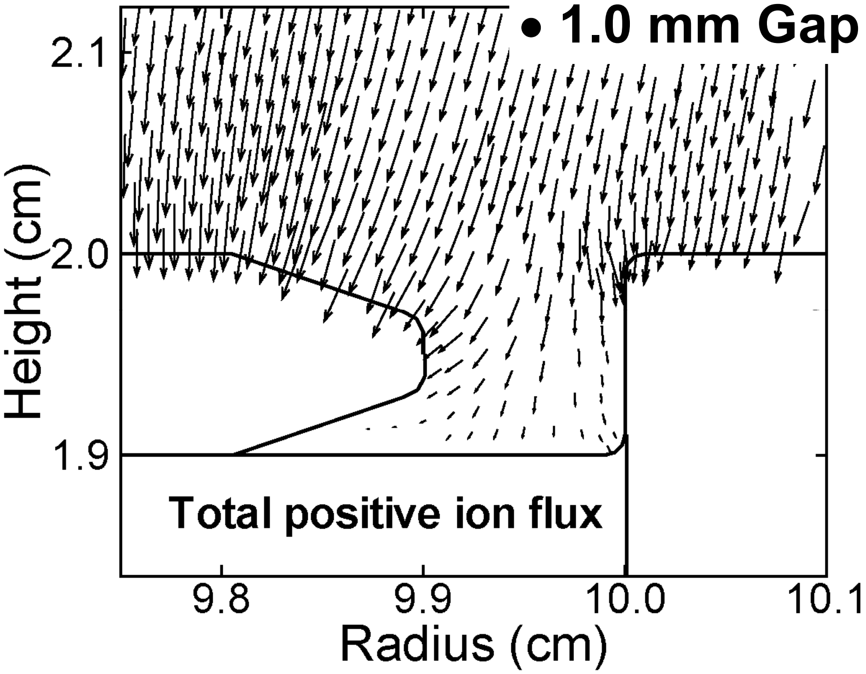
ION FOCUSING



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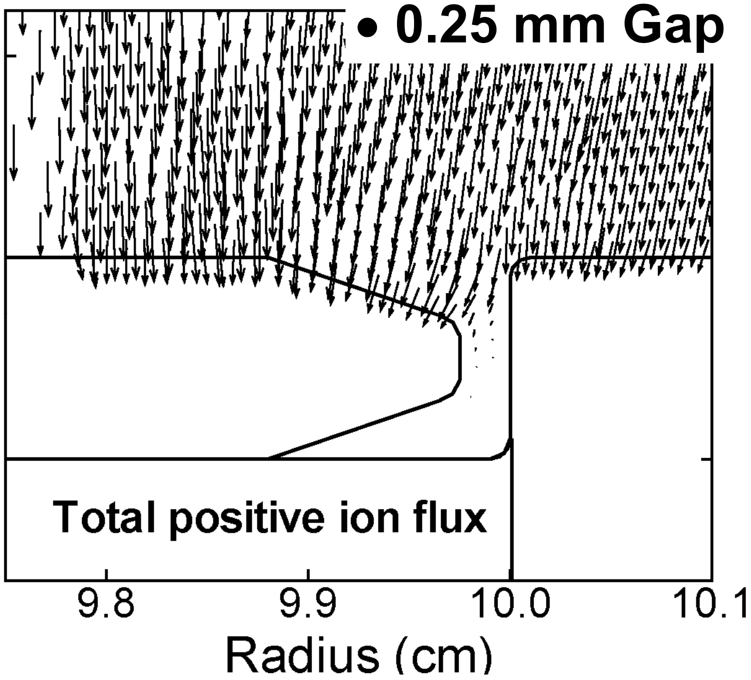

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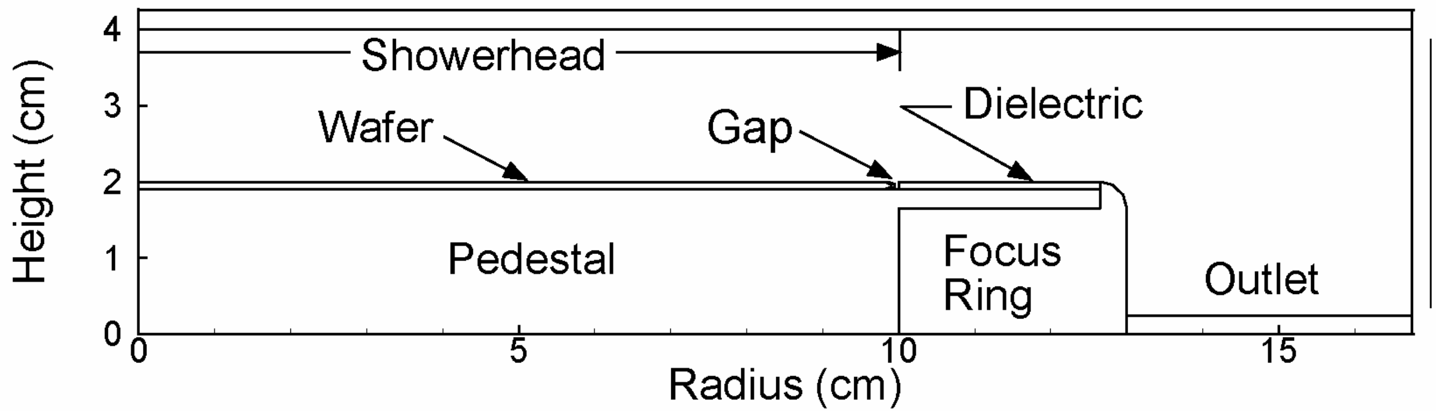
TOOL DESIGN: ION FOCUSING

- **Ion focusing is potentially harmful due to sputtering (etch block materials put into plasma) and erosion of pieces which reduces lifetime.**
- **Tool design can greatly influence ion erosion.**



- **Example: Extension of biased substrate under dielectric focus ring of differing conductivity.**

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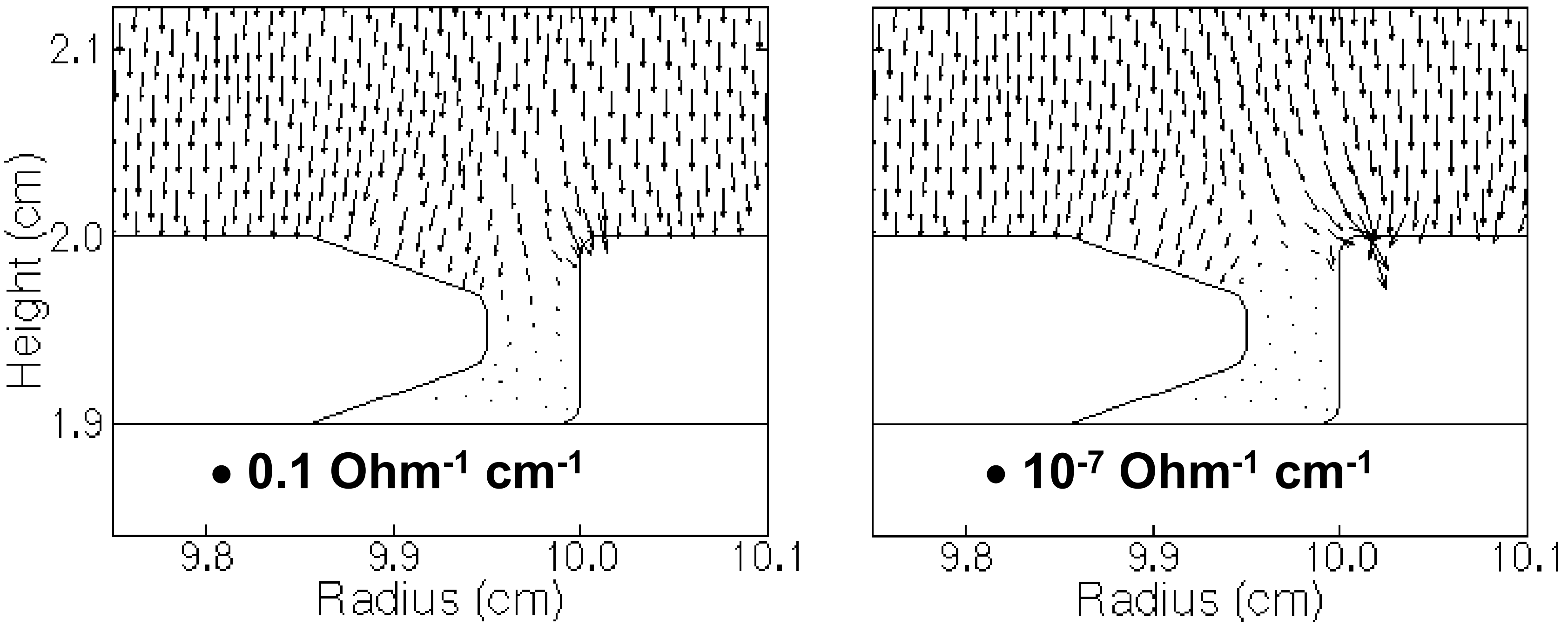
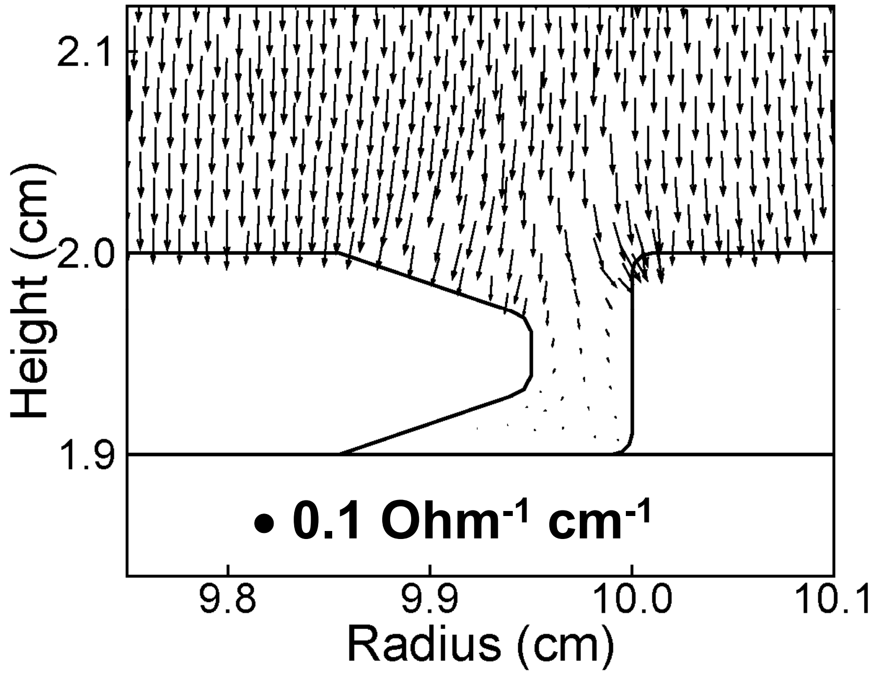
ION FOCUSING vs RING CONDUCTIVITY

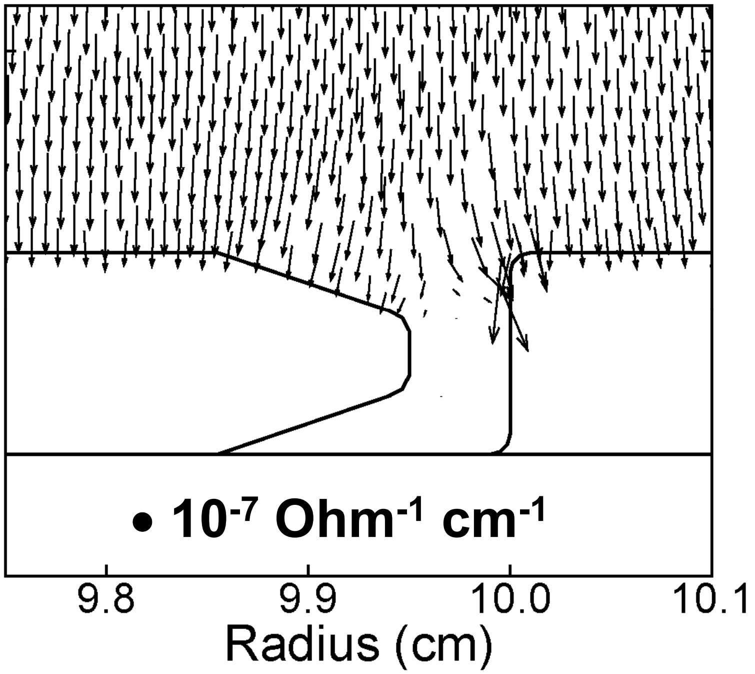


- **Low conductivity ring charges more negatively during anodic part of cycle; and so more focuses ion fluxes.**
- **High conductivity ring has less focusing but allows more ion flux into gap; lack of charging reduces radial E-field.**
- **Ar/CF$_4$ = 97/03, 10 MHz, 90 mTorr**

Animation Slide

ION FOCUSING vs RING CONDUCTIVITY





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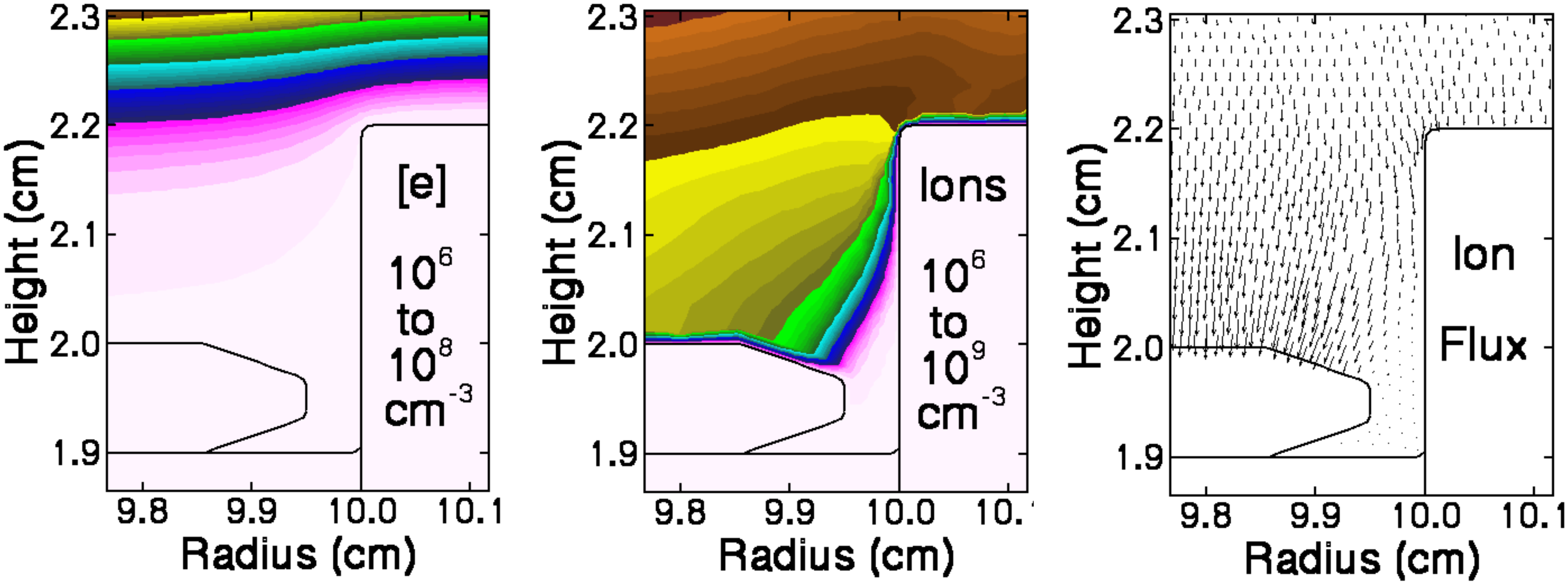
PLASMA PENETRATION: HIGH FOCUS RING



- **Shielding of plasma from gap by using tall ring intensifies focusing of ions into end of ring.**
- **Ar/CF$_4$ = 97/03, 10 MHz, 90 mTorr, 300 V, 300 sccm**

Animation slide

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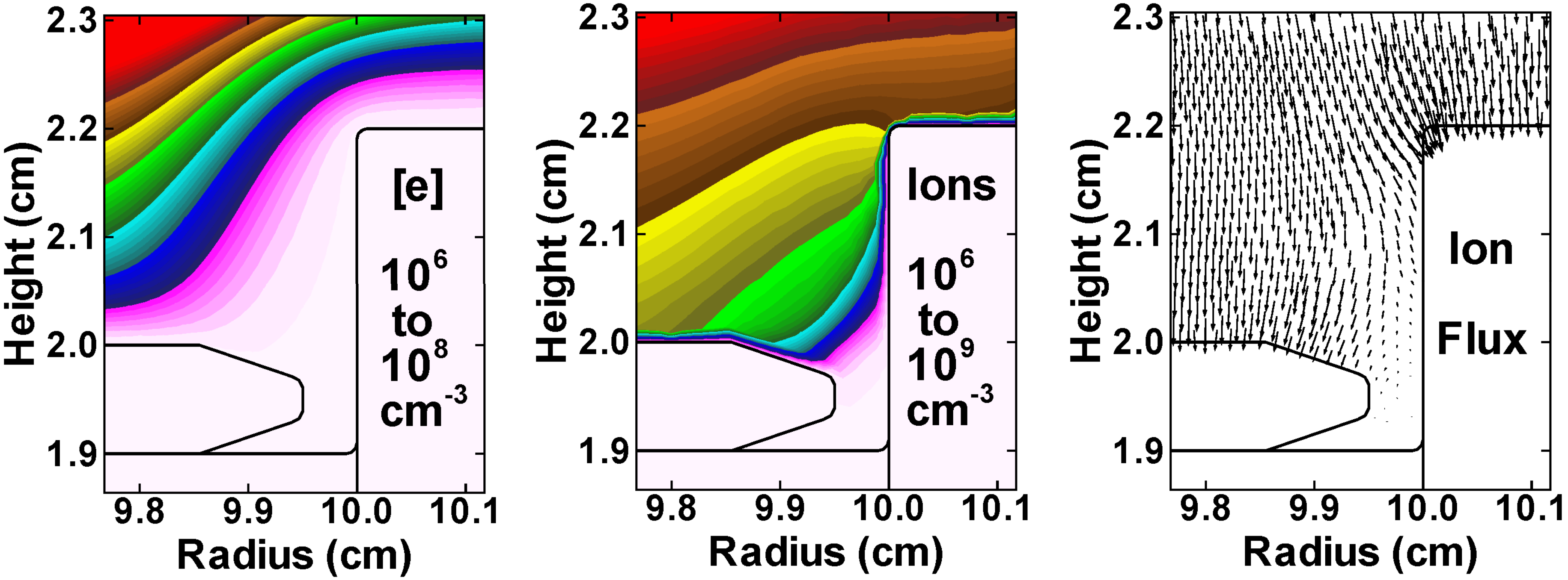
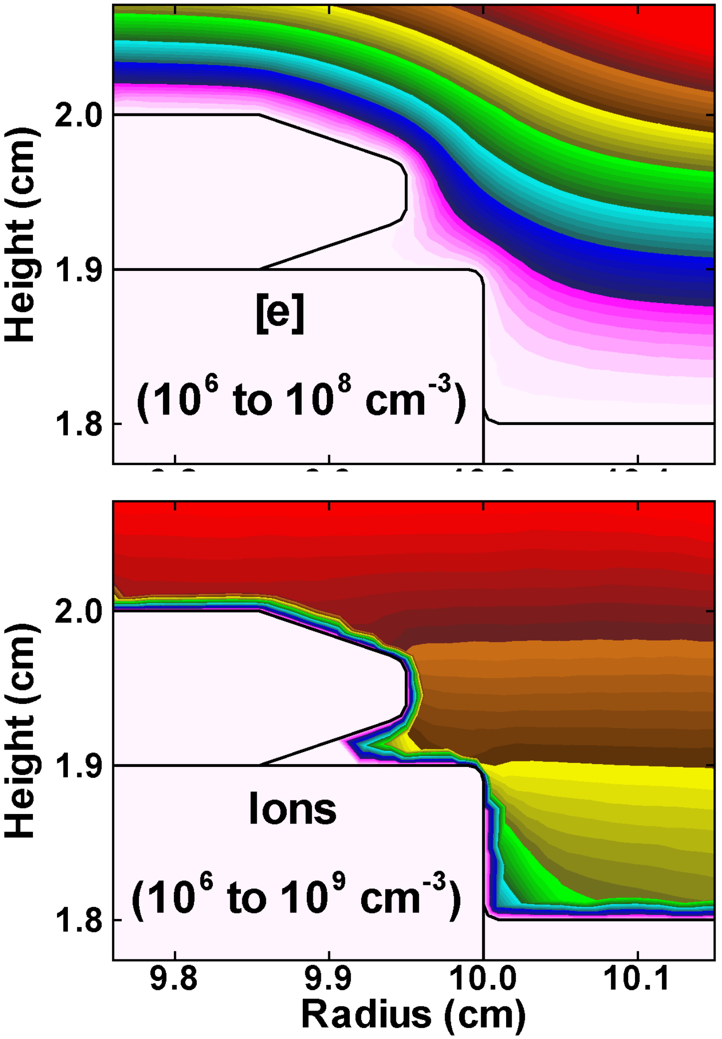
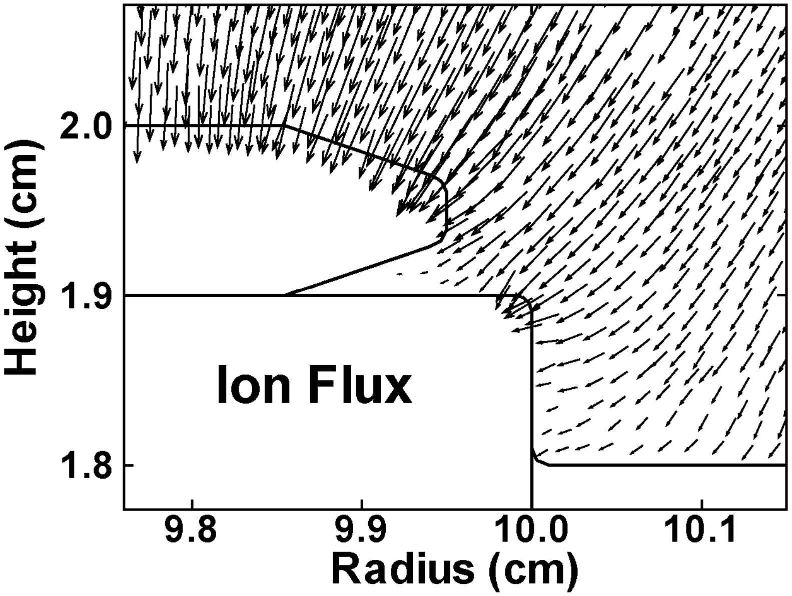


- Shielding of plasma from gap by using tall ring intensifies focusing of ions into end of ring.
- Ar/CF_4 = 97/03, 10 MHz, 90 mTorr, 300 V, 300 sccm

PLASMA PENETRATION: LOW FOCUS RING





- **Exposing underside of bevel by lowering focus ring allows deep ion penetration.**

- **Ar/CF$_4$ = 97/03, 10 MHz, 90 mTorr**

MIN **MAX**

Log scale

CONCLUDING REMARKS

- Penetration of plasma into wafer-focus ring gap of an RIE discharge was computationally investigated.
- Plasma penetration depends on size of gap relative to sheath thickness.
- For test conditions (Ar/CF_4, 90 mTorr, 300 V, $[M^+] = 10^{10}$ cm^{-3}) significant penetration occurs for gap < 0.5 mm.
- More penetration expected for high plasma densities.
- Polymerization inside gap is magnified by reduction in ion sputtering.
- Ion focusing into edges depends on gap size and tool design (e.g., conductivity of ring).