CONTROL OF UNIFORMITY IN CAPACITIVELY COUPLED PLASMAS CONSIDERING EDGE EFFECTS*

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AGENDA

- Edge effects in Capacitively Coupled Plasmas
- Description of the model
- Origins of the edge effects
- Conclusions

EDGE EFFECTS IN CCPs

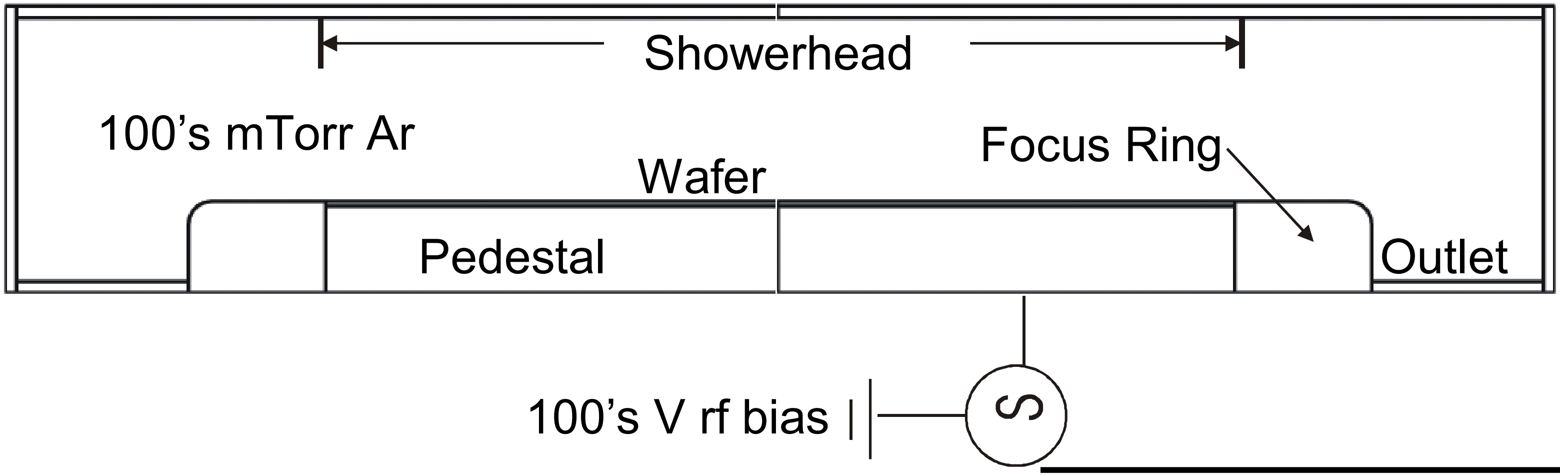
- Edge effects (the perturbation of features near the edge of the wafer) are an increasing concern as wafers increase in size and more product is at larger radius.

- Edge effects are ultimately produced by perturbation of reactant fluxes produced by

  - Method of "terminating" wafer and matching to tool materials
  - Chuck design
  - Aspect ratio
  - Flow characteristics

INVESTIGATION OF EDGE EFFECTS

- **To illustrate the consequences of tool design on edge effects, a computational investigation has been performed in an idealized CCP reactor:**
    - **Focus ring placement**
    - **Focus ring materials**
    - **Gap Height**
- **A new 2-d plasma hydrodynamics model using an unstructured mesh was developed.**



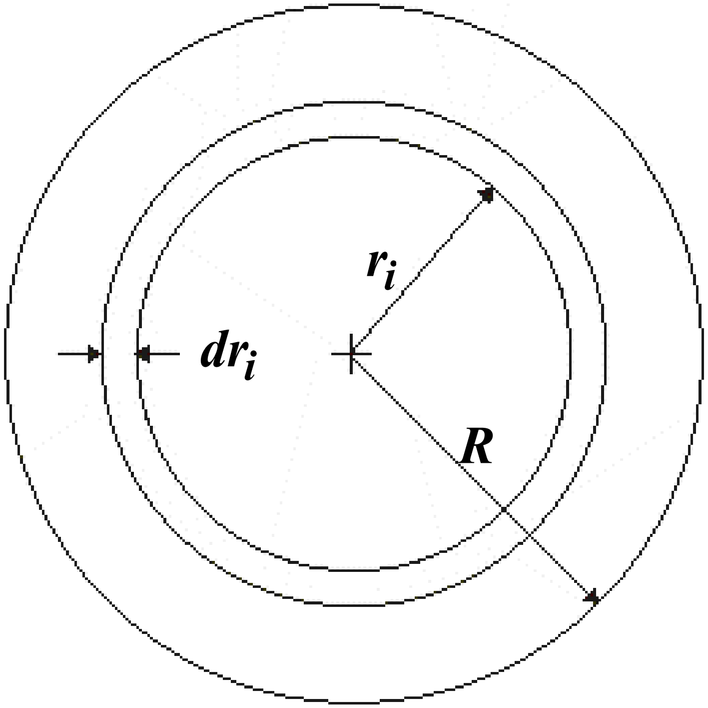
2D PLASMA DYNAMICS MODEL

- 2d rectilinear or cylindrical unstructured mesh model.
- Poisson's equation for potential.
- Surface charge equation.
- Sources due to electron impact, heavy particle reactions, and secondary emission are included.
- Multi-fluid charged species transport equations are discretized using the Scharfetter-Gummel technique.
- Finite volume discretized set of governing equations is solved using Newton's method.
- Electron energy equation coupled with Boltzmann solution for electron transport coefficients.
- Secondary electrons are modeled by the Monte Carlo method.

AREA WEIGHTED ION FLUX NONUNIFORMITY

- **To assess edge effects, a nonuniformity factor is used:**

Integration over wafer



$$\Phi_{ave} = \frac{\sum_i \Phi_i 2\pi r_i dr_i}{\pi R^2}$$

Φ_{ave}: area weighted average flux

Φ_i : flux to sub-area i

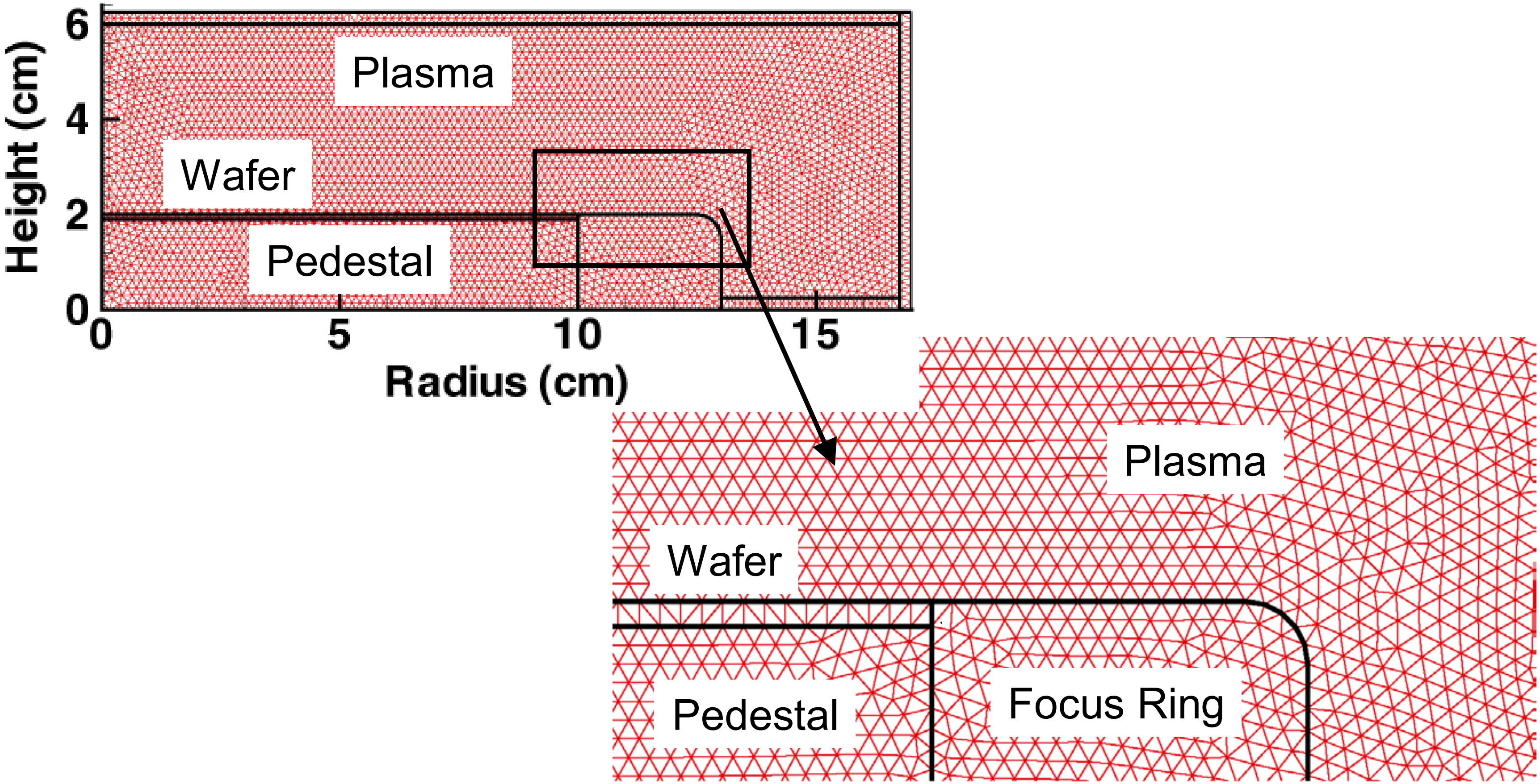
$$\alpha = \frac{\sum_i \left|\Phi_{ave} - \Phi_i\right| 2\pi r_i dr_i}{\Phi_{ave} \pi R^2}$$

$\alpha = 0,$ perfectly uniform

$> 0,$ nonuniform

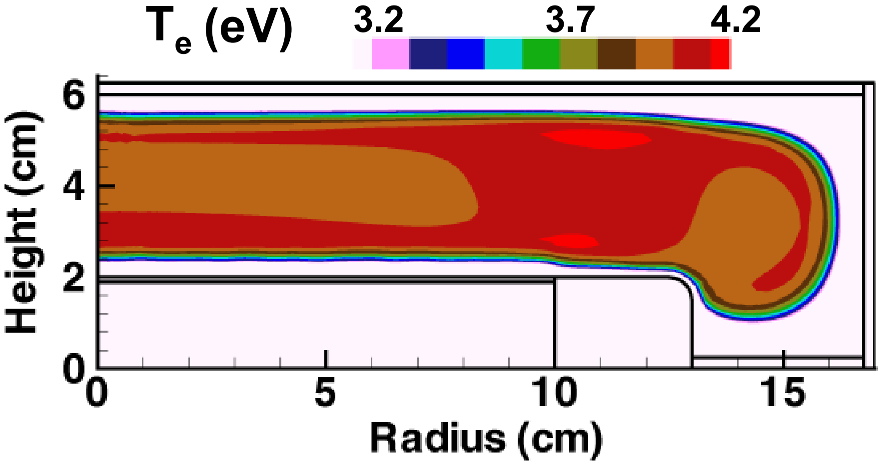
2D UNSTRUCTURED MESH

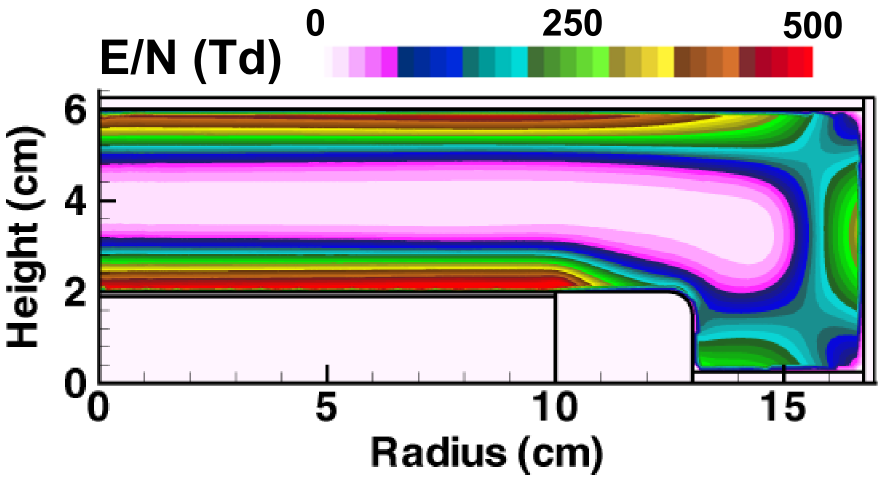
- **The 2d triangular unstructured mesh was generated by Skymesh2, a commercial mesh generator.**



TIME AVERAGED T_e and E/N FOR THE BASE CASE

- T_e is slightly double peaked near the electrodes and > 4 eV.
- The E/N is large near the electrodes and almost 0 in the center of the reactor.
- The strong gradient in E/N near the wafer edge is caused by charging of the focus ring, which acts like a 2d capacitor.
    - 100 mTorr Ar, 100 sccm
    - 200 V, 10 MHz
    - Showerhead to wafer distance (d) = 4 cm
    - Dielectric constant of focus ring = 4.0





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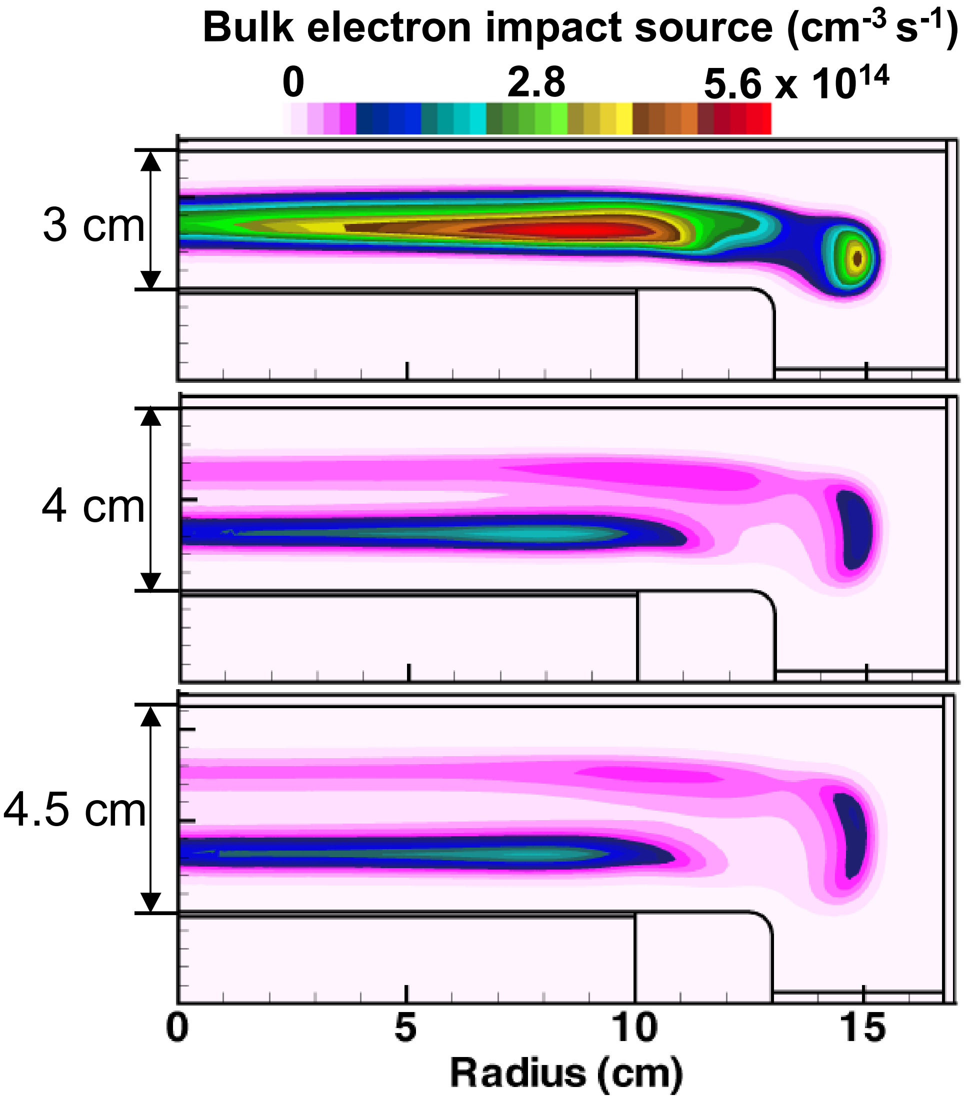
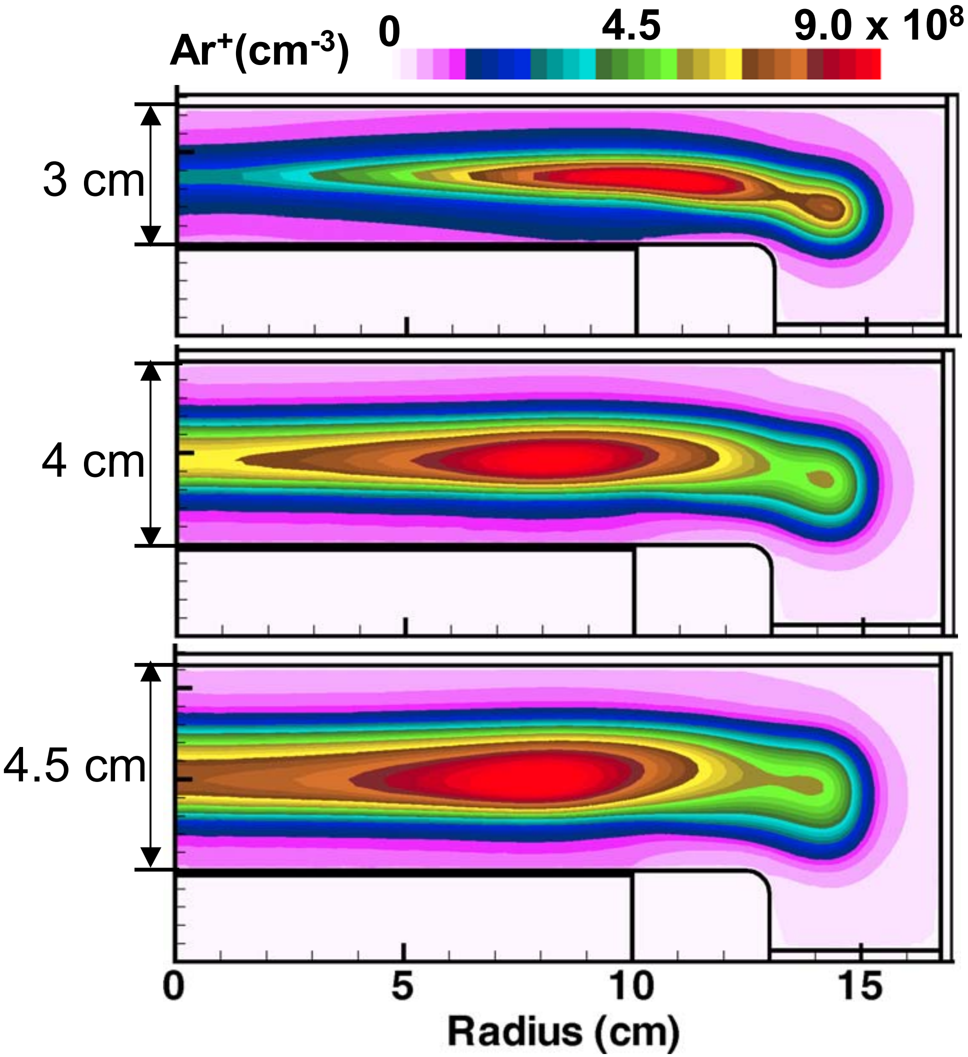
BULK ELECTRON IMPACT SOURCE vs GAP HEIGHT



- **Ar, 100 mTorr, 200 V, 10 MHz**

- **Most of the electron impact ionization occurs in the presheath.**
- **For a small gap height of 3 cm, the two presheath ionization regions coalesce into one.**
- **The bulk electrons accounts for > 85% of the ionization.**
- **Island of ionization results from convergence of top and sidewall presheaths.**

Ar^+ DENSITY vs GAP HEIGHT

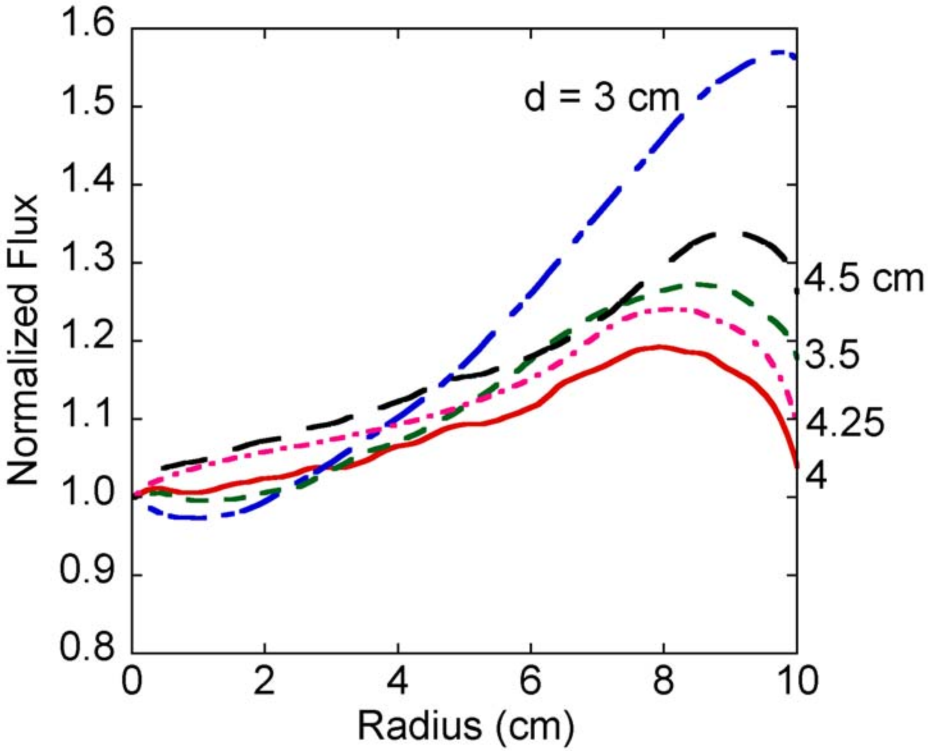


- **As the gap decreases, axial diffusion losses increases while lateral diffusion is unaffected.**
- **The Ar^+ density vs radius for smaller gaps therefore mirror ionization sources.**
- **Larger gaps, with less axial loss, allow lateral diffusion to smooth ionization sources.**

- **Ar, 100 mTorr, 200 V, 10 MHz**

Ar^+ FLUX vs GAP HEIGHT

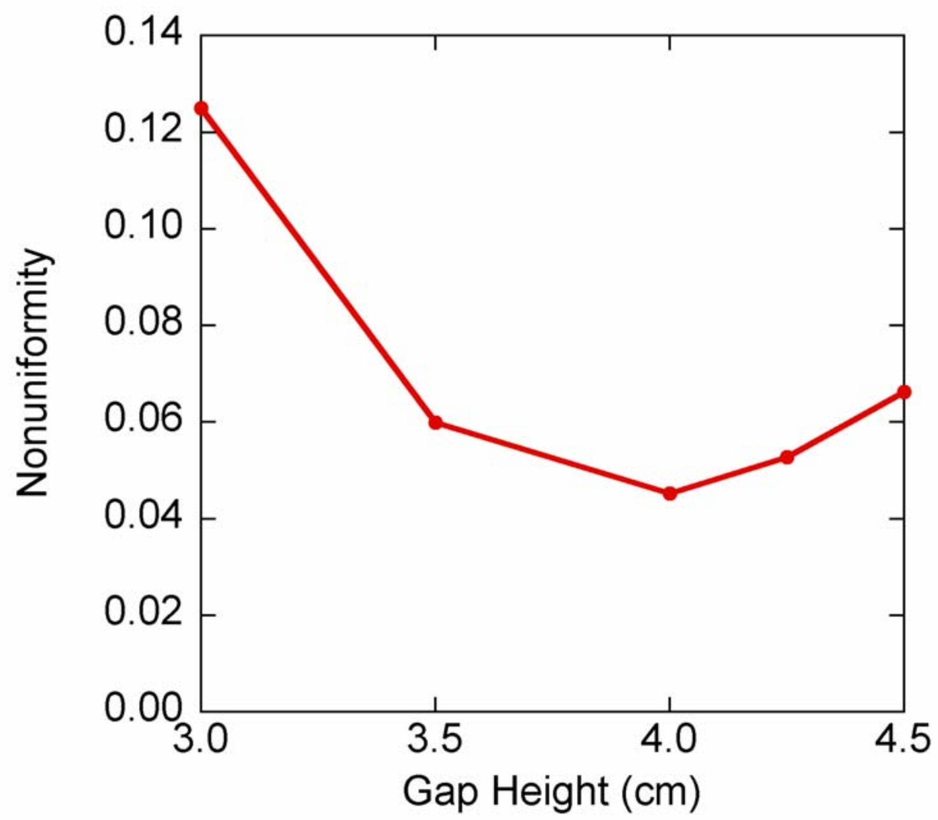
- The overlapping of presheath electron sources is responsible for the large ion density and flux near the wafer edge with small gaps.
- As d increases, smoothing of electron sources by lateral diffusion improves flux uniformity.
- For very large d, presheath ionization sources separate and uniformity decreases.



- Ar, 100 mTorr, 200 V, 10 MHz

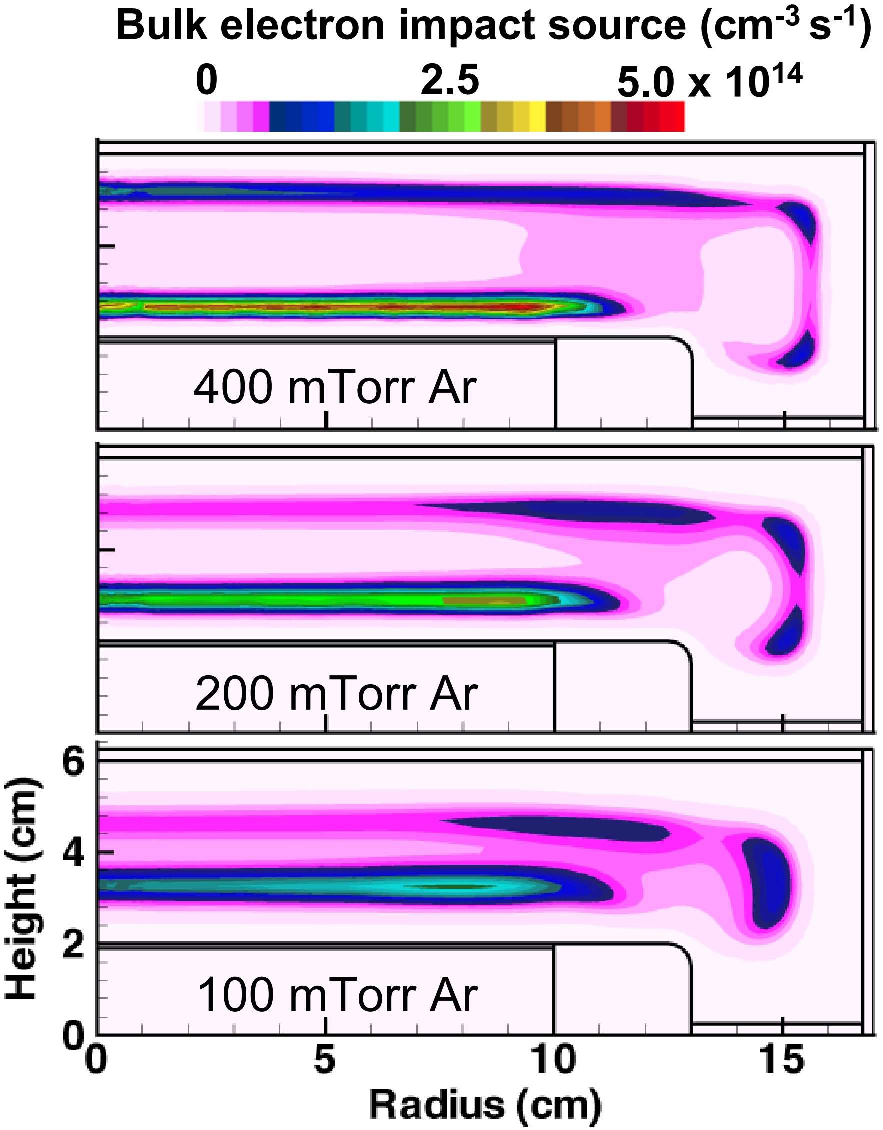
Ar^+ FLUX NONUNIFORMITY vs GAP HEIGHT

- **Uniformity of ion flux is controllable with gap height by engineering the overlap of presheath ionization regions.**



- **Ar, 100 mTorr, 200 V, 10 MHz**

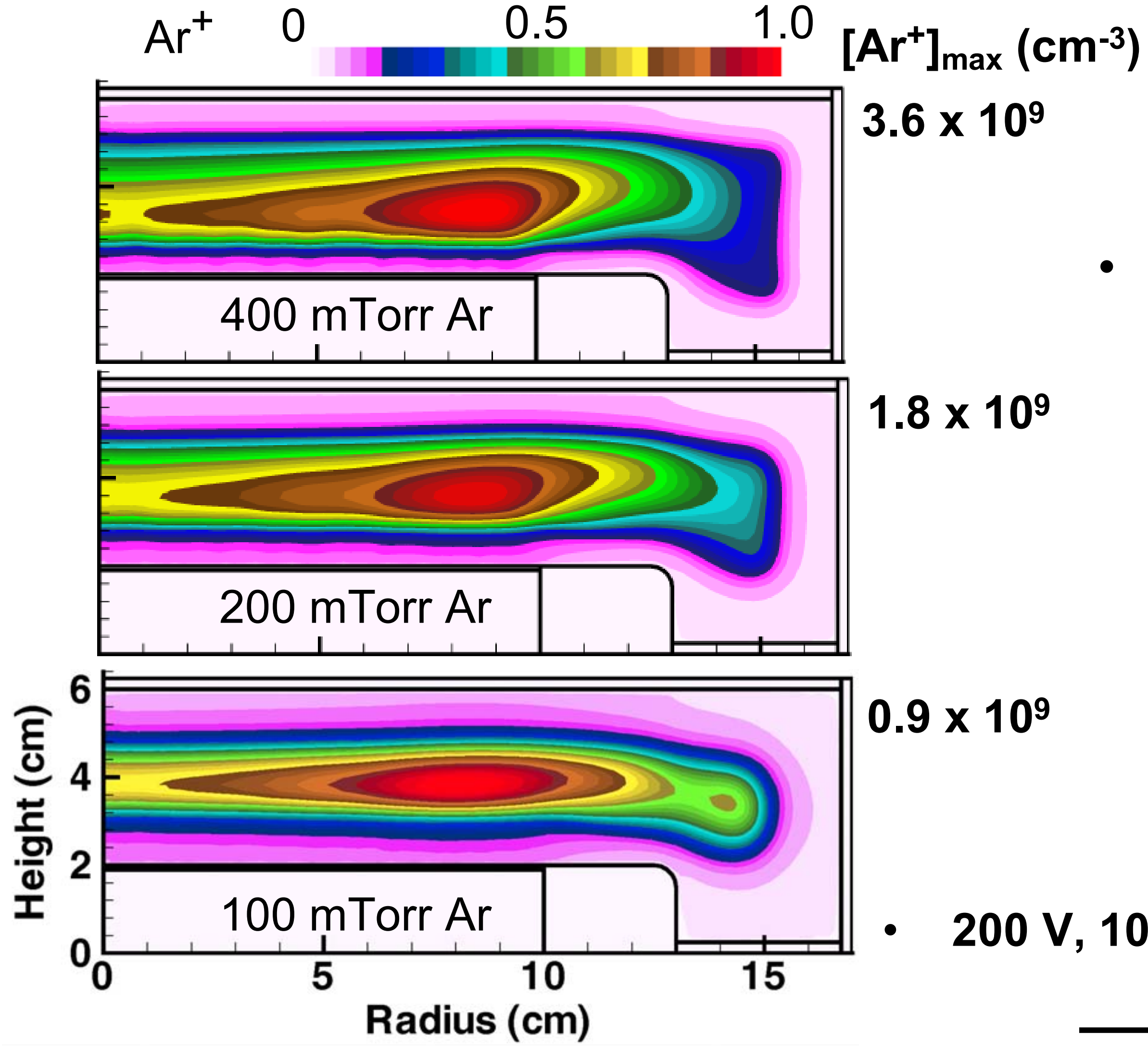
BULK ELECTRON IMPACT SOURCE vs PRESSURE



- **200 V, 10 MHz**

- **As pressure increases, ionization sources are more localized near the wafer due to local maximum in T_e.**
- **The influence of the focus ring in localizing ionization is greater at higher pressures.**

NORMALIZED Ar^+ DENSITY vs PRESSURE

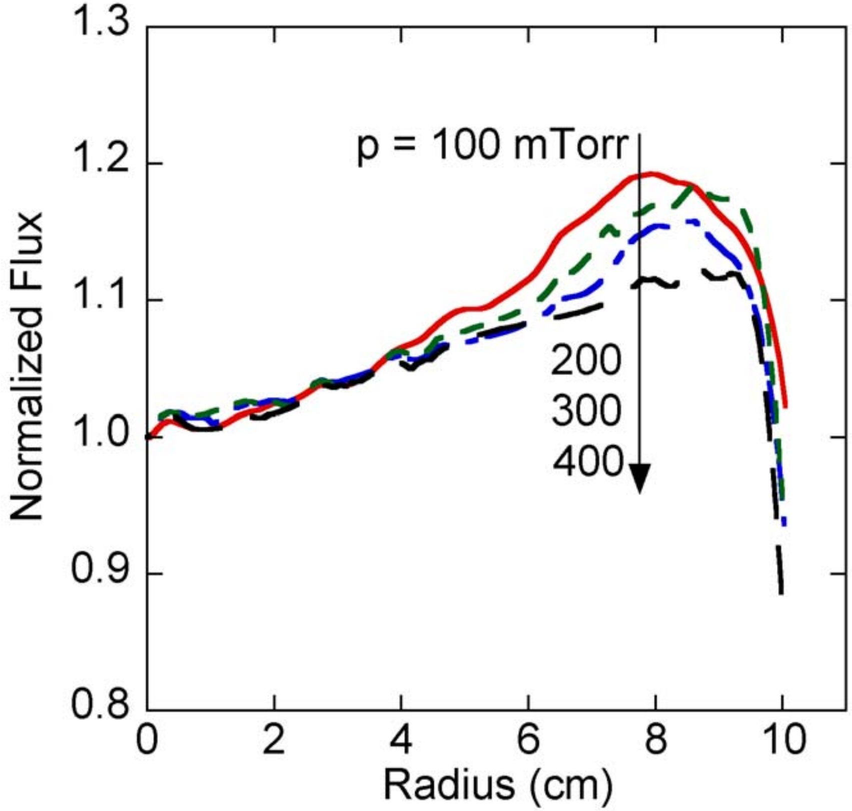


- **The more local ionization sources at higher pressure and the influence of the focus ring produce a more confined plasma.**

- **200 V, 10 MHz**

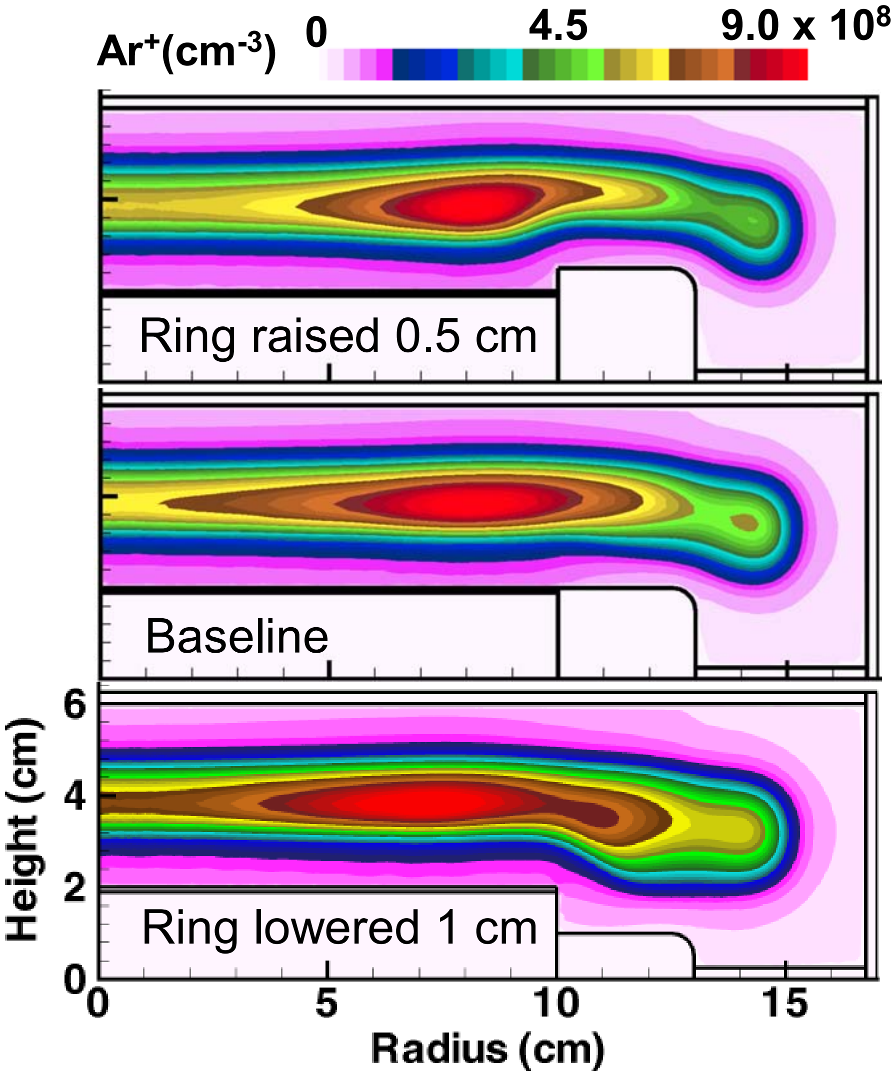
Ar^+ FLUX vs PRESSURE

- **In spite of increased uniformity at intermediate radii, decrease in flux at the very edge of wafer at large pressures potentially reduce overall uniformity.**



- **200 V, 10 MHz**

Ar$^+$ DENSITY vs FOCUS RING HEIGHT



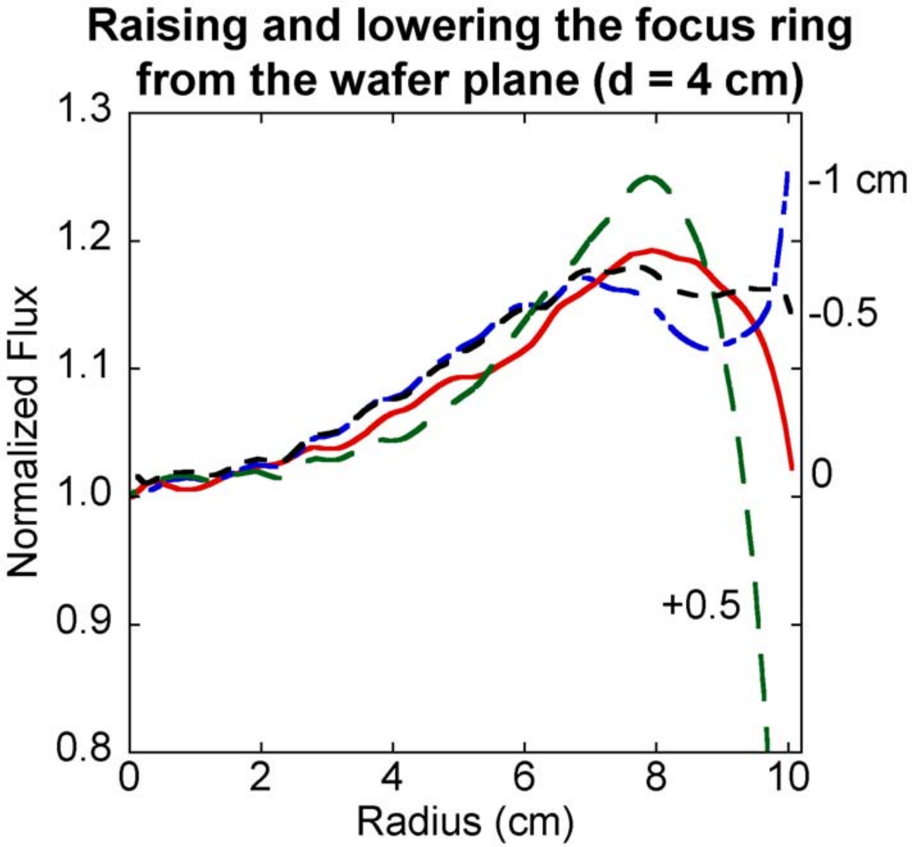
- The focus ring is a recombination surface for ions.

- When the focus ring is lowered, the Ar$^+$ expands and the Ar$^+$ density near the wafer edge increases.

- Ar, 100 mTorr, 200 V, 10 MHz

Ar$^+$ FLUX vs FOCUS RING HEIGHT

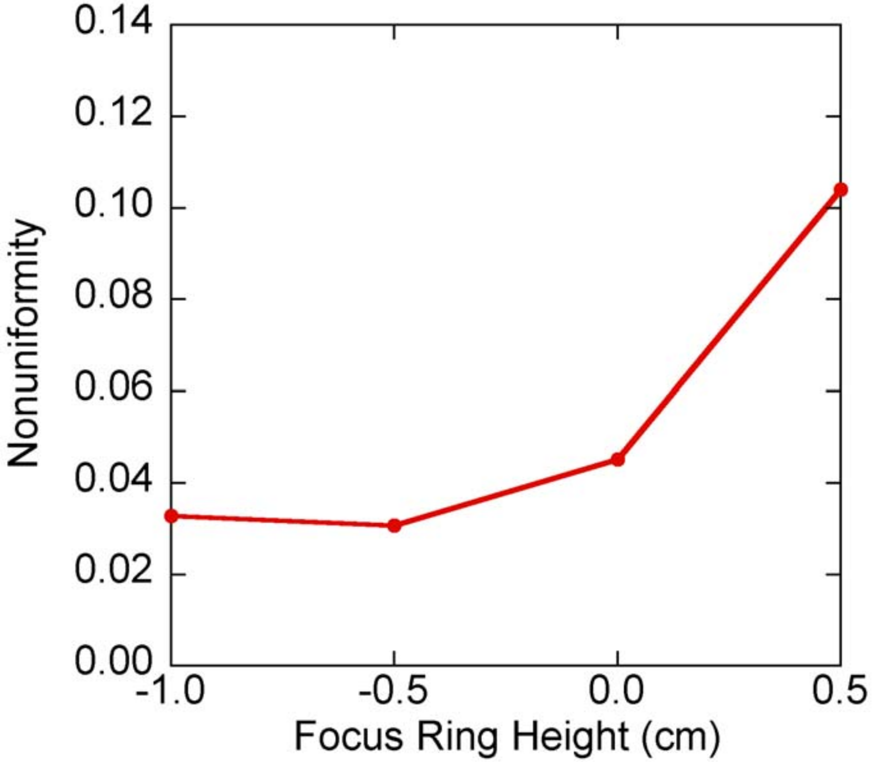
- **Lowering the focus ring reduces the peak and increases the flux at the wafer edge due to the shifts in Ar$^+$ density.**
- **This could be beneficial or detrimental to the flux uniformity.**
- **Raising the focus ring above the wafer cuts off fluxes to the wafer edge and increases the nonuniformity.**



- **Ar, 100 mTorr, 200 V, 10 MHz**

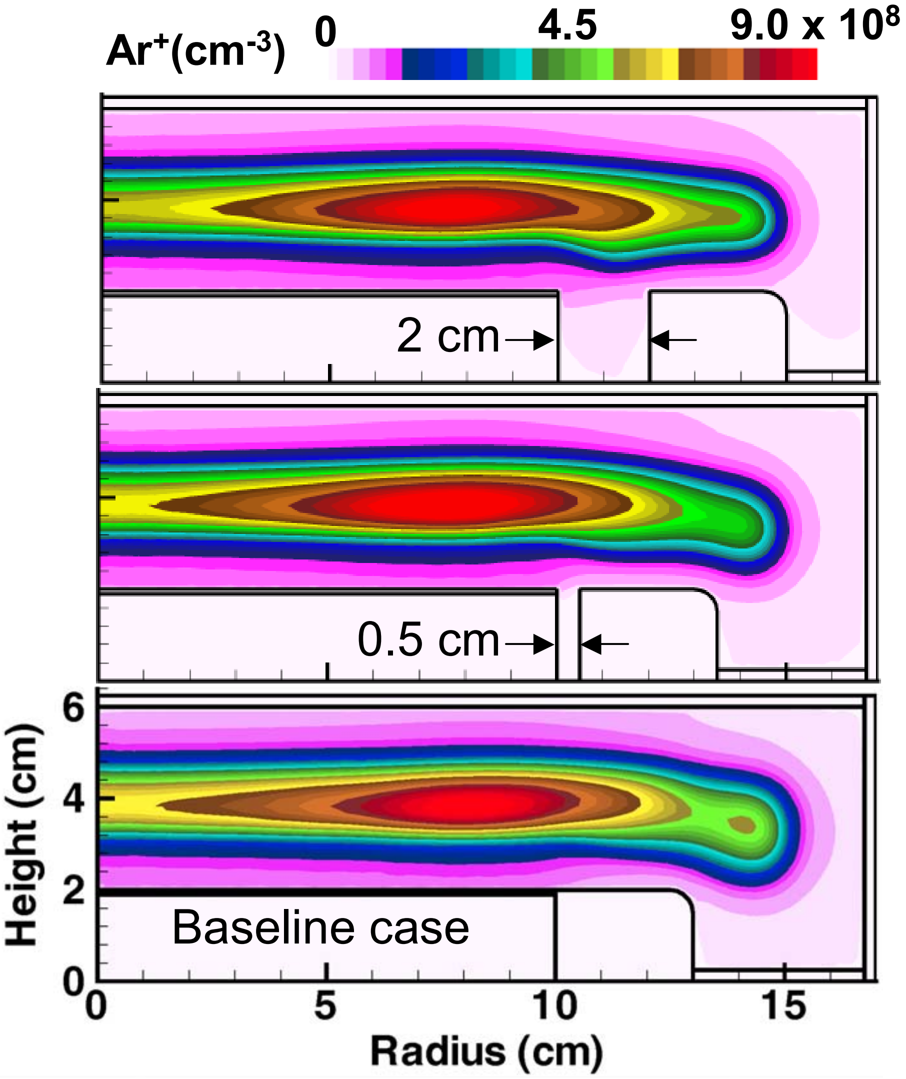
Ar^+ FLUX NONUNIFORMITY vs FOCUS RING HEIGHT

- **In general, lower heights may be better.**
- **However, due to the complex structure of ion flux with height of focus ring, α may not capture subtle flux variations.**



- **Ar, 100 mTorr, 200 V, 10 MHz**

Ar^+ DENSITY vs FOCUS RING GAP

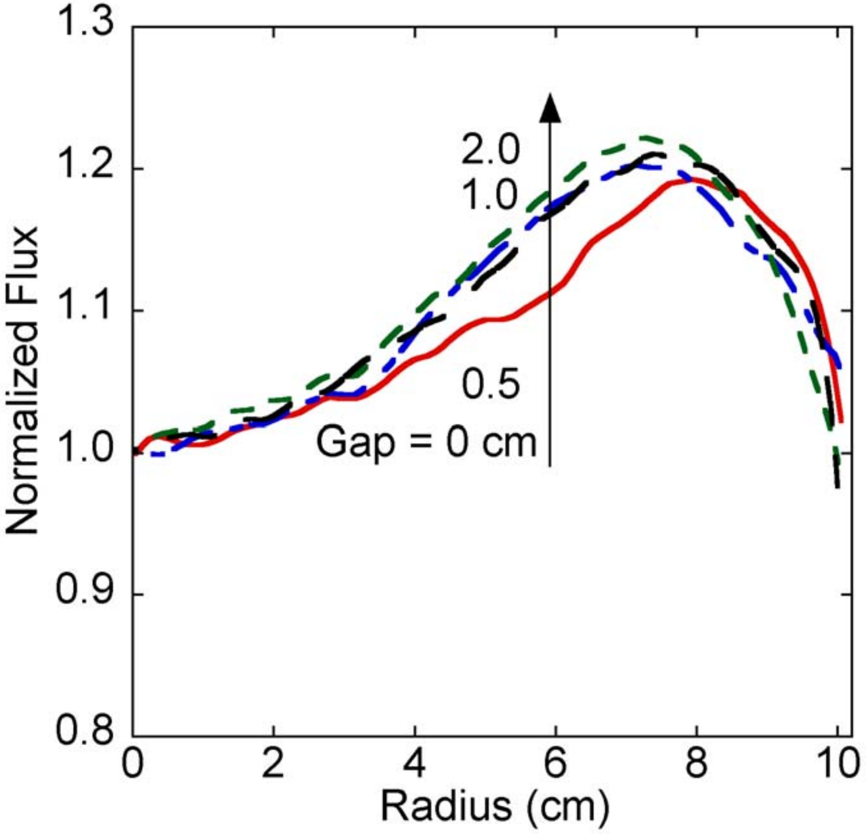


- **The focus ring gap has a surprisingly small effect on ion densities.**

- **There is a slight broadening and shift of the Ar^+ density.**

- **Ar, 100 mTorr, 200 V, 10 MHz**

Ar^+ FLUX vs FOCUS RING GAP



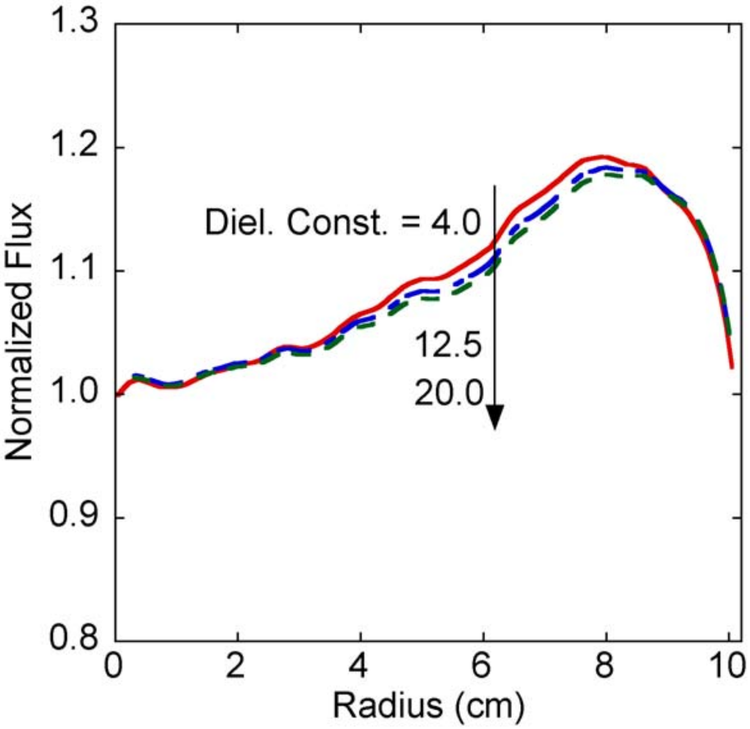
- Tuning of the ion flux uniformity can be achieved with the focus ring gap.

- Ar, 100 mTorr, 200 V, 10 MHz

DIELECTRIC CONSTANT OF THE FOCUS RING

- **The dominant factors for ion density profiles and ion flux uniformity are the diffusion loss, the density gradient, and the source and sink for ions.**
- **The displacement current through the focus ring is proportional to dielectric constant.**
- **Under these conditions, the displacement current is small enough not to perturb total current.**

- **Ar, 100 mTorr, 200 V, 10 MHz**



- **The only significant effect of the dielectric constant is the surface charges, which are shielded from the plasma by the sheath.**

CONCLUSIONS

- Tuning of the ion flux uniformity, particularly near the edge, can be achieved by
  - Regulation of gap and pressure
  - Redesign of focus ring
- Adjustable height or placement of the focus ring could aid in having different processes performed in a single tool.