LARGE DIAMETER CCPs: FREQUENCY, PRESSURE, GAS MIXTURE, GEOMETRY – THEY ALL MATTER*

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AGENDA

- Wave effects in capacitively coupled plasmas
- Scaling Large Area CCPs
  - Frequencies
  - Pressures
  - Gas Mixtures
- What about 450 mm?
- Segmented Electrodes?
- Concluding Remarks

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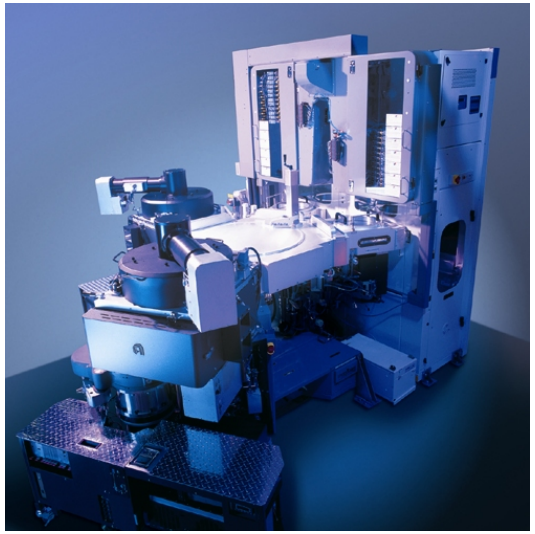
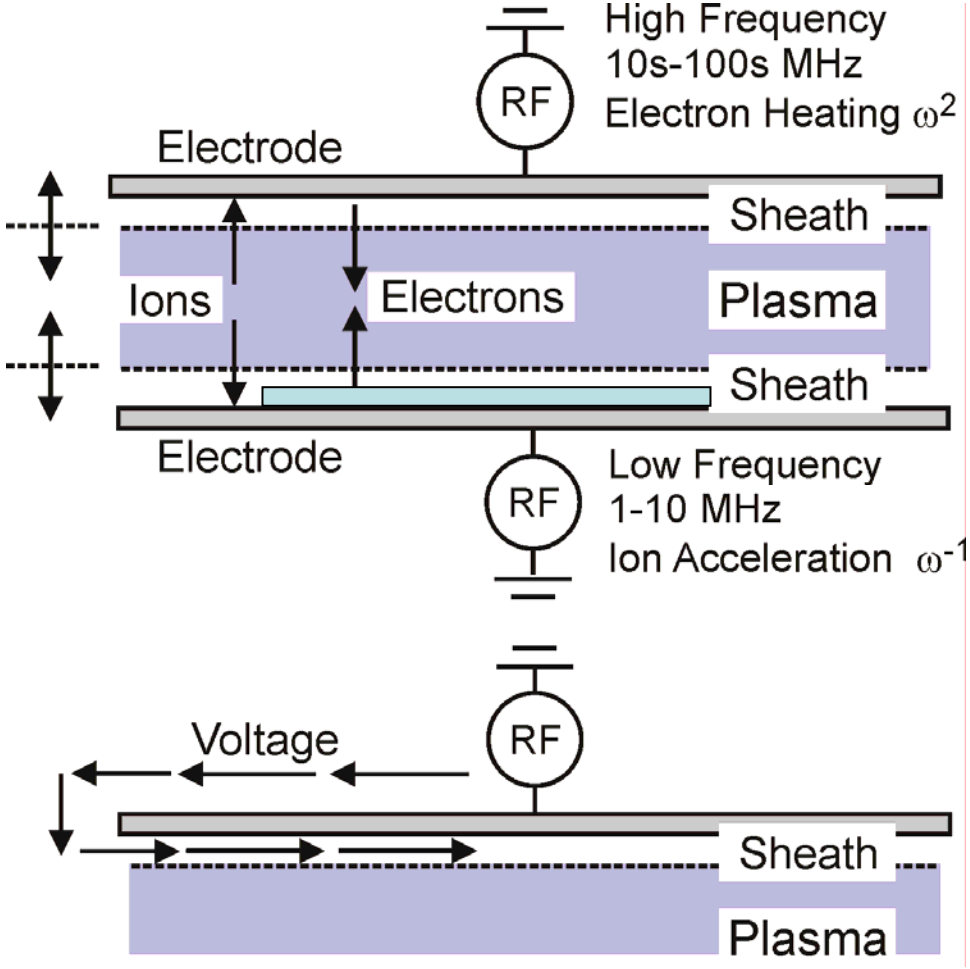
MULTI-FREQUENCY PLASMA ETCHING REACTORS

- **State of the art plasma etching reactors use multiple frequencies to create the plasma and accelerate ions into the wafer.**

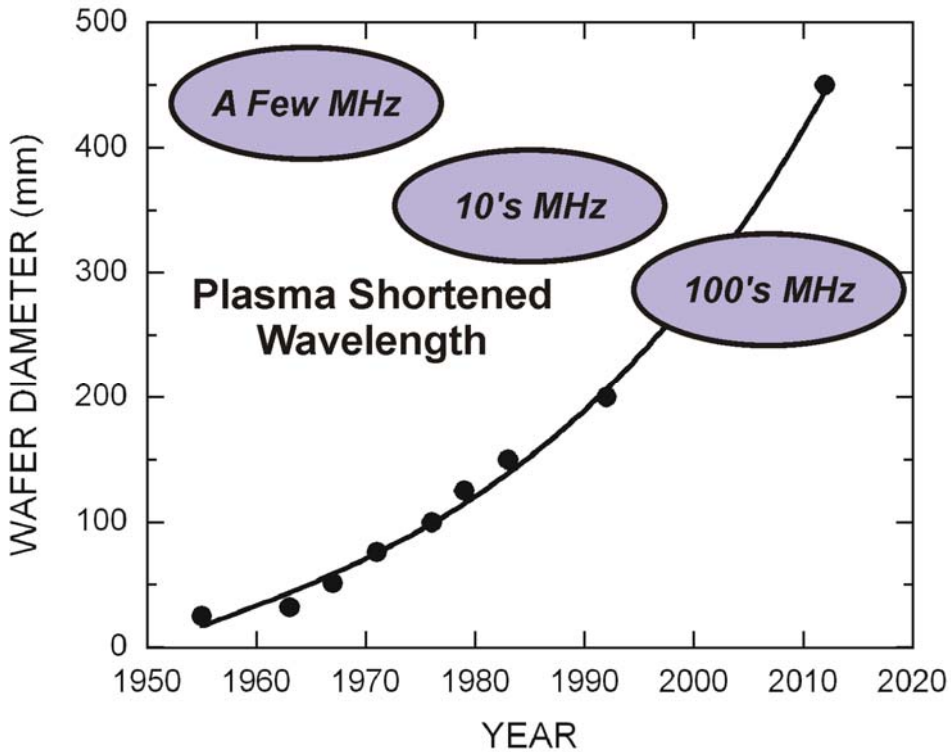


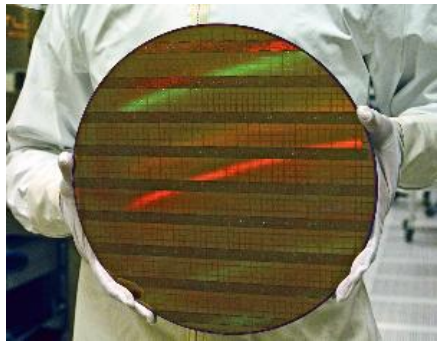


- **Voltage finds its way into the plasma propagating around electrodes (not through them).**

  - **Ref: S. Rauf, AMAT**

WAVE EFFECTS CHALLENGE SCALING





- **As wafer size and frequencies increase - and wavelength decreases, "electrostatic" applied voltage takes on wavelike effects.**
- **Plasma shortened wavelength:** $\lambda = \lambda_0 \big/ \left(1 + \Delta/s\right)^{1/2}$

  Δ = min(half plasma thickness, skin depth), s = sheath thickness

Lieberman, et al PSST 11, 283 (2002)
http://mrsec.wisc.edu

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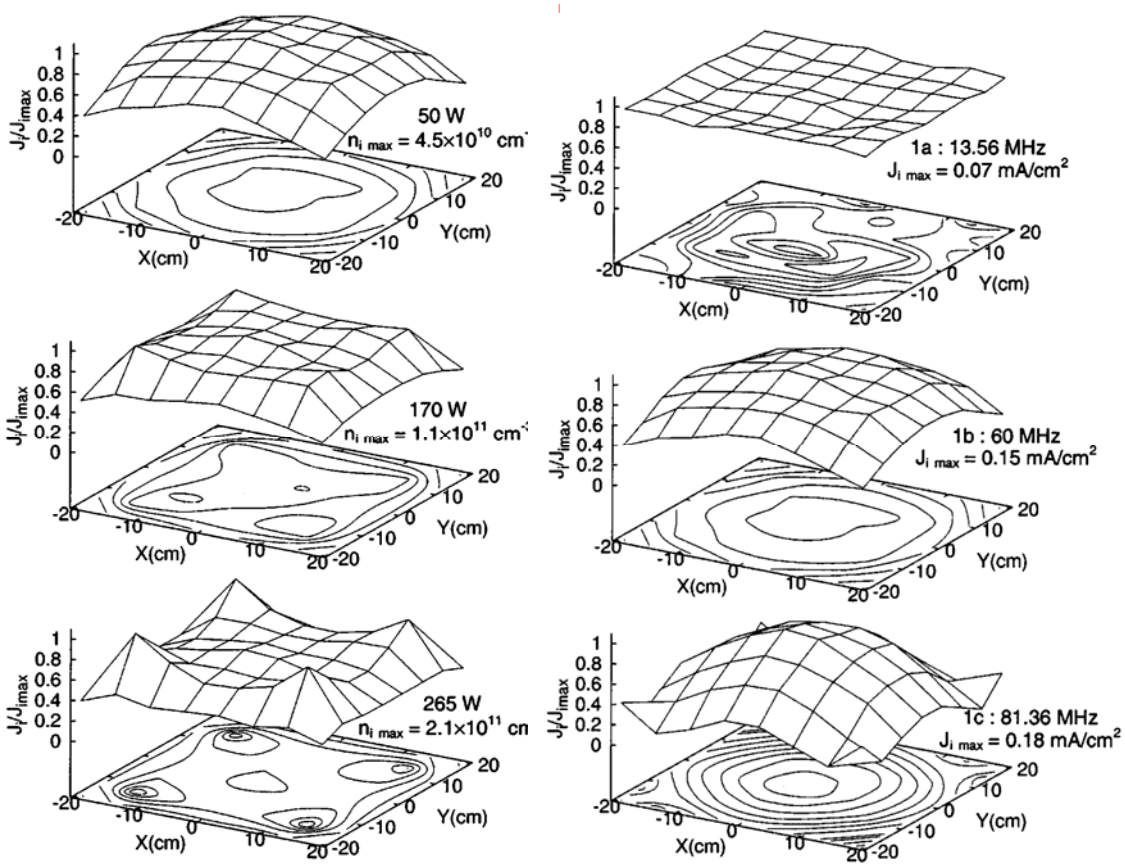
ELECTROSTATIC TO ELECTROMAGNETIC TRANSITION (CAPACITIVE TO INDUCTIVE)



- **Wave effects are observed when increasing…**
- **Frequency (smaller λ/D)**
- **Power (shorter skin depth)**

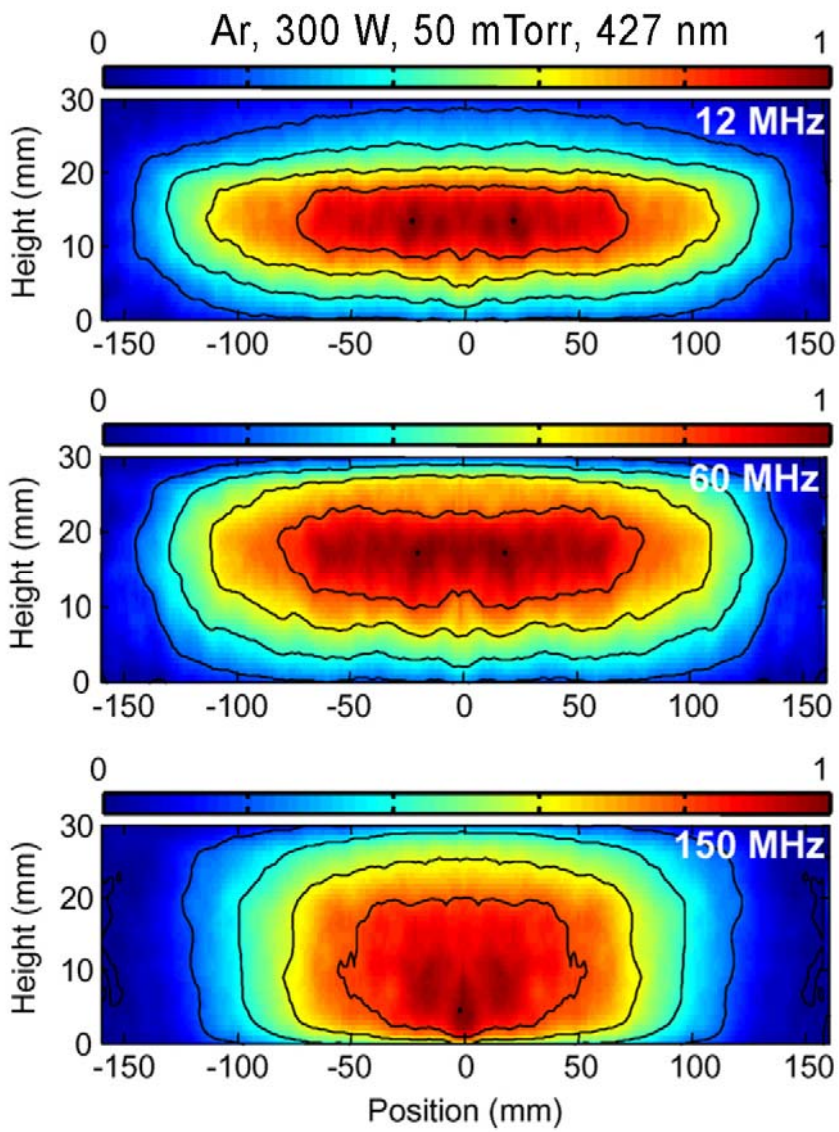
$$\lambda = \lambda_0 \left(1 + \Delta / s\right)^{-1/2}$$

APPLIED PHYSICS LETTERS VOLUME 83, NUMBER 2 14 JULY 2003

Ion flux nonuniformities in large-area high-frequency capacitive discharges

A. Perret,[a] P. Chabert, J.-P. Booth, J. Jolly, J. Guillon, and Ph. Auvray
Laboratoire de Physique et Technologie des Plasmas, UMR 7648, Ecole Polytechnique, F-91128 Palaiseau, France

CONSTRUCTIVE INTERFERENCE



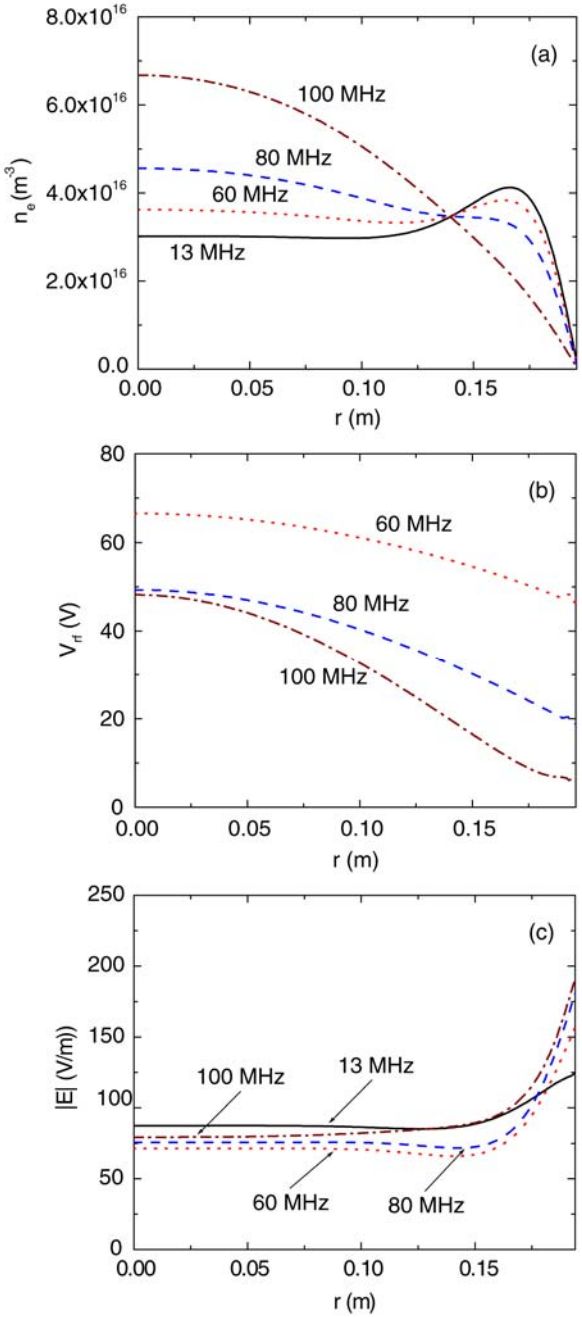
- **Constructive interference occurs when waves approach center the center of the wafer from the edges, possibly creating standing waves.**
- **Plasma emission collapses to center as the frequency increases and constructive interference occurs.**

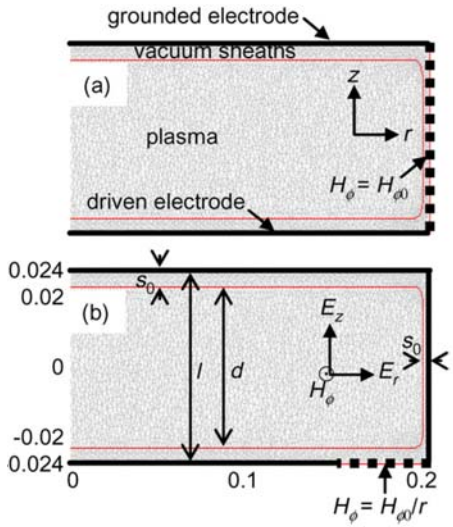
Frequency dependent plasma characteristics in a capacitively coupled 300 mm wafer plasma processing chamber

Gregory A Hebner , Edward V Barnat , Paul A Miller Alex M Paterson and John P Holland

Plasma Sources Sci. Technol. **15** (2006) 879–888

MODELING AND SCALING OF WAVE EFFECTS





- **Finite-element modeling of plasma combined with Maxwell solver demonstrates edge-to-center transition.**
- **Mixed capacitive-inductive coupling is ultimately a function of conductivity and skin-depth.**

Plasma Sources Sci. Technol. **17** (2008) 015018 (16pp)

Modeling electromagnetic effects in capacitive discharges

Insook Lee , D B Graves and M A Lieberman

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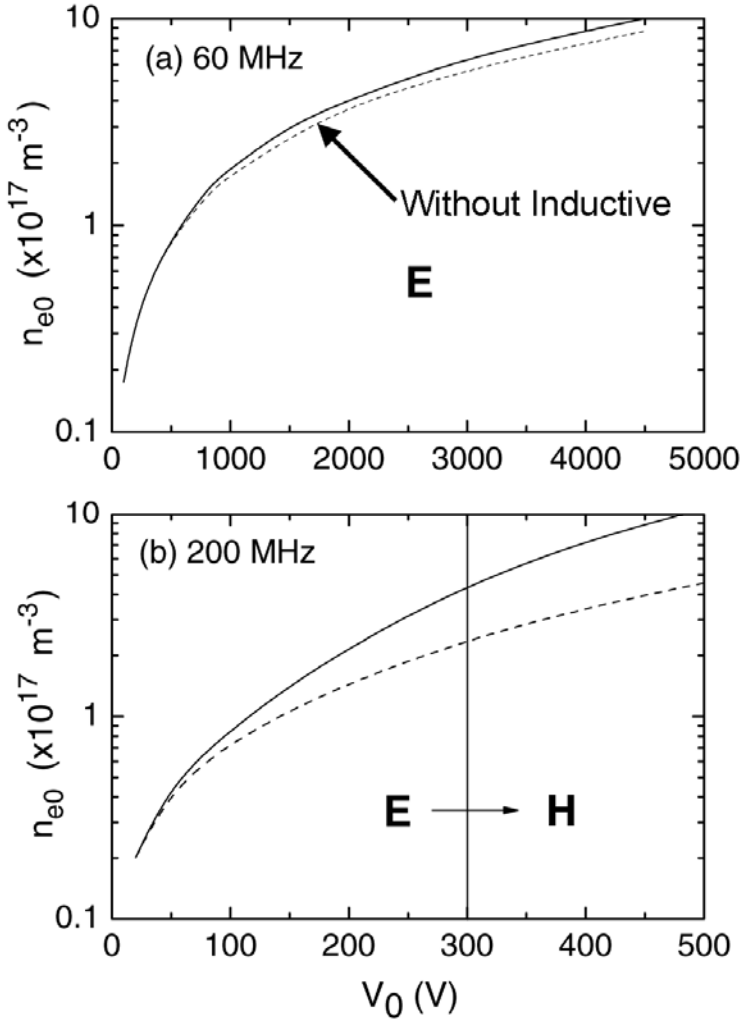
SOURCES OF NON-UNIFORMITY



J. Phys. D 40 (2007)

Electromagnetic effects in high-frequency capacitive discharges used for plasma processing

P Chabert

- The standing wave effect, which enhances power deposition at the discharge centre (power deposition provided by the usual capacitive electric field, perpendicular to the electrode). In particular, it was shown that the standing wave wavelength in the presence of plasma, λ, is shorter than that in vacuum, λ_0, with $\lambda/\lambda_0 \approx 40 V_0^{1/10} l^{-1/2} f^{-2/5}$ where λ_0 and l are in metres, V_0 is the applied rf voltage amplitude in volts and f is the rf frequency in hertz.
- Edge effects: an electrostatic edge effect always exists in capacitive discharges. There is also an electromagnetic edge effect, due to the abrupt change in permittivity at the radial plasma edge [14]. The edge asymmetry of reactors also causes perturbations in the plasma potential to propagate radially inwards [20, 21, 28].
- The skin effect: at high electron density, the radial current in the electrodes induces an electric field parallel to the electrodes, maximal near the plasma edges. This inductive field may dominate at high voltage and the discharge may experience an E-to-H transition [23]. Depending on the pressure regime, transitions are either spatial or global [27].

GOALS: SCALING OF CCPS TO LARGE AREAS

- Develop a computational infrastructure for self-consistent and general implementation of Maxwell's equations into a plasma equipment model.
- Investigate sources of non-uniformities under industrial processing conditions.
  - Feeds, materials, geometries
  - Gas mixture
  - Frequency
  - Pressure
- Look forward to challenges of 450 mm scaling and new technologies to enable scaling.

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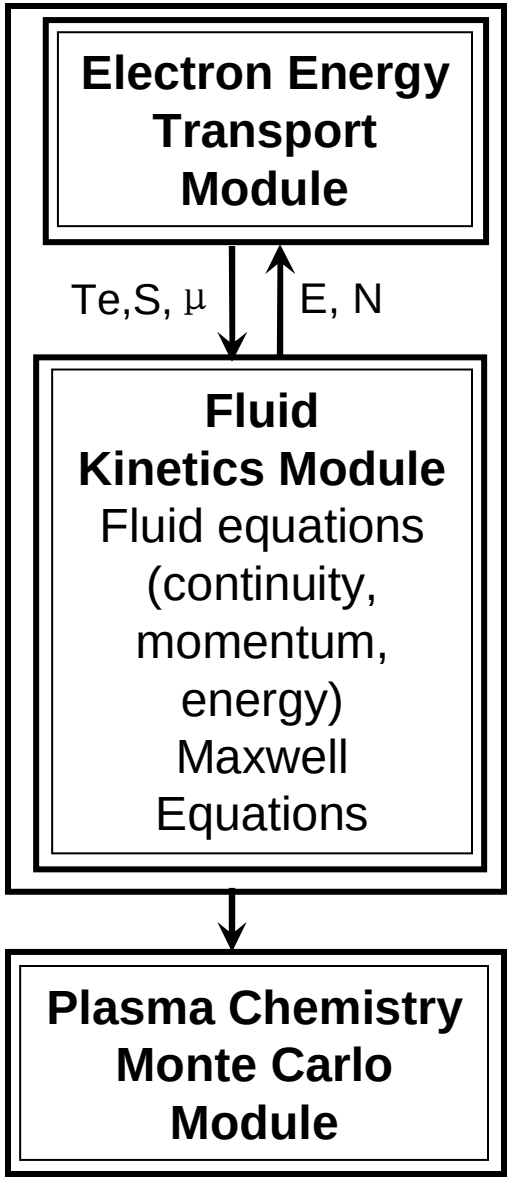
HYBRID PLASMA EQUIPMENT MODEL (HPEM)



- **<u>Electron Energy Transport Module:</u>**
  - **Electron Monte Carlo Simulation provides EEDs of bulk electrons**
  - **Separate MCS used for secondary, sheath accelerated electrons**
- **<u>Fluid Kinetics Module:</u>**
  - **Heavy particle and electron continuity, momentum, energy**
  - **Maxwell's Equation**
- **<u>Plasma Chemistry Monte Carlo Module:</u>**
  - **IEADs onto wafer**

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METHODOLOGY OF THE MAXWELL SOLVER

- **Full-wave Maxwell solvers are challenging due to coupling between electromagnetic (EM) and sheath forming electrostatic (ES) fields.**
  - **EM fields are generated by rf sources and plasma currents**
  - **ES fields originate from charges (e.g., blocking capacitor or applied dc voltage).**
- **Methodology: Separately solve for EM and ES fields and sum the fields for plasma transport.**

$$\vec{E} = \vec{E}_{EM} - \nabla \Phi_{ES}$$

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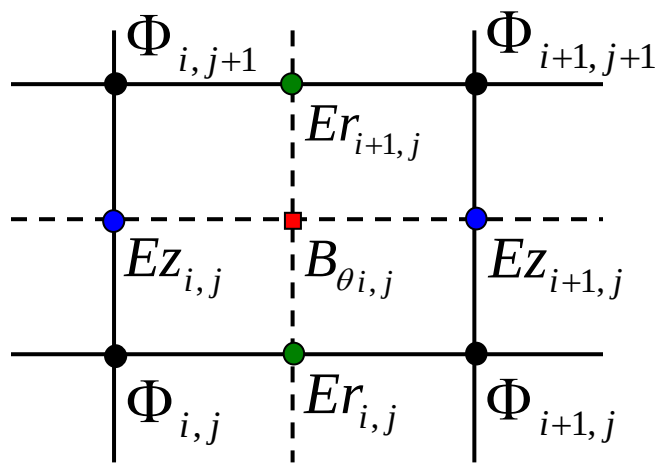
ELECTROMAGNETIC SOLUTION

- **Launch rf fields where power is fed into the reactor.**
- **For cylindrical geometry, TM mode gives E_r, E_z and H_θ .**
- **Solve EM fields using Finite Difference Time Domain (FDTD) techniques with Crank-Nicholson scheme on a staggered mesh:**

$$\frac{\partial E_r}{\partial z} - \frac{\partial E_z}{\partial r} = -\mu_0 \frac{\partial H_\theta}{\partial t}$$

$$-\frac{\partial H_\theta}{\partial z} = J_r + \varepsilon_0 \varepsilon_r \frac{\partial E_r}{\partial t}$$

$$\frac{1}{r}\frac{\partial (r H_\theta)}{\partial r} = J_z + \varepsilon_0 \varepsilon_r \frac{\partial E_z}{\partial t}$$



- **Sub-divide mesh (smaller than plasma) for numerical stability.**

ELECTROSTATIC SOLUTION

- **Solve Poisson's equation semi-implicitly:**

$$\nabla \cdot (\varepsilon \nabla \Phi(t+\Delta t)) = \rho(t) + \frac{d\rho(t, \Phi(t+\Delta t))}{dt} \Delta t$$

- **Boundary conditions on metal: Self generated dc bias by plasma or applied dc voltage.**

- ***Implementation of this solver:***
  - **Specify the location that power is fed into the reactor.**
  - **Address multiple frequencies in time domain for arbitrary geometry.**
  - **First order boundary conditions for artificial or nonreflecting boundaries (i.e., pump ports, dielectric windows).**

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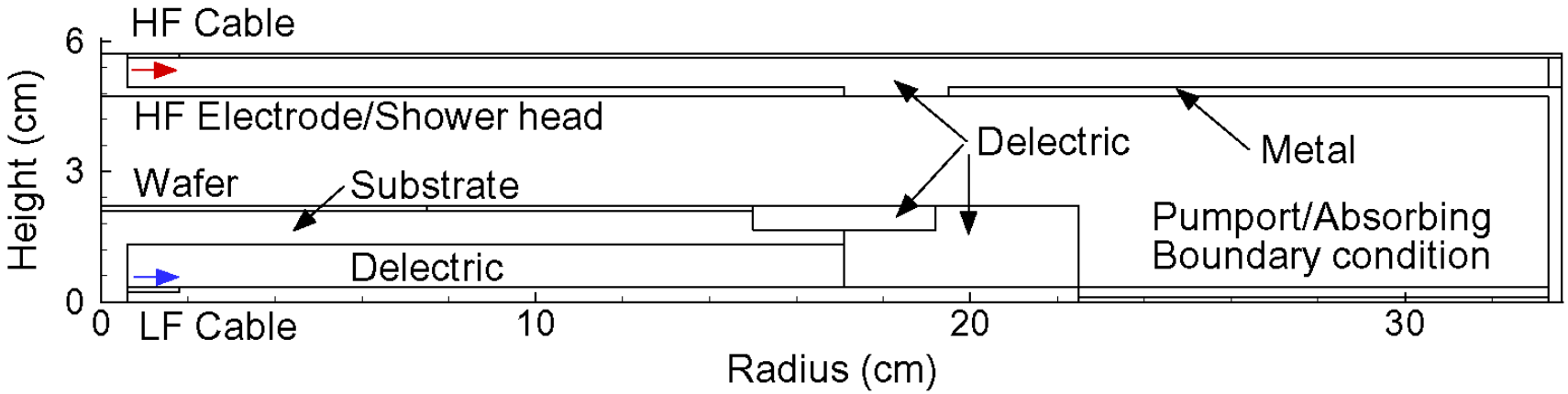
REACTOR GEOMETRY



- **2D, cylindrically symmetric.**
- **Base conditions**
  - **Ar/CF_4 =90/10, 50 mTorr, 400 sccm**
  - **HF upper electrode: 10-150 MHz, 300 W**
  - **LF lower electrode: 10 MHz, 300 W**
- **Specify power, adjust voltage.**

- **Main species in Ar/CF_4 mixture**
  - **Ar, Ar*, Ar^+**
  - **CF_4, CF_3, CF_2, CF, C_2F_4, C_2F_6, F, F_2**
  - **CF_3^+, CF_2^+, CF^+, F^+**
  - **e, CF_3^-, F^-**

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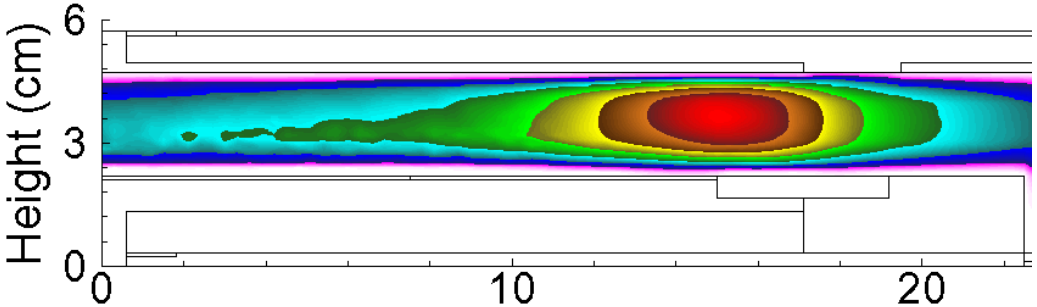
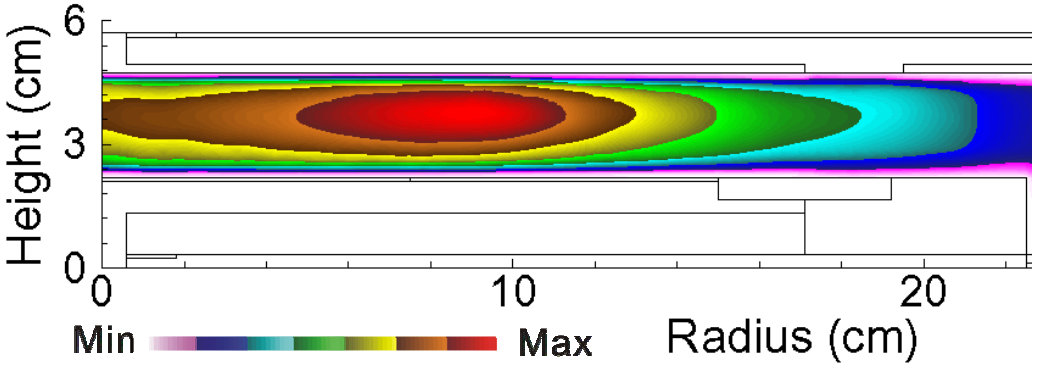
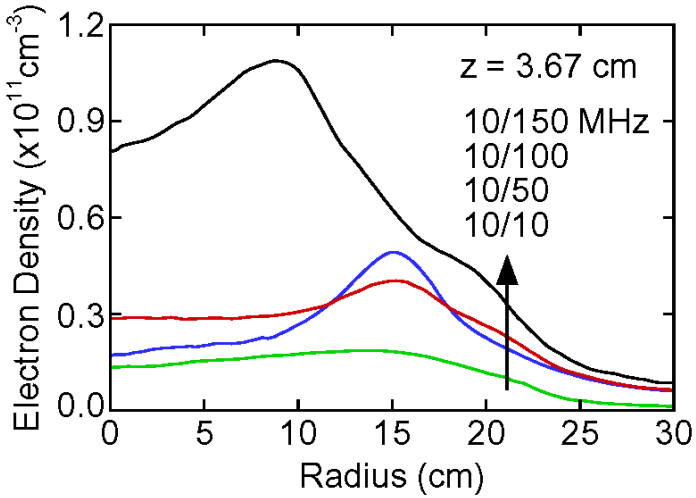
ELECTRON DENSITY vs FREQ: Ar/CF_4 = 90/10

- HF = 50 MHz, Max = 5.9 x 10^{10} cm^{-3}



- HF = 150 MHz, Max = 1.1 x 10^{11} cm^{-3}





- **Increasing HF changes produces higher plasma density due to more efficient heating.**
- **Shorter wavelength, smaller skin depth produces mix of electrostatic and wave coupling.**

- Ar/CF_4=90/10
- 50 mTorr, 400 sccm
- HF: 10-150 MHz/300 W
- LF: 10 MHz/300 W

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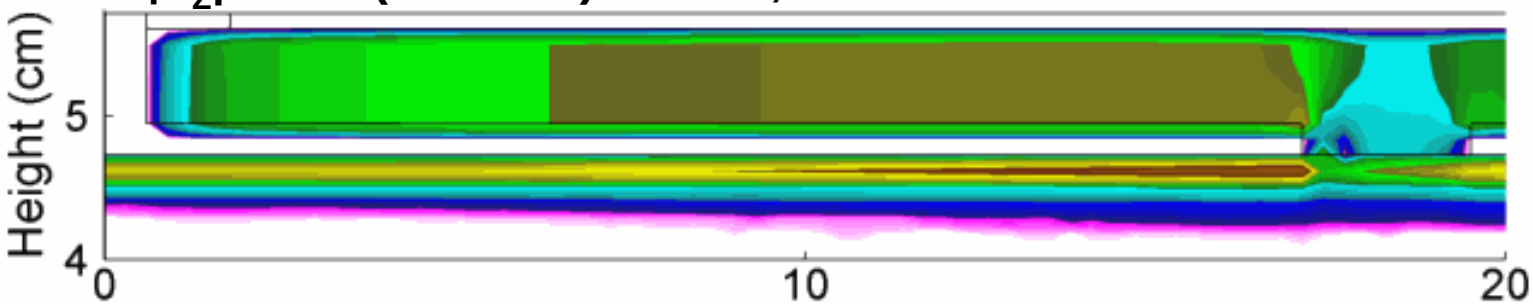
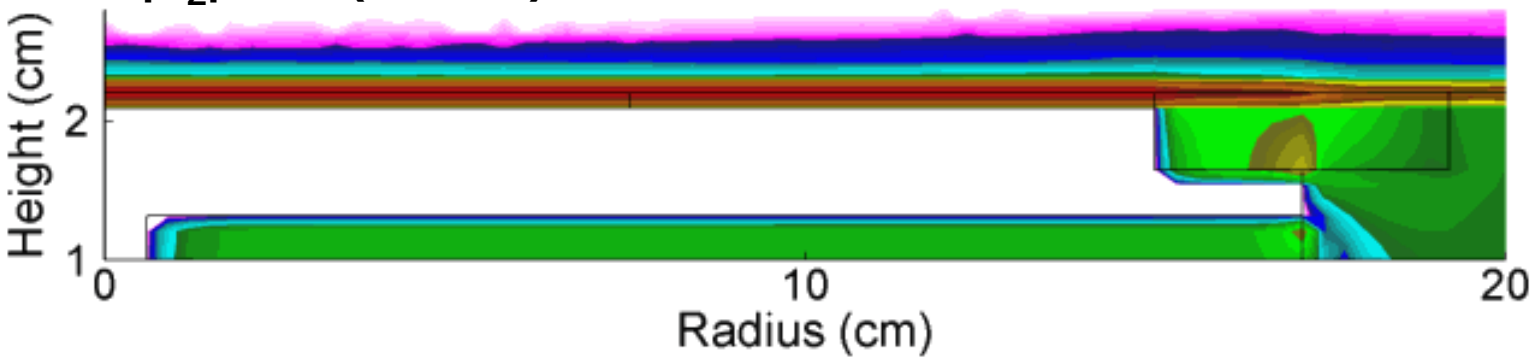
AXIAL E-FIELD IN HF AND LF SHEATH: 10/150 MHz

- $|E_z|$ in HF (150 MHz) Sheath, Max = 1500 V/cm



- HF Electrode

- $|E_z|$ in LF(10 MHz) Sheath, Max = 1700 V/cm



- LF Electrode

- Significant change of $|E_z|$ across HF sheath in form of traveling wave.
- HF source also modulates E-field in LF sheath (which should be electrostatically uniform).

ANIMATION SLIDE-GIF

- Ar/CF_4=90/10
- 50 mTorr, 400 sccm

- HF: 150 MHz/300 W
- LF: 10 MHz/300 W

Min  Max

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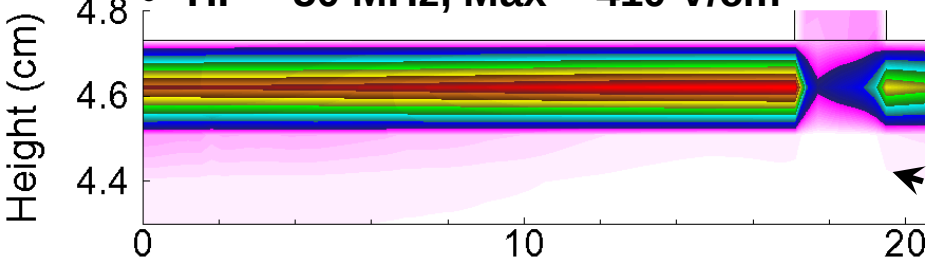
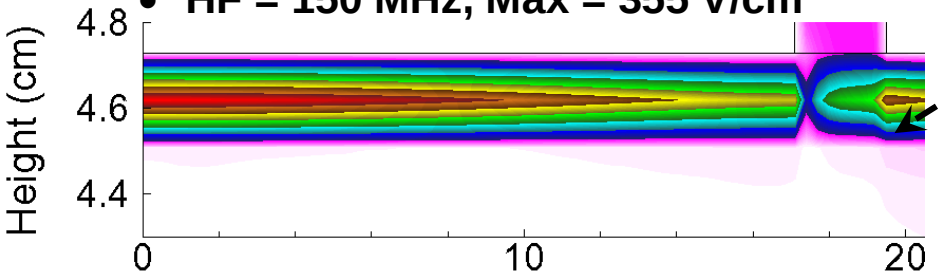
AXIAL TIME AVERAGED EM FIELD IN SHEATHS

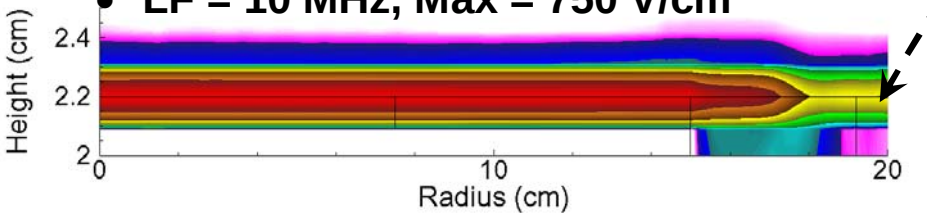
- HF = 50 MHz, Max = 410 V/cm



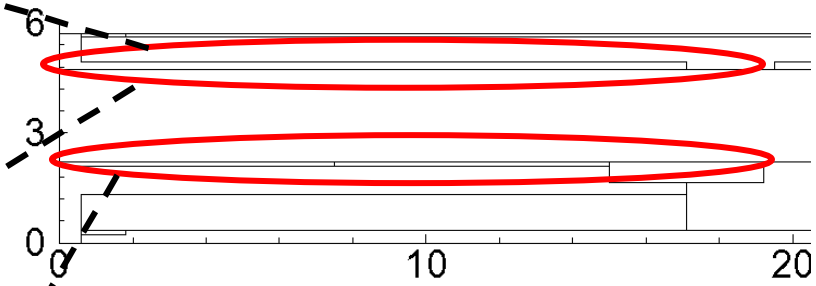
- HF = 150 MHz, Max = 355 V/cm



- LF = 10 MHz, Max = 750 V/cm



- Ar/CF_4=90/10, 50 mTorr, 400 sccm
- HF: 300 W, LF: 10 MHz/300 W



- Low frequency – electrostatic edge effect.
- High Frequency – Constructive interference of waves in center of reactor.

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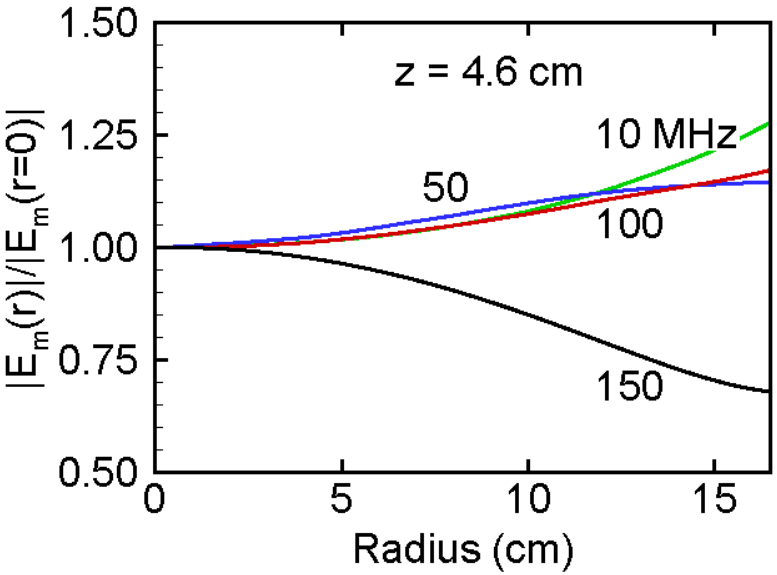
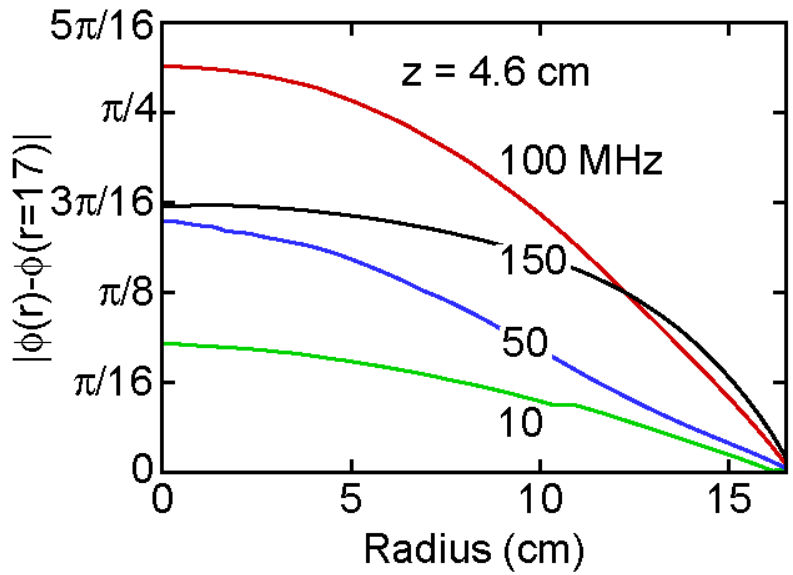
EM PROPERTIES IN HF SHEATH

- **Total Electric Field [$E(r)/E_m(r=0)$]**



- **Relative Phase**



- **With increasing HF, EM field transitions from edge peaked to center peaked with increasing phase difference.**
- **Nonlinear phase behavior between 100 and 150 MHz due coalescing of traveling and standing waves.**

- **Ar/CF_4=90/10**
- **50 mTorr, 400 sccm**
- **HF: 150 MHz/300 W**
- **LF: 10 MHz/300 W**

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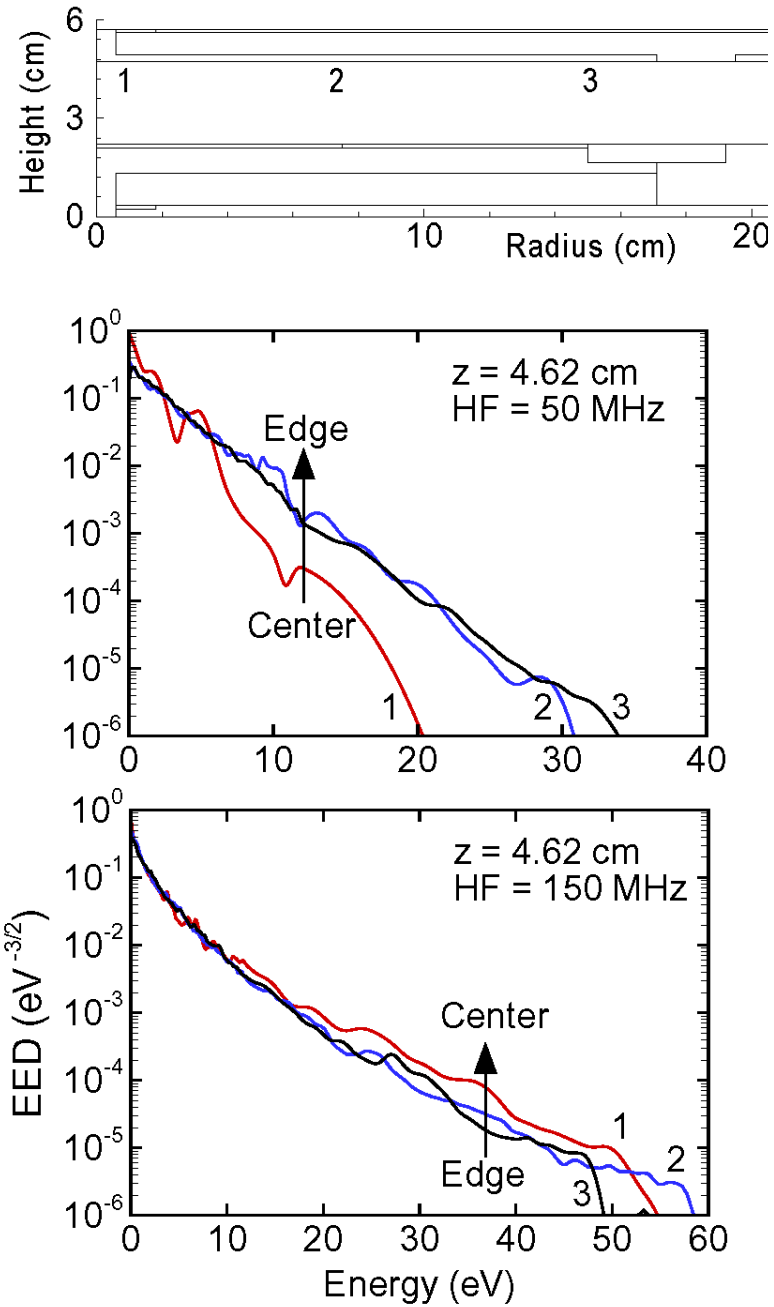
ELECTRON ENERGY DISTRIBUTIONS: HF SHEATH



- **The "higher" the EED in the tail, the more excitation and ionization occurs.**
- **50 MHz: Populated tails for r ≥ 7 cm due to electrostatic edge effect.**
- **150 MHz: elevated tails in the center where sheath field is largest.**
- **From 50 MHz to 150 MHz: 1 temperature EED transits to 2 temperature.**

- **Ar/CF_4=90/10, 50 mTorr, 400 sccm**
- **HF: 10-150 MHz/300 W, LF: 10 MHz/300 W**

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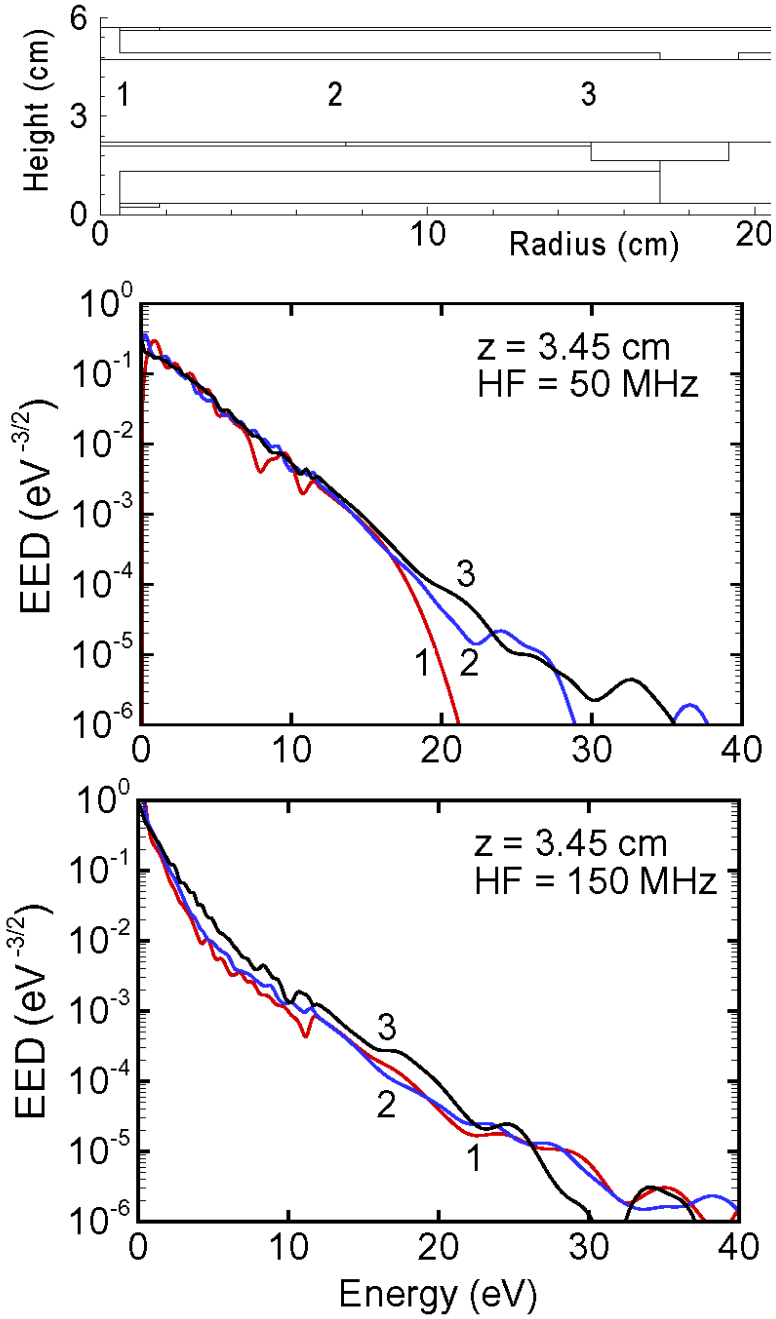
ELECTRON ENERGY DISTRIBUTIONS: BULK PLASMA



- **The EEDs in the bulk plasma are dominated by the high frequency due to more efficient heating.**
- **50 MHz: High tails at the edge.**
- **150 MHz: Nearly uniform EEDs across the plasma.**

- **Ar/CF_4=90/10, 50 mTorr, 400 sccm**
- **HF: 10-150 MHz/300 W, LF: 10 MHz/300 W**

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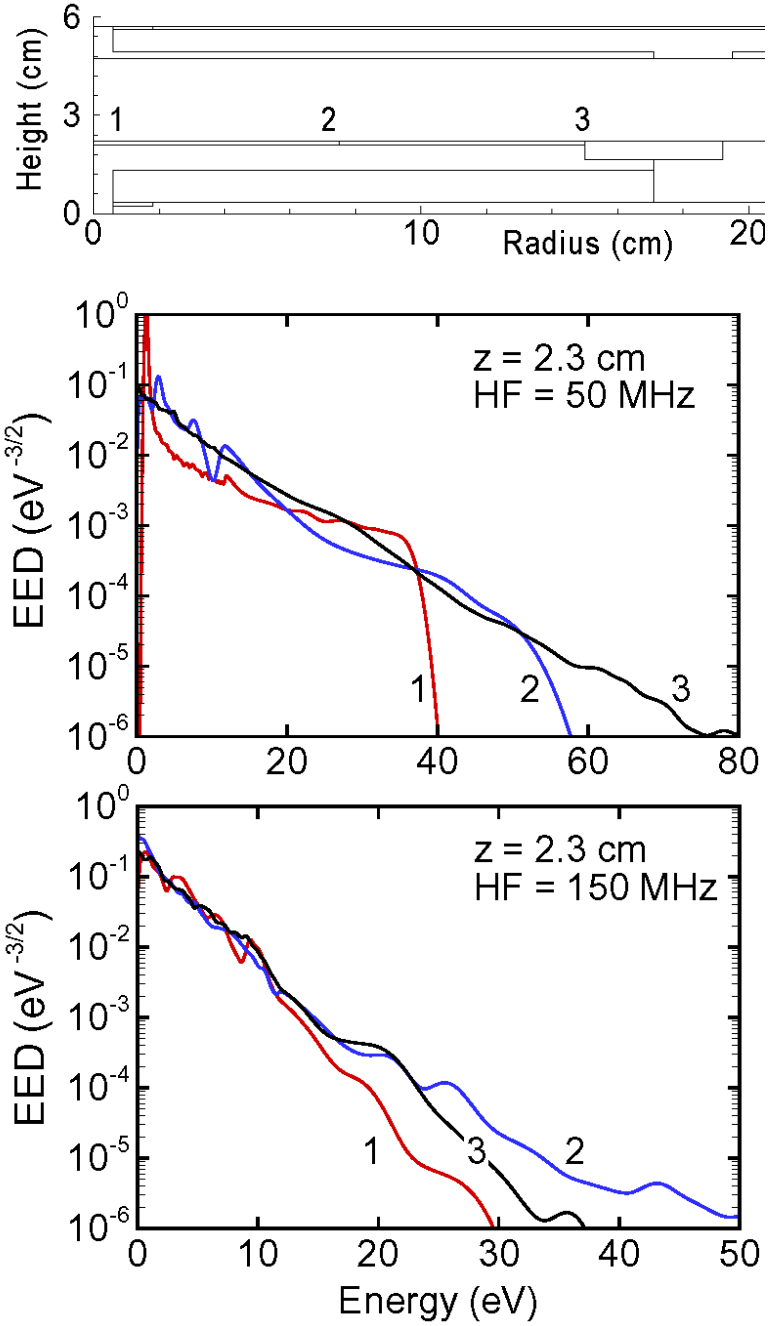
ELECTRON ENERGY DISTRIBUTIONS: LF SHEATH



- **With 10 MHz on the lower electrode, electrostatic effects should dominate.**
- **50 MHz: Edge effect produce high energy tail.**
- **150 MHz: Modulation from upper sheath extends to lower electrode and lifts towards center of wafer.**

- **Ar/CF_4=90/10, 50 mTorr, 400 sccm**
- **HF: 10-150 MHz/300 W, LF: 10 MHz/300 W**

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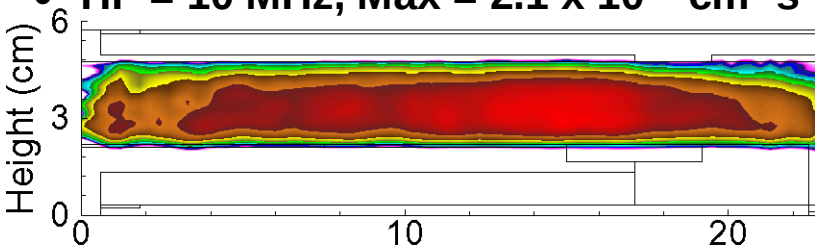
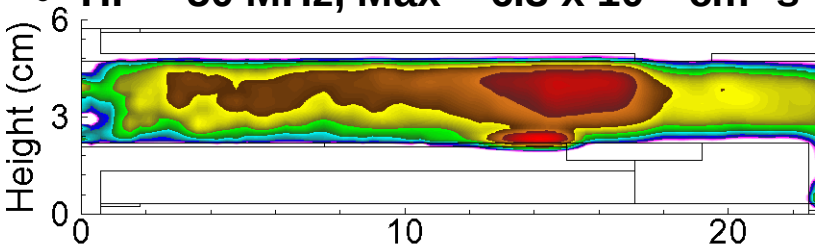
ELECTRON IMPACT IONIZATION SOURCE FUNCTION

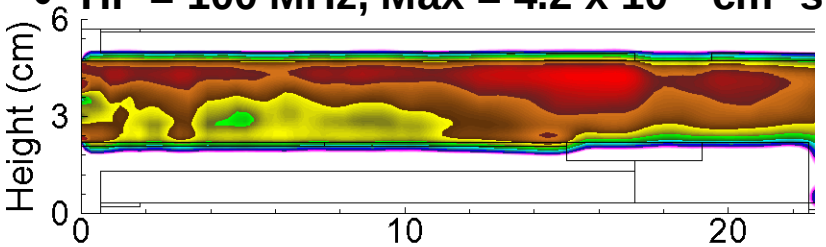
- HF = 10 MHz, Max = 2.1 x 10^{15} $cm^{-3}s^{-1}$



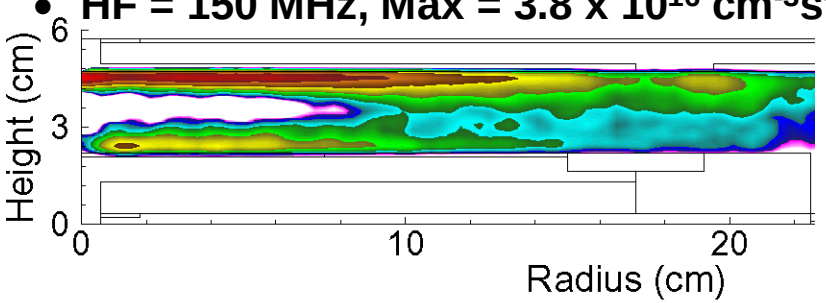
- HF = 50 MHz, Max = 6.3 x 10^{15} $cm^{-3}s^{-1}$



- HF = 100 MHz, Max = 4.2 x 10^{15} $cm^{-3}s^{-1}$



- HF = 150 MHz, Max = 3.8 x 10^{16} $cm^{-3}s^{-1}$



- Combined source from bulk and secondary electrons.
- ≤ 50 MHz: bulk ionization from Ohmic heating, edge peaked due to electrostatic field enhancement.
- 150 MHz: ionization dominated by sheath accelerated electrons (stochastic heating).
- 100 MHz: has both features, but edge effect dominates.

- Ar/CF_4=90/10
- 50 mTorr, 400 sccm
- HF: 10-150 MHz/300 W
- LF: 10 MHz/300 W

Min  Max

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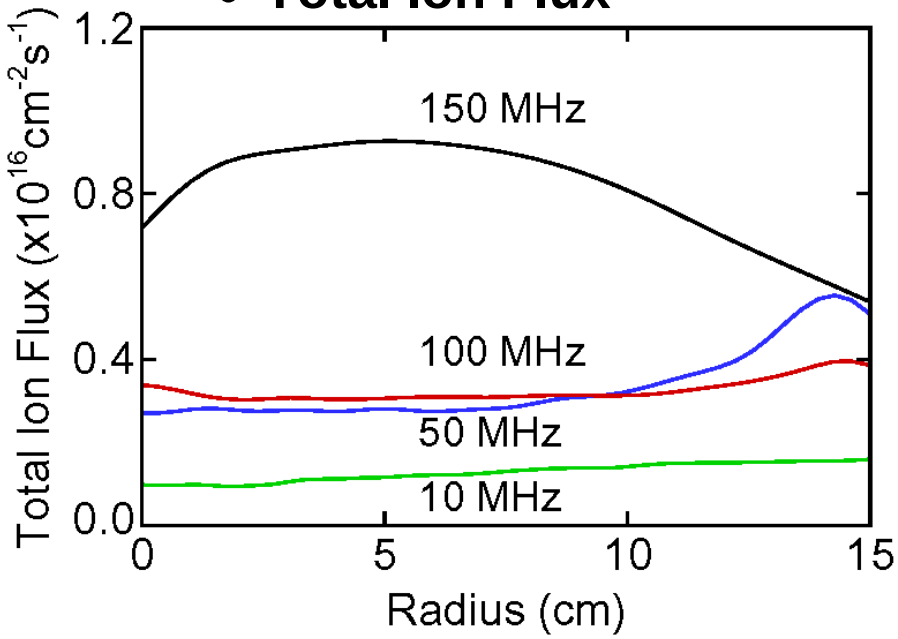
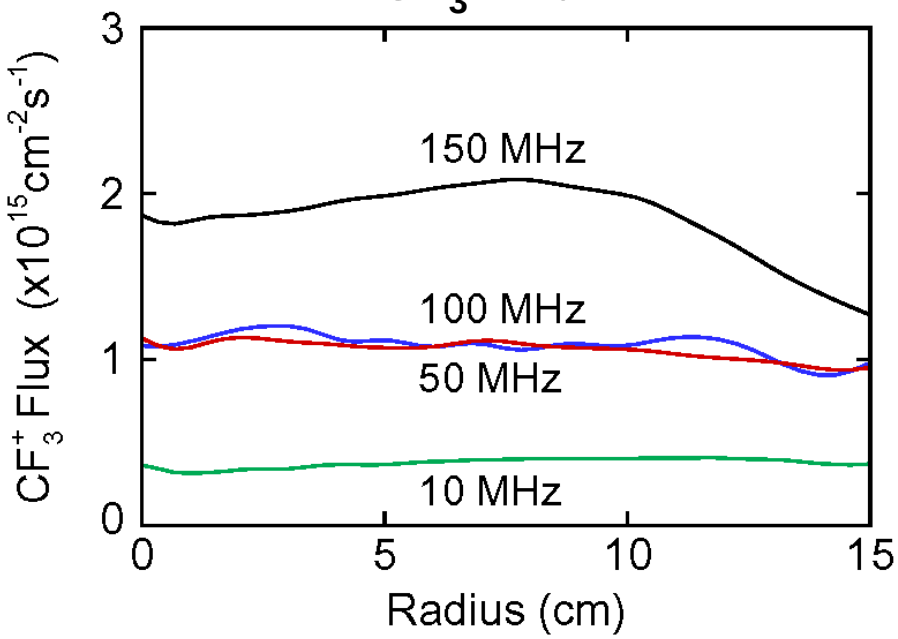
ION FLUXES INCIDENT ON WAFER

- **Total Ion Flux**



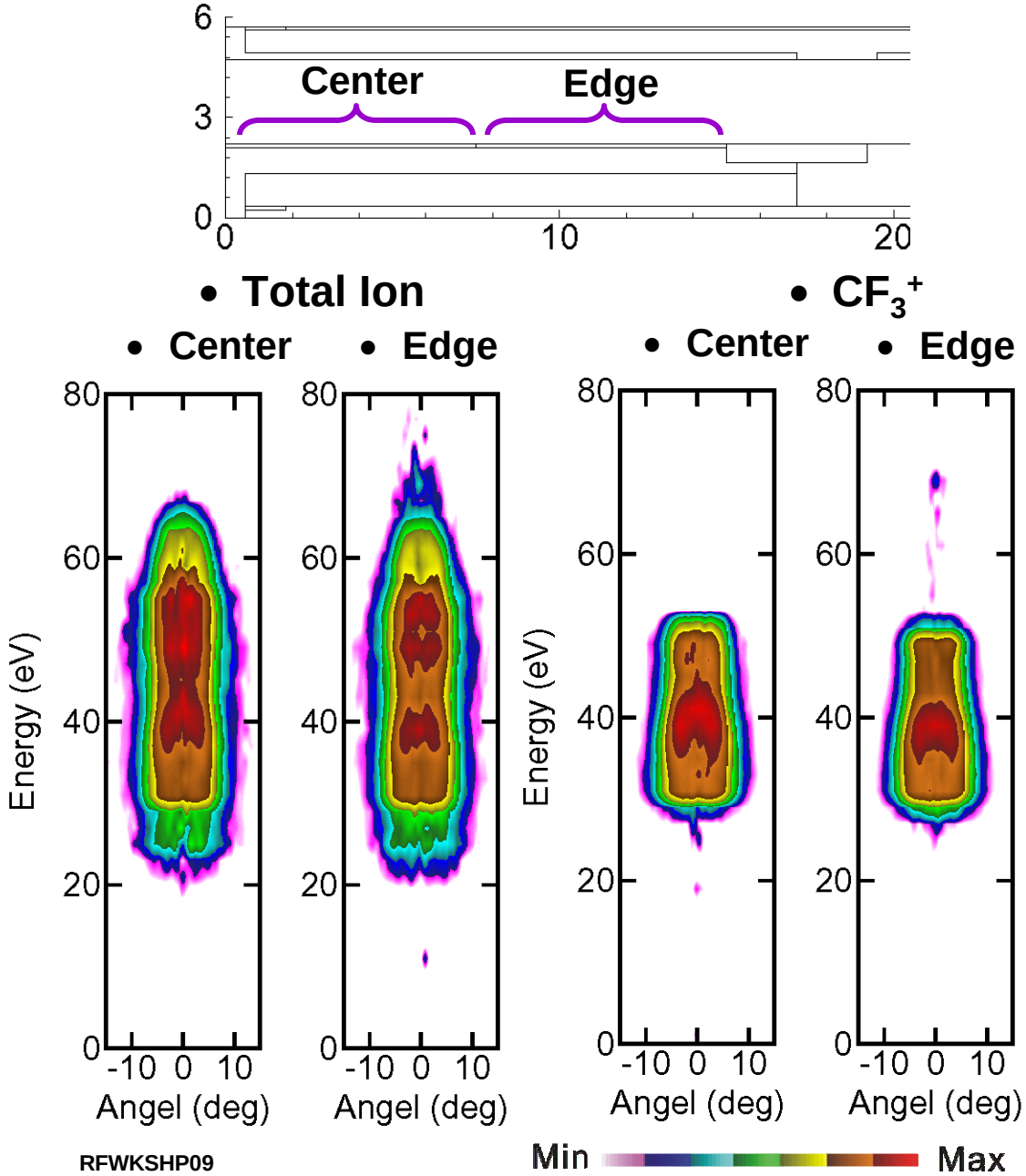
- **CF_3^+ Flux**



- **Ion fluxes to wafer reflect the plasma uniformities, though are somewhat more uniform due to electronegativity of plasma.**
- **Due to differences in excitation and dissociation rates vs position, partial ion fluxes may differ from total flux.**

- **Ar/CF_4=90/10**
- **50 mTorr, 400 sccm**
- **HF: 10-150 MHz/300 W**
- **LF: 10 MHz/300 W**

IEADs INCIDENT ON WAFER: 10/10 MHz



- Many factors may produce center-to-edge differences in IEADs: sheath thickness, sheath potential, mixing of ions …
- 10/10 MHz is dominated by electrostatics.
- Subtle differences in IEADs to wafer between center-and-edge, but otherwise uniform.

- Ar/CF_4=90/10, 50 mTorr, 400 sccm
- HF: 10 MHz/300 W
- LF: 10 MHz/300 W

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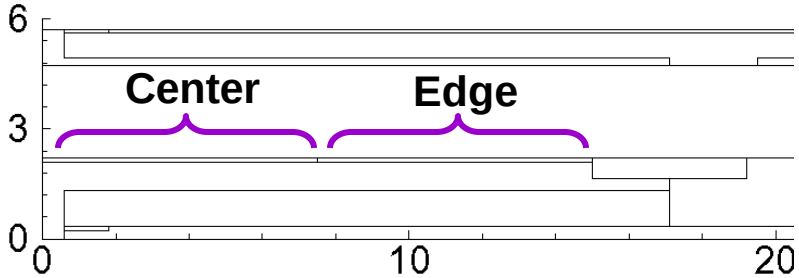
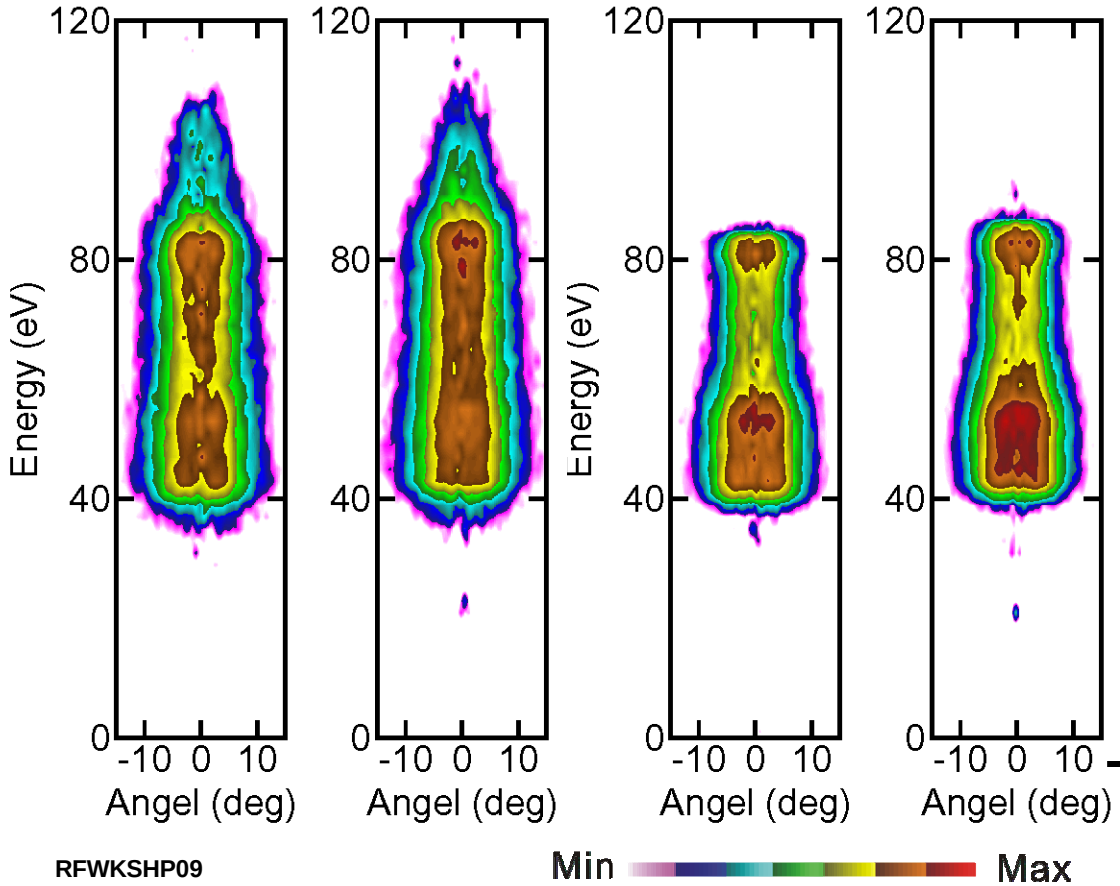
IEADs INCIDENT ON WAFER: 10/100 MHz



- Total Ion
  - Center
  - Edge
- CF_3^+
  - Center
  - Edge



- At 10 MHz LF / 100 MHz HF, begin to differentiate from center-to-edge as wave effects begin to become important.

- Ar/CF_4=90/10, 50 mTorr, 400 sccm
- HF: 100 MHz/300 W
- LF: 10 MHz/300 W

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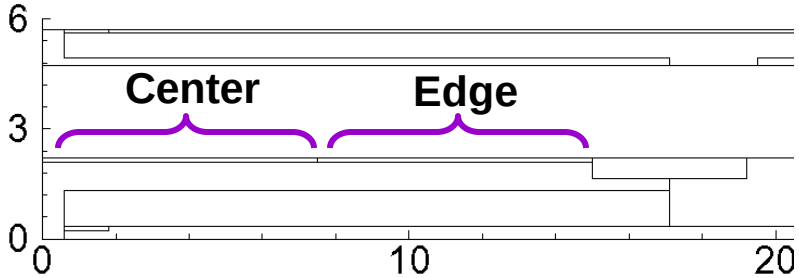
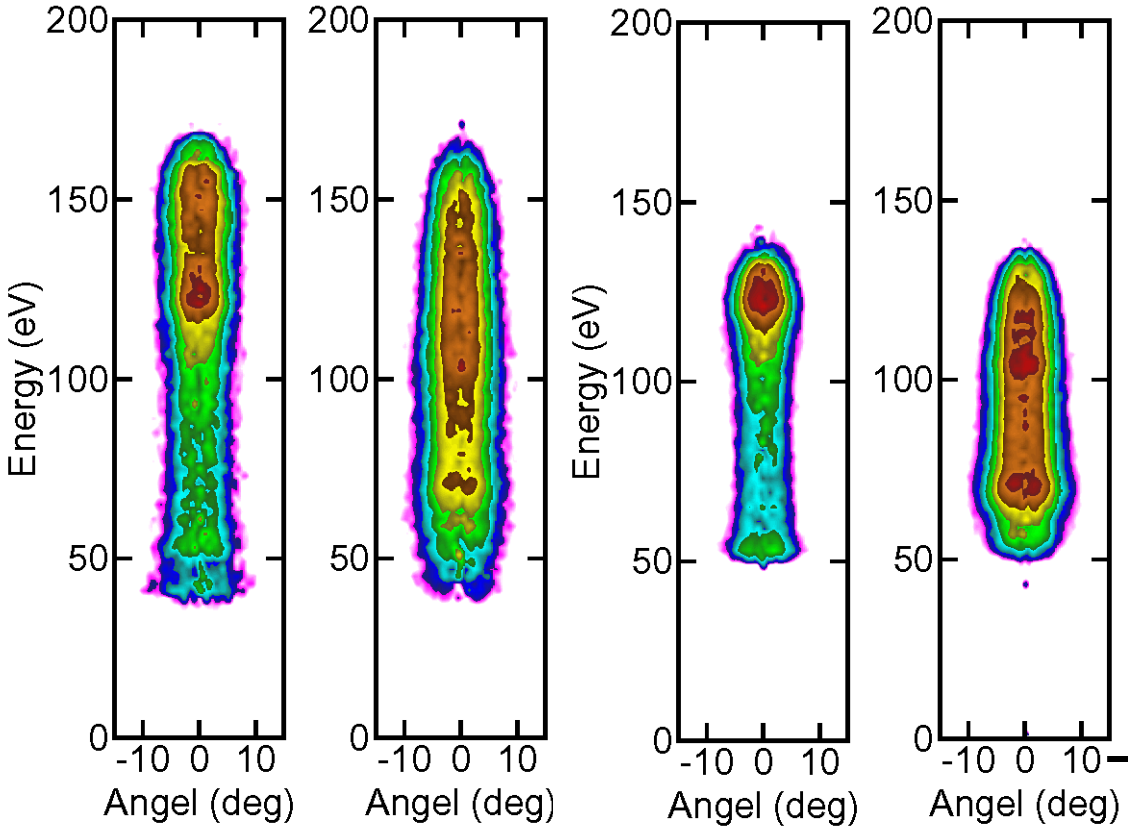
IEADs INCIDENT ON WAFER: 10/150 MHz



- Total Ion
  - Center
  - Edge
- CF_3^+
  - Center
  - Edge



- With 150 MHz excitation, sheath thickness and potential vary from center to edge.
- IEADs at edge are downshifted in energy, broadened in angle.

- Ar/CF_4=90/10, 50 mTorr, 400 sccm
- HF: 150 MHz/300 W
- LF: 10 MHz/300 W

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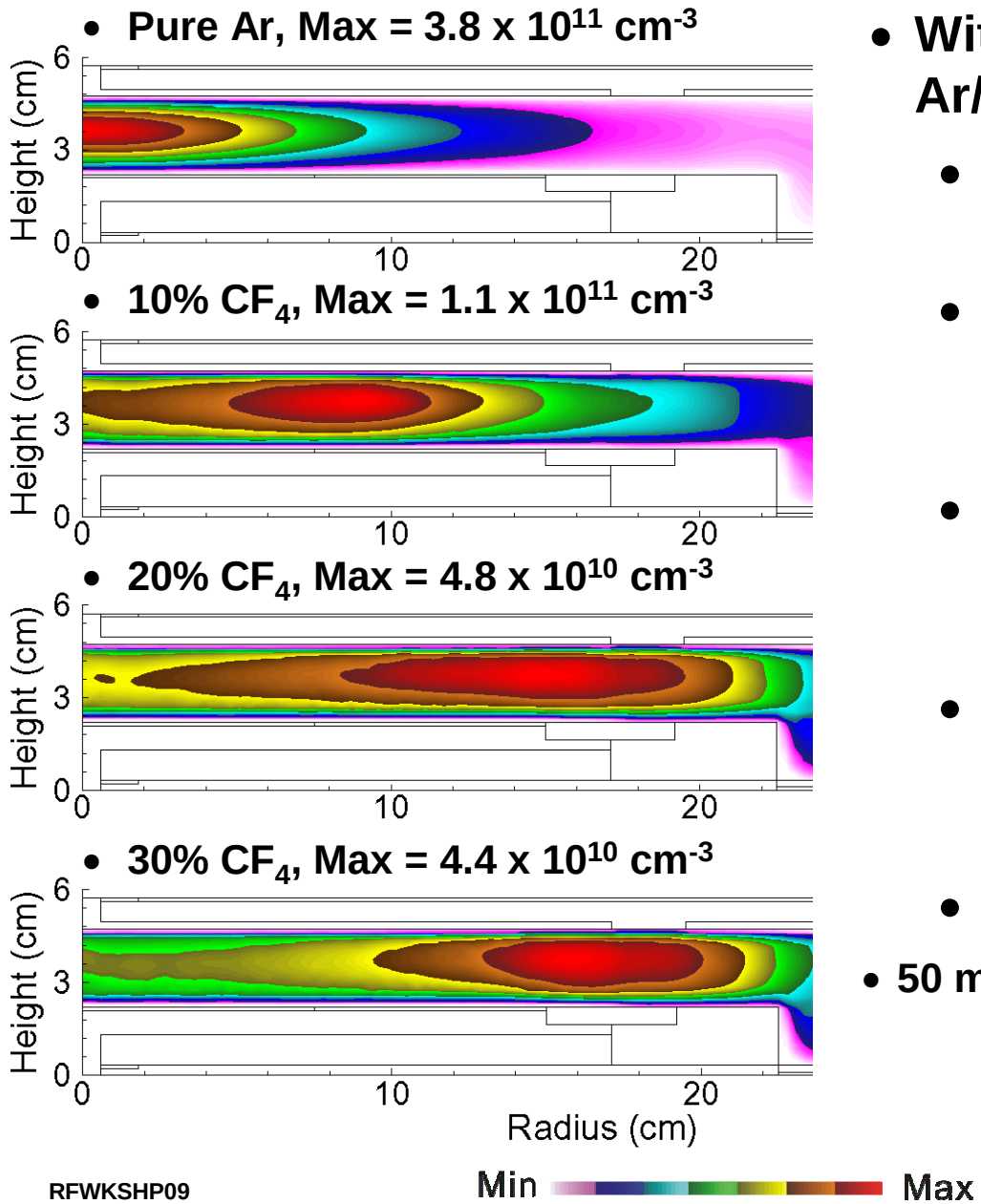
CONSEQUENCES OF CHEMISTRY: Ar/CF_4, 10/150 MHz



- With increasing fraction of CF_4 in Ar/CF_4.
  - [e] decreases thereby decreasing conductivity.
  - Weakens constructive interference of EM fields by increasing wavelength.
  - Shorter energy relaxation length shifts maximum of [e] shifts towards HF electrode.
  - Skin depth also increases which encreases penetration of EM fields.
  - More uniform [e] results.

- 50 mTorr, 400 sccm
- HF: 150 MHz/300 W
- LF: 10 MHz/300 W

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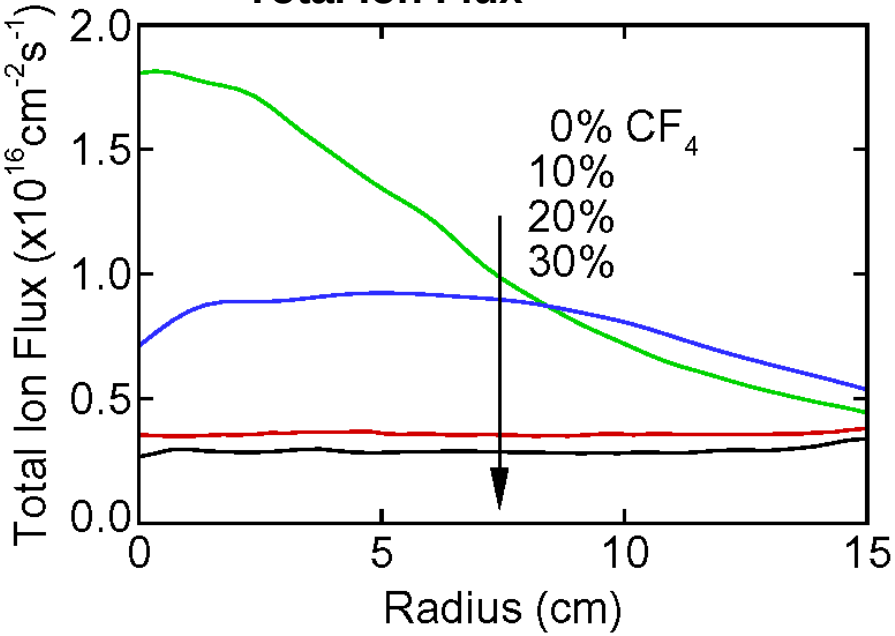
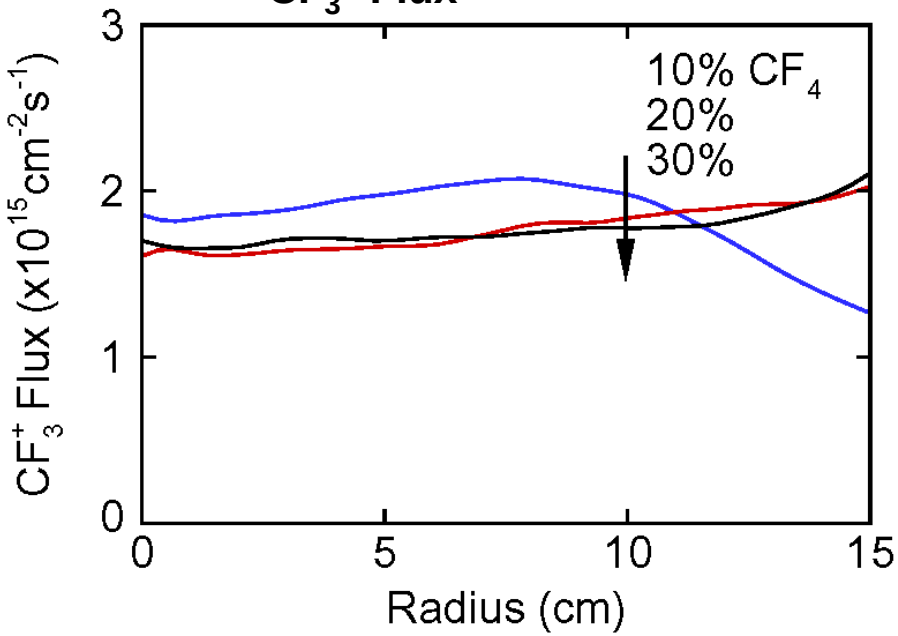
ION FLUXES TO WAFER: Ar/CF_4 10/150 MHz

- **Total Ion Flux**



- **CF_3^+ Flux**



- **Uniformity of ion fluxes can be tuned with chemistry, which ultimate tunes the conductivity.**
- **Strong 2nd order effect with changes in EEDF.**

- **50 mTorr, 400 sccm**
- **HF: 150 MHz/300 W**
- **LF: 10 MHz/300 W**

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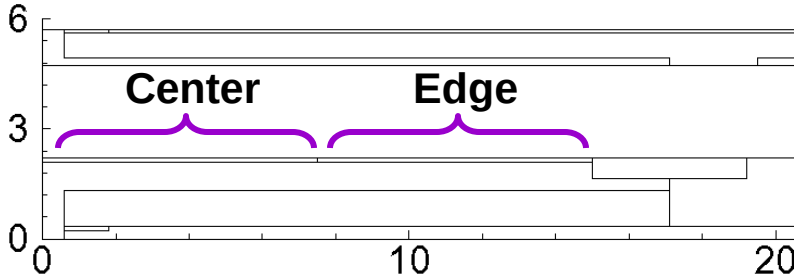
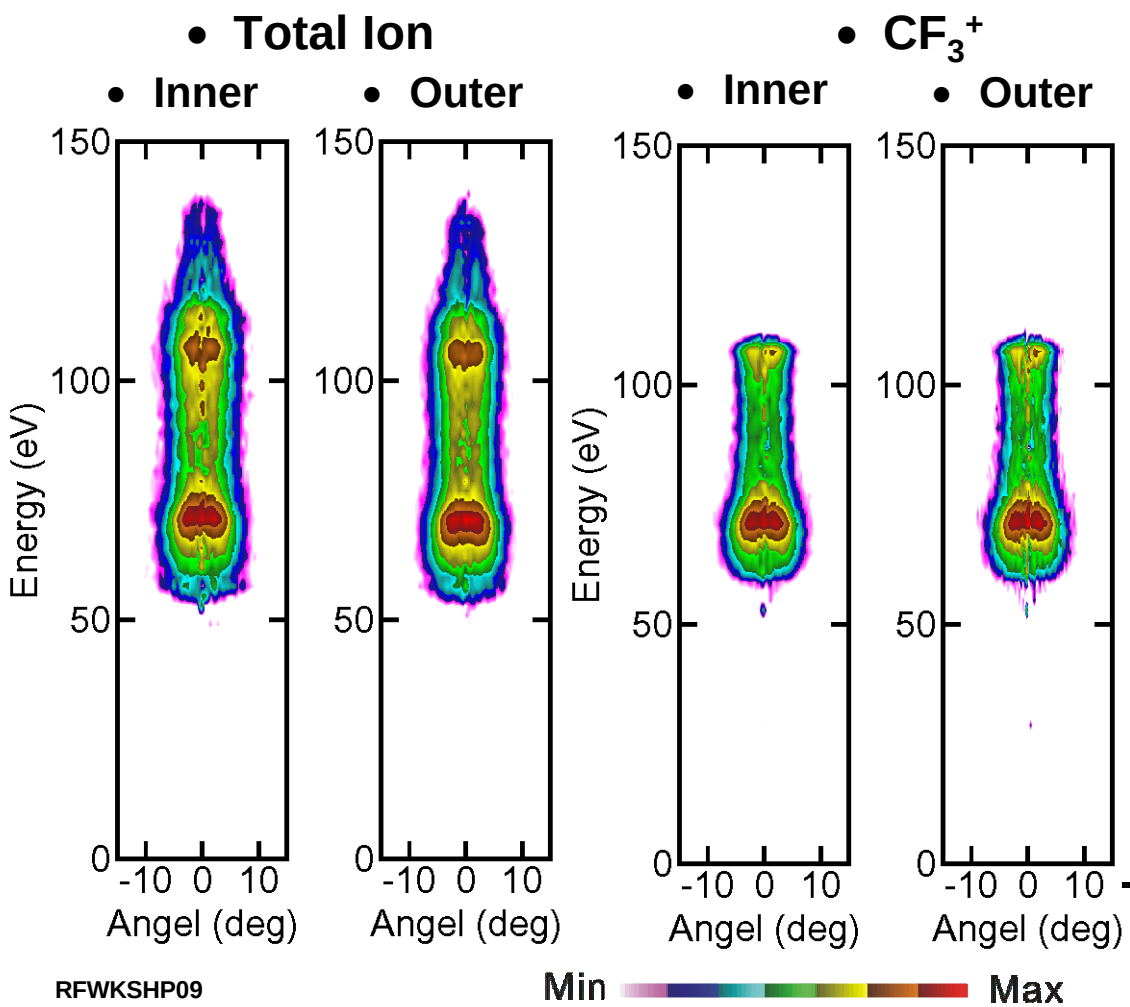
IEADs ONTO WAFER: Ar/CF_4 = 80/20, 10/150 MHz





- Less radial variation across the wafer due to better radial uniformity of sheath thickness and potential.
- Demonstrates ability to "tune" uniformity with changes in gas mixture.
- Primarily a conductivity effect – with strong 2nd order of effects of EEDF.

- Ar/CF_4=80/20, 50 mTorr, 400 sccm
- HF: 150 MHz/300 W
- LF: 10 MHz/300 W

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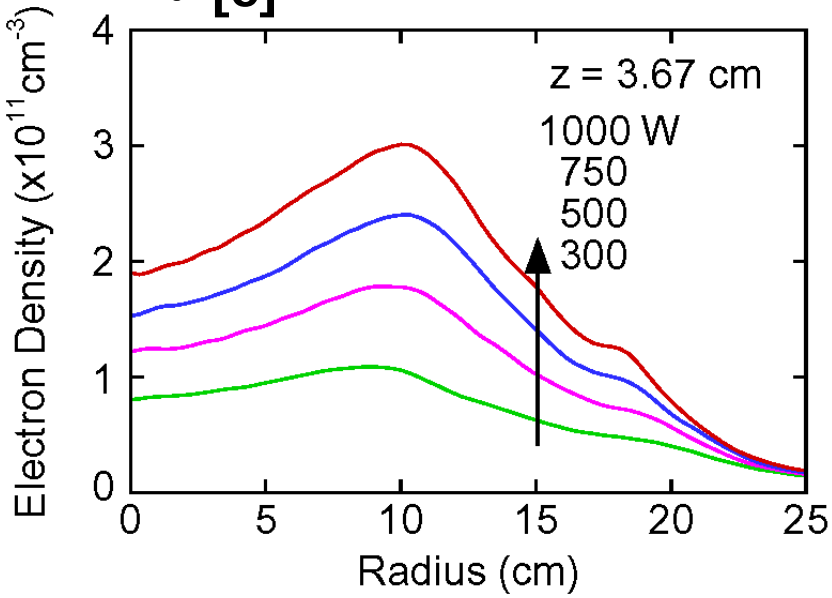
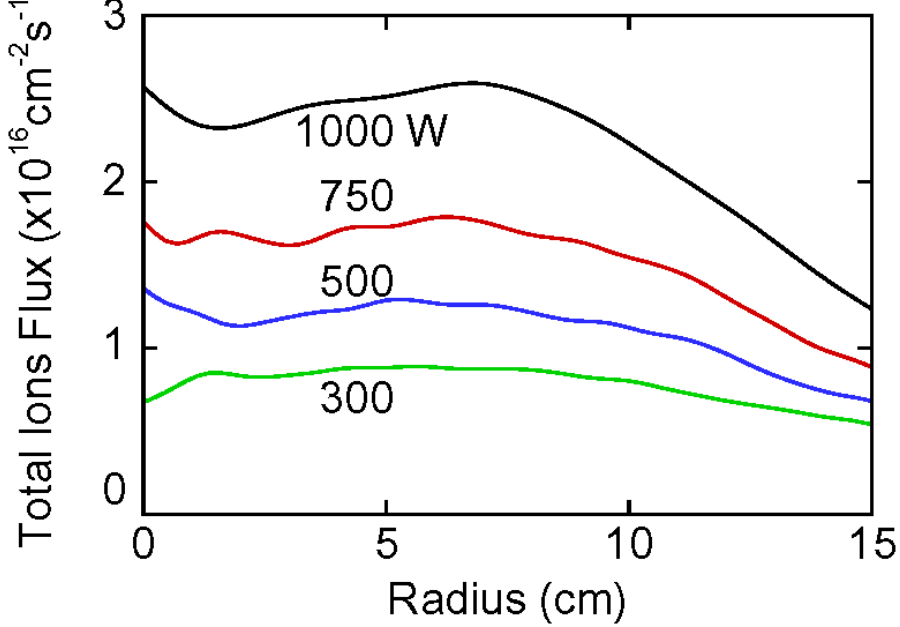
SCALING WITH HF POWER: 10/150 MHz

- [e]



- Total Ion Flux



- **Increasing HF power reduces plasma uniformity by increasing conductivity and shortening skin depth.**
- **Effect is not dramatic in electronegative plasmas where negative ions do not significantly contribute to conductivity (power that produced electrons ends up in negative ions…)**

- **Ar/CF_4=90/10**
- **50 mTorr, 400 sccm**
- **HF: 50-150 MHz**
- **LF: 10 MHz/300 W**

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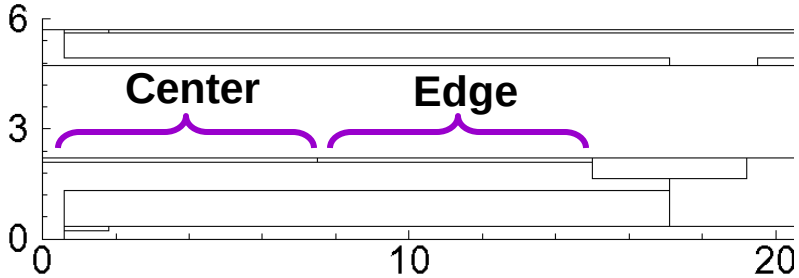
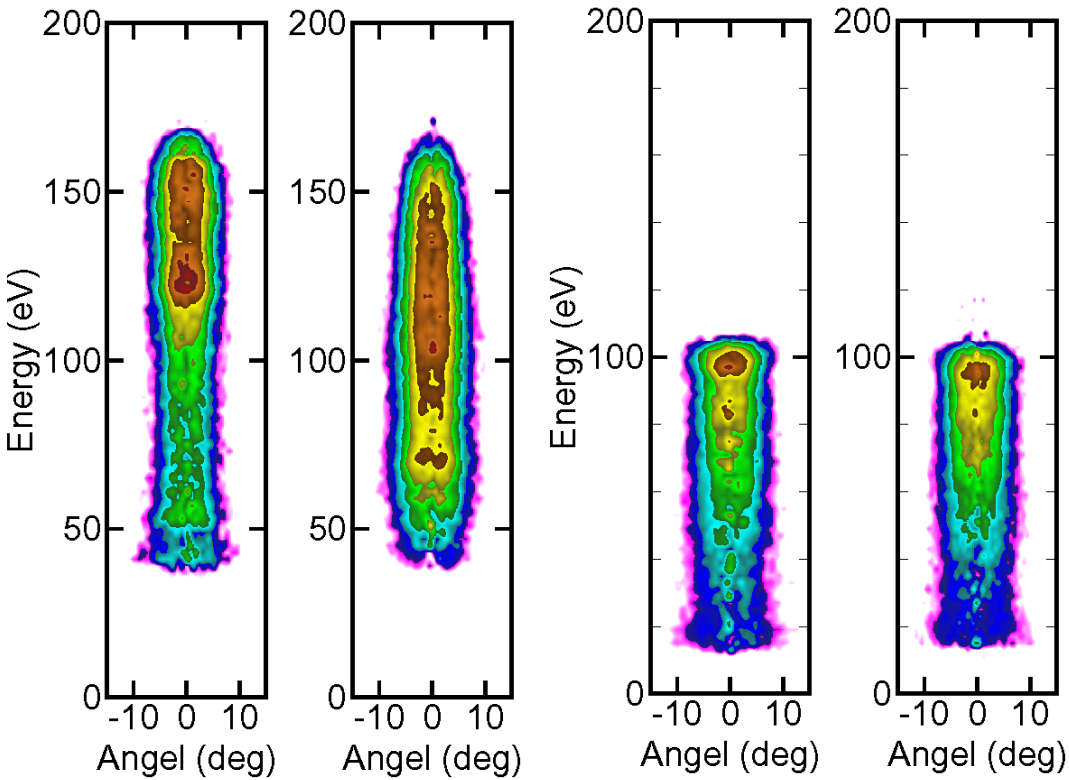
TOTAL IEAD vs POWER



- 300 W
  - Center
  - Edge
- 1000 W
  - Center
  - Outer



- Dynamics of negative ions pooling towards center of reactor actually improve uniformity of sheath at high power.
- With increasing HF power (increasing [e]), LF voltage decreases to keep LF power constant.

- Ar/CF_4=90/10, 50 mTorr, 400 sccm
- HF: 150 MHz
- LF: 10 MHz/300 W

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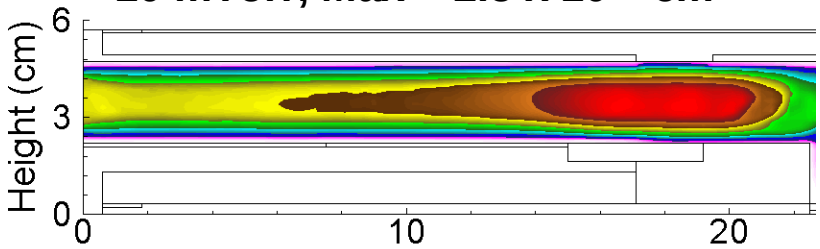
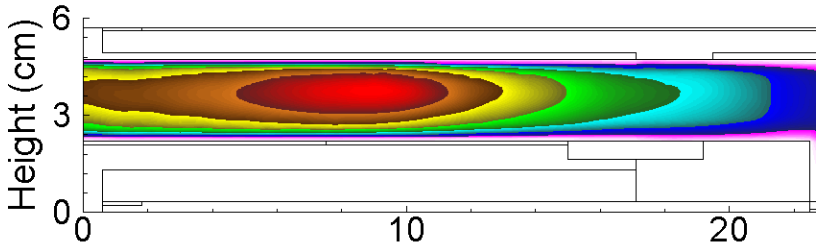
SCALING WITH PRESSURE: Ar/CF_4 = 90/10

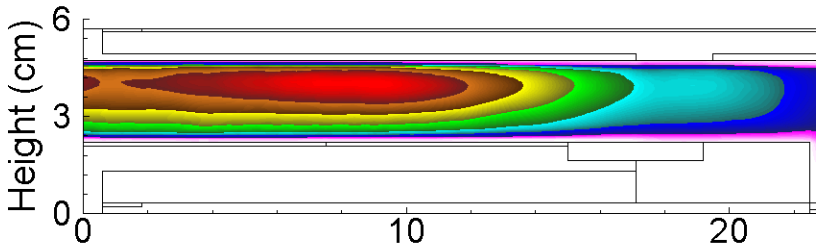
- 10 mTorr, Max = 2.5 x 10^{10} cm^{-3}



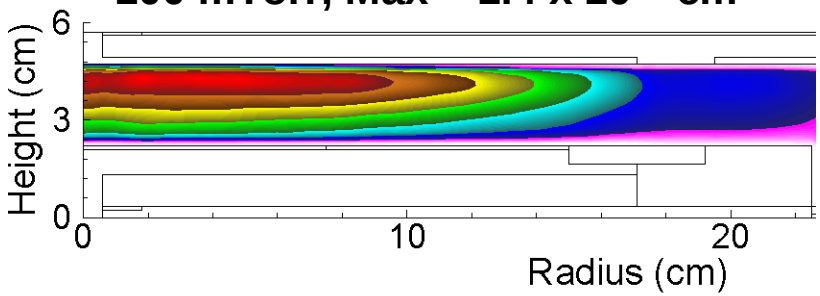
- 50 mTorr, Max = 1.1 x 10^{11} cm^{-3}



- 75 mTorr, Max = 1.2 x 10^{11} cm^{-3}



- 100 mTorr, Max = 1.4 x 10^{11} cm^{-3}



Min Max

- With increasing pressure:
  - Increase in [e].
  - Shift in maximum of [e] towards the HF electrode and the center of the reactor.
- Finite wavelength effect is NOT responsible for this shift.
- Decreasing energy relaxation distance localizes excitation.

- Ar/CF_4=90/10
- 400 sccm
- HF: 150 MHz/300 W
- LF: 10 MHz/300 W

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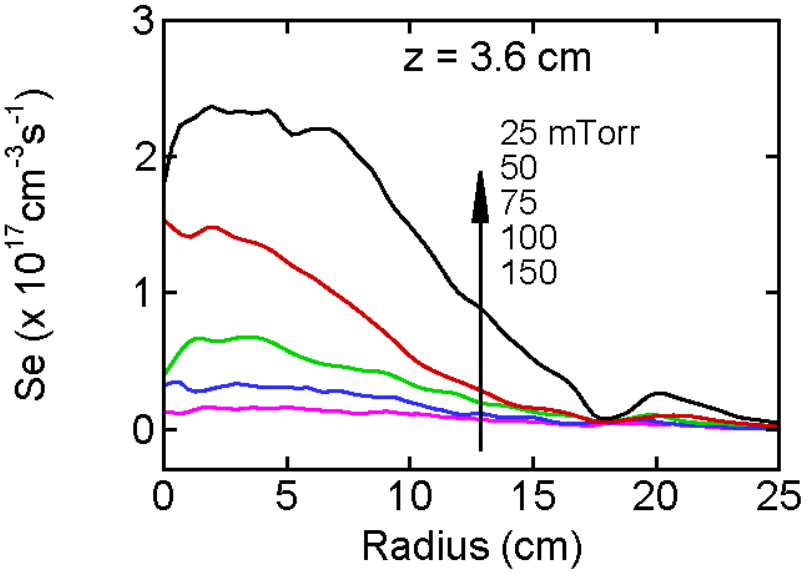
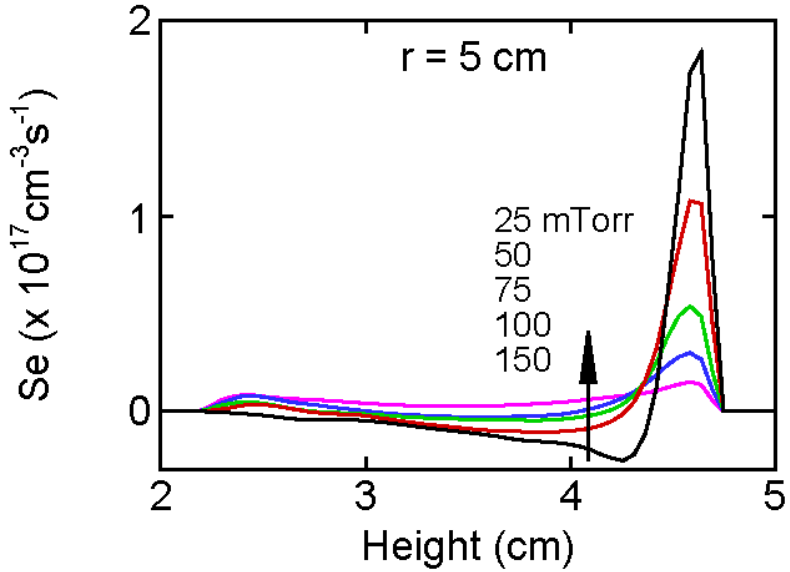
ELECTRON IMPACT IONIZATION SOURCE (S_e)





- **Increasing pressure results in decreasing skin depth and energy relaxation distance, which causes**
  - **Radial direction: profile of S_e increasingly mirrors that of HF field.**
  - **Axial direction: S_e increasingly peaked in the HF sheath.**

- **Ar/CF_4=90/10**
- **50 mTorr, 400 sccm**
- **HF: 150 MHz/300 W**
- **LF: 10 MHz/300 W**

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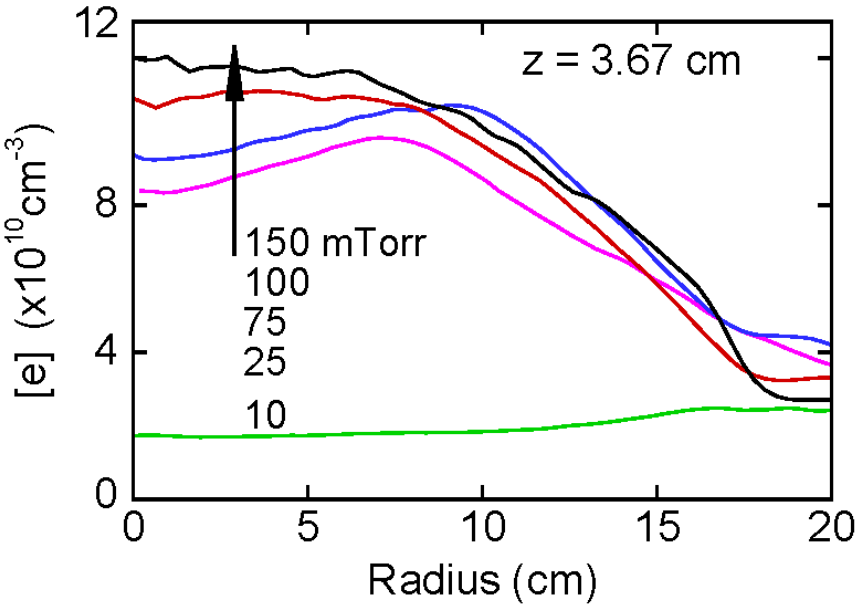
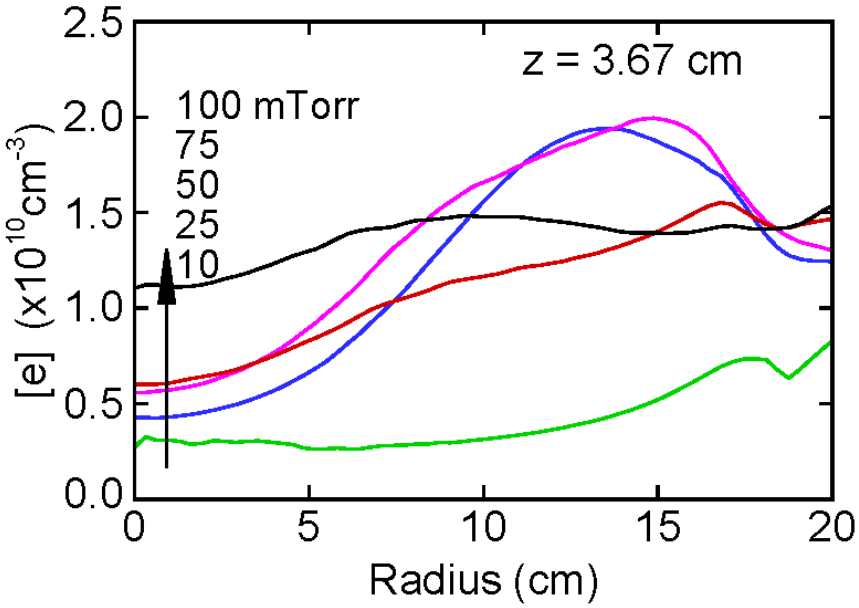
ROLE OF THE LOWER FREQUENCY

- **With LF (10 MHz, 300 W)**



- **Without LF**



- **Ionization by secondary electrons accelerated by LF sheath matters.**
- **Beam ionization "fills in" plasma density in center of reactor at lower frequencies where edge effects dominate.**

- **Ar/CF_4=90/10**
- **50 mTorr, 400 sccm**
- **HF: 150 MHz/300 W**

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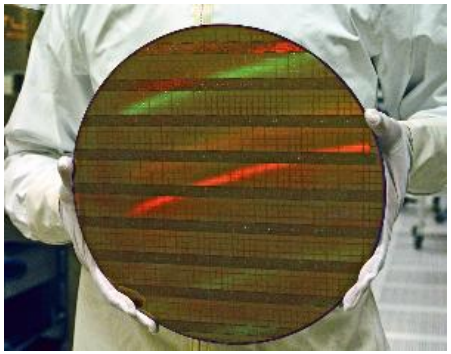
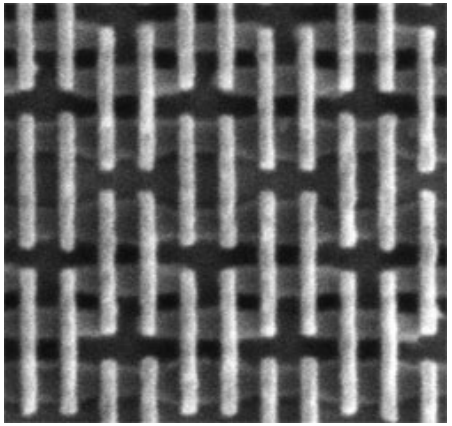
WHAT ABOUT 450 mm and 16 nm?

THE TRANSITION TO 450 mm AND 16 nm

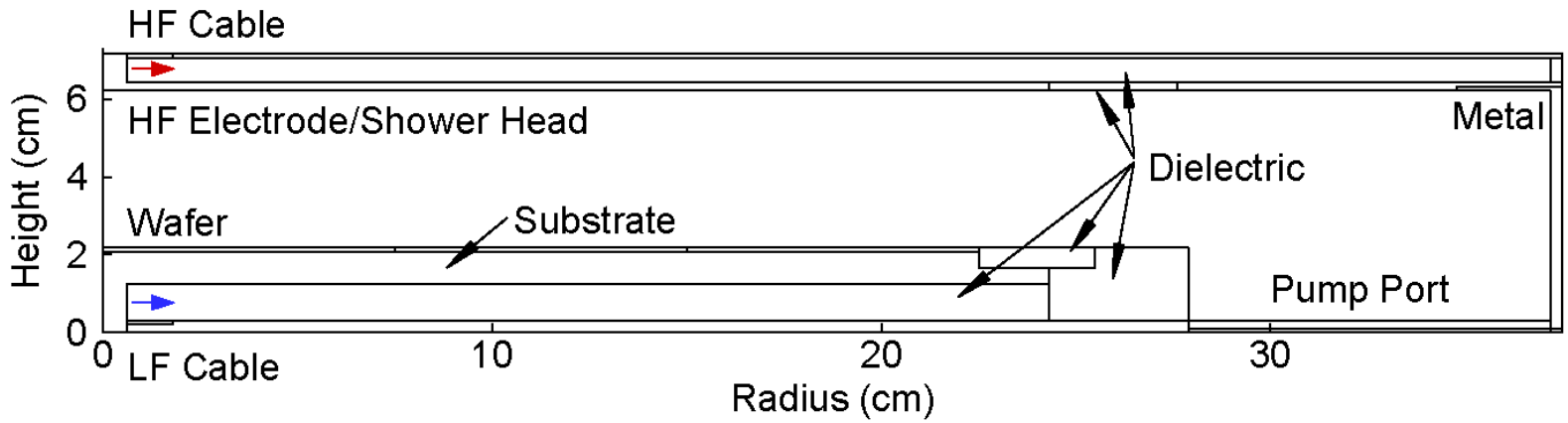
- Wafer diameters will soon transition to 450 mm at a time when devices size shrink to 16 nm.
- The transition to 450 mm wafers will require a huge investment – estimates of $30-$40 billion.
- A toolset may cost $100 million.
- Modeling needs to play a greater larger role during this transition to reduce the cost and speed the process.





- IBM 22 nm SRAM

450 mm REACTOR GEOMETRY



- **2D, cylindrically symmetric.**
- **Ar, 50 mTorr, 600 sccm**
- **Base conditions**
  - **HF upper electrode: 10-150 MHz, 450 W**
  - **LF lower electrode: 10 MHz, 450 W**
- **Specify power, adjust voltage.**
- **Note: Increase in gap compared to 300 mm.**

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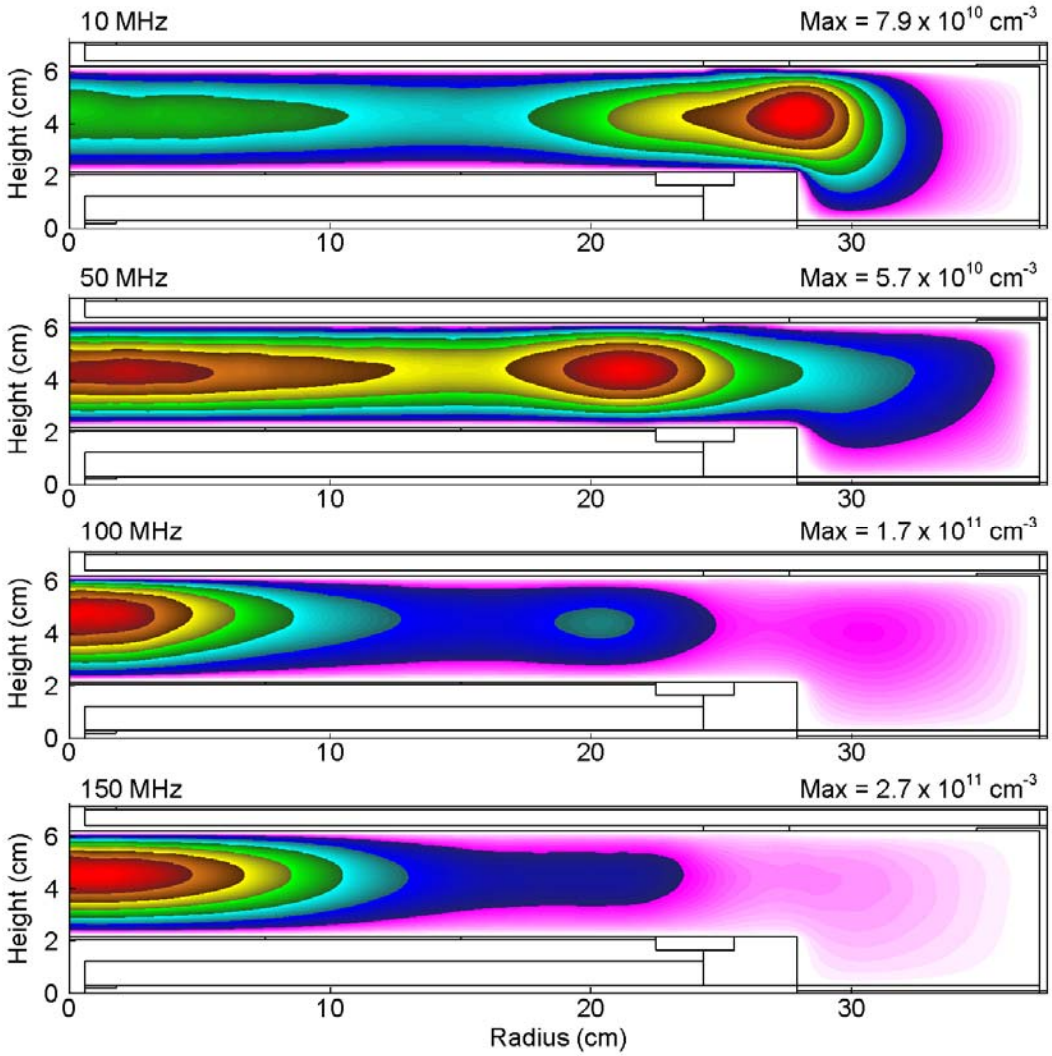
450 mm: ELECTRON DENSITY vs FREQUENCY



- Compared with plasmas sustained in 300 mm tools:
  - More prominent finite wavelength effect.
  - Center and edge peaks for HF ≤ 50 MHz due to the coupling of wave and electrostatic effects.

- Ar
- 50 mTorr, 600 sccm

- HF: 10-150 MHz/450 W
- LF: 10 MHz/450 W

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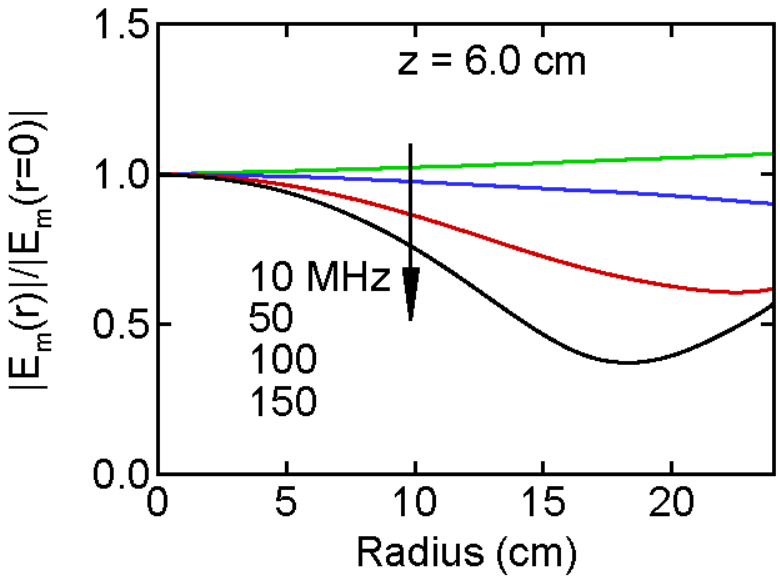
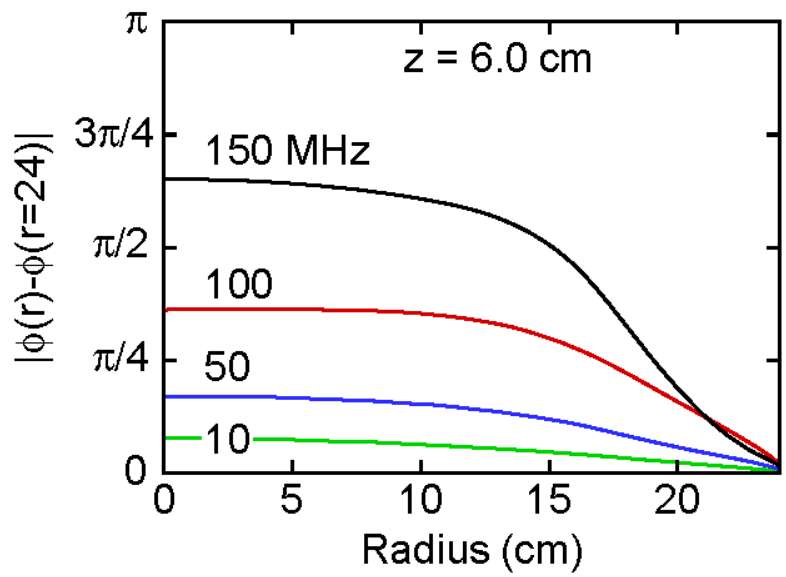
450 mm: EM PROPERTIES IN HF SHEATH

- **Total Electric Field (Normalized by E_m at r = 0)**



- **Relative Phase (With respect to the electrode edge)**



- **With increasing HF, EM field is more radially dependent.**
- **Diminishing phase change in the reactor center due to formation of standing wave.**

- **Ar**
- **50 mTorr, 600 sccm**
- **HF: 150 MHz/450 W**
- **LF: 10 MHz/450 W**

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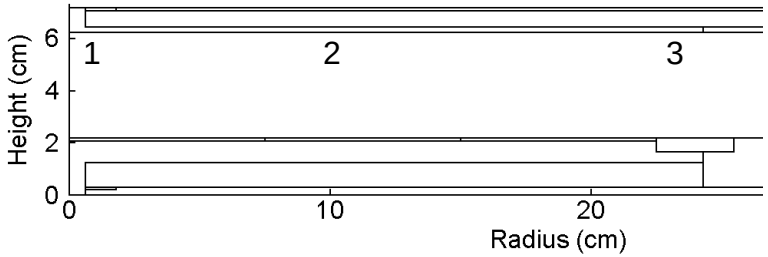
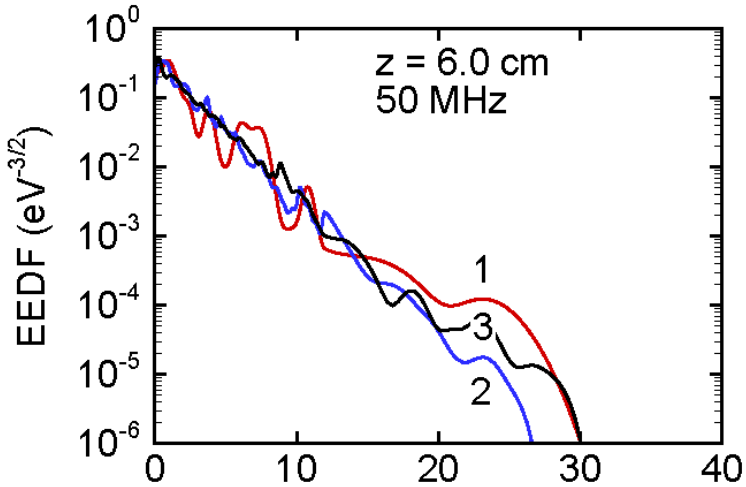
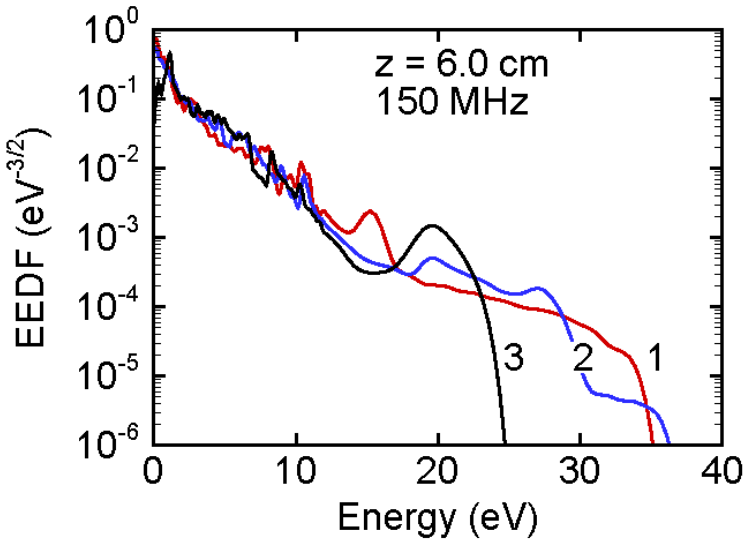
450 mm EEDs: HF SHEATH







- **Trends in EEDs are similar to 300 mm but more pronounced.**
- **50 MHz: Uniform spatial distribution due to coupling of wave and edge effects.**
- **150 MHz: elevated tails in the center where sheath field is largest.**

- **Ar, 50 mTorr, 600 sccm**
- **HF: 10-150 MHz/450 W, LF: 10 MHz/450 W**

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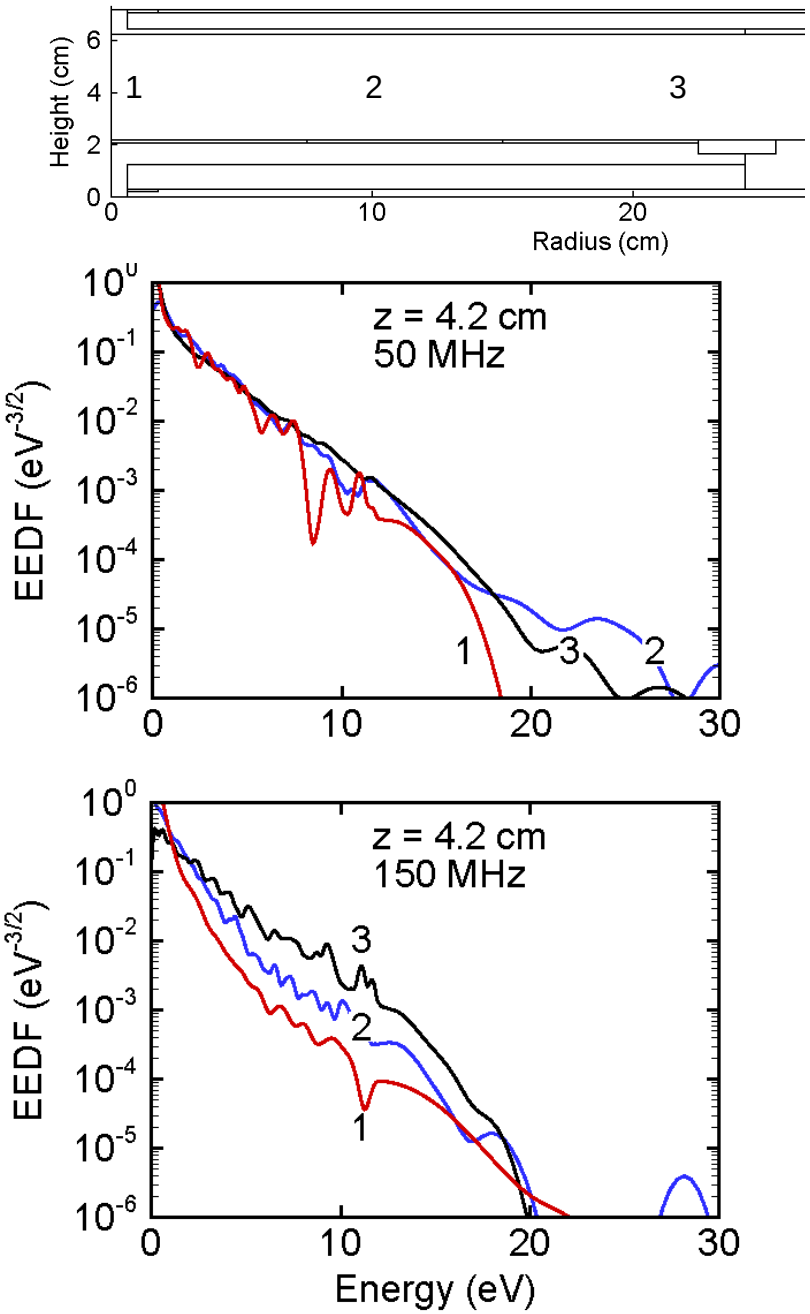
450 mm EEDs: BULK PLASMA



- **The EEDs in the bulk plasma are dominated by the high frequency due to more efficient heating.**
- **50 MHz: High tails at the middle and edge.**
- **150 MHz: EEDs differs radially as Ohmic heating weakened in the center where electron density is largest.**

- **Ar, 50 mTorr, 600 sccm**
- **HF: 10-150 MHz/450 W, LF: 10 MHz/450 W**

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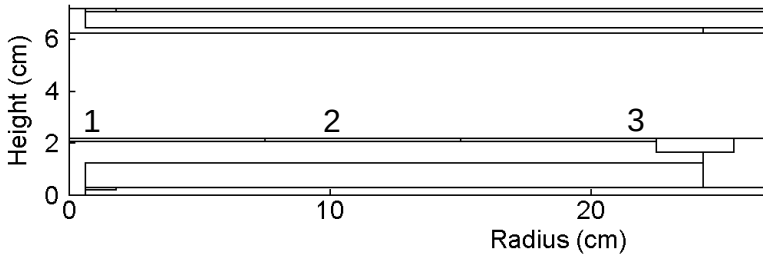
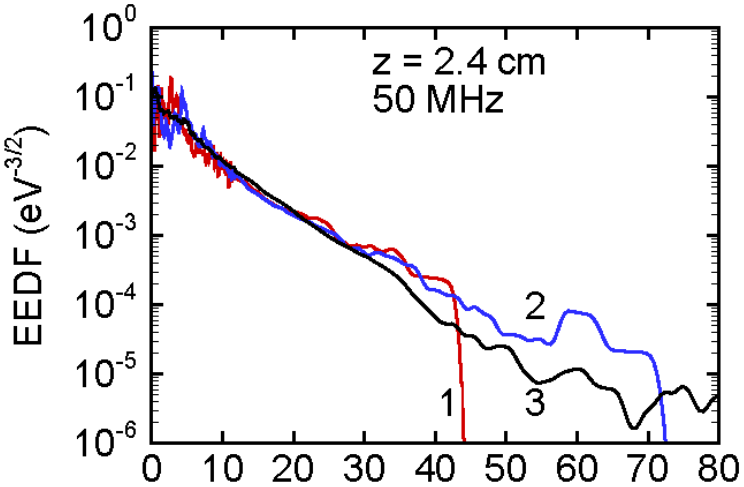
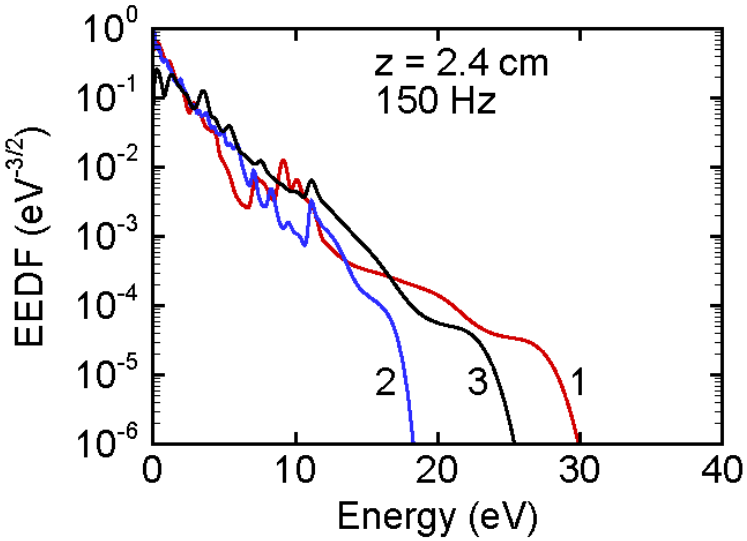
450 mm EEDs: LF SHEATH







- **Same trends as those in 300 mm tools.**
- **With 10 MHz on the lower electrode, electrostatic effects should dominate.**
- **50 MHz: Edge effect produces high energy tail.**
- **150 MHz: Modulation from upper sheath extends to lower electrode and lifts tail at center of wafer.**

- **Ar, 50 mTorr, 600 sccm**
- **HF: 10-150 MHz/450 W, LF: 10 MHz/450 W**

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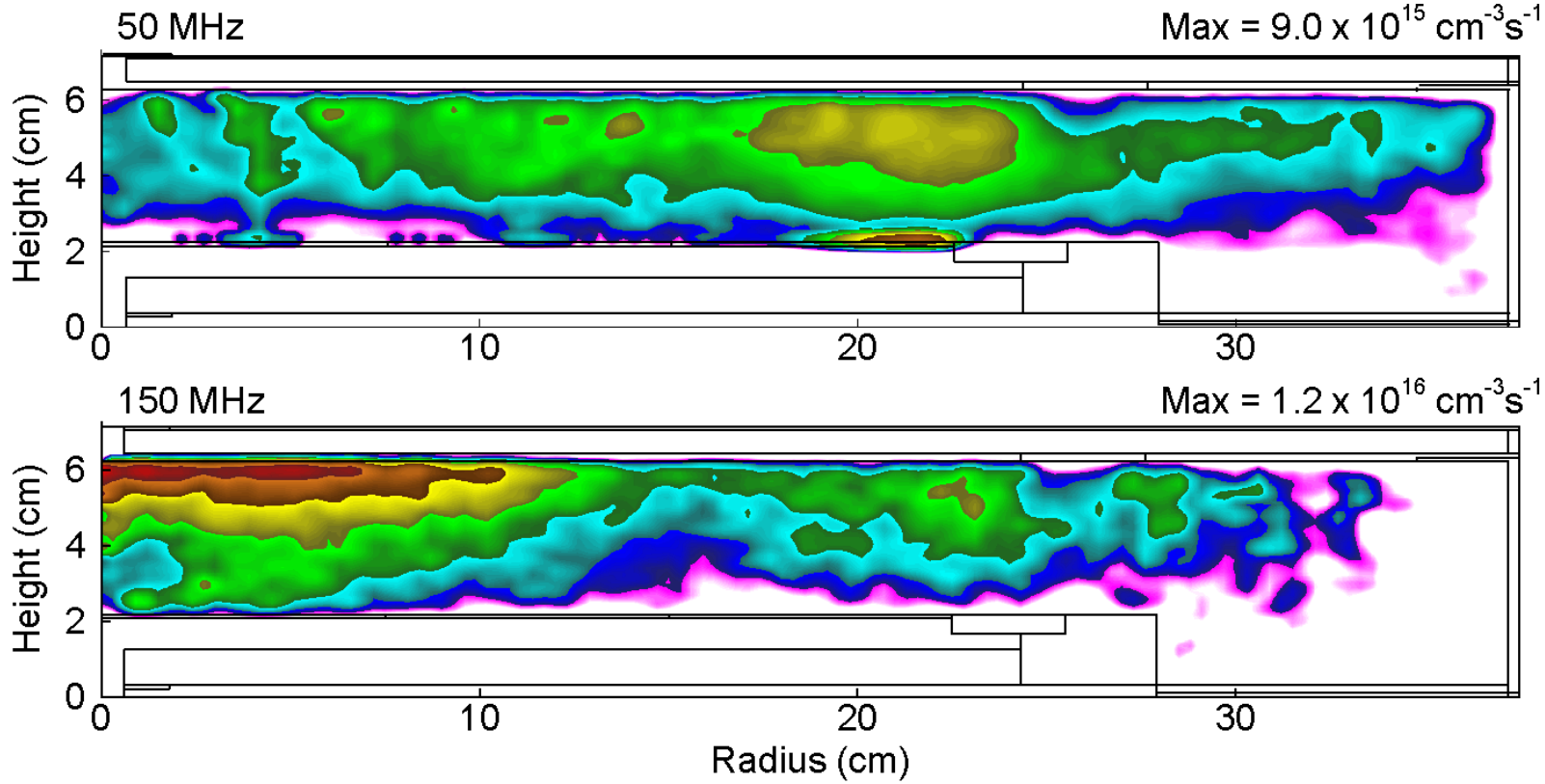
ELECTRON IMPACT IONIZATION SOURCES



- **Ionization peaked at where tails of EEDs are elevated.**
- **Localized near HF electrode at 150 MHz due to the shorter skin depth.**

- **Ar**
- **50 mTorr, 600 sccm**
- **HF: 10-150 MHz/450 W**
- **LF: 10 MHz/450 W**

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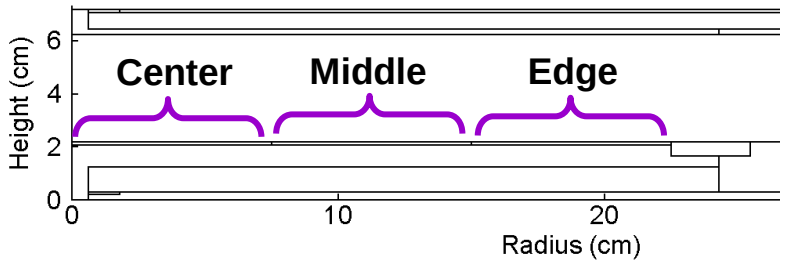
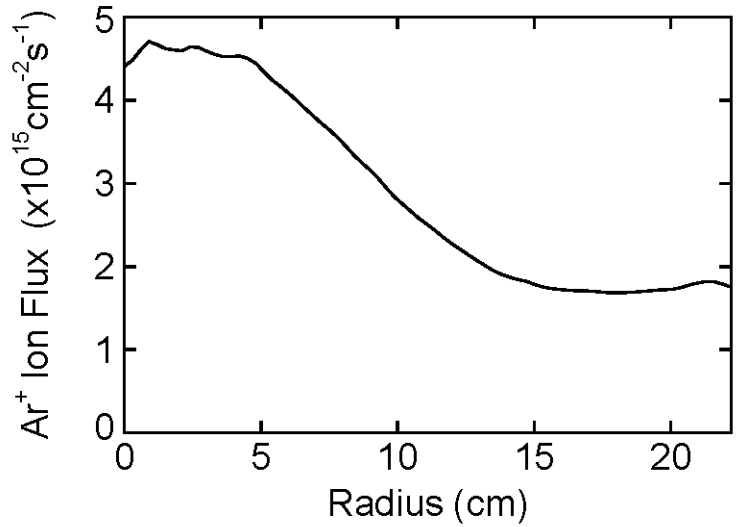
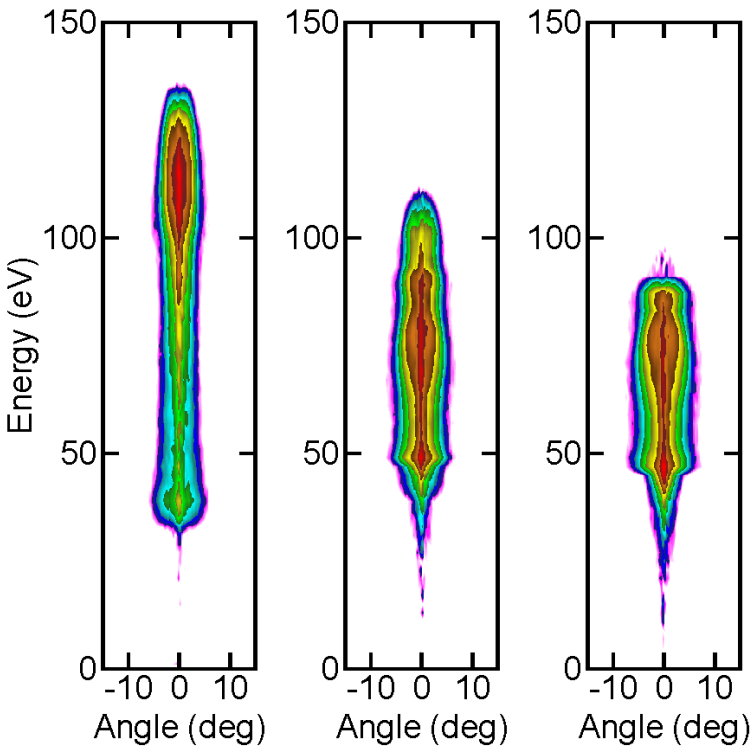
ION FLUX AND IEADs INCIDENT ON WAFER



- Ion Flux



- Center
- Middle
- Edge



- **Ultimately, E&M finite wavelength effects translate to differences in IEADs and ion flux onto wafer.**

- **Ar, 50 mTorr, 600 sccm**
- **HF: 150 MHz/450 W, LF: 10 MHz/450 W**

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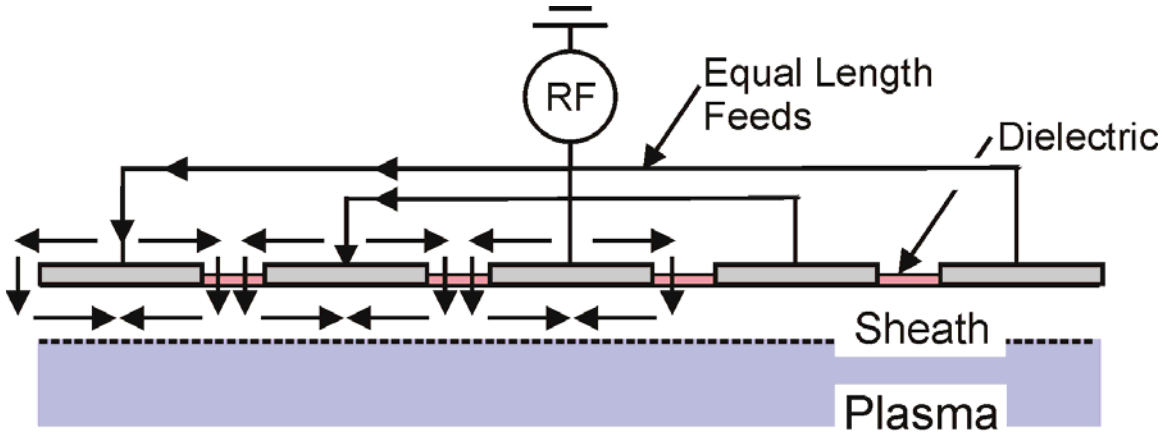
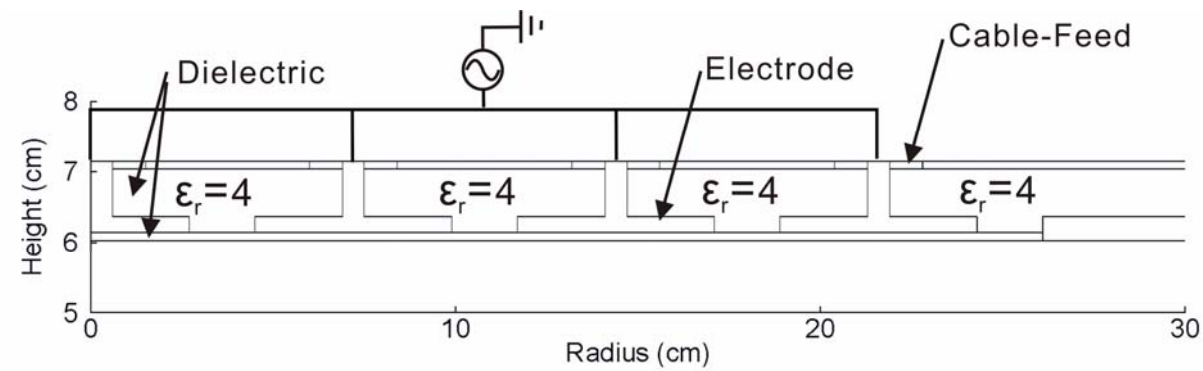
CAN WE INNOVATE AROUND THE PHYSICS?





- **For uniform processing at 450 mm, the electrical distance from rf feed-to-plasma must be equal.**
- **Segmented electrodes are used in large area plasma processing for LCD panels and solar cells.**
- **Has their day come for microelectronics?**
- **Let modeling answer that question…**

- **The model….segmented electrodes.**

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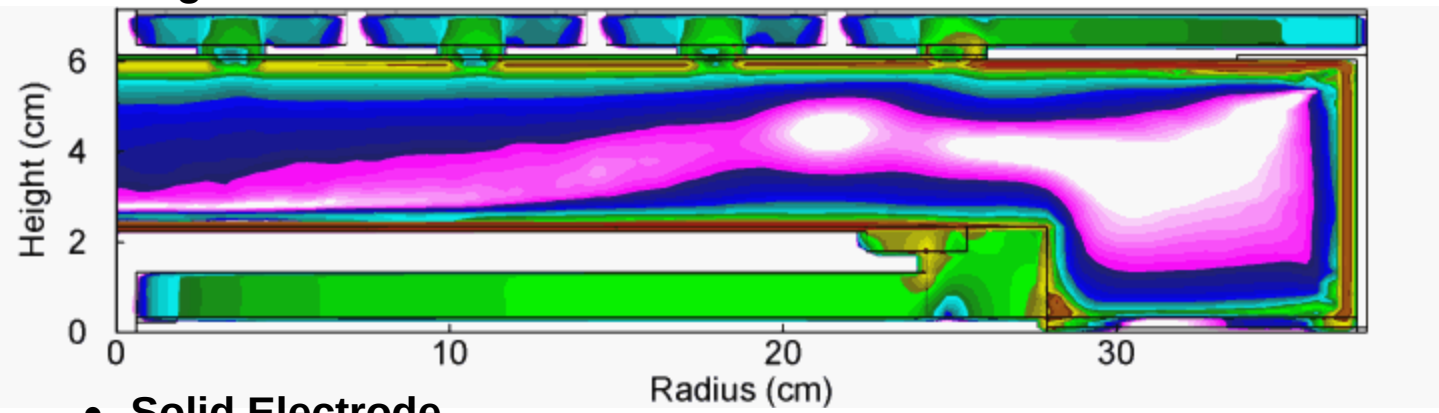
PROPAGATION OF EM WAVE

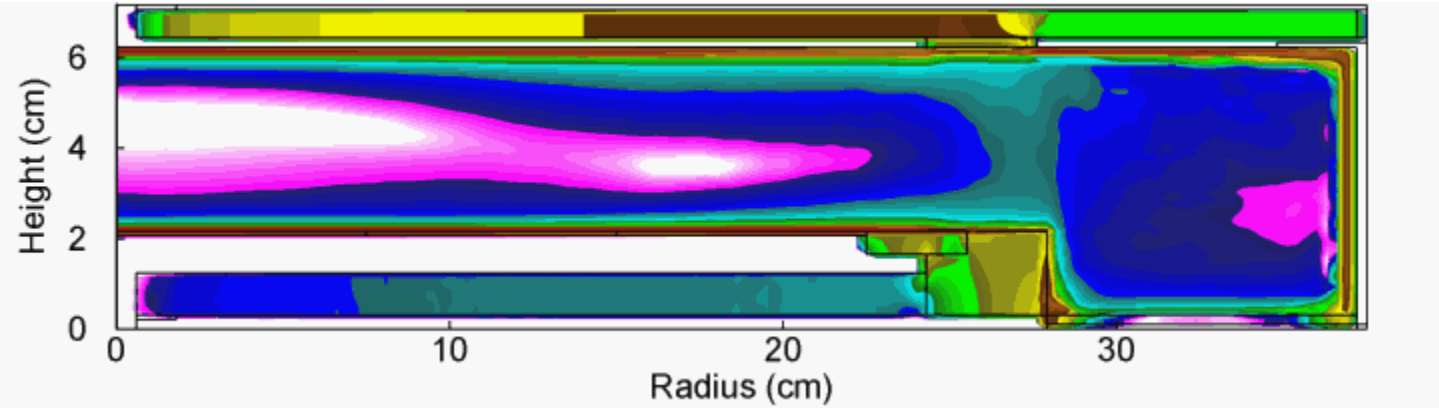
- **Segmented Electrode**



ANIMATION SLIDE-GIF

- **EM Amplitude Max = 650 V/cm**

- **Solid Electrode**



- **EM Amplitude Max = 950 V/cm**

- **EM fields propagate along the sheath and into the bulk plasma with deeper penetration in low [e] region due to less absorption.**
- **More radially uniform penetration with segmented electrode.**
  - **Ar, 50 mTorr, 600 sccm**
  - **HF: 150 MHz/450 W, LF: 10 MHz/450 W**

Min Max

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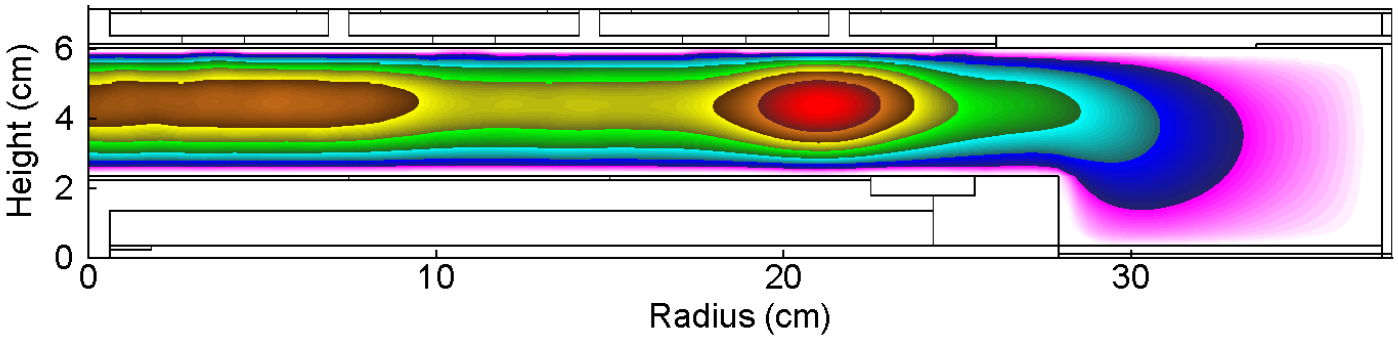
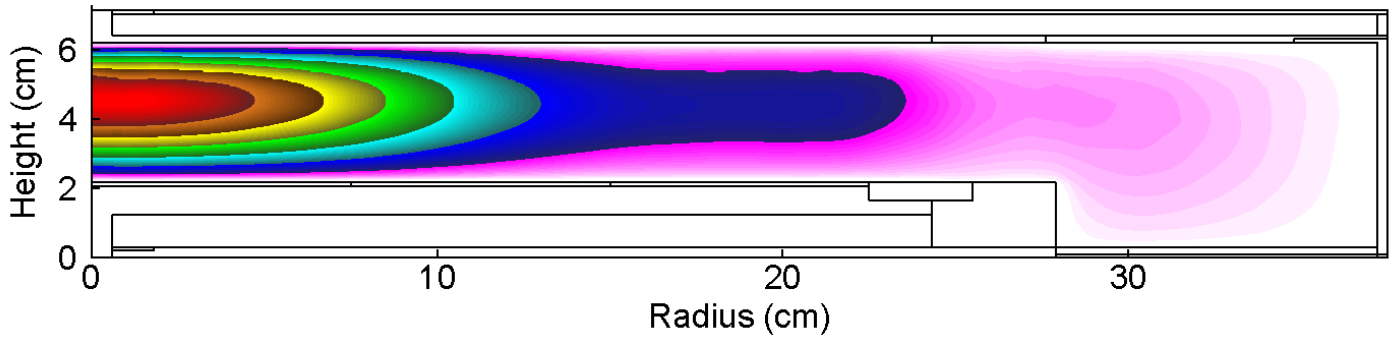
PLASMA DISTRIBUTION

- **Segmented Electrode**



- **[e], Max = 3.6×10^{10} cm^{-3}**

- **Solid Electrode**



- **[e], Max = 2.7×10^{11} cm^{-3}**

- **Center and peaked plasma density with segmented electrode: still need some tuning, segmentations with different widths?**

- **Ar, 50 mTorr, 600 sccm**
- **HF: 150 MHz/450 W, LF: 10 MHz/450 W**

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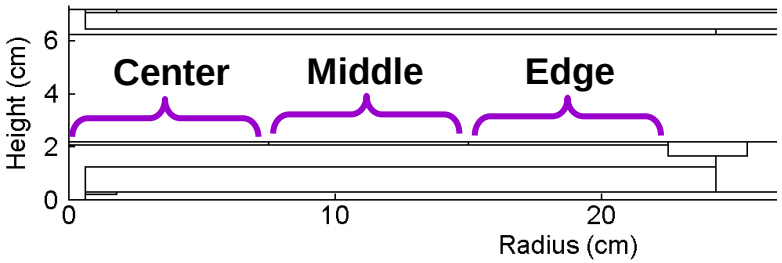
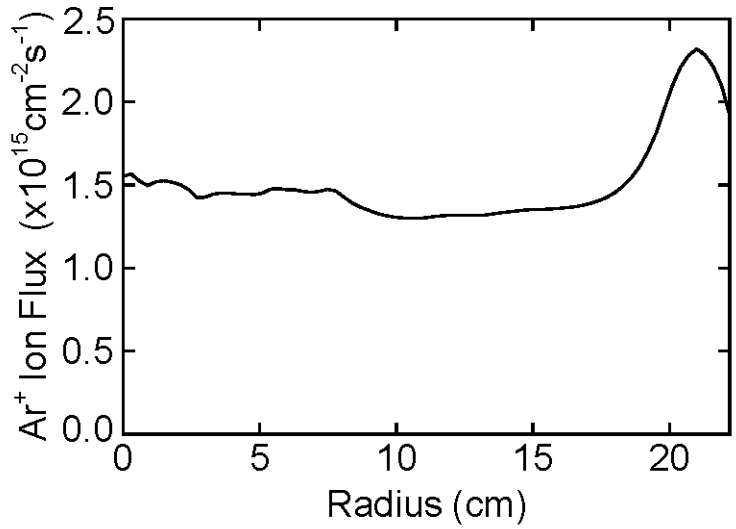
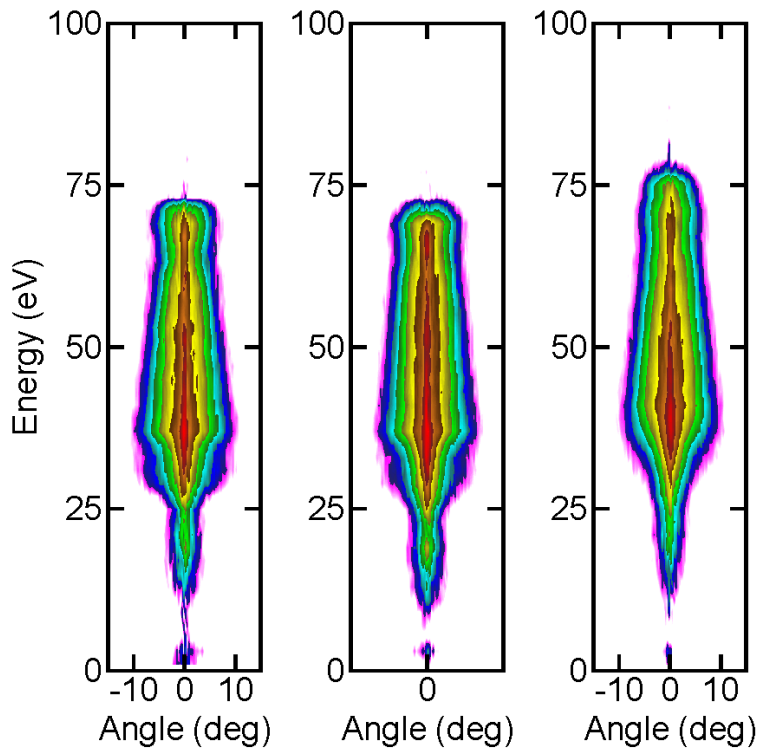
ION FLUX AND IEADs INCIDENT ON WAFER



- Ion Flux



- Center
- Middle
- Edge



- **Ion fluxes – need some tuning (real-time-control?) of electrode structures for uniformity.**
- **IEADs – Electrical symmetry provides more uniformity.**

- **Ar, 50 mTorr, 600 sccm**
- **HF: 150 MHz/450 W, LF: 10 MHz/450 W**

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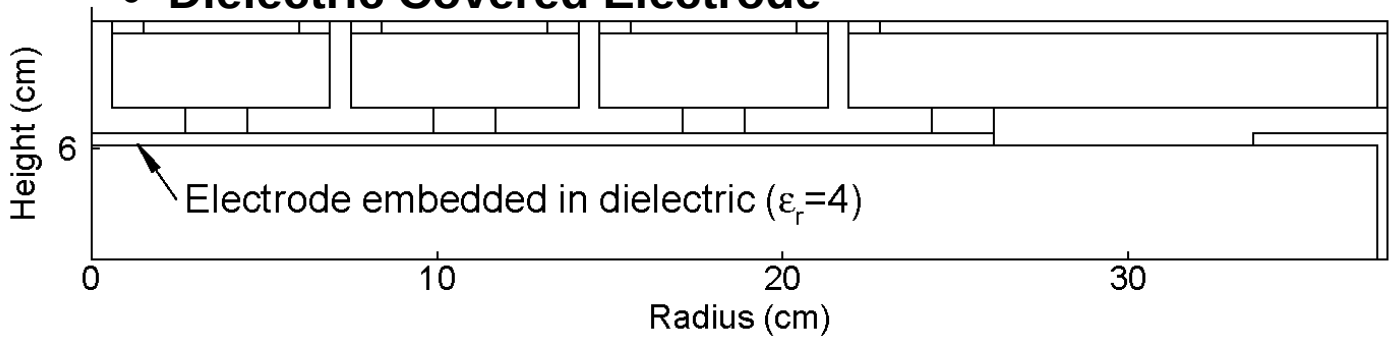
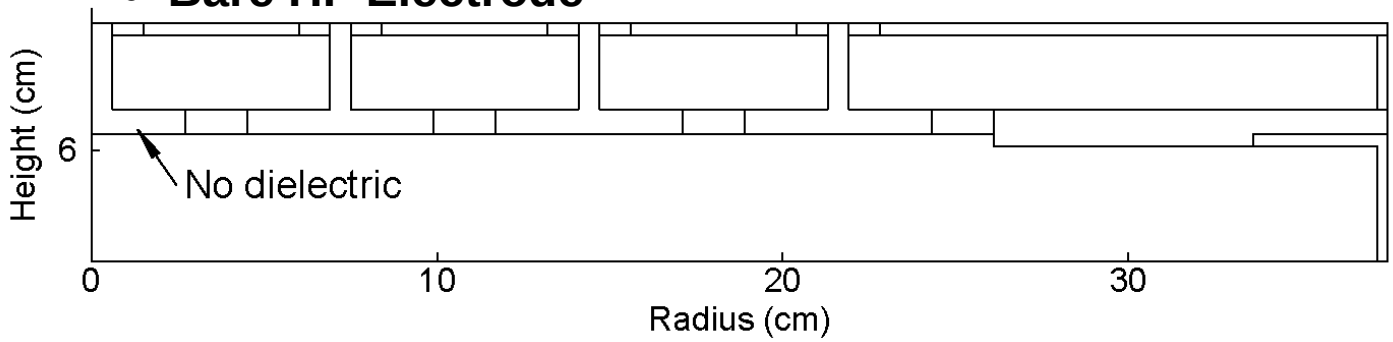
SENSITIVITY TO DETAILS OF REACTOR DESIGN

- **Dielectric Covered Electrode**



- **Bare HF Electrode**



- **At 150 MHz, HF power is distributed in a wave-manner, sensitive to intervening materials.**
- **2 designs were investigated.**
  - **Ar/CF_4=90/10, 50 mTorr, 600 sccm**
  - **Top HF: 150 MHz / 450 W**
  - **Bottom: 10 MHz / 450 W**

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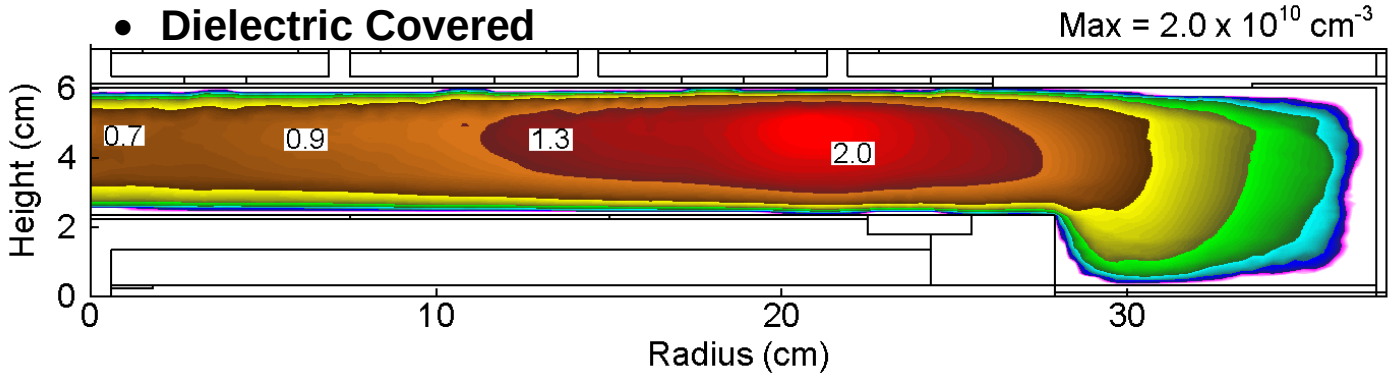
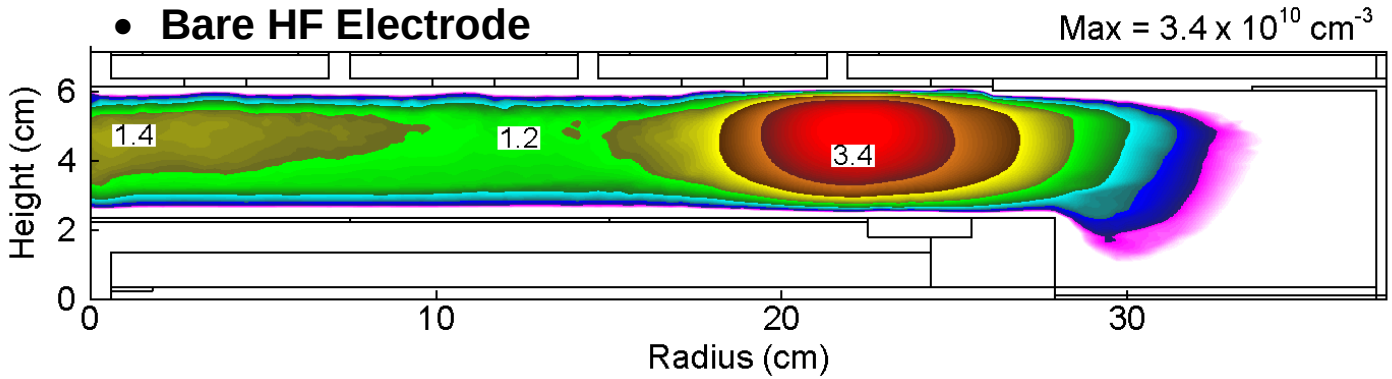
PLASMA DISTRIBUTION

- **Dielectric Covered**



- **Bare HF Electrode**



- **Subtleties of propagation and interaction of EM fields produce differences in the plasma distributions.**
- **With bare HF electrode, [e] is more uniform over the inner 2/3 of the wafer.**

- **Ar/CF_4=90/10**
- **50 mTorr, 600 sccm**
- **HF: 150 MHz/450 W**
- **LF: 10 MHz/450 W**

Min  Max

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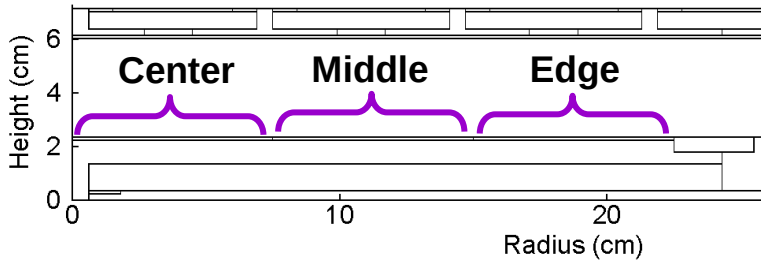
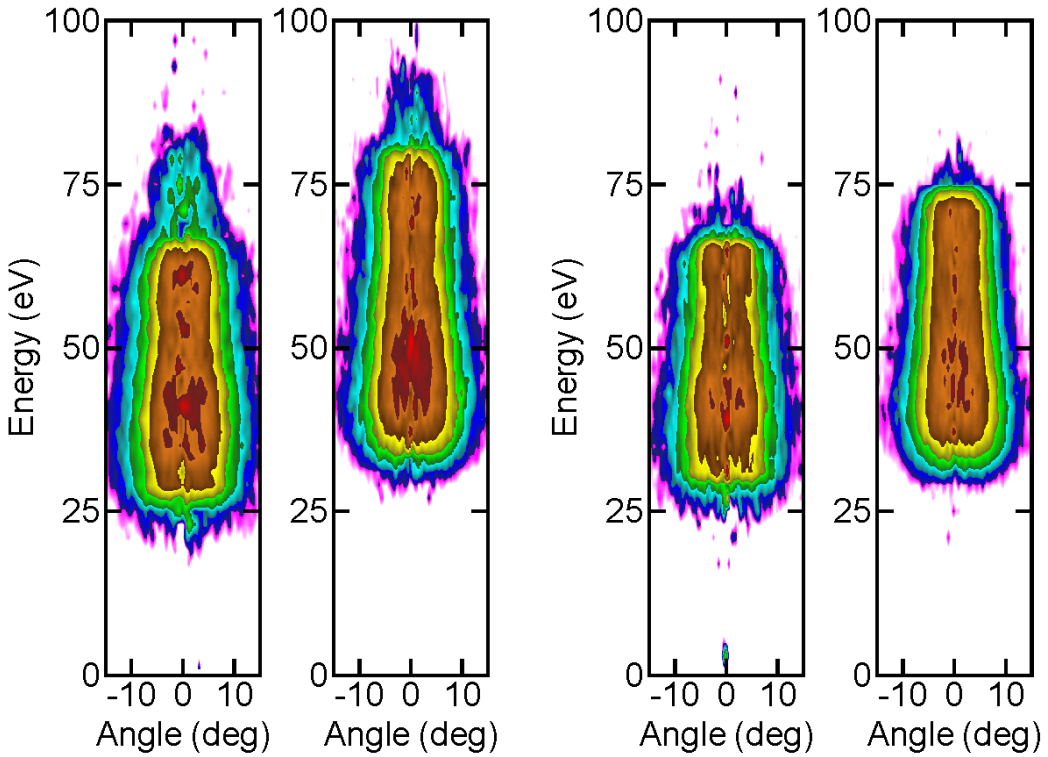
IEADs INCIDENT ON WAFER



- Dielectric Covered
- Center
- Edge

- Bare HF Electrode
- Center
- Edge



- With bare HF electrode, IEAD is less varied across the wafer.

- Ar/CF_4=90/10
- 50 mTorr, 600 sccm
- HF: 150 MHz/450 W
- LF: 10 MHz/450 W

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CONCLUDING REMARKS

- Scaling of dual-frequencies CCPs has been numerically investigated for HF up to 150 MHz.
- Finite wavelength effects…not a simple scaling exercise.
  - Ultimately, a function of conductivity with a strong 2nd order effect of feedback of EEDs on ionization sources.
  - Gas mixtures, pressures are strong 1st order effects in both conductivity and EEDs.
- Issues become only more pronounced at 450 mm.
- It is unclear that conventional CCP designs (at high frequency) will serve well at 450 mm.
- Perhaps segmented electrodes will see their day.

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