EFFECT OF PRESSURE AND ELECTRODE SEPARATION ON PLASMA UNIFORMITY IN DUAL FREQUENCY CAPACITIVELY COUPLED PLASMA TOOLS *

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AGENDA

- Optimization of multiple frequency plasma etching reactors
- Description of the model
- Scaling with:
  - Pressure
  - Electrode separation
- Concluding remarks

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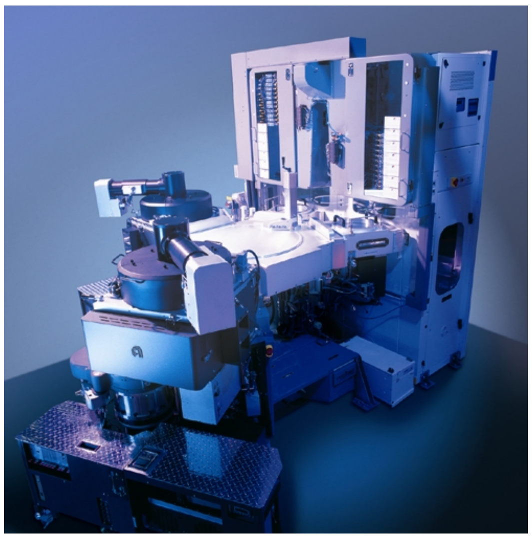
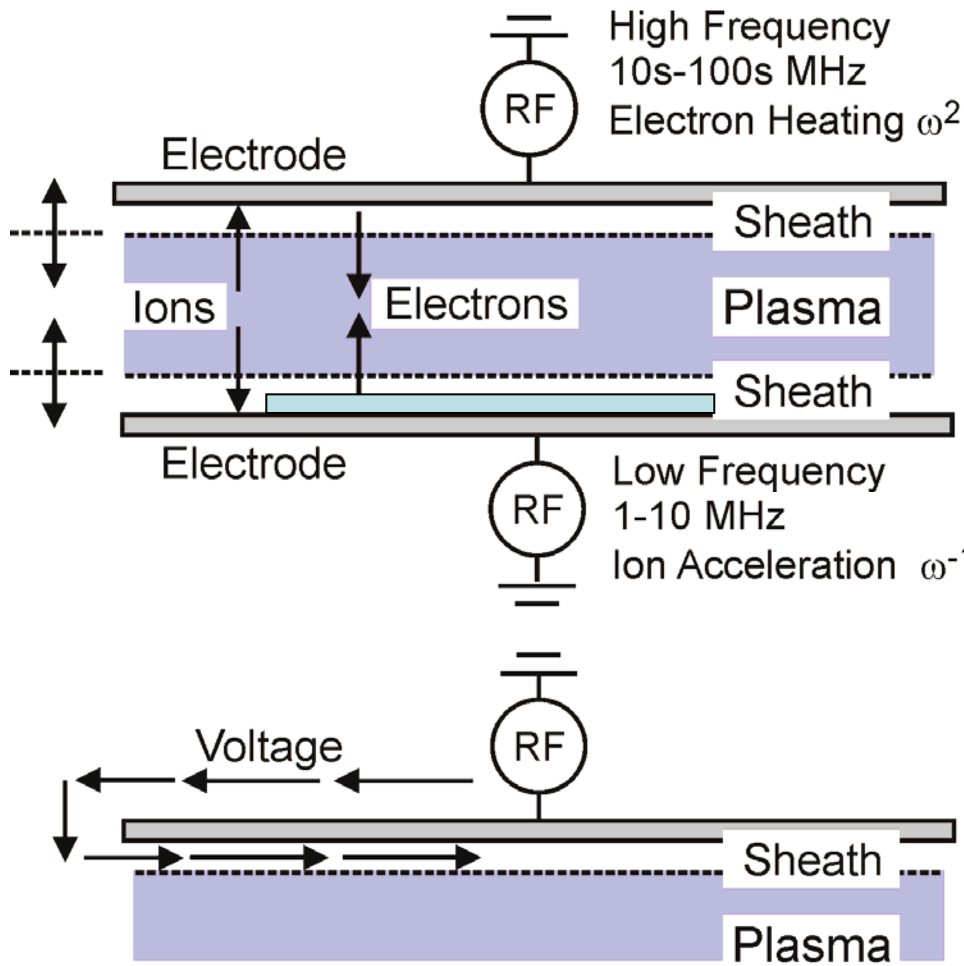
MULTI-FREQUENCY PLASMA ETCHING REACTORS

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

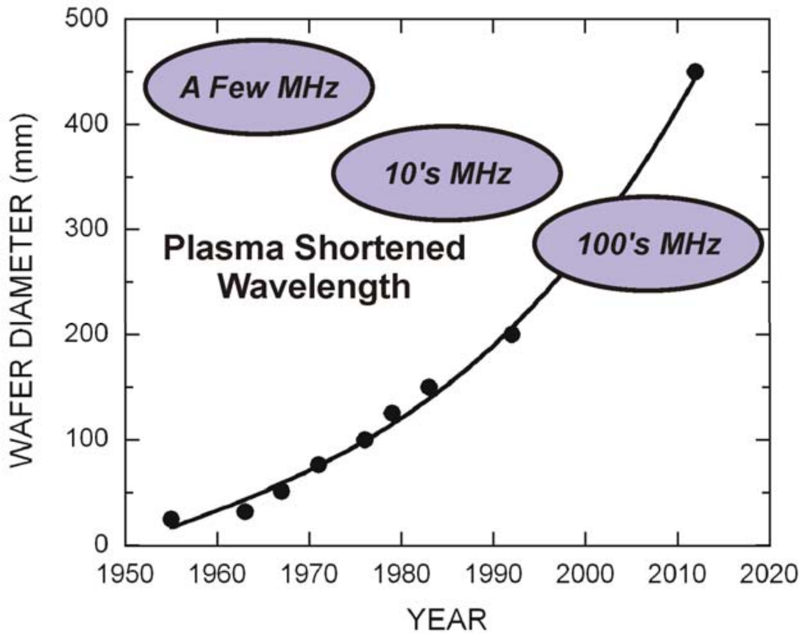


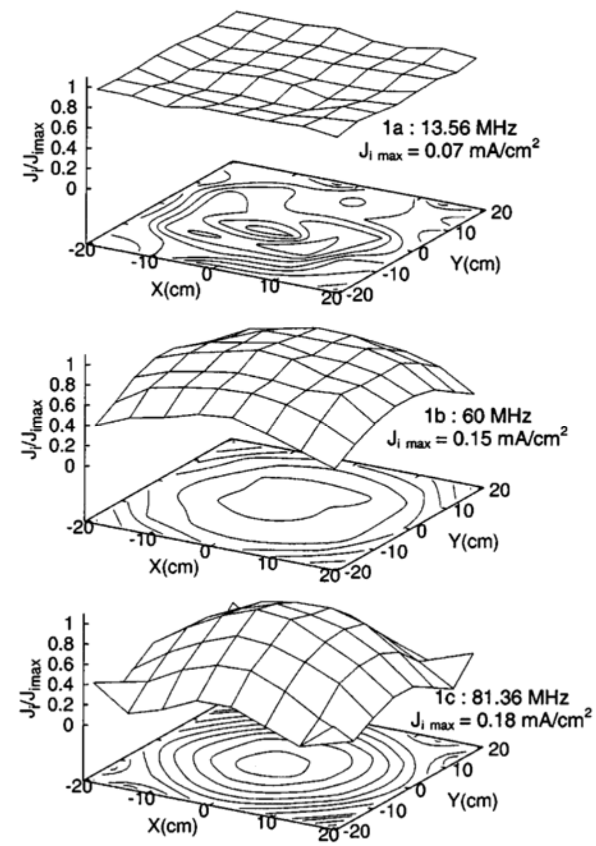


- **Voltage finds its way into the plasma propagating around electrodes (not through them).**

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

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

Lieberman, et al PSST 11 (2002)
A. Perret, APhL 83 (2003)
http://mrsec.wisc.edu

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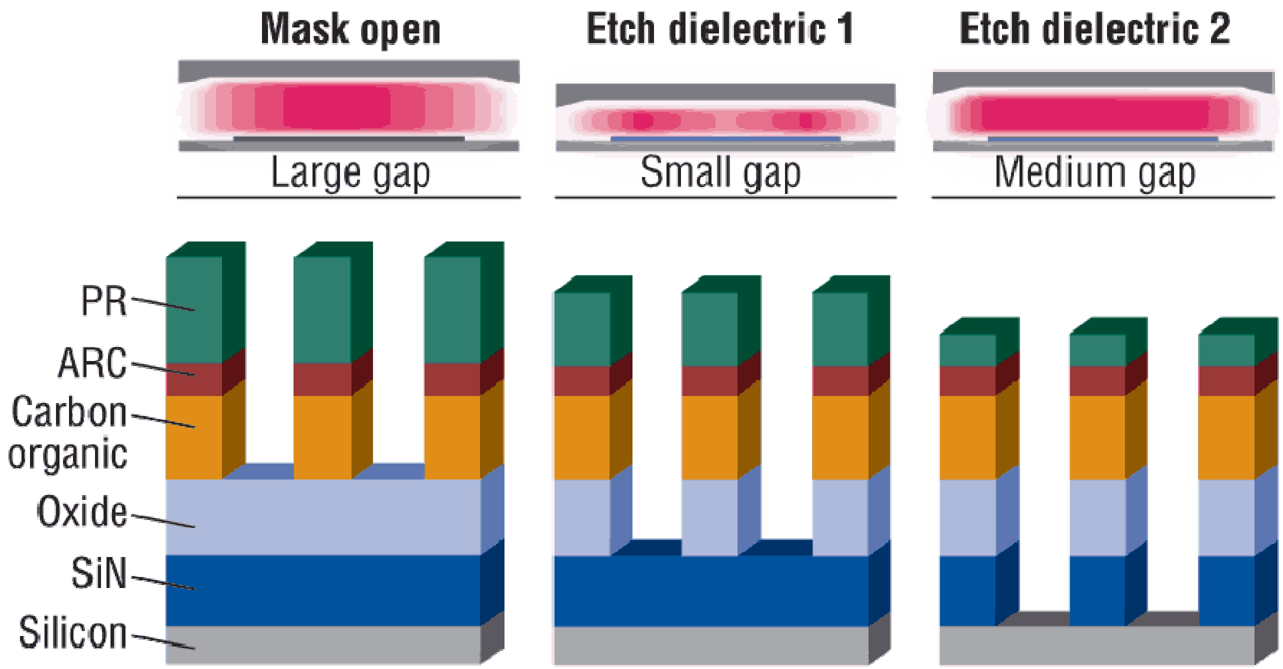
AN EXAMPLE: ADJUSTABLE GAP CONTROL



- Adjusting the gap (electrode separation) of capacitively coupled plasmas (CCPs) enables customization of the radical fluxes.
- Enables different processes, such as mask opening and trench etching, to be separately optimized.

V. Vahedi, M. Srinivasan, A. Bailey, Solid State Technology, 51, November, 2008.

COUPLED EFFECTS IN HIGH FREQUENCY CCPs

- **Electromagnetic wave effects impact processing uniformity in high frequency CCPs.**
- **When coupled with changing gap and pressure, controlling the plasma uniformity could be more difficult.**
- **Results from a computational investigation of impacts of pressure and gap on plasma uniformity in dual frequency CCPs (DF-CCPs) will be discussed.**

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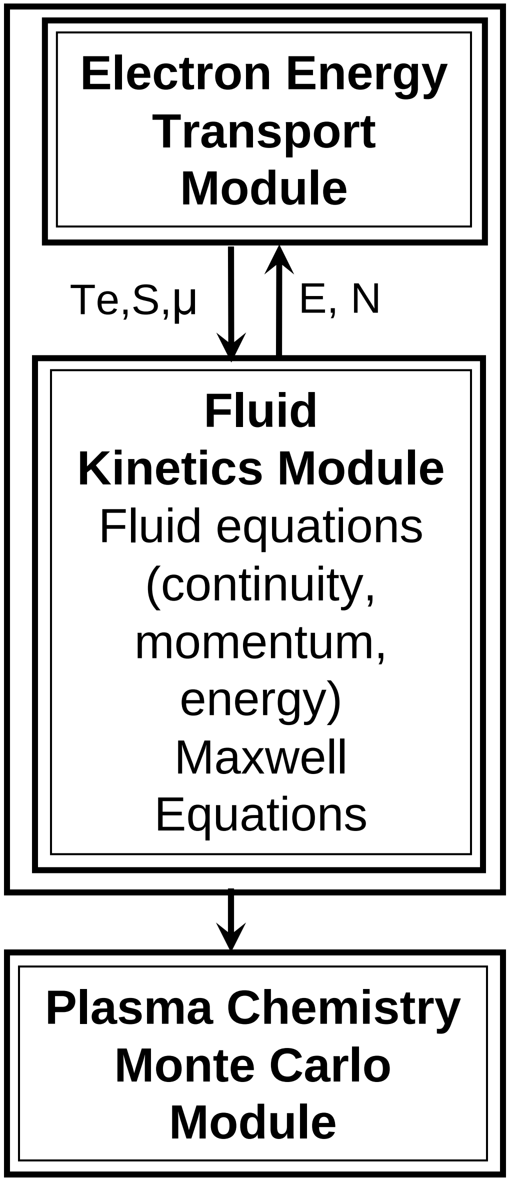
HYBRID PLASMA EQUIPMENT MODEL (HPEM)



- **Electron Energy Transport Module:**
  - **Electron Monte Carlo Simulation provides EEDs of bulk electrons**
  - **Separate MCS used for secondary, sheath accelerated electrons**
- **Fluid Kinetics Module:**
  - **Heavy particle and electron continuity, momentum, energy**
  - **Maxwell's Equations**
- **Plasma Chemistry Monte Carlo Module:**
  - **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.**
- **We separately solve for EM and ES fields and sum the fields for plasma transport.**

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

- **Boundary conditions (BCs):**
  - **EM field: Determined by rf sources.**
  - **ES field: Determined by blocking capacitor (DC bias) or applied DC voltages.**

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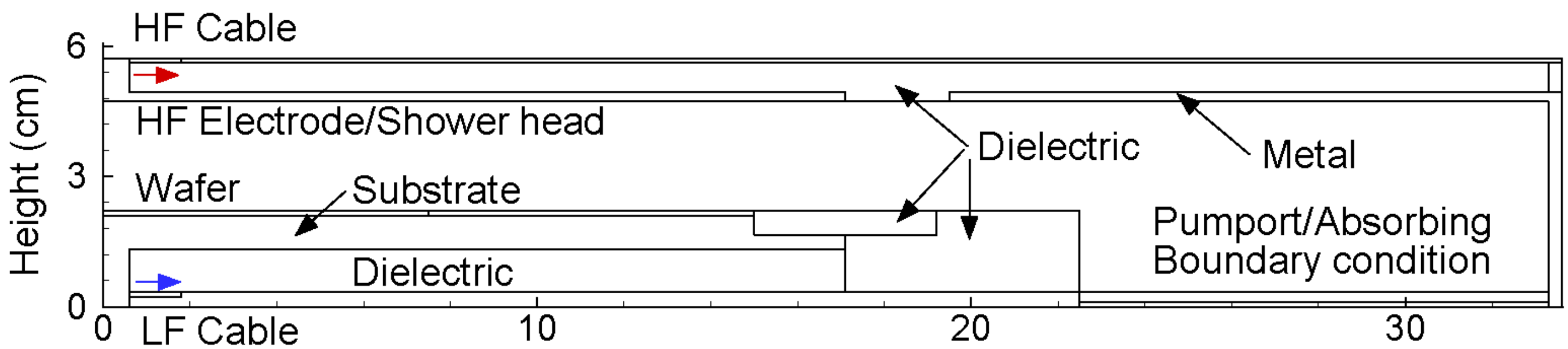
REACTOR GEOMETRY



- **2D, cylindrically symmetric.**
- **Base conditions**
  - **Ar/CF_4 =90/10, 400 sccm**
  - **High frequency (HF) upper electrode: 150 MHz, 300 W**
  - **Low frequency (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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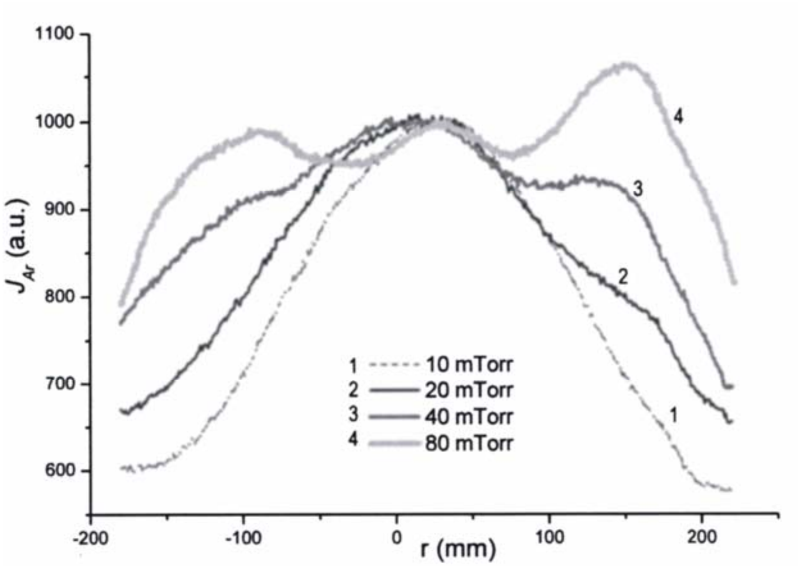
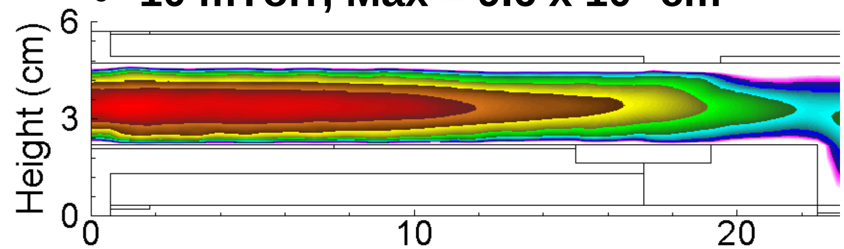
Ar PLASMA IN SINGLE FREQUENCY CCP



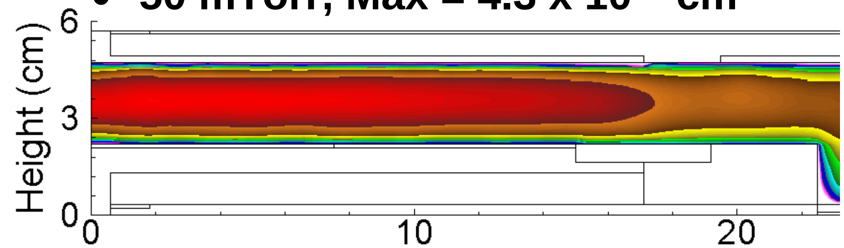
- With increasing Ar pressure, electron density transitions from center high to edge high.
- Agrees with experimental trend, albeit in a different geometry.
- DF-CCP at higher frequency, with electronegative gas…trends?

V. N. Volynets, et al., J. Vac. Sci. Technol. A 26, 406, 2008.

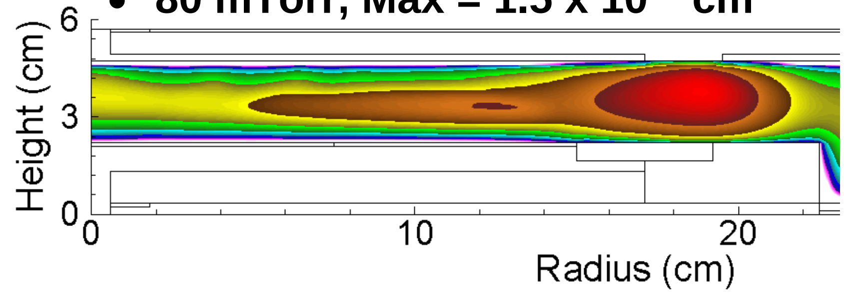
- [e]
- 10 mTorr, Max = 9.6×10^9 cm^{-3}



- 50 mTorr, Max = 4.3×10^{10} cm^{-3}



- 80 mTorr, Max = 1.5×10^{11} cm^{-3}



- Ar, 100 MHz/750 W from upper electrode.

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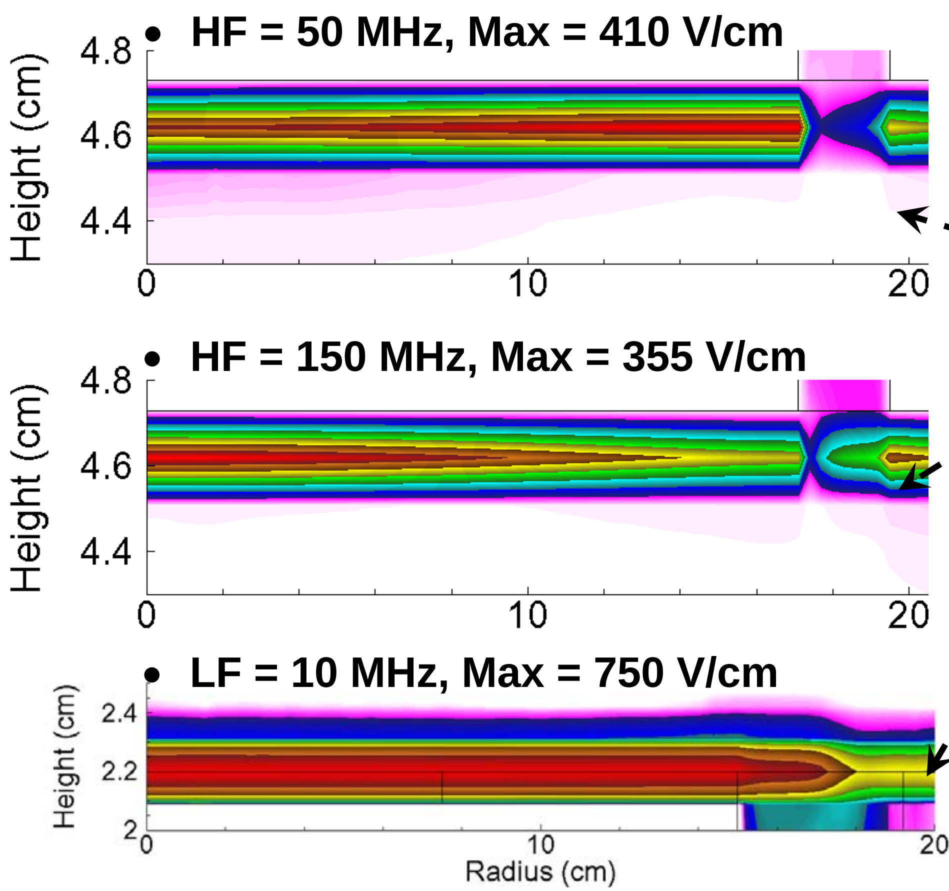
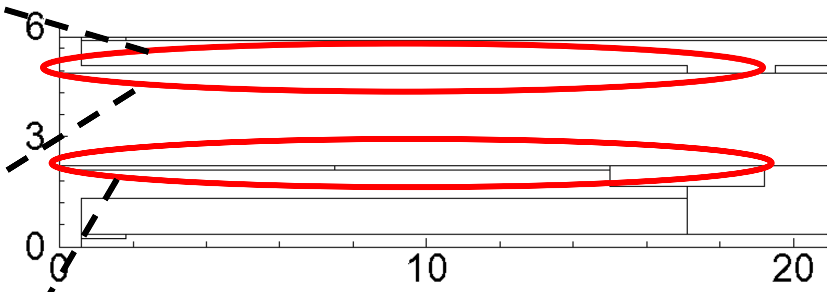
EM EFFECTS: FIELD IN SHEATHS



- 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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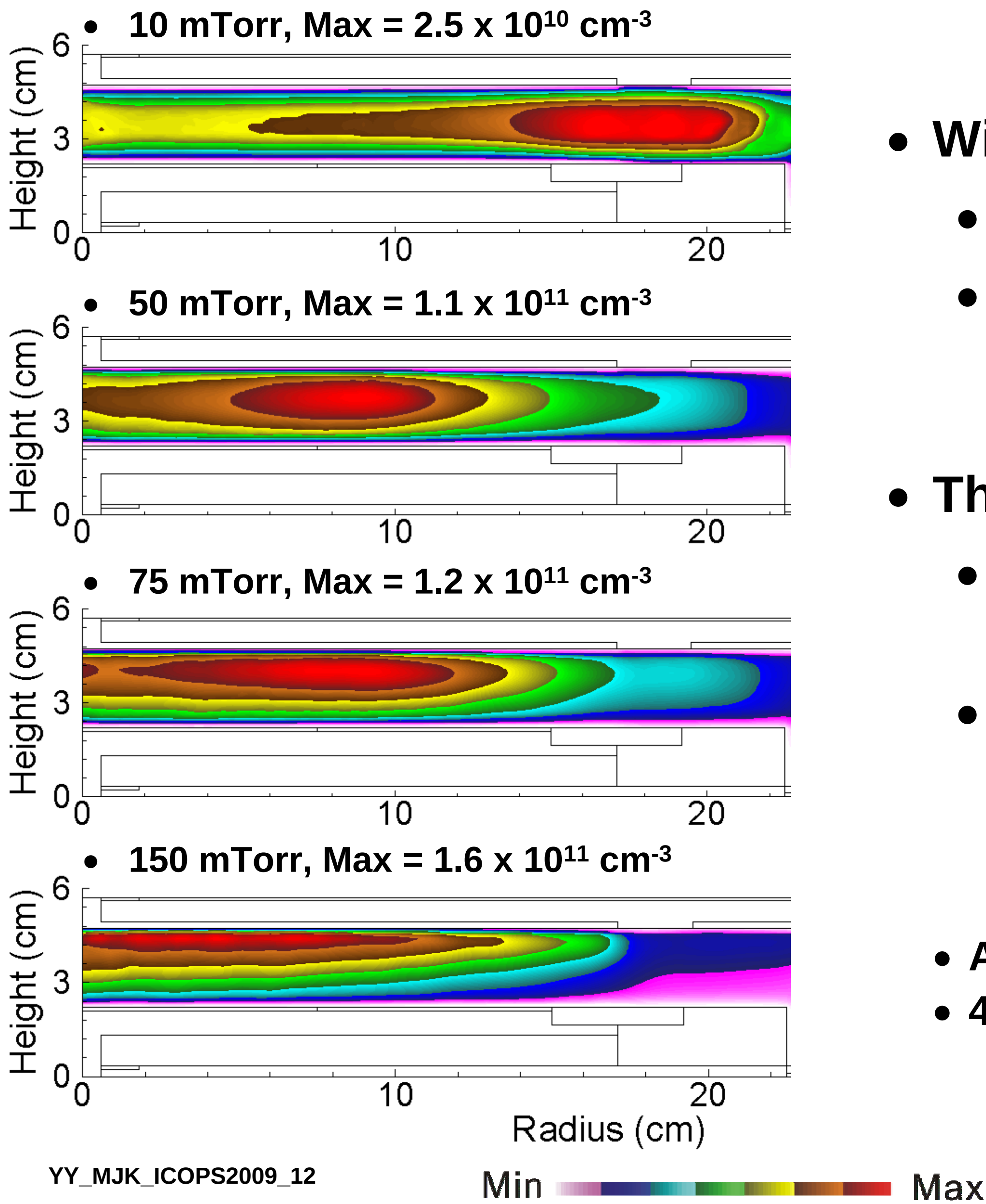
SCALING WITH PRESSURE IN DF-CCP



- With increasing pressure:
  - Concurrent increase in [e].
  - Shift in maximum of [e] towards the HF electrode and the center of the reactor.
- The shift is a result of
  - Shorter energy relaxation distance.
  - Combination of finite wavelength and skin effect.

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

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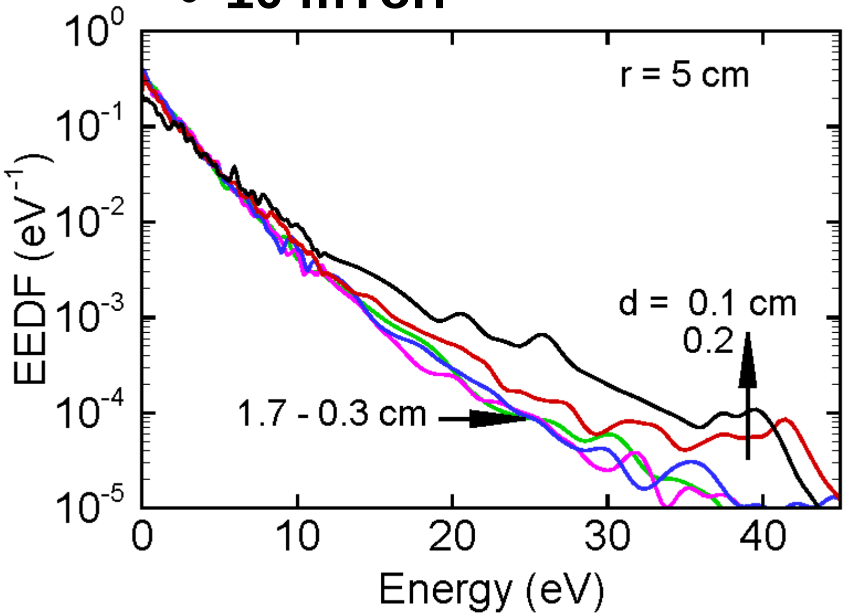
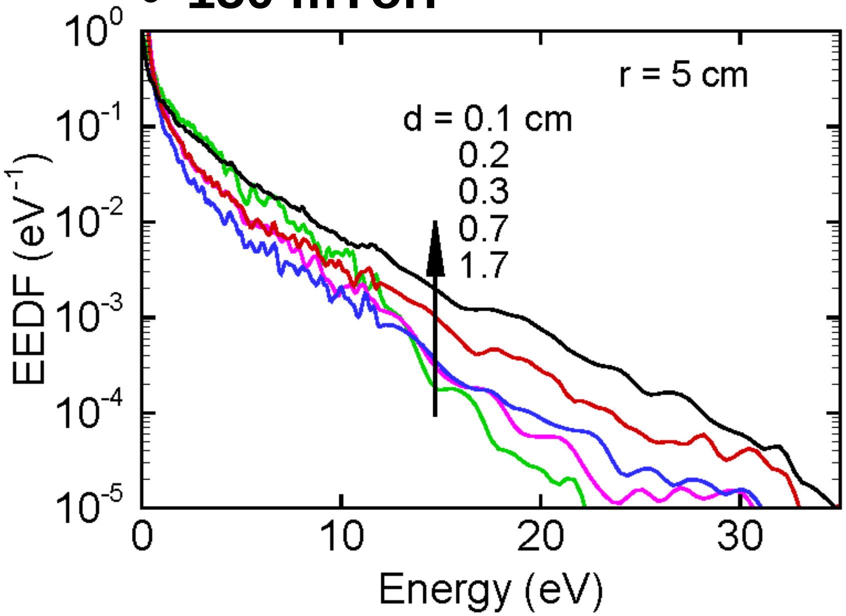
ELECTRON ENERGY DISTRIBUTIONS (EEDs)

- **10 mTorr**



- **150 mTorr**



- **d = distance to the upper electrode.**
- **EEDF as a function of height:**
  - **10 mTorr — no change in bulk plasma with tail lifted in sheath.**
  - **150 mTorr — Tails of EEDs lift as HF electrode is approached.**
- **Produce different spatial distribution of ionization sources.**

- **Ar/CF_4=90/10**
- **400 sccm**

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

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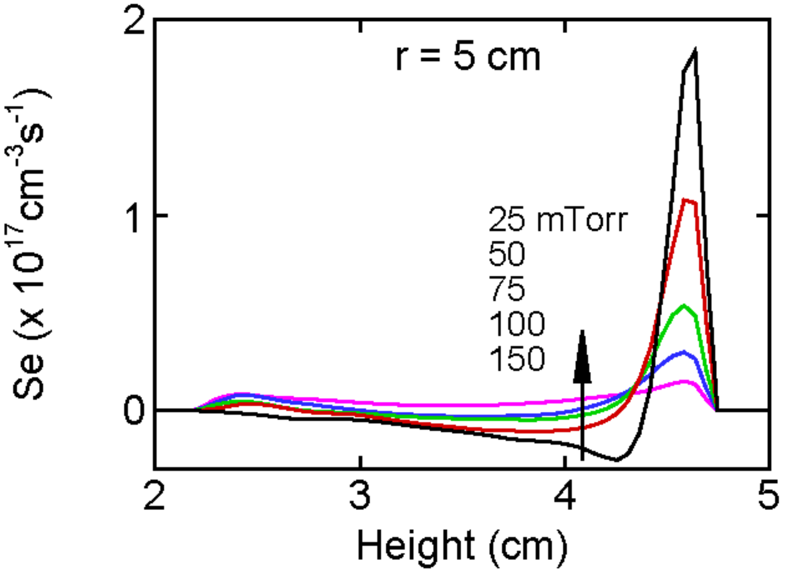
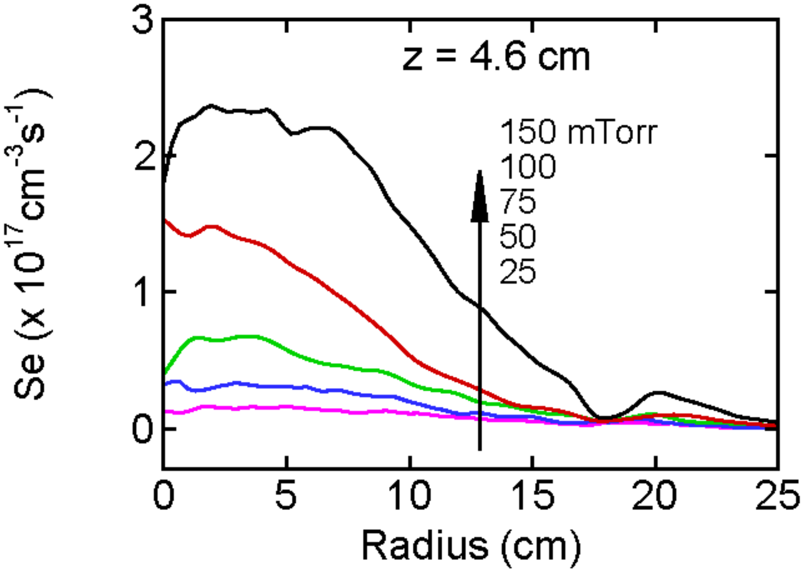
ELECTRON IMPACT IONIZATION SOURCE (S_e)

- **Axial Direction**



- **Radial Direction (In the HF Sheath)**



- **With increasing pressure:**
  - **Axial direction: Energy relaxation distance decreases and so sheath heating is dissipated close to electrode – transition to net attachment.**
  - **Radial direction: As energy relaxation distance decreases, S_e mirrors the constructively interfered HF field - more center peaked.**

- **Ar/CF_4=90/10**
- **400 sccm**

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

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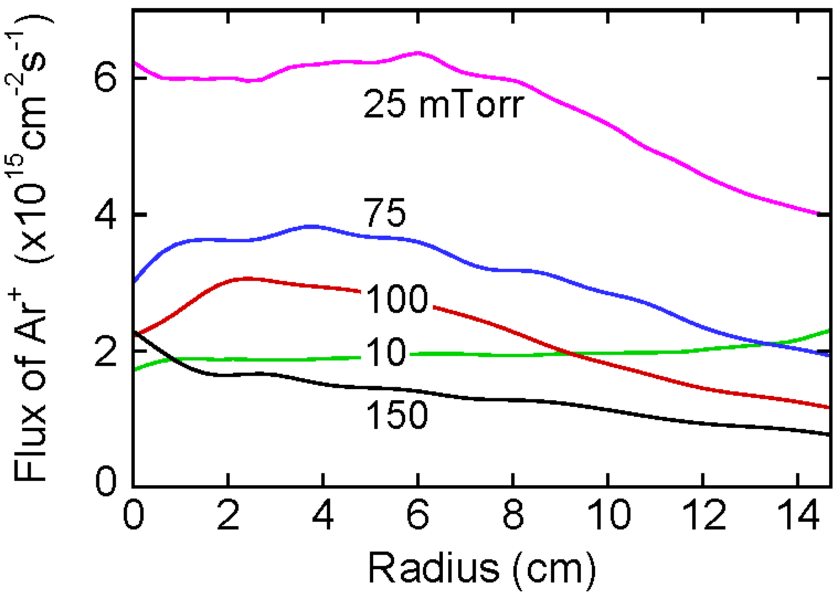
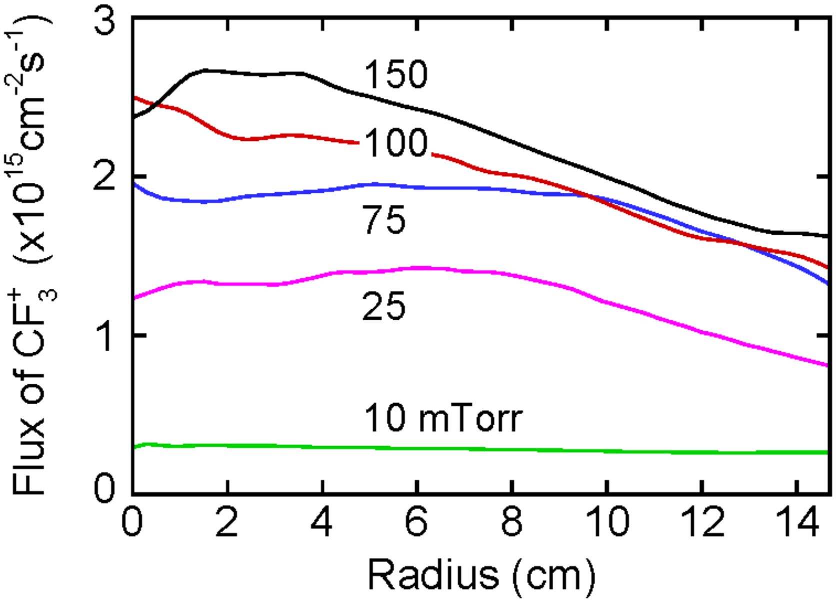
ION FLUX INCIDENT ON WAFER

- **Flux of Ar^+**



- **Flux of CF_3^+**



- **With increasing pressure, ionization source increases but moves further from wafer..**
- **Ar^+ flux is depleted by charge exchange reactions while diffusing to wafer – and is maximum at 25-50 mTorr.**

- **Ar/CF_4=90/10**
- **400 sccm**

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

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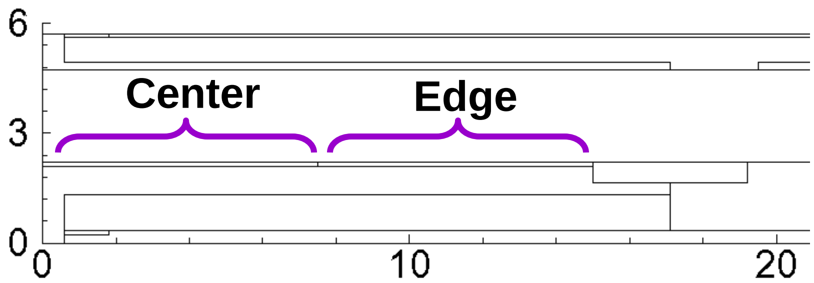
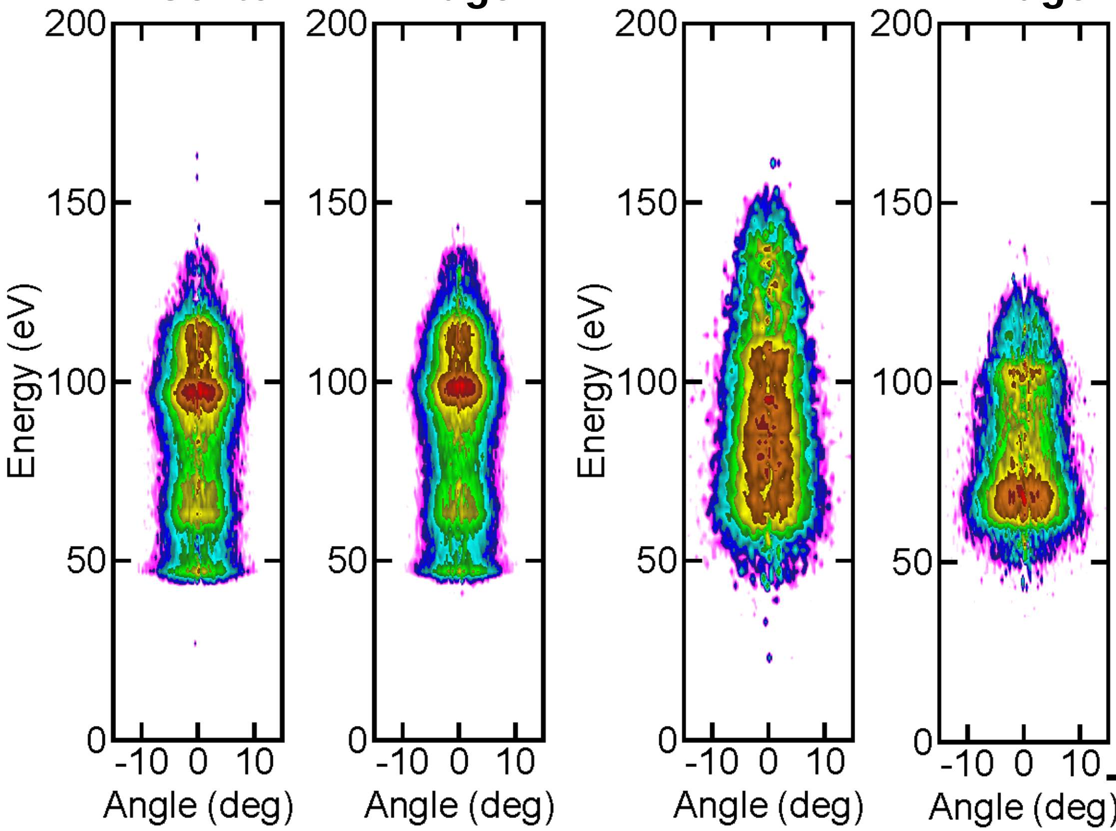
TOTAL ION IEADs INCIDENT ON WAFER: Ar/CF_4 = 90/10



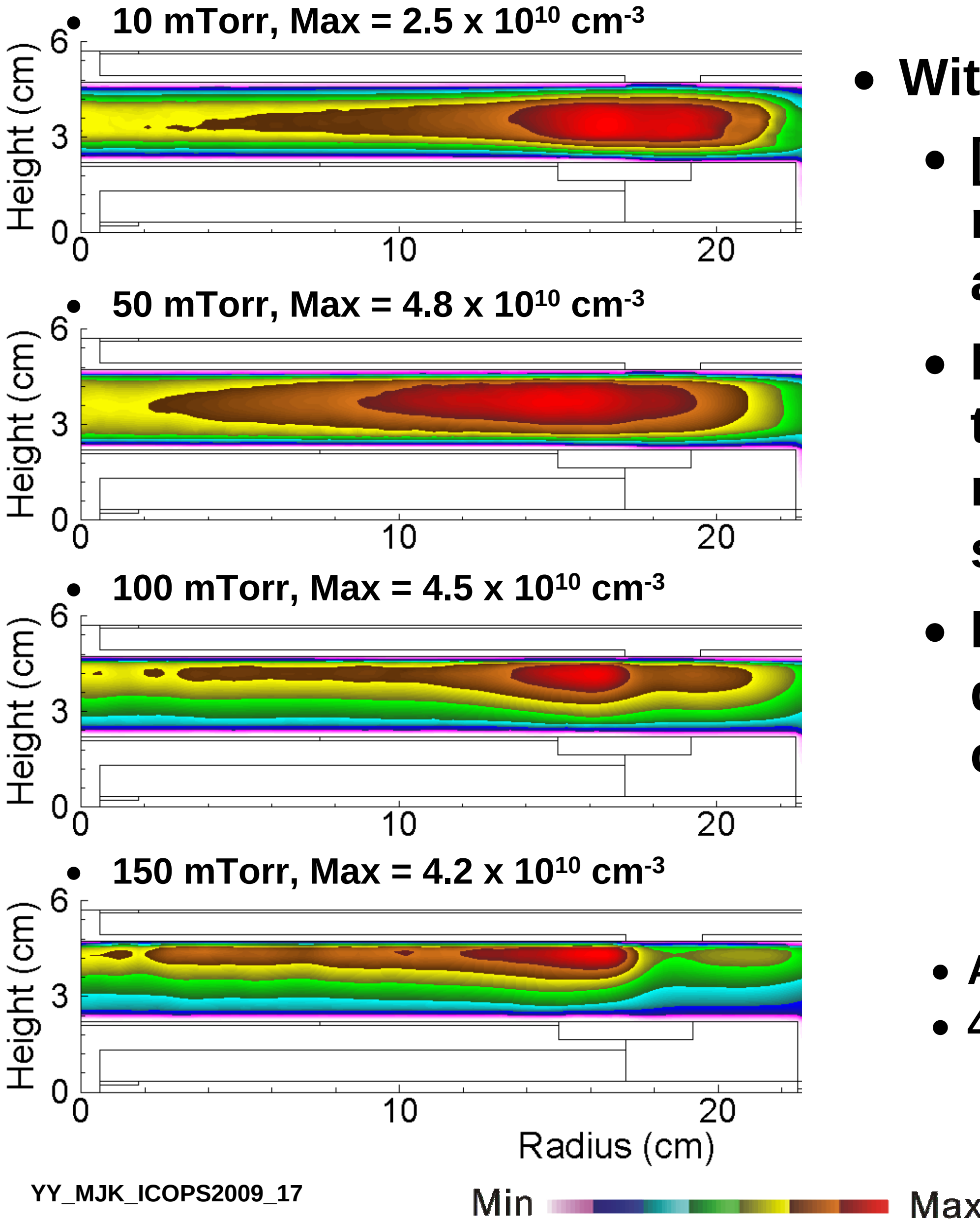
- 10 mTorr
  - Center
  - Edge
- 150 mTorr
  - Center
  - Edge



- **IEADs are separately collected over center and edge of wafer.**
- **Bimodal to single peak transition with increasing pressure.**
- **10 mTorr: uniform**
- **≥50 mTorr: larger radial variation.**

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

SCALING WITH PRESSURE: Ar/CF_4 =80/20



- **With increasing pressure:**
  - **[e] decreases from 50 to 150 mTorr owing to increasing attachment losses.**
  - **Maximum of [e] still shifts towards the HF electrode and the reactor center…a less dramatic shift than Ar/CF_4=90/10.**
  - **Electrostatic component remains dominant due to lower conductivity.**

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

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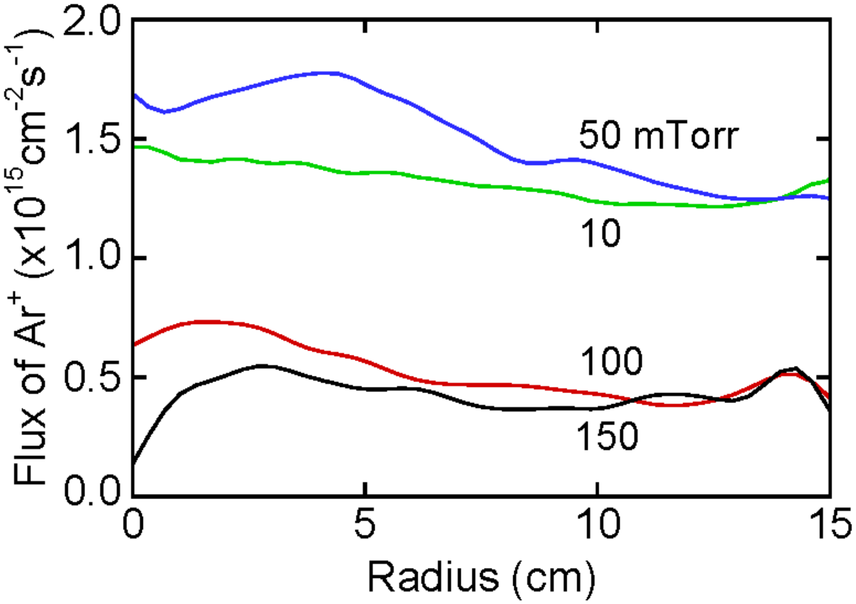
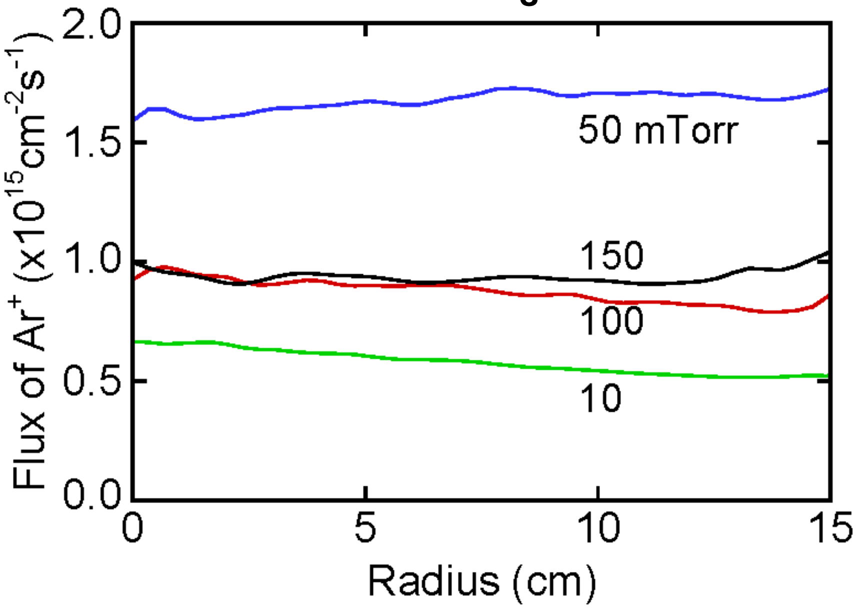
ION FLUX INCIDENT ON WAFER: Ar/CF_4 =80/20

- **Flux of Ar^+**



- **Flux of CF_3^+**



- **Compared with Ar/CF_4 = 90/10…**
  - **More rapid depletion of Ar^+ flux by charge exchange.**
  - **CF_3^+ flux also maximizes at intermediate pressure — consequence of more confined plasma.**

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

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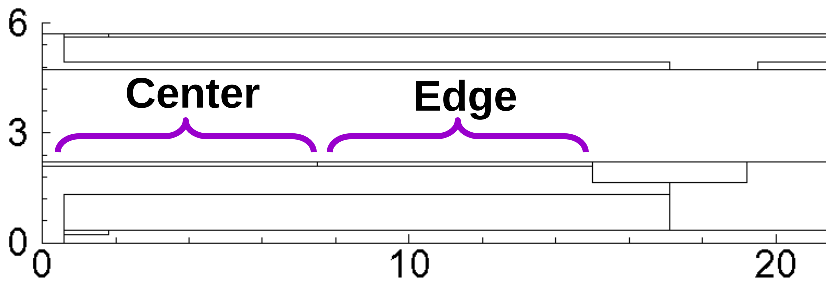
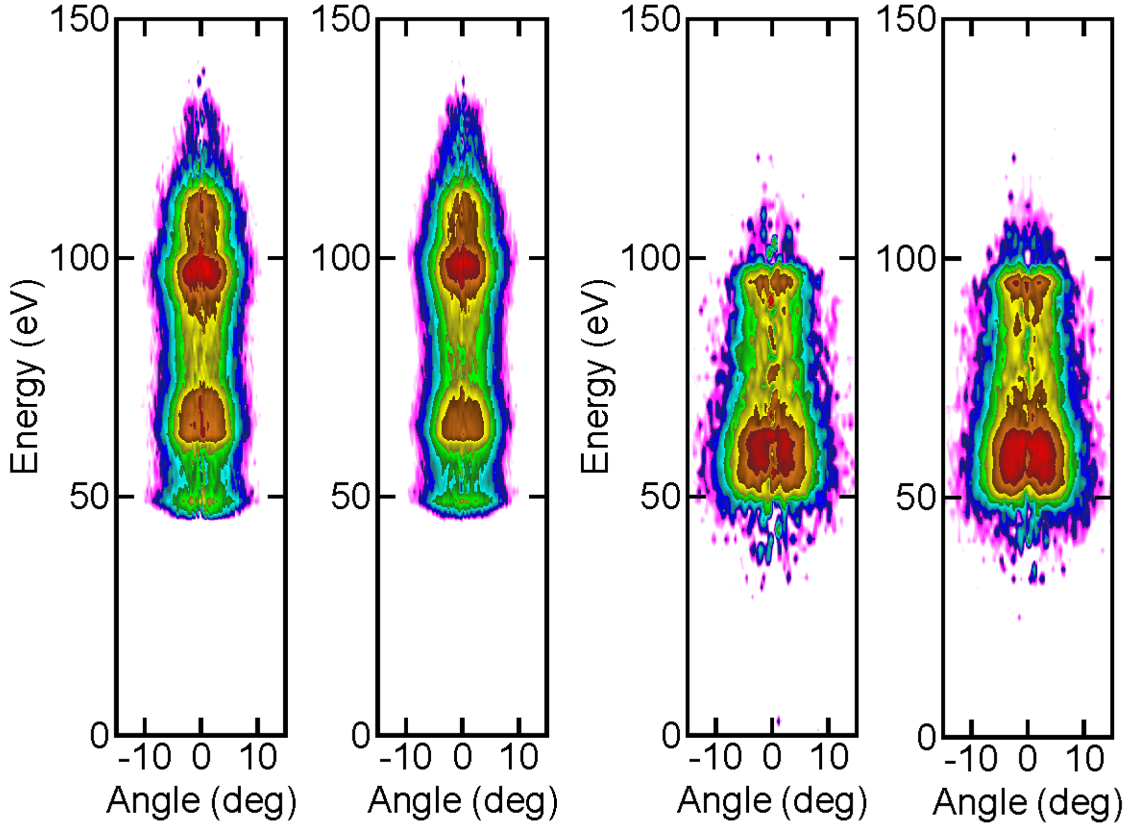
TOTAL ION IEADs INCIDENT ON WAFER: Ar/CF_4 = 80/20



- 10 mTorr
  - Center
  - Edge
- 150 mTorr
  - Center
  - Edge



- At Ar/CF_4 =80/20 plasma is peaked near HF electrode edge, and largely uniform over the surface of wafer.
- Improved uniformity of IEADs at all pressures.

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

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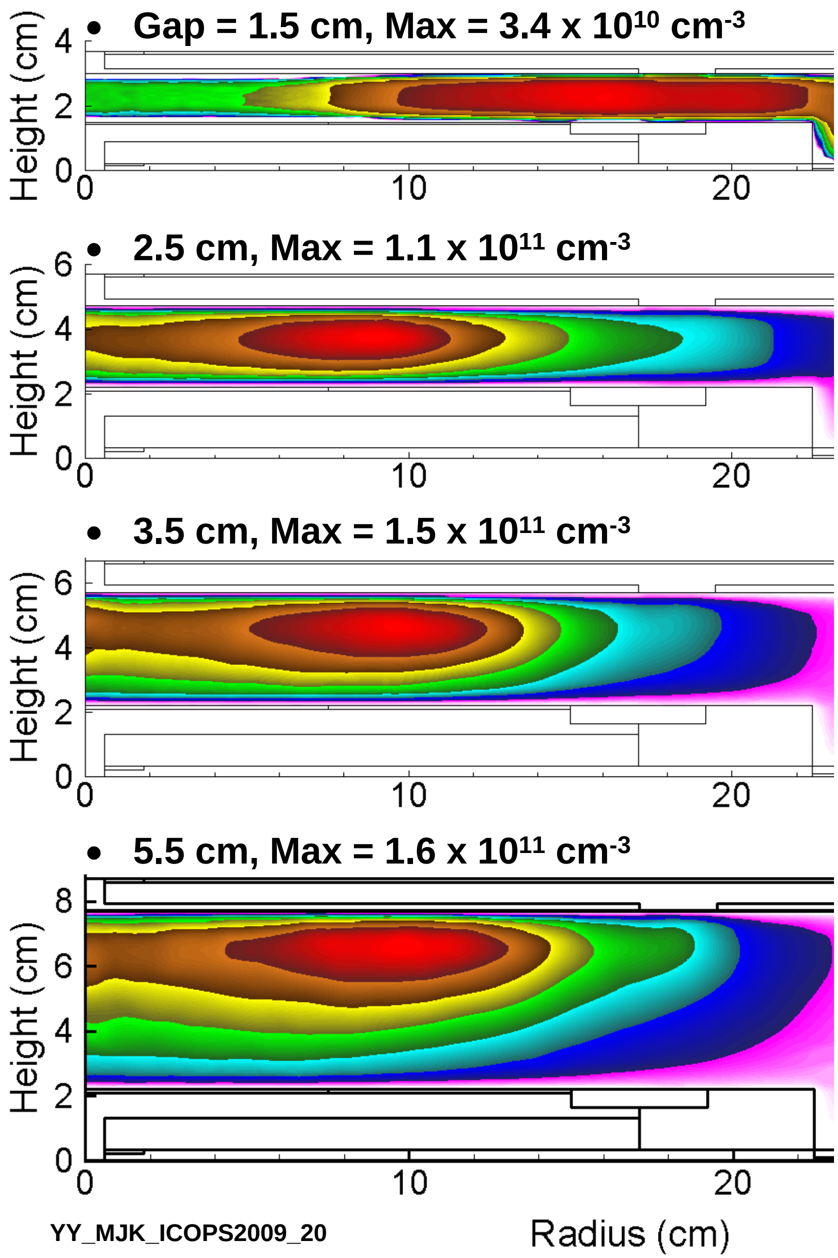
SCALING WITH GAP: Ar/CF_4 =90/10



- **With increasing gap:**
  - **[e] increases as diffusion length increases and loss decreases.**
  - **Edge peaked [e] at gap = 1.5 cm, due to electrostatic edge effect.**
  - **Maximum of [e] shifts towards the HF electrode.**
- **For gap > 2.5 cm, radial [e] profile is not sensitive to gap.**
- **Electrode spacing exceeds energy relaxation length and power deposition mechanism does not change.**

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

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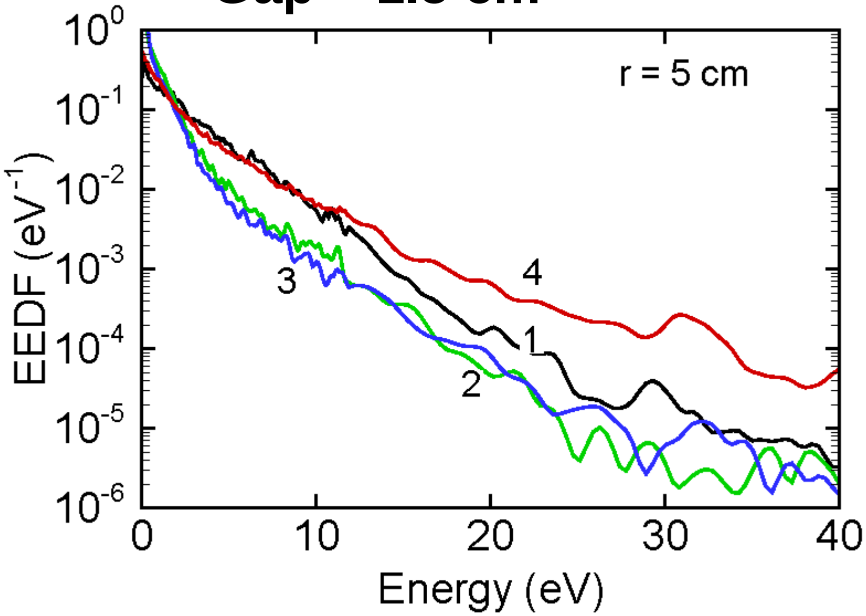
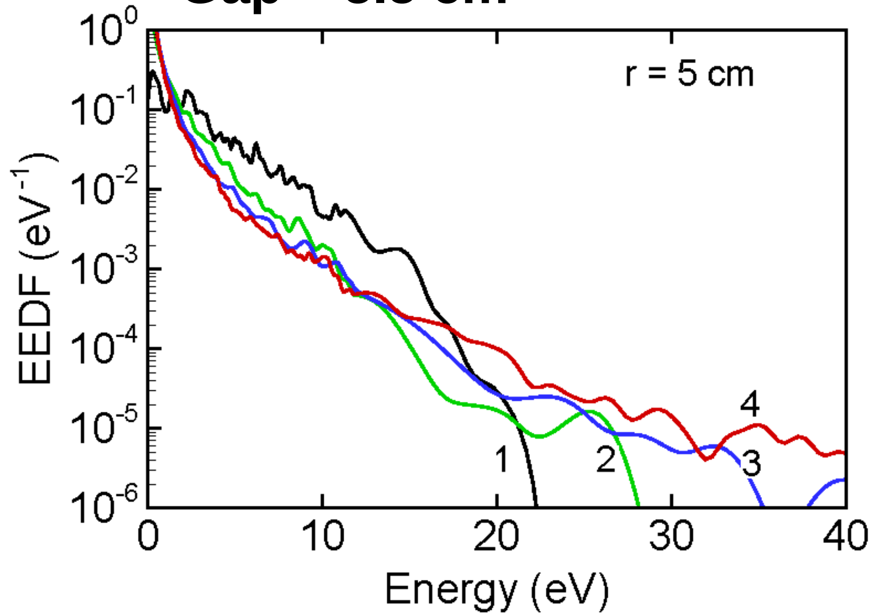
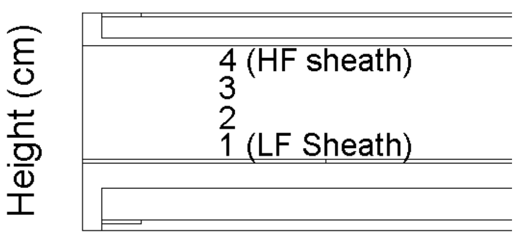
EEDs vs GAP

- **Gap = 1.5 cm**



- **Gap = 5.5 cm**





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

- **2.5 cm: Little change across bulk plasma; tail in LF sheath lifted owing to HF wave penetration.**
- **5.5 cm: Systematic tail enhancement towards the HF electrode — larger separation between HF and LF waves, system functions more linearly.**

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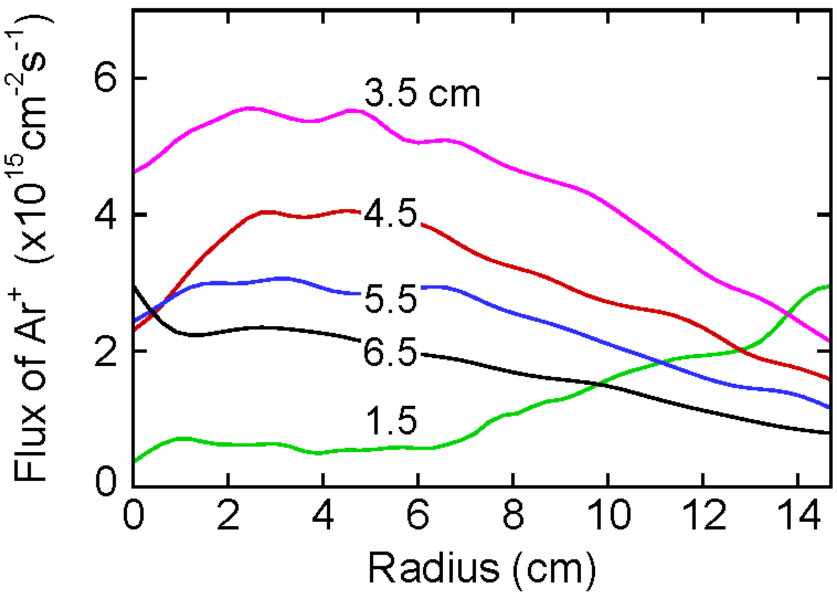
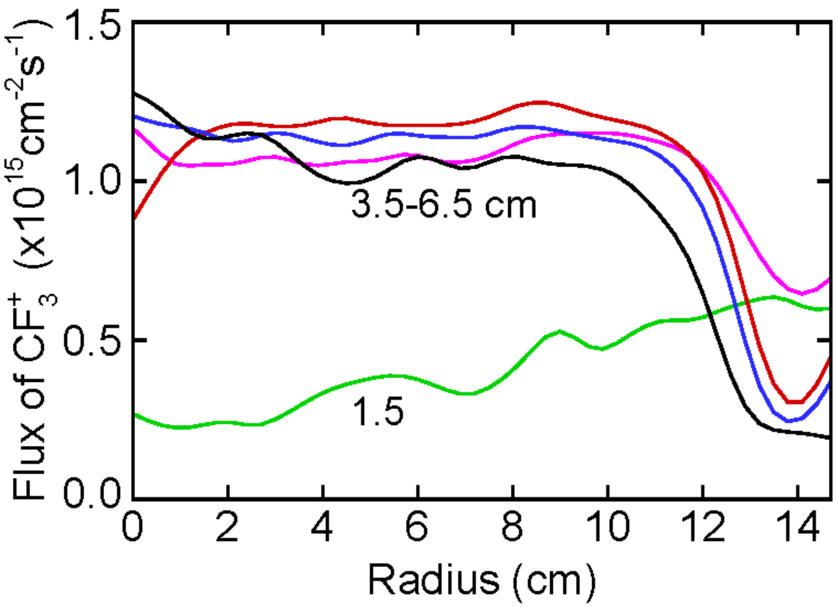
ION FLUX INCIDENT ON WAFER

- **Flux of Ar^+**



- **Flux of CF_3^+**



- **1.5 cm: edge peaked flux due to electrostatic edge effect.**
- **2.5-5.5 cm: middle peaked flux due to electrostatic and wave coupling.**
- **6.5 cm: center peaked flux (with a middle peaked [e]): edge effect reduced at larger gap.**

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

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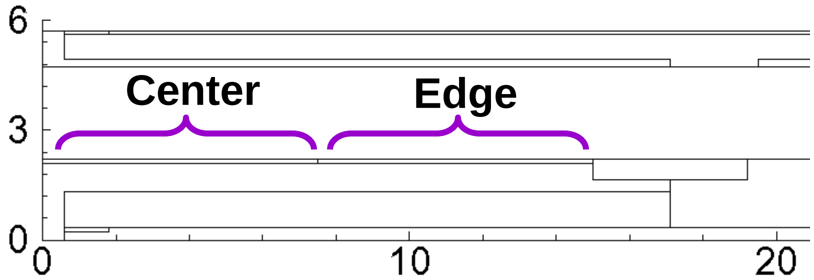
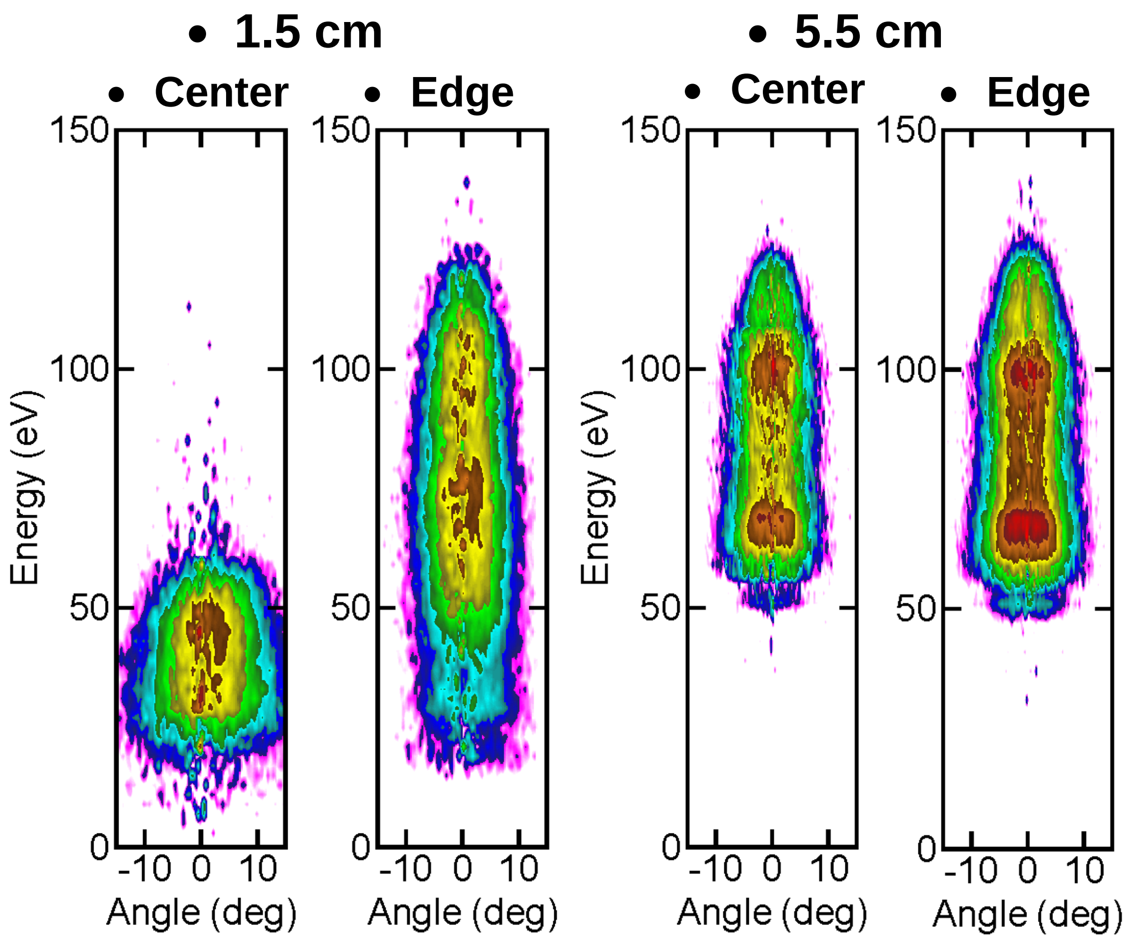
TOTAL ION IEADs INCIDENT ON WAFER vs GAP





- Narrow gap has large center-to-edge non-uniformity due to change in sheath width.
- Narrower sheath near edge produces broaded IEAD.
- Large gap enables more diffusive and uniform sheath properties – and so more uniform IEADs.

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

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CONCLUDING REMARKS

- **For DF-CCPs sustained in Ar/CF_4=90/10 mixture with HF = 150 MHz:**
  - **With increasing pressure, maximum of ionization source (S_e) shifts towards the HF electrode as energy relaxation distance decreases.**
  - **S_e mirrors EM field, which is center peaked from constructive interference and [e] profile transitions from edge high to center high.**
  - **Increasing fraction of CF_4 to 20% results in more uniform ion fluxes and IEADs incident on wafer.**
- **Effects of gap size in Ar/CF_4=90/10 mixture:**
  - **Between 2.5 and 6.5 cm, [e] profile is not sensitive to gap size since larger than energy relaxation distance.**
  - **Small gaps have more edge-to-center non-uniformity in IEADs due to strong edge effects.**