SCALING OF DUAL FREQUENCY CAPACITIVELY COUPLED PLASMA ETCHING TOOLS APPROACHING AND EXCEEDING 100 MHz*

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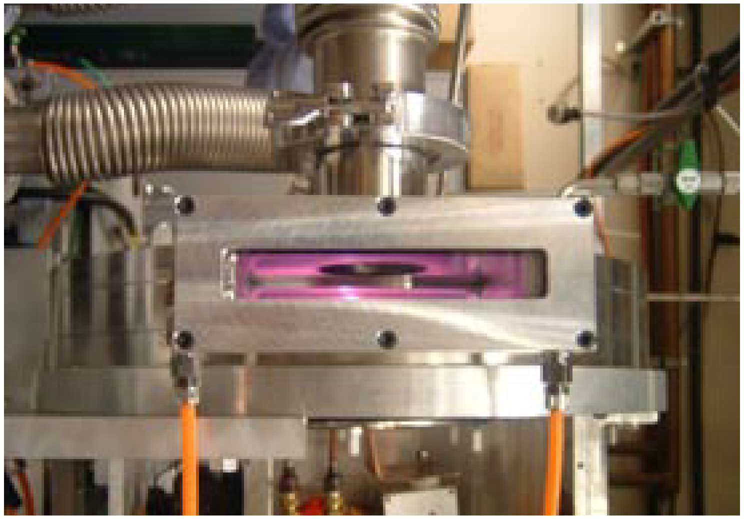
AGENDA

- Introduction to dual frequency capacitively coupled plasma (CCP) sources
- Description of the model
- Plasma properties of 10MHz/100MHz case
- Scaling of dual frequency CCP properties
  - High Frequency
  - HF power
  - LF power
- Concluding Remarks

DUAL FREQUENCY CCP SOURCES

- Goals of dual frequency CCPs:
  - Separately controlling fluxes and Ion energy distributions (IEDs)
  - Providing additional tuning of IEDs



- Decoupling between LF and HF is critical:
  - Nonlinear interaction when the frequencies are close results different plasma and electrical characteristics.
  - Even with constant LF voltage, IEDs depends on HF properties due to changes in sheath thickness and plasma potential.

http://www.eecs.berkeley.edu/~lieber/
V. Georgieva and A. Bogaerts, JAP 98, 023308(2005)

SCALING ISSUES IN DUAL FREQUENCY CCPS

- Basic criterion for functional separation of two frequencies

$$\frac{\omega_h^2}{\omega_l^2} >> \frac{V_l}{V_h} >> 1$$

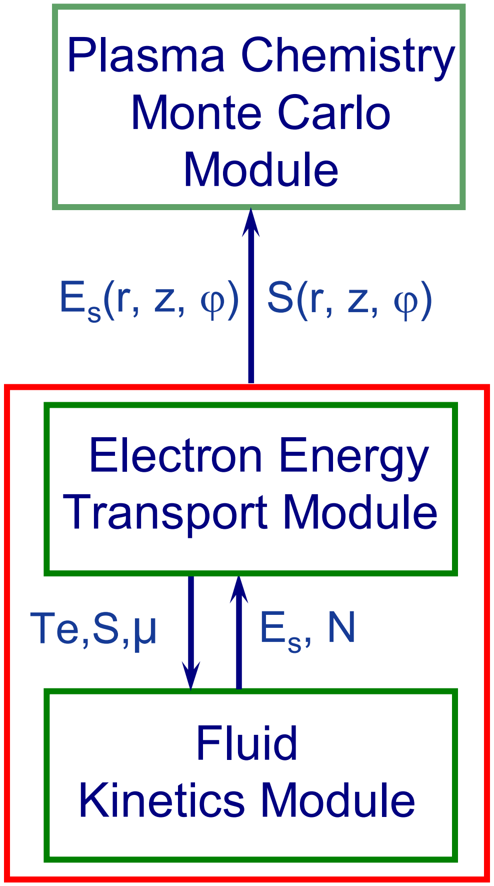
- Physical issues in dual frequency CCPs:
  - Multi-frequency coupling and effect on plasma properties
  - Ion and electron heating mechanisms
  - Standing and surface wave effects
  - Effect of tool design (e.g,, rf feed connections)
- Improvement of precision and uniformity of 2-f CCP RIE tools over large area wafer requires properly addressing those issues.

M. A. Lieberman et al, SEMICON Korea Etching Symposium, p.23(2003)

GOALS OF THE INVESTIGATION

- **In this talk, results from a computational investigation will be discussed with the goals of:**
  - **Effect of HF on plasma properties, electron energy distributions (EEDs) and IEDs for constant power.**
  - **Effect of HF and LF power on plasma properties, EEDs, IEDs.**
- **Following techniques are incorporated to give a better depiction of the physics:**
  - **Fully implicit algorithm for electron transport.**
  - **Electron Monte Carlo simulation for EEDs.**
- **Finite surface wave effects are not addressed.**

HYBRID PLASMA EQUIPMENT MODEL (HPEM)



- **<u>Electron Energy Transport Module:</u>**
  - **Electron Monte Carlo Simulation with e-e collisions provides EEDs.**
  - **MCS used for secondary, sheath accelerated electrons**
- **<u>Fluid Kinetics Module:</u>**
  - **Heavy particle and electron continuity, momentum, energy**
  - **Poisson's Equation**
- **<u>Plasma Chemistry Monte Carlo Simulate Module:</u>**
  - **Ion energy and angular distribution**

FULLY IMPLICIT ALGORITHM FOR ELECTRON TRANSPORT

- **The fundamental problem is to integrate electron continuity equation with Poisson's equation.**
- **Semi Implicit Solution:**

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

- **Fully Implicit Solution:**
  - **Poisson Equation (2D)**

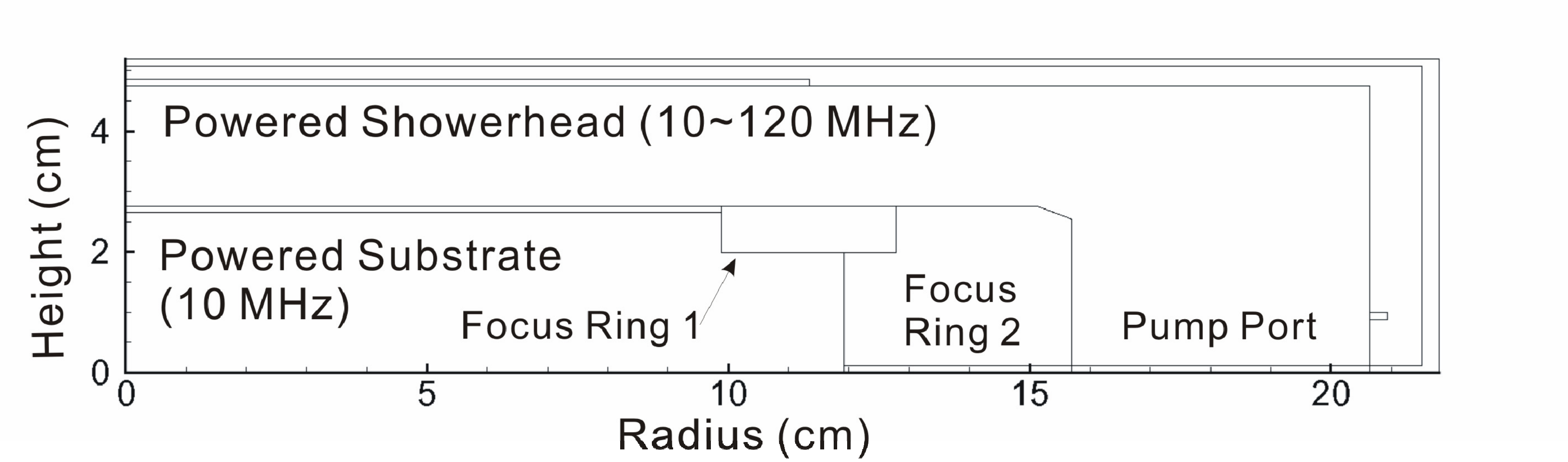
$$\nabla \cdot \varepsilon \nabla \Phi(t+\Delta t) = \rho(t) + \sum_{Ions} (-\nabla \cdot \phi_{Flux}(t) + S) \cdot \Delta t + n_e(t+\Delta t)$$

  - **Electron Continuity Equation (2D)**

$$n_e(t+\Delta t) = n_e(t) - \nabla \cdot \phi_{Flux}(t+\Delta t) \cdot \Delta t + S \cdot \Delta t$$

- **Most challenging computationally but provides closest coupling between Φ and n_e.**

2-FREQUENCY CCP REACTOR



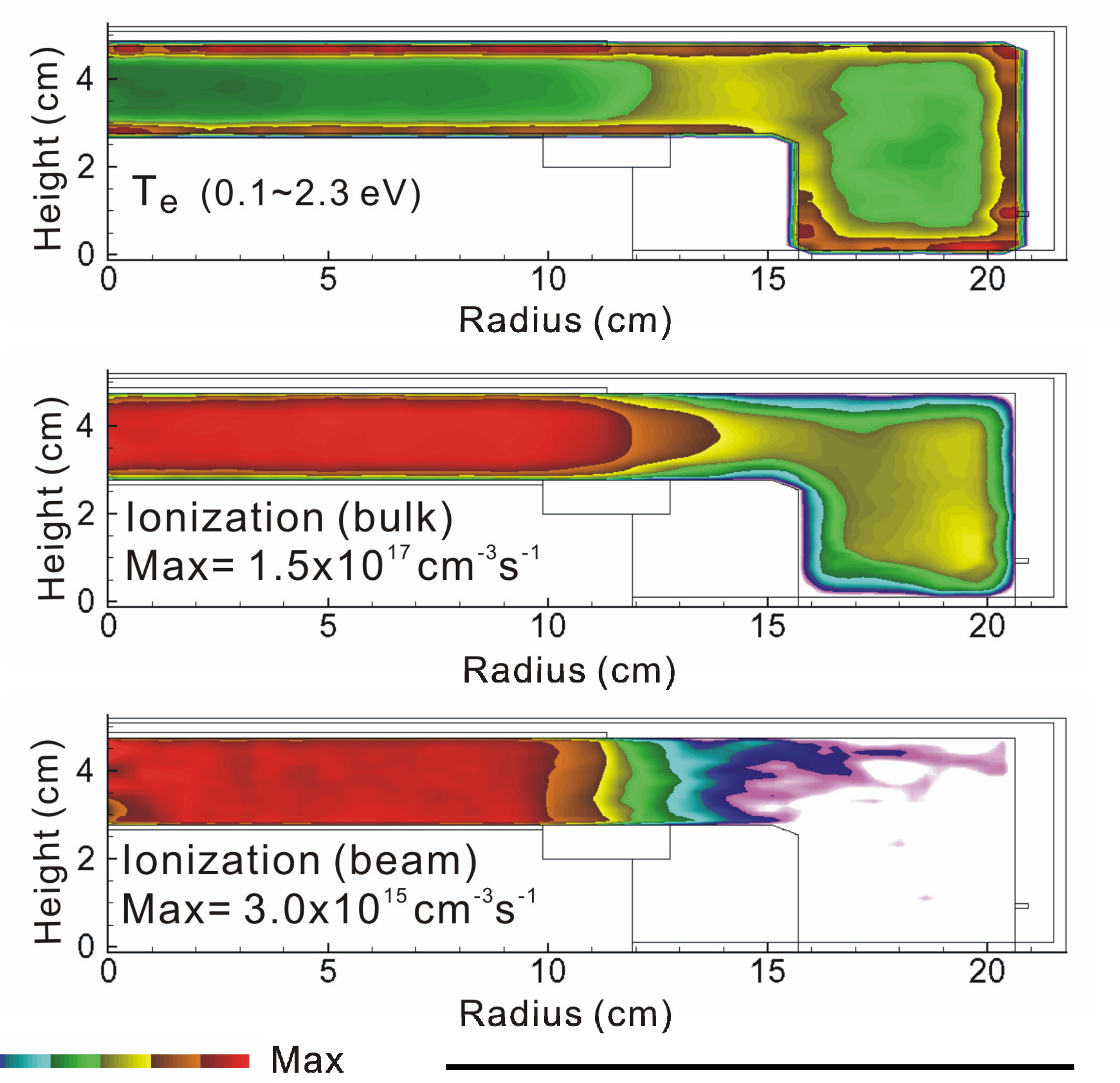
- 2D, cylindrically symmetric.
- Ar/Cl_2=80/20, 40 mTorr, 300 sccm
- Base case conditions:
  - Low Frequency: 10 MHz, 500 W
  - High Frequency: 100 MHz, 500 W
- Specify POWER; adjust voltage.

- Species for Ar/Cl_2 chemistry
  - Ar, Ar*, Ar^+
  - Cl_2, Cl, Cl*
  - Cl_2^+, Cl^+, Cl^-
  - e

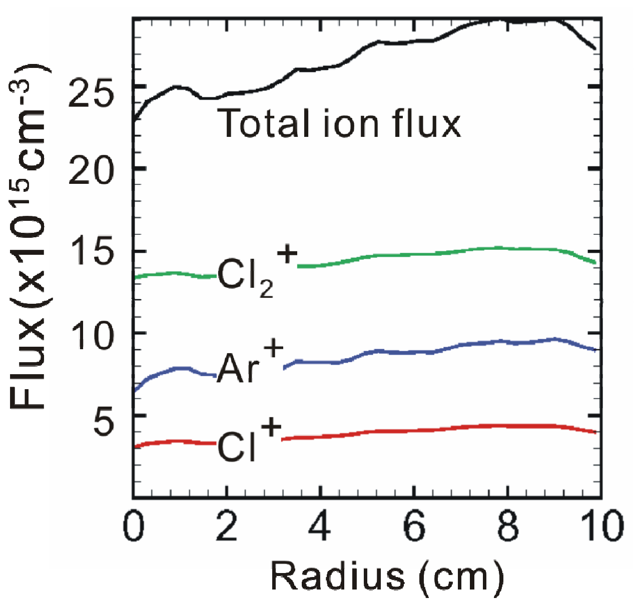
2-FREQUENCY CCP (10/100 MHz): ELECTRON SOURCES

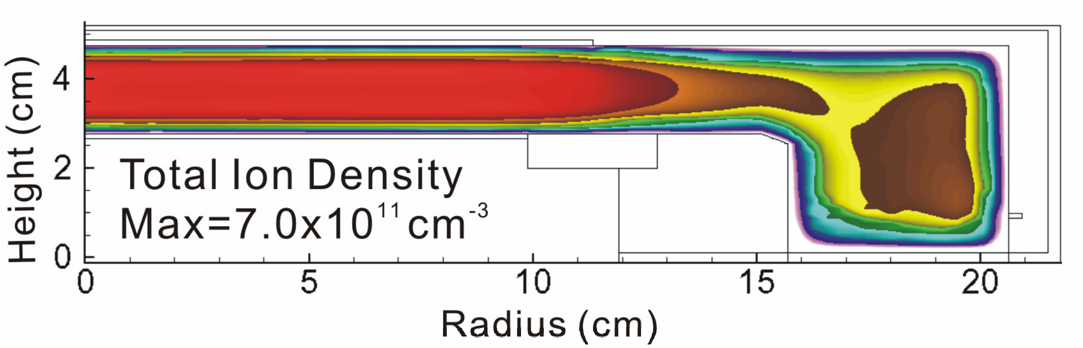
- T_e peaked near electrodes due to strong stochastic heating.
- Bulk ionization follows electron density.
- Secondary electrons penetrate through plasma; small contribution to ionization.

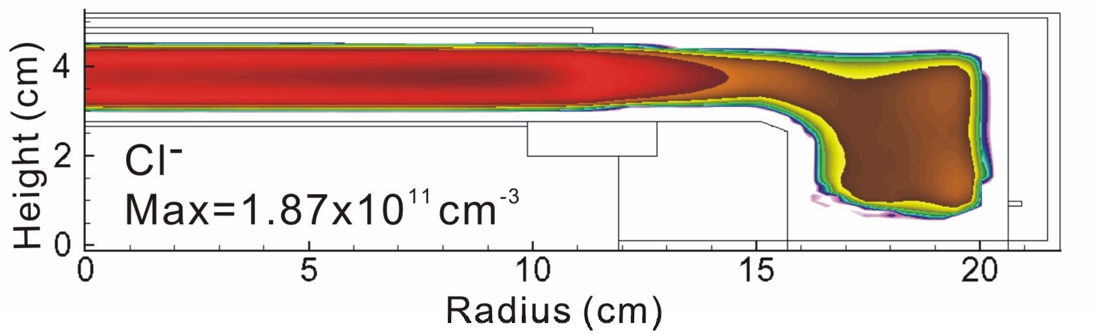
- Ar/Cl_2, 40 mTorr, 300 sccm
- LF: 10 MHz, 500 W, 185 V
- HF: 100 MHz, 500W, 101 V



ELECTRON AND ION DENSITIES





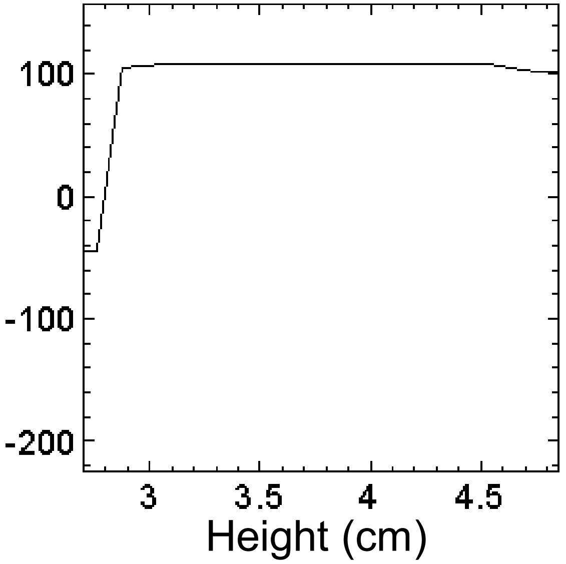


- **[e] peaked near electrode edge due to electric field enhancement. Large electronegativity enables more uniform ion fluxes.**
- **Cl_2^+ distributed uniformly between electrodes (low mobility, low ionization threshold energy).**

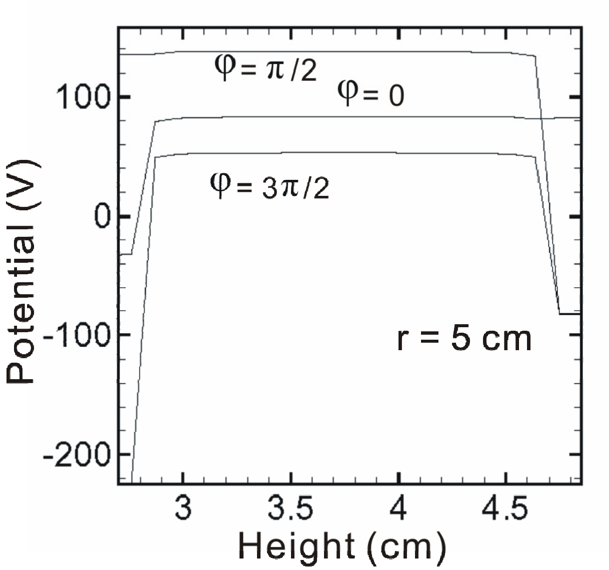
- **Ar/Cl_2, 40 mTorr, 300 sccm**
- **LF: 10 MHz, 500 W, 185 V**
- **HF: 100 MHz, 500W, 101 V**

Min ▬ Max

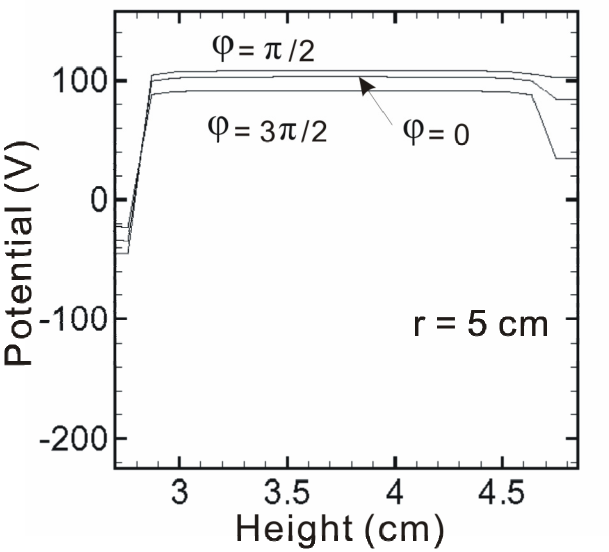
PLASMA POTENTIAL



- LF



- HF

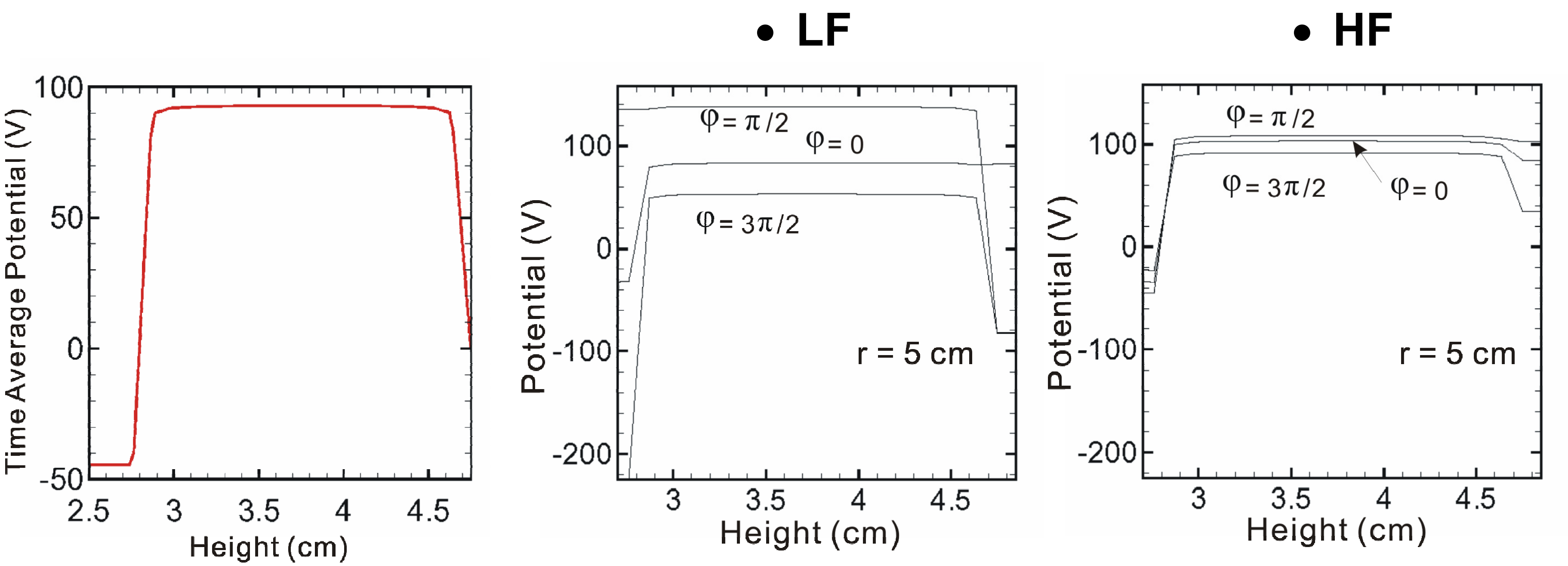


- **Sheaths maintain electropositive nature through LF and HF cycles.**
- **Bulk plasma potential is nearly flat and oscillates with both LF and HF components.**
- **The role of LF potential component is similar to a carrier wave, which is modulated by HF component.**

Animation Slide

- **Ar/Cl_2, 40 mTorr, 300 sccm**
- **LF, 10 MHz, 500 W, 185 V**
- **HF: 100 MHz, 500W, 101 V**

PLASMA POTENTIAL



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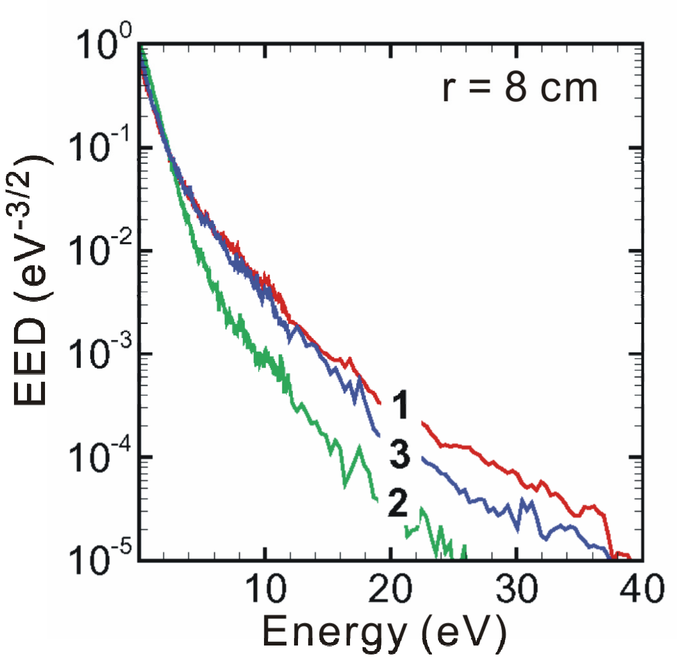
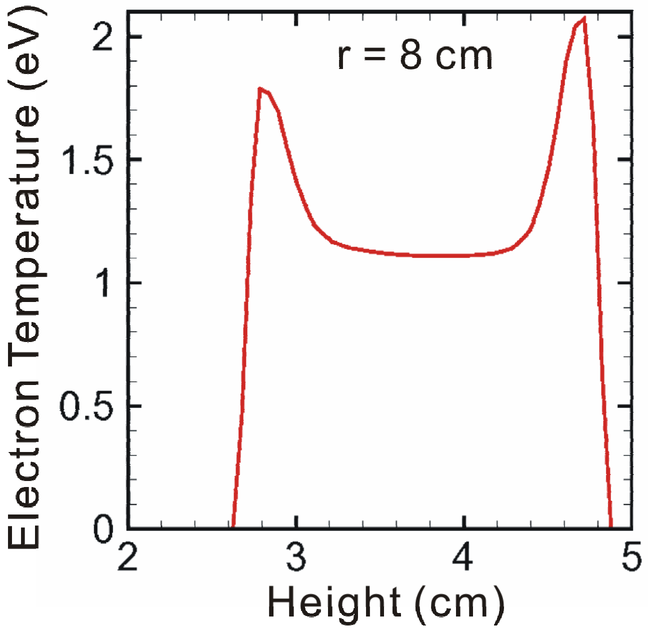
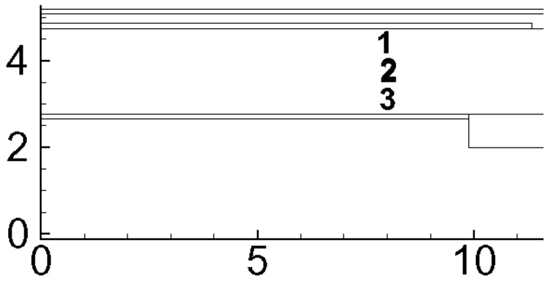
- **Ar/Cl_2, 40 mTorr, 300 sccm**
- **LF, 10 MHz, 500 W, 185 V**
- **HF: 100 MHz, 500W, 101 V**





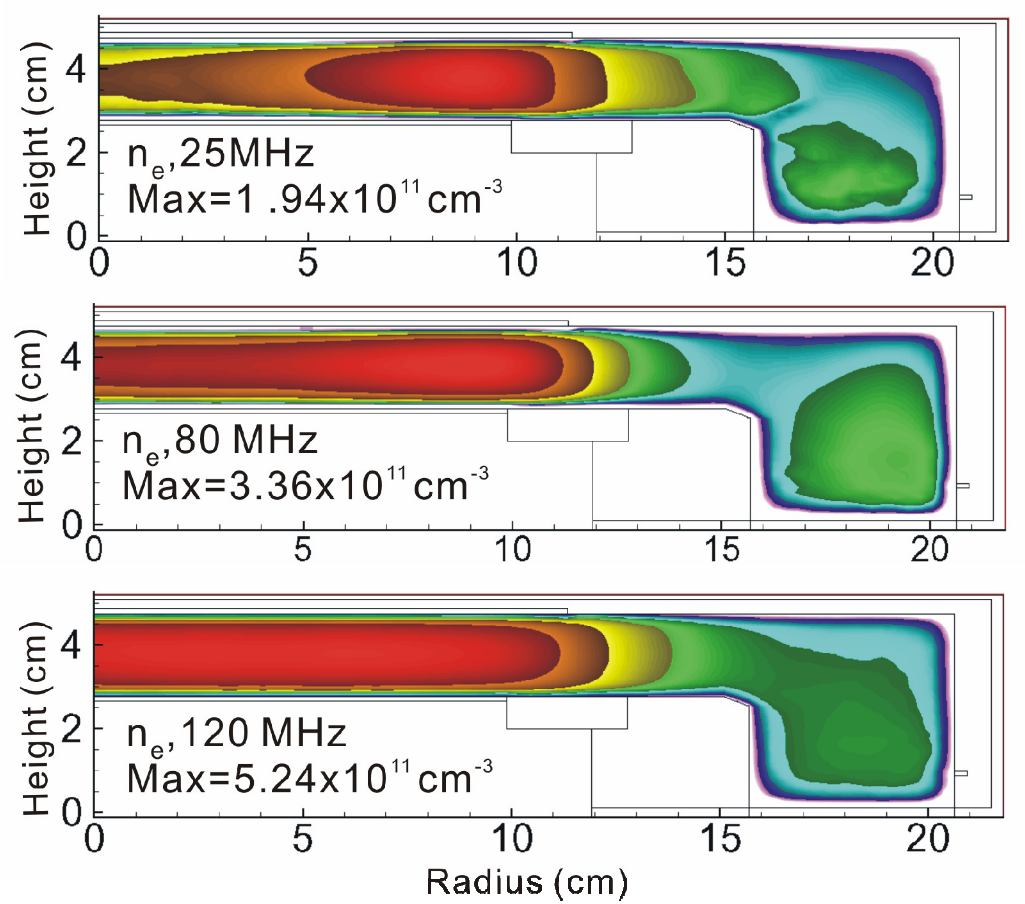
ELECTRON ENERGY DISTRIBUTION FUNCTIONS



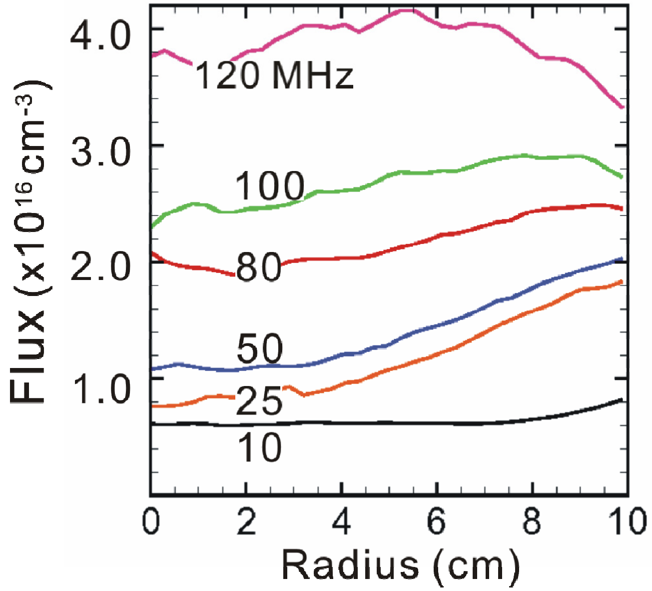
- **EED in mid-gap (2) where [e] is large is more Maxwellian due to e-e collisions.**
- **Tails of EEDs in sheath regions are lifted up by stochastic heating.**
- **For same power, tail of EED (ε > 15 eV) at HF sheath is more prominent due to more efficient heating at larger ω .**

  - **Ar/Cl_2, 40 mTorr, 300 sccm**
  - **LF, 10 MHz, 500 W, 185 V**
  - **HF: 100 MHz, 500W, 101 V**

HIGH FREQUENCY CONSTANT POWER

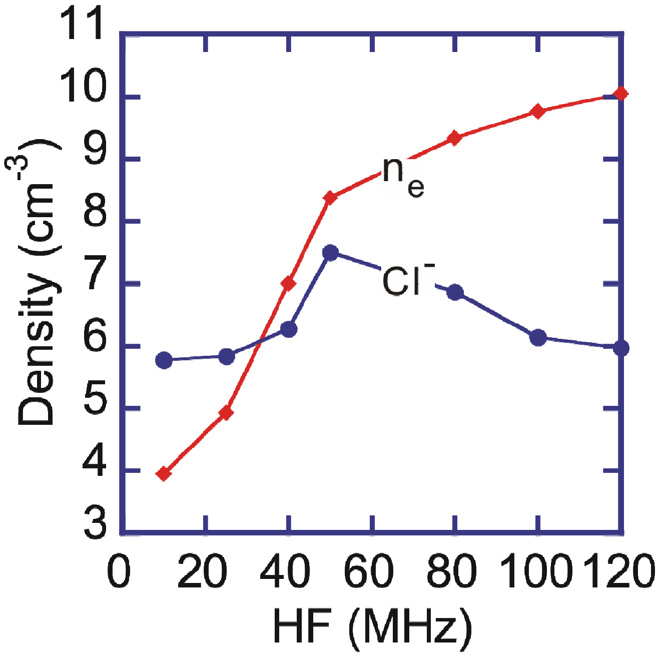


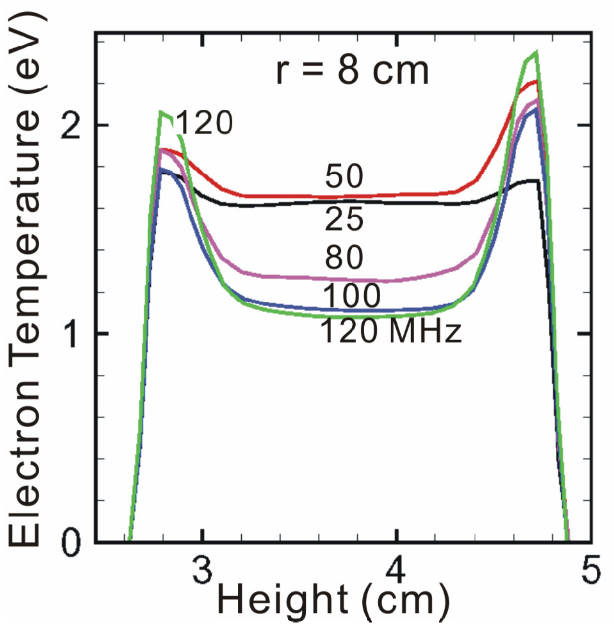
- **Total Ion Flux**



- **Plasma densities increase with increasing HF reflecting more efficient electron heating.**
- **Electric field enhancement is less prominent at higher frequencies resulting in more uniform fluxes.**
- **Ar/Cl_2=80/20, 40 mTorr, LF=10 MHz, 500 W, HF=500 W.**

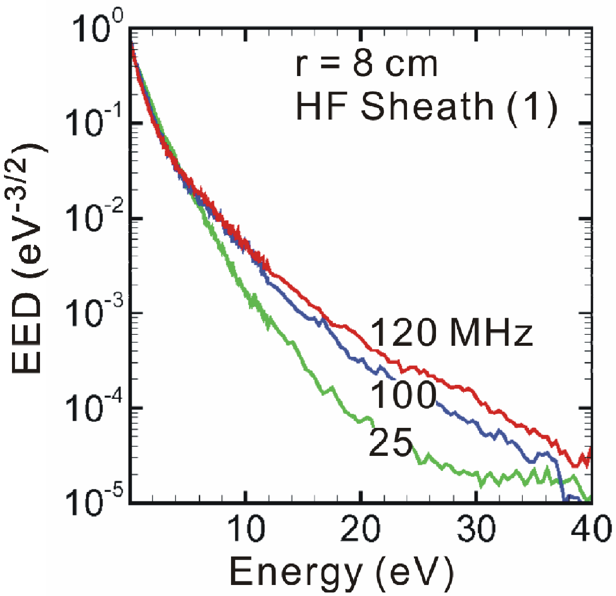
PLASMA PROPERTIES vs HF

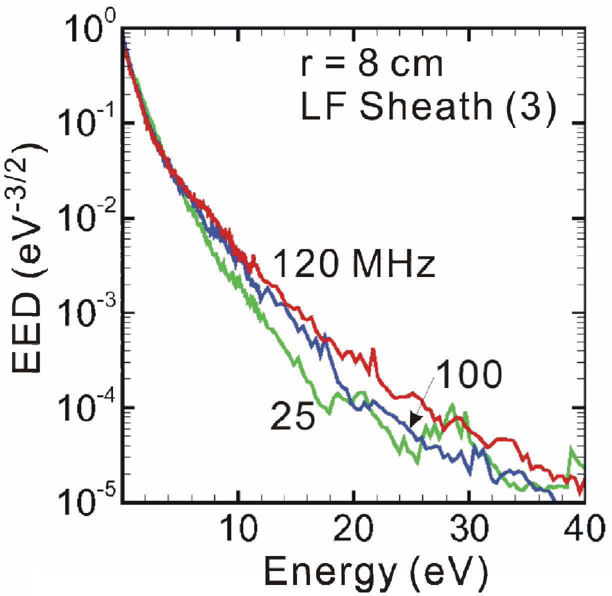


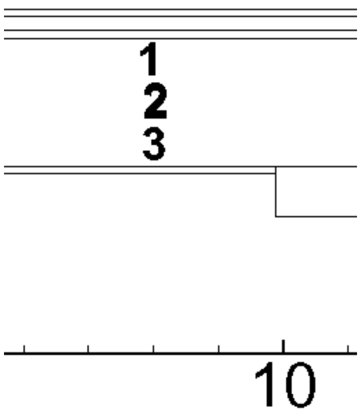


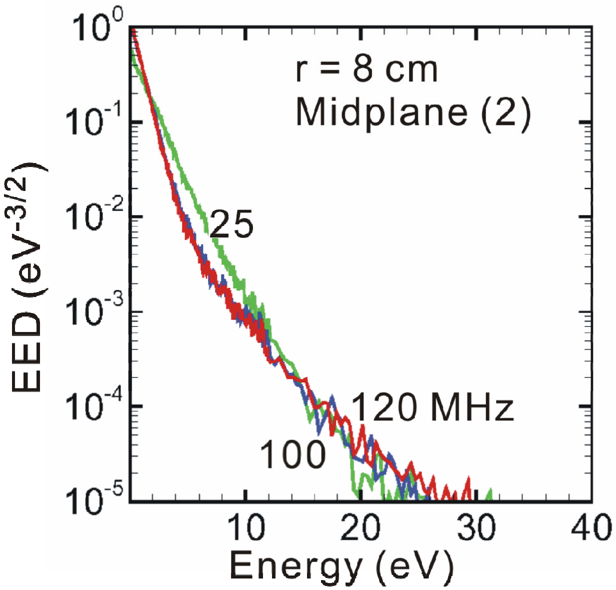
- As [e] increases with increasing HF, dissociation reduces [Cl_2] consequently eventually reducing [Cl^-].
- Higher conductivity of plasma at larger HF reduces bulk electron heating while sheath heating increases.
- Below 50 MHz, compromise between more sheath heating and less bulk heating.

EED vs HF





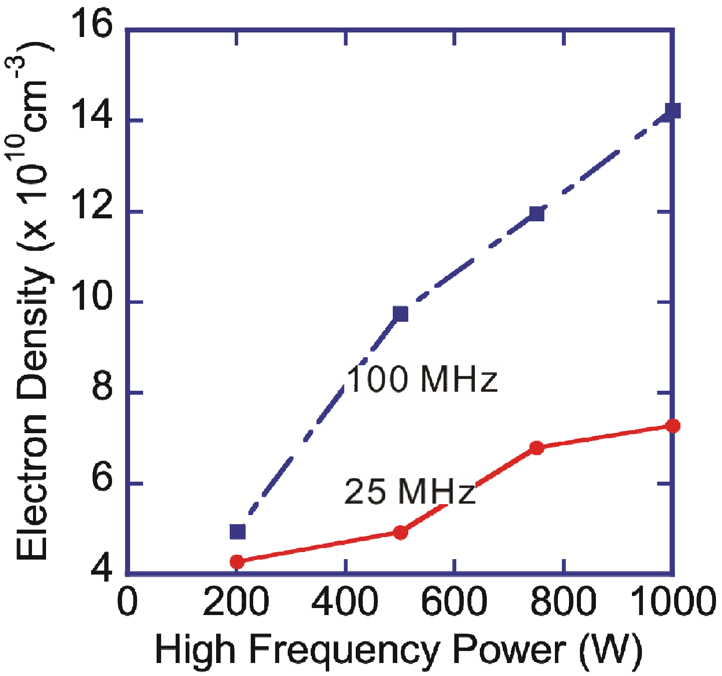


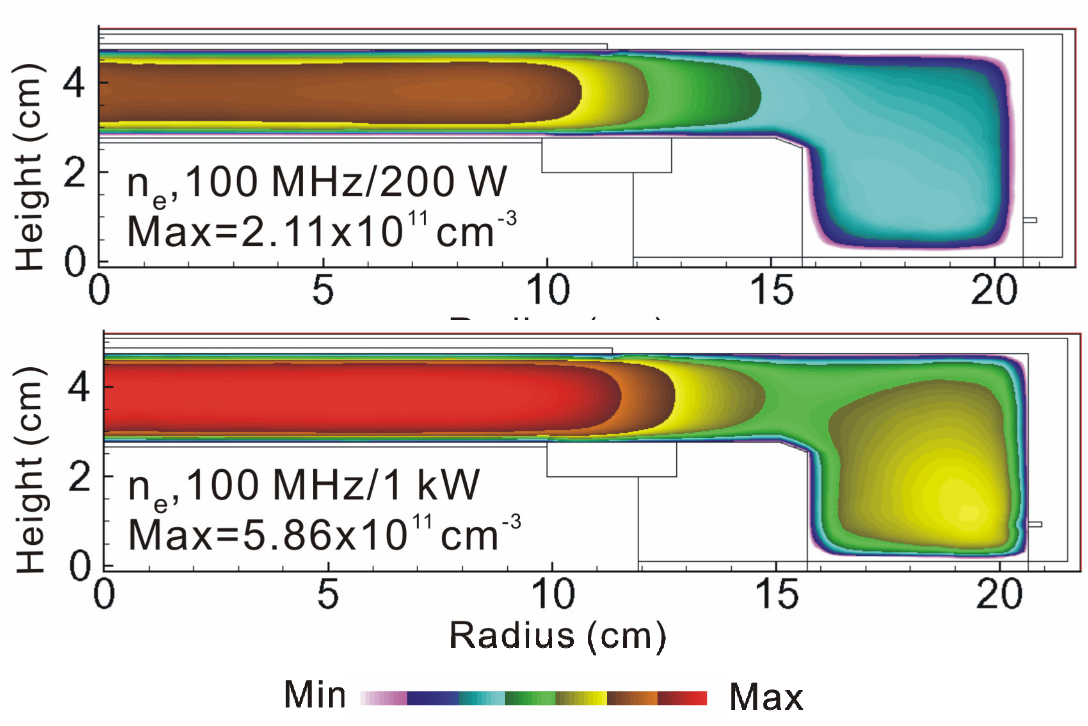


- **EEDs at high energies increase with increasing HF (stronger stochastic heating).**
- **Tail of EEDs in bulk plasma are little affected.**
- **Tail of EEDs near LF electrode are heated since bulk plasma potential oscillates at both HF and LF.**

- **Ar/Cl_2, 40 mTorr, 300 sccm**
- **10 MHz: 500 W; HF: 500 W**

ELECTRON DENSITY vs HF POWER

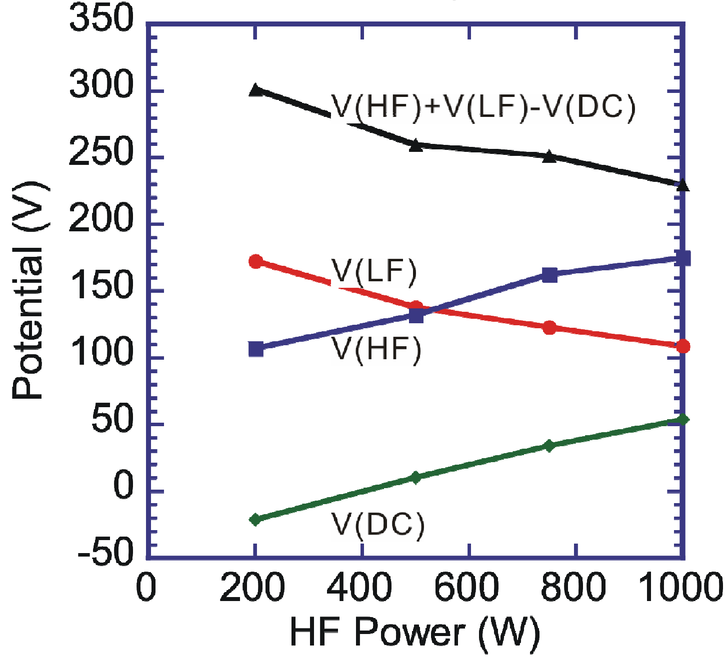




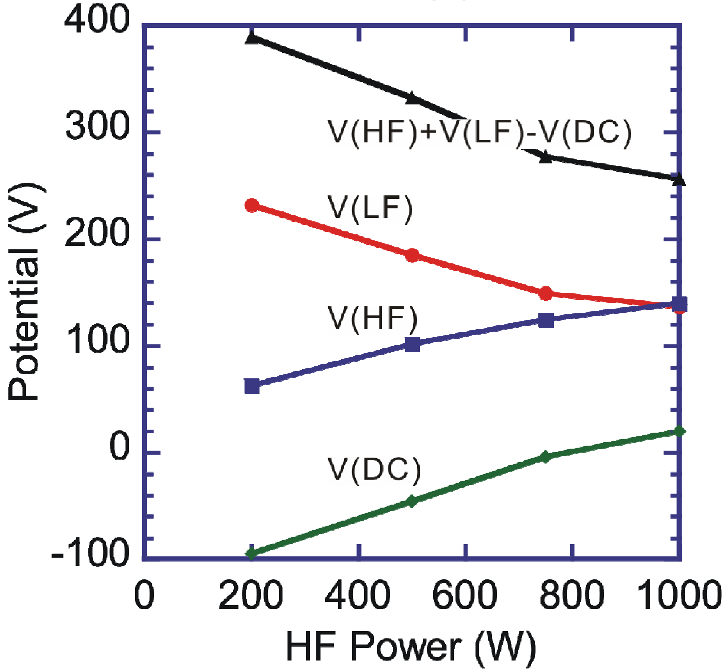
- **[e] increases nearly linearly with HF power (and becomes more uniform).**
- **Some evidence of nonlinear interactions between LF and HF when they are commensurate which affects scaling.**
  - **Ar/Cl_2, 40 mTorr, 300 sccm**
  - **LF= 10 MHz: 500 W**

VOLTAGES vs HF POWER

- **HF = 25 MHz**



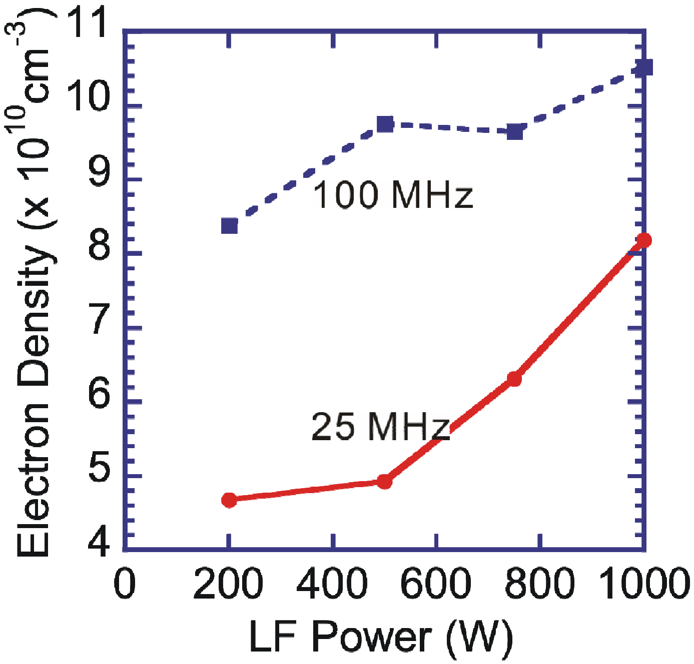
- **HF = 100 MHz**



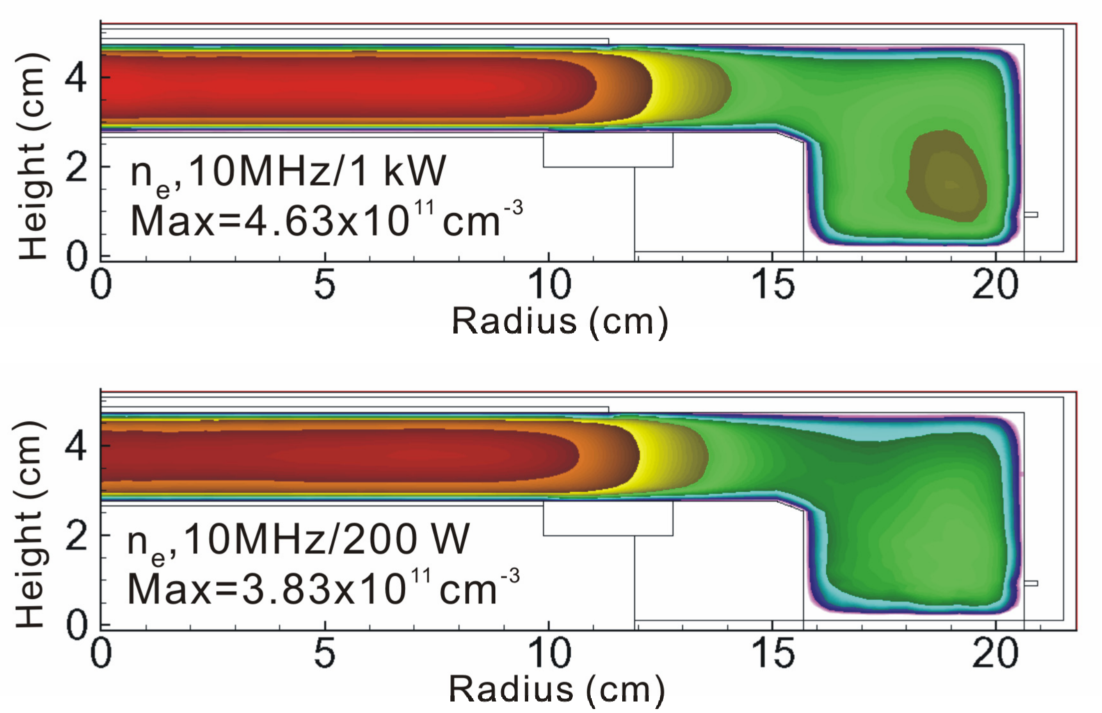
- **Increasing HF power increases V(HF) and ion current. For constant LF power, V(LF) decreases.**
- **DC bias becomes less negative as plasma is more confined and uniform.**
- **Maximum ion energy scales as V(HF)+V(LF)-V(dc).**

- **Ar/Cl$_2$, 40 mTorr, LF= 10 MHz: 500 W**

ELECTRON DENSITY vs LF POWER



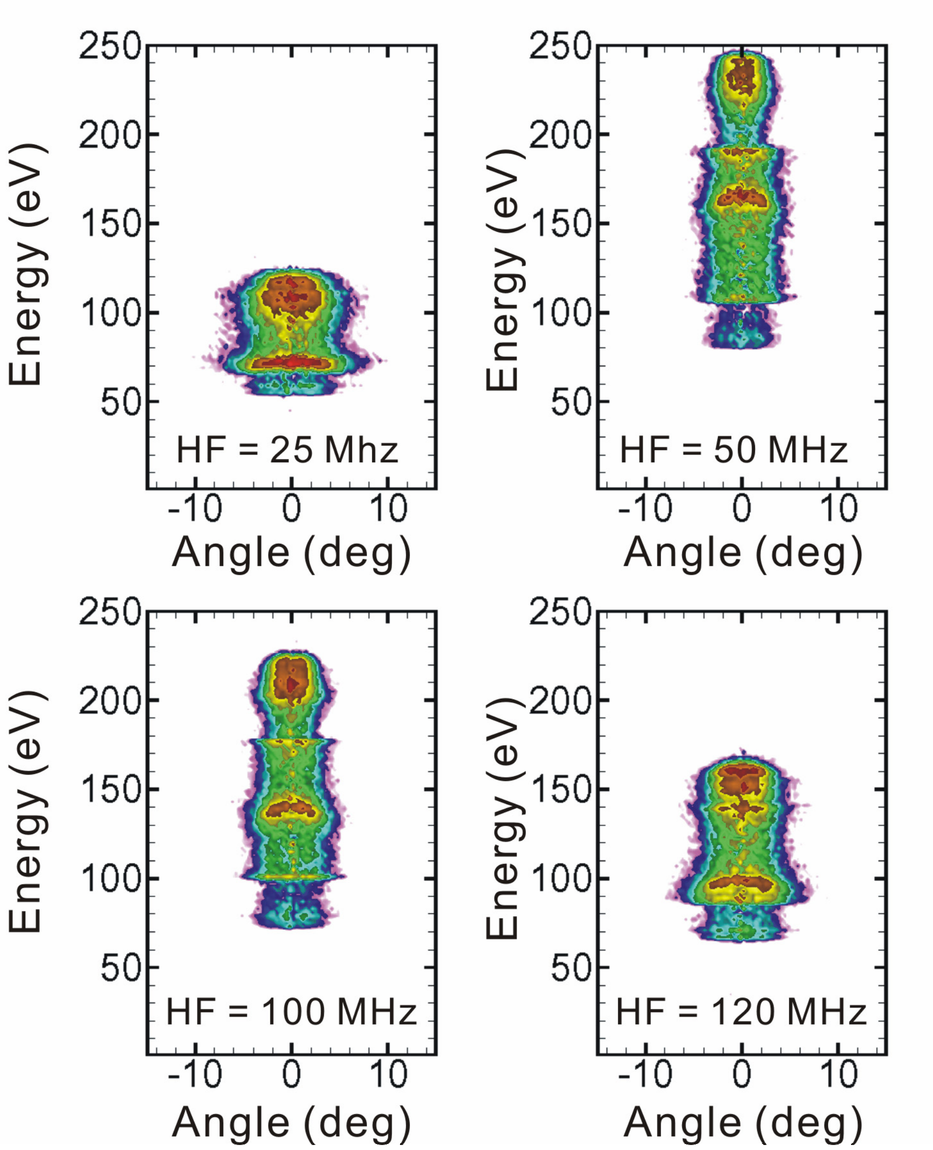
- **HF = 100 MHz**



- **The higher [e] and thinner sheaths with HF = 100 MHz reduces the electron heating at low frequency. Contribution of LF to ionization is smaller.**
- **Commensurate LF and HF increases contribution of LF to ionization.**
  - **Ar/Cl_2, 40 mTorr, LF =10MHz; HF=500 W**

IEDs vs ω(HF)

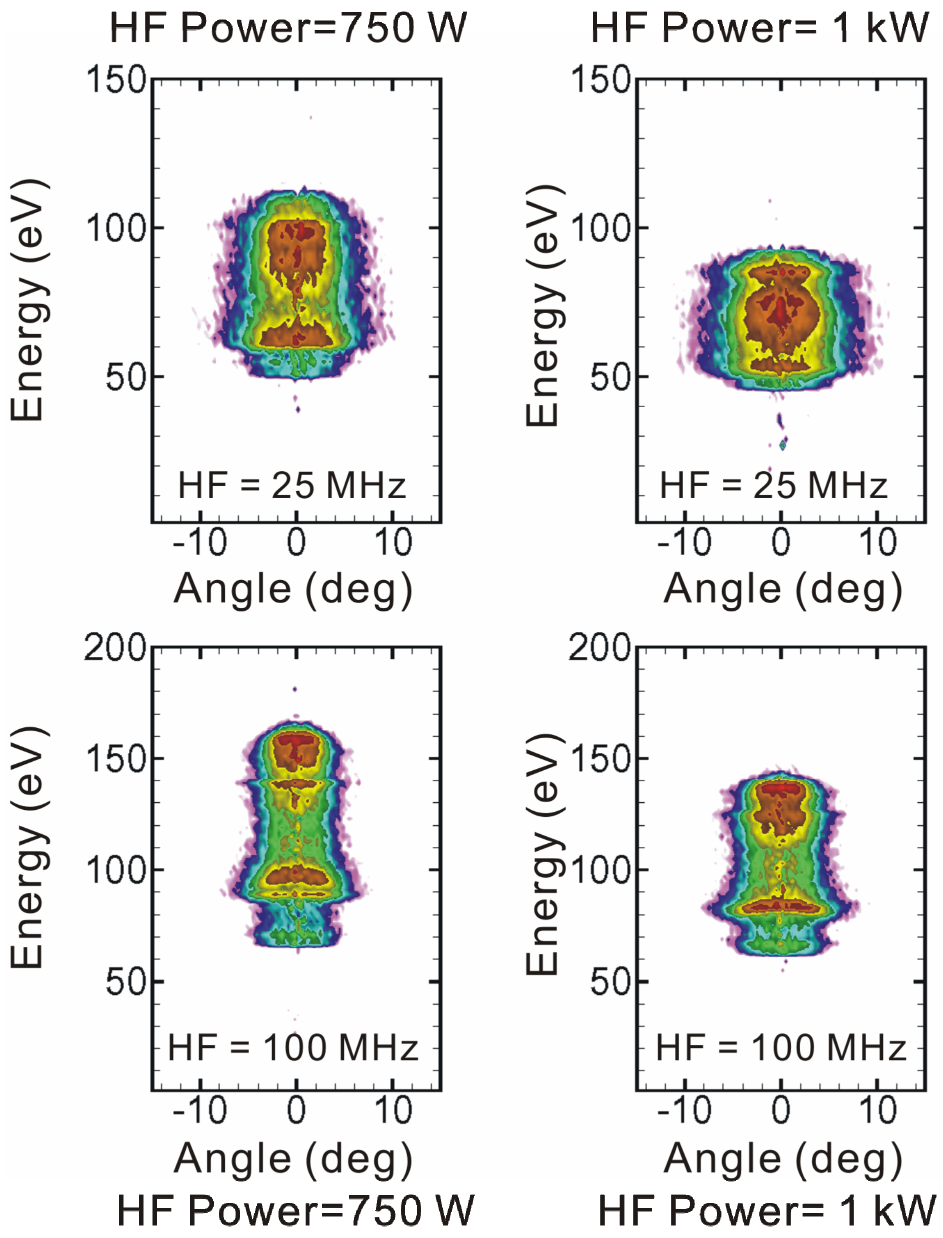
- **Total Ion Energy Distribution**



- **When keeping power constant, LF and HF voltages, and sheath thickness change with ω(HF).**
- **Average ion energy "stabilizes" only for HF > 50 MHz.**
- **Total IEDs have multiple peaks due to different mobility of Ar^+, Cl_2^+, Cl^+.**

- **Ar/Cl_2, 40 mTorr, 300 sccm**
- **10 MHz: 500 W; HF: 500 W**

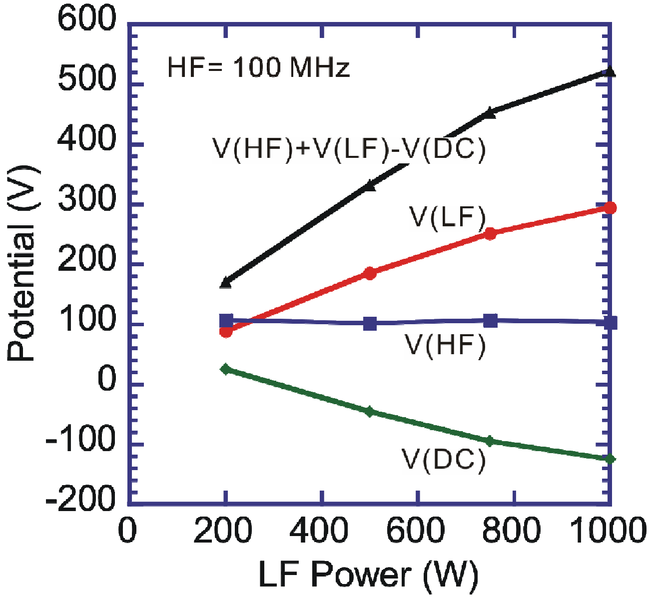
IEDs vs HF POWER



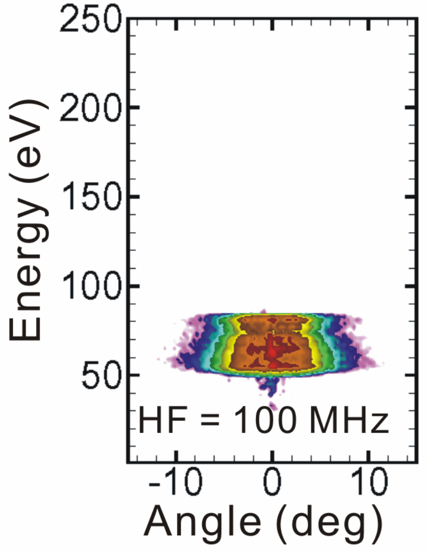
- **HF modulates IEDs at all frequencies.**
- **Increasing HF power moves IEDs to lower energy as V(HF)+V(LF)-V(DC) decreases.**
- **Stronger interactions between 2 sources when frequencies are commensurate..**

- **Ar/Cl_2, 40 mTorr, 300 sccm**
- **LF=10 MHz, 500 W**

IEDS vs LF POWER

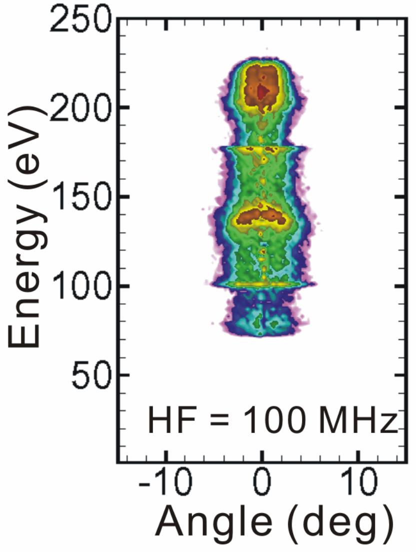


LF Power=200 W



HF Power=500 W

LF Power= 500 W



HF Power=500 W

- **V(LF) increases nearly linearly with LF power.**
- **With large separation of frequencies, increasing LF power level broadens IEDs.**
- **Significant changes in the structure of IEDs with LF power.**
- **…Differences in mobility of Ar^+, Cl_2^+, Cl^+ with changes in sheath voltage and thickness.**
  - **Ar/Cl_2, 40 mTorr, 300 sccm**
  - **LF=10 MHz,**
  - **HF=100 MHz, 500 W**

CONCLUDING REMARKS

- Scaling laws for a dual frequency CCP reactor were computationally investigated.
- With increasing high frequency:
  - Electron density increases linearly above 80MHz.
  - Nonlinear behavior for bulk T_e due to tradeoff between less bulk heating and increasing stochastic heating.
  - Tails of EEDs increase (at both electrodes).
- With increasing HF power, IEDs shift to lower energies as V(LF) decreases to keep LF power constant.
- With increasing LF power
  - Electron density increases but less so at higher HF.
  - IEDs shift to higher energies.