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CONSEQUENCES OF MODE STRUCTURE ON ION FLUXES IN ECR SOURCES FOR MATERIALS PROCESSING*

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AGENDA

- Electron Cyclotron Resonance (ECR) Modeling
- Hybrid Plasma Equipment Model (HPEM)
- Finite Difference Time Domain Module (FDTD)
- Device Geometry and Operating Conditions
- Parametric Studies
    - Plasma Parameters
    - Ion Flux To The Substrate
    - Effects of Higher Order Transverse Electric Field Modes
- Conclusions and Future Work

INTRODUCTION TO ECR PROCESSING

- Due to their ability to produce high degrees of ionization at low gas pressures, electron cyclotron resonance (ECR) sources are being developed for downstream etching and deposition, and the production of radicals for surface treatment.

- The spatial coupling of microwave radiation to the plasma is a concern due to issues related to process uniformity. Studies suggest that certain waveguide electromagnetic mode fields tend to provide better uniformity over larger areas.

- To investigate these issues, we have developed a finite difference time domain (FDTD) simulation for microwave injection and propagation. The FDTD simulation has been incorporated as a module in the two dimensional Hybrid Plasma Equipment Model (HPEM).

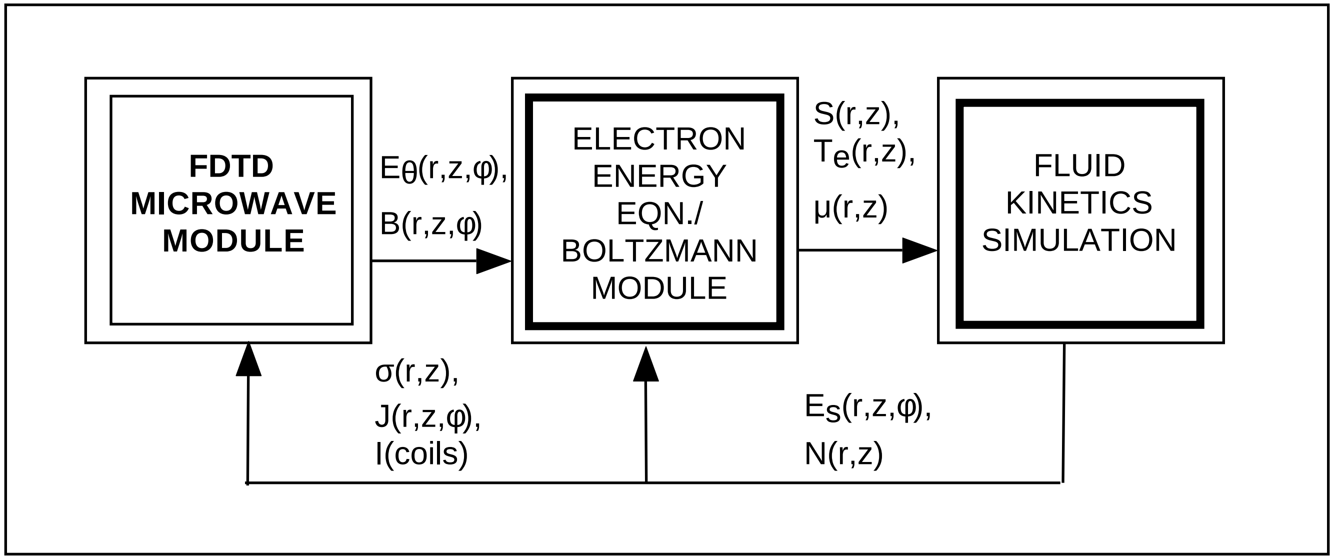
- Parametric studies have been performed to determine dependence of ion flux uniformity with varying reactor parameters such as mode of excitation, pressure, and power.

HYBRID PLASMA EQUIPMENT MODEL

- The base two-dimensional HPEM consists of an electromagnetics module (EMM), an electron energy transport module (EETM), and a fluid kinetics simulation (FKS).

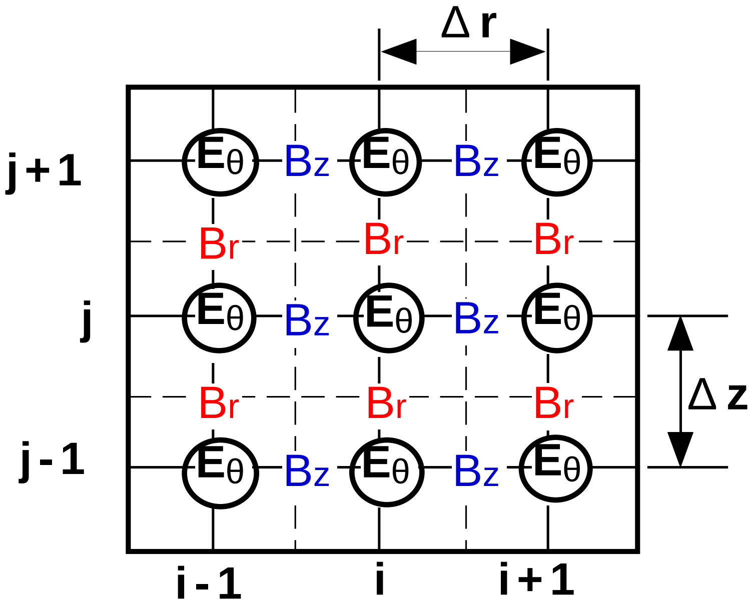
- In these simulations, ion transport was calculated by time integrating the continuity and momentum equations, while electron energy transport was determined by time integrating the electron energy conservation equation.

- An ambipolar approximation was used to solve a Poisson-like equation for the electric potential during early iterations, followed by direct solution of Poisson's equation.



FINITE DIFFERENCE TIME DOMAIN (FDTD) MODEL

- The FDTD simulation uses an alternating direction implicit (ADI) scheme. Electromagnetic (EM) fields are calculated using a leap-frog scheme for time integration of Maxwell's equations.



- Plasma dynamics are coupled to the EM fields through a tensor form of Ohm's law.

$$\mathbf{x}\,\frac{\mathbf{B}}{\mu} = \bar{\bar{\sigma}} \cdot \mathbf{E} + \varepsilon \frac{\partial \mathbf{E}}{\partial \mathbf{t}}$$

$$\text{where, } \bar{\bar{\sigma}} = q\, n_e\, \bar{\bar{M}}^{-1},\quad \bar{\bar{M}} = \begin{pmatrix} \alpha & -B_z & B_\theta \\ B_z & \alpha & -B_r \\ -B_\theta & B_r & \alpha \end{pmatrix},$$

$$\alpha = \frac{m_e}{q}\left(i\omega + \nu_m\right)$$

- Maxwell's equations represent real, instantaneous fields, therefore only the real part of the complex azimuthal conduction current density is considered.

$$J_\theta = \mathrm{Re}\left[\tilde{J}_\theta\right] = \left[\frac{n_e\, q^2\, \nu_m}{2 m_e}\left(\frac{1}{\nu_m^2 + (\omega - \omega_c)^2} + \frac{1}{\nu_m^2 + (\omega + \omega_c)^2}\right)\right] E_\theta = \sigma\, E_\theta$$

DOPPLER SHIFTING OF ELECTRONS

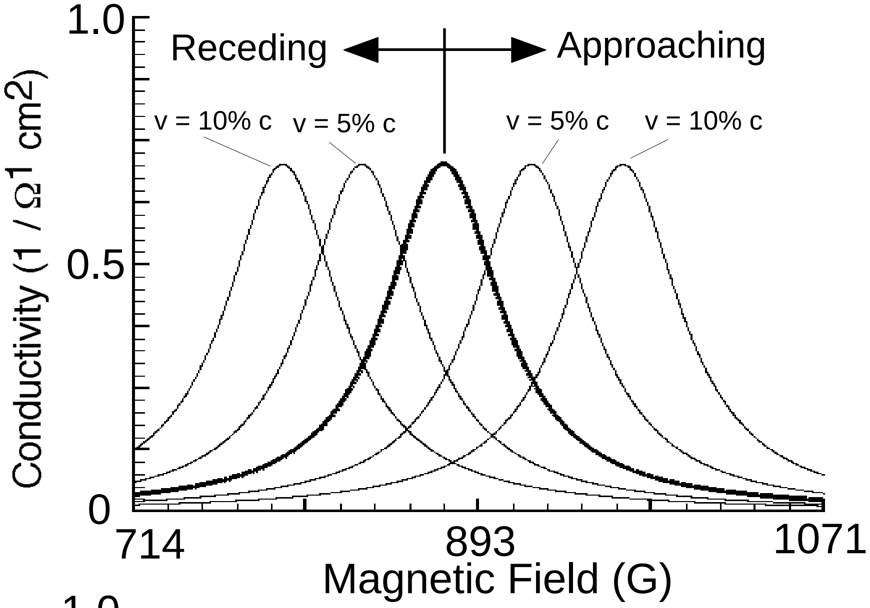
- Doppler shifting of electrons into resonance can shift the location of conductivity peak. (2.45 GHZ = 875 G)

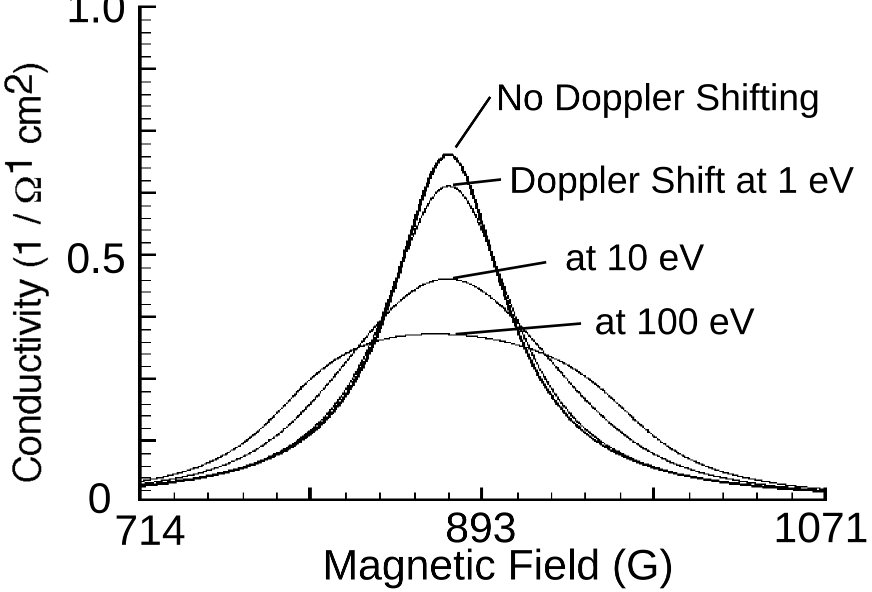
- The effects of Doppler shifting have been incorporated by using a modified velocity-space averaged conductivity.

$$\bar{\sigma} \quad = \iiint \frac{\sigma \quad f(\bar{v})}{f(\bar{v})} \, d\bar{v}$$

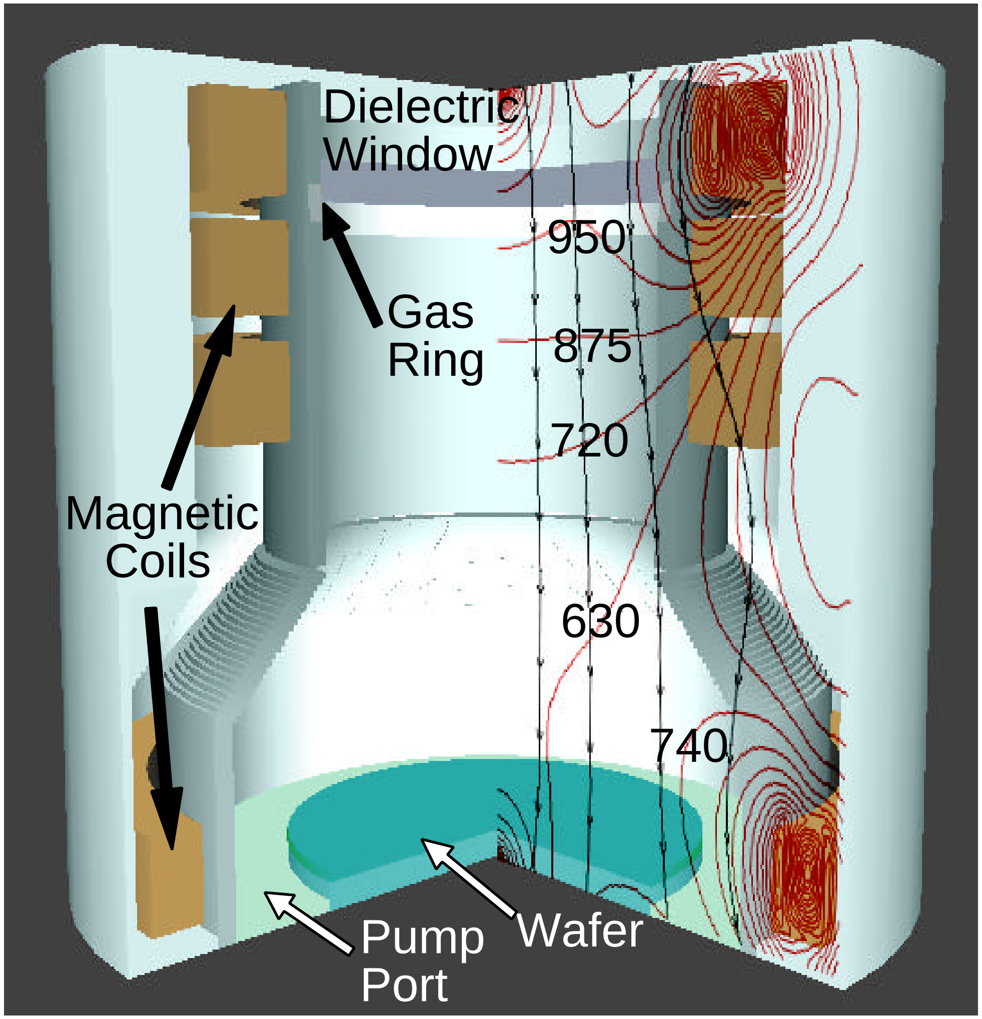
- Numerical integration over velocity space is done by assuming a Boltzmann distribution.

$$f(\bar{v}) \; = \; \exp\left(- \frac{1}{2} \frac{m_e \bar{v}}{kT_e} \right)$$





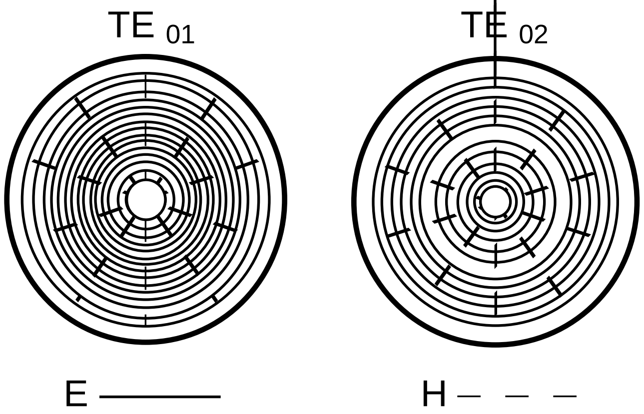
REACTOR GEOMETRY AND OPERATING CONDITIONS



- Schematic of ECR tool with magnetic flux and field intensity (Gauss) inside processing chamber.

- Range of Operating Conditions:
  - Gas Pressure : 0.5 - 50.0 mTorr
  - Microwave Power : 500 - 1500 Watts
  - Flow Rates : 5 - 10 sccm
  - Microwave Field : Circular TE(0,n) modes (2.45 GHz)

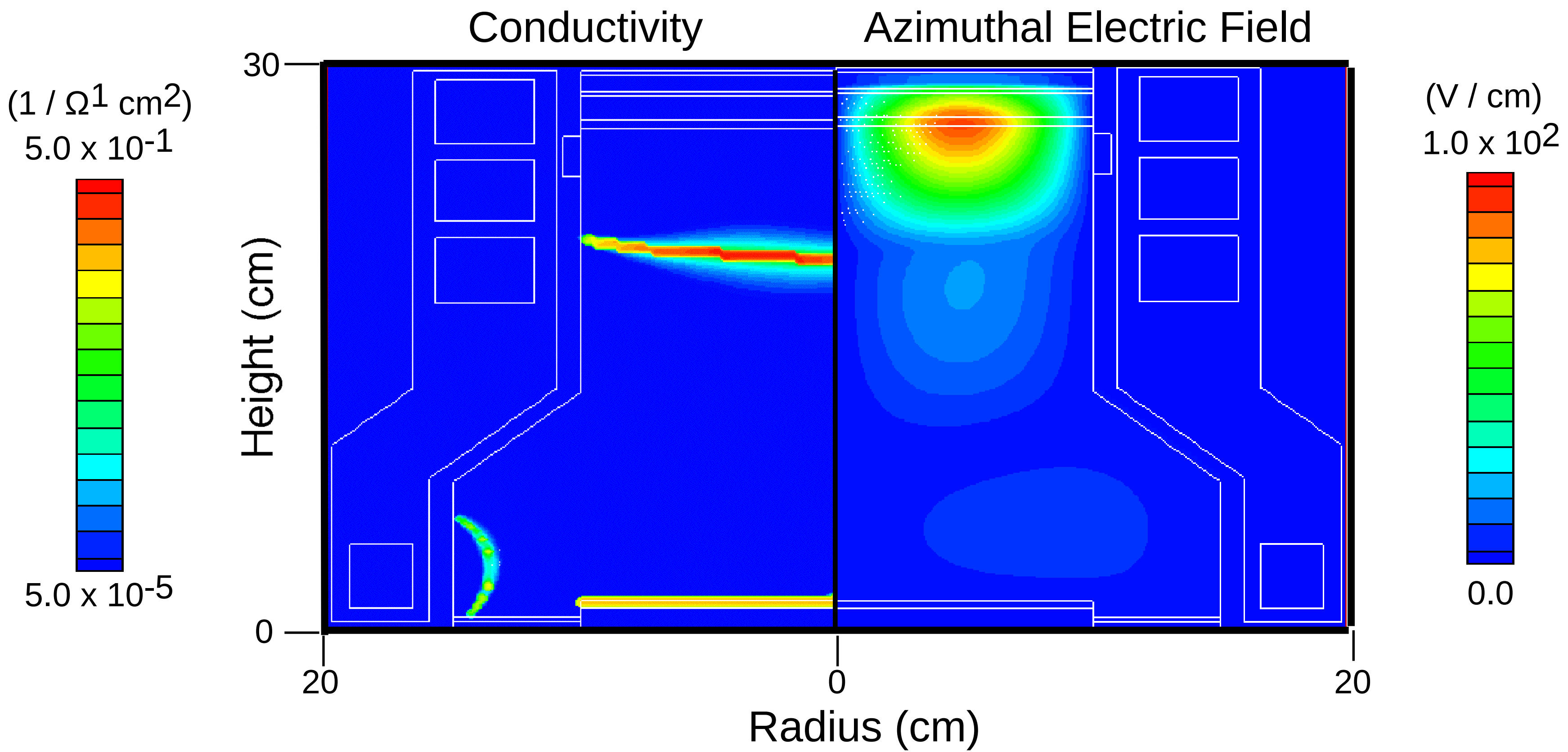
- Microwave Field Modes:



CONDUCTIVITY AND ELECTRIC FIELD

- In the resonance zone, the conductivity has a Lorentzian line shape with a full width at half maximum in the magnetic field equal to twice the electron collision frequency.

- As the electromagnetic field approaches the resonance zone most of the wave energy (>90%) is absorbed through cyclotron heating of the electrons.

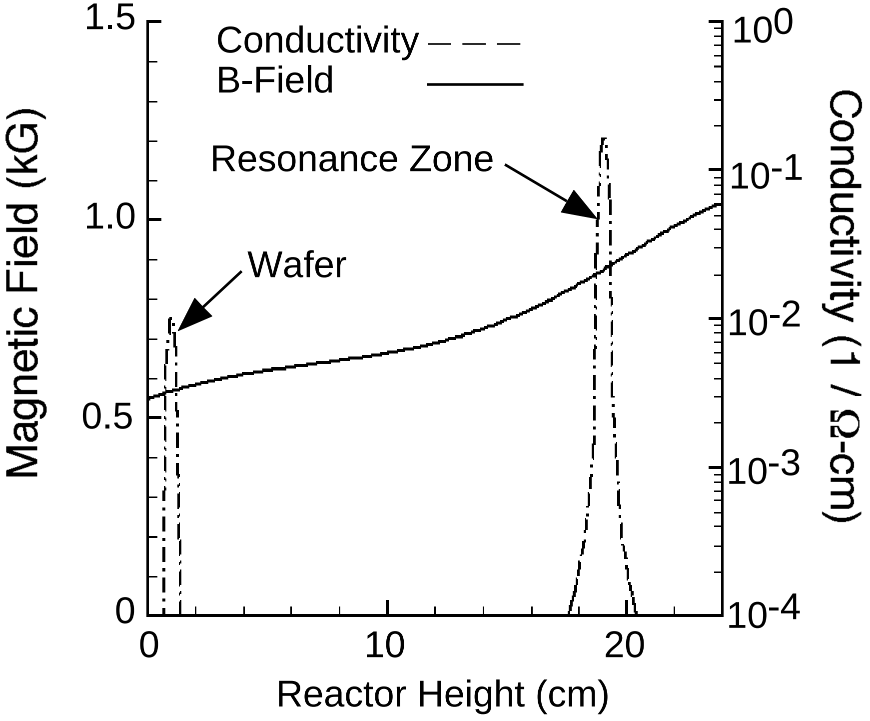


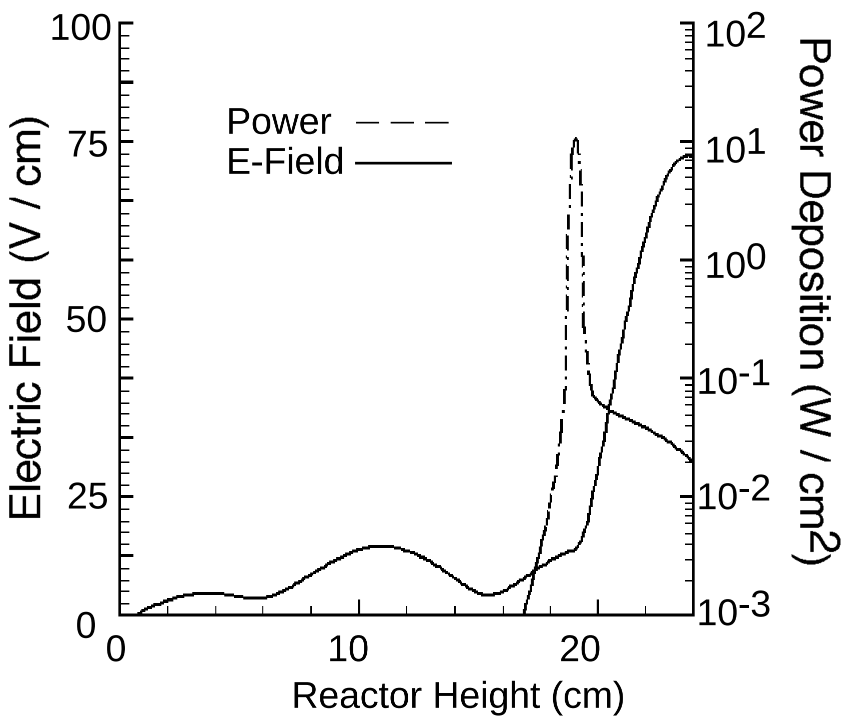
•N_2, 750 Watts, 1 mTorr, 10 sccm

AXIAL PROFILES OF PLASMA PARAMETERS

- Power deposition peaks near the location of resonance. However, the continual absorption of the incident electromagnetic wave in the upstream region produces power deposition that constitutes 20% of the total.

- Transmission of the electromagnetic wave is a sensitive function of the chamber pressure. At these operating conditions a small amount of the incident wave is transmitted into the downstream region.



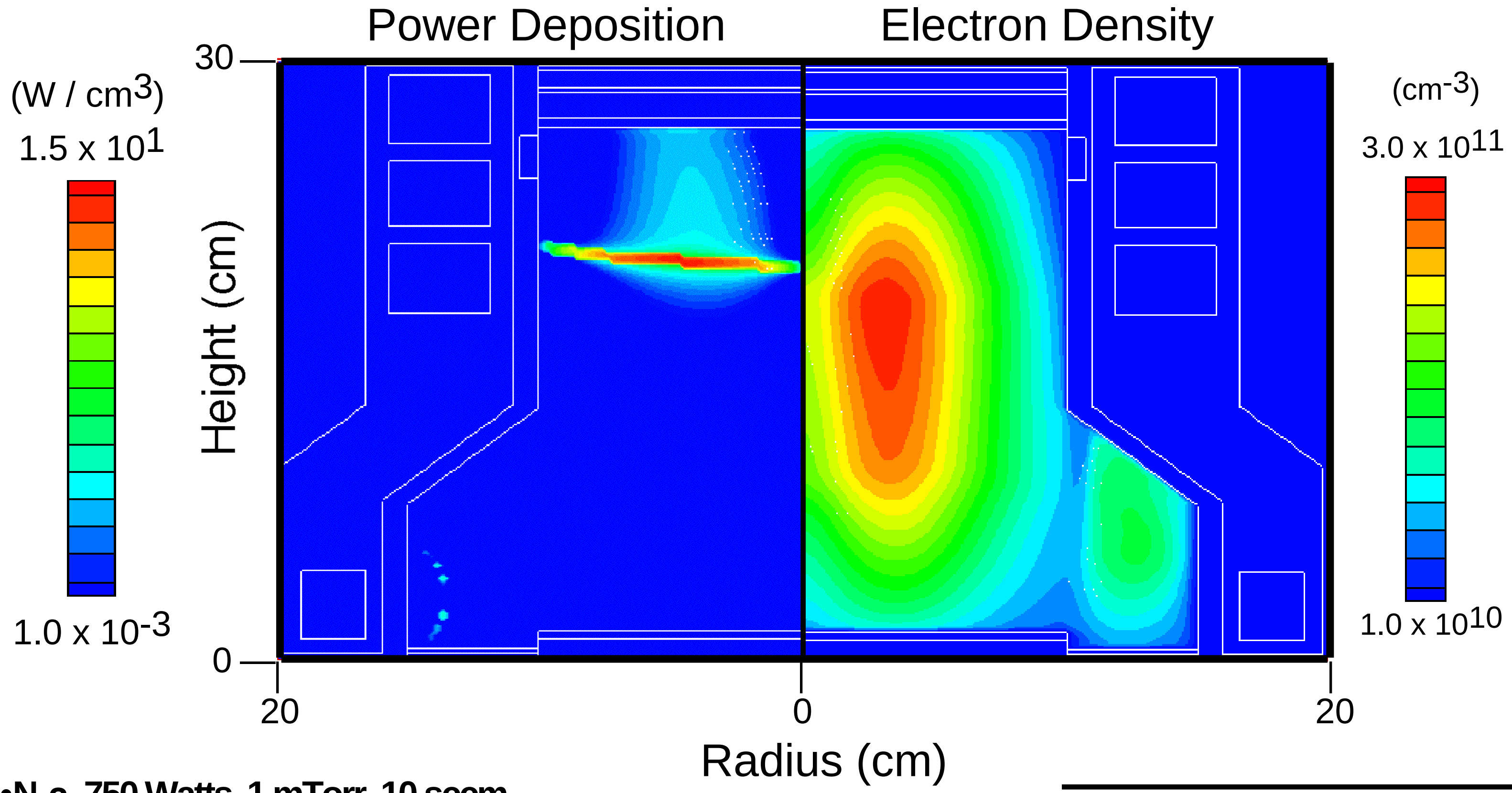


- **N_2, 750 Watts, 1 mTorr, 10 sccm**

POWER DEPOSITION AND ELECTRON DENSITY

- The power deposition profile in the radial direction reflects the incident electric field profile, producing an off axis peak.

- At these operating conditions, the radial electron density reflects the off axis peak in the power deposition. Due to enhanced mobility along the magnetic field lines the off axis distribution is maintained in the downstream region.

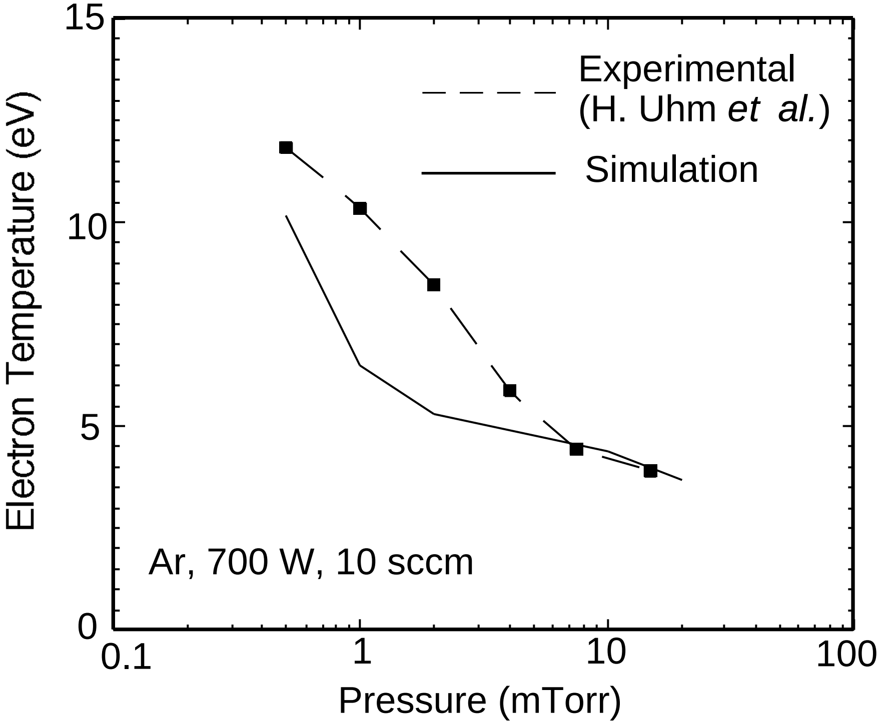


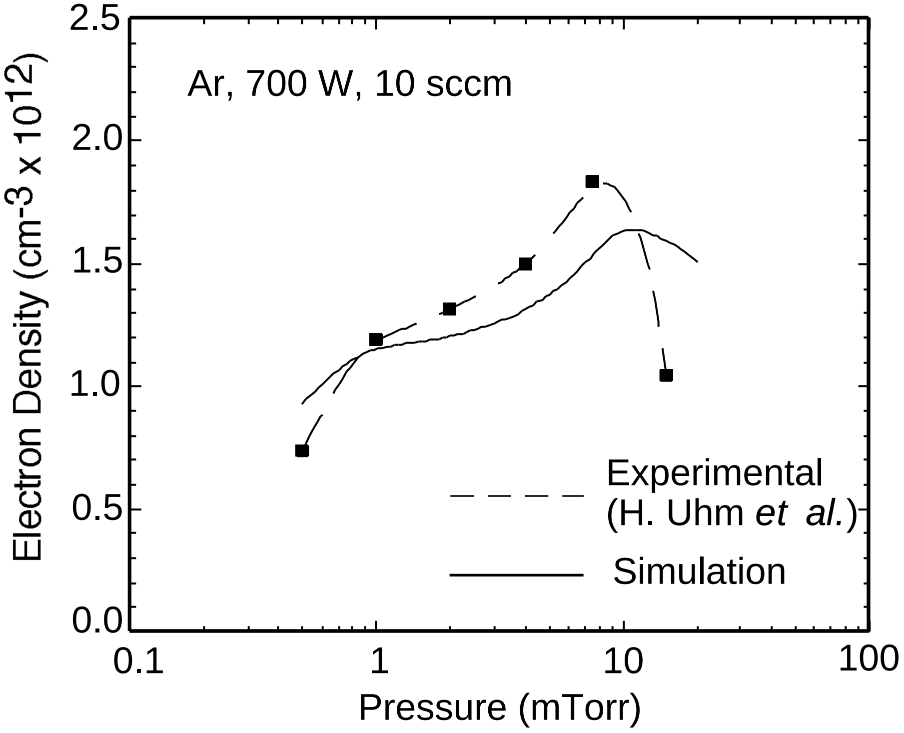
•N_2, 750 Watts, 1 mTorr, 10 sccm

ELECTRON TEMPERATURE AND DENSITY : PRESSURE

- The increase in electron temperature in the low pressure regime is due to an increased efficiency for absorbing microwave energy and a decrease in collisional cooling.

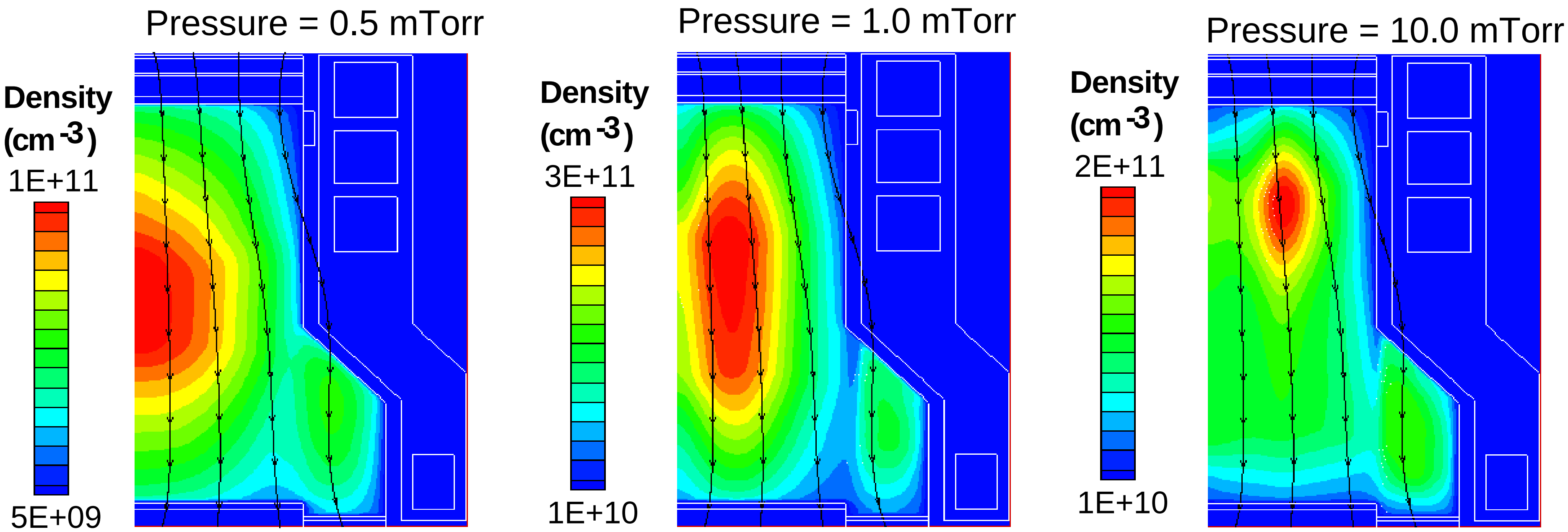
- In the low pressure regime, ion diffusion along the axial magnetic field lines dominates. As the pressure is increase radial losses become increasingly significant, thereby producing an optimal pressure for maximum plasma density.





(H. Uhm *et al.*, IEEE Trans. Plasma Sci., Vol. 23, No. 4, Aug. 1995, pp.628)

ELECTRON DENSITY DISTRIBUTION : PRESSURE



- **N_2, 750 Watts, 10 sccm, TE(0,1) mode**

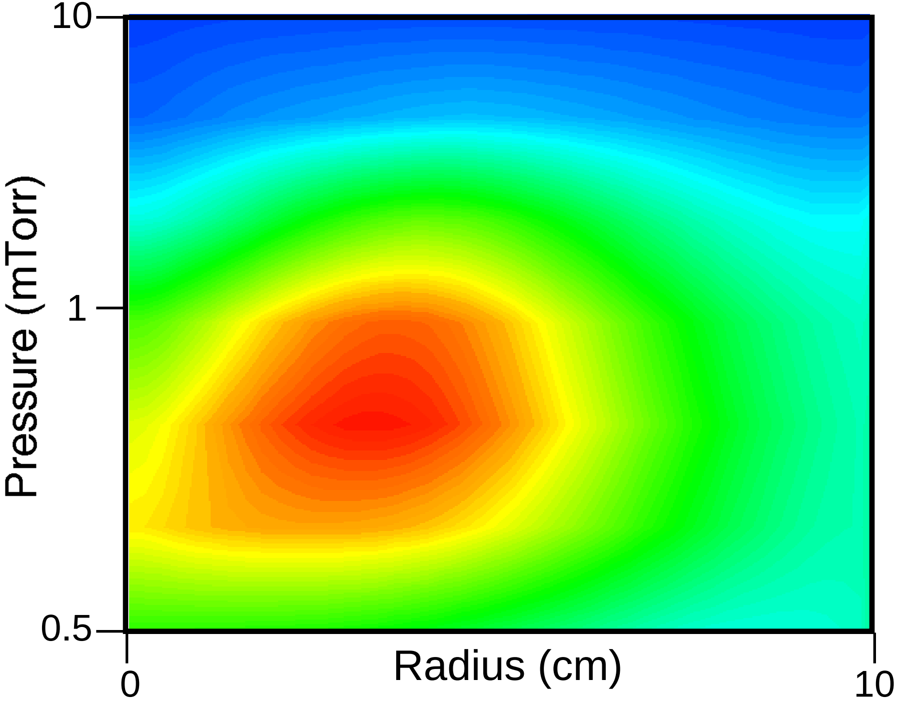
- As pressure is decreased below 2 mTorr, there is shift in the peak density towards the center of the reactor. Such a result implies that the perpendicular diffusion is enhanced at lower pressures.
- For the pressures examined the collision frequency was much smaller than the cyclotron frequency. In this regime, the perpendicular diffusion coefficient goes as the collision frequency; $D_{perp.,} \sim \nu_m$.
- The parallel diffusion coefficient goes as the inverse of the collision frequency; $D_{para.,} \sim 1 / \nu_m$.

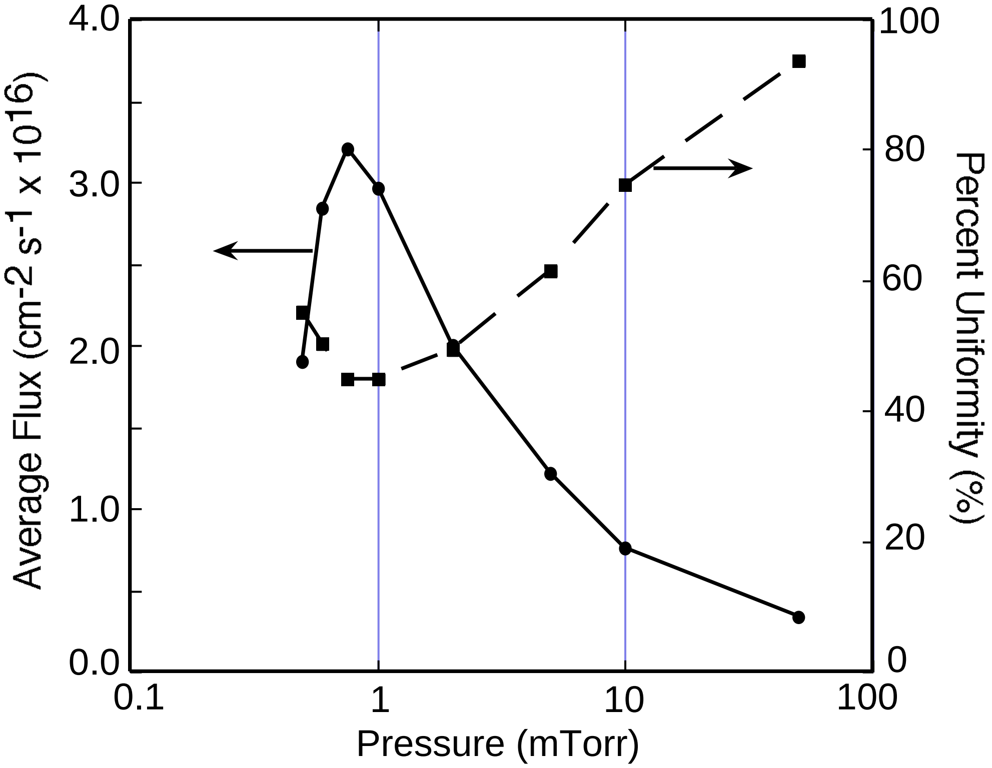
TOTAL ION FLUX TO THE SUBSTRATE

- The ion flux profile, at the substrate, reflects the shift in peak density at lower pressures.
- At higher pressures the magnitude of the average ion flux follows an inverse pressure dependence, while the ion flux profile becomes increasingly uniform due to enhanced cross field diffusion.

Ion Flux to Substrate

[MAX. = 5.0 x 10^{16} /cm2-s]





- **N_2, 750 Watts, 10 sccm, TE(0,1) mode**

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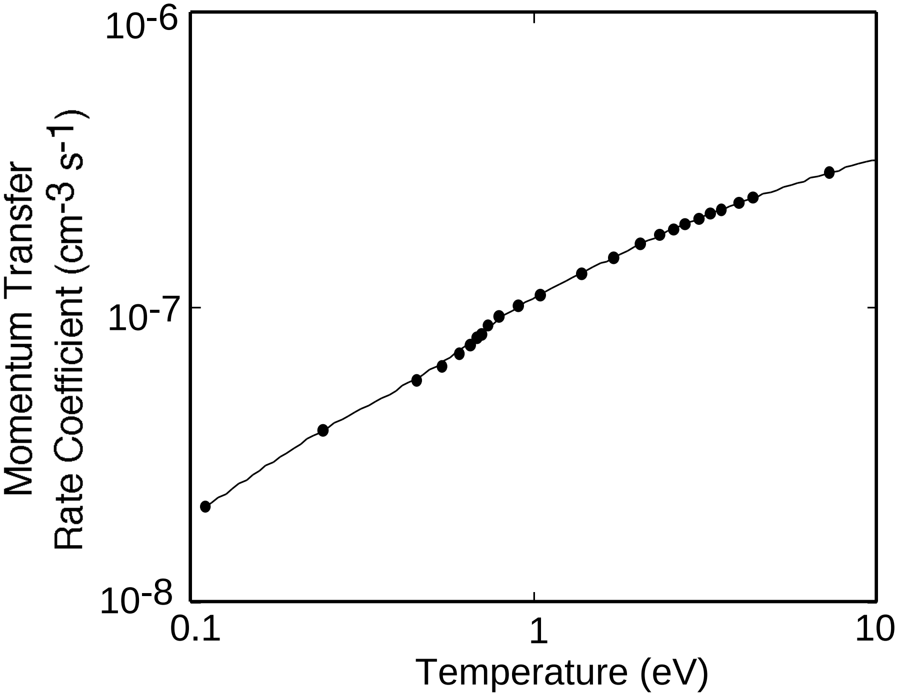
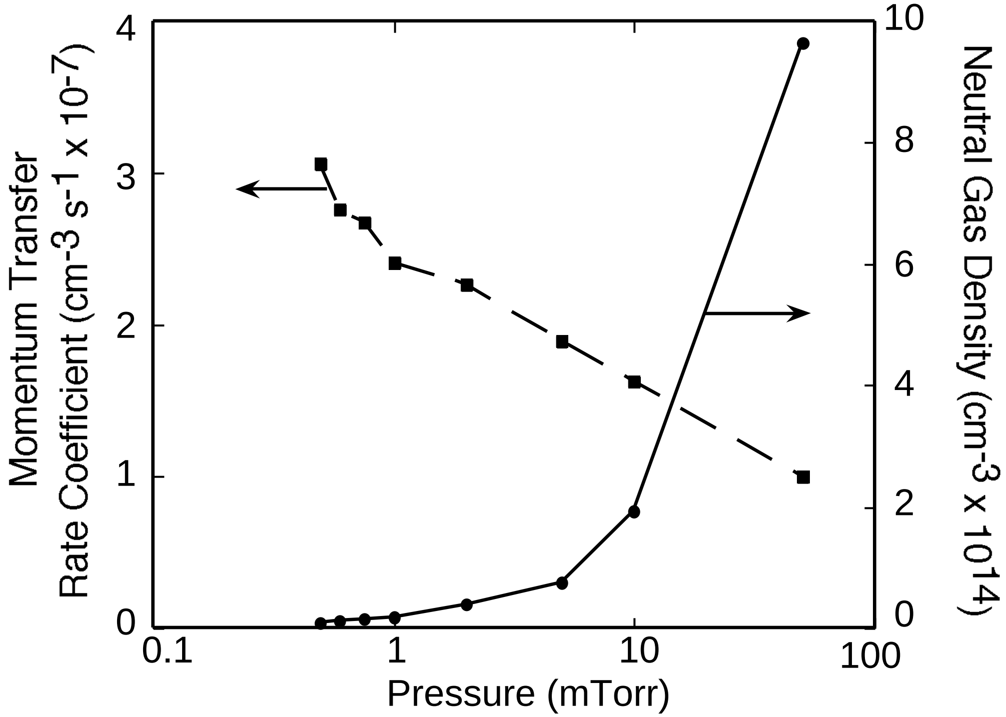
EFFECTS OF COLLISION FREQUENCY ON CROSS FIELD DIFFUSION





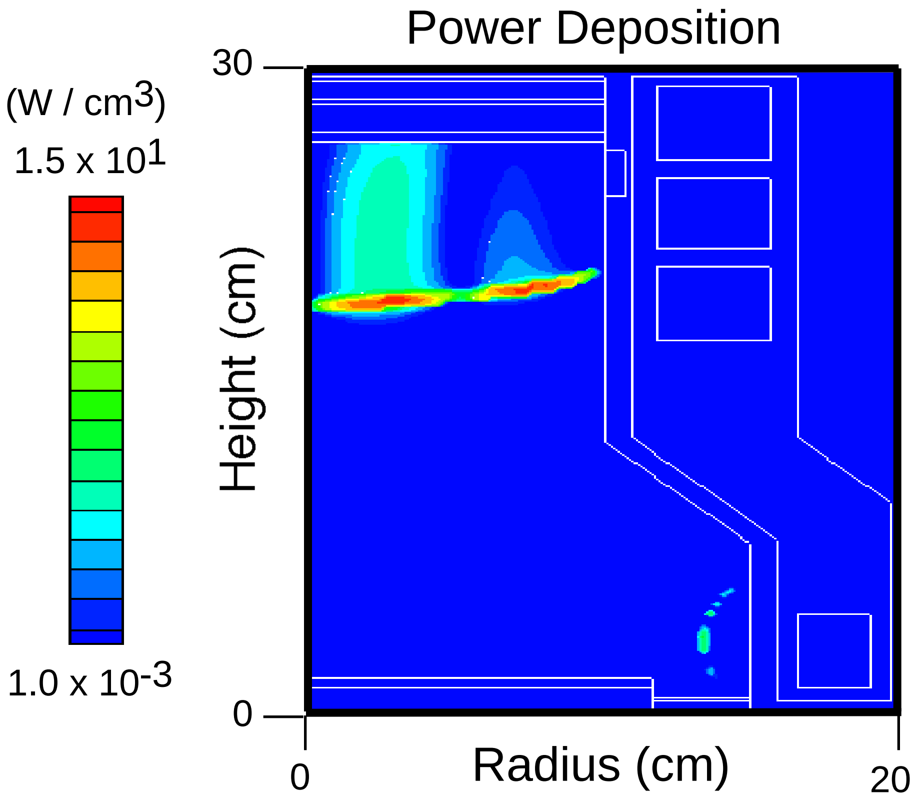
- At pressures below 2 mTorr, the electron temperature increases due to enhanced power coupling of the incident wave to the plasma.

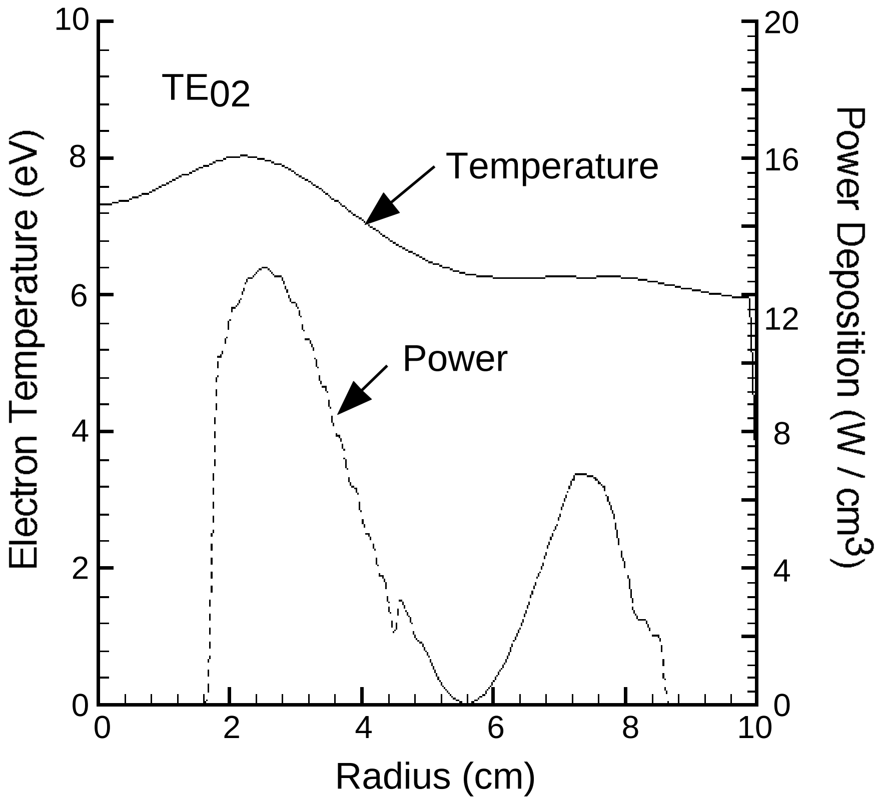
- In the low pressure regime, the high temperature increases the collision frequency. At higher pressures the collision frequency depends on the neutral gas density.

- Such results indicate that there exists an optimal pressure for maximizing ion flux and flux uniformity to the substrate.

POWER DEPOSITION AND ELECTRON TEMPERATURE : TE(0,2)

- In the TE(0,2) mode the off axis zero results in two separate regions of power depositon. Such a power profile reflects the incident electric field profile.
- The superposition effects of both power peaks cause the temperature distribution to be constant outside the first node in the electric field.

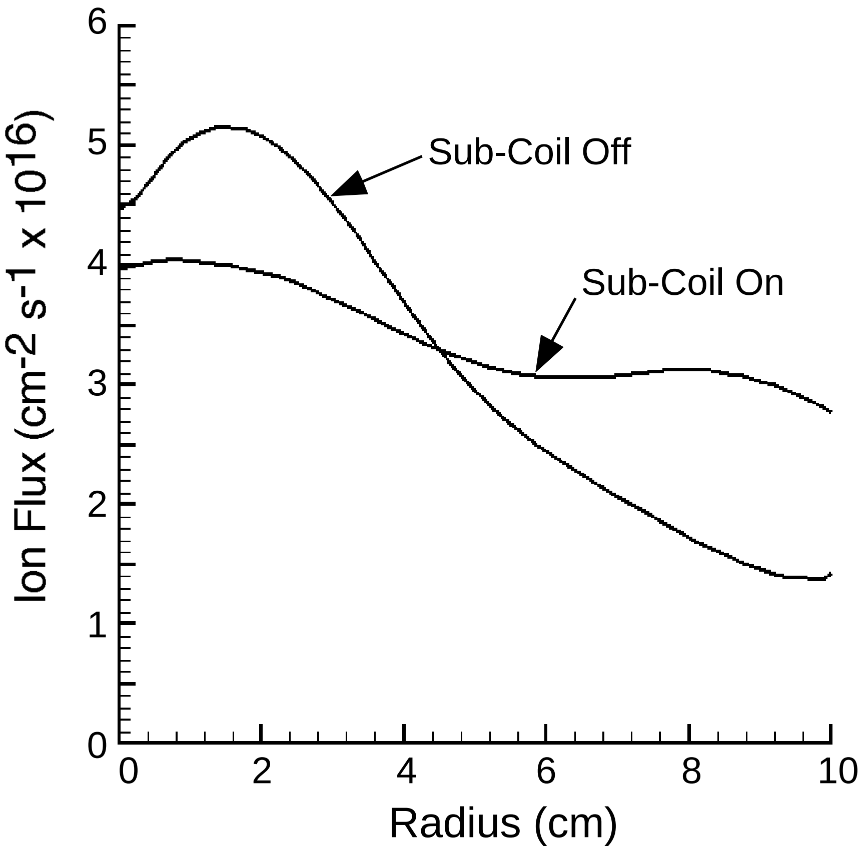


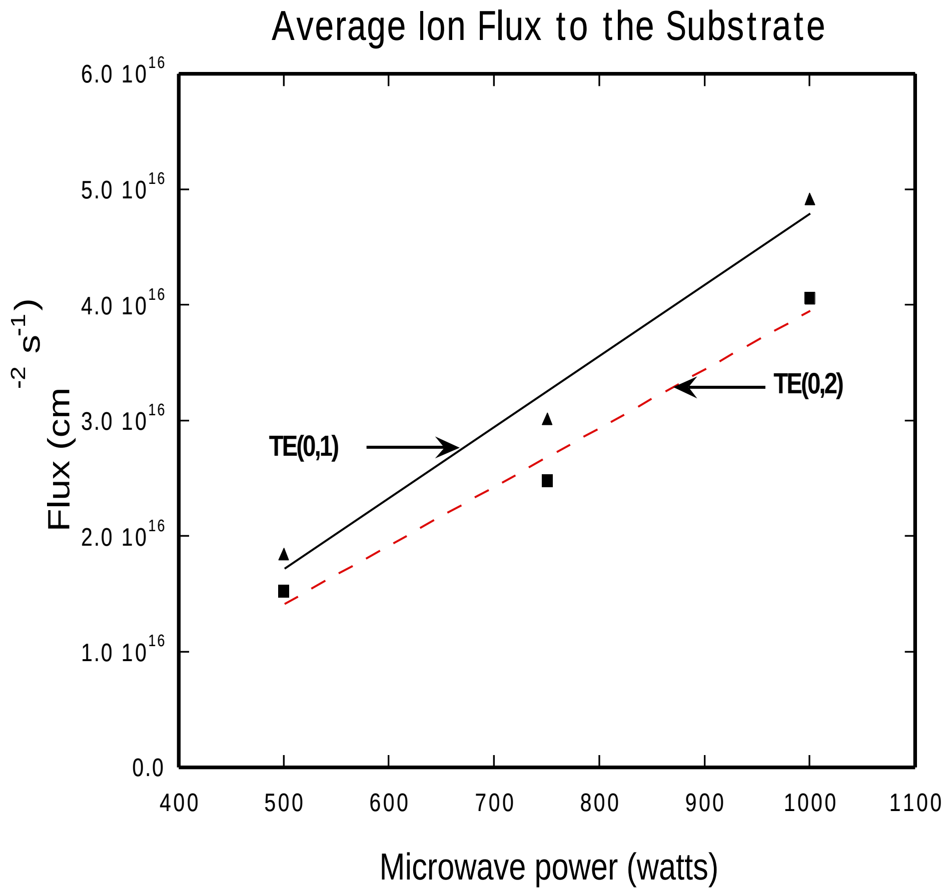


•N_2, 750 Watts, 1 mTorr, 10 sccm

ION FLUX TO SUBSTRATE TE(0,2)

- Flux of ions to the substrate reflects their off-axis production rates, and “tieing” of flux to magnetic field lines.
- These results suggest that ion flux uniformities depend more strongly on ionization locations than heating mechanisms.





CONCLUSIONS: ECR SOURCE MODELING AND FUTURE WORK

- The HPEM-2D has been expanded to simulate an ECR system used for materials processing.

- Simulation of such an ECR system indicates that magnetic field configuration, electromagnetic waveguide modes, and pressure strongly influence flux profiles to the substrate.

- Studies suggest that uniform fluxes at the substrate may require a power profile peaked off-axis.

- Lower order TE(0,n) modes tend to produce higher ion fluxes to the substrate, while higher order modes provide greater uniformity across the substrate.

- Studies indicate that there exists an optimal pressure for maximum flux to the substrate and maximum flux uniformity.

- Future work involves expanding capabilities of three dimensional hybrid plasma equipment model (HPEM-3D) to allow simulation of wave-heated discharges such as ECR and Helicon sources.