25th IEEE International Conference on Plasma Science
Raleigh, North Carolina
June 1-4, 1998

SIMULATIONS OF ECR PROCESSING SYSTEMS SUSTAINED BY AZIMUTHAL MICROWAVE TE(0,n) MODES*

Ron L. Kinder and Mark J. Kushner
Department of Electrical & Computer Engineering
University of Illinois, Urbana-Champaign
e-mail : rkinder@uigela.ece.uicuc.edu
mjk@uigela.ece.uiuc.edu

* Sponsored by SRC and NSF (ECS94-04133, CTS9412-565)

AGENDA

- Introduction
- Description of Hybrid Plasma Equiptment Model (HPEM)
- Finite Difference Time Domain Module
- Simulation Device Geometry and Operating Conditions
- Simulation Results (Power, Ionization Rate, Electron Density Distributions)
- Experimental Validation
- Results from Parametric Studies
- Conclusions

INTRODUCTION

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

- One advantage of ECR sources is their ability to provide uniformity over large areas. As industry begins to move toward larger wafers, industrial scaleup of these sources is in progress. LAM currently markets a 200 mm deposition tool (scaling to 300 mm). Hitachi has recently announced a 300 mm etch tool.

- 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 FDTD simulation for microwave injection and propagation. The FDTD simulation has been incorporated as a module in the 2-dimensional Hydrid 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 distribution module (EEDM), and a fluid kinetics simulation (FKS).

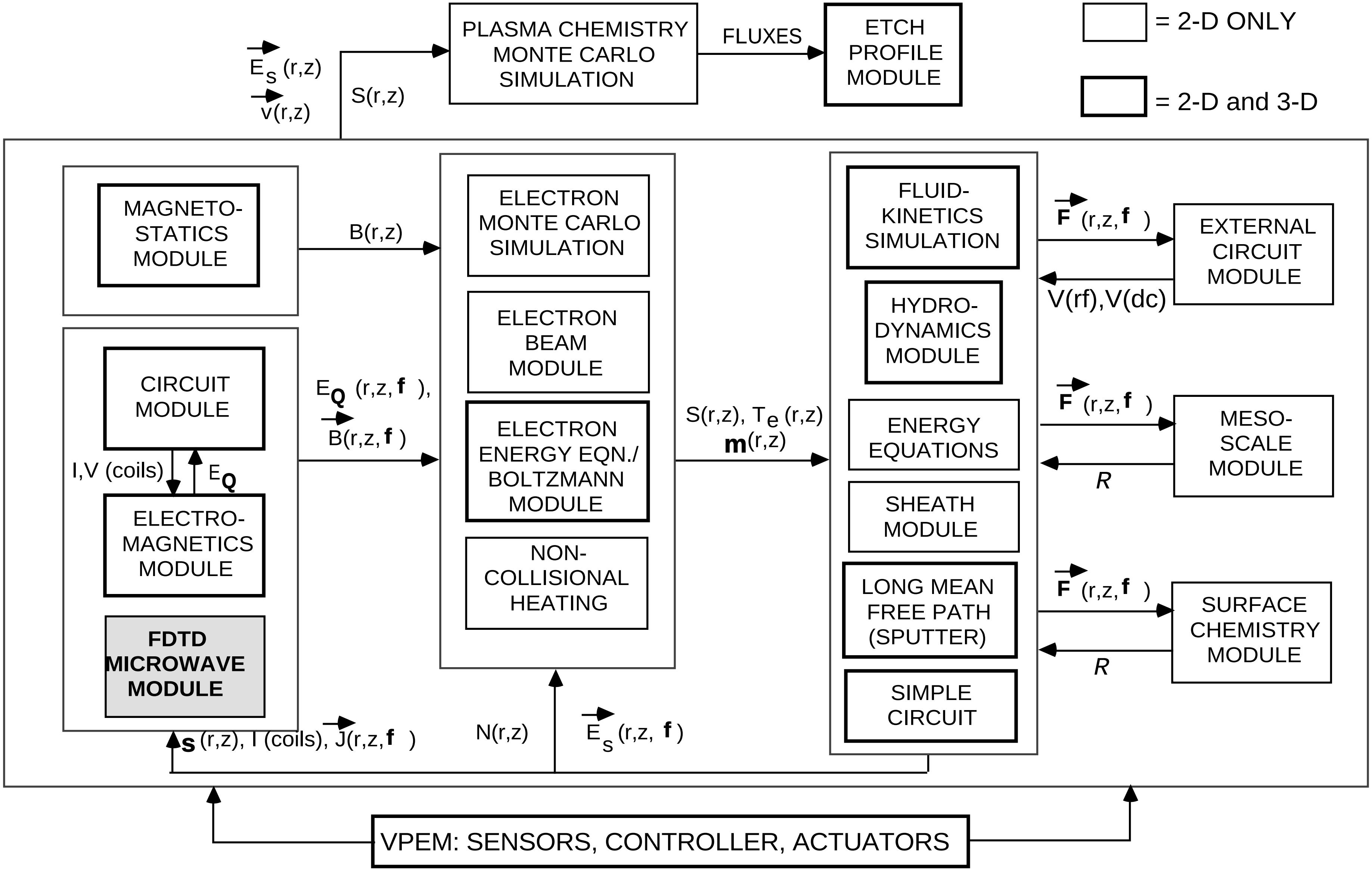
- Ion transport was calculated by time integrating the continuity and momentum equations, while electron energy transport was determined by time integrating the electron energy conservation equation.

- Neutral transport was determined by solving the neutral momentum 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.

- Due to the vastly different kinetic time scales for the kinetic reactions compared to convection, such an approximation, allowed for the use of larger time steps, while maintaining stability, during each iteration.

SCHEMATIC OF 2-D/3-D HYBRID PLASMA EQUIPMENT MODEL



DESCRIPTION OF THE 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, with time steps that are 30% of the Courant limit.

- Plasma dynamics are coupled to the EM fields through a tensor form of Ohm’s law which addresses static B-fields.

$$\mathbf{x}\ \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial \mathbf{t}}$$

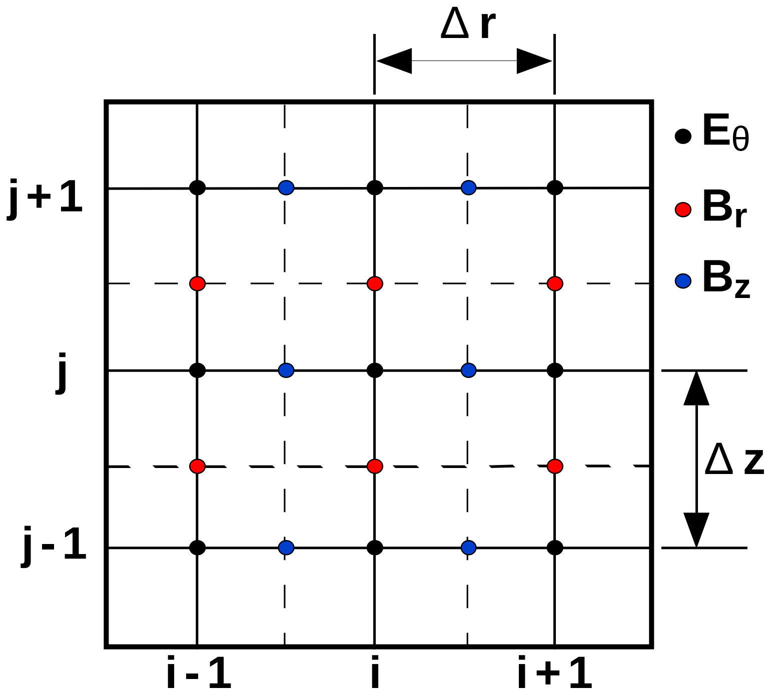
$$\mathbf{x}\ \frac{\mathbf{B}}{\mu} = \overline{\overline{\sigma}} \cdot \mathbf{E} + \varepsilon \frac{\partial \mathbf{E}}{\partial \mathbf{t}}$$

where, $$\overline{\overline{\sigma}} = q\, n_e\, \overline{\overline{M}}^{-1}$$

$$\overline{\overline{M}} = \begin{pmatrix} \alpha & -B_z & B_\theta \\ B & \alpha & -B_r \\ -B_z & B_r & \alpha \end{pmatrix}$$

$$\alpha = \frac{m}{q}\,(i\omega + \nu_m)$$

2(1/2)-D Alternating Grid:



ABSORBING BOUNDARY CONDITIONS FOR FDTD

- When time domain electromagnetic field equations are solved using finite difference techniques in unbounded space, there must be a method limiting the domain in which the field is computed.
- This is achieved by truncating the mesh and using absorbing boundary conditions at its artificial boundaries to simulate the unbounded surroundings.
- Due to the nature of the 2(1/2)-D alternating direction implicit scheme, boundary conditions using constant gradients for electric and/or magnetic fields cause spurious reflections of the incident waves.
- To remove unwanted reflections, a linearized first order wave equation was imposed as a boundary condition to simulate unbounded surroundings.

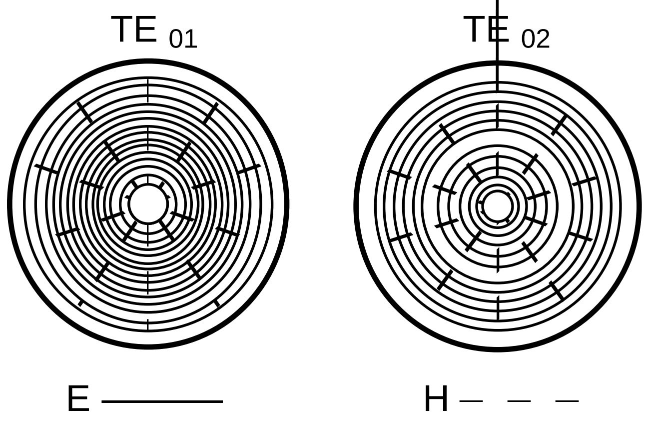
Linearized First Order
Wave Equation:

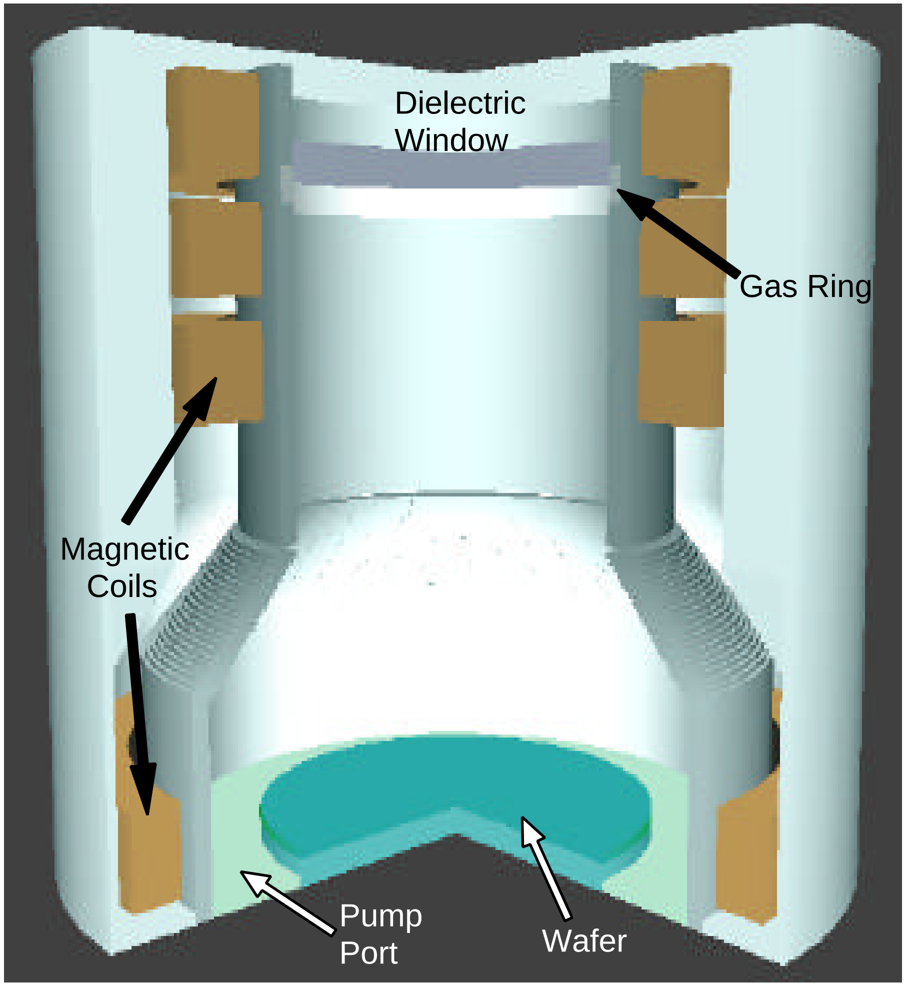
$$\frac{\partial E_{\theta}^{n+1}}{\partial z} + \frac{\partial E_{\theta}^{n}}{\partial z} = \frac{1}{c}\frac{\partial E_{\theta i,j}}{\partial t} + \frac{1}{c}\frac{\partial E_{\theta i,j-1}}{\partial t}$$

REACTOR GEOMETRY AND OPERATING CONDITIONS

- Range of Operating Conditions:
  - Gas Pressure Range : 0.5 - 5.0 mTorr
  - Microwave Power : 500 - 1500 Watts
  - Flow Rates : 5 - 10 sccm
  - Microwave Field : Circular TE(0,n) modes (2.45 GHz)

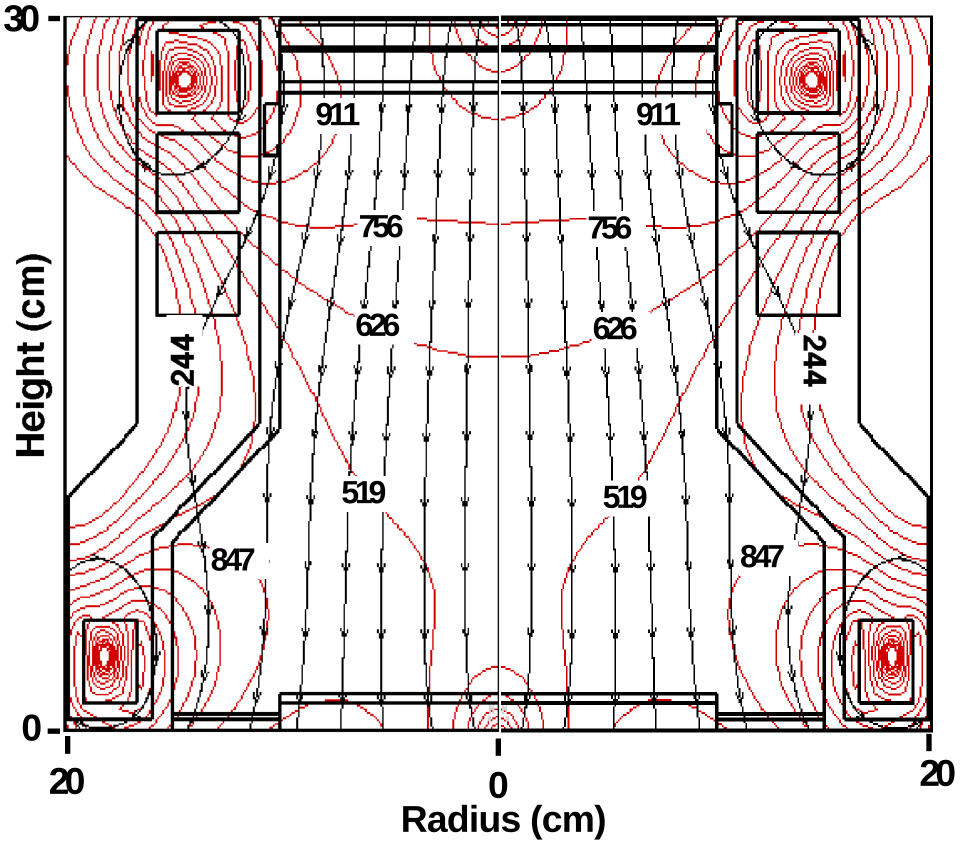
- Microwave Field Modes:



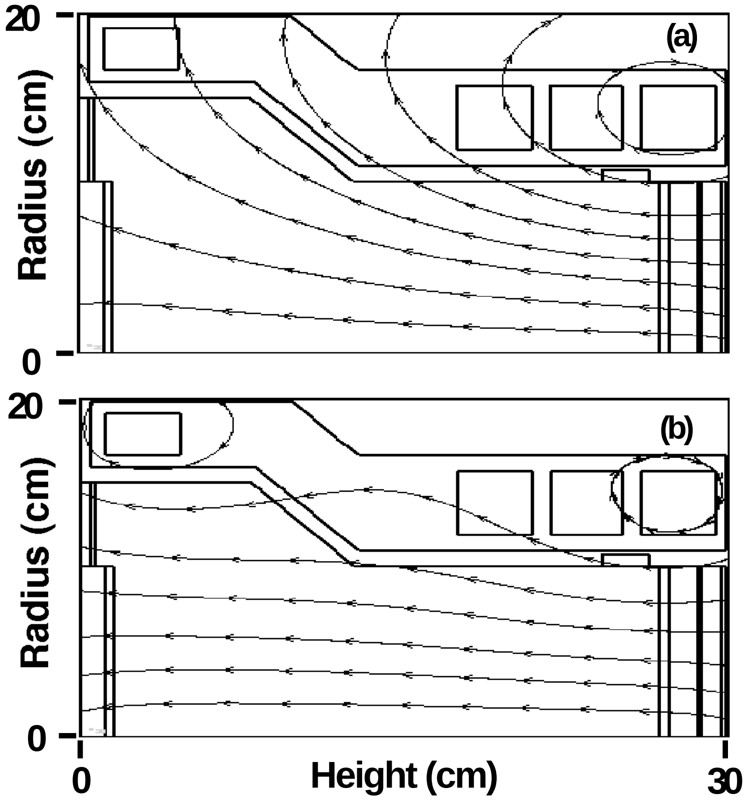


UNIVERSITY OF ILLINOIS
OPTICAL AND DISCHARGE PHYSICS

MAGNETIC FIELD CONFIGURATION



- Schematic representation of magnetic flux field lines (arrows) and magnetic field intensity, in gauss, (contours) inside an ECR processing chamber. ECR resonance, for 2.45 GHz, occurs at 875 gauss.

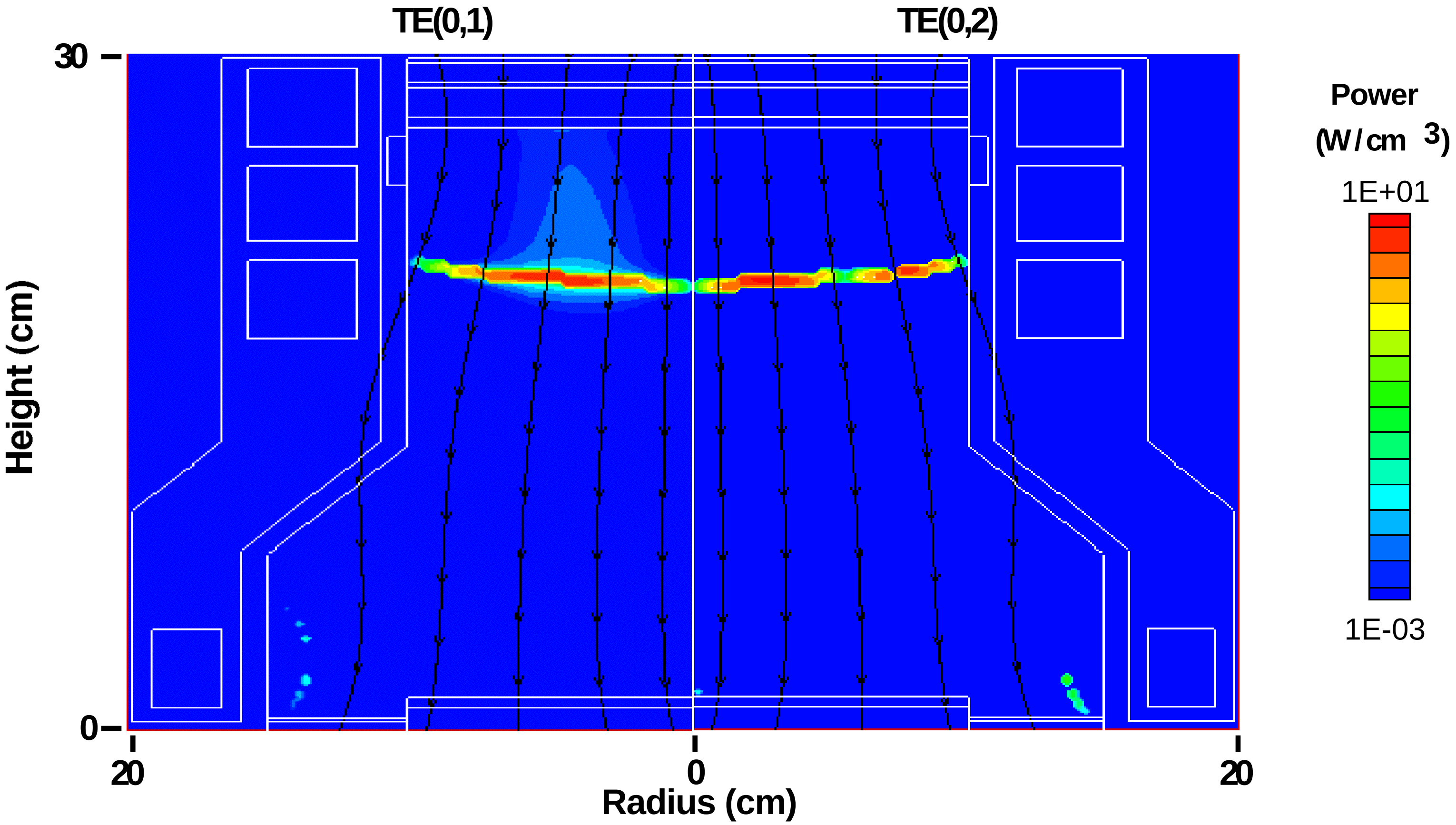


- Schematic representation of the magnetic flux density in the downstream of the reactor chamber. The magnetic flux is presented (a) without activation of the submagnetic coil and (b) with submagnetic coil activation.

POWER DEPOSITION: TE(0,1), TE(0,2)

- Power deposition occurs predominantly within 3% of the resonance zone (875 G). Although a small amount of power deposition occurs near the bottom coils due to a second resonance region created by the subcoil.

- In the TE(0,2) mode the off axis zero results in two separated regions of power deposition. Such power profiles reflect incident electric field profiles.

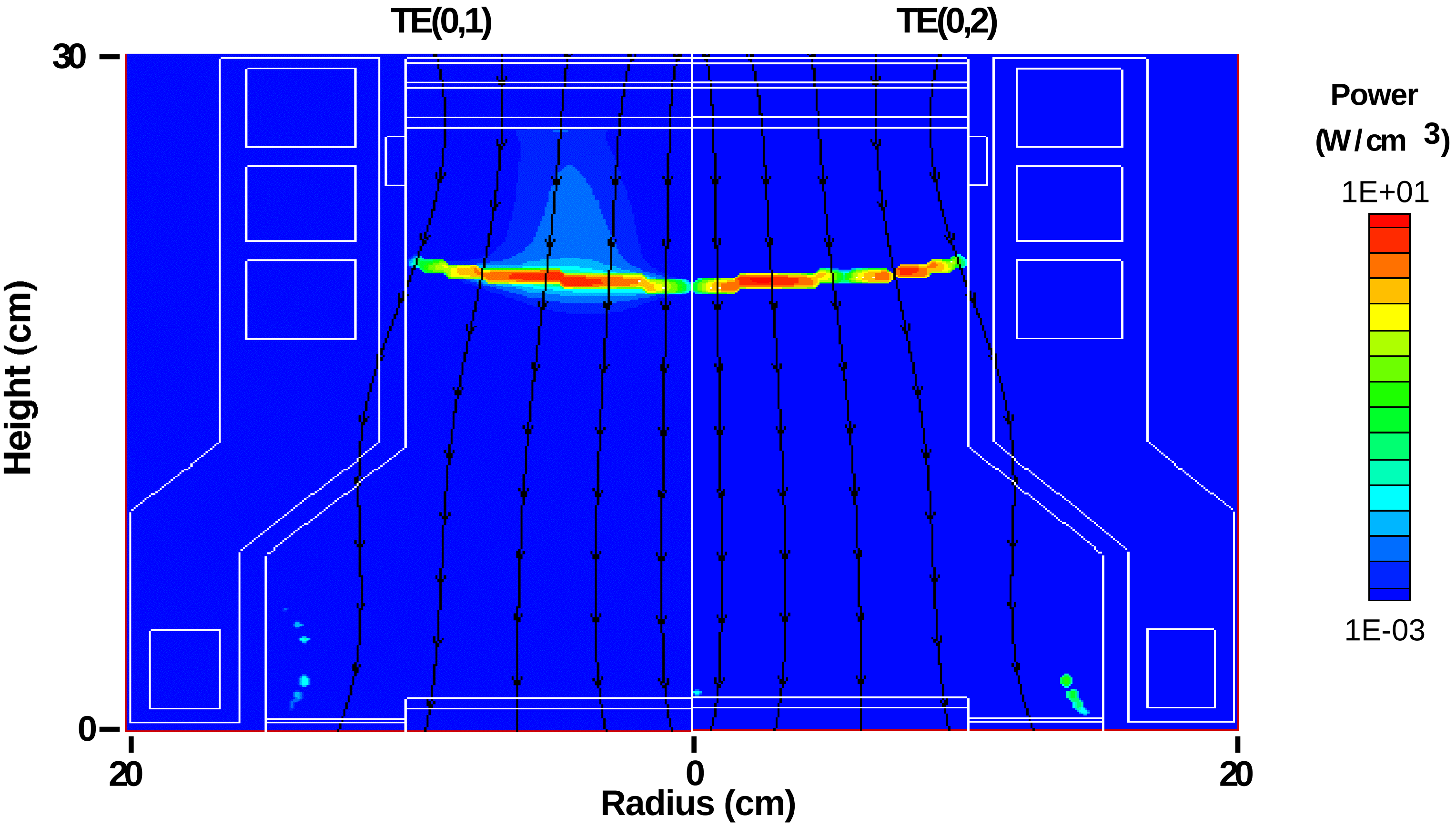


- N_2, 500 Watts, 1 mTorr, 10 sccm

POWER DEPOSITION: TE(0,1), TE(0,2)

- Power deposition occurs predominantly within 3% of the resonance zone (875 G). Although a small amount of power deposition occurs near the bottom coils due to a second resonance region created by the subcoil.

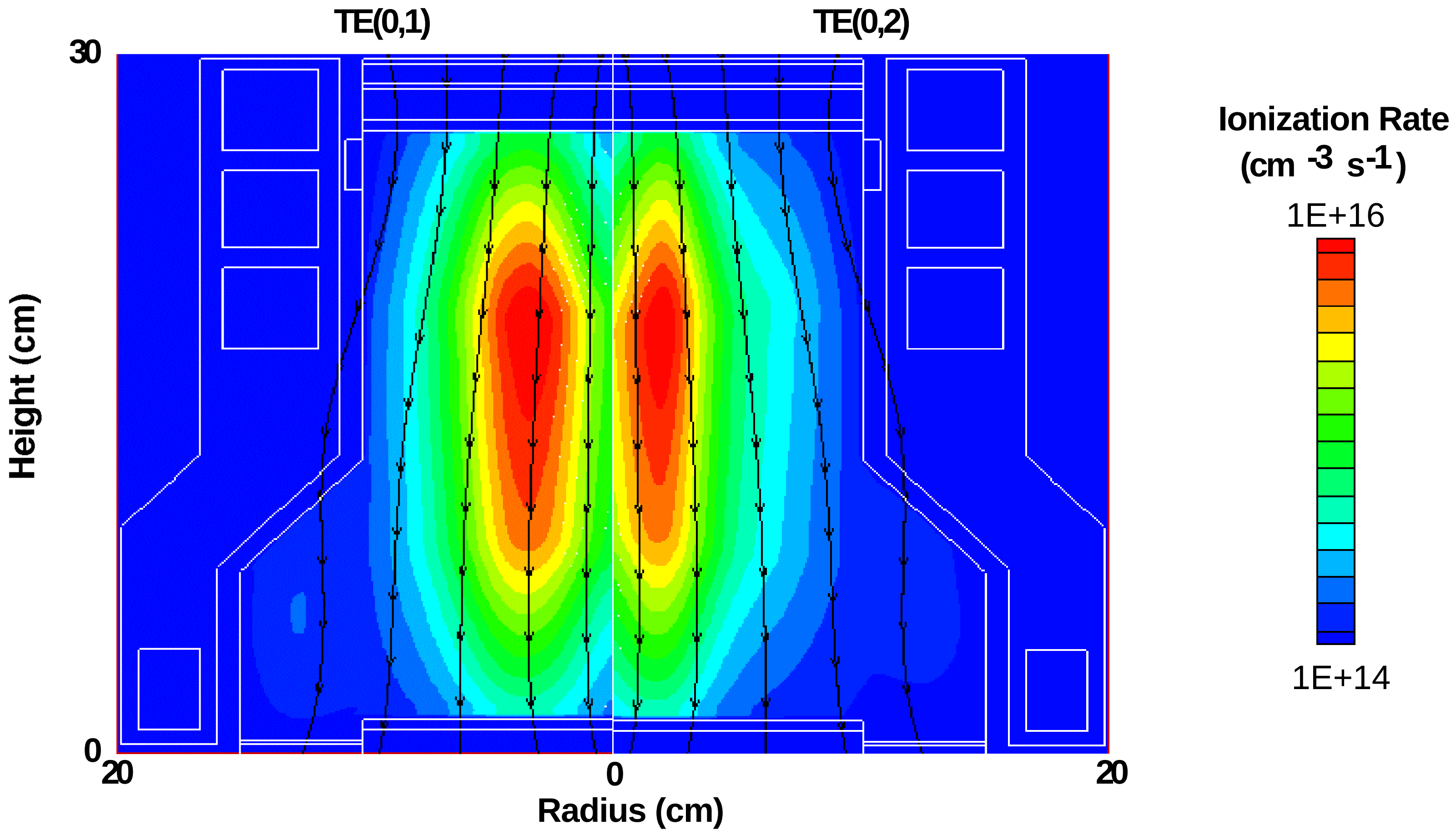
- In the TE(0,2) mode the off axis zero results in two separated regions of power deposition. Such power profiles reflect incident electric field profiles.



- N_2, 500 Watts, 1 mTorr, 10 sccm

IONIZATION RATES: TE(0,1), TE(0,2)

- Ionization rates follow power deposition profiles and are peaked off-axis.
- There is considerable ionization away from the resonance zone due to enhanced confinement of high energy electrons by static magnetic field lines.

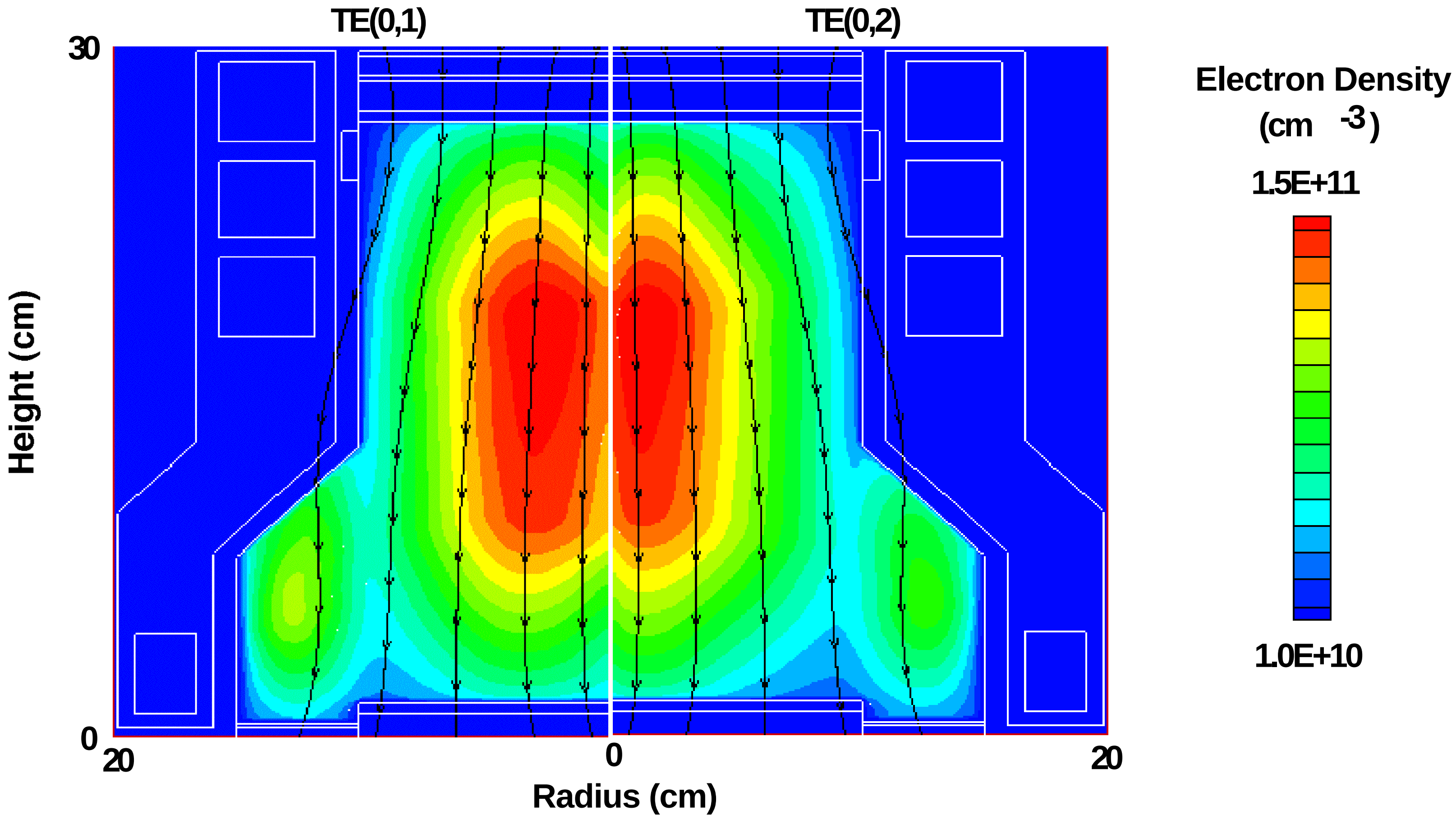


- N_2, 500 Watts, 1 mTorr, 10 sccm

ELECTRON DENSITIES: TE(0,1), TE(0,2)

- Due to the enhanced confinement of electrons by magnetic field lines, densities tend to reflect sources. (Note the local maximum in density by the lower coil.)

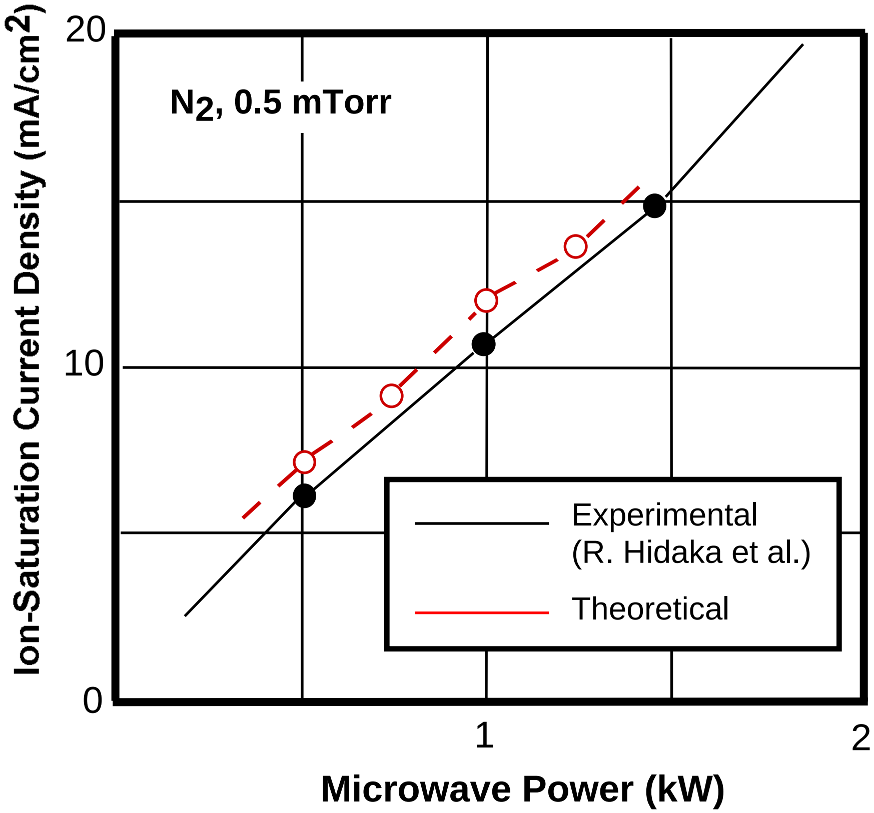
- To account for anamolous diffusion of electrons across magnetic fields, a small isotropic correction factor was introduced for electron transport.

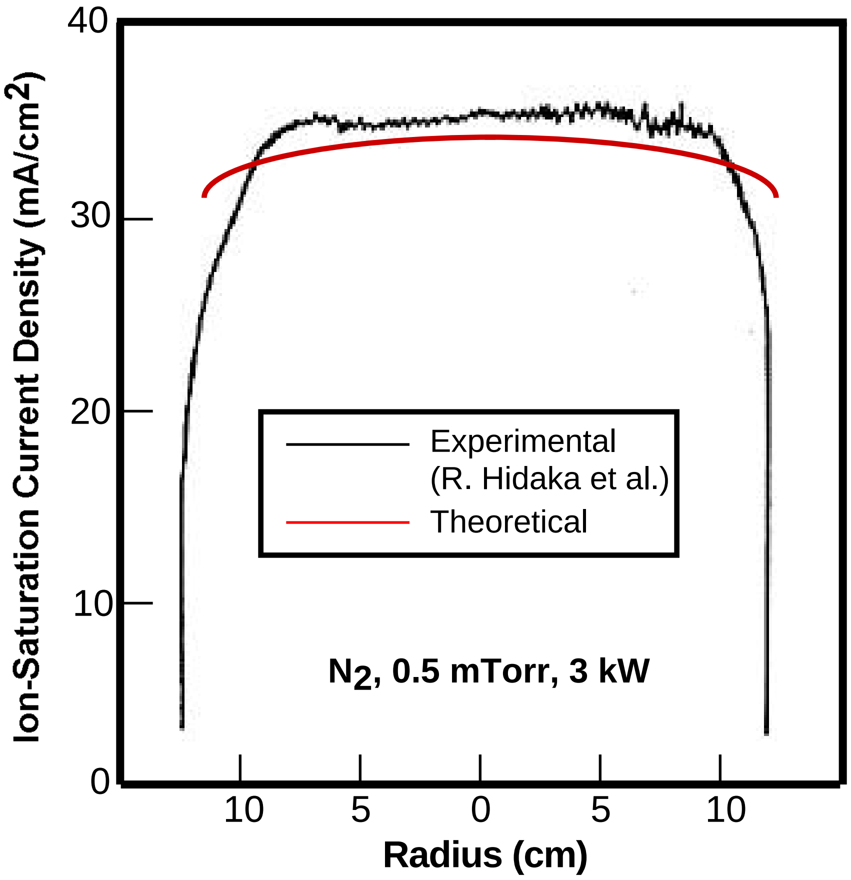


•N_2, 500 Watts, 1 mTorr, 10 sccm

ION SATURATION CURRENT VALIDATION

- To validate flux to the substrate trends, control experiments conducted at Kyushu Univeristy, Japan (R. Hidaka*et al.*, Jpn. J. Appl. Physc. Vol. 32 (1993), pp. 174) were simulated.

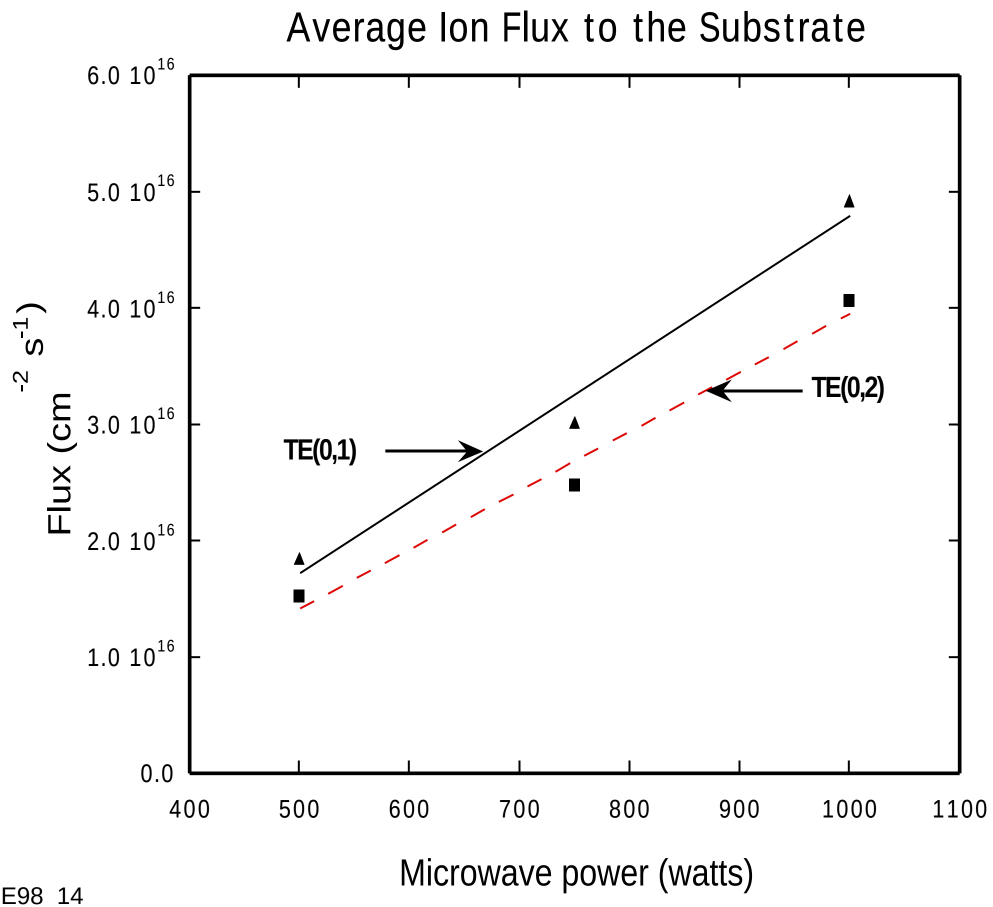


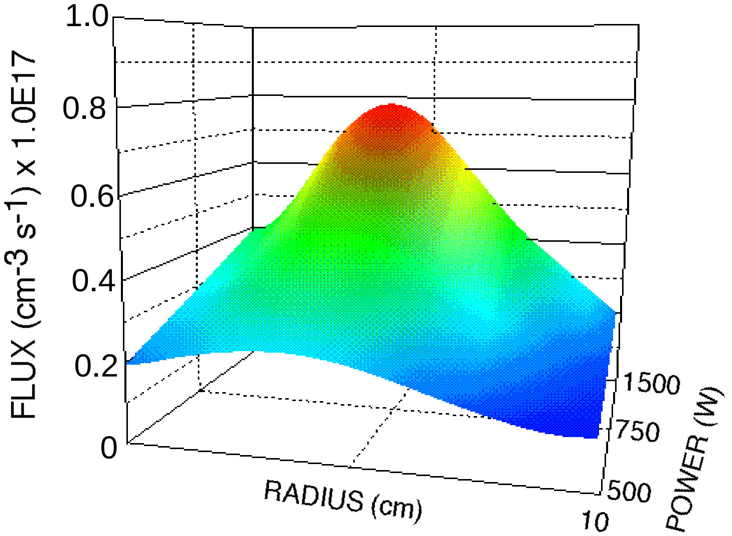


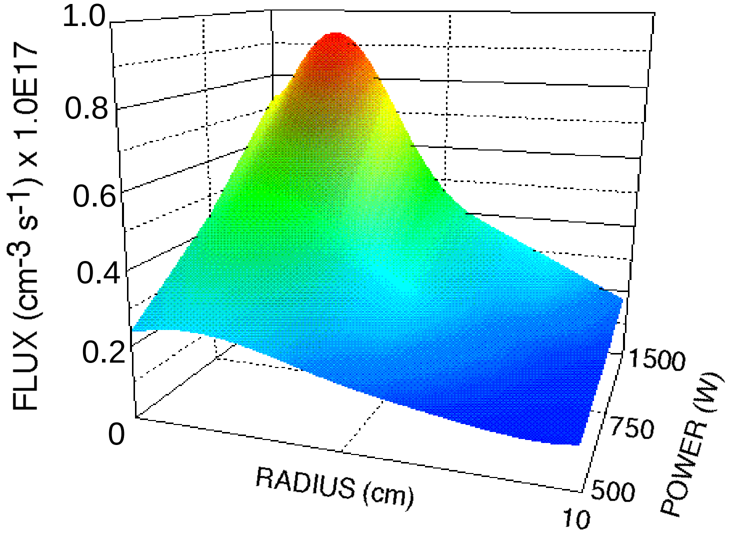
- Radial distribution of the ion saturation current density in the case of the TE(0,1) mode shows the ion saturation current is uniform within 5% over and 8 inch diameter.

TOTAL ION FLUX TO SUBSTRATE

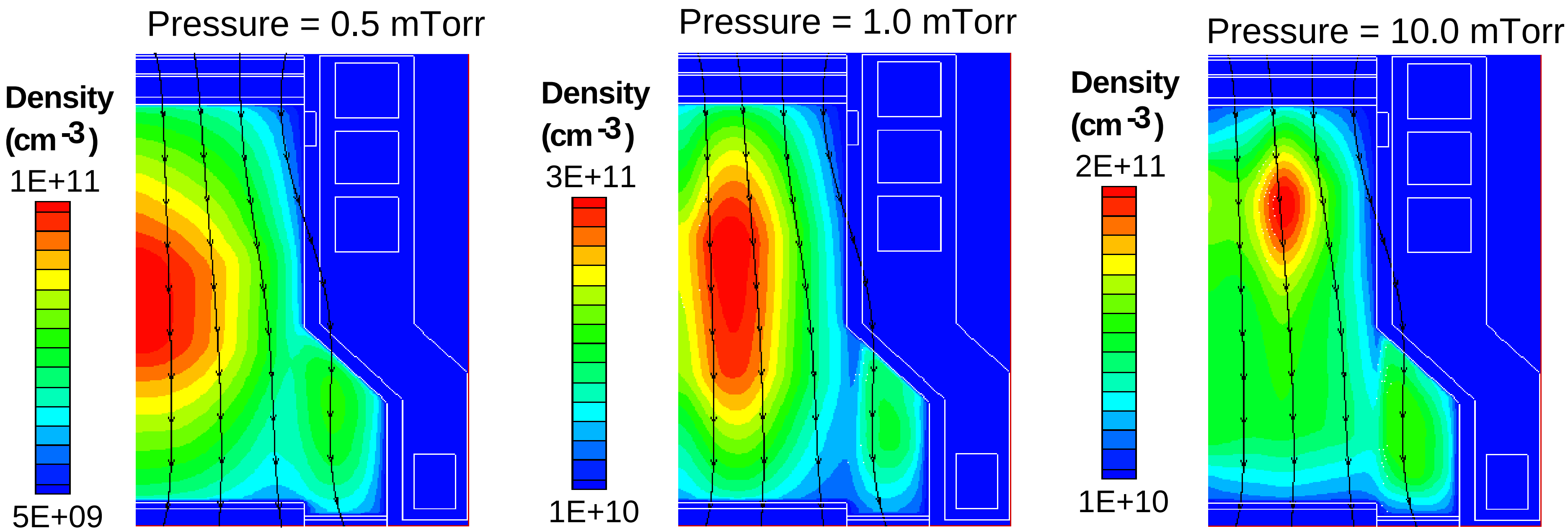
- Flux of ions to the substrate reflects their off-axis production rates, and "tieing" of flux to magnetic field lines.
- These results suggest that ion flux uniformities depend more strongly on ionization locations than heating mechanisms.


Average Ion Flux to the Substrate


Radial Ion Flux Profile for TE(0,1) Mode


Radial Ion Flux Profile for TE(0,2) Mode.

ELECTRON DENSITY DISTRIBUTION VERSUS PRESSURE



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

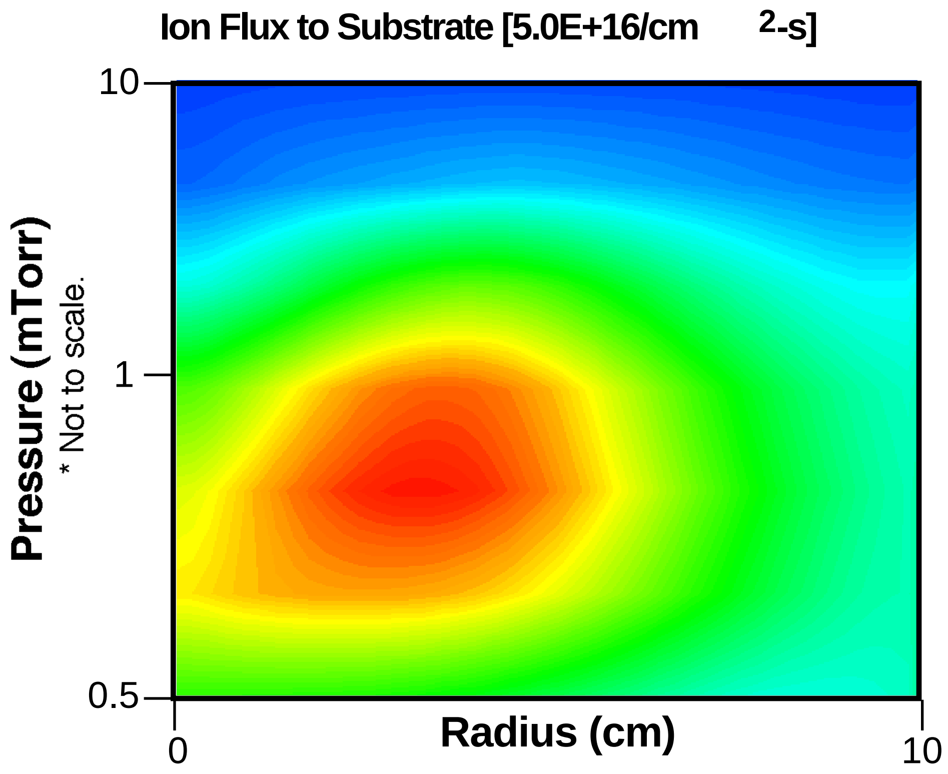
- As pressure is decreased below 2 mTorr, there is shift in the peak density towards the center of the reactor. Such a result implies that the perpendicular diffusion is enhanced at lower pressures.
- For the simulations performed the collision frequency was much smaller than the cyclotron frequency. 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

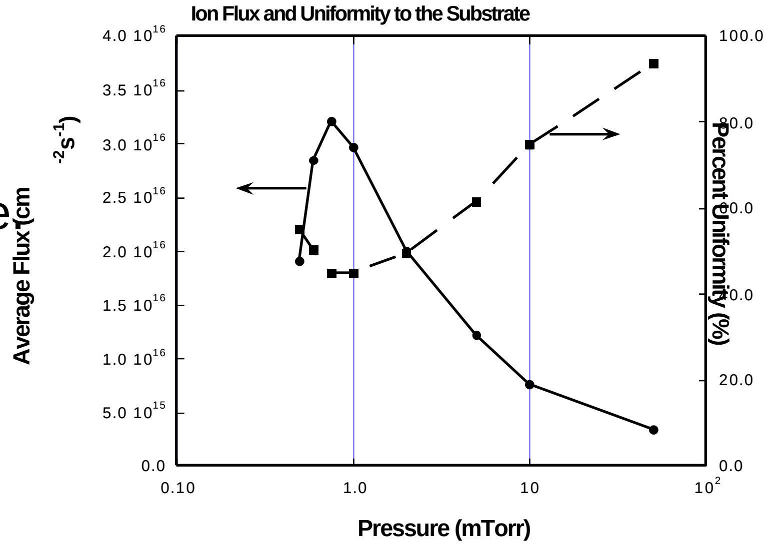
- The ion flux profile, at the substrate, reflects the shift in peak density at lower pressures.

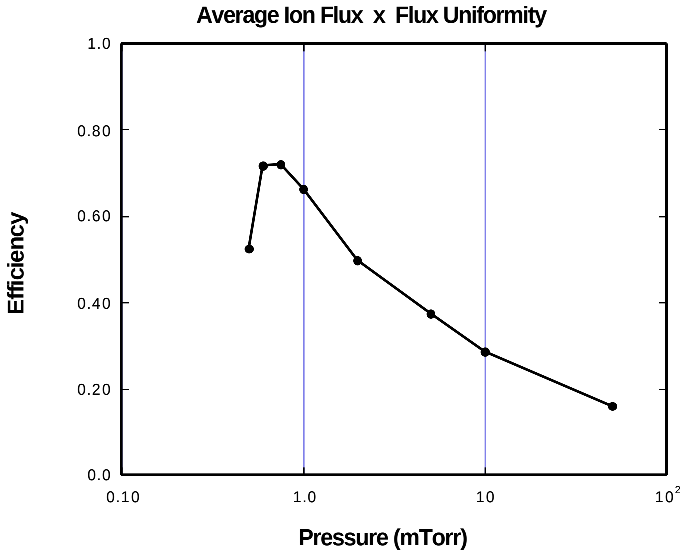
- The magnitude of the average ion flux, above 1 mTorr, follows an inverse pressure dependence.

- At higher pressures, the ion flux profile becomes increasingly uniform due to enhanced cross field diffusion.

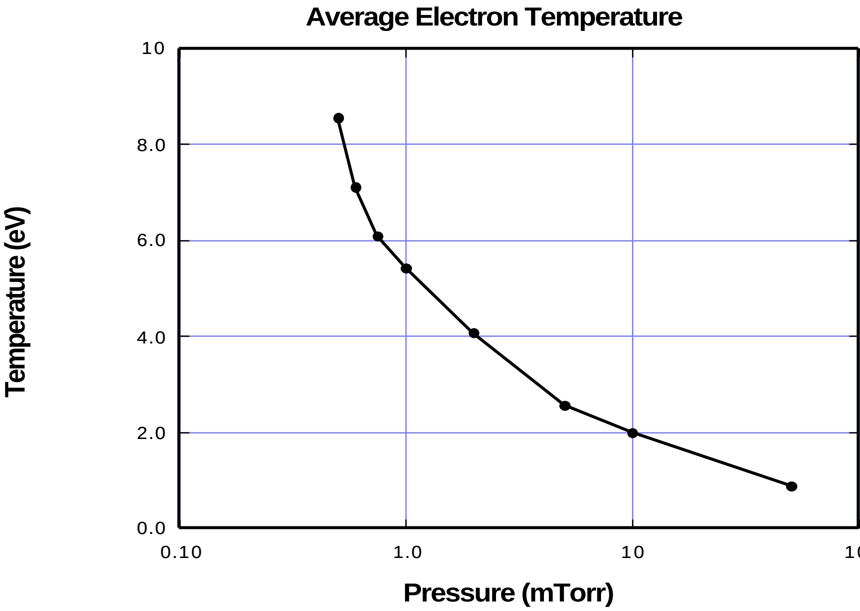


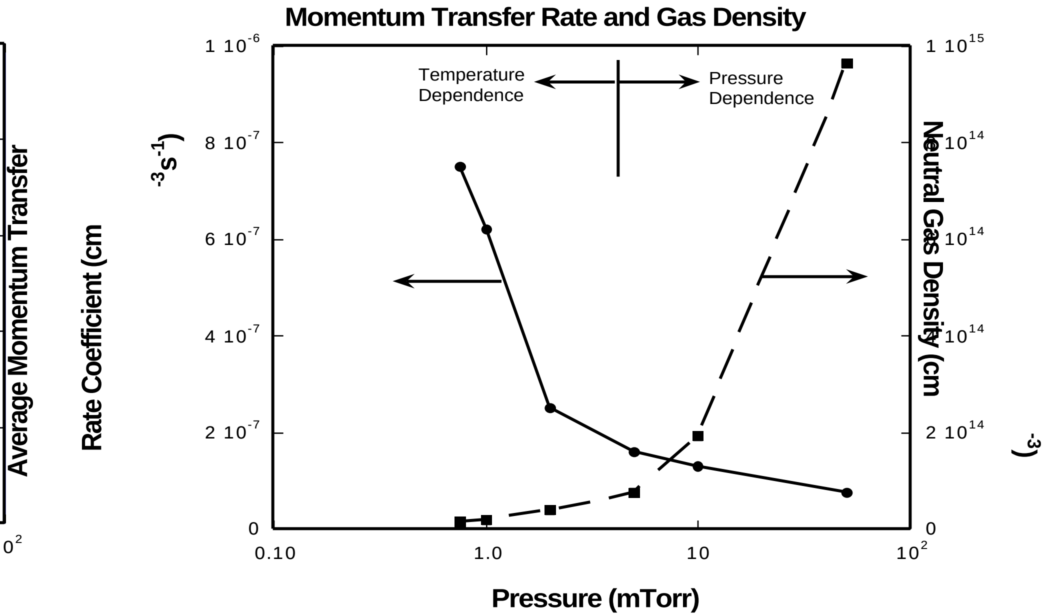
- **N_2, 750 Watts, 10 sccm, TE(0,1) mode**





EFFECTS OF COLLISION FREQUENCY ON CROSS FIELD DIFFUSION





- **N$_2$, 750 Watts, 10 sccm, TE(0,1) mode**

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

- In the low pressure regime, the high temperature significantly affects the momentum transfer rate coefficient, thereby increasing 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.

CONCLUSIONS: ECR SOURCE MODELING

- Simulation of such ECR systems indicate that magnetic field configuration, electromagnetic waveguide modes, and location of resonance 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 tends to produce higher ion fluxes to the substrate, while higher order modes allow for greater uniformity across the substrate.

- At low pressures, < 1 mTorr, plasma dynamics depend highly on electron temperature. Cross field ion diffusion is enhanced by an increased momentum transfer rate coefficient.

- While at higher pressures, the electron temperature falls off due to thermalization and a decreasing efficiency in power coupling between the incident wave and the plasma. This leads to a cross field diffusion that is sensitive to neutral gas densities.

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