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MODELING OF AN ECR SOURCE FOR MATERIALS PROCESSING USING A TWO DIMENSIONAL HYBRID PLASMA EQUIPMENT MODEL

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AGENDA

- Computational Optical and Discharge Physics Group (CODPG)
- Introduction to Electron Cyclotron Resonance (ECR) Modeling
- Description of Hybrid Plasma Equipment Model (HPEM)
- Finite Difference Time Domain Module (FDTD)
- Simulation Device Geometry and Operating Conditions
- Experimental Validation of Ion Saturation Current
- Parametric Studies
  (Dependence on Magnetic Field Configuration, Field Mode, Power and Pressure)
- Conclusions and Future Work

COMPUTATIONAL OPTICAL AND DISCHARGE PHYSICS

- The Computational Optical and Discharge Physics Group (CODPG) develops computer aided design tools of plasma equipment and process.

- Some of the applications for which the CODPG has recently developed simulations and CAD tools are:

  - Plasma etching and deposition for fabrication of microelectronics
  - Flat panel display fabrication
  - Plasma etch and deposition surface kinetics and profile models
  - Lasers
  - Pulse power switches
  - Plasma remediation of toxic gases
  - Lighting sources
  - Nanocrystal generation for the fabrication of nanophase materials
  - Nucleation, growth and transport of particles in plasmas
  - Contamination free manufacturing of microelectronics

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.

- One advantage of 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.

- 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 2-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 HPEM is a plasma equipment model that has the capability of modeling complex reactor types (i.e. ICP, RIE, ECR), a wide variety of operating conditions and gas chemistries.

- The base two-dimensional HPEM consists of an electromagnetics module (EMM), an electron energy distribution module (EEDM), 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.

- 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.

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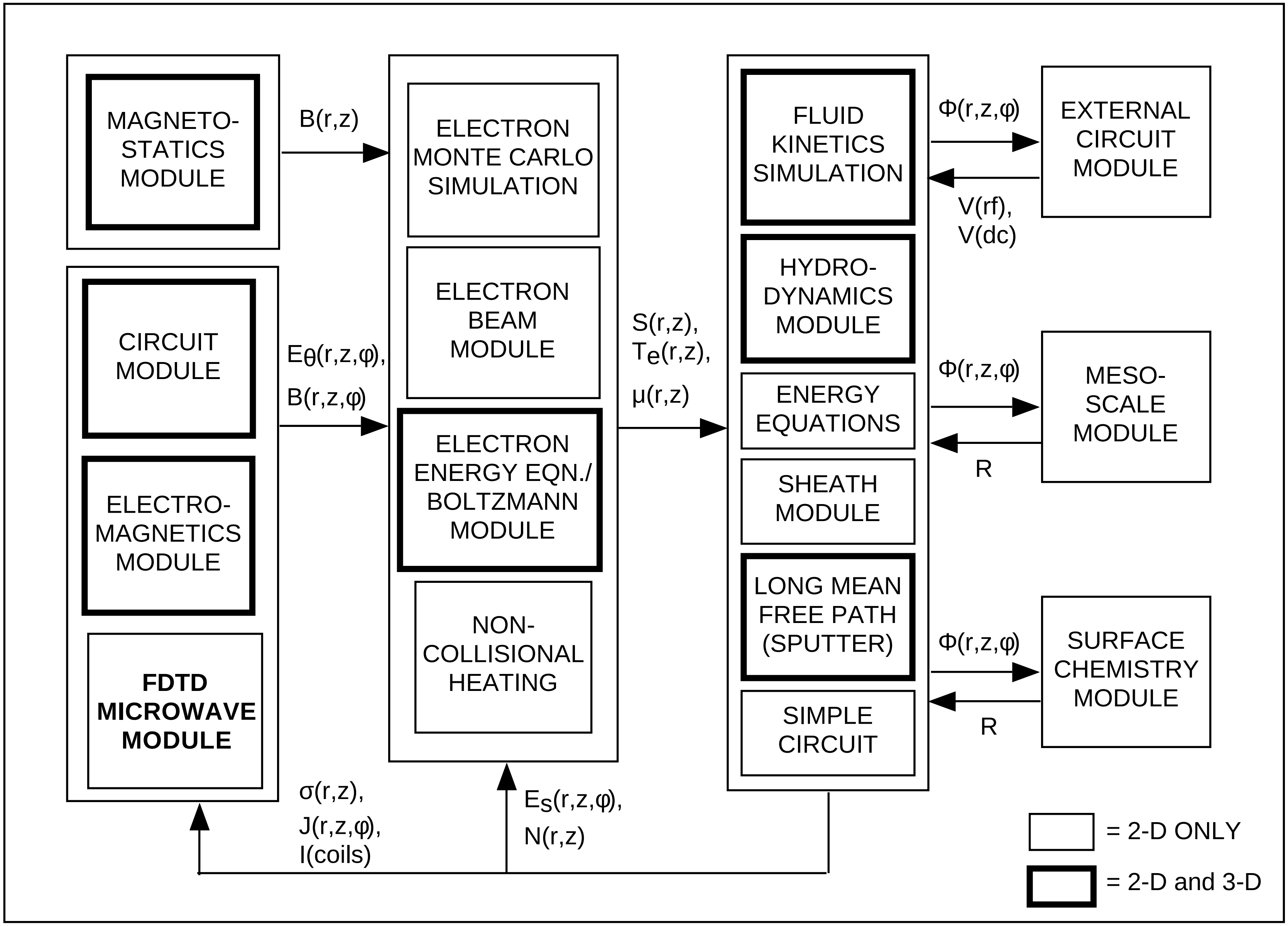
HYBRID PLASMA EQUIPMENT MODEL



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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.

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

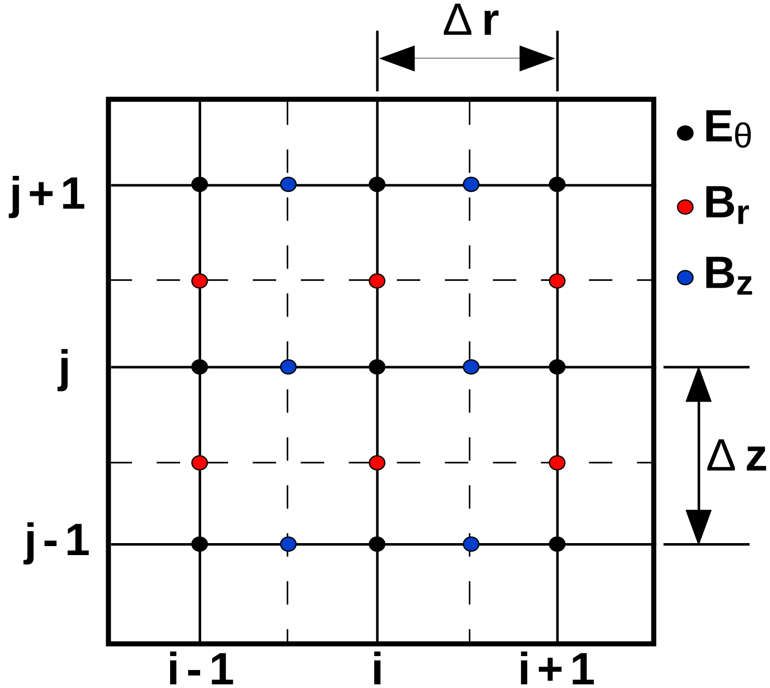
$$\times \frac{\mathbf{B}}{\mu} = \bar{\bar{\sigma}} \cdot \mathbf{E} + \varepsilon \frac{\partial \mathbf{E}}{\partial \mathbf{t}}$$

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

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

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

2(1/2)-D Alternating Grid:



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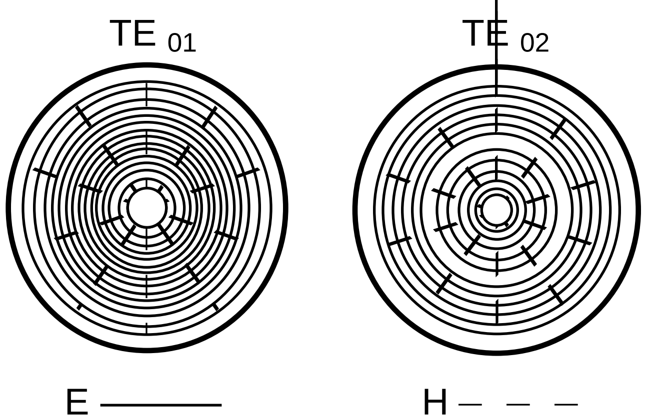
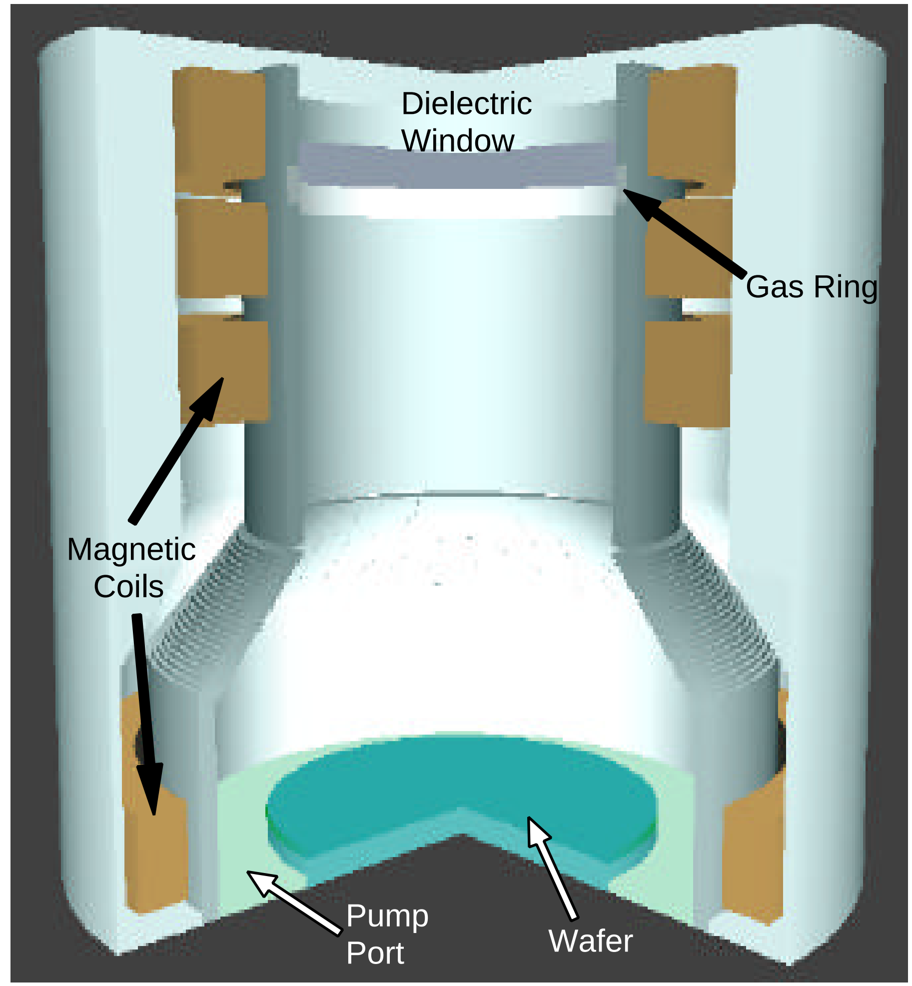
REACTOR GEOMETRY AND OPERATING CONDITIONS

- Range of Operating Conditions:
  - Gas Pressure : 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:





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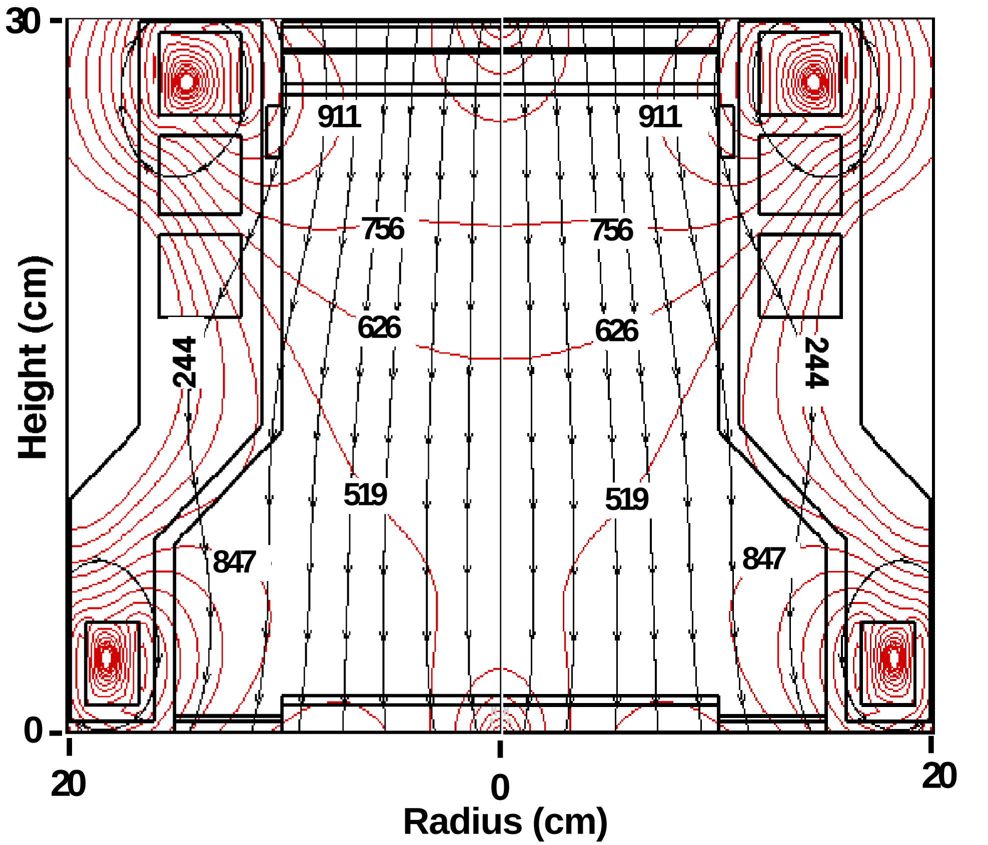
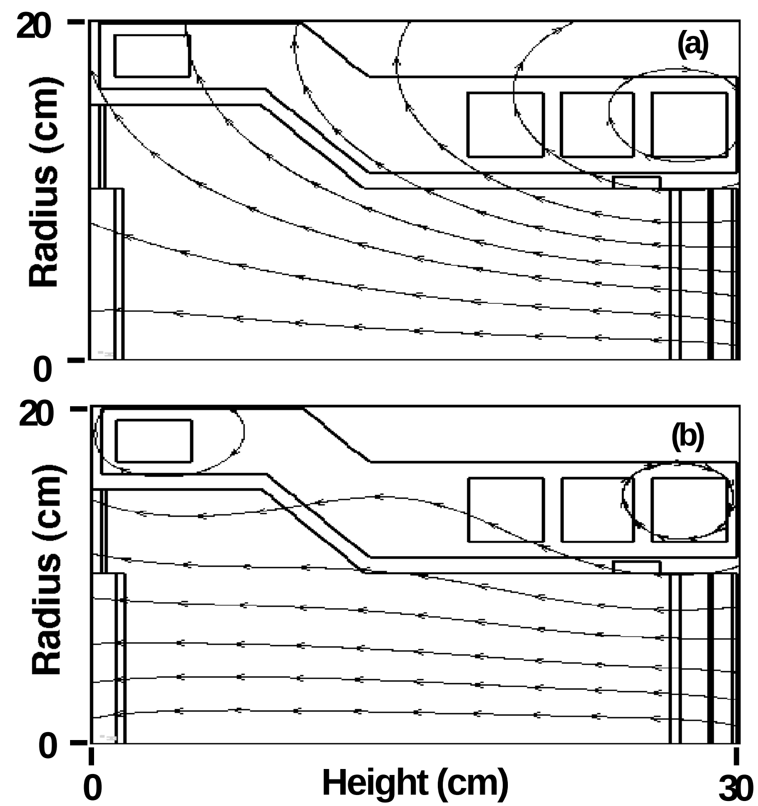
MAGNETIC FIELD CONFIGURATION





- Schematic 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 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.

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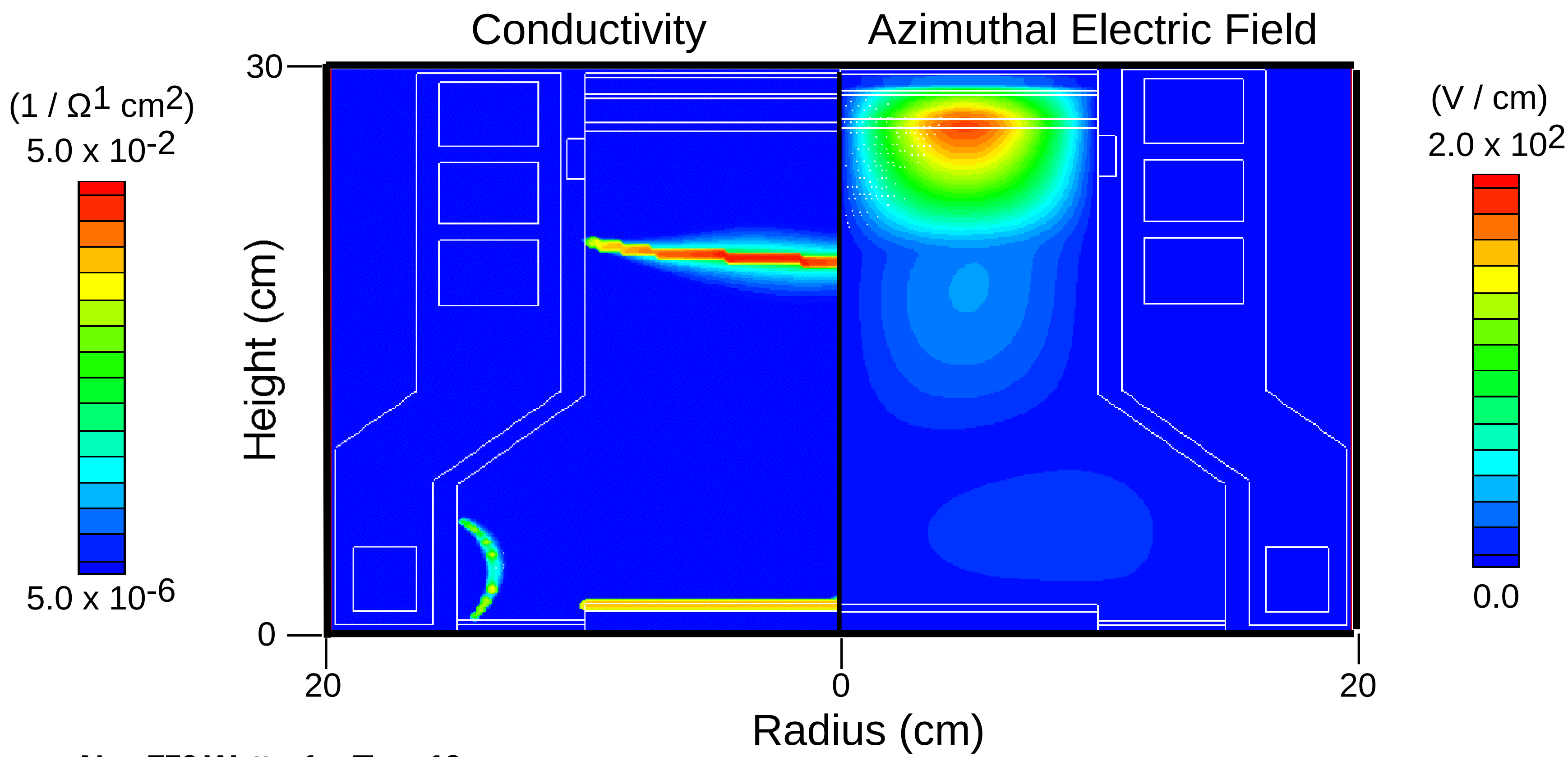
CONDUCTIVITY AND ELECTRIC FIELD

- 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

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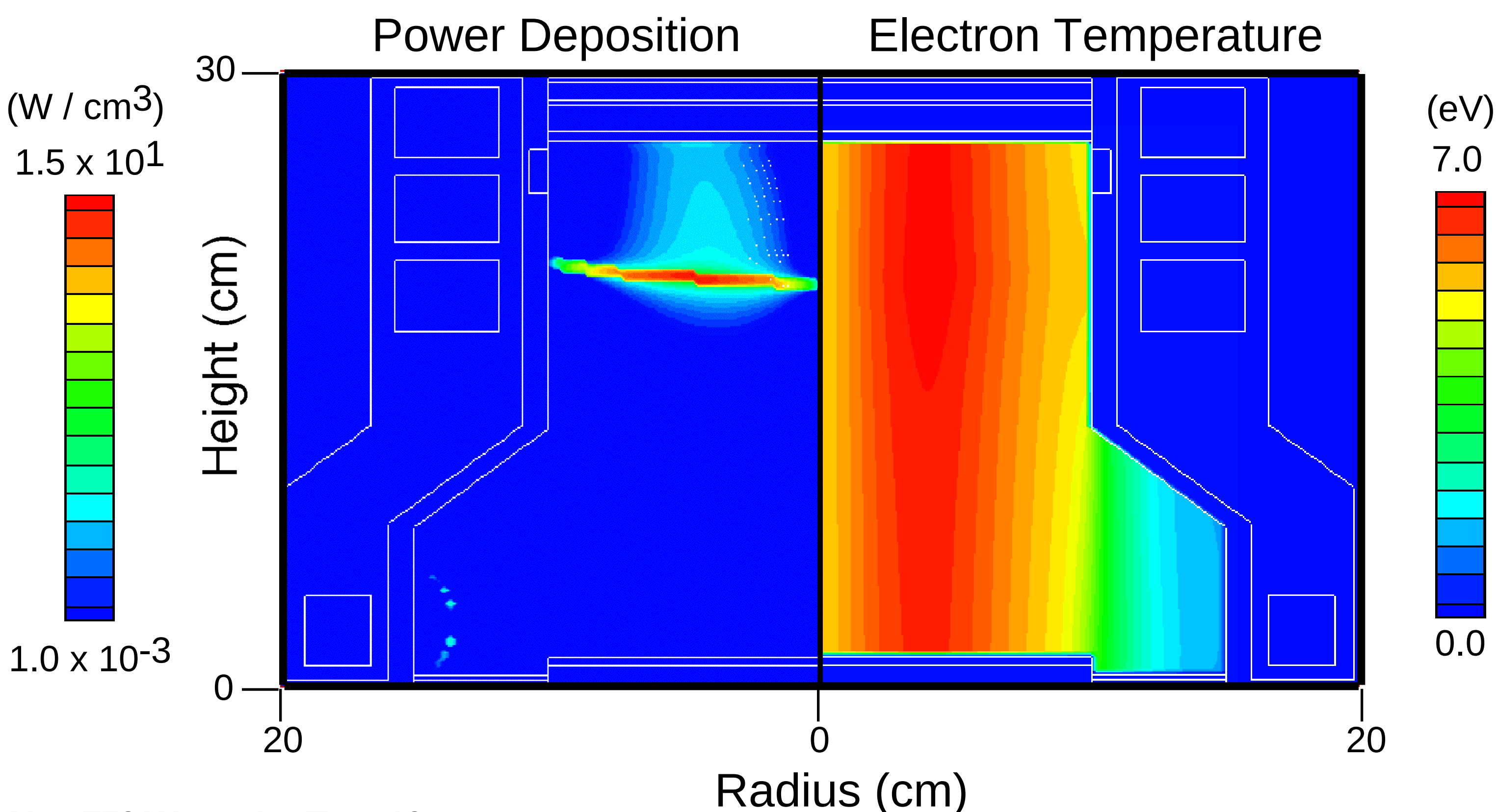
POWER DEPOSITION AND ELECTRON TEMPERATURE

- Power deposition occurs predominately within 3% of the resonance zone, although a small amount of power deposition occurs near the bottom coil due to the second resonance region created by the subcoil.

- Electron temperatures in the resonance zone reflect radial power deposition distributions. Enhanced diffusion along magnetic field lines allows the radial electron temperature to maintain its profile far into the downstream region.



•N_2, 750 Watts, 1 mTorr, 10 sccm

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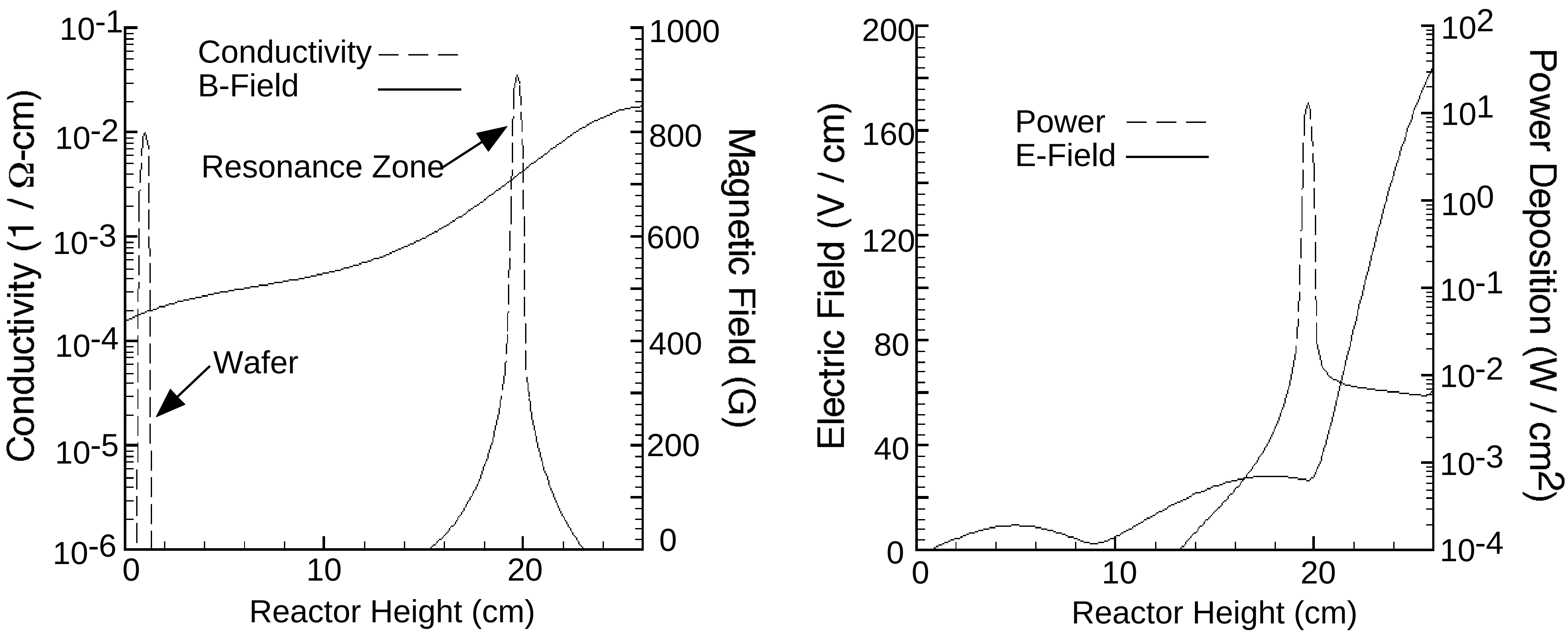
AXIAL PROFILES OF PLASMA PARAMETERS

- Power deposition peaks near the location of resonance. However, the continual absorption of the incident electromagnetic wave in the upstream region produces a small amount of power deposition that constitutes about 2% 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

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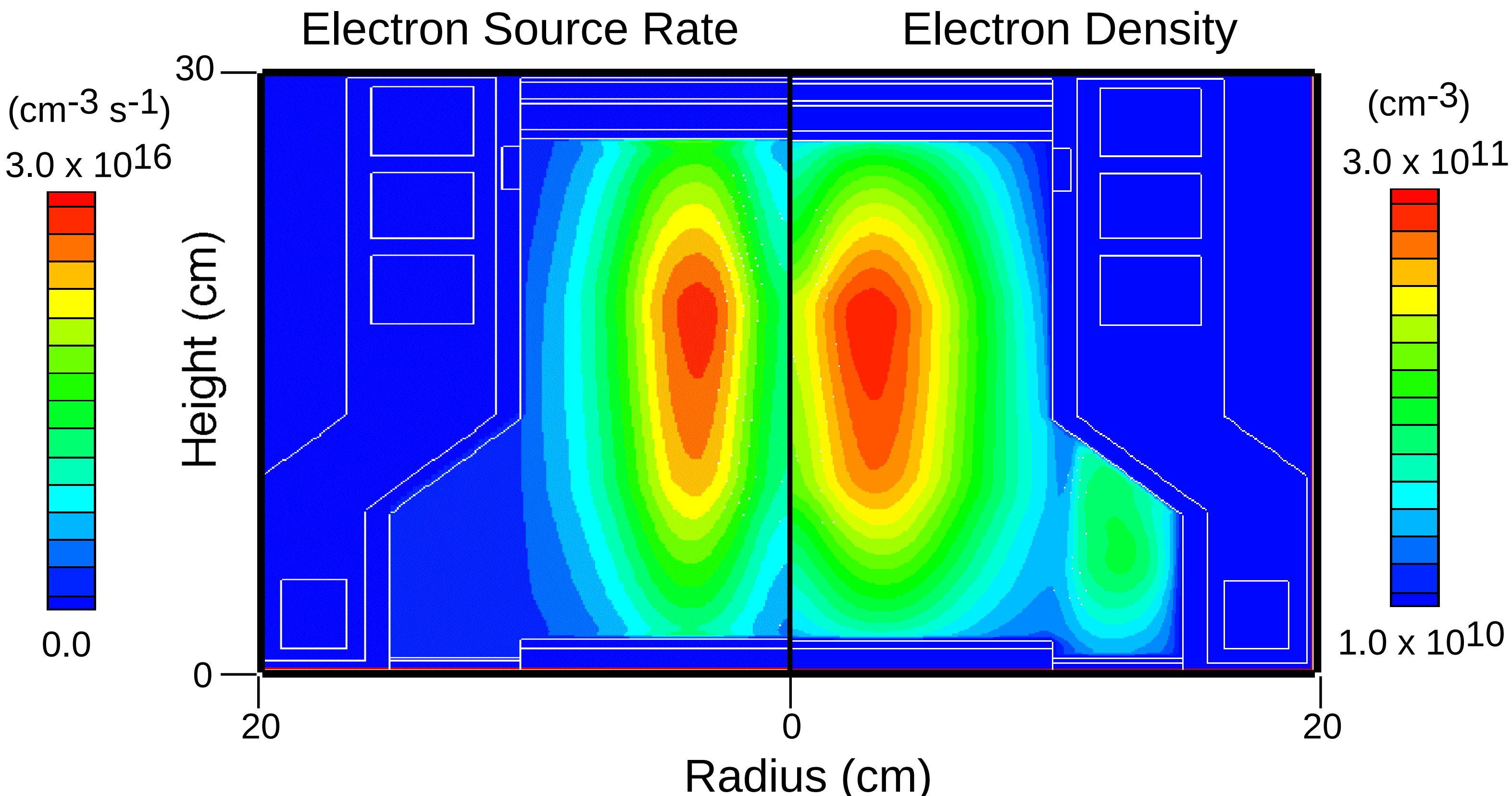
ELECTRON SOURCE RATE AND DENSITY

- The ionization rate follows the power deposition distribution in the resonance zone. Enhanced transport along the magnetic field lines allows for ionization to occur downstream.
- At these operating conditions, the radial distribution of densities tend to reflect their radial sources. Due to a small amount of power deposition that occurs near the subcoil, there is a local peak in the electron density.



•N_2, 750 Watts, 1 mTorr, 10 sccm

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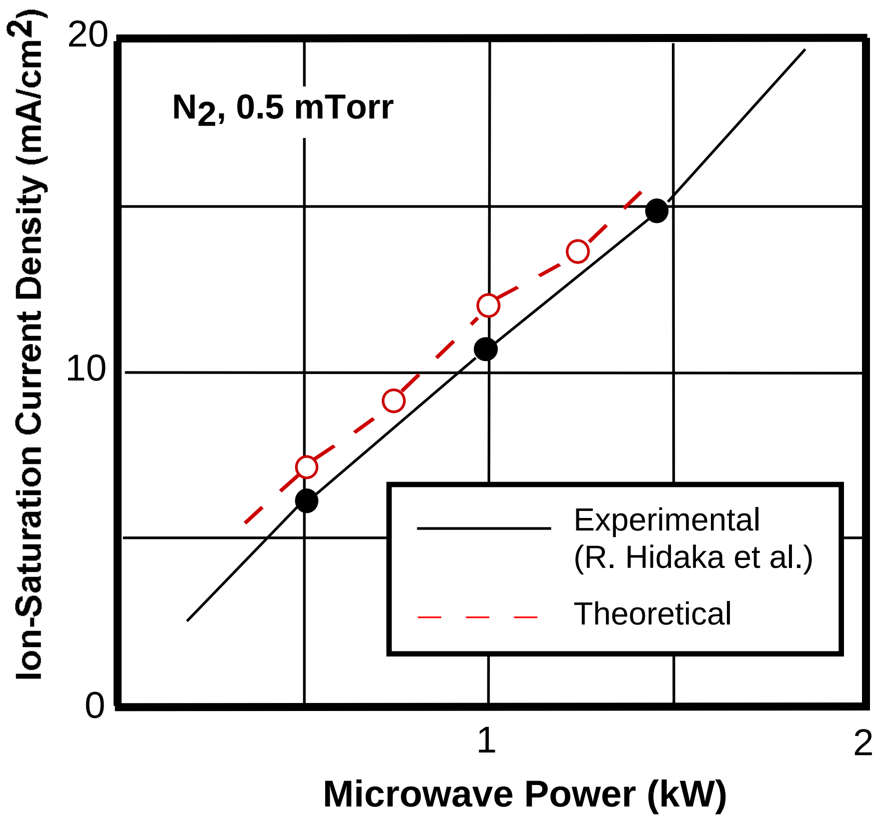
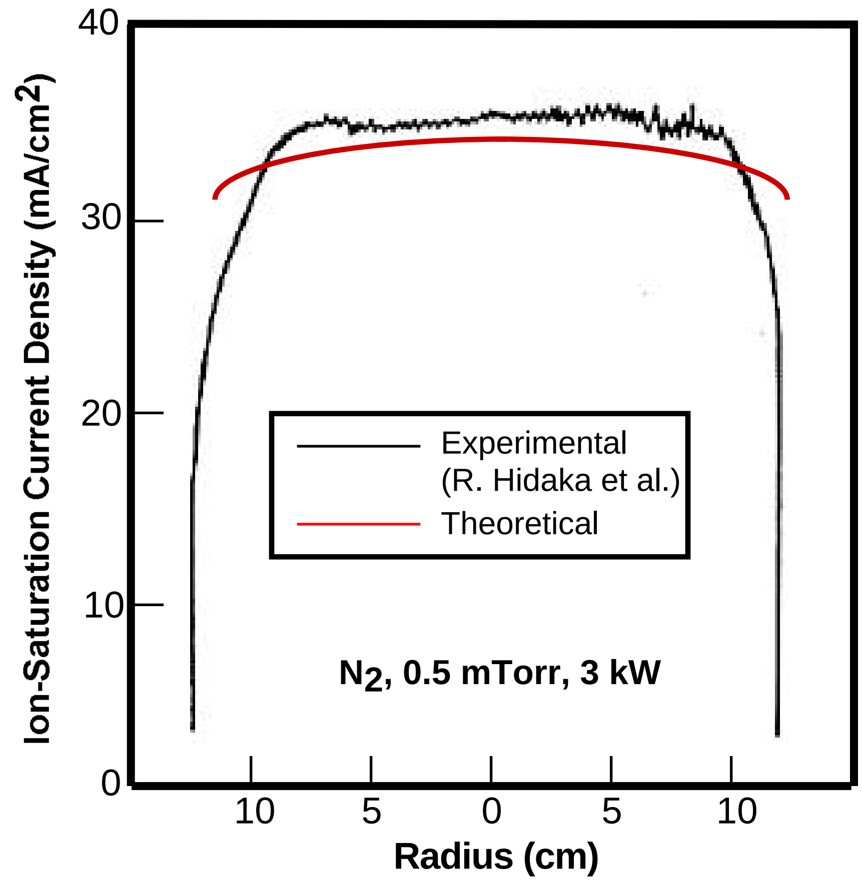
ION SATURATION CURRENT VALIDATION

• To validate trends of flux to the substrate, control experiments conducted at Kyushu University, Japan (R. Hidaka *et al.*, Jpn. J. Appl. Phys. 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.

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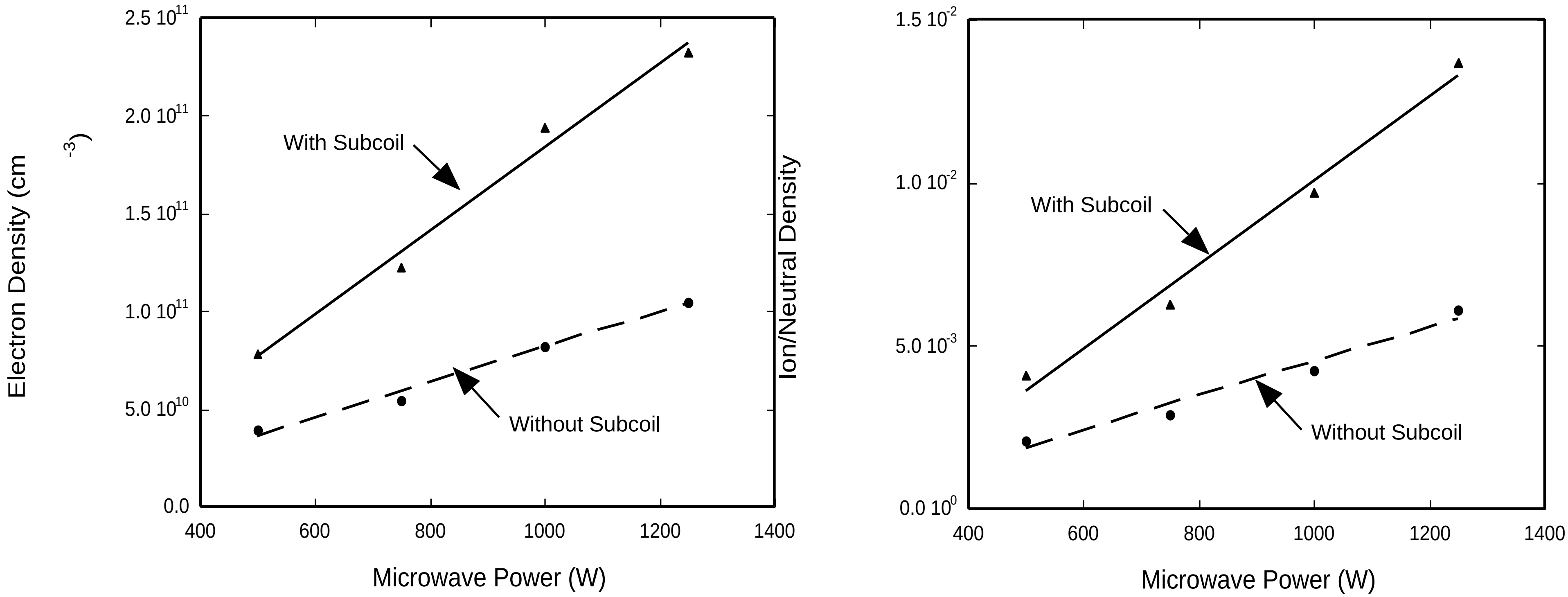
EFFECTS OF SUBCOIL ON PLASMA DENSITY

- By producing a solenoidal magnetic field configuration, diffusion losses to walls are significantly reduced.
- Ionization efficiency of the neutral gas is enhanced with the activation of the subcoil.



•N_2, 1 mTorr, 10 sccm

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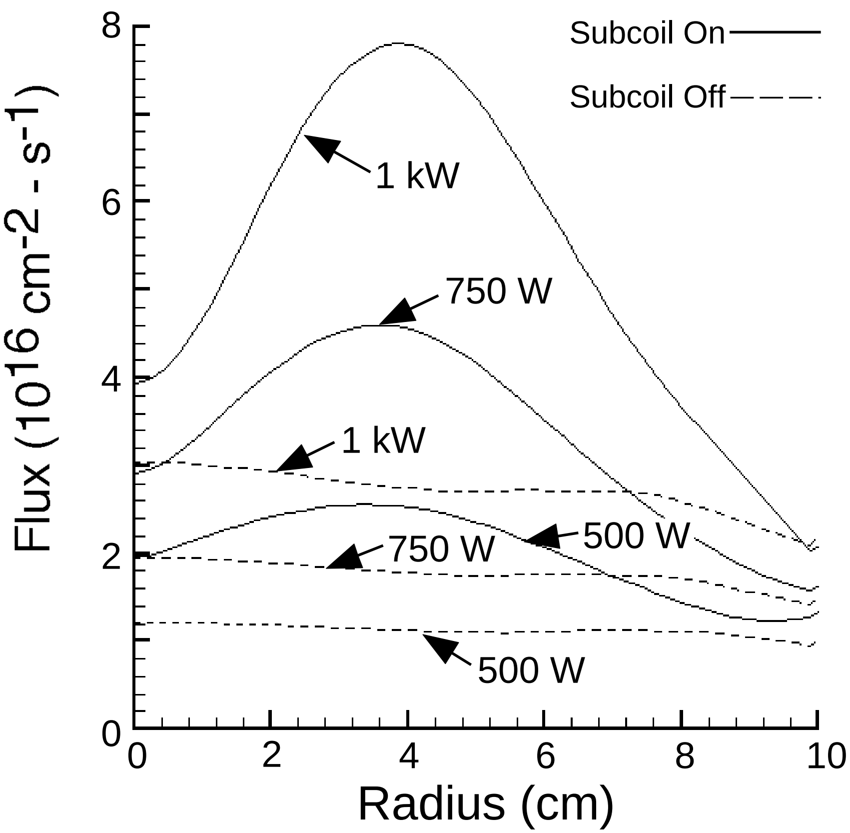
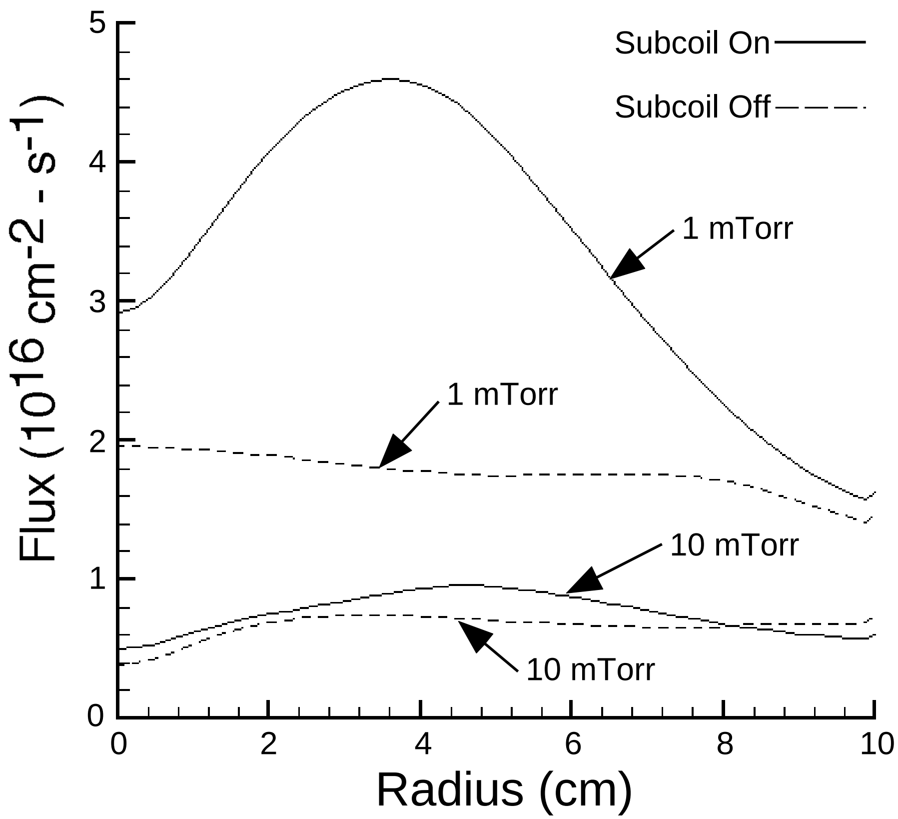
EFFECTS OF SUBCOIL ON ION FLUX TO THE SUBSTRATE

- The use of the subcoil causes the flux to the substrate to more closely reflect reactor density profiles. An increase in power leads to the enhancement of any non-uniformities present in the flux profile.

- At higher pressures the sensitivity on subcoil activation is decreased and the uniformity of the flux is improved.





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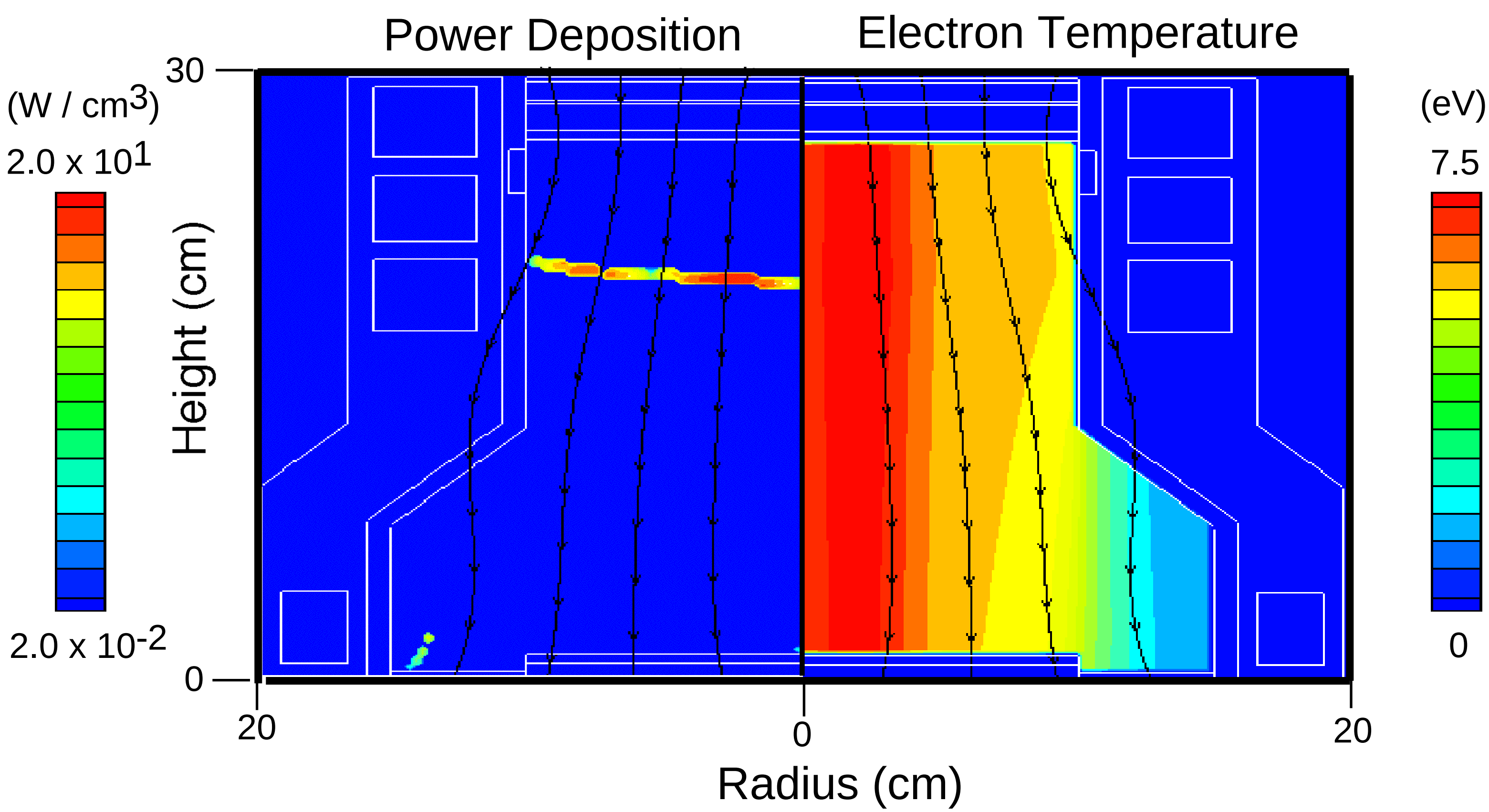
POWER DEPOSITION AND ELECTRON TEMPERATURE : TE(0,2)

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

- Enhanced diffusion along the magnetic field lines allows the radial electron temperature to maintain its profile far into the downstream region.



•N_2, 750 Watts, 1 mTorr, 10 sccm

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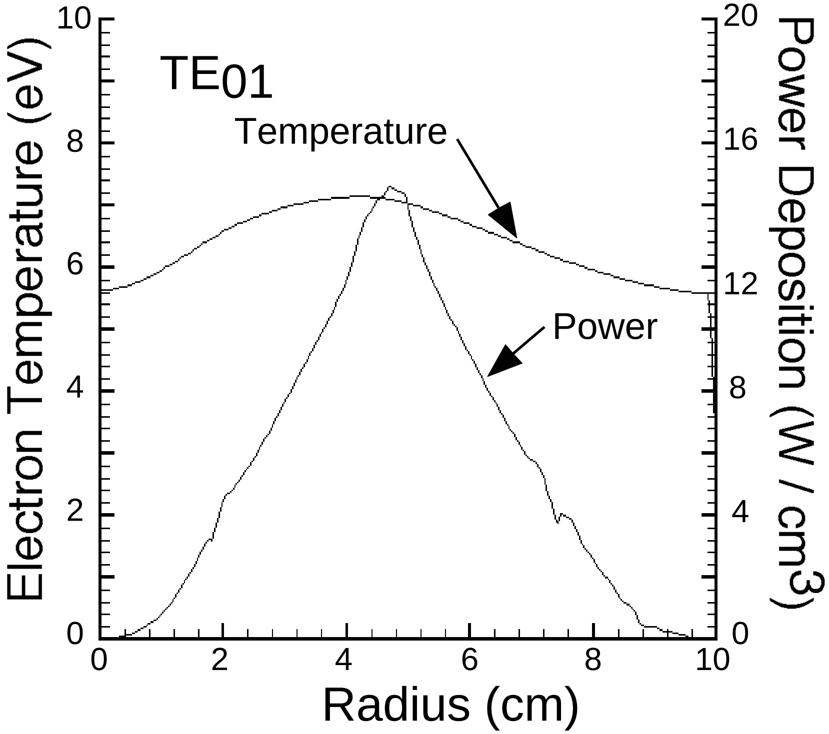
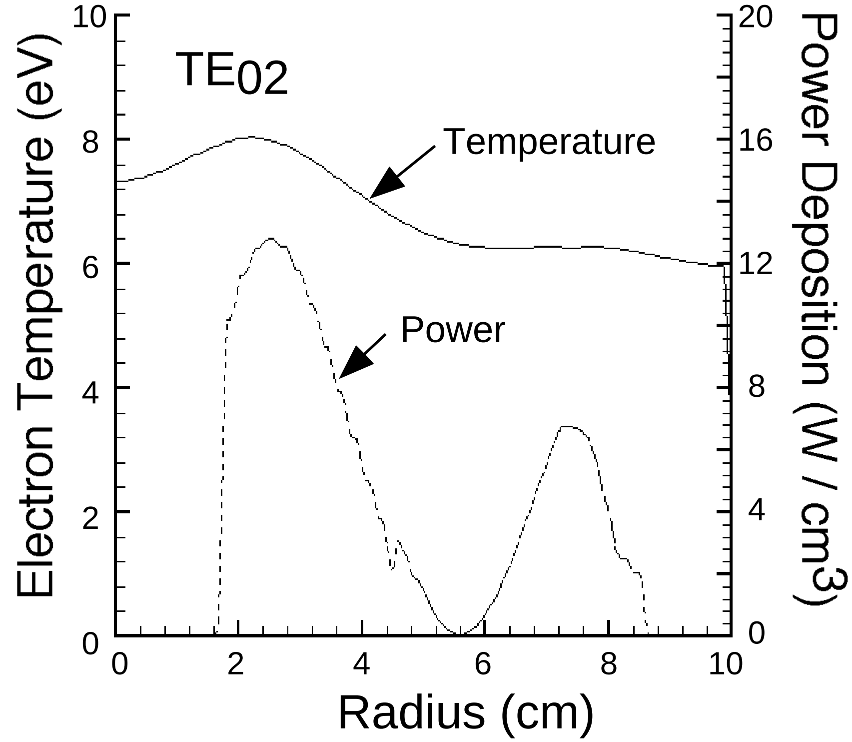
AXIAL PROFILES OF PLASMA PARAMETERS : TE(0,2)

- Radial electron temperature for higher order modes does not directly reflect the radial power deposition profiles. For the TE(0,2) mode, the radial electron temperature profile exhibits only one off axis peak.

- The superposition from both peaks in the power deposition for the TE(0,2) mode causes the temperature distribution to be constant outside of the first node in the power deposition radial profile.





•N_2, 750 Watts, 1 mTorr, 10 sccm, (in resonance zone).

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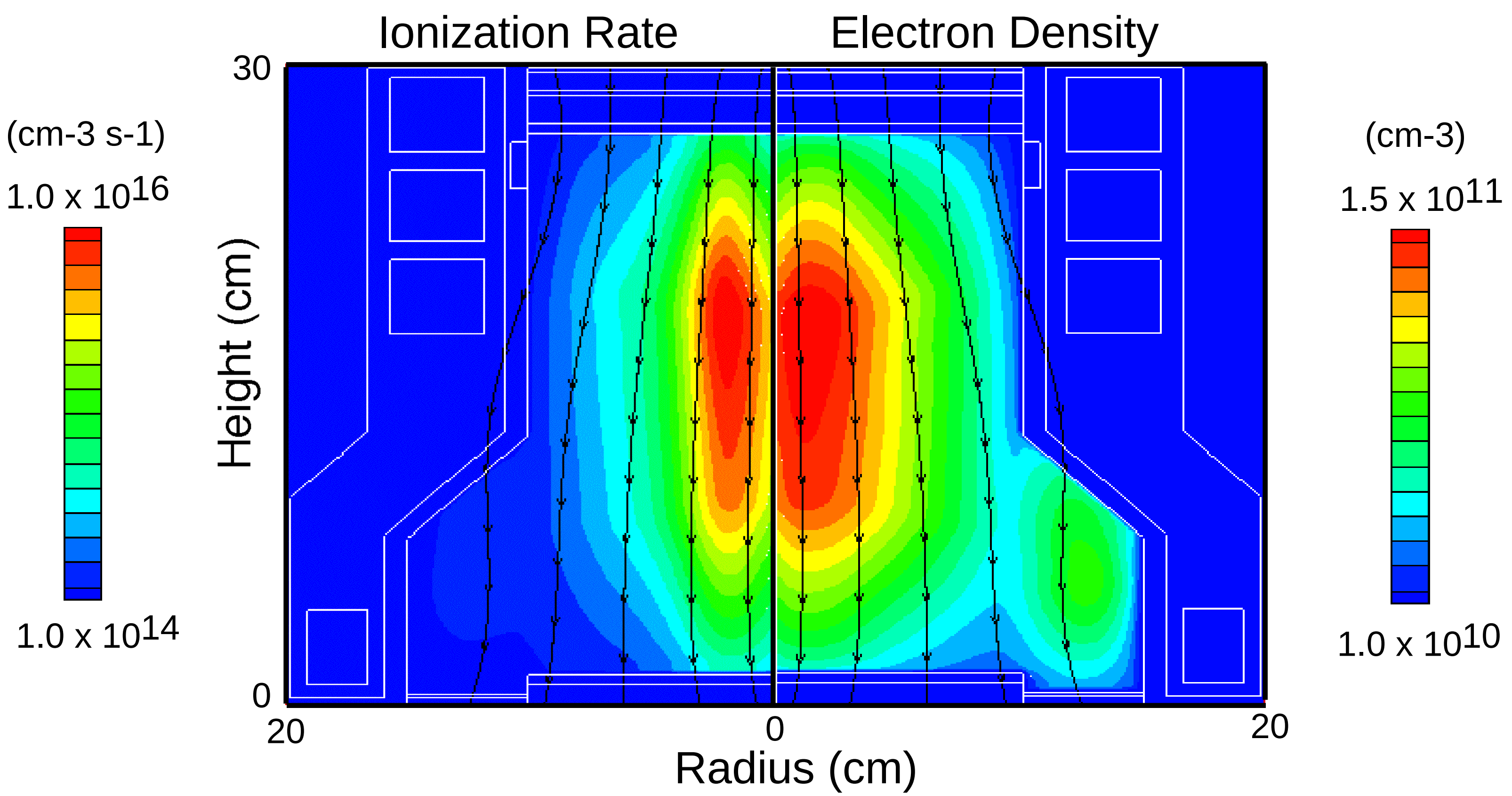
ELECTRON SOURCE RATE AND DENSITY : TE(0,2)

- The central peak in the radial temperature for the TE(0,2) case produces ionization rates that are peaked closer to the axis of symmetry than those produced for the TE(0,1) mode.

- At these operating conditions, the radial distribution of the electron density reflects the ionization rate.



•N_2, 750 Watts, 1 mTorr, 10 sccm

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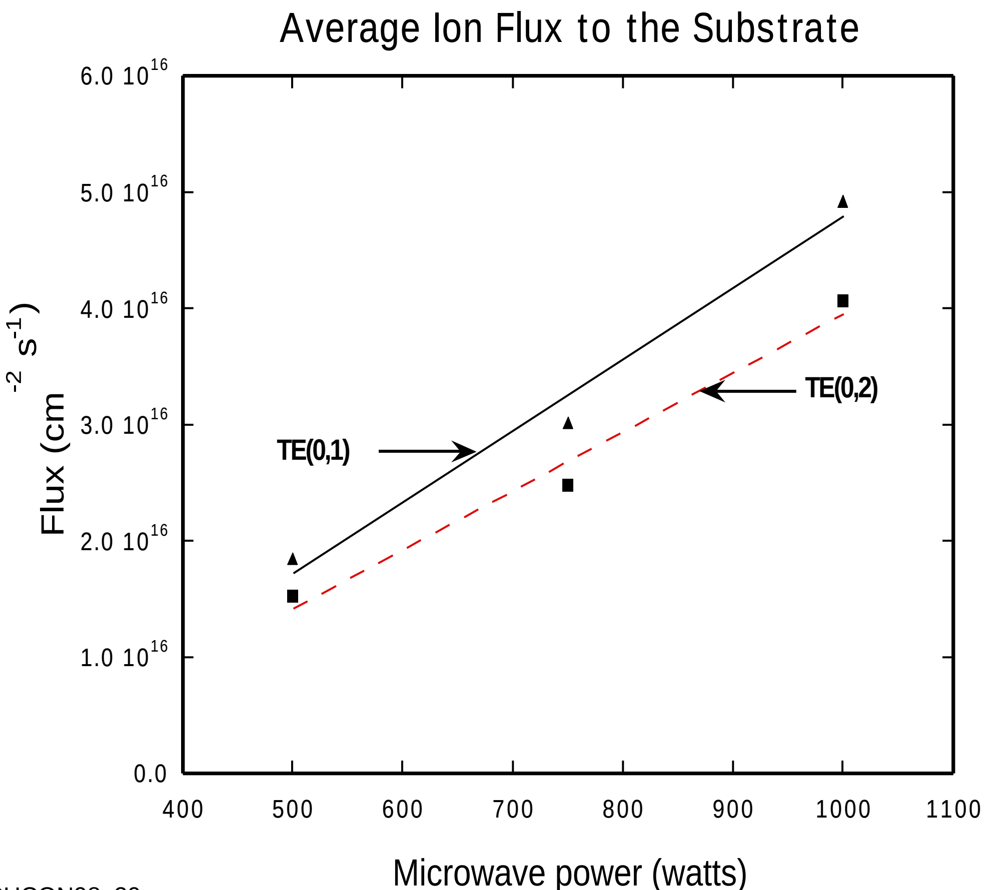
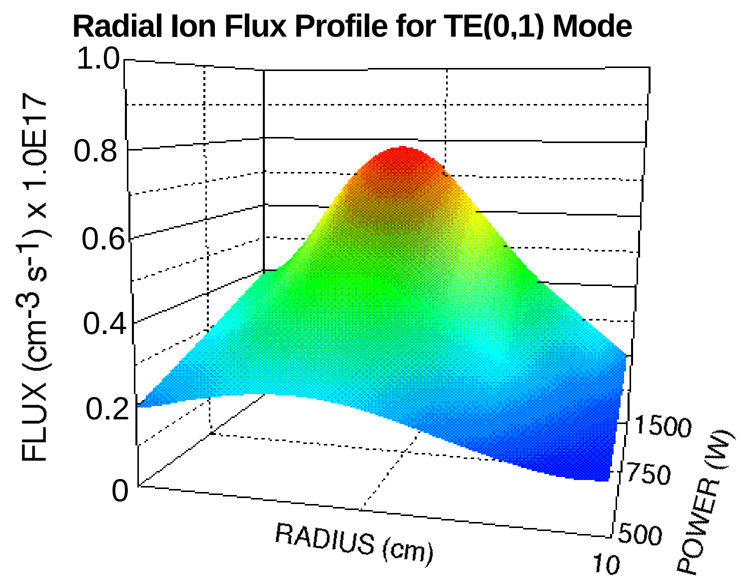
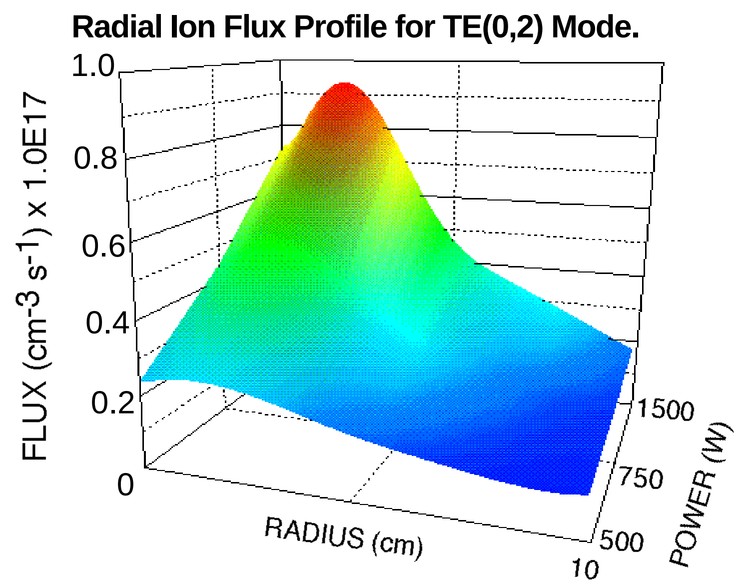
TOTAL ION FLUX TO SUBSTRATE FOR TE(0,1) AND TE(0,2)

- 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.







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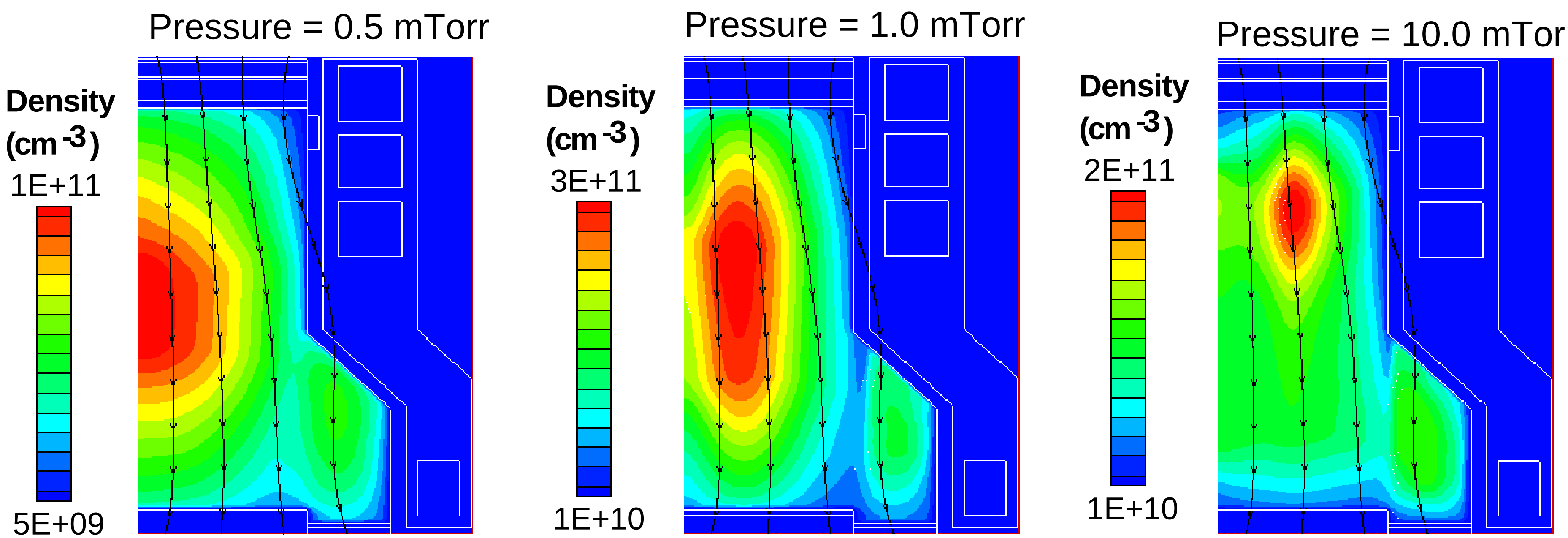
ELECTRON DENSITY DISTRIBUTION VERSUS PRESSURE



- **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 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; $D_{para.} \sim 1 / \nu_m$.

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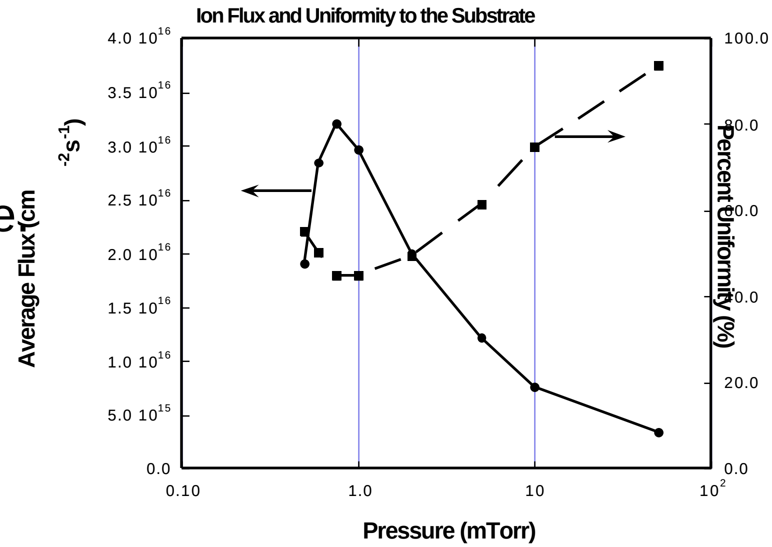
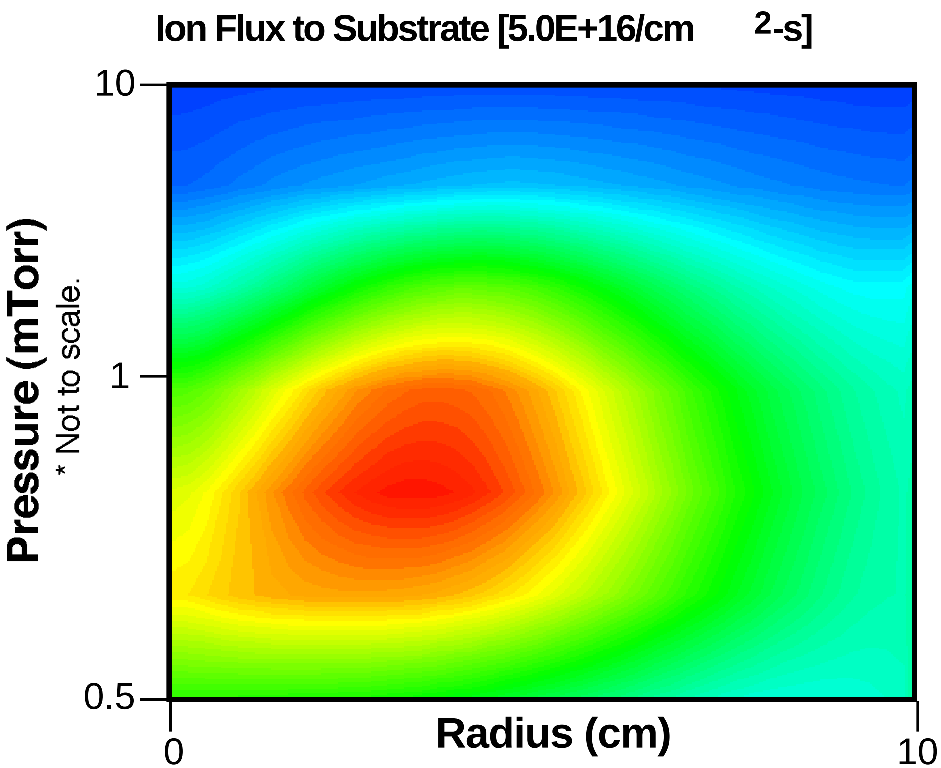
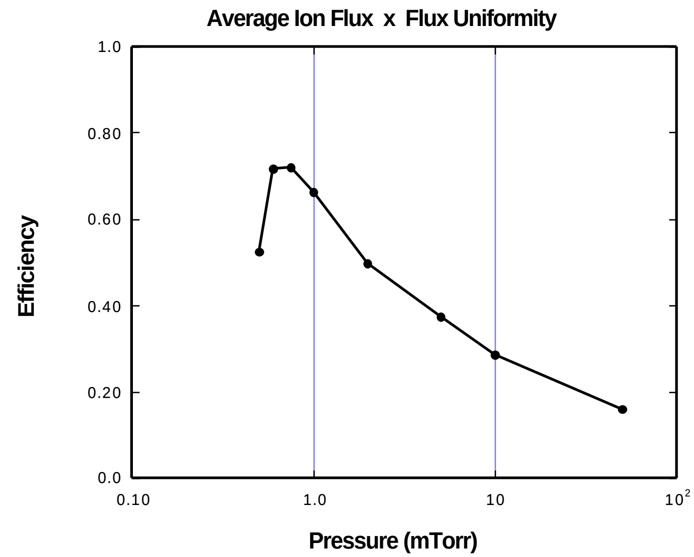
TOTAL ION FLUX TO THE SUBSTRATE

- 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.







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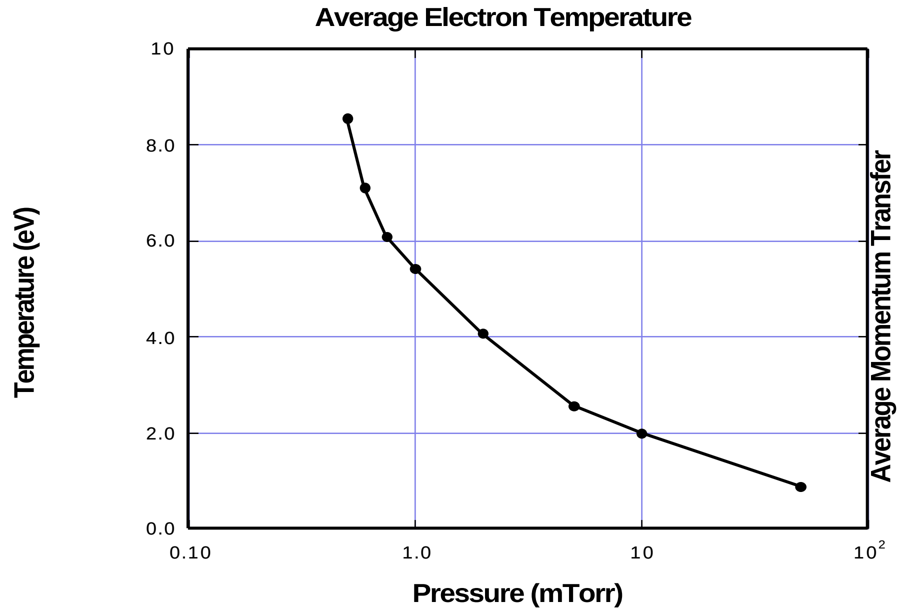
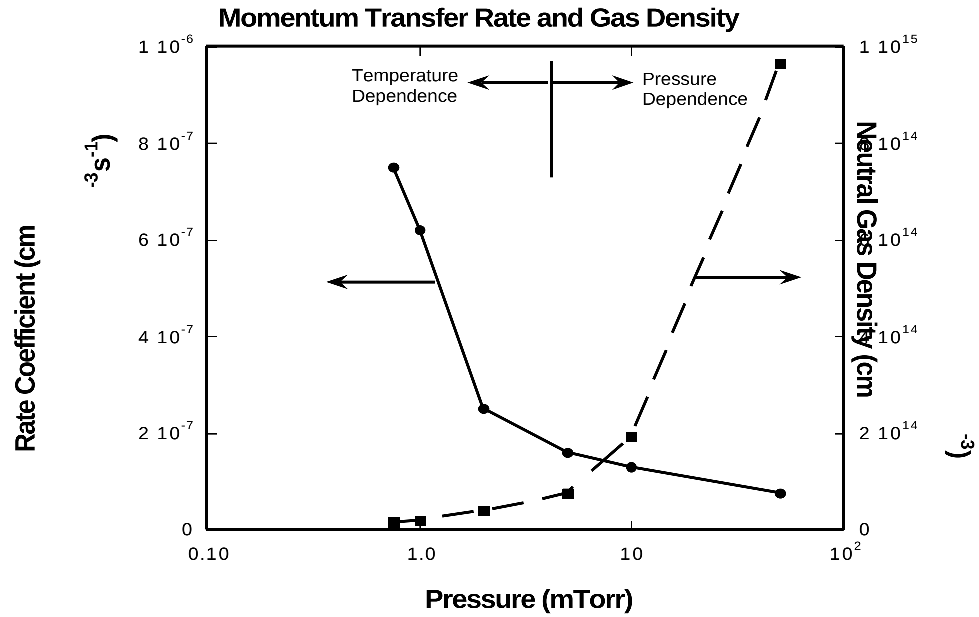
- N_2, 750 Watts, 10 sccm, TE(0,1) mode

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.

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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 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.
- 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.