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SIMULATIONS OF LOW FIELD HELICON DISCHARGES USING A TWO DIMENSIONAL HYBRID PLASMA EQUIPMENT MODEL*

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AGENDA

- Introduction to Helicon Discharges
- Hybrid Plasma Equipment Model (HPEM)
- Cold Plasma Tensor and Collisionless Heating
- Helicon Behavior in a Solenoidal Field
  - Low Field Inductive to Cyclotron Mode Transition
  - High Field Inductive-Helicon Mode
- Helicon Tool Design
- Conclusions and Future Work

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INTRODUCTION TO HELICON DISCHARGES

- Due to their high ionization efficiency, high flux density and their ability to deposit power within the volume of the plasma, helicon reactors are being developed for downstream etching and deposition.

- The power coupling of the antenna radiation to the plasma is of concern due to issues related to process uniformity.

- Furthermore, operation of helicon discharges at low magnetic fields (5 -20 G) is not only economically attractive, but lower fields provide greater ion flux uniformity to the substrate.

- To investigate these issues, we have improved the electromagnetics module of the HPEM to resolve the helicon structure of a m = 0 mode.

- Results for process relevant gas mixtures are examined and the dependence on magnetic field strength, field configuration, and power are discussed.

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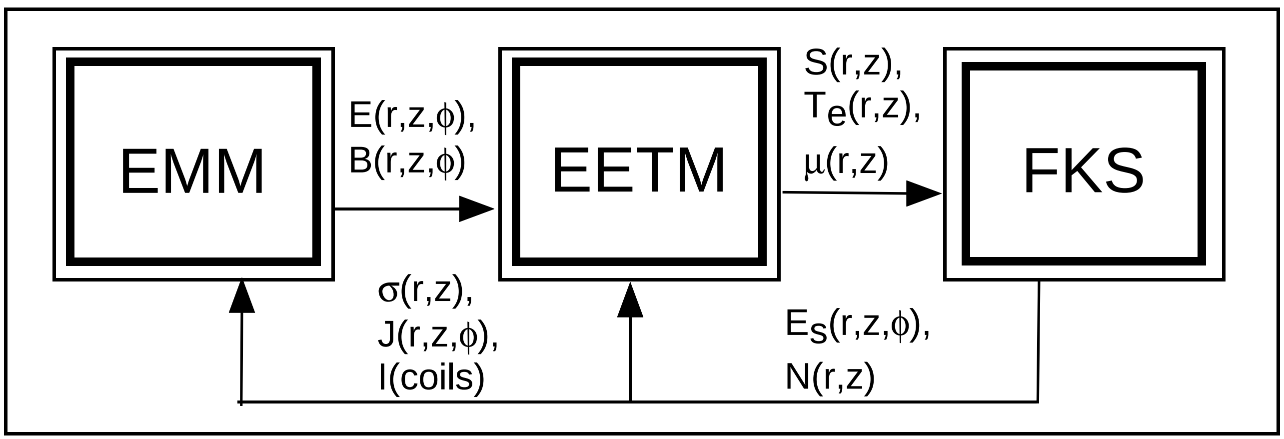
HYBRID PLASMA EQUIPMENT MODEL

- 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.



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COLD PLASMA CONDUCTIVITY TENSOR

- Algorithms were developed to enable investigations of helicon plasma tools using HPEM-2D. A full tensor conductivity was added to the Electromagnetics Module (EMM) which enables one to calculate 3-d components of the inductively coupled electric field based on 2-d applied magnetostatic fields.

$$-\nabla \cdot \left(\frac{1}{\mu} \nabla \bar{E} \right) = -i\omega \bar{\bar{\sigma}} \cdot \bar{E} - i\omega \bar{J}_{ext} + \omega^2 \varepsilon \bar{E}$$

- The plasma current in the wave equation is addressed by a cold plasma tensor conductivity.

$$\bar{\bar{\sigma}} = \sigma_o \frac{m_e \nu_m}{q\alpha} \left(\frac{1}{\alpha^2 + B^2} \right) \begin{pmatrix} \alpha^2 + B_r^2 & \alpha B_z + B_r B_\theta & -\alpha B_\theta + B_r B_z \\ -\alpha B_z + B_r B_\theta & \alpha^2 + B_\theta^2 & \alpha B_r + B_\theta B_z \\ \alpha B_\theta + B_r B_z & -\alpha B_r + B_\theta B_z & \alpha^2 + B_z^2 \end{pmatrix}$$

where, $\sigma_o = \frac{q^2 n_e}{m_e \nu_m}$ and, $\alpha = \frac{m_e}{q} (\nu_m + i\omega)$

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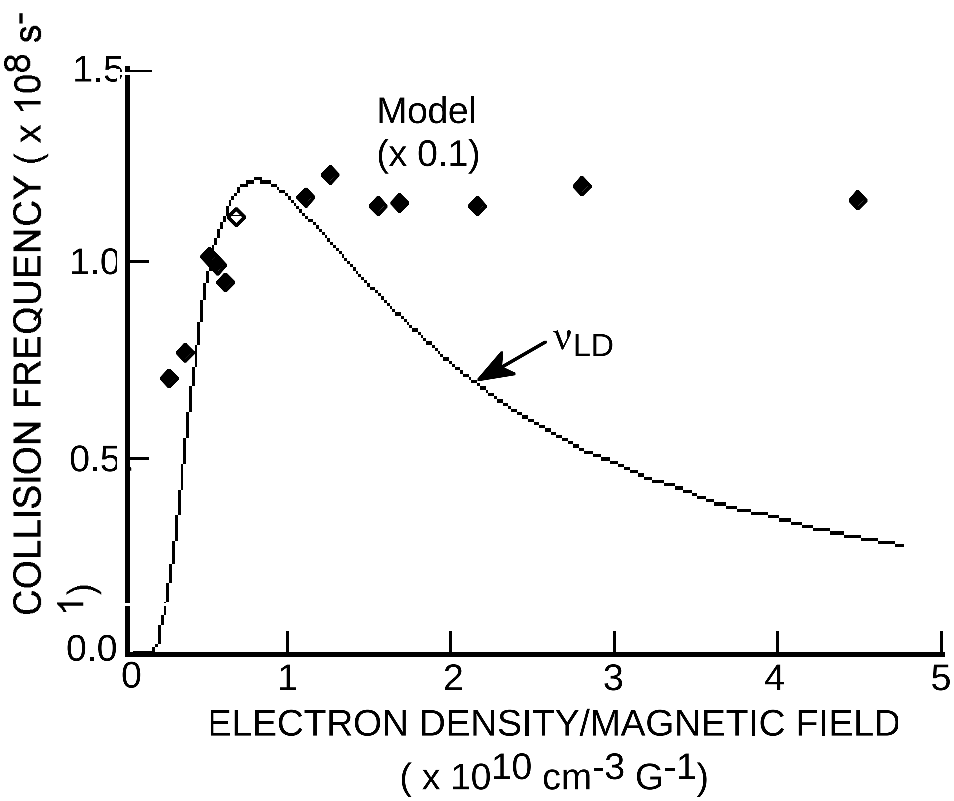
COLLISIONLESS HEATING - LANDAU DAMPING

- There is considerable evidence that collisional absorption is too weak to account for energy deposition at low pressures (< 10 mTorr Ar). Chen (1991) estimated the effective collisional frequency for Landau damping of the helicon mode as,

$$\nu_{LD} = 2\sqrt{\pi}\,\omega x^{3} \exp\left(-x^{2}\right) \quad \text{where,} \quad x = \frac{\omega}{k_z \sqrt{2}\, v_{th}}$$



- Landau damping contributes to about 10% of the momentum transfer collision frequency (at 10 mTorr Ar).

- In the low electron density and high magnetic field regimes, Landau damping significantly affects the power deposition efficiency.

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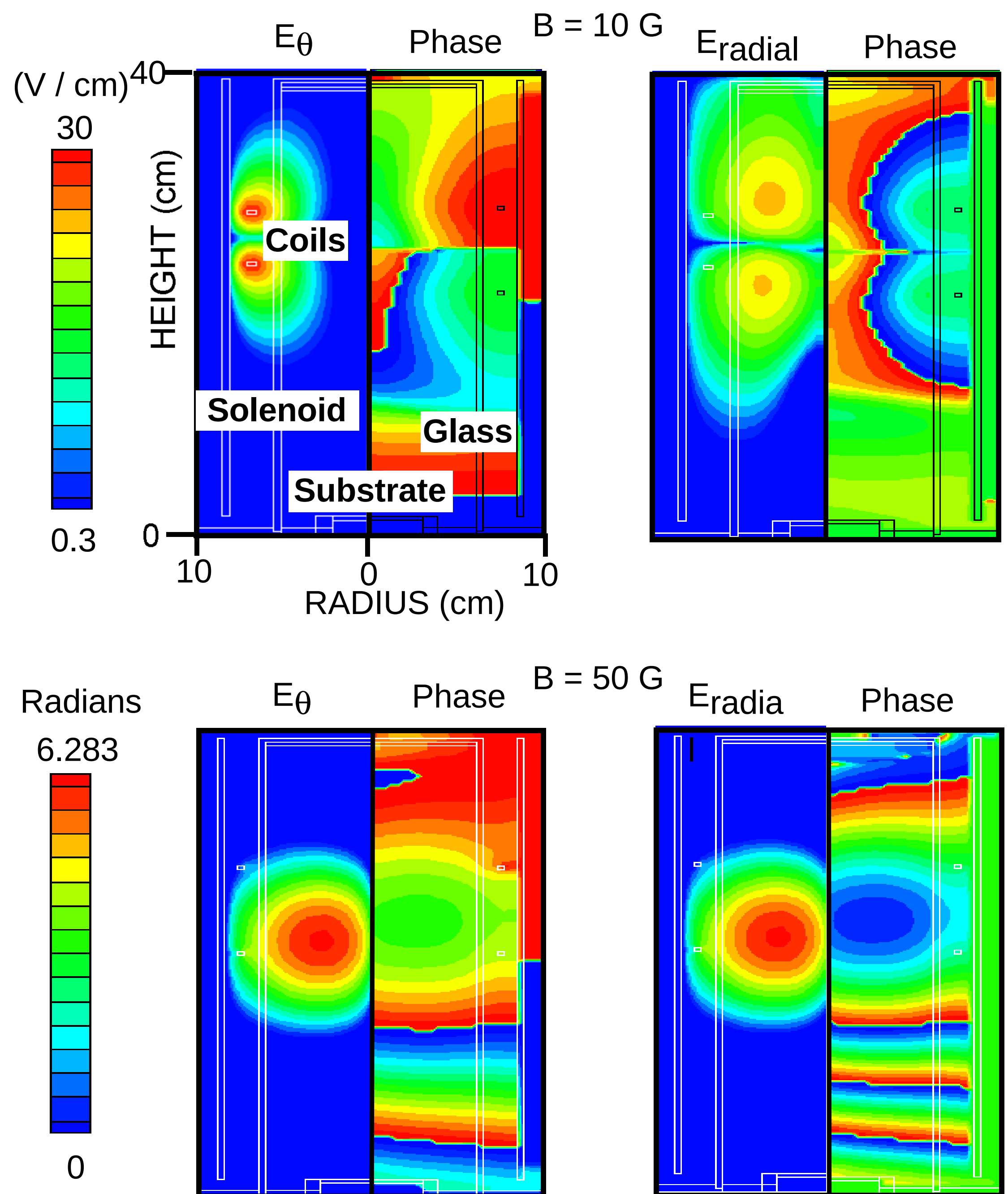
LOW FIELD INDUCTIVE TO HELICON TRANSITION



- At a critically low magnetic field, the electric fields remain inductively coupled, however a radially traveling wave dominates.
- As the magnetic field strength increases, the damped Helicon wave appears, propagating in the axial direction.
- In a solenoidal field the propagation of the *m* = 0 mode changes from purely azimuthal to purely radial with an axial wavelength of ~ 15 cm.
- Ar, 1 mTorr, 1 kW, 20 sccm

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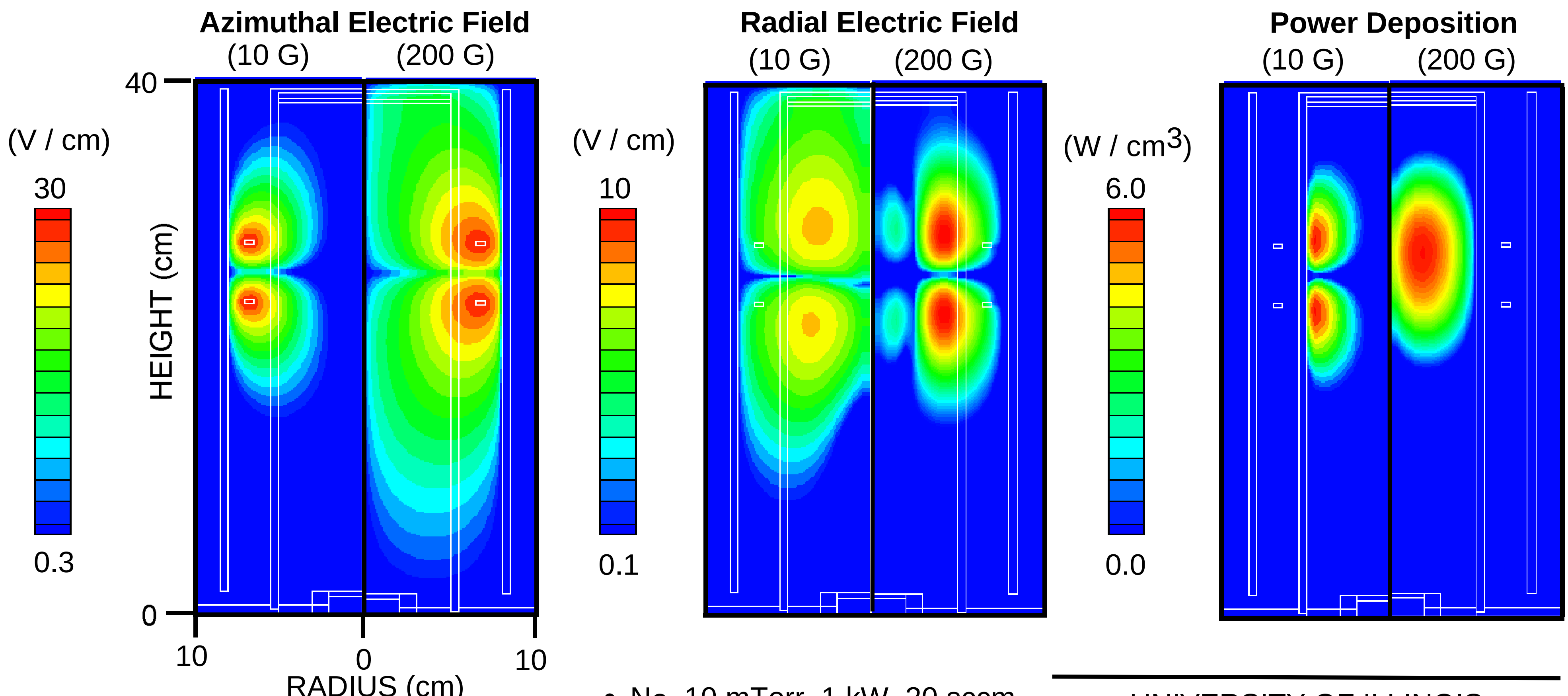
HELICON: ELECTRIC FIELDS AND POWER

- At high magnetic fields (200 G) standing wave patterns can be observed in the radial electric field indicative of helicon behavior.

- For certain combinations of magnetic field and power, the radial electric field is of the order of the azimuthal electric field. This allows the skin depth of the power deposition to increase into the plasma.



- N_2, 10 mTorr, 1 kW, 20 sccm

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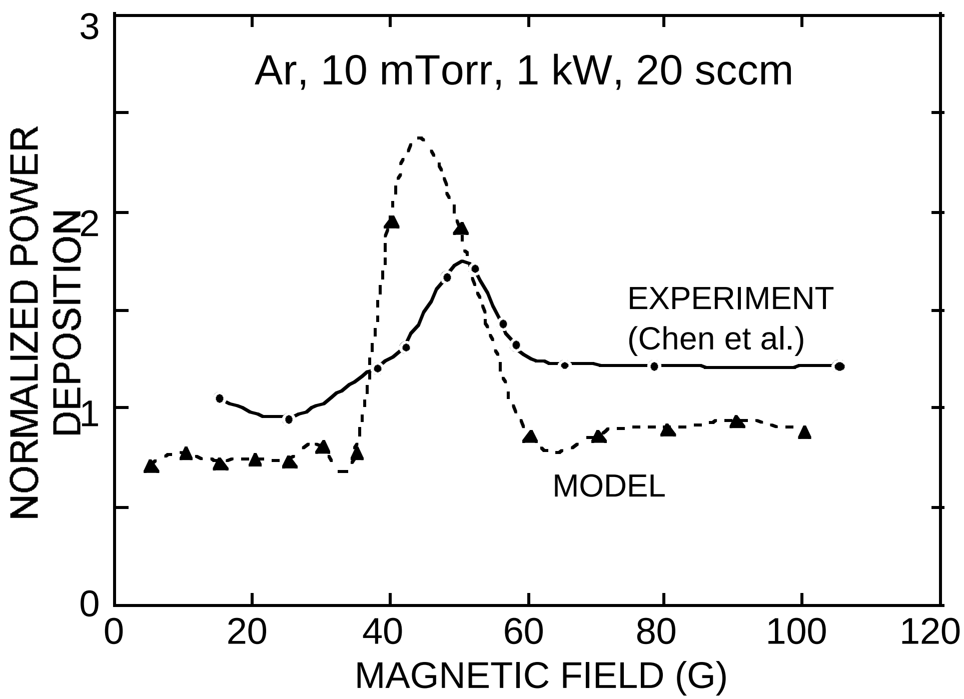
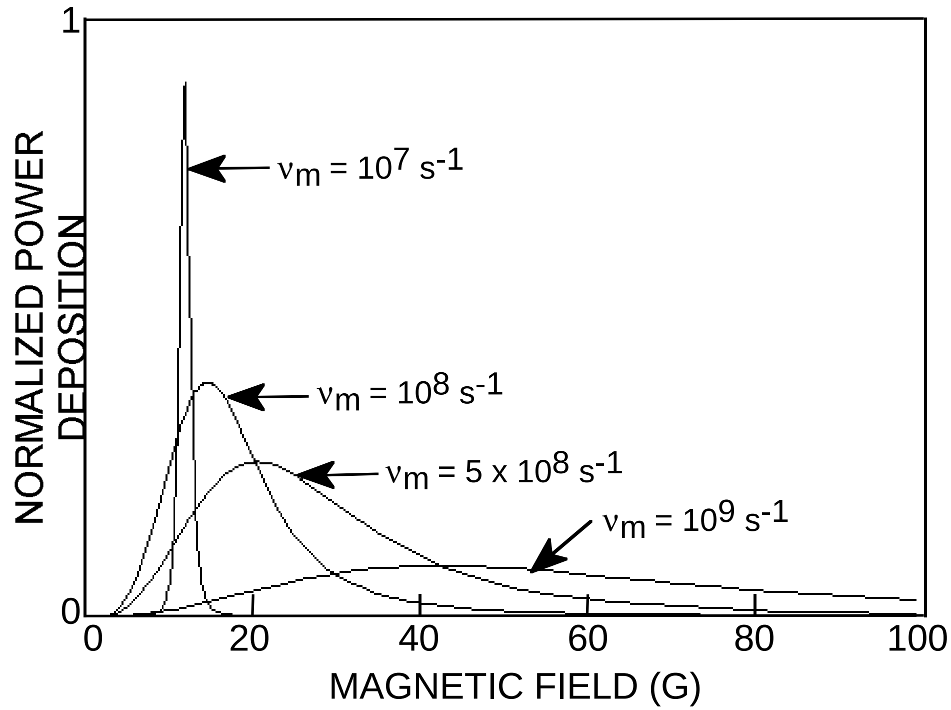
LOW FIELD CYCLOTRON PEAK

- Power coupling of antenna radiation to the plasma at low B-fields (< 100 G) was investigated. This mode of operation is not only economically attractive, but lower magnetic fields enable one to more easily tailor uniform ion fluxes to the substrate.

- Parametric studies in the low B-field range show a resonant peak in the plasma density in the downstream region. Results, compared to experiments by Chen, are attributed to "off resonant" electron-cyclotron heating.





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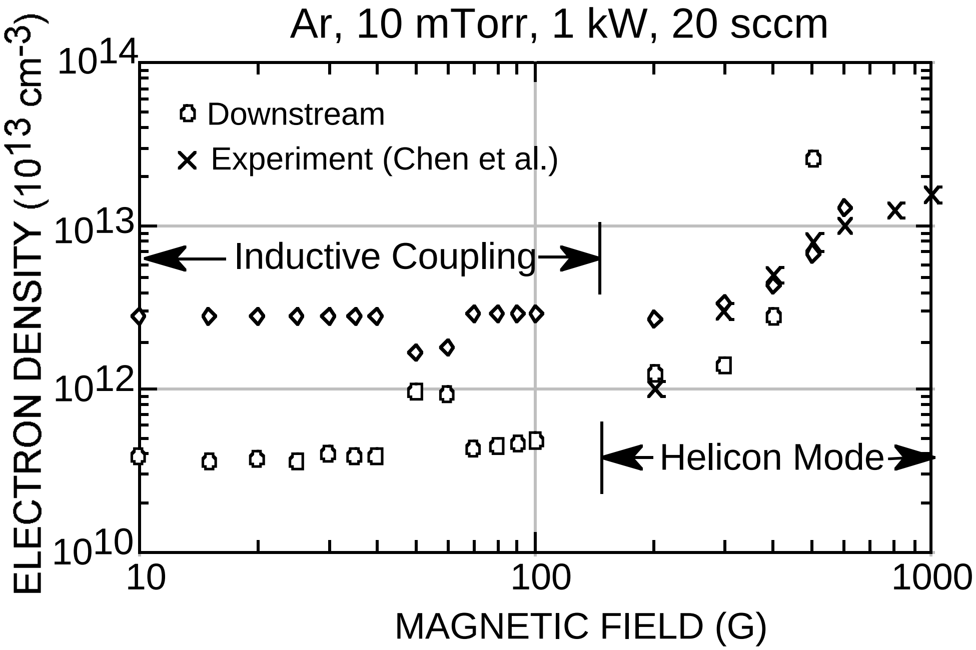
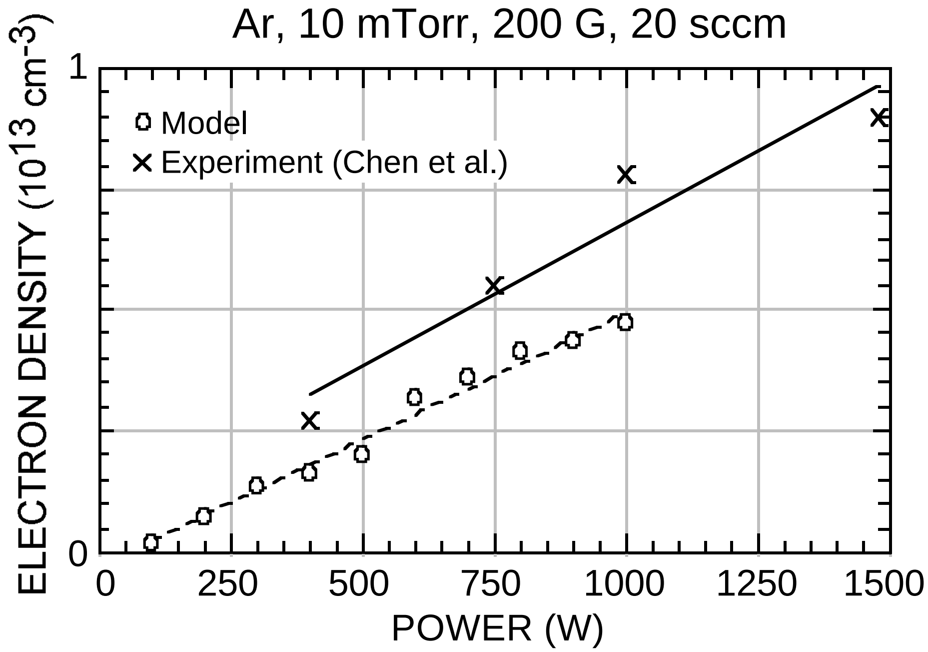
INDUCTIVE - HELICON MODE TRANSITION

- The transition from inductive coupling to helicon mode appears to occur when the fraction of power deposited through the radial and axial fields dominates.

- The improved HPEM has been able to reproduce Inductive to Helicon transitions in the magnetic field spectrum. Differences between the simulation and experimental results are attributed to small variations in geometry and antenna design.

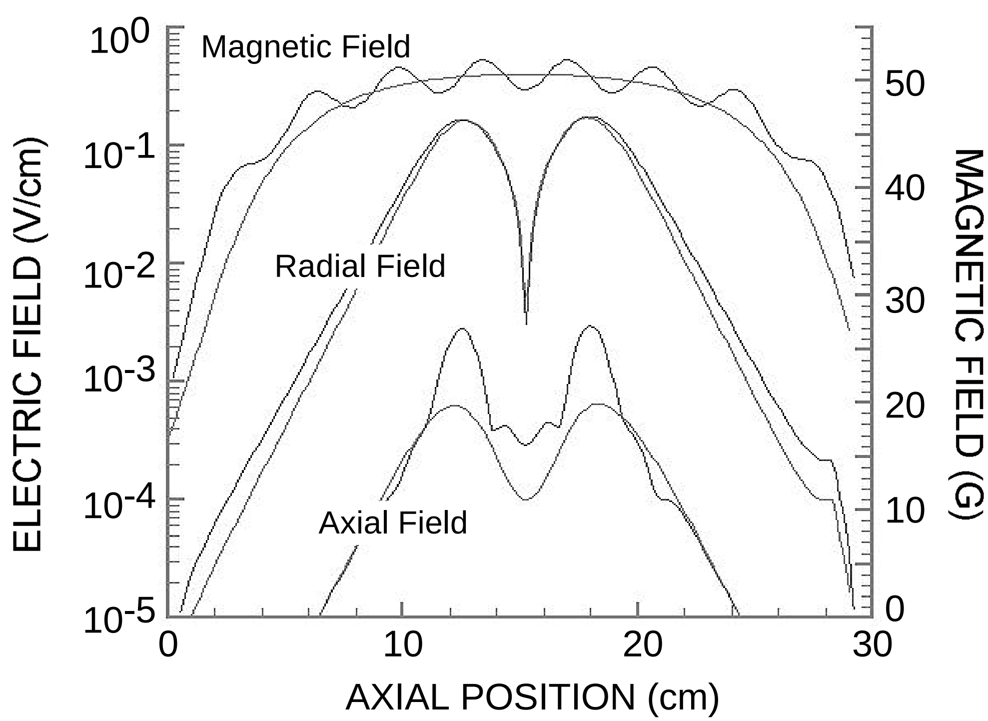


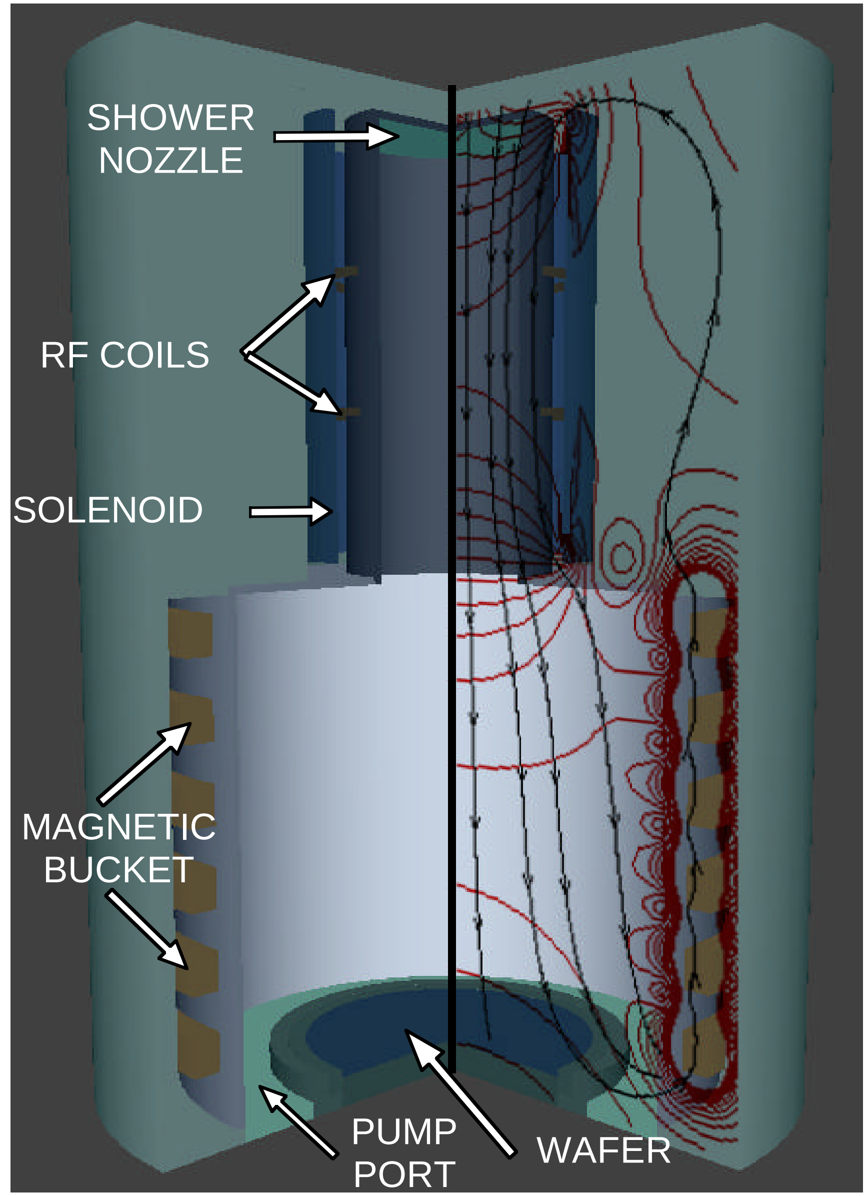


APPLICATION OF HPEM TO HELICON TOOL DESIGN

- Investigations have begun applying the HPEM to helicon tool design.

- Preliminary results show that the axial electric field has a strong dependence on details of the magnetic field configuration, and could control the inductive-helicon mode transition.





- Ar, 10 mTorr, 1kW, 20 sccm

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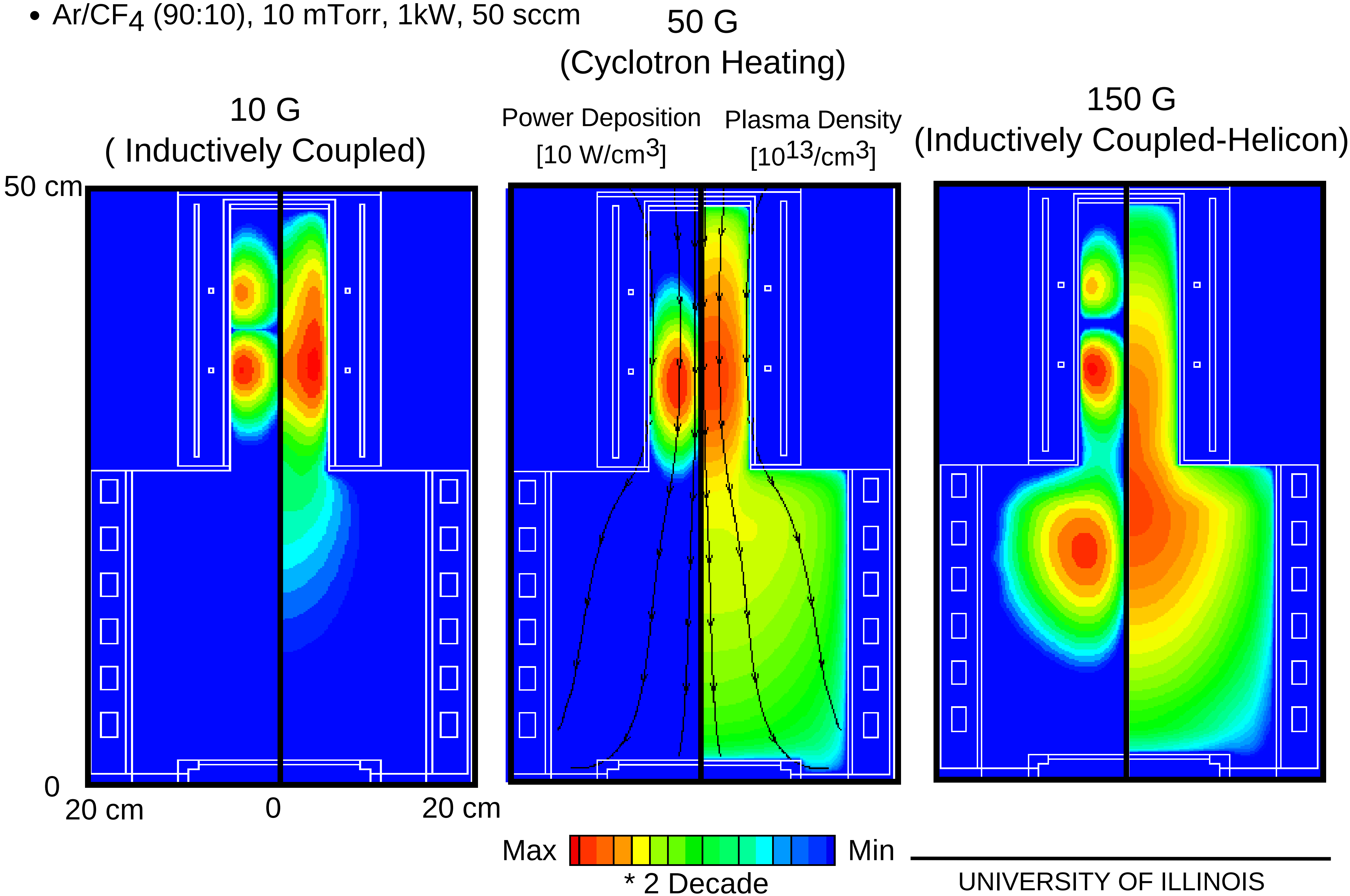
APPLICATION OF HPEM TO HELICON TOOL DESIGN

- Ar/CF_4 (90:10), 10 mTorr, 1kW, 50 sccm



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CONCLUDING REMARKS

- Algorithms were developed to enable investigations of helicon plasma tools using HPEM-2D. In the low electron density and high magnetic field regimes, Landau damping significantly affects the power deposition efficiency.

- Parametric studies in the low magnetic field range show three well defined regimes
  - i) enhanced inductively coupled mode.
  - ii) a resonant peak in the power deposition efficiency and plasma density, an effect attributed to off-resonant cyclotron heating.
  - iii) inductively coupled - helicon mode regime.

- The transition from inductive coupling to helicon mode appears to occur when the fraction of power deposited through the radial and axial fields dominates.

- Studies have begun applying the improved HPEM to tool design. Improvements wil be transferred to HPEM-3D.

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