

# **SIMULATIONS OF HELICON DISCHARGES USING A TWO DIMENSIONAL HYBRID PLASMA EQUIPMENT MODEL\***

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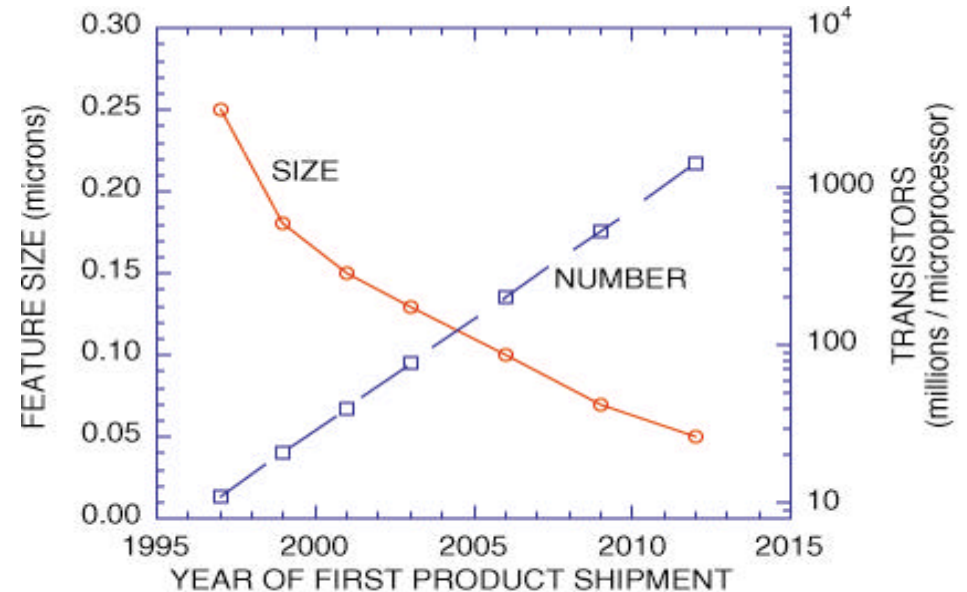
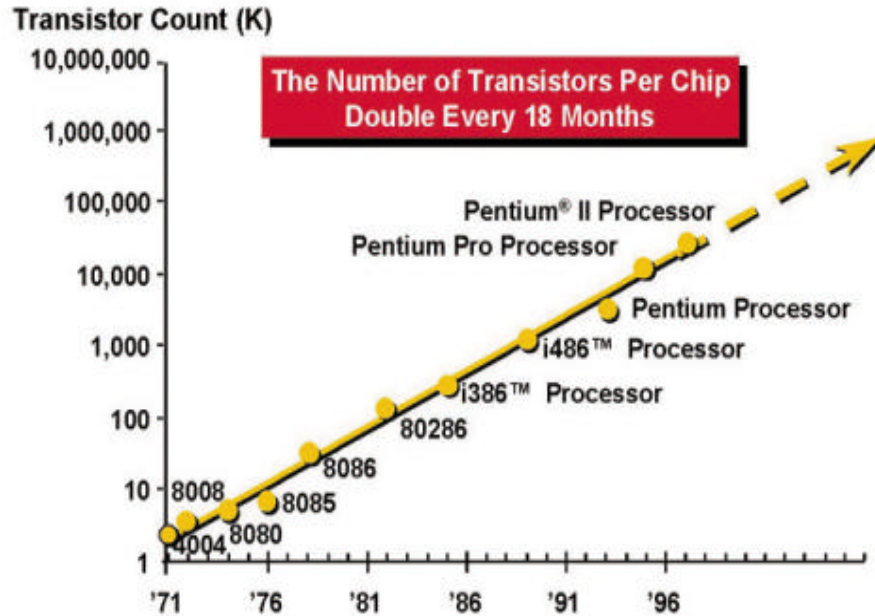
# AGENDA

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- Foreword: Plasma Processing
- 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

# NATIONAL TECHNOLOGY ROADMAP FOR SEMICONDUCTORS

- In the early 1980's, Gordon Moore (Intel) observed that the complexity and performance of microelectronics chips double every year and a half.

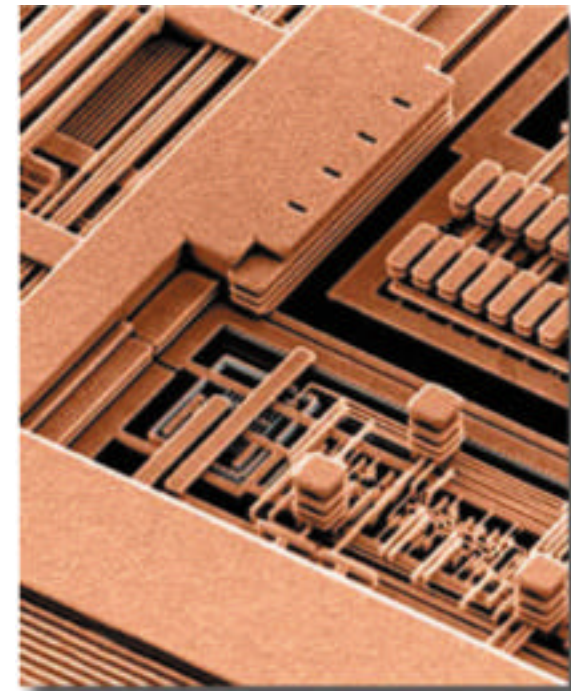
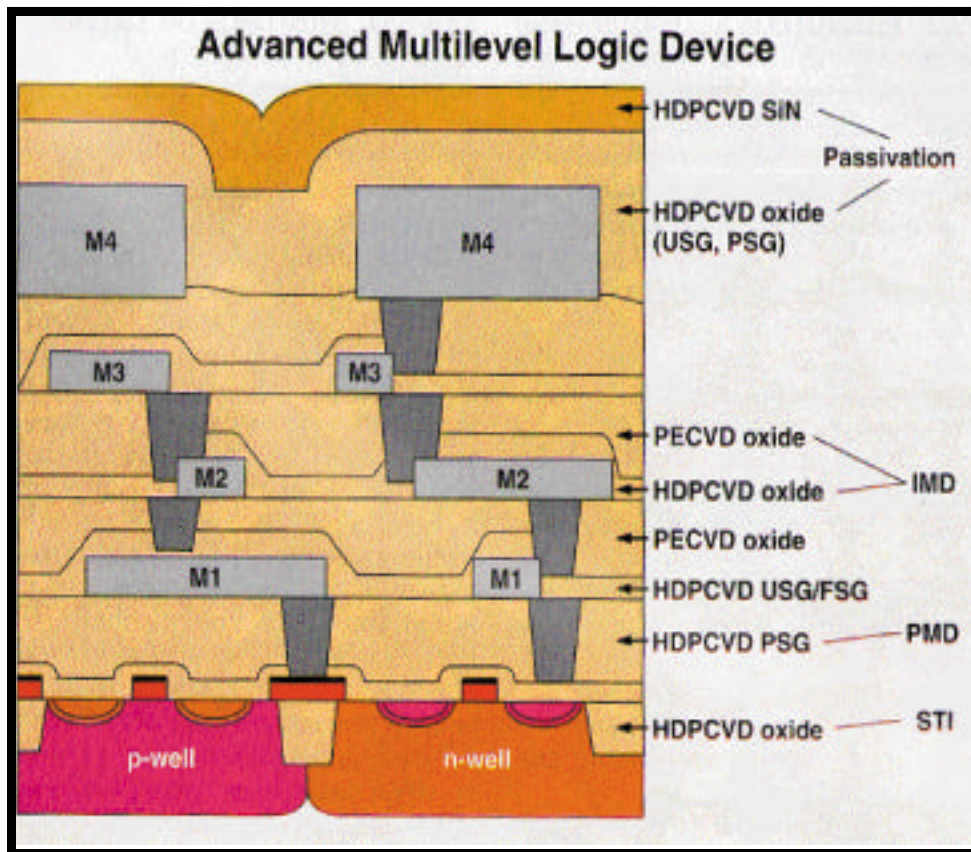


• Ref: "National Technology Roadmap for Semiconductors", SIA, 1997.

- The NTRS sets goals for the microelectronics fabrication industry for future generations of devices.
- Feature size will continue to shrink with more transistors per chip while...

# INCREASED COMPLEXITY REQUIRES NEW SOLUTIONS

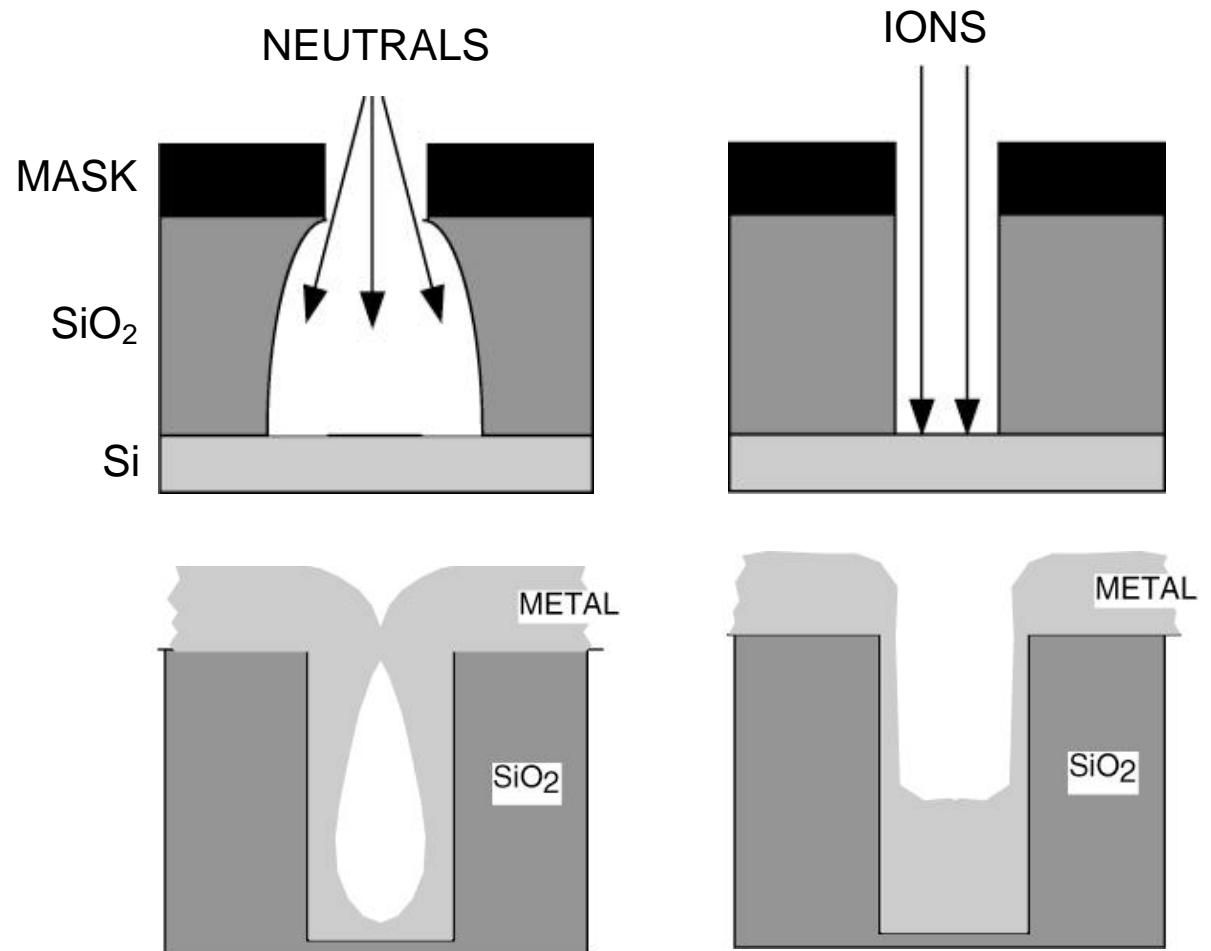
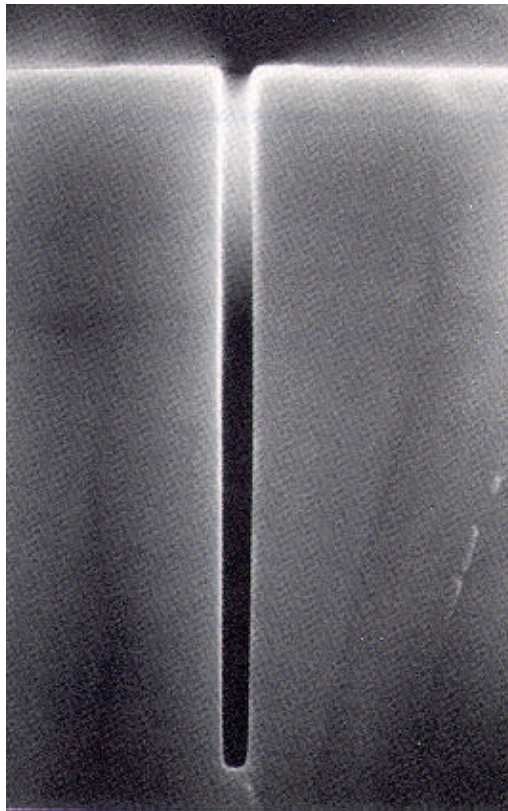
- The levels of interconnect wiring will increase to 8-9 over the next decade producing unacceptable signal propagation delays. Innovative solutions such as copper wiring and low-k dielectrics are being implemented.



Ref: IBM Microelectronics

# PLASMA ARE ESSENTIAL FOR ECONOMICALLY FABRICATING FINE FEATURES IN MICROELECTRONICS

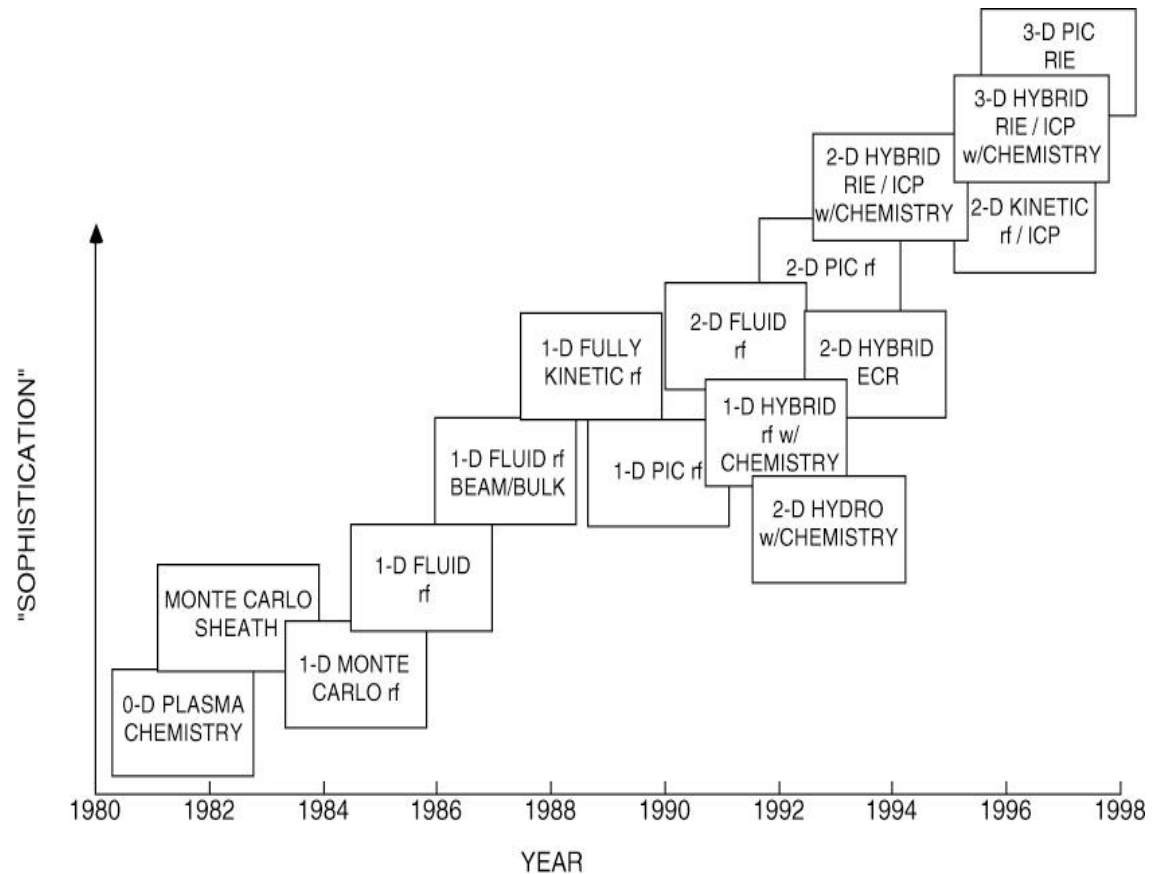
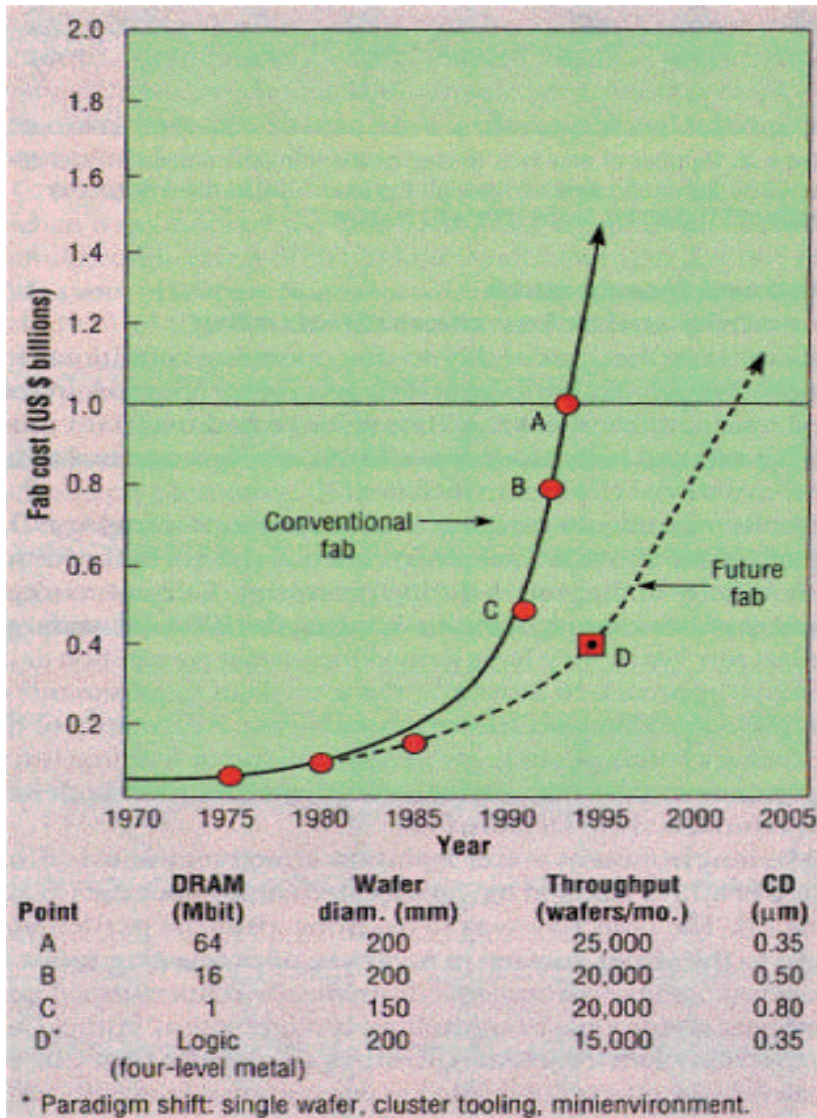
- In plasma processing, ions are accelerated nearly vertically into the wafer, thereby activating etch and via filling processes which produce straight walled, anisotropic features.



Ref: "Principles of Plasma Discharges and Materials Processing, Michael A. Lieberman and Allan J. Lichtenberg, p.2, 1994

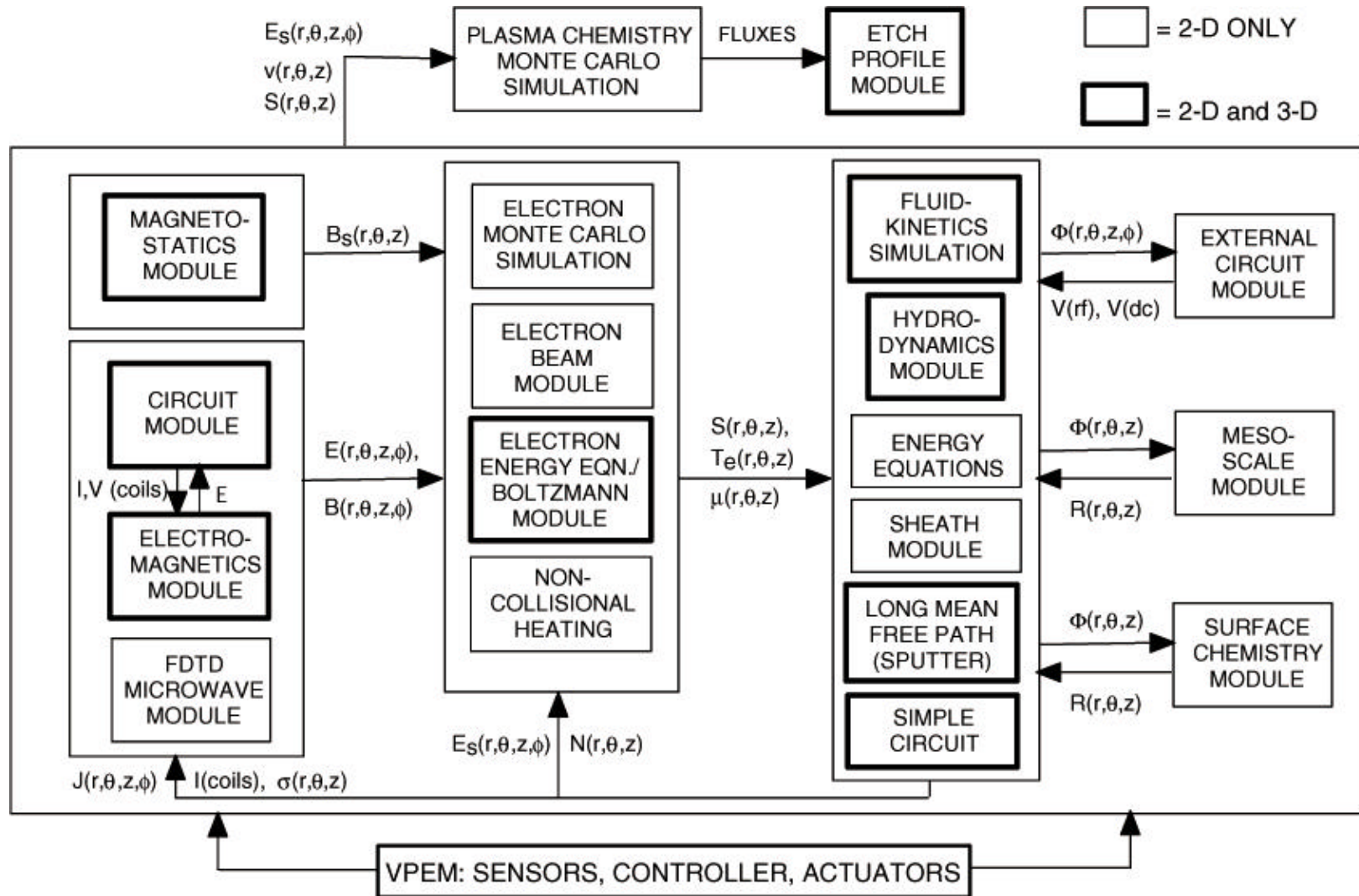
# NEED FOR PLASMA PROCESSING EQUIPMENT MODELS

- An increasing fraction of the cost for building a major fabrication facility is on processing equipment.



# HYBRID PLASMA EQUIPMENT MODEL (HPEM)

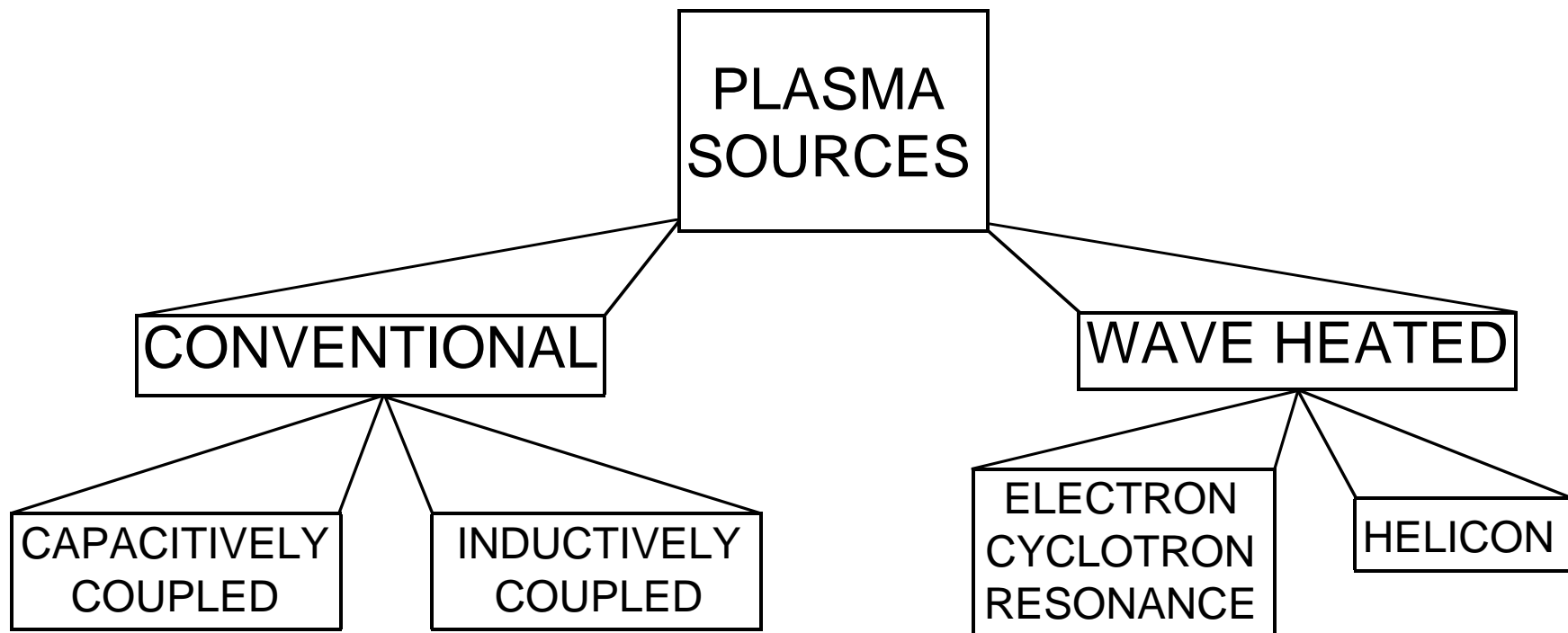
- The Computational Optical and Discharge Physics Group (CODPG) develops computer aided design tools of plasma equipment and process.



# HPEM USING WAVE HEATED DISCHARGES

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- In order to encompass a larger range of plasma processing reactors, the HPEM has been enhanced to enable simulation of wave heated discharges.





# MOTIVATION FOR USE HELICON DISCHARGES

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- 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.

# COLD PLASMA CONDUCTIVITY TENSOR

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- 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.

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

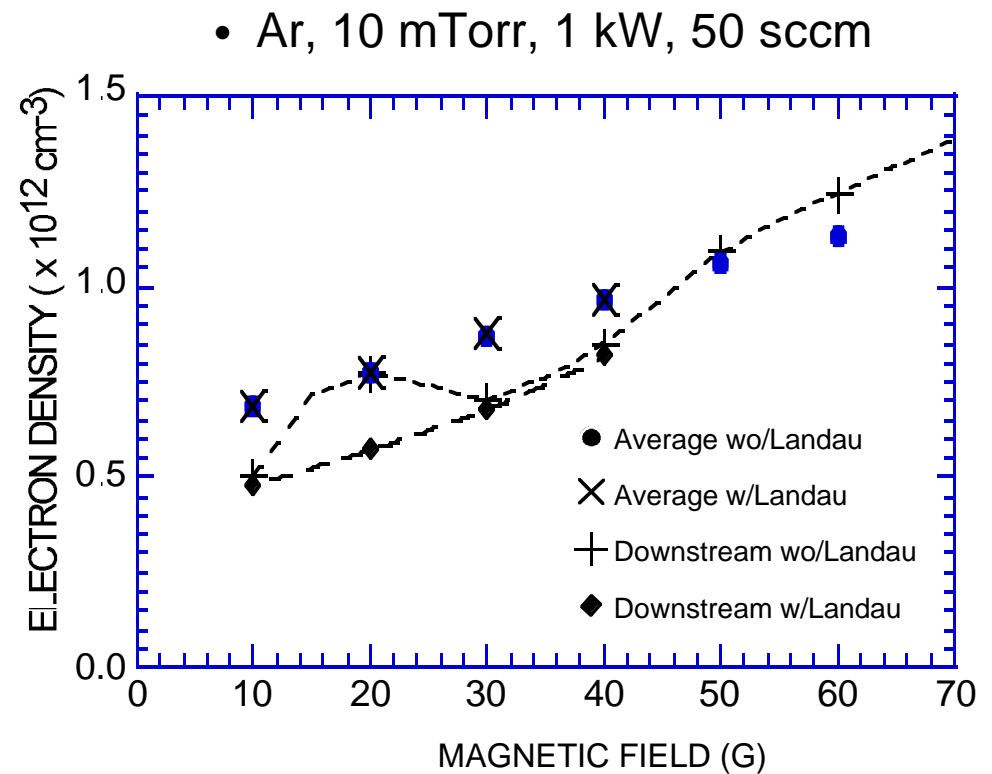
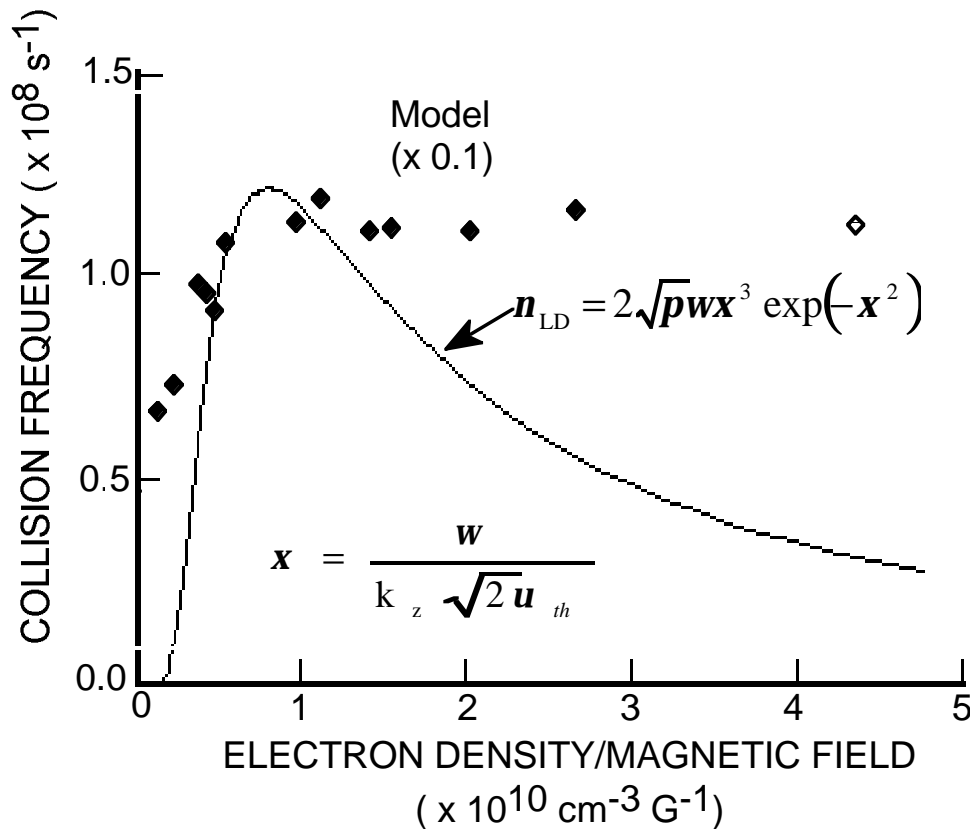
- The plasma current in the wave equation is addressed by a cold plasma tensor conductivity.

$$\bar{\boldsymbol{\sigma}} = \sigma_0 \frac{m_e v_m}{q\alpha} \left( \frac{1}{\alpha^2 + B^2} \right) \begin{pmatrix} \alpha^2 + B_r^2 & \alpha B_z + B_r B_\theta & -\alpha B_\theta + B_r B_z \\ -\alpha B_z + B_r B_\theta & \alpha^2 + B_\theta^2 & \alpha B_r + B_\theta B_z \\ \alpha B_\theta + B_r B_z & -\alpha B_r + B_\theta B_z & \alpha^2 + B_z^2 \end{pmatrix}$$

$$\text{where, } \sigma_0 = \frac{q^2 n_e}{m_e v_m} \quad \text{and, } \alpha = \frac{m_e}{q} (v_m + i\omega)$$

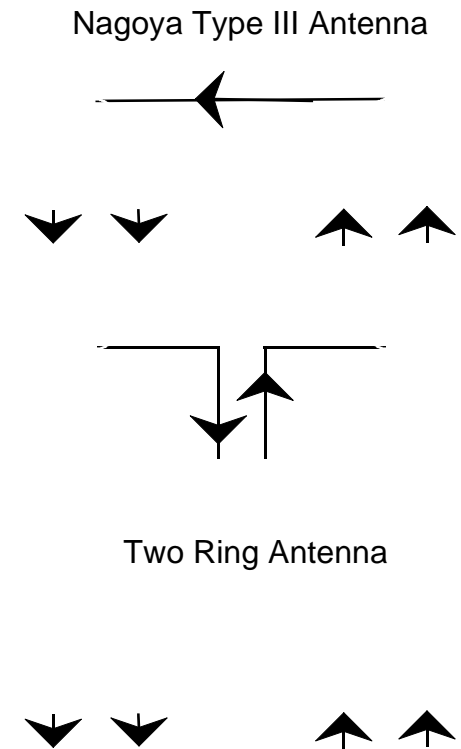
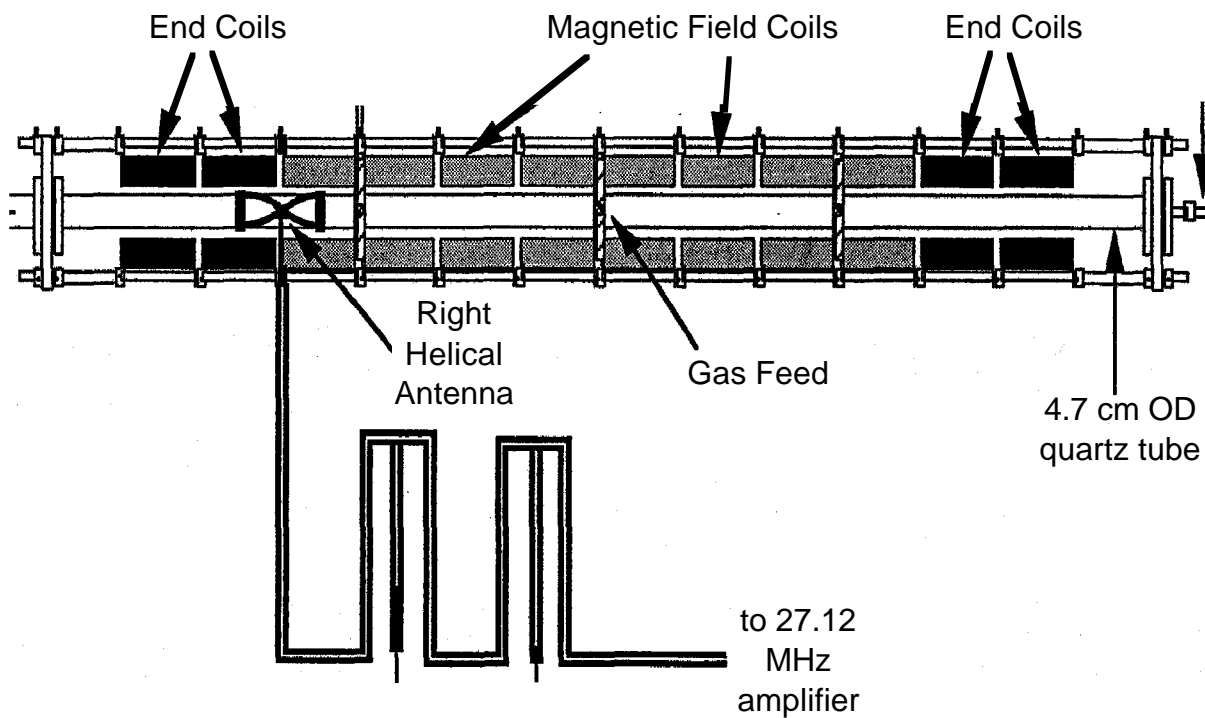
# COLLISIONLESS HEATING - LANDAU DAMPING

- 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 shown below.
- In the low electron density and high magnetic field regimes, Landau damping significantly affects the power deposition efficiency. Furthermore in the electron cyclotron mode of operation, Landau damping shift or remove resonant heating.



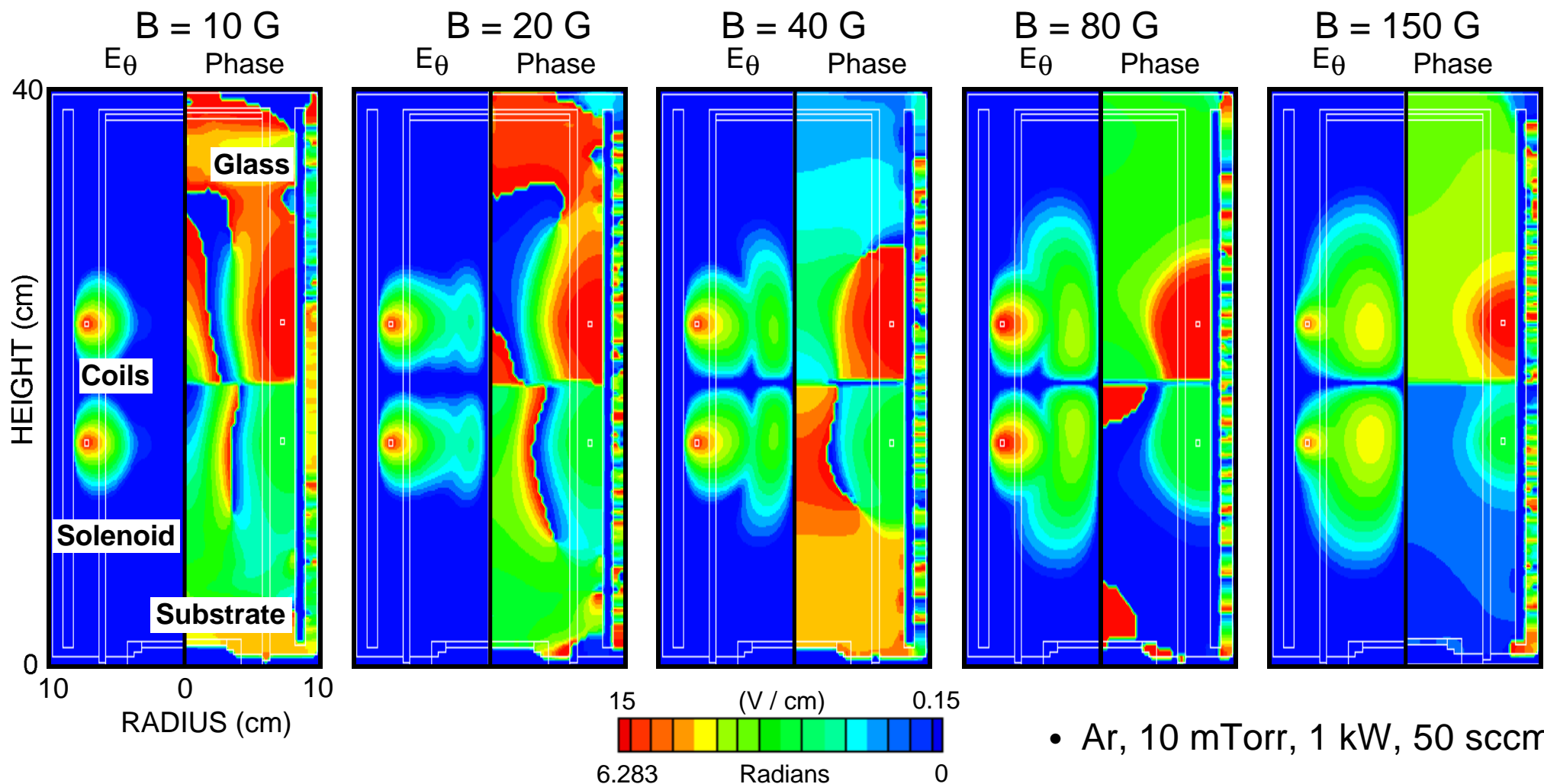
# SIMULATION OF SOLENOIDAL GEOMETRY

- Since Helicon sources are more complex than other plasma sources, we have conducted preliminary studies in a solenoidal geometry similar to that used by Chen *et al.*
- However, since simulation were two dimensional in nature, we begun studies with the use of a two coil antenna which produces an  $m = 0$ .



- 15 mTorr Ar, RF power of 2kW at 27.12 MHz, 0-1.2 kG

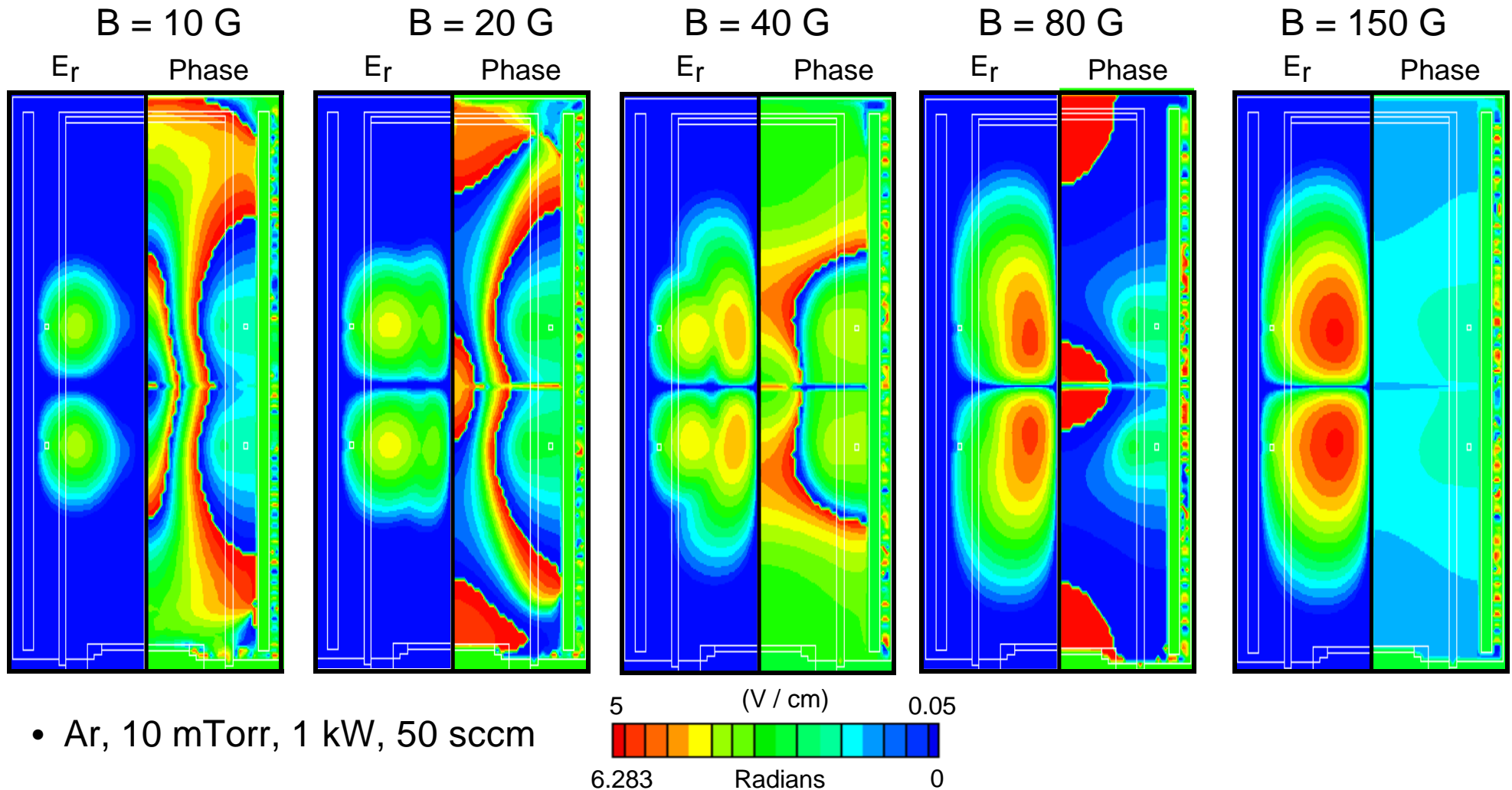
# LOW FIELD INDUCTIVE TO HELICON TRANSITION - AZIMUTHAL



• Ar, 10 mTorr, 1 kW, 50 sccm

- At a critically low magnetic field, the azimuthal electric field remains inductively coupled and a radially propagating wave dominates.
- As magnetic fields is increased, standing wave patterns arise in radial direction and the electric field begins to propagate in the axial direction.

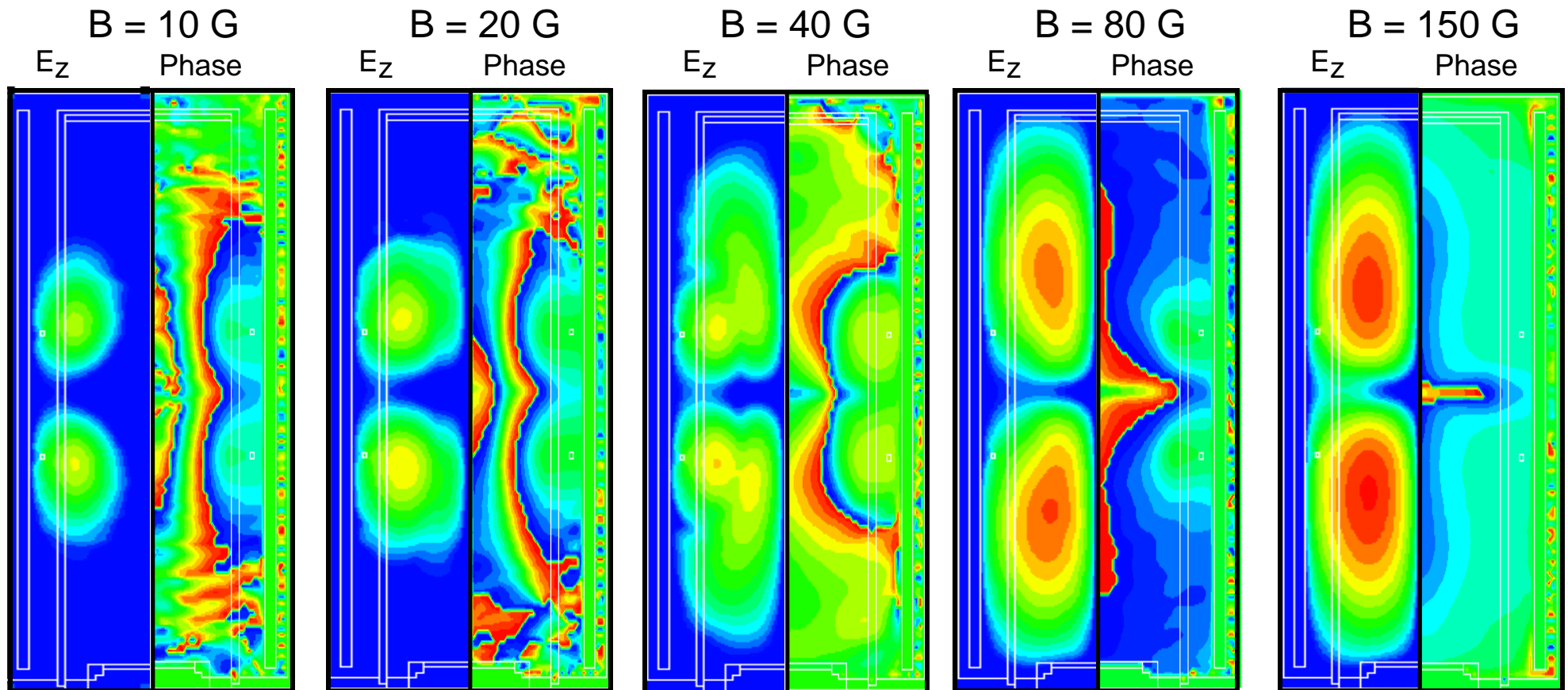
# LOW FIELD INDUCTIVE TO HELICON TRANSITION - RADIAL



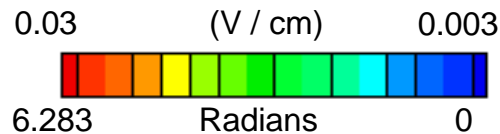
• Ar, 10 mTorr, 1 kW, 50 sccm

- Effects similar to those for the azimuthal electric field can be seen in the distribution and propagation of the radial electric field.
- Initially propagation is dominantly in the the radial direction, showing the existence of a highly damped wave.

# LOW FIELD INDUCTIVE TO HELICON TRANSITION - AXIAL

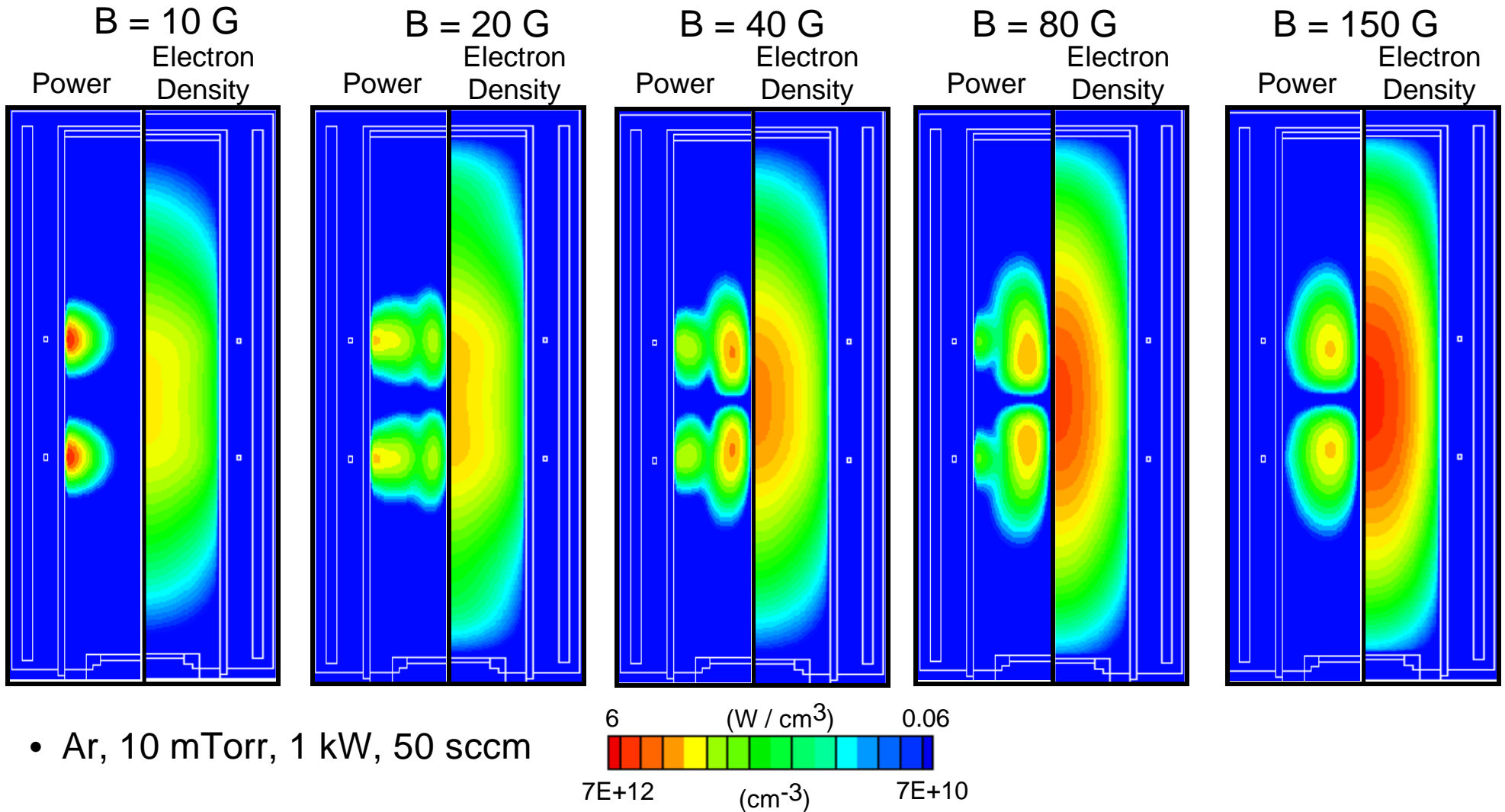


- Ar, 10 mTorr, 1 kW, 50 sccm



- The axial electric field distribution has a greater dependence on radial static magnetic field gradients than magnetic field magnitudes.
- In the magnetic field spectrum shown, the propagation of the axial electric fields is in the radial direction and does not significantly contribute to the power deposition.

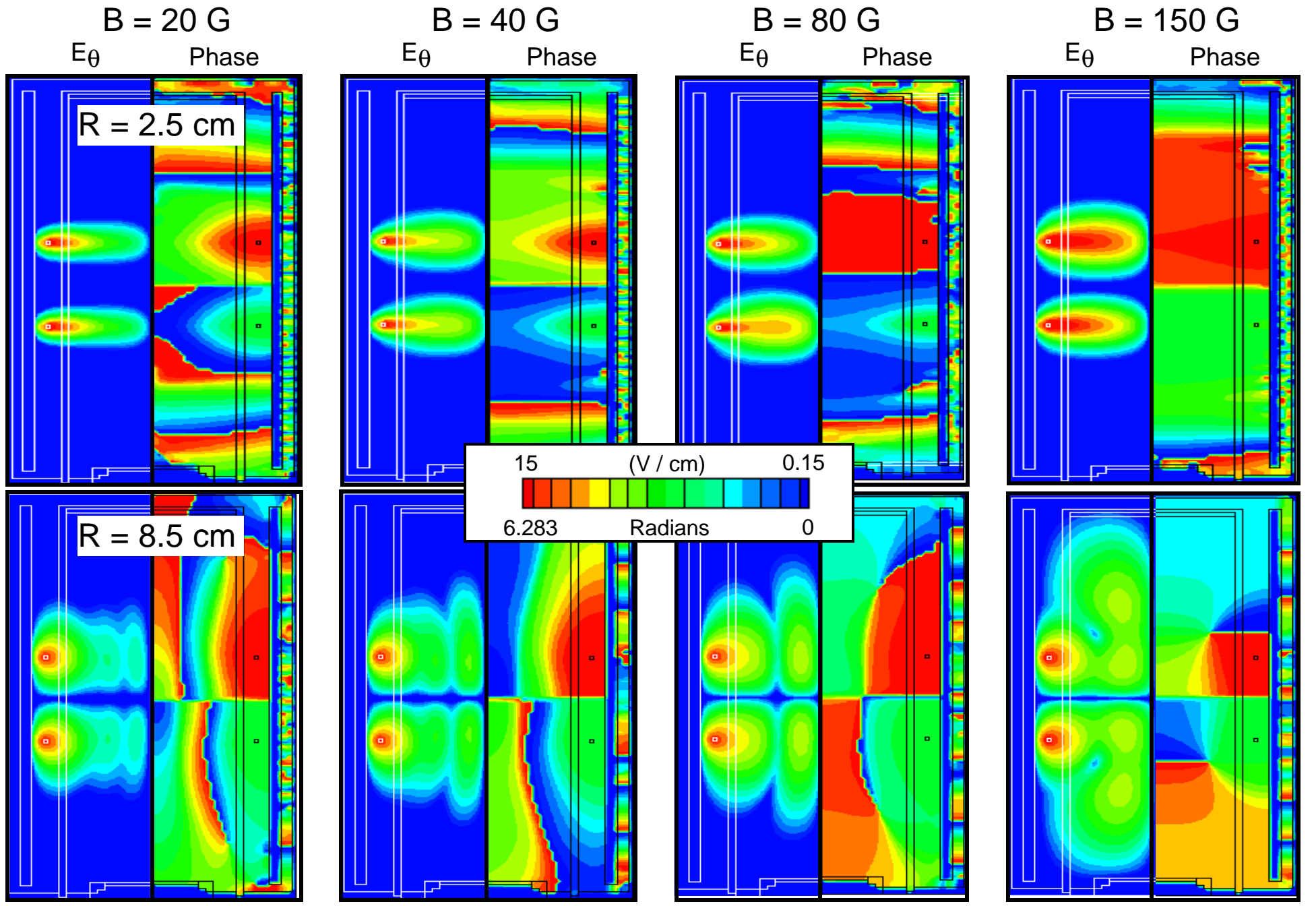
# LOW FIELD INDUCTIVE TO HELICON TRANSITION - POWER



- At low magnetic fields power deposition is inductively coupled and occurs near the coils
- As nodal structure develops in the azimuthal and radial fields, the skin depth of the power deposition is increased to within the volume of the plasma.

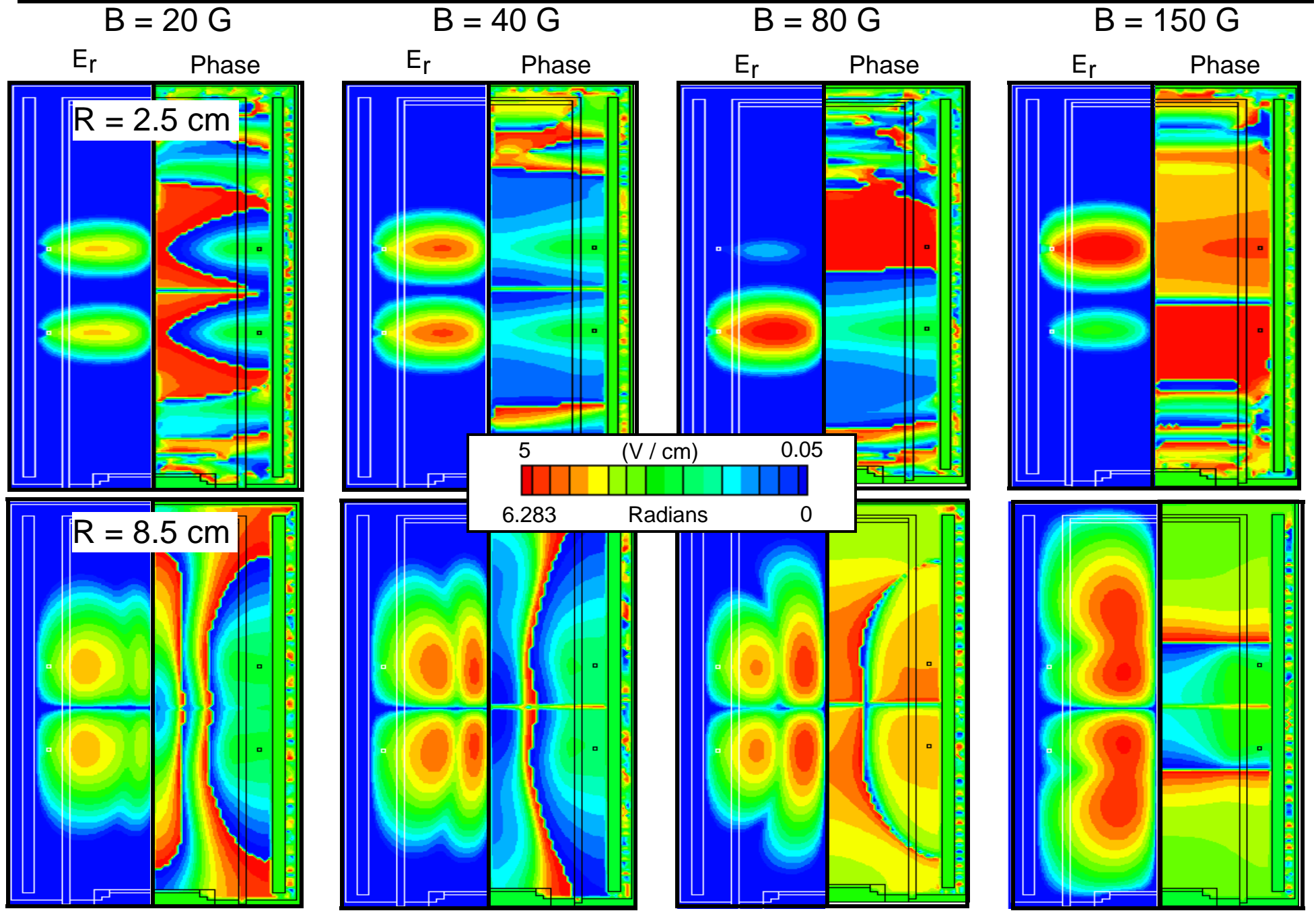


# GEOMETRIC DEPENDENCE OF WAVE STRUCTURE - AZIMUTHAL

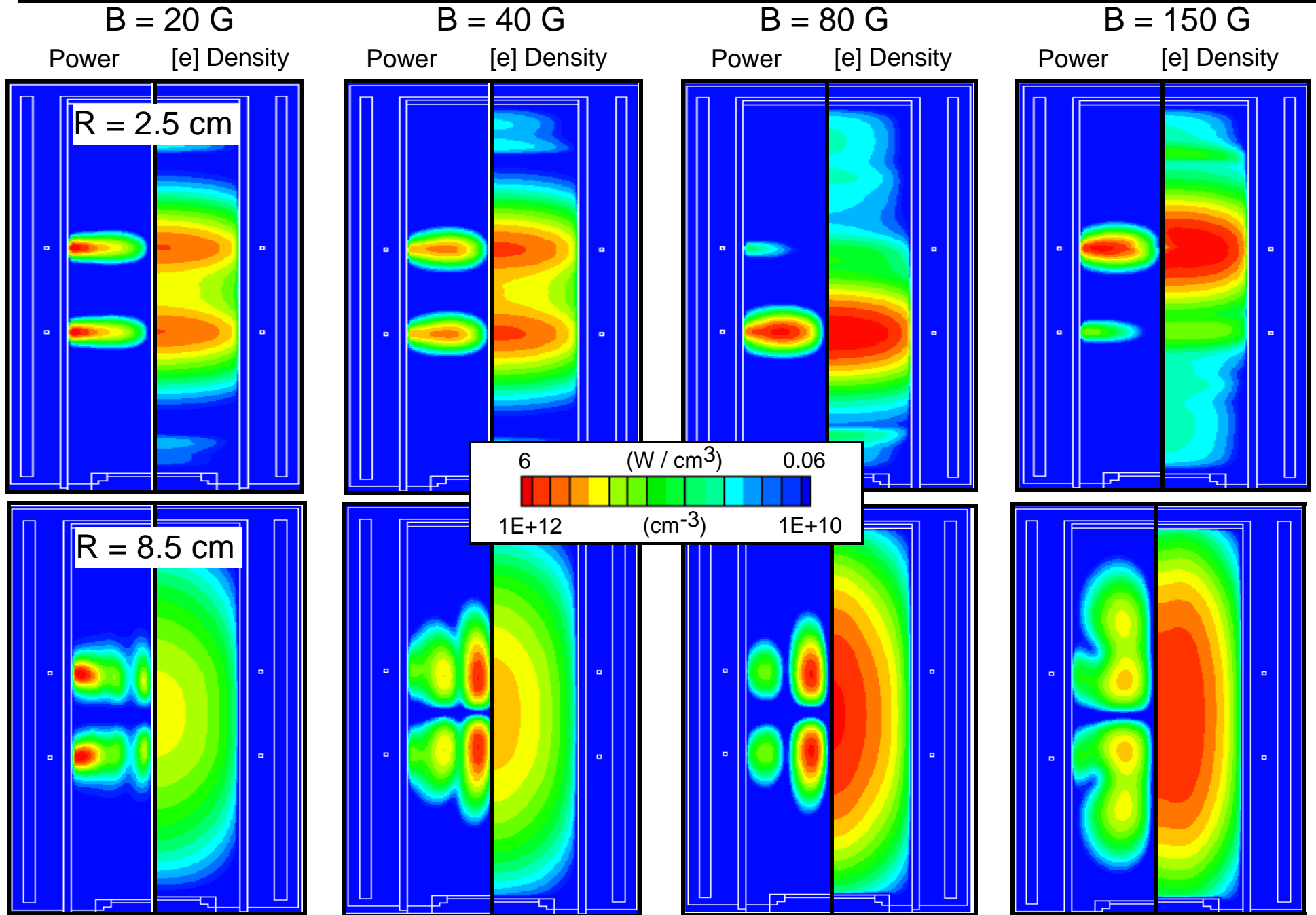


\*Not to scale.

# GEOMETRIC DEPENDENCE OF WAVE STRUCTURE - RADIAL

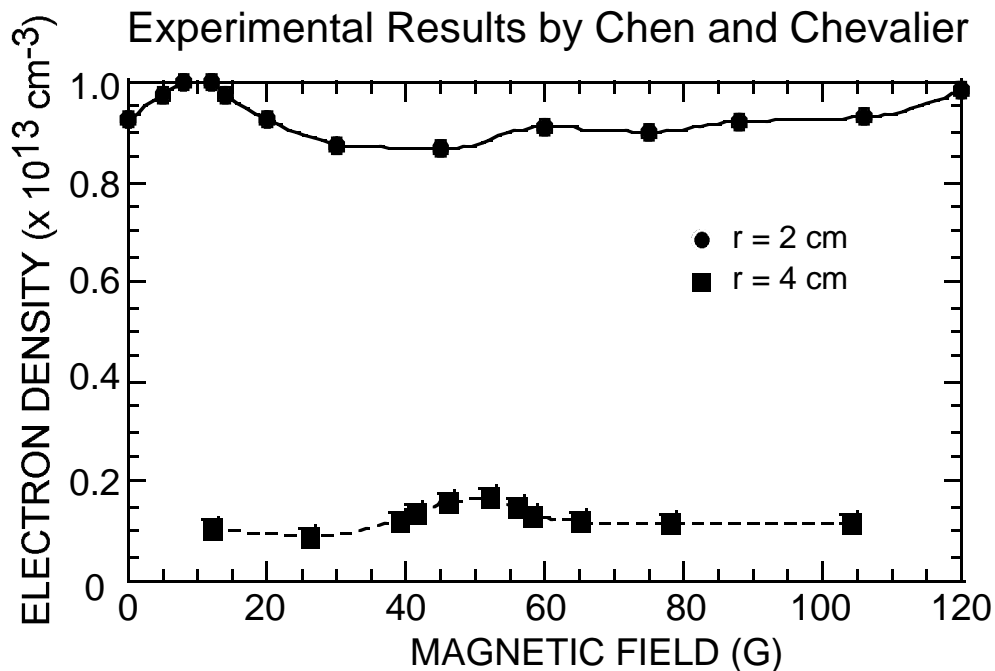


# GEOMETRIC DEPENDENCE OF WAVE STRUCTURE - POWER

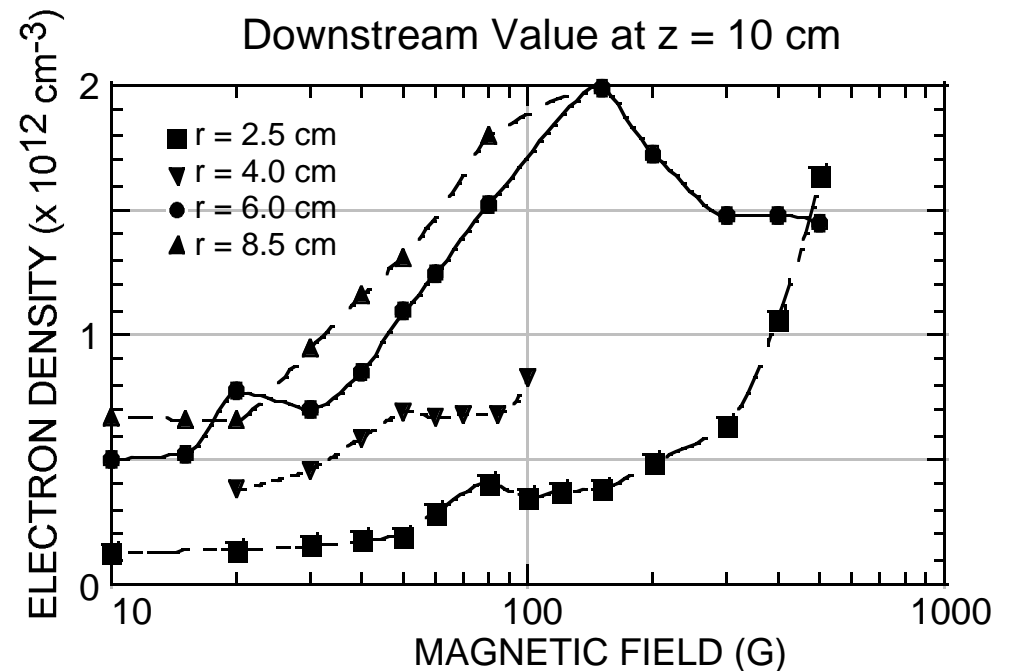


# LOW FIELD DENSITY PEAK IN THE DOWNSTREAM

- Previous indications taken with a Nagoya Type III antennas in uniform magnetic fields, by Chen and Chevalier, in the low magnetic field regime show a small peak in the electron density in the downstream region.
- A similar result is observed in simulations conducted with varying tube radius.



Ref: Chen, F.F. and Chevalier, G., *J. Vac. Sci. Technol. A*, 10, 1389 (1992).

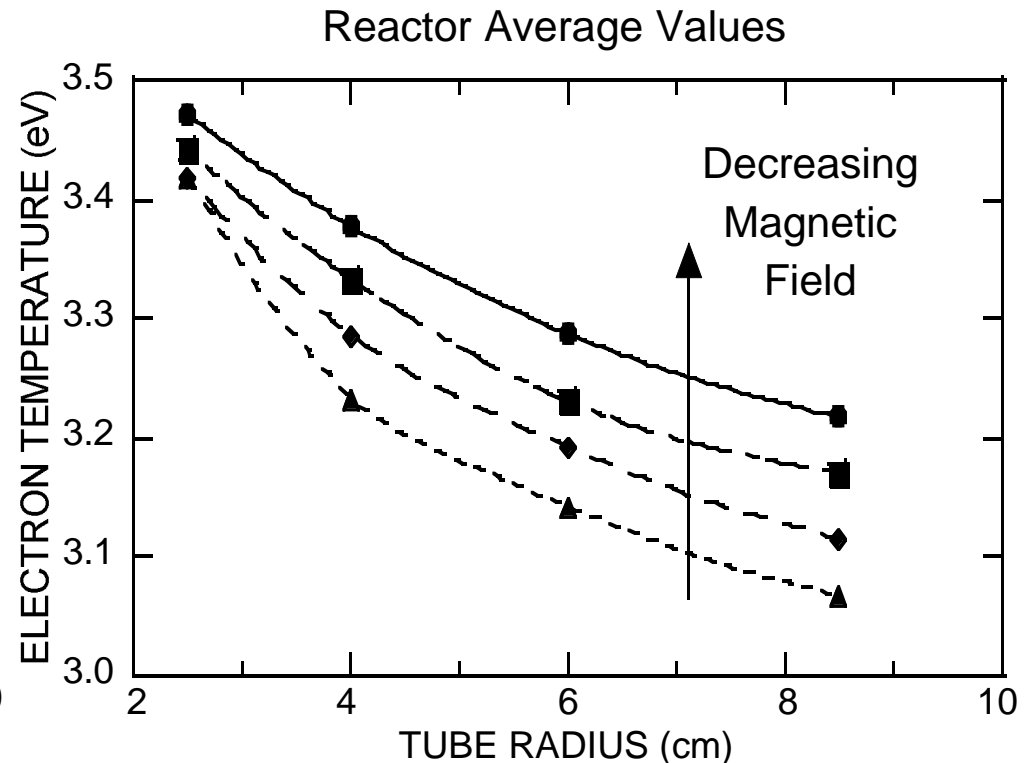
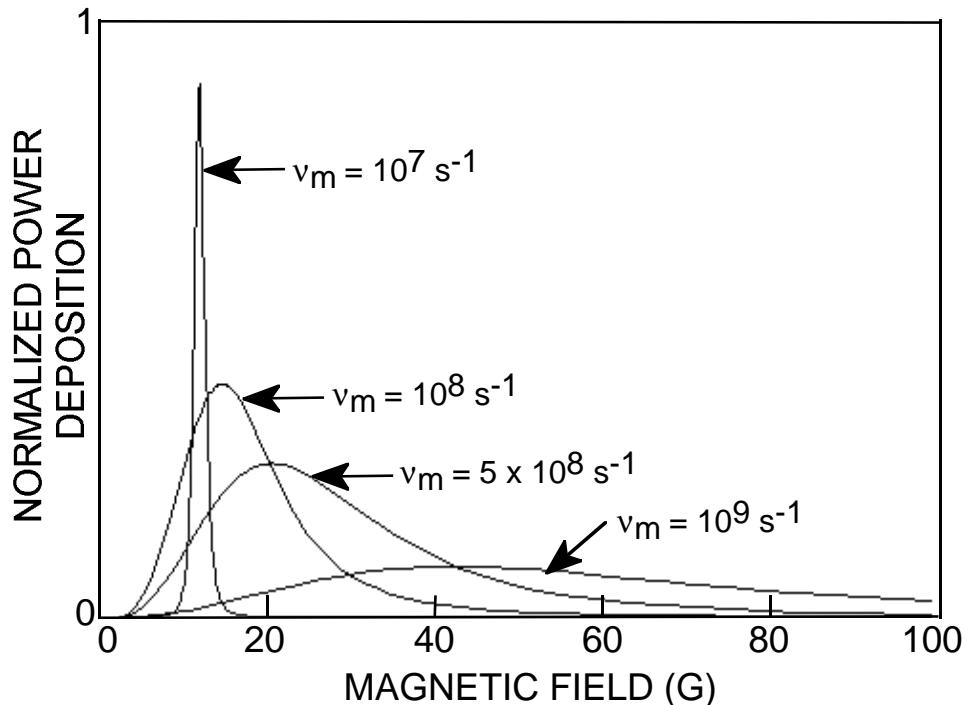


Ar, 5 mTorr, 1 kW, 50 sccm

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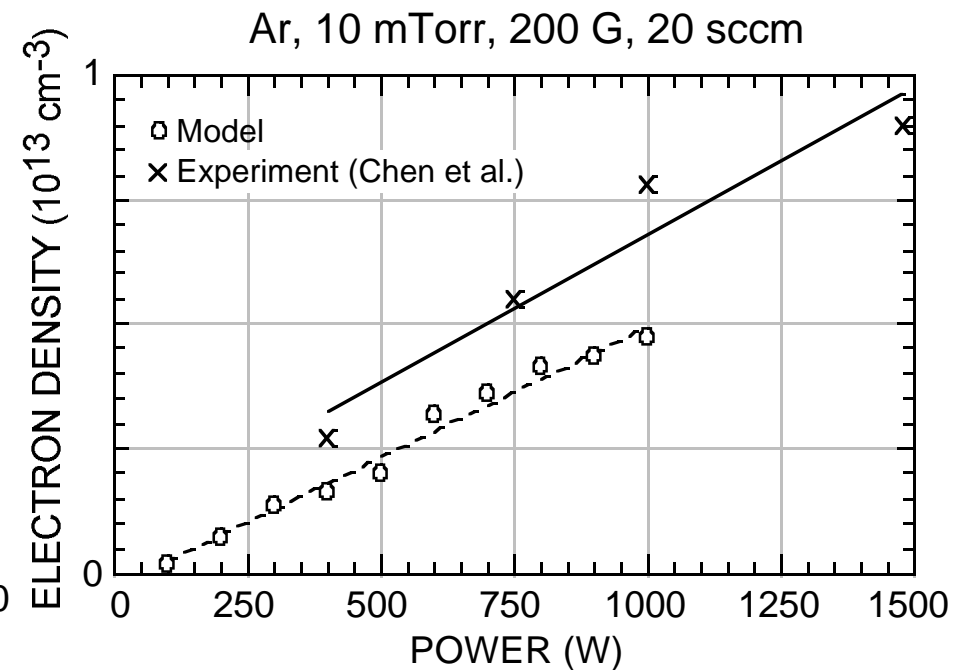
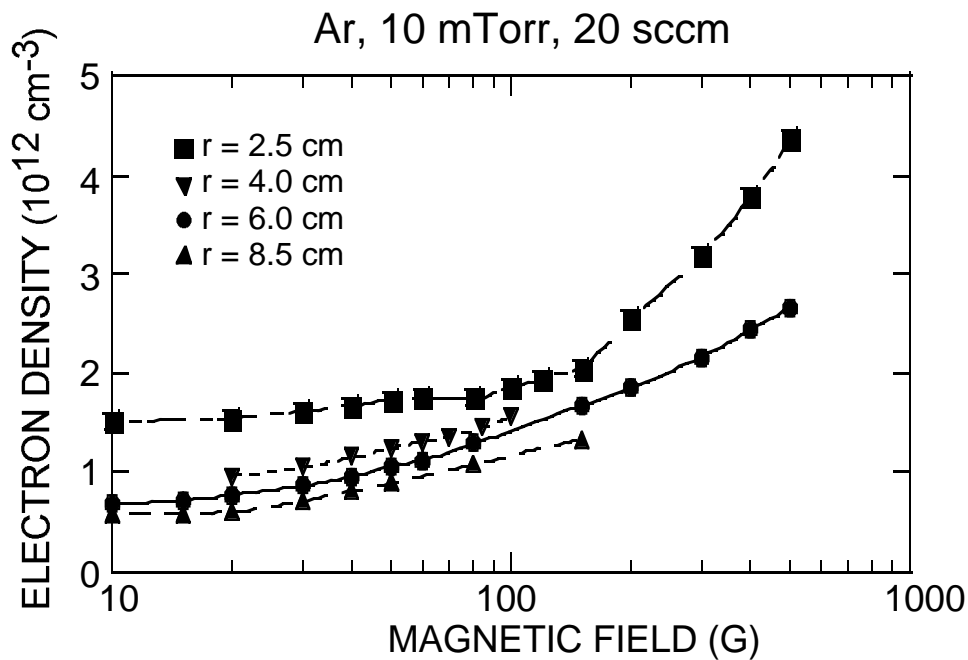
# LOW FIELD DENSITY PEAK IN THE DOWNSTREAM

- The position of most efficient power deposition along the magnetic field spectrum depends on the total momentum transfer collision frequency.
- A shift of the ECR position toward higher magnetic fields as the tube radius is decreased occurs because of the subsequent increase in electron temperature.



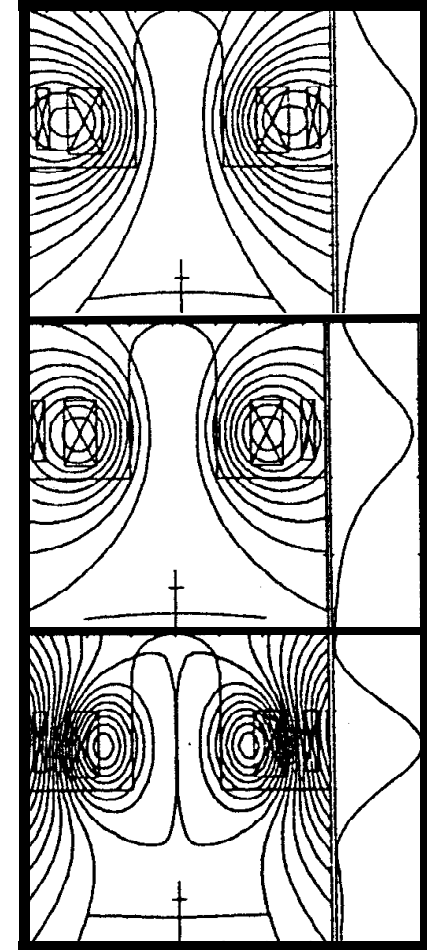
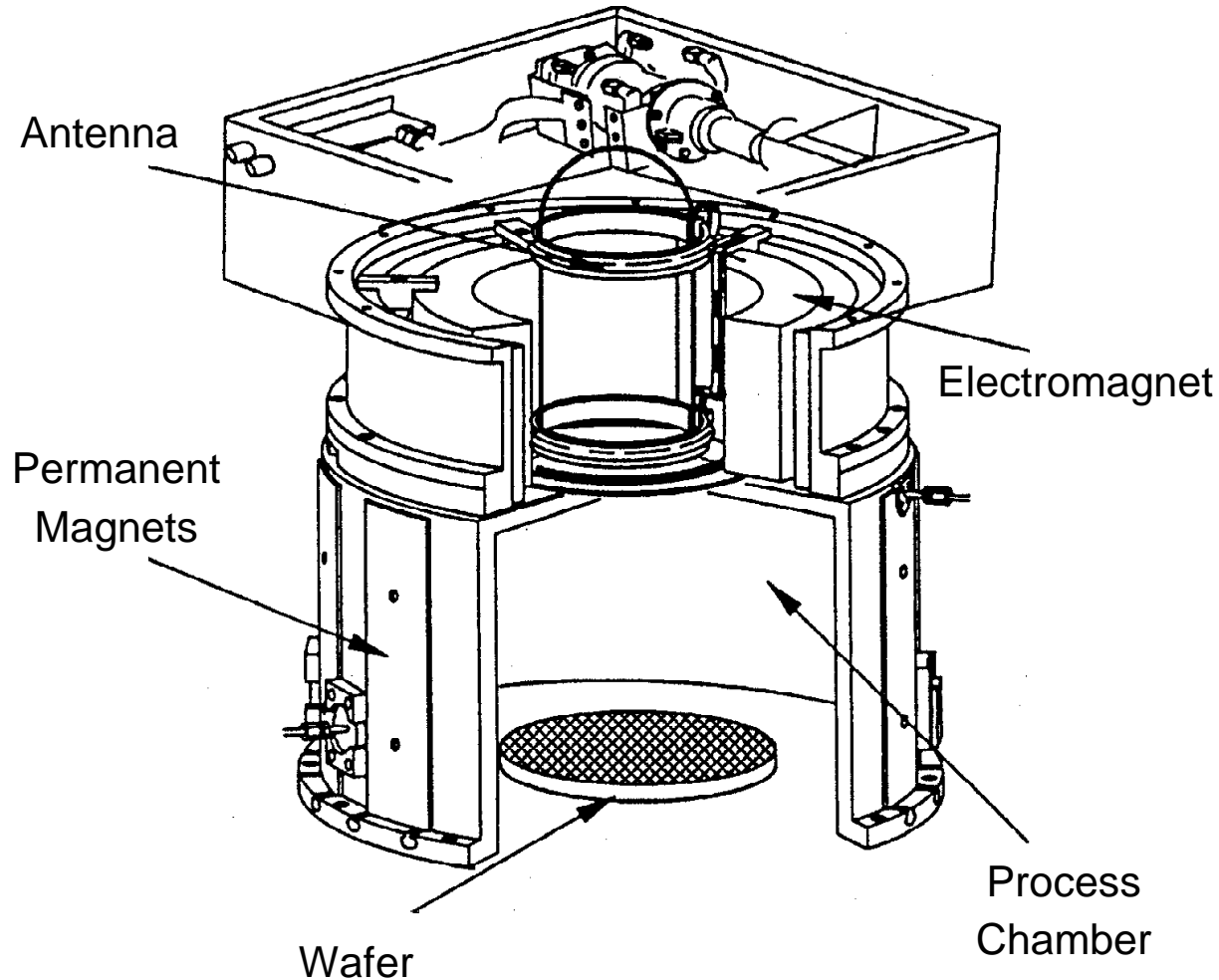
# REACTOR AVERAGE PLASMA DENSITY

- 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.



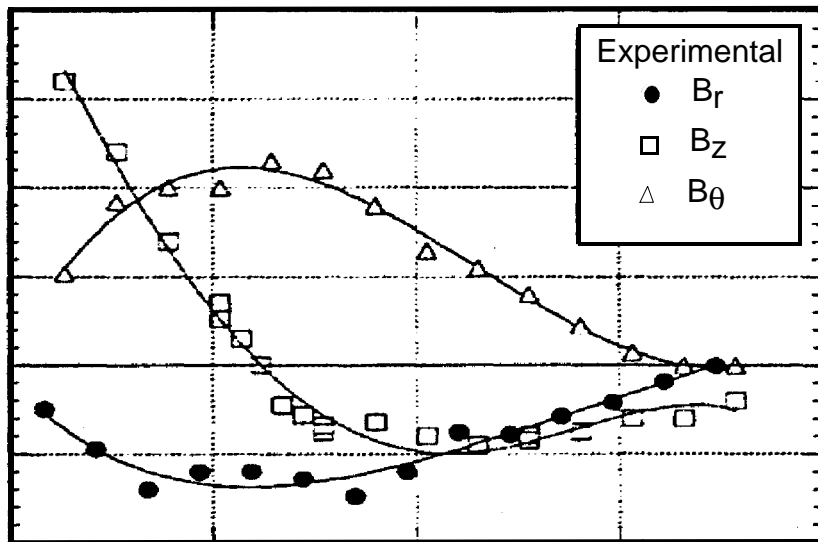
# TRIKON MORI™ 200 HELICON PLASMA SOURCE

- A commercial Trikon Technologies, Inc., Pinnacle 8000 helicon source plasma system will be used to validate simulation models.

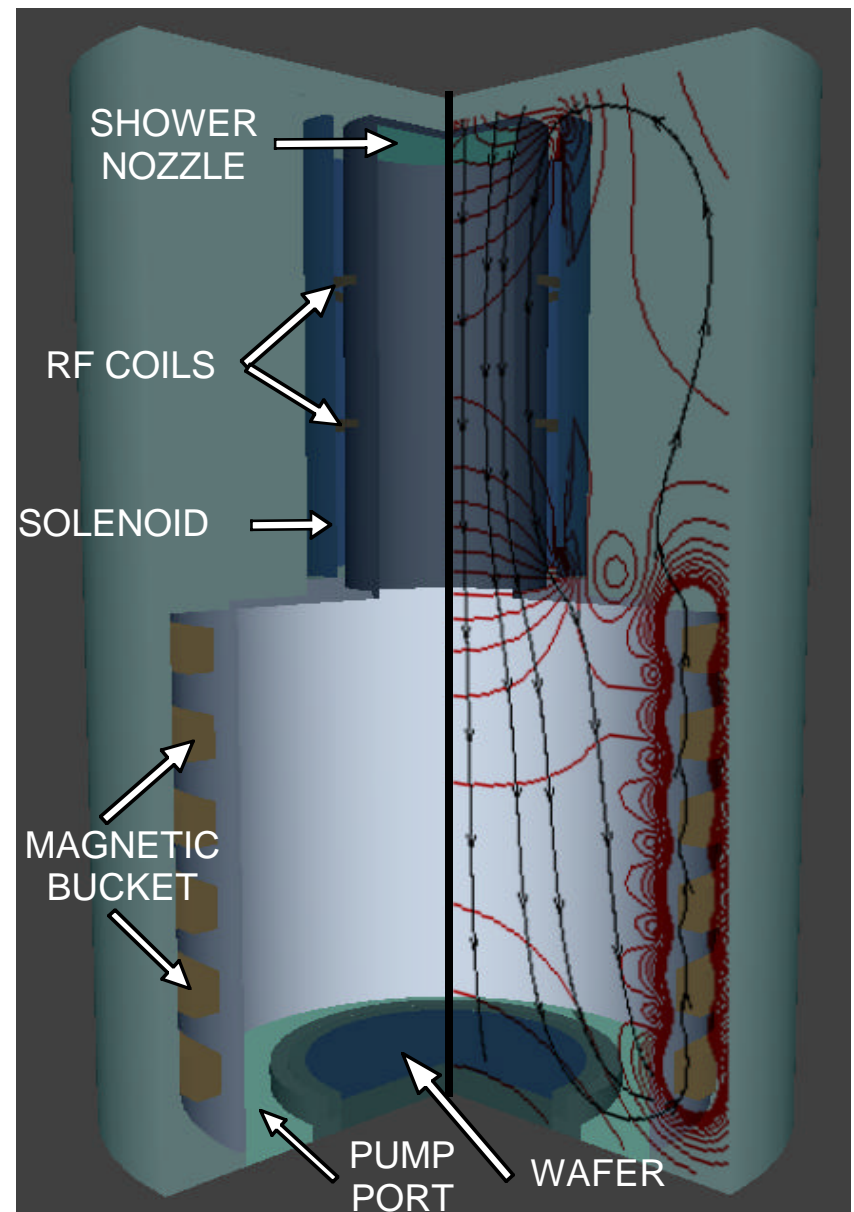


# APPLICATION OF HPEM TO HELICON TOOL DESIGN

- 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.



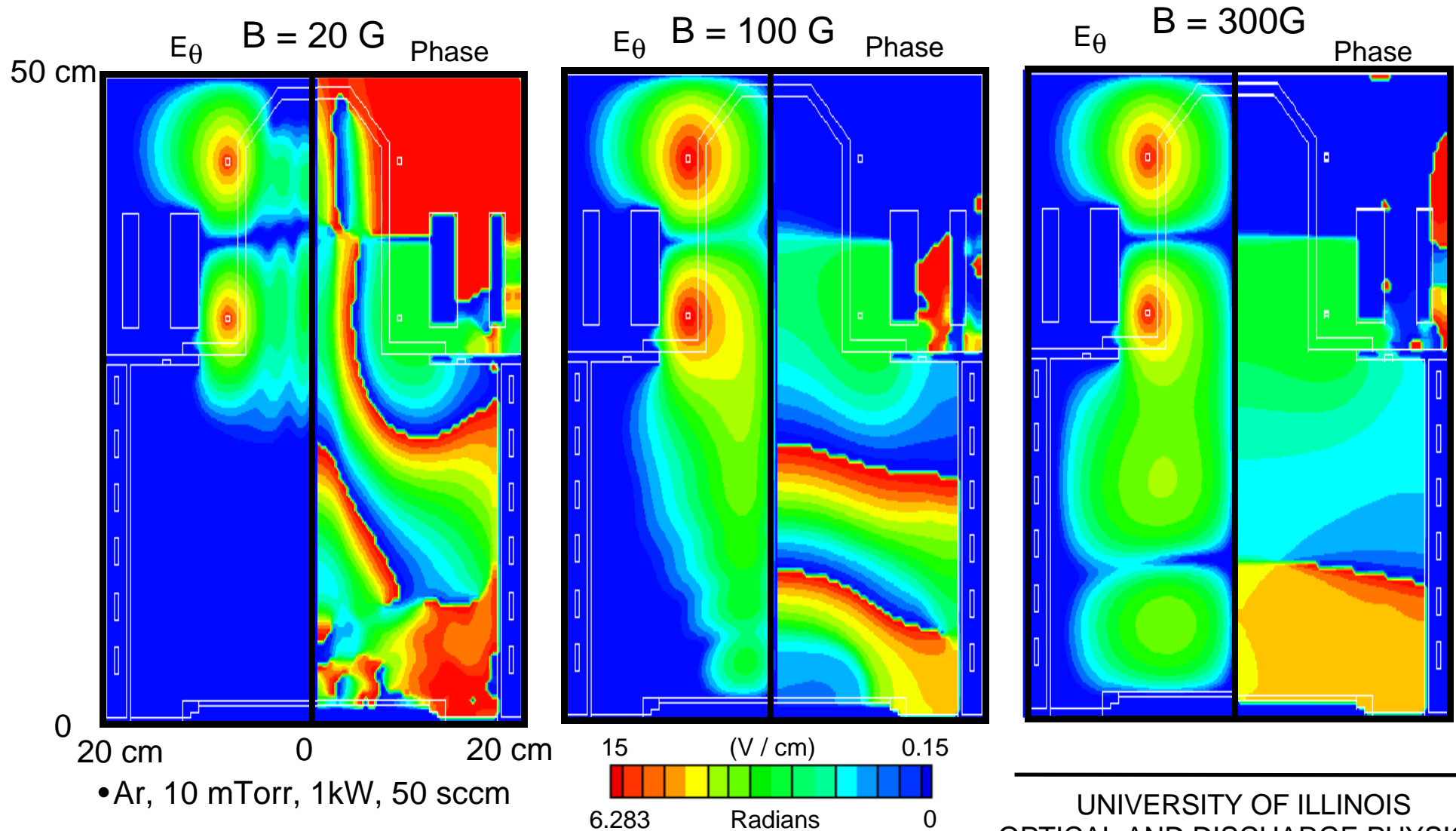
- Experiment - Ar, 10 mTorr, 1kW
- Simulation - Ar, 10 mTorr, 1kW, 20 sccm





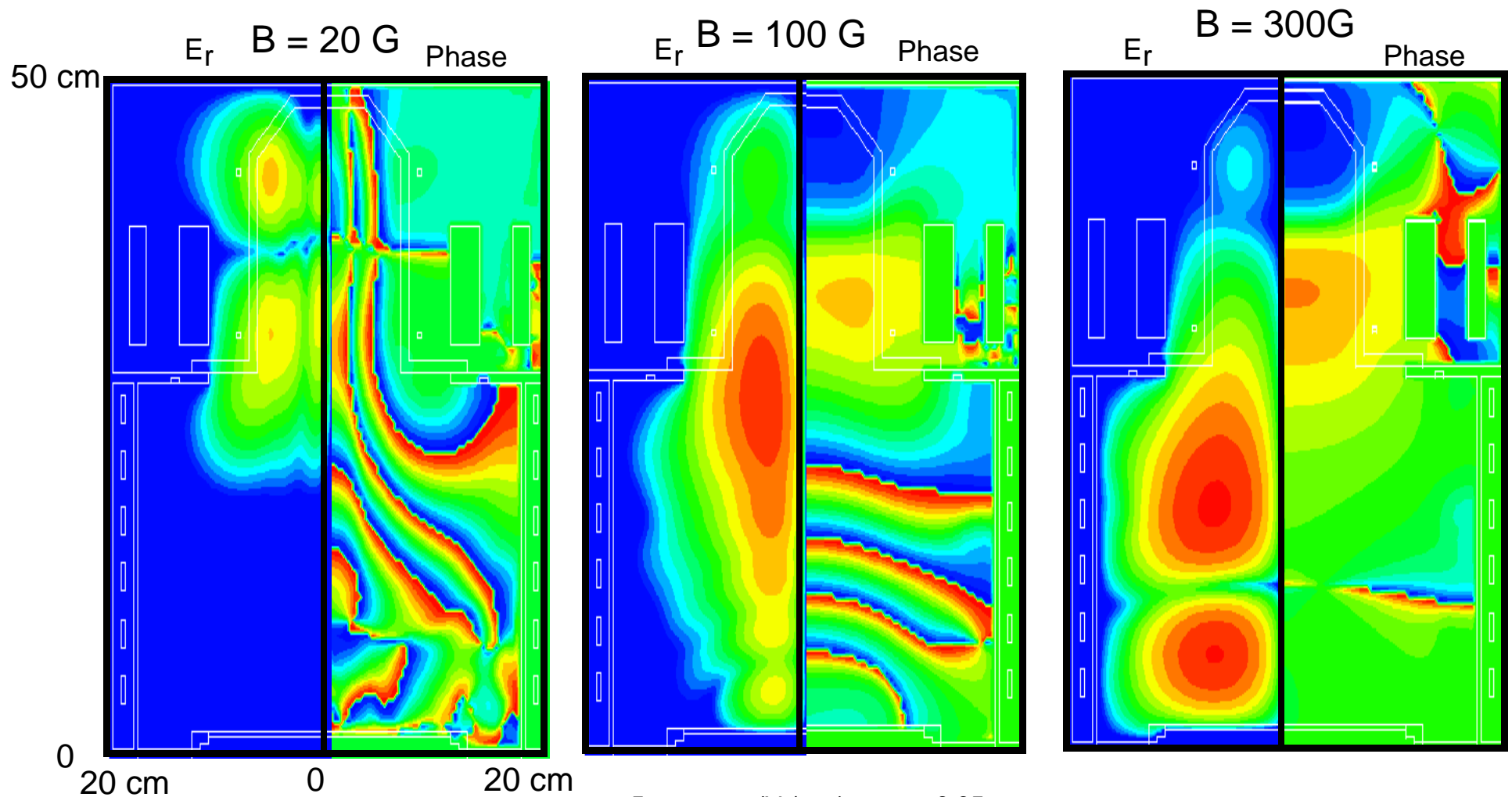
# APPLICATION OF HPEM TO HELICON TOOL DESIGN

- At low fields, the electromagnetic propagation is mainly radial, producing standing wave pattern in the radial direction.
- However as the field increases, propagation dominates in the axial direction, shifting standing wave patterns in the direction of propagation.

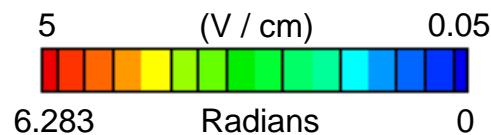


# APPLICATION OF HPEM TO HELICON TOOL DESIGN

- Similar effects can be seen in the radial electric field profile and propagation.
- Antenna coupling seems to have a significant effect at higher magnetic fields.



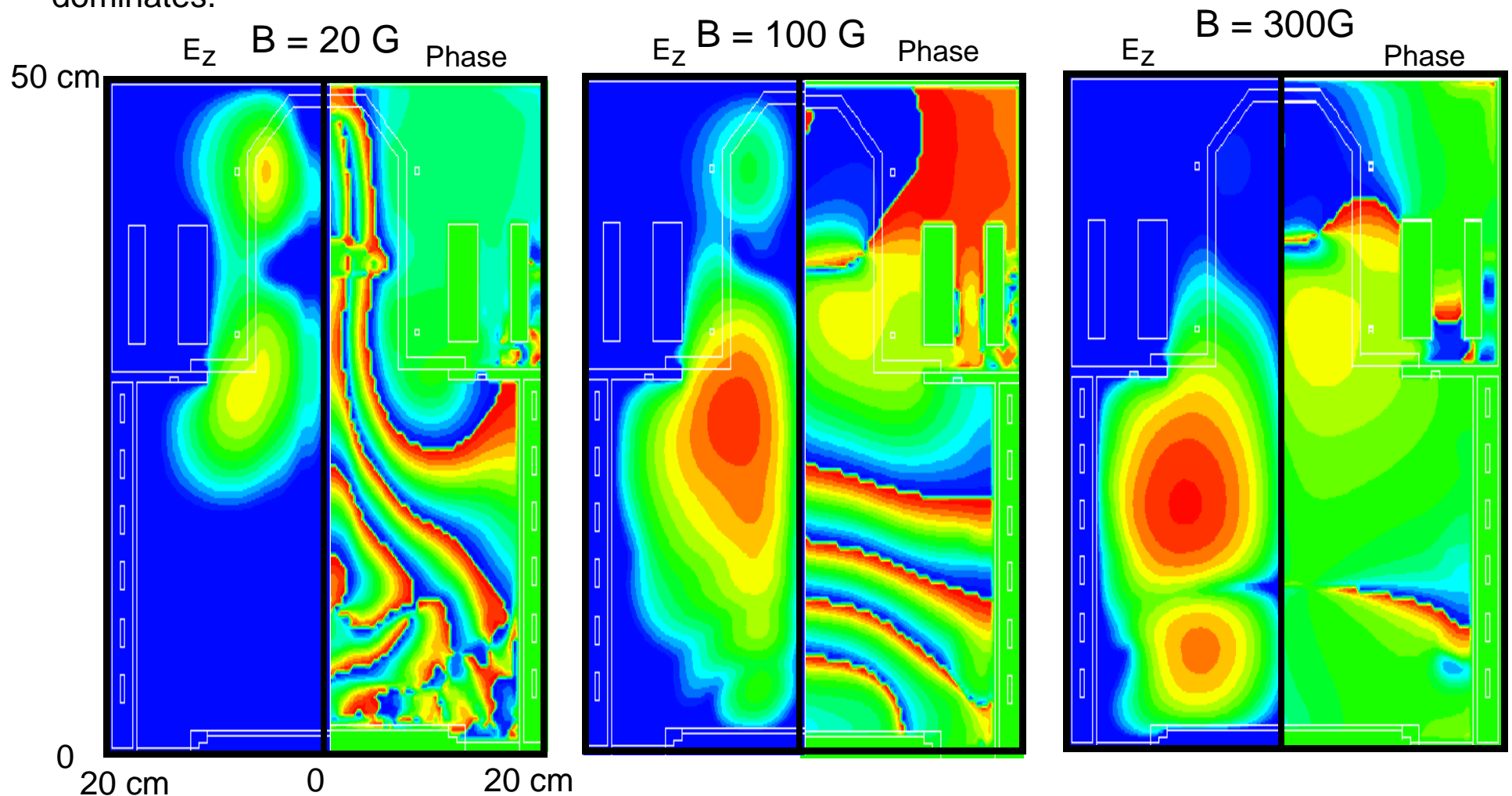
• Ar, 10 mTorr, 1kW, 50 sccm



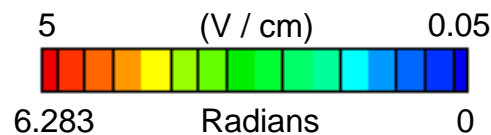
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# APPLICATION OF HPEM TO HELICON TOOL DESIGN

- Axial electric field propagation and wave pattern resembles radial electric fields.
- As magnetic fields are increased, overall electric field propagation in the axial direction dominates.



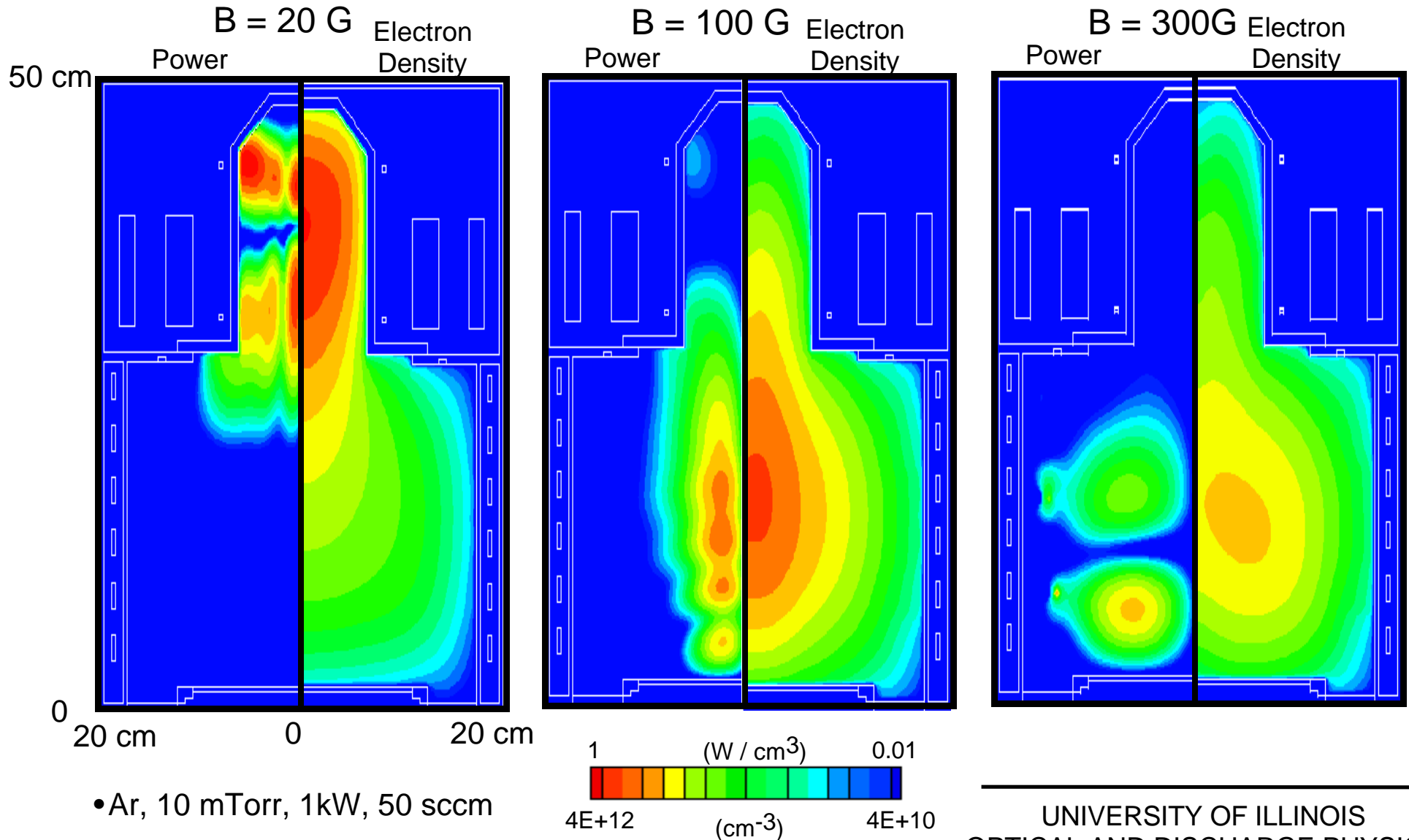
• Ar, 10 mTorr, 1kW, 50 sccm



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# APPLICATION OF HPEM TO HELICON TOOL DESIGN

- As the magnetic fields increase, axial propagation dominates depositing power in the downstream region.
- An increase in ion current to the substrate comes at the loss of flux uniformity.



# CONCLUDING REMARKS

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- 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 will be transferred to HPEM-3D.