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HEATING MECHANISMS AND WAVE PROPAGATION IN MAGNETICALLY ENHANCED INDUCTIVELY COUPLED PLASMAS*

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MOTIVATION FOR MAGNETICALLY ENHANCED ICPs

- In order to maintain process uniformity over large areas (> 300 mm) efficient new plasma sources are being developed.

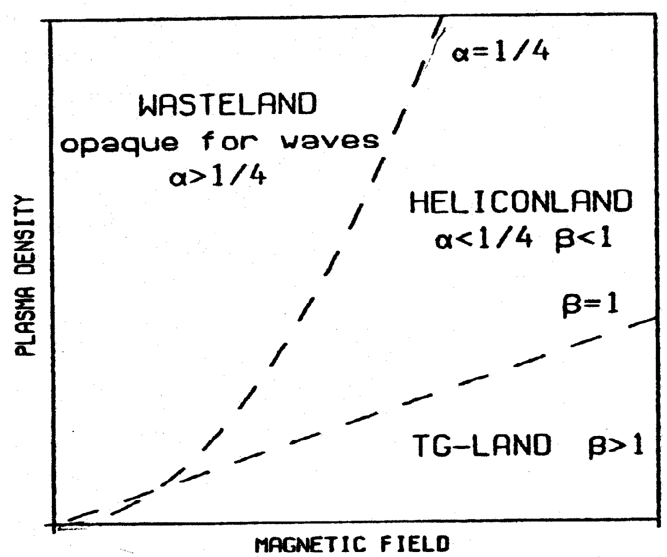
- Magnetically Enhanced Inductively Coupled Plasma (ME-ICPs) sources are being investigated due to their high ionization efficiency and their ability to deposit power within the volume of the plasma.

- The location of power deposition can substantially vary depending on the mode of operation and reactor conditions.

- The coupling of electromagnetic fields to the plasma occurs through two channels.

    - Helicon Wave
    - Electrostatic Wave (TG)

- Under certain conditions the electrostatic wave can be suppressed resulting in the helicon component depositing the majority of the power within the plasma volume.



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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).

- A full tensor conductivity was added to the EMM to calculate 3-d components of the inductively coupled electric field based on 2-d applied magnetostatic fields.

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

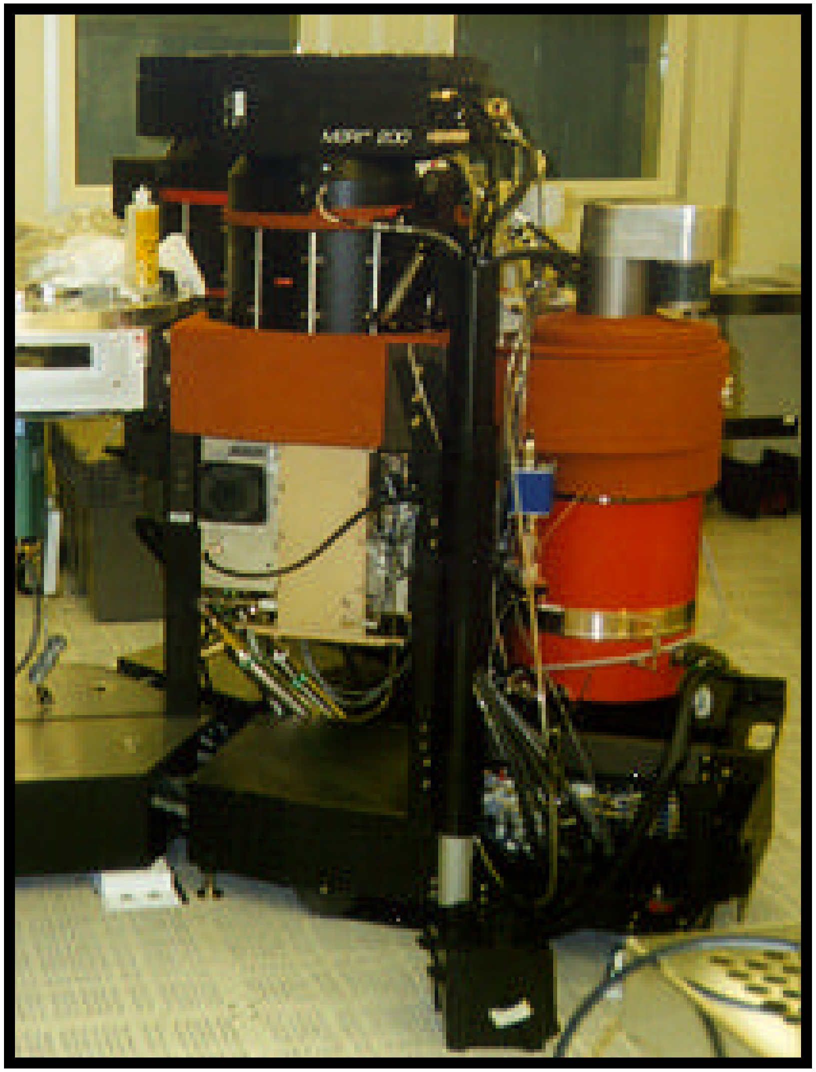
- Particle transport:

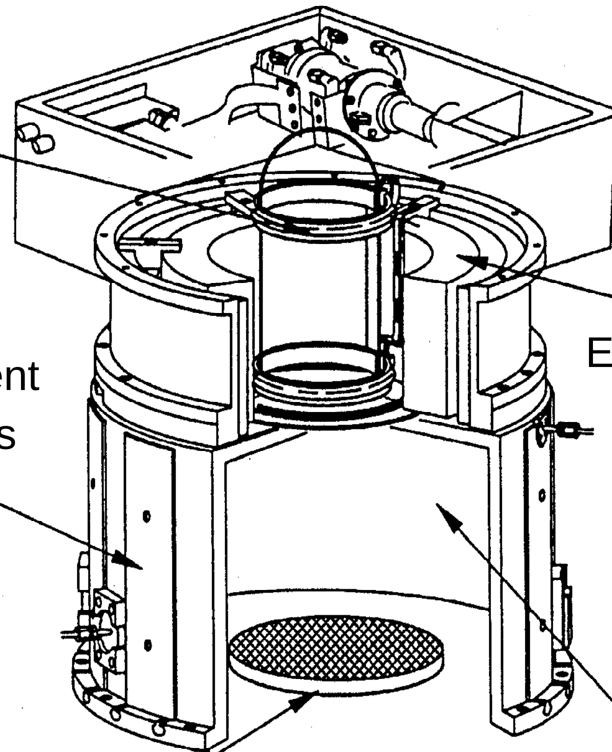
  Ions: Continuity, Momentum, Energy
  Electrons: Drift Diffusion, Energy
  EEDF: Monte Carlo

- Potentials: Poisson

TRIKON MORI™ 200 PLASMA TOOL

- **A commercial Trikon Technologies, Inc., Pinnacle 8000 plasma tool was used to validate the model.**





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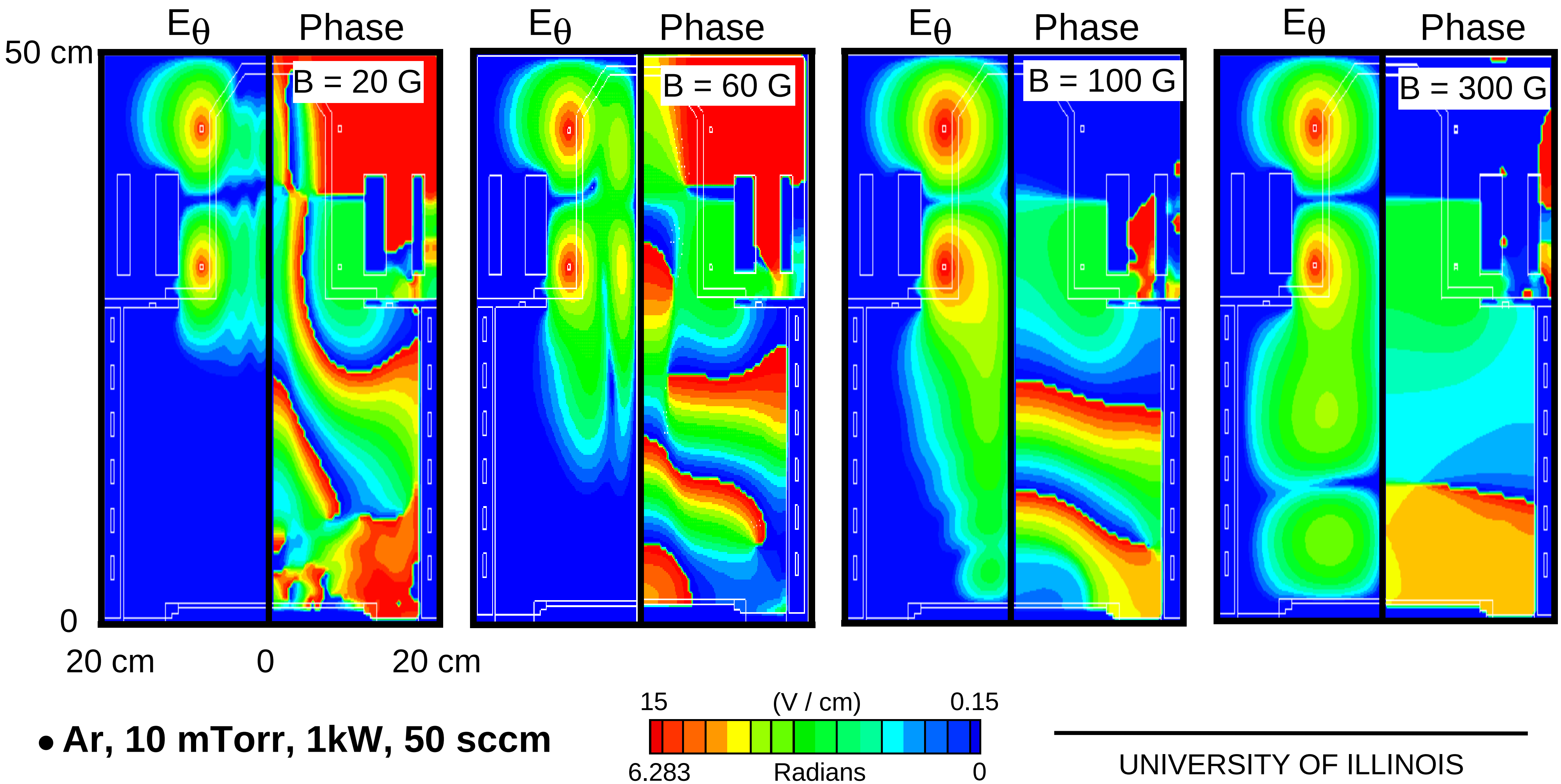
ANALYSIS OF TRIKON PLASMA TOOL : E_θ

- At low fields, the electromagnetic propagation is mainly radial, producing standing wave patterns in the radial direction.

- However as the field increases, propagation dominates in the axial direction, shifting standing wave patterns in the direction of propagation.



- Ar, 10 mTorr, 1kW, 50 sccm

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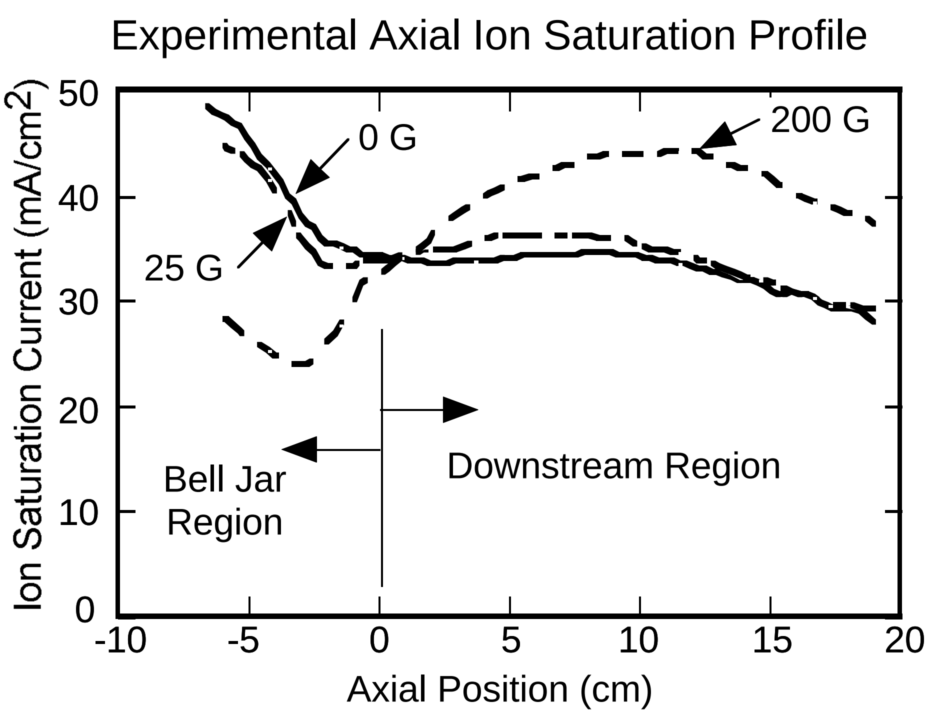
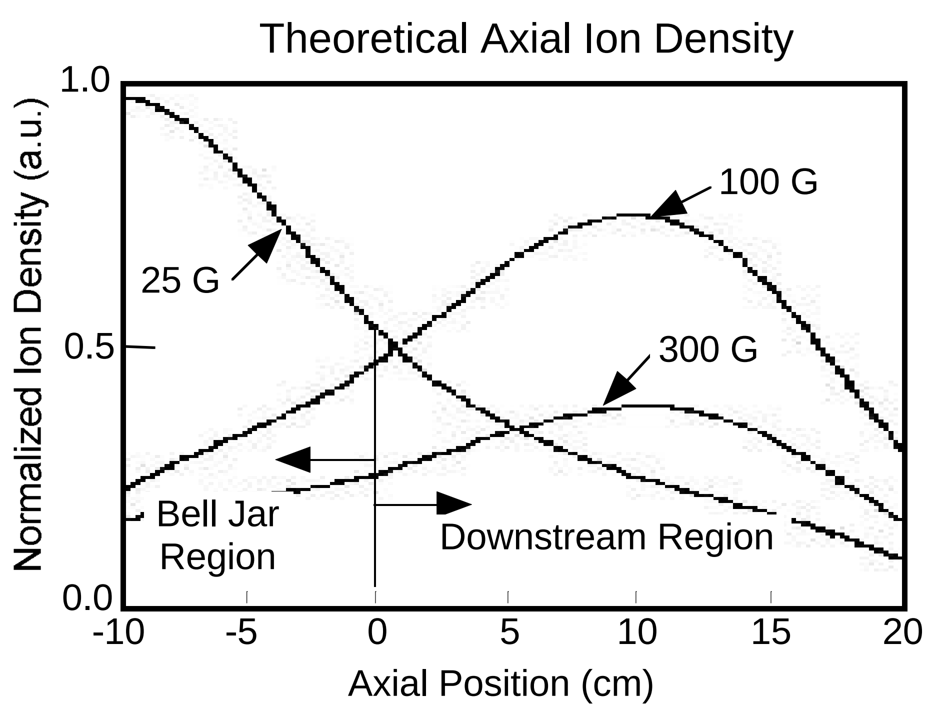
ANALYSIS OF TRIKON PLASMA TOOL: VALIDATION

- **As static magnetic field increases, the ion saturation current peaks further downstream. Simulations show a similar trend for the ion saturation profile.**

- **For simulations at constant power, downstream peak decreases with increasing static magnetic fields since plasma peaks at larger radius (i.e. larger plasma volume).**



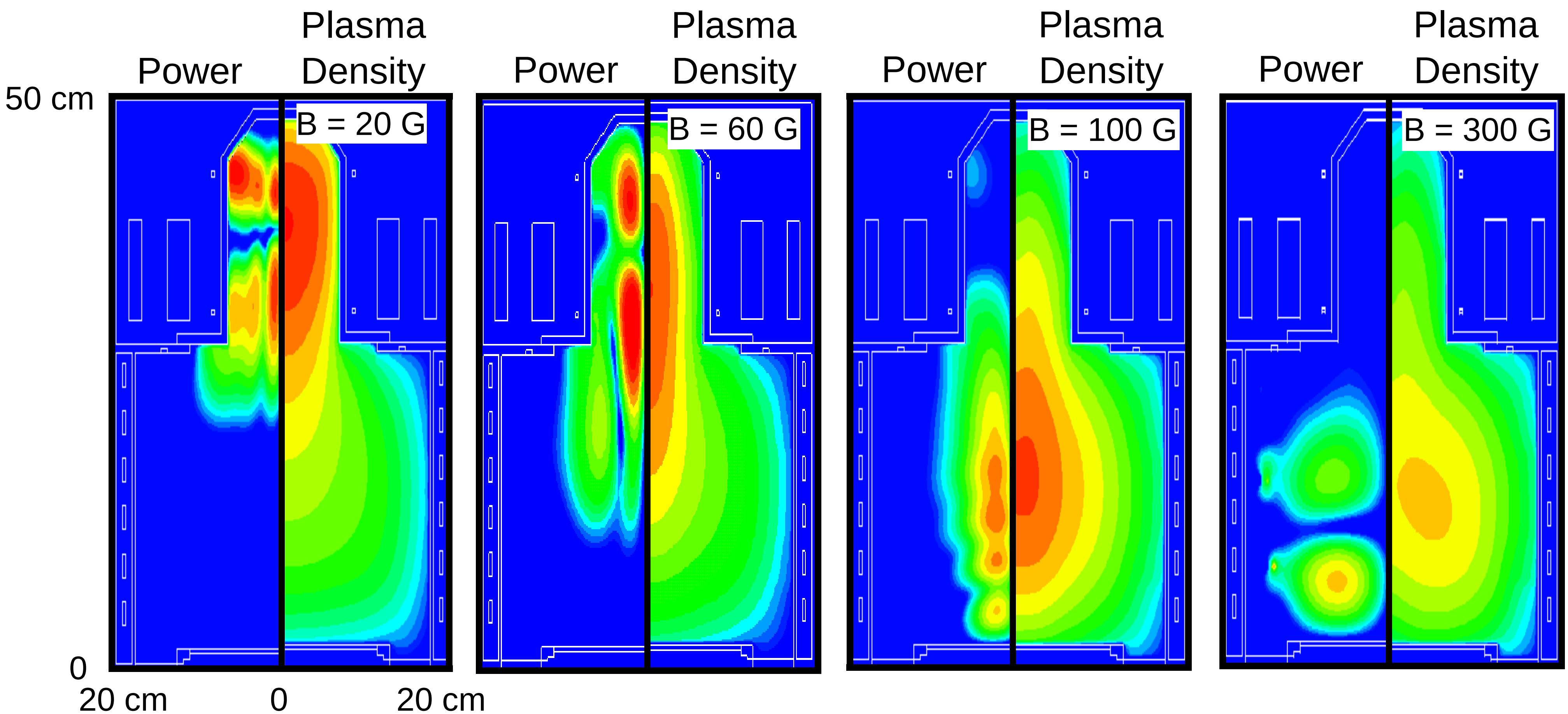


- **Ar, 2.3 mTorr, 1kW (Trikon Technologies, Inc.)**

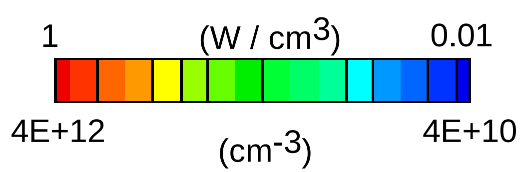
- **Ar, 10 mTorr, 1kW, 50 sccm**

ANALYSIS OF TRIKON PLASMA TOOL : POWER AND ELECTRON DENSITY

- **As the magnetic fields increase, axial propagation dominates depositing power in the downstream region.**



- **Ar, 10 mTorr, 1kW, 50 sccm**



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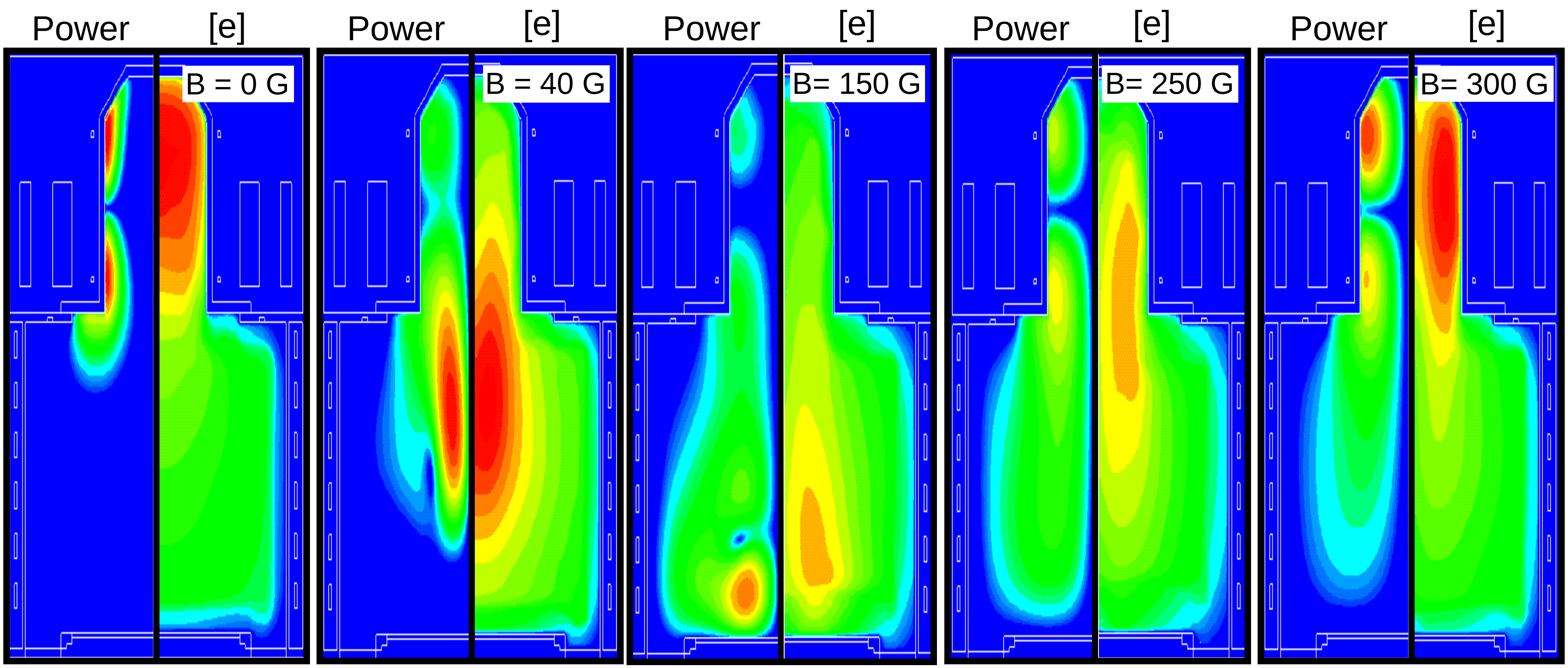
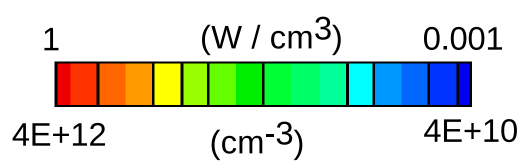
ANALYSIS OF TRIKON PLASMA TOOL : Ar/Cl_2

- For an Ar/Cl_2 mixture, over the same magnetic range as the Ar simulation, power deposition cycles back upstream, resembling ICP behavior.

- At high enough magnetic fields, the electric field wavelength is larger than the reactor size and is unable to sustain a standing wave pattern.



- Ar/Cl_2 4:1, 10 mTorr, 1kW, 50 sccm



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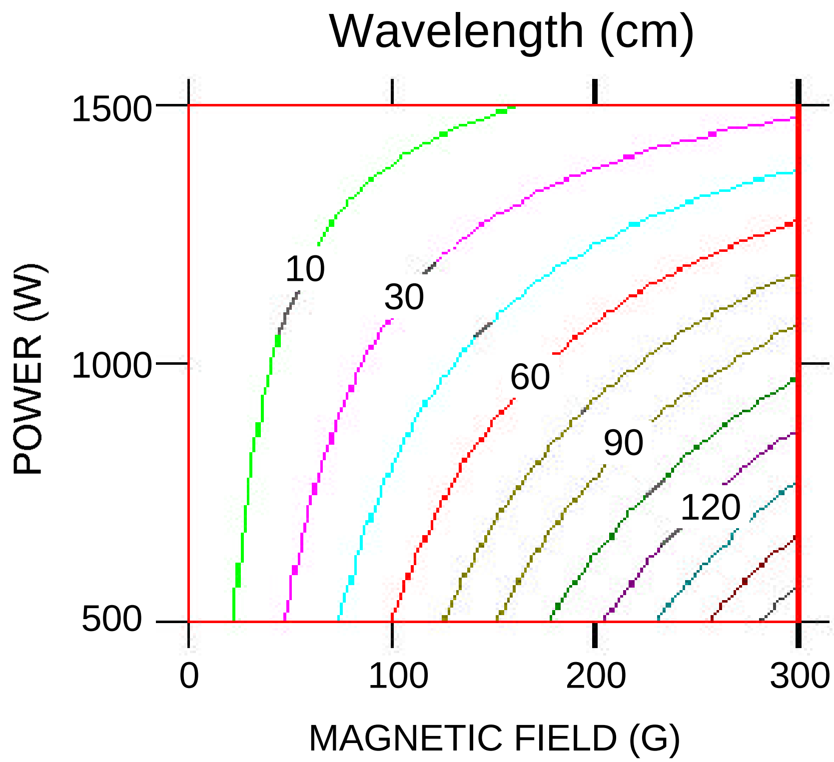
ANALYSIS OF TRIKON PLASMA TOOL : Ar/Cl_2

- **The ability to deposit power downstream is limited by the wavelength of the helicon-like wave.**

- **If the plasma is significantly electronegative, in the low power-high magnetic field regime, the power deposition will resemble conventional ICP.**

- **For a *m* = 0 mode, in a cylindrical geomerty, the wavelength goes as,**

$$\lambda_{z\ (cm)} = \frac{7.6 \times 10^6}{R_{cm}} \left(\frac{B_o\ (Gauss)}{n_{e\ (cm^{-3})}} \right)^{0.6}$$



- **Ar/Cl_2 4:1, 10 mTorr, 50 sccm**

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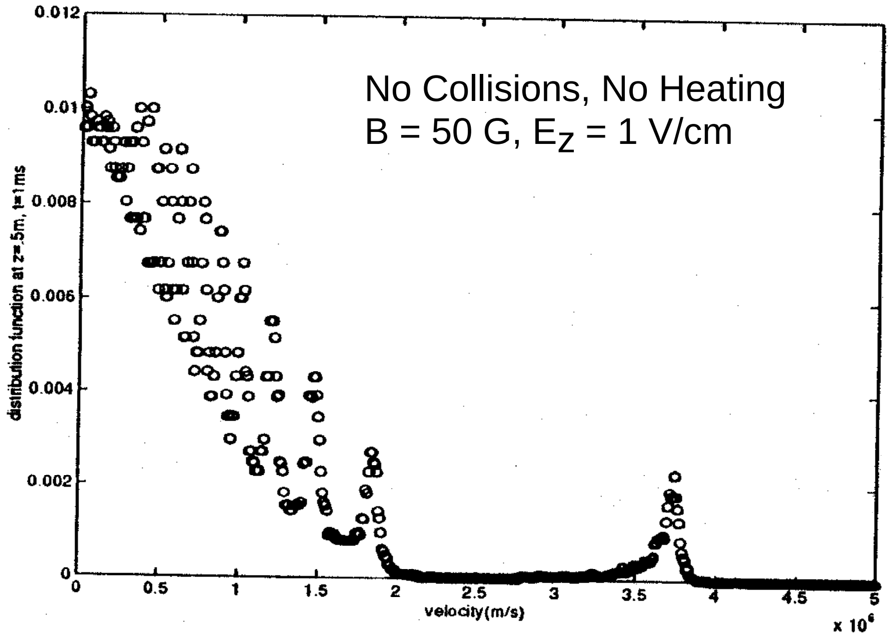
COLLISIONLESS HEATING

- **Helicon waves have the property that their parallel phase velocities can be easily matched to the thermal velocities of electrons in the 20 - 200 eV range.**

- **Chen has suggested Landau damping as a collisionless heating mechanism. If the wave grows fast enough, it can trap thermal electrons and accelerate them to the phase velocity.**

- **Sharer *et al.* found that trapped particles appear as the wave intensity increases, producing *f*(ε) with energies higher than the ionization potential of the gas.**

- **J. E. Scharer and H. Gui, *Nonlinear Trapping Simulations for Helicon Plasma Sources*, IEEE ICOPs, Monterey, CA, 1999**



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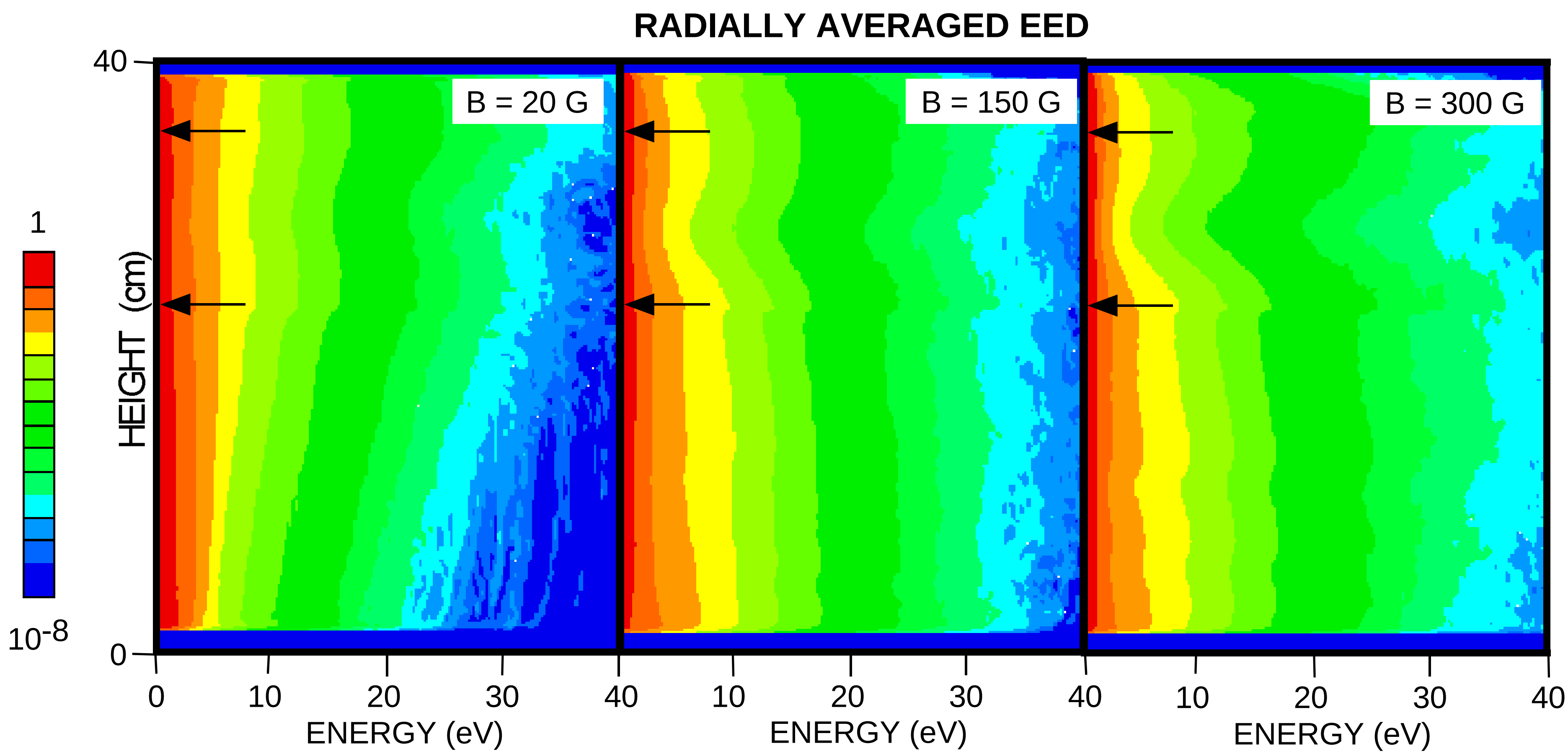
COLLISIONLESS HEATING

- The electron energy distribution (EED) was obtained from the EMCS.
- The tail of the EED is peaked near the coils.
- As the magnetic field is increased there is an increase in the high energy tail downstream.



- **Ar, 10 mTorr, 1 kW, 50 sccm**

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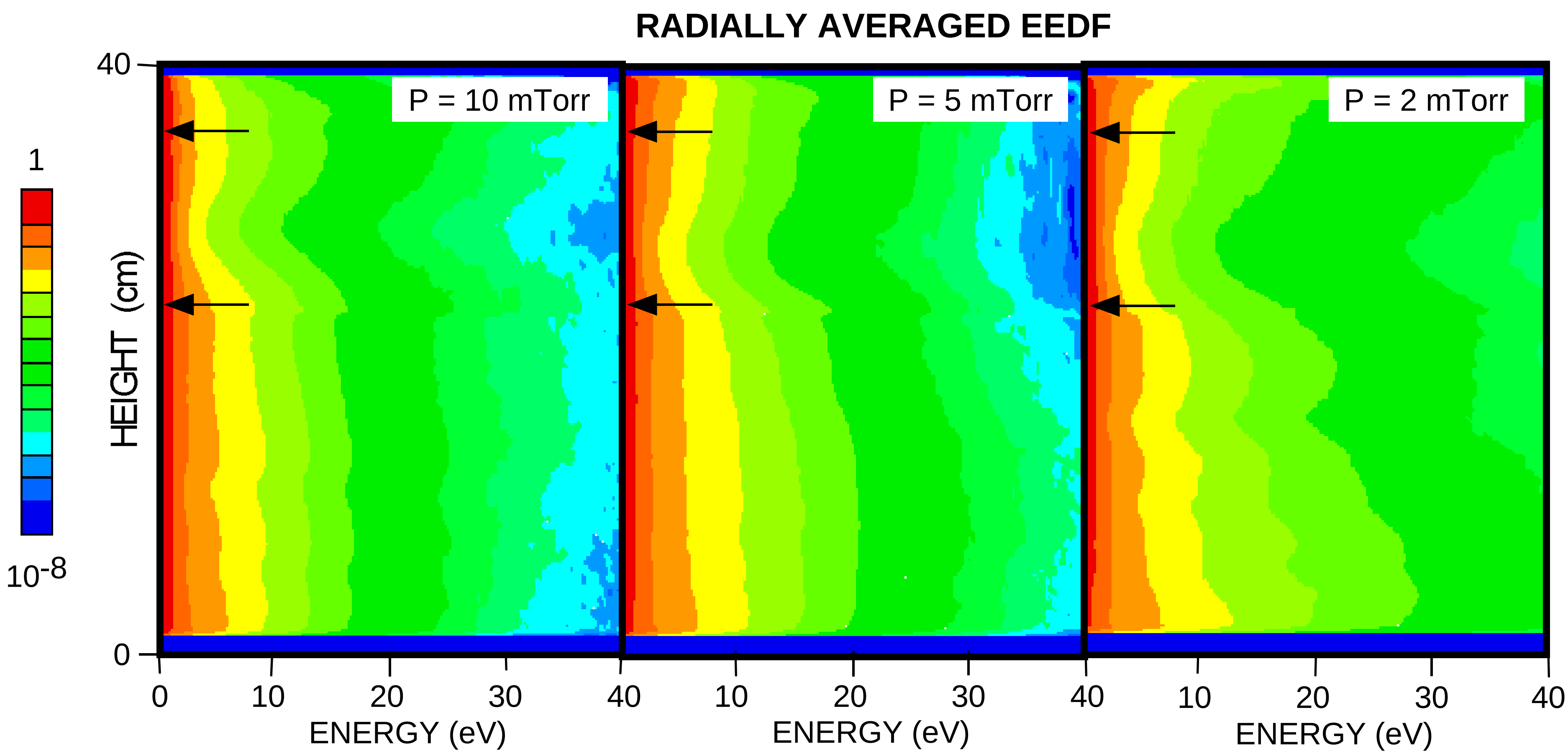
COLLISIONLESS HEATING

- **As the pressure is decreased, the collisionless heating mechanisms become more dominant.**

- **There is significant heating in the downstream region.**



- Ar, 1 kW, 50 sccm, 300 G

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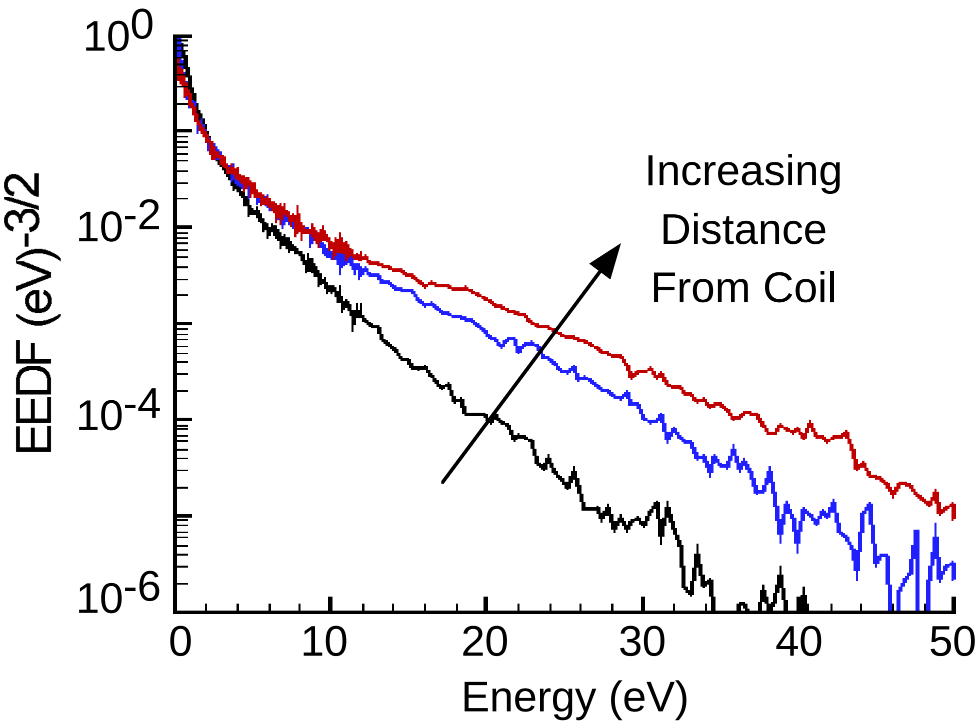
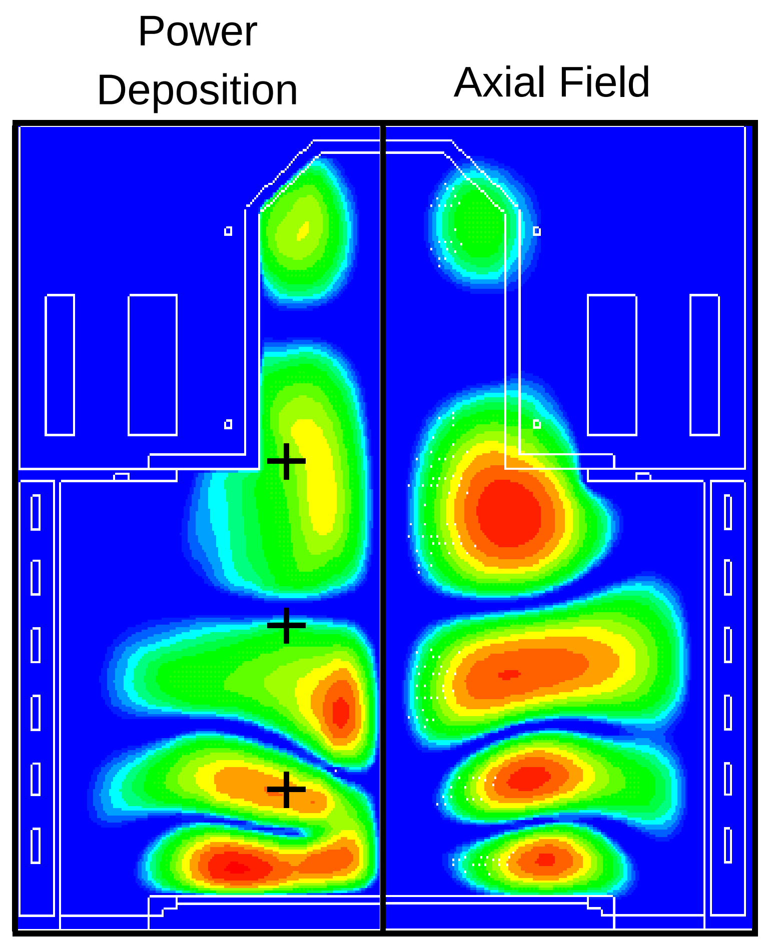
COLLISIONLESS HEATING

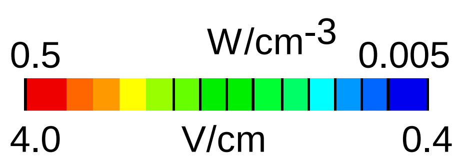
- **The tail end of the EEDF increases with increasing distance from the coil.**

- **The axial component of the electromagnetic field is responsible for most of the power deposition.**





- Ar, 1 kW, 300 G, 2mTorr



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COLLISIONLESS HEATING : TG MODE

- **Recently it has been suggested (Chen) that much of the electron heating comes from the electrostatic component of the helicon wave (i.e. the Trivelpiece Gould (TG) mode).**

- **If plasma neutrality is not enforced, the divergence term in the wave equation must be included. Effects of the electrostatic TG mode can then be resolved.**

$$\nabla\left(\frac{1}{m}\nabla\cdot\overline{E}\right)-\nabla\cdot\left(\frac{1}{m}\nabla\overline{E}\right)=w^2e\overline{E}-iw\overline{\overline{s}}\cdot\overline{E}$$

TG Wave Helicon Wave

- **The divergence of the electric field is equal to the perturbed electrons.**

$$\nabla\cdot\overline{E}=\frac{r}{e}=\frac{q\Delta n_e}{e}$$

where,

$$\Delta n_e=\frac{-\nabla\cdot\left(\dfrac{\overline{\overline{s}}\cdot\overline{E}}{q}\right)}{\left(w_{Damp}+iw\right)}$$

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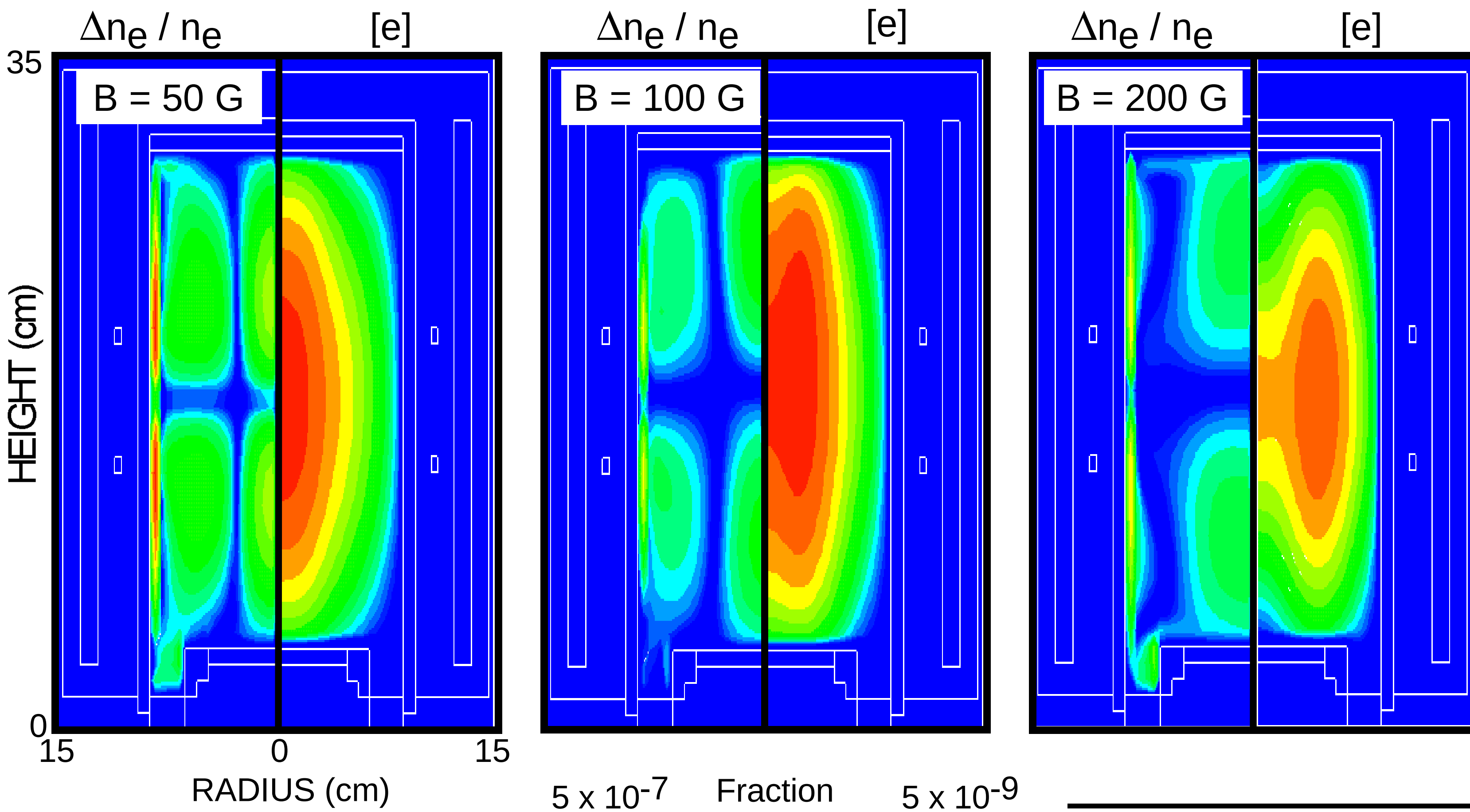
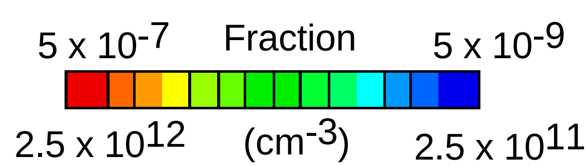
TG MODE AND ELECTRON DENSITY

- **The gradient of the perturbed electrons, represents a current sink due to the TG mode.**

- **As the magnetic field increases, the TG mode is strongly damped near the surface with a less penetration in the plasma volume.**





- **Ar, 10 mTorr, 1 kW, 50 sccm**

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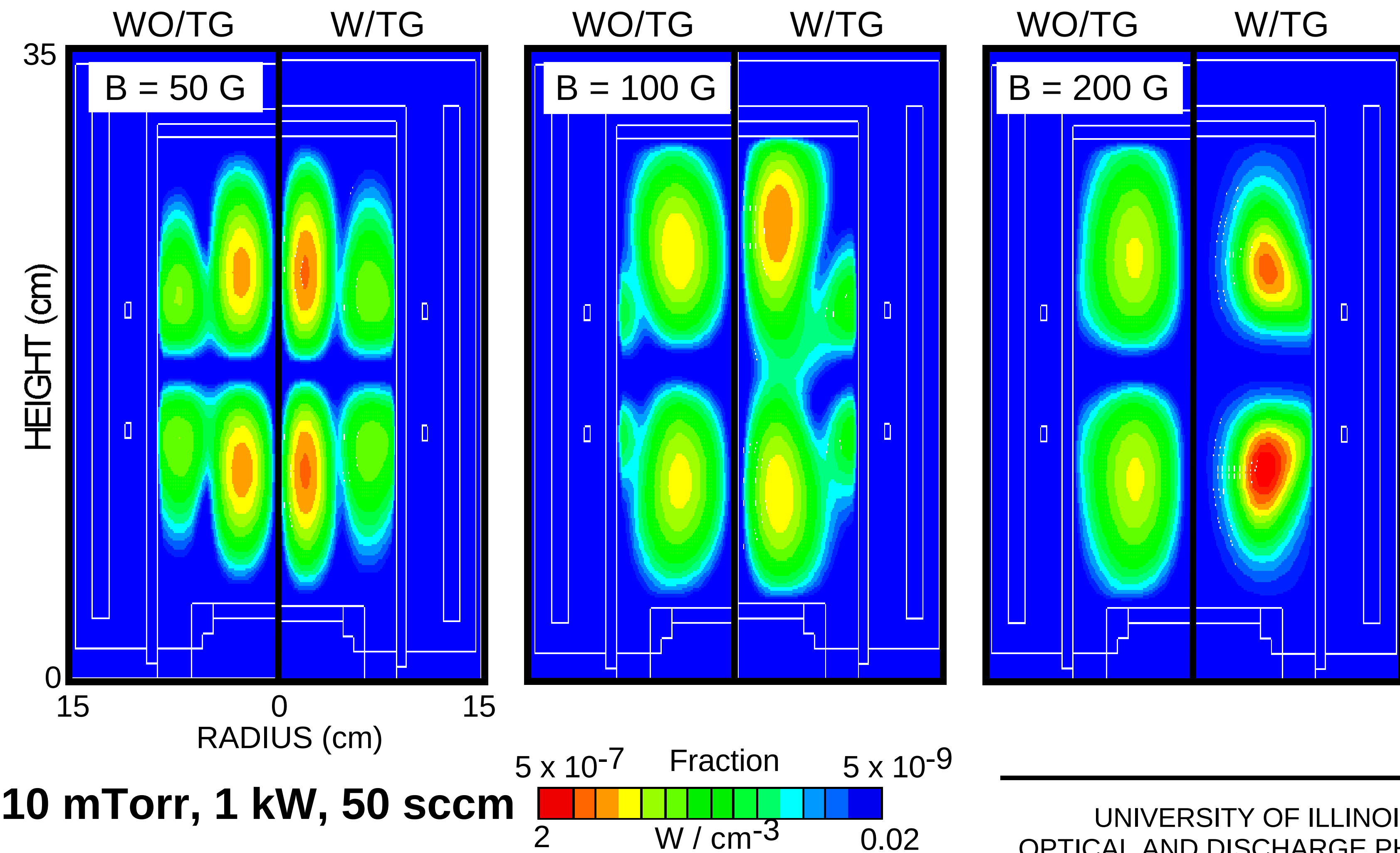
TG MODE AND POWER DEPOSITION

- At low magnetic fields, the TG mode is weakly damped and is strongly coupled to the helicon wave, therby penetrating into the plasma volume.

- As the magnetic field increases, the TG mode is strongly damped near the surface and power deposition occurs closer to the surface.



- Ar, 10 mTorr, 1 kW, 50 sccm

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CONCLUSIONS

- Simulations of a $m = 0$ mode were conducted in a commercial helicon plasma tool. In the absence of the TG mode, with increasing B-field, electric field propagation progressively follows B-field lines and significant power can be deposited downstream.

- Electron Monte Carlo Simulations have shown an increase in the tail of the EEDs in the downstream region indicating some amount of collisionless heating.

- Volumetric power deposition is ultimately limited by damping of the TG mode and the helicon wavelength. Wave propagation can be suppressed in electronegative gas mixtures in the low power - high B-field range, where the wavelength exceeds the chamber dimension.

- Investigations on the dependence of the TG mode must be established to understand the coupling of electromagnetic field and power deposition to the plasma.

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