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Electron Transport and Power Deposition in Magnetically Enhanced Inductively Coupled Plasmas

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AGENDA

- Motivation

- Plasma Modeling - Hybrid Plasma Equipment Model (HPEM)

- Trikon Mori Helicon Source
  - Validation
  - Effects of TG Mode

- Analysis of Helicon Component

- Non-Collisional Heating
  - Axial Acceleration
  - Phase Matching

- Conclusions

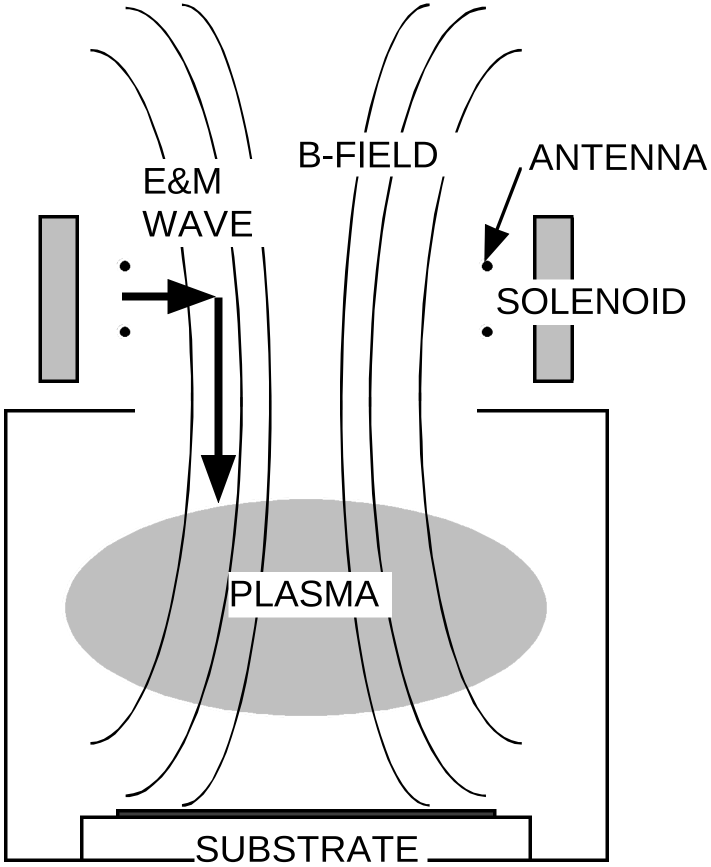
MOTIVATION FOR MAGNETICALLY ENHANCED ICPs

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

- **It is often desirable to produce plasmas in the "volume" of large reactors. This is difficult to accomplish using ICPs due to their finite skin depth.**

- **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.**



PROPERTIES OF MAGNETICALLY ENHANCED ICPs

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

  - Helicon Wave
  - Electrostatic Wave (TG)

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

- Chen and Boswell have 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.

- More recently it has been suggested that much of the electron heating comes from the TG component of the wave.

- Here we report on power deposition on MEICPs by these mechanisms.

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

- Potentials: Poisson Equation

HPEM ELECTROMAGNETICS : TG MODE

- **If plasma neutrality is not enforced, the divergence term in the wave equation must be included.**

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

TG Wave **Helicon Wave**

- **The divergence of the electric field is equal to the wave perturbed electron density.**

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

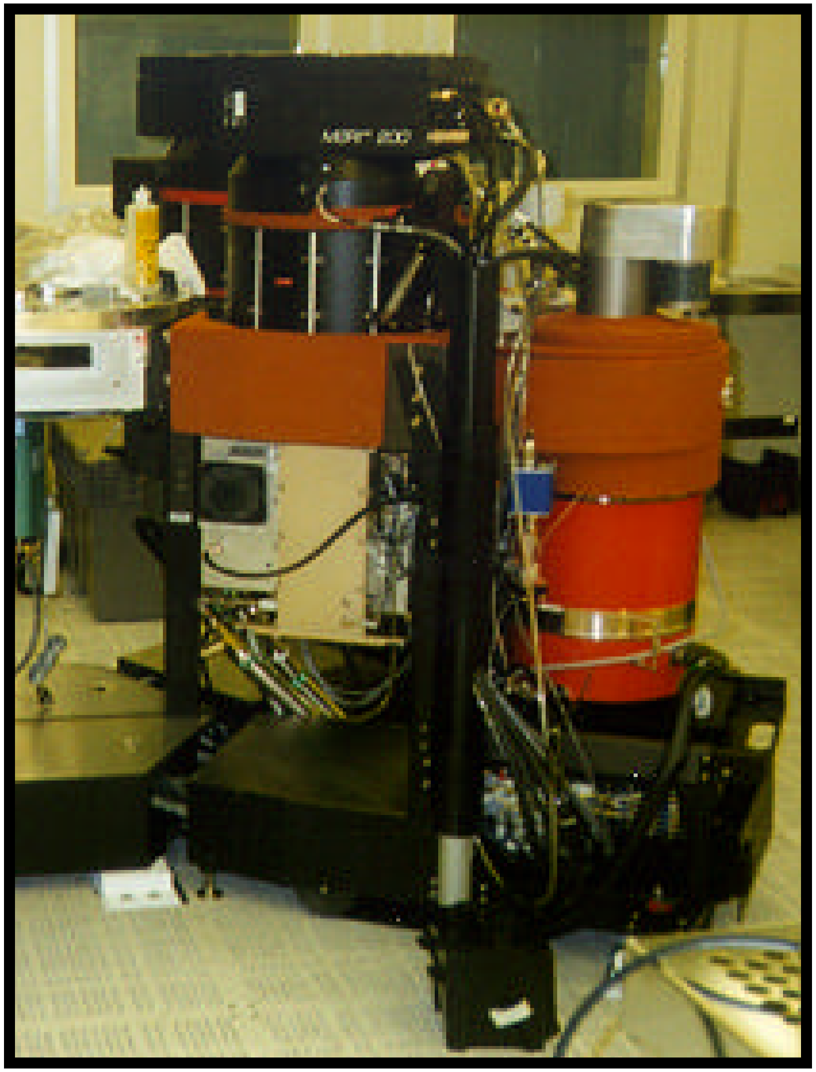
where,

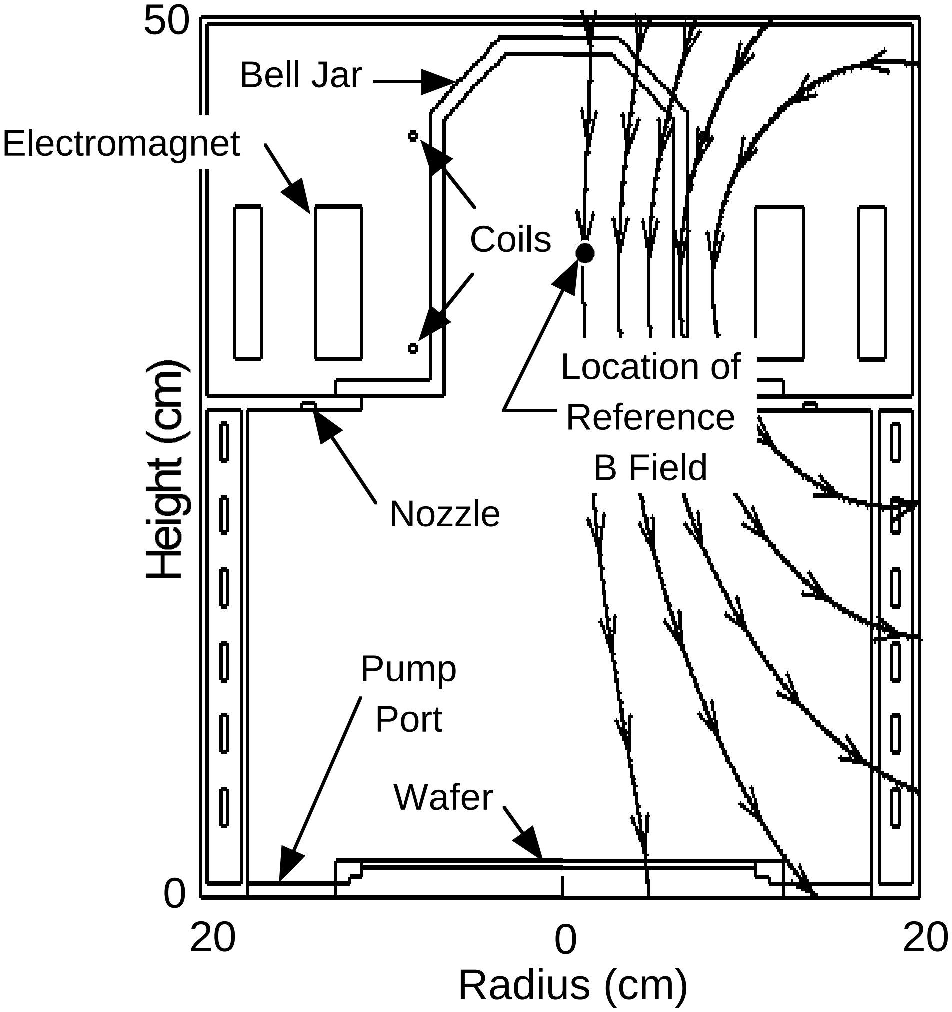
$$\Delta n_{e}=\frac{-\nabla\cdot\left(\frac{\overline{\overline{s}}\cdot\overline{E}}{q}\right)}{\left(w_{Damp}+iw\right)}$$

- **The gradient of the perturbed electron density, represents an effective current sink due to the TG mode.**

TRIKON MORI^{TM} 200 PLASMA TOOL

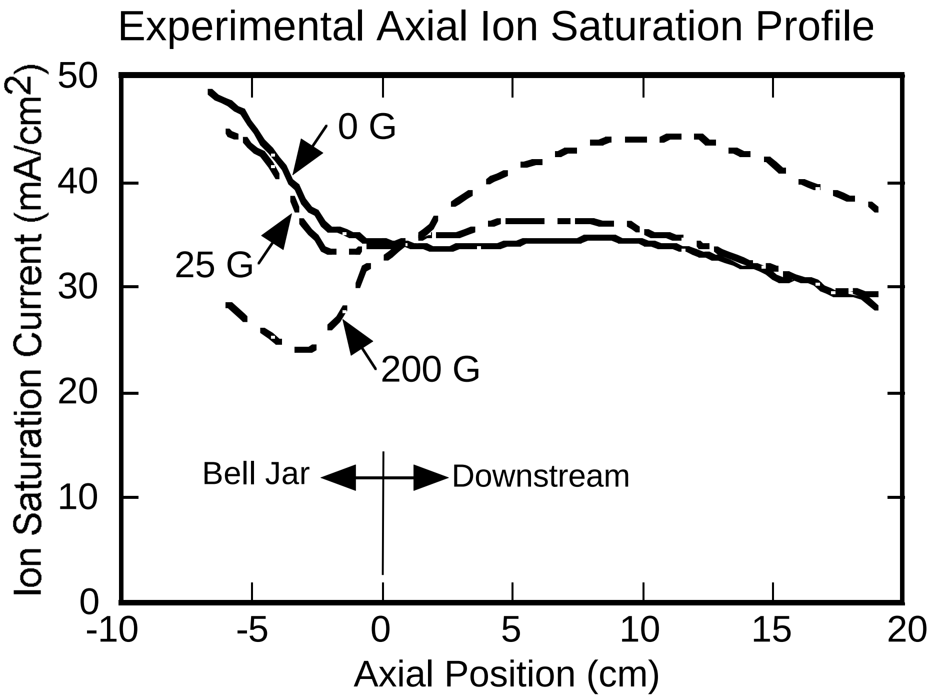
- **A commercial Trikon Technologies, Inc., Pinnacle 8000 plasma tool was used to validate the model.**



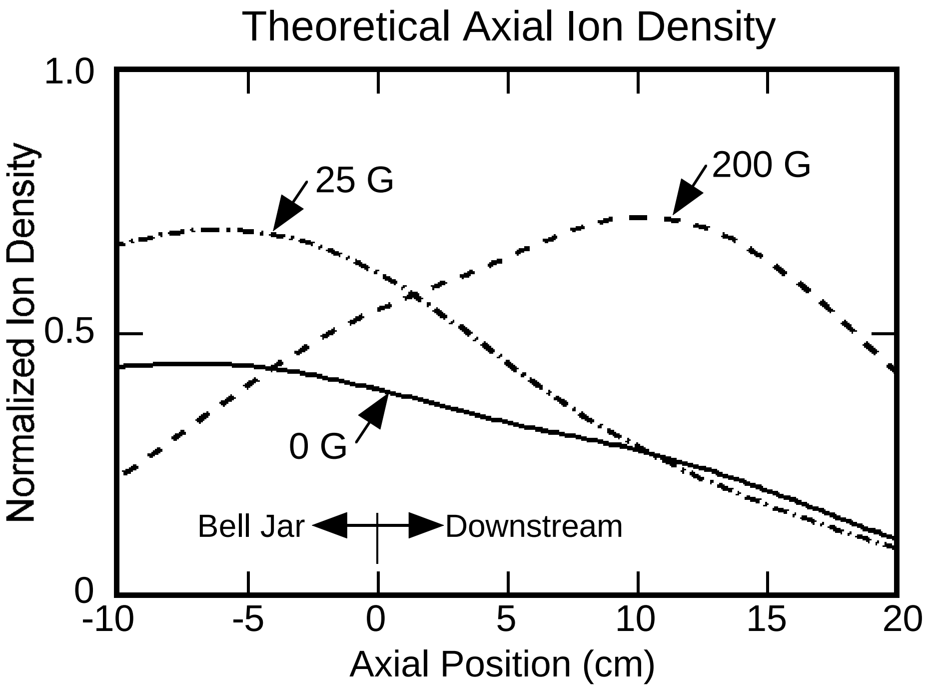


ANALYSIS OF TRIKON PLASMA TOOL: VALIDATION

- As static magnetic field increases, the ion saturation current peaks further downstream. Simulations show a similar trend for the ion profile.
- With increasing magnetic field, electric field propagation progressively follows magnetic flux lines and significant power can be deposited downstream.


Experimental Axial Ion Saturation Profile

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

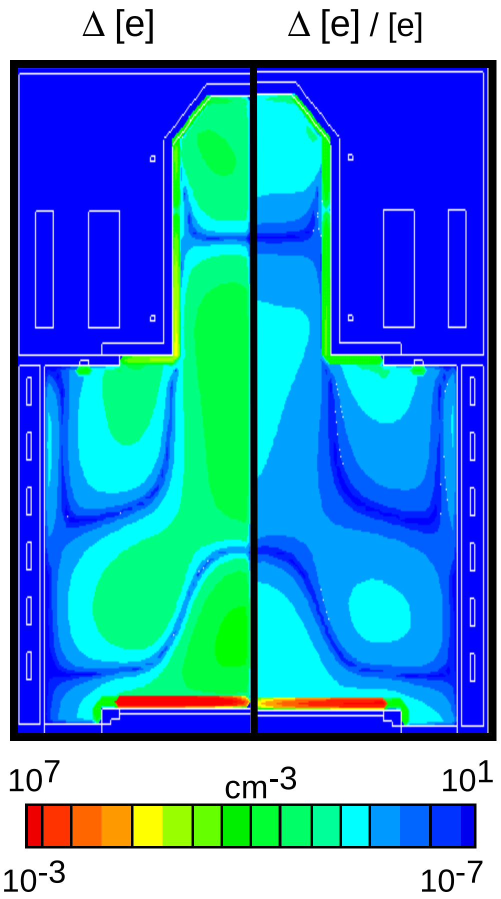

Theoretical Axial Ion Density

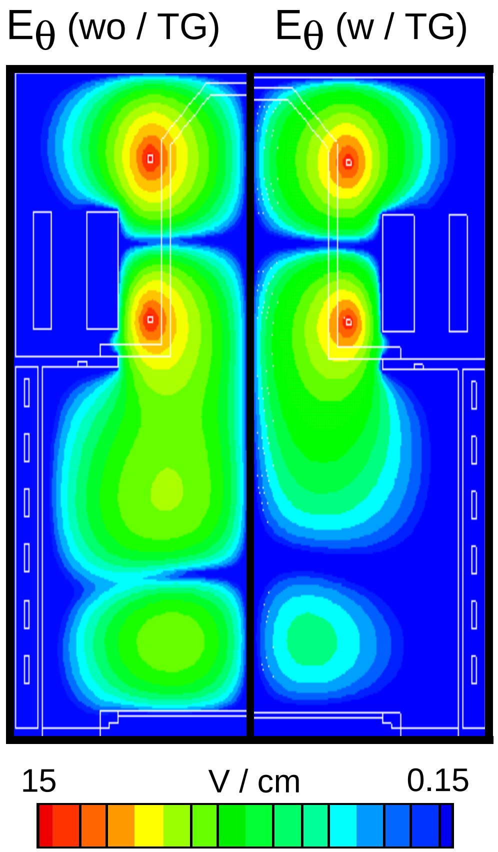
- Ar, 2.3 mTorr, 1 kW, 50 sccm

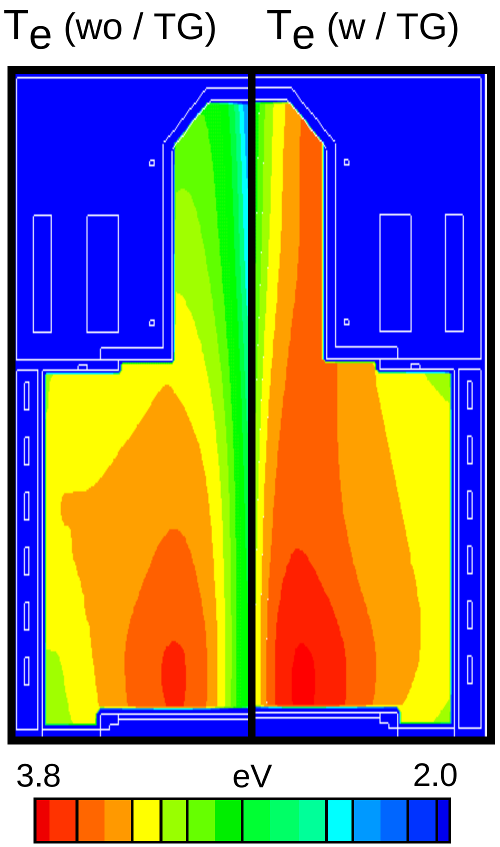
EFFECTS OF TG MODE ON PROPAGATION

- At 300 G, TG mode is strongly damped at the dielectric-plasma surface. The percent of perturbed electrons in this region can reach 1%.

- The TG mode couples power more efficiently per electron produced. At a constant input power, this results in a higher temperature and lower plasma density.





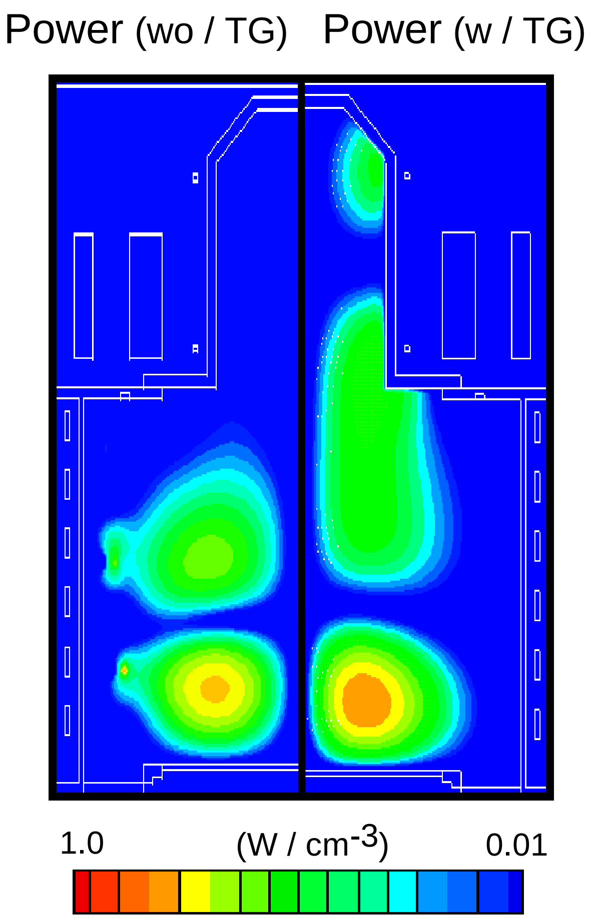


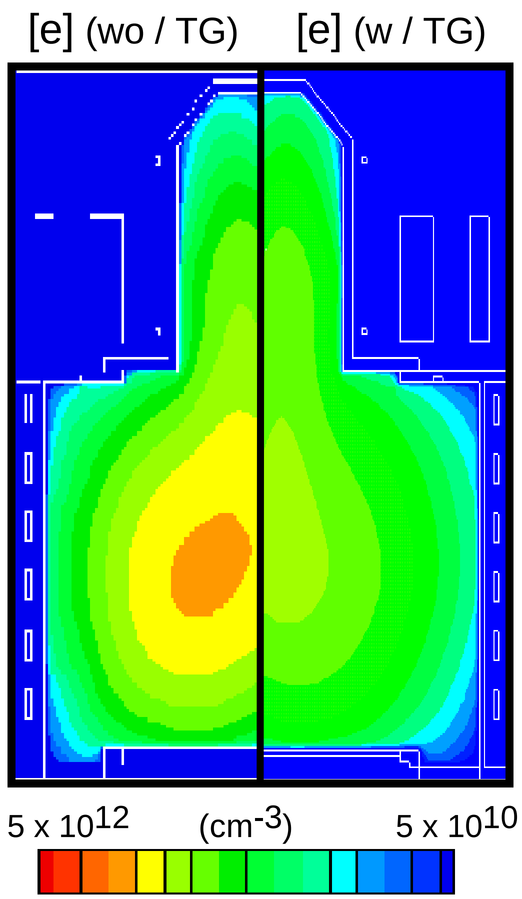
- Ar 10 mTorr, 1 kW, 50 sccm, 300 G

EFFECTS OF TG MODE ON PROPAGATION

- Initial studies indicate that the effect of the TG mode is to restructure the power deposition profile near the coils.

- However, the propagation of the helicon component is little affected, particularly at large magnetic fields where the TG modes is damped.



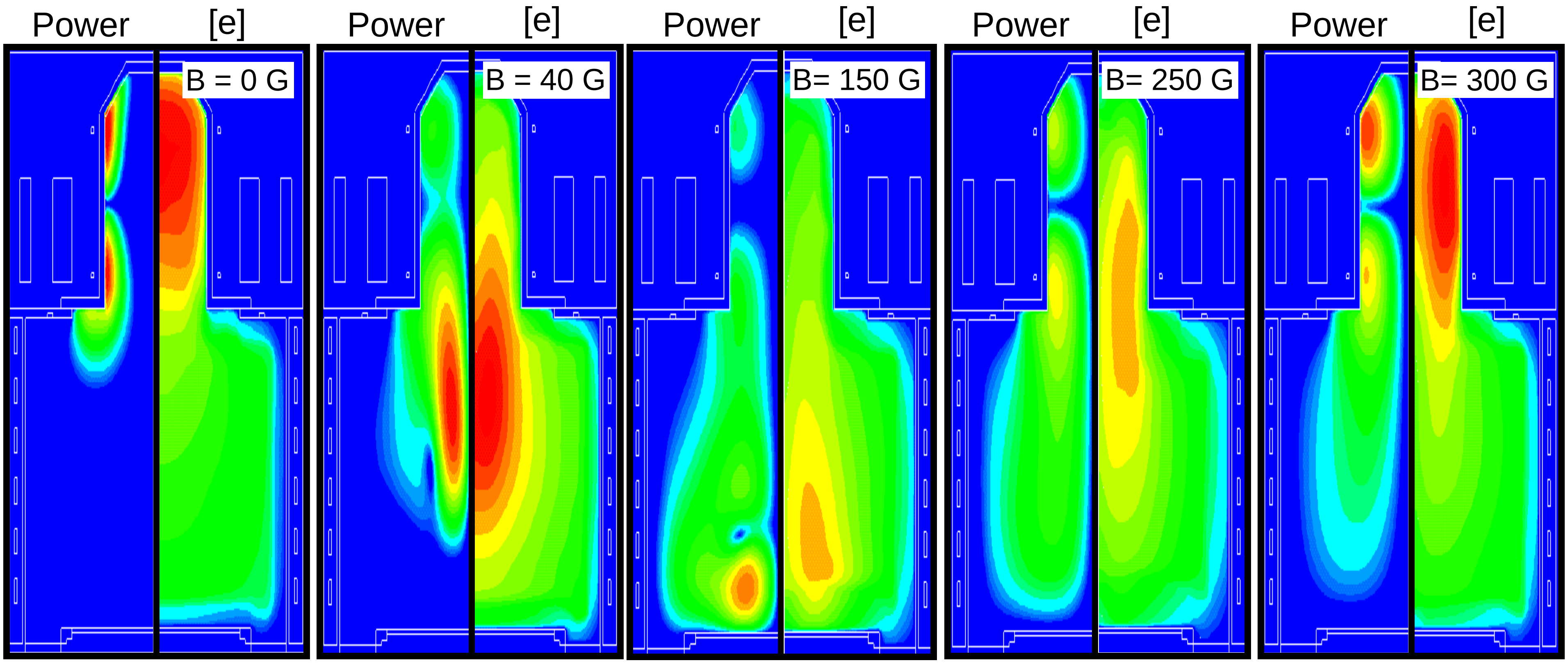


- **Ar 10 mTorr, 1 kW, 50 sccm, 300 G**

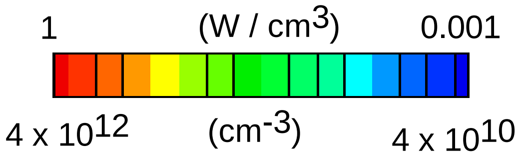
ANALYSIS OF PLASMA TOOL : POWER

- **For Ar/Cl_2, power deposition, at high magnetic fields, cycles back upstream, resembling an ICP.**

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



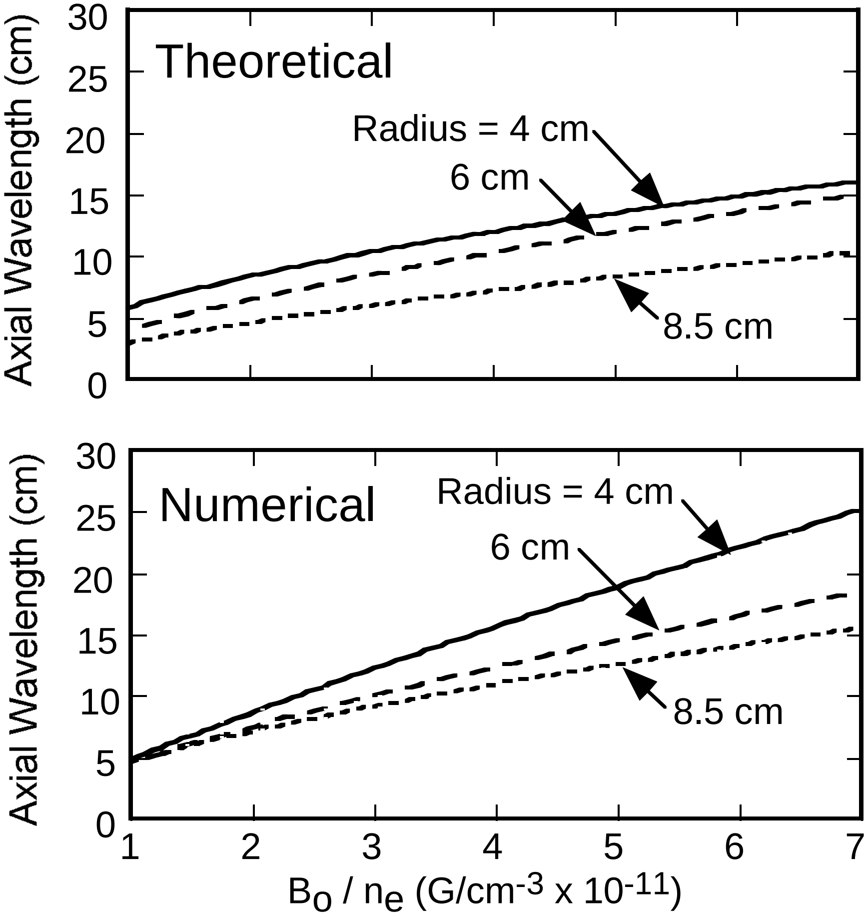
- **Ar/Cl_2 80:20, 10 mTorr, 1 kW, 50 sccm**

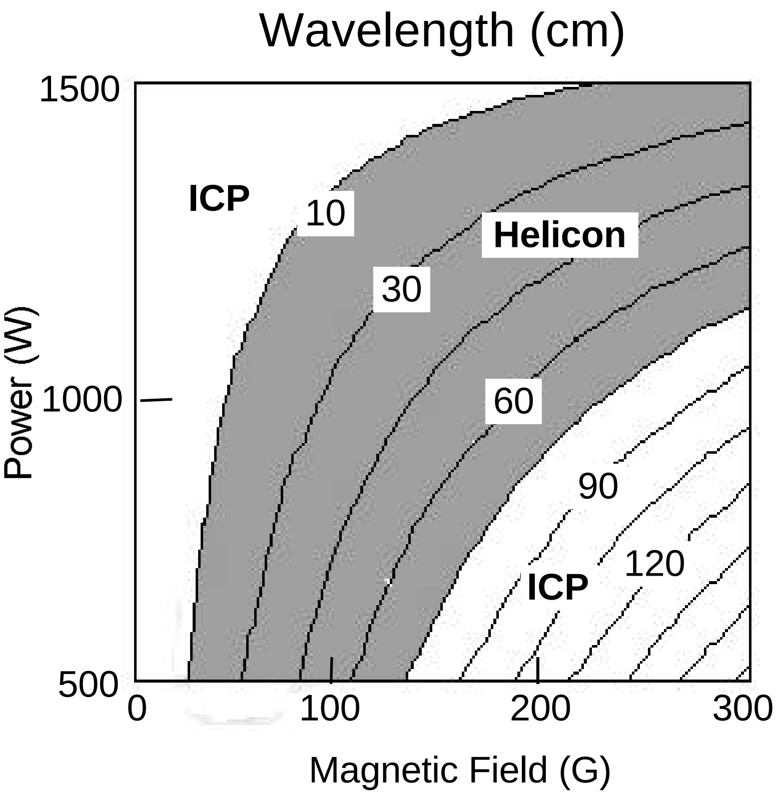


ANALYSIS OF HELICON COMPONENT: WAVELENGTH

- **Neglecting the TG mode, the ability to deposit power downstream is limited by the wavelength of the helicon-like wave.**

- **For an *m* = 0 mode,** $\lambda_{z\ (\mathrm{cm})} = \dfrac{7.6 \times 10^6}{R_{\mathrm{cm}}} \left(\dfrac{B_o\ (\mathrm{Gauss})}{n_e\ (\mathrm{cm}^{-3})} \right)^{0.6}$



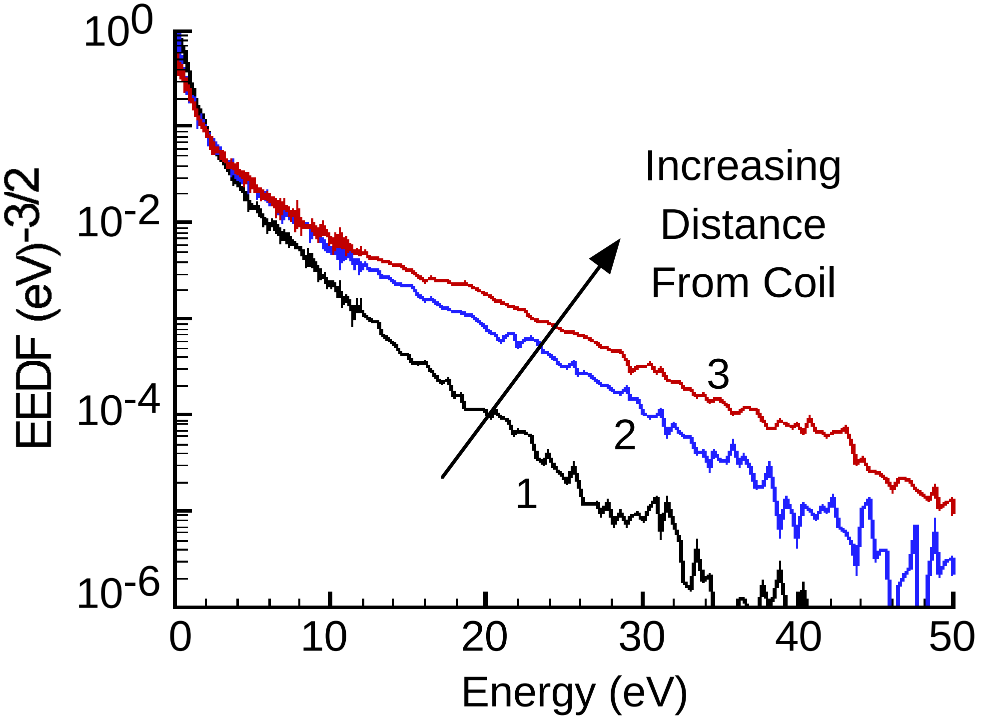


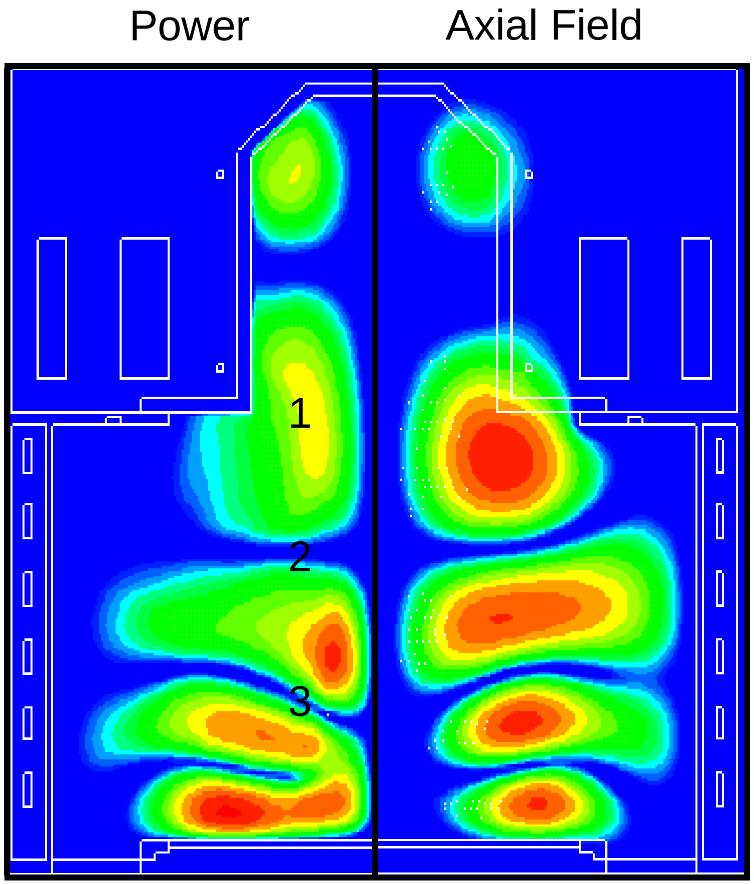
- **Ar/Cl_2 80:20, 10 mTorr, 50 sccm**

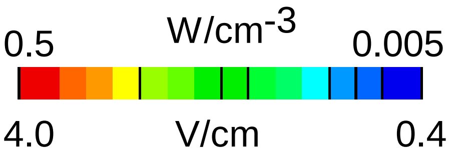
COLLISIONLESS HEATING : AXIAL ACCELERATION

- **The electron energy distribution (EED) was obtained from the EMCS. The tail 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.**







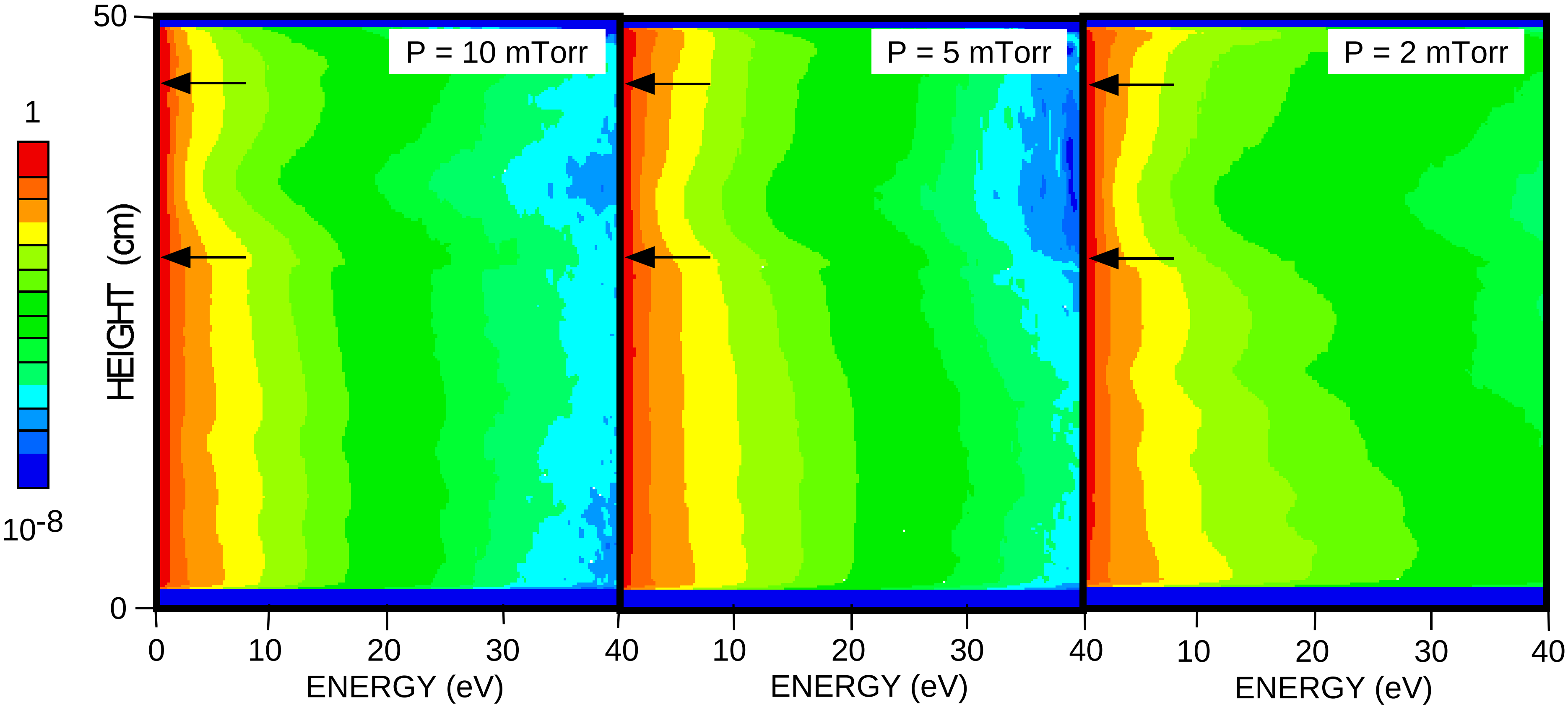
- Ar, 1 kW, 300 G, 2 mTorr

COLLISIONLESS HEATING : PRESSURE

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

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

RADIALLY AVERAGED EEDF



- Ar, 1 kW, 50 sccm, 300 G

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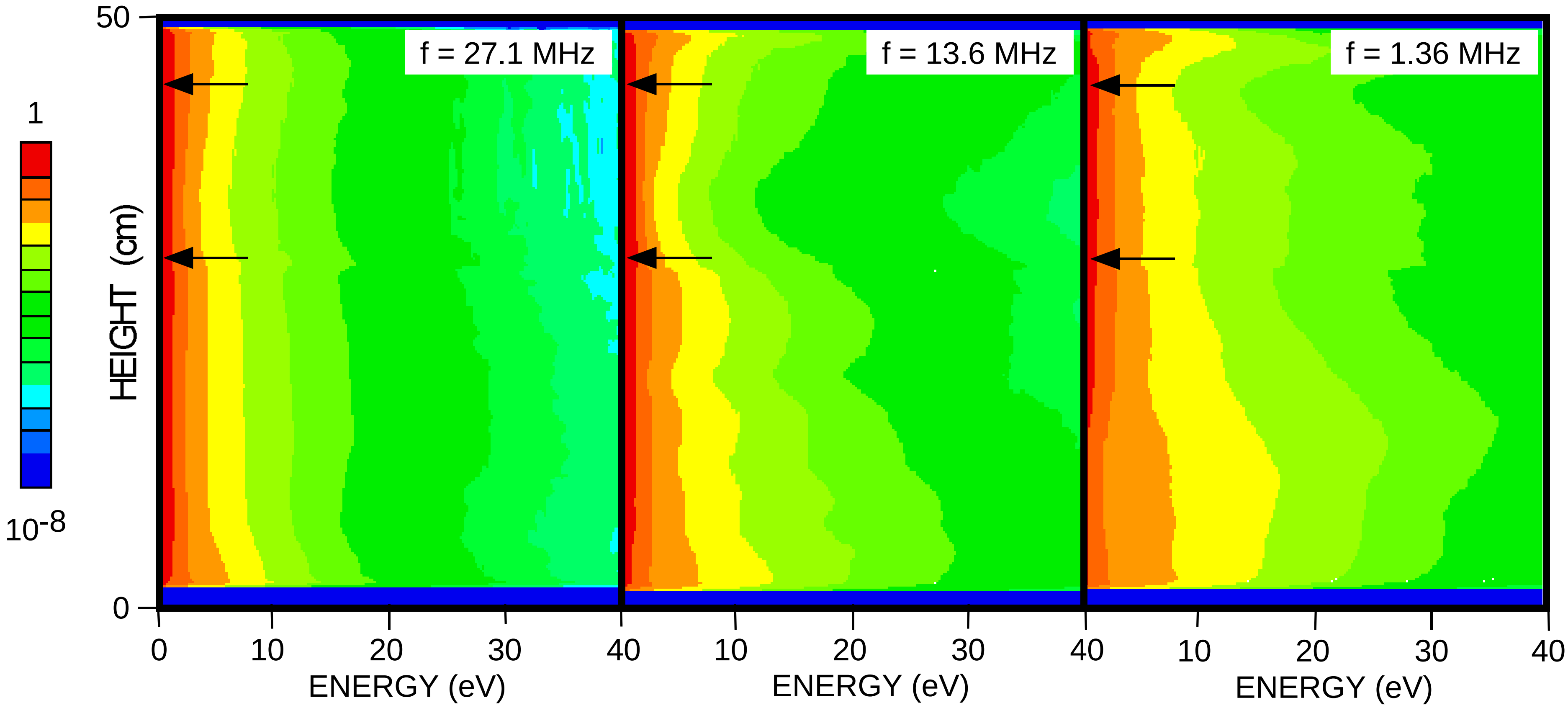
PHASE MATCHING

- **The parallel phase velocity of the electric fields is linearly proportional to the input rf frequency.**

- **As the frequency is decrease non-collisional heating throughout the reactor becomes more prevalent due to better phase matching with thermal electrons.**

RADIALLY AVERAGED EEDF



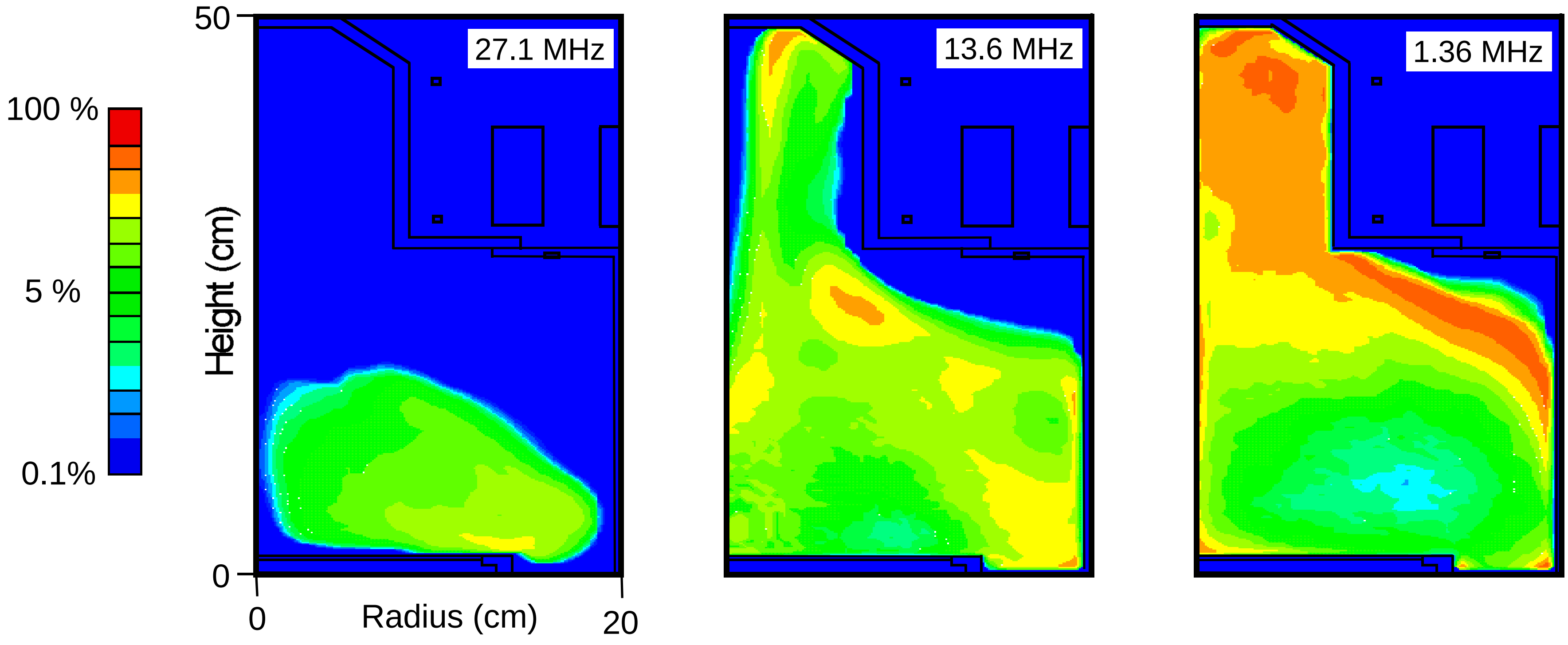
- Ar, 1 kW, 50 sccm, 300 G, 2 mTorr

PHASE MATCHING

- **Phase matching of the parallel phase velocity with the thermal velocity is required for acceleration.**

- **At lower frequencies the fraction of electrons in phase with the propagating electric field is larger.**

PERCENTAGE OF ELECTRONS IN PHASE



- Ar, 1 kW, 50 sccm, 300 G, 2 mTorr

CONCLUSIONS

- MEICPs are being studied for their ability to deposit power within the volume of the plasma.

- Study effects of TG mode on power deposition and ability for the helicon wave component to produce non-local heating.

- Initial studies indicate that the effect of the TG mode is to restructure the power deposition profile near the coils.

- However, the propagation of the helicon component is little affected, particularly at large magnetic fields where the TG modes is damped.

- For conditions where the TG mode is surpressed, the helicon component deposits the majority of the power within the volume of the plasma.

- At low pressures and rf frequencies, non-collisional heating becomes more prevalent since the thermal velocities match input rf phase velocity.