ELECTRON ENERGY DISTRIBUTIONS AND NON-COLLISIONAL HEATING IN MAGNETICALLY ENHANCED INDUCTIVELY COUPLED PLASMAS*

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AGENDA

- Wave heating in Magnetically Enhanced ICPs
- Description of the Model
- Transition from ICP to Helicon Heating
- Electron Energy Distributions: Continuous Acceleration
- Phase Matching Requirements
- Concluding Remarks

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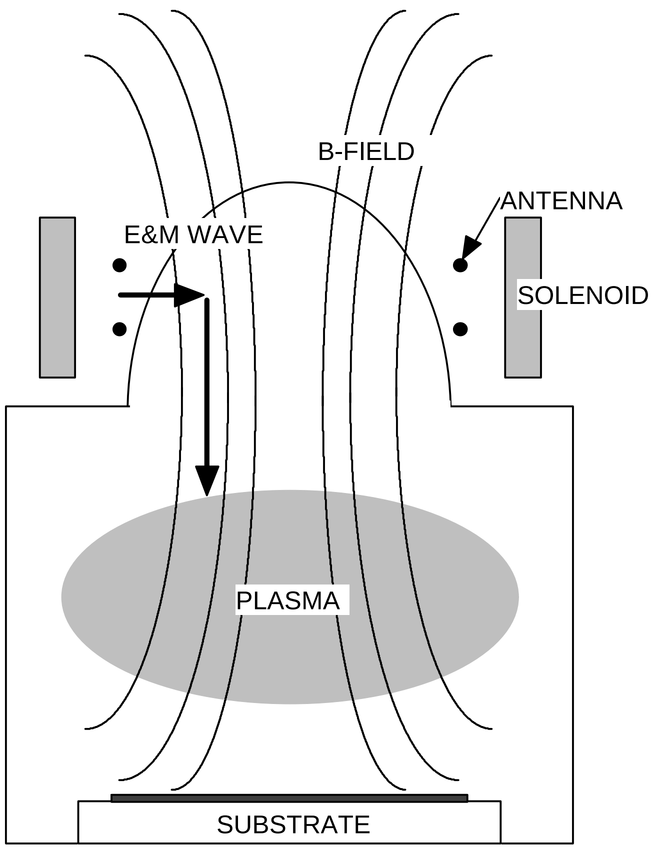
MAGNETICALLY ENHANCED ICPs

- **It is often desirable to produce plasmas in the "volume" of large reactors.**
- **This is difficult to accomplish using Inductively Coupled Plasmas (ICPs) due to the finite electromagnetic skin depth, typically a few cm at 10s MHz and 10^{11} cm^{-3} plasma density..**



- **By applying solenoidal dc magnetic fields, the resulting tensor conductivity produces all 3-components of the rf electric field.**

- **The end result is electromagnetic wave propagation along the magnetic field lines which deposits power both in the volume and remotely from the antenna.**

- **These systems are Magnetically Enhanced ICP, one manifestation being helicon devices.**

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POWER DEPOSITION IN MEICPs

- The coupling of electromagnetic fields to the plasma occurs through two channels: Helicon Wave and Electrostatic Wave (TG).
- Parallel phase velocities of helicon waves may match thermal speeds of 20 - 200 eV electrons, enabling continuous, non-collisional acceleration.
- Chen and Boswell have suggested Landau damping as such a collisionless heating mechanism. Evidence of non-collisional heating has been found experimentally and computationally in previous works:
  - A. Dageling and R. Boswell, Phys. Plasmas 4, 2748 (1997): *Ionization waves move away from the antenna at the phase velocity of the electromagnetic waves.*
  - Y. Mouzouris and J. Scharer, Phys. Plasmas 5, 4253 (1998): *At high B-field, helicon wave propagation dominates power deposition by resonant electron acceleration.*
- Here we report on computational investigations of non-collisional power deposition in MEICPs, and consequences on electron energy distributions (EEDs).

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COMPUTATIONAL PLATFORM

- **The computational platform used in this study is the Hybrid Plasma Equipment Model (HPEM).**
- **Geometry: 2-dimensional cylindrically symmetric**
- **<u>Electromagnetics Module</u>: 3-d components of rf E- and B-fields based on 2-d magnetostatic fields**
- **<u>Electron Monte Carlo Simulation</u>: EEDs, transport coefficients and source functions**
- **<u>Fluid Kinetics Module</u>:**
    - **Ions: Continuity, Momentum, Energy**
    - **Neutrals: Continuity, Momentum, Energy**
    - **Electrons: Continuity, Momentum, (energy from EMCS)**
    - **Electric Potential: Poisson's Equation**

ELECTROMAGNETICS MODULE

- **The wave equation is solved in the frequency domain:**

$$-\nabla\left(\frac{1}{m}\nabla\cdot\overline{E}\right)+\nabla\cdot\left(\frac{1}{m}\nabla\overline{E}\right)=\frac{\partial^2\left(e\overline{E}\right)}{\partial t^2}+\frac{\partial\left(\overline{\overline{s}}\cdot\overline{E}+\overline{J}\right)}{\partial t}$$

$$\vec{\mathrm{E}}(\vec{\mathrm{r}},\mathrm{t})=\vec{\mathrm{E}}'(\vec{\mathrm{r}})exp(-\mathrm{i}(w\mathrm{t}+j(\vec{\mathrm{r}})))$$

$$\Delta n_e=\frac{-\nabla\cdot\left(\frac{\overline{\overline{s}}\cdot\overline{E}}{q}\right)}{\frac{1}{t}+w}$$

- **The TG-mode can be resolved by including the divergence term based on a perturbation expansion for electron density.**

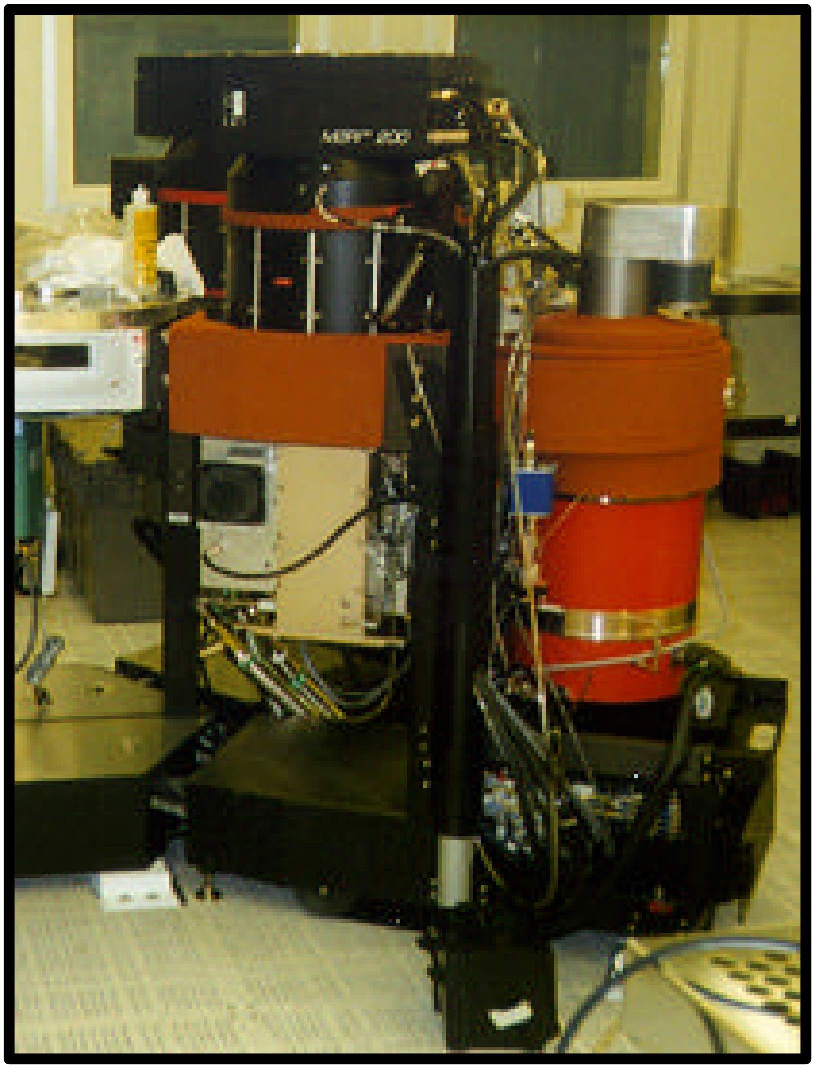
- **Conductivities are tensor quantities producing 3-d components of rf E- and B-fields based on 2-d magnetostatic fields.**

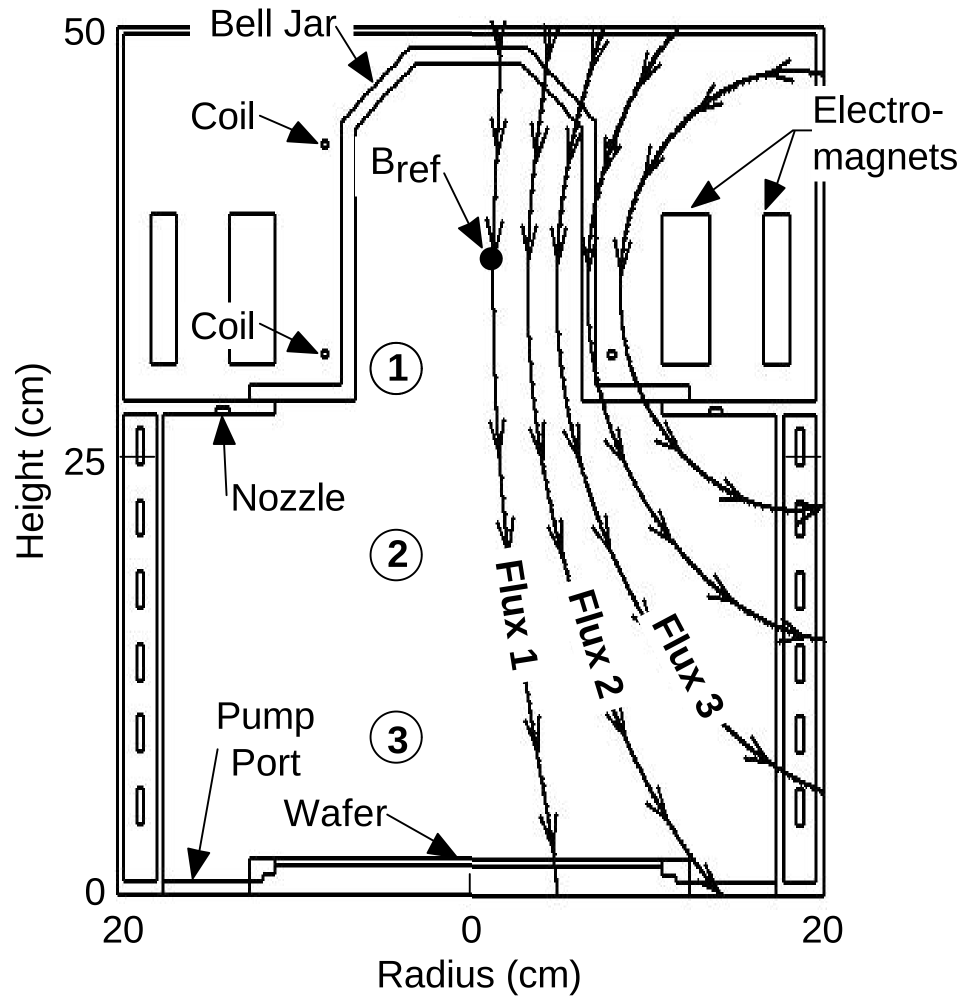
$$\overline{\overline{s}}=s_o\frac{mn_m}{qa}\frac{1}{\left(a^2+\left|\vec{B}\right|^2\right)}\begin{pmatrix}a^2+B_r^2 & aB_z+B_rB_q & -aB_q+B_rB_z\\ -aB_z+B_rB_q & a^2+B_q^2 & aB_r+B_qB_z\\ -aB_q+B_rB_z & -aB_r+B_qB_z & a^2+B_z^2\end{pmatrix}$$

$$\vec{j}=\overline{\overline{s}}\cdot\vec{E}\qquad a=\frac{\left(iw+n_m\right)}{q/m},\quad s_o=\frac{q^2n_e}{mn_m}$$

TRIKON MORI MEICP TOOL

- **The model geometry is based on the Trikon Mori MEICP source.**





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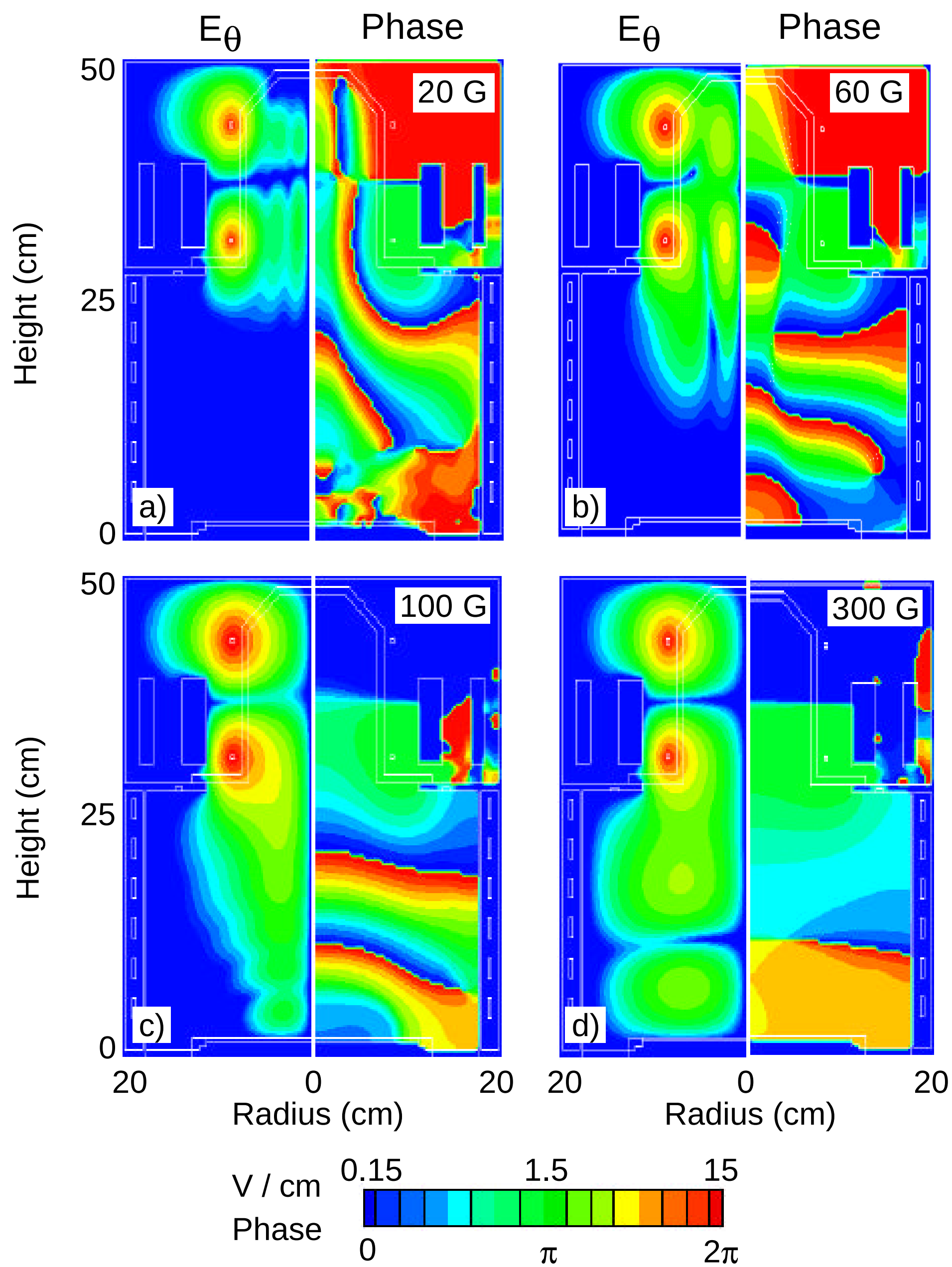
TRANSITION FROM ICP TO HELICON: AZIMUTHAL E-FIELD



- **At low static magnetic fields, simple inductive coupling dominates.**
- **With increasing B-field, the skin depth increases and wave propogation occurs along the field lines.**
- **13.56 MHz, Ar, 10 mTorr, 1 kW**

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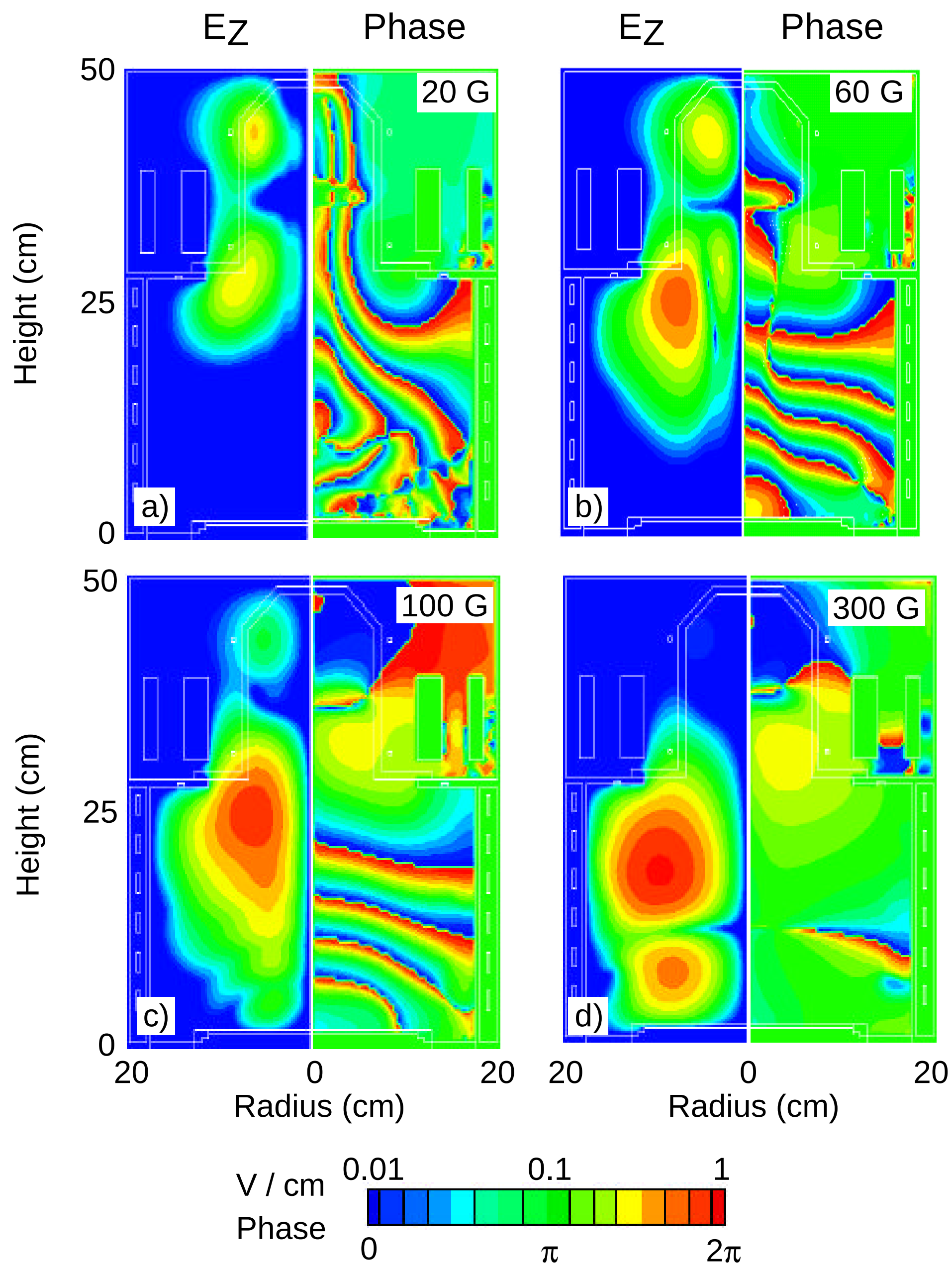
TRANSITION FROM ICP TO HELICON: AXIAL E-FIELD



- **With increasing magnetic field, radial and axial components of the electric field are produced.**
- **Helicon operation occurs when power deposition is dominated by axial electric field.**
- **The large axial electric fields provide for efficient acceleration of electrons along the B-field lines.**
- **13.56 MHz, Ar, 10 mTorr, 1 kW**

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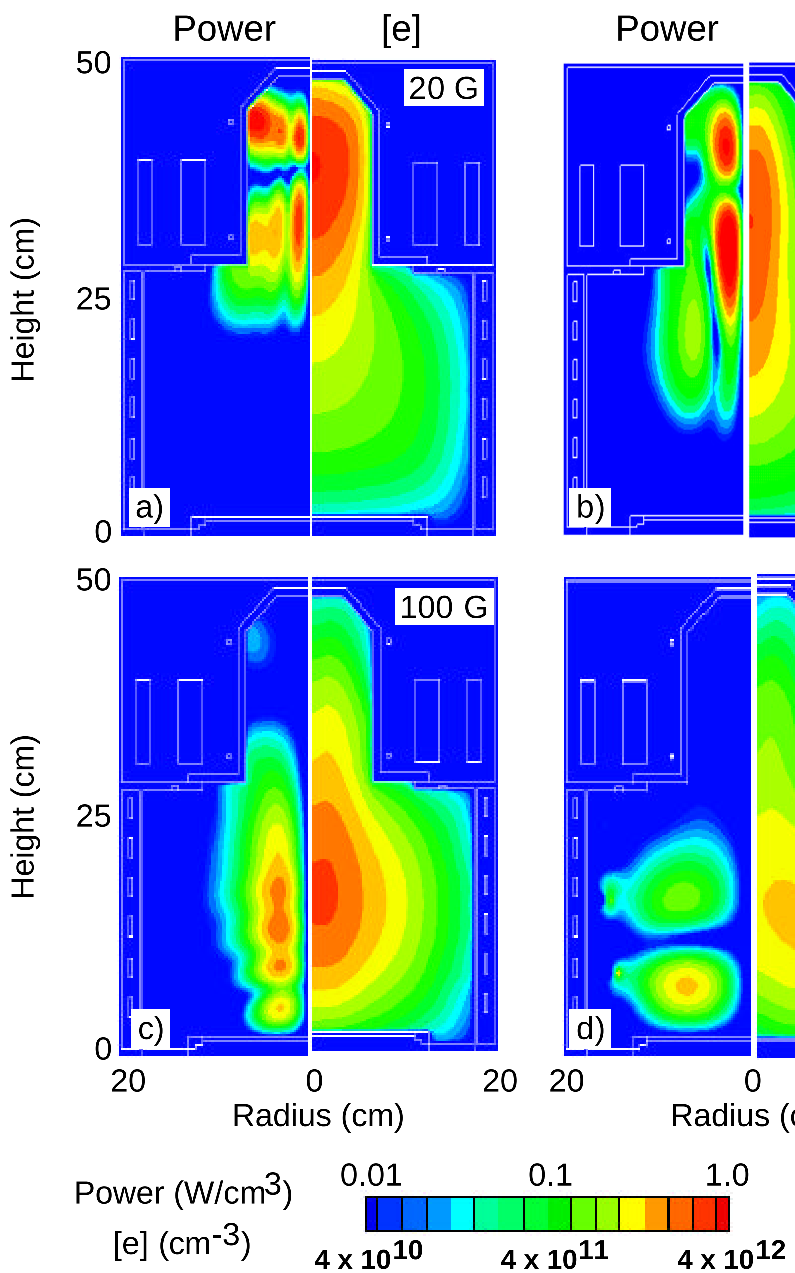
TRANSITION FROM ICP TO HELICON: POWER AND [e]



- The transition from ICP to helicon results in power deposition shifting downstream.
- The peak plasma density follows the shift in power deposition downstream.
- 13.56 MHz, Ar, 10 mTorr, 1 kW

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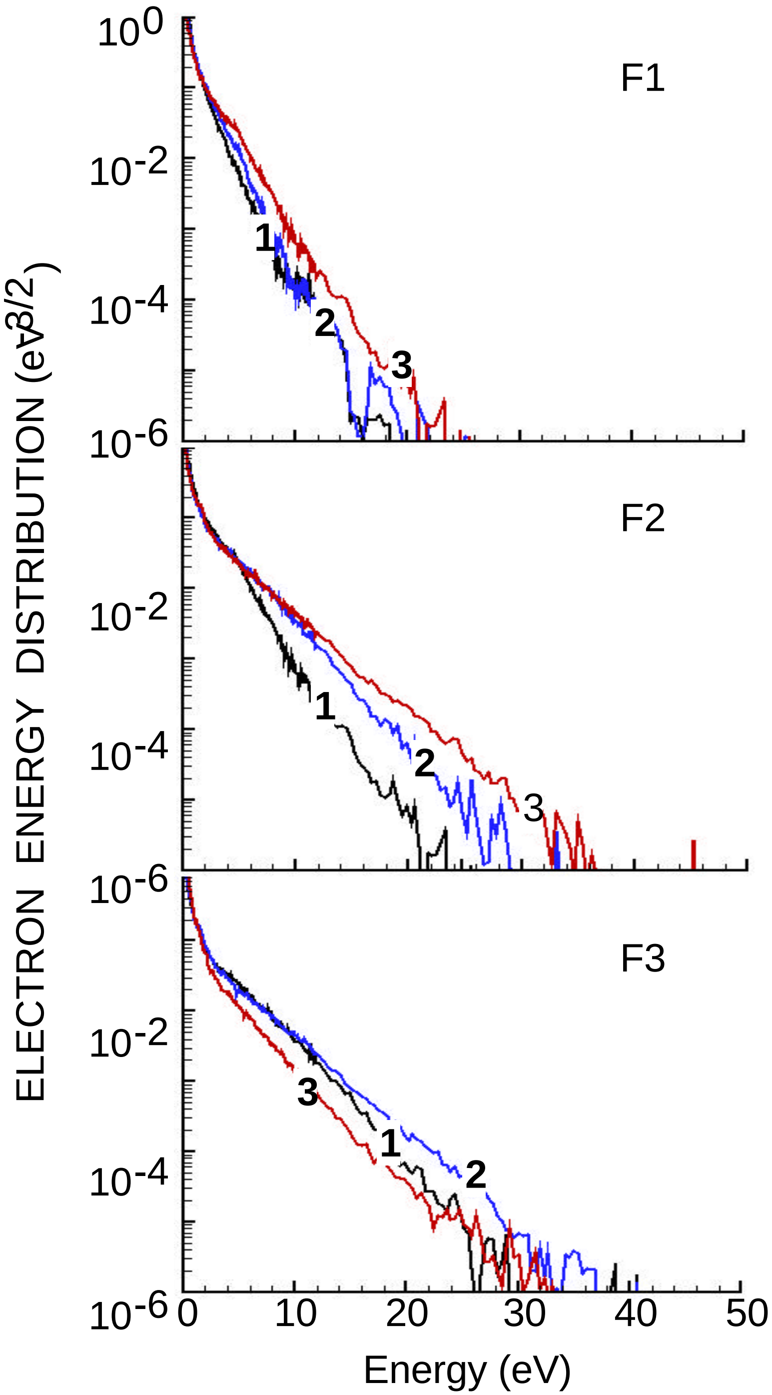
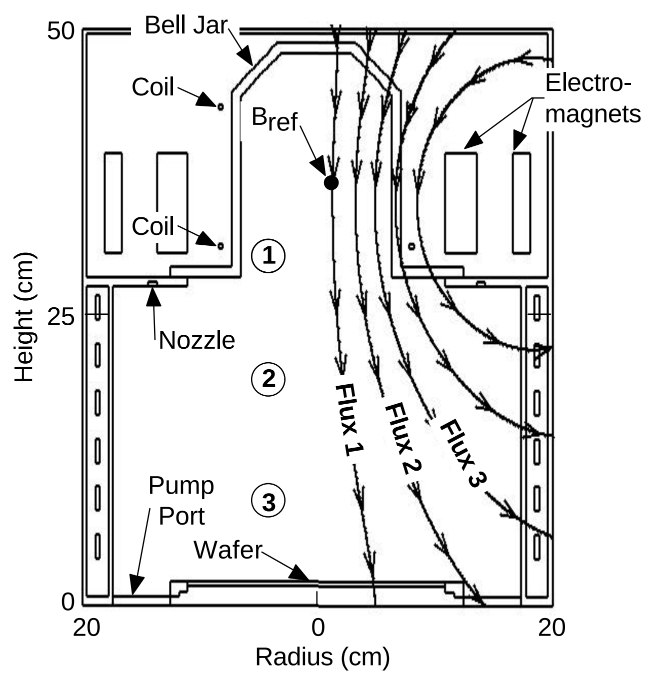


ELECTRON ENERGY DISTRIBUTIONS (10 mTorr)

- Electrons on flux line F1 experience little "tail lifting" near the axis.
- ....on F2 e's are resonantly accelerated with downstream tail lifting.
- ....on F3 e's have less tail lifting due to larger column density of traversed gas and lower fields in periphery of reactor.



- 13.56 MHz
- Ar
- 10 mTorr
- 1 kW

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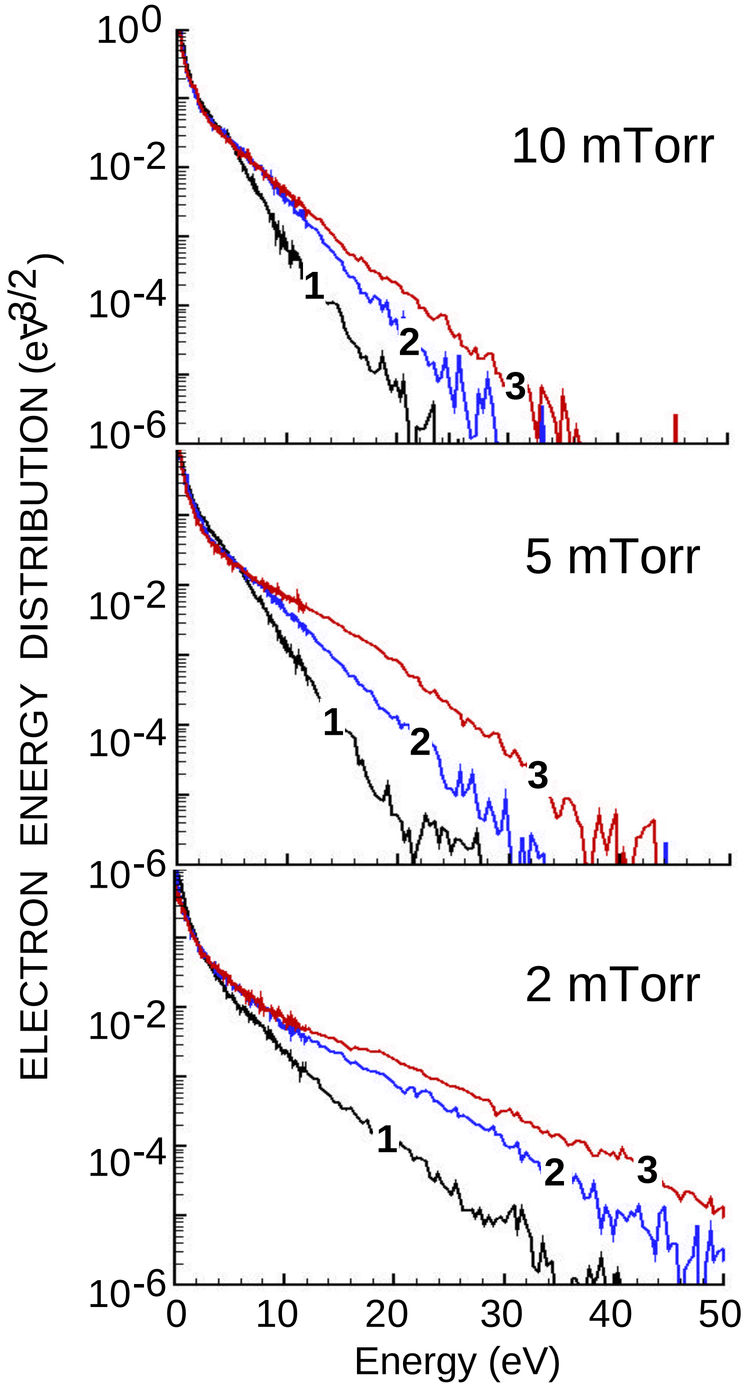
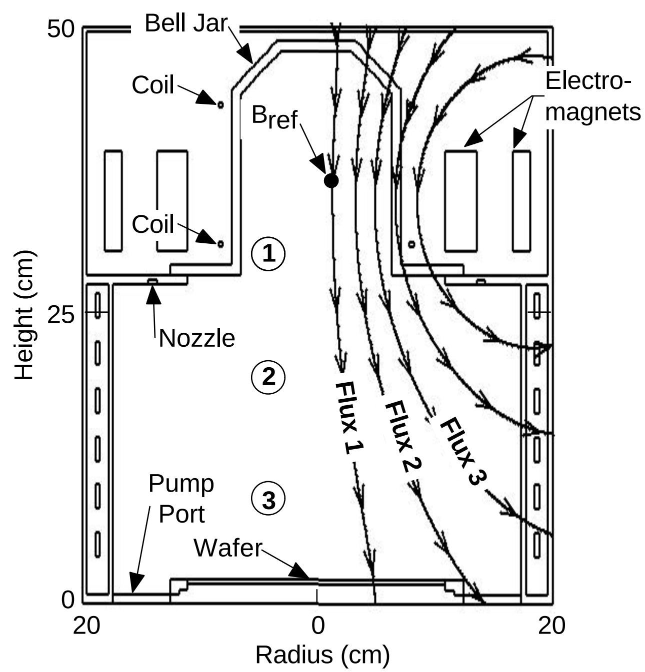


ELECTRON ENERGY DISTRIBUTIONS vs PRESSURE

- With decreasing pressure, electron mean free paths increase as does non-collisional acceleration.
- The tails of the EEDs are progressively lifted with distance downstream.



- 13.56 MHz
- Ar
- Fluxline 2
- 1 kW

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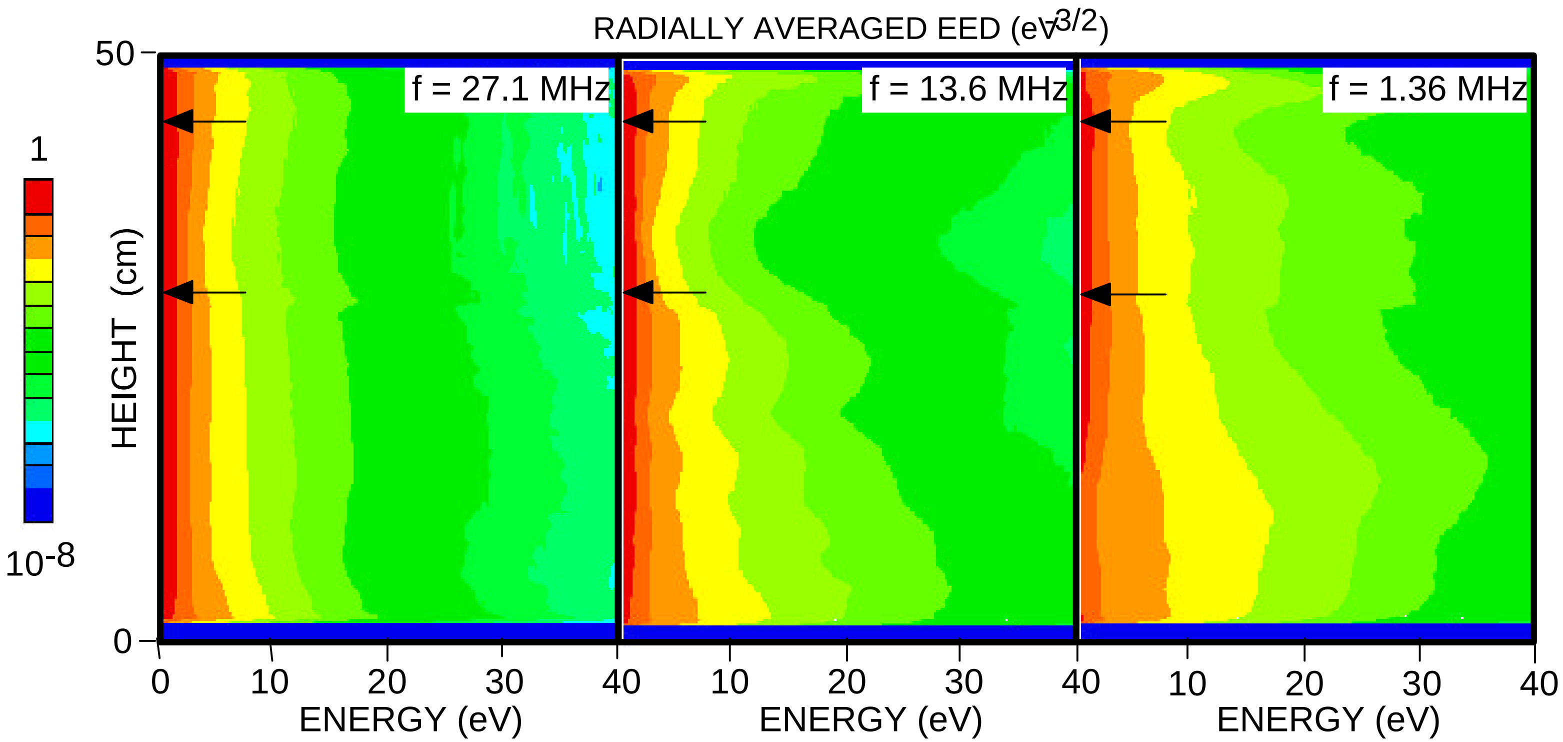
PHASE MATCHING

- For electrons to be continuously accelerated downstream, the phase velocity of the axial rf field must be well matched to the speed of the electrons to avoid slipping into phases of deceleration.
- The parallel phase velocity of the E-fields is proportional to the rf frequency.



- As the rf frequency decreases non-collisional heating is more significant due to better phase matching with thermal electrons.

  - Ar, 2 mTorr, 300 G, 1 kW

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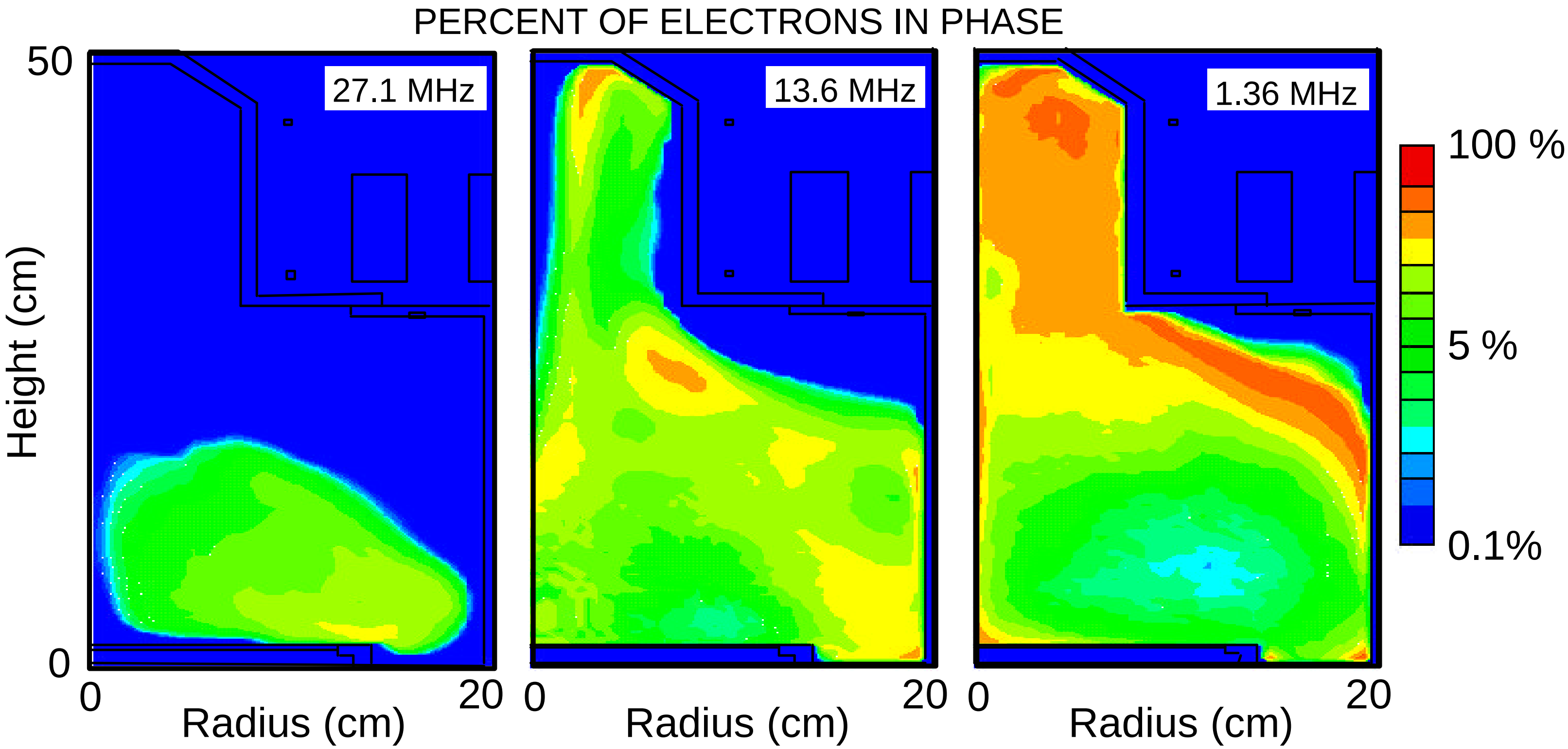
FRACTION CAPABLE OF PHASE MATCHING

- A measure of the total amount of collisionless heating is the fraction of electrons with thermal speeds capable of phase matching to the wave.
- This fraction not only increases with decreasing frequency, but also extends across a larger proportion of the reactor.



- Ar, 2 mTorr, 300 G, 1 kW

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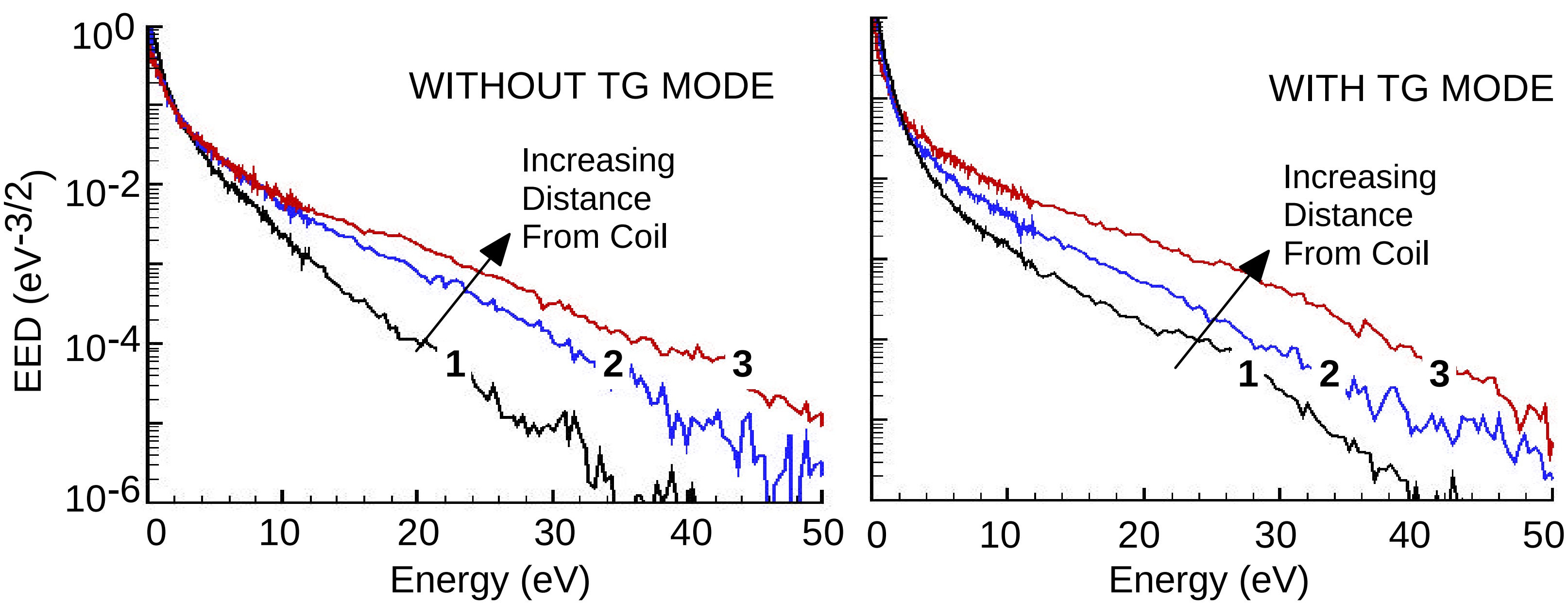
CONSEQUENCES OF TG MODE

- The Trivelpiece-Gould mode can be suppressed at high magnetic field and high power deposition.

- At high magnetic fields (> 10s G) EEDs with and without electrostatic terms in Maxwell's equation, as well as most bulk plasma properties, are similar.



- **Ar, 2 mTorr, 300 G, 1 kW**

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CONCLUDING REMARKS

- A model has been developed to investigate EEDs in wave heated MEICP reactors.

- The transition from ICP to helicon heating occurs when a signficant fraction of the power deposition is produced by axial and radial components of the wave.

- Non-collisional heating results in significant raising of the tail of the EED downstream of the antenna above 10s G and below 10 mTorr.

- "Tail-raising" requires matching of the phase velocity of the wave and thermal speed of the electrons. This can be facilitated by adjusting the frequency of excitation for a given power deposition.

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