Physics Impacts to Plasma Wave Thruster Design

James Gilland

Ohio Aerospace Institute

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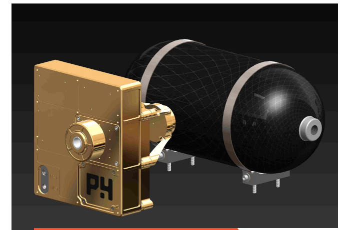
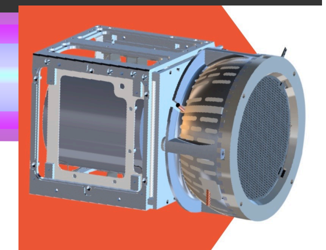
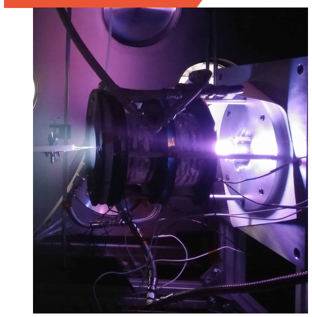


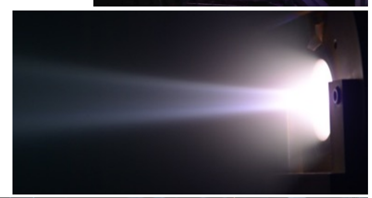
RF thruster advantages

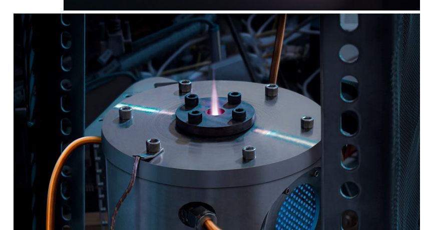


- Electrodeless
  - Potential for long life
  - Multiple propellants (if coupled to electrons)
  - Quasineutral plasma – no neutralizer



- Rf thruster concepts
  - Phase Four – Inductive (www.phasefour.io/maxwell/)
  - ThrustMe – Capacitive (gridded) www.thrustme.fr/products/npt300
  - Universidad Carlos III de Madrid – "Helicon" (ep2.uc3m.es/#projects)
  - ONERA – ECR –Minotor (www.minotor-project.eu/overview/ecra-technology-3)
  - Momentus – Microwave thermal (cr. Momentus Ardoride)
  - VASIMR – Helicon/Ion cyclotron (www.adastrarocket.com/home/





ASPECTS OF RF WAVE THRUSTERS

- Helicon wave source example
- Wave coupling
  - Dispersion and antennae
- Ionization
  - Collisionless vs. collisions
  - Density limits
- Thruster Impacts from wave coupling
  - Thruster size vs. wave coupling
  - "Double layers"

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Plasma waves in thrusters

- A ”zoo” of possible waves can propagate under the right conditions
- Not every rf thruster is a plasma wave thruster
- Let’s consider the helicon wave as an example:
  - Propagation in applied magnetic field
  - Same regime as whistler waves:
    - $\Omega_i << \Omega_{LH} << \omega << \Omega_e$
    - Waves couple to electrons
      - Species independent
  - For $\omega > \Omega_e/2$, the helicon wave becomes the “electron cyclotron wave”

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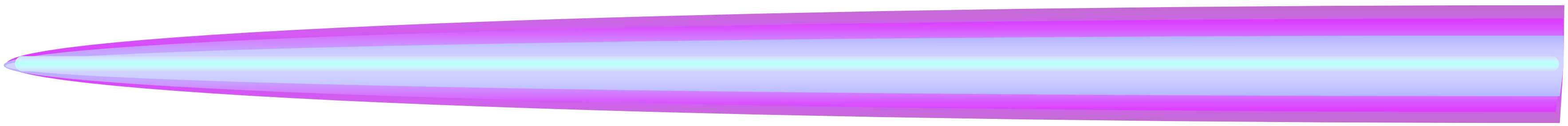

"Typical" Helicon Source

(Univ. of Wisconsin Phaedrus source)

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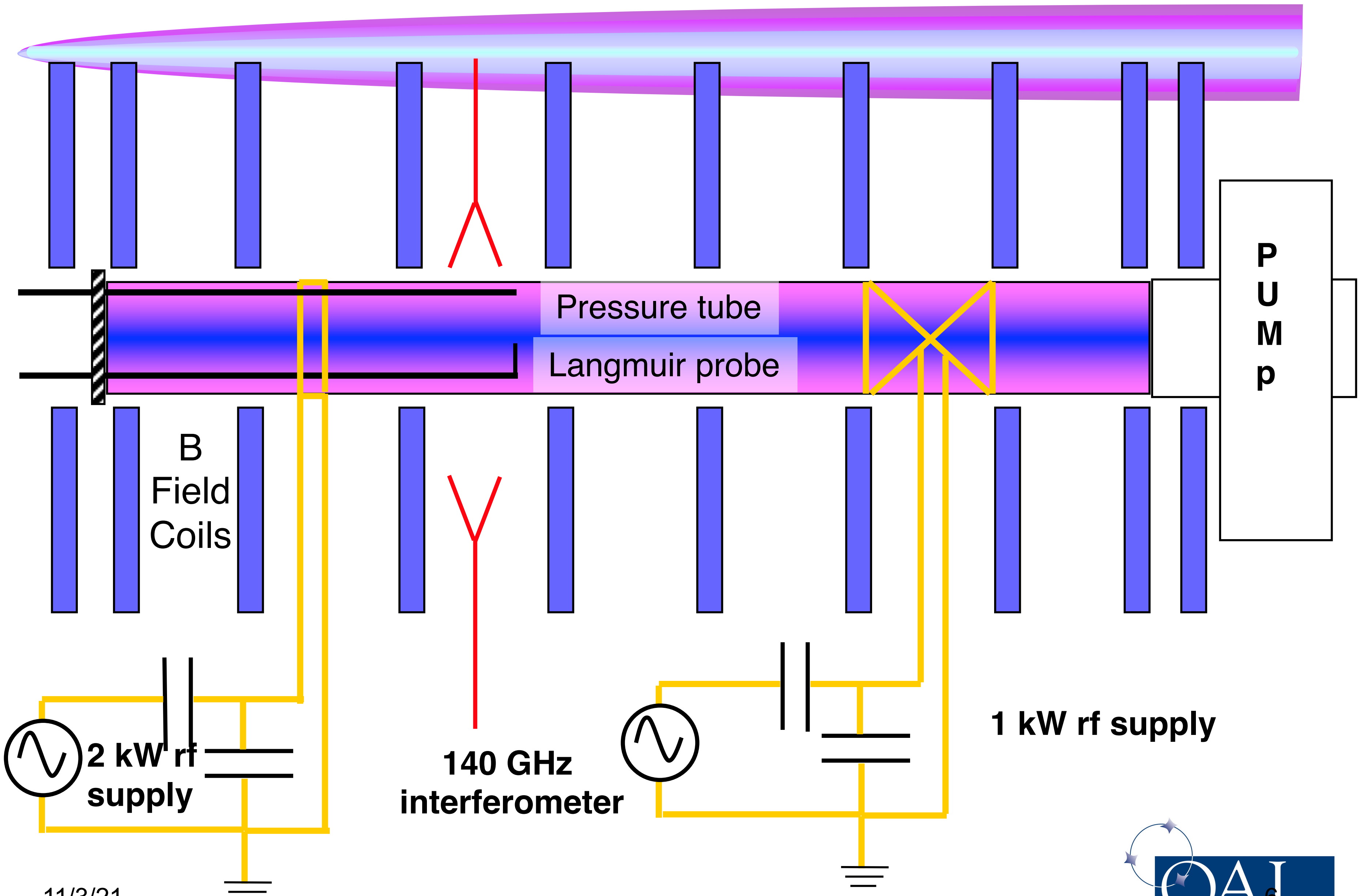
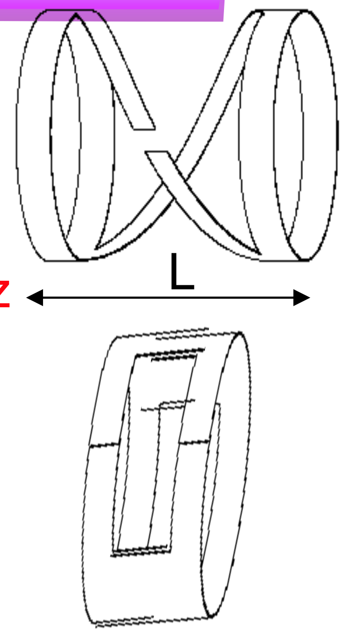
The Phaedrus helicon experiment

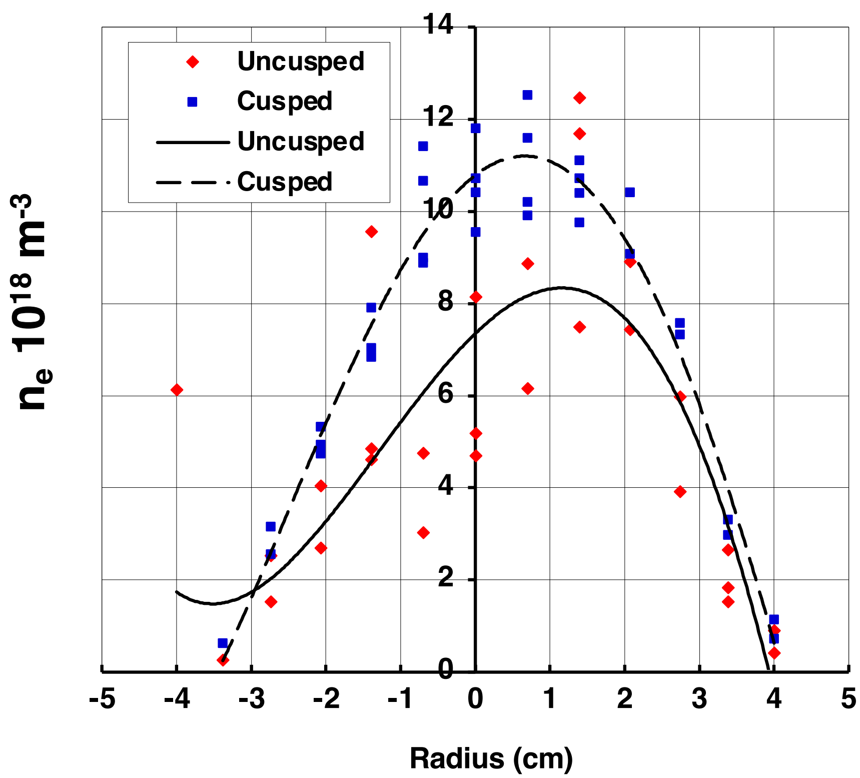


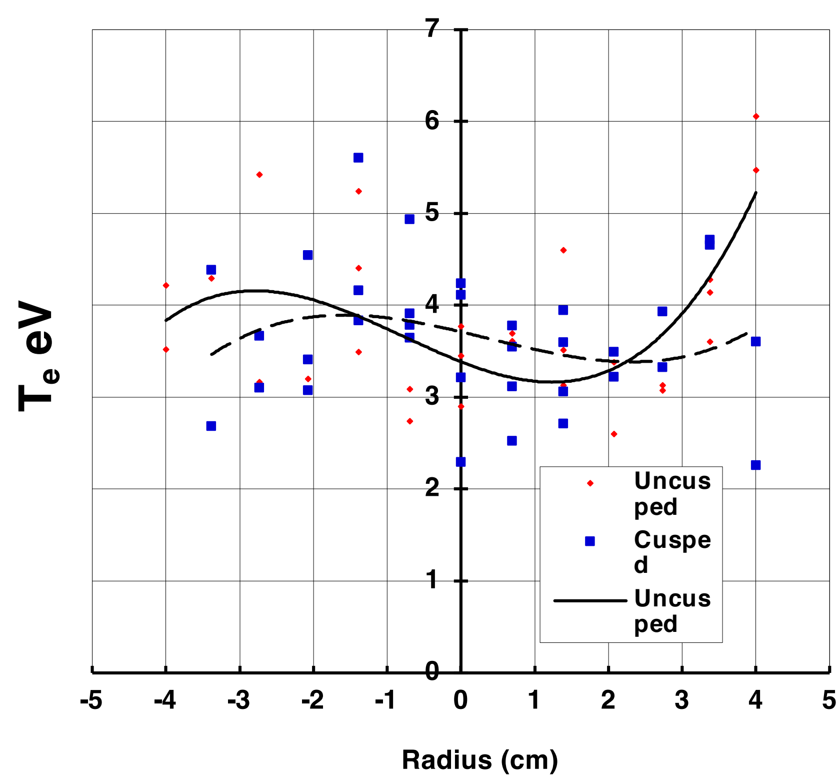
Helicon source operating conditions



- Steady state operation to allow pressure equilibration
- 5-30 mtorr base pressure
- 300 - 800 W continuous rf Power at 13.56 MHz
- 1-3 kW pulsed (50 ms) rf power, variable frequency (13.56 MHz currently)
- Uniform Axial Field
  - 500 - 1250 Gauss
- Argon Plasma
- 4 Antenna Options
- Diagnostics
  - **Langmuir Probe** - *plasma profiles*
  - **Magnetic Field Probe** to measure helicon wave B fields
  - **Capacitive Manometer** located at end of 1m Pyrex (9mm ID) pressure sampling tube
  - **140 GHz Microwave Interferometer** to remotely measure line-averaged density

Steady state helicon plasma profiles





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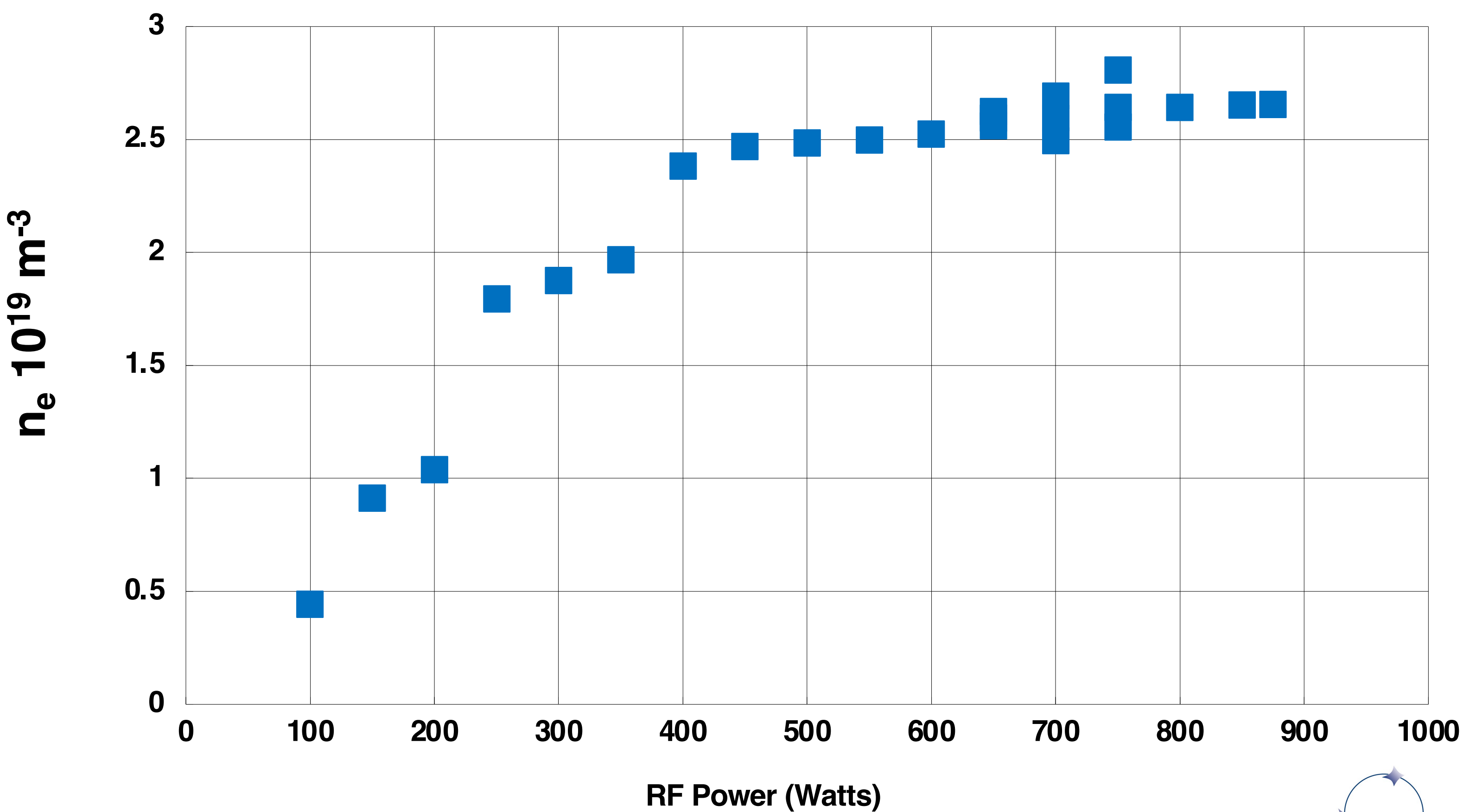
Peak steady state helicon plasma density



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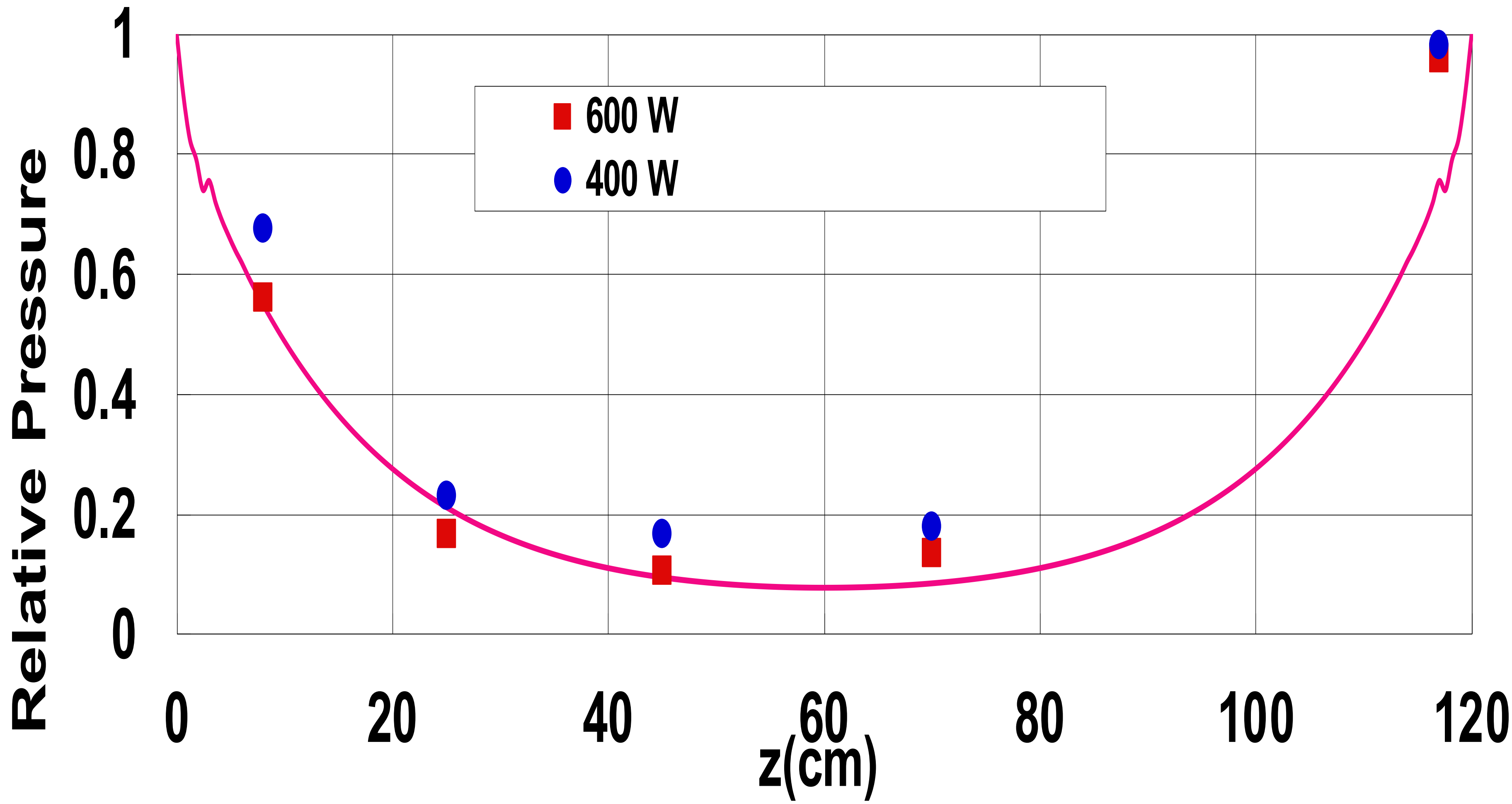
Ionization reduces neutral pressure to ~10% of initial value



Observations from helicon sources

- Density does not continue to increase with power
- Some antennae work better than others (observed in multiple sources)
- Strong decrease in neutral pressure during plasma operation
- How do these effects impact source/thruster design?

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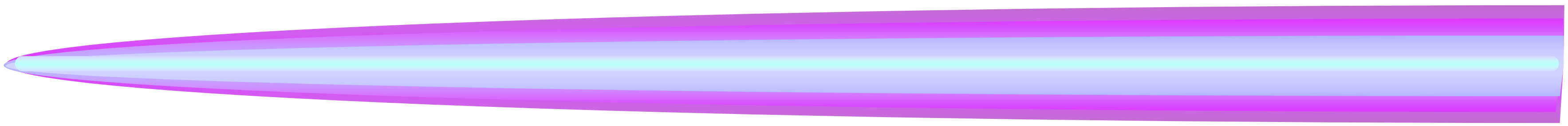

Plasma Wave Dispersion

Impact of the dispersion on plasma parameters

- Dispersion relation defines wavelengths in plasma
  - k_z, $k_\perp$ are related through ω, density (ω_{pe} or n_e), applied magnetic field (Ω_{ce} or B)
  - Cold plasma dispersion relation ($\vec{B} = B_0\hat{z}$)
  - Neglects ion motion ($\omega >> \Omega_{ci}$)

$$\begin{vmatrix} S - n_z^2 & -iD & n_z n_\perp \\ iD & S - n^2 & 0 \\ n_z n_\perp & 0 & P - n_\perp^2 \end{vmatrix}$$

$$S = 1 - \frac{\omega_{pe}^2}{\omega^2 - \Omega_{ce}^2}$$

$$D = -\frac{\omega_{pe}^2 \Omega_{ce}}{\omega(\omega^2 - \Omega_{ce}^2)}$$

$$n = \frac{\omega}{k\,c} \qquad k = \frac{2\pi}{\lambda}$$

$$P = 1 - \frac{\omega_{pe}^2}{\omega^2}$$

$$\Omega_{ce}^2 = \frac{q\,B}{m_e} \qquad \omega_{pe}^2 = \frac{n\,q^2}{m_e\,\epsilon_0}$$

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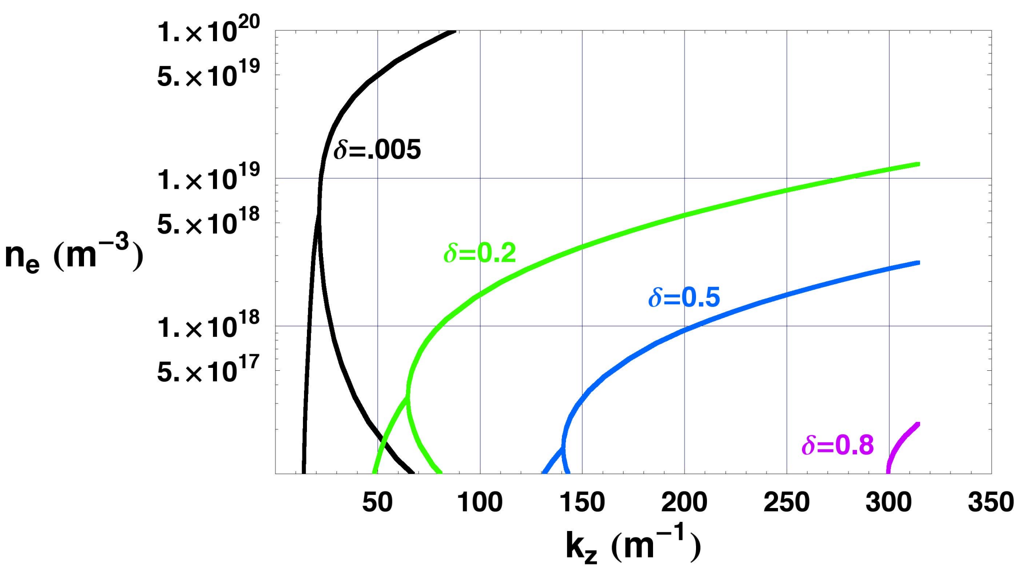
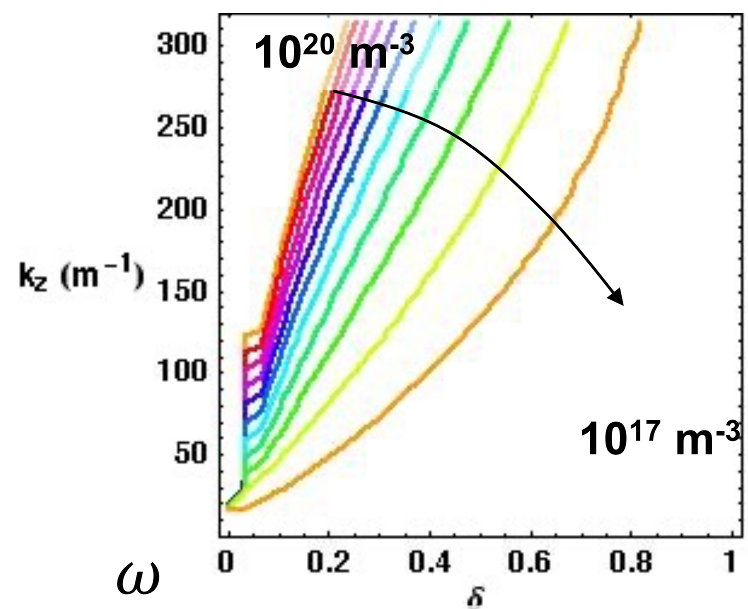
Dispersion and plasma characteristics





$$\delta = \frac{\omega}{\Omega_{ce}}$$

Narrow Source, high $k_\perp$

- Frequency, density contours with wavelength
- Calculated from dispersion for a fixed $\mathbf{k}_\perp$

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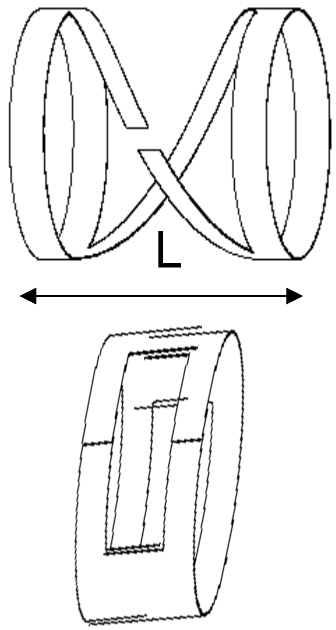
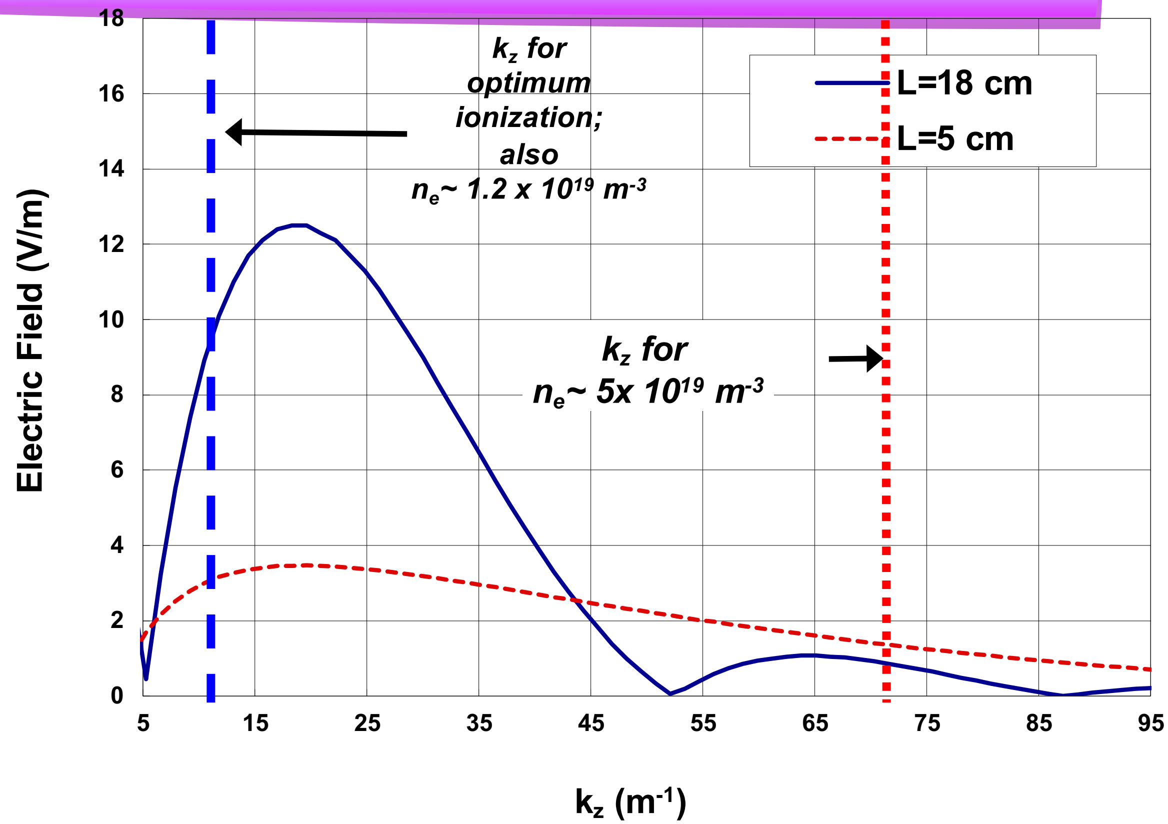
Antenna coupling to plasma wave





- Antenna spectra has to match plasma wavelength for the desired density and B field
- At high density, kz is high (length is short)

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Plasma Generation/Ionization

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Wave ionization processes

- Several possible mechanisms for wave absorption have been proposed:
  - **Coulomb Collisions**
    - at 3 eV, 10^{13} cm^{-3}, $\nu_{ei} \sim 30$ MHz
  - **Collisionless**
    - **Landau damping (F.F. Chen)**
      - $\omega = k\, v$
      - $(\omega/k)^2 \sim$ maximum energy for electron-neutral cross-section (~ 80 eV)
      - k determined by antenna length (λ=2L)

$$\nu_{LD} = 2\sqrt{\pi}\,\omega\,\zeta^3\; e^{-\zeta^2} \;\; ; \zeta = \left(\frac{\omega}{\mathbf{k}}\right)\sqrt{\frac{m}{2\,T_e}}$$

      - Peak damping at $\zeta \sim 1$
    - **Near field effects (Ellingboe, Borg)**
      - Acceleration of electrons in phase with near fields
      - Helicon phase velocity couples to electrons at peak in ionization cross section

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Compare Ionization, Depletion, and Dispersion Effects

- Dispersion relation indicates:
  - Increasing density requires decreasing wavelength
- Ionization processes indicates:
  - Wavelength dependence for collisionless heating
  - Limit based on neutral depletion
- Examine these effects experimentally and theoretically

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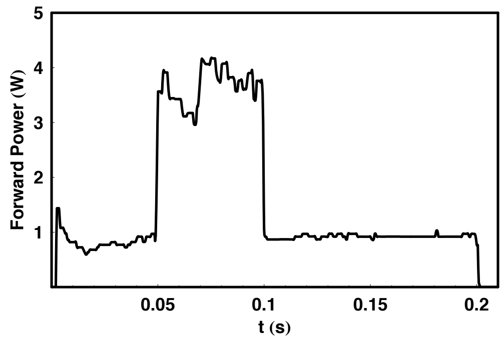
Experiment

- Helicon source with two antennae:
  - Longer antenna for initial plasma generation
  - Shorter antenna for higher density coupling
- Higher power to short antenna to address particle and power balance
- Two antennae operated 1 MHz apart to differentiate waves



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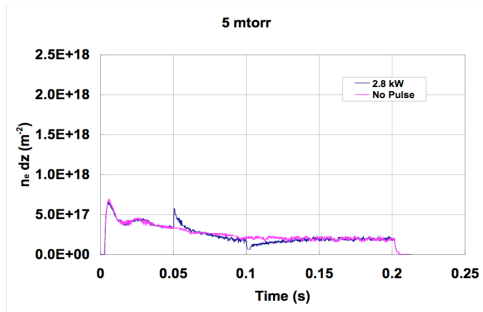
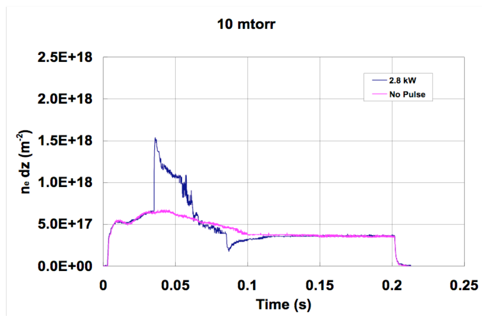
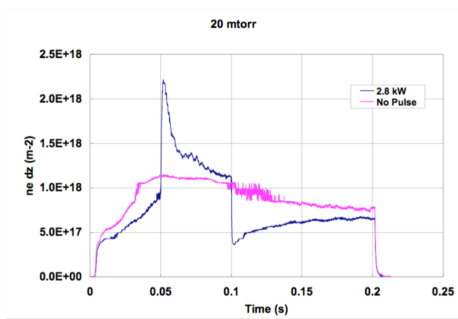
Results from Pulsed Operation

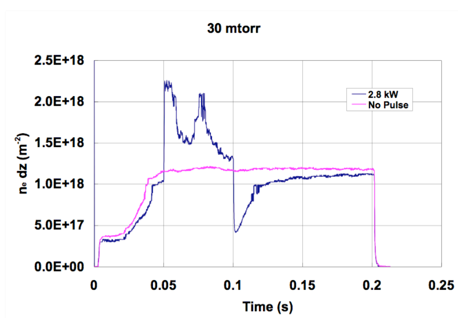
- Two antennae, two wavelengths
- Varying power to shorter antenna
- Interferometer response shown
- Edge temperatures were also measured; not discussed here.

Increasing Pressure

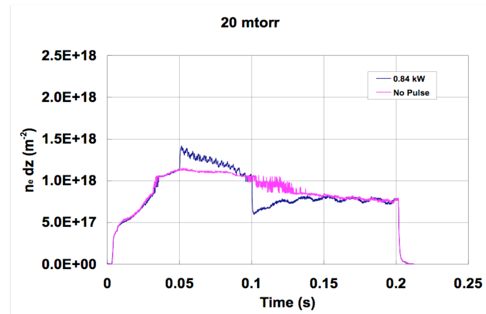


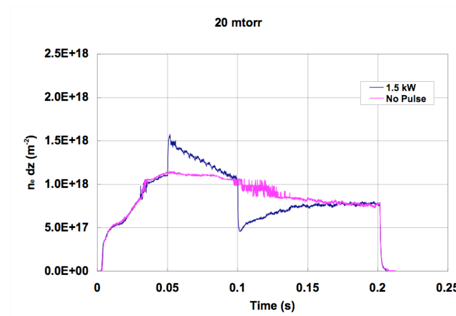


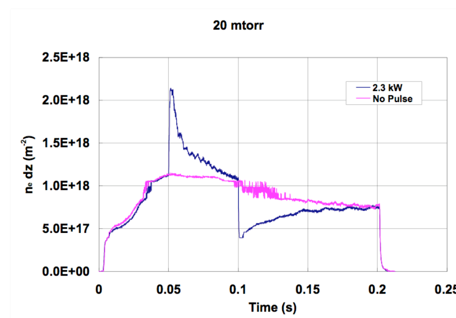


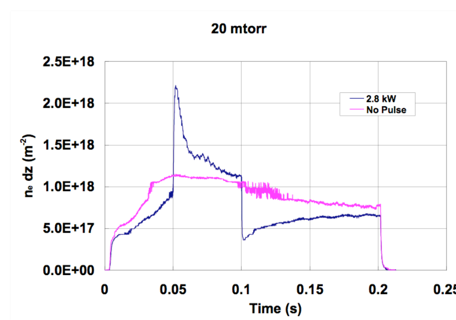


Increasing Power









Trends of pulsed power

- Note that the shorter antenna was unable to start a high density plasma by itself (also seen by other researchers)
- Higher power pulses (at fixed pressure) do result in increased density but peak density decays
- High neutral pressure allows for density increases – relaxation oscillations occur at highest pressures

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Transient Neutral Pumping Model Developed for Helicon Source

- Coupled electron, neutral, and energy balance equations
  - 0 space dimensions
  - rf power input taken from measured forward power
  - Ionization terms
    - First ionization from electron impact
    - Second ionization of neutral
    - Second ionization of ion
  - Includes helicon near-field ionization term from Degeling et al. – trapped electrons

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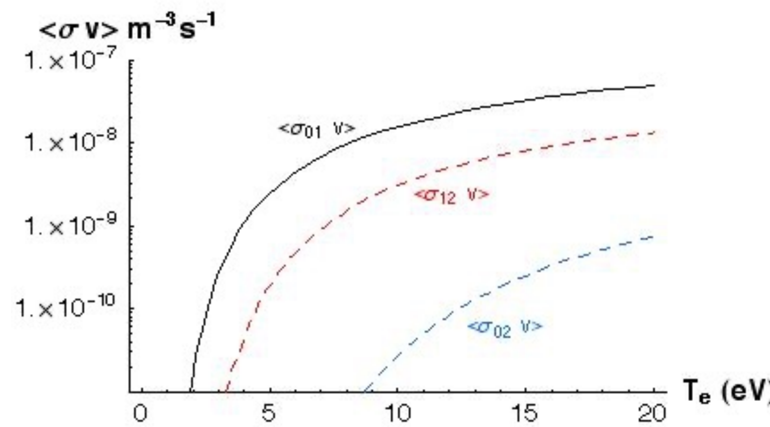
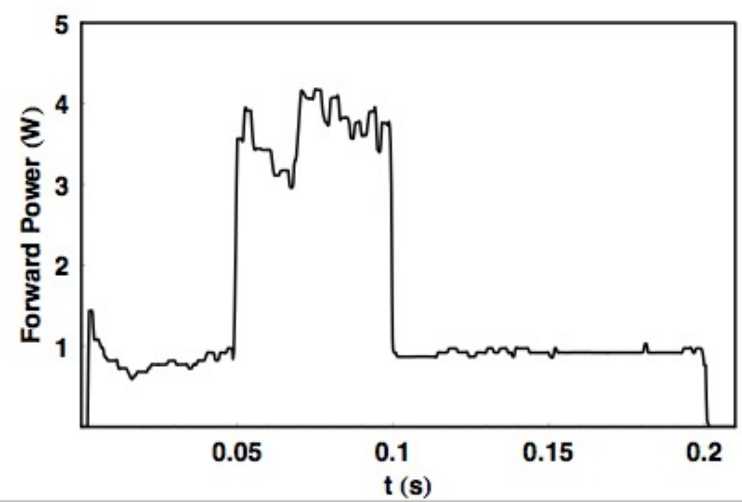
Inputs used in model

- Zero-D Plasma, electron, and power balance
- Coupling:
  - Non-linear trapped electrons related to phase velocity – at low density
  - Collisional ionization at high densities
  - σ_{01} = first ionization
  - σ_{12} = first - second ionization
  - σ_{02} = neutral - second ionization
- Forward power measured at 3 kW forward power
- Pulse shape used with varying magnitude for different input power values





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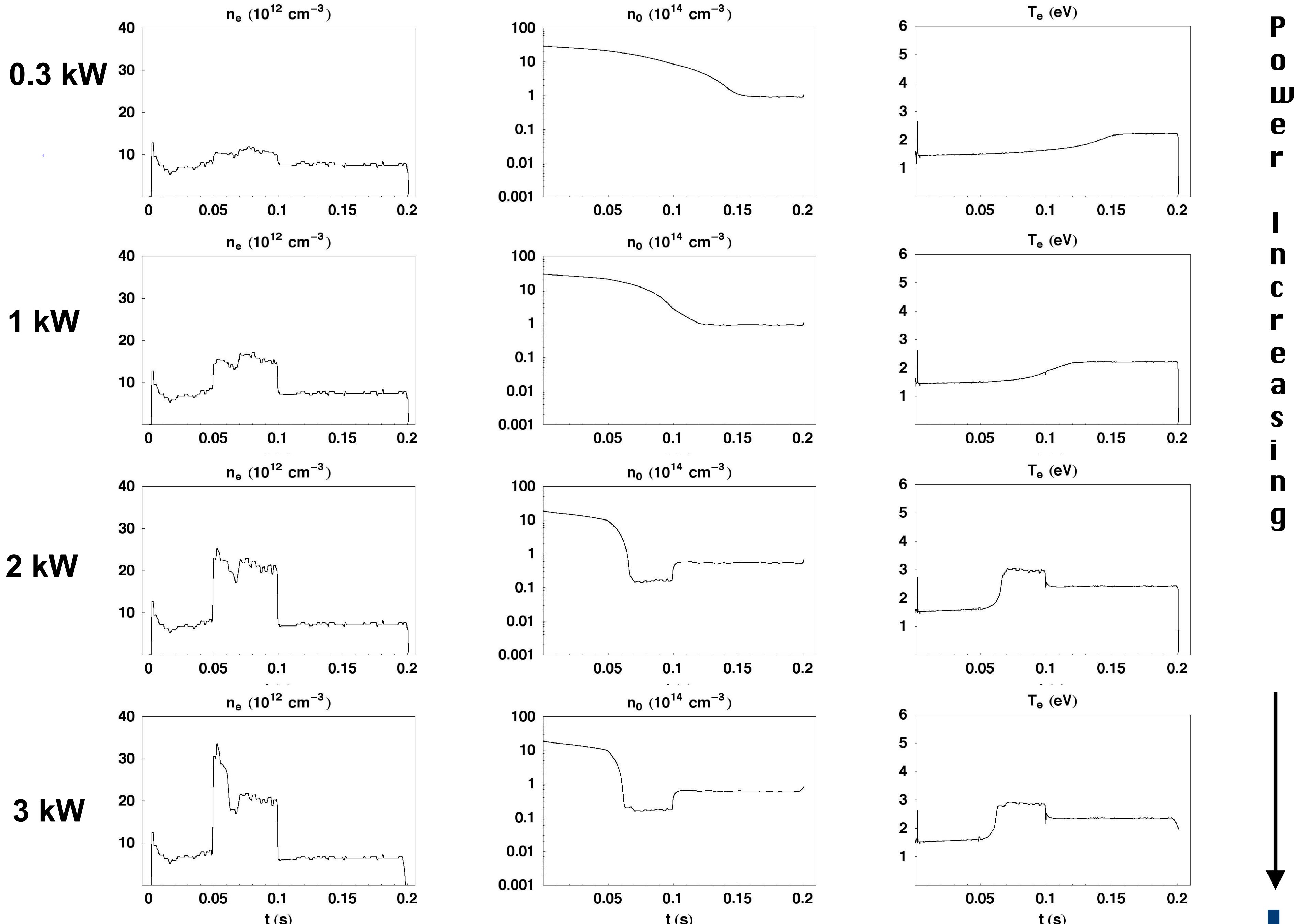
Model Results

1. Increasing Power
2. Increasing Pressure


0.3 kW
1 kW
2 kW
3 kW
n_e (10^{12} cm^{-3})
n_0 (10^{14} cm^{-3})
T_e (eV)
t (s)
Power Increasing

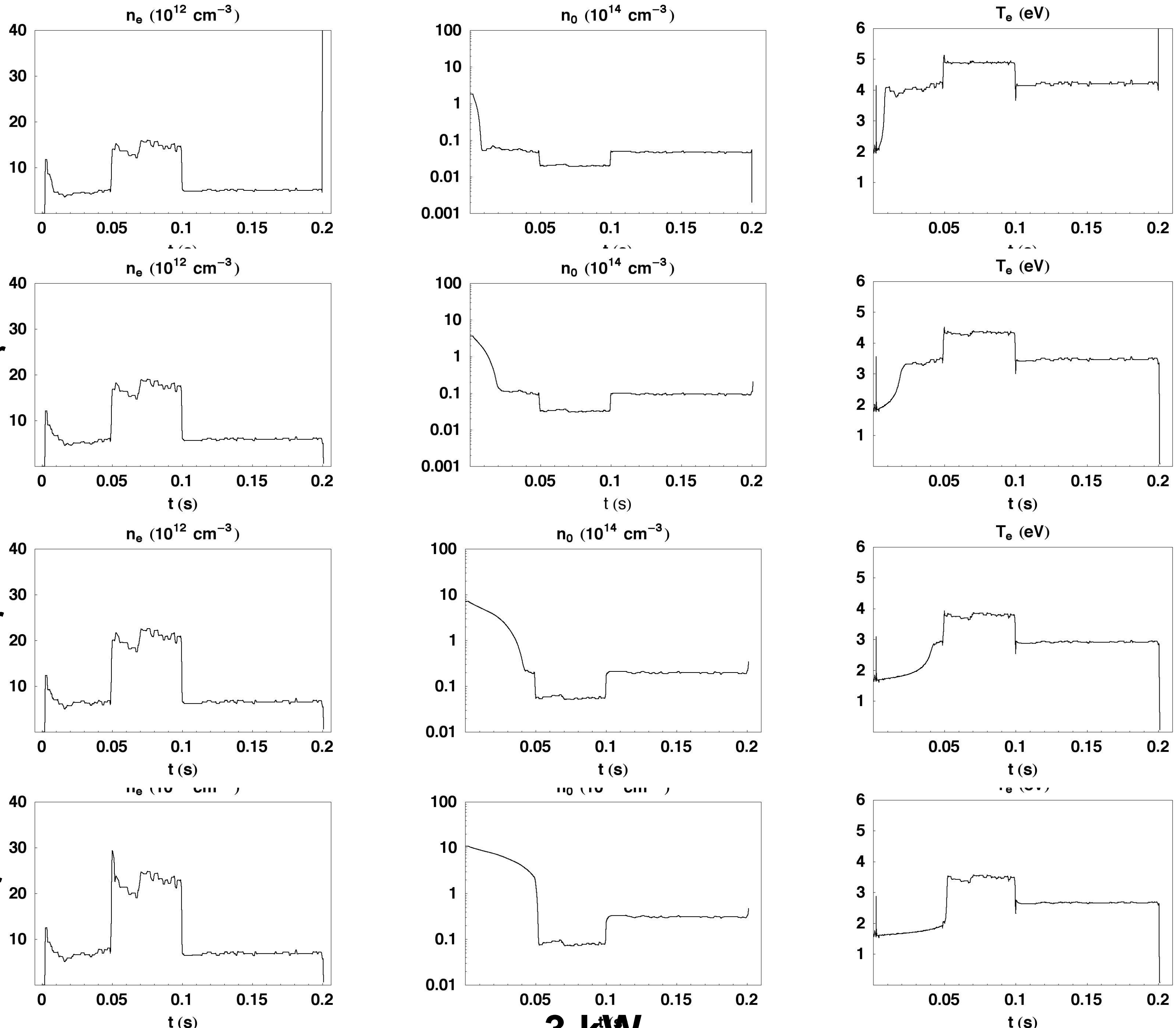
50 mTorr

5 mTorr

10 mTorr

20 mTorr

30 mTorr



Pressure Increasing

3 kW

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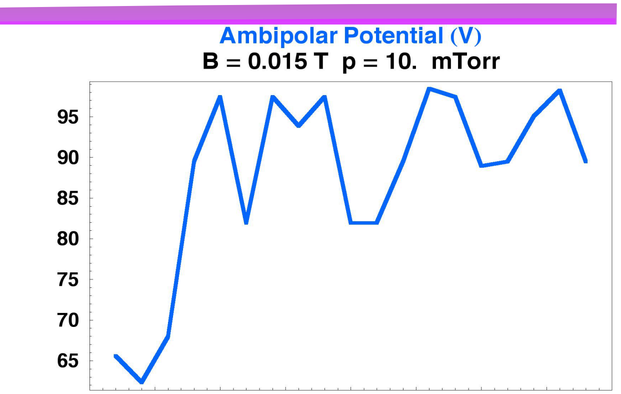
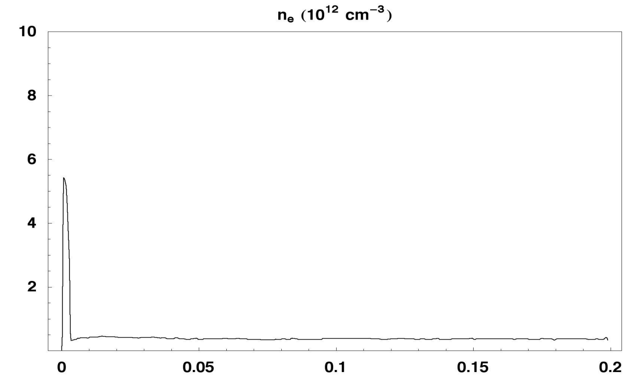
Extension of Model to Double Layers

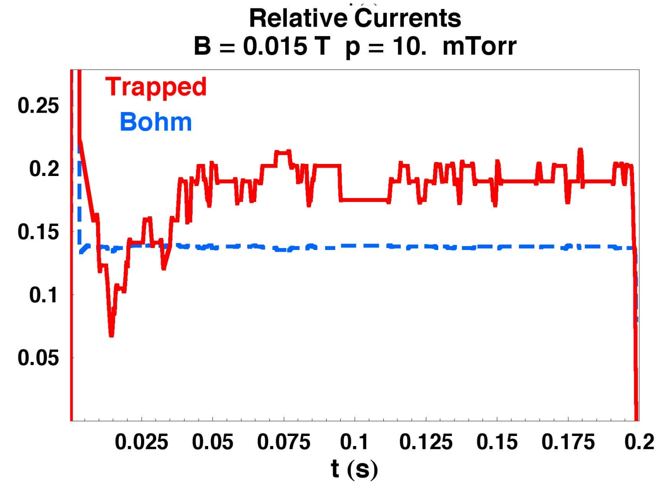
- Double layer:
  - High energy beam of one species (electrons)
  - Conservation of charge leads to potential accelerating of second species (ions)
  - Examine trends for potential formation, degree of trapped electron beam with magnetic field, density

Low pressure/Low Field

- 0.015 T, 10 mTorr
- Induced Potential ~ 90 V
- Density < 10^{18} m^{-3}
- Trapped Current, total current – Trapped dominated

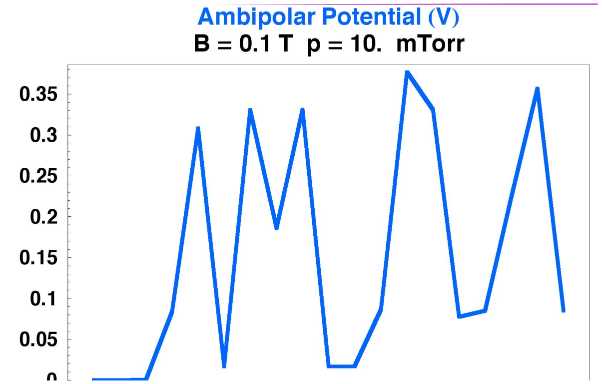


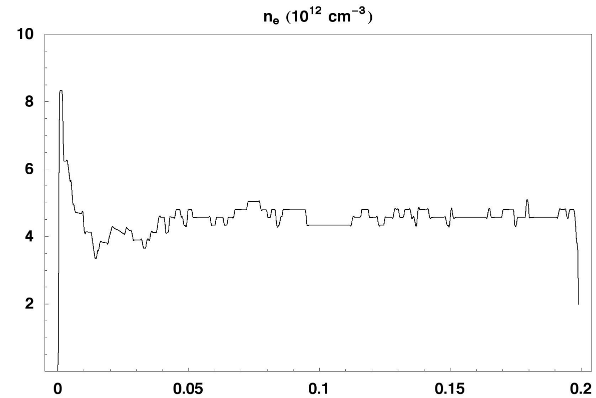


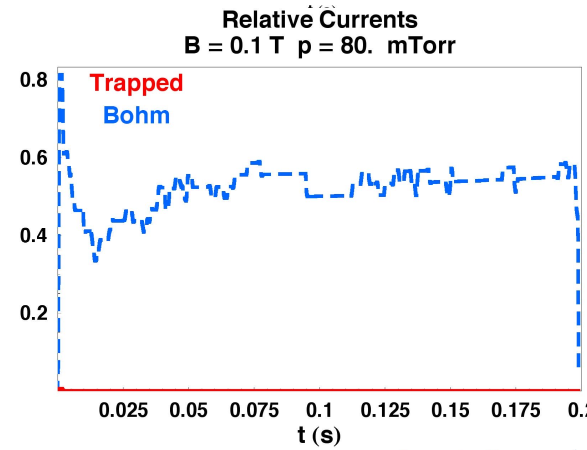


Low Pressure/High Field

- 0.1 T, 10 mTorr
- Induced Potential ~ 0.3 V
- Density ~ 4x 10^{18} m^{-3}
- Trapped Current, total current – Bohm dominated

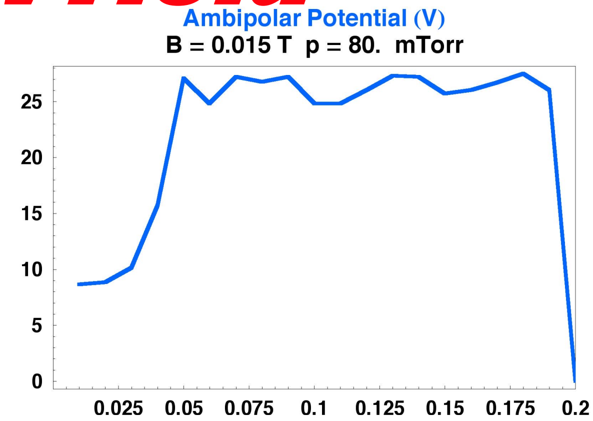


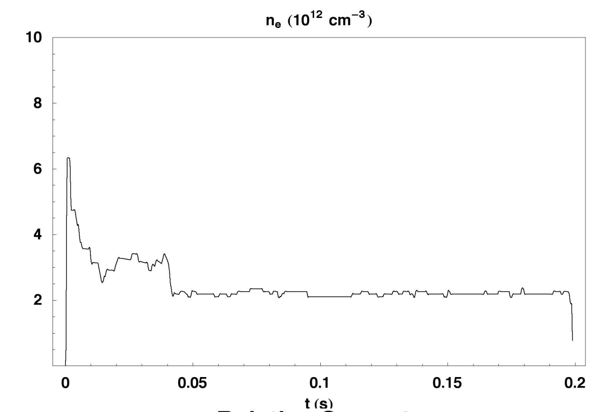


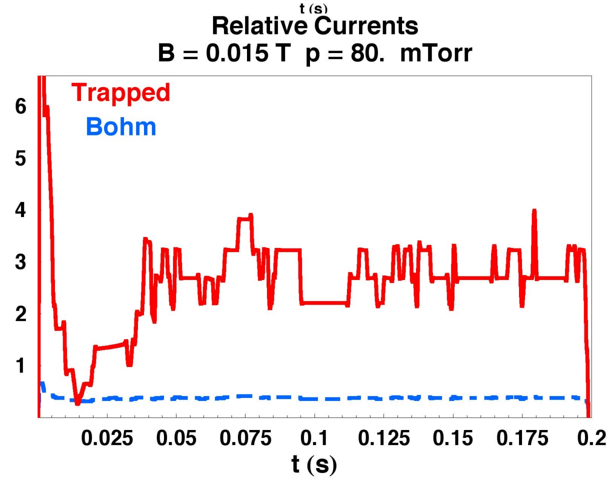


High Pressure/Low Field

- 0.015 T, 80 mTorr
- Induced Potential ~ 25 V
- Density ~ 2 x 10^{18} m^{-3}
- Trapped Current, total current – Trapped dominated



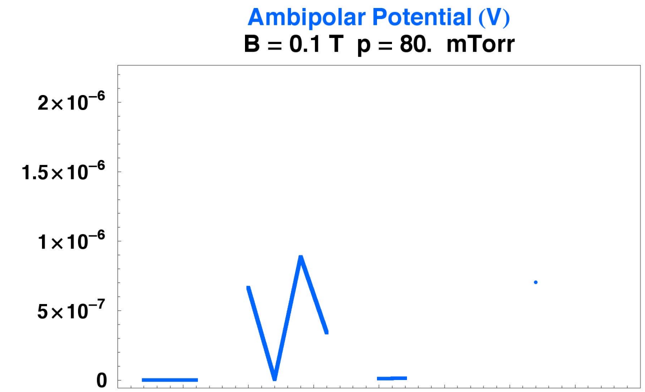


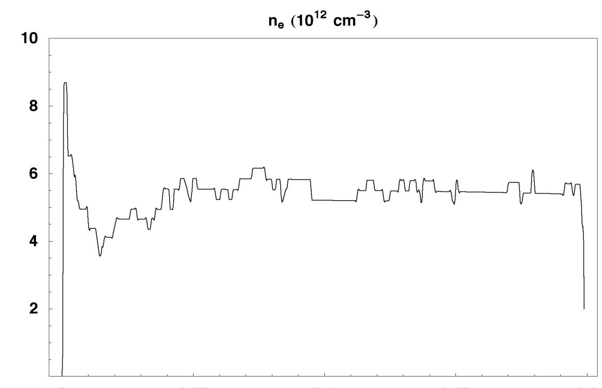


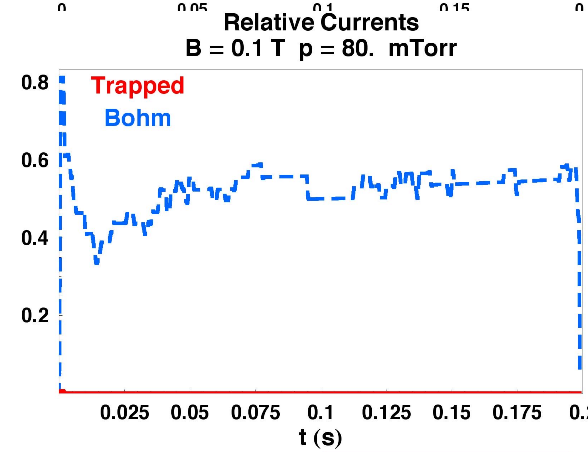
ion

High Pressure/High Field

- 0.1 T, 80 mTorr
- Induced Potential ~ 0.0 V
- Density ~ 6 x 10^{18} m^{-3}
- Trapped Current, total current – Bohm dominated







Predicted conditions for Ambipolar Acceleration

- Ambipolar acceleration (independent of magnetic field expansion) may be possible in an helicon source under certain conditions
  - Low field
  - Low density
  - Drives collisionless wave coupling, which is also more sensitive to wavelength

Implications for Wave Based Sources

- Plasma generation and possible acceleration mechanisms are interconnected
  - Density is limited most strongly by neutral depletion
  - Wavelength, collisionality drive coupling, ambipolarity
  - Collisionless vs. Collisional operation will drive source propulsive capabilities

Questions

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