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Electron Cyclotron Thruster
New Modeling Results
Preparation for Initial Experiments

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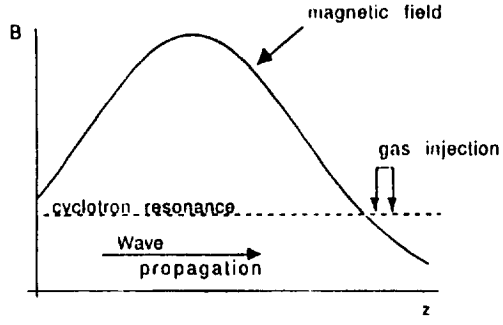
Whistler-Based ECRH Thruster — Concept

- A thruster using ECRH has no electrodes and, is thus less sensitive to materials problems than arc-based thrusters such as the Magneto-Plasma Dynamic (MPD) arc.



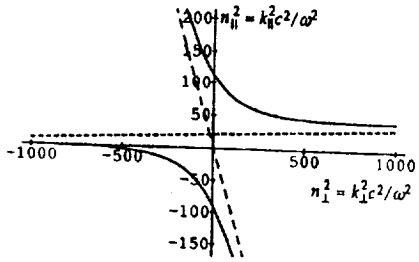
- Rear wall bombardment can be minimized, by a large mirror ratio between the resonance and peak field. (The flow across the mirror is reduced by approximately the mirror ratio from that downfield.) This:
  - o Maximizes efficiency by minimizing energy loss to the wall
  - o Maximizes lifetime by minimizing material damage

Cross-field Coupling in the Helicon Approximation

- Coupling is expected to be strongest if the magnetic field has a small gradient. Thus, we consider coupling at the peak of the magnetic mirror. There, ω_c/ω, $\omega_p/\omega \gg 1$. We illustrate the coupling at $\omega_c/\omega = 10$, $(\omega_p/\omega)^2 = 1000$. This is the helicon regime, with

$$\frac{k^2c^2}{\omega^2} \approx 1 - \frac{\omega_p^2}{\omega(\omega - \omega_c \cos\theta)} \approx \frac{\omega_p^2}{\omega\,\omega_c \cos\theta}$$

- The wave characteristics can be seen from a plot of the squared parallel vs perpendicular indices of refraction



- Waves in the upper-right quadrent are propagating both along z and radially. These are the waves of interest
- There are two such waves at a given parallel index of refraction, but one is at very large perpendicular index of refraction and not of interest in the finite-radius plasma column
- The finite-radial geometry will pickout particular values of $n_\perp$

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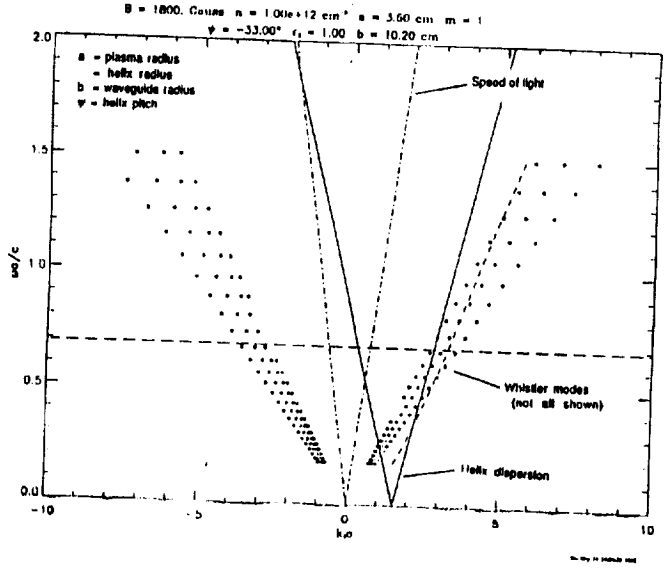
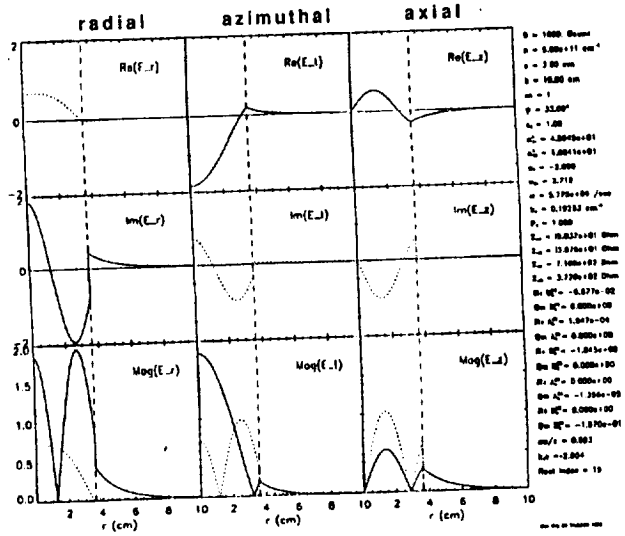
Wave propagation: Waveguide with helix and plasma column

- Several modes with different radial structure propagate in the system



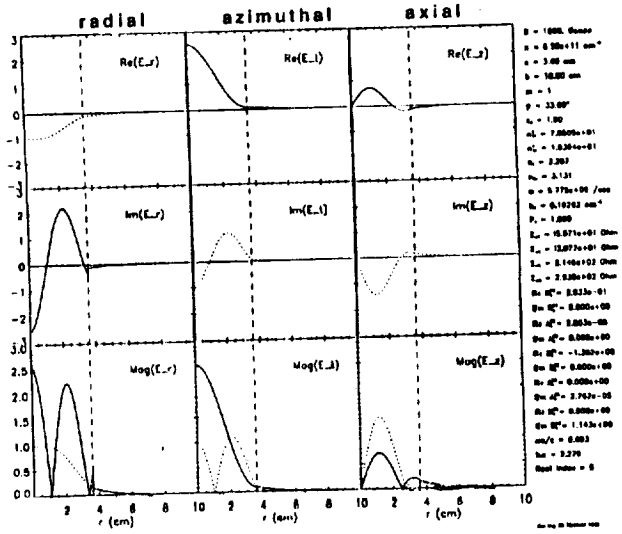
Wave structure: Low impedance mode

- Electric field = solid lines, magnetic field = dashed lines
- Note jump in magnetic field corresponding to current flow in helix



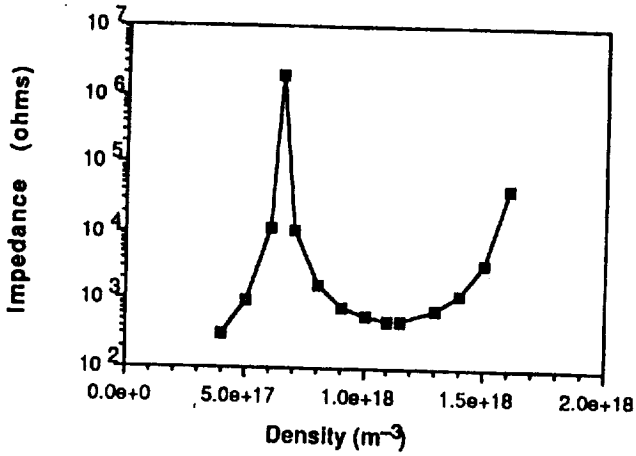
Wave structure: High impedance mode

- Electric field = solid lines, magnetic field = dashed lines
- Note no jump in magnetic field corresponding small current flow



System impedance varies with plasma density

- The experiment is designed to allow tuning of the microwave system



Wave Absorption at the Cyclotron Resonance

- As the whistler wave approaches the cyclotron resonance, the value of $k_{\parallel}$ becomes very large and the phase velocity becomes small

  This has two favorable consequences for absorption:

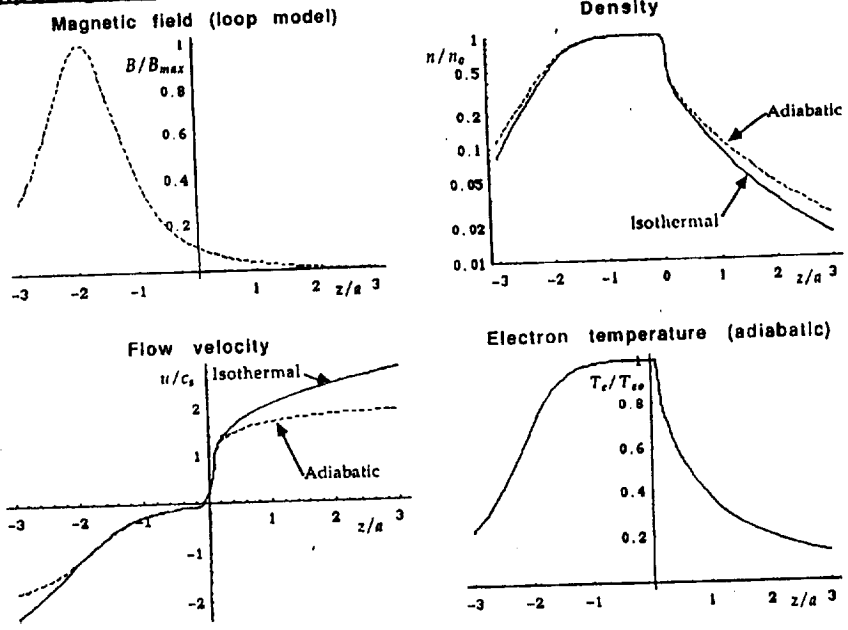
  - o The direction of propagation becomes nearly along the field and at short wavelength so that reflection is very small
  - o The phase velocity becomes comparable to the thermal velocity of the particles, so that the Doppler-shifted resonance ($\omega - \omega_c - k_{\parallel} v_{e\parallel} = 0$) couples to the bulk electrons

- Furthermore, there is no electromagnetic plasma mode at high density and $\omega > \omega_c$, so the wave cannot tunnel through the resonance
- Absorption is consequently nearly 100% for the whistler wave at the cyclotron resonance
- Absorption at high power will generally generate a nonthermal electron velocity distribution. Calculations are needed to quantify this and its consequences

Flow sensitivity to electron distribution function

- The isothermal and adiabatic limits illustrate the sensitivity of the flow to the thermal conductivity and thus to the electron distribution function
- For ECRH the electron distribution may be ansiotropic and nonthermal in nature, with significant consequences for thermal conductivity, particle and energy flow, plasma recycling at the rear wall, etc.
- Understanding the distribution resulting from the heating, as a function of plasma density and microwave power, is thus key to predicting performance.

Comparing isothermal and adiabatic plasma flow



ECR thruster modeling: heating and plasma flow

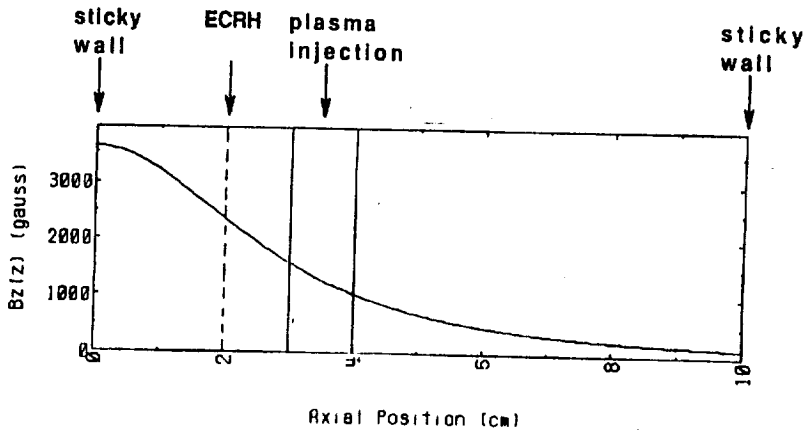
- A particle-in-cell code – ICEPIC – has been used to model the thruster plasma heating and motion along the magnetic field
- Individual particles are followed in the guiding center approximation
  - o Electrons are heated by rf with velocity-space diffusion in the quasilinear approximation
  - o For the present cases, the electrons are weakly collisional
  - o The ion mass is 100m_e to speed up calculations
- Plasma is injected on the side of a magnetic hill and heated up the hill from the injection point
- Two cases are compared

	Injected T_e	Injected T_i	ECRH
No ECRH	100 eV	5 eV	None
ECRH	5 eV	5 eV	E_{rf} = 320 V/cm

Geometry for PIC code model

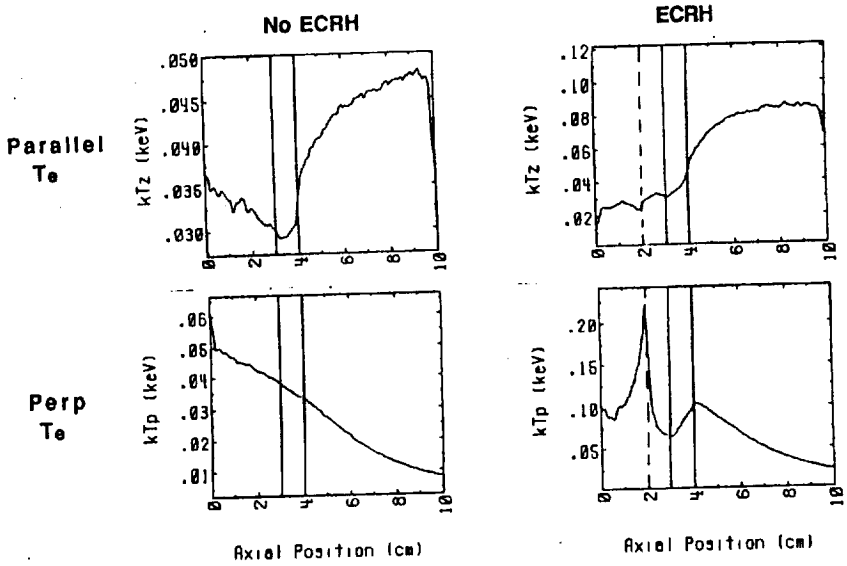
Magnetic field strengths

z(cm)	0	2	3.5	10
B(gauss)	3650	2350	1250	125
B(0)/B	1	1.6	2.9	29



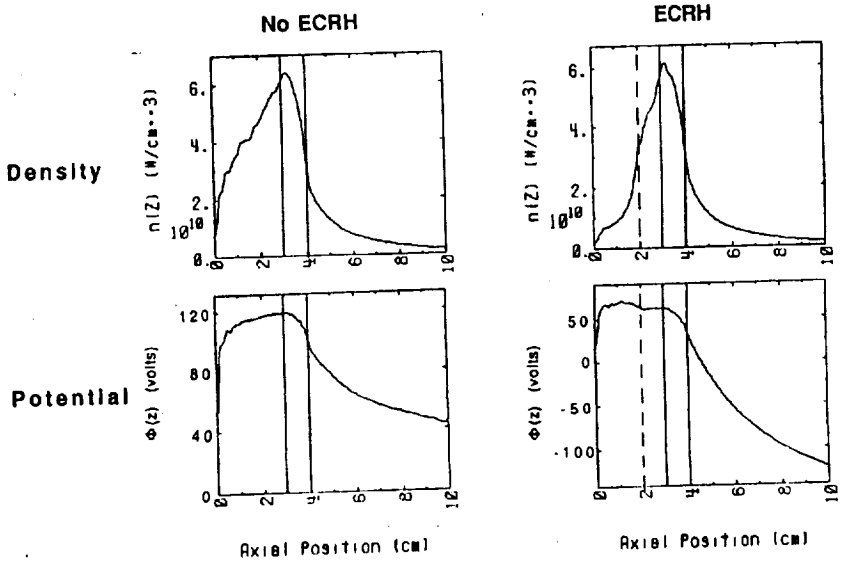
Electron "temperature" moment in the flow

- The electrons are highly anisotropic even without ECRH
- The electron temperature is highly nonuniform along B
- Strong electron heating by ECRH is evident perpendicular to B

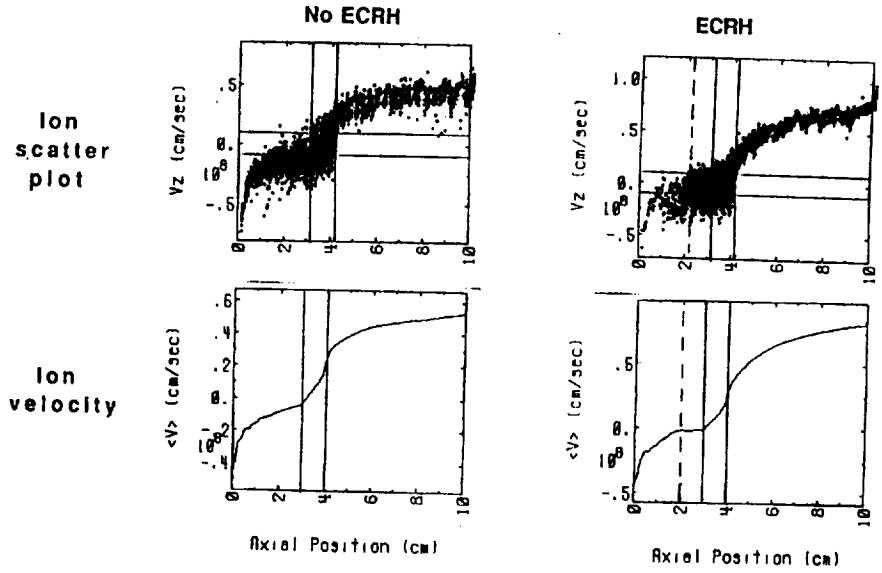


Density and potential are strongly affected by ECRH

- Note the rise in potential upfield of the ECRH. It reduces the flow of ions to balance the μ∂B/∂s force on the electrons and maintain quasineutrality

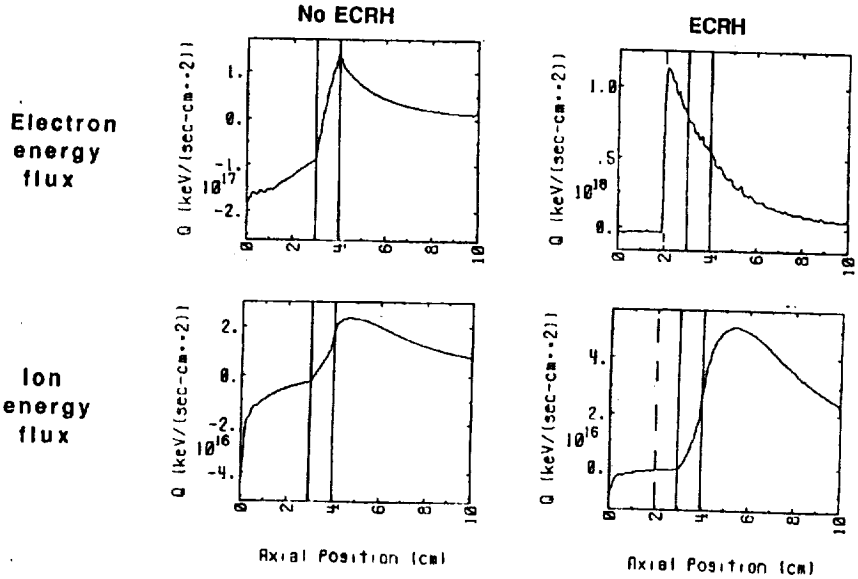


Electron energy is converted into ion flow



Energy flow up the field is suppressed by ECRH

- The total energy flow is proportional to the flux bundle area, which is a factor of 29 larger at the exit than at the magnetic field peak



Initial experimental tests: preparation

- Initial experiments will be conducted at NASA LeRC (tank 7)
  - o Space has been provided; magnets and SCR controller for pulsing microwave power have been sent to LeRC
  - o Microwave components have been delivered to LeRC
  - o Vacuum vessel, helical coupler, and gas box have been constructed and are undergoing final bench tests at LLNL
- First experiments will be directed to forming the plasma and making preliminary measurements of density, electron temperature
- Subsequent experiments will explore the details of the plasma for comparison with modeling
  - o Electron anisotropy
  - o Suppression of flow to rear wall
  - o Efficiency
- Measurements will also be made of the separation of the plasma plume from the magnetic nozzle