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:
  - Maximizes efficiency by minimizing energy loss to the wall
  - 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, \( \omega_c/\omega, \omega_p/\omega \gg 1 \). We illustrate the coupling at \( \omega_c/\omega = 10, (\omega_p/\omega)^2 = 1000 \). This is the helicon regime, with

\[
k^2_{\perp \parallel} = 1 - \frac{\omega^2}{\omega^2 - \omega \omega_c \cos \theta - \omega \omega_p \cos \theta}
\]

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

- Waves in the upper-right quadrant 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 \( n_L \).

Wave propagation:

Waveguide with helix and plasma column

- Several modes with different radial structure propagate in the system.

![Wave propagation diagram](image-url)
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

![Impedance vs Density Graph]

Wave Absorption at the Cyclotron Resonance

- As the whistler wave approaches the cyclotron resonance, the value of $k$ 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 ($\omega - \omega_c = k_s v_{th}$) 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 anisotropic 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

Magnetic field (loop model)

Density

Electron temperature (adiabatic)

Flow velocity

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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.
  - Electrons are heated by rf with velocity-space diffusion in the quasilinear approximation.
  - For the present cases, the electrons are weakly collisional.
  - The ion mass is 100me 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:

<table>
<thead>
<tr>
<th>Injected Te</th>
<th>Injected Ti</th>
<th>ECRH</th>
</tr>
</thead>
<tbody>
<tr>
<td>No ECRH</td>
<td>100 eV</td>
<td>5 eV</td>
</tr>
<tr>
<td>ECRH</td>
<td>5 eV</td>
<td>5 eV</td>
</tr>
</tbody>
</table>

Geometry for PIC code model

<table>
<thead>
<tr>
<th>Magnetic field strengths</th>
</tr>
</thead>
<tbody>
<tr>
<td>z(cm)</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>B(gauss)</td>
</tr>
<tr>
<td>B(0)/B</td>
</tr>
</tbody>
</table>

[Diagram of magnetic field strengths and plasma injection]

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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 $\mu B/\psi$ 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.

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Initial experimental tests: preparation

- Initial experiments will be conducted at NASA LeRC (tank 7)
  - Space has been provided; magnets and SCR controller for pulsing microwave power have been sent to LeRC
  - Microwave components have been delivered to LeRC
  - 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
  - Electron anisotropy
  - Suppression of flow to rear wall
  - Efficiency
- Measurements will also be made of the separation of the plasma plume from the magnetic nozzle