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, $\omega_e/\omega, \omega_p/\omega \gg 1$. We illustrate the coupling at $\omega_e/\omega = 10, (\omega_p/\omega)^2 = 1000$. This is the helicon regime, with

$$k_n^2 = 1 - \frac{\omega_p^2}{\omega^2} \frac{\omega}{\omega - \omega_e \cos \theta}$$

- 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 pick out particular values of $n_l$.

Wave propagation:

Waveguide with helix and plasma column

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

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**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 $k_\| \rho$ becomes very large and the phase velocity becomes small.

This has two favorable consequences for absorption:

- The direction of propagation becomes nearly along the field and at short wavelength so that reflection is very small.

- The phase velocity becomes comparable to the thermal velocity of the particles, so that the Doppler-shifted resonance ($\omega - \omega_c - k_\| V_\| = 0$) 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 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

Flow velocity

Electron temperature (adiabatic)
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></th>
<th>Injected ( T_e )</th>
<th>Injected ( T_i )</th>
<th>ECRH</th>
</tr>
</thead>
<tbody>
<tr>
<td>No ECRH</td>
<td>100 eV</td>
<td>5 eV</td>
<td>None</td>
</tr>
<tr>
<td>ECRH</td>
<td>5 eV</td>
<td>5 eV</td>
<td>( E_r f = 320 ) V/cm</td>
</tr>
</tbody>
</table>

Geometry for PIC code model

**Magnetic field strengths**

<table>
<thead>
<tr>
<th>( z(\text{cm}) )</th>
<th>0</th>
<th>2</th>
<th>3.5</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>( B(\text{gauss}) )</td>
<td>3650</td>
<td>2350</td>
<td>1250</td>
<td>125</td>
</tr>
<tr>
<td>( B(0)/B )</td>
<td>1</td>
<td>1.6</td>
<td>2.9</td>
<td>29</td>
</tr>
</tbody>
</table>

![Graph showing magnetic field strengths and injection points](image)
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

![Graphs showing electron temperature (Te) and ion temperature (T_i) variations with and without ECRH.]

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 $\mu dB/dt$ force on the electrons and maintain quasineutrality.

![Graphs showing density (n) and potential ($\phi$) variations with and without ECRH.]

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Electron energy is converted into ion flow

No ECRH

Ion scatter plot

Ion velocity

Axial Position [cm]

ECRH

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.

No ECRH

Electron energy flux

Ion energy flux

Axial Position [cm]

ECRH

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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