Experimental Evidence of Lower Hybrid Wave Scattering in ALCATOR C-MOD due to Scrape Off Layer Density Fluctuations

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COLLABORATORS

Cornwall Lau (ORNL, FMNSD) → leader of the simulation effort

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Edge Turbulence Alters Lower Hybrid Wave Propagation

**Direct Experimental Measurement**

$E_{\text{LH}} = $ Lower hybrid wave electric field vector

LH wave absorption negligible in SOL near the launcher

Strong LH wave scattering is occurring in the SOL

SOL density fluctuations predict LH wave scattering
Lower Hybrid Current Drive Provides Off-Axis Current at High Efficiency

- External current drive is necessary for the steady state reactor.
  - off-axis current
  - high efficiency

- Lower hybrid current drive has been successfully demonstrated in the low density regime.

- High density plasmas
  - Loss of efficiency at high density ($n_e > 10^{20} \text{ m}^{-3}$)
  - WHY and will a measurement of $E_{\text{LH}}$ help?
### Lower Hybrid Current Drive on C-Mod

**PRESENTED DATA**

<table>
<thead>
<tr>
<th></th>
<th>C-Mod</th>
<th>Reactor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Field</td>
<td>5.4 T</td>
<td>5 T</td>
</tr>
<tr>
<td>Density</td>
<td>13 ( \cdot 10^{19} ) m(^{-3})</td>
<td>5-10 ( \cdot 10^{19} ) m(^{-3})</td>
</tr>
<tr>
<td>Frequency</td>
<td>4.6 GHz</td>
<td>5.0 GHz</td>
</tr>
<tr>
<td>Shape</td>
<td>Diverted</td>
<td>Diverted</td>
</tr>
<tr>
<td>Launched (n_{</td>
<td></td>
<td>})</td>
</tr>
</tbody>
</table>

**local \(n_e\) profile**

**REQUIRED FOR ACCURATE SIMULATIONS OF \(|E_{\text{LH}}|\)**

- X-mode reflectometer horns
- Langmuir probes
THE DIAGNOSTIC AND IMPLEMENTATION ON ALCATOR C-MOD

COMSOL FULL-WAVE 3D SIMULATIONS

COMPARISON OF EXPERIMENTAL AND SIMULATION RESULTS
Polarized measurement of optical emission having a specific polarization.

Optical emission spectroscopy → passive measurement of the $D_\beta$ spectrum.

$E_{\text{LH}}$ is determined from a systematic fit to the shape of the spectral line profiles.

**Polarized Optical Emission Spectroscopy**

- **Polarizing beam splitter**

- $B=4.2 \, \text{T}$
σ and π spectra were measured at 7 locations using a periscope.
The time dependent Schrödinger equation is fit to the experimentally measured $\sigma$ and $\pi$ spectra.

\[
i\hbar \frac{\partial \Psi}{\partial t} = \left[ H + H^B + HE(t) + \hat{H} \right] \Psi
\]

unperturbed Hamiltonian $f(B)$ perturbed Hamiltonian $f(E_{LH})$

$E_{\parallel} = 0.0 + 0.2 \text{ kV/cm}$

$E_{\perp r} = 1.8 \pm 0.1 \text{ kV/cm}$

$E_{\perp p} = 1.7 \pm 0.2 \text{ kV/cm}$
OUTLINE

THE DIAGNOSTIC AND IMPLEMENTATION ON ALCATOR C-MOD

COMSOL FULL-WAVE 3D SIMULATIONS

COMPARISON OF EXPERIMENTAL AND SIMULATION RESULTS
3D simulations of $E_{LH}$ are required because LH resonance cone is strongly localized.

Assumed axisymmetry in $n_e$ and reduced problem to Fourier sum of toroidal modes.

$$E_{LH}(r, z, \theta) = \sum_{m=1}^{N_m} A_m E_m(r, z)e^{im\theta}$$

The $n_e$ profile is set by reflectometry measurements and a synthetic turbulence model.

$$n_e = n_{eo} \left[ (1 + \tilde{n}_e e^{-\frac{(r-r_c)^2}{r_w} \sin(\frac{2\pi p}{\lambda_{ne}}) - \frac{(p-p_c)^2}{p_w^2}}} \right]$$
**E\(_{LH}\) Definitions**

\[
E_{LH} = E_{\|} \hat{e}_{\|} + E_{\perp r} \hat{e}_{\perp r} + E_{\perp p} \hat{e}_{\perp p}
\]

- Direction of \(E_{LH}\):
  - Parallel to \(B\)
  - Perpendicular to \(B\)

- Magnitude of \(E_{LH}\):

\[
\approx \tan^{-1} \left( \frac{E_{\perp r}}{E_{\perp p}} \right)
\]

\[
= |E_{LH}|
\]
THE DIAGNOSTIC AND IMPLEMENTATION ON ALCATOR C-MOD

COMSOL FULL-WAVE 3D SIMULATIONS

COMPARISON OF EXPERIMENTAL AND SIMULATION RESULTS

\[ n_e = n_{eo} \left[ (1 + \tilde{n}_e \frac{(r-r_0)^2}{r_w} \sin \left( \frac{2\pi r}{\lambda n_e} \right) - \frac{(p-p_0)^2}{p_w^2} \right] = 0 \] WITHOUT DENSITY FLUCTUATIONS
|E_{LH}| was averaged over the vertical and horizontal measurement locations to study power distribution between $-n_{||}$ and $n_{||}$ waves.

Averaged $|E_{LH}|$ results indicated a majority of the power is being distributed to $-n_{||}$ wave.
The spatially variation of $|E_{\text{LH}}|$ is in good agreement with the simulation.

LH wave power is not being strongly absorbed in SOL near the launcher.
LH wave scattering was found to increase as the midplane is approached.

Strong disagreement was found between simulation and experiment, not sensitive to the $n_e$ profile.
OUTLINE

THE DIAGNOSTIC AND IMPLEMENTATION ON ALCATOR C-MOD

COMSOL FULL-WAVE 3D SIMULATIONS

COMPARISON OF EXPERIMENTAL AND SIMULATION RESULTS

\[ n_e = n_{eo} \left[ (1 + \tilde{n}_e e^{\frac{(r-r_c)^2}{r_w}} \sin(\frac{2\pi p}{\lambda_{ne}}) \frac{(p-p_c)^2}{p_w^2}) \right] \]

WITH DENSITY FLUCTUATIONS
Synthetic turbulence model is based on experimental observations [1] and a BOUT simulation [2].

Density fluctuations peak at midplane [1]

Density fluctuation scale length $\approx 1$ cm [2]
Synthetic turbulence having $\lambda_{ne} = 5 \text{ mm}$ and $\bar{n}_e = .75$ can be used to explain experimental and simulation discrepancy in both vertical and horizontal sets of measurements.

Wide range of $\lambda_{ne}$ and $\bar{n}_e$ values yield similar results.
Scattering of $k_\perp$ by density blobs can change evolution of $k_\parallel$ along the ray ➔ different damping profile.

![Graph showing comparison between w/o Blob and with Blob scenarios with n_perp scattering](image)

Viewing chord [a.u.]
CONCLUSIONS

LH wave absorption negligible in SOL near the launcher

Strong LH wave scattering is occurring in the SOL

SOL density fluctuations predict LH wave scattering
HFS LHCD simulation of DIII-D discharge 147634 using GENRAY-CQL3D shows excellent wave penetration and single pass damping.

HFS SOL is quiescent - density fluctuations seem to be absent!

WEST has installed HFS optics.

Polarizers will be installed early next year, yielding 12 sightlines.

Have spectrometer... Will travel...

FWHM = 0.007 nm
QUESTIONS
The spectral line profile is uniquely sensitive to all components of the $E_{\text{LH}}$ vector.

- Transitions with $\sigma$ polarization
- Transitions with $\pi$ polarization

- 8 substates
- 32 substates

$B = 4.2 \text{ T}$
Spectral Line Profile Sensitivity to $E_{\text{LH}}$

$$E_{\text{LH}} = 0.0 \hat{x} + 0.0 \hat{y} + 2.5 \hat{z} \text{ kV/cm}$$
COMSOL model was validated using GENRAY.

- $P_{LH} = 330 \text{ kW}$
- $n_e (1.3 \times 10^{20} \text{ m}^{-3})$
- $B_t (5.4 \text{ T})$
- $I_p (0.80 \text{ MA})$

**Toroidal mode number**

- $m = -170$
- $m = 509$

**Graph**

- Normalized Signal vs. Time (s)

**Diagrams**

- Counter-current propagating wave
- Co-current propagating wave
**Vertical View Scan of \( |E_{LH}| \) vs. \( P_{LH} \)**

![Diagram](image)

- Vertical Views
- Net LH Power (kW)
- \( |E_{LH}| \) (kV/cm)