Characterization of onset of parametric decay of lower hybrid waves
:Progress toward steady-state regimes in Alcator C-Mod


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Loss of lower hybrid current drive efficiency in ITER-relevant high density plasmas needs to be understood.

- Onset of parametric decay instability (PDI) of LH waves in multi-pass regime
  - PDI away from the launcher due to low single pass absorption
  - PDI correlates with the change in edge density

- Convective growth is more important than the homogeneous growth rate ($\gamma$)
  - Amplification of the sideband LH mode:
    \[ A \propto \exp(\gamma \Delta t), \text{ where } \Delta t = \Delta \xi/v_{g,\xi} \]

- New additional launcher design to enhance single-pass absorption
  - Minimizing the presence of LH waves in the edge plasmas

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1G. M. Wallace, PoP, 19, 062505 (2012)
LHCD experiments in Alcator C-Mod use a single grill, consisting of an array of 4x16 waveguides grill.

ITER-relevant parameters:

<table>
<thead>
<tr>
<th></th>
<th>C-Mod</th>
<th>ITER</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f_0$ (GHz)</td>
<td>4.6</td>
<td>5</td>
</tr>
<tr>
<td>$N_{\parallel}$</td>
<td>1.5 - 3</td>
<td>~2</td>
</tr>
<tr>
<td>$\bar{n}_e$ ($10^{20}$ m$^{-3}$)</td>
<td>0.5 – 1.5</td>
<td>0.5 - 1</td>
</tr>
<tr>
<td>$B_T$ (T)</td>
<td>3 - 8</td>
<td>5</td>
</tr>
<tr>
<td>Magnetic Configuration</td>
<td>LSN / USN / DN / Limited</td>
<td>LSN</td>
</tr>
<tr>
<td>LH wave propagation</td>
<td>Multi-pass regime</td>
<td>Single-pass regime</td>
</tr>
</tbody>
</table>

- Coupled power: ~ 1 MW
- Coupling efficiency: 70 ~ 80 %
- Pulse length$^1$: ~ 1 sec

$^1$G. Wallace, Accepted to Nuclear Fusion
Collisional loss and full-wave effects become significant in low single-pass absorption plasmas.

- Pump propagates in the plasma edge and SOL.
- Collisional loss\(^1\)
  - Reduces effective LH power
- Full wave effects\(^2\)
  - Up-shift \(n_\parallel\) after the reflection at the inner wall

\[ \text{Driven Current: } j_{lh} \propto \frac{P}{n_e n_\parallel^2} \]

\[ \log_{10}(|E_\parallel|) \text{ V/m} \]

\(^1\)G. Wallace, PoP 17, 082508 (2010)
\(^2\)O. Meneghini, RF Conference (2011)
PDI can redistribute pump power to two decay waves, resulting in lower current drive efficiency.

- Decay of pump LH wave into two daughter waves
  \[ \mathbf{k}_0 \approx \mathbf{k}_1 + \mathbf{k} \quad \omega_0 \approx \omega_1 + \omega \]
  - Pump (0): LH wave
  - Decay wave (1): LH wave with higher \( n_{||} \)
  - Decay wave
    - ion sound quasi-mode\(^2,3\)
    - ion cyclotron quasi-mode\(^1,4\)

- Loss of current drive efficiency due to PDI
  - Pump power: ↓
  - \( n_{||} \) of sideband LH wave: ↑

\[^1\text{M. Porkolab, Phys. Fluids, 20, 2058 (1977)}\]
\[^2\text{Y. Takase, Phys. Fluid, 26 (1983), 2992}\]
\[^3\text{R. Cesario, Nucl. Fusion, 46 (2006), 462}\]
\[^4\text{C. Liu, Phys. Fluids 27, 1709 (1984)}\]
Spectral recorders are developed to continuously monitor LH frequency spectra around the C-Mod tokamak.

- Development of spectral recorders
  - Heterodyne system
  - Resolution bandwidth: ~ 100 kHz
  - Frequency bandwidth: ~ 250 MHz
  - Sweep time: ~ 25 ms

PDI is excited above $\bar{n}_e \approx 1.0 \times 10^{20} \text{ m}^{-3}$, indicating that PDI may explain the discrepancy between the experiments and simulations.

- Ion cyclotron PDI is dominant.
- Ion cyclotron PDI is excited at different radial locations with different strength, depending on magnetic configurations.\(^1\)

\(^1\)S. G. Baek, PPCF, 55, 052001 (2012)
PDI excited at the LFS edge

\[ n_e \approx 1.2 \times 10^{20} m^{-3} \]

\[ n_e \approx 1.3 \times 10^{20} m^{-3} \]

\[ n_e \approx 1.2 \times 10^{20} m^{-3} \]
In USN plasmas, ion cyclotron PDI is excited near the LFS edge above $n_e \approx 1 \times 10^{20} \text{ m}^{-3}$

- @ $n_e \approx 1.2 \times 10^{20} \text{ m}^{-3}$
  - Instability occurs at the outer edge
  - $P_{\text{sideband}} \ll P_{\text{pump}}$

- Consistent with past observations in other tokamaks$^{1,2,3}$
  - PDI generated at the LFS
  - Sidebands remain weak unless $\omega / \omega_{\text{LH}}(0) \rightarrow 2$ ($n_e \approx 2 \times 10^{20} \text{ m}^{-3}$)
  - Broadband feature is independent from the probe locations

- Sideband LH waves appear to propagate along the pump.
  - $n_||$ may not much differ from $n_||,\text{pump}$

1M. Porkolab, PRL, 38, 230 (1977)
At the edge near the launcher, perpendicular coupling results in weaker convective growth.\textsuperscript{1,2,3}

Coupling coefficient\textsuperscript{1} determines $\gamma$, where $\omega = \omega_R + i \gamma$

$$(\mu^-)^2 \propto \frac{(k_-^2 E_{0\perp}^2 \sin^2 \theta)}{\omega_0^2 \omega_{ce}^2} + \frac{(k_+^2 E_{0\parallel}^2)}{\omega_0^4}$$

\begin{itemize}
  \item Perpendicular Coupling
  \item Parallel Coupling
\end{itemize}

\begin{figure}
\centering
\includegraphics[width=\textwidth]{figure}
\caption{Growth Rate Spectra}
\end{figure}

\begin{figure}
\centering
\includegraphics[width=\textwidth]{diagram}
\caption{Diagram of perpendicular and parallel coupling}
\end{figure}

\textsuperscript{1}M. Porkolab, Phys. Fluids, \textbf{20}, 2058 (1977)
\textsuperscript{2}Y. Takase, Phys. Fluids, \textbf{28}, 983 (1985)
\textsuperscript{3}R. Cesario, Nucl. Fusion, \textbf{46} (2006), 462
At the edge, parallel coupling term can lead to stronger convective growth.\textsuperscript{1,2}

Sideband group velocity:
\[ \vec{v}_g\perp = \left| v_{g\perp} \right| (\cos \theta \hat{x} + \sin \theta \hat{y}) \]

*Note that spatially homogeneous plasma is assumed.

\[ (\mu^-)^2 \propto \frac{(k^-)^2 E_0^2 \sin^2 \theta}{\omega_0^2 \omega_{ce}^2} + \frac{(k^-)^2 E_0^2}{\omega_0^4} \]

- Perpendicular Coupling
- Parallel Coupling

\[ A = e^{\gamma \Delta t}, \text{ where } \Delta t = \Delta x / v_{g,x} \]
Growth rate itself cannot explain the observed onset of PDI.

- Density and temperature profiles of two USN plasmas
  - $\bar{n}_e = 0.9 \times 10^{20} m^{-3}$: no PDI
  - $\bar{n}_e = 1.2 \times 10^{20} m^{-3}$: PDI

- $\gamma$ due to parallel coupling is comparable, suggesting that convective growth is more important.
The underlying mechanism of the observed onset of PDI is possibly due to weaker radial penetration of pump LH waves.

- Weaker radial penetration in high density plasmas

\[
\frac{v_{g\perp}}{v_{g\parallel}} \approx \frac{\omega}{\omega_{pe}} \propto \frac{1}{n_e}
\]

- As density increases, pump spends longer time at the edge.
  - Higher $\gamma$ at the edge
  - Longer $\Delta x$ in the parallel coupling limit\(^1,2\)
  - Longer $\Delta t(=\Delta x/v_{gx})$
  - Stronger convective growth

\(^{1}\text{Y. Takase, Phys. Fluids, 28, 983 (1985)}\)
\(^{2}\text{R. Cesario, Nucl. Fusion, 46, 462 (2006)}\)
\[ \bar{n}_e \approx 1.2 \times 10^{20} \text{ m}^{-3} \] for LSN

\[ \bar{n}_e \approx 1.3 \times 10^{20} \text{ m}^{-3} \] for IWL

\[ \bar{n}_e \approx 1.2 \times 10^{20} \text{ m}^{-3} \] for USN

PDI excited at the HFS edge
In LSN plasmas, ion cyclotron PDI is excited near the inner plasma edge above $\bar{n}_e \approx 1 \times 10^{20} \text{ m}^{-3}$.

- No ion cyclotron PDI occurring at the outer edge within the detector sensitivity
- Inner wall probe detects ion cyclotron PDI occurring at the inner edge
- Spatially localized effect
  - Sideband may have higher $n_\parallel$
  - $\gamma \sim n_\parallel$ as shown in the model\(^1\)
  - Sideband LH waves may result in lower current drive efficiency

\[ \text{Driven Current: } j_{lh} \propto \frac{P}{n_e n_\parallel^2} \]

\(^1\) Y. Takase, Phys. Fluids, 28, 983 (1985)
HFS PDI shows a classical PDI behavior: evidence of pump depletion and pump broadening.

- Pump broadening at the HFS:
  - correlates with the onset of ion cyclotron PDI

- Pump broadening
  - ion sound quasi mode
  - scattering of LH waves by turbulence

3 N. Bertelli, PPCF, 55, 074003 (2013)
Local plasma condition near the HFS SOL is more prone to PDI than the condition at the LFS SOL.

- **HFS SOL**: higher density, lower temperature
  - $\gamma$ increases with higher density and lower temperature\(^1\)

- Asymmetric behavior of edge plasma parameters\(^2\)
  - Due to the temperature gradient on the open field lines
  - Pressure is constant along the open field lines

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\(^1\)Y. Takase, Phys. Fluids, 28, 983 (1985)
\(^2\)LaBombard, Nucl. Fusion 44 (2004), 1047
Growth rate itself cannot explain the strong onset of HFS PDI and the absence of LFS PDI.

- Discrete ion cyclotron peaks are observed.
  - Ion sound peaks appear in the colder SOL region (away from the LCFS)

- Finite $\gamma$ is seen both at LFS and HFS
  - Cannot explain
    - the onset of PDI at the HFS
    - the absence of PDI at the LFS

- Convective growth needs to be considered.
Spatial broadening of LH waves and the reduced radial group velocities may lead to higher convective growth at the HFS edge.

- Ray tracing code: GENRAY*

- Resonance cone is broadened after the reflection
  - May reduce $\gamma$ but can also reduce the convective loss

- Radial group velocity slows down at the inner plasma edge
  - Longer residence time within the pump when $v_{g,x} \approx 0$, for fixed $\Delta x$

\[
\Delta x = v_{g,x} \cdot \Delta t
\]

Amplitude of the sideband LH $\sim e^{\gamma \Delta t}$

- Similar to the PDI limit\(^1\)
  - $v_g$ slows down significantly in the limit $\omega/\omega_{lh}(0) \rightarrow 2$, leading to higher amplification factor


\(^1\)M. Porkolab, Phys. Fluids, 20, 2058 (1977)
Absence of PDI excited at the LFS edge

\[ n_e \approx 1.2 \times 10^{20} m^{-3} \]

\[ n_e \approx 1.3 \times 10^{20} m^{-3} \]

\[ n_e \approx 1.2 \times 10^{20} m^{-3} \]
IWL plasmas exhibit lower SOL density in front of the launcher and weaker LFS PDI.

- Changing magnetic geometry affects edge density profiles
  - Inner gap scan with fixed $n_e$, $n_{\parallel}$, LH power
  - Lower SOL density in front of the launcher in IWL plasmas

\[ \bar{n}_e \approx 1.35 \times 10^{20} \text{ m}^{-3} \]

C. Lau, PPCF, 55, 025008 (2013)

\[ \text{constant } \bar{n}_e \approx 1.35 \times 10^{20} \text{ m}^{-3} \]
Strength of LFS PDI and pump broadening correlates with the SOL density in front of the launcher.

- When above the edge density threshold,
  - Pump width at -30dBc\(^1\) increases abruptly
  - Sideband power (pump broadening + sidebands) increases abruptly

- Edge plasma conditions are important.\(^2,3\)
  - Can affect how pump LH waves propagate

- The sideband power is not significant.

\(^1\)R. Cesario, Nature Communications, 1, 55, (2010)
\(^2\)Y. Takase, Phys. Fluids, 28, 983 (1985)
\(^3\)R. Cesario, Nucl. Fusion, 27, 435 (1987)
Quantitative analysis is necessary to evaluate the power loss due to PDI.

- We see a different PDI behavior between LSN/USN plasmas, yet similar hard X-ray count rate.

Questions:
- HFS PDI: Is it a spatially localized effect?
- LFS PDI: Are we looking at the proper region? Is it excited on the first pass?

High single pass absorption can isolate loss mechanisms near the launcher (e.g., LFS PDI) from the loss mechanisms away from the launcher (e.g., collisional loss, full wave effects, HFS PDI)

Need more extensive measurements!
Identified loss mechanisms are exacerbated in multi-pass regime.

- Enhancing **single pass absorption** will suppress most of the identified loss mechanisms\(^1\).
  
  - By enhancing single pass absorption, LH power will be absorbed to the plasma before reaching to the HFS edge.
  
  - This will prevent PDI at the HFS edge.
  
  - This approach can also mitigate collision loss and full-wave effects.

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\(^1\) S. Shiraiwa, Submitted to Nucl. Fusion
Future plan is to double LH power (2 MW) and enhance single-pass absorption by adding additional off-mid-plane launcher.$^{1,2}$

- Additional launcher (LH3) on C-Mod is under preparation$^{1,2}$
  - Optimizing phase space interactions with the existing launcher.
  - Strong single pass absorption (80%) is expected at $n_e \approx 1.5 \times 10^{20} \text{ m}^{-3}$
  - LH driven current at $r/a \sim 0.6$, providing an ideal CD tool for accessing advanced tokamak regime.

$^{1}$S. Shiraiwa, IAEA (2012)
$^{2}$G. Wallace, IAEA (2012)
Goal: Use LHCD as actuator to study and optimize ITER relevant steady-state regimes in C-Mod

- Use of LHCD to supplement bootstrap current in achieving steady-state tokamak operation for $t >> \tau_{CR} \approx 200$ ms

- Scoping study$^1$ for Alcator C-Mod:

![Simulated Current Density Profile](image)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B_T$</td>
<td>4 - 6 (T)</td>
</tr>
<tr>
<td>$\bar{n}_e$</td>
<td>$1.5 \times 10^{20}$ (m$^{-3}$)</td>
</tr>
<tr>
<td>$f_{bs}$</td>
<td>60 - 70 (%)</td>
</tr>
<tr>
<td>$P_{LH}$</td>
<td>2.5 - 3.0 (MW)</td>
</tr>
<tr>
<td>$P_{ICRF}$</td>
<td>5 (MW)</td>
</tr>
<tr>
<td>$T_{e0}$</td>
<td>5 - 7 (keV)</td>
</tr>
<tr>
<td>$I_p$</td>
<td>1 (MA)</td>
</tr>
<tr>
<td>$\beta_n$</td>
<td>2.5 - 3</td>
</tr>
</tbody>
</table>

$^1$P. T. Bonoli, Nucl. Fusion 40, 1251 (2000)
Conclusion: Strong single pass absorption may suppress most of the identified loss mechanisms.

- PDI is excited above $1 \times 10^{20}$ m$^{-3}$, where the discrepancy between the simulations and experiments remain.
  - PDI away from the launcher can occur in multi-pass absorption plasmas.

- The role of PDI needs further experimental and theoretical investigation.
  - PDI at the LFS appears to be weak.

- Enhancing single pass absorption is expected to mitigate most of the loss mechanisms arising due to low single pass absorption.