Characterization of onset of parametric decay instability of lower hybrid waves in ITER-relevant high-density plasmas


Plasma Science and Fusion Center, MIT, Cambridge, USA
*University of Tokyo, Japan

55th Annual Meeting of the Division of Plasma Physics
Denver, Colorado
November 11, 2013
LHCD experiments on Alcator C-Mod are ITER-relevant.

A single grill consists of an array of 4x16 waveguides grill.

<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} \text{ 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 sec
Loss of lower hybrid current drive efficiency in reactor-relevant high density plasmas needs to be understood.

- LHCD operation with $\bar{n}_e > 1 \times 10^{20}\, \text{m}^{-3}$ is critical for achieving fully non-inductive regimes with high bootstrap fraction in Alcator C-Mod.

- When $\bar{n}_e > 1 \times 10^{20}\, \text{m}^{-3}$, simulations over predict current drive efficiency $\eta$ and hard X-ray count rates.\(^1,2\)

- Configuration dependent ion cyclotron parametric decay instabilities (PDI) were reported at the Providence APS meeting\(^3\) and suggested to be linked to loss of $\eta$.

- In this talk, the focus is on understanding the observed ion cyclotron PDI that are excited at the high-field side edge in lower null C-Mod plasmas.

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\(^1\)G. M. Wallace, PoP, 19, 062505 (2012)
\(^3\)S. G. Baek, 54\(^{th}\) APS-DPP Meeting (2012)
PDI can redistribute pump power to decay waves, resulting in lower current drive efficiency.

- E.g., decay of pump LH wave into two decay waves

\[ \vec{k}_0 \approx \vec{k} + \vec{k}_1 \quad \omega_0 \approx \omega + \omega_1 \]

- Pump (0): LH wave
- Decay wave (1): LH wave with higher \( n_{||} \)
- Another 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: ↑

\[ \Delta f \approx \text{local } f_{ci} \text{ where PDI occurs} \]

Driven Current: \( j_{lh} \propto \frac{P}{n_e n_{||}^2} \)

\(^1\) M. Porkolab, Phys. Fluids, 20, 2058 (1977)  
\(^2\) Y. Takase, Phys. Fluid, 26, 2992 (1983)  
\(^3\) R. Cesario, Nature Comm. 1, 55 (2010)  
Spectral recorders were developed to continuously monitor LH frequency spectra from probes around the C-Mod tokamak.

- Development of heterodyne detection system\(^1\)
  - Resolution bandwidth: \(~ 100 \text{ kHz}\)
  - Frequency bandwidth: \(~ 250 \text{ MHz}\)
  - Sweep time: \(~ 25 \text{ ms}\)

- Frequency response of probes was flat in the range of interest. Relative response among probes was calibrated to within \(~ 6 \text{ dB}\).

\(^1\)S. G. Baek, Rev. Sci. Instrum., 83, 10E325 (2012)
In LSN plasmas, ion cyclotron PDI are excited near the inner plasma edge above \( \bar{n}_e \approx 1 \times 10^{20} \text{ m}^{-3} \).

- \( @ \bar{n}_e \approx 1.2 \times 10^{20} \text{ m}^{-3} \)
  - No ion cyclotron PDI occur at the outer edge within the detector sensitivity.
  - Inner wall probe detects ion cyclotron PDI occurring at the inner edge.
  - Spatially localized effect
    - Simulations show that growth rate \( \gamma \sim n_{\parallel, \text{sideband}} \), favoring higher \( n_{\parallel} \) decay LH waves than pump \( n_{\parallel} \).
    - Sideband LH waves have lower current drive efficiency

**Driven Current:** \( \dot{j}_{lh} \propto \frac{P}{n_e n_{\parallel}^2} \)
HFS PDI show a classical PDI behavior: evidence of pump depletion and pump broadening.

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

- Two possible mechanisms
  - ion sound quasi mode
  - scattering of LH waves by turbulence\(^1,2\)
    - Simulations indicate insignificant loss of fast electrons\(^3\)

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\(^3\) N. Bertelli, PPCF, 55, 074003 (2013)
Growth rate itself cannot explain the strong onset of HFS PDI and the absence of LFS PDI.

\[ A \sim \exp(\gamma \Delta t) = \exp\left(\gamma \frac{\Delta x}{|v_{gx}|}\right) \]

where \( \gamma \) is found from the parametric dispersion relation\(^1,^2\)

\[ \varepsilon \varepsilon_1 = -\mu^2 \frac{(1 + \chi_i) \chi_e}{4} \]

- Amplitude of the sideband LH wave

- Growth rates are comparable in LFS and HFS edge plasmas.
  - Cannot explain
    - the onset of PDI at the HFS
    - the absence of PDI at the LFS

- Convective growth (\( \Delta t \) term) needs to be considered.
  - The distance (or, the time) that the sideband LH wave stays within the pump LH resonance cone

\(^1\)M. Porkolab, Phys. Fluids, 20, 2058 (1977)
Spatial broadening of LH waves and the reduced radial group velocities may lead to higher convective growth at the HFS edge.

- 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 $\Delta x$

$$A \sim \exp(\gamma \Delta t) = \exp\left(\gamma \frac{\Delta x}{v_{g,x}}\right)$$

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

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1M. Porkolab, Phys. Fluids, 20, 2058 (1977)
Conclusion: Observed PDI at the HFS edge is likely responsible for loss of current drive efficiency at high densities.

- Experimental evidence that ion cyclotron PDI at the HFS edge can decrease LHCD efficiency.
- Wave propagation behavior, which determines convective growth, is likely to be important in determining the onset of the observed PDI at the HFS edge.
- Enhanced single pass absorption (ITER regime) will suppress HFS PDI and most of the identified parasitic loss mechanisms\(^1\).
- Alcator C-Mod LH system upgrade (now on hold) is designed to test this approach.
- If successful, ITER-relevant non-inductive regimes with high bootstrap fraction and sustained by LHCD can be explored in C-Mod.

\(^1\) S. Shiraiwa, Nucl. Fusion (2013), Accepted
Collisional loss and full-wave effects degrade the LHCD performance particularly in multi-pass regime.

- LH waves propagate 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

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

Ray Tracing Simulation

Full Wave Simulation$^2$

$\log_{10}(|E_\parallel|) V/m$
Goal: Use LHCD to study and develop reactor-relevant steady-state regimes on Alcator C-Mod

- Use of LHCD to supplement bootstrap current in achieving advanced tokamak operation for $t >> \tau_{CR} \approx 200$ ms at $\bar{n}_e \approx 1.5 \times 10^{20}$ (m$^{-3}$)

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

Simulated Current Density Profile

$J_{\text{total}}$, $J_{\text{bootstrap}}$, $J_{\text{LH}}$, $J_{\text{seed}}$

<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>$P_{\text{LH}}$</td>
<td>2.5 – 3.0 (MW)</td>
</tr>
<tr>
<td>$P_{\text{ICRF}}$</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)
The ray tracing simulation indicates the upshift of the pump $n_\parallel$ at the inner wall.