Experimental Characterization of Parametric Decay Instabilities of Lower Hybrid waves on Alcator C-Mod

T. Shinya*, S. G. Baek, G. M. Wallace, J. Hughes, B. Labombard, R. R. Parker, S. Shiraiwa, Y. Takase*

MIT Plasma Science and Fusion Center
*University of Tokyo

58th Annual Meeting of the Division of Plasma Physics
San Jose, CA
October 31, 2016

This work was conducted on the Alcator C-Mod tokamak, a DoE Office of Science user facility, and supported by U.S. DoE Cooperative Agreement No. DE-FC02-99ER54512 and Japan/U.S. Cooperation in Fusion Research and Development.
Lower hybrid current drive experiment on Alcator C-Mod is ITER relevant.

<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>$n_{</td>
<td></td>
<td>}$</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 / Limited / DN</td>
<td>LSN</td>
</tr>
<tr>
<td>LH wave propagation</td>
<td>Multi-pass Regime</td>
<td>Single-pass regime</td>
</tr>
<tr>
<td>SOL Distance</td>
<td>~2 cm</td>
<td>~20 cm</td>
</tr>
</tbody>
</table>

- C-Mod LH system
  - Net coupled power ~ 1 MW.
  - Pulse length ~ 1 sec.
Understanding the PDI onset condition may provide insights into current drive performance at high density.

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

- At high density, current drive effects decrease anomalously, attributed to multiple edge loss mechanisms [Wallace, PoP 17, 082508 (2010), Meneghini, PhD Thesis, MIT (2012)]

- The increase in hard X-ray count rates, an indication of the fast electron population, with plasma current points toward the importance of edge/SOL plasmas in understanding the LH density limit problem.

- With the increase in plasma current, the (ion cyclotron) PDI onset at the low-field-side is also found to be delayed, due to the decrease in edge/SOL density.

Baek, Nucl. Fusion (2015) 55, 043009
Previously, the PDI onset is found to be delayed to a higher line-averaged density by lowering the edge density.

The C-Mod SOL density is a function of Greenwald density fraction [LaBombard, Phys. Plasmas15 05610 (2008)]. By raising current at the fixed line-averaged density, the SOL density decreases.

The PDI onset is delayed to a higher line-averaged density at a higher current with the decrease in SOL density.

Baek, Nucl. Fusion (2015) 55, 043009
A magnetic loop probe placed near the launcher confirms the plasma current dependence of PDI threshold.

- Magnetic loop antennas are installed on a movable scanning probe head.
  [Baek, PoP 23, 050701 (2016), Shinya, Submitted to Nucl. Fusion]

- It is placed in the SOL where magnetically mapped to the LH launcher on the first pass.

- The PDI onset (4.57 GHz sideband) vs. density is delayed at higher current.
Recent observations (1/4): the onset of PDI sideband is likely to occur near the launcher.

- A new probe array closer to the launcher still detects the onset of the PDI sideband. The rates at which pump power decreases are similar between the two locations.
Recent Observations (2/4): Raising core temperature does not suppress the PDI onset.

- With ICRF heating of 3 MW, the core temperature is raised to 6 keV.
- LH spectral measurements at various locations show that the PDI threshold density (line-averaged density) is not affected by this change.
- Current drive effects are not significantly improved as compared to a reference ohmic shot with Te0 ~ 2 keV, suggesting that edge effects might play a role in determining the loss of efficiency.
Recent Observations (3/4): The density near the separatrix could be important in determining PDI threshold.

- The left figures compare PDI threshold between a standard 0.8 MA plasma, and a locked 1.2 MA plasma (as opposed to a standard 1.2 MA plasma).

- The locked plasma exhibits a broader density profile with high edge density. As a result, PDI sidebands are seen with low density below $n_e = 1 \times 10^{20} \text{ m}^{-3}$.

- The PDI density threshold at the separatrix is at $4 \sim 5 \times 10^{19} \text{ m}^{-3}$. (Preliminary – Thomson under calibration.)
Recent Observations (4/4): Increasing current further to 1.2 MA raises the PDI threshold density.

- Previous PDI measurements up to 1.1 MA.
- At \(I_p = 1.2\) MA, the PDI sideband is not observed up to the line-averaged density of \(1.4 \times 10^{20} \text{ m}^{-3}\) (helium, 7.8T).
- In another deuterium plasma with 1.2 MA and 5.4 T, the PDI threshold is increased to \(1.3 \times 10^{20} \text{ m}^{-3}\).
- This measurement also indicates the importance of edge/SOL condition.
A rule of thumb that predicts the PDI limit toward $\omega_0/\omega_{lh} (\bar{n}_e) \rightarrow 2$ is not in agreement with C-Mod experimental results.

- Raising the magnetic field from $B_{t0} = 5.4$ T to 7.8 T lowers $\omega_0/\omega_{lh}(\bar{n}_e)$ toward PDI limit at the fixed line-averaged density. However, this does not appear to be the case as shown in the previous slide.

- In the past, $\omega_0/\omega_{lh}$ has been estimated by taking the central magnetic field and density (or line-averaged density).

- An underlying assumption in the $\omega_0/\omega_{lh}$ scaling is that the edge density is only a function of core density, which misses the role of plasma current (next slide).
The C-Mod SOL profile is a function of Greenwald density fraction, rather than core density only [LaBombard, Phys. Plasmas15 05610 (2008)].

- The near SOL appears to be important in understanding PDI because the H-mode far SOL density is lower than that in L-mode plasmas.

- This is consistent with PDI growth rate calculations that show the peak growth rate near the separatrix.

[LaBombard, Phys. Plasmas15 05610 (2008)].

[Baek, MIT thesis (2014)].
In the ICRF heated case, LH frequency spectra up to 4~5\textsuperscript{th} harmonics were observed, consistent with the growth rate calculation (shown in the previous slide).

- $\bar{n}_e \approx 1.2 \times 10^{20} \text{ m}^{-3}$,
- $P_{\text{LH}} = 500 \text{ kW}$,
- $N_|| = 105 \text{ deg}$,
- $T_e(0) \sim 4 \text{ keV}$,
- $T_e(a) \sim 1.4 \text{ keV}$

- $\bar{n}_e$ is not much different in typical LH experiments in L-mode experiments, yet much stronger PDI sidebands are observed.

- ICRF is known to affect SOL profiles, which may have affected PDI excitation and wave propagation.
- This measurement suggests PDI onset near separatrix.
The SOL of inner-wall limited (IWL) plasmas is also a function of Greenwald fraction.

- As Greenwald fraction increases, the shoulder in the far SOL develops, as seen in the diverted plasmas.
- However, at the given Greenwald fraction, the SOL density profile in IWL is similar to that at a lower Greenwald fraction case in the diverted plasma by about 70%.
- This relative low SOL density correlates with the observation that IWL exhibits a higher PDI threshold.
In C-Mod, PDI threshold is found to be $\bar{n}_e/n_G \approx 0.2$.

PDI threshold at high current approaches to that found in Alcator C that had a narrow SOL width due to a circular limiter [Takase, Phys. Fluids 28, 983 (1985)].

The data points align at $\bar{n}_e/n_G \approx 0.2$, consistent with the observation that SOL density profile is a function of Greenwald fraction, and PDI is a local phenomenon at the edge. (Note $\bar{n}_e/n_G \approx 0.32$ for Alcator C)
The threshold $\omega_0/\omega_{lh}$ has a dependence on plasma current.

- The threshold $\omega_0/\omega_{lh}$ varies as a function of plasma current, because of edge/SOL density scales as a function of Greenwald fraction.

- Previously, this current dependence was reported on limited tokamaks: Alcator C [Takase, Phys. Fluids 28, 983 (1985)] and FT [Cesario, Nucl. Fusion 27, 435 (1987)], but it was not understood in terms of Greenwald fraction.

- This figure suggests that, in evaluating $\omega_0/\omega_{lh}$, one needs to consider the current dependence of SOL profile in a diverted tokamak.
The $\omega_0/\omega_{lh}$ scaling suggests why PDI sidebands are not strong in EAST with 4.6 GHz, Tore Supra, and possibly FTU.

<table>
<thead>
<tr>
<th></th>
<th>Mag. Conf.</th>
<th>$f_0$ (GHz)</th>
<th>$B_t0$ (T)</th>
<th>$I_p$ (MA)</th>
<th>Minor radius (m)</th>
<th>Threshold nebar for PDI $\left(10^{20} \text{ m}^{-3}\right)$</th>
<th>nebar / nG</th>
<th>$\omega_0/\omega_{lh}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>EAST</td>
<td>Diverted</td>
<td>2.45</td>
<td>2.3</td>
<td>0.5</td>
<td>0.45</td>
<td>0.2</td>
<td>0.25</td>
<td>4.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4.6</td>
<td></td>
<td>0.4</td>
<td></td>
<td>No signature up to 0.26</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tore Supra</td>
<td>Limited</td>
<td>3.7</td>
<td>3.85</td>
<td>1.0</td>
<td>0.7</td>
<td>0.4</td>
<td>0.62</td>
<td>4.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(50 dB down)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>FTU</td>
<td>Limited</td>
<td>8.0</td>
<td>5.2</td>
<td>0.36</td>
<td>0.3</td>
<td>Claimed to be none.</td>
<td>0.78</td>
<td>6.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>5.9</td>
<td>0.6</td>
<td>0.3</td>
<td>1.0 for HXR limit</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.5</td>
<td>6.2</td>
</tr>
<tr>
<td>C-Mod</td>
<td>diverted</td>
<td>4.6</td>
<td>5.4</td>
<td>0.8</td>
<td>0.22</td>
<td>1.1</td>
<td>0.21</td>
<td>3.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>7.8</td>
<td>1.2</td>
<td>0.22</td>
<td>1.4</td>
<td>0.18</td>
<td>3.2</td>
</tr>
</tbody>
</table>

- C-Mod operates LH at the lowest $\omega_0/\omega_{lh}$.

- The C-Mod Greenwald fraction for PDI onset is not universal because different machines are expected to have different Greenwald fraction scaling (e.g., limited vs. diverted)
The observed onset of ion cyclotron PDI correlates with the anomalous decay of hard X-ray count rates.

- HXR count rates generally decreases exponentially as a function density, attributed to broadening in the spectral gap with the decrease in temperature.

- But the observed break-in slope in HXR count rates correlates with the PDI onset (in black in the C-Mod data, in blue in Tore Supra, and in red/purple in EAST).
Spectral broadening near the source frequency increases with density.

- As density increases, the 4.6 GHz source power decreases rapidly, whereas the wave power of the adjacent frequency components increases until roll-over.

- Could be either due to scattering with turbulence\(^1\) and ion sound PDI.

\(^1\)P. Bonoli, Phys. Fluids 25, 359 (1982)
Further study is necessary to clarify the role of the observed spectral broadening mechanisms on the loss of efficiency.

- On C-Mod, PDI onset and loss of efficiency is correlated, but it does not prove causation.
- The observed correlation between spectral broadening and the loss of efficiency on C-Mod suggests that undesirable effects could occur on the first pass.
- Proposed Experiment: LH experiment in a strong single pass regime at a low current could help identify the role of ion cyclotron PDI.
Summary

- Plasma current dependence on PDI threshold suggests the importance of the edge condition.

- On C-Mod, the PDI threshold is found to be: $\bar{n}_e/n_G \gtrsim 0.2$. This results in an $I_p$ dependence on the $\omega_0/\omega_{lh}$ scaling.

- At higher current, the PDI threshold $\omega_0/\omega_{lh}$ approaches to $\omega_0/\omega_{lh}$ found in Alcator C.

- Further investigations are necessary to understand mechanisms that lead to PDI onset at this density and role(s) of PDI on the observed loss of efficiency.

- It would be interesting to cross-examine SOL conditions across multiple machines.