Lower Hybrid Current Drive Experiments at Reactor-Relevant Densities on Alcator C-Mod


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

41th European Physical Society, Berlin, Germany
June 23 -27, 2014
Introduction: Lower hybrid current drive (LHCD) can drive non-inductive toroidal current to realize steady-state tokamak operation with high bootstrap current fraction (> 50 %).

- The momentum and energy of RF waves can be transferred to electrons via Landau damping.\(^1\)

- Landau damping accelerates electrons with \(v \approx \frac{\omega_0}{k_{||}}\),

- The resulting asymmetric resistivity can contribute efficient current drive.

- Lower Hybrid Current Drive (LHCD)
  - LH wave: Electrostatic wave in the frequency range: \(\Omega_{ci} \ll \omega_0 \ll \Omega_{ce}\)
  - \(\omega_0 \sim 3-5 \times \omega_{lh}\), with small \(k_{||}\)
  - Known to be the most efficient in driving plasma current

LHCD can supplement bootstrap current to operate tokamaks non-inductively.

\(^{1}\)N. J. Fisch, PRL\(45\), 720 (1980)
**LHCD experiment on C-Mod conditions are relevant to ITER and future reactor regimes in terms of magnetic field and densities.**

<table>
<thead>
<tr>
<th>ITER relevant parameters</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>5.4</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
However, unlike in ITER, LH waves can reach HFS edge on the first pass in Alcator C-Mod high density plasmas due to weak Landau absorption.

In C-Mod, Landau absorption relies on toroidal and poloidal up-shifts of $n_{||}$ in multiple passes

- Rays with low $n_{||}$ suffers from inaccessibility conditions and edge collisional absorption can lead to lower current drive efficiency.

- These imply that edge parasitic loss mechanisms can play a role in lowering efficiency.$^{1,2,3}$

---


$^{1}$G. Wallace, PoP 17, 082508 (2010)


$^{3}$S. G. Baek, 54th APS-DPP Meeting (2013)
Motivation: Understanding anomalous loss of lower hybrid current drive efficiency \( \eta \) in multi-pass regimes above \( \bar{n}_e = 1 \times 10^{20} \text{ m}^{-3} \) is critical in realizing reactor-relevant steady-state tokamak operations.

- Above \( 1 \times 10^{20} \text{ m}^{-3} \), current drive effects greatly diminish.
- Simulations with the SOL can reproduce falloff in hard X-rays up to \( \bar{n}_e \approx 1 \times 10^{20} \text{ m}^{-3} \).
- When \( \bar{n}_e > 1 \times 10^{20} \text{ m}^{-3} \), simulations over-predict \( \eta \) and hard X-ray count rates.

Hypothesis: This density-dependent discrepancy has been postulated to be due to the onset of parametric decay instabilities for \( \bar{n}_e > 1 \times 10^{20} \text{ m}^{-3} \).

The following presents recent experimental studies conducted in reversed-field plasmas to further examine PDI in an extend density range up to \( \bar{n}_e \approx 1.4 \times 10^{20} \text{ m}^{-3} \) with \( n|| = 1.9 \).

---

Recent experiments examined the onset of configuration-dependent PDI in reversed configurations up to $\bar{n}_e \approx 1.4 \times 10^{20} \text{ m}^{-3}$.

- In the reversed field, both the toroidal magnetic field and plasma current is in the counter clockwise when viewed from the top of the C-Mod tokamak.

- These experiments complement previous experiments during the 2012 campaign.$^1$

- $B_{t0} = 5.4 \text{ T}$
- $I_p = 500 \text{ kA}$
- $\bar{n}_e \approx 0.8-1.4 \times 10^{20} \text{ m}^{-3}$
- $T_{e0} \approx 2 \text{ keV}$
- Peak $n_{||} = 1.9$
- USN, LSN, DN

$^1$ S. G. Baek, 54th APS-DPP Meeting (2013)
Another goal of the recent experiments was to examine the observed configuration-dependent ion cyclotron PDI at the HFS edge.

- In the 2012 campaign with the forward field, ion cyclotron PDI that are excited at the HFS edge was clearly observed in LSN plasmas.

- SOL (scrape-off-layer) poloidal and toroidal variations (of densities and temperatures) could have resulted in different wave propagations, particularly in weak single-pass absorption regime.

- LSN plasmas in the forward-field correspond to USN plasmas in the reversed-field configuration.
Internal RF probes are used to study LH waves at multiple locations of the Alcator C-Mod tokamak.

Probe location (Poloidal View)  Probe location (Top View)

In addition, a RF loop antenna is placed at the outside of the machine to examine PDI magnetic components.
Three magnetic configurations (USN, LSN, and DN) are made to identify PDI characteristics in different configurations.

- **Summary of experimental results**
  - Regardless of configurations, for $\bar{n}_e \rightarrow 1.4 \times 10^{20} \text{ m}^{-3}$, PDI shows ion-cyclotron LH sidebands that are excited at the LFS edge.
    - LFS PDI are consistent with previous observations on limited tokamak.\(^1\)
  - However, ion cyclotron PDI at the HFS edge was observed to be much intense in USN plasmas at $\bar{n}_e \approx 1.0 \times 10^{20} \text{ m}^{-3}$, consistent with previous observations during the 2012 campaign.\(^2\) However, we have cases that LSN plasmas exhibit HFS PDI.

\(^1\)Y. Takase, Phys. Fluids 28, 983 (1985)
\(^2\)S. G. Baek, 54th APS-DPP Meeting (2013)
Note that, regardless of configurations, anomalous decline of hard X-ray count rates are observed as a function of $\bar{n}_e$.

- Steep decline of current drive effects are observed, regardless of magnetic configurations

- DN plasmas exhibit slightly higher HXR count rates than single-null plasmas
  - Consistent with previous observations\(^1\)

- Ion cyclotron PDI is observed above $\bar{n}_e \approx 1.0\times10^{20}$ m\(^{-3}\), suggesting that PDI is, at least, correlated to loss of current drive efficiency.

\(^1\)G. M. Wallace, PoP, 19, 062505 (2012)
USN plasmas exhibit ion cyclotron PDI that are excited at the HFS edge at $\bar{n}_e \approx 1.1 \times 10^{20} \text{ m}^{-3}$, but ion cyclotron LFS PDI becomes intense at $\bar{n}_e \approx 1.4 \times 10^{20} \text{ m}^{-3}$.

$\omega_{ci} \sim 60 \text{ MHz}$  
30 MHz

<table>
<thead>
<tr>
<th>$\bar{n}_e = 0.9 \times 10^{20} \text{ m}^{-3}$</th>
<th>$\bar{n}_e = 1.1 \times 10^{20} \text{ m}^{-3}$</th>
<th>$\bar{n}_e = 1.4 \times 10^{20} \text{ m}^{-3}$</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1" alt="Launcher" /></td>
<td><img src="image2" alt="Launcher" /></td>
<td><img src="image3" alt="Launcher" /></td>
</tr>
<tr>
<td><img src="image4" alt="Inner Wall" /></td>
<td><img src="image5" alt="Inner Wall" /></td>
<td><img src="image6" alt="Inner Wall" /></td>
</tr>
<tr>
<td><img src="image7" alt="Loop" /></td>
<td><img src="image8" alt="Loop" /></td>
<td><img src="image9" alt="Loop" /></td>
</tr>
</tbody>
</table>

As $\bar{n}_e$ increases, ion cyclotron PDI at the LFS dominate LH frequency spectra.

- The RF loop antenna is not as sensitive as the inner wall probe in detecting HFS PDI. However, it is sensitive in measuring sidebands excited at the LFS edge. (It detects sidebands even when the launcher probe do not detect any.)
In LSN plasmas, probes typically detect sidebands that are downshifted by ~30 MHz from the pump, consistent to those observed in forward-field USN plasmas.

- LSN plasmas exhibit stronger ion cyclotron PDI that are excited at the LFS edge than USN plasmas and no apparent HFS PDI are observed in this case.

☐ LSN plasmas exhibit stronger ion cyclotron PDI that are excited at the LFS edge than USN plasmas and no apparent HFS PDI are observed in this case.
Different PDI characteristics in between LSN and USN plasmas at $n_e \approx 1.1 \times 10^{20} \text{ m}^{-3}$ are thought to be due to different SOL characteristics. E.g., LSN and USN plasmas show different densities measured with upper-divertor probes.

- E.g., higher SOL densities in USN plasmas are observed with the 12th and 14th probes than those in LSN plasmas.
  - In the reversed-field, LH waves propagate towards the upper-divertor region on the first pass.

- These imply different SOL density variations might have affected how LH waves propagate at plasma edges. However, it is not clear at the moment how SOL density variations result in different PDI characteristics.
A complicated role of the SOL is further supported by ray-tracing simulations at $n_e \approx 1.2 \times 10^{20}$ m$^{-3}$, which do not exhibit apparent differences in ray-trajectories in core plasmas between USN and LSN plasmas.

- Ray-tracing/Fokker-Planck simulations using a GENRAY/CQL3D package
  - Different magnetic equilibria
  - Same density and temperature core profiles for $n_e \approx 1.2 \times 10^{20}$ m$^{-3}$

- Power loss due to collisional damping are observed in both cases.

- Rays upshift after reflections at the inner-wall, somewhat consistent with full-wave simulations.

- Rays become much spatially-broadened in USN plasmas, which may reduce convective losses at the HFS edge that could lead to much favorable conditions PDI at the HFS PDI.
In addition, HFS PDI can be observed in a LSN plasma with slight different magnetic shape, suggesting the importance of edge parameters on PDI excitation.

These observations suggest that ion cyclotron PDI at the HFS are inherent in weak single-pass absorption regime.

- At the HFS, $\omega_0/\omega_{lh}$ is lower than that at the LFS due to higher magnetic field.

- $B_{t0} = 5.4$ T

- $I_p = 500$ kA

- $n_e \approx 0.85 \times 10^{20}$ m$^{-3}$
DN Plasmas show weaker HFS PDI for the given $\bar{n}_e \approx 1.1 \times 10^{20} \text{ m}^{-3}$. At higher densities, LH spectra are dominated by ion cyclotron PDI excited at LFS.
Onset of ion cyclotron PDI above $\bar{n}_e \approx 1.0 \times 10^{20} \text{ m}^{-3}$ appears to be correlated with loss of current drive efficiency.

Both pump and sideband power at HFS starts to decrease above $\bar{n}_e \approx 1.2 \times 10^{20} \text{ m}^{-3}$. USN and DN plasmas exhibit similar trends.
Observed pump peak power intensities decrease as a function of $\bar{n}_e$, when measured away from the launcher.

- E.g., the left bottom two panels show pump peak power measured with the inner-wall probe and outer divertor probe decreases as a function of $\bar{n}_e$.
- Pump peak power at the inner wall maintains its strength up to $\bar{n}_e \approx 1.2 \times 10^{20} \text{ m}^{-3}$.
- A number of mechanisms could contribute to this observations:
  - Accessibility and change of wave propagations
  - Parasitic loss mechanisms (collisional damping, wave absorption due to diffraction effects, PDI...)
- These data suggest that Landau absorption should not be relied on geometric $n_\| \uparrow$ up-shift via multi-passes and strong single pass absorption is necessary.
Another off-midplane launcher (LH3)\(^1,2\) is designed in Alcator C-Mod in order to enhance the single pass absorption rate at high densities.

- This launcher will double the available net power to 2 MW.
- It will also enhance the single-pass absorption rate (80\%) at \(\bar{n}_e \approx 1.5 \times 10^{20} \text{ m}^{-3}\) by optimizing phase space interactions with the existing launcher.
  - If successful, ITER-relevant non-inductive regimes with high bootstrap fraction will be demonstrated for the first time.

---

\(^1\)G. M. Wallace, Nucl. Fusion 53, 073012 (2013)

\(^2\)S. Shiraiwa, Nucl. Fusion, 53, 113028 (2013)
Even in strong single pass regimes, one of two remaining questions is how well the observed spectra represent PDI processes that actually occur within plasmas.

- For fixed density and temperature, growth rates increase with $n_\parallel$ of the low-frequency ion mode.
- The observed spectra is peaked at the first harmonic, suggesting that responsible $n_\parallel$ of ion-modes is not likely to high enough.
- However, we may not be able to detect sidebands with high $n_\parallel$ (and higher growth rates) because those sideband LH waves might not be able to propagate toward probe tips due to Landau damping.
Another question is the significance of ion sound PDI and ion cyclotron PDI that are excited on the first pass.

- E.g., FTU\textsuperscript{1} reports that ion sound PDI near the launcher can degrade current drive efficiency.

- No clear experimental evidence is found on Alcator C-Mod whether ion sound PDI plays an important role in understanding loss of efficiency.
  - E.g., C-Mod data indicates that pump broadening is observed to be severe when measured away from the launcher.

- Quantitative estimation of pump power loss due to PDI at the LFS will be possible in single-pass regime, because collisional loss and diffraction effects become severe after reflections at the inner wall.

\textsuperscript{1}R. Cesario, Nature Comm, 1 (2009), 55
These questions will be examined with new magnetic probe measurements, which will allow examining the role of PDI occurring on the first-pass.

- The probe head, that houses 6 RF loop antenna and 1 Langmuir probe are under design.
- Two Rows of 3 RF loop antenna will allow measuring not only frequency spectra but also wavenumber spectra and polarization of LH waves.
- Design and fabrication is under progress.
Conclusion: To recover LHCD efficiency, strong single-pass absorption of LH wave is planned to be examined on Alcator C-Mod.

- Ion cyclotron PDI is observed to be excited above $\bar{n}_e \approx 1.0 \times 10^{20} \text{ m}^{-3}$.
  - PDI can occur at the HFS in multi-pass regimes.
  - Regardless of magnetic configurations, ion cyclotron PDI is excited at the LFS edge well above $\bar{n}_e \approx 1.0 \times 10^{20} \text{ m}^{-3}$.
  - However, quantitative analysis (e.g., amount of power loss due to PDI) is not possible at the moment.

- Measured pump peak power away from the launcher decreases as a function of $\bar{n}_e$.
  - Implies that Landau absorption should be occurred on the first pass, in order to suppress possible edge parasitic loss mechanisms, including collisional loss, diffraction effects, ionization, and PDIs.

- C-Mod is currently developing additional off-midplane launcher that will enhance single pass absorption rate up to 80%.

- New magnetic probe experiments will allow studying PDI occurring near the launcher.