Efficient Lower Hybrid Current Drive in Alcator C-Mod High Density Plasmas


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Result and Implication

- **Motivation:** A tokamak need an external means to sustain plasma current for steady-state operation.
  - Lower hybrid current drive (LHCD) is the most efficient process with mature engineering advance.

- **Challenge:** Loss of LHCD efficiency at high density, which is attributed to parasitic losses occurring in the scrape-off-layer (SOL)

- **New Result:** Demonstration of LHCD at $\bar{n}_e > 10^{20} \text{ (m}^{-3})$ in a diverted plasma
  - Achieved in a narrow SOL with an increase in $I_p$

- **Implication:** High-field-side launch in a double null configuration is expected to minimize parasitic edge rf interactions in a reactor.
LHCD on C-Mod allows accessing reactor-relevant steady-state tokamak operation.

Simulated Current Density Profile

Simulation Parameters

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<td>60 – 70 (%)</td>
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<td>P_{LH}</td>
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<tr>
<td>(\beta_n)</td>
<td>2.5 - 3</td>
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Alcator C-Mod LHCD system operates at reactor-relevant conditions.

LHCD operation at \(\bar{n}_e > 1 \times 10^{20} \text{ m}^{-3}\) is critical to achieve high bootstrap fraction (> 50%) accessing advanced tokamak operation.

\(^{1}\)P. T. Bonoli, NF 40, 1251 (2000)
Fully non-inductive plasmas\textsuperscript{1,2} are demonstrated at $\bar{n}_e \approx 0.5 \times 10^{20}$ m\textsuperscript{-3}.

- Target $I_p = 600$ kA (to maximize the fraction of non-inductive current)
- Zero loop voltage plasma
- Bulk heating effect
- Engineering efficiency: $\frac{\bar{n}_e I_{LH} R}{P_{LH}} = 0.25 \times 10^{20}$ A/m\textsuperscript{2}/W
  - Consistent with those expected on ITER.

\textsuperscript{1}Shiraiwa, NF 53, 113028 (2013)
\textsuperscript{2}Bonoli, PoP 15, 056117 (2008)
At high density, the anomalous loss of current drive efficiency is observed.

- The hard X-ray count rates, a proxy for fast electron population, rapidly falls off without CD and heating effects\(^1\).

- Large discrepancy between the simulation result and the experiment.
  - Initial model did not allow wave propagation to the SOL.
  - Interaction of the wave with the boundary plasma is missing!

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\(^1\)Wallace PoP 17, 082508 (2010)
Divertor operation worsens the “LH density limit” problem.

- A frequency scaling of “LH density limit” based on the onset of parametric decay instabilities (PDI)\(^1\) at \(\omega_0/\omega_{LH} \rightarrow 2\)

  \(\leftrightarrow\) C-Mod shows a loss of efficiency at a lower density (\(\omega_0/\omega_{LH} < 4\)).

- FTU demonstrates improved LHCD\(^2\) with the rise in edge \(T_e\) (from \(T_{e,95} = 40\) eV to 80 eV)
  - A circular machine with a limiter
  - Wall-conditioning & fueling-control

  \(\leftrightarrow\) Raising \(T_{ped}\) upto 1 keV on C-Mod results in a modest increase in LHCD.

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At high density, a prompt wave power deposition near the LCFS in a diverted configuration.

- Wave power is deposited near the separatrix in a fast time scale ($t < \tau_E$).

- At high density, most of the input LH power is conducted to the diverotor or radiated.

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1Faust, PoP 23, 056115 (2016)
Four edge-damping mechanisms are identified.

- **Electron-ion collisions**\(^1\) can be significant in a cold, dense plasma near the divertor.

- **\(n/I\)-upshifts**\(^2\) after the reflection at the inner wall, causing edge power damping
  
  Meneghini, MIT Phd Thesis (2013)

- **Parametric decay instabilities** are intensified\(^3\) above \(\overline{n}_e \approx 10^{20} \text{ m}^{-3}\).
  
  Baek, NF 55, 043009 (2015)

- **Wave Scattering by turbulence**\(^4\)

  Andrew and Perkins, PoF 26, 2546 (1983)

  Martin, this conference EX/8-2

\(1\) Wallace, PoP, 17, 082508 (2010)

\(2\) Shiraiwa, AIP Conf. 1689, 030016 (2015)

\(3\) Meneghini, MIT Phd Thesis (2013)

\(4\) Baek, NF 55, 043009 (2015)
At fixed $\bar{n}_e$, the increase in $I_p$ minimizes the SOL width and turbulence level there.

- At fixed $\bar{n}_e$, the SOL density profile is a function of Greenwald fraction $^{1} \bar{n}_e/n_G$ where $n_G = I_p/\pi a^2$.

- The decrease in convective particle SOL flux $^{2}$ above $\bar{n}_e/n_G < 0.2$ can decrease the scattering events.

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$^{1}$LaBombard, PoP 15, 056106 (2008)

$^{2}$LaBombard PoP 8, 2107 (2001)
At high $I_p$ (low $\bar{n}_e/n_G$), the interaction of the wave with the boundary is suppressed.

The PDI onset is delayed toward a higher line-averaged density\textsuperscript{1}.

- Pump peak power measured at the inner wall side maintains its strength at high $I_p$\textsuperscript{1}.

\textsuperscript{1}Baek, NF 55, 043009 (2015)
At $I_p = 1.4$ MA, parasitic wave interactions are suppressed up to the core accessibility limit ($\bar{n}_e \approx 1.5 \times 10^{20}$ m$^{-3}$)

- Absence of the sidebands
  - PDIs are suppressed
  - In line with the PDI convective growth rate analysis

- Minimized pump broadening
  - Wave scattering is weakened.

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

\[I_p = 0.55 \text{ MA}\]

\[\bar{n}_e/n_G = 0.36\]

\[\bar{n}_e = 1.4 \times 10^{20} \text{ m}^{-3}\]

\[I_p = 1.4 \text{ MA}\]

\[\bar{n}_e/n_G = 0.15\]
At a low Greenwald fraction, recovery in CD efficiency is observed.

\[ \frac{\Delta V}{V} \approx 0.2 \text{ for the input power of 600 kW} \]

• In line with the low-density experimental result

\[ \eta_0 \approx 2.5 \times 10^{19} \text{ AW}^{-1} \text{m}^{-2} \]

\[ \bar{n}_e = 3.5 - 7 \times 10^{19} \text{ m}^{-3} \]

\[ P_{\text{LH}} = 120 - 830 \text{ kW} \]

\[ I_p = 500 \text{ & } 700 \text{ kA} \]
Improvement in the hard X-ray production rate is observed in a low Greenwald fraction plasma.

• The GENRAY/CQL3D calculation with a simple SOL model is in reasonable agreement with the experimental result.

• In a low current plasma, the model over-predicts the X-ray level, requiring additional loss mechanisms\(^1\).

• LHCD on the Alcator C tokamak\(^2\) exhibited a similar level of efficiency at high density.

\[\text{Importance in the control in the SOL plasma in a divertor configuration!}\]

\(^1\)Wallace PoP 17, 082508 (2010)
\(^2\)Porkolab, PRL 53,450 (1984)
Implication: Low-field-side launch at high Greenwald fractions (> may not be favorable due to strong wave scattering.

- Tore Supra\textsuperscript{1} and FTU\textsuperscript{2} operates at $\omega_0/\omega_{LH}$>4 without the PDI onset, yet a steep decrease in the HXR production rate is observed.

- Operation at a high Greenwald fraction (~1) may lead to strong wave scattering events.

\textsuperscript{1}Goniche, NF 53, 033010 (2013)
\textsuperscript{2}Cesario, Nat. Comm. 1, 55 (2010)
High-field-side SOL may be an optimum place to eliminate wave-edge interactions.

- Wave scattering by PDI and turbulence is expected to be minimized at the HFS SOL.
- Coupling will remain stable.
- Improved core wave physics is expected with HFS launch\(^1\).
- HFS LHCD experiment on DIII-D can test key physics issues associated with the first-pass loss.

\(^1\)Bonoli, NF (in-press)
Extra
HFS LHCD experiment on DIII-D can test key physics issues associated with the first-pass loss.

- A strong single pass is expected with the HFS LHCD (reactor condition).
- Collision and PDI is expected to be negligible.
- Effects of wave scattering can be examined with a magnetic balance control.

Design Parameter (see also FIP/3-3 by Wallace)
- Coupler top at the mid plane
  - 2 MW with 8 modules
  - Directivity: 51%
  - 40 MW/m²
- Standard WR187 waveguide (1”x2”) is routed under cryopump, divertor shelf and floor tiles.
- Scheduled to begin operation in FY21 (Oct 2020 -)

HFS LHCD Launch Design on DIII-D
Wukitch, EPJ Web of Conf. 157, 02012 (2017)
**Alcator C-Mod LHCD system operates at reactor-relevant condition.**

<table>
<thead>
<tr>
<th></th>
<th>C-Mod</th>
<th>ITER</th>
</tr>
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<tbody>
<tr>
<td>$f_0$ (GHz)</td>
<td>4.6</td>
<td>5</td>
</tr>
<tr>
<td>$n_\parallel$</td>
<td>~2</td>
<td>~2</td>
</tr>
<tr>
<td>$(10^{20} \text{ m}^{-3})$</td>
<td>0.5~1.5</td>
<td>~ 1</td>
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<tr>
<td>$B_T$ (T)</td>
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<td>5</td>
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<tr>
<td>Magnetic Configuration</td>
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<td>LSN</td>
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<td></td>
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<td>LH wave propagation</td>
<td>Multi-pass</td>
<td>Single-pass</td>
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<tr>
<td></td>
<td>Regime</td>
<td>regime</td>
</tr>
<tr>
<td>SOL Distance</td>
<td>~ 2 cm</td>
<td>~ 20 cm</td>
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LH grill antenna on C-Mod
Goal: Use of LHCD to supplement bootstrap current to demonstrate ITER-relevant steady-state tokamak operation for $t \gg \tau_{\text{CR}} \approx 200$ msec.

- Scoping study\(^1\) for Alcator C-Mod shows that LHCD operation at $n_e > 1 \times 10^{20}$ m\(^{-3}\) is critical to achieve high bootstrap fraction (> 50%), which will enable advanced scenario operation.

**Simulated Current Density Profile\(^1\)**

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\(^{1}\)P. T. Bonoli, Nucl. Fusion **40**, 1251 (2000)
Parasitic wave interactions at the plasma boundary are largely suppressed at high current.

- Ion cyclotron PDIs are suppressed, in line with the convective analysis.

- Pump broadening is also reduced, implying wave scattering by turbulence\(^1\) is reduced.

\(^1\)Andrews and Perkin, Phys. Fluids 26, 2546 (1983)
Fully non-inductive plasmas are demonstrated at $\bar{n}_e \approx 0.5 \times 10^{20}$ m$^{-3}$.

Zero-loop voltage! (Ip = 600 kA)

Engineering Efficiency:

$$\frac{n_e I_p R}{P_{LH}} = 0.25 \times 10^{20} \text{A/m}^2/\text{W},$$
consistent with those expected on ITER.

ITER will operate at $\bar{n}_e \approx 0.9 \times 10^{20}$ (m$^{-3}$).

Shiraiwa, NF (2013)
At high density, there is no signatures of current drive.

- LH density limit @ $n_e \approx 1.0 \times 10^{20} \text{ (m}^{-3}\text{)}$
Parametric instabilities are also excited at the high-field-side...

- Strong sidebands separated from the pump wave by $\omega_{ci}$ that is characteristic of the high-field-side (inboard) of the tokamak.

- $\bar{n}_e \approx 1.0 \times 10^{20} \text{ (m}^{-3})$

- This PDI onset away from the launcher is not problematic in a reactor.

Baek, PPCF 5, 052001 (2013)
The growth rate spectrum calculated with the PDI dispersion relation is qualitatively in agreement with the observation.

- Growth rates are found from the PDI dispersion relation\(^1,2,3\)

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

\[\gamma \sim \mu^2 \sim |E_\perp|^2 \sim \sqrt{n_e}\]

- The most unstable region is found to be near the LCFS.

- PDI may be one mechanism that can result in edge damping, lowering or eliminating current drive efficiency.

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\(^1\)Porkolab, Phys. Fluids, 20, 2058 (1977)
\(^3\)Baek, PoP 21, 061511 (2014)
Pump broadening at high density is correlated with an increase in the outward radial particle flux.

- A broadened spectrum around the 4.6 GHz is observed at high density.

- The increased convective particle SOL flux above $\bar{n}_e/n_G > 0.2$ can increase the scattering events and smear the wave-field, leading to a different $n_{//}$ spectrum compared to the launched $n_{//}$ spectrum*.

Bonoli, Phys. Fluids
Key innovation is high-field-side LHCD launch\(^1\).

- Quiescent and steep HFS SOL profiles will allow coupler next to plasma with good coupling.
- HFS LHCD significantly improves core wave physics.
- If proves to be successful, it may solve many of the LHCD challenges.
- Work on-going at the PSFC to install a LHCD antenna on DIII-D.
- KSTAR could be another important testbed for HFS LHCD.

\(^1\)Bonoli, APS 2016
Effect of plasma turbulence to the LH waves?

Frequency Spectrum w/ Probe Outside V.V.

B-dot probe array on EAST
Goal: Use of LHCD to supplement bootstrap current to demonstrate ITER-relevant steady-state tokamak operation for $t \gg \tau_{CR} \approx 200 \text{ msec}$.

- Scoping study\(^1\) for Alcator C-Mod shows that LHCD operation at $\bar{n}_e > 1 \times 10^{20} \text{ m}^{-3}$ is critical to achieve high bootstrap fraction ($> 50\%$), which will enable advanced scenario operation.

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\(^1\)P. T. Bonoli, Nucl. Fusion 40, 1251 (2000)
Wave scattering by turbulence may be an issue in a reactor at the LFS \((n_e/n_G > 0.6)\)

- PDI onset condition is generally correlated with the loss of efficiency.

- But, on Tore Supra\(^1\) and FTU\(^2\), a steep decrease in the X-ray level is observed with \(\omega_0/\omega_{LH} > 4\).

\(^1\)Goniche, NF 53, 03310 (2013)
Broadening of wave power deposition is observed at a high current.

- Less peaked profile in a high current plasma
  - Generally attributed to the increase in core temperature and poloidal up-shift
  - Our experiments suggest it may also due to the weakening of the deleterious wave-edge interactions.

- A peaked HXR profile in a low current plasma
  - Attributed to the modification in the launched spectrum due to wave-edge interactions
  - In line with our observations
  - More comparison with the model is necessary.
Multi-Junction Module Proposed

- Single wave-guide module will deliver 250 kW.
  - 2 MW with 8 modules
  - Directivity is 51 %
  - 40 MW/m²

- Toroidal split is by a six-way split (bi-junction, followed by tri-junction)

- Poloidal split is by a four-way splitter.

- Waveguide dimension: 47 mm x 7mm

A. Seltzman