Effects of lithiation and wave frequency on the efficiency of lower hybrid current drive on EAST

S. G. Baek, G. M. Wallace, P. T. Bonoli (MIT PSFC)
W. Choi, F. Poli, S. Shiraiwa (PPPL)

10th US-PRC Magnetic Fusion Collaboration Workshop
March 22-26, 2021
Motivation

• Lower hybrid current drive (LHCD) is known for its high efficiency for generation of off-axis non-inductive current and for current-profile control.

• Interactions of RF waves with the boundary plasma play a critical role to understand RF physics.

• Anomalous loss of CD efficiency at high density\textsuperscript{1,2,3}
  • Identify an approach to mitigate and control parasitic losses at the plasma boundary.

• EAST is equipped with two LHCD systems at 2.45 and 4.6 GHz with availability of lithium wall conditioning.
  • Can we extend effective LHCD with lithiation?
  • Is there a frequency dependence?
  • Can we quantify the amount of wave power absorption?
    • Useful for the construction of the control-level LHCD database

Baek et al, NME 26, 100955 (2021)

\textsuperscript{1}Wallace et al, PoP 17, 082508 (2010)
\textsuperscript{2}Cesario et al, Nat. Comm. 1, 55 (2010)
\textsuperscript{3}Ding et al, NF 53, 113027 (2013)
MIT is supporting development of an 8 RF B-dot probe array installed next to the 4.6 GHz LH antenna.

- Installation of the 8 probes in a row allow deducing wave $n_{\parallel}$.
- The $n_{\parallel}$ identified agrees with the imposed $n_{\parallel}$ at the antenna at low density.
- Wave-SOL interactions on the first-pass will be investigated.

Wang et al, RSI 91, 073502 (2020)
The experiments examined the interactions of LH waves with the boundary plasma under lithium wall conditioning.

- Lithium wall conditioning on EAST lowers the SOL turbulence and density.
  - Expected to minimize parasitic wave-SOL interactions

- On EAST, two LHCD systems at 2.45 GHz and 4.6 GHz with $I_p$ scan allow accessing a wide range of $f_G$ and $\omega_0/\omega_{LH}$ (representative of PDI strength)
Lithiation mitigates the fast fall-off of the hard X-ray emission rates and suppress parasitic losses for 2.45 GHz.

- HXR emission is an indicative of fast electron populations generated by LH waves.

- HXR emission is significantly increased for the 2.45 GHz case with lithiation.

- Experimental indications of parasitic losses are observed for \( \bar{n}_e > 3 \times 10^{19} \text{ m}^{-3} \) (vs. \( 2 \times 10^{19} \text{ m}^{-3} \) without lithiation)

Huang et al, PPCF (2020)
High-density, high-current (700 kA) operation on EAST broadens current profile and increases the off-axis HXR count rates.

- $l_i$ decreases from 1.5 to 1. (300 kA -> 700 kA)
- May be ideal for developing scenarios with ICRF at high density
- New experiment is proposed to EAST for upcoming campaign
With lithiation, LH heating and current drive are extended to high density.

- A comparable drop of loop voltage by \(~ 0.3\) V is observed for both 2.45 GHz (1.5 MW) and 4.6 GHz (1.1 MW).
  - LH plasma heating accounts for 70% of the loop voltage change.
  - The remaining change of \(< 0.1\) V (\(< 60\) kA) is from current drive.

- A typical discharge at a density of \(~ 4 \times 10^{19} \text{ m}^{-3}\) would exhibit a complete loss of current drive efficiency with a use of 2.45 GHz.
Power absorption to the confined plasma at 2.45 GHz is ~60% of that at 4.6 GHz.

- Wave power absorption coefficient, $\alpha$, is from two expressions for the confinement time
  - $\tau_{\text{exp}} = \frac{W}{P_{\text{tot}}}$
    - $W$: plasma stored energy
    - $P_{\text{tot}} = P_{\text{oh}} + \alpha P_{\text{LH, injected}}$
  - $\tau_{\text{scaling}} = \tau_{\text{oh}} \times (P_{\text{tot}}/P_{\text{oh}})^{-0.5}$
    - $\tau_{\text{oh}}$: the ohmic reference $\tau$ without LH power

<table>
<thead>
<tr>
<th>Power Dependence</th>
<th>$\alpha$ (4.6 GHz)</th>
<th>$\alpha$ (2.45 GHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P^{-0.5}$</td>
<td>0.57</td>
<td>0.36</td>
</tr>
</tbody>
</table>

1 P.N. Yushmanov et al, NF 30, 1999 (1990)
Increased levels of parasitic power damping is observed at 2.45 GHz for $\bar{n}_e > 3 \times 10^{19} \text{ m}^{-3}$.

- LHCD at 2.45 GHz loses its efficiency faster than that at 4.6 GHz, as indicated by a higher voltage.
- RF ionizations are observed near and away from the antenna.
  - The electron density measured at the launcher surface increases strongly.
  - Simultaneously, $D_\alpha$ emission near the X-point increases strongly.
- LHRF power at 2.45 GHz may induce an earlier divertor transition\textsuperscript{1,2}, possibly due to power damping in the plasma periphery
  - Can result in the increased levels of collisional loss

\textsuperscript{1}Niemczewski et al, NF 37 151 (1997)
\textsuperscript{2}Meng et al, PPCF 62 065008 (2020)
Onset of parametric decay instabilities (PDI) is correlated with the rise in the launcher density.

- Ion cyclotron PDIs are excited in the 2.45 GHz case only
- In line with the PDI model that predicts higher growth rates at a lower frequency\(^1\)
- A control of the launcher density is critical to suppress the onset of decay instabilities.

Inclusion of SOL plasma in the model can match the experimental power absorption coefficient.

- GENRAY/CQL3D ray-tracing\textsuperscript{1}/Fokker-Planck\textsuperscript{2} code
- The scrape-off-layer model assumes the exponential decay outside the LCFS.
  - The SOL decay length is a free parameter.
  - Collision is a only power-loss mechanism.

<table>
<thead>
<tr>
<th></th>
<th>$\alpha$ (4.6 GHz)</th>
<th>$\alpha$ (2.45 GHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exp</td>
<td>0.57</td>
<td>0.36</td>
</tr>
<tr>
<td>Model</td>
<td>0.63</td>
<td>0.36</td>
</tr>
</tbody>
</table>

- The lower power absorption coefficient at 2.45 GHz is attributed to the lower cut-off density($\sim \omega^2$), leading to enhanced collisional power damping.

\textsuperscript{1}Smirnov and Harvey, Bull. Amer. Phys. Soc. 40,1837 (1995)
\textsuperscript{2}Harvey and McCoy, US DCO NITS Docu. No. DE93002962
Power absorption coefficient evaluated provides a guidance on effective wave power absorption.

- A potential role of turbulent wave scattering in LHCD is being studied on EAST.
  - Four well-diagnosed non-inductive H-mode discharges by A. Garofalo NF 57, 076037 (2017).
  - Identified an optimum rotation angle (+40 deg) of the perpendicular wave-vector that can reproduce experimental profiles, possibly due to wave scattering.
- Results will used to construct a simulation database of LH power deposition and current drive in EAST (Bonoli, Thursday).
Summary

• Highlights
  • Effective LHCD is extended to high density under lithium wall conditioning (lithiation).
  • Experimental evidence of LH power loss in the scrape-off-layer/divertor plasma is characterized.
  • Frequency-dependent wave power absorption is evaluated using the confinement time scaling law.
  • The experimental power absorption coefficient was reproduced in the ray-tracing /Fokker-Planck model.
  • A potential role of turbulent wave scattering in LHCD is investigated on EAST

• Implication
  • Control of neutral and electron densities in front of the launcher may be a key to improve LHCD further.
Extra Slides
Lithiation is dominant over the change in Greenwald fraction in determining the SOL behavior.

- Frequency spectra at 2.45 GHz are shown here at a density level at which ion cyclotron PDIs are typically observed without wall conditioning ($\bar{n}_e \sim 2 \times 10^{19} \text{ m}^{-3}$).

- With lithium wall conditioning, frequency spectra (2.45 GHz) indicate no systematic response to the change in Greenwald fraction, unlike observations made on C-Mod.

- SOL is expected to be quiescent with lithium wall conditioning.
The 2-point SOL model may help accurately describe ray propagation in the divertor region.

- The model is based on the previous study done on C-Mod\(^1\).
- The model implies that the divertor SOL can provide a path for the rays to propagate to the cold and dense divertor, leading to additional power damping.
- We continue the modeling investigation at high density.

\(^1\)Shiraiwa, RFPPC (2015)
With the increase in the D-alpha signal and the PDI onset, nonthermal electron cyclotron emission (ECE) shows a rapid decrease.

- Effective wave power absorbed within the LCFS could be decreasing as the parasitic wave interactions become evident.
- A further investigation is needed to understand the different trend between the HXR and ECE measurements.
Power absorption to the confined plasma is lower at 2.45 GHz than at 4.6 GHz.

- Wave power absorption coefficient, $\alpha$, is evaluated by finding $\alpha$ that matches the experimental confinement time ($\tau_{\text{exp}}$) to the confinement time scaling law ($\tau_{\text{scaling}}$).

  \[ \tau_{\text{exp}} = \frac{W}{P_{\text{oh}} + \alpha P_{\text{LH}}} \]
  - $\tau$: energy confinement time
  - $W$: plasma stored energy

  \[ \tau_{\text{scaling}} = \tau_{\text{oh}} \times \left(\frac{P_{\text{tot}}}{P_{\text{oh}}}\right)^{-0.5} \]
  - $\tau_{\text{oh}}$: the ohmic reference $\tau$ without LH power
  - $P_{\text{tot}} = P_{\text{oh}} + \alpha P_{\text{LH}}$

<table>
<thead>
<tr>
<th>Scaling Law</th>
<th>$\alpha$ (4.6 GHz)</th>
<th>$\alpha$ (2.45 GHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P^{-0.5}$</td>
<td>0.57</td>
<td>0.36</td>
</tr>
<tr>
<td>$P^{-0.7}$</td>
<td>no solution</td>
<td>0.66</td>
</tr>
</tbody>
</table>

- No $\alpha$ is found for 4.6 GHz with the scaling law of $P^{-0.73}$, implying that the confinement time degradation may be weaker than $P^{-0.73}$ on EAST.
Lithiation is dominant over the change in Greenwald fraction in determining the SOL behavior.

- Frequency spectra at 2.45 GHz are shown here at a density level at which ion cyclotron PDIs are typically observed without wall conditioning ($\bar{n}_e \sim 2 \times 10^{19} \text{ m}^{-3}$).

- With lithium wall conditioning, frequency spectra (2.45 GHz) indicate no systematic response to the change in Greenwald fraction, unlike observations made on C-Mod.

- SOL is expected to be quiescent with lithium wall conditioning.

Wave Frequency Spectrum ($\bar{n}_e = 2.6 \times 10^{19} \text{ m}^{-3}$)

- $I_p = 300 \text{ kA}, f_G = 0.55$
- $I_p = 500 \text{ kA}, f_G = 0.33$
- $I_p = 700 \text{ kA}, f_G = 0.24$

**Minimal broadening at $f = 2450 \text{ MHz}$**

**Suppression of ion cyclotron PDIs at $f = 2435 \text{ MHz}$**