Investigation of lower hybrid wave polarization in WEST

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Theoretical studies [1] identified the potential for $k_\perp$ rotation to impact lower hybrid (LH) wave propagation and absorption, and recent experimental analysis [2] showed consistency between experimental LH current drive observations and modeling including $k_\perp$ rotation for Alcator C-Mod. Investigations on C-Mod indicate that rotation of $k_\perp$ may be due to scattering of the waves from density fluctuations [3, 4]. The DSELF diagnostic [5] on WEST [6] measures the LH wave electric field components (E_R, E_z, E_ϕ) near the antenna via dynamic Stark effect spectroscopy [5], which then constrains the angle of $k_\perp$ rotation used at the launch point of rays in the model ($\sim \arctan(E_z/E_R)$). Conventional ray-tracing of LH waves assumes $k_\perp$ to be normal to the flux surface at the starting point of the ray based on the poloidal mode number spectrum imposed by the antenna at the plasma edge. This rotation of $k_\perp$ impacts the up/down-shifts of $k_{||}$ as well as the ray trajectory itself, generally leading to broader deposition of the LH waves rather than a sharp peak at a particular radius. Simulations including $k_\perp$ rotation for WEST are presented in this work and compared with experimental hard X-ray and current drive data.

The Tungsten(**W**) **E**nvironment in **S**teady-state **T**okamak (WEST) experiment [6] relies on non-inductive LH current drive (LHCD) to sustain plasmas for long pulses as well as for additional electron heating of the core plasma. Two antennas, the fully-active multi-junction (FAM) and the passive-active multi-junction (PAM), operate at a frequency of 3.7 GHz and peak parallel refractive index $n_{||} = 2 \pm 0.3$ for the FAM (1.7 ± 0.3 for the PAM) [7]. The two antennas combine for up to 7 MW LHCD power.

Ray-tracing/Fokker-Planck simulations with GENRAY[8]/CQL3D[9] set the initial orientation of $k_\perp$ parallel to $\nabla\psi$ (*i.e.* $k_\perp = k_r$, where k_r is the minor-radial component of $\vec{k}$) for each ray by default, however the angle $\xi_{n\perp}$ between $k_\perp$ and $\nabla\psi$ is an input parameter. The default of $\xi_{n\perp} = 0^\circ$ is based on the antenna spectrum, which is designed to launch waves with no poloidal component of k. Although introducing finite $\xi_{n\perp}$ does not change $k_{||}$ at the point of the scattering event (the starting point of the ray in this study), $\xi_{n\perp}$ has a profound impact on the evolution of $k_{||}$ along the ray trajectory by introducing a non-zero poloidal mode number [1, 10, 11, 2].

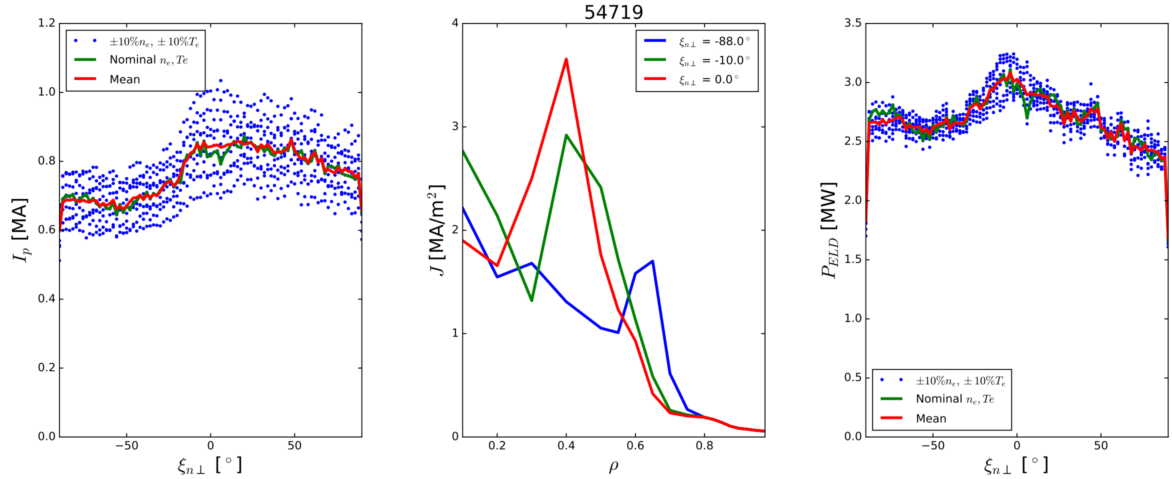

Figure 1: GENRAY/CQL3D simulation results for 54719. (left) Simulated plasma current as a function of $\xi_{n\perp}$. The scattered blue points represent $\pm 10\%$ variation in the n_e and T_e profiles used in the model, while the solid green curve represents simulations with the nominal kinetic profiles, and the solid red curve is the average. (center) Simulated current density profile for three values of $\xi_{n\perp}$ with nominal kinetic profiles. (right) Power absorbed by electron Landau damping (ELD) as a function of $\xi_{n\perp}$.

The **D**ynamic **S**tark **E**ffect **LH** **F**ield (DSELF) diagnostic on WEST is similar to diagnostics deployed previously on Tore Supra [5] and Alcator C-Mod [3] but with the addition of polarizers and other hardware upgrades to improve the accuracy of the measurement. DSELF provides a measurement of the radial and poloidal components of the LH wave electric field in the vicinity of the antenna, which constrains $\xi_{n\perp}$ for electrostatic LH waves:

$$|\xi_{n\perp}| \simeq \tan^{-1}\frac{|k_\theta|}{|k_r|} \simeq \tan^{-1}\frac{|E_\theta|}{|E_r|} \qquad (1)$$

where E_θ and E_r are the poloidal and radial components of the LH wave electric field. Note that the DSELF diagnostic can only determine the magnitude of $\xi_{n\perp}$; the sign of $\xi_{n\perp}$ remains ambiguous.

This paper focuses on two WEST discharges at similar line average density ($\bar{n}_e \sim 4.75 \times 10^{19}$ m^{-3}) and plasma current (0.5 MA). The first discharge, 54719, exhibits roughly twice as much hard x-ray (HXR) flux from fast electron bremsstrahlung as the second discharge, 54582. 54719 also has a significantly higher core electron temperature (3 keV vs 1.1 keV). Significant (3,1) MHD mode activity at 2.3 kHz may be responsible for the poor energy confinement of 54582. Measurements from DSELF put the value of $|\xi_{n\perp}|$ at $\sim 10^\circ$ for 54719 and $\sim 50^\circ$ for 54582. The MHD activity may also be responsible for the larger value of $\xi_{n\perp}$ in 54582 due to increased density and/or density fluctuations in the edge and scrape-off-layer (SOL) regions, but this hypothesis remains to be tested.

Figures 1 and 2 summarize a parametric scan of $\xi_{n\perp}$ with GENRAY/CQL3D for these dis-

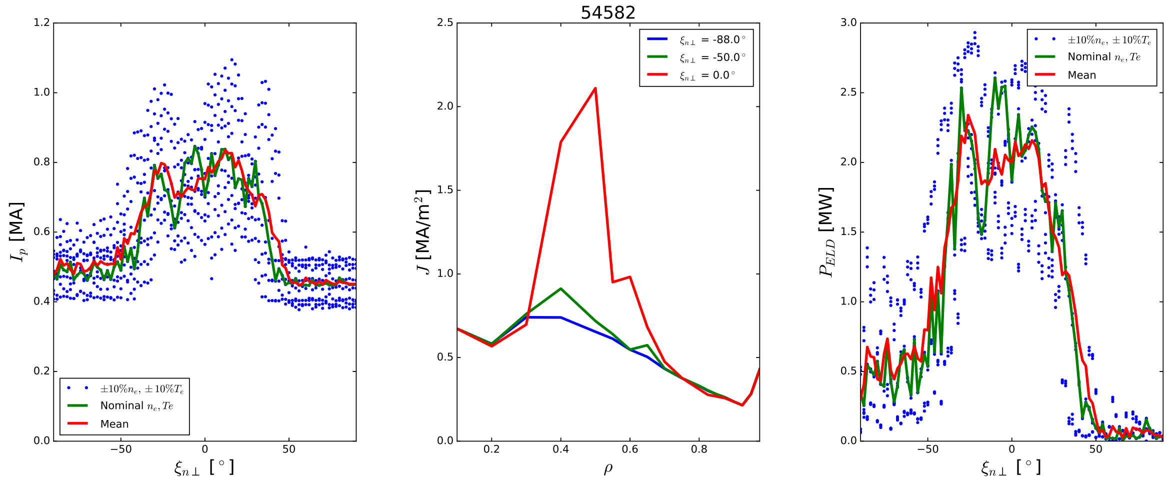

Figure 2: GENRAY/CQL3D simulation results for 54582. (left) Simulated plasma current as a function of $\xi_{n\perp}$. The scattered blue points represent $\pm 10\%$ variation in the n_e and T_e profiles used in the model, while the solid green curve represents simulations with the nominal kinetic profiles, and the solid red curve is the average. (center) Simulated current density profile for three values of $\xi_{n\perp}$ with nominal kinetic profiles. (right) Power absorbed by electron Landau damping (ELD) as a function of $\xi_{n\perp}$.

charges. A scaling factor of $\pm 10\%$ applies to the density and temperature profiles, represented by the scattered blue points in the left and right panels. The solid green and red curves in the left/right panels represent the simulation results with the nominal kinetic profiles and the average of the different profiles for each value of $\xi_{n\perp}$, respectively.

The simulated plasma current for shot 54719 is not particularly sensitive to $\xi_{n\perp}$ around the value measured by DSELF ($|\xi_{n\perp}| \sim 10°$) and the current profile at $-10°$ is quite similar to that for $0°$ (center panel of Figure 1). Most of the LH power (3.5 MW) is absorbed by electron Landau damping (right panel of Figure 1) for all values of $\xi_{n\perp}$. As a result there is a significant LHCD effect for all values of $\xi_{n\perp}$. The center panel of Figure 1 shows a distinct peak in the current profile which moves outward as $\xi_{n\perp}$ decreases from $0°$ to $-88°$.

By contrast, shot 54582 exhibits a significant difference between $\xi_{n\perp} = 0°$ and $\pm 50°$, the value measured by DSELF for 54582 (see Figure 2). Power absorption in the core of 54582 is poor for $|\xi_{n\perp}| \geq 45°$ (right panel of Figure 2) and the model predicts most of the power damps by collisions in the SOL. Consequently the current profiles for $-50°$ and $-88°$ look very much like an Ohmic + bootstrap current profile. An examination of the ray trajectories shows an initial downshift in $n_{||}$ for $|\xi_{n\perp}| \geq 45°$, which results in poor accessibility when combined with the high edge density of 54582. Shot 54719 has a lower edge density, and consequently there is no accessibility problem across the full range of $\xi_{n\perp}$. Edge reflectometry data is absent for 54719, which may explain the lower reconstructed edge density measurement as compared with

54582, however the small value of $\xi_{n\perp}$ measured by DSELF (10°) is insufficient to create an accessibility problem even with the higher edge density.

Hard x-ray (HXR) emissivity profiles can be used as a proxy for the fast electrons generated by LHCD. For 54719 the HXR emissivity peaks at $\rho = 0.3$, in qualitative agreement with the current profiles for 0° and -10° in Figure 1. The HXR emissivity for 54582 peaks at $\rho = 0.6$. The emissivity for 54719 is roughly double that of 54582. Recent work concerning the partial screening of high Z impurities in WEST shows that including this effect will be important for quantitative comparisons with experiment [12, 13].

The analysis presented here does not provide a conclusive causal link between edge density fluctuations, $k_\perp$ rotation, and current drive performance, but it does motivate additional investigation. In particular, future work will examine the connection between edge density fluctuations, MHD, and DSELF measurements, as well as searching for more discharges to analyze.

Acknowledgements

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