 Novel experimental measurements of the lower hybrid (LH) wave electric field vector, $E_{\text{LH}}$, obtained in Alcator C-Mod using dynamic Stark spectroscopy are presented. Three key results were obtained by comparison with 3D full-wave COMSOL simulations using the cold plasma dielectric tensor and reflectometry measured density profiles. (1) As a function of space and LH power, the magnitude of $E_{\text{LH}}$ was found to agree with the simulated values. (2) The direction of $E_{\text{LH}}$ was found to have a substantial poloidal component and is in strong disagreement with the nearly radial simulation result. (3) The addition of scrape off layer density fluctuations in the simulation can be used to explain the $E_{\text{LH}}$ direction discrepancy. It is therefore concluded that diffraction and scattering by turbulence driven scrape off layer density fluctuations is the responsible mechanism behind the modification in the direction of $E_{\text{LH}}$. These results further support the proposition that edge turbulence is an important mechanism behind the anomalous drop in LH current drive efficiency for diverted plasmas in the high density regime.

1. INTRODUCTION

In high density plasmas, lower hybrid current drive (LHCD) experiences a strong anomalous drop in efficiency as the density is increased [1] and was found to be inefficient in Alcator C-Mod for line-averaged densities approximately greater than $10^{20}$ m$^{-3}$ [2]. Several mechanisms have been identified as parasitic to LHCD such as low frequency scrape off layer (SOL) density fluctuations [3,4], parametric decay instability [5], collisional absorption [6], and pondermotive forces [7]. Recent experiments have determined that the edge region is responsible for the loss of current drive [8] and that turbulence plays a significant role [9]. These observations suggest that minimizing SOL density fluctuations is an important step towards efficient LHCD. However, the ordering of importance associated with the suspect phenomena has not been established. Detailed knowledge of the relative significance of each physical mechanism is necessary to develop appropriate launcher designs and mitigation techniques to address the drop in LHCD for high density diverted plasmas.

To gain insight into the phenomena responsible for the anomalous drop in LHCD efficiency, the LH electric field vector, $E_{\text{LH}}$, was directly measured in the edge region of Alcator C-Mod using dynamic Stark spectroscopy (DSS). Using a synthetic diagnostic, the experimental results were compared with 3D full-wave COMSOL simulations implementing the cold plasma dielectric tensor and reflectometry measured density profiles. It was determined that the magnitude of $E_{\text{LH}}$ agreed with the simulation. However, when comparing the direction of $E_{\text{LH}}$ a strong disagreement was observed. Experimentally, $E_{\text{LH}}$ was found to be composed of similar poloidal and radial components. In the simulation, $E_{\text{LH}}$ was found to be dominated by the radial component. Based on these results and previous work indicating that edge turbulence causes severe scattering of the LH wave in $k_L$ space [3,4], SOL density fluctuations were added to the simulation. This addition produced a substantial poloidal component in the $E_{\text{LH}}$ vector and was able to predict the experimental results.

2. DYNAMIC STARK SPECTROSCOPY

The one-electron atom has a quantum structure that is highly sensitive to the electric field. This structure can be directly probed through a measurement of the spectral line profile, yielding a powerful diagnostic for electric
fields in the fusion device. The DSS measured $E_{\text{LH}}$ vector results presented in this paper are determined by fitting the Schrödinger equation to the shape of the spectral line profile.

2.1. Diagnostic implementation on Alcator C-Mod

Polarized passive optical emission spectroscopy was implemented on Alcator C-Mod to measure two orthogonally polarized $D_B$ spectra. For a pure electric (E) or magnetic (B) field, the orthogonally polarized spectra are referred to as $\pi$ (parallel to E or B-field) and $\sigma$ (perpendicular to E or B-field). Decomposing the unpolarized spectrum into its polarized components can be extremely beneficial because the field effects the $\pi$ and $\sigma$ polarized spectra differently. If these spectra are measured and fit to the Schrödinger equation simultaneously, an additional constraint is provided allowing the field to be determined with greater accuracy. A nomenclature with respect to the magnetic field is adopted here because the Zeeman effect is significant stronger than the dynamic Stark effect.

The experimental setup consists of two periscopes connected fiber optically to a f=500 mm Acton spectrometer having a 2400 line/mm grating. The scientific camera used to acquire the spectral data was a Princeton Instruments ProEM CCD and was programmed to integrate optical emission over a 50 ms window. The periscopes consist of a polarizing beam splitter and two lens focusing the $\pi$ and $\sigma$ polarized emission into fiber optics. Four spectra were acquired every 50 ms: $\pi$ and $\sigma$ polarization at two measurement locations. Fig. 1 presents a top down cross-section of Alcator C-mod indicating the position of the periscopes and the sightline geometry used to observe the polarized $D_B$ spectra.

**FIG. 1.** Top down cross-section of Alcator C-Mod indicating the location of the two periscopes used to observed the $\pi$ and $\sigma$ polarized $D_B$ spectra (periscope dimensions not to scale). The 27 field aligned measurement locations are shown as red circles in the image of the LH launcher. The measurement location of the presented data is highlighted in white.

The periscopes were aligned such that the polarizing beam splitter’s axis was 14 degrees clockwise from vertical. This resulted in nearly parallel and perpendicular polarization with respect to the equilibrium magnetic field. Optical emission is observed in two regions within a sightline, labelled as 1 and 2 in Fig. 1, due to the large ionization fraction in the core. The diameter of the sightline at region 1 is 12 mm and at region 2 is 35 mm. A diverging sightline was designed to maximize the collection volume in region 2, where $E_{\text{LH}}$ is being measured. The mounting bracket for the periscopes was designed to allow access to 27 predetermined magnetic field aligned views of the LH launcher. The periscopes were backlight to determine the exact measurement location. A composite image of the LH launcher showing the 27 available measurement locations as red circles is present in Fig. 1. The white highlight locations are associated with data presented in this paper.

2.2. Spectra fitting for extraction of $E_{\text{LH}}$

The spectral line profile is calculated using the Explicit Zeeman Stark Spectral Simulator (EZSSS). This code solves the time dependent Schrodinger equation non-perturbatively for the electron’s quantum structure considering a static magnetic field vector and time periodic electric field vector. The spectral line profile is then calculated using first order time dependent perturbation theory, the electric dipole connection operator, and the sightline geometry in which optical emission is observed. Ref. [10,11] contain further details and a complete derivation. It is important to note that both the electric and magnetic field vectors must be consider
simultaneously in the Schrodinger equation due to nonlinear coupling. To determine \( E_{\text{LH}} \), the \( \pi \) and \( \sigma \) polarized \( D_\beta \) spectra were fit simultaneously using the spectralFIT (sFIT) code. A global optimization routine is implemented in sFIT to minimize the mean square error between the experimental and theoretical spectrum. EZSSS is used in sFIT for the theoretical calculations.

The model used to fit the spectral data consists of three components: two outboard (regions 1 and 2 of Fig. 1) and one inboard. The latter was found to be necessary due to reflections from the surface terminating the sightline. The spectra associated with the outboard components are calculated using the equilibrium magnetic field determined from EFIT (4.1 T), sightline geometry, polarizing beam splitter angle, neutral temperature (0.8 eV), and density determined from edge Thompson scattering \((5 \times 10^{19} \text{ m}^{-3})\). The neutral temperature and density are required to calculate the Doppler and Stark broadening, respectively. Additionally, for region 2, the \( E_{\text{LH}} \) vector is included as the fit variable. The region of origin associated with the inboard emission is unknown. Therefore, a zero LH power spectrum was recorded for each discharge and fit with \( E_{\text{LH}}=0 \) to determine the parameters (intensity, magnetic field, Doppler shift, etc.) representing the inboard component spectrum. The intensity of the inboard component was typically 10% of the total spectrum. The outboard \( D_\beta \) radial intensity profile was calculated using a 1D kinetics neutral transport code, KN1D, [12] and was found to peak near the last closed flux surface. Integrating over the sightline volume, it was determined that the intensity ratio of region 2 to region 1 is 1.8. The three components of \( E_{\text{LH}} \) are the only fit variables for spectra obtained when the LH launcher was powered.

In order to increase accuracy and reduce systematic errors in \( E_{\text{LH}} \), the \( \pi \) and \( \sigma \) polarized \( D_\beta \) spectra were fit a total of eight times using different wavelength boundaries. The average is reported as the \( E_{\text{LH}} \) vector. Fig. 2 presents spectral fits for four of the eight wavelength windows. The markers are associated with the experimental spectra and the solid lines with the fit. The net LH power was 378 kW and the location of the measurement is 1D (see Fig. 1). The fit determined values of the \( E_{\text{LH}} \) components are listed in Fig. 2.

![Fig. 2. Experimental (markers) and fit (line) \( \pi \) and \( \sigma \) polarized spectra associated with measurement location 1D (see Fig. 1) for a launched LH power of 378 kW. Multiple wavelength boundaries were used to fit the same spectra to increase accuracy and reduce systematic errors in \( E_{\text{LH}} \).](image)

The error in \( E_{\text{LH}} \) was calculated using a Monte Carlo approach. Spectra were simulated using the model implemented to fit the experimental data. Twenty sets of noise based on random and Poisson statistics were generated. Each set was added to the spectra and a fit was carried out. The standard deviation with respect to the simulated value was calculated and assigned as the error.

3. 3D FULL WAVE MODELING OF THE LOWER HYBRID WAVE

3.3. Simulation model

LH waves have been modelled previously using 2D and 3D full-wave simulations [13,14]. The simulation model presented in this paper adapts similar techniques by solving the vector wave equation in 2D axisymmetric geometry using COMSOL Multiphysics. This is done for an arbitrary but fixed toroidal mode number. The extension to 3D is achieved by summing over many toroidal mode numbers determined from the toroidal spectrum specified by the LH launcher. A full 3D model is very memory intensive and not achievable with the
available computational resources. The 2D axisymmetric vector wave equation is given by Eq. (1) and the Fourier sum of toroidal modes is given by Eq. (2)

\[
\nabla \times \left[ \nabla \times E_{LH,m}(r, z) \right] - \frac{\omega^2}{c^2} \left[ \nabla \cdot E_{LH,m}(r, z) \right] = 0
\]

\[
E_{LH}^{3D}(r, z, \varphi) = \sum_m A_m E_{LH,m}(r, z) e^{im\varphi}
\]

where \( \omega \) is the LH wave angular frequency, \( m \) is the toroidal mode number, \( \vec{\varepsilon} \) is the cold plasma dielectric tensor, \( c \) is the speed of light, \( A_m \) is the amplitude of the \( m \)th toroidal mode, \( E_{LH,m} \) is the 2D LH electric field vector associated with the \( m \)th toroidal mode, and \( E_{LH}^{3D} \) is the 3D LH electric field vector. The radial density profile was measured by SOL reflectometry [15] and edge Thomson scattering [16] and is assumed to be constant on a magnetic flux surface. Radial and poloidal magnetic field profiles were provided by EFIT. The density and magnetic field profiles are necessary inputs for the cold plasma dielectric tensor. Collisions have been included through an effective imaginary component in the electron mass. A spatially constant collision frequency was assumed for the simulations. The collision frequency was found to have an insignificant effect on the direction of \( E_{LH}^{3D} \) and a small effect on the magnitude of \( E_{LH}^{3D} \) in the region of interest. The LH launcher dimensions and 90° input phasing of its 16 columns are used to determine \( A_m \).

Fig. 3 presents the 3D full wave simulation of the magnitude of \( E_{LH}^{3D} \) for a net LH power of 330 kW and a line averaged density of \( 1.3 \times 10^{20} \text{ m}^3 \). A composite image of the LH launcher showing the 27 measurement locations as red circles is superimposed. The white highlighted locations are associated with data presented in this paper. Four resonance cones are clearly visible and correspond to the four rows of the LH launcher. It was found that the \( E_{LH}^{3D} \) direction was impervious to these parameters (~3% change) while the magnitude experienced a significant alteration (~50% change). The simulation accuracy has important implications for the interpretation of the results presented in Sec. 4.

\[
\text{FIG. 3. 3D full-wave COMSOL simulation of the magnitude of } E_{LH}^{3D} \text{ for a LH net power of 330 kW and a line averaged density of } 1.3 \times 10^{20} \text{ m}^3 \text{. An image of the LH launcher showing the magnetic field aligned measurement locations as red circles is superimposed. The measurement location of the presented data is highlighted in white.}
\]

### 3.4. Scrape off layer density fluctuation model

The simulation model presented in Sec. 3.3 assumes the radial density profile is constant on a magnetic flux surface. Previous experimental work presents strong evidence that the LH wave is scattered in both real and kL space by SOL density fluctuations [3,4]. Based on these findings, a synthetic turbulence model was formulated. The functional form is given by Eq. 3

\[
n_e = n_{eo} \left[ 1 + \bar{n}_e \ e^{-\frac{(r-r_c)^2}{\rho_w^2}} \sin^2 \left( \frac{\pi p}{\lambda_{ne}} \right) \frac{(p-p_0)^2}{\lambda_{ne}} \right]
\]

where \( n_{eo} \) is the reflectometry measured radial density profile, \( \lambda_{ne} \) is the poloidal wavelength of the fluctuations, and \( \bar{n}_e \) is the density fluctuation amplitude. The parameters controlling the density fluctuation
poloidal location and width and radial location and width are: \( p_p \), \( p_w \), \( r_c \), and \( r_w \), respectively. The value of these location and width parameters are chosen such that the density fluctuations occur in the near SOL and peak at the midplane. This behavior is prescribed based on experimental turbulence measurements [17,18] and a BOUT simulation of a similar Alcator C-Mod discharge [19]. This simplified model was solely designed to provide an estimate on the effect of turbulent-driven SOL density fluctuations on \( E_{\text{m}} \).

It was found that the inclusion of synthetic turbulence over a range of \( \lambda_{n_e} \), spanning 0.5 to 20 mm, and \( \bar{n}_e \), spanning 0.15 to 0.95, significantly altered both the magnitude and direction of \( E_{LH} \). Additionally, the propagation of the LH wave was substantially modified and complete reflection in the far SOL was observed in some cases. Fig. 4 presents the magnitude of \( E_{LH,m} \) for the dominant toroidal mode incorporating synthetic turbulence into the simulation having \( \lambda_{n_e} = 5 \) mm and \( \bar{n}_e \) varied from 0 to 0.9.

![FIG. 4. 2D full-wave COMSOL simulation of the magnitude of \( E_{LH,m} \) for the dominant toroidal mode \( m = -170 \). The synthetic turbulence model described by Eq. (3) was incorporated with \( \lambda_{n_e} = 5 \) mm and \( \bar{n}_e \) varied from 0 to 0.9.](image)

### 3.5. Synthetic diagnostic for \( E_{\text{m}} \)

The DSS diagnostic implements a passive spectroscopic technique to acquire \( D_B \) spectra, resulting in an integrated measurement over the sightline volume. In order to directly compare the 3D full wave simulation result (\( E_{LH}^{2D} \)) with the experimentally determined LH wave electric field vector (\( E_{\text{m}} \)) a weighted volumetric average over the sightline is calculated. The radial intensity profile of the \( D_B \) optical emission is used as the weighting function. This quantity is calculated from KN1D using the radial plasma density and temperature profiles measured from reflectometry and Thomson scattering, neutral pressure from an ionization gauge, and wall geometry.

### 4. RESULTS

The target plasma was an H-mode discharge with a line averaged density of 1.3x10^{20} m^3. The equilibrium magnetic field was 5.4 T and the plasma current was 0.8 MA. The LH power was ramped stepwise up to 400 kW. The timing was synchronized such that the LH power was held constant during the acquisition of spectral data. Results obtained at seven spatial locations in front of the LH launcher are presented. In Fig. 1 and 3 the measurement locations are highlighted in white and correspond to a vertically aligned column (1C, 2C, 5C, and 6C) and a magnetic field aligned row (1B, 1C, 1D, and 1E). These sets of data will be referred to as the ‘vertical’ and ‘horizontal’ locations, respectively. The coordinate system used to reference the location of the vertically and horizontally grouped measurements has its origin at the center of the LH launcher.

### 4.6. Magnitude of \( E_{\text{m}} \)

The simulated magnitude of \( E_{\text{m}} \) was found to be very sensitive to the radial density profile, measurement location, and SOL density fluctuations. This results in a larger error associated with the simulation (~50%) when compared to the experiment (~30%). An average over space and LH power was performed to yield an accurate insight into the global behavior of LH wave power. The average was performed on \( E_{\text{m}} \) determined as a function of space and LH power. Fig. 5 presents the magnitude of \( E_{\text{m}} \) spatially averaged over the vertical (left) and horizontal (right) measurement locations as a function of LH power. The error associated with the simulation is approximately 0.5 kV/cm. Excellent agreement with the full-wave simulation result was found. The expected
theoretical scaling, proportional to the square root of LH power, is observed for both vertical and horizontal location averages. The black dashed line is a fit to the experimental data. This trend is identical to the DSS results obtained in Tore Supra for an L-mode discharge having a high fraction of plasma current being sustained by LHCD [11].

The magnitude of $E_{\text{LH}}$ as a function of space was investigated by performing an average over LH power. This provides insight into absorption near the launcher because the LH wave power is proportional to the square of $E_{\text{LH}}$. Fig. 6 presents the magnitude of $E_{\text{LH}}$ averaged from 200 to 400 kW of LH power as a function of vertical (left) and horizontal (right) measurement location. The simulation was conducted with and without SOL density fluctuations. The parameters of the synthetic turbulence model were $\lambda_{\text{ne}}=5$ mm and $n_{\text{K}}=0.75$. Agreement within uncertainties was found between the experimental and simulation data without SOL density fluctuations. With the addition of synthetic turbulence, similar results are produced. However, two of the seven measurement locations (1B and 1C) experience a strong increase in their simulated value, leading to a substantial disagreement. This is believed to be driven by the static nature of the synthetic turbulence model and the strong localization of the LH resonance cones. Additionally, the synthetic turbulence model significantly increased the simulations sensitivity to collisionality and was found to produce an artificially high $E_{\text{LH}}$ magnitude. The overall agreement in the magnitude of $E_{\text{LH}}$ indicates that LH wave power is not being absorbed near the launcher.

Unlike the magnitude of $E_{\text{LH}}$, the direction was found to be insensitive to the radial density profile and measurement location. Only SOL density fluctuations were observed to significantly affect its value. This resulted in a simulation error (~3%) much smaller than the experimental error (~30%). It was found for both the experimental and simulated $E_{\text{LH}}$ vector that the parallel component was much smaller than the perpendicular components. Thus, the direction of $E_{\text{LH}}$ is presented as the inverse tangent of the perpendicular components.
ratio. At the midplane, the poloidal and radial directions correspond to 0 and 90 degrees, respectively. Fig. 7 presents the direction of $E_{LH}$ averaged from 200 to 400 kW of LH power as a function of vertical (left) and horizontal (right) measurement location.

![Graph](image)

**FIG. 7.** Direction of $E_{LH}$ averaged over LH power as a function of the white highlighted vertical (left) and horizontal (right) locations of Fig. 1. At the midplane, the poloidal and radial directions correspond to 0 and 90 degrees, respectively.

It was found experimentally that $E_{LH}$ contained a poloidal component having a magnitude on the order or greater than that of the radial component. The poloidal component was found to be a function of poloidal angle, increasing towards the midplane, and weakly dependent on the toroidal angle, remaining approximately constant. This result strongly disagrees with the nearly radial direction simulated without SOL density fluctuations. Incorporating synthetic turbulence having $\lambda_{ne}=5\text{ mm}$ and $\bar{n}_e=0.75$ in the simulations resulted in a significant alteration in the direction of $E_{LH}$ such that agreement within uncertainties was achieved. A parametric study of $\lambda_{ne}$ and $\bar{n}_e$ was conducted to determine the applicability of the synthetic turbulence model. Fig. 8 presents the direction of $E_{LH}$ as a function of $\lambda_{ne}$ and $\bar{n}_e$ simulated at measurement location 1C. It was determined that a wide range of values could be used to obtain similar results to those presented in Fig. 7.

![Graph](image)

**FIG. 8.** Simulated direction of $E_{LH}$ including SOL density fluctuations as a function of $\lambda_{ne}$ and $\bar{n}_e$ at location 1C.

5. CONCLUSIONS

The DSS measured magnitude of $E_{LH}$ provides two insights into the global behavior of the LH wave power in the SOL near the launcher. First, the LH wave power was found to follow the theoretically predicted scaling with respect to launched LH power. Second, the spatial distribution of LH wave power is in overall agreement with the simulations with and without SOL density fluctuations. These results indicate that the LH wave is not being strongly absorbed near the launcher. A significantly different result was found for the direction of $E_{LH}$. When SOL density fluctuations are not included, the simulation predicts a nearly radial direction. Experimentally, a poloidal component on the order or greater than that of the radial component was observed. The poloidal component was found to be a function of poloidal angle, increasing towards the midplane, and weakly dependent on the toroidal angle, remaining approximately constant. This result is in strong disagreement with the simulation and even trends oppositely with respect to the measurement location. Including synthetic
turbulence, the simulation was able to predict the behavior of the experimentally determined $E_{\alpha\nu}$ direction within uncertainties. Furthermore, a wide range of $\lambda_{te}$ and $\bar{n}_e$ values produce a similar effect. These results lead to the conclusion that strong scattering of the LH wave in $k_z$ space caused by SOL density fluctuations is occurring, supporting the hypothesis of previous work [3,4]. It is expected that SOL turbulence can have a detrimental effect on LHCD performance due to diffraction and scattering of the LH wave. Reactor relevant scenarios are likely to experience enhanced turbulence in the SOL, further motivating the need to test innovative solutions such as the high field side launch lower hybrid scheme tentatively scheduled for installation on DIII-D.

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