SOL Effects on LH Wave Coupling and Current Drive Performance on Alcator C-Mod


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Abstract. On Alcator C-Mod, the LH wave coupling was observed to degrade at higher launched $n_{\|} \equiv c k_{\|}/\omega$, suggesting that the waves have to tunnel through a millimetric evanescent layer between the plasma and the launcher. Subsequent edge density profile measurements by means of an X-mode SOL reflectometer were able to accurately document density depletion in the presence of high power LHRF. Good coupling was recovered for non-perturbative power level experiments (few Watts), confirming the role of high power LHRF waves on the edge plasma profiles. The measured reflection coefficients and density profiles were well reproduced by means of a fullwave Finite Element Method (FEM) simulation in which the density depletion by ponderomotive forces is self-consistently taken into account via an iterative approach. This model has been verified with previous 1-D calculations and has been seamlessly extended to efficiently model arbitrary 2-D or 3-D geometries. Considering a realistic geometry further exacerbates the density depletion in front of the launcher and is a key ingredient to get good agreement with the reflectometer measurements. The characterization of the plasma behavior in the vicinity of the coupler fits into a broader investigation taking place at Alcator C-Mod, which aims at understanding the role of the SOL on the LHCD efficiency. In particular, focus has been given to the loss of current drive which is observed at high density. Several experimental observations, supported by ray tracing/Fokker-Planck modeling, suggesting this is due to parasitic absorption in the SOL. Initial results using the LHEAF fullwave code and a 2D SOL model which includes the effects of flux expansion and parallel heat transport are presented.

Keywords: Lower Hybrid, ponderomotive, fullwave, reflectometer, POND, LHEAF

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LH WAVE COUPLING IN THE NON-LINEAR REGIME

Linear coupling theory for Lower Hybrid waves [1] has been validated in several experiments but it has shown to break down at high power densities. Even though all current drive experiments ultimately operate at high power, the wave coupling in the non-linear regime is still poorly understood and a definitive theoretical model is missing.

On Alcator C-Mod, coupling measurements showed that although the average reflection coefficient measured at the input of the splitters can be reduced to be as low as $\sim 15\%$ in optimized conditions, its amplitude is usually higher than simulations predicted at the design stage for typical SOL density parameters [2]. Figure 1 shows the power reflection coefficient as a function of average edge density for two sets of three discharges at $n_{\|}$ of 1.5, 1.9 and 2.3. One set for the launcher being 0.1 mm behind the protecting limiter, the other for 1 mm. A wide range of experimental observation were reproduced with the GRILL code [1] (black and white dots in Fig. 1), provided that the
FIGURE 1. Power reflection coefficient as a function of average probe density for different phasing and launcher radial positions behind the private limiters. The measurement reproduce the typical trend predicted by linear coupling theory [1], the reflections rapidly increasing for densities close to the cutoff density and reaching a minimum which is more pronounced at lower phasing. The experiments were carried out at magnetic field of 5.4 T and peak core densities of \( n_e(r/a = 0) = 4.5 \times 10^{19} \text{ m}^{-3} \), so the LH waves were fully accessible throughout the whole plasma. Coupling simulations required the addition of a vacuum layer in the density profile, in order to reproduce the experimental measurements.

Density profiles included the presence of a vacuum gap [3, 4] of the order of 1 mm. This density model is supported by the observation that the reflection coefficient is observed to increase at higher phasing, suggesting that the waves tunnel through an evanescent region. The density at the coupler is measured by the Langmuir probes while the density gradient is estimated by taking the edge-most channel of the Thomson scattering system.

The inclusion of a vacuum gap has been widely used to explain LH wave coupling on several machines including Alcator C-Mod [5], ToreSupra [6], T’d eV [7], ASDEX [8], PBX-M [9] and ITER [10]. However, the presence of this gap has never been measured and its existence often questioned. On Alcator C-Mod for the first time the depletion of the density profile in front of the launcher was directly measured with the SOL X-mode reflectometer diagnostic [11, 12] as shown in Fig. 2. A density depletion is observed within the first few mm away from the grill mouth, while further inside of the plasma the density increases, possibly due to RF-induced ionization or convective cells formation.

Common practice has been to use the ambiguity of the edge density profile to fit coupling simulations to the experimental measurements. The availability of accurate density profile measurements eliminates these free parameters and enables self-consistent study of the wave coupling problem in the linear and non-linear regimes. As summarized in the following table, 2D slab coupling simulations using COMSOL Multiphysics software [13] were found to agree within few % of the measured reflection coefficient.
FIGURE 2. (left) SOL measurements during a power modulation experiment ($n_{e0} = 0.8 \times 10^{20}$). This type of experiment has been used to generate the average density profiles shown in the (right) figure for three line averaged densities of $0.8, 1.0$ and $1.4 \times 10^{20} \text{ m}^{-3}$. Solid and dashed lines represent the profiles in presence and absence of high power LH waves, respectively.

Comparison between the LH and OH phases suggest the high reflections which are measured experimentally are caused by the low edge density (below or close to cutoff) and the steep gradients (especially for the high density cases). To verify that lower reflections could actually be achieved for ohmic-like density profiles, a non-perturbative low power (< 5 Watts) experiment was carried out. The power reflection coefficients for this setup are lower than what is generally observed at high power and in this case simulations did not require a vacuum gap to match the experimental measurements.

<table>
<thead>
<tr>
<th>$n_{e0}$</th>
<th>$0.8 \times 10^{20}$</th>
<th>$1.0 \times 10^{20}$</th>
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<tr>
<td>$\Gamma^2$ experiment</td>
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<tr>
<td>$\Gamma^2$ simulation (LH phase)</td>
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<tr>
<td>$\Gamma^2$ simulation (OH phase)</td>
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In view of the low power experiment effects, such as shadowing from the local limiters or mismatching of the plasma/antenna curvatures [9, 7] can be excluded, ultimately pointing to ponderomotive forces as the leading candidates to explain this observation [14, 3, 15]. Ponderomotive forces push charged particles that are in an inhomogeneous oscillating electromagnetic field towards the weaker field areas. In a plasma this results in a depletion of the density where the wave fields are high. The formulation of the nonlinear problem consists in the conventional cold plasma wave equation where the density is a function of the electric field. The plasma density $n(\vec{E})$ can be described as a perturbation $\delta n(\vec{E})$ to the density in absence of waves $n_0$, so that $n \approx n_0 + \delta n$, where $\delta n = -n_0 e^{r(\Phi_p + \Phi_v)} k (T_e + T_i)^{-1}$. In this expression, $\Phi_p$ is the ponderomotive
FIGURE 3. The iteration scheme of the POND code is shown on the left. On the right, a 2D slab simulation of the Alcator C-Mod grill shows the LH wave resonance cones leaving the launcher and the consequent enhancing of the density depletion due to the standing wave pattern.

potential, which for a magnetized plasma $\mathbf{B} = B_0 \hat{z}$ (derived from the Hamiltonian of the particles oscillation center in a oscillating electromagnetic field) is given by Ref. [16] to be $\Phi_P = \frac{e}{m} \left[ \frac{|E_z|^2}{\omega^2} + \frac{|E_x|^2 + |E_y|^2}{\omega^2 - \Omega^2} + \text{Im} \left\{ \frac{\Omega(E_y^*E_x - E_x^*E_y)}{\omega(\omega^2 - \Omega^2)} \right\} \right]$ where a magneto-static field is assumed to be the $\hat{z}$ direction. This expression relies only on the assumption of the wave power being in the same order of the temperature, so that $\varepsilon_0 |E|^2 / n_e T_e \sim O(1)$. In this expression the plasma temperature plays the important role of a feedback mechanism, since it is observed to increase in presence of high LH power (as shown in Fig. 2).

To find an analytic solution to the ponderomotive problem, past analysis have considered only slow wave propagation and assumed a monochromatic wave spectrum and low density. In our case instead, the solution was found by means of a fullwave finite element (FEM) simulation in which the non linear coupling between the wave electric fields and the density depletion by ponderomotive forces is taken into account via the iterative approach depicted in Fig. 3. To start, the wave electric field is calculated from the radial density profile in absence of the LH waves. The density perturbation is then calculated and a new radial density profile is obtained by averaging the density perturbation in the direction of the magnetic field. The resulting radial density profile is used for the new iteration step. The new code has been named POND and has been verified in 1D against the results published in Ref. [14].

The FEM fullwave method is very generic and is readily extendable to 2D or 3D geometries and other plasma waves. Considering 2D/3D geometry has proved to be important to consider the enhanced density depletion caused by the standing wave pattern of resonance cones, as shown in Fig. 3. Other effects which were not (but could be) considered for this analysis are $\vec{B}$ tilt, curvatures, poloidal/toroidal non-uniformities. As shown in Fig. 4, the density depletion from the POND simulations were found to be compatible with the measurements of the SOL reflectometer system. The availability of SOL density depletion profiles allowed an unprecedented strong validation of the ponderomotive theory and our conclusions in agreement with existing work [17, 14, 3, 15, 18].

Future work in this area include the investigation of the vortex structures which are routinely observed on the visible camera diagnostic on Alcator C-Mod during high
FIGURE 4. POND simulation of the density depletion (black dotted line). The simulations start from reflectometer ohmic density profile (dashed line) and should be compared with the profile during LH phase (solid line). Only the first few mm in front of the launcher are shown, since ionization is not included in the model. 2D and 3D simulations do not show significant difference.

ANOMALOUS LOSS OF LHCD AT HIGH DENSITY

Several tokamak experiments including Alcator C-Mod [21, 22], ToreSupra [23, 24], FTU [25] and JET [26] report loss of LHCD for increasing plasma densities. This effect is readily seen in the non-thermal bremsstrahlung (HXR) emission, that is a sensitive proxy for the population of fast electrons generated by LHCD. Figure 5 shows that the HXR emission from the Alcator C-Mod core plasma over the energy range of 40 to 200 keV drops by over four orders of magnitude by tripling the line averaged density. Although the reason for this variation is still under investigation, different theories agree that the SOL region plays a key role in the loss of driven current. Possible loss mechanisms in the SOL include electron-ion collisional absorption, ionization [27], wave scattering by density fluctuations [28, 29] and parametric decay instability [26].

For the case of Alcator C-Mod, ray-tracing Fokker-Planck modeling was found to recover good agreement when a collisional SOL is included in the model. In these simulations the temperature and density in the SOL consist of exponentially decaying profiles based on the distance from a point in the SOL to the last closed flux surface. For the density, the e-folding length may be defined as a function of poloidal angle. Within these constraints, the SOL model was implemented to best represent the experimental measurements.

To evaluate more accurately the power lost in electron-ion collisions, we have used the LHEAF code [30] with a fully 2D SOL model which includes the effects of flux expansion and parallel heat transport. Not only does the FEM formulation at the base of LHEAF treat seamlessly the SOL region, but the code has also been recently coupled to
FIGURE 5. The left plot shows the HXR emissivity as a function of density for different discharge parameters. Lines represent GENRAY/CQL3D simulations. Highlighted are the data points of the discharge #1080429007, which has been simulated using LHEAF and whose time traces are shown on the right plot. The LHEAF symbols in the left plot indicate the simulation results from the LHEAF code.

A 3D Fokker Plank solver and features a synthetic HXR diagnostic. The LHEAF 2D SOL model is based on the experimental observation that pressure is constant also on open flux surfaces and that temperature and density are very small on open flux surfaces which do not map to midplane [31]. If the pressure is known at a point $s_{\parallel 0}$ on a flux surface, then the density $n_e(s_{\parallel})$ can be deduced if the temperature $T_e(s_{\parallel})$ is known. In this notation $s_{\parallel}$ is the coordinate along a field line. To first approximation one can assume [32] that parallel heat flux is dominated by classical Spitzer conductivity \[ q_{\parallel} = -\kappa_0 T_e^{5/2} \frac{dT_e}{ds_{\parallel}} \left[ \frac{W}{m^2} \right]. \]

Assuming a constant heat source, the temperature along a field line can be calculated as \[ T(s_{\parallel}) = \left[ T_{s_{\parallel 0}}^{7/2} - \left( T_{s_{\parallel 0}}^{7/2} - T_{s_{\parallel 1}}^{7/2} \right) \frac{s_{\parallel 1}^2}{L^2} \right]^{2/7}, \] where $L = |s_{\parallel 0} - s_{\parallel 1}|$ and $s_{\parallel 1}$ is the location along a flux surface where the density and temperature measurements are taken and $s_{\parallel 0}$ represents the vacuum vessel walls. On Alcator C-Mod the flux surface measurements are provided by the Thomson scattering system and by reciprocating Langmuir probes [31], while the wall measurements come from a rich set of forty Langmuir probes which are installed in the divertors.

The 2D density and temperature distribution for the discharge #1080429007 at 1.14s are shown in Fig. 6 and the resulting LHEAF wave fields and the power deposition distribution are shown in Fig. 7. The LHEAF simulation predicts only a small amount of power to be lost in electron-ion collisions (6 kW at $n_e = 0.6 \times 10^{20} \text{ m}^{-3}$ and 10 kW at $n_e = 1.0 \times 10^{20} \text{ m}^{-3}$) compared to raytracing which (with a different SOL model) predicts as much as 200 kW at $n_e = 1.0 \times 10^{20} \text{ m}^{-3}$. The HXR results are shown as LHEAF symbols in Fig. 5. These results suggest the importance of running LHEAF simulations at higher densities and performing a more systematic comparison between raytracing and fullwave simulations using the same plasma density and temperature distributions.
FIGURE 6. 2D distribution of the plasma temperature and density which are input to the LHEAF simulation for the discharge #1080429007 at 1.14s. For reference, the electron-ion collisionality is also reported.

FIGURE 7. Logarithmic plot of the parallel electric field magnitude and of the power deposition distribution as simulated by LHEAF for the discharge #1080429007 at 1.14s. The power absorbed in the SOL amounts only for a small fraction of the total power.

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REFERENCES