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Ray Tracing Analysis of LH Fast Waves in CCT*

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ABSTRACT

Lower hybrid fast wave field profiles have been measured in the CCT tokamak. These field maps exhibit characteristics of large $n_{//}$ wave components, with $n_{\perp}/n_{//} \approx 1$, and the wave energy appears to be heavily damped in the toroidal direction. We use a 3-D toroidal ray tracing code to study this wave behavior. The spectral filtering of the fast wave can be partially attributed to mode conversion to the slow wave for the low $n_{//}$ components. In most parameter regimes, subsequent strong absorption of the converted slow wave via electron Landau and higher harmonic ion damping results.

INTRODUCTION

Current drive was observed in the UCLA Continuous Current Tokamak (CCT) when the fast wave was launched from a toroidal array of 8 large-area loops.[1] While the current drive mechanism is being resolved, we take advantage of the steady state feature of CCT to study the detailed propagation and absorption physics of the fast wave launched into the torus. We have measured the wave field profiles of the fast wave in the lower hybrid (LH) range of frequencies, using specially constructed, movable magnetic probes.[2] The wave is generated either by a single large-area antenna module or by a small loop which can be inserted radially along the equatorial plane inside the plasma. The field maps depict characteristics of large $n_{//}$ wave components, with $n_{\perp}/n_{//} \approx 1$, while the wave energy appears to be heavily damped in the toroidal direction. Independent probe measurements also confirm the existence of short wavelength electrostatic modes in some parameter regimes, pointing to the possibility of <u>m</u>ode <u>c</u>onversion to the <u>s</u>low <u>w</u>ave (MCSW).

RAY TRACING MODEL

In this paper, we study the LH fast wave in CCT with a 3-D toroidal ray tracing code,[3] in order to verify the observed wave characteristics and identify the damping mechanisms. For the cases we study, $\omega \gg \omega_{LH}$, so that the cold plasma dispersion relation $D(\vec{r},\vec{k},\omega)=0$ can be used. The ray equations are solved in (R,ϕ,Z) space while the plasma profiles are described in flux-surface coordinates (ρ,θ,ϕ). Absorption along the ray is expressed in terms of the damping decrement γ, defined by $\gamma=2\,\mathrm{sign}(\partial D/\partial\omega)D_I/|\partial D/\partial\vec{k}|$ where D_I is the imaginary part of D due to a specific damping process. For electron Landau damping, $D_{Ie}=2\pi^{1/2}(\omega_{pe}^2/\omega^2)n_{\perp}^2 n_{//}^2 x_{oe}^3 \exp(-x_{oe}^2)$, where $x_{oe}=\omega/k_{//}v_e$, while for ion harmonic damping, $D_{Ii}=2\pi^{1/2}(\omega_{pi}^2/\omega^2)n_{\perp}^4 x_{oi}^3 \times\exp(-x_{oi}^2)$, with $x_{oi}=\omega/k_{\perp}v_i$, which is valid for $\frac{1}{2}k_{\perp}^2\rho_i^2 \gg 1$.[4] The last term is usually significant only for the slow mode. For Coulomb collisional absorption, D_{Ic} is obtained simply by replacing m by $m(1+i\nu_{ei}/\omega)$ in D, with $\nu_{ei}=9.2\times10^{-11}Z^2n_e(cm^{-3})T_e^{-3/2}(keV)\ln\Lambda$.

In the LH regime, cutoff and mode conversion between the fast and slow waves involve turning points in 3 dimensions, which, for all practical purposes, do not coincide along the ray. As such WKB approximation is always valid and mode conversion and reflection are adequately described by the ray equations.[5] We start each ray at a fixed distance inside the plasma, where only a window of incident n_ϕ can propagate, being bounded by coalescence with the slow wave from below and by evanescence from above. The ray is allowed to undergo specular reflection as it hits the wall.

NUMERICAL RESULTS

We investigated the LH fast wave in two regimes: (A)high field(1kG),high frequency(80MHz), and (B)low field(250G),low frequency(21MHz). The plasma is a weakly ionized He gas with $Z_i=1$, being sustained by energizing the OH primary at a frequency of 3 kHz. The plasma profiles take the form: $n_e=n_{eo}(1-(\rho/a)^2)^{\mu_N} + n_{ea}$ and $T=T_o(1-(\rho/a)^2)^{\mu_T} + T_a$. For our calculations, $n_{eo}=2\text{-}4\times10^{13}cm^{-3}$, $n_{ea}=2\times10^{10}cm^{-3}$, $\mu_N=1\text{-}1.5$, $T_{eo}=20eV$, $T_{ea}=10eV$, $T_i=0.5T_e$, $\mu_T=0.5$, $q(0)=1.$, $q(a)=40(I_p=1kA)$. The CCT plasma has the following geometry: R=150cm, a=40cm, elongation $\kappa=1$ and axis shift $\delta=0\text{-}0.5$.

<u>Case (A)</u> $B_0=1kG$, f=80MHz: In this case, $n_{eo}=2\times10^{11}cm^{-3}$, $\mu_N=1$ and $\delta=0$. Five rays are launched from the outboard edge along the equatorial plane and followed for about 2 toroidal transits, with initial n_ϕ of 2.5, 3.0, 3.5, 4.0 and 5.0. Their trajectories are plotted in Fig.1(a) in the form of ρ/a as a function of $L/2\pi R$, where L is the arclength. We note that for $n_\phi=2.5$ and 3.0, the incident wave undergoes MCSW which then propagates radially outward. The $n_\phi=2.5$ ray is confined to the outer periphery of the plasma while for $n_\phi=3$, MCSW actually takes place deep inside the plasma. For the other 3 rays, penetration to the core occurs in almost every radial transit, without MCSW. From Fig.1(a), we see that the higher n_ϕ is, the more readily the rays penetrate to the center. Apparently, these are also waves with high values of $V_{g\perp}/V_{g//}$. In fact, for maximum $V_{g\perp}/V_{g//}$, it can be shown that $n_{//}^2=0.77\omega_{pe}^2/(\omega\omega_{ce})$, $n_\perp/n_{//}=0.83$ and $(V_{g\perp}/V_{g//})_{max}=0.31$. In Fig.1(b),(c), we plot respectively $|n_\perp/n_{//}|$ and $|V_{g\perp}/V_{g//}|$ along the toroidal distance for initial $n_\phi=5$. $|V_{g\perp}/V_{g//}|$ reaches a maximum of 0.31 at the plasma center while on the average $|n_\perp/n_{//}|=1$. We conclude that the experimentally observed field pattern has features similar to those of the waves with maximum $V_{g\perp}/V_{g//}$. It should be noted that at higher densities, the characteristic $n_{//}$ is observed to increase as $n_e^{1/4}$, but still $n_\perp/n_{//}=1$. However, for these rays, only weak damping has been observed over the length of the trajectories.

<u>Case (B)</u> $B_0=250G$, f=21MHz: For this case, $n_{eo}=4\times10^{11}cm^{-3}$, $\mu_N=1.5$ and $\delta=0.3$, the outward shift being set by the vertical field. Rays are launched from three locations, namely: outboard, inboard and top. These rays all have similar trends with respect to their incident n_ϕ. At the lower end of the propagating n_ϕ window, the wave quickly undergoes MCSW, which is subsequently trapped in the plasma

periphery, suffering weak collisional absorption. For intermediate values of n_ϕ, the wave usually mode converts during its initial transit, reflects from the wall with an anomalous increase in $n_{//}$ and is then damped by electrons, ions or both. An example of this is *shown in Fig.2 for a ray with* n_ϕ=8 incident from the inboard midplane. In this case, electrons account for 46% of the absorbed power while the rest is deposited in the ions. In Fig.2(d), at ϕ=2 rad, MCSW is clearly indicated. Much of the absorption takes place on the outer half of the plasma and in some cases, it takes only one toroidal transit for total absorption. On the high end of the n_ϕ window, waves launched from the inboard side and top still get converted, but the slow wave is only weakly damped by electrons. For those launched from the outboard edge, the fast wave is well focused in the magnetic axis, suffering moderate electron damping.

We also studied the case of a small loop being placed in the geometric center of the torus and aligned to excite mainly the fast wave.[2] Because of the location of the launcher, only high n_ϕ(>18) wave components can propagate in its vicinity. Mode conversion and subsequent damping can occur for the lower n_ϕ waves. For higher n_ϕ, the fast wave persists and is observed to focus towards the magnetic axis, on which most of the power is deposited.

CONCLUSIONS

Much of the experimentally measured LH fast wave characteristics have been demonstrated by 3-D ray tracing analyses. Mode conversion to the slow wave can take place deep inside the plasma and lead to strong damping of the wave energy by both electrons and ions. However, higher n_ϕ wave components are less susceptible to this process and thus dominate the global wave structure. Finally, wave scattering off density fluctuations may also play an important role and ray tracing studies in such a medium may have to be considered.

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FIGURE CAPTIONS

1. (a) Ray trajectories with initial n_ϕ=2.5,3.0,3.5,4.0,5.0 for case(A). (b) $|n_\perp/n_{//}|$ and (c) $|V_{g\perp}/V_{g//}|$ as a function of toroidal angle ϕ for initial n_ϕ=5.0 in case(A).
2. Example of a ray in case(B): (a) trajectory in (R,Z) space, (b) normalized ray power along R, (c) $n_{//}$ evolution and (d) $(n_\perp/n_{//})^2$ of fast(F) and slow(S) waves along ray.

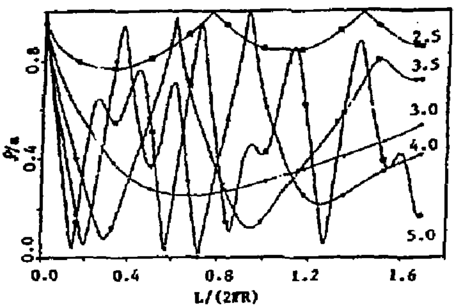

Fig.1(a)

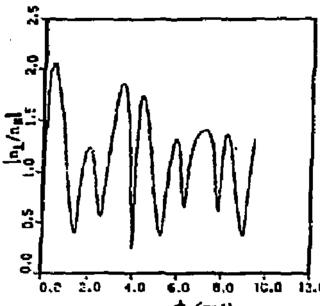

Fig.1(b)

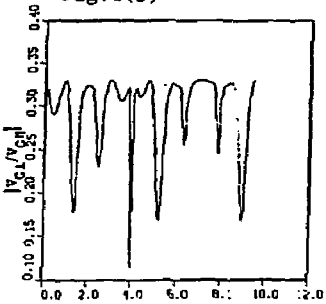

Fig.1(c)

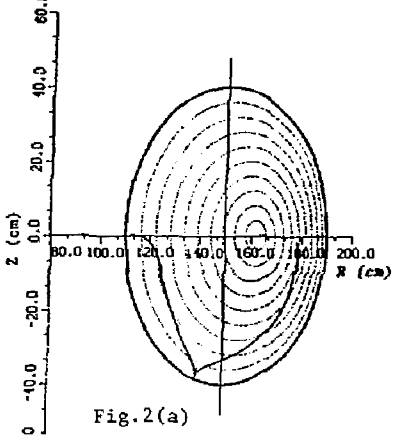

Fig.2(a)

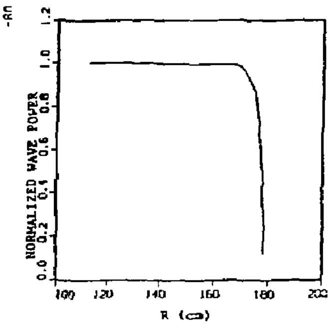

Fig.2(b)

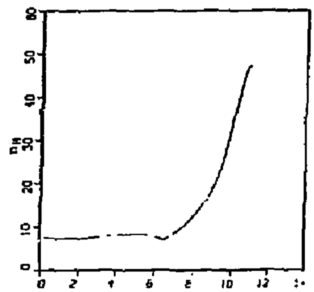

Fig.2(c)

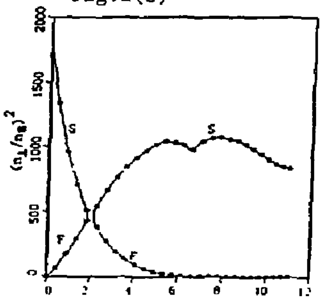

Fig.2(d)