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Penetration and Scattering of Lower Hybrid Waves by Density Fluctuations

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Abstract. Lower Hybrid [LH] ray propagation in toroidal plasma is controlled by a combination of the azimuthal spectrum launched from the antenna, the poloidal variation of the magnetic field, and the scattering of the waves by the density fluctuations. The width of the poloidal and radial RF wave spectrum increases rapidly as the rays penetrate into higher density and scatter from the turbulence. The electron temperature gradient [ETG] spectrum is particularly effective in scattering the LH waves due to its comparable wavelengths and parallel phase velocities. ETG turbulence is also driven by the radial gradient of the electron current density giving rise to an anomalous viscosity spreading the LH-driven plasma currents. The scattered LH spectrum is derived from a Fokker-Planck equation for the distribution of the ray trajectories with a diffusivity proportional to the fluctuations. The LH ray diffusivity is large giving transport in the poloidal and radial wavenumber spectrum in one -or a few passes - of the rays through the core plasma.

Keywords: Lower hybrid heating, lower hybrid current drive, diffusion of rays.
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LOWER HYBRID CURRENT DRIVE IN TURBULENCE

Here we outline a theoretical model that gives insight for antenna design compensating for the scattering of RF waves by drift wave fluctuations. Real-time control of electron transport barriers by RF power in ITER is envisioned. An adaptive-real time controlled RF antenna may also provide an effective method for bringing down the plasma current rapidly when the signatures of a disruption are detected. Typical lower hybrid spectra and current drive efficiencies are estimated for the ITER plasma in Decker et al. [1]. The launched RF waves have wavelengths of 6 cm with electric field of a few times 10^2 kV/m and associated magnetic fields of a few mT. In the lower density plasma near the antenna the associated toroidal Poynting flux is of order 10-30 MW/m^2.

For the wave propagation in the frequency range of the LH heating the dispersion relation gives a fast and a slow wave. The slow wave is quasi-electrostatic with a low perpendicular phase velocity. Depending on the ITER plasma conditions, this branch is expected to drive current somewhere between r/a=0.7 and the separatrix [1]. The antenna also couples to the fast wave eigenmode with a higher perpendicular phase velocity in the low density plasma. The fast wave is expected to be the dominant eigenmode in the core of a high plasma beta. This wave is an electromagnetic plasma wave with a right-hand circular polarization that is ubiquitous in space plasmas and is known to accelerate electrons to MeV energies in the Earth's radiation belts. In the large, high beta plasma of the ITER one expects the fast wave to become important in the core plasma.

Eigenmodes from the Stix plasma wave dispersion relation give the local spatial increase in the perpendicular wavenumbers as the waves propagate into the high-density plasma. Peysson et al. [2] developed the CP3O code to calculate the rays and their absorption in the toroidal geometry. As the wave propagates to region of higher temperature, the wave is damped on electrons with a parallel velocity about 3 to 5 times the thermal velocity, thereby producing the forward peaked x-ray spectrum as first reported by Stephens et al.[3] in lower hybrid current drive (LHCD) plasma experiments. From numerous experimental works and subsequent theoretical studies we know that lower-hybrid driven plasmas are characterized by a high relativistic forward electron temperature T_F, a lower backward temperature T_B in addition to some increase of the bulk thermal temperature. This three-component electron energy spectrum is used in calculating the ETG turbulence [4]. The anisotropic x-ray spectrum from the plasma is a primary diagnostic tool.

The electromagnetic dispersion relation gives two waves for the LHCD plasma. One wave is quasi-electrostatic with a slow phase velocity and a quasi-electrostatic polarization. The second wave is the fast electromagnetic wave with a smaller $E_{\|}$. Both branches have the perpendicular electric fields rotating owing to the $E \times B$ drift of the electrons that is not compensated in the ion motion. These same waves are ubiquitous in space plasmas. In toroidal

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geometry the eikonal equations are Hamiltonian in structure with $\omega(k_r, k_m, r, \theta)$ being the Hamiltonian for the ray trajectories. The poloidal variation of the plasma gives the ray equations two degrees of freedom with overlapping resonances in the phase space. This introduces chaos in the ray trajectories as shown in Moreau and the Tore Supra Team [5]. The parallel wavenumber $k_{\|}$ has a strong dependence on r,θ making the wave packet propagation qualitatively different from that in a cylinder where k_z is a good quantum number and constant of the motion. In the torus the parallel wavenumber has a strong spatial dependence as the wave propagates in radius and poloidal angle. Phase space resonances occur when $m_r\Omega_r+m_\theta\Omega_\theta=\omega^{LF}(q)$ with low-order integers for m_r and m_θ. Here, where $\vec{q}$ is the wavenumber vector of the low frequency $\omega^{LF}(q)$ drift wave. This interaction is a scattering of the of the high frequency plasma wave as shown in Fig.1.

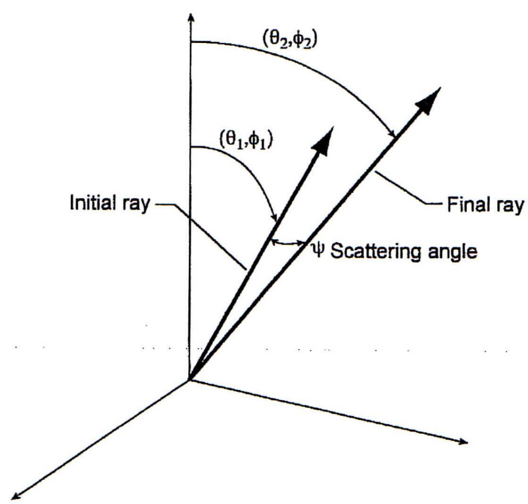

FIGURE 1. Schematic for the angle scattering of a LH ray by the density fluctuations derived from the linearized Fokker-Planck equation for the distribution of the rays in the plasma with electron density fluctuations. Owing to the low frequency of the density fluctuations compared with the gigahertz RF frequency, the ray scattering is elastic.

The spectrum of the launched waves in a vacuum is shown in Fig. 2 for an LHCD antenna designed for Tore Supra using a set of $TE_{\{1,0\}}$ wave guide modes with two TM modes running at 3.7GHz. The launched spectral distribution is expressed in terms of the indices of refraction $n_{\|} = ck_{\|}/\omega_{RF}$ and $n_y = ck_y/\omega_{RF}$. The peaking parallel or toroidal $n_{\|} = ck_{\|}/\omega_{RF}$= -1.7 drives waves propagating parallel to the electron parallel fluid velocity producing the plasma current.

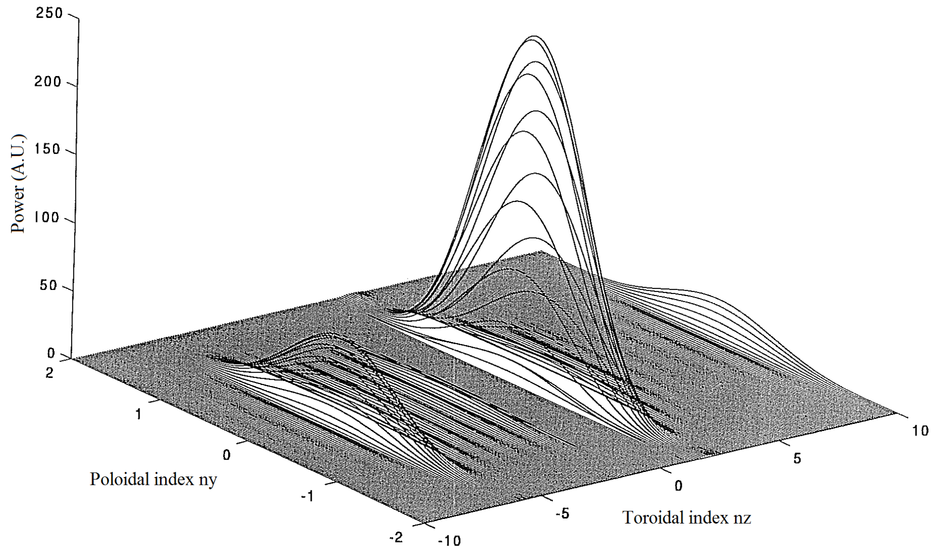

FIGURE 2. The launched power spectrum for a 3.7 GHz antenna called C2 used in Tore Supra as computed from the ALOHA antenna code developed by Berio [6]. The current ITER grill antennas are C3 and C4 have a 180^0 degree poloidal phase shifts that moves the peak of the poloidal wavenumber spectrum to $n_y \sim 1$ driving larger poloidal mode numbers m= $k_y r_{ant}$. The waveguides are closed with beryllium-oxide windows that have low reflection R=0.02 coefficients. The C4 PAM antenna has an aggressive cooling system designed for steady state operation at the multi-megawatt power levels.

DISTRIBUTION FUNCTION OF THE RAYS IN TURBULENT PLASMAS

Let $F\left(\vec{x}, \vec{k}, t\right)$ be the probability density for the numbers of rays at the LH frequencies $\omega^{\mathrm{LH}}(n_e, \vec{k})$. The density fluctuations from drift waves on space-time scale $\vec{q},\Omega$ produce a perturbation $\delta F(\vec{q},\Omega)$ in the probability density of the rays governed by plasma turbulence. The density fluctuations produce a $\delta F(\vec{q},\Omega)$ in the probability density of the rays that is governed by

$$\frac{\partial}{\partial t}\delta F + \vec{v}_k \cdot \frac{\partial \delta F}{\partial \vec{x}} - \frac{\partial \vec{k}}{\partial \vec{x}} \cdot \frac{\partial F}{\partial \vec{k}} = 0$$

$$\frac{\partial \vec{k}}{\partial \vec{x}} = -\frac{\partial \omega(n_e, \vec{k})}{\partial n_e} \sum n_{q,\Omega}\, i\vec{q} e^{i\vec{q}\cdot\vec{x} - i\Omega t} \quad . \tag{1}$$

The reaction of the scattering on the probability density is given by the diffusion tensor

$$\vec{\vec{D}}(\vec{k},\vec{x}) = \left(\frac{\partial \omega(\vec{k},n_e)}{\partial n_e}\right)^2 \sum_{q,\Omega} \left|\delta n_{\vec{q}\Omega}\right|^2 \vec{q}\vec{q}\pi\delta\left(\Omega - \vec{q}\cdot\vec{v}_k\right). \tag{2}$$

In the plasma the mean probability density for the rays evolves as

$$\frac{\partial}{\partial t}F + \vec{v}_k \cdot \frac{\partial F}{\partial \vec{x}} - \frac{\partial}{\partial \vec{k}} \vec{\vec{D}}(\vec{k},\vec{x}) \cdot \frac{\partial F}{\partial \vec{k}} = 2\gamma_{\vec{k}}(\vec{x})F \quad . \tag{3}$$

From drift wave turbulence theory or simulations, one computes the ray diffusivity in Eq. (2). The scattering from magnetic turbulence is complicated -- producing a change in the polarization of the RF waves -- in addition to a spread in the wavenumber spectrum. For a drift wave spectrum $<\left|\delta n_{q,\Omega}\right|^2>$ the diffusion coefficient

$\vec{\vec{D}}(k) = D_\perp(\vec{\vec{I}} - \hat{b}\hat{b}) + D_\parallel \hat{b}\hat{b}$ with $D_\perp \gg D_\parallel$ producing a fast spreading of $< k_\perp^2(t) >= 2D_\perp t$. The anisotropy of $\vec{\vec{D}}$ follows from computing $\vec{k} \cdot \vec{\vec{D}} \cdot \vec{k}$ and noting that $|\Omega(\vec{q})| \ll |\vec{q}||\vec{v}_k|$. Early works [5] give chaotic rays with a slow chaos from the Lyapunov exponents. The scattering from the density turbulence is faster. The steady state LHCD problem has a source S_{ant} at r_{ant} and absorption in the core plasma from Landau damping. The steady state solution with the source and sink give phase space densities $F_\alpha(r,k)$ for the slow (α=1) and fast (α=2) waves spanning the region from the antenna to the regions of absorption by the tail electrons. The regions of absorption follow from the slow and fast wave parallel velocities $\omega^{RF}/k_\parallel = \omega_{pe}/k_\perp$ and $\omega^{RF}/k_\parallel = c^2 k\, \omega_{ce}/\omega^2_{pe}$, for α=1,2 respectively.

CONCLUSIONS

Simulations are being carried out for δF_α, D_α and F_α for the scattering of the rays by the turbulence. The scattering is essentially elastic scattering owing to the low-frequency fluctuations compared to the RF frequency. The steady state solution with the source and sink gives $F_\alpha(r,k)$ distribution functions spanning the region from the antenna to the regions where the waves are absorbed by damping from thermal $T_e(r,t)$ the electrons. The flux surface average of Eq.(3) gives a radial transport problem for F(k, r, t). For example, the ETG turbulence gives

$$D(k,r) = \pi\left(\omega^{\mathrm{RF}}\right)^2 \int_{q_m^2}^{\infty} dq^2 \left|\frac{\delta n_e(q)}{n_e}\right|^2 \frac{q^2}{\Delta q v_k} \tag{4}$$

For the ETG spectrum the ray diffusivity reduces to $\Delta q \sim < q^2 >^{1/2} \sim 10\, cm^{-1}$ and the ray diffusion rate becomes $D = 10^{11} < \delta n_e^2 / n_e^2 > / cm^2 s$ which rises rapidly as the rms density fluctuation level increases from the core to the scrape-off layer. The mean wavenumber rate of upward drift from Eq.(3) is $dk/dt = \partial D/\partial k = 10^4 / cm.s$ to 10^5/cm.s. Including the RF source S_{ant} and sink gives

$$\frac{\partial \bar{F}}{\partial t} - v_g \frac{\partial \bar{F}}{\partial r} - \left(\frac{\partial \omega}{\partial r} + \frac{\partial D}{\partial k}\right)\frac{\partial \bar{F}}{\partial k_r} = -2\gamma_k(r)\bar{F} + S_{\mathrm{ant}}\delta(r-a) + D\frac{\partial^2 \bar{F}}{\partial k^2} \;. \tag{5}$$

The distribution F maximizes near $r_m / a = S_{\mathrm{ant}} / v_{g2} / \left[S_{\mathrm{ant}} / v_{g2} + 2 < \gamma_k > \Delta / v_{g1}\right]$ showing that the peak of the LH power density shifts towards the edge plasma with increasing antenna power - when other parameters are held constant. Thus, there is an optimal power level for current drive operation in a large plasma volume. In future work the magnetic fluctuations will be included and the cross-polarization from scattering will be examined.

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