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On Self-consistent Simulation of the Lower Hybrid Current Drive

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Introduction

Numerical simulations of lower-hybrid current drive (LHCD) are generally based on ray-tracing calculations to determine the LH wave characteristics and on Fokker-Planck (FP) calculations with quasilinear (QL) diffusion to determine the phase-space distribution function and thus calculate the driven current [1]. In most simulations a large number of rays is used in order to fill the spectral gap [2], which leads to long calculation times and restrict the use of this method, for example, in integrated tokamak modeling simulations. Besides, a spectral width $\Delta N_{||}$ must be associated with each ray in order to obtain a finite diffusion coefficient and calculate the distribution function. In simulations using many rays, the values of $\Delta N_{||}$ that must be taken to ensure the stability of kinetic calculations is much larger than the incremental spectral separation between rays, thus preventing any physical interpretation or justification for the choice of $\Delta N_{||}$.

In this work, ray-tracing calculations are coupled to the kinetic code DKE [3], which calculates the ray damping consistently with the distribution function in order to properly account for QL effects. The power deposition profile is found to be completely determined by QL coupling and is independent of the number of rays used in the simulation. From these results, a simulation scheme using only one ray is proposed. This method provides significant gains in computational time as well as a prescription and a physical interpretation for the spectral width $\Delta N_{||}$ associated with the ray.

Self-consistent damping of ray power

In the region where LH waves are damped, the suprathermal part of the electron distribution function f can be strongly distorted. This distortion does not affect much the ray propagative properties, such as the real part of the wave vector and the polarization, because these characteristics are derived from the non-resonant (hermitian) part of the dielectric tensor and thus mostly depend upon the bulk of f. The ray trajectories and propagative properties can thus be determined from a Maxwellian distribution. However, ray power absorption is derived from the resonant (antihermitian) part of the dielectric tensor and thus depend specifically on the part of f that is distorted by QL effects. Therefore, the ray damping and f must be calculated self-consistently, which is obtained by a convergent iterative process described here.

The LH wave is assumed to be modeled by a set of rays $y = 1, \cdots, N_y$. The power $P_y(\psi)$ flowing in a ray y is obtained by expressing the energy conservation at each step along the ray path

$$\frac{dP_y(\psi)}{dV(\psi)} = P_y^{\text{abs}}(\psi) \tag{1}$$

where $dV(\psi)$ is the incremental volume of a FS and $P_y^{\text{abs}}(\psi)$ is the density of power absorbed from the incremental ray section in this FS. Then, a QL diffusion coefficient $D_{\parallel\parallel}(\psi)$ is built by adding the contributions $D_{\parallel\parallel}^y(\psi)$ of all rays with some portion of their trajectory in the volume $dV(\psi)$

$$D_{\parallel\parallel}(\psi) = \sum_y D_{\parallel\parallel}^y(P_y, \psi) \tag{2}$$

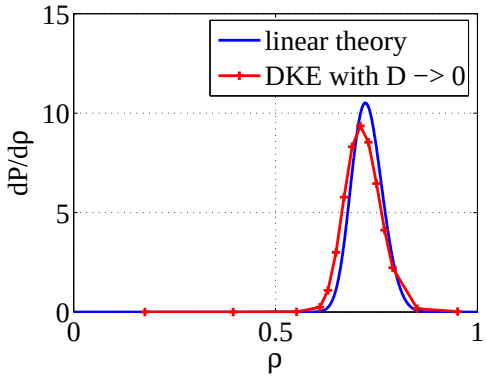

Figure 1: Power deposition profile of a single LH ray propagating in TS along the equatorial plane with initial power $P = 1e^{-6}$ MW and the spectral characteristics $N_\parallel = 3.5$ and $\Delta N_\parallel = 0.1$. Calculations by DKE are compared to linear theory.

The evaluation of $D_{\parallel\parallel}^y$ includes contributions of all polarization components [4]. The electron distribution function is then calculated by solving the bounce-averaged FP equation on each FS

$$C(f) + \frac{\partial}{\partial p_\parallel}\left[D_{\parallel\parallel}\frac{\partial f}{\partial p_\parallel}\right] = 0 \tag{3}$$

In (3), $p_\parallel$ is the momentum component in the direction parallel to the magnetic field and $f = f(p, \xi, \psi)$ where p is the total momentum and $\xi = p_\parallel/p$. The current and absorbed power densities are then calculated as moments of f in 2-D momentum space.

$$J(\psi) = 2\pi \iint q_e v_\parallel f \quad p^2 dp d\xi \tag{4a}$$

$$P_y^{\text{abs}}(\psi) = 2\pi \iint \varepsilon(p) \frac{\partial}{\partial p_\parallel}\left[D_{\parallel\parallel}^y \frac{\partial f}{\partial p_\parallel}\right] \quad p^2 dp d\xi \tag{4b}$$

with $\varepsilon(p)$ being the electron kinetic energy. By reinserting $P_y^{\text{abs}}(\psi)$ into (1) and iterating the sequence (1)-(4) until convergence, self-consistent ray damping and distribution function are calculated. In the limit where all $P_y \to 0$, the density of power absorbed calculated by DKE should agree with linear theory. The linear limit thus provides a benchmarking of DKE calculations as shown in Fig. 1.

Application to a generic full-LHCD discharge

A steady-state Tore Supra LHCD plasma [$T_{e0} = 4.2$ keV, $n_{e0} = 3 \times 10^{19}$ m^{-3}, $B_T = 3.3$ T, $I_P = 0.5$ MA] is considered. An initial LH wave spectrum of total power $P = 1.9$ MW and

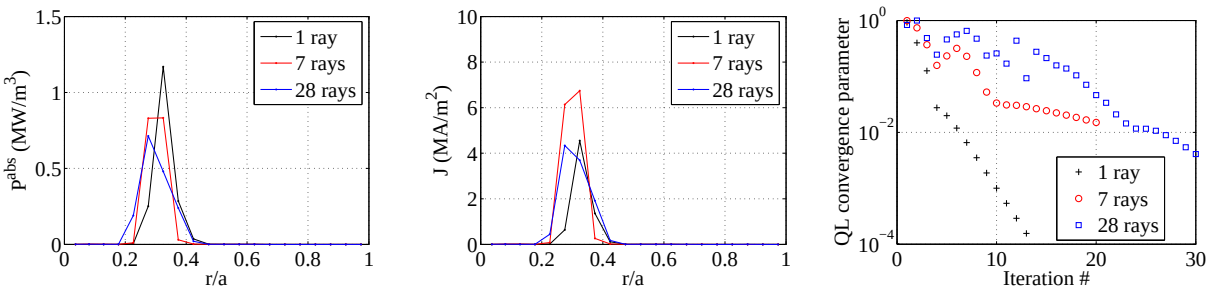

Figure 2: Absorbed power (a) and current (b) densities and convergence rate (c) obtained using 1, 7 and 28 rays, respectively.

Gaussian shape centered at $N_{\|0} = 1.7$ with half width $\Delta N_{\|0} = 0.2$ is discretized into 28 rays. The rays path and propagative characteristics in the plasma are calculated using the ray-tracing code from DELPHINE [5]. Three different calculations are compared: the initial 28 rays case, a case using 7 rays uniformly selected, and a case using the central ray in the wave spectrum. In the 7 and 1 rays cases, the power in the rays is adjusted such that the same total power is launched into the plasma. In kinetic calculations, a spectral width $\Delta N_{\|}$ is assigned to each ray to obtain a finite $D_{\|\|}$. For the results presented in Fig.2, $\Delta N_{\|}$ is constant along ray trajectories and the DELPHINE prescription $\Delta N_{\|} = 0.1$ is used in the 28-rays case. In the 7-rays and 1-ray cases, $\Delta N_{\|}$ is increased to 0.2 and 0.4, respectively. When the number of rays is increased, the rate of convergence for the QL self-consistency is lowered considerably while the computational time required for calculating $D_{\|\|}$ and P_y^{abs} increases significantly. The LH power deposition profile, strongly dominated by QL inter- and intra-ray coupling effects, is rather independent of the number of rays used in the simulation. However, the CD efficiency is smaller by 40% when only one ray is used, which indicates that the spectral gap is not properly filled. If $\Delta N_{\|}$ is reduced below 0.2 or increased above 0.6 in the 1-ray case, linear power absorption becomes dominant and the CD efficiency drops.

In order to account for the ray divergence, $\Delta N_{\|}$ is set to be proportional to $N_{\|}$ along the ray path. This prescription ensures that the spectrum is continuous and that the spectral gap is properly filled. The ratio $\Delta N_{\|}/N_{\|}$ is adjusted to maximize the QL intra-ray coupling and thus the CD efficiency (Fig. 3d). With $\Delta N_{\|}/N_{\|} = 0.15$ the power deposition is similar to the $\Delta N_{\|} = 0.4$ case (Fig. 3c) and the CD efficiency ($I/P = 0.41$ A/W) is very close to the 28-rays result ($I/P = 0.42$ A/W). The strong Landau damping condition $N_{\|} \geq 6.5/\sqrt{T_{e\,[\mathrm{keV}]}}$ (Fig. 3a) determines the location of deposition ($r/a \approx 0.3$) where more than half of the LH power is absorbed in single pass as a result to strong intra-ray QL coupling (Fig. 3b). With a lower $\Delta N_{\|}/N_{\|} = 0.05$ ratio the spectral gap is not sufficiently filled and the power is absorbed linearly

during the $N_{\|}$ upshift. With a higher $\Delta N_{\|}/N_{\|} = 0.35$ the power is absorbed mostly in the first pass, but QL effects are limited and the CD efficiency is lower. When the QL interaction process is not complete two peaks are present in the deposition profile (Fig. 3c).

From this work it is concluded that a single-ray simulation can provide the same results as many-ray calculations [2] in terms of power deposition and CD efficiency, provided that the spectral gap is properly filled to ensure quasilinear coupling of low-$N_{\|}$ ray portions. This situation is obtained by varying $\Delta N_{\|}/N_{\|}$ such as to optimize CD efficiency. Besides providing considerable gains in calculation time and robustness, the one-ray approach is compatible with the interpretation of $\Delta N_{\|}$ as the spectral width of a spatially localized wavepacket. This study also calls for the development of an heuristic description of LH-wave / plasma coupling.

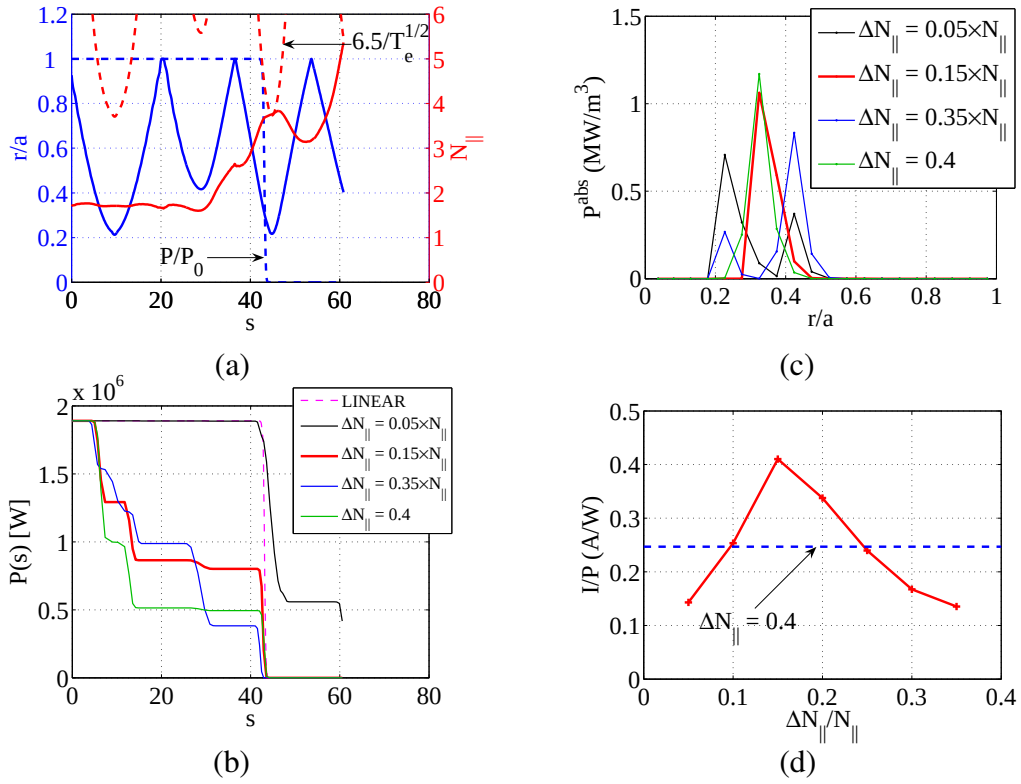

Figure 3: Propagation (a), damping (b), power deposition (c), and CD efficiency (d) of a single ray with varying $\Delta N_{\|}$.

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