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Introduction

Spherical tori (ST) are tight aspect ratio machines ($R_0/a \sim 1.5$ in NSTX, where R_0 is the major radius and a is the minor radius) that are attractive as fusion energy devices due to their accessibility to high-β regimes ($\beta = 2\mu_0\overline{p}/B_0^2$, where $\overline{p}$ is the volume averaged pressure and B_0 the plasma toroidal field on axis). Since STs are overdense ($\omega_{ce} \ll \omega_{pe}$, where ω_{ce} is the electron cyclotron frequency and ω_{pe} is the electron plasma frequency), current drive (CD) using electron cyclotron (EC) waves is difficult and inefficient, particularly near the outboard edge where trapping of electrons in the magnetic field is significant. However, it has been shown that, in the EC range of frequencies, it is possible to externally excite electron Bernstein waves (EBW) by mode conversion (MC) at the outboard edge of a ST plasma [1]. In addition, EBWs can propagate in the plasma without density limits and are strongly damped at any harmonic of the EC resonance [2]. Current drive by EBW has been recently demonstrated in toroidally confined fusion plasmas [3]. Using our kinetic code DKE [4], we solve the kinetic equation with Fokker-Planck (FP) collisions and quasilinear (QL) diffusion due to EBW. In addition, we account for the effects of magnetic trapping of electrons, which are important in ST. We show that large current densities can be driven in high-β regimes of ST, and that off-axis current is primarily driven by the Ohkawa [5] mechanism while near-axis current is driven by the Fisch-Boozer [6] mechanism.

Modeling of CD by EBW

In this study, we do not investigate the problem of EBW excitation and propagation, which requires a modeling of the MC and also ray-tracing calculations [1, 2]. Instead, we concentrate on the EC resonance (ECR) region. Because of the strong, complete absorption of the EBW power at the Doppler-shifted ECR, the width of the radial power deposition profile is typically very narrow compared to the equilibrium scale lengths in the plasma. As a consequence, it is reasonable to assume the parallel index of refraction $N_{\|}$ to remain constant across the deposition region, where, in addition, the propagation path is assumed to be locally straight. Consequently, in our simulations, the EBW beam is modeled by a single, straight ray with a Gaussian parallel spectrum centered around a constant $k_{\|}$, and is assumed to be well focused, meaning that the poloidal extent of the beam satisfies $\Delta\theta_b \ll 2\pi$. The ray is then characterized by a parallel spectrum width $\Delta k_{\|} \simeq 1/(r\Delta\theta_b)$. In addition, we assume a circular cross-section plasma.

Given the plasma equilibrium and the $k_{\|}$ spectrum of the wave, we calculate $k_{\perp}$ and the wave polarization and power flow by solving the wave equation, using our fully relativistic dispersion solver R2D2 [7].

We use these wave properties to evaluate the EBW QL diffusion coefficient and calculate the steady-state FP Equation with QL diffusion. The electron guiding-center drift velocities across flux-surfaces are generally small compared to the streaming velocities along the field lines, and can be neglected in first approximation. In addition, for the equilibrium under consideration, we are in the low-collisionality (banana) regime in which the bounce time of trapped electrons is much shorter than the collisional detrapping time. As a consequence, the distribution function is uniform along the field lines, and can be obtained by solving the 2D momentum space $(p_{\|}, p_{\perp})$ bounce-averaged FP equation $\{C(f) + Q(f)\} = 0$. We solve the FP equation using the code DKE and calculate the distribution function. Taking moments of the distribution, we calculate the flux-surface averaged current density $\langle J \rangle$ and density of power absorbed $\langle P \rangle$. From these moments we calculate the local normalized figure-of-merit $\eta = (J/en_e v_{Te})/(P/n_e m_e \nu_e v_{Te}^2)$, where n_e is the electron density, ν_e is the e-e collision frequency and $v_{Te} = \sqrt{\kappa T_e/m_e}$ is the thermal velocity.

Kinetic Calculations of Ohkawa EBWCD in NSTX

In order to study EBWCD in a realistic ST scenario, we consider a typical NSTX plasma, with the following NSTX-type parameters: $R_0 = 0.9$ m, $a = 0.6$ m, $B_0 = 0.35$ T, $I_0 = 0.8$ MA, $T_{e0} = 3.0$ keV, $n_{e0} = 3.0 \times 10^{19}$ m^{-3}. In this high-β regime, the poloidal magnetic field off-axis becomes comparable to the toroidal magnetic field, which creates a dip in the total magnetic field profile, as shown in Figure 1, where we plot the Doppler-shifted second harmonic of the cyclotron frequency. We choose a frequency between the first and the 2$^{\text{nd}}$ harmonic on the LFS, $\omega/2\pi = 12$ GHz, which is shown as a red line in Fig. 1. The value $N_{\|} = 1.5$ is chosen because it is the one for which we find the largest driven current. It is interesting to note that the

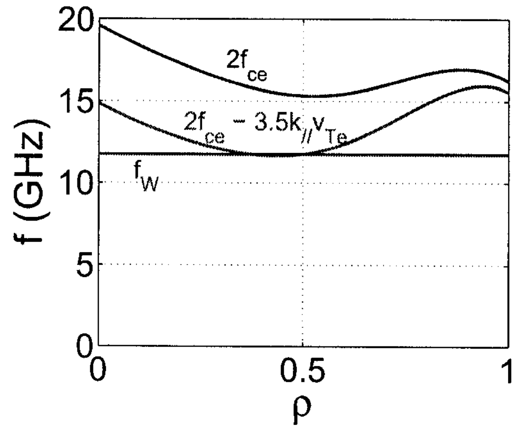

Figure 1: Frequency versus minor radius: EBW (red), $2f_{ce}$ (blue), and Doppler-shifted for $N_{\|}$ =1.5 (green).

maximum CD is obtained for a value of $N_{\|}$ such that the EBW frequency is tangent to the profile of Doppler-shifted 2$^{\text{nd}}$ harmonic cyclotron frequency. This result can be explained by the fact that in the present optimized case, the magnetic field profile is locally flat, meaning that the optical depth in very large. As a consequence, the power is deposited on energetic electrons far in the tail, which leads to larger CD efficiencies. The non-monotonic magnetic field profile has therefore important and positive implications for EBWCD in STs. The driven current density profile is shown

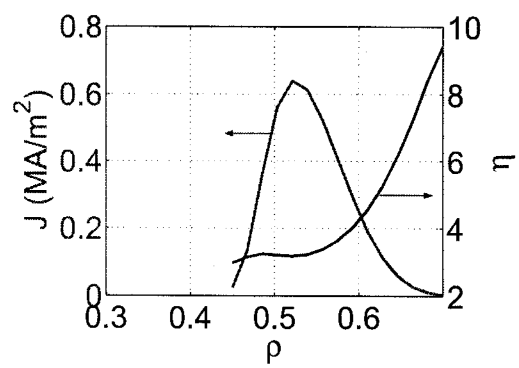

Figure 2: Driven current density (red) and figure of merit (blue) versus minor radius.

in Figure 2. It is centered around the peak value $\rho_{\text{peak}} = 0.53$. We also show the figure of merit η. In this case, a total beam power of $P_{\text{inc}} = 1$ MW is absorbed, and a total current of $I = 87$ kA is driven.

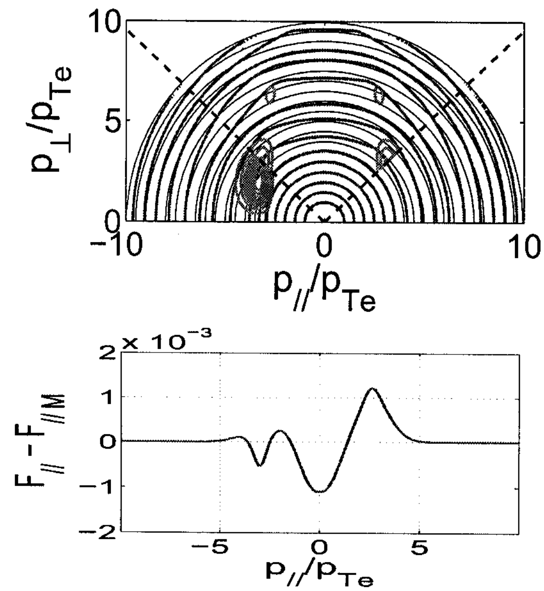

Figure 3: Top: Distribution function in EBWCD (red) and EBW QL diffusion coefficient (green). The unperturbed Maxwellian is in black. Bottom: Parallel distribution function.

In general, EBW are mostly electrostatic waves and therefore $N_\perp \gg 1$. In the present case, we have $N_\perp = 12$ at $\rho = \rho_{\text{peak}}$. As a consequence, finite Larmor radius (FLR) effects are significant, and the QL diffusion coefficient, shown as green lines in momentum space in Figure 3 (top), has several peaks in the $p_\perp$ direction. In this figure are also plotted the unperturbed Maxwellian and the steady-state distribution function in EBWCD. The region of maximum diffusion is situated very near the trapped/passing boundary, and, since the diffusion is mostly in the perpendicular direction, a large EBW-induced trapping takes place. As a consequence, a large Ohkawa current is driven. This current is more easily visualized on the "parallel" distribution function, obtained by integration over $p_\perp$

$$F_\parallel \left(p_\parallel\right) = 2\pi \int_0^\infty p_\perp \, dp_\perp \, f\left(p_\parallel, p_\perp\right) \tag{1}$$

The depletion of electrons due to wave-induced trapping on the resonant side, and the accumulation of electrons due to detrapping on the opposite side, both contribute to driving a large Ohkawa current.

Conclusion

We have shown that a large Ohkawa EBW current could be driven off-axis ($\rho > 0.5$) in ST plasmas. The Ohkawa effect is dominant because of (1) the large fraction of trapped particles, (2) the dominantly perpendicular QL diffusion, and (3) the large FLR effects which allow a positioning of the diffusion region right near the trapped/passing boundary in momentum space. The large figure of merit is due to the very strong damping of the EBW, so that most of the power is deposited on very energetic, weakly collisional electrons. This effect can be enhanced, and the figure-of-merit improved, by locally flat magnetic field profiles in high-β ST. The resulting CD efficiency turns out to be several times larger than for typical off-axis (Fisch-Boozer) ECCD efficiencies in tokamaks.

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