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ELECTRON BERNSTEIN WAVE HEATING AND CURRENT DRIVE IN AXISYMMETRIC TOROIDAL PLASMAS

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Electron Bernstein Wave Heating and Current Drive in Axisymmetric Toroidal Plasmas

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Electron Bernstein waves (EBWs) may be used in overdense plasmas where $\omega_p \gg \omega_c$ and thus heating and current drive (H&CD) by electromagnetic electron cyclotron (EC) waves (the X and O modes) is not possible [1]. From the study of linear EBW properties it is predicted that these waves could generate currents with efficiencies that are significantly larger than ECCD in plasmas with similar density, temperature and fraction of trapped electrons [2]. Recently, EBW heating by O-X-B mode conversion (MC) was demonstrated in the Tokamak à Configuration Variable (TCV) both near the edge [3] and in the center [4] of the plasma. In the present work, general properties of EBWCD are investigated for a variety of plasma conditions and wave characteristics. This study is then used to analyse recent EBW experiments in TCV.

Modeling of EBWCD

The current generated by EBWs results from the balance between the effects of collisions and wave-particle interaction. It can be calculated as a moment of the electron distribution function f obtained from solving the bounce-averaged Fokker-Planck equation in momentum space

$$\nabla \cdot \left[\mathbf{S}^C(f) + \mathbf{S}^{RF}(f) \right] = I^C(f) \tag{1}$$

where $\mathbf{S}^C$ and I^C are the differential and integral parts of the linearized collision operator and $\nabla \cdot \mathbf{S}^{RF}$ is the RF quasilinear operator. This equation accounts for the effect of electron trapping as well as the quasilinear distortion of the distribution function in the presence of high-power RF fields. Equation 1 is solved using the code LUKE [5], while $\mathbf{S}^{RF}$ is calculated with the code R2D2 [6] to determine the fully relativistic dispersion relation and the code ART [7] for EBW ray-tracing calculation.

From the driven current I and power deposited P_{RF} calculated with LUKE [5], the normalized current drive efficiency $\xi_{RF} = 32.7 \times I R_p n_{[20]} / (T_{[\mathrm{keV}]} P_{RF})$ [8] is derived (the temperature and density are calculated at the location of maximum power deposition). This definition provides an intrinsic efficiency measure of the current drive mechanism.

EBWCD characteristics

It was demonstrated that linear EBW characteristics such as the normalized wave vector $k_\perp \rho_T$, the polarization, and the normalized power flow $\phi_\perp$ are essentially independent of the normalized electron density ω_p^2/ω^2 (away from the MC region), the normalized electron temperature $\beta_T^2 = kT/(mc^2)$, and the parallel index of refraction $n_\parallel$. However, they depend strongly upon the ratio ω/ω_c and whether an EC harmonic is approached from the low-field side (LFS) $(\omega/\omega_c > n)$ or the high-field side (HFS) $(\omega/\omega_c < n)$ of the resonance [2]. These definitions of LFS/HFS are not to be confused with outboard side $(R > R_p)$ and inboard side $(R < R_p)$ of the plasma. Indeed, in high-β plasmas as found in spherical tori, it is possible to obtain HFS damping using outboard launching because of the presence of a magnetic well on the outboard side [9]. Thus, for the sake of a general study, EBWCD can be calculated by varying ω/ω_c while assuming that ω_p^2/ω^2, β_T and $n_\parallel$ are constant across the EBW power deposition region as the wave approaches a given harmonic of the EC frequency. Other independent parameters in these calculations are the effective charge Z_{eff}, the local inverse aspect ratio $\varepsilon = r/R$, which determines the fraction of trapped electrons, and the incident wave power density $S_\perp$.

LUKE calculations show that ξ_{RF} is also essentially independent of ω_p^2/ω^2, β_T and $n_\parallel$ (as long as $|n_\parallel| \gg \beta_T$) [10]. However, ξ_{RF} can be strongly reduced by harmonic overlapping due to the Doppler shift, which is proportional to β_T and $n_\parallel$. In addition, quasilinear effects do not affect the EBWCD efficiency significantly, except at very high incident power density on the flux-surface $S_\perp \gtrsim 1\text{MW/m}^2$ [10]. The Z_{eff} effect on ξ_{RF} is found to follow the analytical predictions [11].

EBWCD is calculated as a function of ε with deposition either on the outboard side $(\theta = 0)$ or on the inboard side $(\theta = \pi)$ of the magnetic axis. Here θ is the poloidal angle. A pure deuterium plasma with $S = 1\text{W/m}^2$, $\omega_p^2/\omega^2 = 10$, $\beta_T = 0.05$, and $n_\parallel = -1$ is considered. The results are shown in Fig. 1. In the core $(\varepsilon = 0)$, an efficiency of $\xi_{RF} = 1.0$ is found for LFS deposition while $\xi_{RF} = -0.7$ for HFS deposition. In both cases, the Fisch-Boozer (FB) mechanism generates the driven current, and the sign difference relates to the parallel velocity of resonant electrons, which is opposite in LFS and HFS interactions. Such values for ξ_{RF} are significantly higher than typical ECCD values for similar conditions of density and temperature, because EBW power is deposited further in the tail of the electron distribution function.

On the inboard side where the power is deposited on passing electrons only, the FB effect always dominates. Yet, the CD efficiency decreases with ε as the trapped electron region enhances the effect of pitch-angle scattering between co- and counter-passing regions. On the outboard side, the FB effect dominates when the fraction of trapped electron is small, up to a

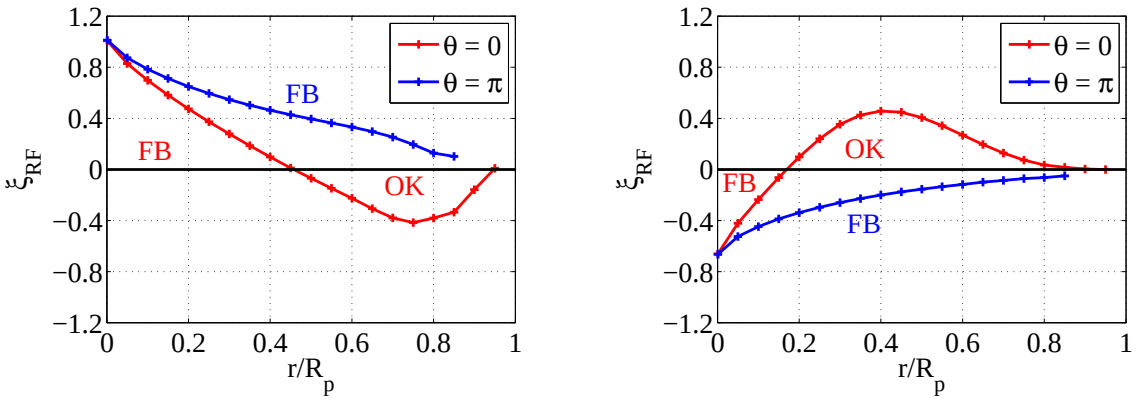

Figure 1: EBWCD as a function of ε with deposition on the LFS (left) or the HFS (right) of the EC resonance, for the cases in which it is located either on the outboard $(\theta = 0)$ or on the inboard $(\theta = \pi)$ side of the plasma.

given value of ε for which the FB and Ohkawa (OK) effects compensate exactly and the driven currents cancel out. For larger values of ε the OK effect dominates. Yet, the threshold value is much larger in the LFS case $(\varepsilon = 0.45)$ than in the HFS case $(\varepsilon = 0.15)$. These observations can be explained by the momentum-space localization of wave-particle interaction and by the parallel component of the momentum space diffusion direction $\mathbf{V}$: $V_{\|}/V_{\perp} \simeq \beta_T n_{\|} p_{\perp}$. In LFS interaction, $k_{\perp}\rho_T \gg 1$ is very large such that the power is deposited close to the $p_{\|}$ axis and far from the trapped region; in addition, $\mathbf{V}_{\|}$ is directed away from the trapped region. In HFS interaction, $k_{\perp}\rho_T \lesssim 1$ is much smaller such that the power is deposited at higher values of $p_{\perp}$, closer to the trapped region; in addition, $\mathbf{V}_{\|}$ is directed towards the trapped region. In summary, LFS interaction favors FBCD while HFS interaction favors OKCD.

EBWCD in TCV

By coupling LUKE to the ray-tracing code ART, which calculates the EBW propagation including the mode-conversion process, EBW experiments in TCV can be modeled [4]. Two different heating configurations are analyzed here, and the results are shown in Fig. 2. In the first shot #31541, the EBW propagates far above the midplane and thus undergoes strong $n_{\|}$ variations along the wave path [12]. As a consequence of the strong Doppler-shift, the EBW power is rapidly absorbed by LFS interaction at $r/a = 0.8$, in accordance with experimental observation [3]. The predicted driven current is $I = 1.5$ kA. Such a low value of I is explained by the very low local value of the temperature T and the competition between FBCD and OKCD so far off-axis. Nevertheless, the normalized efficiency $(\xi_{RF} = 0.3)$ is remarkably high for CD using EC waves in the presence of such a large fraction of trapped electrons, and is in accordance with the results of Fig. 1 $(r/R_p = 0.23)$.

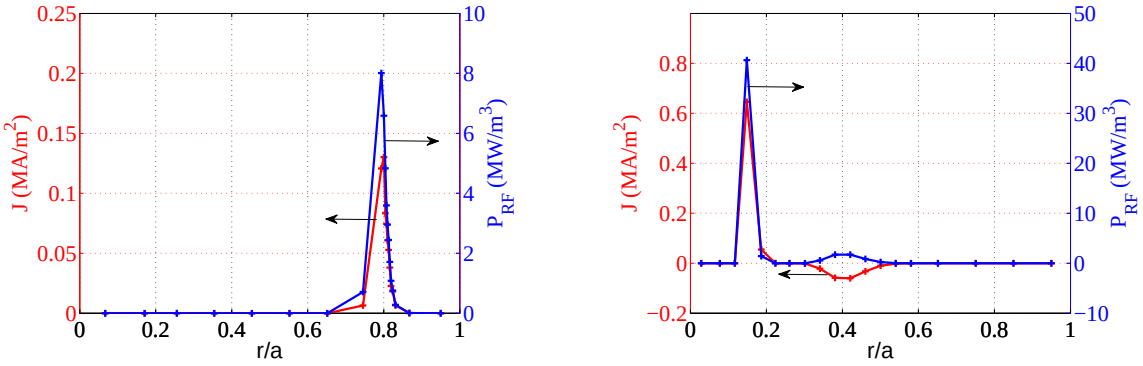

Figure 2: Driven current and Power deposition calculated by ART-LUKE with launching above (#31541, left) or near (#34465, right) the horizontal midplane.

A larger current could be expected with equatorial launching, which limits $n_{||}$ variations and allows the wave to propagate further inside. Such experiment was conducted with the shot #34465. Simulations find that the power is absorbed partly at $r/a = 0.4$ (40% of the power) and partly at $r/a = 0.2$ (60%), in agreement with experimental measurements [4]. The existence of two deposition regions is explained by the evolution of $n_{||}$, which remains nearly constant at $n_{||} \sim 0.6$ until $r/a \sim 0.4$ where it undergoes a strong downshift until the power is fully absorbed at $r/a \sim 0.2$ and $n_{||} \sim -0.5$. Because the two depositions correspond to opposite signs of $n_{||}$, they drive currents in opposite directions and the resulting current calculated is very small: $I = -0.2$ kA. A larger current may be obtained by displacing the launching position vertically in order to modify slightly the $n_{||}$ evolution and damp the full power in a single location.

In conclusion, EBWCD properties depend mostly upon the type of approach to the EC harmonic (LFS/HFS) and the fraction of trapped particles. The location of EBW power deposition, however, varies with $n_{||}$, which depends strongly upon the vertical launching position.

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