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Linear Estimation of Electron Bernstein Current Drive (EBCD) in inhomogeneous plasmas

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Introduction

Apart from the well-known absence of density cut-off values for Electron Bernstein Waves (EBW), they have shown to be a suitable tecnique to drive current, low order rationals positioning, and magnetic shear modification in stellerators. Operation sustainment in tokamaks is also an aplication of interest that Electron Bernstein Current Drive (EBCD) points out [1].

The fully relativistic linear estimation of the current drive efficiency for electromagnetic waves was developed for inhomogeneous plasmas up to the second Larmor radius order and applied to the TJ-II stellarator [2]. Recent calculations have been carried out for EBW and have shown larger efficiency values than those for electromagnetic waves. This was expected since for values of the paralell refractive index ($N_{\parallel}$) larger than 1 the resonance condition in momentum space changes its elliptical shape to a hyperbolic one, thus allowing the high speed electrons to resonate. The Bessel functions of the first kind, that are present in the calculation, have also been expanded iteratively up to the Larmor radius order at which the convergence of the serie took place, including in this way finite Larmor radius effects, which cannot be neglected for large values of $N_{\perp}$. Together with particle trapping phenomena, included considering the Okhawa effect, a useful and accurate tool is available for its inclusion into the ray tracing code TRUBA [3], currently used at TJ-II. This last point is developed in this work, and completes our description with the refraction effects and the complex geometry of the device, what makes our result more reliable for a first experimental approach to the recently installed electron Bernstein heating system in TJ-II.

Efficiency function and current generated

Our calculation of the current drive efficiency is based on the asymmetric modification of the electron resistivity in momentum space in its relativistic formulation. The paralell current density is defined as

$$J_{\parallel} = A\int d\mathbf{u}\,\eta_T(\mathbf{u})\,w_s(\mathbf{u}),\ \text{with}\ A = \frac{2\pi\varepsilon_0^2 mc^2}{n\Lambda e^3}. \tag{1}$$

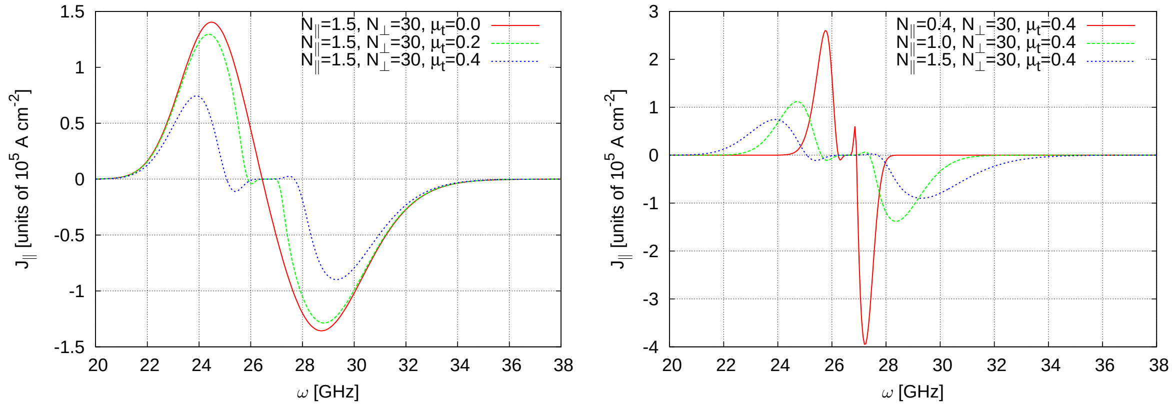

Figure 1: On the left, paralell current density gerenated as a function of the frequency for fixed values of both $N_{\parallel}$ and $N_{\perp}$, and different values of trapping parameter μ_t, for $T_e = 1$ keV, $n_e = 1\times10^{19}$ m^{-3} and $B = 0.95$ T. On the right, dependence of $J_{\parallel}$ on the frequency for different values of the paralell refractive index $N_{\parallel}$, for $N_{\perp} = 2$ and $\mu_t = 0.4$, and also for $T_e = 1$ keV, $n_e = 1\times10^{19}$ m^{-3} and $B = 0.95$ T.

where n is the electron density, m the mass, e the electric charge, c the speed of light, Λ the Coulomb logarithm, and $\eta_T(\mathbf{u})$, with $\mathbf{u} = \mathbf{p}/mc$, is the microscopic efficiency function including particle trapping as it was presented in [2]. The absorbed power density in momentum space at harmonic s, w_s, is expressed as follows

$$w_s\left(u_{\parallel}\right) = \frac{\pi\varepsilon_0\mu^2\omega_p^2}{4\omega K_2(\mu)}\left|\vec{\Pi}_s\cdot\vec{E}\right|^2\exp\left(-\mu\gamma\right),\ \text{with}\ \vec{\Pi}_s = \left(\frac{sJ_s(\rho)}{\rho}, -\mathrm{i}J_s'(\rho), J_s(\rho)\frac{u_{\parallel}}{u_{\perp}}\right). \quad (2)$$

where $\gamma = \left(1+\mathbf{u}^2\right)^{1/2}$ is the Lorentz relativistic factor, ω_p the plasma frequency, ω the wave frequency, $\mu = mc^2/T$, with T the temperature, and K_2 the second order MacDonald function. In the polarization term $\left|\vec{\Pi}_s\cdot\vec{E}\right|$, $\vec{E}$ is the wave electric field and $J_s(\rho)$ are the Bessel functions of the first kind with argument $\rho = N_{\perp}u_{\perp}\omega_c/\omega$. Then the macroscopic efficiency function $\gamma(\mathbf{r})$ at a point of the traced ray is calculated as

$$\gamma(\mathbf{r}) = \frac{J_{\parallel}(\mathbf{r})}{P_d(\mathbf{r})} = \frac{\int \eta_T(\mathbf{u})\,w_s(\mathbf{u})\,d\mathbf{u}}{\int w_s\left(u_{\parallel}\right)du_{\parallel}}. \quad (3)$$

Trapped particles satisfy the condition $\left(u_{\parallel}/u\right) \le \mu_t \equiv \left(1 - B/B_{max}\right)^{1/2}$. They have been considered not to contribute to the current, taking into account the trapping regions for the integral limits in Eq. (1). In Fig. 1, the dependence of $J_{\parallel}$ with different values of μ_t and the refractive index components are shown, and the Okhawa effect can be observed.

Adaptation to the ray tracing code TRUBA

With all the needed parameters provided by TRUBA, the macrocopic efficiency function at each position of the ray trajectory using Eq. (3) is obtained. For the current density calculation the average absorbed power density at a magnetic surface and harmonic s (W_s) is also needed,

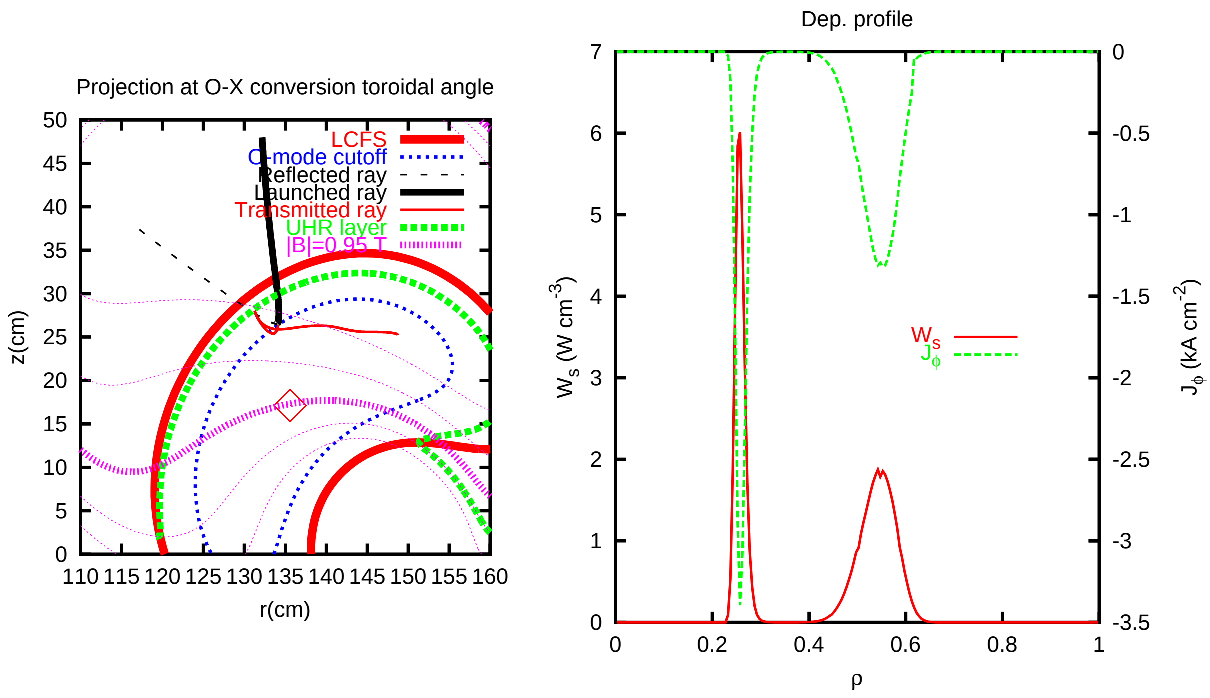

Figure 2: On the left, the projection ot the launched (thick line), reflected (dotted line), and transmitted (thin line) ray trajectories in the toroidal TJ-II plane where the O-X conversion occurs is represented. On the right power deposition and toroidal current density profiles are shown.

since the driven paralell current calculation depends on this quantity as: $J_{\|} = \gamma(\mathbf{r})W_s$. W_s can be approximated by $W_s(\mathbf{r}) = \Delta P/\Delta V$, where ΔP is the power deposition between two consecutive ray steps, which is provided by TRUBA, and ΔV is the volume, and can be aproximated by: $\Delta V = 2\pi^2 R_0[2\langle r\rangle\Delta\langle r\rangle + (\Delta\langle r\rangle)^2]$, where $R_0 = 1.5$ m is the major radius of the TJ-II stellarator, $\langle r\rangle$ the mean minor radius of the magnetic surface, and $\Delta\langle r\rangle$ is the variation of the mean minor radius in the ray step. The toroidal current density J_ϕ is easily obtained: $J_\phi = J_{\|}(\mathbf{r})B_\phi(\mathbf{r})/B(\mathbf{r})$, where $B_\phi(\mathbf{r})$ is the toroidal magnetic field and $B(\mathbf{r})$ its module. Finally, the integration on the cuts of the magnetic surface must be performed to obtain the total current generated,

$$I = \int \mathbf{J}\cdot d\mathbf{S} = 2\pi\int_0^a \langle r\rangle J_\phi(\langle r\rangle)\, d\langle r\rangle. \tag{4}$$

The power deposition W_s and toroidal current profiles J_ϕ are represented on the right of Fig. 2, for the ray trajectories plotted on the left [4]. A total current of $I = -22.32$ kA has been obtained. Fig. 3 shows the current efficiency $\gamma(s)$ as a function of the ray trajectory. As it can be seen, the efficiency changes the sign with the paralell refractive index $N_{\|}$, and remains zero in a interval where no resonant electrons are found.

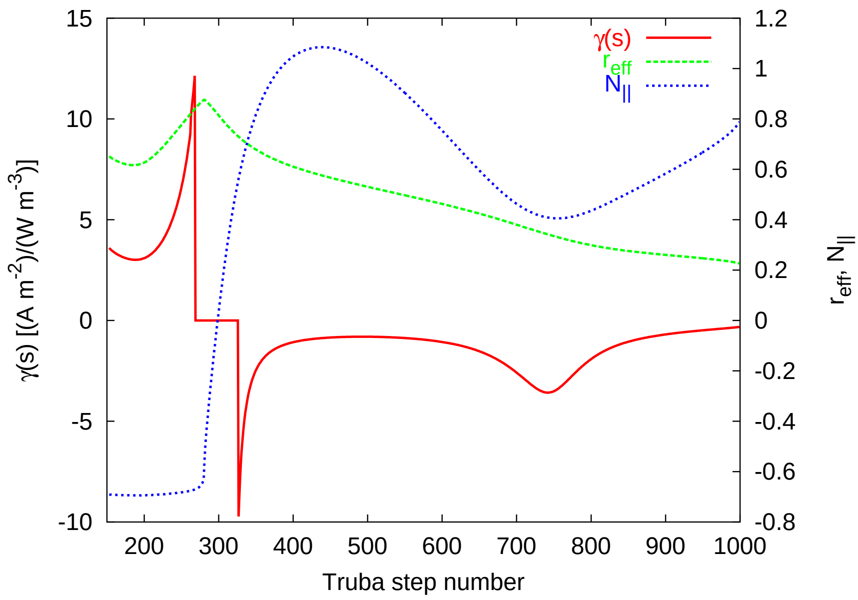

Figure 3: Efficiency function (continuous red line) for the transmitted ray trajectory of Fig. 2. Evolution with the ray step of the paralell refractive index (dotted blue line) and effective radius (dashed green line). An integrated current I=-22.32 kA is obtained for a total injected power of 300 kW.

Conclusions

The current driven by EBW in TJ-II has been estimated, showing higher efficiency than the one found for electromagnetic waves. The current has been calculated by introducing the macroscopic efficiency function in the ray tracing code TRUBA, which was developed to compute EBW propagation and absorption in TJ-II. The macroscopic efficiency function has been adapted to be valid for any value of the refracftive index, i. e., for any Larmor radius order and for $|N_{||}| > 1$. Despite of the fact that the efficiency function changes its sign (see Fig. 3), the driven current has always the same sign, due to the fact that absorption happens always in the low field side. In this way, the current drive efficiency is maximum, since no current is driven in the opposite direction.

References

[1] H. P. Laqua, *Plasma Phys. Control. Fusion* **41**, R1-R42 (2007).

[2] F. Castejón, C. Alejaldre and J. A. Coarasa, *Phys. Fluids B* **4**, No. 11, p. 3697 (1992).

[3] M. A. Tereshchenko *et. al*, *Proceedings of the 30th EPS Conference on Contr. Fusion and Plasma Phys.*, **27A**, P-1.18 (2003).

[4] F. Castejón, A. Cappa, M. A. Tereshchenko, S.S. Pavlov, A. Fernández, Fusion Science and Technology **52**, p. 230 (2007).

[5] J. M. García-Regaña *et. al*, *Proceedings of the 15th Joint Workshop on ECE and ECRH* (2008).