# Modelling of mode conversion current drive in ion cyclotron frequency range *

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Mode conversion in a plasma with two sorts of ions can be used for generation of a steady state current in a tokamak (see, e.g. [1]). In the case of light minority and large enough poloidal magnetic field so that it's effect dominates over the finite Larmor radius effects, FMSW converts into a slow wave (SW) which propagates from the high field side towards the minority ion cyclotron resonance zone. While approaching this zone, component of SW wave vector in the direction of major radius increases and becomes dominant in the parallel wave vector. As the result, absorption of SW drives the currents of opposite signs at the upper and lower parts of torus. Since these currents tend to cancel each other, in order to drive the current, the up-down asymmetric excitation of fast magnetosonic wave (FMSW) is necessary. If the minority concentration is small, both, mode conversion and SW absorption by the minority ions and electrons are localized in a relatively narrow region compared to the plasma radius. Therefore, this case can be studied with help of a slab model taking into account a finite poloidal field of a tokamak. Within such a model adopted in this paper magnetic field has two components, poloidal $B_R = const$ and toroidal $B_\varphi = B_{\varphi,0} R_0/R$, where $R$ is the major plasma radius, (subscript 0 here corresponds to the values at the cyclotron resonance point) plasma parameters are constant, and curvature of magnetic field is

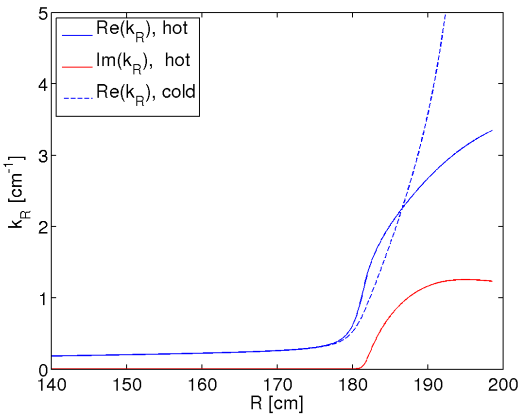


Figure 1: Real and imaginary parts of wave vector component $k_R$ in cold and hot plasma.

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ignored in the solution of Maxwell equations. The parameters are close to those of TEXTOR, $R_0 = 200$ cm, $B_{\varphi,0} = 2.1$ T, $B_R/B_{\varphi,0} = 0.05$, plasma density $n_e = 2.4 \cdot 10^{19}$ m$^{-3}$, temperatures of all particle species are $T = 3$ keV, and 16% hydrogen minority ions in the deuterium plasma have been assumed. At this point, finite Larmor radius effects have been ignored in the study.

It is demonstrative to consider first mode conversion with help of the WKB approximation. In Fig. 1 the real and imaginary parts of the wave vector component normal to the the slab, $k_R$, are shown for the hot plasma described by the local dispersion equation and for the cold plasma described by MHD approximation. Here the FMSW incident from the high field side is coupled to the SW which corresponds to the Alfven wave (Stix wave). For the cold plasma, following the "magnetic beach" scenario, SW becomes infinitely short at the cyclotron resonance point, however thermal effects due to the parallel particle motion in the hot plasma modify the dispersion so that SW achieves high values of $k_R$ much closer to the conversion point and, due to the respective increase of the parallel wave number, is almost immediately absorbed by the minority ions what can be seen from Fig. 2. This absorption leads to the current drive by ions which generates the current in the same direction as Cherenkov absorption by electrons, i.e., current is weakly dependent on the toroidal wave vector component and is driven towards the high field side. This can be seen from Fig. 3 where the canonically averaged components of quasilinear diffusion tensor corresponding to diffusion over energy are shown for the minority ions and electrons (coefficients have been normalized in the figures so that they have the same scale). Due to its strong damping, SW interacts mainly with the tail of minority ion distribution

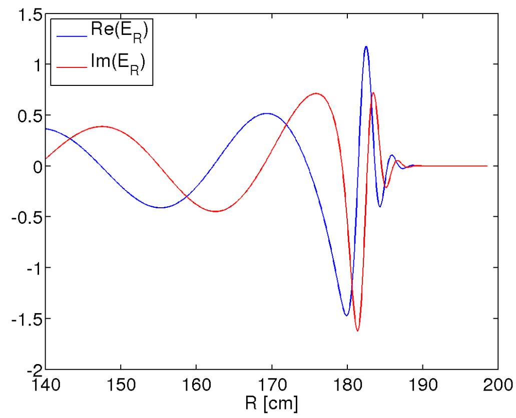


Figure 2: Real and imaginary parts of the electric field component $E_R$ for the WKB solution.

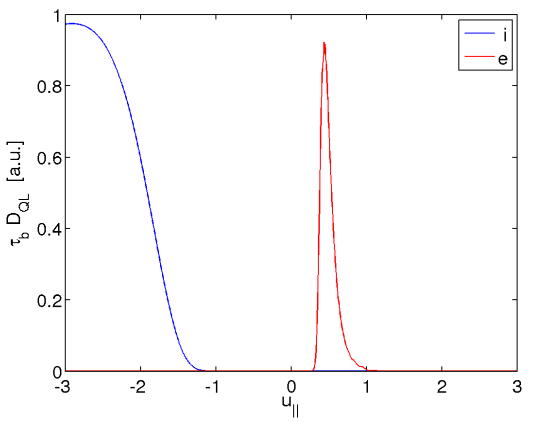


Figure 3: Normalized quasilinear diffusion coefficients for the ions (i) and electrons (e).

while the interaction with electrons is weak. Due to the relatively low parallel phase velocity of the SW it interacts mainly with slow electrons which in absence of toroidicity could lead to high current drive efficiency. Current drive efficiency defined for a particular particle species $s$ as a ratio of the flux surface averaged parallel current and absorbed power densities is calculated ignoring in the narrow resonant interaction zone the change of parallel velocity due to the magnetic mirroring force as follows,

$$\eta_s \equiv \frac{\langle j_{\|s}\rangle}{\langle p_s^{abs}\rangle} = \frac{el_c}{2T}\left(\sum_{\pm}\int_0^{\infty} \mathrm{d}u_\perp\, u_\perp \int_{-\infty}^{\infty} \mathrm{d}u_\| \mathrm{e}^{-u^2} |u_\|| \,\tau_b D_{QL}\right)^{-1} \tag{1}$$
$$\times \sum_{\pm}\int_0^{\infty} \mathrm{d}u_\perp\, u_\perp \int_{-\infty}^{\infty} \mathrm{d}u_\| \mathrm{e}^{-u^2} \frac{1}{u_\|}\left[\frac{\partial g}{\partial u_\|} - \frac{n\omega_c}{\omega}\left(\frac{\partial g}{\partial u_\|} - \frac{u_\|}{u_\perp}\frac{\partial g}{\partial u_\perp}\right)\right] |u_\|| \,\tau_b D_{QL}$$

where $T$, $l_c$, $\omega_c$, $\omega$ and $n$ are temperature, mean free path, cyclotron frequency, wave frequency, and cyclotron harmonic number, respectively, $g$ is the velocity space current drive efficiency (Green's function which for electrons is the same with the generalized Spitzer function), $\tau_b$ is bounce time and $D_{QL}$ is the coefficient of the quasilinear diffusion over energy. Here the velocity space integration is over the invariants of motion - normalized to the thermal velocity parallel and perpendicular components of particle velocity at the centers of resonant interaction regions on a given flux surface. The summation is over two such regions located at the upper and lower parts of the flux surface. Green's function $g$ and $\omega_c$ must be evaluated at the centers of these regions. Green's functions have been calculated here by the kinetic equation solver SYNCH [4] which has been recently upgraded for the treatment of ion current drive. The non-local quasilinear diffusion coefficients $D_{QL}$ for the Cherenkov ($n = 0$) interaction of electrons and fundamental cyclotron ($n = 1$) interaction of minority ions are computed here numerically from the solution of Maxwell equations in the lowest order Larmor radius approximation. Although it is demonstrative, the WKB approximation is violated in the conversion region being of interest. Therefore, more accurate computations of the electromagnetic field distribution have been done using the resonant layer method, RLM [2]. In this method, FMSW field is calculated in most of the plasma where SW is absent using the iterations starting from the MHD solution in

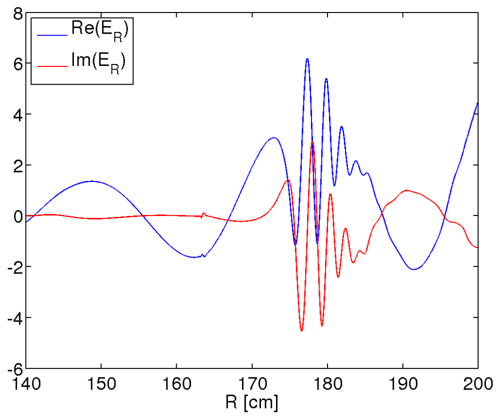


Figure 4: Electric field component $E_R$ for the full wave solution.

absence of the poloidal field. Thermal effects connected with fundamental minority resonance are taken into account with help of thermal correction field derived in [3]. Then the exact full wave problem taking into account non local wave-plasma coupling is solved in the mode conversion/absorption region and the resulting full wave solution is matched with the fast wave solution. It can be seen that distribution of electric field resulting from RLM (Fig. 4) qualitatively confirms the main features of the WKB estimate for the SW. In particular, quasilinear diffusion coefficients of electrons shown in Fig. 5 are very similar to the WKB result. As a result electron efficiency is also practically the same, 1.16 Am/W, independent of $k_z$, compared to 1.21 Am/W for the WKB solution. At the same time, quasilinear diffusion due to the fast wave absorption missing in WKB solution, modifies the ion coefficient adding some diffusion at positive velocities what reduces strongly the ion current drive efficiency - from 0.57 Am/W for the WKB solution to 0.14 Am/W with $k_z = -0.03$ cm$^{-1}$ and 0.04 with $k_z = 0.03$ cm$^{-1}$. Since ions absorb in this case more that 90% of the power, this leads to the significant reduction of the overall efficiency to 0.3 Am/W and 0.14 AM/W for $k_z < 0$ and $k_z > 0$, respectively. Thus, an obvious conclusion is that FMSW excitation from the high field side is preferable to the standard low field side excitation considered here. Note that an approximation used here ignores Larmor radius effects. It is valid if the second harmonic resonance for the bulk ions stays away from the minority cyclotron absorption region, or poloidal field is strong enough.
Actually, this is not the case for proton minority in the deuterium plasma since these resonance points are the same. Nevertheless, these results are useful for different light minority scenarii such as $^3$He in deuterium.

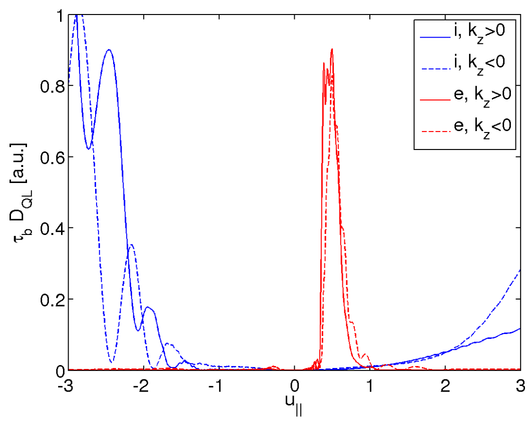


Figure 5: Quasilinear diffusion coefficients for the full wave solution for $k_z = 0.03$ cm$^{-1}$ (solid) and $k_z = -0.03$ cm$^{-1}$ (dashed).

## References


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