1-d MODEL FOR PROPAGATION AND ABSORPTION OF H.F. WAVES NEAR ION CYCLOTRON RESONANCES IN TOKAMAK PLASMAS

M.Brambilla, T. Krücken

Max-Planck-Institut für Plasmaphysik, Euratom Association
D-8o46 Garching, FRG

Ray tracing has proven an attractive tool for modeling of ICRF heating of large plasmas /1/, not lastly because of the simplicity of its numerical implementation. To be really useful, however, it has to be supplemented by the full-wave analysis of ion cyclotron and ion-ion hybrid resonance. The equations to be solved for this purpose must include the poloidal magnetic field, full parallel dispersion, and perpendicular dispersion to 2d order in the Larmor radius; they have been derived in /2/-/4/. In their general form, they are a set of integro-differential equations in two space variables. In a layer around resonance, however, they can be made one-dimensional: the vertical component of the wavevector, k_z, and the elements of the metric can namely be regarded as constants, compared to the horizontal variation induced in the HF response of the plasma by the vicinity of the resonance itself. This approximation has been discussed in /5/, where expressions were obtained for the mode conversion efficiency and absorption, in a form apt to be used in a ray-tracing code /6/.

The equations solved in /5/ were, however, further idealised by artificially separating mode conversion from cyclotron absorption; in the important scenario of H^+ minority in D^+ plasma, moreover, only the limiting cases of very low and high concentration could be solved analytically, and only a plausible interpolation suggested in between. To overcome these limitations, we have written a numerical code (ONEDIM), which solves the one-dimensional equations in their full generality. They are of the form:

$$\left\{\left(u^*\frac{d}{dx}+iv^*\right)\left[\left(1+2\lambda_e+2\lambda_i+\frac{k_\varphi^2}{P}\right)\left(u\frac{d}{dx}+iv\right)\right]-2\left(k_\varphi^2-\hat{\nu}-L\right)\right\}E_+ +$$

$$-\left\{\left(u\frac{d}{dx}+iv\right)\left[\left(1+2\lambda_e-\frac{k_\varphi^2}{P}\right)\left(u\frac{d}{dx}+iv\right)\right]\right\}E_- = 0$$

$$-\left\{\left(u^*\frac{d}{dx}+iv\right)\left[\left(1+2\lambda_e-\frac{k_\varphi^2}{P}\right)\left(u^*\frac{d}{dx}+iv^*\right)\right]\right\}E_+ +$$

$$+\left\{\left(u\frac{d}{dx}+iv\right)\left[\left(1+2\lambda_e+\frac{k_\varphi^2}{P}\right)\left(u^*\frac{d}{dx}+iv^*\right)\right]-2\left(k_\varphi^2-\hat{\nu}-R\right)\right\}E_- = 0$$

$$\hat{\mathcal{D}} = \alpha^2 \frac{d^2}{dX^2} - 2i\beta \frac{d}{dX} + \gamma$$

where u, v, α, β, γ, are constants depending on the orientation of the incident wavefronts relative to magnetic surfaces and to the resonance layer; R, L(x), P are the elements of the dielectric tensor in the limit of zero Larmor radius, but with kinetic damping: $\lambda_i(x)$ and $\lambda_e(x)$ are the FLR corrections due to ions (1st harmonic IC damping) and electrons (electron magnetic pumping, (EMP)) respectively; electron Landau damping (ELD) is alo included to lowest order in m_e/m_i. Equations (1) are supplemented by the assumption that a fast wave is incident from one side, and by outward radiation conditions for the transmitted and reflected waves, both fast and slow.

The code ONEDIM is based on a finite element discretisation of (1), with cubic Hermite interpolating functions. The advantages of FEL for problems of this kind, and the outstanding convergence properties of cubic Hermite interpolation in particular, have been emphasied in /7/, and were confirmed by our results. Efficiency was improved by chosing the mesh step to be a fraction of the shortest wavelength existing at each point according to the dispersion relation: typically 200 elements suffice in a JET size plasma with a resonance layer of 30 to 50 cm to achieve an accuracy of at least 10^{-5} both in the field itself and in the energy balance. The integration is fast enough to make possible the incorporation of ONEDIM into the ray tracing code; in the following examples however it has been run as an independent package.

An example of the electric field distribution predicted by the code is shown in Fig. 1 (3 % H^+ in D^+, $n_e = 5 \cdot 10^{13}$ cm^{-3}, $T_e = T_i = 2$ keV, $B_{Tor} = 3.5$ T, $B_{pol} = 0.35$ T, f = 50 MHz, R = 3.2 m at $\omega = \Omega_H = 2\Omega_D$; incoming fast wave from the low magnetic field side along the equatorial plane, with $k_z = 0$ and $n_\varphi = 10$). The ion Bernstein wave to the left of the ion-ion resonance (R = 3.12 m) is clearly visible. In spite of its large amplitude it transports only 5.5 % of the incident power, against 6.3 % transmitted to the fast wave: this is due to its partially electrostatic polarisation, which is however not enough for efficient ELD (in the tokamak, absorption by ELD will be enhanced by refraction as this wave propagates towards regions of shorter and shorter wavelengths; the lack of absorption in the 1-dim. model shows that power deposition in the electrons could be appreciably broader than usually admitted). The ions absorb 39.0 % of the power; the rest, i.e. 49.2 %, is reflected. These figures are in excellent agreement with the estimates made in /5/; for example, they confirm the relatively large optical thickness of the evanescence layer in large devices, which reduces the efficiency of mode conversion of low n_φ partial waves with LMFS excitation.

A more systematic comparison of the predictions of the ONEDIM code with the estimates used in ray tracing is made in Fig. 2, which shows the energy balance under the same conditions as above, varying the H^+ concentration. For the low n_φ value considered here, the transition from the minority to the mode conversion regime occurs at about 5 % H^+ concentration.

Figure 3 shows a run with 3 % He_3^{++} minority in a H^+ plasma (n_e = $8 \cdot 10^{13}$, f = 35.6 MHz, n_φ = 10, other parameters as in Fig. 1). In this case FLR terms are negligible near the ion-ion resonance, and the cold plasma shear Alfven wave (n^2 = (R+L)/2) is excited. This wave propagates away from the IC resonance of He_3^{++}, and is accurately irrotational, hence unaffected by IC and EMP damping. The strong absorption which is nevertheless visible in Fig. 3 is entirely due to ELD. This points to the importance of keeping this damping in two-dimensional simulations as well, not only for a correct evaluation of electron heating, but also to attenuate somewhat the difficulty of having to resolve very short wavelength features.

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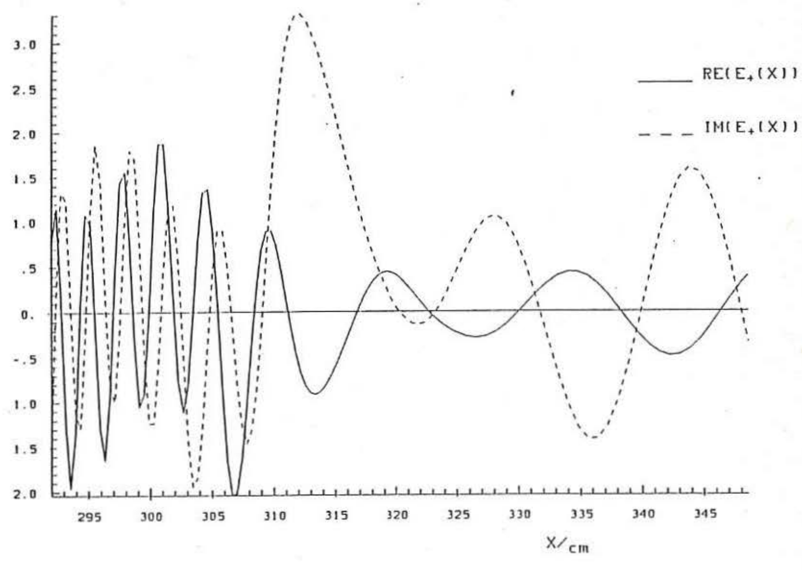

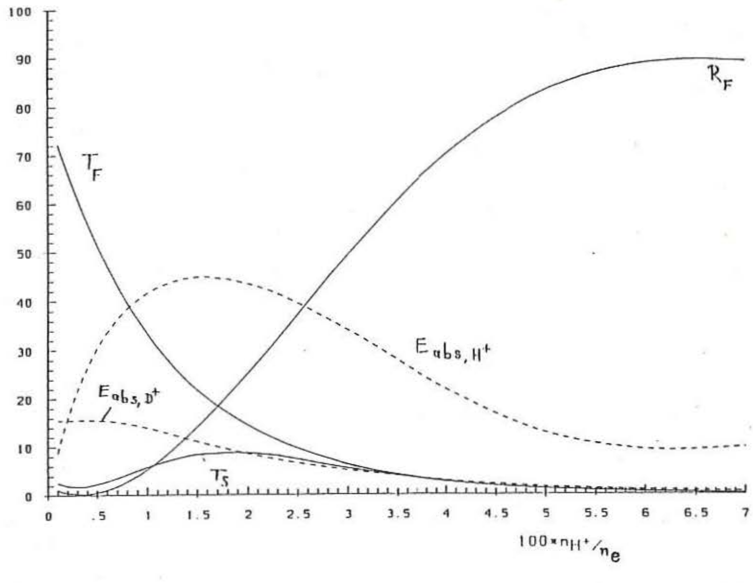

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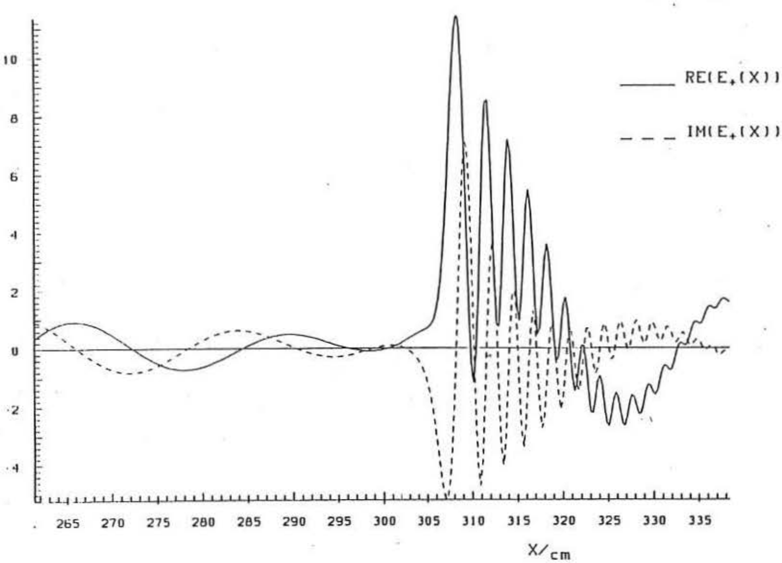

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