GLOBAL MODELING OF R.F. WAVES IN TOKAMAKS IN THE ION CYCLOTRON FREQUENCY DOMAIN

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Simulation of ICRH of tokamak plasmas has mostly used one-dimensional models or methods borrowed from geometric optics (Ray Tracing, [1]). Only recently the first global numerical solutions of Maxwell equations in toroidal plasmas have been developed. Although on the whole confirming the predictions of simpler approaches, a number of questions were still beyond their reach. Cold plasma codes [2] with ad hoc damping near wave resonances should correctly describe depletion of the Fast Wave energy there, but cannot investigate the details of mode conversion and of cyclotron absorption. Hot plasma codes [3] have confirmed that Bernstein waves are excited near resonances, but the geometry was simplified by neglecting the poloidal component of the static magnetic field.

The finite Larmor radius wave equations including kinetic damping in tokamak geometry have been written by Brambilla and Ottaviani [5] generalising previous work by Swanson, and Colestock and Kashuba [4]. They are a system of two integro-differential equations in two space variables; the integral operators are a consequence of spatial dispersion and rotational transform. They are listed in flux coordinates in [6] for plasmas of arbitrary cross-section. Although neglecting some important toroidal effects such as R.F. driven toroidal trapping, these equations should be an excellent approximation for the description of wave propagation and absorption. They includes the full equilibrium geometry, FLR terms, ion cyclotron absorption near $\omega = \Omega_{ci}$ and $\omega = 2\Omega_{ci}$, electron Magnetic Pumping and Landau Damping; the latter is evaluated to lowest order in m_e/m_i.

Here we present the first results of a code which solves these equations for circular plasmas. To cope with the integral nature of the plasma constitutive relation we have adopted a semispectral discretisation, using a Fourier serier representation in the poloidal angle θ, and Finite Elements with cubic Hermite interpolating functions in the radial variable r. The advantage of Fourier modes is that they make it possible to express the integral operators in terms of known functions. However they are not even approximate eigenfunctions of the problem, so that a large number of terms is required for convergence. The number of modes and the radial mesh step required are estimated *a priori* from the shortest wavelengths which have to be resolved, deduced in turn from the local dispersion relation. Collisional damping was taken into account to speed up convergence near the plasma edge, and to deal with modes with low effective $k_{\|} = (n_\phi + m_\theta/q)/R$ (n_ϕ, m_θ are the toroidal and poloidal wavenumbers, q the safety factor, R the torus radius). It has also proved necessary to assume a kind of stochastic damping of Bernstein waves with small $k_{\|}$, to make shure that they do not propagate beyond the radius at which their wavelength becomes shorter than one ion Larmor radius (if this is not done, numerical damping often takes its place). Systematic use of the FFT allows a relatively fast evaluation of the Stiffness Matrix; the inversion subroutine was kindly provided by Dr. W. Kerner.

The computer time grows as the cube of the number of poloidal modes, which in turn increases linearly with the plasma radius. This puts a sharp limit to the size of plasmas for which the code can be used. ASDEX ($R = 165$ cm., $a = 40$ cm) lies close to it. We have simulated a minority heating shot with simultaneous NB heating (4% H^+ in D^+, $B_o = 2.24$ T., I = 380 kA, $n_e(0) = 4\ 10^{13}\ cm^{-3}$, $T_e = 1.5$ keV, $T_i = 2$ keV, f = 33.5 Mhz) in which the H-regime was transiently reached. We have run the toroidal modes $n_\phi = 0$, 10, 20 and 30, which span well the radiated spectrum, using 64 poloidal modes. Convergence, checked by inspection of the poloidal modes amplitude at several radii, was poor for $n_\phi = 0$, acceptable for $n_\phi = 10$, and good for $n_\phi = 20$ and 30. Tests in a smaller plasma indicate that incomplete convergence causes some aliasing in the BW pattern (shown in Fig. 1 for $n_\phi = 10$), but hardly affects the power deposition profiles as long as BW do not spill over to the wrong side of the resonance; even the $n_\phi = 0$ case did satisfy this criterion well.

The power radiated by the antenna ($< \vec{J} \cdot \vec{E} >$) and the total power deposited in the plasma agreed within 7%, 2%, 1% and 0.1% respectively. Modes $n_\phi = 0$ and 10 are in the mode conversion regime, and show large amplitude BW on the h.m.f. side of the resonance. Modes $n_\phi = 20$ and 30 are in the minority regime, dominated by H^+ cyclotron damping. The global power balance is summarized here (cfr. also Fig. 2):

n	0	10	20	30	total
Power fraction	0.489	0.283	0.169	0.059	1.00
H cycl. damping	60.44%	80.89%	82.04%	84.05%	71.30%
D harm. damping	17.96%	13.46%	10.50%	5.80%	14.71%
electron TTMP	$< 0.01\%$	1.60%	6.04%	8.78%	2.00%
electron Landau d.	0.42%	0.39%	0.45%	1.37%	0.47%
stoch. BW damping	14.02%	5.85%	2.39%	0.18%	9.05%

The sum of the last two lines gives the efficiency of mode conversion. These figures agree well with ray tracing estimates. A rough estimate of the antenna resistance gives 5.2 Ω. The weighted sum of the power deposition profiles in the minority ions is shown in Fig. 3. The contribution from $n_\phi = 0$ is modulated by standing waves; those from higher n_ϕ are localised near the equatorial plane and Doppler broadened.

For $n_\phi = 0$ odd poloidal modes are more excited than even ones, in spite of the fact that the antenna is symmetric in θ; there is also evidence of a relatively large standing wave ratio of the FW to the h.m.f. side of the resonance. For higher n_ϕ the FW field pattern ressembles more closely the one predicted by ray tracing. BW are dominated by modes such that $\omega/k_{\|}v_{te} >> 1$, so that electron Landau damping is weaker than usually assumed, and extends to larger radii. They are manifestly backward waves, and their wavefronts tend to align with constant $|B|$ surfaces.

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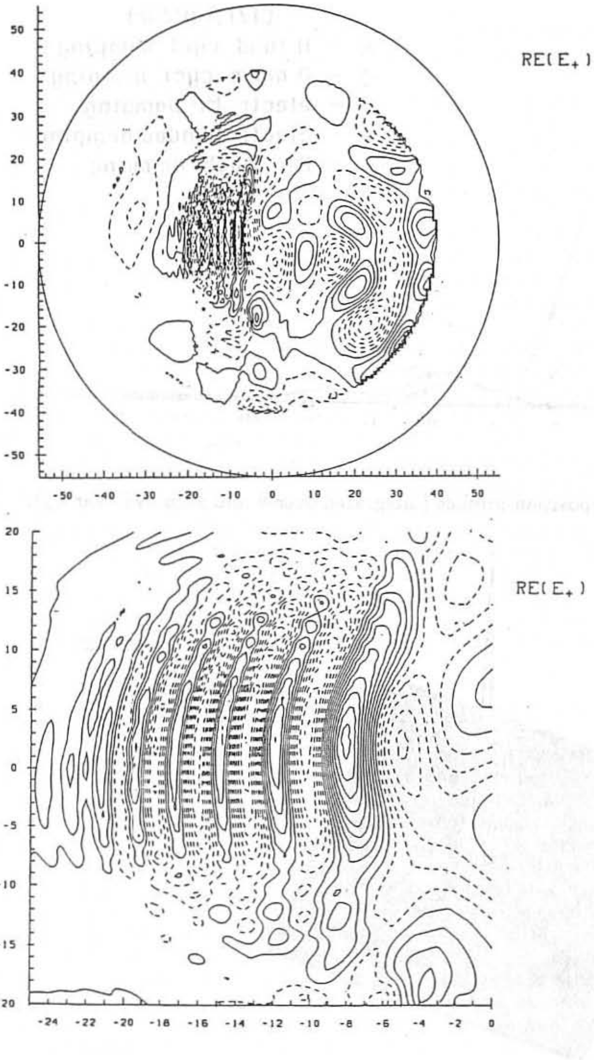

Fig. 1 - Electric field pattern ($n_\phi = 10$): a) whole plasma; b) Bernstein waves.

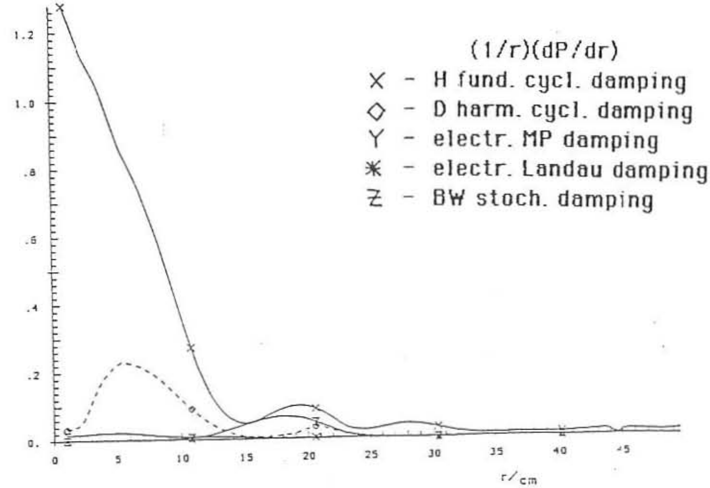

Fig. 2 - Power deposition profiles (integrated over θ and summed over n_ϕ).

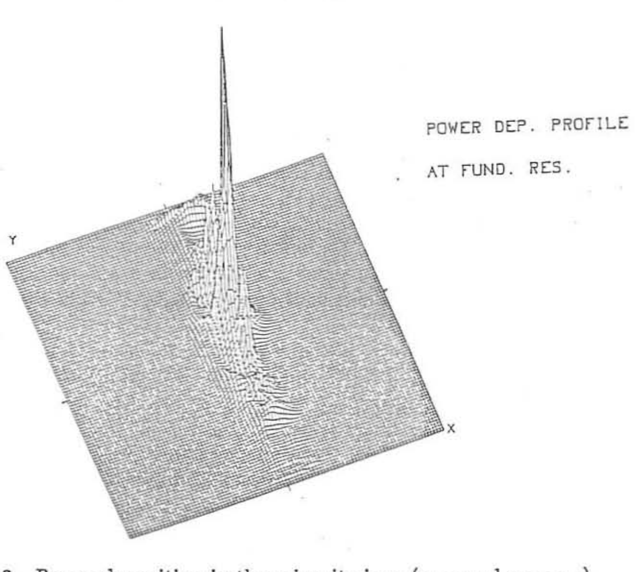

Fig. 3 - Power deposition in the minority ions (summed over n_ϕ).