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Ray tracing of Ion Bernstein waves excited by mode conversion in Tokamak plasmas

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Abstract. We have developed a ray tracing code RAYIBW for ion Bernstein (IB) waves in axisymmetric tokamak geometry. RAYIBW usefully complements the full-wave code TORIC in the ion cyclotron (IC) frequency range, giving information on the propagation and absorption of these short-wavelength waves, which is not accessible to the full-wave code because of the limited numerical resolution available.

Introduction. In heating and current drive experiments in Tokamaks in the ion cyclotron (IC) range of frequencies, an appreciable fraction of the power can be absorbed by the electrons via ion Bernstein (IB) waves excited by mode conversion at ion-ion resonances. An example, simulated with the full-wave code TORIC[1], is shown in fig. 1 (10% Hydrogen in Deuterium, $B_0 = 2.1$ T, $n_0 = 6\ 10^{19}$ m^{-3}, $T_{e0} = T_{i0} = 3$ keV, $f = 30$ Mhz, toroidal wavenumber $n = 6$, in ASDEX Upgrade). IB waves are clearly visible to the high-field side of the Hydrogen IC resonance, located roughly on axis. Such simulations, based on the finite Larmor radius (FLR) wave equations[1], are not trivial. In the FLR approximation, electron Landau damping (ELD) of IB waves is negligible, so that these waves propagate nearly undamped away from the mode conversion layer with rapidly decreasing wavelength. Therefore, to obtain a reasonably convergent run it is necessary to add a damping term sufficient to absorb these waves before they are numerically suppressed by lack of mesh resolution, without interfering with the efficiency of mode conversion and the propagation of the compressional wave. In TORIC this is done by modifying the coefficient of the highest order term of the FLR wave equations in such a way that the corresponding local dispersion relation predicts the same damping rate as the full hot plasma dispersion relation at each point where the IB waves are propagative. The details of this procedure are explained in [2].

The local rate of ELD depends on the parallel phase velocity, hence on the value of the effective parallel wavenumber $k_\zeta^{mn} \simeq (m + qn)/qR$, where q is the safety factor, R is the major radius, and m the poloidal wavenumber. Mode conversion is most efficient when k_ζ^{mn} is sufficiently small (depending on the minority concentration and on the plasma temperature) so that damping in the mode conversion region is weak. ELD, on the other hand, sets in when k_ζ^{mn} is sufficiently large to bring ω/k_ζ^{mn} in the vicinity of the electron thermal velocity. In the case of IB waves, the required change of k_ζ^{mn} is easily produced by refraction in the non-uniform tokamak configuration. From the point of view of TORIC, strong refraction implies a correspondingly large change of the representative poloidal wavenumbers m, up to values of several tens. Although TORIC has recently been successfully run with such a large number of poloidal modes [3], this cannot be done routinely because of the huge CPU memory required. In normal runs,

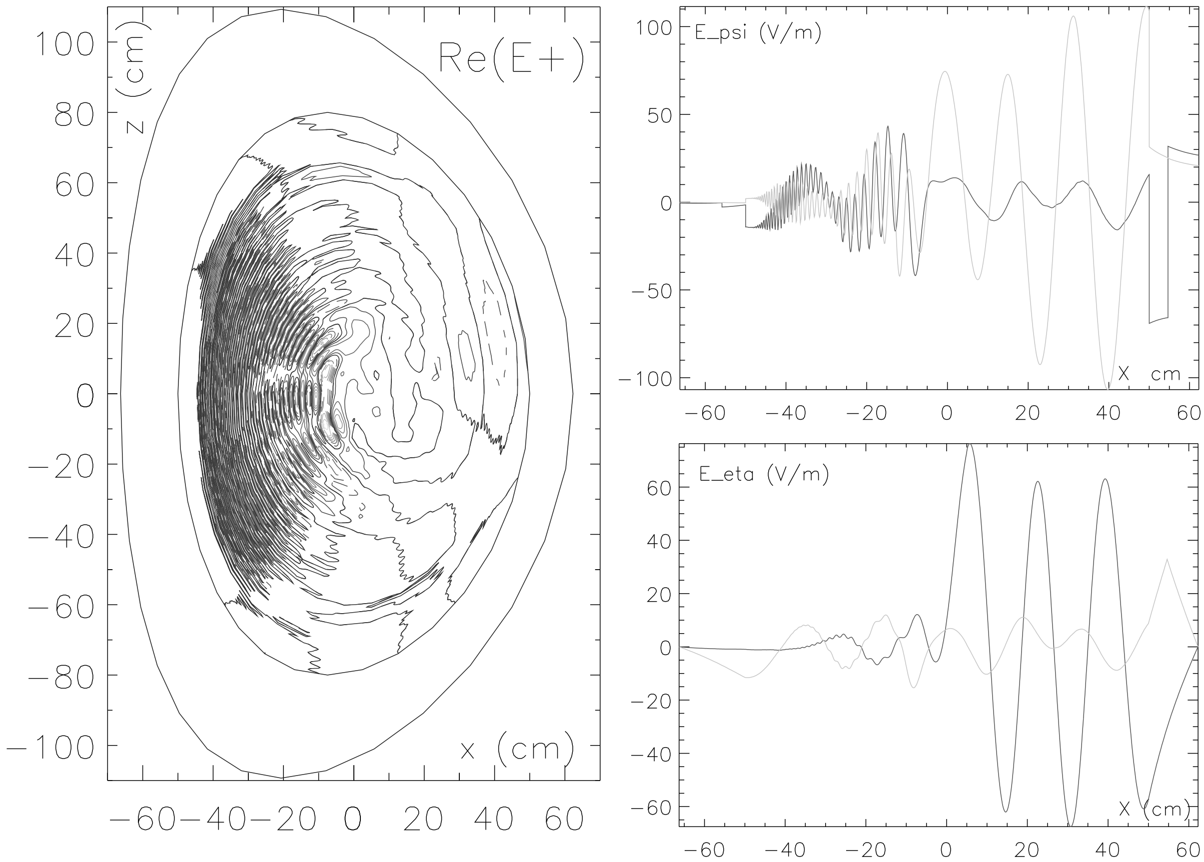

Fig. 1 Full wave solution with the TORIC code: a) Contour plot of E_+ in the poloidal plane; b) E_ψ and E_η along the equator.

typically 16 ($|m| \leq 8$) or 32 ($|m| \leq 16$) modes can be retained, much less than would be needed to follow refraction of IB waves. To circumvent this limitation, the rate of ELD is estimated using at each point, instead of the actual value of m, a 'corrected' value $m_{\rm eff}$ chosen to simulate refraction.

Ray tracing of ion Bernstein waves. The arbitrariness in the choice of $m_{\rm eff}$ was one of the motivations for the development of the ray tracing code RAYIBW. Its most important characteristics are: a) the dispersion relation used is fully electromagnetic, since the electrostatic approximation necessarily fails near mode conversion; b) exploiting axisymmetry, a well-defined toroidal wavenumber n is assumed (as in TORIC). Thus rays and wavefronts need to be followed only in a poloidal cross-section. A large number of rays is followed, both to obtain a power deposition profile as smooth as possible, and, by the density of the starting points, to implement accurately the procedure outlined below to determine the shape of the initial wavefront.

To get information on refraction, it is important to know with sufficient accuracy the geometry of an initial wavefront, which determines the initial direction of the rays. This information could in principle be obtained from TORIC, but this would be difficult and inaccurate. Fortunately, it turns out that the characteristics of the IB wave dispersion relation strongly constrain the shape of wavefronts near mode conversion.

Before refraction can play a role, but sufficiently far from mode conversion for the WKB approximation to hold, the IB wave must still have essentially the same k_ζ^{mn} as the fast wave (FW), but already a much larger $k_\perp$. These two conditions can be simultaneously fulfilled only if the radial component k_ψ of the wavevector is much larger than k_η (the component perpendicular to $\vec{B}_0$ but lying in the magnetic surface), and thus if the wavefront is close to a magnetic surface. In RAYIBW a first ray starting point is chosen on the equatorial plane on the propagative side of the ion-ion resonance, and then the shape of the initial wavefront is determined by ensuring that it remains perpendicular to the local wavevector specified by the assigned value of n, k_ζ^{mn} (and thus m and k_η), and of k_ψ as obtained from the local dispersion relation. This procedure still leaves some arbitrariness, since the FW already has a spectrum of m-values. This range, however, is so narrow compared to the values required to appreciably alter the initial value of k_η of the IB wave, that the results are practically independent from the particular value of m assumed. In RAYIBW one can either take $m = 0$, which usually correspond to the poloidal mode of the FW with largest amplitude, or $m = -qn$ i.e. $k_\zeta^{mn} = 0$ on the initial wavefront, which presumably corresponds to the most efficient mode conversion. The result are essentially unaffected by this choice. The only remaining arbitrariness is the distribution of the power among different rays. For simplicity, we have divided the mode converted power equally among them.

We have used RAYIBW to investigate absorption of IB waves in the example of fig. 1. We find that refraction is gradual, as shown in fig. 2, and the values of $k_\parallel$ required for the onset of ELD are reached at different distances from mode conversion depending on the vertical position, so that power deposition profiles are broad, $\Delta r \gtrsim 0.3a$. In all cases, the parallel phase velocity of IB waves in the region where according to RAYIBW most of the power is deposited is found to be less than twice the electron thermal velocity. The value of m_{eff} in TORIC is chosen to satisfy this criterion, under the additional condition that $k_\perp \rho_i$ is sufficiently large.

Conclusions. Some additional considerations can be made based on the results of RAYIBW. Current-drive by IB waves excited by mode conversion is unlikely to have a satisfactory efficiency, since refraction effectively destroys any memory of the imposed antenna spectrum. Even if the spectrum could be to some extent preserved (e.g. by imposing a sufficient up-down asymmetry with the launching structure), absorption occurs in the thermal region, where efficiency is lowest. We may add that the broad power deposition profiles imply a rather low power density, such that the normalized quasilinear diffusion coefficient is appreciably smaller than unity. Under these conditions the assumption made in the code that the electron distribution function remains close to a Maxwellian is well justified, and the conclusion that absorption occurs at phase velocities in the thermal range is sound.

By contrast, the FW cannot suffer large refraction. By chosing the antenna spectrum appropriately, the FW can be made to damp on suprathermal electrons, so that direct current drive by the FW can in principle be made considerably more efficient. The

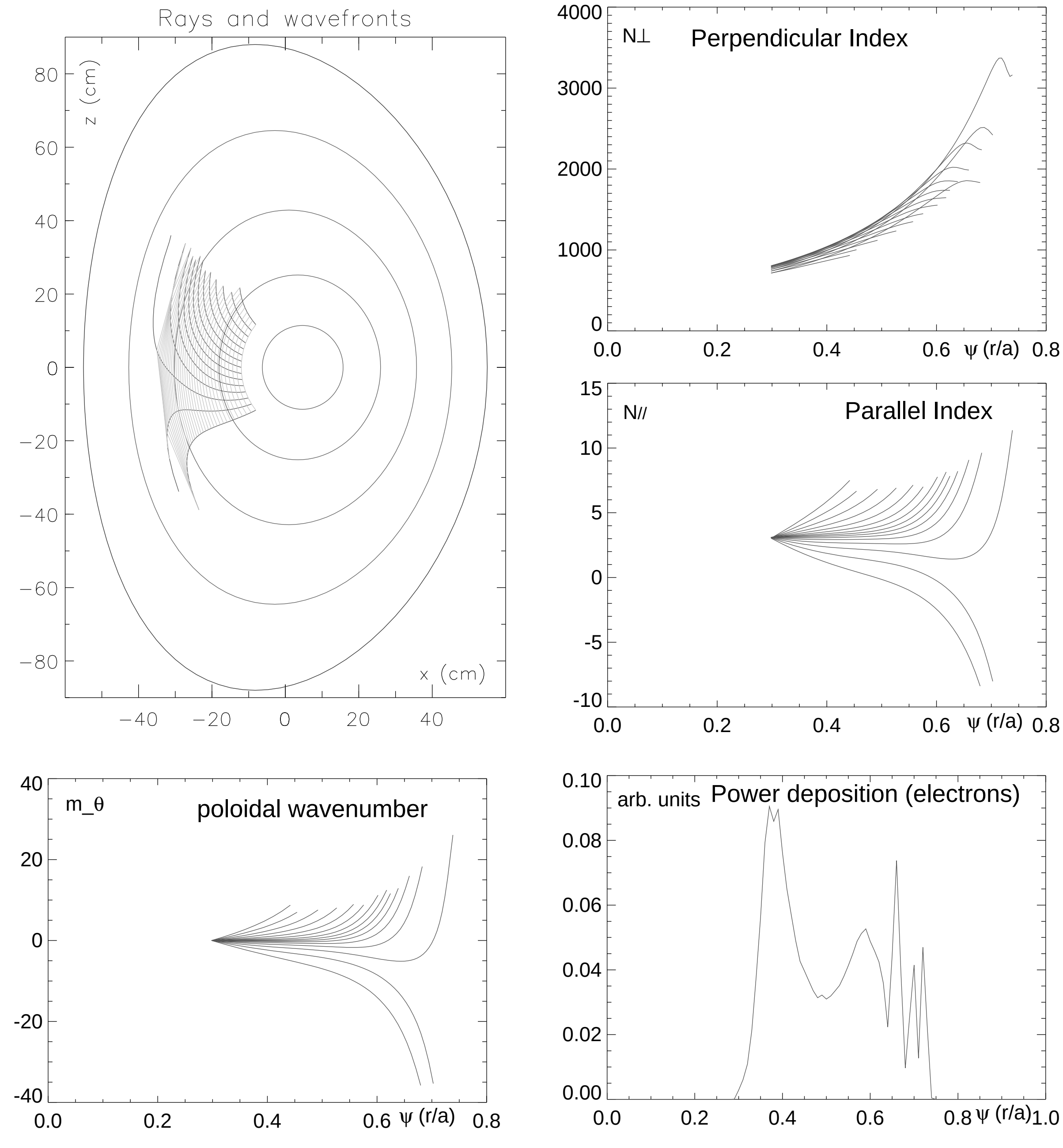

Fig. 2 Ray-tracing of IB waves for the same case as in fig. 1.

price, however, might be weak single-pass absorption, leading to large electric fields, and possibly parasitic effects at the edge.

References.

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