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Observation of the Ion Bernstein Wave Propagation by Magnetic Probe in a Tokamak

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Heating ions by directly launched ion Bernstein wave (IBW) was first advocated by M. One *et al.* and extensive study has been conducted in ACT-1 low-temperature toroidal device.[1,2] Later, heating experiments in tokamaks have been done in JIPPT-II-U,[3,4] PLT[5] and TNT-A,[6,7] resulting in fairly good bulk ion heating. To ensure the efficient heating, study of the wave propagation and damping must be performed. Detections of the mode converted IBW at cyclotron harmonic layers have been conducted by several authors.[8] However, observation of the directly launched IBW has not yet been carried out fully in a tokamak. In this brief note, we report first the wave magnetic field measurement of IBW in a tokamak.

In a high density plasma, IBW becomes quasi-electrostatic and the energy density stored in the wave magnetic field becomes comparable to or even larger than in the wave electric field. The ratio of the toroidal component of the wave magnetic field (B_z) to the radial component of the wave electric field (E_x) can be written as

$$\frac{cB_z}{E_x}=\frac{n_\perp K_{xy}}{K_{yy}-n_\perp^2-n_{\parallel}^2}, \tag{1}$$

where K_{xy} and K_{yy} are the elements of the plasma dielectric tensor in the Cartesian coordinates,[9] $n_\perp$ and $n_{\parallel}$ are the perpendicular and parallel refractive indices, respectively. This ratio increases as the wave goes into the high-β region, and decreases as the ion cyclotron harmonic layer is approached. Note that B_z is non-vanishing in the limit of $n_{\parallel}\to 0$ (pure IBW[10]).

The experiment was done in the TNT-A tokamak with electron and ion temperatures $T_e(0)\sim 50$ eV, $T_i(0)\sim 30$ eV, mean plasma density $\bar{n}_e\simeq 6\times 10^{12}$ cm^{-3}, concentration ratio $n_D/(n_H+n_D)=0.1$ (n_D, n_H: deutrium and hydrogen densities, respectively). A Faraday shielded E_z antenna was used to excite IBW with the frequency of $f=10.5$ MHz. Toroidal magnetic field was varied from 0.350 T to 0.400 T to change the location of the hydrogen second harmonic resonance layer. Wave magnetic field B_z was measured by a radially movable magnetic probe separated toroidally by 90 deg from the launcher. A reference probe was set near the launcher and the obtained B_z was normalized to this reference value. The plasma current is fixed to 5 kA. The variation of B_z observed at the 90 deg port due to the insertion of the reference probe (normally outside the plasma) is less than 5 percent. The changes in mean plasma density and one turn loop voltage are also small ($\lesssim 5\%$). The experimental data were compared with the calculated value from the ray tracing code developed by M. Ono *et al.*[11,12] In the case of ray tracing in a tokamak magnetic field, the ray turns at

$$n_{\parallel}^2=K_{xx}+\frac{K_{xy}^2}{n^2}=0, \tag{2}$$

and the toroidal excursion of the ray trajectory varies with the initial value of $n_{\parallel}$. In TNT-A, only waves with the toroidal mode number of $N\leq 4$ ($n_{\parallel}\leq 45.5$) can penetrate into the plasma; waves with larger N are electron Landau damped at the plasma edge. In the present case, the amplitude variation of the Fourier components of the antenna current $J_z(N)$ in the region $N\leq 4$ is less than 25 percent. Since the wave dispersion characteristic is mainly determined by the local ion gyroradius ρ_i, radial B_z profile is a weak function of the initial $n_{\parallel}$ as long as the wave penetrates into the plasma and electron Landau damping is not so heavy. Thus we can expect the observed B_z profile to exhibit the same property as that obtained by ray tracing.

The experimental data are shown in Fig. 1, in which the positions of $\omega=2\,\Omega_H$ are indicated by the arrows, and the corresponding B_z calculated from ray tracing are shown in Fig. 2 with the initial value of $n_{\parallel}=11.4$. As we see in Fig. 1, the amplitude of B_z has maximum slightly before the $\omega=2\,\Omega_H$ layer, revealing the same property as that of Fig. 2. This

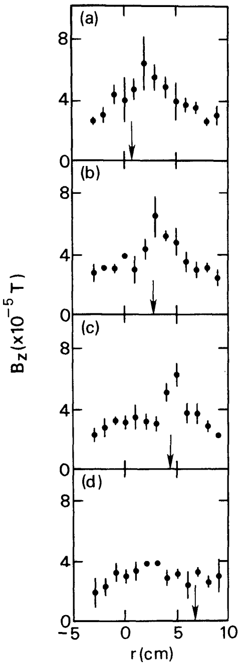

Fig. 1

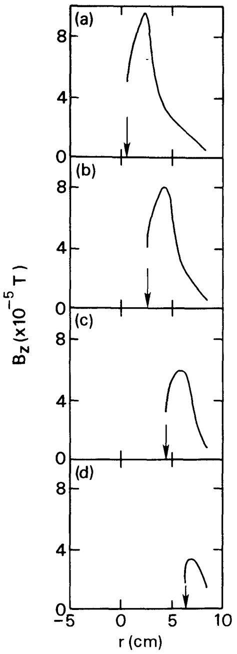

Fig. 2

Fig. 1. Observed toroidal component of the wave magnetic field B_z, with the static magnetic field of (a) 0.350 T, (b) 0.367 T, (c) 0.383 T and (d) 0.400 T. The arrows show the position of $\omega=2\,\Omega_H$.

Fig. 2. Wave magnetic field B_z with the same condition as in Fig. 1, calculated from ray tracing. The position of $\omega=2\,\Omega_H$ is also shown.

peak moves with the resonance layer as the static magnetic field is varied. The absolute value of B_z agrees with that from the calculation within a factor of two.

There remains a possibility of exciting the fast magnetosonic wave. Ray tracing of the fast wave, though it may be difficult to apply this technique to such long wave length mode, gives a "plateau" B_z profile, which is not the case in this experiment. Moreover, in higher harmonic cases, coupling of IBW and the fast wave is weak, so that the disturbance that the fast wave suffers will be little and localized to the resonance layers. Even if we excited the fast wave in the same condition, obtained B_z profile would be a "plateau" one.

To summarize, IBW propagation is observed in TNT-A tokamak and the obtained radial B_z profile is in good agreement with that from ray tracing calculation.

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