JAPANESE JOURNAL OF APPLIED PHYSICS
VOL. 26, NO. 3, MARCH, 1987, pp. 505-506

**Short Note**

# Parameter Dependence of Ray Trajectory and Damping for the Ion Bernstein Wave in the TNT-A Tokamak

Shunjiro SHINOHARA, Osamu NAITO, Katsumi IDA† and Kenro MIYAMOTO
*Department of Physics, Faculty of Science, University of Tokyo, Bunkyo-ku, Tokyo 113*
*†Institute of Plasma Physics, Nagoya University, Nagoya 464*

(Received October 13, 1986; revised manuscript received December 3, 1986; accepted for publication January 24, 1987)

The dependence of ray trajectories and damping on various plasma parameters was studied using three-dimensional ray tracing for an ion Bernstein wave in the TNT-A tokamak. The condition for wave power absorption dominated by electron Landau damping was also estimated.

In recent years, plasma heating by an ion Bernstein wave (IBW)[1] has been expected and actively pursued in ACT-1 (a low-temperature toroidal device),[2,3] JIPPT-II-U tokamak,[4] PLT[5] and TNT-A.[6,7] Theoretical studies on IBW are not sufficient and ray-tracing calculations are becoming increasingly important because of the short wavelength of IBW. However, there are few results concerning this type of calculation;[6,8] these results do not fully describe the behavior of wave propagation and damping over a wide range of plasma parameters.

In this letter, the parameter dependence of the IBW phenomena using ray tracing is reported in order to understand how to heat ions or electrons at a desired position of a tokamak plasma. We have numerically calculated ray trajectories and damping in the TNT-A tokamak,[6,7] utilizing a code originally developed by Ono *et al.*[8] In this code, Hamilton's equations[9] of the frequency and wave vector are used with the full dielectric tensor. The obtained parameter dependence can also be utilized for other machines.

Figure 1 shows wave propagation upon changing the initial parallel refractive index $n_z$. Here, the ratio of the major and minor radii $R/a$ is 40(cm)/8.5(cm); the concentration ratio $n_H/(n_H+n_D)$ is 0.9 (where $n_H$ and $n_D$ are the hydrogen and deuterium densities, respectively); the frequency $f$ is 5.6 MHz; the toroidal field $B_t$ is 2.47 kG (*i.e.*, $\omega=3\omega_D$ where $\omega_D$ is the deuteron cyclotron frequency); the central electron, proton and deuteron temperatures are $T_e(0)=50$ eV, $T_H(0)=T_D(0)=20$ eV (electron and ion temperatures take the form of $(1-x^2)^{1.67}$); $n_e(0)=1.2\times10^{13}$ cm$^{-3}$ (parabolic density profile); and the safety factors $q_a$(edge)$=7$, $q_0$(center)$=2$. From this figure, wave propagation along the toroidal and poloidal directions is enhanced as the initial $n_z$ value increases. This wave changes its propagating direction due to the presence of a poloidal field. The perpendicular refractive indexd $n_x$ decreases slowly, then increases from $x\sim4$ cm; an abrupt increase in $n_x$ was observed near the $3\omega_D$ layer.

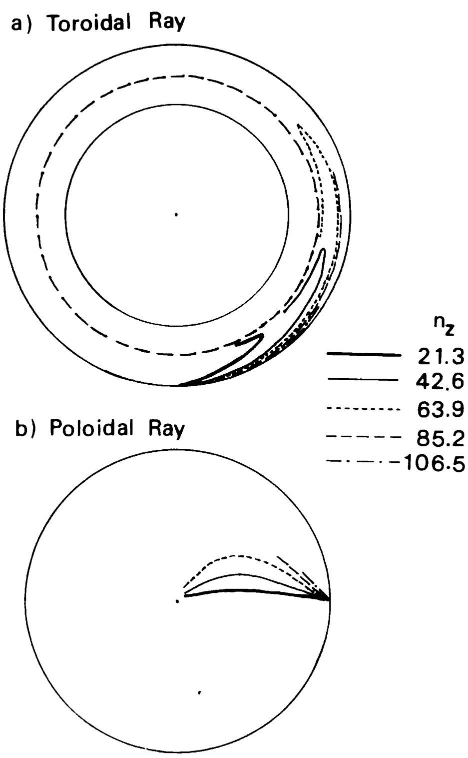


Fig. 1. Toroidal (a) and poloidal (b) projections of wave propagation with $n_H/(n_H+n_D)=0.9$, changing initial $n_z$ value. Here, $n_z=21.3$ corresponds to a toroidal mode number $n=1$ and parallel wave number $k_z=0.025$ cm$^{-1}$.

When the deuterium concentration is increased ($n_H/(n_H+n_D)=0.1$), wave propagation exhibits a different behavior (Fig. 2). The $n_x$ value is larger for the same initial $n_z$; also, frequent changes in the sign of $n_z$ have been found.

Figure 3 shows a wave power profile for the case of Figs. 1 and 2. A decrease in the wave power, except the

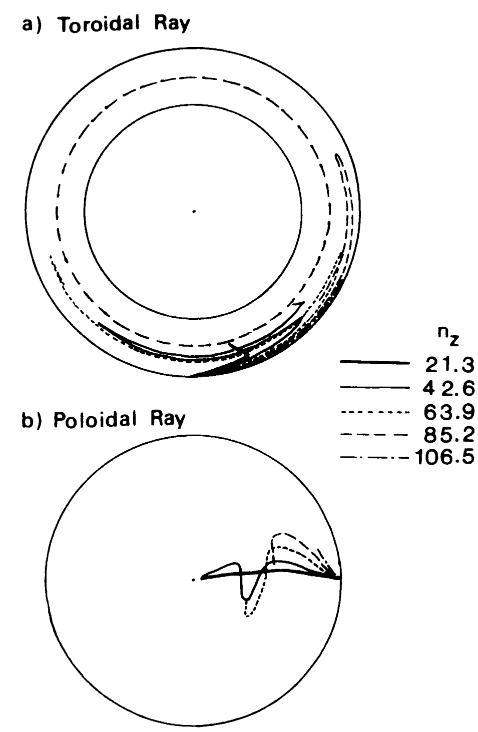


Fig. 2. Toroidal (a) and poloidal (b) projections of wave propagation with $n_H/(n_H+n_D)=0.1$, changing initial $n_z$ value.

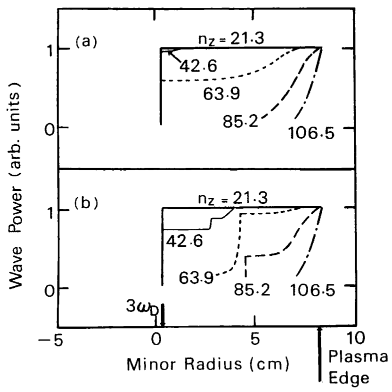


Fig. 3. Radial profile of wave power for different initial $n_z$ values. Figures 3(a) and (b) are for $n_H/(n_H+n_D)=0.9$ (Fig. 1) and 0.1 (Fig. 2), respectively.

$3\omega_D$ layer, reflects electron Landau damping (ELD). With an increase in the initial $n_z$, the wave power absorption by ELD near the outer plasma region becomes dominant compared with that by ion cyclotron damping. From Fig. 3, it can be seen that a low concentration of deterium is effective for heating the plasma core. Generally, if the odd (even) number harmonic frequency of a deuteron is used, $n_x$ and ELD become larger with an increase in the deuterium (hydrogen) concentration due to the presence of a deuteron (proton) resonance.

When the safety factor is lowered with a constant value of $q_a/q_0$, wave propagation along the poloidal direction is enhanced. Therefore, the total arc length near the outer plasma region increases, and wave power absorption by ELD increases. As $q_a/q_0$ increases with a constant $q_0$ value, the power absorption by ELD also increases. On the other hand, the wave propagates only radially and toroidally (not poloidally), and wave absorption near the outer plasma region increases slightly when $q_a$ and $q_0$ become infinity (no toroidal plasma current).

A peaked electron temperature profile is favorable for heating the plasma core, though the effect of this profile on the power deposition is weak. With an increase in the electron temperature, the power absorption by ELD becomes dominant since the volume satisfying the ELD condition at the outer plasma region increases and this damping beomes stronger.

So far, we have used the TNT-A plasma parameters: the $n_z$ value $n_{zl}$, which satisfies the ELD condition that the phase velocity equals the electron thermal velocity, is $\sim 100$ and the upper $n_z$ value of the excited antenna current spectrum $n_{zs}$ is $\sim 300$.[6,7] In the JIPPT-II-U tokamak,[4] $n_{zl}$ is $\sim 30$ and $n_{zs}$ is $\sim 8$. In a reactor-size machine with $T_e=10$ keV and $f=200$ MHz, $n_{zl}$ is $\sim 7$ and $n_{zs}$ is $\sim 1.5$ if the antenna or waveguide length $L$ is of order 0.5 m. Therefore, contrary to the TNT-A tokamak case, the power absorption ratio by ELD becomes smaller as the machine parameters increase, *i.e.*, $n_{zl}/n_{zs} \propto fL/T_e^{0.5}$. However, the dependence of wave propagation and damping on plasma parameters obtained in this paper can be utilized even in large machines.

Finally, a calculation was achieved at $\omega=4\omega_D$, $5\omega_D$ and $6\omega_D$. If the $4\omega_D$ resonance layer is located in the plasma center, the $5\omega_D$ layer is within the plasma cross section (outer side of a torus) for an aspect ratio $A \lesssim 4$. The $5\omega_D$ as well as $6\omega_D$ layers (and the $6\omega_D$ as well as $7\omega_D$ layers) can also be present for the case of $A \lesssim 5$ and $\lesssim 6$, respectively. Therefore, considering the standard aspect ratio in any device, it is necessary to use a frequency of $\omega \lesssim 4\omega_D$ in order to heat the plasma core; otherwise, plasma surface heating may occur.

In conclusion, three-dimensional ray tracing calculations for IBW in a tokamak have been made over a wide range of plasma parameters. As the initial $n_z$ increases, the wave power absorption by ELD becomes dominant compared with that by ion cyclotron damping; this Landau damping region approaches the plasma surface. The value of $n_{zl}/n_{zs}$, which is a measure of power absorption by ELD, is proportional to $fL/T_e^{0.5}$. As the deuterium concentration increases (decreases), $n_x$ and ELD become dominant for the odd (even) number harmonic frequency of a deuteron. Poloidal propagation is enhanced when the safety factor is lowered. From the view point of heating a plasma core, it is shown that a wave frequency of $\omega \lesssim 4\omega_D$ is favorable.

The authors wish to express their thanks to Dr. M. Ono for the use of his ray-tracing code.

## References

1) I. B. Bernstein: Phys. Rev. **109** (1958) 10.
2) M. Ono, K. L. Wong and G. A. Wurden: Phys. Fluids **26** (1983) 298.
3) M. Ono, G. A. Wurden and K. L. Wong: Phys. Rev. Lett. **52** (1984) 37.
4) M. Ono, T. Watari, R. Ando, J. Fujita, Y. Hirokura, K. Ida, E. Kako, K. Kawahata, Y. Kawasumi, K. Matsuoka, A. Nishizawa, N. Noda, I. Ogawa, K. Ohkubo, M. Okamoto, K. Sato, S. Tanahashi, Y. Taniguchi, T. Tetsuka, K. Toi, K. Yamazaki: Phys. Rev. Lett. **54** (1985) 2339.
5) J. Hosea, R. Bell, M. Bitter, A. Cavallo, S. Cohen, P. Colestock, G. Greene, G. Hammett, E. Hinnov, H. Hsuan, D. Hwang, R. Kaita, E. Mazzucato, D. McNeill, M. Ono, D. Schuresko, C. Skinner, S. Suckewer, J. Wilson: *Proc. 12th European Conf. Controlled Fusion & Plasma Physics*, **2** (1985) 120.
6) S. Shinohara, O. Naito, Y. Ueda, H. Toyama and K. Miyamoto: J. Phys. Soc. Jpn. **55** (1986) 2648.
7) S. Shinohara, O. Naito and K. Miyamoto: Nucl. Fusion **26** (1986) 1097.
8) M. Ono, T. H. Stix, K. L. Wong and R. Horton: *Proc. the Second Joint Grenoble-Varenna Int. Symp. on Heating in Toroidal Plasma* **1** (1980) 593.
9) T. H. Stix: *The Theory of Plasma Waves*, (McGraw-Hill, New York, 1962).