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

Shunjiro Shinohara, Osamu Naito, Katsumi Id
t and Kenro Miyamoto

Department of Physics, Faculty of Science, University of Tokyo, Bunkyo-ku, Tokyo 113
1Institute 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.\(^9\) 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 \(n_d/(n_H+n_D)\) 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., \(ω=3\omega_D\) where \(ω_D\) is the deuterium cyclotron frequency); the central electron, proton and deuteron temperatures are \(T_e(0)=50\,\text{eV}\), \(T_n(0)=T_D(0)=20\,\text{eV}\) (electron and ion temperatures take the form of \((1-x^2)^{-0.2}\); \(n_e(0)=1.2 \times 10^{13}\,\text{cm}^{-3}\) (parabolic density profile); and the safety factors \(q_d(\text{edge})=7\), \(q_d(\text{center})=2\). 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 index \(n_z\) decreases slowly, then increases from \(x \sim 4\,\text{cm}\); an abrupt increase in \(n_z\) was observed near the \(3\omega_D\) layer.

When the deuterium concentration is increased \((n_d/(n_H+n_D)=0.1)\), wave propagation exhibits a different behavior (Fig. 2). The \(n_z\) 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
3ωD layer, reflects electron Landau damping (ELD). With an increase in the initial n₀, 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 deuterium is effective for heating the plasma core. Generally, if the odd (even) number harmonic frequency of a deuteron is used, n₀ 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 qₐ/q₀, 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 qₐ/q₀ increases with a constant q₀ 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 qₐ and q₀ 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 becomes stronger.

So far, we have used the TNT-A plasma parameters: the nt value nₐt, which satisfies the ELD condition that the phase velocity equals the electron thermal velocity, is ~100 and the upper nt value of the excited antenna current spectrum nₐ is ~300. In the JIPPT-II-U tokamak, nₐ is ~30 and nₐ is ~8. In a reactor-size machine with Tₑ = 10 keV and f = 200 MHz, nₐ is ~7 and nₐ is ~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., nₐ/nₐ ∝ L/Tₑ². 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 ω = 4ωD, 5ωD and 6ωD. If the 4ωD resonance layer is located in the plasma center, the 5ωD layer is within the plasma cross section (outer side of a torus) for an aspect ratio A ≤ 4. The 5ωD as well as 6ωD layers (and the 6ωD as well as 7ωD layers) can also be present for the case of A ≤ 5 and ≤ 6, respectively. Therefore, considering the standard aspect ratio in any device, it is necessary to use a frequency of ω ≤ 4ωD 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 nt 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 nₐ/nₐ, which is a measure of power absorption by ELD, is proportional to fL/Tₑ². As the deuteron concentration increases (decreases), n₀ 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 ω ≤ 4ωD is favorable.

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

References