§ 14. Propagation and Power Damping of Ion Bernstein Wave in LHD

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Fast wave heating in Ion Cyclotron Range of Frequency (ICRF) on the LHD demonstrated that ICRF heating is one of important heating method also in helical device. In the mean time, slow wave heating brought about several interesting experimental result, especially in ion Bernstein wave (IBW) heating in tokamaks; i.e., peaked profiles of electron density, electron temperature and ion temperature, confinement improvement, and etc.

There are plans for IBW experiments on the LHD using a folded waveguide antenna, which has been installed in the weaker magnetic field side. Helium plasma is used. The radio frequency is chosen so that the third cyclotron resonance layer of helium ions locates just behind the antenna. The wave propagates into the central region and is damped near the second harmonic resonance layer of ion cyclotron frequency. In order to execute efficiently experiments, the wave propagation and damping mechanism were investigated by using a ray tracing method$^{1)}$. The ray trajectory is calculated by differential equations:

$$\frac{\mathrm{d}\boldsymbol{k}}{\mathrm{d}t} = -\frac{\partial \mathrm{Re}D}{\partial \boldsymbol{r}} / \frac{\partial \mathrm{Re}D}{\partial \omega}, \quad \frac{\mathrm{d}\boldsymbol{k}}{\mathrm{d}t} = \frac{\partial \mathrm{Re}D}{\partial \boldsymbol{r}} / \frac{\partial \mathrm{Re}D}{\partial \omega}$$

where D, $\boldsymbol{r}$, $\boldsymbol{k}$, t, and ω are the dispersion relation, the position vector, the wave number vector, the time, and the frequency, respectively. Assuming that an imaginary part of the wave number vector $\boldsymbol{k_i}$ is much smaller than a real part, a ratio of wave power P to initial value P_0 is given:

$$\frac{P}{P_0} = \exp\left(-2\int \boldsymbol{k_i} \cdot \mathrm{d}\boldsymbol{r}\right) = \exp\left(-2\int \frac{\mathrm{Im}D \ \mathrm{d}t}{\partial \mathrm{Re}D/\partial\omega}\right)$$

A rigorous selection of magnetic field and flux surface data set are required due to a property of IBW; i.e., a ray travels along a magnetic field. In this work, the expression of magnetic field and flux surface proposed in Ref.$^{2)}$ is adopted in order to ensure the required accuracy.

A typical result is shown in Fig.1. In this calculation, the following parameters are used: magnetic field strength on the axis of 2.5T, electron density in plasma center of $1.0 \times 10^{19}\mathrm{m}^{-3}$, and electron and ion temperature in plasma center of 1keV. The rays are started at major radius $R = 4.35$m on the equatorial plane in the horizontally elongated plasma cross-section, that is, $(x, y, z) = (0.0\mathrm{m}, 4.35\mathrm{m}, 0.0\mathrm{m})$ in Cartesian coordinates. The tracing of the ray is continued until the wave power damps to 1% of the initial value. The ray is started with refractive index along to magnetic field $N_{\parallel} = 3.8$, corresponding to wave number $k_{\parallel} = 3.0\mathrm{m}^{-1}$, and the initial value of the perpendicular wave number is given by solving the dispersion relation, the sign of which is determined taking into consideration the fact that IBW is a backward wave. In this result, the ray transfers into helical motion after it moved some distance towards the magnetic axis. Most energy is absorbed through electron Landau damping before the ray reaches the second harmonics layer of helium ion cyclotron frequency. A power deposition profile is shown in Fig.2. Magnetic field strength, profiles of electron and ion temperatures and plasma density at the edge region, initial value of wave number parallel to the magnetic lines of force, starting position and direction of wave number were scanned. In many practical cases, however, electron Landau damping is so strong that the wave is absorbed in the peripheral region. This result is due to up shift of refractive index along to magnetic field $N_{\parallel}$. In impractical case of low temperature or small initial parallel refractive index, up shift of $N_{\parallel}$ does not occur. The ray reaches cyclotron resonance layer before electron Landau damping occurs, and the power is absorbed by helium ions.

A ray shows unique variation of $N_{\parallel}$ and associated wave damping mechanism in each configuration. The ray tracing calculation was performed also in a circular tokamak and straight helical configuration for comparison. In the tokamak configuration, $N_{\parallel}$ up shift does not occur, so that power is not absorbed by electrons. In the straight helical configuration, $N_{\parallel}$ increases gradually as the ray approaches the core of the plasma and electron Landau damping become strong. In the LHD, as is mentioned above, $N_{\parallel}$ up shift occurs in the first swing of the ray and the power is absorbed through strong electron Landau damping, which may be attributed to the presence of mixed helical ripple and toroidal ripple.

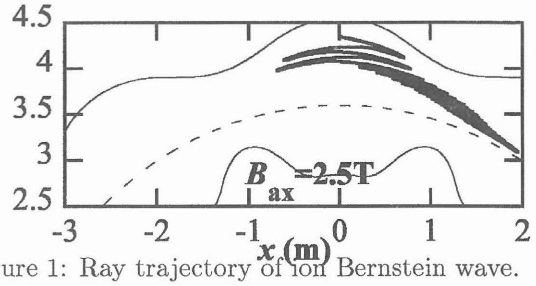

Figure 1: Ray trajectory of ion Bernstein wave.

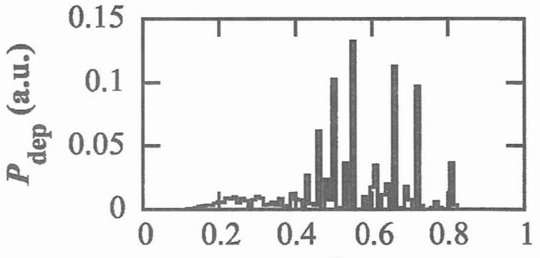

Figure 2: Power deposition profile. Power is absorbed completely by electrons.

Reference

1) B. D. McVey, Nuclear Fusion, **19** (1979) 461

2) T. Watanabe, private communication