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Ion Cyclotron Heating Mechanism of Fast Magnetosonic Wave in the TNT-A Tokamak

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Ion heating mechanism of fast magnetosonic wave in the ion cyclotron range of frequency (ICRF) has been studied in the TNT-A tokamak. Ion temperature measurements have been made with mass separated neutral particle analyser. The effects of the fundamental proton cyclotron resonance layer (ICR) and the two-ion hybrid resonance layer (HBR) on ion heating are observed. In the case of hydrogen minority (ICR and HBR in the plasma), where the ratio of hydrogen-to-deuterium concentration, n_H/n_D, is 0.05, the increase in hydrogen temperature is larger than that in deuterium, and most of RF power is absorbed by hydrogen.

§1. Introduction

Recently, the ion cyclotron range of frequency (ICRF) heating becomes one of the most important additional heating methods of a tokamak plasma. In ICRF heating experiments, there are two schemes such as fast magnetosonic wave heating[1] and ion Bernstein wave heating.[2] Main works of the fast magnetosonic wave heating experiment have been made with mixed species plasma, such as H and D, and ^{3}He and D. In most of these cases, H and ^{3}He are minority species, and wave frequency is fitted with ion cyclotron frequency of these species, and strong ion heating has been observed.[3-6] However, there are some differences of ion heating mechanism in various experiments. In the case of hydrogen minority, where the ratio of hydrogen-to-deuterium concentration, n_H/n_D, is about 0.04, experimental results are summarized as follows; In PLT[7] and TFR,[8] RF power was deposited in hydrogen only via fundamental cyclotron damping, In JFT-2[5] and JIPP-TII,[6] RF power was deposited in not only hydrogen but also deuterium, via second harmonic damping. From these experimental results, the studies on ion cyclotron heating mechanism by fast magnetosonic wave in the plasma containing two species do not seem to be sufficient.

In this paper, roles of resonance layers, such as the fundamental proton cyclotron resonance layer (ICR) and the two-ion hybrid resonance layer (HBR), on ion heating by ICRF waves in the TNT-A tokamak and ion heating mechanism are reported. In §2, the TNT-A tokamak device, ICRF systems and ion temperature diagnostics are described. In §3, the increase in ion temperature under various conditions is presented. In §4, discussion on the experimental results and conclusion are presented.

§2. Experimental Setup

The non-circular tokamak device TNT-A[9] has a plasma whose major radius and minor radius are 0.4 m and 0.09 m, respectively, and elongation ratio is 1.3. The maximum toroidal magnetic field is 4.25 kG. The RF generator is operated at the frequency of $f = 5.6$ MHz.[10] In order to study the effects of the resonance layers, three conditions are chosen, that is, "HBR+ICR", "ICR only", and off resonance. In the case of "ICR+HBR", deuterium gas is fed only, however, in the presence of hydrogen desorbed from the vacuum wall, the ratio of hydrogen-to-deuterium concentration, n_H/n_D, is 0.05. The wave frequency is 5.6 MHz and the toroidal field is 3.74 kG at the plasma center, so that ICR and HBR are located near the plasma center. The mode conversion takes place, that is estimated with the equation for the condition of existence of hybrid resonance from ref. 11. In the case of "ICR only", the wave frequency and the toroidal field are the same as those of "ICR+HBR" and n_H/n_D is 1.0. In the case of off resonance, there are no harmonic ion cyclotron resonance layer in the plasma. The ratio, n_H/n_D, is determined from the line intensities of H_α (656.28 nm) and D_α (656.10 nm) during discharges.

A single half-turn loop antenna is installed at the outer (low field) side of the torus. The antenna is made of all-metal and the central conductor plate is separated from the plasma by a single screen of Faraday shield. The schematic view of the antenna is shown in Fig. 1.

The energy spectra of hydrogen and deuterium ions are measured by $E \perp B$ type mass separated neutral particle analyser. The ion detector is a ceratron, whose signals are transformed to square pulses with finite width and height with a discriminator. The integral of these square pulses is plotted on a X-Y recorder. A stripping cell is filled with nitrogen gas, whose pressure is about 1 mTorr. The cross sections for charge transfer of hydrogen and deuterium in nitrogen gas obtained by C. F. Barnett, J. A. Ray[12] are used to calculate the ion flux.

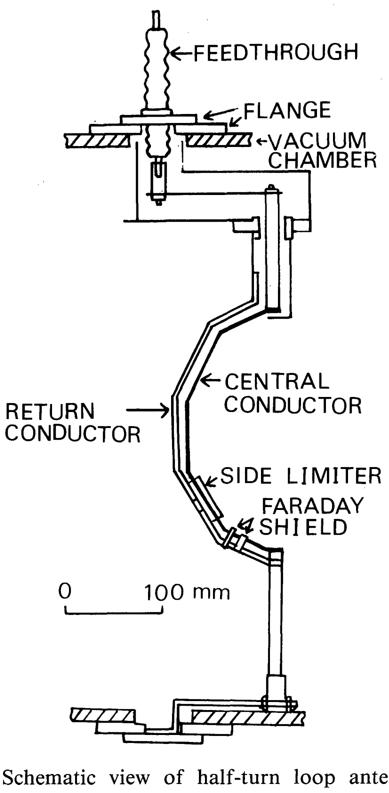

Fig. 1. Schematic view of half-turn loop antenna. This all metal antenna with single screen of Faraday shield is located on low field side.

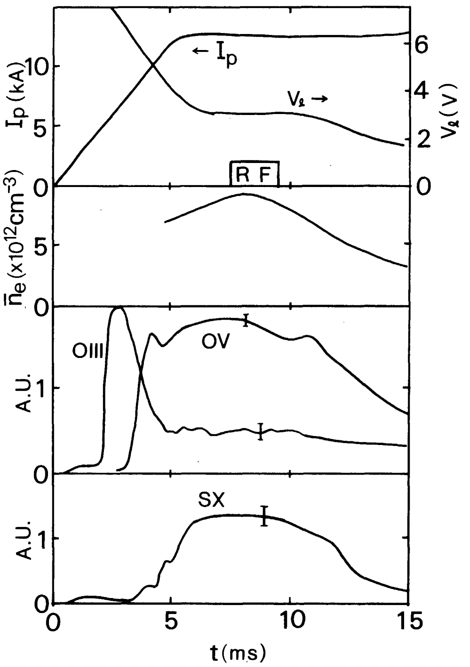

Fig. 2. Time evolution of the plasma parameters. RF pulse duration time is 2 ms.

The time evolution of the plasma parameters is shown in Fig. 2. The plasma parameters before RF pulse are as follows; plasma current $I_p = 11$ kA, loop voltage $V_l = 3.0$ V, line averaged density $\bar{n}_e \approx 0.8 \times 10^{13}$ cm^{-3}, electron temperature $T_e = 120-150$ eV, ion temperature $T_i \approx 60$ eV. The soft X-ray emissivity along a plasma central chord is observed by surface barrier diode (SBD) with 1 μm polypropylene filter that has the sensitivity for photon above energy of 150 eV. The oxygen line intensities of OV (278.1 nm) and OIII (304.7 nm) are also shown. The RF duration time is 2 ms and the net RF power absorbed by the plasma P_{net} is up to 11.4 kW in this experiment. This value is about one third of the ohmic heating power.

§3. Experimental Results

In Fig. 3, the charge exchange energy spec-

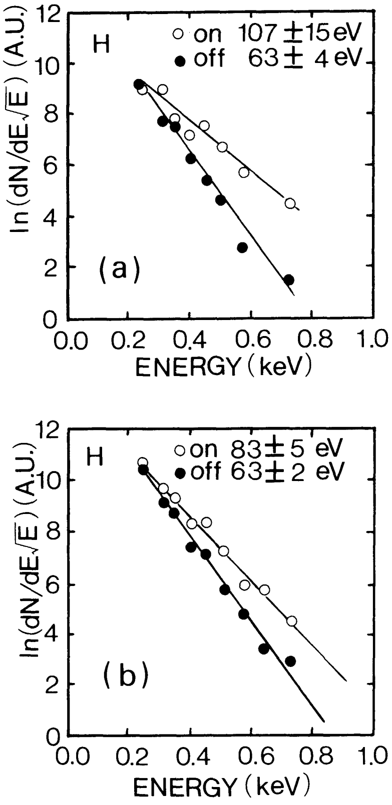

Fig. 3. Hydrogen charge exchange energy spectra of (a) for "ICR+HBR" and (b) for "ICR only" with and without RF. The solid lines show the fitted distribution function. Net RF input powers are 11.4 kW for (a) and 7.5 kW for (b).

tra of hydrogen are shown. The ion temperature is estimated from the inclination of the straight line obtained by a least square fitting of the logarithms of $\mathrm{d}N/\mathrm{d}E\sqrt{E}$. The energy range of the particles, which it is possible to measure with the neutral particle analyser, is narrow, since the ion temperature in TNT-A is low ($\leq$110 eV). In many cases of ICRF heating experiments, the ion energy spectra have high energy tail. Therefore, it must be clear whether the ion energy spectra belong to the bulk ion or the high energy tail. The estimation of the energy distribution function of the ion have been made with the solution deduced by T. H. Stix.[1] From these results, the ion high energy tail does not appear in the energy range under 0.8 keV. The other experiments[13,14] show that the high energy tail caused by RF heating appears above the ion energy $E\approx 5T_\mathrm{i}$. Therefore, the ion temperature in Fig. 3 appears to be the bulk ion temperature. In the cases of both "ICR+HBR" for (a) and "ICR only" for (b), no high energy tails are observed in the energy range under 0.8 keV.

In Fig. 4, the increase in ion temperature is plotted versus P_net. In the case of "ICR+HBR", the increase in hydrogen temperature is larger than that in deuterium. In the case of "ICR only", the difference between the increase in hydrogen and deuterium temperatures is small.

The increase of the soft X-ray intensity with RF pulses is less than 10% in all cases. The impurity line intensities, such as OV (278.1 nm) and OIII (304.7 nm), increase by less than 5% with RF pulses. The line-averaged density, $\bar{n}_\mathrm{e}$, do not change with RF pulses. These results suggest that the increase in electron temperature is less than 10 eV. In the case of "ICR+HBR" and "ICR only", the increase in majority ion temperature is more than that in electron (20 eV for "ICR only", 12 eV for "ICR+HBR"). These results indicate that in the presence of ICR the wave power is directly

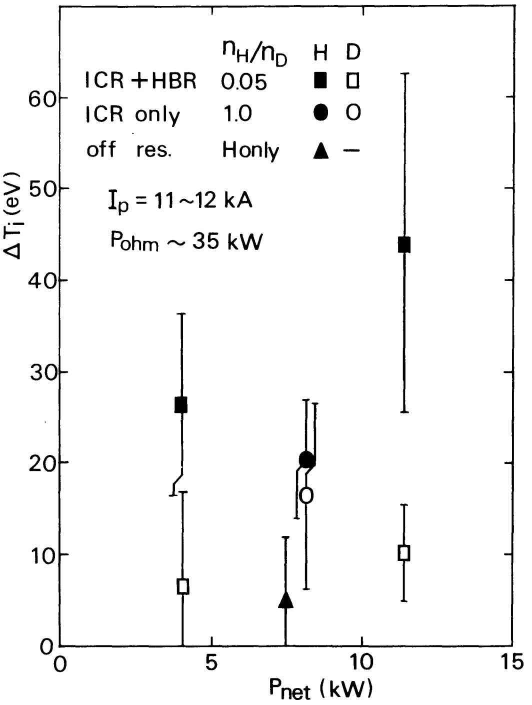

Fig. 4. Increase in ion temperature ΔT_i with RF vs RF net power P_net under three conditions with I_p=11–12 kA and ohmic input power $P_\mathrm{ohm}\approx$35 kW.

absorbed by ions.

§4. Discussion and Conclusion

In the analysis of the experimental results, we solve the power balance equation. The local power balance equation of the ions can be written as follows;

$$\frac{3}{2}\frac{\mathrm{d}}{\mathrm{d}t}(n_k T_k) = -\nabla\cdot Q_k + W_{\mathrm{e}-k} - W_{k-k'} + W_{\mathrm{RF}-k}, \quad (1)$$

where suffix k denotes the ion species of either hydrogen or deuterium. In eq. (1), Q_k, $W_{\mathrm{e}-k}$, $W_{k-k'}$ and $W_{\mathrm{RF}-k}$ are heat flux, electron-to-ion collisional heat transfer, k-th to k'-th ions collisional heat transfer and power absorption from RF waves, respectively. Since only the steady state is considered, the left-hand-side of eq. (1) is assumed to be zero. The charge exchange loss and the ionization loss of the ions are less than 10% from the calculation of the 1-D transport code without RF pulse. In the case of TNT-A experiment, ICRF heating does not enhanced these losses, since the increase in the ion temperature is small. Therefore, the charge exchange loss and the ionization loss are neglected in this calculation.

The heat flux loss term $\nabla\cdot Q_k$, is described near the plasma center as follows;

$$\nabla\cdot Q_k = -\frac{1}{r}\frac{\mathrm{d}}{\mathrm{d}r}\left(r\kappa_\perp \frac{\mathrm{d}T_k}{\mathrm{d}r}\right) = 4\kappa_\perp T_{k0}/a^2, \quad (2)$$

with the assumption of $T_k = T_{k0}(1-(r/a)^2)$ in the cylindrical coordinate, where a denotes the plasma minor radius, and the heat conductivity $\kappa_\perp$ is assumed to be constant near the plasma center. The heat flux loss is assumed to follow the neoclassical theory. The heat conductivity $\kappa_\perp$ in the plateau regime is described as

$$\kappa_\perp = n_k q^2 \rho_k^2 \nu_{\mathrm{p}} = n_k \frac{q}{R} m_k^{1/2} \frac{T_k^{3/2}}{e^2 B^2}, \quad (3)$$

where q is the safety factor, ρ_k is the Larmor radius of k-th species, and ν_p is the frequency at the boundary between the plateau region and the Pfirsh-Shlüter region. The frequency ν_p is defined as $\nu_p = (1/Rq)\, v_{\mathrm{THe}}$, where v_{THe} denotes the electron thermal velocity. The value of ν_p is estimated about 8×10^6 sec^{-1}. The frequency at the boundary between the banana regime and the plateau regime, ν_b, is defined as $(r/R)^{3/2}\nu_p$, where r denote the plasma radial position. The value of ν_b is less than 7×10^5 sec^{-1}. The electron-ion collision frequency ν_{ei} near the plasma center is 3×10^6 sec^{-1}. Therefore, ν_{ei} stays between ν_p and ν_b, and the plasma is in the plateau regime.

The ion heat flux loss in this power balance calculation is assumed to be in proportion to that of the neoclassical theory. We represent the heat flux loss term $\nabla\cdot Q_k$ as follows;

$$\nabla\cdot Q_k = C\times n_k T_k^{5/2} A_k^{1/2}, \quad (4)$$

where C is constant including the safety factor and the magnetic field. The mass number A_k is 1 for hydrogen and 2 for deuterium. This constant C is assumed to be the same for hydrogen and for deuterium, and is obtained from the power balance calculation without RF pulse. In this calculation, the following parameters at the plasma center are used; the electron temperature, the electron density (the density profile is assumed to be parabolic), the majority ion temperature and density. The constant C is obtained from these parameters, and the minority ion temperature is also obtained. The difference of the ion temperature between the majority and the minority is about 1 eV in all cases. This heat flux loss $\nabla\cdot Q_k$ is $0.8-1.4\times(\nabla\cdot Q_k)_{\mathrm{neo}}$, which denotes the neoclassical heat flux loss calculated from eqs. (2) and (3).

In order to calculate the power balance with RF pulse, the hydrogen and the deuterium temperature measured with the charge exchange analyser are used. As was described, the increase in electron temperature with RF pulse is small, therefore, the electron temperature without RF pulse is used in the case of the power balance calculation with RF pulse. The constant C in the heat flux term is assumed to be the same as that without RF pulse. Under this assumption, the power absorption from the RF waves can be obtained for hydrogen and deuterium, separately.

In Fig. 5, the ion power balance at the plasma center is shown in the case of "ICR+HBR". RF power absorbed by hydrogen is much larger than that by

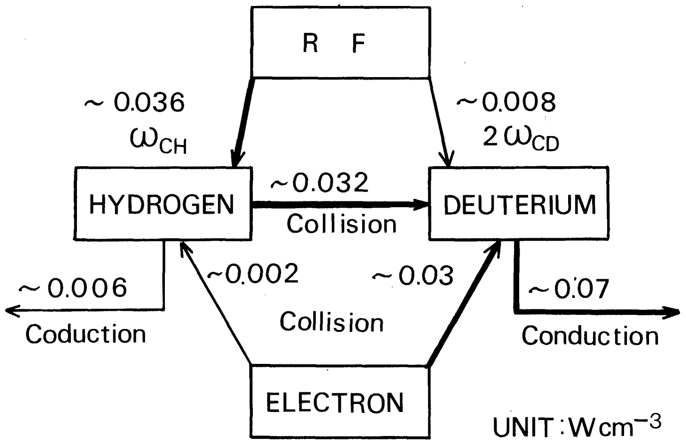

Fig. 5. Ion power balance at the plasma center with $T_H=107$ eV, $T_D=75$ eV, $T_e=150$ eV, $n_e=1.2\times10^{13}$ cm^{-3} and $n_H/n_D=0.05$ assuming neoclassical heat conductivity. Experimental error is comparable to RF power deposition in deuterium.

deuterium. Deuterium heating power consists mainly of the collisional heat transfer from electron and hydrogen. According to the calculation with a hot slab model described in ref. 15, hydrogen absorbs most of the wave power near ICR via fundamental cyclotron damping. The power deposition on deuterium via second harmonic damping process is much smaller than that on hydrogen, which is consistent with the power balance analysis shown in Fig. 5.

In the case of "ICR only", since hydrogen-deuterium temperature relaxation time is much shorter than that of "ICR+HBR" because of higher hydrogen density, the difference between the increases in hydrogen and deuterium temperatures is small, compared with the experimental error. Therefore, the mechanism of the ion heating cannot be proved.

In the case of "ICR+HBR" with the net RF input power of 11.4 kW, the volume averaged net RF input power is 0.18 Wcm^{-3}, which is larger than the power absorption into hydrogen and deuterium (≈ 0.044 Wcm^{-3}), obtained from the power balance calculation. The reason is considered as the poor confinement of the fast ion. In TNT-A, because of the low plasma current ($I_p\approx 10$ kA), the minimum loss cone energy is less than 1 keV. Therefore, the RF power is not effectively used for the plasma heating.

In conclusion, ICRF heating experiments by the fast wave excited in the low field side have been made in TNT-A. The ion temperatures of hydrogen and deuterium are measured with $E\perp B$ type mass separated neutral particle analyser with RF pulses. In the case of "ICR+HBR", the increase in hydrogen temperature is larger than that in deuterium. According to the power balance analysis, the RF power is deposited mainly in hydrogen.

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