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Abstract

Wave-heating at the fundamental ion-cyclotron frequency was applied to a hydrogen plasma in the Large Helical Device (LHD) over a range of plasma densities from 0.2–8 $\times 10^{19}\,\mathrm{m}^{-3}$. Substantial heating was observed for all densities. In the low-density plasma (less than 0.4 $\times 10^{19}\,\mathrm{m}^{-3}$) ion-cyclotron-wave (shear Alfven wave) heating was effective. For high-density plasmas, a fast-wave should be excited, and in this case also, effective heating was observed with the presence of the NBI beam component. The wave damping mechanism may be attributed to the finite gyro-radius effect on beam ions by the right-handed polarized wave. The experimental results were compared with an analysis using the full-wave code. The heating performance was a little worse than that of the usual two-ion hybrid-heating mode.

I. Introduction

In 1999, ICRF heating was successfully applied to the LHD, which is a large heliotron-type device with super-conducting windings. Most of the ICRF experiments were conducted using two ion species so as to utilize the two-ion hybrid-heating mode, including minority heating and mode-conversion heating [1],[2],[3]. In addition to this normal heating mode, other heating modes were utilized to achieve high performance plasmas when operating with pure hydrogen gas. Hydrogen-gas operation simplifies analysis of the transport properties of the plasma. This paper reports on slow- and fast-wave heating with the fundamental cyclotron-resonance-frequency over a wide density range.

II. Ion-Cyclotron-Wave (Shear Alfven Wave, Slow-Wave) Heating Mode

For low-density plasmas, ion-cyclotron-waves can propagate to the plasma core, and this method has been used for plasma heating from the time of the C-stellerator at Princeton. It is a left-hand-polarized slow-wave which propagates along the magnetic field-line, and loses energy by ion-cyclotron damping at the magnetic beach. The propagation region for the

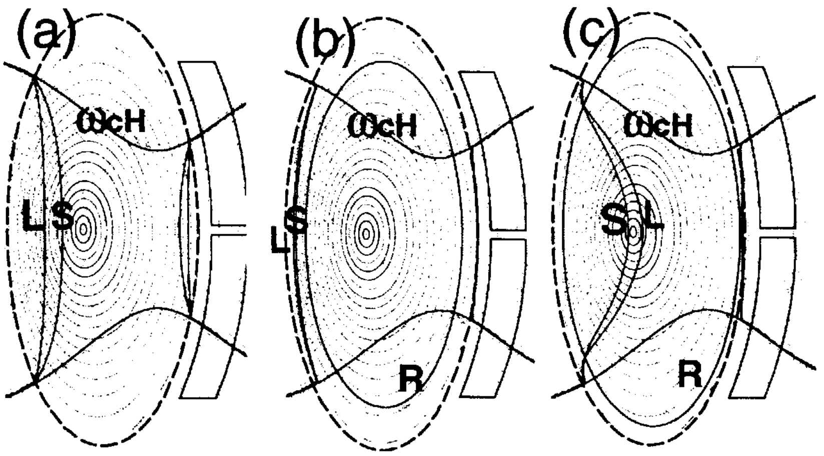

Fig.1 Cyclotron resonance, ω_{cH}, $n_{//}^2=S$ resonance, S, and $n_{//}^2=L$ cut-off, L, layers in LHD cross sections.
((a) $n_{e0}=0.3x10^{19}m^{-3}$, (b) $n_{e0}=6x10^{19}m^{-3}$,H:100%,$k_{//}=10m^{-1}$),
((c) $n_{e0}=2x10^{19}m^{-3}$, He:70%(H:30%),$k_{//}=5$), B=2.9T, f=38.5MHz

slow-wave is within the crescent-shaped regions between S and L shown in Figs. 1(a) and (b). Only for low-density plasmas can the slow-wave propagate in the core plasma region as shown in Fig. 1(a). Figure 1(c) shows the configuration for the normal two-ion hybrid-heating mode. For this mode, the crescent area is an evanescent region.

The stored energy of an ICRF-maintained plasma is plotted as a function of plasma density in Fig. 2. Slow-wave heating is shown by the closed circles. This method can maintain only low-density plasmas having densities less than 0.4 x10^{19} m^{-3}. Typical plasma parameters are: T_{eo} = 1.5 keV, n_e = 0.3 x10^{19} m^{-3}, T_{i_NPA} = 2.8 keV. The ion temperature was higher than the electron temperature, which implies that the wave mainly heated the ions. In Fig. 2 the boxes show the data for the two-ion hybrid-mode, which are shown for comparison. The heating performance for the slow-wave was a little lower than that of the two-ion mode, but is still useful for heating hydrogen plasmas. The observed strong dependence on density can be explained by the calculated shift in position of the slow-wave propagation region of Fig. 1 (a). The normalized radius of the L-cut-off, and the S-resonance at z = 0 is plotted as a function of the plasma density for three different parallel wave numbers $k_{//}$. The LHD antenna launched the wave of wave number less than 15 m^{-1}. This calculation shows that the slow-wave does not heat the core plasma for densities higher than 0.5 x$10^{19}m^{-3}$. The same behavior was observed at the ICRF heating of Heliotron E [4].

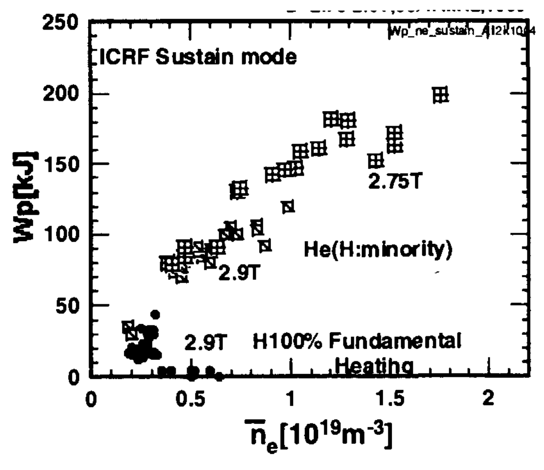

Fig.2 Plasma stored energy in ICRF sustain mode (Slow wave(closed circles) and Two-ion hybrid fast-wave mode(boxes))

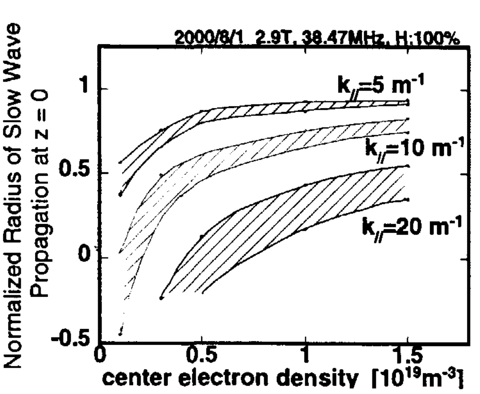

Fig.3 Slow-wave propagating region on the line of z=0 is shown for different k//. Positive normalized radius is inward direction of the toroid and negative is the outward.

III. Fast-Wave Heating at the Fundamental Cyclotron-Resonance Frequency

For a high-density plasma, the ion-cyclotron-wave (slow-wave) cannot propagate to the core region of the plasma. This is in contrast to the fast-wave as shown in Fig. 1 (b). The propagating region is inside the oval line labeled R (right-hand cut-off). This fast-wave is a right-hand circularly-polarized wave, and experiences very little damping compared to that from the two-ion hybrid-heating mode. Due to the small damping, the fundamental frequency of this mode is not usually used for plasma heating experiments.

In the LHD experiment, we observed a substantial heating gain using the fundamental cyclotron-resonance frequency for a high-density plasma. In Fig. 4, the time evolution of the plasma parameters is shown. The plasma was initiated by ECH, and heated by NBI to a high density and high stored energy level. Five pellets were injected continuously at the timing of around 0.75 sec, and improved confinement was achieved. The stored energy of the plasma was apparently increased by ICRF wave-heating.

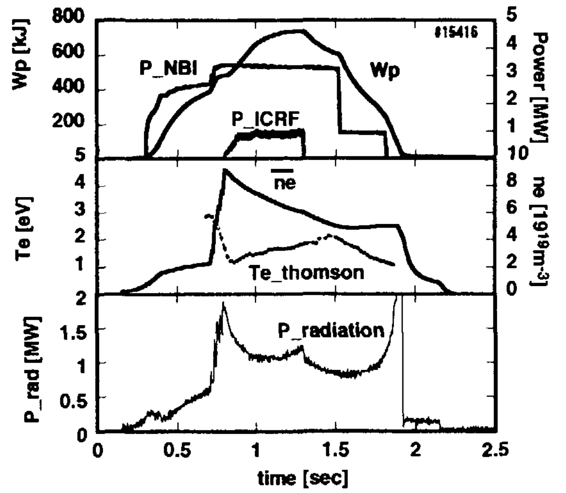

Fig.4 High density fundamental heating plasma. (Shot No.15416, B=2.75T, f=38.5MHz,H2gas puff H2 pellets)

For the plasma maintained by NBI, an increase in stored energy by additional ICRF was observed over a wide range of plasma densities. Figure 5 shows the heating efficiency, and the stored-energy increments over a wide density range. The closed circles are the result of fundamental cyclotron-heating with the NBI beam, and the boxes represent the result of adding two-ion hybrid-heating. The fundamental heating mode had a lower heating efficiency than the two-ion hybrid-mode, but still had useful efficiency over a wide density range. The highest stored energy of a plasma during 1999, used the conditions that led to the data of Fig.4.

For densities greater than 0.5 $\times 10^{19}$ m^{-3}, no heating was observed for plasmas maintained with ECH and ICRF. Meaningful heating was observed only on the NBI-maintained plasma. Therefore it is natural to conclude that the high-energy ion-beam component had an important effect on the

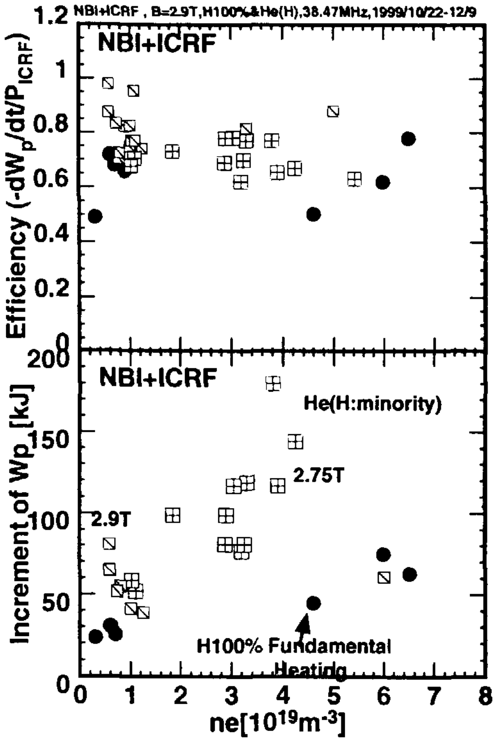

Fig 5. Increment of stored energy ,Wp, and heating efficiency by fundamental frequency heating of fast-wave at NBI plasma.

wave-damping mechanism. The NBI beam-injection energy was around 140 keV in tangential direction, and ions with energies up to 50 keV were observed in the perpendicular direction by NPA detectors. These ions have a finite gyro-radius effect on the damping mechanism of a right-hand-polarized fast-wave. The following equation explains the interaction of the ions with the wave electric field [5].

$$\Delta v_{\perp}=\frac{q}{2m}Ie^{-in\phi_r}\times\left[|E_+|J_{n-1}(k_{\perp}\rho)+|E_-|J_{n+1}(k_{\perp}\rho)\right]$$

In the above, n is the cyclotron harmonic number, equal to unity in the current calculation, and I is a function of the staying-time in the resonance region. The second term shows the velocity increment from the right-hand circularly polarized electric field, $|E_-|$, due to the finite gyro-radius effect.

This effect was also reproduced in the full-wave calculation for one-dimensional wave-propagation analysis of the LHD cross section [6]. Figure 6 shows the result of changing the temperature of the tail ion on the power transfer from the fast-wave to the ions and the electrons, the electric field of the wave at the plasma axis, and the antenna loading-resistance. This calculation assumes a tail-ion component of 3%. As the tail-ion temperature increases, the wave energy is transferred to the tail ions, and the electric field decreases. The antenna loading-resistance also increases with increasing tail-ion temperature. The finite gyro-radius effect is effective only on right-hand-polarized waves as described in the equation. The calculation therefore shows that absorption of the right-hand wave by the injected beam of ions may play a major role in the effective heating over a wide range of plasma densities.

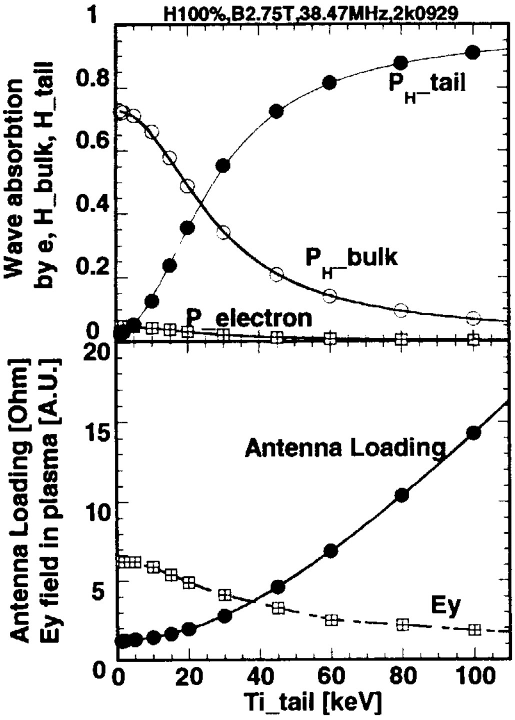

Fig.6 Calculation of the wave absorption to plasma species, the electric field in plasma and the antenna loading resistance by 1-D full wave code analysis.
(neo = $5x10^{19}m^{-3}$, $T_{eo}=T_{io}=2$ keV, H 100 %, High energy tail ions of 3%.)

This is the first successful fundamental ion-cyclotron-frequency heating of a high-density plasma in a toroidal device.

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