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Abstract

Ion heating experiments have been carried out in LHD using ECH (82.5, 84.0, 168GHz, ≤1MW), ICRF (38.5MHz, ≤2.7MW) and NBI (H° beam: 160keV, ≤8MW). The central ion temperature has been obtained from Doppler broadening of TiXXI (2.61Å) and ArXVII (3.95Å) x-ray lines measured with a newly installed crystal spectrometer. In ECH discharges on-axis heating was recently done with the appearance of high $T_e(0)$ of 6-10keV and high ion temperature of 2.2keV was observed at $n_e=0.6\times10^{13}cm^{-3}$. A clear increment of T_i was also observed with enhancement of the electron-ion energy flow when the ECH pulse was added to the NBI discharge. These results demonstrate the feasibility toward ECH ignition. The clear T_i increment was also observed in ICRF discharges at low density ranges of $0.4-0.6\times10^{13}cm^{-3}$ with appearance of a new operational range of $T_i(0)=2.8keV>T_e(0)=1.9keV$. In the low power ICRF heating (1MW), the fraction of bulk ion heating is estimated to be 60% to the total ICRF input power, which means $P_i>P_e$. Higher $T_i(0)$ up to 3.5keV was obtained for a combined heating of NBI (<4MW) and ICRF (1MW) at density ranges of $0.5-1.5\times10^{13}cm^{-3}$. The highest $T_i(0)$ of 5keV was recorded in Ne NBI discharges at $n_e<1\times10^{13}cm^{-3}$ with the achievement of $T_i(0)>T_e(0)$, whereas the $T_i(0)$ remained at relatively low values of 2keV in H_2 or He NBI discharges. The main reasons for the high T_i achievement in the Ne discharge are; 1) 30% increment of deposition power, 2) increase in P_i/n_i (11 times, $P_i/n_i>>P_e/n_e$, $P_i<P_e$) and 3) increase in τ_{ei} (3 times). The obtained $T_i(0)$ data can be plotted by a smooth function of P_i/n_i.

1. Introduction

Experiments in helical devices have been limited so far to only the electron-heating regime ($P_i<P_e$) [1]. The ISS-95 sterallator scaling [2] was obtained from such ECH and NBI discharges. If the experiments in the ion-heating regime ($P_i \geq P_e$) are realized, an increment of T_i and improvement of τ_E are expected, since the ion confinement is generally better than the electron confinement. The heating experiments have been extensively carried out in LHD in order to obtain higher T_i and understand the heating mechanism. In this paper the results are reported, especially on the ion temperature behavior [3]. Ion temperature at the plasma center has been measured from Doppler broadening of ArXVII and TiXXI x-ray lines using a newly installed crystal spectrometer with a CCD [4]. The difference in ion temperature between the measured impurity ions (Ar^{16+}, Ti^{20+}) and bulk ions (ECH and NBI: H^+, He^{2+}, ICRF: He^{2+}, neon discharge: Ne^{10+}) is estimated to be smaller than 50eV at n_e=0.5x10^{13}cm^{-3}.

2. H_2 and He discharges

2.1 ECH; Results from the off-axis ECH heating (82.7, 84 and 168GHz) are plotted in Fig.1(a). The $T_e(0)$ is obtained from the YAG Thomson scattering measurement. The $T_i(0)$ is much lower than $T_e(0)$ in the low-density range and becomes equal at n_e~1x10^{13}cm^{-3}. The electron-ion heat exchange time, τ_{ei}, becomes equal to the energy confinement time, τ_e, (~150ms) at n_e~1.1x10^{13}cm^{-3}. The power flow from electrons to ions at the plasma center ranges in 3-6kWm^{-3} at n_e>0.5x10^{13}cm^{-3} and 0.4-2kWm^{-3} at n_e<0.5x10^{13}cm^{-3}. If the ion confinement time of (3-5)*τ_e is taken into account, the $T_i(0)$ can be roughly explained by the

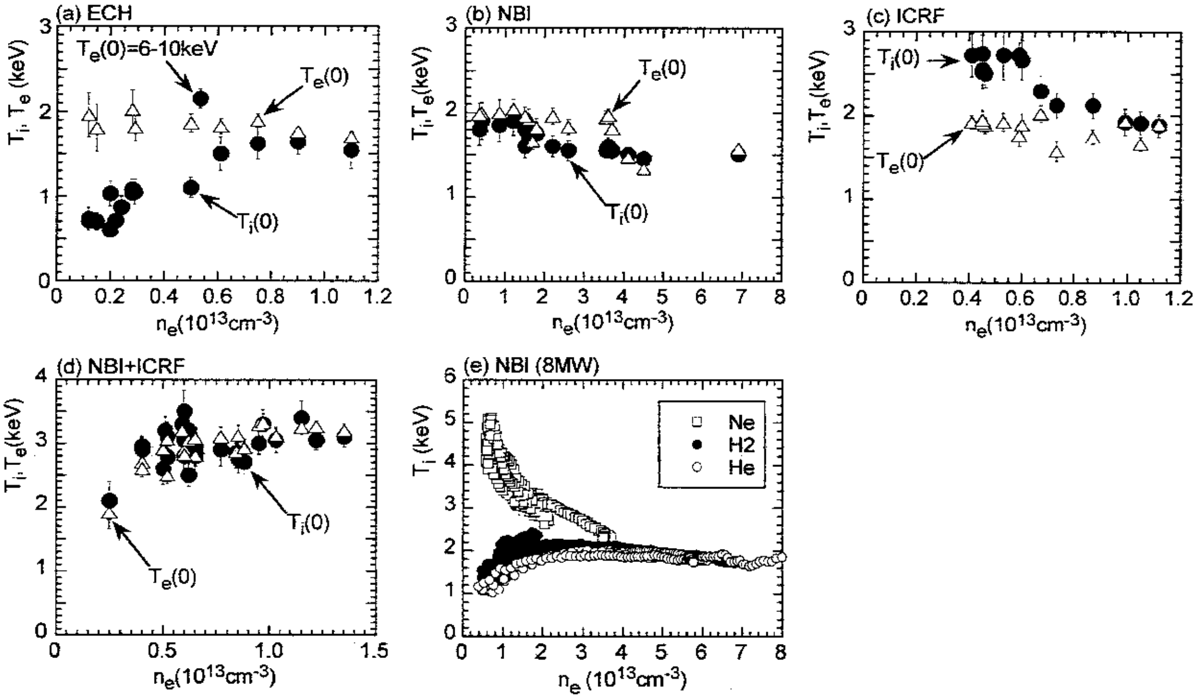

Fig.1 Comparison between $T_i(0)$ (•) and $T_e(0)$ (Δ) as a function of line-averaged density n_e in (a) ECH (0.4MW), (b) NBI (<4MW), (c) ICRF (1MW), (d) NBI+ICRF (<4MW+1MW) and (e) high-power NBI discharges (≤8MW). Open squares in (e) indicate $T_i(0)$ from Ne discharges.

power input from electrons. Recently, on-axis ECH heating was carried out, and a high $T_i(0)$ of 2.2keV has been observed with the appearance of a high $T_e(0)$ such as 6-10keV [5,6]. The power flow from electrons to ions increased 2-3 times (see also Fig.1(a)). Furthermore, the ECH pulse was added to the NBI discharge. A clear increment of $T_i(0)$ was also observed as shown in Fig.2. These results strongly suggest the feasibility of ECH ignition in future high-power and high-density ECH discharges.

2.2 NBI; NBI heating in LHD is carried out at the high beam energy of 160keV [7,8]. The beam shine-through power becomes considerably high (50% at $1\text{x}10^{13}\text{cm}^{-3}$) and an input power greater than 70% is absorbed by electrons ($P_i<P_e$, $P_i/n_i<P_e/n_e$). The ion heating in NBI discharges is entirely inefficient. As a result (see Fig.1(b)) the ion and electron temperatures obtained were roughly the same. Here, the fraction deposited to bulk ions (P_i/P_{NBI}) was 20% at T_e=2keV and 13% at T_e=1keV. The total P_i becomes 0.3-0.4MW at $n_e=1\text{x}10^{13}\text{cm}^{-3}$ and 0.2MW at $n_e=0.5\text{x}10^{13}\text{cm}^{-3}$ in the case of P_{NBI}=3MW.

2.3 ICRF; Successful results [9-11] from 38.5MHz ICRF (H: minority, He: majority, P_{ICRF}=1MW) discharges are shown in Fig.1(c). An increment of $T_i(0)$ was clearly observed in a range of $0.4\leq n_e\leq 0.6\text{x}10^{13}\text{cm}^{-3}$. The bulk ions are heated through high-energy H^+ ions accelerated up to 200keV ($T_{tail}(H^+)$~25keV). The deposition profiles are calculated with a 5-D code by Murakami [12]. The results showed a broad $q_i(r)$ with a certain central deposition of $q_i(0)=7\text{kwm}^{-3}$ and a narrow $q_e(r)$ localized at near $\rho=0.5$. The fraction of bulk ion heating, P_i/P_{ICRF} was roughly 60%. The bulk ion heating power of 7kWm^{-3} at $\rho=0$ and 18kWm^{-3} at $\rho=0.5$ had a broad radial deposition profile, whereas the bulk electron heat deposition profile was located in a range of $0.4\leq\rho\leq 0.8$. Thus, a new operational range of $T_i>T_e$ was established with a successfully performed ion heating regime ($P_i>P_e$, $P_i/n_i>P_e/n_e$).

2.4 ICRF+NBI; The ICRF pulse was added to the NBI discharge. The result is shown in Fig.1(d). Since the ICRF heating, at present, is not effective at $n_e>2\text{x}10^{13}\text{cm}^{-3}$, the data are plotted in the lower density range. We understand that the ion temperature also can be raised

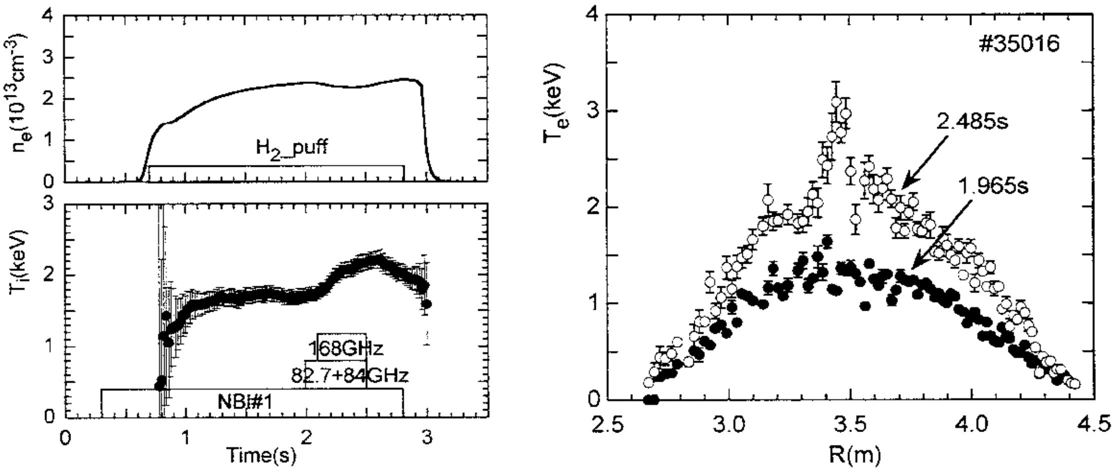

Fig.2 Ion heating during additional ECH pulse in NBI discharge (left) and electron temperature profiles before (1.965s) and during (2.485s) the ECH pulse (right).

up by the combination with NBI because of the further increase in P_i.

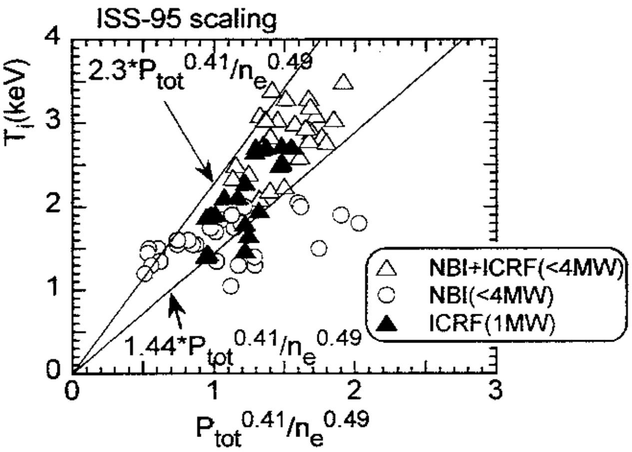

Fig.3 T_i plot by ISS-95 scaling.

The obtained T_i was compared with ISS-95 scaling under the assumption of T_i=T_e (Fig.3). The value expected from the scaling is traced with the lower solid line of $1.44*P_{tot}^{0.41}/n_e^{0.49}$. In NBI discharges the $T_i(0)$ is a weak function of P_{tot}/n_e. On the contrary, most of the data from the ICRF and NBI+ICRF discharges exceed the scaling value, and those suggest an improvement of the heating efficiency of 60% at the maximum indicated by the upper solid line of $2.3*P_{tot}^{0.41}/n_e^{0.49}$. This increment of $T_i(0)$ originates in the presence of ICRF pulse.

3. Neon discharge

Neon discharges [13,14] were tried using NBI to obtain a higher T_i. A pure Ne discharge (Z_{eff}~9) was successfully obtained because the main part of the neon radiation could be excluded from the core plasma and emitted in the ergodic layer outside ρ=1, which characterizes LHD. The highest ion temperature of 5keV was obtained with the achievement of $T_i(0)>T_e(0)$ in the Ne discharges (Fig.1(d)). The global energy confinement was the same as the H_2 and He discharges. The main reasons why the high-T_i range was extended are; 1) increase in the NBI deposition at lower density ranges (+30%) (Fig.4(a)), 2) increase in the bulk ion heating fraction following the T_e increase (Fig.4(b)), 3) increase in P_i/n_i (11 times, $P_i/n_i>>P_e/n_e$, $P_i<P_e$) and 4) increase in τ_{ei} (3 times) (Fig.4(c)). Here, the $q_i(0)$ becomes ~100kWm^{-3} at $n_e=0.6\times10^{13}$cm^{-3} for P_{NBI}=8MW if the orbit loss of the NBI particle and the charge exchange loss can be neglected.

The obtained ion temperatures are plotted against P_{tot}/n_e (Fig.5(a)). The difference between the Ne and H_2 discharges is notable. The same data set as in Fig.5(a) was also

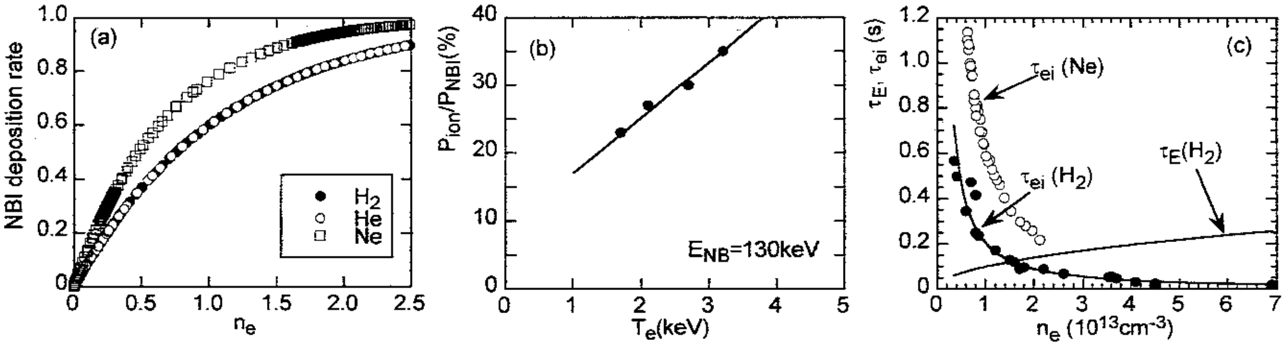

Fig.4 (a) NBI deposition rate of H_2, He and Ne, (b) ratio of bulk ion heating to total NBI input power and (c) τ_E for H_2 discharge and τ_{ei} for H_2 and Ne discharges.

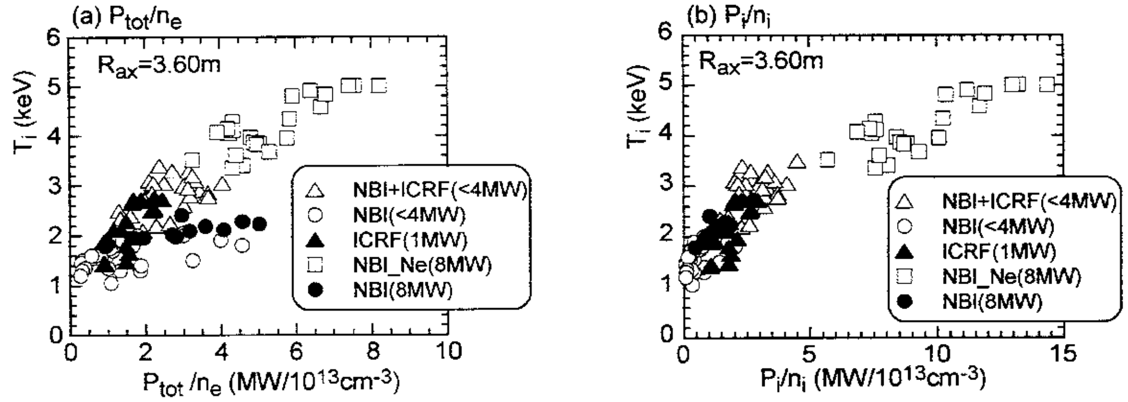

Fig.5 $T_i(0)$ as a function of (a) P_{tot}/n_e and (b) P_i/n_i (P_{tot}: total input power, P_i: input power to bulk ions, n_i: bulk ion density, NBI_Ne: neon discharge).

replotted as a function of P_i/n_i (Fig,5(b)). The two figures suggest the importance of the direct power input to the bulk ions in order to realize higher ion temperature. However, the increment of $T_i(0)$ is somewhat suppressed in the Ne discharges ($q_i(0)$~100kW), whereas good heating efficiency appears in the ICRF discharges ($q_i(0)$~7kW). It possibly predicts a confinement degradation for ions at high heating power and high T_i ranges. The influence of hydrogen neutrals on the fast ions is now being investigated, especially in low-density discharges. Further study of the ion behavior is needed.

In conclusions, a new parameter range of $T_i>T_e$ was found in LHD for ICRF and Ne-seeded NBI plasmas. The highest ion temperature of 5keV was achieved in the Ne NBI discharge. The T_i increase by on-axis ECH heating also revealed a feasibility toward ECH ignition.

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