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Effect of Additional Neutral Beam Heating on High Ion Temperature Mode in CHS Heliotron/Torsatron Plasmas

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Abstract

Additional heating of ctr-injected neutral beam was applied to the co-based High-T_i mode scenario plasma. The energy deposition by neutral beam was estimated for co-injected and co/ctr-injected cases at the plasma center. The analysis indicates that the ion temperature is strongly correlates with the energy deposition from fast ions to a single bulk ion. The analysis suggests that reduction of the fast ion loss is effective to increase ion temperature.

Keywords:

CHS, High-T_i mode, neutral beam heating, fast ion loss

1. Introduction

The ion temperature of ~800 eV was recently achieved in CHS [1]. This temperature is obtained by a so called High-T_i mode scenario [2, 3], which is characterized by a peaked ion temperature profile and a peaked electron density profile attained by a beam fueling to low density and low recycling plasma without any gas puff. The counter neutral beam (32 keV/700 kW) was injected into a low density plasma sustained by co-injected neutral beam (36 keV/1 MW).

The injection timing of the second neutral beam was scanned to see the optimum condition for injection, as shown in Fig. 1. The ion temperature tends to reach its maximum about 10 ms after the injection of the second neutral beam and saturate at certain temperature. The ion temperature starts to decrease after the stored energy saturates.

In this paper, we will discuss on the heating effect of neutral beams at the plasma center. The analysis is done by comparing the estimated ion heating rate by neutral beam to the ion temperature obtained by neutral particle analyzer. The analysis is based on the co-only injected plasma. For the case of both co/ctr-NB injected plasma, co-NB only phase and the first 10 msec of co/ctr-NB injection phase is our phase of interest.

2. Estimation of Heating Power by Neutral Beam

The energy of a beam particle after the injection to a plasma can be expressed as [4];

$$E_b(t) = E_{b0}\Big(\exp(-3t/\tau_{se}) - (E_c/E_{b0})^{3/2}\big(1-\exp(-3t/\tau_{se})\big)\Big), \tag{1}$$

where E_c is a critical energy [4, 5], $\tau_{se} = \dfrac{3(2\pi)^{1/2} T_e^{3/2}}{m_e^{1/2} m_b A_D}$ and $A_D = \dfrac{n_e e^4 (\ln \Lambda)}{2\pi\varepsilon_0^2 m_b^2}$. The direct heating of bulk ions (E_i) and electrons (E_e) by a beam particle will be [4];

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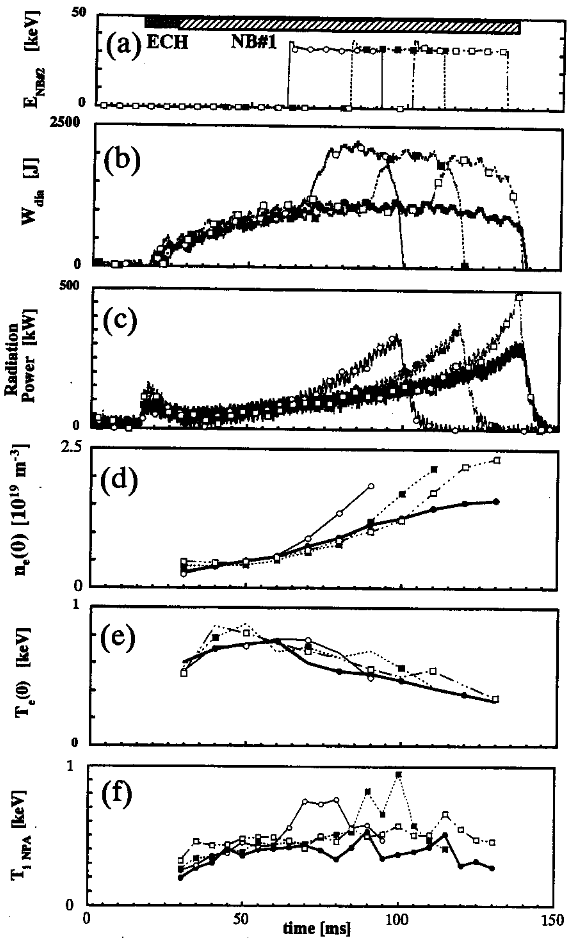

Fig. 1 Time evolution of the discharge parameters. The lines with closed circles show the discharge of co-NB only and the other lines show the discharges where an additional ctr-NB injection is applied. The lines with open circles, closed squares, and open squares show the discharges of ctr-NB injected at t = 60 ms, 80 ms, and 100 ms, respectively. The end of NB#1 injection coincides with the end of NB#2 injection when the NB#2 is applied. (a) Injection timing of NB#2 (ctr), (b) stored energy, (c) radiation power, (d), (e) central electron density and temperature obtained by Thomson scattering measurement, (f) ion temperature obtained by a neutral particle analyzer.

$$E_{\mathrm{i}} = \int_0^{\tau} (\mathrm{d}E_{\mathrm{b}}/\mathrm{d}t)\, f_{\mathrm{i}}\, \mathrm{d}t \text{ and } E_{\mathrm{e}} = \int_0^{\tau} (\mathrm{d}E_{\mathrm{b}}/\mathrm{d}t)\, f_{\mathrm{e}}\, \mathrm{d}t,$$

where

$$f_{\mathrm{i}} = \left(\alpha E_{\mathrm{b}}/(\alpha E_{\mathrm{b}} + \beta/E_{\mathrm{b}}^{1/2})\right),$$

$$f_{\mathrm{e}} = \left(\beta/E_{\mathrm{b}}^{1/2}/(\alpha E_{\mathrm{b}} + \beta/E_{\mathrm{b}}^{1/2})\right),$$

$$\tau = (\tau_{\mathrm{se}}/3)\ln\left(1 + (E_{\mathrm{b0}}/E_{\mathrm{c}})^{3/2}\right),$$

$$\alpha = \frac{2m_{\mathrm{e}}^{1/2}}{3(2\pi)^{1/2}\,T_{\mathrm{e}}^{3/2}} \text{ and } \beta = \frac{m_{\mathrm{b}}^{3/2}}{2^{3/2}\,m_{\mathrm{i}}}.$$

In the low density plasma, it is reported that the loss of fast ions (mainly due to charge exchange loss) is significant [6] in CHS. In this paper, this loss effect is taken into account by an exponential function (exp(-t/τ_c)) with beam confinement time τ_c (τ_c = 10–20 ms, typically in CHS). The heating power density by injected beam particles to bulk ions and electrons can be expressed as;

$$P_{\mathrm{i}} = \int_0^{\tau} \sum_j \left(n_{\mathrm{b0},j} f_{\mathrm{i},j} (\mathrm{d}E_{\mathrm{b}}/\mathrm{d}t)_j \exp(-t/\tau_{\mathrm{c}}) \right) \mathrm{d}t, \qquad (2)$$

and

$$P_{\mathrm{e}} = \int_0^{\tau} \sum_j \left(n_{\mathrm{b0},j} f_{\mathrm{e},j} (\mathrm{d}E_{\mathrm{b}}/\mathrm{d}t)_j \exp(-t/\tau_{\mathrm{c}}) \right) \mathrm{d}t, \qquad (3)$$

where n_{b0} is the deposition rate of beam particles at the plasma center and j denotes the j-th energy components (j = 1, 2, 3 : full, half, and 1/3 energy components) of the beam.

The central beam deposition rate is calculated by PROCTR-code [7] using the electron temperature and density profile for the co-NB plasma. This calculational result can be expressed, using central electron density n_{e0}, as;

$$n_{\mathrm{b0},j} = a_j - b_j \exp(-c_j n_{\mathrm{e0}}), \qquad (4)$$

where a_j, b_j, c_j are shown in Table 1.

The result of a numerical integration of Eqs. (2) and (3) are shown in Fig. 2, where the beam injection energy (E_b) of 36 keV and beam confinement time (τ_c) of 20 ms are assumed. In Fig. 2, calculated energy deposition to ions and electrons are normalized by the density of ions and electrons, where $n_i = n_e$ are assumed.

The upper left corner of Fig. 2(a) is strongly affected by the effect of τ_c, since the slowing down time of a fast ion is longer in this region. If longer τ_c is applied, the absolute value of energy deposition to ions increases in the whole region of (n_{e0}, T_{e0}) and the

Table 1 Fitting coefficient of central beam deposition rate for NB#1 (E_b = 36 keV, P_b = 1 MW is assumed)

Coefficient	Full Energy (j=1)	Half Energy (j=2)	1/3 Energy (j=3)
a_j [cm^{-3}sec^{-1}]	9.0736×10^{14}	7.1553×10^{14}	1.7868×10^{14}
b_j [cm^{-3}sec^{-1}]	9.0091×10^{14}	6.7590×10^{14}	1.7517×10^{14}
c_j [cm^3]	4.4737×10^{-14}	8.2628×10^{-14}	1.1070×10^{-13}

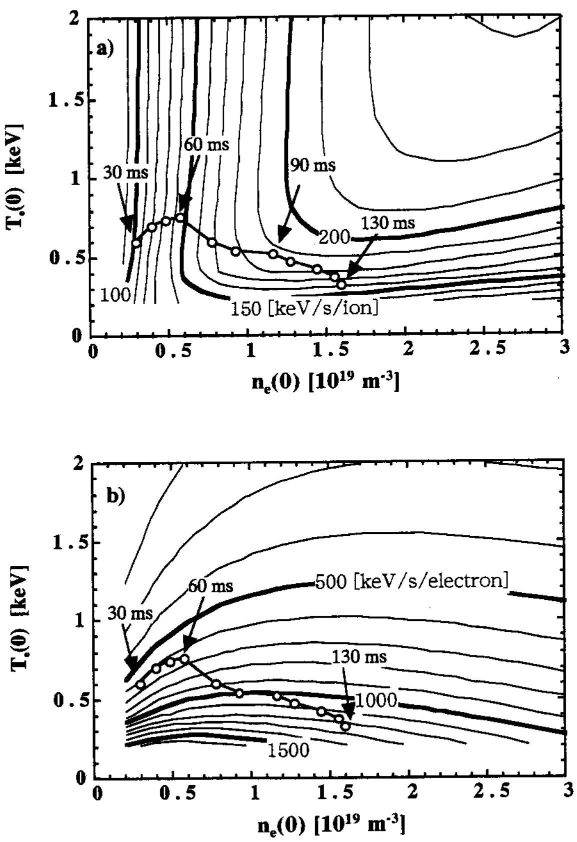

Fig. 2 Estimated heating power to a single bulk ion (a) and electron (b) by injected beam. Beam injection energy of the 36 keV and τ_c = 20 ms are assumed. The lines with open circles show the traces of the co-NB injected discharge.

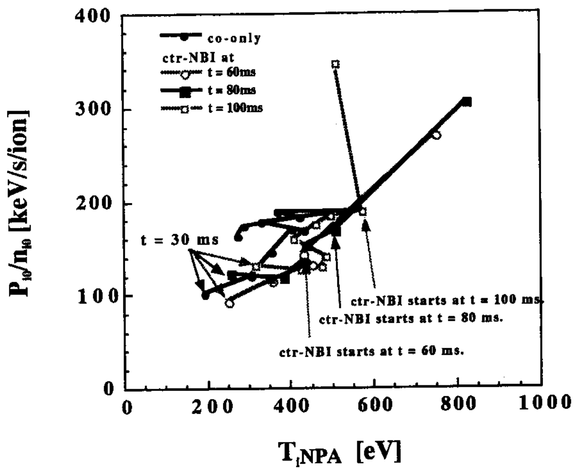

Fig. 3 Correlation between ion temperature obtained by NPA (T_iNPA) and heating power to a single bulk ion (P_{i0}/n_{i0}). The lines with open circles, closed circles, open squares, and closed squares show the case of co-NB injected discharge, co/ctr-NB injected (ctr-NB at t = 60 ms), co/ctr-NB injected (ctr-NB at t = 80 ms), and co/ctr-NB injected (ctr-NB at t = 100 ms), respectively.

Table 2 Fitting coefficients of central beam deposition rate for NB#2 (E_b = 32 keV, P_b = 0.7 MW is assumed)

Coefficient	Full Energy (j=1)	Half Energy (j=2)	1/3 Energy (j=3)
a_j [cm^{-3}sec^{-1}]	6.4010×10^{14}	4.9796×10^{14}	1.2599×10^{14}
b_j [cm^{-3}sec^{-1}]	6.3589×10^{14}	4.9461×10^{14}	1.2631×10^{14}
c_j [cm^3]	5.5011×10^{-14}	1.0510×10^{-14}	1.3222×10^{-13}

region where the maximum energy input to a single ion is obtained moves to the left side in Fig. 2(a).

3. Discussion

In Fig. 2, the time trace of the co-NB only discharge is plotted by lines with open circles. The energy input to a single ion (P_{i0}/n_{i0}) increases during t = 30–60 ms. After that, the energy input is gradually changing with time, and reaches its maximum at t = 90 ms. This tendency resembles to that of ion temperature obtained by NPA (T_iNPA). In Fig. 3, P_{i0}/n_{i0} at each point is plotted against T_iNPA together with those of co/ctr-NB injection discharges. To simplify the analysis, the same electron density profile and temperature profile dependence against n_{e0} are assumed for the discharges of co/ctr-NB injection. The calculated coefficients of Eq. (4) are shown in Table 2. To avoid the change in plasma characteristics, the time of interest was limited to the first 10 ms of ctr-NB injection. Between T_iNPA and P_{i0}/n_{i0}, strong correlation is found. The ion temperature of the discharge seems to be dominated by the energy input to a single ion by fast ions. In Fig. 3, there is one point which strongly deviates from the line of the correlation. This might be due to the enhancement of fast ion loss during the radiation collapse phase of the plasma [8], but careful analysis is necessary for this case.

The fact that the ion temperature correlates with P_{i0}/n_{i0} suggests the effectiveness of τ_c increase. Since τ_c is thought to be dominated by charge exchange reaction with background neutrals [6], immense wall conditioning to reduce the neutral particles might be effective in increasing T_i in CHS.

Figure 2 indicates that the increase in T_e does not affect the increase in T_i in the experimental region where High-T_i mode is performed, since no increase in

P_{i0}/n_{i0} can be expected. This is consistent with the result that no T_i increase was observed when T_e increased with an application of ECH to High-T_i mode plasma [1]. To see the effect of T_e on T_i, it is also necessary to reduce the density of background neutrals.

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