Rapid Communications

A New Method of Rapid Plasma Heating Using a Combination of NBI and Rapid Density Increase

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A method for rapid plasma heating is proposed, in which the combination of neutral beam injection (NBI) and fast density increase is used. The neutral beam is injected into a low density plasma until a significant amount of charge-exchanged hot ions is accumulated. After that, the plasma density is rapidly raised, then the energy of hot ions is thermalized and a large power input to the thermal plasma can be obtained.

Keywords:
nuclear fusion, magnetic confinement, rapid plasma heating, NBI, rapid density increase

A new method of rapid plasma heating is proposed, in which a high power neutral beam is injected into a low density plasma, whose density is low enough to achieve a long slowing down time (τ_{slow}) for hot ions, but high enough for trapping a considerable part of the injected beam particles. After a significant amount of charge-exchanged hot ions is accumulated, the plasma density (n) is rapidly raised in a time sale (τ_n) shorter than or comparable to the plasma confinement time (τ_E). The τ_{slow} then becomes short and the energy of the hot ions is rapidly thermalized. Consequently, a short but strong power input to the thermal plasma is obtained.

For examining the feasibility of this idea, the possible operating density region is estimated. The charge transfer cross section between hydrogen atom and proton is approximately 5×10^{-20} m^2 for the beam energy, E_b ~20–30 keV [1,2] and the mean free path of the neutral beam ranges in 2 – 2.5 m for n ~1×10^{19} m^{-3}. This value is not too long when the medium size of the torus (major/minor radii are R/a~ 1.5 m/0.5 m) and the tangential injection are considered. The τ_{slow} is about 50 ms for the plasma with n ~1×10^{19} m^{-3} and temperature T ~2 keV [3]. This value is not too short for accumulating a considerable amount of hot ions.

In a zero dimensional simple model, the power balance equations between the hot ion component and thermal plasma can be expressed as

$$dW_H/dt = -W_H/\tau_{loss} - W_H/\tau_{slow} + P_{NBI}$$

$$dW_p/dt = -W_p/\tau_E + W_H/\tau_{slow} + P_{OH} = -W_p/\tau_E + P_{in}$$

where W_H is the total energy of hot ions, τ_{loss} the direct energy loss time of hot ions, P_{NBI} the charge exchanged NBI power input, W_p the plasma thermal energy, and P_{OH} the Ohmic input power. The τ_{slow} is the function of n, T and E_b [3]. Assuming $T_e = T_i$, the T is given by $T = W_p/(3nV)$, where V is the plasma volume. In this estimation, the following conditions are used; D plasma, H beam, R/a = 1.5 m/0.5 m, I_p = 0.8 MA, B_t = 3 T, circular cross section and heating power $P = P_{NBI} + P_{OH}$.

Figure 1 shows the time variations of W_p, W_H, input power to plasma P_{in}, and power loss from plasma $P_{loss} = W_p/\tau_E$. The n is raised from 1×10^{19} m^{-3} to 5×10^{19} m^{-3} in τ_n = 5 ms starting at t = 0.2 s, and P_{NBI} = 5 MW, P_{OH} = 0.4 MW, E_b = 30 keV and τ_E = 28 ms. The L-mode scaling of the tokamak is used for τ_E [4]. For simplicity, the τ_{loss} is assumed to be equal to τ_E. The NBI is started at t = 0 and the plasma almost reaches an

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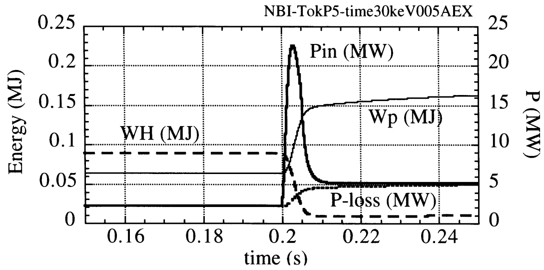

Fig.1 Time variations of total energies of plasma (W_p; thin solid line), hot ions (W_H; long broken line), input power to plasma (P_{in}; bold solid line) and plasma power loss (P_{loss}; short broken line). L-mode τ_E, ~28 ms.

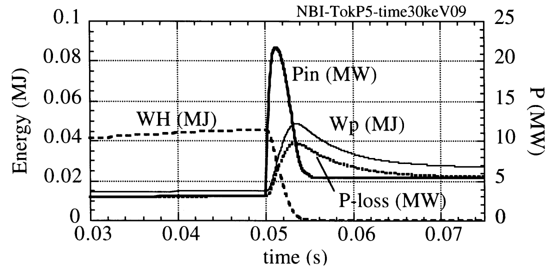

Fig. 2 The same quantities as shown in Fig.1. Short τ_E = 5 ms = τ_n is assumed. Time scale is expanded.

equilibrium state with $n = 1 \times 10^{19}$ m^{-3} at t = 0.2 s.

In this case where the τ_E is longer than τ_n, the following features are given.

(1) At the initial equilibrium, 60% of the total energy is contained in the hot ions, the main part of which is directly lost before being thermalized.

(2) The contained W_H is rapidly converted to W_p in ~10 ms during the rise of n, since the τ_{slow} is reduced to 1.3 ms by the increase of n and decrease of T. The P_{in} can reaches 23 MW, which is ten times larger than that in the initial equilibrium and is five times larger than that in the final equilibrium.

(3) After the increase of n, the plasma reaches an equilibrium state at t ~ 0.35 s corresponding to $n = 5 \times 10^{19}$ m^{-3}. The W_p becomes almost three times larger than that at t = 0.2 s. This value, however, is the same with that in the final equilibrium state where the NBI is used for $n = 5 \times 10^{19}$ m^{-3} plasma from t = 0. The difference is only in the rising speed of W_p, and neither W_p nor P_{loss} exceeds the equilibrium values unless the confinement condition improves during the density increase.

These results indicate that this heating method in the region with $\tau_E \gg \tau_n$ will be effective only for operations where the rapid rise of W_p is required, such as the survey of the high beta limit.

However, in the case with τ_E comparable to τ_n, not only the increase of P_{in} but also increases of W_p and P_{loss} can be transiently obtained. They become almost two times greater than the final equilibrium values. An example is shown in Fig.2, where the same quantities as in Fig.1 are shown under the same conditions except different values of τ_E = 5 ms, τ_{loss} = 20 ms, and initial density (increasing from 5×10^{18} m^{-3} to 5×10^{19} m^{-3} in 5 ms starting at t = 50 ms).

These results clearly show the possibility for realizing rapid and strong heating using the combination of the NBI and rapid density increase. In addition, this method can also be used in other systems such as RFP, helical, mirror systems, etc.

However, it should be noted that several factors, which may be important and could be fatal, are not considered in the present estimation; for example, the increase of the charge exchange loss of hot ions during the density rise, instabilities caused by the hot ion component which will enhance the direct loss and limit the accumulation of hot ions, etc. The effects of profile variations of density, temperature and other quantities should also be taken into account for precise estimation, which play important roles in the energy balance of plasma with rapid heating.

Despite the above mentioned weakness, the interesting possibility of rapid plasma heating is now demonstrated and it may be worthwhile to examine by using more practical and sophisticated calculations.

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