Regime of Improved Confinement in Neutral-Beam–Heated Limiter Discharges of a Tokamak

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A new operational regime has been observed in neutral-beam–heated JFT-2M limiter discharges. This regime is characterized by confinement times close to those of Ohmic and divertor *H*-mode (good confinement mode) discharges. The properties of these discharges are similar to the divertor *H* mode. The incremental energy-confinement time due to the heating is found to be independent of the plasma density up to the maximum density.

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The recent confinement studies on discharges of large tokamaks with additional heating have shown that the break-even condition is hardly achieved by the *L*-mode energy-confinement–time scaling (reviewed in Kaye and Goldston[1]). The discharges with enhanced energy-confinement time (first discovered in the Asymmetric Divertor Experiment tokamak as the *H* mode[2] and then in other medium-size tokamaks[3–6]) provide the possibility of overcoming this problem. Since the energy-confinement times of Ohmic, *H*- and *L*-mode discharges are comparable at low density, an *H*-mode discharge is defined here as a discharge with sudden transitions. Such transitions are the increase in stored energy, in density, and in edge temperature, and the decrease in particle recycling. Because of these transition phenomena and also of broad density and temperature profiles, the *H* mode is distinguished from other improved discharge modes in limiter discharges such as scoop mode,[7] *Z* mode,[8] and *P* mode.[9] The *H* mode has, however, been obtained in previous experiments only in divertor operation and by the supplying of several megawatts of heating power. This Letter reports the first achievement of an *H* mode in limiter discharges heated by neutral-beam injection (NBI). The fact that the *H* mode has not been realized in limiter discharges so far may be explained as follows. First, higher impurity content prevents the formation of the *H* mode as has been demonstrated by impurity injection experiment in the Asymmetric Divertor Experiment tokamak.[2] Secondly, the control of the pressure of neutral particles and of the particle recycling at the plasma edge yields the transition from *L* mode to *H* mode or vice versa in the following experiments: Doublet-III LR (low recycling) divertor experiment,[3] poloidal divertor open/closed-divertor experiment,[5] Doublet-III *P*-mode/*H*-mode experiment,[10] and JFT-2M non-neutral-buildup divertor experiment.[6] These experiments imply that the plasma-edge cooling by impurities or by neutral particles prevents the development of the *H* mode in limiter discharges.

In JFT-2M, the buildup of neutral particles at the plasma periphery in the high-density regime can be prevented by a method of fueling with desorbed hydrogen from the graphite wall (limiter-divertor plate).[6] For a discharge with an international-tokamak-reactor–type stubby open divertor,[11] the *H* mode is observed first for relatively low beam power (about 0.2 MW of the minimum threshold power).[6] With use of a similar fueling situation the *H*-mode–type discharge is observed now even in limiter discharges.

The detailed description of JFT-2M is given by Shoji *et al.*[12] The cross-sectional view of JFT-2M is shown in Fig. 1. The minor and major radii, $a_p \times b_p$ and R_p, are 30.5 cm×14.1 cm and 127 cm. The plasma current and toroidal magnetic field strength are fixed as $I_p = 220$ kA and $B_T = 1.23$ T throughout this experiment. The plasma is shifted toward the inner limiter and the clearance between the outermost magnetic surface and the outer limiter is 9 cm (see Fig. 1). The *H*-mode transition occurs only if this clearance at the outside of the torus is

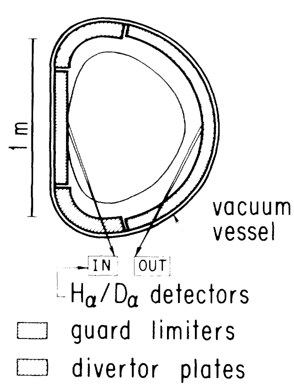

FIG. 1. The cross section of JFT-2M. The H_α/D_α detectors are looking at the inner (IN) or outer (OUT) wall between the limiters.

sufficiently large. This limiter H mode can be achieved when the beam power P_{NB}, which is deposited into the plasma, is higher than 0.5 MW. The L-mode discharges at this power level occur for cases with intense gas-puff fueling keeping the other conditions the same. About 30% of the wall area is covered with graphite guard limiters and divertor plates distributed around the torus in six and eighteen positions, respectively. The interior ungettered wall is conditioned only by Taylor-type discharge cleaning after wall baking at about 150 °C. A considerable amount of hydrogen atoms are absorbed in the graphite wall in this phase. The plasma is mainly fueled by deuterium gas puffing in the Ohmic heating (OH) phase and by desorbed hydrogen from the wall in NBI phase (wall fueling[6]). The plasma density is clamped during NBI in the earlier experiments without graphite wall. This kind of fueling results in a very low pressure of the neutral gas at the edge ($\simeq 10^{-7}$ Torr) during the heating phase, since the required gas flow rate is quite low (much lower than 10 Torr l/s). This pressure is much lower than that in the Princeton Large Torus closed-divertor discharges ($\simeq 10^{-5}$ Torr[13]). The NBI system consists of coinjectors and counterinjectors labeled with respect to the direction of the plasma current. A counterinjector is only used for the highest power case reported in this Letter. The beam power P_{NB} is estimated from beam deposition calculations including loss processes such as shine through, orbit loss, and charge-exchange loss. The estimated P_{NB} is consistent with the time derivative of the energy stored in the plasma, when the beam is switched on.

Property of limiter H mode.—The temporal evolution shown in Fig. 2 yields the properties of the limiter H mode. These discharges differ only in the gas flow rate after the beam onset as shown in Fig. 2(b) (3.3 Torr l/s for the L mode and 0 Torr l/s for the H-mode discharges). Figure 2(a) shows the increase in the stored energy $W^{\rm diam}$ in the H-mode phase (indicated as H in the figure), which is deduced from diamagnetic measurement. A sudden increase in the edge electron temperature is observed in this phase. The increase in line-averaged electron density $\bar{n}_e$ [Fig. 2(b)] together with the sudden decrease in particle recycling at the plasma periphery is mainly due to improved particle confinement. The particle recycling is inferred from the hydrogen and deuterium Balmer α emissivities $I_{{\rm H}_\alpha/{\rm D}_\alpha}$ [Fig. 2(c)] and plasma television viewing. The total radiation loss power P_R (including charge-exchange loss power) increases shortly after the transition [Fig. 2(d)]. Since the line emissivity of iron impurities of higher charge states increases while that of lower charge states decreases at the H-mode phase, the drastic increase of P_R is presumably caused by impurity accumulation at the core plasma due to the improved particle confinement. This impurity accumulation terminates the H mode. In the H-mode phase, the global energy-confinement time

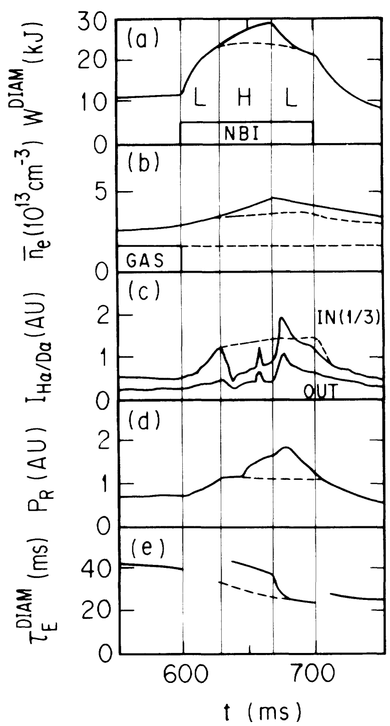

FIG. 2. The time evolution of typical parameters for the H-mode (solid lines) and L-mode (dashed lines) discharges: (a) Plasma stored energy obtained by diamagnetic measurement $W^{\rm diam}$; (b) line-averaged electron density $\bar{n}_e$; (c) intensities of recycling light $I_{{\rm H}_\alpha/{\rm D}_\alpha}$ (IN and OUT) (AU for arbitrary unit); (d) radiation loss power (including charge-exchange loss power) P_R; and (e) global energy-confinement time $\tau_E^{\rm diam}$. The deposited beam power is 0.67 MW and the gas flow rate of the OH phase is 3.3 Torr l/s.

recovers to values of the OH phase [Fig. 2(e)]. Here the global energy-confinement time is defined as $\tau_E^{\rm diam} = W^{\rm diam}/(P_{\rm OH} + P_{\rm NB} - dW^{\rm diam}/dt)$, where $P_{\rm OH}$ is the input power of the OH. The highly transient case ($dW^{\rm diam}/dt \le -100$ kW or ≥ 200 kW) is omitted. The values of $\tau_E^{\rm diam}$ and $W^{\rm diam}$ for the OH, H-, and L-mode phases with various heating power are plotted against $\bar{n}_e$ in Figs. 3(a) and 3(b). In the OH phase, $\tau_E^{\rm diam}$ increases in proportion to $\bar{n}_e$ up to a critical density ($\bar{n}_e^c = 2.0 \times 10^{13}$ cm^{-3}; above this limit the peripheral neutral pressure builds up[6]) and saturates at around 40 ms. This degradation of $\tau_E^{\rm diam}$, or Ohmic stored energy $W_{\rm OH}$, is always accompanied with the enhancement of radiative cooling as shown in Fig. 3(c). The energy-confinement times of the H-mode discharges are comparable to those of the OH discharges in the higher-density regime ($\bar{n}_e > \bar{n}_e^c$), while those of the L-mode discharges are degraded to 20 ms.

Incremental confinement time in the limiter H mode.—The concept of an incremental confinement time of additionally heated plasma was first proposed by Bell *et al.*[14] as $\tau_E^{\rm inc} = dW_T/dP_T$, where W_T and P_T are the to-

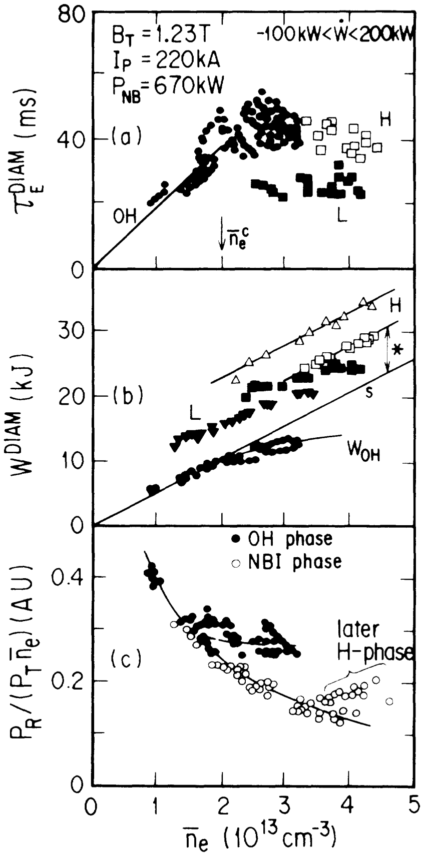

FIG. 3. The density dependences of (a) τ_E^{diam} for OH (filled circles), H- (open squares), and L- (filled squares) mode phases at quasisteady state ($\dot{W}$ for dW/dt); (b) W^{diam} at the quasisteady state [the deposited beam power of $P_{\text{NM}} = 1.0$ MW (open triangles), 0.67 MW (open and filled squares), and 0.46 MW (filled triangles) at $\bar{n}_e > 2\times 10^{13}$ cm^{-3}; open and filled symbols are for the H mode and L mode, respectively]; and (c) radiation enhancement factor defined as $P_R/P_T\bar{n}_e$. A critical density $\bar{n}_e^c$ is shown by an arrow. ΔW^* is defined as an increment from line s as shown by an arrow with asterisk.

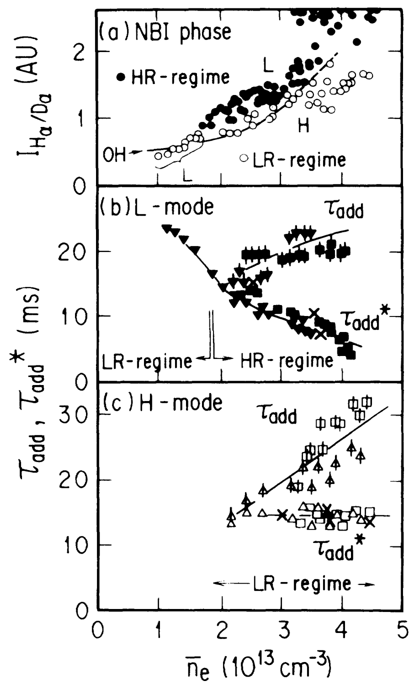

FIG. 4. The density dependence of (a) intensity of the recycling light I_{H_α/D_α} from inner-wall side for the OH, L- and H-mode phases; (b) the incremental confinement times τ_{add}^* and τ_{add} for the same data set of the L mode as in Fig. 3(b) with the same key; and (c) same plots as in (b) for the H mode. Low- or high-recycling regimes are indicated by LH or HR regimes referring to the OH level. Crosses in (b) and (c) denote τ_E^{inc} obtained by a power scan.

tal stored energy and input power. This quantity is a good measure of heating efficiency. Here we define the incremental confinement time as $\tau_{\text{add}}^* = \Delta W^*/\Delta P$ [the incremental stored energy and power are measured from the Ohmic base values: $\Delta W^* = W_T - W_{\text{OH}}^*$ and $\Delta P = P_{\text{NB}} + \Delta P_{\text{OH}}$, where W_{OH}^* is the extrapolation of W_{OH} from the lower-density regime ($\bar{n}_e < \bar{n}_e^c$), shown by line s in Fig. 3(b), and where ΔP_{OH} is the change in P_{OH} due to the beam]. In the H-mode discharges, ΔW^* is independent of the density in contrast to the L mode [see Fig. 3(b)]. The peripheral recycling levels are comparable to or less than those of the OH phase in the H mode. This result also holds for the lower-density-regime L-mode phases (low-recycling regime) as shown in Fig. 4(a). In the L-mode discharges, the recycling increases (high-recycling regime) and τ_{add}^* decreases to 5 ms when the electron density is raised by the increase in the gas flow rate [$\tau_{\text{add}}^* \propto \bar{n}_e^{-1}$ as shown in Fig. 4(b)]. In the H-mode phase, where the gas-puff valve is closed, τ_{add}^* is independent of $\bar{n}_e$ [about 15 ms as shown in Fig. 4(c)]. The values of τ_{add}^* are consistent with τ_E^{inc} obtained by a power scan both in the L- and H-mode discharges [crosses in Figs. 4(b) and 4(c)]. The incremental confinement time τ_{add}, which is based on the degraded part of W_{OH} as in the preliminary results from JFT-2M reported by Odajima *et al.*,[15] is different from τ_E^{inc} as shown in Figs. 4(b) and 4(c). It appears that the degraded W_{OH} recovers to the undegraded value (W_{OH}^*) in the additional heating phase. This is presumably due to the change in fueling. In the high-density OH phase, the fueling relies heavily on the local cold gas puffing which leads to the buildup of neutral gas and to the degradation of fueling efficiency. This is different in the phase with additional heating.[6] The density dependence of the L-mode incremental confinement time obtained here contradicts the claim of Ref. 15 where no dependence on the density is reported. However, in Ref. 15, no systematic density scan has been done and the values for the confinement time vary from 12 to 21 ms in the higher-density regime.

In conclusion, we have observed for the first time a transition from L to H mode together with improved confinement in a limiter discharge. A proper wall fueling enables us to maintain a very low edge-neutral pressure ($\simeq 10^{-7}$ Torr) together with a low gas feed during the NBI phase. This leads to the lower particle recycling or to the case without a formation of neutral gas buildup in the high-density regime and, thus, to the development of an H mode even with relatively low beam power (about 0.5 MW). The global energy-confinement time of the limiter H mode recovers to that of the OH phase. The incremental confinement time of the H mode does not depend on the density ($\tau^*_{\rm add} = 15$ ms), while it does in the L-mode discharges.

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