Observation of the low to high confinement transition in the large helical device

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The low to high confinement transition has been observed on the large helical device [A. Iiyoshi, A. Komori, A. Ejiri et al., Nucl. Fusion 39, 1245 (1999)], exhibiting rapid increase in edge electron density with sharp depression of \( H_n \) emission. The transition occurs in low toroidal field \( (B_t = 0.5 \sim 0.75 \text{ T}) \) discharges and are heated by high power neutral beam injection. The plasma thus has a relatively high value \(( \sim 1.5\% ) \) of the volume averaged \( \beta \) value. The electron temperature and density profiles have steep gradients at the edge region which has high magnetic shear but is at a magnetic hill. Formation of the edge transport barrier leads to enhanced activities of the interchange type of modes with \( m = 2/\pi = 3 \) \((m, n \text{ are the poloidal and toroidal mode numbers}) \) in the edge region. At present, these magnetohydrodynamic activities limit the rise of the stored energy; the resultant increment of the stored energy remains modest. © 2005 American Institute of Physics.

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Since the discovery of rapid transition from the low \( (L) \) mode to high confinement regime \( (H) \) mode in the axisymmetric divertor experiment (ASDEX),\(^3\) the low to high confinement (LH) transition has been observed for the past two decades in various tokamak configurations. These include the double- and single-null poloidal divertor configurations and also limiter configurations with circular and D-shaped cross sections.\(^7\) The LH transition was also observed in stellarator or helical devices. These plasma are bounded by a limiter in the compact helical system (CHS) heliotron/torsatron\(^3,4\) or by a limiter and/or an island chain in the Wendelstein 7-AS shearless stellarator.\(^5,6\) Recently, the LH transition was observed also in spherical tori with very low aspect ratio.\(^7,8\) Aside from high confinement, a universally observed signature of the transition was the formation of the edge pedestal and the edge transport barrier (ETB). Although many theoretical models of the transition in tokamaks and helical devices have been proposed,\(^9\sim11\) the understanding of the LH transition mechanism and the formation of the edge pedestal is still insufficient. In particular, the magnetohydrodynamic (MHD) stability of a plasma with ETB has attracted much attention due to its impact on the possibility of sustaining a \( H \)-mode plasma with favorable divertor action at steady state. In tokamaks, the plasma is situated at a magnetic well which enhances the MHD stability of the plasma, especially in the edge region. The edge localized modes (ELMs) (Ref. 12) have variably been correlated with the stability of the ideal/resistive ballooning mode or kink/peeling mode. However, there is yet no complete understanding of the characteristics of the ELMs to allow their control during the operation of a reactor grade plasma.

Therefore, achievement of the LH transition in large helical device (LHD),\(^13\) which has a magnetic configuration different from those reported so far, provides insight to the underlying dynamics of the LH transitions and the accompanying behavior of the ELMs. The plasma in LHD is essentially net toroidal current-free. It is confined in a three-dimensional magnetic configuration with full helical divertor that is realized by two helical coils and three sets of poloidal coils. The nested magnetic surfaces are surrounded by an ergodic layer which is caused by breaking of helical symmetry due to toroidal effect.\(^14\) The magnetic topology in the poloidal cross section is shown in Fig. 1. The divertor is an open type of double-null divertor in which the separatrix is twisted helically with ten field periods around the magnetic axis. To provide good drift orbits for energetic particles, this plasma is shifted inward relative to the vacuum vessel and is labeled \( R_{ax} = 3.6 \text{ m} \) \((R_{ax} \text{ is the position of the magnetic axis})\).
of the vacuum configuration). The whole plasma region of this inward-shifted configuration is situated in a magnetic hill in the case that the volume-averaged toroidal beta ($\beta_v$) is very low ($\leq 1\%$). With the increase in $\beta_v$, the magnetic hill at the plasma core is converted into a magnetic well, allowing a higher $\beta$ limit. However, the edge region near the last closed flux surface (LCFS) remains in the magnetic hill. It is an interesting and important question to ask whether an ETB can be generated in the magnetic hill region and can also be sustained. So far in LHD, the MHD stability of the plasma core region against Mercier mode and low $n$ interchange modes has been experimentally investigated\textsuperscript{15} for only the $L$-mode plasmas without ETB. In LHD, although plasma with a steep pressure gradient near the edge was obtained previously without the LH transition, the $\langle \beta_v \rangle$ was too low to study the effect of the steep pressure gradient on the edge MHD stability.\textsuperscript{16} This paper describes the characteristics of LH transition achieved in magnetic hill region of LHD with a helical divertor and its effect on edge MHD stability.

In LHD, the observed LH transition takes place in hydrogen plasmas with high power (up to $\sim 5$ MW) neutral-beam-injection (NBI) heating and at fairly low toroidal field ($B_t=0.5-0.75$ T). So far, the transition is achieved only in the inward-shifted magnetic configurations of $R_{av}=3.6$ m and 3.55 m. Although a detailed power scan has yet to be done, the minimum absorbed power from NBI heating is estimated to be more than $\sim 2.5$ MW for the range of the line averaged density $n_e$ of $(1.5-3) \times 10^{19}$ m$^{-3}$ at $B_t=0.75$ T. In all discharges in which the LH transition takes place, the $\langle \beta_v \rangle$ reaches a relatively high value ($\geq 1.5\%$) immediately before the transition. Thus the power threshold for transition is about 1.5 times higher than the ITER $H$-mode power threshold scaled for hydrogen plasma.\textsuperscript{17} The time history of a typical discharge in hydrogen with the LH transition is shown in Fig. 2(a), in which $R_{av}=3.55$ m, toroidal field $B_t=0.75$ T, and the absorbed NBI power $P_{NBI}=4.3$ MW. The transition took place at $t=1.749$ s, exhibiting the signature of rapid increases in $\langle n_e \rangle$ and $\langle \beta_v \rangle$, together with rapid depression of $H_a$ signal. At the transition, the electron density is preferentially increased in the edge region inside of the ETB and decreased outside as can be seen from Fig. 2(b). In the $H$-mode shots, the electron temperature profile at the very edge shows a small but clearly visible pedestal structure just after the transition. As seen from Figs. 3(a)–3(c), the clear pedestal is in the region of $R=2.6-2.8$ m of the horizontally elongated section in which the electron temperature profile is measured by Thomson scattering. Obviously flattened regions are observed around the major rational surfaces with $i/2\pi=1$ and $3/2$, suggesting locations of island formation [Figs. 3(a) and 3(b)]. The formations of the islands may have impeded the formation of substantial electron temperature pedestal and keep the pedestal at the very modest level. As can be seen from Fig. 3(a), the plasma boundary in this high $\beta$ plasma has apparently expanded by about 10% into the ergodic layer beyond LCFS of the original vacuum magnetic surface. This boundary expansion has also been reported in high $\beta$ $L$-mode plasmas.\textsuperscript{18} The effect of the ergodic layer and boundary expansion on the transition is currently being investigated.

As can be seen from Fig. 4, at the transition, the $H_a$ light is depressed by about 15% and the transition is followed by a quiescent phase for a short time interval ($\sim 15$ ms) in which $\langle n_e \rangle$ and $\langle \beta_v \rangle$ increase linearly with time. Subsequently, the $H_a$ light is modulated by small but frequent ELMs with a frequency of up to 250 Hz. The dependence of the frequency of the ELMs on the heating power has not yet

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FIG. 1. (Color online). The vacuum magnetic configuration of $R_{av}=3.6$ m. The region with closed field lines is surrounded by an ergodic layer in the (a) vertically and (b) horizontally elongated sections. This configuration has two null lines that helically rotate around the magnetic axis. The magnetic configuration of $R_{av}=3.55$ m has almost the same characteristics as that of $R_{av}=3.6$ m with a slightly reduced averaged minor radius.

FIG. 2. (Color online). (a) A typical LH transition in hydrogen plasma with a quiescent phase of $\sim 10$ ms and the ensuing EL-Ming phase. This discharge has $B_t=0.75$ T, $R_{av}=3.55$ m, and $P_{NBI}=4.3$ MW. (b) Time evolution of line-integrated electron density measured on the outboard side of the vertically elongated section, together with $H_a$ signal. The ETB in the vertically elongated section is located between the positions of $R=4.119$ m and $R=4.209$ m.
been clarified. From the density rise and reduction of $H_a$ light, the improvement of the particle confinement time is estimated to be about 30%. The improvement factor of the global energy confinement time $H$ for the ISS95 scaling has been evaluated to be $H \sim 1.2$ prior to the LH transition. It rises to $H \sim 1.4$ in the quiescent $H$ phase and maintains $H \sim 1.25$ during the ELMing phase, in these we have taken into account the correction of the time derivative of the stored energy on the evaluation of the energy confinement time.

The occurrence of ELMs limits the further increase in $k_B t L$. Saturation of $k_B t L$ due to the action of the ELMs is more visible when controlled gas puffing is used to further raise $k_B t L$ linearly with respect to time as shown in Fig. 4.

We also investigate the correlation between the saturation of $\langle \beta \rangle$ in the $H$ phase and MHD activities. As shown in Fig. 5, just after the LH transition of the LHD plasma, amplitudes of the coherent magnetic fluctuations are clearly enhanced with the increase in $\langle \beta \rangle$. The dominant modes are $m=2/n=3$ ($m, n$ are the poloidal and toroidal mode numbers). The mode rational surface of this mode is traced to be near or outside LCFS of the vacuum field and on the formed ETB region (for instance, as seen from Fig. 3). In this shot, the amplitude of the $m=1/n=1$ mode is also enhanced. Comparison between the $H_a$ light and magnetic probe signals with improved time resolution indicates that ELM like spikes in $H_a$ light synchronizes with bursts of edge MHD modes such as the $m=2/n=3$ mode, as seen from Fig. 5. The edge region where the $i/2\pi=3/2$ surfaces are located has high global magnetic shear $[\rho d(1/r)/dr \sim -3-4]$ but is in the magnetic hill. Resistive or ideal interchange mode is the most likely candidate of the above-mentioned edge MHD modes such as $m=2/n=3$ mode. Measurement of the radial electric field $E_r$ and its shear $E_r'$ is a crucial and desirable topic for the study of LH transition. For the very edge region of these plasmas, data of $E_r$ and $E_r'$ from charge recombination spectroscopy are not available due to the relatively low...
edge temperature. Fast reciprocating Langmuir probe could also be a possible method for the measurement of $E_r$ and $E_r'$. However, this method is not applicable to $H$-mode plasmas produced through high power NBI heating on LHD. Heavy ion beam probe is being developed on LHD for these measurements with high time and spatial resolutions.

In the following, we would like to provide the reasoning for the preferential occurrence of the LH transition in high $\langle \beta_\parallel \rangle$ and low $B_t(=0.5–0.75 \text{ T})$ plasmas in LHD. With the increase of $\langle \beta_\parallel \rangle$ in LHD, the pressure profile tends to broaden. This leads to the steepening of the pressure gradient near the edge and also the accompanying development of the strong $E_r$ and $E_r'$. This in turn may lead to the LH transition. In the present experiments, the conditions for the transition may have barely been passed. High density is also needed for the achievement of high $\langle \beta_\parallel \rangle$. This is also why the LH transition has so far never been observed in the low density ($n_e <= 1.5 \times 10^{19} \text{ m}^{-3}$) plasmas even with high heating power in which the plasma beta $\langle \beta_\parallel \rangle$ stays at less than 1.5%. The characteristics of LHD are that its edge is at a magnetic hill region enhancing the ETB formation at the edge magnetic hill region.

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2 ITER Physics Expert Groups on Confinement and Transport and Confinement Modeling and Database, Nucl. Fusion 39, 2175 (1999), and references therein.