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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_α emission. The transition occurs in low toroidal field ($B_t = 0.5-0.75$ 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 β 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 $m=2/n=3$ (m,n 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),[1] 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 diverter configurations and also limiter configurations with circular and D-shaped cross sections.[2] 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,[9–11] 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 $R_{ax}=3.6$ m (R_{ax} is the position of the magnetic axis

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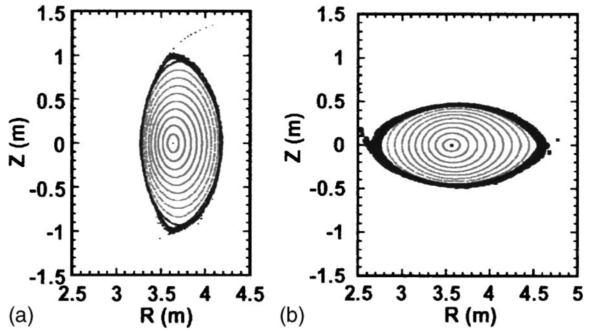

FIG. 1. (Color online). The vacuum magnetic configuration of $R_{ax}=3.6$ m. The region with closed field lines is surrounded by an ergodic layer in the (a) vertically and (b) horizontally elongated sections. This configuration has two null lines that helically rotate around the magnetic axis. The magnetic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

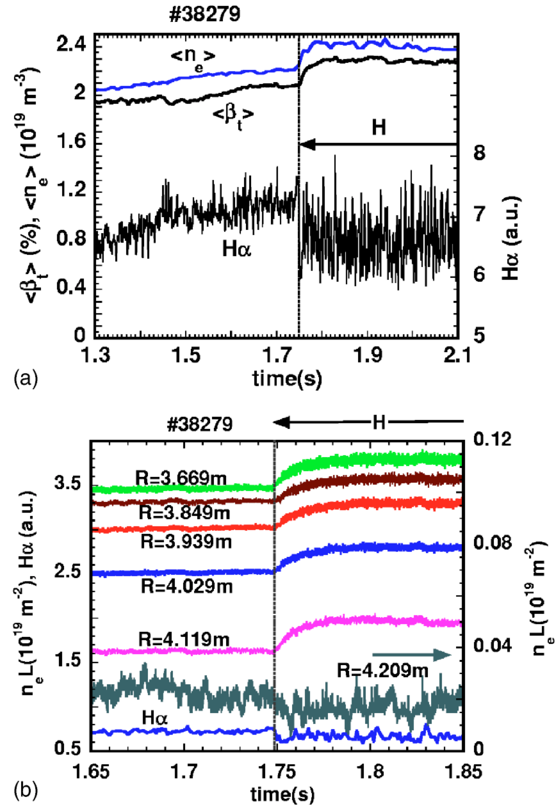

FIG. 2. (Color online). (a) A typical LH transition in hydrogen plasma with a quiescent phase of ~10 ms and the ensuing ELMing phase. This discharge has $B_t=0.75$T, $R_{ax}=3.55$ m, and $P_{NBI}=4.3$ MW. (b) Time evolution of line-integrated electron density measured on the outboard side of the vertically elongated section, together with H_α signal. The ETB in the vertically elongated section is located between the positions of $R=4.119$ m and $R=4.209$ m.

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 $\langle\beta_t\rangle$ is very low ($\ll 1\%$). With the increase in $\langle\beta_t\rangle$, the magnetic hill at the plasma core is converted into a magnetic well, allowing a higher β 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[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 $\langle\beta_t\rangle$ was too low to study the effect of the steep pressure gradient on the edge MHD stability.[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 ~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 $R_{ax}=3.6$ 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 ~2.5 MW for the range of the line averaged density $\langle n_e\rangle$ of $(1.5$–$3)\times 10^{19}$ m^{-3} at $B_t \leqslant 0.75$ T. In all discharges in which the LH transition takes place, the $\langle\beta_t\rangle$ reaches a relatively high value ($\geqslant 1.5\%$) 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.[17] The time history of a typical discharge in hydrogen with the LH transition is shown in Fig. 2(a), in which $R_{ax}=3.55$ 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 $\langle\beta_t\rangle$, together with rapid depression of H_α 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 $R\simeq 2.6$–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 $\iota/2\pi=1$ 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 β 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 β L-mode plasmas.[18] The effect of the erogodic layer and boundary expansion on the transition is currently being investigated.

As can be seen from Fig. 4, at the transition, the H_α light is depressed by about 15% and the transition is followed by a quiescent phase for a short time interval (~15 ms) in which $\langle n_e\rangle$ and $\langle\beta_t\rangle$ increase linearly with time. Subsequently, the H_α 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

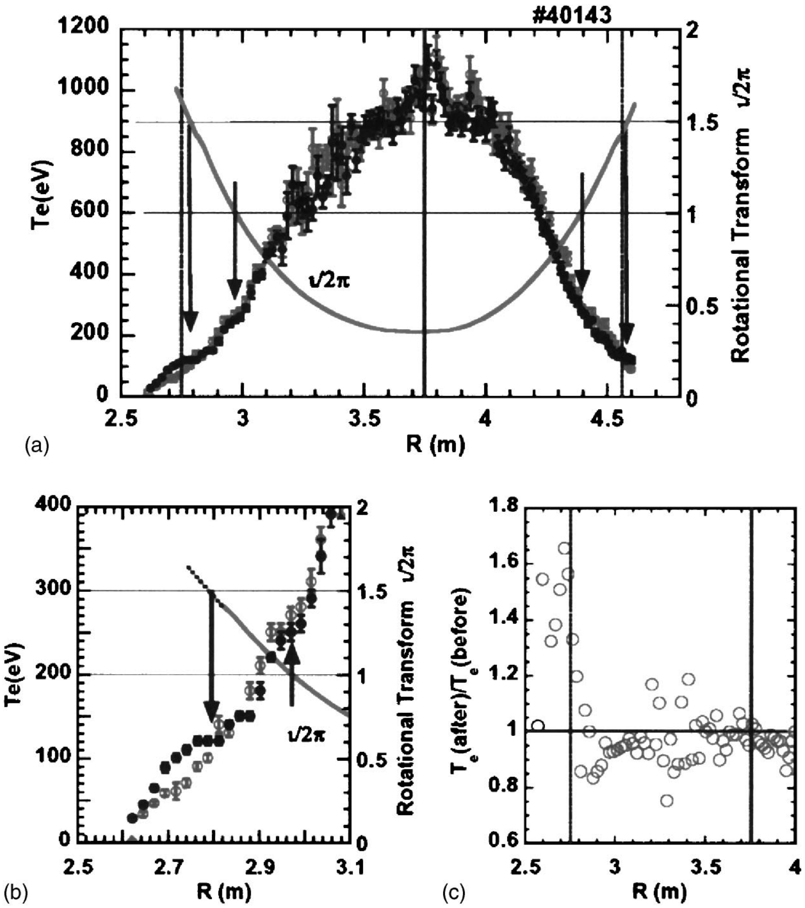

FIG. 3. (Color online). (a) Radial profiles of the electron temperature measured by Thomson scattering just before (open circles) and after (solid circles) the transition in the $R_{ax}=3.6$ m configuration. The profile for the rotational transform of the configuration which fits the measured electron temperature profile is shown as the solid curve. The vertical arrows indicate the major rational surfaces of $\iota/2\pi=1$ and $3/2$. A vertical solid line at $R\sim 3.75$ m corresponds to the position of the magnetic axis of this high β shot before and after the transition. Two vertical dotted lines stand for the LCFS of the vacuum magnetic surface. (b) Expanded view of electron temperature profile in the edge region on the inboard side. (c) Radial profile of the relative increase of the electron temperature induced by the transition.

been clarified. From the density rise and reduction of H_α 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[19] 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 $\langle\beta_t\rangle$. Saturation of $\langle\beta_t\rangle$ due to the action of the ELMs is more visible when controlled gas puffing is used to further raise $\langle n_e\rangle$ linearly with respect to time as shown in Fig. 4.

We also investigate the correlation between the saturation of $\langle\beta_t\rangle$ 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 $\langle\beta_t\rangle$. 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_α light and magnetic probe signals with improved time resolution indicates that ELM like spikes in H_α 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 $\iota/2\pi=3/2$ surfaces are located has high global magnetic shear $[\rho\iota d(1/\iota)/d\rho\sim -3--4]$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

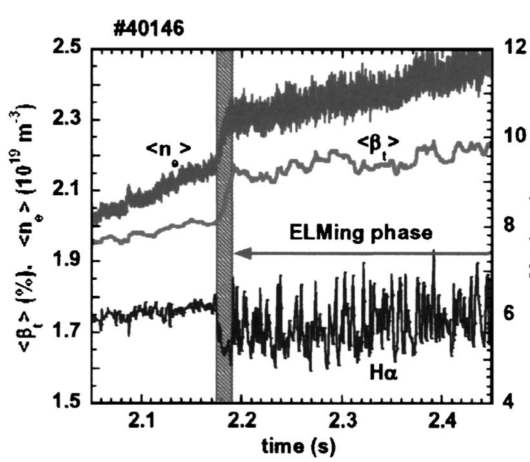

FIG. 4. (Color online). Time evolution of $\langle\beta_t\rangle$, $\langle n_e\rangle$, and H_α signal in a H-mode discharge. In this discharge, the $\langle\beta_t\rangle$ is clearly affected by the ELMs, whereas $\langle n_e\rangle$ is continuously increased by gas puffing. The quiescent phase is indicated as the shaded zone.

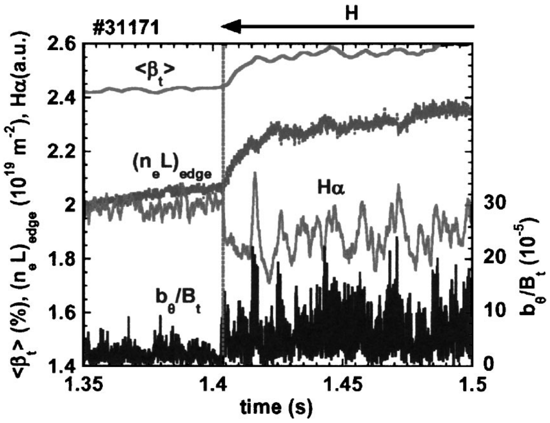

FIG. 5. (Color online). Shown are the traces in time of $\langle\beta_t\rangle$, the H_α signal, the line-integrated electron density near the edge $(n_eL)_{edge}$ and the amplitude of the coherent magnetic fluctuations of the $m/n=2/3$ edge MHD mode. The amplitude of the magnetic fluctuation is evaluated at the magnetic probe position and is normalized by the local B_t value.

edge temperature. Fast reciprocating Langmuire 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 $\langle\beta_t\rangle$ and low $B_t(=0.5-0.75\ \text{T})$ plasmas in LHD. With the increase of $\langle\beta_t\rangle$ in LHD, the pressure profile tends to broaden.[15] 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 $\langle\beta_t\rangle$. This is also why the LH transition has so far never been observed in the low density $(\langle n_e\rangle \leq 1.5\times 10^{19}\ \text{m}^{-3})$ plasmas even with high heating power in which the plasma beta $\langle\beta_t\rangle$ stays at less than 1.5%. The characteristics of LHD are that its edge is at a magnetic hill which may impede the formation of a steep edge pressure gradient to produce the required E_r and E_r'. The plasma edge becomes even less stable to the edge MHD modes, which eventually limits the possible confinement enhancement brought about by the transition. We speculate that tailoring of the E_r profile in the edge region may affect the power threshold for the transition. It could also reduce the growth rates or saturation levels of the resistive interchange mode or suppress them,[20] and lead to a further improvement of the global confinement of the *H* mode.

In summary, the LH transition has been observed on LHD in plasmas with high plasma betas $(\langle\beta_t\rangle \geq 1.5\%)$ at low B_t in the open type and full helical divertor configuration. The particle confinement time is improved by up to 30%, whereas the enhancement of the energy confinement time from that of the *L* phase is rather modest (up to ~15%). The ETB formation at the edge magnetic hill region enhances the MHD activity of the $m=2/n=3$ edge MHD mode and induces small but frequent ELMs. They impede a large increase in $\langle\beta_t\rangle$ after the transition. Our observation of the LH transition in the very unique LHD magnetic configuration contributed to the *H*-mode and ELM physics of toroidal plasmas. Mechanisms of the LH transition and pedestal formation, and roles of magnetic islands and ergodic layer on the transition are important and interesting issues for clarifying the physics of the *H* mode and are being further investigated.

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[1] F. Wagner, G. Becker, K. Behringer *et al.*, Phys. Rev. Lett. **49**, 1408 (1982).
[2] ITER Physics Expert Groups on Confinement and Transport and Confinement Modeling and Database, Nucl. Fusion **39**, 2175 (1999), and references therein.
[3] K. Toi, S. Okamura, H. Iguchi *et al.*, *Proceedings of the 14th IAEA Conference on Plasma Physics and Controlled Fusion Res., Würzburg, 1992* (IAEA, Vienna, 1993), Vol. 2, p. 461.
[4] K. Toi, S. Ohdachi, T. Morisaki *et al.*, Plasma Phys. Controlled Fusion **38**, 1289 (1996).
[5] V. Erckmann, F. Wagner, J. Baldzuhn *et al.*, Phys. Rev. Lett. **70**, 2086 (1993).
[6] F. Wagner, J. Baldzuhn, R. Brakel *et al.*, Plasma Phys. Controlled Fusion **36**, A61 (1994).
[7] R. J. Akers, G. F. Counsell, A. Sykes *et al.*, Phys. Rev. Lett. **88**, 035002 (2002).
[8] E. J. Synakowski, M. G. Bell, R. E. Bell *et al.*, Nucl. Fusion **43**, 1653 (2003).
[9] J. W. Connor and H. R. Wilson, Plasma Phys. Controlled Fusion **42**, R1 (2000).
[10] K. C. Shaing, Phys. Rev. Lett. **76**, 4364 (1996).
[11] L. Garcia, B. A. Carreras, V. E. Lynch, J. N. Leboeuf, and D. E. Newman, Phys. Plasmas **4**, 3282 (1997).
[12] J. W. Connor, Plasma Phys. Controlled Fusion **40**, 191 (1998).
[13] A. Iiyoshi, A. Komori, A. Ejiri *et al.*, Nucl. Fusion **39**, 1245 (1999).
[14] T. Morisaki, K. Narihara, S. Masuzaki *et al.*, J. Nucl. Mater. **313–316**, 548 (2003).
[15] S. Sakakibara, H. Yamada, K. Y. Watanabe *et al.*, Plasma Phys. Controlled Fusion **44**, A217 (2002).
[16] N. Ohyabu, K. Narihara, H. Funaba *et al.*, Phys. Rev. Lett. **84**, 103 (2000).
[17] ITPA Conf. and H-mode Threshold Database working group and J. A. Snipes, *19th IAEA Fusion Energy Conference, Lyon, 2002.*
[18] K. Narihara, K. Y. Watanabe, I. Yamada *et al.*, Phys. Rev. Lett. **87**, 135002 (2001).
[19] U. Stroth, M. Murakami, R. A. Dorry, H. Yamada, S. Okamura, F. Sano, and T. Obiki, Nucl. Fusion **36**, 1063 (1996).
[20] H. Sugama and M. Wakatani, Phys. Fluids B **3**, 1110 (1991).