Characterization of multi-transitions between intermediate and high confinement in the HL-2A tokamak

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1. ***Introduction.*** In magnetically confined plasmas, the H-mode related issues have been studied for more than quarter-century [1]. One of the most urgent objectives is to predict the H-mode power threshold for not only ITER but also future fusion devices. Recently, much attention has been paid on the physics of an intermediate confinement phase (referred as 'I-phase') between the L- and H-mode with marginal heating power close to the L-H transition power threshold [2]. This I-phase is characterized by a periodic limit cycle oscillation (LCO) between sheared flows and turbulence levels, and the interplay in between may play a significant role for the L-H transition. Besides, experimental observations on the reduction of the L-H transition power threshold [3, 4] suggest important effects of edge neutrals activities, effective charge Z_{eff} on L-H transition physics[5]. This paper reports the phenomenon of multi-transitions between I-phase and H-mode in the HL-2A tokamak. The roles of internal mode and LCO in sustaining a confinement regime and confinement transition are analyzed.

2. ***Multi-transitions.*** With marginal auxiliary heating power (1MW NBI) in HL-2A, multiple I-H transitions have been observed between I-phase and H-mode (without ELMs). Figure. 1 shows main plasma parameters of a typical discharge. The plasma current, toroidal magnetic field and NBI heating power are illustrated in Fig. 1(a). The divertor Da signal shows a distinctive feature in the H-mode and I-phase. In the H-mode, the plasma has very low recycling rate described by very low

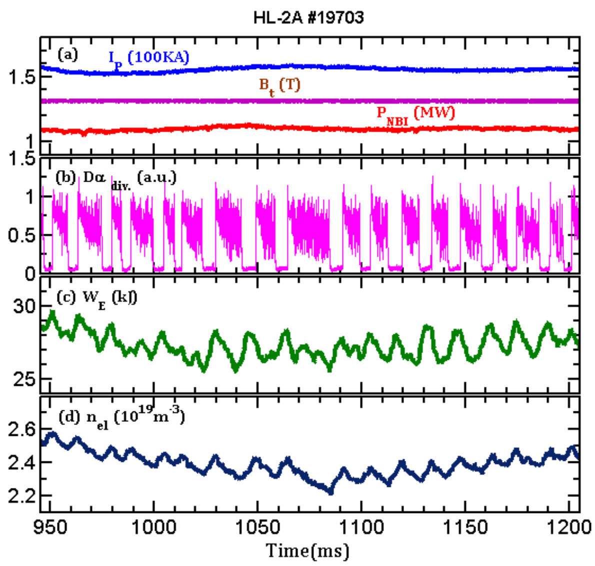

Figure 1. Time evolution of the main parameters in a typical discharge with multiple transitions.

intensity of the Da signal as shown in Fig. 1b. The duration of the stationary H-mode is only 5-10 ms and then the plasma transits to the I-phase. Obviously, the Da signal shows many oscillations appeared in I-phase and has relatively higher intensity compared to that of H-mode. After 10-20 ms I-phase, the plasma transits back to the H-mode. Thus multi-transitions occur in this shot and can be identified from the divertor Da signal. Due to the multi-transitions, the alternation of confinement improvement and degradation characterized by plasma stored energy (Fig. 1c) is observed. And the line averaged electron density decreases in the I-phase and increases in the H-mode as Fig. 1d shown. Moreover, the electron density measured by reflectometry [6] and electron temperature measured by ECE diagnostic [7] increases obviously when the plasma transits from I-phase to H-mode, owing to the higher pedestal gradient. The turbulence intensity measured by the reflectometry in the pedestal region (r/a ~ 0.9) is strongly reduced as seen in Fig. 2a, demonstrating the confinement improvement. On the contrary, the confinement is degraded in I-phase compared to that in H-mode.

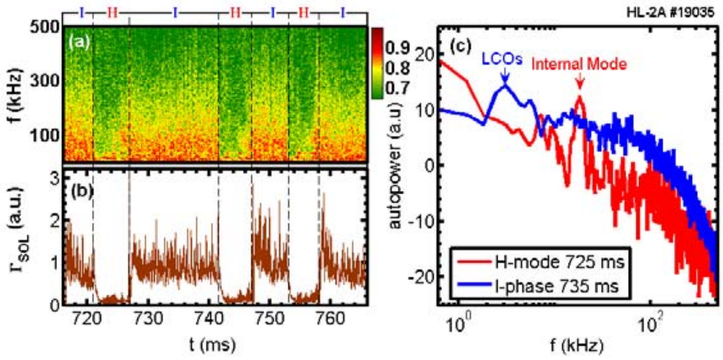

Figure 2. (a) Spectrogram of density fluctuation in pedestal region, (b) particle flux in SOL region, (c) spectra of particle flux in I-phase and ELM-free H-mode phase.

3. ***Additional particle loss***. Besides the particle transport process such as diffusion in ELM-free H-mode, LCOs and MHD induces an additional particle loss which is transported across the last closed flux surface into SOL and divertor region. The particle loss can be evaluated by the particle flux measured by Langmuir probe in

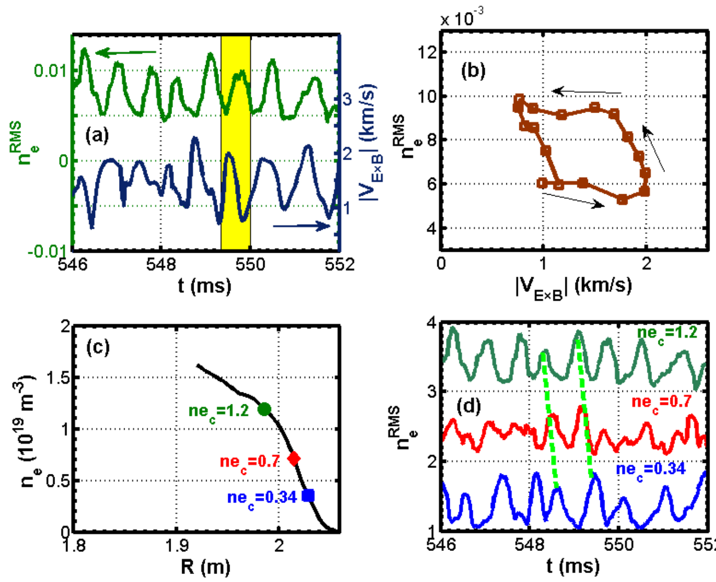

Figure 3. (a) Time evolution of density fluctuation level and $|V_{E\times B}|$, (b) trajectories of density fluctuation level and $|V_{E\times B}|$, (c) measured locations of three independent reflectometers, (d) time evolution of the density fluctuation level caused by LCOs at different radii.

SOL region (Fig. 2b). Apparently, the particle loss is much lower in ELM-free H-mode phase than that in I-phase. Two spectra of the particle flux are shown in Fig. 2c. The spectrum in ELM-free phase indicates that an additional particle loss is mainly caused by a coherent mode (f ~ 20 kHz) while the recycling rate is low. By using perturbation analysis from ECE signals [8], the mode is identified as an internal interchange-like mode whose phase is almost constant near the mode location. Beside the enhancement of the turbulence as Fig. 2a shown, the LCOs induce a considerable particle loss as shown in Fig. 2b. From Doppler reflectometry, the E × B velocity and density fluctuation level can be obtained. As Fig. 3a shown, the oscillation is quasi-sinusoidal with a frequency about 2-5 kHz. Given in Fig. 3b is the trajectory of $|V_{E\times B}|$ velocity and density fluctuation level during a LCO. The result shows a counter-clockwise direction between $|V_{E\times B}|$ and ne_{RMS}, corresponding to type J LCOs as Ref. 2 firstly dubbed, meaning E_r leading turbulence. Furthermore, the temporal-spatial evolution of LCOs in pedestal region is characterized by three independent reflectometers, the measured locations are labelled in Fig. 3c. Fig. 3d is the evolution of density fluctuation level induced by LCOs at different locations, where the ne_c is the electron density of the cut-off layer for different reflectometry. The result indicates that the LCO radially propagates outward in pedestal region. For additional particle loss, the LCOs cause high loss level and degrade the confinement performance in I-phase.

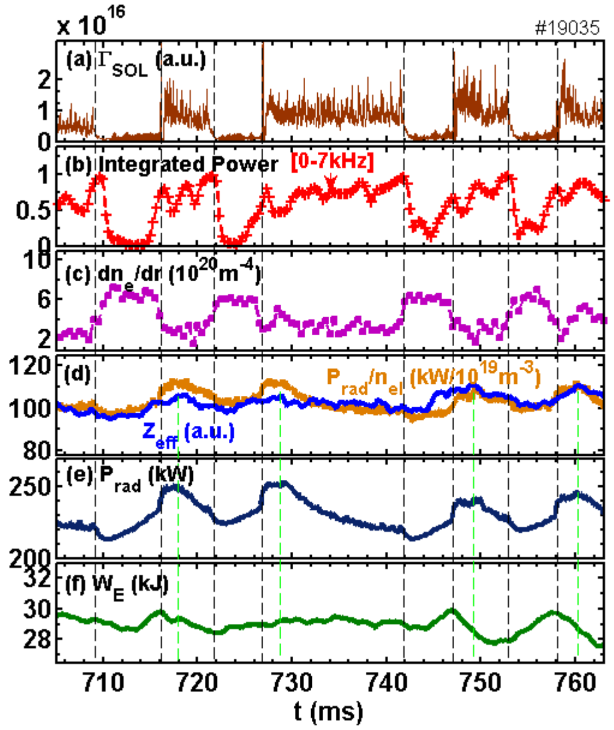

Figure 4. (a) SOL particle flux, (b) integrated power for LCOs (0-7kHz), (c) pedestal density gradient, (d) effective charge number and the ratio of total radiation power to line averaged density, (e) total radiation power and (f) plasma stored energy.

4. ***Impurity accumulation***. As described above, alternative transition occurred. However, why doesn't the plasma sustain a stationary ELM-free H-mode or a continuous I-phase during the NBI heating with constant power? During ELM-free phase, even though the internal mode induces an additional particle loss, the pedestal has high electron density gradient (Fig. 4c) and the impurity density accumulates as seen in Fig. 4d. Here, the P_{rad}/n_{el} is an indication of the

impurity density. The radiation power is increasing during the H-mode phase (Fig. 4e). At last, the H-mode ends in a radiation collapse due to the impurity accumulation. From the aspect of effective power, the absorbed power of the plasma is reduced and it is insufficient to sustain the H-mode. It should be noted that the impurity density and radiation power continually increases for around 2 ms after the H-I transition. Then the plasma stored energy decreases during I-phase as shown in Fig. 4f. While for the I-phase, LCOs cause considerable particle loss and reduce the pedestal gradient and the impurity density. In spite of the considerable particle loss, it transits from I-phase to H-mode after 10-20 ms duration. This transition is possibly induced by an increasing pressure gradient and then an enhanced sheared flow, or additionally triggered by a MHD activity [9].

5. ***Conclusions***. The multi-transitions between I-phase and ELM-free H-mode have been observed and characterized in HL-2A. In I-phase, the LCOs induce a considerable particle loss, which reduces the impurity accumulation and limits the pedestal density gradient. The analyses indicate that the LCO is type J LCO firstly demonstrated by Doppler reflectometry in HL-2A, meaning E_r leading turbulence and radially propagates outward in pedestal region. The H-mode without ELMs is only sustained for 5-10 ms even though the internal mode induces particle loss, and then is terminated by a radiation collapse due to the impurity accumulation. From the alternative evolutions of the relevant parameters, the analyses indicate that a favourable quiescent H-mode should have an enhanced particle transport which not only limits pressure gradient increase but also reduces impurity accumulation.

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