Evolutions of mean flow and fluctuating flow during the L-I-L mode transition in the edge of HL-2A

D.F. Kong[1],T. Lan[1],A.D. Liu[1],L.W. Yan[2],H.L. Zhao[1],H.G. Sheng[1],R. Chen[1],J.L. Xie[1],
H. Li[1],W.D. Liu[1],C.X.Yu[1],W.Y. Hong[2],J. Cheng[2],K.J. Zhao[2],
J.Q. Dong[2],X.M. Song[2],X.R. Duan[2]

[1] *CAS Key Laboratory of Geospace Environment, Department of Modern Physics, University of Science and Technology of China, Hefei, Anhui 230026, China*

[2] *Southwestern Institute of Physics, P.O. Box 432, Chengdu, Sichuan 610041, China*

Introduction

The high confinement mode (H-mode) has attracted great attentions since its first discovery thirty years ago. Yet, a clear understanding of the L-H transition mechanism has not been made. It is difficult to study the L-H transition mechanism because of the quick change time, of millisecond magnitude. By slowly increasing the power of Neutral Beam Injection, an intermediate stage named I-phase between L mode and H mode was discovered by G. D. Conway et al. on ASDEX-U[2]. This experiment reveals that the competition between GAM and mean flow inducing the I-phase. Experiment results on TJ-II stellarator show low frequency ($2kHz$) oscillations with the NBI power approaching to the power threshold of L-H transition[4]. Recently, this intermediate stage has also been observed in other devices: NSTX[5], DIII-D[3] and EAST[1]. This work shows the evolution characteristics of I-phase observed on HL-2A tokamak, indicating two different of the I-phase.

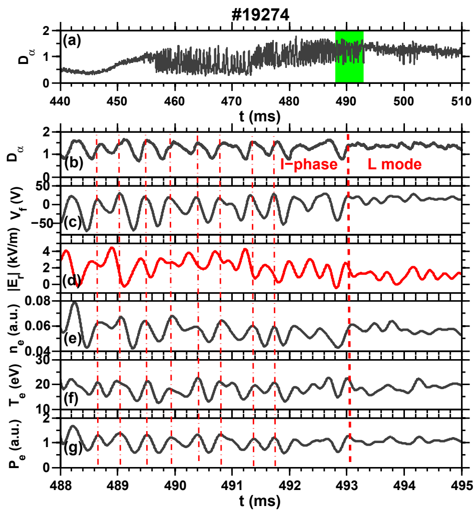

Figure 1: Time evolution of (a)(b) D_α signal((b) is the zoom of green range of (a)); (c) floating potential V_f; (d) electric field $|E_r|$; (e) electron density n_e; (f) electron temperature T_e, and electron pressure P_e across the transition from limit cycle oscillations (LCO) to L mode with low pass filtering of $< 4kHz$.

Experimental arrangement

The experiment was carried out in deuterium plasma with the divertor configuration under the following conditions:$I_p = 150 \sim 180kA$, $B_t = 1.3T$, $q_a \sim 4$,$\bar{n}_e = (1.8 \sim 2.6) \times 10^{-19}m^{-3}$. Three Langmuir probe arrays were used to measure floating potential, electron density and temperature of edge plasma, two of which are separated in $11cm$ polodially and in $220cm$ toroidally to measure the polodial (m) and torodial (n) mode number, respectively. One of the probe array studies the radial propagation features with probe tips in four radial steps.

Experimental results

Fig. 1(b) shows the time history of the divertor D_α signal across the transition from limit cycle oscillations (LCO) to L mode, which is the zoom of Fig. 1(a) as the green color range. The LCO here is the I-Phase stage between H-mode and L-mode. The LCO is induced by the neutral beam power of $P_{inj} = 0.8MW$, which the value is L-H just above the H-mode transition power threshold. The probe arrays are set about $1cm$ inside the separatrix in shot #19274, while the displacement of edge plasma is approximately constant during $480ms$ to $500ms$. The time evolutions of floating potential V_f, amplitude of electric field $|E_r|$, electron density n_e, temperature T_e and pressure P_e can be measured at $r - a = 5mm$, as illustrated in Fig. 1 and applied with a low pass filter of $f < 4kHz$. The limit cycle oscillations can be observed simultaneously in all those signals mentioned above. It can be seen that V_f, n_e, T_e and P_e lags the amplitude of electric field E_r by about a quarter of the LCO period ($\pi/2$ in phase), suggesting that LCO of V_f, n_e, T_e and P_e may be induced by the time evolution of electric field.

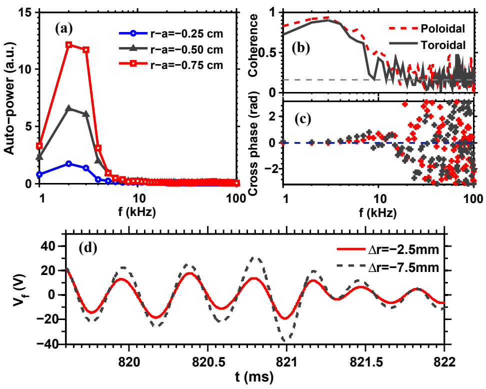

Figure 2: (a)Auto-power spectra of V_f at radial positions of $r-a=-0.25cm$, $r-a=-0.50cm$ and $r-a=-0.75cm$; coherence and cross phase spectra of V_fs with torodial and polodial separations of $223cm$ and $11cm$, respectively. Time history of L-COs in V_f at different radial positions.

Fig. 2(a) illustrates the auto-power spectra of the V_f measured inside the separatrix. A coherent mode peaking at $2 \sim 3kHz$ with strong power can be observed in the figure, which corresponds LCO here. Amplitude of LCO decreases sharply along the radial direction. The characteristics of the mode structure of LCO in floating potential V_f have been studied by three probe arrays with toroidal separation of $223cm$, as illustrated in Fig. 2(b)(c). The coherence at $2 \sim 3kHz$ of two V_fs is close to 0.95, indicating that L-CO is a mode with long-range correlation structure in the toroidal direction. The cross phase of LCO is close to 0, indicating that toroidal mode number $n = 0$. Using similar method, we confirmed that poloidal mode number $m = 0$, as the black solid line in Fig. 2(b)(c). Those results show the axisymmetric ($n = m = 0$) feature of the oscillating flow (LCO). It is interesting to find that no GAM can be observed during the I-phase (LCO) discharging stage. Fig. 2(d) illustrates time history of LCOs in V_f with band pass filtering of $1kHz \sim 4kHz$ at $\Delta r \equiv r-a = -2.5mm$ and $-7.5mm$, respectively. The two oscillating V_fs show around zero time lag, implying that radial wave number of LCO is close to zero, i.e. $k_{r,LCO} \sim 0$. Torodial/poloidal symmetry of

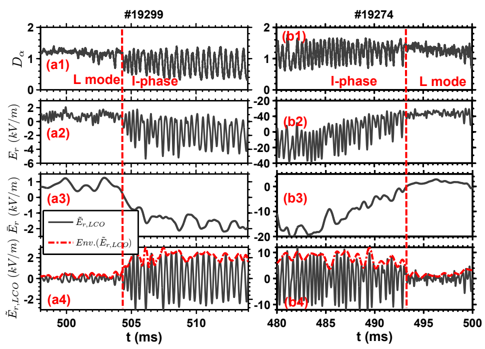

Figure 3: Time evolutions of (a1)(b1) D_α signal; (a2)(b2) total electric field E_r; (a3)(b3) mean electric field $\bar{E}_r$; and (a4)(b4) fluctuating electric field $\tilde{E}_{r,LCO}$ across the transitions (a) from L mode to L-CO and from LCO to L mode, respectively.

the observed flow oscillation is consistent with the mode characteristics of the low frequency zonal flow (LFZF). Yet, LCO can also be found in electron density n_e obviously, which conflict with the theoretical prediction that no (or weakly) density oscillation can be induced by LFZF, as well as the experimental observations on HL-2A.

The time evolution of electric field E_r across the transition from L mode to LCO and back transition from LCO to L mode have been studied, as illustrated in Fig. 3(a2)(b2), which can be measured from the difference of V_fs with radial separation of $\Delta r = 2.5mm$. E_r can be divided into two parts, mean electric field $\bar{E}_r$ ($f_{mean} < 1kHz$) and fluctuating electric field $\tilde{E}_r$ ($1kHz < f_{LCO} < 4kHz$), as illustrated in Fig. 3(a3,b3)(a4,b4). The probe arrays are set at $\Delta r = -0.3cm$ and $\Delta r = -1.0cm$ for #19299 and #19274, respectively. As shown in Fig. 3(a3), $\bar{E}_r$ starts to decrease fleetly just when the L-I transition happens, then $\bar{E}_r$ trends to a saturated level after several milliseconds ($\sim 4ms$) from the transition moment. Meanwhile, Fig. 3(a4) shows a fast growth of the amplitude of fluctuating electric field $Env.(\tilde{E}_{r,LCO})$ (red dash line). For the transition from LCO to L mode (I-L) back transition, $Env.(\tilde{E}_{r,LCO})$ shows a fast reduction after I-L transition, at the same time, mean $|\bar{E}_r|$ slowly decrease to a low level after the transition, as illustrated in Fig. 3(b3)(b4).

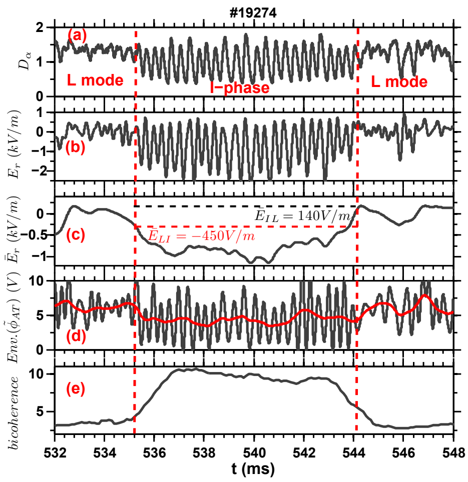

Figure 4: Time evolution of (a) D_α signal; (b) total electric field E_r; (c) mean electric field $\bar{E}_r$; (e) envelope of ambient turbulence $Env.(\tilde{\phi}_{AT})$ (with red line as mean value of $Env.(\tilde{\phi}_{AT})$); and (e) bicoherence between LCO and AT across the L-I-L mode transition.

Using similar method mentioned before, the time evolution of total E_r and mean $\bar{E}_r$ across L-I-L mode transition have been studied, as illustrated in Fig. 4(b)(c). At the L-I transition time of $t_{LI} = 535.2ms$, $\bar{E}_{LI} = -450V/m$, which is more negative than the value of I-L mode back transition time ($\bar{E}_{IL} = 140V/m$), as shown in Fig. 4(c). The results imply that the $\bar{E}_r$ trace of L-I transition is distinct with that of I-L mode transition, which is consistent with the theoretical predictions by S-I. Itoh. Envelope analysis technique has been applied to calculate time dependent amplitude of ambient turbulence $Env.(\tilde{\phi}_{AT})$, as shown in Fig. 4(d). Ambient turbulence have been suppressed and modulated by $E_{r,LCO}$ during LCO discharging. The intensity of nonlinear coupling between LCO and ambient turbulence is strong, comparing to the L-mode discharging (Fig. 4(e)).

Discussion and Conclusion

An intermediate stage (I-phase) between L-mode and H-mode has been observed on HL-2A when heating power is close to power threshold of L-H mode transition. Langmuir probe arrays have been performed to measure the physical parameters inside LCFS as potential ϕ_f, electric field E_r, density n_e, temperature T_e and pressure P_e. The experimental results reveal that an oscillation with frequency of $\sim 2kHz$

can be found in all those parameters which lag with amplitude of electric field $|E_r|$ by $\pi/2$, implying that the oscillations in n_e T_e and P_e are induced by the time changing of $|E_r|$. The amplitude of ambient turbulence $|\tilde{\phi}_{AT}|$ estimated from envelope analysis, as well as pressure gradient, are also found lags with $|E_r|$ by $\pi/2$, as illustrated in Fig. 5(b)(c)(d). The result does not support with the predictions of "Predator-Prey" model. Moreover, magnetic hystersis loop of mean electric field $\bar{E}_r$ has been found during the L-I transition and I-L back transition, which is consistent with the prediction of the transition model by S-I. Itoh[6].

References

[1] G. S. Xu et al., Phys. Rev. Lett. **107**, 125001 (2011).

[2] G. D. Conway et al., Team, Phys. Rev. Lett. **106**, 065001 (2011).

[3] L. Schmitz et al., Phys. Rev. Lett. **108**, 155002 (2012).

[4] T. Estrada et al., Plasma Phys. Controlled Fusion **51**,124015 (2009).

[5] S. J. Zweben et al., Phys. Plasmas **17**, 102502 (2010);

[6] S-I. Itoh et al., Phys. Rev. Lett. **20**, (1988).

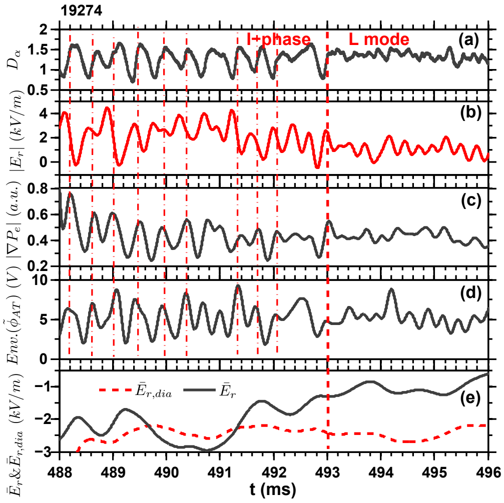

Figure 5: Time evolution of (a)(b) D_α signal((b) is the zoom of green range of (a)); (c) floating potential V_f; (d) electric field $|E_r|$; (e) electron density n_e; (f) electron temperature T_e, and electron pressure P_e across the transition from limit cycle oscillations (LCO) to L mode with low pass filtering of $< 4kHz$.