Letter

Study of instability driving inward particle flux during the formation of transport barriers at the edge of the HL-2A tokamak

D.F. Kong¹,², T. Lan², A.D. Liu², C.X. Yu², H.L. Zhao¹, H.G. Shen², L.W. Yan³, J.Q. Dong¹, M. Xu³, K.J. Zhao³, J. Cheng³, X.R. Duan¹, Y. Liu¹, R. Chen¹, X. Sun², J.L. Xie³, H. Li², W.D. Liu³ and The HL-2A Team³

¹ Institute of Plasma Physics, Chinese Academy of Sciences, Hefei 230031, People’s Republic of China
² CAS Key Laboratory of Geospace Environment, Department of Modern Physics, University of Science and Technology of China, Hefei 230026, People’s Republic of China
³ Southwestern Institute of Physics, PO Box 432, Chengdu, Sichuan 610041, People’s Republic of China

E-mail: lantao@ustc.edu.cn

Received 9 June 2016, revised 15 September 2016
Accepted for publication 26 September 2016
Published 11 November 2016

Abstract

An electrostatic coherent mode with a frequency of 20 ~ 100 kHz can be observed during the formation of transport barriers in high-confinement-mode plasma in the HL-2A tokamak, using reciprocating Langmuir probes. The mode drives a strong inward particle flux measured directly with four-tip probes with values comparable to the particle flux at the striking point in the divertor, which has also been validated by the measurement of other diagnostics. Several characteristics simultaneously indicate that the mode is an ion mode excited at the edge, which plays an important role in the formation of transport barriers besides particle diffuson.

Keywords: pedestal turbulence, edge-localized mode, particle flux, Langmuir probe, H mode, zonal flow

(Some figures may appear in colour only in the online journal)
in China [11–14], and the kinetic ballooning mode (KBH) at DIII-D in the USA [15–17], but some of these modes contribute to saturating the pedestal, whereas others are accompanied by fast development of the pedestal. Experiments aimed at distinguishing the type of mode in the H-mode pedestal are thus to be encouraged.

To address this question, we report the experimental detection of a strong low-frequency coherent mode (LFM) with \( f_{\text{LFM}} = 20 \sim 100 \text{ kHz} \) in the steep-gradient pedestal region of the HL-2A tokamak. The LFM is detected both during the formation of the pedestal after the transition between low- and high-confinement modes and during the recovery stage of the pedestal after the crash of the edge-localized mode (ELM). We also provide a detailed measurement of the mode structure of the LFM. The results provide the first direct evidence that the LFM can contribute strong inward particle transport during pedestal formation. We also discuss the propagating characteristics of the LFM, and the results indicate that this mode propagates in the ion-diamagnetic-drift direction in the plasma frame and could be an ion mode excited at the edge of the HL-2A tokamak plasma.

The experiments were performed on the HL-2A tokamak (\( R = 1.65 \text{ m}, a = 0.4 \text{ m} \)) with the divertor configuration under the following discharge parameters: magnetic field \( B_t = 1.3 \text{ T} \), plasma current \( I_p = 180 \text{ kA} \), safety factor at the plasma surface \( \rho = \rho/a = 0.95 \), and line-averaged density at the mid-plane \( n_e = 1.5 \sim 1.8 \times 10^{19} \text{ m}^{-3} \). The discharge gas was deuterium. Measurements were performed using two radially reciprocating probe systems labeled A and B. Both probe systems were inserted at the mid-plane of the tokamak. Probe system A was a standard four-tip probe and could be used to measure the electron temperature \( T_e \), the density \( n_e \) and floating potential \( \Phi_f \) [18, 19]. Probe B consisted of a single Langmuir probe and was used to measure the floating potential at different toroidal positions. The deepest measurement position for probe B was \( \rho = 0.95 \). The effect of neglecting electron temperature fluctuations on probe fluctuation measurements, in particular the turbulent particle flux and relative fluctuation level of the plasma potential, has been studied before [20, 21]. The results of these works show that neglecting fluctuations does not fundamentally change the estimation results. Therefore, floating potential \( \Phi_f \) is applied to study the potential characteristics of turbulence.

Figure 1(a) shows the dynamics of the divertor signal \( D_e \) for a typical dithering L–I–H mode transition at HL-2A, which is triggered by a neutral beam injection of power \( P_{\text{NBI}} = 0.8 \text{ MW} \) combined with an electron-cyclotron resonance heating (ECRH) power of \( P_{\text{ECRH}} = 1.0 \text{ MW} \). After the transition, the line-averaged density and stored energy continue to increase until the first type-III ELM crash. Two significant coherent modes with frequencies \( 20 \sim 120 \text{ kHz} \) and \( 140 \sim 400 \text{ kHz} \) appear in the potential fluctuations, as shown in figure 1(c). To differentiate between the two coexisting coherent modes, they are referred to herein as the low-frequency mode (LFM) and the high-frequency mode (HFM). The Mirnov coils positioned at \( r = 50 \text{cm} \) were used to measure the magnetic fluctuations. Figure 1(d) reveals that the magnetic component of the LFM is only weakly detected, which indicates that the LFM is an electrostatic mode. The observation of the LFM is a common phenomenon in the type-III ELMy H-mode in HL-2A. By using Langmuir probes, we found at least 20 shots with LFM at different parameters. Because the weak amplitude of the HFM contrasts with that of the LFM, the characteristics of the HFM are not discussed here but will be reported in a future paper.

The power spectrum of potential fluctuations \( \Phi_f(f) \) positioned at \( r - a = -1.0 \text{ cm} \) has been estimated, as shown in figure 2(a). The central LFM frequency is \( f_{\text{LFM}} = 35 \text{ kHz} \) and the half-width is \( \Delta f = 8 \text{ kHz} \) with \( \Delta f/f \ll 0.2 \), which is slightly larger than the QCF half-width \( \Delta \omega/\omega \sim 0.1 \) observed on PDX [7]. Figure 2(b) shows the radial distribution of the LFM amplitude; note that the LFM can only be observed inside the separatrix. To further study the mode structure of the LFM, the two-point cross-correlation technique [22] has been applied to estimate the local wavenumber-frequency spectrum \( S(k, f) \) at \( r - a = -1.0 \text{ cm} \), as shown in figure 2(c). The spectra \( S(k, f) \) of the LFM and HFM show significant differences, as shown in figure 2(c). The LFM frequency ranges from 20 to 120 kHz and the poloidal wavenumber ranges from \( k_\theta,\text{LFM} = 0.2 \sim 1.5 \text{ cm}^{-1} \). The group velocity of LFM in the laboratory frame is calculated from the slope of the contour plot to be \( v_g = \partial \omega/\partial f \sim 6.0 \text{ km s}^{-1} \). A positive \( v_g \) indicates that the LFM propagates in the electron-diamagnetic direction in the laboratory frame. The wavenumber spectrum of the LFM at the central frequency is shown in figure 2(d). The weighted mean wavenumber of the LFM can thus be calculated from \( \bar{k}_f = \int k \cdot S(k, f) dk \sim 0.7 \text{ cm}^{-1} \). For \( n = n_{\phi}q_{95} \), the poloidal and toroidal mode numbers of the LFM are estimated to be \( m \sim 28 \) and \( n \sim 10 \), respectively, with \( q_{95} = 2.8 \) for the discharge. The phase velocity of the LFM is calculated to be \( v_p = \omega/k \sim 6.2 \text{ km s}^{-1} \), which is close to the LFM group velocity.

The normalized poloidal scale of the LFM is \( k_\phi \rho_1 \sim 0.1 \). Here, \( \rho_1 = (T_m/\rho_d)^{1/2}eB \) is the ion Larmor radius with the assumption of \( T_e = T_i \); this value is consistent with observations of the KBH at DIII-D \( (k_\rho \rho_1 < 1) \) [15], the ECM at EAST \( (k_\rho \rho_1 < 0.1) \) [11], the QCFs at PDX with \( 20 < \rho_1 < 120 \) [7], and with the simulation results for the KBH \( (k_\rho \rho_1 < 1) \) and the ion-temperature-gradient (ITG) mode. Thus, based solely on the characteristics of the mode structure, differentiating the LFM from the pedestal modes observed at other tokamaks is difficult.

A four-step probe array fixed on probe system A was applied to investigate the excitation mechanism of the LFM. The probe can simultaneously measure the electron density \( n_e \), temperature \( T_e \), pressure \( P_e \), and their gradients at different radial positions [23]. The steps cover 7.5 mm in the radial direction with the deepest probe tips fixed at \( r - a = -0.6 \text{ cm} \). Figure 3 shows a typical repeating H-mode discharge \( (481 \sim 486 \text{ ms} \sim 489 \sim 496 \text{ ms}) \) induced by heating from neutral-beam injection with a heating power close to the threshold value of the L–H transition. Figure 3(b) shows a time-frequency resolved potential fluctuation spectrogram compiled from probe measurements at \( r - a = -0.6 \text{ cm} \). The LFM is clearly observed after the I–H or L–H transition in the contour plot. The LFM amplitude is estimated from the envelope of the \( \Phi_f(f, t) \) spectrum; it starts to increase several milliseconds after the transition and saturates several milliseconds.
Figure 1. Time evolutions of (a) $D_\alpha$, (b) line-averaged electron density and stored energy, (c) the power spectrum of floating potential fluctuations and (d) magnetic fluctuations during the L–I–H transition.

Figure 2. (a) Auto-power spectrum of floating potential $|\Phi(f)|^2$, (b) radial distribution of LFM amplitude $|\tilde{\Phi}_{L,F,M}(r)|$ with red dashed line indicating separatrix, (c) conditional wavenumber-frequency spectrum $S(k_0|f)$ from two $\tilde{\Phi}$s with poloidal separation of 0.7 cm, and (d) wavenumber spectrum at $f_{\text{LFM}} = 35$ kHz.
later, as illustrated by the red line in figure 3(a). At saturation ($t = 493$ ms), the LFM amplitude seems to be modulated by low-frequency perturbations ($f < 5$ kHz). This result is similar to the observations at EAST [12] and PDX [7] and to the predictions of the prey–predator model [24]. The low-frequency perturbations ($f < 5$ kHz) may be low-frequency zonal flow, which gains energy from the LFM when the LFM amplitude reaches a threshold value. However, determining the type of mode requires further study of the mode structure of the perturbations ($f < 5$ kHz).

Figure 3(b) also shows that, with the appearance of the LFM, the central frequency undergoes a characteristic redshift from $\sim$140 to $\sim$70 kHz within the first time window. For the second time window, $f_{\text{LFM}}$ decreases from $\sim$120 to $\sim$75 kHz and maintains its value since $t = 492$ ms. The LFM frequency in the laboratory frame may be defined as $f_{\text{lab}} = f_{E\times B} + f_\ast$. Here, $f_{E\times B}$ is the Doppler frequency and $f_\ast$ is the mode frequency of the LFM in the plasma frame. Figure 3(e) shows the radial electric field $E_r$ as a function of time calculated from the difference between two adjacent probes. We find that $E_r$ continues to decrease until the end of the H-mode. In magnetically confined plasma, the Doppler frequency depends on the plasma-rotation velocity and turbulence wavenumber:

$$f_{E\times B} = \frac{v_\text{q} k_\perp}{(2\pi)} \approx \frac{E_r k_\perp}{(2\pi B)}.$$  

For a fixed $k_\perp$ of the LFM, $f_{E\times B}$ would increase as $E_r$ becomes more negative. Furthermore, a statistical analysis shows that the mode frequency in the stationary state depends weakly on the local magnetohydrodynamic (MHD) ballooning parameter $\alpha_{\text{MHD}} = 2\mu_0 B^2 q^2 R / \rho_0$ [25]. After the L–H transition, the pressure gradient increases approximately twofold, as shown in figure 3(c), which indicates that the LFM frequency $f_\ast$ also increases. If we assume that the LFM propagates in the electron-diamagnetic direction in the plasma frame, where both $f_{E\times B}$ and $f_\ast$ increase during the H-mode discharge, the summed value $f_{\text{lab}}$ should also increase. However, this deduction conflicts with the actual LFM frequency in the laboratory frame, which appears redshifted, as shown in figure 3(b). One derivation is that the LFM should propagate in the ion-diamagnetic direction in the plasma frame and the increase in intrinsic frequency should be greater than or equal to the increase in $f_{E\times B}$. In addition, if we assume the same variations in $f_\ast$ within the two H-mode intervals, then the rate of change of $E_r$ within the first interval is less than that within the second interval, which may explain why the LFM frequency dynamics differ within these two intervals.

The derivation that the LFM propagates in the ion-diamagnetic direction in the plasma frame is consistent with the predictions of ITG [26] and KBM [27]. In addition, following the L–H mode transition at EAST, the characteristic redshift is also observed in the ECMs at EAST [11–14], which suggests that the ECMs at EAST may also propagate in the ion-diamagnetic direction. Figure 3(d) illustrates the electron-pressure length scale in the form of $P_e / \nabla P_e$. The length scale decreases immediately after the transition and
remains at \( \sim 0.95 \) cm after the appearance of the LFM. A similar phenomenon appears in the second time window. These results indicate that the LFM plays an important role in saturating the electron-pressure length scale.

Figure 4 shows detailed results of the probe measurement in the time interval \( t = 697 \) ms to \( 703 \) ms between two ELMs. In the early stages following the ELMy crash, no LFM appears until \( t = 700 \) ms. Subsequently, the LFM is excited and increases in amplitude until its saturation (figure 4(c)), which is calculated from the envelope of \( \tilde{\phi}_{LFM} \) filtered from 20 to 120 kHz and is consistent with the results shown in figure 4(a).

The particle flux driven by the LFM at the outboard mid-plane is defined as \( n_e B / n_e E_\theta \) and can be directly measured by a four-tip probe fixed at \( r - a = -1.0 \) cm, illustrated by the red dashed line in figure 4(d). Here, \( E_\theta \) can be calculated from the difference between two floating potentials with a poloidal separation of 0.7 cm. The fact that \( \Gamma_i \) is negative means that the LFM contributes to inward particle transport. In addition, the particle flux contributed by the LFM is mostly negative.

Comparing the envelopes of \( \tilde{\Phi}_{LFM} \) and \( \Gamma_{LFM} \) (i.e. the two black lines in figures 4(c) and (d)) it is clear that they show an inverse evolution trend, suggesting that the inward particle flux due to the LFM increases with LFM amplitude. We also estimated the ion-particle flux at the striking point of the outboard divertor by using the divertor probe arrays with \( \Gamma_{\text{Divertor}} = n_e E_\theta \sim f \tilde{j} e = 4 - 9 \times 10^{22} \text{m}^{-2}\text{s}^{-1} \).

The dynamics of the LFM amplitude \( \text{Env}(\tilde{\phi}_{LFM}) \) and \( \Gamma_{\text{Divertor}} \) are out of phase, as shown in figures 4(b) and (d). This indicates that when the amplitude of the LFM increases, the divertor detects a reduced particle flux; when the amplitude of the LFM decreases, the particle flux of the divertor will increase. At least these results show that the LFM does not provide outward particle flux, which is consistent with the observations from the Langmuir probe. This conclusion can be further supported by the dynamics of the emissions of the divertor \( D_\alpha \), which decreases slightly once the LFM appears, as shown in figure 4(a).

At the early stages after the ELM crash, \( n_e \) and \( T_e \) increase gradually up to \( t \sim 700 \) ms, following which their rate of increase speeds up because of LFM excitation. These results imply that the LFM accelerates the recovery of the pedestal after the crash of ELMs. The mean floating potentials at \( r = 40 \) cm and \( r = 37 \) cm are shown in figure 4(f). These dynamics are consistent with the results reported in figure 3, which suggests that the LFM leads to characteristics for the formation stage after the L–H transition that are similar to those of the recovery stage after the ELMy crash.

In conclusion, this paper reports the experimental observations of a low-frequency mode (\( f_{LFM} = 20 \) kHz to \( 120 \) kHz) by using reciprocating probes on HL-2A. The LFM is an electrostatic mode which can be both observed in the pedestal region during the construction of the pedestal after the

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**Figure 4.** Dynamics of (a) emission from divertor \( D_\alpha \) and (b) ion flux at the striking point in the outboard divertor. Dynamics of (c) the probe measured envelope of the LFM (20 kHz to 120 kHz), (d) the LFM-driven particle flux \( \Gamma_i \) (red dashed line) and envelope of \( \Gamma_i \) (black line), (e) \( n_e \) and \( T_e \) at \( r - a = -1.0 \) cm during the discharge between two ELMs, and (f) the evolutions of mean \( \tilde{\Phi}_s \) at \( r = 37 \) cm and \( r = 40 \) cm.
L–H mode transition or the recovery stage after the type-III ELM crash. The mode structure study shows that the dominant modes are \( m \approx 28 \) and \( n \approx 10 \) with \( k_{\rho m} \sim 0.1 \). With the appearance of the mode, the scale length of pressure becomes smaller. We provide direct evidence that the LFM can contribute strong inward particle flux \( (I_p,_{\text{LFM}}) \), which is comparable with the ion particle flux \( (I_p,_{\text{Divertor}}) \) at the striking point of the divertor. Additionally, the time evolutions of \( I_p,_{\text{LFM}} \) and \( I_p,_{\text{Divertor}} \) are out of phase, which further demonstrates that the LFM can contribute inward particle flux. Those results indicate that the LFM may play an important role in the formation of the pedestal. In addition, we have also discussed the propagating characteristics of the LFM and obtained a derivation that the LFM propagates in the ion-diamagnetic direction in the plasma frame, suggesting that the LFM may be the well-known ITG or KBM, or a new ion mode excited on the pedestal. However, more experimental studies are needed to confirm the type of mode directly.

Acknowledgments

The authors thank the HL-2A team for their support of these experiments, as well as PH. Diamond, Y.H. Xu, Y. Xiao, P.B. Snyder and X.Q. Xu for their helpful comments. This work is supported by the NSFC under grant nos. 10990210, 10990211, 11405214, 11375188, 11275234, 11305208, 11305215 and 11505221, and the China National Fusion Project for ITER under grant nos. 2014GB106000, 2013GB106002 and 2014GB106003.

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