Letter

Dynamics of the pedestal in the recovery phase between type-III ELMs

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Abstract

Dynamics of the pedestal between type-III ELMs have been studied by a particular designed four-step probe array on HL-2A tokamak. The recovery of the edge transport barrier (ETB) can be divided clearly into three different phases. Inconsistent with the dynamics during the type I ELMy discharge, our results on HL-2A show that the (electron) temperature pedestal is recovered first, well before the ELM crash, while the density and pressure pedestals are still evolving slowly until the next ELM. The fast recovery of the temperature pedestal can trigger a low-frequency electrostatic coherent mode (LFM) (20–120 kHz) in the edge plasma. Direct and indirect measurements reveal that the LFM can drive strong inward particle flux. After the excitation, the LFM can slow down the further recovery of the temperature pedestal. Yet, the excitation of the LFM may help the recovery of the density pedestal. The structure and excitation studies indicate that the LFM may be the ion temperature gradient driving mode (ITG) excited in the edge plasma and plays a critical role in the recovery of pedestal between type-III ELMs.

Keywords: pedestal, tokamak, ITG, edge local mode, zonal flow

(Some figures may appear in colour only in the online journal)
edge pedestal [6–9]. In addition to the neo-classical particle-diffusion channel, another important channel is the turbulence transport. Reversal of the fluctuation-induced transport has been reported during low to high transitions in the H-1 Heliac Plasma [10]. More detailed fluctuation measurements localized in the pedestal region as well as gyrokinetic simulations of small scale edge instabilities are thus to be encouraged.

The letter reports the experimental detection of a strong low-frequency electrostatic coherent mode (LFM) with $f_{\text{LFM}} = 20–100$ kHz in the recovery phase of the type-III ELM on HL-2A tokamak. Direct and indirect measurements reveal that the LFM can drive strong inward particle flux, and is excited after the fast recovery of the temperature gradient. Here, the temperature is the electron temperature by default. After the excitation, the LFM can slow down the further recovery of the temperature pedestal, indicating that the LFM may act like some temperature driving mode. Our observations that density pedestal lags behind the temperature pedestal in type-III ELMy H-mode discharge are inconsistent with the dynamics of the pedestal reported on DIII-D [3], ASDEX Upgrade [4] and JT-60U [5] which performed on type-I ELMy H-mode discharge. In the grassy ELM case operated in high collisionality $\nu_e^* \sim 1.5$, N. Oyama’s study on JT-60U shows that localized collapses in the electron temperature were observed in the middle of the pedestal at $r/a \sim 0.95$, while the collapse of the density pedestal was not so clear [11].

The experiments are carried out on HL-2A ($R = 1.65$ m, $a = 0.4$ m) with divertor configuration under the following discharge parameters: magnetic field $B_t = 1.3$ T, plasma current $I_p = 180$ kA, safety factor at the $\rho = r/a = 0.95$ $q_{95} \sim 2.8$, and line-averaged density of the mid-plane $n_e = 1.5–1.8 \times 10^{19}$ m$^{-3}$. The discharge gas is deuterium. There are 16 toroidal magnetic coils on HL-2A. The toroidal ripple is 0.78% at separatrix ($r = 40$ cm) on the outside mid-plane. Measurements are carried out by the radially reciprocating probe systems. A particular designed four-step probe array is applied to measure the electron temperature $T_e$, the density $n_e$ as well as the pressure $P_e$ at four different radial positions simultaneously [12]. Besides, the four-tip probe has been well used to calculate the particle flux driven by turbulence and measure the direction of the flux. The deepest insert position of the probe tip is fixed at $\rho = 0.95$.

Figure 1 shows a typical type-III ELM H-mode discharge on HL-2A with averaged period between two ELMs around 5 ms. The H-mode plasmas are achieved with combined neutral beam injection (NBI) and electron-cyclotron resonance heating (ECRH) at a power of $P_{\text{ECRH}} = 1.0$ MW and $P_{\text{NBI}} = 0.7$ MW, which is just above the low-high transition threshold power, as shown in figures 1(a) and (b). The neutral beam injection on HL-2A is performed in co-current and anti-magnetic direction. The line averaged density $n_e$ and the stored energy will keep increasing until the next onset of the ELM, as shown in figure 1(d). To study the details of the pedestal dynamics, the reciprocating probe arrays were injected inside the separatrix and fixed at $r - a = -1$ cm since $t = 695$ ms. The measured time evolutions of original floating potential signal $\phi_f$ and power spectrum of $\phi_f$ are illustrated in Figure 2.
figures 1(e) and (g), respectively. Strong instabilities can be observed in the original signal of $\phi_f$, which are mainly consisted of the low-frequency mode (LFM) with the frequencies from 20 kHz to 120 kHz (figure 1(g)). Here, the LFM is named to distinguish our previous observations of high-frequency mode (HFM) with 140 kHz $< f_{HFM} < 400$ kHz [13]. The LFM can be well observed inside the separatrix between type-III ELMs with different discharging parameters. To further study the mode structure of the LFM, the two-point cross-correlation technique has been applied to estimate the local wave-number spectrum of two $\phi_f$s with poloidal separation of $\Delta \theta = 0.7$ cm. The weighted mean wavenumber of the LFM with maximum power density is $k_0 \sim 0.7$ cm$^{-1}$. Thus, the normalized poloidal scale of the LFM is $k_0 \rho_i \sim 0.1$. Here, $\rho_i = (T_i m_i)^{1/2}/eB$ is the ion Larmor radius with the assumption of $T_e = T_i$. For $n = n q_\theta q_\phi$, the poloidal and toroidal mode numbers of LFM are estimated to be $m \sim 28$ and $n \sim 10$, respectively, with $q_\theta q_\phi \sim 2.8$ in this shot.

The amplitude of LFM has been estimated, as illustrated in figure 1(d). It is interesting to find that just before each ELM crash, the amplitude of the LFMs keep increasing till a saturated level. Yet, the LFM can hardly be observed after the ELM crash. The amplitude of the LFM is near $80$ V. The instability is so strong that the normalized amplitude of the LFM gets $|\hat{\phi}_{LFM}|/T_e \sim 100\%$, which is much larger than the value of turbulence observed in the edge during the L-mode discharge in HL-2A [14]. The Mirnov coils positioned at $r = 50$ cm were used to measure the magnetic fluctuations. The result reveals that the magnetic component of the LFM is very weak, indicating that LFM is an electrostatic mode.

Figure 2 illustrates the details of probe measurements in a specific time intervals ($697$ ms $< t < 703$ ms) of figure 1, which is a typical discharge between two ELMs on HL-2A. At the first stage within 2 ms after the ELM onset, the LFM can be hardly observed. LFM starts to appear since $t \sim 699$ ms, the amplitude keeps increasing until a saturated level is reached since $t \sim 701$ ms, as shown in figure 2(a). The red line in figure 2(a) is estimated from the envelope of LFM with band-pass filtering frequency from 20 kHz to 120 kHz, which cover the main power range of LFM, as shown as the contour plot of $\hat{\phi}_f(f, t)$. The particle flux driven by LFM at outboard mid-plane is defined as $\Gamma_r \equiv \langle \bar{n_r} \bar{v_r} \rangle = \langle \bar{n}, \bar{E}_\theta \rangle / B$. Here, $\bar{E}_\theta$ is calculated from the difference between two poloidally positioned $\phi_f$s on the four-tip probe. The angular bracket means ensemble average which is well used in the spectral statistics. It is interesting to find that the sign of $\Gamma_r$ is negative, indicating that the LFM can drive inward particle flux, as shown in figure 2(b). It needs to be mentioned that the intensity of the inward particle flux driven by LFM can reach $\sim 9 \times 10^{22}$ m$^{-2}$ s$^{-1}$ which is comparable to the change of particle flux at the strike point of outboard divertor ($20 \sim 40 \times 10^{15}$ m$^{-2}$ s$^{-1}$), as illustrated the brown dash line in figure 4(b).

Figure 3 shows the comparisons of radial particle flux $\Gamma_r$ and its components between the H-mode discharge with LFM (red dash line) and L-mode discharge without the LFM (black solid line). The frequency resolved formula of radial particle flux is defined as: $\Gamma_r(f) = 2 \bar{n_r} \bar{E}_\theta / \gamma_n \bar{E}_\theta \sqrt{\langle P_r \rangle \langle P_{E \theta} \rangle \cos \alpha_{n, E_\theta}}(f)$ [15, 16]. Here, $\gamma_n \bar{E}_\theta$ is the coherence between $\bar{n_r}$ and poloidal electric field $\bar{E}_\theta$. $P_r$ and $P_{E \theta}$ are the power of $\bar{n_r}$ and $\bar{E}_\theta$, respectively. In L-mode discharge, turbulence with frequency from 15–100 kHz contribute the main outward particle flux, which shows great difference to the H-mode discharge case with the LFM. The negative sign of $\Gamma_r$ means that LFM drives the inward particle flux, as shown in figure 3(a). It’s needed to be mentioned that the modes with $f < 15$ kHz can drive outward particle flux for both L and H discharges (figure 3(b)). This phenomenon can be explained by the cross-phase
spectrum between density fluctuations and poloidal electric field fluctuations $\dot{E}_p$ with the $\cos(\theta_{n_e}k_xE_p)$ changes from positive value of modes with $f < 15$ kHz to the negative value of LFM, as shown in figure 3(d).

The phase difference of $\dot{n}_e$ & $\dot{E}_p$ has been discussed a lot before [17–19]. $\dot{E}_p(f) = k_0(f) \cdot \phi_f(f)$, thus the phase difference can be changed in two ways. One depends on the transport direction of a mode (f) in plasma frame since $k_0$ being a vector. Our previous study [13] indicates indirectly that LFM propagates in the ion diamagnetic direction in the plasma frame. This result may explain the great change of cross phase between $\dot{n}_e$ and $\dot{E}_p$ in figure 3(d). The other depends the change of cross phase between the density $\dot{n}_e$ and potential fluctuations $\phi_f$, which may act like some intrinsic characteristic for a mode (f).

Figure 4(a) illustrates the detail evolutions when amplitude of the LFM reaches a saturated value. The time-frequency resolved spectrums of potential fluctuations $\phi_f$ is illustrated in figure 4(d). The evolutions reveal that amplitude of $\phi_f$ consist mostly of the LFM is modulated by a lower frequency oscillations with $f \approx 2$ kHz. Similar phenomenon can also be observed in the envelope of $|\dot{\phi}_f|$, as shown in figure 2(a). This result is similar to the observations at pedestal region on EAST [20] and PDX [21]. Determining the type of mode requires further study of the mode structure of the perturbations ($f < 5$ kHz).

Figure 4(b) shows the time evolutions of $D_n$ emission and particle flux at target of outboard divertor with $\Gamma_{\text{Divertor}} = n_c j_s / e$. Here, the $n_c$ and $j_s$ are the electron density at the Divertor targets and the ion saturation density measured by the Divertor Langmuir probes, respectively. $\Gamma_{\text{Divertor}}$ contains the particle flux contributed by the pedestal instabilities, which is sometimes used to represent the total particle flux $\Gamma_{\text{total}}$ contributed by the pedestal instabilities, a.s. LFM, qualitatively. It needs be noticed that $\Gamma_{\text{LFM}}$ measured at the outside mid-plane can not represent the $\Gamma_{\text{total}}$ without the particle flux measurements of LFM at different poloidal positions. Figures 4(b) and (c) show that the amplitude of LFM which is proportional to particle flux contributed by LFM in figure 2 exhibits strong inverse connection with $\Gamma_{\text{Divertor}}$. The increase of LFM does not lead to the increase of $\Gamma_{\text{Divertor}}$, at least indicating that LFM does not contributed strong outward particle flux, indirectly. Thus, $0 < \Gamma_{\text{total}} \ll \Gamma_{\text{Divertor}}$ for outward total particle flux, or $\Gamma_{\text{total}} < 0$ for inward total particle flux. Besides, figure 2 directly shows that LFM can contributed strong inward particle flux which is comparable to the flux $\Gamma_{\text{Divertor}}$ at the strike point. Thus, it is of high opportunity for $\Gamma_{\text{total}} < 0$, implying that LFM may help the recovery of the density pedestal which has been further discussed in figure 5. Yet, without the integration of LFM-driving particle flux on total magnetic flux, it is hard to discuss the impact of LFM on the formation of the pedestal, quantitatively.

The spectrum of magnetic fluctuations and the envelope have also been estimated, as shown in figures 4(e) and (c), respectively. Two magnetic fluctuations with different frequencies ($f < 50$ kHz and $f \sim 150$ kHz) can be observed in figure 4(e), while the magnetic component of LFM with $40$ kHz $< f < 100$ kHz can hardly be found in the spectrum. The dynamics of the LFM amplitude $\text{Env.}(\phi_f)$ and $\Gamma_{\text{Divertor}}$ exhibits reverse evolutions, while the amplitude of magnetic fluctuations $\text{Env.}(\partial B_\theta / \partial t)$ and $\Gamma_{\text{Divertor}}$ is almost synchronous with $\Gamma_{\text{Divertor}}$ lagging behind by only $\sim 30\mu$s. The results reveal that the magnetic fluctuations can trigger outward particle flux. The increase of $\Gamma_{\text{Divertor}}$ is contributed by the increase of the magnetic fluctuations. It needs to be noticed that those magnetic fluctuations can’t be observed by the Langmuir probe positioned on the mid-plane of low-field side, which may indicate that those magnetic fluctuations are excited at different poloidal positions.

In order to investigate the excitation mechanism of the LFM as well as the dynamics of pedestal between type-III ELMs, a particular designed four-step probe array has been applied to measure the electron density $n_e$, temperature $T_e$, pressure $P_e$, potential $\phi_f$, and their gradients at four different radial positions, simultaneously [12]. Those measurements cover $7.5$ mm in the radial direction with the deepest probe tips fixed at $r - a = -0.6$ cm. The time-frequency resolved spectrums of the floating potential perturbations $\phi_f$ measured at $r - a = -0.6$ cm is illustrated in figure 5(a). The LFM with frequency of $40$–$100$ kHz can be significantly
observed between two type-III ELMs. Besides, the evolutions of important information of electron temperature $T_e$, electron density $n_e$, and pressure $P_e$, e.g. radial scale length and radial gradient value, are shown in figures 5(b)–(g). Here, the $n_e, T_e$ and $P_e$ are measured at the same radial location as $\phi_f$ at $r-a = -0.6\text{ cm}$. For other gradient parameters, they are calculated from the difference between two radial positions with $\Delta r = 2.5\text{ mm}$. Thus, the radial location of the gradient parameters is $r-a = -0.475\text{ cm}$.

According to the evolutions of parameters shown in figure 5, the typical recovery process of the edge transport barrier (ETB) between type-III ELMs can be divided clearly into three different phases. (i) 1–1.5 ms after the ELM onset (Phase I) a semi-quiescent edge state is reached, characterized by the slow evolutions of edge parameters and greatly suppressed turbulence (figure 5(a)). (ii) After that, the edge transport barrier (ETB) recovers until the next ELM. The evolutions of $\nabla T_e$, $\nabla n_e$ and $\nabla P_e$ indicate that the temperature gradient is recovered first, well before the ELM crash, while the density gradient remain almost the same in Phase II. Thus, $\eta_e \equiv L_{ne}/L_{Te}$ increases significantly in Phase II, $\eta_e$ being the ratio of the density gradient scale length to the electron temperature gradient scale length. This process is short and lasts for only $\sim 1\text{ ms}$. (iii) In Phase III, the increase of temperature gradient slows down and trends to a saturated value, while the density starts to evolve slowly until the next ELM. Those dynamics of pedestal structure observed here (type-III ELM) are inconsistent with the observations in DIII-D [3], ASDEX Upgrade [4] and JT-60U [5] in type-I ELM discharges. The inter-ELM evolution of the pedestal in JT-60U is characterized by a fast recovery of the density, followed by saturation of $n_{e\text{PED}}$ before the next ELM, and by a linear increase in the ion and electron temperatures at the pedestal top. Besides, it seems that in grassy ELM case on JT-60U, the edge plasma has just undergone the phase i and phase ii before another ELM crash [11].

Figure 5 also shows that the fast recovery of the temperature gradient is followed by the excitation of the LFM since $t = 491\text{ ms}$. While at the same time, the gradient of density remains almost the same. Those results reveal that the LFM may be driven by the temperature gradient. After that, the recovery of the temperature gradient slows down which is limited by the growth of the LFM in Phase III. As mentioned before, the LFM can contribute the strong inward particle, which can explain the observations that gradient of electron density starts to recover since the excitation of the LFM, as shown in figure 5(c). This unique relation between the LFM and $\nabla n_e$ may support the hypothesis that a strong particle pinch may offset strong particle diffusion in the edge pedestal [6–8]. Although, the gradient of the $T_e$ slows down since the excitation of LFM, the $\nabla n_e$ still keeps increasing, thus the gradient of pressure $\nabla P_e$ keeps increasing too during the whole recovery phase of the pedestal. When $\nabla P_e$ reaches some threshold value, it is argued that ballooning instabilities will be triggered and followed by the crash of the type-III ELM.

The LFM frequency in the laboratory frame may be defined as $f_{lab} = f_{E \times B} + f_s$. Here, the $f_{E \times B}$ is the Doppler frequency and $f_s$ is the mode frequency of LFM in the plasma frame. Figures 5(f) and (h) show the pressure and radial electric field $E_r$ as a function of time calculated from the difference between two adjacent probes. We can find that $E_r$ continues to decrease until the end of the phase III. As $f_{lab}$ of LFM remains almost the same while $f_{E \times B}$ keeps increasing, we can derive that LFM may propagate in the ion-diamagnetic direction in the plasma frame, which has been discussed in detail in our previous work [13]. The propagating direction of LFM is consistent with the predictions of ITG [22] and KBM [23, 24]. Considering the observations that LFM gets weak magnetic component and seems like some temperature-gradient driving mode (LFM is excited when $\eta_e$ reaches a threshold value, as shown in figure 5(e)), LFM may be an ion-temperature gradient driving mode which is excited on the edge of tokamak and contributes inward particle flux. Yet, the temporal evolution of ion temperature and its gradient need further research.
In conclusion, a particular designed four-step probe array is applied to study the dynamics of pedestal in the recovery phase between type-III ELMs. Our studies indicate that dynamics of temperature pedestal and density pedestal show great difference. The typical recovery process of the edge transport barrier can be divided clearly into three different phases. The temperature pedestal recovers first, well before the ELM crash, while the density and pressure pedestals are still evolving slowly until the next ELM. A strong electrostatic LFM can be observed in the steep-gradient pedestal region when gradient of temperature reach some threshold value. After the excitation, the LFM can slow down the further recovery of temperature gradient. It is interesting to find that LFM can drive strong inward particle flux. The details of the mode structure of LFM have been studied. All those results suggest that LFM acts like an ion temperature gradient driving mode (ITG) excited in edge plasma. Although, the gradient of the \( T_e \) slows down since the excitation of LFM, the \( \nabla P_e \) still keeps increasing, thus the gradient of pressure \( \nabla P_e \) keeps increasing too during the whole recovery phase of pedestal. When \( \nabla P_e \) reaches some threshold value, it is argued that ballooning instabilities will be triggered and followed by the crash of the type-III ELM. Thus, the LFM plays a critical role in the recovery of pedestal between type-III ELMs. However, more experimental studies, especially the evolutions of ion temperature and density on the edge, are needed to confirm the type of mode directly.

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