The observation of small ELM post-cursor mode in EAST

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Abstract

A 'post-cursor’ quasi-coherent mode with frequency \(\sim 50\) kHz has been observed following the crash of small edge localized modes (ELMs) in the Experimental Advanced Superconducting Tokamak by using a reciprocating Langmuir probe system inserted at the outboard midplane. This mode with strong potential and magnetic perturbations propagates in the electron-diamagnetic drift direction in the laboratory frame. In addition, these quasi-coherent fluctuations appear to be modulated by a MHD mode with lower frequency (~5 kHz). The bi-coherence analysis shows that the post-cursor mode and the MHD mode have nonlinear interaction through three-wave coupling. The understanding on post-cursor mode can enhance our knowledge of ELMs and pedestal physics, and give new insight into the ELM process itself.

Keywords: post-cursor mode, H-mode, small ELM

(Some figures may appear in colour only in the online journal)

1. Introduction

The high confinement mode (H-mode) with outstanding energy confinement is the foreseen baseline operation scenario for future reactor-relevant devices, i.e. International Thermonuclear Experimental Reactor [1]. The main feature of H-mode is the formation of an edge transport barrier (ETB). The ETB is characterized by steep gradients and significant edge current, which would not only lead to superior improvement on the confinement performance, but also results in MHD instabilities like the edge localized modes (ELMs) [2, 3] when the ETB reaches some critical limit. Commonly ELMs are considered as a combination of peeling and ballooning modes driven by steep pedestal pressure gradients and currents, respectively [4]. The periodic collapse and recovery of small ELMs result would drive intermittently substantial energy and particles transport out of the pedestal region into the SOL, which are thought to be favor of the sustainment of H-mode [5–7]. However, the prompt loss of particles and energy and high transient heat loads associated with the giant or type-I ELMs probably lead to enormous erosion of the divertor target plates and plasma facing wall of the device, which probably reduce the lifetime of plasma facing components in large devices [8–12]. Based on these considerations, how to control ELMs is one of the primary topics in the present tokamak research. Understanding the dynamics of the ELMs has attracted broad interest in the magnetic confinement fusion. Insight on ELM physics is the key for their successful mitigation and control. Various theories have been proposed to interpret the ELM physics [13, 14]. Based on linear MHD stability theories, the onset of the ELM is regarded to be a coupled ballooning and peeling instability [5]. The nonlinear phase of ELMs is still not well understood. To explore plasma behaviors prior to and after
ELM crash can give new insight on the ELM process and help understand of the dynamic and electromagnetic feature of ELMs.

It has been found the ELM precursor modes preceding type-III ELMs on COMPASS-D [15], DIII-D [16], JT-60U [17], as well as the post-cursor modes following type-I ELMs on JET [18, 19]. Because the post-cursor mode observed on JET show many harmonic frequencies, this typical of signature resembles the leaves of a palm tree. In this paper, we will report a new so-called 'post-cursor' mode following small ELM bursts detected on EAST tokamak, which is different from the palm tree signature observed on JET. The post-cursor mode has been detected by the edge Langmuir probes near the low-field-side midplane on EAST tokamak. We will show some properties of this post-cursor modes. The layout of the paper is as follows: a description of the diagnostic systems in section 2; some features about the post-cursor mode following small ELMs and the lower frequency MHD modes as well as clear evidence of strong interaction between them is then presented in detail in section 3; finally, a brief discussion and summary will be given in section 4.

2. Experimental set-up

To study the ELM dynamics, some pedestal/edge diagnostics with high temporal-spatial resolution are required, since ELM is a fast MHD event locally occurred in the steep and narrow pedestal region. The Magnetic pick-up coil arrays with good temporal resolution can detect ELM-associated magnetic perturbation is a good candidate for ELM study. Nevertheless, there is no spatial resolution from the magnetic pick-up coil. To get good spatial resolution from the magnetic pick-up coil, a probe head equipped with both multi-pin Langmuir probe tips and magnetic pick-up coils, which has been comprehensively implemented to observe the structures as well as dynamics of the ELM and ELM filament in the scrape-off layer (SOL) [20]. The electronic-magnetic probe head, as shown in figure 1, has been mounted on the reciprocating manipulator to observe the ELM post-cursor in the SOL region. The probe consists of three Langmuir probes (black components) poloidally separated by 5 mm on the top of cylindrical graphite and two magnetic pick-up coils (red components) radially separated by 1 cm and 1 cm below the probe head top. The Langmuir probes are used to measure the floating potentials. The magnetic coils are served to measure the time derivative of the three magnetic field components. All the signals are digitized by 1 MHz digitizer. In this experiment, the electronic-magnetic probe can move radially from a position behind the limiters to inside the separatrix [21].

3. Survey of post-cursor activity following small ELMs

The small ELMy H-modes has been obtained in EAST in 2012 experimental campaign. The discharge (#41364) was carried out with plasma current \( I_p = 0.4 \text{ MA} \) and toroidal field \( B_t = 1.8 \text{ T} \) on the magnetic axis. The experiment was performed with a typical double null divertor configuration with elongation ratio \( \kappa = 1.74 \) and central-line-averaged density \( n_e \sim 3.0 \times 10^{19} \text{ m}^{-3} \). Both \( B_t \) and \( I_p \) are in the counter clockwise directions as viewed from the top. Combination of auxiliary heating power applied in these experiments includes
0.6 MW lower hybrid current drive at 2.45 GHz and additional 1.2 MW ion cyclotron resonance heating [22]. After the L-H transition, small ELM appears following a quiescent phase with turbulence being deeply suppressed. As is shown in figures 2(a) and (b), the line-averaged density and plasma stored energy slowly increase during the ELM regime, presumably because that the ELMs provide particle and power exhaust, which is beneficial to sustain H-mode. And then it appears ELM-free phase (3.44–3.51 s), as shown in figure 2(e). Subsequently, three post-cursor mode associated with corresponding ELM emerge. The line-averaged density slowly increases, but plasma stored energy remains unchanged at this stage. After the last post-cursor appears, the plasma radiation rises sharply, indicated by the edge XUV radiation (see figure 2(d)), and plasma stored energy decreases.

Figure 3 shows the probe measurements of three ELMs whose time window is the gray area of figure 2. The raw signal of floating potential \( \phi_f \) and the poloidal magnetic perturbation \( \partial B_p / \partial t \) are shown in figures 3(b) and (c). As shown in figures 3(d) and (e), it can be clearly found that the post-cursor structures generally appear followed the crash of
natural small ELM, with a constant frequency about 50 kHz, in both magnetic signal and floating potential fluctuations. It indicates that the mode is an electromagnetic mode. In addition, as shown in figure 4, the cross correlation analysis between the two 5 mm poloidally separated floating potentials reveals a peak which exists at nearly 50 kHz with strong correlation coefficient $\sim0.9$. In addition, from the phase spectrum, the postcursor mode propagates in the electron diamagnetic drift direction in the lab frame with the poloidal wave number $k_{p}\sim1.2 \text{ cm}^{-1}$. The poloidal wavelength $\lambda_{p}\sim5 \text{ cm}$. It is noted that the magnetic perturbation can only be detected by the magnetic coil in the reciprocating probe, but not observed at the Mirnov coil, that is possibly because the location of the Mirnov coil is far from plasma relative to the magnetic pick-up coil on the reciprocating manipulator. Figure 5(a) shows the raw signal of the poloidal magnetic perturbation $\partial B_{p}/\partial t$ (black line) and corresponding envelop (thick black line). The raw signal of the floating potential $\phi_{f}$ (red line) and corresponding envelop (thick red line) can be seen in figure 5(b). The envelope is calculated by using the Hilbert transform of the high-pass-filtered potential fluctuation with frequency higher than 20 kHz. It is remarkable that each post-cursor mode corresponds to a chain of many regular oscillations in the floating potential as well as in the magnetic perturbation signal. It is also interesting to note that the spikes appear periodically modulated. The spikes reveal quasi-periodicity with a period around 200 $\mu$s in the time domain. Furthermore, the time-varying envelop of $\partial B_{p}/\partial t$ and $\phi_{f}$ appears to be modulated by a lower frequency mode ($\sim5$ kHz). Since there is no ion saturation current, the information on transport driven by the spike cannot be obtained.

Next, we try to find the low-frequency mode. Considering such a short characteristic time scale involved in the precursor phase, collapse phase and post-cursor phase, it is difficult to analyze the temporal evolution of the amplitude with the standard Fourier analysis. A special spectral analysis designed for transients is essential for such short-lived perturbation. The wavelet transform is one of the best tools to study the spectral properties of post-cursor phase. The wavelet analyses of $\phi_{f}$ and $\partial B_{p}/\partial t$ are illustrated in figures 6(a) and (b), respectively. It clearly shows the existence of a lower frequency mode about 5 kHz, which is obvious of the poloidal magnetic perturbation signal, as shown in figure 6(b). However, it is unexpected that evidence is unobvious for floating potential in figure 6(a).

In order to explore the detailed nonlinear interaction during the post-cursor mode, the bi-coherence spectrum and integrated wavelet bi-coherence analysis using a complex Gaussian wavelet have been employed. The bi-coherence [23–25] is estimated as $b(f_{1}, f_{2}) = \frac{|\tilde{\phi}_{f}(f_{1})\tilde{\phi}_{f}(f_{2})\tilde{B}_{p}(f_{1})\tilde{B}_{p}(f_{2})|}{\sqrt{|\tilde{\phi}_{f}(f_{1})\tilde{\phi}_{f}(f_{2})|^{2}+|\tilde{B}_{p}(f_{1})\tilde{B}_{p}(f_{2})|^{2}}$, where $f = f_{1} \pm f_{2}$, the star represents the complex conjugate. Using complex Gaussian wavelet analysis calculated frequency spectrum. Figure 7 plots the characteristic of the bi-coherence spectrum. As shown in figure 7, the $f_{2} > 0$ region corresponds to sum coupling $f = f_{1} + f_{2}$ and the $f_{2} < 0$ region corresponds to other coupling $f = f_{1} - f_{2}$. The bright structures suggest there exists significant three-wave coupling between the sum frequencies ($f = f_{1} + f_{2} > 10$ kHz) and difference frequencies ($f = f_{1} - f_{2} > 10$ kHz) coupling with $(f_{1}, f_{2})$. In addition, as can be seen in figure 8, the summed bi-coherence, calculated as $b^{2}(f) = \sum f_{1}, f_{2} b^{2}(f_{1}, f_{2})$, shows that there exist strong three-wave coupling peaks at $\sim$20, 30, 40 and 50 kHz in low frequency range.

4. Discussion and conclusion

Following small ELMs a post cursor mode with a frequency of 50 kHz has been observed for the first time. The post cursor mode has been investigated by means of electrostatic and magnetic probes close to the separatrix. It is invariant that the frequency of the post-cursor mode observed on EAST, which is different from the Palm tree mode with increasing frequency and many harmonic frequencies observed on JET [19]. It is clearly shown that the post-cursor mode propagates in the electron-diamagnetic drift direction in the lab frame. The electromagnetic feature of the modes has been identified. In addition, each post-cursor mode corresponds to a chain of many oscillations in the potential fluctuation as well as in the magnetic perturbation, and the oscillations regularly changed which seem to be modulated. The evidence of modulation has also been obtained by using a complex Gaussian wavelet analysis. There is a lower frequency ($\sim$5 kHz) modulating the post-cursor. There is strong three-wave coupling between them. The low frequency mode exists in during the post-cursor mode and the interaction between them is another difference from the Palm tree mode observed on other devices. As a part of inter-ELM, understanding this post-cursor mode could give new insight on the ELM process. However, limited by diagnostic, the detailed dynamic structure of both the post-cursor mode and the lower frequency MHD mode are unknown. So the physics behind the interaction are beyond the extent of the present research. This will be report in future work.
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Figure 7. (a) Bi-coherence of $\phi_1$ using a complex Gaussian wavelet, (b) bi-coherence of $\partial B_p / \partial t$ using a complex Gaussian wavelet.

Figure 8. (a) Integrated wavelet bi-coherence spectrum of $\partial B_p / \partial t$, (b) integrated wavelet bi-coherence spectrum of $\phi_1$.
References