GROWING NONLINEARITY IN KSTAR FIRE MODE PEDESTAL PROVIDES CLUE TO UNDESIRABLE H-MODE TRANSITION IN I-MODE PLASMAS

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Plasmas that achieve energy confinement comparable to that of high-confinement mode (H-mode) while avoiding type-I edge-localised modes (ELMs) are attracting significant interest within the tokamak community [1–7]. In KSTAR, active research has discovered fast ion-regulated enhancement mode (FIRE mode) [1] that exhibits both an internal transport barrier and a pedestal structure in ion temperature profile when operating in an unfavourable configuration [2], displaying edge characteristics similar to those of improved confinement mode (I-mode) [3]. However, one of the unresolved concerns is the undesirable H-mode transition, an issue that is similarly encountered in I-mode observed in other tokamaks [4, 5]. We report the gradual development of a nonlinear coupling between pedestal turbulence and near-zero frequency zonal quantities, detected by beam emission spectroscopy (BES), providing the first evidence towards explaining the elusive transiency in these plasmas.

The unfavourable configuration, a diverted configuration with a single-null shape in which the ion ∇B drift is directed away from the active X-point, nearly doubles the power threshold required for the H-mode transition [4]. Thus, this configuration is extensively adopted to achieve I-mode and FIRE mode plasmas, given that it markedly broadens their operational window. Nevertheless, a gradual evolution is sometimes observed in these plasmas, ultimately leading to the H-mode transition. Their key advantages are only effective when the H-mode transition is suppressed. Therefore, this issue must be addressed before they can be regarded as a viable alternative operational regime for ITER.

Figure 1 depicts this evolution, which occurred without any external operational interventions. The plasma was generated in the unfavourable configuration, with the toroidal magnetic field B_T of 1.8 T and plasma current I_p of 0.5 MA. The plasma shape was kept constant. Figure 1(a) shows the total neutral beam (NB) injection power, the only external heating source. The line-averaged electron density $\bar{n}_\mathrm{e,edge}$, measured by the two-colour interferometry channel with the outermost tangency radius, exhibits a gradual increase that becomes prominent from about 6.5 s, as illustrated in Fig. 1(b). Close to the dashed vertical line indicating the H-mode transition, the increasing trend of $\bar{n}_\mathrm{e,edge}$ intensifies. Figure 1(c), depicting the D_α signal, offers another indication of the gradual evolution. A quasi-periodic burst with low amplitude appears at first, then grows in amplitude and becomes explosive just prior to the H-mode transition. The burst amplitudes and the rising trend in $\bar{n}_\mathrm{e,edge}$ align closely, suggesting that these two phenomena are intimately connected. The existence of small, intermittent bursts has been already reported [2, 6, 7]. Previous works have revealed that detailed features such as precursors or frequencies differ [7]; however, the common factor is that they frequently manifest before the H-mode transition. In KSTAR, bicoherence analysis demonstrates that nonlinear coupling between edge turbulence and ZD occurs only when these bursts are present [2].

The spectrogram of edge electron density fluctuations $\tilde{n}_\mathrm{e}$, shown in Fig. 1(d), does not yield a meaningful explanation for the observed transiency and bursts. Consequently, we next examine the role of nonlinearity by analysing the time variance of bicoherence for $\tilde{n}_\mathrm{e}$ using the following approach. The time interval for computing bicoherence is minimised by ensemble averaging over the BES channels at the radial position of $\sqrt{\psi_\mathrm{N}} \approx 0.96$, which corresponds the centre of the ion temperature pedestal [2]. The smallest interval that still achieves an acceptable significance level is 0.1 s. The interval is then shifted in steps of 0.01 s, thereby incorporating 10% new fluctuation signals with each step. This method enables capturing the overall trend in the nonlinear coupling.

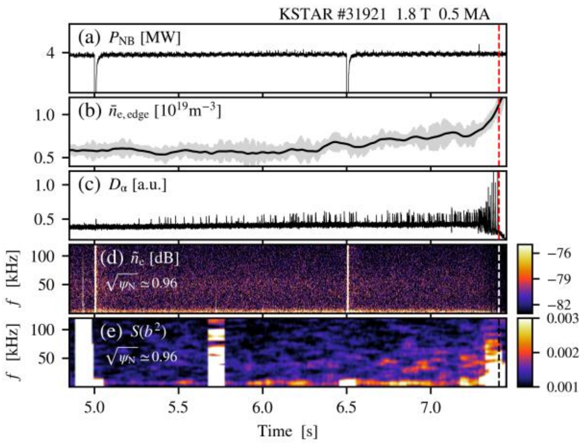

Figure 1 Time evolution of the FIRE mode discharge #31921.

Figure 1(e) presents the spectrogram of the summed auto-bicoherence of $\tilde{n}_e$, demonstrating the prominence of nonlinear coupling at every frequency. Intervals affected by anomalous diagnostic noise (around 4.9 s and 5.7 s in Fig. 1(d)) or NB blips (5.0 s and 6.5 s in Fig. 1(d)) compromise the reliability of the spectra, and must therefore be omitted from the analysis. A distinct correlation is evident between Figs. 1(b)–1(c) and Fig. 1(e); the brightness and bandwidth of the clusters in Fig. 1(e) correspond to the trend observed in Fig. 1(b) and the burst amplitudes in Fig. 1(c). Two clusters appear in the near-zero frequency domain and in a band centred around $f \approx 50$ kHz. The cluster at the higher frequencies is indicative of the nonlinear coupling between ZD and turbulence referred to as weakly coherent mode (WCM) [3]. As the H-mode transition nears, the spectrogram in Fig. 1(e) exhibits explosive behaviour, with the nonlinear coupling spanning a considerably broader spectrum.

The nonlinear coupling between ZD and the WCM observed in density fluctuations strongly suggests the existence of zonal flow (ZF), widely considered a trigger for the H-mode transition. Thus, the existence of ZF is examined by calculating the cross-bicoherence between $\tilde{n}_e$ and the poloidal velocity fluctuation $\tilde{v}_\theta$. A time-delay estimation technique [8] is adopted for estimating $\tilde{v}_\theta$. Three distinct time intervals are selected. The first interval contains very few bursts, the second is characterised by only low-amplitude bursts, and the third shows bursts with progressively increasing amplitude. Figure 2 shows the cross-bicoherence for each time interval. A diagonal cluster along $f_3 = f_1 + f_2 \approx 0$ kHz means that $\tilde{v}_\theta$ with near-zero frequency is in phase with $\tilde{n}_e$, implying that ZF may be nonlinearly driven by ambient turbulence.

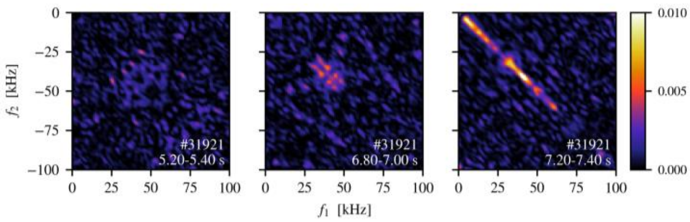

Figure 2 Cross-bicoherences between $\tilde{n}_e$ and $\tilde{v}_\theta$ for three different time intervals at a radial position of $\sqrt{\psi_N} \approx 0.96$.

The increasing trend of nonlinear coupling between turbulence and near-zero frequency components aligns well with the other transient features observed prior to the H-mode transition. This suggests that the bursts might be related to turbulence modulation by ZF. As nonlinearity offers an initial framework for understanding the gradual evolution, further investigations are underway to clarify its relationship with the bursts.

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