Experimental Observation of Multi-scale Interactions in the HL-2A Core NBI Plasmas

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Different scale instabilities are important components of complex dynamics in fusion plasmas. To unravel the underlying physics mechanism of them, studies of multi-scale physics including observation, modeling and simulation, are needed. In the present paper, we will report that experimental observations of multi-scale interactions in the HL-2A core NBI plasmas.

1)Nonlinear coupling of m/n=1/1 Kink and AITG/KBM/BAE mode–The spectrograms of microwave interferometer and Mirnov signals are shown in the Fig.1. It is found that there are several sawtooth crashes during the plasma current ramp-up at $t = 600-750ms$, and the low-frequency MHD fluctuations with $f = 3-7kHz$ and high-frequency MHD fluctuations with $f = 40-90kHz$ are driven unstable before each sawtooth crash. The low-frequency mode has a dominant $m/n = 1/1$ component according to its 2D ECEI mode structure, so that it is identified with kink mode. The high-frequency fluctuations localize in the core regions ($\rho <$ 0.25), and have strong electromagnetic characteristics. Their frequencies are more than BAE-CAP frequencies $\omega = (7/4+T_e/T_i)^{1/2}(2\beta_i)^{1/2}v_A/R_0$ but less than TAE frequencies $\omega_{TAE} = v_A/2qR_0$. The analysis from the generalized fishbone-like dispersion relation (GFLDR) suggests they belong to AITG/KBM/BAE instabilities[1, 2, 3]. It needs to be emphasized that these high frequency modes here look like collective excitations because the phenomena can be observed hardly without the low frequency kink mode. Namely, these modes are not linearly unstable, but can be driven by nonlinear coupling processes.

2)Synchronous coupling between m/n=1/1 kink and m/n=2/1 TM–These low frequency modes often have an $m/n = 2/1$ component except dominant $m/n = 1/1$ one, and they are shown in the Fig.2. It suggests that the $m/n = 1/1$ kink and $2/1$ tearing mode (TM) have same rotation frequency and different localization, namely there is a synchronous coupling between the kink and TM. Some theories do also suggest that the stability of the m/n=2/1 TM can be affected by coupling to the m/n=1/1 component in toroidal geometry, and this coupling is linear[4]. Some experimental results suggest that the fluctuation amplitudes of kink and TM are

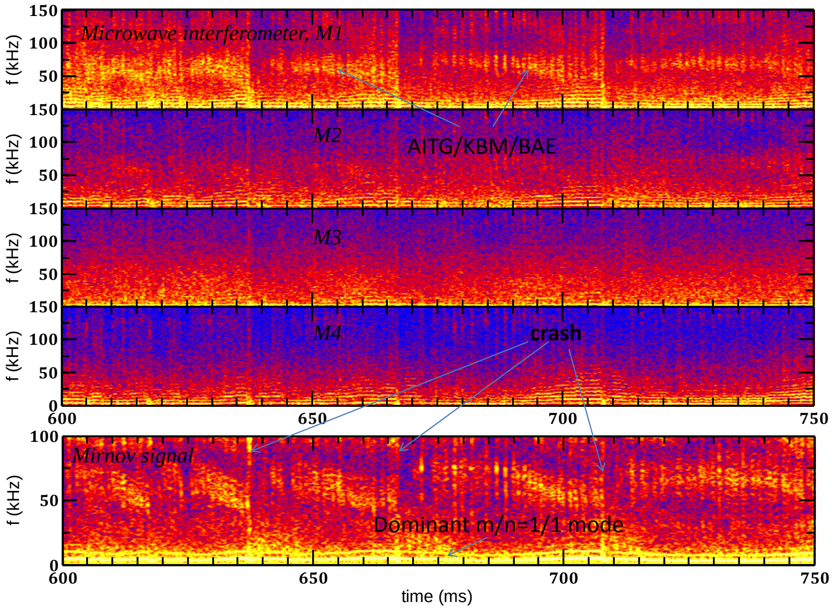

Figure 1: Spectrograms of microwave interferometer (M1-M4) and Mirnov signals with multi-scale interactions (Shot I). Ramp-up plasma current $I_p \simeq 120-140$kA, $n_e \simeq (1.2-1.8)\times 10^{19}m^{-3}$, $B_t \simeq 1.3T$, and $P_{NBI} \simeq 1MW$. Chordal distance: 5cm (M1), 11cm (M2), 18cm (M3) and 24cm (M4).

able to strongly affect the high-frequency instabilities[5].

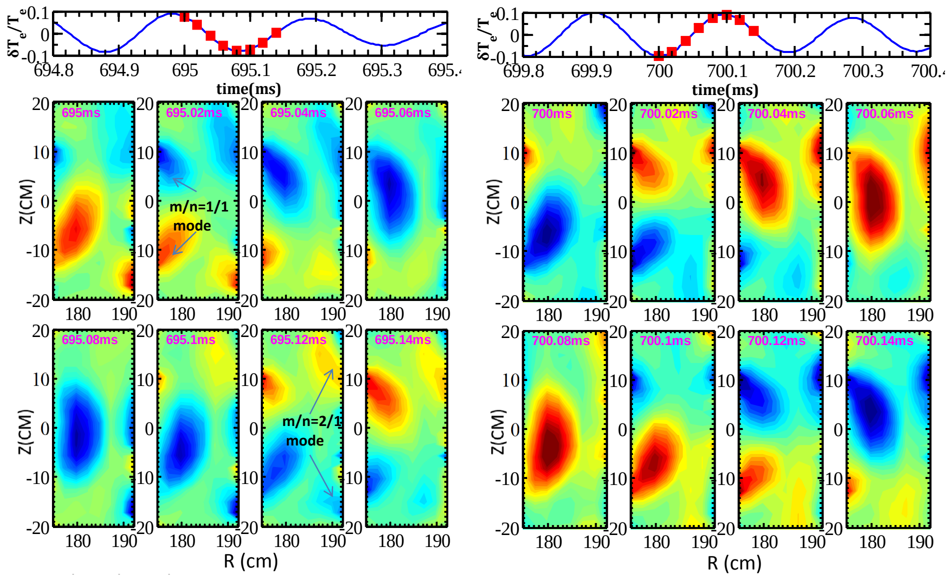

Figure 2: 2D mode structures of the kink and TM from the ECEI at two different time traces.

3)Nonlinear coupling of m/n=2/1 TM and AEs–When the $m/n = 2/1$ TM becomes strong the high-frequency multi-branch BAE and TAE are excited by the nonlinearity, resulting in the subsequent generation of Alfvénic sidebands including the co-/counter-propagating AEs and n=0 axi-symmetry MHD activities[6]. Actually, the magnetic island of TMs can affect the magnetic topology, modify Alfvén continuum and create new modes[7]. Recently, the hybrid kinetic-MHD code (CLT-K) code[8] simulation suggests that the large magnetic island with $m/n = 2/1$ can affect the saturation of TAE modes with n and f_n, and nonlinearly create new TAEs with $n \pm 1$ and $f_{n\pm1} = f_n \pm f_{TM}$. Further multi-type nonlinear couplings can exist simultaneously when the kink and TM are both strong.

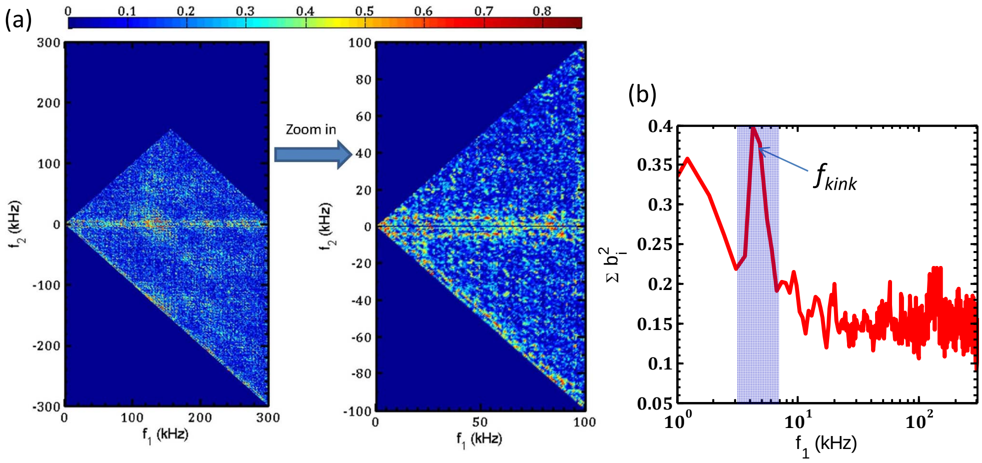

Figure 3: Auto- (a) and squared-bicoherence (b) of the envelope of the microwave interferometer (M1) in the range $\triangle f = 300 - 40kHz$ for shot I.

Bicoherence and envelope analysis–For studying the nonlinear multi-scale couplings, the squared bicoherence is given by $\hat{b}^2(f_1, f_2) = \mid \hat{B}_{XYZ}(f_1, f_2) \mid / < \mid X(f_1)Y(f_2) \mid^2 >< \mid Z(f_3) \mid^2 >$ with the Fourier bispectral $\hat{B}_{XYZ}(f_1, f_2) =< X(f_1)Y(f_2)Z^*(f_3) >$, $f_3 = f_1 \pm f_2$. It is convenient to represent the contribution of the nonlinear coupling from multiple modes to one mode with the summed squared bicoherence, which is defined as $\Sigma b^2_{XYZ} = \Sigma_{f=f_1 \pm f_2} \hat{b}^2(f_1, f_2)/N(f)$. Meanwhile, the nonlinear coupling is also present by analyzing the envelope of the high-frequency fluctuations in the range $\triangle f = f_2 - f_1$. The envelope $P(t)$ of signal $x(t)$ is calculated as $P(t) = (\int_{f_1}^{f_2} x(f)e^{i2\pi ft}df)^2$. Fig.3 shows the auto- and squared-bicoherence of the envelope of the core microwave interferometer in the range $\triangle f = f_2 - f_1 = 240 - 40kHz$. It is found that $\mid f_2 \mid = f_{kink}$ and $\mid f_2 \pm f_1 \mid = f_{kink}$ are strong coupling lines. It suggests the nonlinear interaction between the kink with $f_{kink} \simeq 4.5kHz$ and high-frequency fluctuations at each different time. Figure 4 shows the PSDs of the envelopes of microwave interferometer, core ECEI and Mirnov signals at the different filter ranges. Each of them exhibits a clear peak at the kink mode frequency which shows the nonlinear modulation of high-frequency fluctuations by the kink. These results suggest that there exist the nonlinear couplings between kink and AITG/KBM/BAE ($f = 40 - 90kHz$), and between kink and high-frequency turbulence ($f = 90 - 240kHz$). They also indicate that Alfvenic fluctuations have an important contribution to the high-frequency turbulence spectra ($f = 40 - 240kHz$) and the couplings reveal the electromagnetic character.

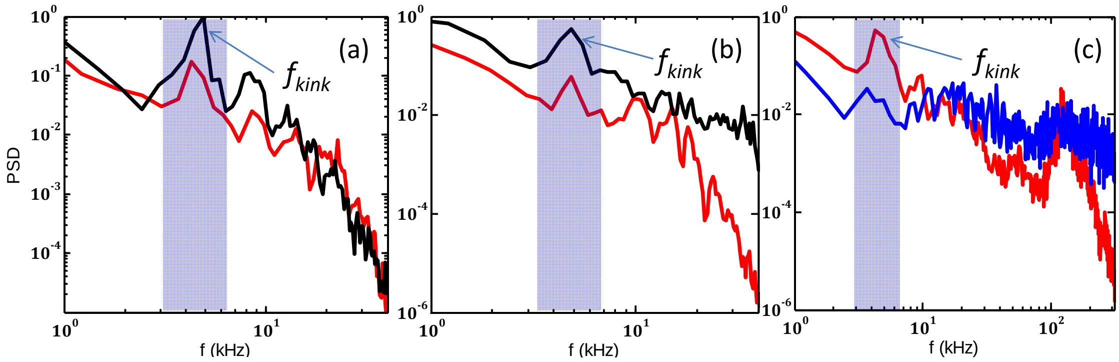

Figure 4: Power spectrum densities (PSDs) of the envelopes of microwave interferometer (M1)(red), core ECEI ($R = 175.13cm$, $Z = 3.45cm$)(blue) and Mirnov (black) signals at $t = 642 - 664ms$ for shot I. Filter range: (a) $40 - 90kHz$, (b) $90 - 240kHz$ and (c) 40-240kHz.

In summary, multi-scale interactions have been observed on HL-2A, including the synchronous coupling between m/n=1/1 kink mode and m/n=2/1 tearing mode, nonlinear couplings of TAE/BAE and m/n=2/1 TM near q=2 surface, AITG/KBM/BAE and m/n=1/1 kink mode near q=1 surface, and between m/n=1/1 kink mode and high-frequency turbulence. Experimental results suggest that several couplings can exist simultaneously, such as kink and tearing mode, kink and AITG/KBM/BAE, kink and high-frequency turbulence. The couplings present the nonlinear modulation processes. Alfvénic fluctuations (e.g., AITG/KBM/BAE) have an important contribution to the high-frequency turbulence spectra.

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