Kinetic Electromagnetic Instabilities in an ITB Plasma with Weak Magnetic Shear

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The shear Alfvén-acoustic continuum structure will be modified by diamagnetic drift effects while density and temperature gradients are large, so that there is a transition from the BAE (beta-induced Alfvén eigenmode) branch to the pure pressure-gradient driven and small-scale kinetic ballooning branch. Furthermore, finite ∇T_i-effects give rise to another potentially unstable branch, namely, the AITG mode which, in absence of EPs, can become unstable while the ion compression effects couple to SAWs and $\Omega_{*ip} \sim \sqrt{7/4+\tau q}$ is fulfilled, where $\Omega_{*ip} = \omega_{*ip}/\omega_{ti}$ is the ratio of ion-diamagnetic-drift and thermal-ion-transit frequencies and $\tau = T_e/T_i$ is the ratio of electron and ion temperatures. It can be understood as a branch connecting KBM (diamagnetic effects be dominant, $\Omega_{*ip} \gg \sqrt{7/4+\tau q}$) and BAE (ion compression effects be dominant, $\Omega_{*ip} \ll \sqrt{7/4+\tau q}$)[1, 2, 3]. Simulation results from GYRO code present that the AITG/KBM modes are unstable at very low beta, and the closer to the core with $s \sim 0$ the more unstable they become[4]. Recently, the results from LIGKA code suggest that the effect of increasing T_i is found to depend on the proximity to a rational surface. Near rational surfaces, a strongly destabilizing effect is observed due to the increased ITG drive. The destabilized instabilities are classified as the local limits of KBM/AITGs in the low-frequency domain ($\omega \sim \omega_{*ip}$), and KBAE/AITG modes in the high-frequency domain ($\omega_{BAE} < \omega < \omega_{TAE}$)[5]. The quantitative analysis had been done using local theories (GFLDR and KBM equation) in the later sections. Further a more complete stability analysis will require a kinetic global simulation, however it is very difficult at present.

These instabilities (i.e., following HFCMs) can be observed by core soft X-ray and microwave interferences in the NBI plasmas, occasionally measured by Mirnov coils, and this phenomenon is perfectly reproducible. Figure 1 shows a typical experimental result. After the NBI is switched on, with core-T_i increasing, many high-frequency coherent modes (HFCMs) are visible around $f = 80-200$ kHz in the spectrogram of core microwave interferometer signal with chordal distance r_d= 5 cm at $t = 610-800$ ms, however they are almost invisi-

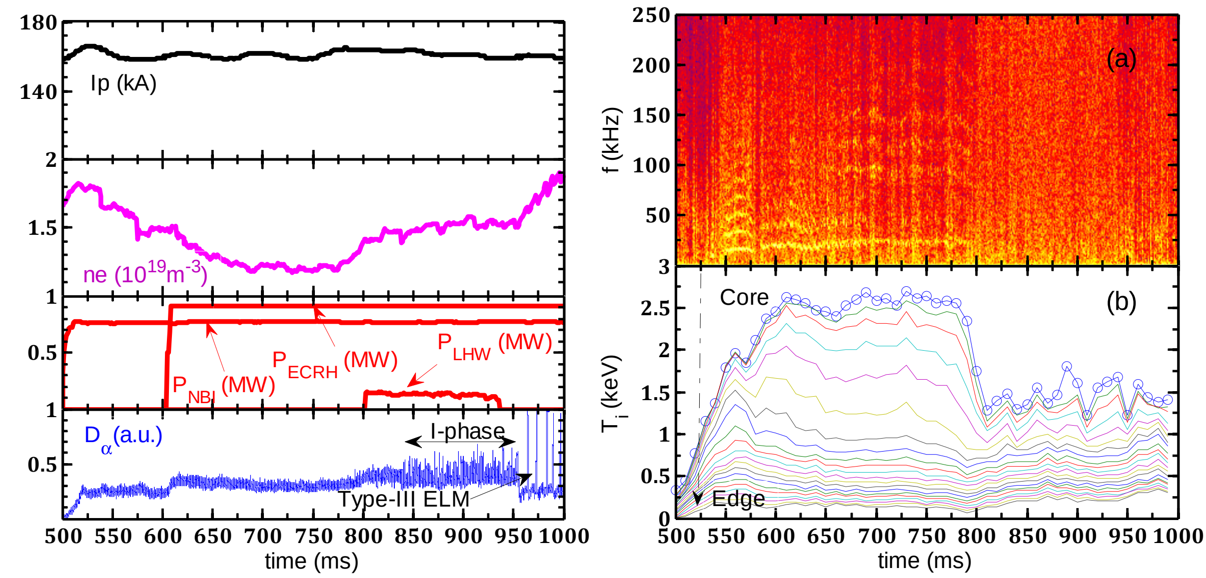

Figure 1: A typical discharge with high-frequency (f=80-200 kHz) coherent modes (HFCMs). Left col.: plasma current (Ip), line-averaged electron density (ne), heating powers (P_{NBI}, P_{ECRH} and P_{LHW}), D-alpha (D_α) in the divertor; Right col.: spectrogram of core microwave interferometer signal with chordal distance $r_d = 5$ cm (a), and time traces of ion temperatures (T_i) (b). The circle marker denotes the acquisition time point of the CXRS.

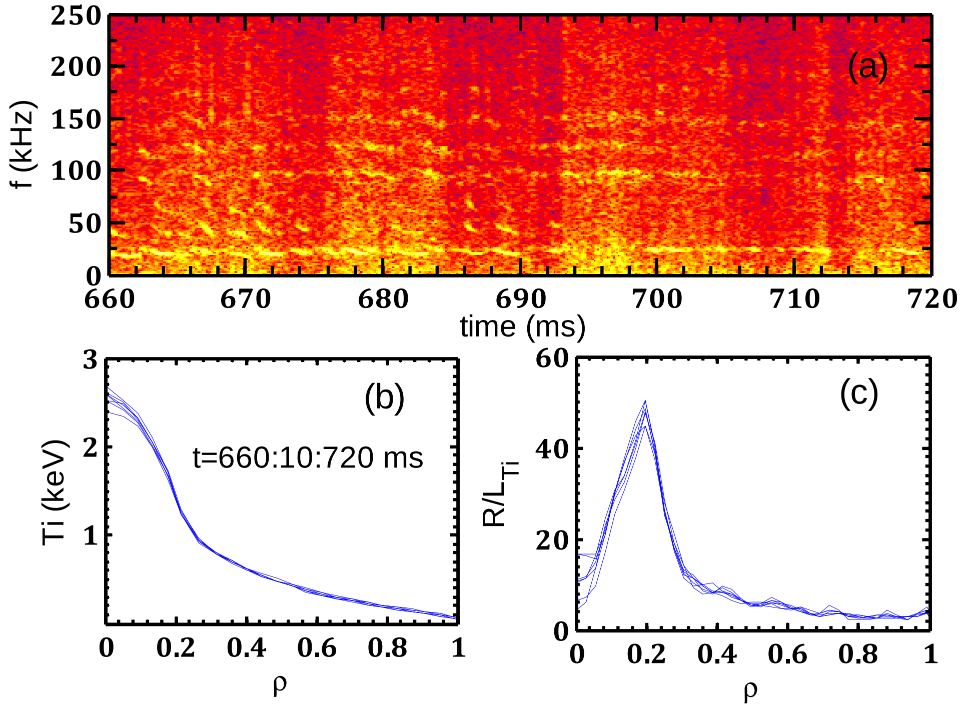

Figure 2: Spectrogram corresponding to Fig.1(a) at different times (t=660-720 ms, interval time: 10 ms) (a), T_i proflies (b) and R/L_{Ti} profiles (c) during the observation of HFCMs.

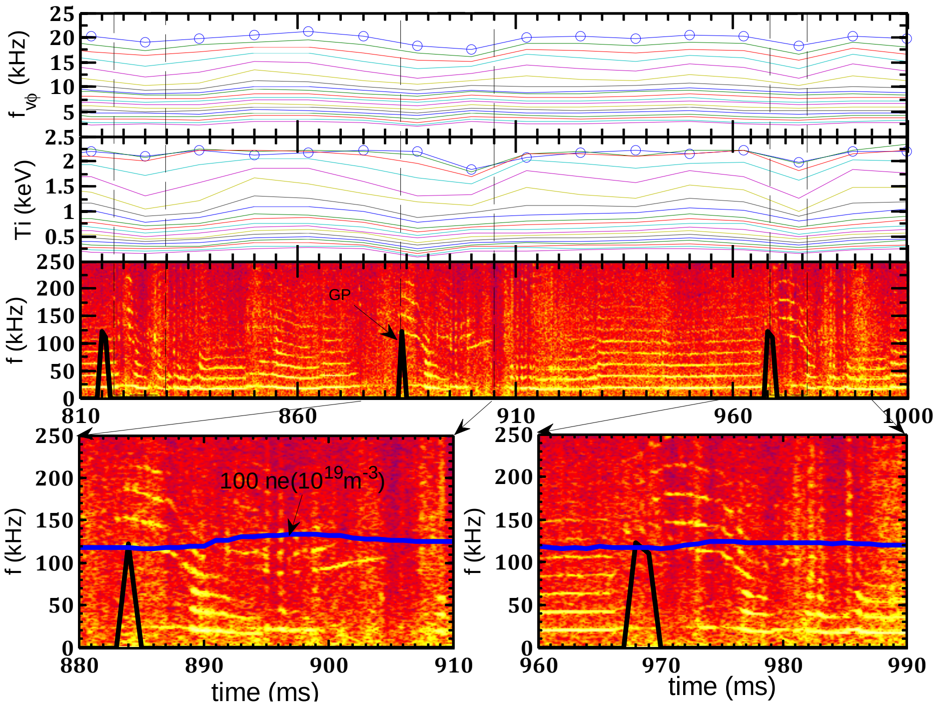

Figure 3: Effect of gas-puffing (GP) on the stability of HFCMs. Time traces of toroidal rotation frequency ($f_{v\phi}$) and ion temperature (T_i), and spectrogram of core microwave interferometer signal.

ble in spectrograms with $r_d \geq 11$ cm, it indicates that the HFCMs localize in the plasma core. While the LHW is injected at $t = 800$ ms, the plasma enters into I-phase and Type-III ELMy H-mode and HFCMs disappear with the core-T_i decreasing and n_e-increasing. Figure 2 shows that there exist strong and steady internal transport barriers (ITBs) at T_i-profiles during the observation of HFCMs, and the normalized length scales of T_i-gradients are very large, i.e., $R/L_{Ti} > 40$. Therefore, it implies that the stability of HFCMs is relevant to the ITBs and the strong T_i-gradients have important effects on the HFCMs, potentially. Figures shows that there are also fishbone/long-live modes(LLMs)[6] with the fundamental frequency $f \sim 25$ kHz except HFCMs in the plasma core.

Figure 3 gives an experimental result associated with the effect of gas-puffing (GP) on the stability of HFCMs. It is found that the core T_i and toroidal rotation frequency $f_{v\phi}$ drop slightly after the GP is injected, and the density increases weakly, meanwhile the HFCMs are driven and multi-harmonics LLMs with $n \geq 2$ are suppressed obviously, but the LLM with n=1 still exists. This phenomenon suggests further that the pressure and safety-factor profiles maybe affect the stability of HFCMs.

The strong HFCMs can be detected by magnetic probes and reveal electromagnetic charac-

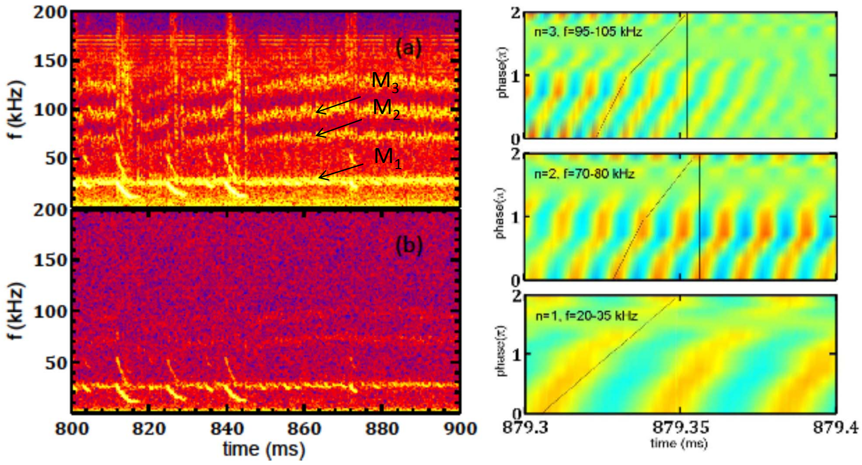

Figure 4: Spectrograms of Mirnov (a) and core soft x-ray (b) signals (left col.) and toroidal mode-numbers (right col.) for three different frequency coherent modes.

ters, so that the toroidal mode-number (n) can be determined and are shown in Figure 4. At $t \sim 879$ ms, they are $n = 1$, $n = 2$ and $n = 3$, respectively, for LLM (M1) with $f_{1c} = 27$ kHz and two HFCMs (M2 and M3) with $f_{2c} = 75$ and $f_{3c} = 102$ kHz, and these mode propagate in the direction of ion diamagnetic drift. Obviously, the match condition of mode-mode couplings satisfies, i.e., $n_3 = n_1 + n_2$ and $f_{3c} = f_{1c} + f_{2c}$. Based on this condition, we can deduce toroidal mode numbers of the observed HFCMs, i.e., n=2-8. Further, the Lissajous curves suggest the phases of M2-M1 ($f_{2c} : f_{1c} \simeq 5 : 2$) and M3-M2 ($f_{3c} : f_{2c} \simeq 4 : 3$) are both locked at $\theta \sim 0.75\pi$.

We report an experimental observation of AITG instabilities in HL-2A ITB plasmas with weak magnetic shears. A group of HFCMs with $f = 80 - 200kHz$ and $n = 2 - 8$ is consistently measured by multiple diagnostics, and are identified with AITG activities. All of experimental and analyzed contents can be found in a recent paper[7].

References

[1] L. Chen and F. Zonca, Rev. Mod. Phys. **88**, 015008 (2016).

[2] F. Zonca, L. Chen and R. A. Santoro, Plasma Phys. Control. Fusion **38**, 2011 (1996).

[3] F. Zonca and L. Chen Phys. Plasmas **21**, 072121 (2014).

[4] S. Moradi *et al.*, Nucl. Fusion **54**, 123016 (2014).

[5] A. Bierwage and P. Lauber, Nucl. Fusion **57**, 116063, (2017).

[6] R. B. Zhang *et al.*, Plasma Phys. Control. Fusion **56**, 095007 (2014).

[7] W. Chen *et al.*, Nucl. Fusion **58**, 056004 (2018).