Observation of Resonant Tearing Mode Induced by Energetic-ion Redistribution Due to Sawtooth Collapse in HL-2A NBI Plasmas

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The tearing modes (TMs) or neoclassical tearing mode (NTMs) are one kind of most dangerous low-frequency magnetohydrodynamic (MHD) instabilities in magnetically confined plasmas [1]. Experimental and theoretical research show that energetic particles (EPs), not only can drive the Alfvén eigenmodes and energetic particle modes [2, 3], but also affect the behaviours of TM/ NTMs, and even resonant with them[4]. The resonance between EPs and TM/NTMs have been found and studied on TFTR[5], ASDEX-U[6], EAST[7], DIII-D[8], KASTAR[9], and HL-2A [10, 11] indicate strong wave-particle resonance between EPs and TMs/NTMs. Direct wave-particle interactions resulting in amplitude-bursting and frequency-chirping fishbone-like m/n=2/1 (m and n are the poloidal and toroidal mode numbers) resonant TMs (r-TMs) have been found in the minimal safety factor q_{min}~1.5 NBI plasmas on HL-2A [10, 11]. The frequencies of r-TMs decrease from 10 to 2 kHz within ~1 ms. R-TMs are excited by co-passing energetic ions (EIs) generated by co-injection NBI directly, and propagate in ion diamagnetic drift direction in poloidal. The nonlinear hybrid kinetic-MHD simulation results from the M3D-K code reveal that r-TMs can be excited by the resonance between TMs and co-passing EIs, and the wave-particle resonance condition is satisfied by $\omega-\omega_\phi+2\omega_\theta=0$, where, ω_ϕ and ω_θ are the toroidal and poloidal transit angular frequencies for passing EIs, and ω is the mode frequency

Recent observations on HL-2A tokamak give new experimental evidences of r-TMs caused by the redistribution of EIs due to sawtooth collapses in high-density NBI plasmas [12, 13]. There is a typical example of r-TMs which are driven by the redistribution of EIs, as shown in Fig.1. The 0.5 MW NBI with beam energy E_b~42 keV switched on at t=900 ms, and the line averaged electron density (n_e) is about 3.3×10^{19} m^{-3}. The I_p and B_t are 165±5 kA and 1.17 T, as shown in Fig.1 (a). Obvious magnetic fluctuations are found from the poloidal Mirnov signal during the injection of NBI in Fig.1 (b). The spectrogram of the Mirnov signal is shown in Fig.1 (c). The usual resistive TM can be found in the whole processes, and the frequencies of TMs is in the range of 5-6 kHz. Strong fishbone modes, with frequencies chirping down from 10 to 7 kHz, are driven by Eis, and are broken by the sawtooth collapses, suddenly. At last, the fishbone-like chirping modes (r-TMs), with frequencies chirping down from 5 to 2.5 kHz within δt~2.5 ms, follow the sawteeth immediately. The phenomenon of frequency chirping-down is the obvious feature that there is a resonance between the mode and EPs. The mode numbers of TM and r-TM can be confirmed by the phase shift from filtered Mirnov signal arrays. It is found that the TM propagates in electron diamagnetic drift direction poloidally, and its mode numbers are m/n=2/1. The mode numbers of r-TM are m/n=2/1. The r-TM also propagates in electron diamagnetic drift direction. It is indicated that the r-TMs are excited by the counter-direction EIs. There is an obvisous decrease of n_e, ion temperature (T_i) and toroidal rotation (f_t) in the core of plasma (safety factor $q\leqslant1$ area) during the strong fishbones and sawteeth. While n_e, T_i and f_t near the q=2 rational surface almost do not be influenced by these MHD modes. Therefore, it can be proved that the frequency chirping-down behaviors of r-TMs are not related with f_t near q=2 rational surface.

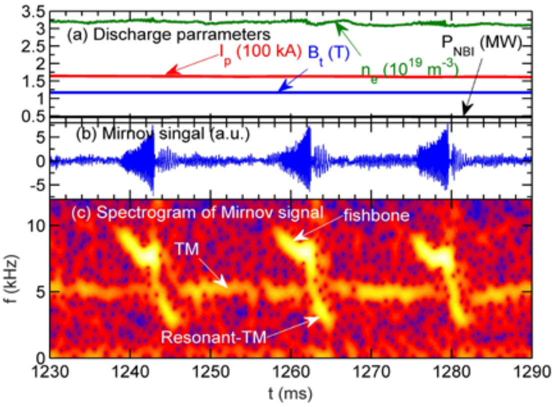

Figure 1: *R-TMs excited by counter-direction EIs in HL-2A NBI plasmas.*

The fluctuations caused by the fishbones combined with sawtooth collapses, TMs and r-TMs, which are labeled by the red, pink and blue curves, can also be found from SXR arrays in different positions, as shown in Fig.2. The strong fluctuations caused by the fishbones can be observed in the core signals of SXR with d=5.3 and 10.0 cm as shown in panels (a) and (b). The fluctuations caused by the usual TMs and r-TMs can be found by the in panels (e) and (f) with d=21.8 and 24.9 cm, and the

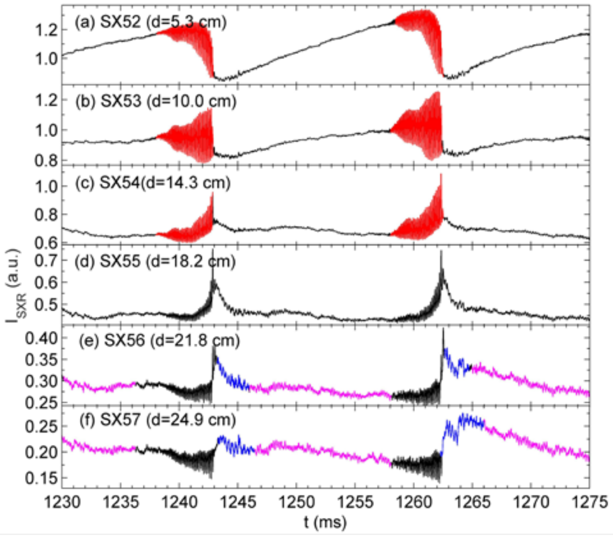

Figure 2: *Fluctuations caused by low-frequency MHD instabilities from SXR arrays. Panels (a)-(f) represent the SXR signals with chord distances d=5.3, 10.0, 14.3, 18.2, 21.8, 24.9, 27.6 and 30.0 cm, respectively.*

reversed sawteeth can be found before the r-TMs in panel (e). The radial transport coeffcient (D_i) and radial velocity (V_i) of the EIs can b estimated by the distance ($\Delta r\approx$25-10=15 cm) and time ($\Delta t\approx$0.5 ms) from the collapses of sawtooth to apperance of r-TMs, i.e., $D_i=\Delta r^2/\Delta t\approx 45$ m^2/s and $V_i=\Delta r/\Delta t\approx 3\times 10^2$ m/s. The estimated D_i and V_i are much higher than classical level.

The wave-particle interactions between counter-direction (trapped or passing) EIs and TM waves are simulated by M3D-K code. The simulation results show that pure resistive m/n=2/1 TMs can be destabilized by pressure gradient when the beta of background plasmas (β_{MHD}) is 0.08% but without EPs, and the resistivity of plasmas is benefit for the destabilization of TMs. The r-TMs will be destabilized obviously when adding the central energetic-ion beta (β_h) equaling to 0.56% EIs. The regular m=2 r-TM mode structures presented by the the perturbed current (δC) in the cross sections are shown in Fig.3 (b). The mode propagates in the electron diamagnetic drift directions. Compared with the mode structures without EIs (Fig.3 (a)), the mode structures become irregular, broadened, twisy and shifted radially outward due to the contribution of Eis (Fig.3 (b)). The frequency chirping-down phenomena of r-TMs can be obtained by the M3D-K code. The normalized frequencies of r-TMs ($\omega=\omega_M/\omega_A$) decrease rapidly form about -8.4×10^{-3} to -7.8×10^{-3} during $t=(290\text{-}570)\tau_A$ when β_h=0.56% and β_{MHD}=0.08%, as shown in Fig.3 (c). The negative sign (-) means the mode propagate in electron diamagnetic drift direction. Based on the discharge parameters, the Alfvén frequency in the core of plasma is $\omega_A/(2\pi)$=1160 kHz, the corresponding mode frequencies (f_m) shift from -9.8 to -9.0 kHz, and the frequency shift down time $\delta t=280\tau_A$=0.24 ms. The toroidal rotation frequency near q=2 rational surface is f_t~5 kHz, which is close to the frequency of resistive TMs observed in experiment. The observed frequency in laboratory (f_{Lab}) and the mode frequency should satisfy the relationship $f_{Lab}=f_m+nf_t$. The initial frequency of r-TMs in experiment (f_{Exp}~5 kHz) is close to the calculated results (f_{Lab}=4.8 kHz).

Figure 3 : *The 2-D mode structure of the perturbed current (δC) simulation of M3D-K, (a) Pure resistive TMs without EPs. (b) r-TMs with EPs and (c) Mode frequency chirping down phenomenon of r-TM.*