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Experiment and simulation results of interactions between energetic ions and tearing modes on HL-2A tokamak

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The tearing modes (TMs) or neoclassical tearing modes (NTMs), driven by the free energy of magnetic flux or plasma pressure, is one of most dangerous low-frequency magnetohydrodynamic (MHD) instabilities in magnetically confined plasmas, which can enhance the local transport, degrade the confinement, and even cause the disruption in high-beta plasmas [1]. In order to prevent the disruption caused by NTM in International Thermal Experimental Reactor (ITER), the high-power electron cyclotron resonant heating system is in plan to suppress NTM, especially for the m/n=2/1 NTM, where, m and n are the poloidal and toroidal mode numbers. Experimental and theoretical research show that energetic particles (EPs), generated by the auxiliary heating and fusion reactions, not only can drive the Alfvén eigenmodes and energetic particle modes [2-4], but also affect the behaviors of TM/NTMs, and even resonant with them [5]. The frequency chirping or changed TMs/NTMs are found and studied on TFTR [6], ASDEX-U [7] EAST [8], DIII-D [9], KASTAR [10] and so on, which are indicated the resonance between EPs and TMs/NTMs. Further, the obvious evidence of resonance between EPs and TMs are found in HL-2A NBI plasmas. Abundant resonant TMs (R-TMs) excited by the co- and counter-passing energetic ions (EIs) have been found in experiment [11,12] and simulated [13, 14] in HL-2A with different confinement conditions.

The direct wave-particle interactions resulting in amplitude-bursting and frequency-chirping fishbone-like m/n=2/1 TM (called R-TM_1) have been found in the low-density HL-2A NBI plasmas [11]. The R-TM1s are excited by the EIs generated by co-injection NBI, and propagate in ion diamagnetic direction, poloidally. There is no fishbone modes are found, and the minimal q (qmin) is obviously higher than unity, i.e., $q_{min}>>1$. The nonlinear hybrid kinetic-MHD simulation results by M3D-K reveal that the R-TM1 is excited by the resonance between TM and co-passing EIs generated by NBI, and the wave-particle resonance condition is satisfied at $\omega_\Phi+2\omega_\theta-\omega=0$, where ω_Φ and ω_θ are the toroidal and poloidal transit angular frequencies for passing EIs, and ω is the mode frequency.

Recently, a new kind resonant TM (called R-TM_2) closely following the fishbone modes and sawtooth collapse is found in the high-density NBI plasmas [12]. The R-TM_2 propagates in electron diamagnetic drift direction, which is opposite to the direction of EIs generated by co-injection NBI. It's indicated that the fishbone and closely followed sawtooth collapse cause the strong redistribution of EIs. The radial velocity of EIs from the positions of core or q=1 to the q=2 surface are estimated as convective transport. The simulation results from hybrid M3D-K code prove that the counter-passing EIs play an important role on the excitation of the R-TM_2. The R-TM_2 is mainly excited by the resonance between counter-passing EIs and TMs, and the main resonant-line is $\omega_\Phi-2\omega_\theta-\omega=0$.

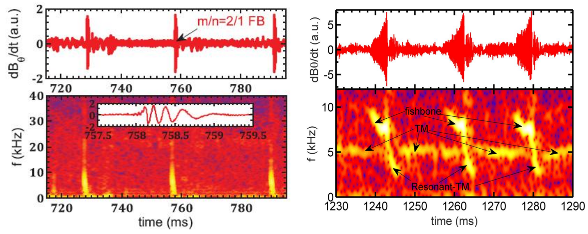

Fig.1 Typical resonant TMs excited by the co- (left) and counter-passing (right) EIs observed on HL-2A Tokamak

Although the R-TM_1, which excited by the resonance between the TMs and co-passing EIs generated by the injection of NBI, have been found in the low-density HL-2A plasmas, there are lots of news and difference for R-TM_2. (1) The R-TM_2 is found in the high-density plasmas, the n_e/n_G~0.78-1.0, where, n_G is the Greenwald density. (2) The R-TM_1 is excited by the co-passing EIs, while the R-TM_2 is excited by the counter-passing EIs. (3) The origination of EIs which induced the two R-TMs are different. The co-passing EIs which drive the R-TM_1 are generated by the injection of NBI directly, while the R-TM_2 is caused by redistribution of EIs due to the sawtooth collapse, which implies the synergies between different instabilities might be important for the EI transport.

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