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Effects of fishbone-like mode on energetic particle transport and loss in tokamak plasmas

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Fishbone-like modes (FLM) are often observed in the wall-stabilized high-β_N (above the no-wall β_N limit) plasmas in JT-60U [1,2] and DIII-D [3,4]. The mode frequency essentially matches the precessional drift frequency of trapped EPs [5,6]. FLMs, which are associated with the XK, can be viewed as an analog to the classical fishbone (FB) associated with the internal kink. During a FLM burst, significant EP losses were observed with the simultaneous decrease of neutron rate and reduction of the plasma rotation [3,4,7,8]. Much fewer studies have been carried out on the influence of the external kink or fishbone-like mode instabilities on EP confinement. More specifically, the effects of the fishbone-like mode on the EP transport and loss were mainly investigated in experiments [2,4], where it was found that the EP transport and losses depend on the mode perturbation and frequency.

The FLM has been observed in the HL-2A high-β_N experiments recently [9]. Therefore, systematic investigations have been produced on the redistribution and loss of energetic particles (EPs) due to three-dimensional (3D) FLM instability, utilizing the MHD stability code MARS-F and the guiding center orbit following code ORBIT. The FLM is identified as an EP driven branch of external kink (XK) [3,6]. The eigenmode structure of XK is employed to mimic the FLM perturbation by scanning the mode frequency. We found that the mode frequency has more significant effects on EP transport than amplitude. A 20 kHz FLM induces dramatic EP transport in both the configuration and particle phase spaces and the loss fraction reaches 46% in the case as shown in Fig 1. EP loss is the dominate process in EP transport in the study

In the EP phase space, EP transport occurs mainly near 10keV energy range and with the particle velocity pitch Λ near 0.6. Both Λ and energy are modified by the resonance interactions between FLM and EPs. The simulated results are qualitatively consistent with that observed in DIII-D experiments [4]. In particular, experimental observations indicate a linear to quadratic transition for the dependence of the EP loss fraction with increasing mode amplitude. The modelled enhancement of the EP loss fraction with increasing perturbation frequency is also in qualitative agreement with that observed in DIII-D.

We also find the particle collisions enhance the EP transport in phase space as shown in Fig 2. As a result, the pitch angle Λ of EP decreases, converting the particle orbit from the passing to the trapped one. The resonance conditions are identified which predict domains in the particle phase space where significant changes to the EP distribution occur. These domains in turn coincide well with that shown in the modelled EP transport results.

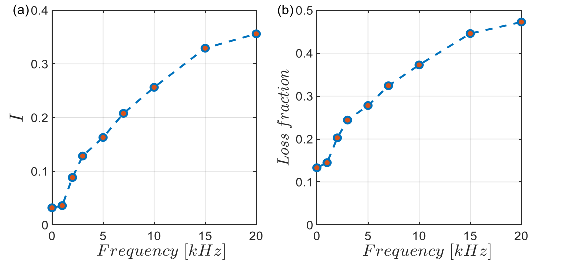

Fig 1. The redistribution factor I (a) and loss fraction (b) versus the FLM frequency.

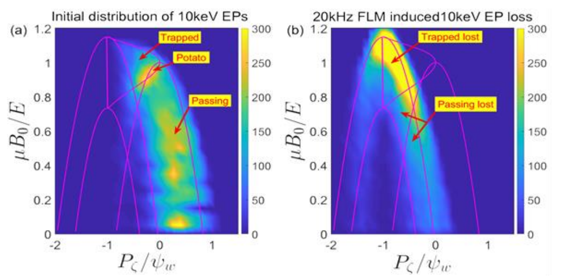

Fig 2. (a) The initial distribution of lost EPs and (b) the distribution of lost EPs in $P_\zeta - \mu$ phase space.

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