Topic: TH-W

Saturation of fishbone modes by self-generated zonal flows in tokamak plasmas

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Zonal flows (ZFs) have been known for decades to dominate the saturation of instabilities arising at the microscopic and mesoscopic scales such as drift-waves and Alfvén eigenmodes, reducing significantly the associated energetic particle (EP) transport. There are expectations that ZFs can play a similar role for macroscopic MHD modes such as the fishbone instability. In past studies [1][2], ZFs were found to have a secondary impact on the fishbone saturation, which were dominated by wave-particle trapping. However ZFs were under-estimated in these kinetic-MHD simulations without kinetic thermal ions, which can affect the mode saturation. In this work, we report the first self-consistent gyrokinetic simulations finding fishbone saturation by zonal flows induced by the fishbone instability itself, in a DIII-D discharge selected for ITER scenario validation. The MHD capability of the GTC code [3] used in this study was recently demonstrated with a V&V exercise on a DIII-D discharge [4]. The fishbone saturation mechanism is identified in phase space, where zonal flows prevent holes and clumps from persisting or drifting with mode down-chirping. This saturation is supported for the first time by DIII-D measurements, the mode saturation amplitude and the neutron emissivity agreeing quantitatively with experimental levels. The zonal flows shearing rate is large enough to damp unstable drift-wave modes, consistent with the ITB observed experimentally. GTC simulations of the fishbone mode in the associated ITER scenario find that ZFs plays a similar role there, with an EP redistribution affecting 2% of population. The development of scenarios in which fishbones naturally occur is then proposed to obtain high fusion performance in ITER.

Mechanism for fishbone saturation by zonal flows -- Zonal flows are found to be force-driven by the fishbone and are the main mechanism for the fishbone mode saturation in GTC simulations. The sheared electric field generated by zonal flows modifies the wave-particle resonance condition of linearly resonant EPs in the late linear phase. It forces the hole and clump structures in phase space to be static or to disappear, while they should respectively drift and persist in the nonlinear phase due to the down chirping of the mode frequency, as observed in GTC simulations without zonal flows. These effects reduce the amount of new EPs that can become resonant in the late linear phase, which leads to the mode saturation. The time evolution of the resonant phase space structures with and without zonal flows is shown in Fig. 1.

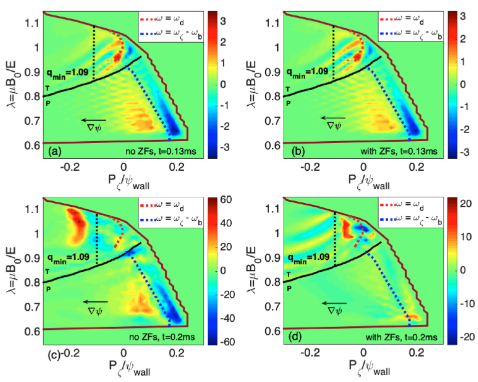
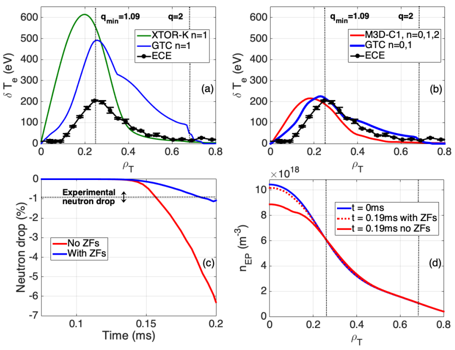


Fig. 1. *Instantaneous EP distribution $\partial_t \delta f$ in the linear (top) and nonlinear (bottom) phases, without (left) and with (right) zonal flows, in the invariants (P_ζ, λ) phase space diagram at fixed μ (μB_0=45 keV).*

Experimental validation of the saturation -- The saturation of fishbone modes by zonal flows is supported by experimental measurements from the DIII-D discharge #178631 [5], chosen for validation purposes of an ITER baseline prefusion scenario. The simulated δT_e profiles obtained from GTC and the kinetic-MHD codes M3D-C1 [6] and XTOR-K [7] after saturation are compared with the electron cyclotron emission (ECE) diagnostic, as observed in Fig. 2. (a-b). Without zonal flows, simulations results agree quantitatively with each other but their amplitude is significantly larger than the experimental value.



With zonal flows however, a quantitative agreement is obtained between GTC, M3D-C1 profiles and the ECE measurements, validating the codes for fishbone saturation and confirming the observed mechanism. This validation is further demonstrated by comparing the neutron drop between the experiment and GTC simulations. A quantitative agreement is obtained with zonal flows, the volume-averaged neutron drop being of order 1%, which leads to a weak EP redistribution as shown in Fig. 2. (c-d).

Fig. 2. *Radial envelope of δT_e after saturation without (a) and with (b) zonal flows. (c) Time evolution of the simulated neutron drop in GTC. (d) EP density profiles in GTC simulations before and after saturation.*

Fishbone-induced ITB formation – Besides saturating the fishbone mode, zonal flows also generate a strong shearing rate $\gamma_{E\times B} \sim 3.10^5$s^{-1} in the core plasma. High-n electrostatic GTC simulations find that the most unstable drift-wave for the configuration is a TEM with a linear growth rate of $\gamma_{TEM} = 1.4.10^5$ s^{-1}, localized close to the plasma core. As shown in Fig. 3. (a-b), the fishbone-induced shearing rate could lead to turbulence modulation by suppressing the TEM growth. This conclusion is consistent with DIII-D measurements from charge exchange recombination spectroscopy (CXRS). As illustrated on Fig. 3. (c), an ITB is observed after fishbone bursts occurring between t=1580-1610 ms, while the plasma heating was constant for several slowing times. A similar behavior is also observed in related DIII-D discharges.

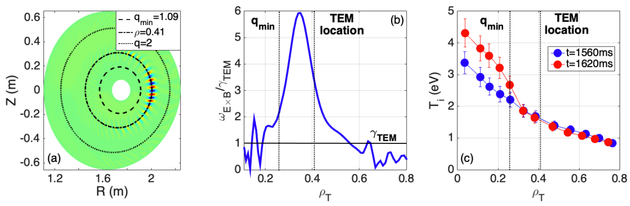


Fig. 3. *(a) Poloidal contour of the electrostatic potential ϕ for the TEM. (b) Fishbone-induced shearing rate profile after saturation (c) Experimental T_i profiles before and after fishbone bursts from CXRS*

EP transport in ITER prefusion baseline -- GTC simulations of an ITER prefusion baseline scenario find that zonal flows play a similar role for the fishbone mode in ITER. ZFs here are also able to lower the fishbone saturation and to generate an $E \times B$ shearing rate larger than the linear growth of the unstable drift-waves, potentially regulating the turbulent transport. The fishbone-induced EP transport in this ITER scenario is marginal, 2% of the initial NBI distribution being transported, which should not affect operationally this configuration. Such transport levels are consistent with previous studies on the alpha fishbone in ITER baseline D-T scenarios [2]. Since fishbone modes tend to weakly redistribute EPs and can regulate turbulent transport, their intentional destabilization in ITER is therefore a possible way to enhance fusion performance.

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