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On the structure of wave-particle interactions and nonlinear Alfvénic fluctuation dynamics

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Shear-Alfvén modes can be driven unstable by energetic particles (EPs) produced by additional heating or nuclear fusion reactions. Alfvénic fluctuations can, in turn, be derimental to EP confinement and lead large EP losses. Understanding the properties of EP confinement largely depends on the insights into Alfvén mode dynamics, with regard to both the linear stability properties; and the nonlinear dynamics, which have recently attracted significant interest both on theoretical and numerical analysis sides. In our work, nonlinear dynamics in intermediate regime between weakly driven AEs close to marginal stability and strongly driven Energetic Particle Modes (EPMs) is investigated by means of the nonlinear hybrid magnetohydrodynamics gyrokinetic code (XHMGC) and compared to the hybrid LIGKA/HAGIS model. Saturation mechanism due to resonance detuning and/or radial decoupling are discussed. It will be shown that saturation field level exhibits a quadratic scaling with the growth rate, in the former case; a linear scaling, in the latter case. The dominance of one or the other mechanism dependends on the linear properties of the mode. These fundamental results/scaling are crucial for any reduced/simplified EP transport model which is needed for fast and flexible predictive tools to be developed in the future. For EPMs, we analyse EPM saturation and the corresponding frequency chirping observed both in experiments and simulations (e.g. chirping electron-fishbone by XHMGC simulation). Phase locking has been proposed, within "fishbone"paradigm, to describe such chirping: the resonance condition with linearly resonant particles is maintained, while particles are radially displaced, through a continuous modification of the mode frequency. We show that an additional scenario is possible: mode radial localization and frequency appear to be locked to the shear Alfvén continuum; once the linear resonance population has exhausted its driving capability (because of local flattening of the phase-space distribution function), the mode is shifted to non-exhausted regions of the phase space. The effect is a succession of resonant excitations from different phase-space regions (each characterized by its own nonlinear evolution time), rather than mode adjustment to the evolution of the linearly-resonant particles.

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