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Frequency chirping with expanding phase-space structures and multiple resonances of energetic particles

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The non-linear phase of the feedback-like interaction between energetic particles (EPs) and weakly damped plasma modes may lead to the excitation of sideband oscillations which can finally evolve into chirping modes. From the perspective of EPs phase-space dynamics, this process involves the formation as well as the evolution of coherent structures, the so-called holes/clumps that evolve adiabatically [1]. In toroidal geometries, the motion of the holes/clumps occurs in the generalized phase-space of EPs, see Fig. 1, resulting in a change in the toroidal momenta. This leads to a change of the EPs flux surface and hence a convective transport of the EPs in the radial direction towards the first wall or the inner plasma core. Therefore, it is essential to understand and control the EP dynamics as a key factor in design and the sustainability of a fusion power plant.

A nonperturbative adiabatic model was developed in Ref. [2] to study the long range frequency chirping in a system where the shape of the plasma wave is updated as the frequency chirps. For deeply passing EPs, treating an expanding separatrix during the frequency chirping was described in Ref. [3] in a numerical scheme where the energy of the EPs is used to characterize them inside the trapping region. In Ref. [4], the long range frequency chirping of the Global Alfven Eigenmodes was studied for deeply passing EPs. The impact of the EPs guiding center orbits on frequency chirping of a plasma wave was studied in Ref. [5]. However, the applicability of this model is restricted to cases where the trapping region inside the perturbed mode i.e. a BGK type mode, does not capture new ambient particles.

In this work, we have developed a model to enable the evolution of an expanding separatrix in Ref. [5]. This allows us to study the simultaneous impact of particle trapping together with the equilibrium orbits on the hard non-linear behavior of the plasma wave. The EPs, trapped in the nonlinear mode, are labelled using their adiabatic invariants (rather than energy) assuming that the mode frequency is evolving adiabatically. In this new model, the effect of particle trapping on the non-linear behavior of the BGK mode during frequency chirping has been investigated in cases where the EPs are magnetically trapped or passing. This includes the evolution of the wave shape and the frequency chirping rate. In addition, we study the effect of EPs destabilizing the mode in higher resonance numbers. Our findings indicate that there are cases where the 2^{nd} resonance can have a considerable contribution to the linear growth rate as well as the nonlinear evolution of the mode.

References

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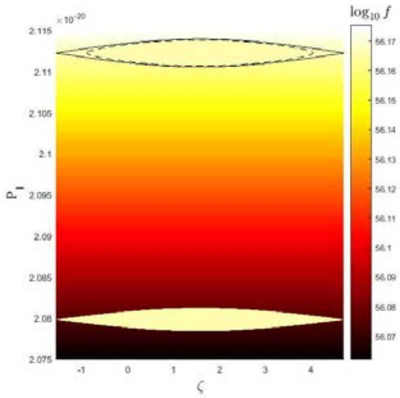

Figure 1 The motion of a clump in the generalized phase-space [4]. The initial separatrix (top) shrinks as it moves downwards during frequency chirping.