Energetic particle nonlinear equilibria and transport processes in burning plasmas

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Energetic particle (EP) transport in burning plasmas is a spatiotemporal multi-scale process due to the crucially important role played by EPs as mediators of cross scale couplings [1]. This makes predictive analyses based on first principle computations very challenging and calls for reduced descriptions, which preserve the necessary physics ingredients.

This is the main motivation of the present contribution, where we propose a theoretical framework describing EP transport in the phase space based on the theory of Phase Space Zonal Structures (PSZS) [2–5].

PSZS are long-lived formations in the particle phase space; that is, PSZS are undamped by (fast) collisionless dissipation mechanisms due to wave-particle interactions. They play important roles in transport processes, since they describe the deviation from local thermodynamic equilibrium and affect the nonlinear dynamic evolution of the system [2-5]. Together with zonal structures, i.e. toroidally symmetric structures in, e.g., the scalar potential, unaffected by collisionless damping, they define the zonal state; that is an evolving nonlinear equilibrium consistent with toroidal symmetry breaking fluctuations and with transport time scale ordering [3]. This definition is particularly important in collisionless burning plasmas, where one cannot always describe transport via evolution of radial profiles of a reference Maxwellian.

In this work, we derive the governing equations for the zonal state. This is an application of gyrokinetic transport theory, where the novelty stands in the explicit identification of the part of the toroidally symmetric δf, the PSZS, that has to be incorporated into the generally non-Maxwellian reference particle distribution function for taking into account plasma evolution due to transport processes and its counterpart; i.e. the long-lived component of toroidally symmetric fields. It is shown that this approach is consistent with the usual evolution of macroscopic plasma profiles under the action of fluctuation induced fluxes, when the deviation of the reference state from local Maxwellian response is small. Furthermore, classical and neoclassical transport are recovered in the proper limits. The usefulness of this formulation becomes clear for long time scale transport calculations, in particular those related with gyrokinetic or hybrid simulation of EP transport, where the non-Maxwellian features and the role of wave-particle resonances is most important.

References:

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