Energetic particle nonlinear equilibria and transport processes in burning plasmas

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The purpose of ITER and of magnetic confinement fusion is to investigate burning plasmas approaching ignition. In ideal conditions, α particles thermalize and sustain the fusion process although collective electromagnetic fluctuations might lead to increased energetic particle (EP) losses. Therefore, being able to accurately describe EPs transport is of main importance. Fluctuations resonantly excited by EPs and ensuing transport have different spatiotemporal scales compared with thermal plasma. More generally, EPs play a critical role as mediators of plasma cross scale couplings [1]. Consequently, a self consistent, first-principle-based theoretical description is mandatory, such as a global gyrokinetic approach. Self-consistent analysis of meso-scales and the weak collisional nature of EPs suggest a full$-f$ formulation, which is computationally demanding, especially on the transport time scales [2]. This is very challenging and, at the same time, calls for reduced descriptions.

A general theoretical framework to describe EPs transport, dubbed the Dyson-Schrödinger model (DSM), has been recently proposed by the authors [2-4] and will be discussed in this work. The necessity of developing a gyrokinetic theory for energetic particle phase space transport will be underlined first [2]. The main differences with multi-scale gyrokinetics [5] will be analyzed, with a special emphasis on the assumption of scale separations between equilibrium and fluctuations, which cannot be assumed for EPs. Then, we will elucidate how defining this theoretical framework leads to a renormalization of the usual plasma equilibrium in the presence of a finite level of electromagnetic fluctuations, dubbed the zonal state. The governing Dyson-like transport equations will be derived, consisting of a novel full f / δf mixed approach. In particular, the nonlinear slowly evolving equilibrium distribution will be described by a full f scheme in a reduced $3D$ phase-space, i.e. the unperturbed constants of motion space, while a δf approach will describe symmetry breaking fluctuations. The significance of this new formulation will be highlighted in particular for long time scale (transport) calculations where the non-Maxwellian features and the role of wave-particle resonances are particularly relevant. The relation with other commonly adopted EPs reduced descriptions, e.g., resonance line broadened quasi-liner model and kick model, and with the usual formalism based on the wave kinetic equation will be discussed. To show the generality of the present approach, which ranges from Tokamak [2-4] and Stellarator [7] studies to the recent analysis of chorus emission [6], we will apply it to explore the effects of sources and collisions on Energetic particle mode (EPM) burst dynamics [6]. Similarities and differences with the energetic-particle driven Geodesic Acoustic Modes (EGAM) will also be illustrated.

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