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Nonlinear equilibria and transport processes in burning plasmas

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Predicting the dynamics of a burning plasma over long time scales, i.e. comparable with the energy confinement time or even longer, is essential in order to understand modern fusion experiments. Extending first-principle-based gyrokinetic simulations to these time scales is a formidable task from a computational resource point of view. This makes predictive analyses very challenging and calls for reduced descriptions which preserve the necessary physics ingredients. Most of the works addressing this problem for the study of core plasma transport are based on a systematic separation of scales between the reference equilibrium and fluctuations. Meanwhile, energetic particle (EP) transport in fusion devices is a spatiotemporal multi-scale process 1 which can invalidate this assumption leading the system toward the formation of long-lived phase space structures that account for the deviation of the EP distribution function from the local balance between sources and collisions. Furthermore, spatio-temporal mesoscales can be observed in drift wave plasma turbulence simulations. In a recent work [2] we have emphasized the fundamental importance of the self-consistency of the adopted description, including the determination of the characteristic spatiotemporal scales of the reference state. This is mandatory to understand present-day magnetic confinement experiments. In the present contribution we propose a theoretical framework to describe transport in the phase space based of the theory of Phase Space Zonal Structures (PSZS). In particular we extend the usual definition of plasma equilibrium in the presence of a residual level of electromagnetic fluctuations [3] introducing the concept of zonal state and deriving its governing equations. 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. Together with zonal structures, i.e. toroidally symmetric structures in, e.g., the scalar potential, they define the zonal state [2]. This definition is particularly important in collisionless burning plasmas, where (as, e.g., for EPs) one cannot readily describe transport via evolution of radial profiles of a reference Maxwellian. In this work, we derive the governing equations for the zonal state using gyrokinetic transport theory. The gyrocenter distribution functions evolve according to the gyrokinetic equation in the presence of sources and
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$$\frac{\partial}{\partial t}\left(D_a F_a\right) + \frac{\partial}{\partial \mathbf{Z}} \cdot \left(D_a F_a \dot{Z}_a\right) = D_a\left(\sum_b C^g_{ab}\left[F_a, F_b\right](\mathbf{Z}, t) + \mathcal{S}_a(\mathbf{Z}, t)\right).$$

We assume an axisymmetric reference magnetic field that can be described adopting toroidal flux coordinates (θ, ϕ, ψ). In the absence of fluctuations, collisions and sources, the particle motion is integrable and characterized by three invariants, i.e. the particle energy (per unit of mass) $\mathcal{E}$, the magnetic moment μ and the toroidal angular momentum P_ϕ. For this reason, we will use $(\theta, \phi, P_\phi, \mu, \mathcal{E})$ as phase space coordinates. Particle velocity can be decomposed as the sum of two contributions, i.e. $\dot{Z}_a = \dot{Z}_{a0} + \delta\dot{Z}_a$, representing, respectively, integrable motion in the reference state and the effect of fluctuations. The operator annihilating the advection in the phase space due to the integrable motion is given by: $\overline{(\ldots)} = \tau_b^{-1}\oint d\theta(\ldots)/\dot{\theta}$, with $\tau_b = \oint d\theta/\dot{\theta}$. The governing equation for PSZS dynamics is obtained by applying this operator to the toroidally symmetric component of the kinetic equation and extracting its low frequency component with respect to the hydrodynamic time scale which is indicated by the S subscript:

$$\frac{\partial}{\partial t}\overline{F_{z0}} + \frac{1}{\tau_b}\left[\frac{\partial}{\partial P_\phi}\overline{\left(\tau_b \delta\dot{P}_\phi \delta F\right)}_z + \frac{\partial}{\partial \mathcal{E}}\overline{\left(\tau_b \delta\dot{\mathcal{E}} \delta F\right)}_z\right]_S = \overline{\left(\sum_b C^g_b\left[F, F_b\right] + \mathcal{S}\right)}_{z\,S}$$

This expression describe transport processes in the phase space due to fluctuations and collisions/sources. Transport equations can be obtained taking its moments in the velocity space. As an example, in Ref. [2] we have calculated the governing equation for the radial density profiles. It can be 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. In particular, classical and neoclassical transport regimes are recovered in the proper limits. In the general case intermediate spatio-temporal scales can be developed by the zonal state. As an application, we calculate PSZS dynamics for an EPM (collisionless) simulation by the HMGC code. In particular, in the left panel of the following figure, we show a "slice"with fixed μ of $\overline{F_{z0}}$ during a phase space avalanche produced by an EPM at a given instant. In the right panel also $\mathcal{E}$ is fixed, consistently with the fact that, for the quasi-coherent spectrum typical of Alfvénic fluctuations, transport on a short time-scale is mainly a $1D$ (radial) process. In this case, PSZS have been depicted before and after the avalanche respectively in black and in blue.

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The usefulness of this formulation becomes clear for long time scale calculations, in particular those related with gyrokinetic or hybrid simulations of EP transport, where the non-Maxwellian features and the role of wave-particle resonances are most important[@biancalani2019gyrokinetic]. We will discuss how nonlinear equilibrium evolution on transport time scale can be calculated by coupling a transport code solving the previous equation in a reduced $3D$ phase space to a $5D$ gyrokinetic code directly evaluating the expressions for nonlinear fluxes.

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