THEORY AND SIMULATION OF PHASE SPACE TRANSPORT IN BURNING PLASMAS

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Reactor relevant burning plasmas are complex self-organized systems, where energetic particles (EP) play a crucial role in processes underlying cross-scale couplings [1,2,3]. In this study, we first review the concept of phase space zonal structures (PSZS) [1,2,3] and their significance in transport analyses [4,5], particularly in burning plasmas. As paradigm case, we illustrate the PSZS evolution due to energetic particle modes (EPM) by means of synthetic diagnostics originally developed for the hybrid code HMGC [6]. We also employ the PSZS diagnostics in the non-linear global gyrokinetic particle-in-cell code ORB5 [7] to verify results obtained by the phase space transport code ATEP [8] and to illustrate phase space transport features of the thermal plasma component. This study provides insights into the unique role of PSZS, which is crucial for accurately capturing transport dynamics with or without energetic particles.

When addressing fusion plasmas, slowly evolving local equilibria are typically assumed to be Maxwellian and, therefore, transport studies involve the solution of 1D advection-diffusion equations where fluxes are calculated using various numerical workflows such as JINTRAC or TRANSP. However, when dealing with EPs and, more generally, with burning plasmas, it is necessary to generalize equilibrium and transport descriptions to accurately account for characteristic self-organization processes [1,2,3]. In Refs. [4,5], we established that the slowly evolving equilibrium distribution function is described by PSZS, whose governing equation can be derived using multi-scale perturbation theory. As demonstrated in numerous analytical calculations (see, e.g., Ref. [4]), this approach allows us to describe the self-consistent modifications of the equilibrium on intermediate (meso-) spatiotemporal scales and the deviations from the local Maxwellian due to resonant transport. By taking the moments of the PSZS, we can recover the usual transport equations [5,9] in the proper limit. This analysis is crucially important as it enables us to consistently describe the EPs equilibrium evolving over long time scales and the corresponding electromagnetic Zonal Fields level [4,5].

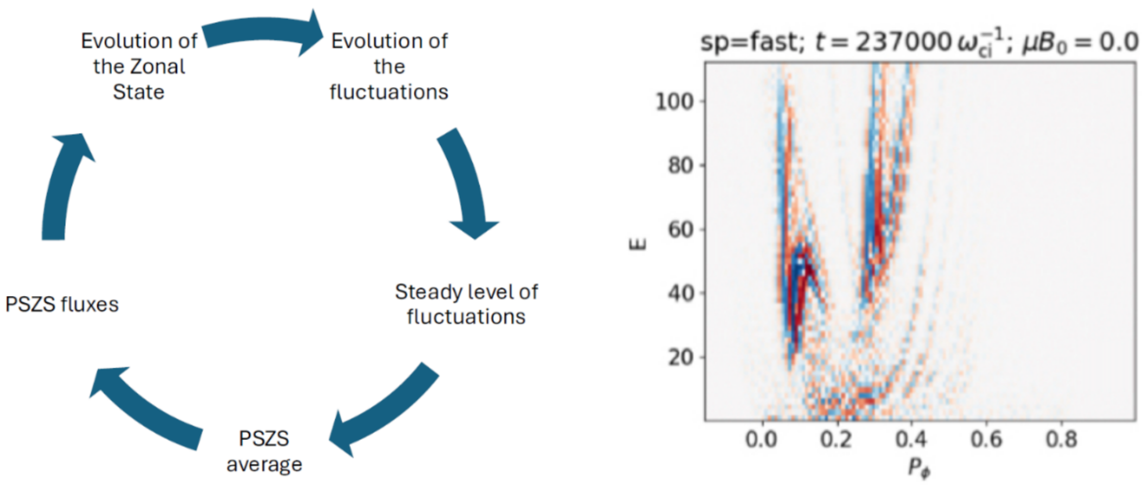

Figure 1: Left Panel: Schematic diagram of a Phase Space Zonal Structure (PSZS) transport workflow such as ATEP [8]. Right Panel: Example of PSZS as calculated by the ORB5 diagnostic.

A phase space transport workflow, analogous to the one described above, is therefore desirable. This is illustrated in the left panel of Figure 1. Conceptually similar to the advection-diffusion equation solved in traditional transport workflows, the fluxes in this case must be described in the action phase space where the PSZS are defined, i.e., the single particle constant of motion space. Restarting a global gyrokinetic code from PSZS and corresponding plasma equilibria as calculated from the phase space transport workflow, will allow for the extension of global gyrokinetic simulations over long time scales, similar to codes such as Trinity [9] or Gene Tango [10], but without postulating a model distribution function accounting for the proximity to local thermodynamic equilibrium.
We will demonstrate how a gyrokinetic code such as ORB5 [7] can be restarted from a PSZS initial distribution function and discuss the crucial role of PSZS and the Zonal Fields intensity for understanding the improvement of core confinement in the presence of a finite level of Alfvénic fluctuations. Additionally, we will illustrate ATEP [8] as a phase space transport code capable of solving the workflow described in the left panel of Figure 1, addressing in particular EP transport by Toroidal Alfvén Eigenmodes in the ITER 15MA case. The evolution of the PSZS will then be compared between two different layers of a hierarchy of transport models [11,12]: nonlinear gyrokinetics solved by ORB5 and quasilinear fluxes solved by ATEP.

ACKNOWLEDGEMENTS

This work has been supported in part by the Italian Ministry of Foreign Affairs under Grant No. CN23GR02 and the National Natural Science Foundation of China under Grant No. 12261131622. This work has also partly been carried out within the framework of the EUROfusion Consortium, funded by the European Union via the Euratom Research and Training Programme (Grant Agreement No. 101052200−EUROfusion). Views and opinions expressed are, however, those of the author(s) only and do not necessarily reflect those of the European Union or the European Commission. Neither the European Union nor the European Commission can be held responsible for them.

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