Advanced energetic particle transport models

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The purpose of ITER and of magnetic confinement fusion is to access reactor relevant burning plasma operations. In ideal conditions, fusion α particles thermalize and sustain the fusion process although collective electromagnetic fluctuations might lead to increased energetic particle (EP) losses. Therefore, understanding and being able to accurately describe EP transport is of main importance. High energies and resonant interactions of EPs cause the related transports to have different spatiotemporal scales and regimes compared to thermal plasma. More generally, EP transport is a multi-scale process where EP play a critical role as mediators of plasma cross scale couplings [1]. Consequently, a self-consistent, first principle-based theoretical description is mandatory, based on a global e.m. gyrokinetic approach. Being able to describe self-consistently produced 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 makes predictive analyses based on first principle-based computations particularly challenging and calls for reduced descriptions.

The Advanced energetic particle transport models (ATEP) EUROfusion Enabling Research project has focused on the construction, implementation, and validation of various reduced transport models for EPs. A general theoretical framework to describe EP transport has been recently established [2,3] and will be described here. The necessity of developing a gyrokinetic theory for EP phase space transport will be presented first [2]. The main differences with multi-scale gyrokinetics [4] will be discussed, with a special emphasis on the assumption of scale separations between fluctuations and equilibrium meso-scale corrugations that do not apply to EPs. Furthermore, it will be shown that 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 phase space transport equations will be derived, resulting in a novel full $f\ /\ \delta f$ mixed approach that will be solved within a hierarchy of models of different complexity and need for numerical resources. The integration of the transport models within the ITER Integrated Modelling & Analysis Suite (IMAS) will be described, based on the stability analysis given by local and global GK codes (DAEPS, LIGKA). It will be shown how the well-known LIGKA/HAGIS suite can been extended to calculate EPs phase space fluxes [5] and how the EP transport equation in phase space is solved for realistic EP populations such as e.g., NBI distributions at ITER. The results will be benchmarked with those from the recently developed DAEPS code [6]. Finally, a dedicated diagnostic to monitor the *zonal state* nonlinear dynamics will be introduced, its importance for verification and validation of EP transport models will be highlighted and its application to ORB5 [7] and HYMAGYK [8] codes will be reviewed.

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