ATEP: A phase space resolved transport model for energetic particles

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In addition to increasingly realistic non-linear global simulations [1], a hierarchy of theory-based reduced models is needed to complement the predictions concerning the performance of future burning plasmas. Large parameter scans, sensitivity studies and multi-scale physics connecting energetic particle transport with neoclassical (transport) time scales require tools that go beyond what is presently feasible with first-principles numerical codes.
In the view of this challenge we report in this work on the implementation and verification of a phase-space resolved energetic particle (EP) transport model [2, 3]. It is based on the Phase Space Zonal Structure transport theory [4, 5, 6, 7] , which extends the conventional transport equations into Phase Space and consistently evolves a (nonlinear) equilibrium referred to as the Zonal State. Its focus is primarily directed toward understanding the meso-scopic character of EPs and its consequences [8] . Compared to the conventional description of thermal radial transport via a one-dimensional radial diffusion equation, the newly developed model is three-dimensional using canonical constants-of-motion (CoM) variables. The model does not assume diffusive processes to be dominant a priori, instead the EP fluxes are self-consistently calculated and directly evolved in CoM space. A Fokker-Planck collision operator with orbit-averaged numerical coefficients evaluated on the same CoM coordinate grid allows us to treat EP sources and wave-induced transport consistently on background transport and EP slowing-down time scales. The code named ATEP-3D is fully embedded in ITER IMAS framework and closely connected to the EP-Stability workflow [9]. The workflow contains a hierarchy of analytical, local and global models that as been automated and tested for an extended set of different Alfvénic instabilities in various Tokamak geometries.
As a first application, the phase space fluxes are determined either in the limit of constant mode amplitudes (kick-limit), or an energy-conserving quasi-linear model. Single and multi-mode cases addressing the transition from isolated to overlapping resonances are discussed and compared with ORB5 [10, 11]. Non-linearly evolving beat-driven zonal fields are included using an analytical model [12] for radial mode structure and saturation. Various strategies and first steps how to couple the workflow to 1-d transport codes are reported.

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