Theoretical, Numerical, and Experimental Studies of Advanced Transport Models for Energetic Particles

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Energetic particle (EP) transport exhibits multiple spatio-temporal scales and nonlinear behaviors. Electromagnetic kinetic effects, EP anisotropy, symmetry breaking and nonlinear and intermittent behaviors are crucial ingredients [1,2,3,4]. The special role of EPs has been addressed in that they not only introduce new classes of resonantly driven instabilities but also interact with micro- and macro-scale plasma perturbations, causing spatio-temporal cross-scale couplings. Unlike thermal ion/electron transport treated in standard transport codes like TGLF [5], EP transport requires consideration of their large radial excursion (banana widths $\sim$ 0.1a) and non-local nature. As the particle moves along its equilibrium trajectory in a tokamak, its orbit can be described in the constants of motion (CoM) space generally used in gyrokinetic simulations of fusion plasma are particle energy E, toroidal canonical momentum P_ζ, and magnetic moment μ. The CoM variables are more than a convenient way to categorize the orbits and provide an appropriate way to describe EP dynamics [6]. Specifically, in full-f simulations, the adoption of the CoM space is necessary to initialize a steady-state distribution with the finite orbit width effects taken into account [7]. A parametric equilibrium distribution function in the CoM space is applicable to gyrokinetic studies investigating the behavior of guiding centers with finite orbit width in axisymmetric tokamak plasmas, as discussed in [8].

The symmetry of tokamak configurations preserves these constants in collisionless plasmas, although they can break down under certain conditions. Near the marginal state of the system, resonant particle dynamics can be treated perturbatively in canonical space [9]. EP transport in realistic 3D space can be reduced to a 1D bump-on-tail model [10]. Phase space zonal structures (PSZS) are effective for defining nonlinear EP equilibrium on spatiotemporal meso-scales [6]. This framework aids in particle transport modeling by evolving the PSZS transport equations, including EP-generated zonal fields, to determine new nonlinear equilibria. It can be shown that simpler approaches such as critical gradient models [11], the 'kick' model [12], and quasi-linear resonance broadening models [13] can be recovered in the appropriate limits.

In light of these challenges, our focus is on the construction, validation, and application of reduced EP transport models. The long-lived toroidally symmetric structures in the particle phase space, known as PSZS, are first implemented in the reduced EP transport code ATEP [14,15]. Our model encompasses comprehensive physics of the nonlinearly-involved turbulence-AE-EP system [6,16]. The EP-stability workflow (EP-WF) [17], based on the code chain HELENA-LIGKA-HAGIS [18,19,20], provides the orbit- and zonally-averaged response of particles to a prescribed set of Alfvénic perturbations, which is used as inputs for the PSZS transport equations [6,16]. The linear gyrokinetic mode information (radial structure, frequency, damping/growth rate) is given by the LIGKA code [19]; the well-established HAGIS code [20] is employed to calculate the collision coefficients and the PSZS for a set of pre-selected sample markers covering the whole CoM space, including co- and counter-passing particles, generated by a code wrapper called 'Orbit-Finder'.

The newly written ATEP code [14,15] is technically closely interlinked with the well-established IMAS (Integrated Modelling and Analysis Suite) framework and its data structures. This integration aids in the validation process and allows for the substitution of elements within the PSZS evolution equations with equivalent codes or models. It benefits from the recently established EP-WF used in this paper to calculate the linear mode spectrum [17]. The interfaces between the different codes employ IMAS data structures, meaning that all operations needed to set up the ingredients for the PSZS evolution equations are replaceable by equivalent codes or models.

Reference [15] details the construction of the ATEP numerical model, showing that without collisions, the problem reduces to a two-dimensional equation in (P_ζ, E), and also solves the two-dimensional PSZS transport equation. Meanwhile, the ATEP-3D solver [14] addresses transport due to collisions in the CoM space for the NBI source by using an implicit method to solve the three-dimensional transport equation. This approach simulates the slowing-down of EPs in the presence of a beam source and compares the results with SPOT. The NEMO/SPOT results are stored as a set of markers in the IDS distribution, containing the complete set of spatial and velocity coordinates, together with the canonical CoM coordinates and the marker weights. Any other code providing the same information can be readily used as comparison.

The ATEP-3D solver effectively handles collisions of EP with the core plasma, and the accuracy of the analysis has been rigorously verified. The method employed by ATEP-3D to address sources and collisions is both accurate and effective, allowing for the simultaneous consideration of fluctuation-induced transport, sources, and collisions [14]. Building on these foundations, I have rewritten the ATEP-3D solver for the three-dimensional transport equation in Fortran using the PETSc library's KSP iterative solver. The updated ATEP-3D solver now employs MPI parallelism and operates on high-performance computing (HPC) systems. While the previous MATLAB version handled small to medium-scale computations, the new parallel version of ATEP-3D can manage grid sizes greater than $100 \times 100 \times 100$ with more than 10^6 degrees of freedom. Both versions remain available, allowing for principle validation in MATLAB and the use of existing diagnostic analysis graphical tools.

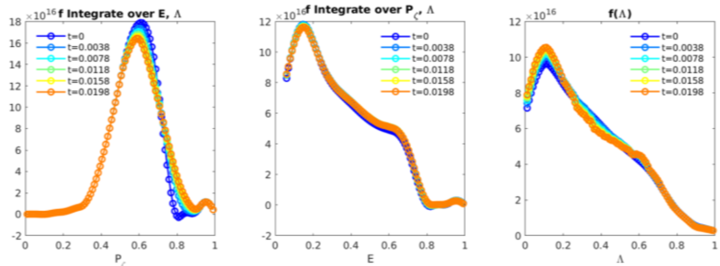

Figure 1. The AE induced PSZS transport equations solved by the 3D solver .

Recently, our model has incorporated additional physical factors. We extracted experimental density and temperature profiles from IDS data to recalculate the orbit-averaged collisional transport coefficients. Notably, the experimental pedestal region exhibits steep density and temperature profile gradients, posing numerical challenges that necessitate higher simulation resolution. Our initial focus is on simulating the core region, using appropriate boundary conditions for better handling. The treatment of phase-space boundaries will be systematically and meticulously addressed in future work. For studies on wave-induced transport, since the PSZS is always localized within the interior of the CoM, special considerations for boundary conditions are not required. The wave-induced PSZSs are rapidly changes in the CoM, also requires high resolution. The parallelized ATEP-3D greatly improves resolution and fully satisfies the necessary requirements. Furthermore, the methods for calculating the advective and diffusive flows resulting from resonance in phase space have been implemented. As shown in Fig. 1, the EP distribution are flattened due to the AE induced PSZS. We are incorporating the effects of various physical phenomena step by step, such as zonal field influences, and calibrating and benchmarking these against other first-principle gyro-kinetic codes.

In summary, the PSZS transport theory and the numerical tools in ATEP-3D offer a novel and promising approach to addressing the challenge of describing EP transport in fusion plasmas. The numerical solution of PSZS is obtained through a newly developed three-dimensional transport model in the CoM space, considering EP source and sink terms, as well as collisions. With their capacity to capture multi-scale physics, account for nonlinear interactions, and forecast transport transitions, these reduced models have significant potential to enhance our understanding of EP transport and provide a comprehensive reduced description of burning plasmas.

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