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

G. Meng[1], Ph. Lauber[1], Z. Lu[1], M. V. Falessi[2], F. Zonca[2]

[1] *Max-Planck-Institut für Plasmaphysik, Garching, Germany*

[2] *ENEA, Fusion and Nuclear Safety Department, C. R. Frascati, Italy*

Energetic particle (EP) transport exhibits multiple spatio-temporal scales and nonlinear behaviours. Electromagnetic kinetic effects, EP anisotropy, and nonlinear and intermittent behaviours are crucial ingredients [1,2,3,4]. EP transport is distinct from the well-understood thermal ion/electron transport as treated in transport codes such as TGLF.

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 Phase Space Zonal Structures (PSZS), are considered a key ingredient of the nonlinearly-involved turbulence-AE-EP system [5,6]. Our model encompasses comprehensive physics, covering critical gradient, kick model, and quasi-linear behaviour within appropriate limits. The EP-stability workflow (EP-WF) [7], based on the code chain HELENA-LIGKA-HAGIS [8,9,10], 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. The linear gyrokinetic mode information (radial structure, frequency, damping/growth rate) is given by the LIGKA code [9], the well-established HAGIS code [10] is employed to calculate the collision coefficients and the PSZS for a set of pre-selected sample markers which covering the whole constants of motion (CoM) space, including co- and counter-passing particles are generated by a code wrapper called 'FINDER'.

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 [11]. The newly written ATEP code [12,11] 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.

In summary, the PSZS transport theory and the numerical tools in ATEP offer a novel and promising approach to addressing the challenge of describing EP transport in fusion plasmas. With their capacity to capture multi-scale physics, account for non-linear interactions, and forecast transport transitions, these reduced models have significant potential to enhance our understanding of EP transport.

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