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In addition to increasingly realistic non-linear global simulations [1, 2, 3], 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 construction, validation and application of reduced energetic particle (EP) transport models pursued within the framework of the EUROFusion enabling research project ATEP (Advanced Transport models for EPs).
The general theoretical framework introduces the concept of long-lived toroidally symmetric structures in the particle phase space (phase space zonal structures, PSZS) that are separated from fast fluctuating contributions [4, 5, 6, 7]. Comprehensive transport equations have been derived that are designed to capture the evolution of PSZSs on collisional transport time scales while keeping the important non-linear interactions in a consistent multi-scale description. The model captures physics beyond simpler models (critical gradient, kick model, quasi-linear) that, however, can be recovered in the appropriate limits. A generalisation of the theory to stellarator geometry has been started [8]. The DAEPS code [9] and the EP-stability workflow (EP-WF) [10] based on the code chain HELENA-LIGKA-HAGIS [11, 12, 13] deliver the necessary input for the PSZS transport equations, i.e. the orbit-and zonally-averaged response for a selected set of markers to a prescribed set of Alfvénic perturbations. In addition, neoclassical transport coefficients [14] for the same set of markers, and general EP distribution functions as calculated by various heating workflows[15] are provided via standardised IMAS interfaces. The transport equation is then consistently evolved, or EP diffusion coefficients are evaluated for the use in standard transport codes. In addition, a 1d reduced model based on the beam-plasma bump-on-tail paradigm that is designed to go beyond the quasi-linear approximation and thus forecast possible EP transport transitions such as avalanching has been successfully compared to the LIGKA/HAGIS model. The formulation of the models allows one to carry out detailed analyses of transport scaling laws (diffusive/non-diffusive) for both Alfvénic gap and energetic particle modes using Lagrangian coherent structures (LCS) [16, 17]. The verification of the reduced models is carried out via comparison to numerical codes in the appropriate limits (HYMAGYC, (X)HMGC, STRUPHY, ORB5, HAGIS/LIGKA [18, 19, 20]). To that end, the implementation of PSZS diagnostics in the various codes [21, 22] provides a natural connection point for benchmarking with the reduced models. Several time-dependent scenarios from present-day and future experiments (in particular AUG [23], JT-60SA, TCV, DTT, JET,ITER) have been collected and are being analysed.
In summary, the PSZS transport theory and the LIGKA-HAGIS workflow ATEP provide a new and promis- ing approach to address the challenge of describing EP transport in fusion plasmas. With their ability 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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