Structure formation and transport in magnetized fusion plasmas

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Transport in magnetized fusion plasmas provides an interesting example of how collective behaviors in complex systems lead to structure formation and self-organization [1]. This occurs because transport is dominated by fluctuations that are excited at the system microscales, characterized by the typical width of charged particle orbits in the strong equilibrium magnetic field. These fluctuations can provide a nonlinear feedback on the plasma equilibrium profiles, i.e., on the system macroscales. Most importantly, however, fluctuation spectra and transport phenomena also yield to structure formation on the mesoscales, which are intermediate between the micro- and the macro-scales, and can be due to both linear wave packet propagation in the slowly evolving and weakly non-uniforma plasma medium as well as to nonlinear couplings. Meanwhile, high temperature, weakly collisional, reactor-relevant fusion plasmas can have velocity space distributions, which deviate from local thermodynamic equilibrium [2, 3, 4, 5]. Thus, transport and structure formation in magnetized fusion plasmas must be necessarily described in the phase space, and studying their nonlinear dynamics requires advanced kinetic treatments of thermal as well as supra-thermal components, including realistic geometries and plasma non-uniformities [1].

This work presents the main findings of a comprehensive approach that enables predicting and describing the long time scale behavior of reactor relevant magnetized fusion plasmas as nonlinear equilibria, which evolve self-consistently with fluctuation spectra as well as sources/collisions [2, 3, 4, 5]. Examples of applications to cases of practical interest are also given, focusing on simplified paradigmatic cases for illustrating the workflow of the Advanced Transport model for Energetic Particle (ATEP) code [6, 7]. In particular, the case of neutral beam injected particles in ITER will be shown, which are redistributed under the action of Coulomb collisions and a fixed amplitude toroidal Alfvén eigenmode [6, 7].

References

[1] L. Chen and F. Zonca, *Rev. Mod. Phys.* **88**, 015008 (2016)

[2] L. Chen and F. Zonca, *Nucl. Fusion* **47**, 886 (2007)

[3] F. Zonca, et al, *Plasma Phys. Control. Fusion* **57**, 014024 (2015)

[4] F. Zonca, et al, *New J. Phys.* **17**, 013052 (2015)

[5] M. V. Falessi, L. Chen, Z. Qiu and F. Zonca, *New J. Phys.* **25**, 123035 (2023)

[6] Ph. Lauber, et al, "ATEP: An advanced transport model for energetic particles", in *Proc. 29th IAEA FEC, London UK (2023)*, submitted to *Nucl. Fusion*

[7] G. Meng, et al, "Energetic particles transport in constants of motion space due to collisions in tokamak plasmas", *Ibid.*, submitted to *Nucl. Fusion*