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Energetic Particle Transport and Zonal State evolution in burning plasmas

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Abstract

- We present a framework for characterizing phase space transport, based on the theory of Phase Space Zonal Structures (PSZS) [1–5].
- We broaden the usual definition of plasma equilibrium in the presence of a finite level of electromagnetic fluctuations, i.e., the Zonal State (ZS).
- We introduce a subcycling approach that captures the dynamics of the ZS over transport time scales consistent with different levels of reduced dynamics.
- We compare PSZS evolution across nonlinear GK simulations, including HMGC [6], GTC [7], and XTOR-K [8], to benchmark nonlinear dynamics across different GK codes.
- We also compare GK results with the ATEP workflow [3] to verify the reduced transport approach adopted in ATEP.

Background

- Predicting the dynamics of a burning plasma over long time scales, comparable with the energy confinement time or even longer, is crucial for understanding next generation fusion experiments.
- The majority of studies on core plasma transport rely on a systematic separation of scales between the reference equilibrium and fluctuations.
- Energetic particle transport in fusion devices is a spatiotemporal multi-scale process.
- Spatio-temporal mesoscales can be observed even in drift wave plasma turbulence simulations [9].
- Recent work [5] emphasized the importance of a self-consistent determination of the characteristic spatiotemporal scales of the reference state.

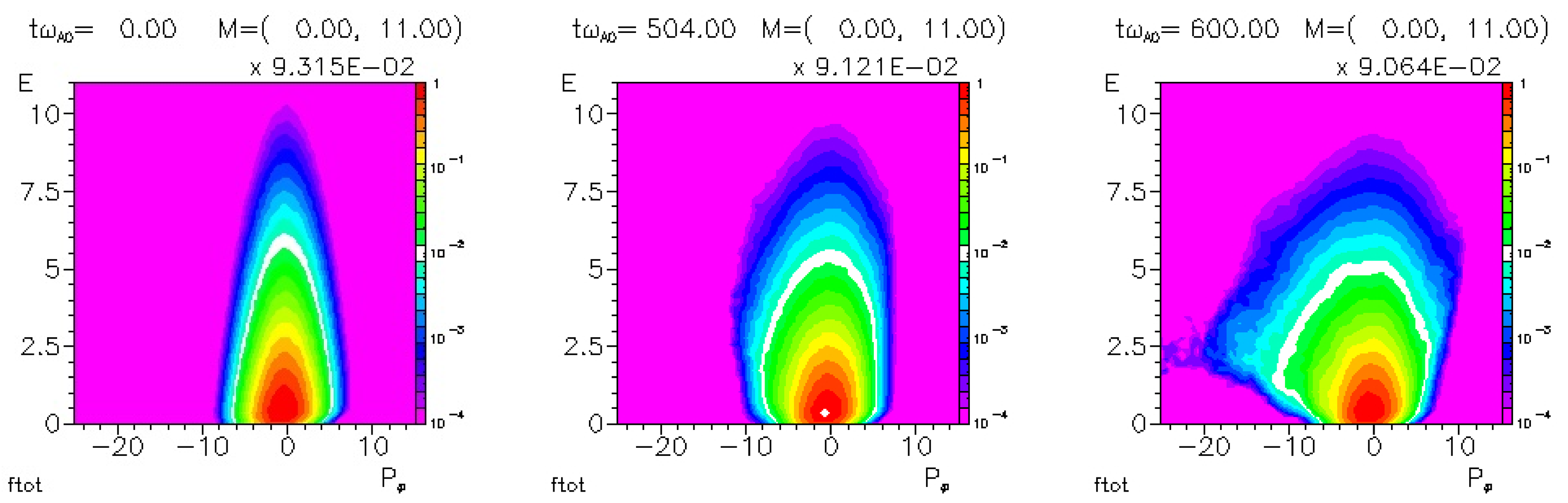
Phase Space Zonal Structures (PSZS)

- PSZS equation is connected with the macro-meso-scopic component of the unperturbed orbit-averaged distribution function.

$$\frac{\partial}{\partial t}\overline{F}_0^{(O)} + \frac{1}{\tau_b}\left[\frac{\partial}{\partial P_\phi}\overline{\left(\tau_b\delta\dot{P}_\phi\delta F\right)}_z^{(O)} + \frac{\partial}{\partial \mathcal{E}}\overline{\left(\tau_b\delta\dot{\mathcal{E}}\delta F\right)}_z^{(O)}\right]_S = \overline{C}_S^{(O)} + \overline{S}_S^{(O)}.$$

- By construction, PSZS evolves only through collisions, sources, and nonlinear phase-space fluxes.
- Fast collisionless oscillations are filtered out of $\overline{F}_0^{(O)}$, making it a natural renormalized equilibrium for burning-plasma transport.
- The toroidally symmetric distribution function can be decomposed so that micro-scales are accounted for separately, while macro- and meso-scales are described by PSZS.
- The evolution of the PSZS during an EPM, obtained with HMGC [6], is shown below.

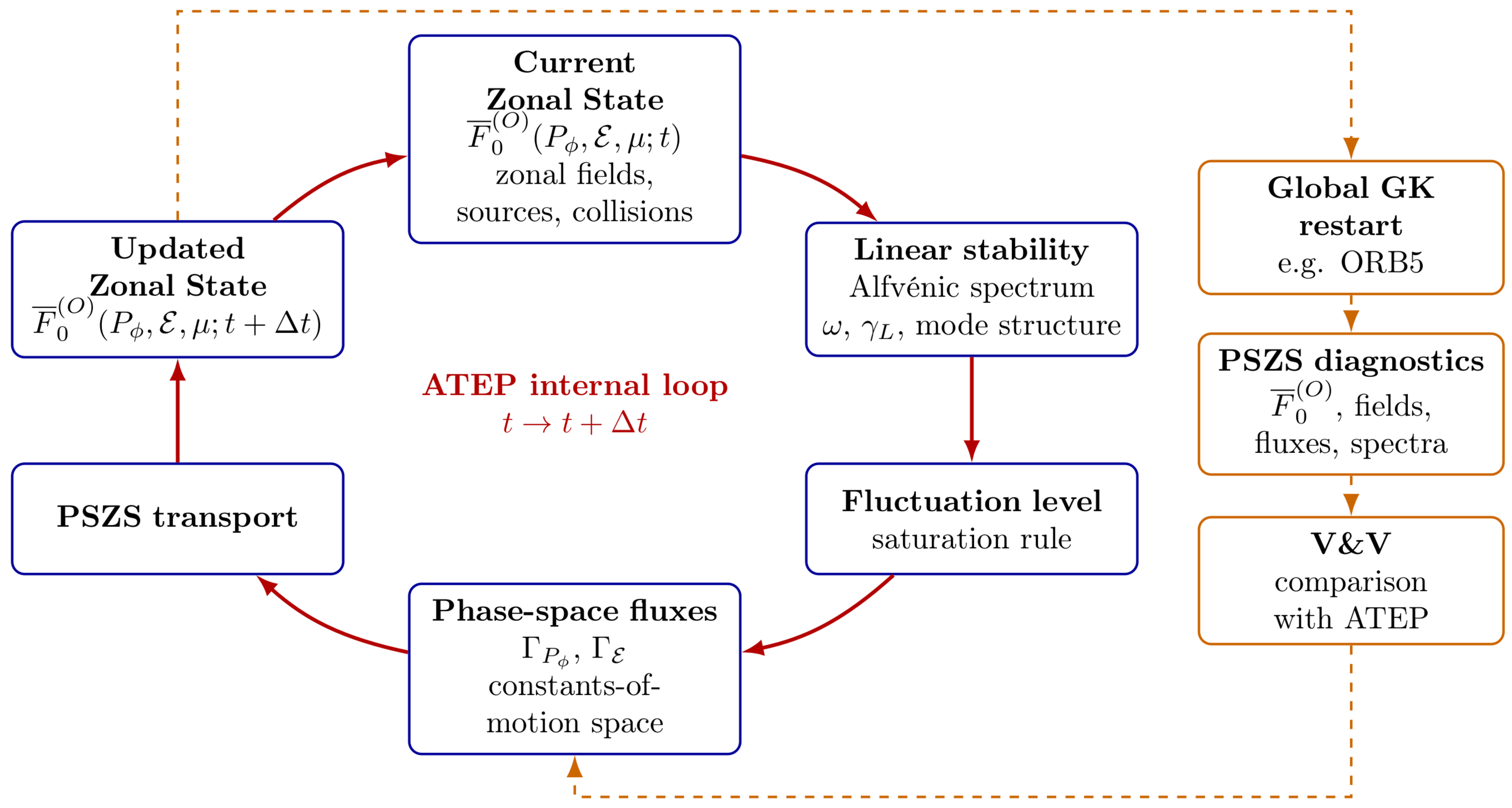
$$F_z = \overline{F_z}^{(O)} + \delta F_z = \overline{F_0}^{(O)} + \overline{\delta F_z}^{(O)} + \delta \overline{F}_z.$$



time increases from left to right

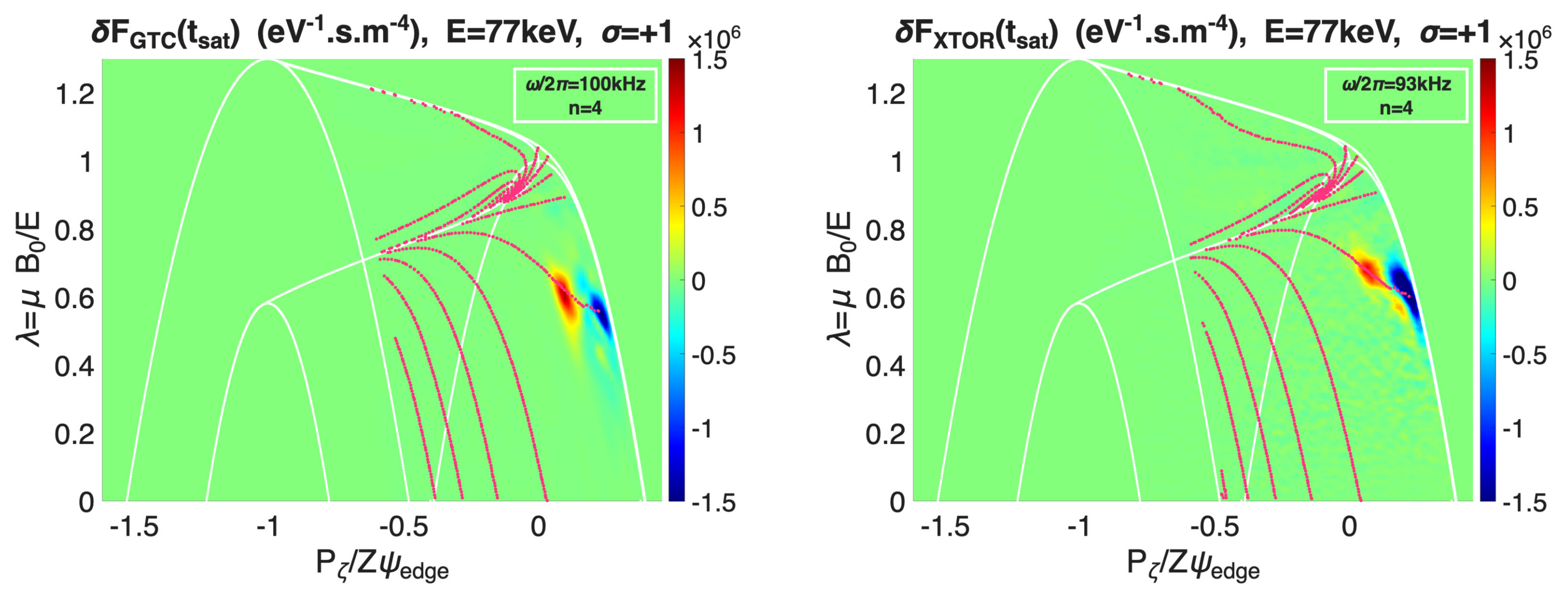
Hierarchical Transport

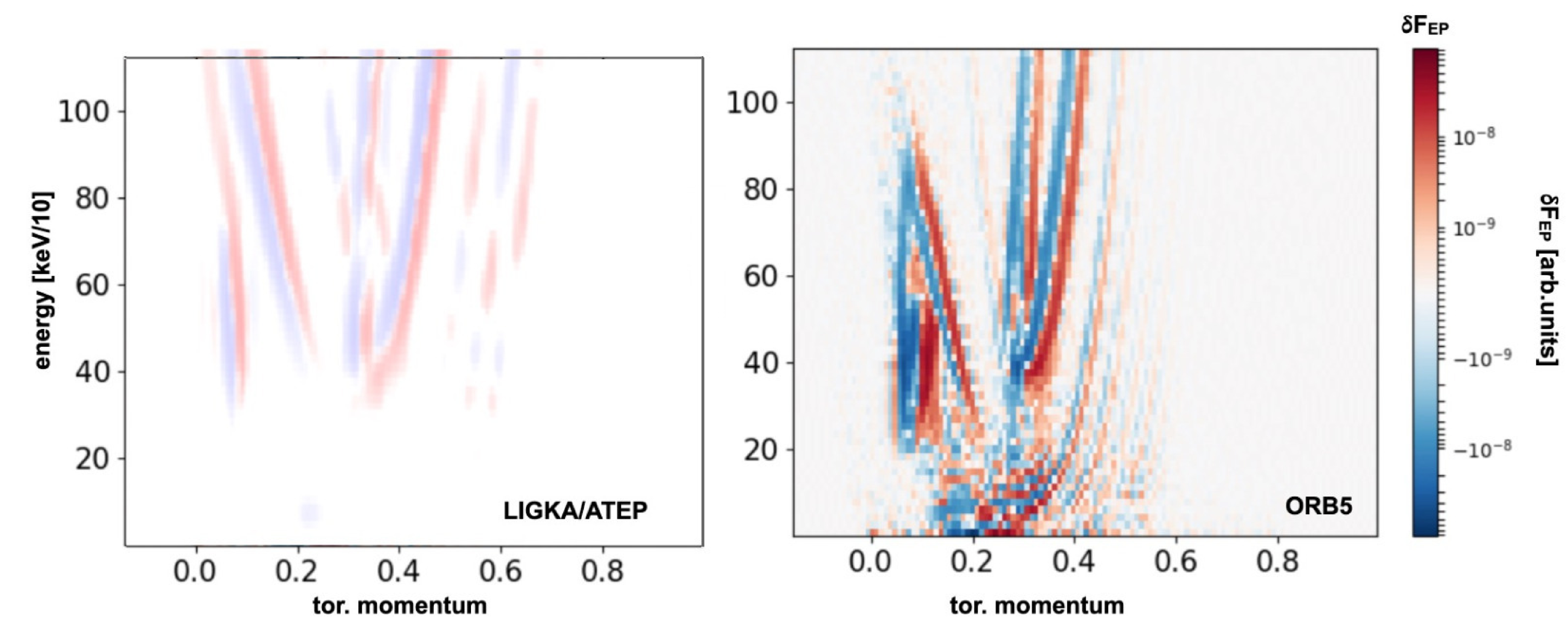
- Highest-fidelity level: fully nonlinear global GK evolves the complete Zonal State and provides the natural verification target.
- Intermediate level: reduced nonlinear envelope or Dyson-Schroedinger dynamics retains coherent mesoscopic and nonlocal effects when $|\gamma_L| \sim \tau_{\rm NL}^{-1} \ll |\omega|$ [5,10].
- Reduced-transport level: quasi-linear, mixing-length, or saturation-rule closures evolve the PSZS over transport time scales with sources and collisions.
- ATEP provides a common workflow in which the same Zonal-State evolution is advanced using different reduced models, while global GK simulations provide the verification target [11,12].



PSZS Benchmarks

- The reduced ATEP evolution can be compared directly with PSZS diagnostics extracted from global GK simulations, providing a systematic route for verification of reduced models [13].
- A successful benchmark is performed for BAE-induced PSZS in a DIII-D plasma [14] using GTC and XTOR-K, with realistic beam-distribution input from the EPCoM code [15].





Acknowledgements / References

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[1] L. Chen and F. Zonca, Reviews of Modern Physics 88.1 (2016). [2] M. V. Falessi and F. Zonca, Physics of Plasmas 26.2 (2019). [3] Ph. Lauber et al., Nuclear Fusion 64 (2024) 096010. [4] F. Zonca et al., New Journal of Physics 17.1 (2015). [5] M. V. Falessi, L. Chen, Z. Qiu and F. Zonca, New Journal of Physics 25, 123035. [6] S. Briguglio et al., Physics of Plasmas 2.10. [7] Z. Lin et al., Science 281, 1835 (1998). [8] G. Brochard et al., Nuclear Fusion (2020), doi:10.1088/1741-4326/ab9255. [9] S. Wang, Z. Wang, and T. Wu, Phys. Rev. Lett. 132, 065106. [10] F. Zonca, L. Chen, M. V. Falessi and Z. Qiu, Journal of Physics: Conference Series 1785 (1), 012005. [11] A. Bottino et al., Journal of Physics: Conference Series 2397. [12] A. Bottino et al., EPS 2023 Proceedings. [13] F. Zonca et al., IAEA 2026 conference paper TH-C, oral presentation. [14] W. W. Heidbrink et al., Nuclear Fusion (2021). [15] G. Brochard et al., Comput. Physics Comm., to be submitted (2026).

Conclusion

- We introduced the concept of zonal state to describe the evolution of the plasma between neighboring nonlinear equilibria.
- The framework provides a scheme to study transport processes in burning plasmas.
- The evolution of the zonal state has been studied by means of nonlinear GK simulations.
- Reduced transport models are verified within the same framework.