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Theory and Simulation of Phase Space Transport in Burning Plasmas

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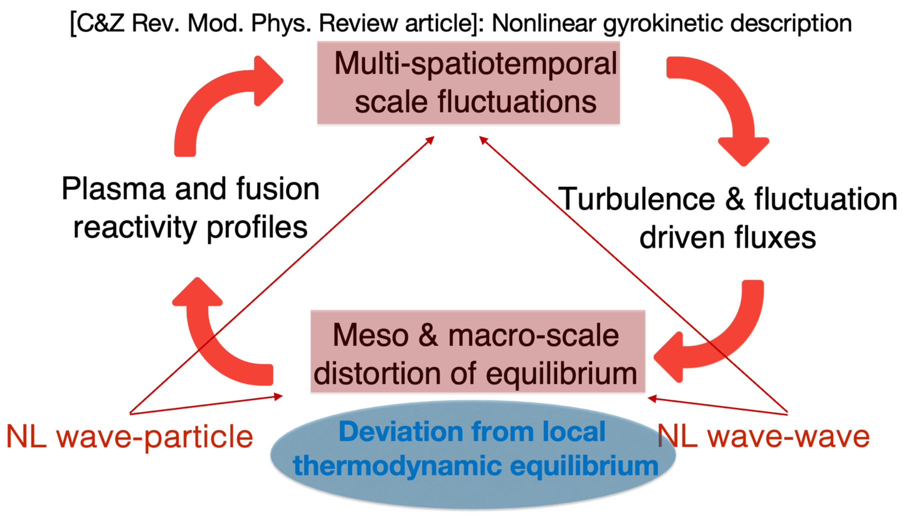
HIGHLIGHTS

- This study reviews the role of phase-space zonal structures (PSZS) in burning plasmas, illustrating their evolution due to Alfvénic fluctuations using synthetic diagnostics with HMGC [6], GTC [16], and ORB5 [7] codes.
- The presented work demonstrates the existence of an overarching and unified theoretical framework for the self-consistent description of fluctuation spectra and corresponding transport in reactor-relevant fusion plasmas.
- The results validate the ATEP [8] code for simulating distribution function evolution in realistic tokamak conditions, including sources and collisions.
- The integration of the ATEP workflow into the ITER IMAS system is complete, and applications to realistic cases of practical interest are in progress.

BURNING PLASMAS AND PHASE SPACE TRANSPORT

- Reactor-relevant burning plasmas are complex, self-organized systems in which energetic particles (EPs) play a crucial role in processes underlying cross-scale couplings. [1-3]



- **Proper nonlinear equilibrium**
  - **Zonal State**: zonal e.m. fields and phase space zonal structures
  - Compute Zonal State in the presence of finite level of fluctuations

$$F_{0*} \equiv F_0 + \overline{e^{-iQ_z} e^{iQ_z}\delta F_z}$$

(orbit averaging)

meso-macro micro-meso

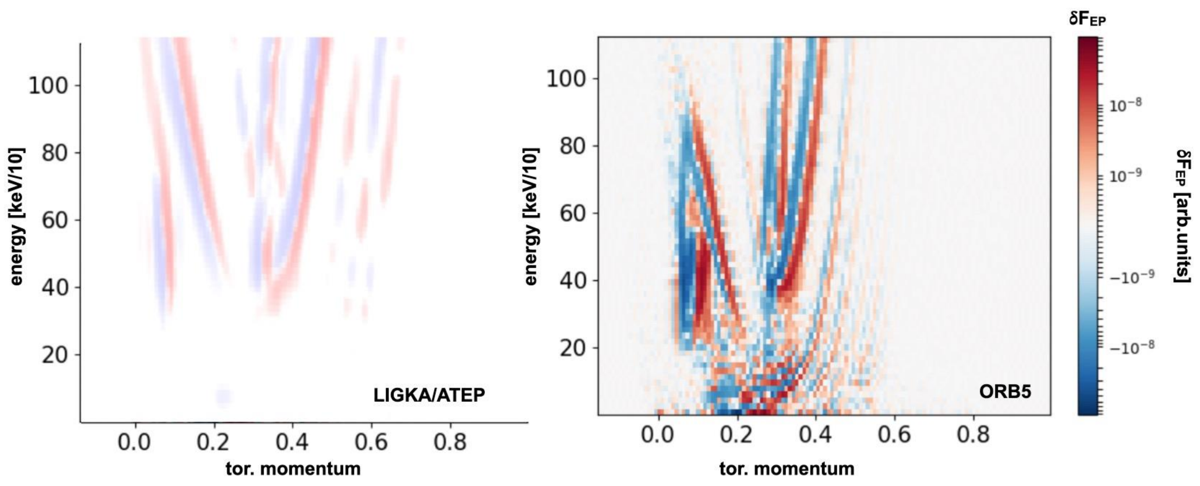
- The phase-space zonal structures (PSZS) depend solely on actions (invariants of motion in a nearly integrable Hamiltonian system)
- The PSZS concept generalizes the local Maxwellian equilibrium, and zonal state evolution equations allow to simulate transport in burning plasmas on long times [4,5]

$$\frac{\partial}{\partial t}\overline{F}_{z0} + \frac{1}{\tau_b}\left[\frac{\partial}{\partial P_\phi}\overline{\left(\tau_b \delta\dot{P}_\phi \delta F\right)}_z + \frac{\partial}{\partial \mathcal{E}}\overline{\left(\tau_b \delta\dot{\mathcal{E}} \delta F\right)}_z\right]_S = \overline{\left(\sum_b C_b^g\left[F, F_b\right] + \mathcal{S}\right)}_{zS}$$

- ATEP code [8] solves zonal state evolution in realistic tokamak conditions with various levels of approximations and is fully consistent with ORB5 nonlinear gyrokinetic code results

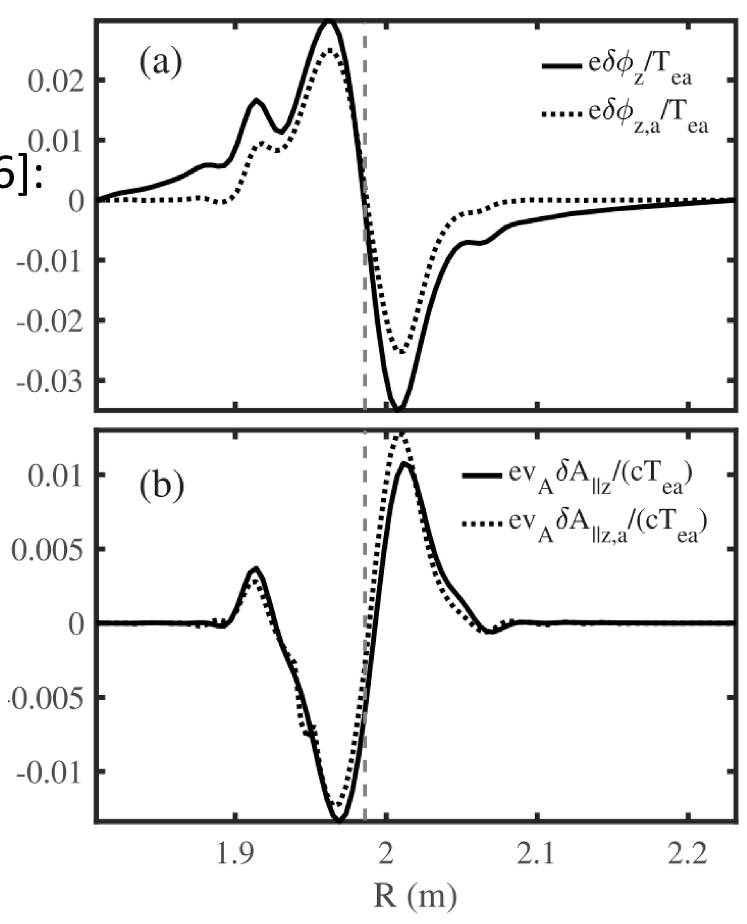
Circulating EP PSZS

ITER NBI case with two TAEs n=18 and n=19 in the non-linear saturation phase



ZONAL STATE BY RSAE IN GTC SIMULATIONS

- Including thermal component is crucial [14] and enables description of phase transitions in zonal state evolution [S.J. Wang et al. PRL 2024, ITB by ITG] [15]
- Core plasma also plays a crucial role in determining the properties of the zonal state
- Reversed shear Alfvén eigenmodes (RSAE) [16]:
  - zonal flow has negligible effect on EP resonance detuning (shearing)
  - zonal e.m. fields enhance the EP drive via phase space zonal structures
  - zonal e.m. fields are dominated by zonal current
  - saturation takes place via downward frequency shift and enhanced damping due to core plasma effects (ongoing work)

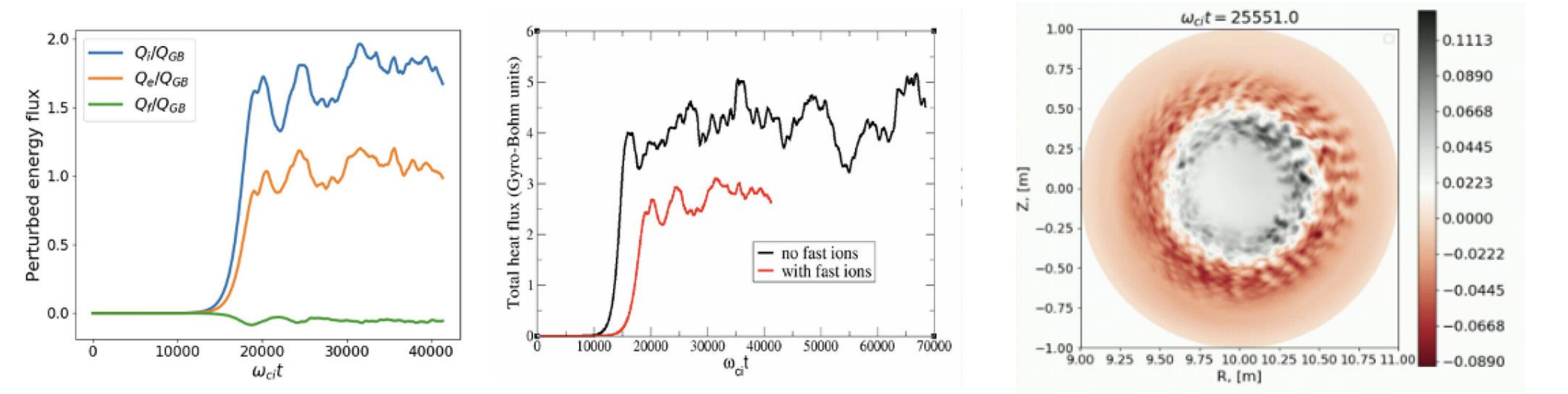


➔ **contrary to common wisdom** ←

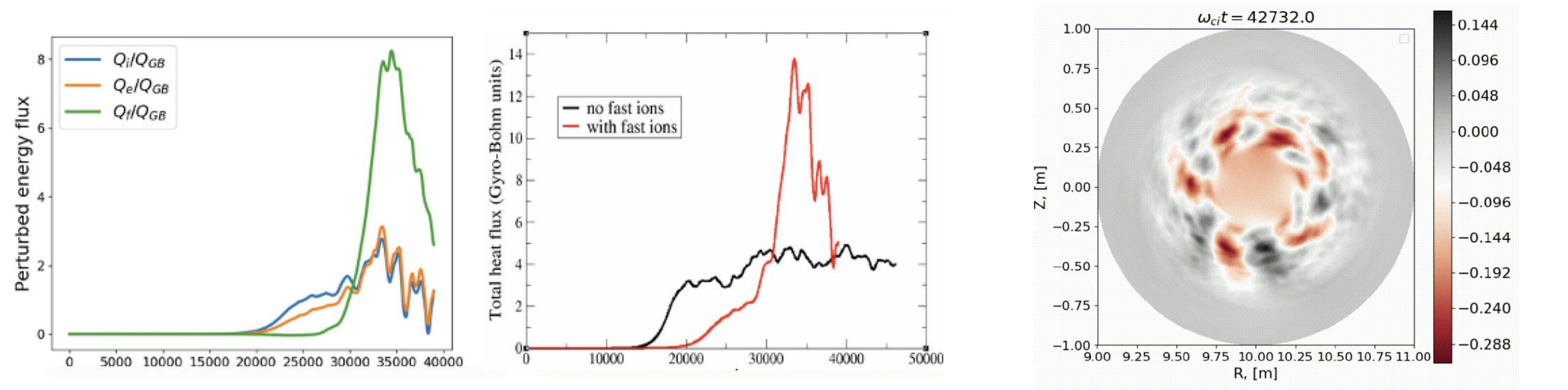
CROSS-SCALE COUPLINGS IN ITG PLASMA TURBULENCE

➔ **A. Könies et al. P6-3470**

- Nonlinear gyrokinetic simulations with ORB5 code demonstrate clear reduction in the heat flux for both the bulk ions and the electrons at $\beta_e = 0.1\%$ in the presence of energetic particles



- Zonal State becomes more global as plasma β is increased. $\beta_e = 0.24\%$ Flute-like and meso-scale structures emerge. Overall transport deteriorates.



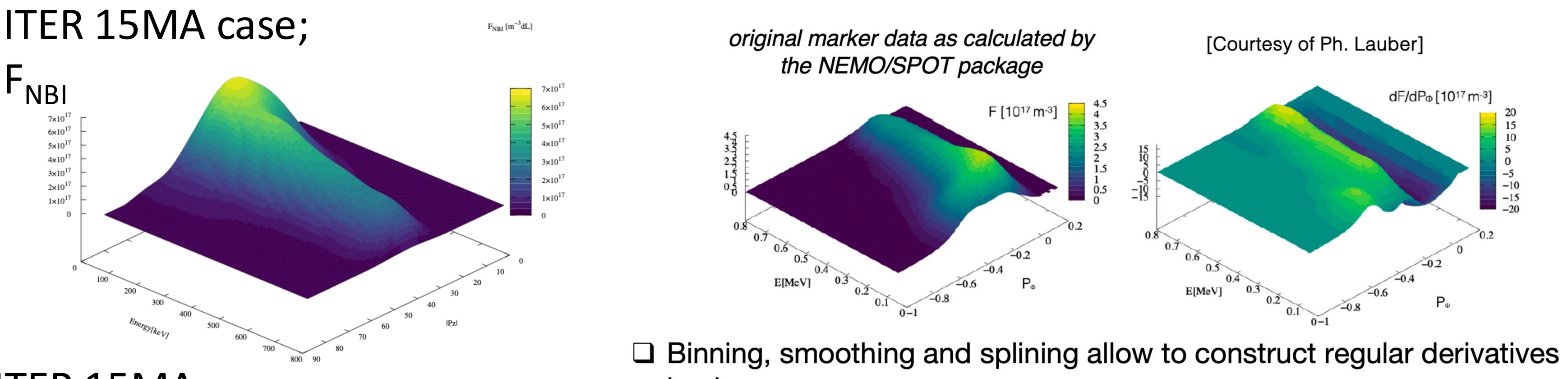
- Meso-scale phenomena, such as kinetic Alfvén wave propagation, need to be captured for a correct description of the plasma dynamics

ATEP-3D code and EP Workflow

- Energetic particle workflow is fully integrated in IMAS [8,21,22]

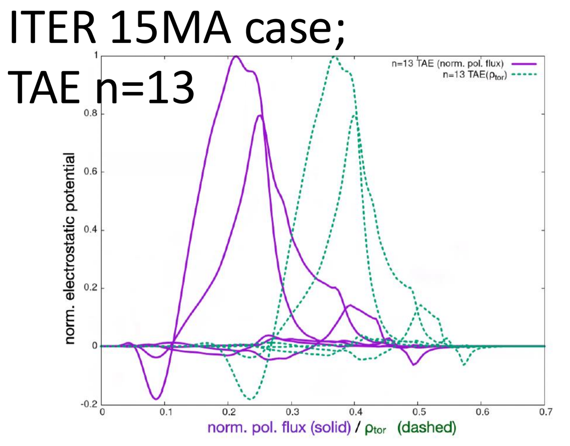
ITER 15MA case;

F_{NBI}



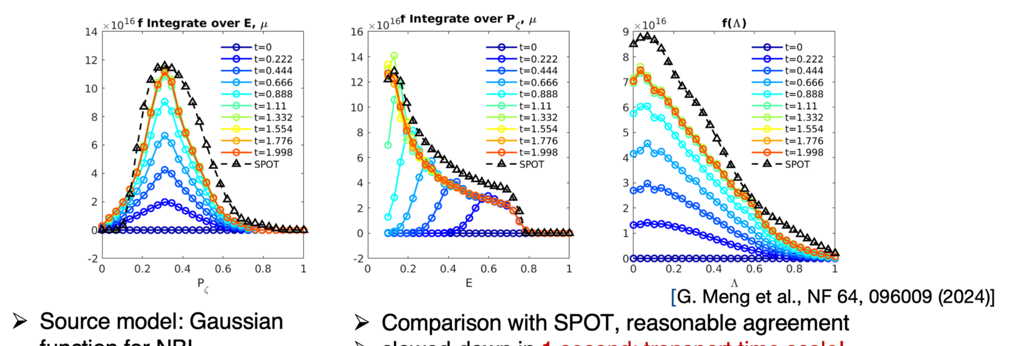
- Binning, smoothing and splining allow to construct regular derivatives in phase space

ITER 15MA case; TAE n=13

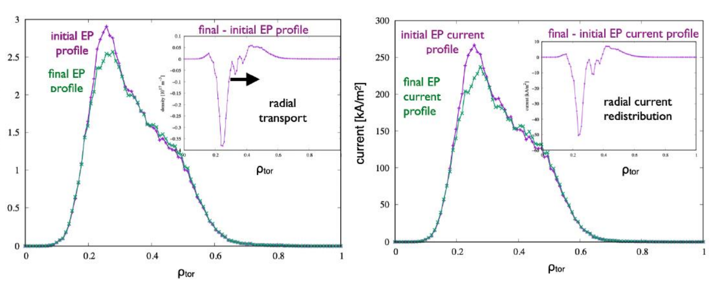


Computed by LIGKA Using EP Workflow

- Steady state solution obtained with sources and collisions



- Source model: Gaussian function for NBI
- Comparison with SPOT, reasonable agreement
- slowed-down in 1 second: transport time scale!
- ATEP-3D, 30 mins/case
- Monte-Carlo code, several days/case



- Off-axis beam relaxation in ITER

Initial (as given by NEMO/SPOT) and final state after evolving the PSZS transport equation for 700ms (1000 time steps) with constant-amplitude n=13 TAE with $\delta B/B = 10^{-5}$

CONCLUSIONS AND DISCUSSIONS

- This work demonstrates a comprehensive theoretical framework for the self-consistent modeling of fluctuation spectra and transport in reactor fusion plasmas.
- Verification efforts, including comparisons between ATEP-3D [8,21,22] and ORB5 [7], demonstrate a good level of consistency in simulating phase-space fluxes and zonal structures. These results validate the numerical tools and the underlying theoretical approach, with the inclusion of source and collision terms.
- The ATEP code has been integrated into the ITER IMAS system, enabling its use for predictive modeling in ITER [22].

ACKNOWLEDGEMENTS

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