EUROfusion

Advanced Energetic Particle Transport Model

Matteo Valerio Falessi[1,2], P. Lauber[3], F. Zonca[1,4], L. Chen[4,5], Z. Qiu[4] and the ATEP team

[1] Center for Nonlinear Plasma Science and C.R. ENEA Frascati, C.P. 65, 00044 Frascati, Italy
[2] National Institute for Nuclear Physics, Rome Department, P.le A. Moro, 5, 00185 Roma, Italy
[3] Max-Planck-Institut fur Plasma Physics, 95748 Garching, Germany
[4] Inst. for Fusion Theory and Simulation and Department of Physics Zhejiang University, Hangzhou 310027, China
[5] Dept. Physics and Astronomy, University of California, Irvine, CA 92697- 4575, USA

CNPS Center for Nonlinear Plasma Science - Since 2020 -

Ministero degli Affari Esteri e della Cooperazione Internazionale

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ENEA AGENZIA NAZIONALE PER LE NUOVE TECNOLOGIE, L'ENERGIA E LO SVILUPPO ECONOMICO SOSTENIBILE

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Transport processes in burning plasmas

- Predicting the dynamics of a burning plasma on long time scales, comparable with the energy confinement time or longer, is essential in order to understand next generation fusion experiments, e.g., ITER;
- the crucial role of energetic particles Zonca et al. 2015; Chen and Zonca 2016, must be properly described;

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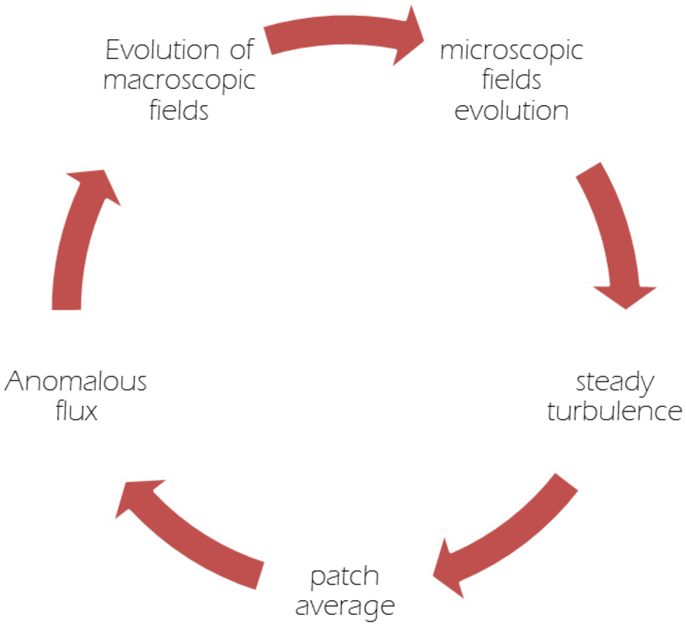
- the crucial role of energetic particles Zonca et al. 2015; Chen and Zonca 2016, must be properly described;
- a first-principle-based, self-consistent approach is crucial;
- extending gyrokinetic simulations to these time scales is a challenging task from the computational resource point of view, i.e., $\sim 10^{24}$ grid points;
- simplifying assumptions based on physics understanding and first principles must be introduced;

Transport processes in burning plasmas

- Transport equations define the evolution of radial profiles

$$\langle \partial_t n \rangle_\psi = -\langle \nabla \cdot (n\boldsymbol{V}) \rangle_\psi \, ;$$

- consistent with a slowly evolving ($\omega^{-1}\partial_t \log p_0 \sim \delta^2$) equilibrium distribution function;



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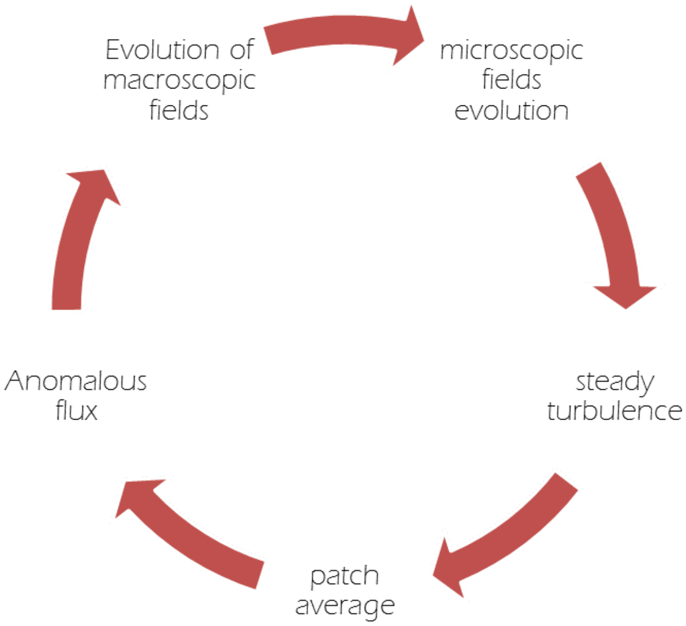
- consistent with a slowly evolving ($\omega^{-1}\partial_t \, \log p_0 \sim \delta^2$) equilibrium distribution function;
- Implicit separation of scales between equilibrium and fluctuations;
- Local Maxwellian is assumed;



Need for generalization!!!

Purpose statement

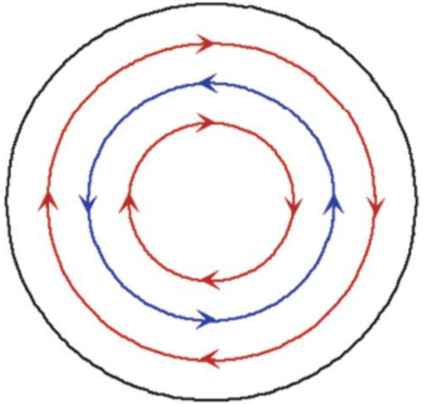
We aim at 1. providing the general expressions describing EPs (plasma) dynamics on long time scales (transport) and 2. introducing a framework to solve these equations within different levels of reduced dynamics.

By means of this approach it will be possible to:

- define the concept of nonlinear equilibrium;
- describe the physics of burning plasmas where alpha particles will play a key role in transport studies by interacting with thermal components;
- the derivation, see Falessi 2017; Falessi and Zonca 2019, is based on the Phase space zonal structures theory, see Chen and Zonca 2016.

Phase Space Zonal Structures

- Coupling between fluctuating fields can generate zonal flows and zonal fields;
- Crucial elements for regulating turbulent fluxes, e.g., by scattering instability turbulence to shorter radial wavelength stable domain…



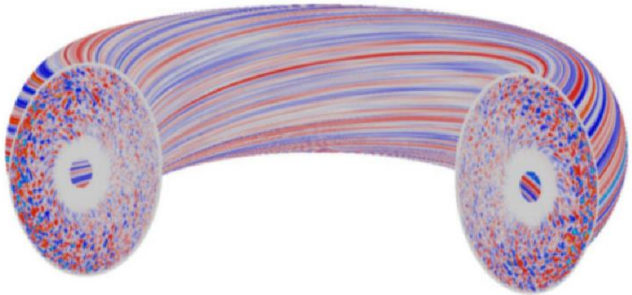
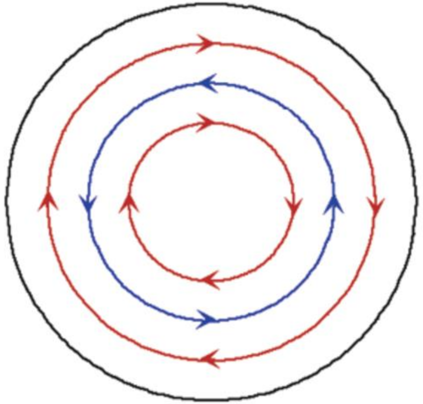
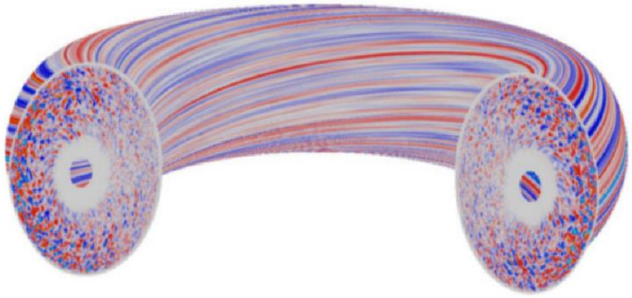


Figure: Courtesy of Y. Xiao et al., PoP 2015.

Phase Space Zonal Structures

- Coupling between fluctuating fields can generate zonal flows and zonal fields;
- Crucial elements for regulating turbulent fluxes, e.g., by scattering instability turbulence to shorter radial wavelength stable domain...
- analogously, zonal structures in the density and temperature profiles are unaffected by rapid collision-less dissipation;
- collision-less undamped fluctuations in the phase space are called phase space zonal structures Chen and Zonca 2016, Falessi and Zonca 2019;





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Orbit averaging

- Particle motion in the reference magnetic field is characterized by three integrals of motion, i.e. $P_\phi, \mu, \mathcal{E}$;
- Phase Space Zonal Structures equation is connected with the macro-/meso- scopic component, i.e. $[\ldots]_S$, unperturbed orbit averaged distribution function (Falessi and Zonca 2019);

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

- This expression describe transport processes in the phase space due to fluctuations, collisions and sources;

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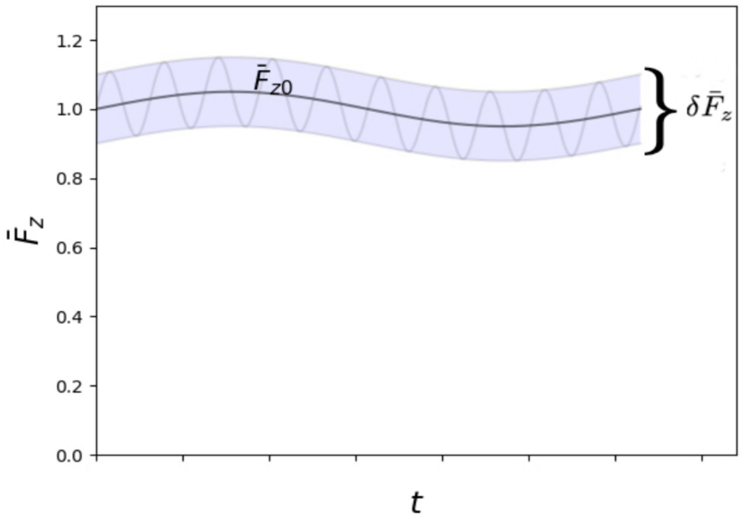
- This expression describe transport processes in the phase space due to fluctuations, collisions and sources;
- Transport equations can be obtained by averaging in the velocity space Falessi and Zonca 2019;
- mesoscales are spontaneously created by the turbulence;

Neighboring nonlinear equilibria

- Having defined Phase Space Zonal Structures, we can decompose the toroidally symmetric distribution function;
- $\overline{F_{z0}}$ describe macro- & meso-scales;
- micro-scales are accounted by $\delta\overline{F}_z$;

$$F_z = \overline{F_{z0}} + \delta\bar{F}_z + \delta\tilde{F}_z$$



Neighboring nonlinear equilibria

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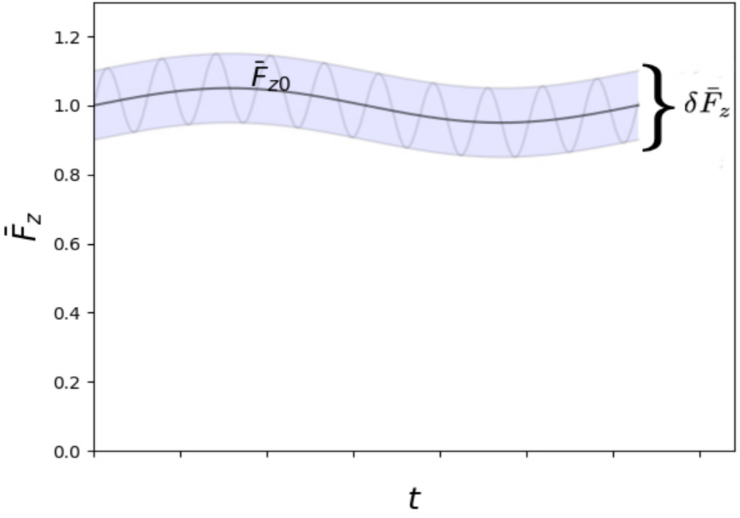
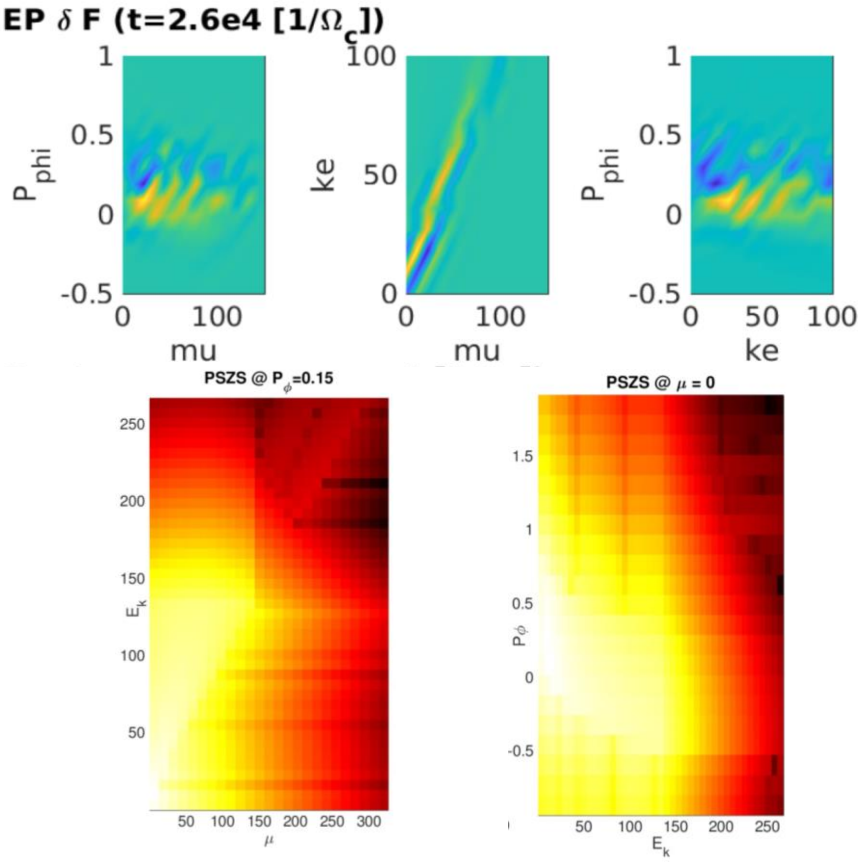
- $\overline{F_{z0}}$ describe macro- & meso-scales;
- micro-scales are accounted by $\delta\overline{F}_z$;
- they describe system transitions between neighboring nonlinear equilibria, see Chen and Zonca 2007; Falessi and Zonca 2019;
- nonlinear equilibria, together with zonal fields, form a zonal state.

$$F_z = \overline{F_{z0}} + \delta\bar{F}_z + \delta\tilde{F}_z$$

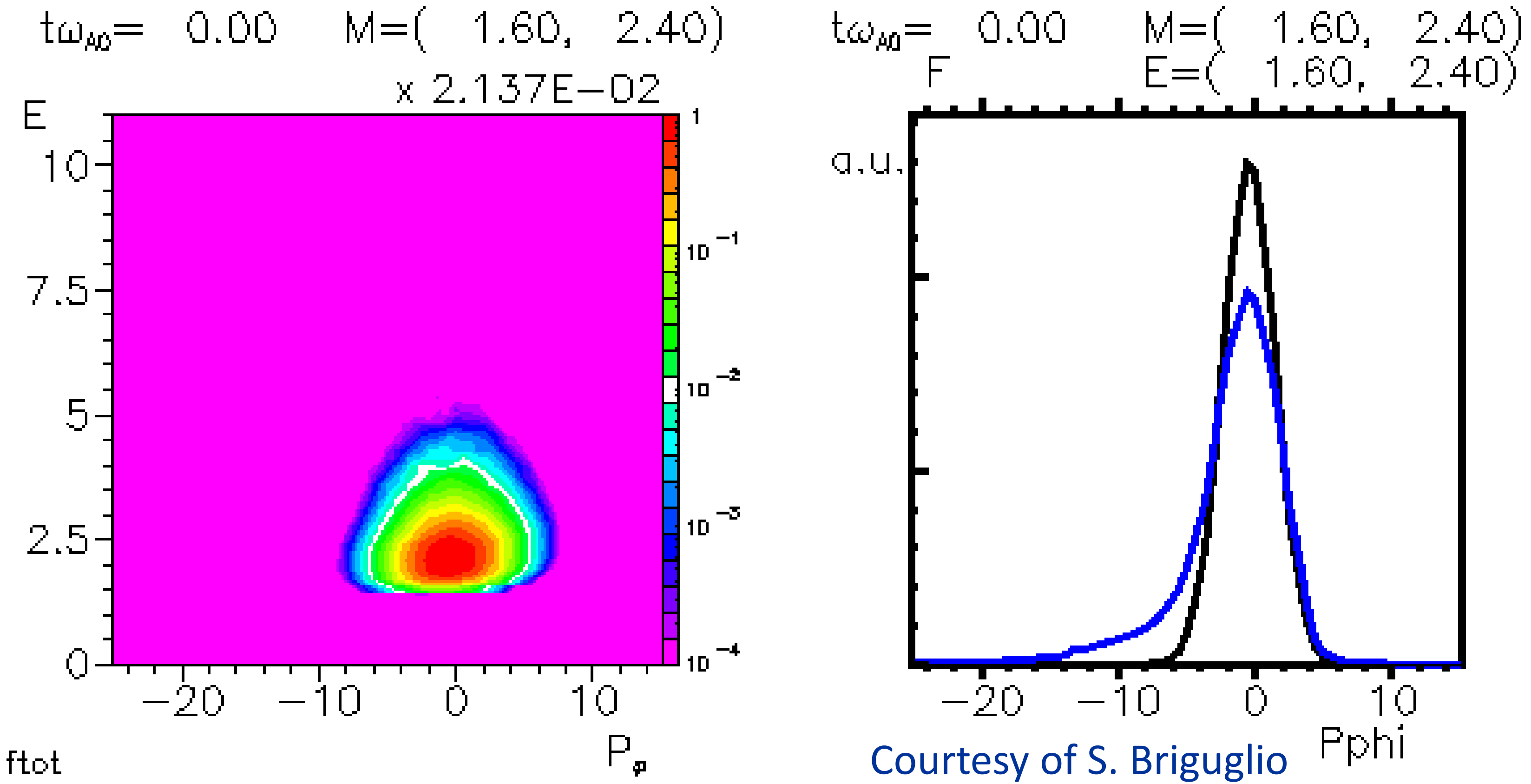


Phase Space Zonal Structures diagnostic in ORB5

- an ORB5 diagnostic for PSZS has been developed, i.e., see Bottino et al (2022);
- PSZS can accumulate over time…
- A restart of ORB5 from PSZS data is the next step, see the contribution by A. Bottino at EPS2023;
- Illustration of ORB5 application to frequency chirping modes (Invited Talk by X. Wang at EPS2023)



PSZS diagnostic in HMGC



Courtesy of S. Briguglio

Reduced transport models

- PSZS transport is studied by means of a hierarchy of verified and validated reduced models within an EUROfusion Enabling Research Project with P. Lauber as P.I.;

- explicit expression of EP fluxes in PSZS equations have been calculated within the following hierarchy of simplifying assumptions:

- the zeroth level of simplification consist in the gyrokinetics description of plasma dynamics;

- the first level of simplification consist in assuming $|\omega| \gg \tau_{NL}^{-1} \sim \gamma_L$, Zonca et al 2021;

- the second and final level of simplification is the quasilinear model

Reduced transport models

DAEPS (Y. Li et al 2020)

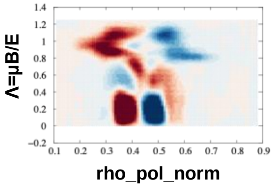
- Ballooning decomposition for fluctuations;
- Based on fish-bone like dispersion relation;
- Mode structure decomposition, separation of radial envelope and parallel mode structure;
- Calculate nonlinear fluxes by the DSM model or a saturation rule.

LIGKA-HAGIS (Lauber et al 2007)

- Fourier decomposition for fluctuations;
- Solve linear gyrokinetic equation;
- Assume fluctuations amplitude, e.g., kick-model or quasilinear;
- Use IMAS-coupled EP stability WF (HAGIS/LIGKA) to calculate Phase Space Zonal Structures fluxes.

ATEP: kick model limit

<dPz/dt>



ATEP code: solve transport equation for PSZS with sources and collisions, Lauber 2022

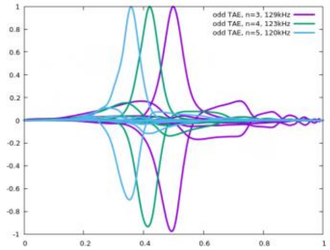
$$\frac{\partial}{\partial t}\overline{F_{z0}} + \frac{1}{\tau_b}\left[\frac{\partial}{\partial P_\phi}\overline{\left(\tau_b \delta \dot{P}_\phi \delta F\right)}_z + \frac{\partial}{\partial \mathcal{E}}\overline{\left(\tau_b \delta \dot{\mathcal{E}} \delta F\right)}_z\right]_S = \overline{\left(\sum_b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

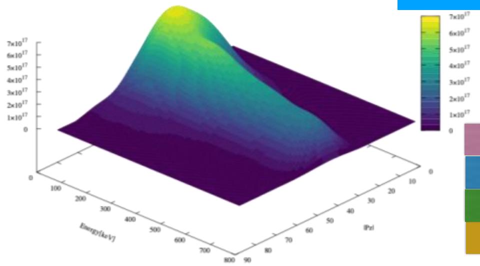
calculate PSZS fluxes with prescribed amplitude

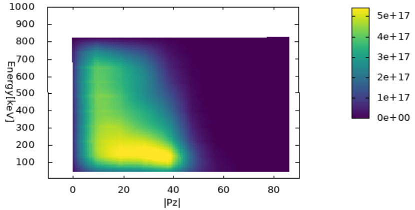
advance F_{EP} and return updated F_{EP} into IDS, or its moments

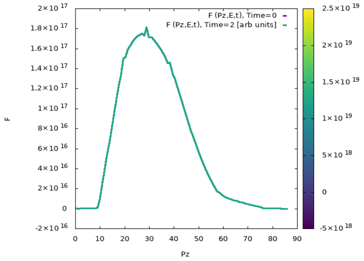
calculate linear mode spectrum

DAEPS and LIGKA Are interchangeable Thanks to IMAS







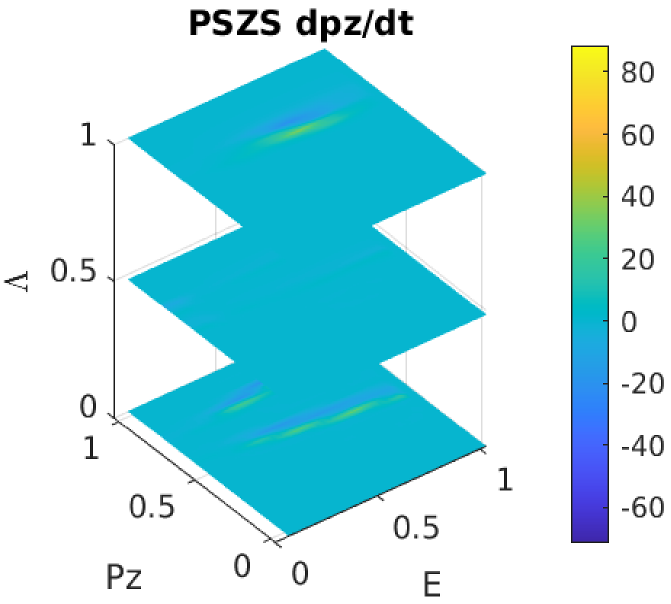


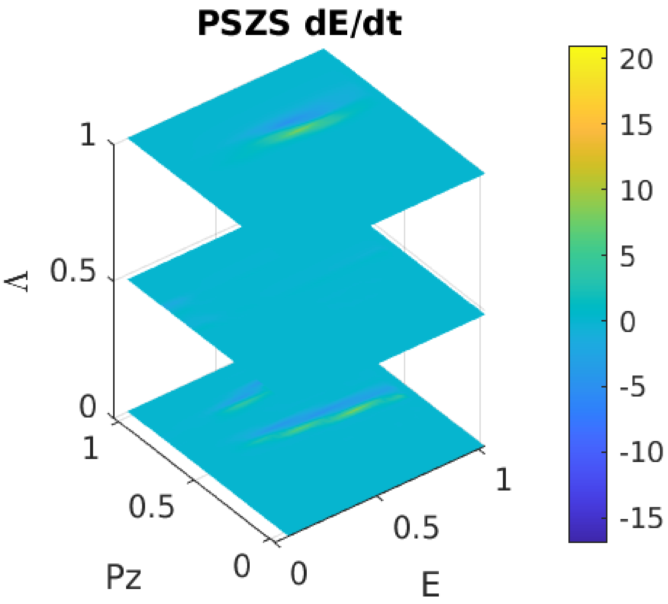
core_transport
equilibrium
mhd_linear
distributions

time

Phase Space fluxes

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



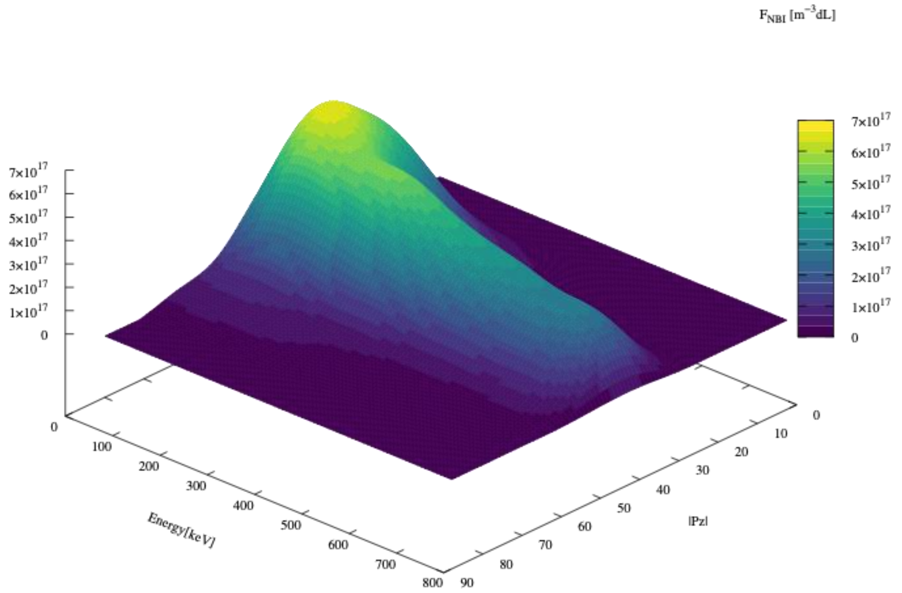


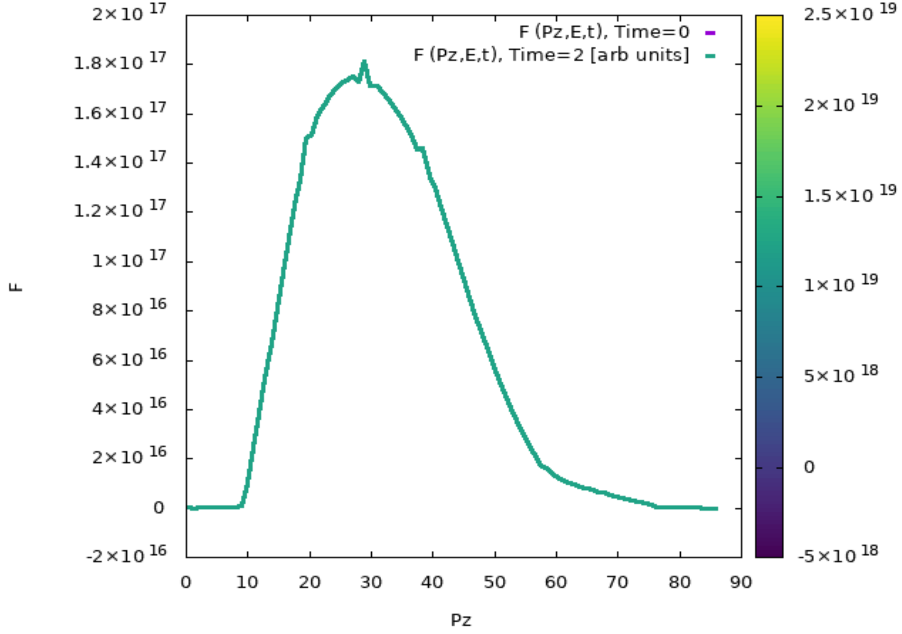
G. Meng et al. 14th International West Lake Symposium

PSZS evolution

ATEP code: solve transport equation for PSZS with sources and collisions, Lauber 2022

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

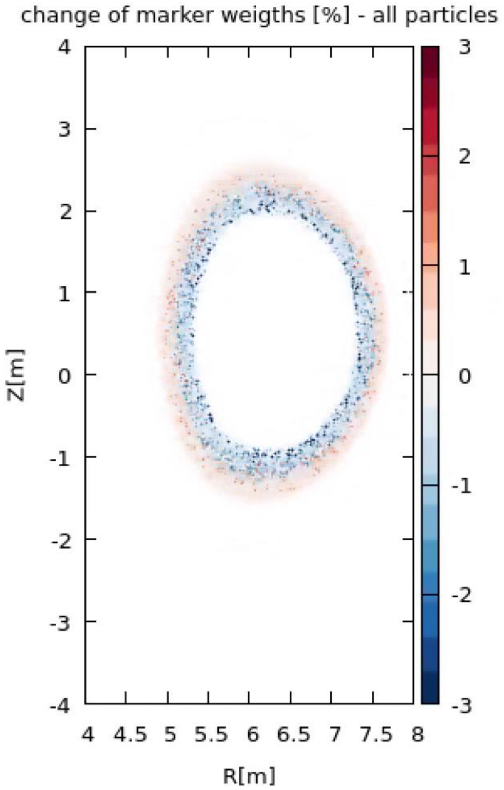


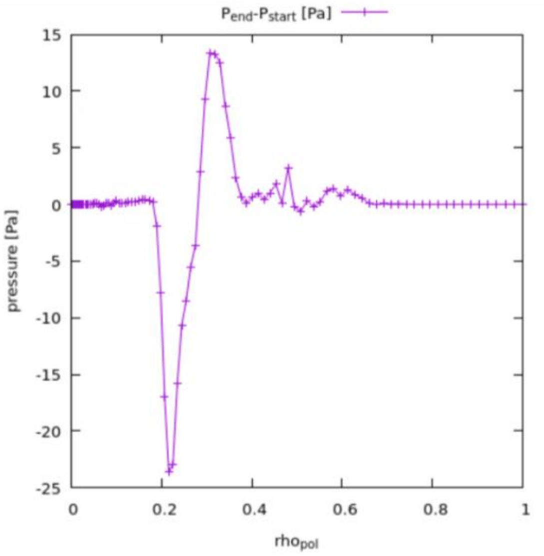


ITER plasma from H&CD WF by M. Schneider

PSZS moments

- Mapping to 1d profile of PSZS is possible;
- a CGL equilibrium can be readily constructed Falessi et al 2023 sub;
- transport is zonal by construction;
- Next step is the calculation of the corresponding magnetic equilibrium;

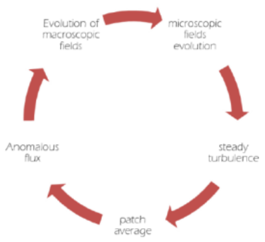




ATEP code: solve transport equation for PSZS with sources and collisions, Lauber 2022

Summary & Conclusions

- Need of predictive transport models on timescales comparable with magnetic fusion experiments, i.e., ITER, properly describing EPs;



Summary & Conclusions

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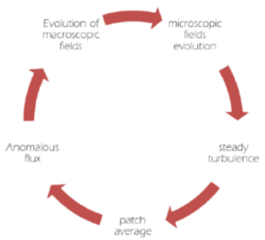
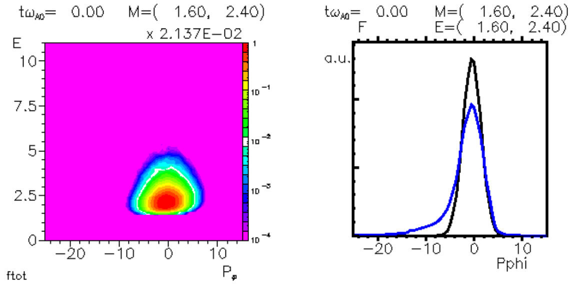
- we have introduced the concept of zonal state to describe the evolution of the plasma between neighboring nonlinear equilibria;





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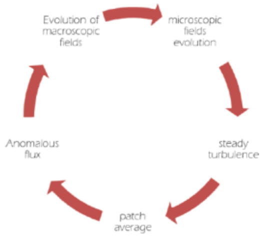
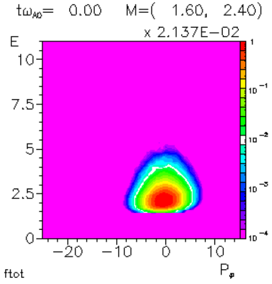
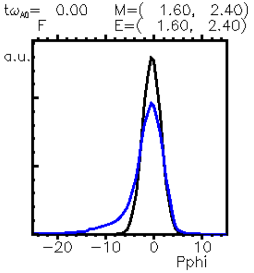
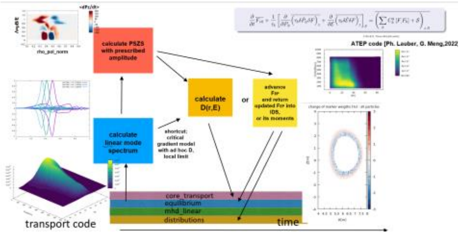
- we have introduced the concept of zonal state to describe the evolution of the plasma between neighboring nonlinear equilibria;

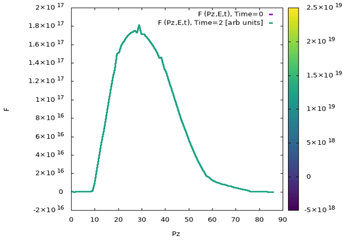
- we have introduced a conceptual framework which allow to study EP phase space transport over long time scales.



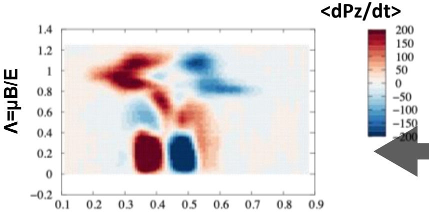




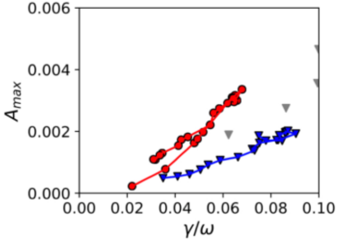




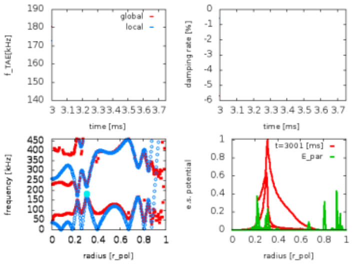
ATEP: Quasilinear model



saturation rule: HAGIS or ORB5



EP WF (LIGKA)



calculate PSZS

use
NL code/model
for intensity closure

calculate
linear mode
spectrum

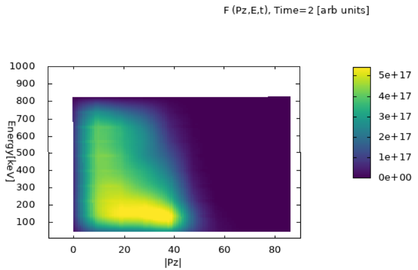
ATEP code: solve transport equation for PSZS with sources and collisions Lauber 2022

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

calculate
D(r,E)

or

advance
F_{EP}
and return
updated distribution
IDS,
or its moments



t

t+1

core_transport
equilibrium
mhd_linear
distributions

transport code

time

Particle transport

- We can re-write the low frequency (transport) component of δf_z in term of the PSZS;
- taking the time derivative of the surface averaged velocity integral we obtain:

$$\partial_t \left\langle \langle \delta f_z \rangle_v \right\rangle_\psi = \frac{e}{m} \left\langle \left[1 - \overline{\left(e^{-iQ_z} J_0 \right)} \, \overline{\left(e^{iQ_z} J_0 \right)} \right] \frac{\partial F_0}{\partial \mathcal{E}} \partial_t \delta \phi_z \right\rangle_v +$$

$$\frac{1}{V\prime} \frac{\partial}{\partial \psi} \left\langle \left\langle V' \overline{\left(e^{-iQ_z} J_0 \right) \left[c e^{iQ_z} R^2 \nabla \phi \cdot \nabla \langle \delta L_g \rangle \delta G \right]} \right\rangle_v \right\rangle_\psi$$

- This equation describes the radial oscillations on any length-scale of the density profile in the absence of collisions and assuming GK ordering Falessi and Zonca 2019;
- mesoscales are spontaneously created by the turbulence;

Zonal fields: macro- /meso- scopic component

- the current $\mathbf{J}_z$ and the pressure tensor $\mathbf{P}$ satisfy the following force balance equation:

$$\sigma \frac{\mathbf{J}_z \times \mathbf{B}}{c} = \nabla P_{\parallel} + (\sigma - 1)\nabla\left(\frac{B^2}{8\pi}\right) + \frac{B^2}{4\pi}\nabla_{\perp}\sigma$$

where $\sigma = 1 + \frac{4\pi}{B^2}\left(P_{\perp} - P_{\parallel}\right)$;

- the self-consistent modification of the equilibrium magnetic field due to PSZS can be calculated solving this equation, e.g.:

$$\Delta^* \psi + \nabla \ln\sigma \cdot \nabla\psi = -\frac{4\pi R^2}{\sigma} - \frac{1}{\sigma^2}\frac{\partial G}{\partial \psi}$$

- where $G \equiv \sigma F^2/2$ is a flux function;

Transport processes in burning plasmas

- EPs are generally non Maxwellian, and transport processes take place in the phase space!
- Separation of scales is questionable…
- Particularly important for ITER physics;
- interplay of meso-scale structures with micro-scales generated by EPs, i.e., $\rho_{LE} \sim (\rho_L L)^{1/2}$, Zonca et al 2015;

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- interplay of meso-scale structures with micro-scales generated by EPs, i.e., $\rho_{LE} \sim (\rho_L L)^{1/2}$, Zonca et al 2015;
- interaction with thermal plasma over long timescales can modify bulk transport processes;
- the derivation, see Falessi 2017; Falessi and Zonca 2019, is based on the theory of Phase space zonal structures (PSZS), see Chen and Zonca 2016.