Advanced Transport Models for Energetic Particles

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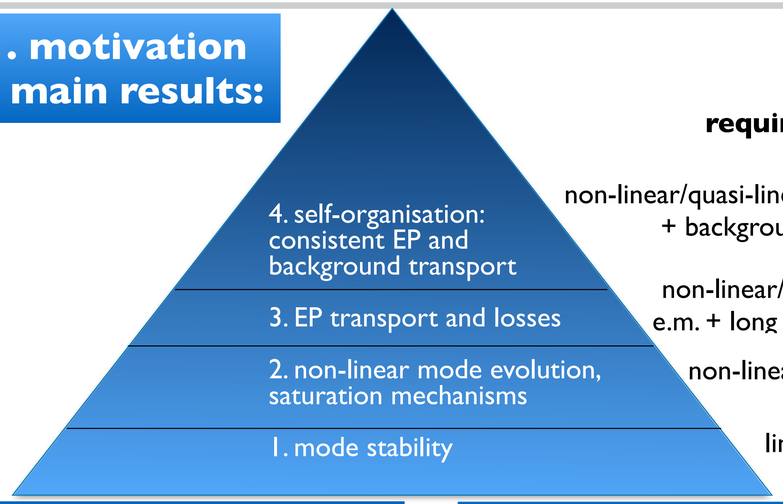
1. motivation & main results:



required models:

non-linear/quasi-linear global kinetic e.m. + background transport

non-linear/quasi-linear global kinetic e.m. + long time scales (source +sink)

non-linear global kinetic e.m.

linear global kinetic e.m.

with comprehensive codes [1-6]:

- difficult to disentangle various non-linearities in comprehensive codes- verify results?
- transport-time scales?
- vast parameter regime - sensitivity scans ?
- how to reduce to reasonably fast models?

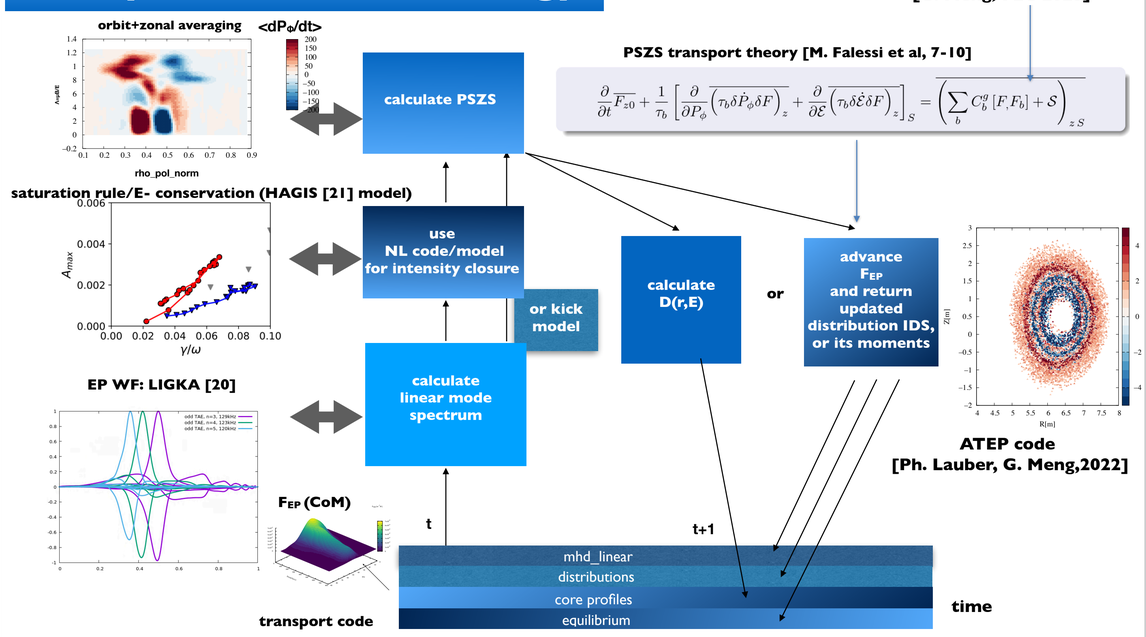
phase space zonal structures (PSZS) are collision-less undamped, long-lived nonlinear deviations of the plasma from a reference state [Falessi, Zonca; refs 7-10] properties:

- n=0, constant along equilibrium orbits
- define new, neighbouring equilibrium reference state
- slow, non-fluctuating component of F_{EP} evolution
- the part of δf that can be absorbed in new F_0

main results:

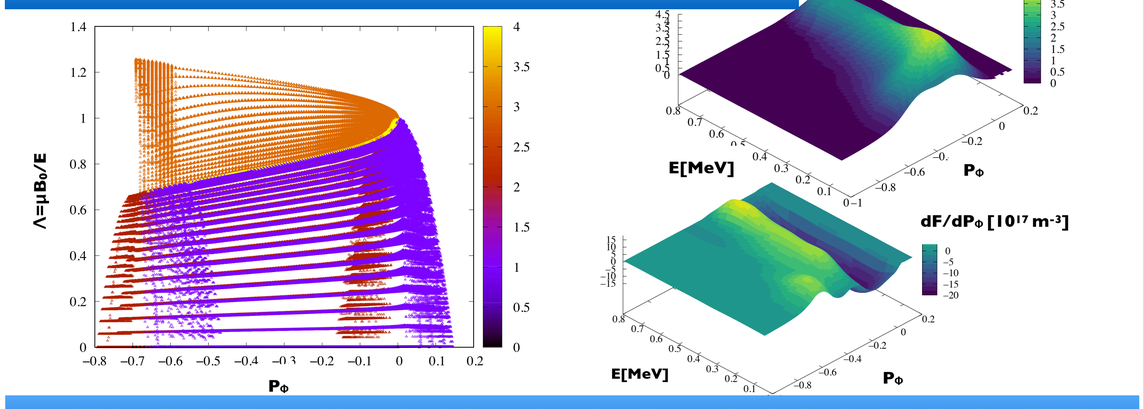
- PSZS transport code developed (ATEP-2D): kick- model and QL limit
- fully embedded into IMAS environment, modular structure
- connected to EP-Stability workflow
- ready to combine with neoclassical ATEP-3D [G. Meng at this conf.]

2. implementation strategy



- fully IMAS based implementation [18]
- modular setup; all components can be replace by equivalent actors

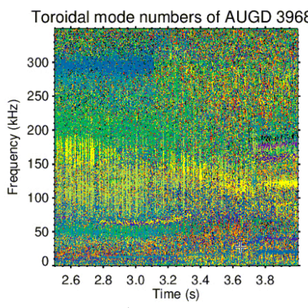
3. distribution function in CoM space



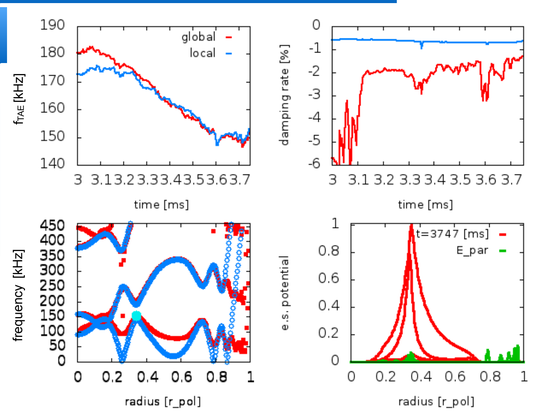
- establish orbit database with marker information given by neoclassical codes [26, Brochard FEC23]
- set up cartesian grid in CoM space, construct 2D splines in each sub-space, establish cubic 3D spline

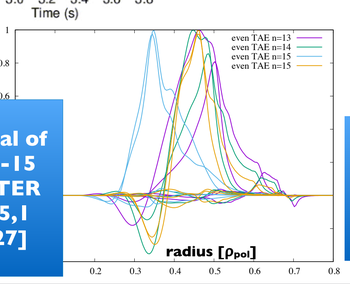
4. linear mode spectrum - EP-Stability workflow

AUG EP 'supershot' scenarios[36, Lauber EPS2022]: D-NBI into D plasma (further development of NLED AUG benchmark case)



IDA + TRVIEW + EP-WF: LIGKA local + EP-WF: LIGKA global



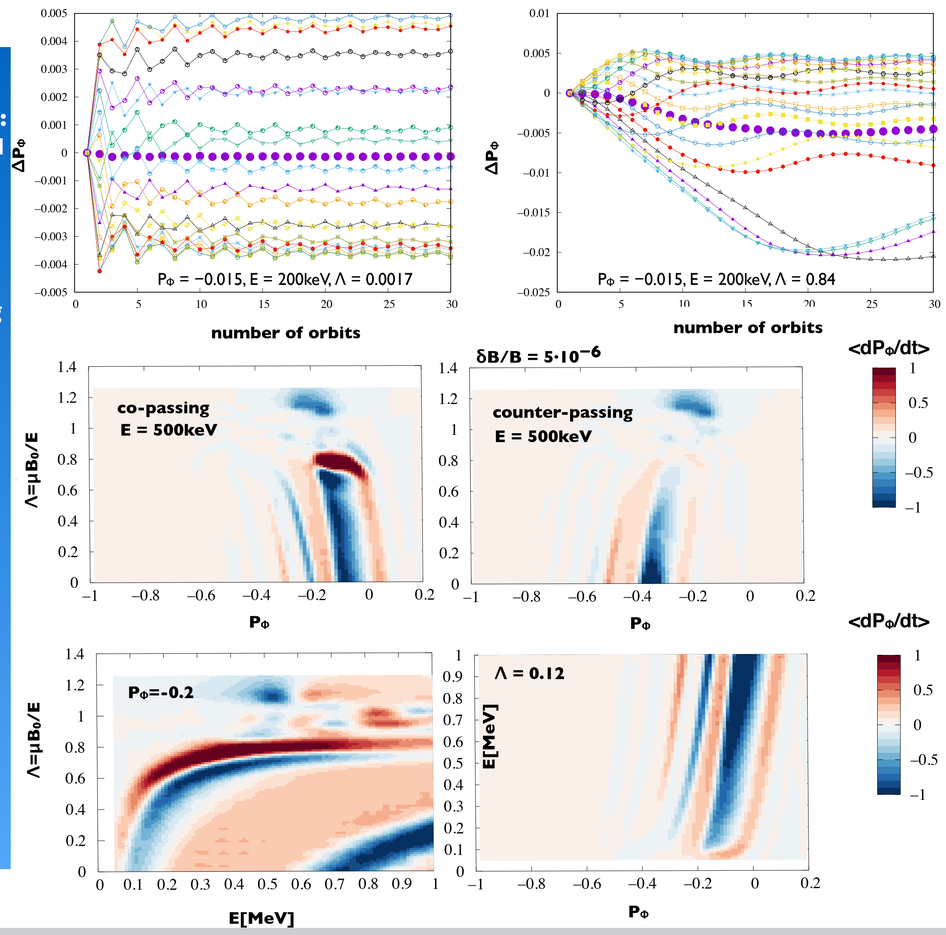


e.s. potential of even n=13-15 TAEs for ITER case 10015,1 [METIS, 27]

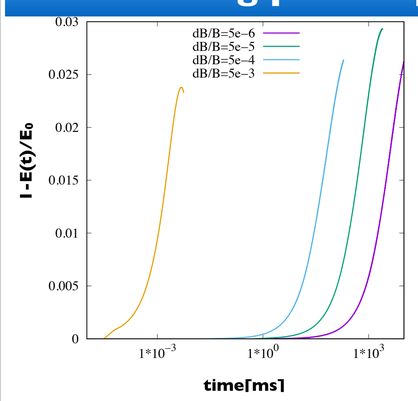
- fully IMAS based python implementation [19]
- hierarchical models ranging from analytical to linear global gyro-kinetic [LIGKA, 20]
- available on ITER cluster as module
- training material available *https://indico.euro-fusion.org/event/2729/*

5. calculating phase space transport coefficients

- start particles with different phase shifts with respect to wave: (2π /n, or random), follow typical 3-5 orbits to account for higher resonances, then average (n=13TAE; δ B/B = 5 · 10−4) [IMAS-HAGIS]
- caveat: this procedure is reducing the full dynamics: valid in small-amplitude/QL/limit, transport time scales
- can be improved, relaxed if needed (ballistic transport cases)
- typically follow 128x40x40x4 markers
- store in IDS (distributions)
- use multi-level spline interpolation [25]
- use cartesian grid in CoM space (96x96x96)
- diffusion coefficients can be determined : $\langle dP_\Phi/dt\rangle^2 \tau_{ac}$

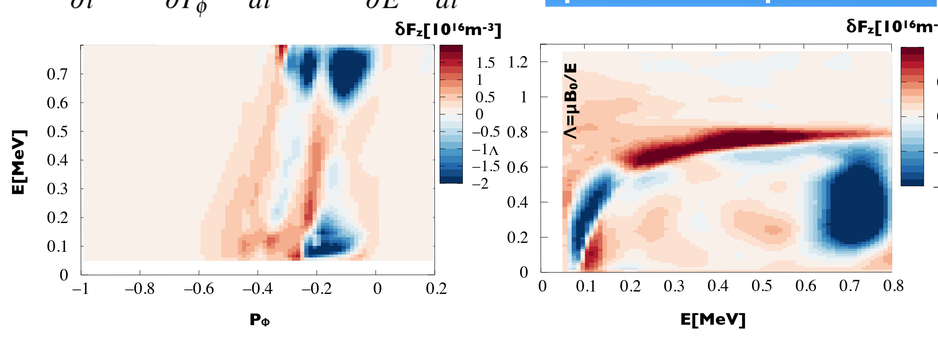


6. evolving phase space transport equation:



$$\frac{\partial F_z}{\partial t} = -\frac{\partial}{\partial P_\phi}\left(\langle\overline{\frac{dP_\phi}{dt}}\rangle F_z\right) - \frac{\partial}{\partial E}\left(\langle\overline{\frac{dE}{dt}}\rangle F_z\right)$$

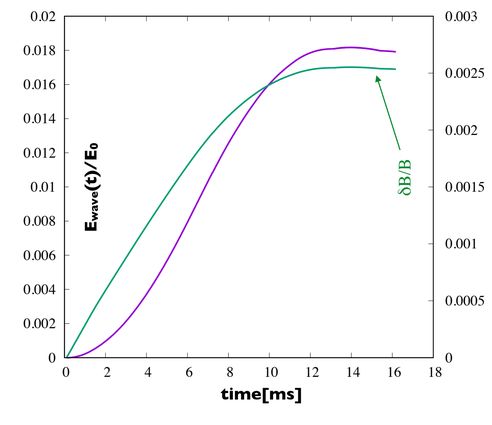
kick-model limit: fixed perturbation amplitude

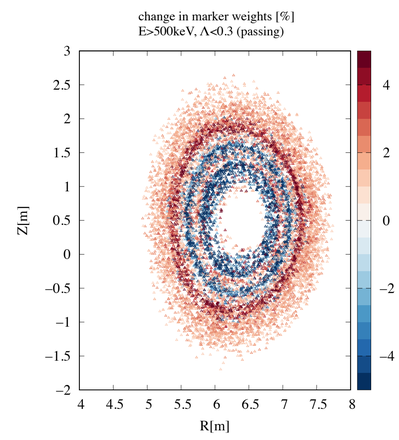


- add energy conservation equation → QL model

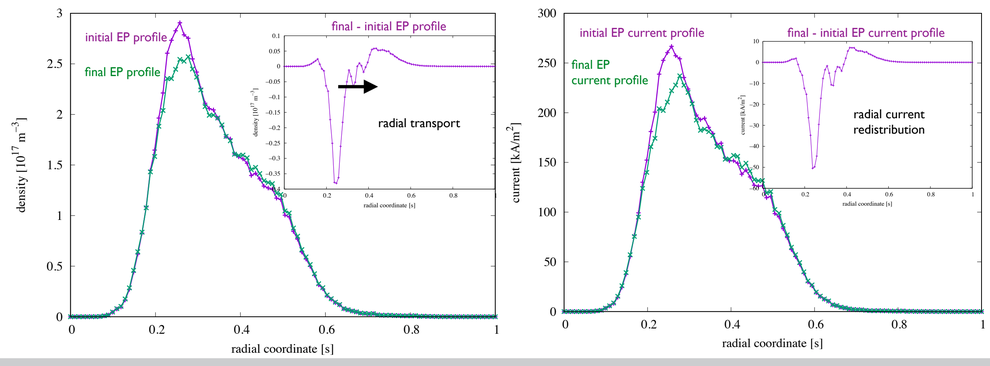
$$\frac{d}{dt}\left(\mathcal{E} + \sum_k W_k\right) = -2\sum_k \gamma_{d,k} W_k$$

$$\mathcal{E}(t) = \int dv_{P_\phi,E,\Lambda} E \cdot F_{EP}(t)$$





- use amplitude dependent transport coefficients:
- calculate $\langle dP_\Phi/dt\rangle$ and $\langle dE/dt\rangle$ as 4D spline for δB/B = [5 · 10-6, 5 · 10-5, 5 · 10-4, , 5 · 10-3]
- map back to real space, using database established previously (see 3.)
- take moments to determine density, current and pressure
- can be used to recalculate new, non-linear equilibrium



7. verify, validate and evolve models - ENR ATEP team effort

- benchmark with DAEPS - calculates fluxes explicitly based on separation of radial and parallel mode structures [9]
- benchmark with full HAGIS model [21]
- compare to 1D beam-plasma system [22]
- tracers dynamics studied with Lagrangian Coherent Structures: relevant structures
- benchmark with XHMGC/HYMAGYC calculations, featuring advanced features for transport analysis: Hamiltonian mapping diagnostics & explicit flux 'measurements'
- benchmark with STRUPHY code: MHD-kinetic hybrid code based on new stringent mathematical formulation: structure preserving geometric finite elements + PIC ⇒ improved non-linear stability [35]
- benchmark with ORB5 PSZS diagnostic [Bottino 2022]
- evolve model to include non-linear interactions ; 3D version [14]; compare with chirping cases, also in presence of turbulence [1,ORB5]
- analyse and plan new experiments at AUG: INPA data of phase space structures! [J. Rueda, FEC 2023]

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