EUROfusion

Advanced transport models for energetic particles

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ATEP team:

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and A. Bottino, M. Schneider, S.D. Pinches, O. Hoenen, TSVV10 team, ASDEX Upgrade team

MAX-PLANCK-INSTITUT FÜR PLASMAPHYSIK

ENEA ITALIAN NATIONAL AGENCY FOR NEW TECHNOLOGIES, ENERGY AND SUSTAINABLE ECONOMIC DEVELOPMENT

CNPS Center for Nonlinear Plasma Science Since 2020

iter china eu india japan korea russia usa

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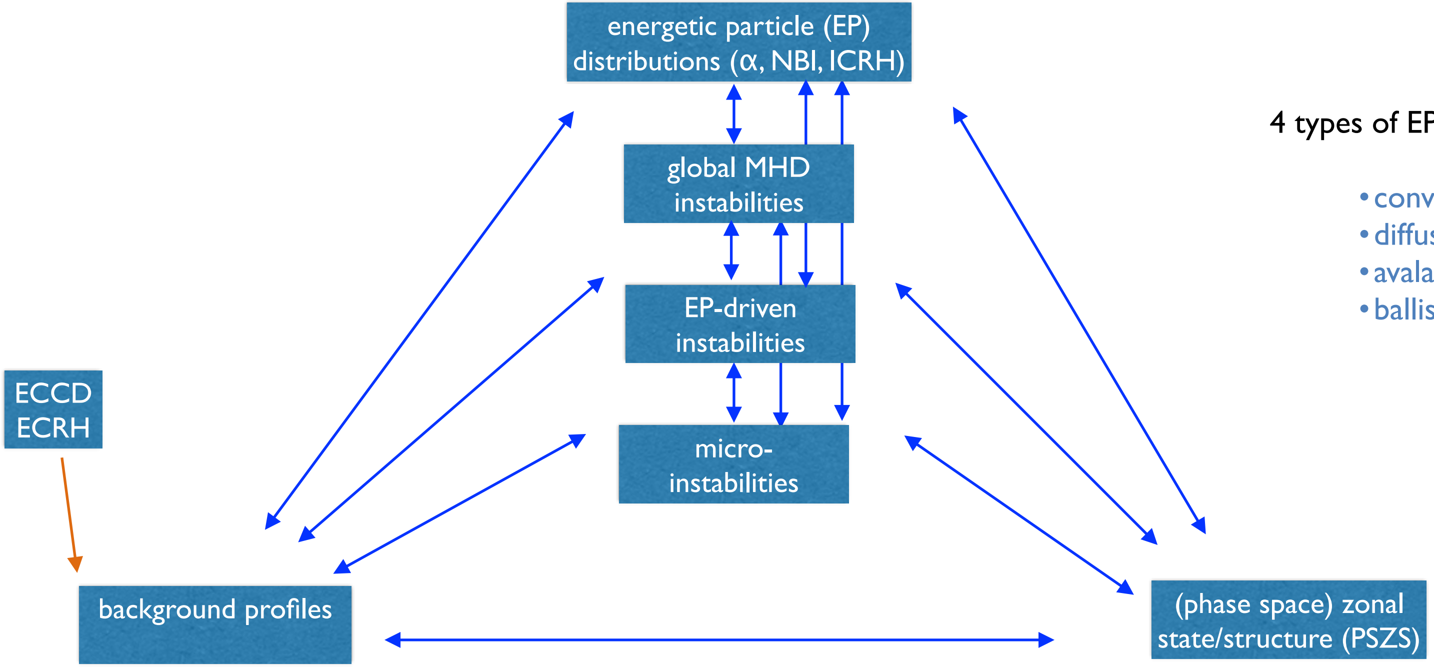
Energetic particle (EPs) transport is a key physics element of burning plasmas



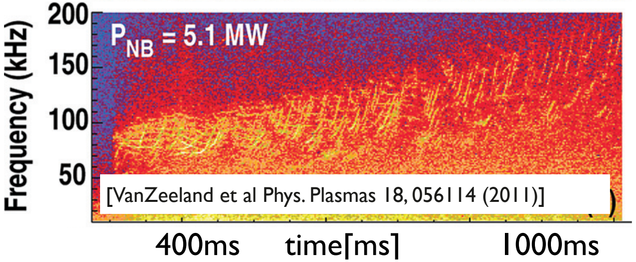
4 types of EP transport:

- convective
- diffusive
- avalanche
- ballistic

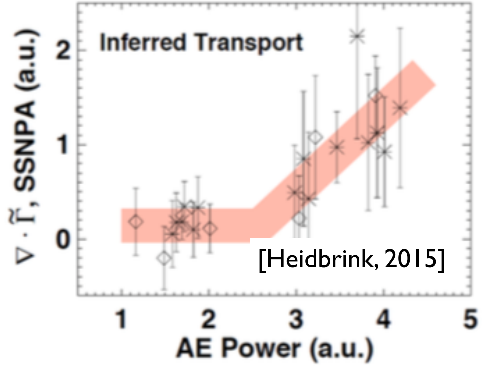
- final goal: predicting the self-organisation of a burning plasma
- challenge: complex interdependence on vastly different spatial and temporal scales

EP transport: experiment

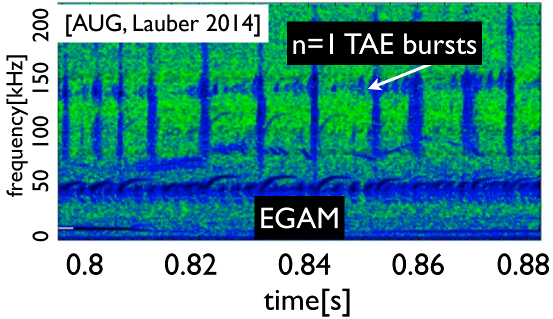
- for multiple overlapping Alfvén eigenmodes (AEs) resonances: stiff EP transport found at DIII-D [Collins, Heidbrink 2015-2018], as predicted by QL theory [Sagedeev&Galeev, Kaufman 1972, …]; high q, large orbits, dominated by losses rather than redistribution
- in JET re-deposition of EPs (ICRH) was observed: core-localised TAEs redistribute EPs, redistributed EPs drive edge-TAE [Nabais et al, PPCF 2019]
- in ITER, both core and edge TAEs are weakly damped and can be driven non-linearly [Pinches, Lauber, Schneller 2014/2015, T Hayward 2019, ORB5]
- mode chirping and avalanches-type events found in many experiments [Kusama, Shinohara, JT-60U 1999+]
- bursting, non-linear mode-mode couplings and EP transport (FIDA, INPA) measured in ASDEX Upgrade EP super-shots [Lauber 2014+], .i.e. further development of AUG NLED benchmarks case [Vlad 2020-2023, Vannini 2019, Rettino 2021-23]



[VanZeeland et al Phys. Plasmas 18, 056114 (2011)]



[Heidbrink, 2015]



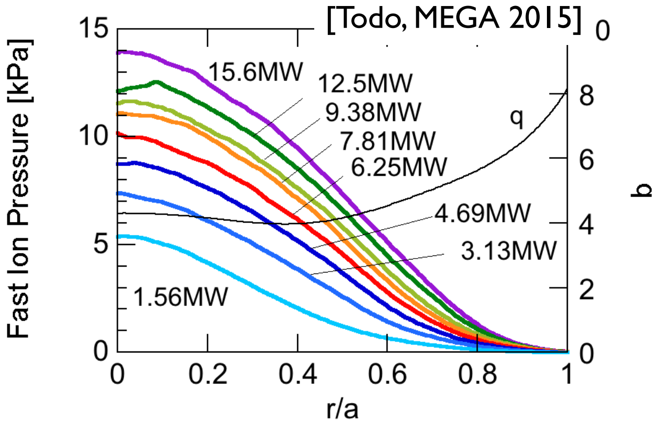
[AUG, Lauber 2014]

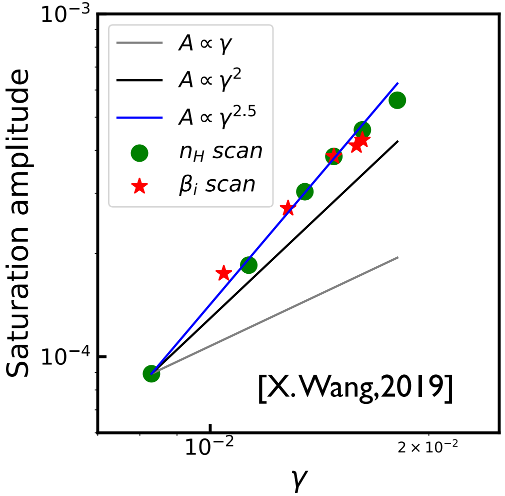
for a comprehensive review please refer to dedicated review articles, e.g. [NF ITPA special issue 2006, update 2023/24, Heidbrink 2008, Breizman& Sharapov 2011, Lauber 2013, Chen&Zonca RMP 2015, Gorelenkov&PinchesToi 2014, Todo 2019,…]

EP transport: modelling

- MHD-hybrid simulations of DIII-D case: transport due to steady and increasingly intermittent EP fluxes for higher power [MEGA, Todo 2015]
- multi-phase MEGA simulations for TAE- avalanches at JT-60U [Bierwage 2016,17];
- at increased EP pressure, so-called energetic particle modes start to exist: simulations as pioneered by (X)HMGC and HYMAGYC teams [Briguglio PoP1998, Bierwage 2012-16]; many dedicated diagnostics developed for phase space analysis
- chirping AE/EPMs: XHMGC simulations [X. Wang, S. Briguglio, 2021]: AE saturation level (and thus related EP transport) due to chirping modes is larger than standard quadratic scaling:

  $A \sim \gamma^{2.5}$
- global GENE and GTC simulations highlight interaction with micro-turbulence [Citrin, diSiena 2019-2023, Brochard 2021-23]
- global ORB5 simulations with increasing complexity start to capture experimentally relevant regimes [A. Biancalani, T Hayward-Schneider, A. Bottino, F. Vannini, B. Rettino 2013-2023] and compare in with MHD-hybrid results [Vlad 2020-23]





- **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?**

EP transport: theory/reduced models

- diffusion coefficients for impurity transport by background turbulence, no e.m. EP-driven modes [Angioni 2009, Püschel, etc]

- critical gradient model [R. Waltz, E. Bass, 2014 -2023]: use local AE stability threshold, add upshift of transport threshold using $(ExB)_{turb}$ shearing rate; above threshold set D_{EP} to ad hoc values [e.g. $10m^2/s$] to clamp EP's radial gradient to critical value

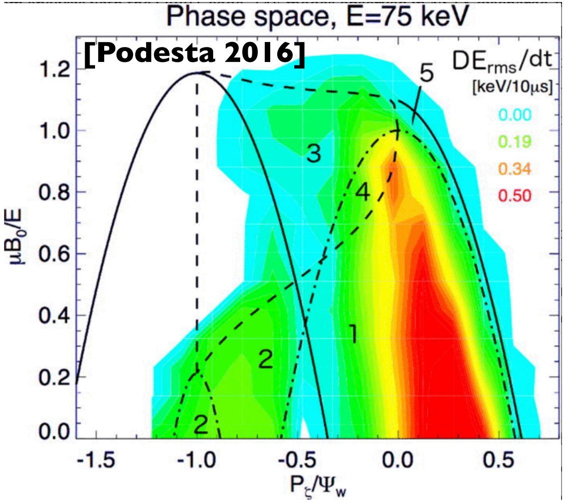
- kick model [M. Podesta, 2014-2022]: calculate probability density function of kick in Pz and E for given amplitude

- RBQ model, 1D, 2D [N. Gorelenkov 2015-2022]: use resonance broadening QL theory connected to NOVA-K to evolve mode amplitude consistently with evolution of F_{EP}

- gyrofluid model [D Spong, 2019-2022], TAEFL code: fluid closures simplify problem, runs on longer time scales

- GENE-Tango model [A. di Siena, 2022-23]: relies on global kinetic GENE runs + power balance

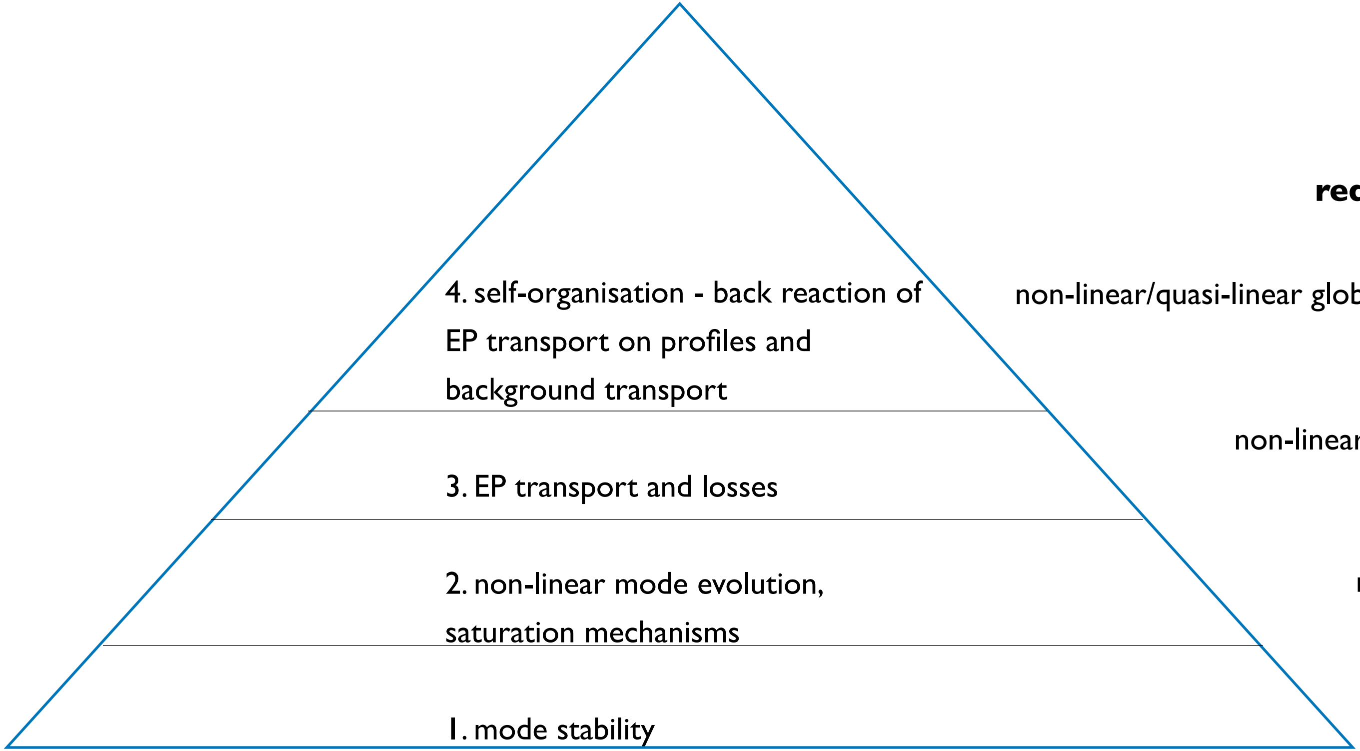
- transport models as derived from general non-linear gyrokinetic theory [Chen, Zonca RMP 2015, Z. Qiu et a 2017-2023] using phase space zonal structure (PSZS) transport theory [M-V. Falessi, F. Zonca, 2017-2023] *see talk M. Falessi at this conference*



within Eurofusion Enabling research project ATEP: based on general theoretical framework, develop and implement hierarchy of (reduced) phase space zonal structure (PSZS) transport models

ingredients for reduced energetic particle (EP) transport models:

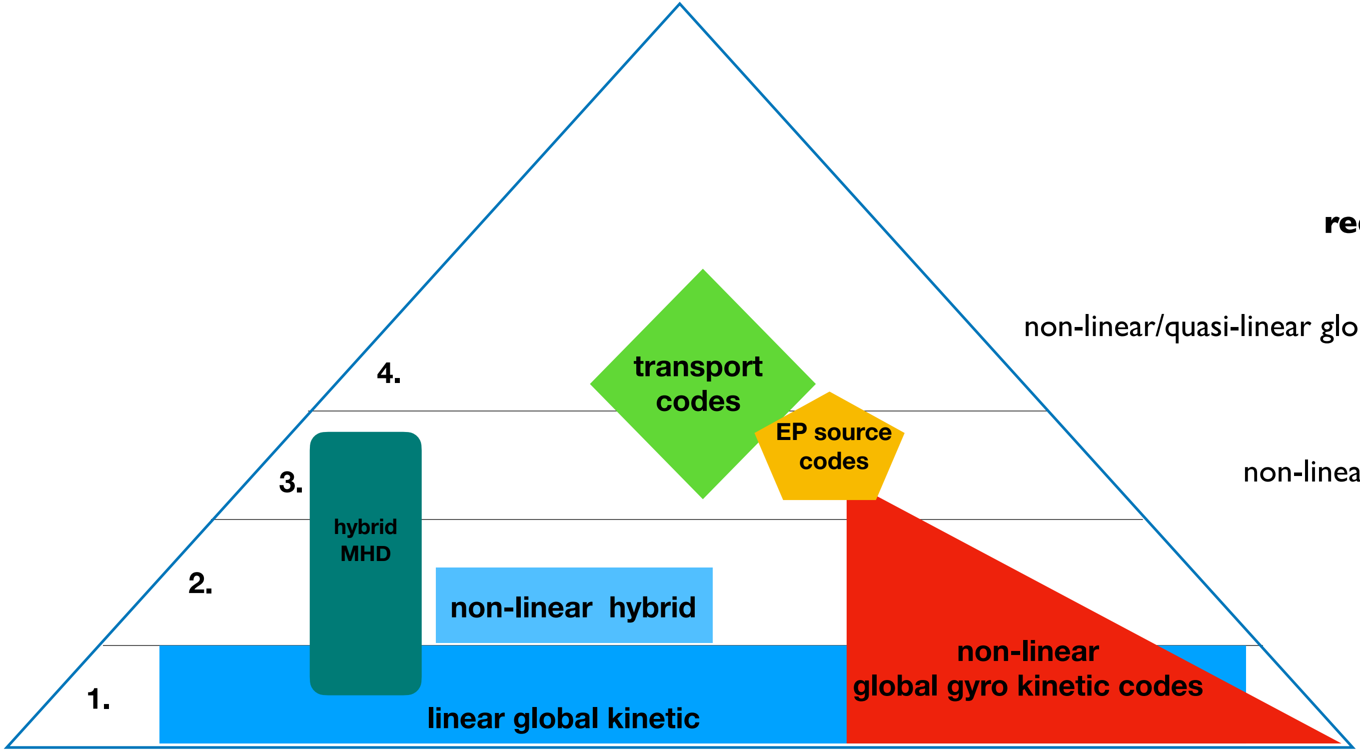
needed for scaling from TCV-AUG-JET, W7X… to JT-60SA-DTT-ITER-DEMO, in particular burning plasmas



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.

modelling hierarchy for plasmas with significant energetic particle pressure



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modelling hierarchy for plasmas with significant energetic particle pressure

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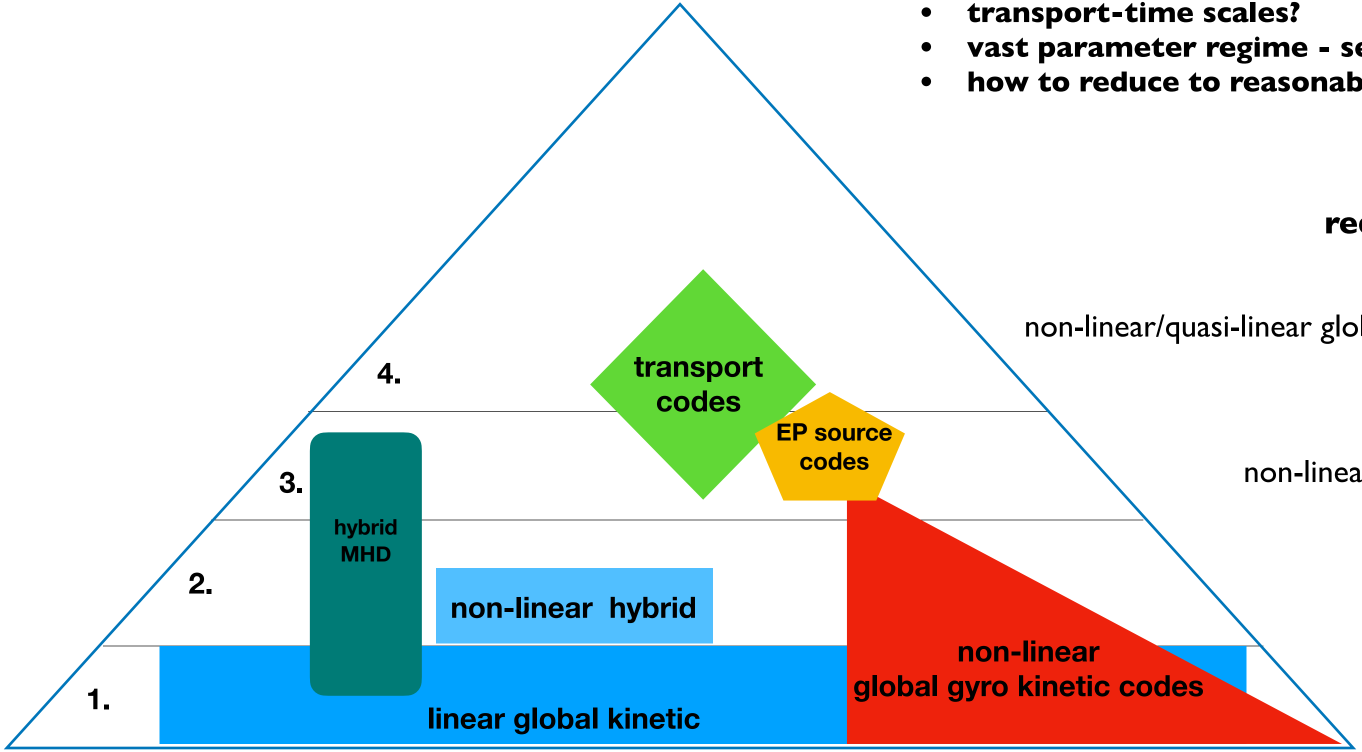

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non-linear/quasi-linear global kinetic e.m.+ background transport

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

non-linear global kinetic e.m.

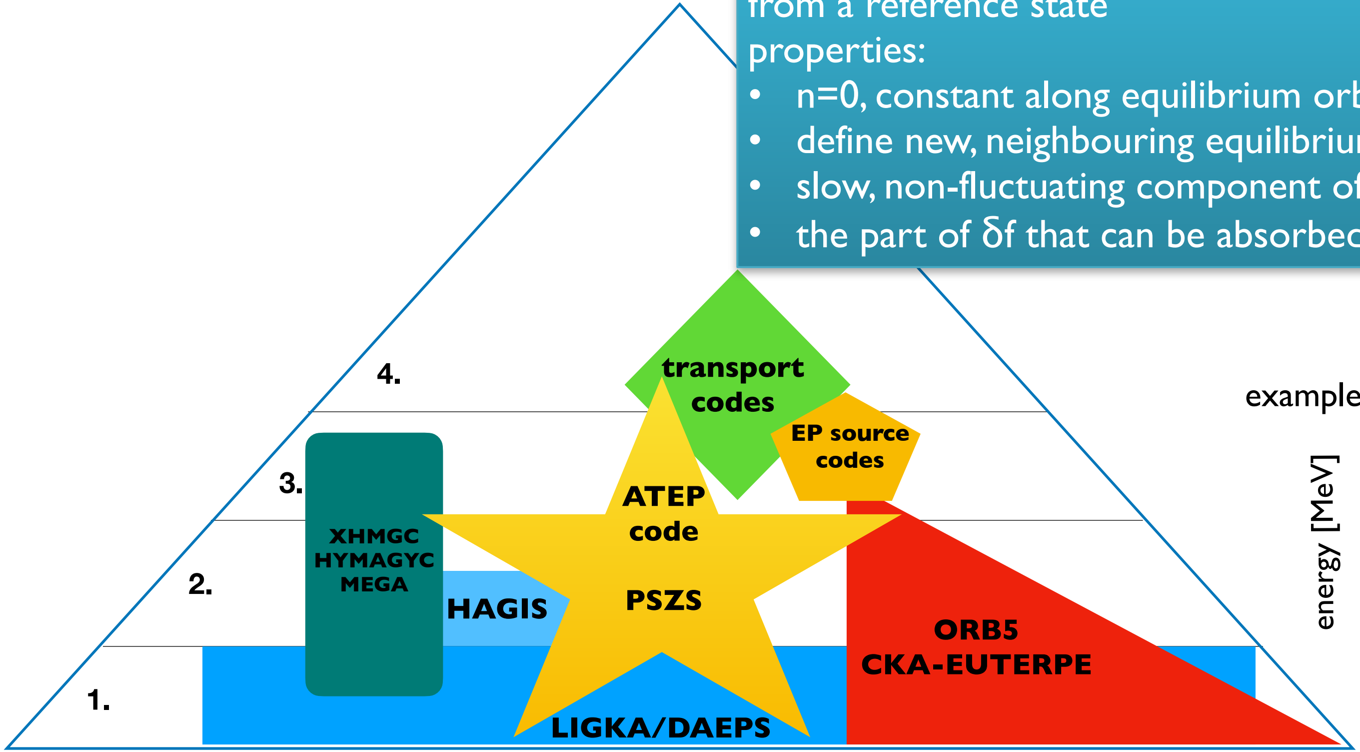
linear global kinetic e.m.

modelling hierarchy for plasmas with significant energetic particle pressure

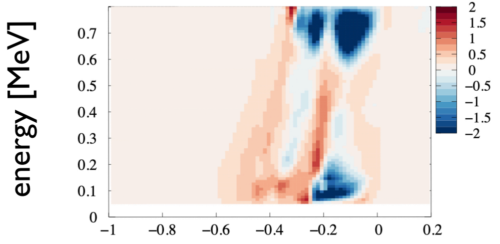
phase space zonal structures (PSZS) are
collision-less undamped, long-lived nonlinear deviations of the plasma from a reference state

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



example in CoM space representation:



canonical toroidal momentum P_Φ

modelling hierarchy for plasmas with significant energetic particle pressure

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collision-less undamped, long-lived nonlinear deviations of the plasma from a reference state
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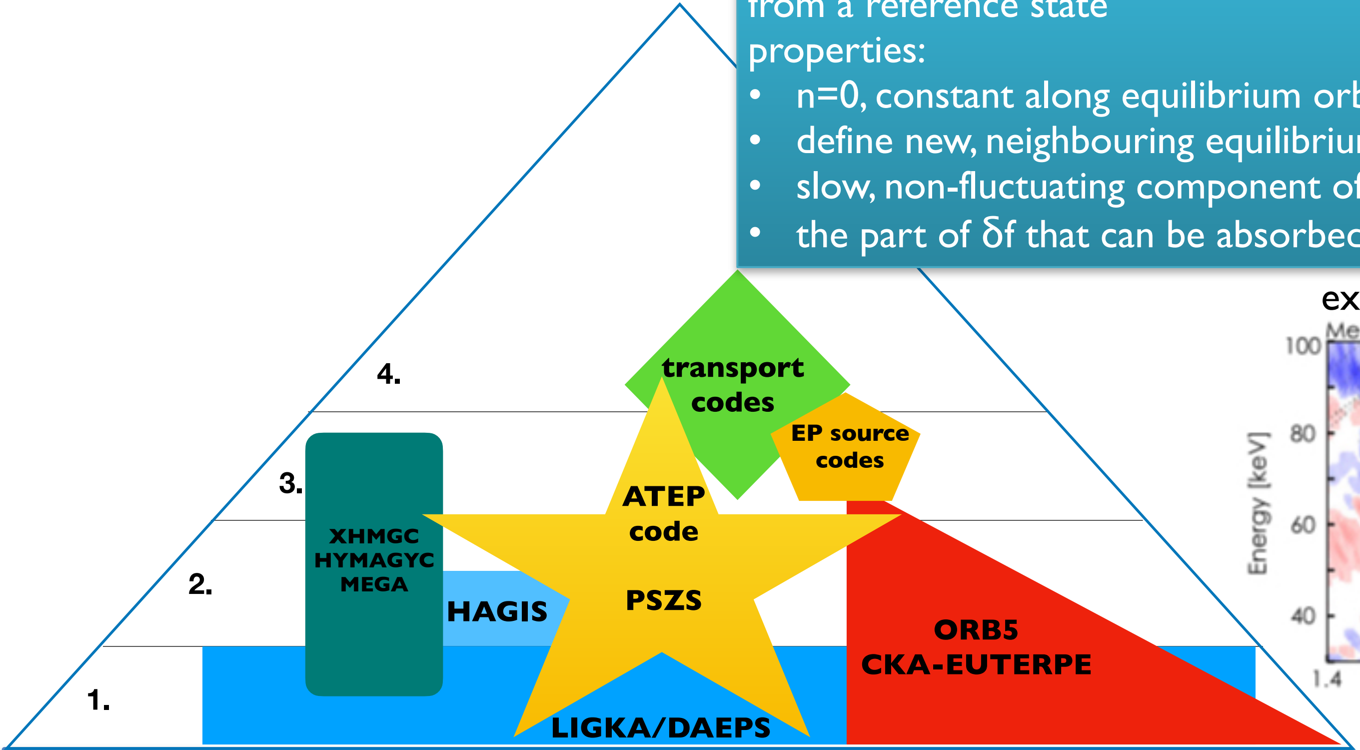
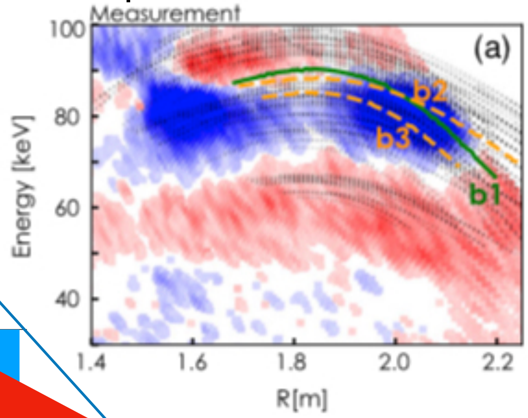


theory: explicit calculation of PSZSs for specific cases (*see talk M. Falessi*)

experiment:



DIII-D, INPA [Du et al PRL 2021]
AUG, INPA J. Rueda [FEC 2023]

outline

- PSZS theory and overall implementation strategy
- general distribution functions in constants of motion space (CoM)
- linear mode spectrum: the Energetic Particle Stability Workflow (EP-WF)
- phase space transport coefficients
- evolve transport equation in kick model and quasi-linear (QL) limit
- back mapping to real space and non-linear equilibria
- verification and validation - common effort of ENR ATEP team

PSZS transport theory and its connection to kick and QL limits

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

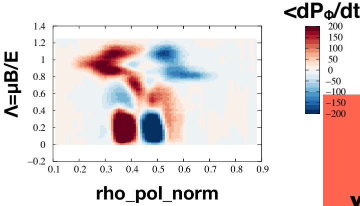
$\nabla_z \cdot \Gamma$ collisions + source

wave-induced phase space flux

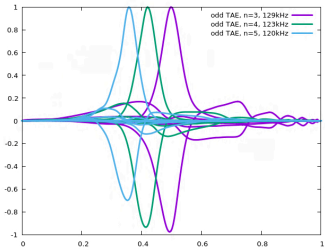
[M-V. Falessi, F. Zonca, 2017-2023]
continuity equation in phase space;
valid for single or multiple modes
in general valid for all regimes;
interactions with background fluctuations can be consistently kept

- kick limit: fix perturbations amplitudes for calculating $\langle dP_\Phi/dt \rangle$ and evolve continuity equation in CoM space
- in the QL limit, assuming overlapping resonances, flux can be split into convective and diffusive component [L Chen, JGR 104, 1999]
- diffusion coefficients can be evaluated by determining $D_{P\Phi P\Phi} = |dP_\Phi/dt|^2\, \tau_{ac}$, similar for D_{EE}, and off diagonal terms (if present), resonant and non-resonant contributions can be separated
- in [L Chen, JGR 104, 1999] also the importance of $E_{//}$ is discussed (KAW physics), leading to additional convective flux contributions (linear GK code LIGKA provides this information - see below)

implementation using IMAS: kick model limit

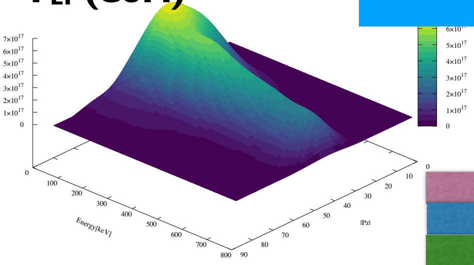


calculate transport with prescribed amplitude



calculate unstable linear mode spectrum

F$_{EP}$ (CoM)



calculate D(r,E)

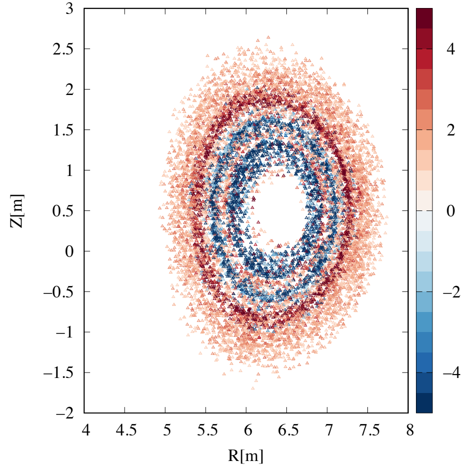
shortcut: critical gradient model with ad hoc D, local limit

or

advance F$_{EP}$ and return updated F$_{EP}$ into IDS, or its moments

PSZS transport theory [M. Falessi 2017-2022]

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



newly developed ATEP/ ATEP-3D code [Ph. Lauber, G. Meng,2022-23]

t

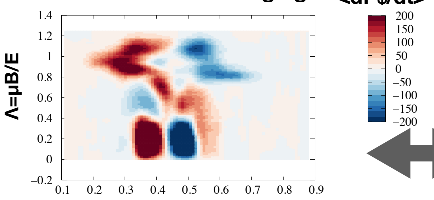
t+1

mhd_linear
distributions
core profiles
equilibrium

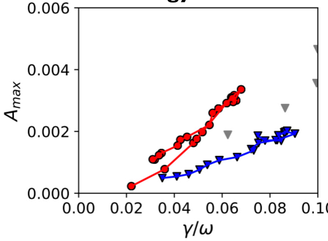
time

implementation: QL limit

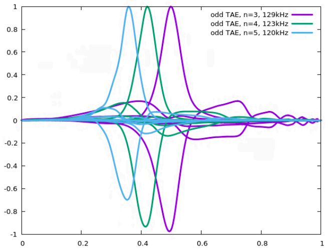
orbit+zonal averaging



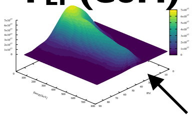
saturation rule/energy conservation (HAGIS model)



EP WF (LIGKA)



F_{EP} (CoM)



calculate PSZS

use NL code/model for intensity closure

calculate linear mode spectrum

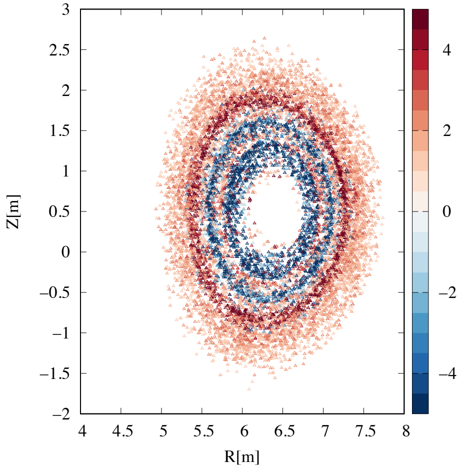
PSZS transport theory [M. Falessi 2017-2022]

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

calculate D(r,E)

or

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



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t

t+1

mhd_linear

distributions

core profiles

equilibrium

transport code

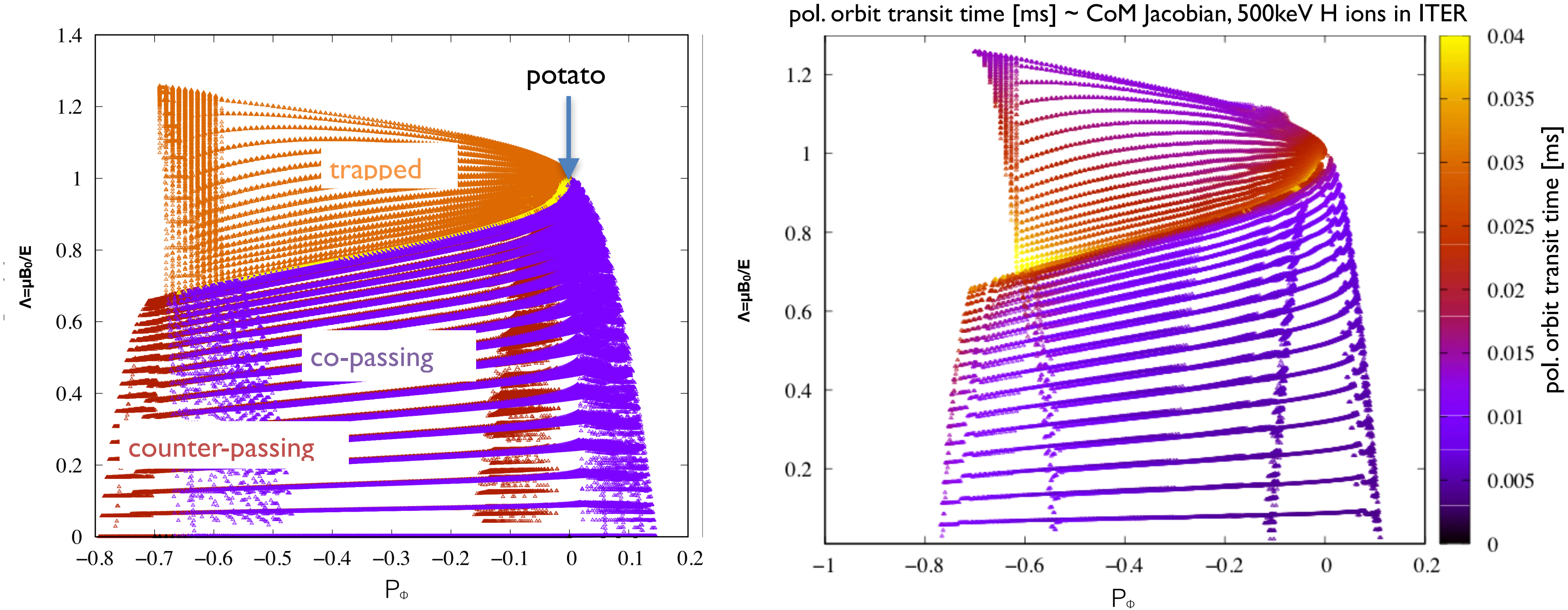
time

determining F_{EP} in constants of motion space (CoM)

determining F_{EP} in constants of motion space (CoM)

several recent papers [Bierwage 2022, G. Brochard, FEC 2023, Salewski 2020-21] using a similar procedure:

- establish orbit database to classify particles
- determine CoM Jacobian (P_Φ,E,Λ,μB_0/E,σ)
- set up grid in CoM space
- bin markers as given by neoclassical physics codes [NEMO/Spot, ASCOT, RABBIT, etc…], here ITER H-pre-fusion case 100015,1 [M. Schneider, 2018]



determining F_{EP} in constants of motion space (CoM)

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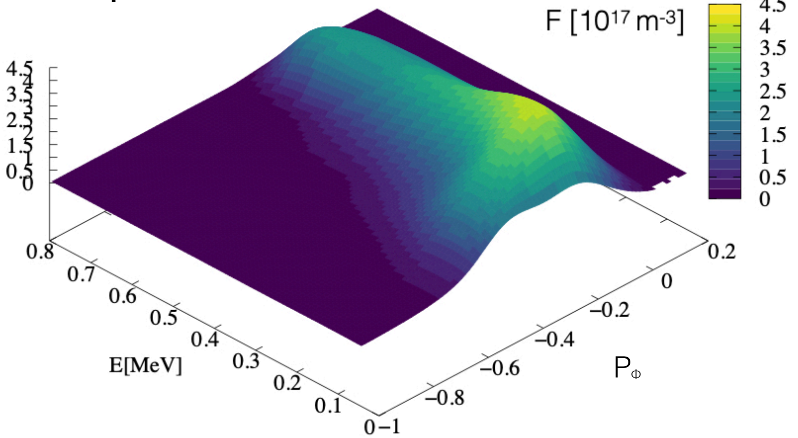
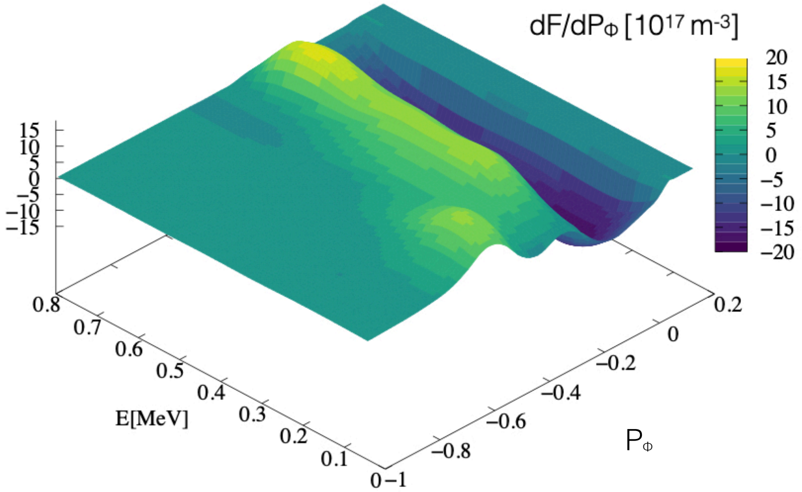
- use 2D cubic splines in each sub-space to create fine sub-grids, then create 3D spline for F_{EP}
- back-transform in other coordinate systems possible, if needed
- here, all calculations are using IMAS interfaces (equilibrium, transport code, orbit tracer (HAGIS [S.D. Pinches]), ATEP code)

slice for $\Lambda=\mu B_0/E = 0.5$





Calculating the mode spectrum

Linear mode spectrum: Energetic particle stability workflow (LIGKA)

LIGKA [Qin 1998, Lauber 2003, JPC 2007, Lauber PLREP 2013, Bierwage&Lauber 2017, Lauber JPCS 2018]

https://git.iter.org/projects/STAB/repos/ligka/

- gyrokinetic moment equation (GKM):

shear Alfvén law

$$-\frac{\partial}{\partial t}\left[\nabla\cdot\frac{1}{v_A^2}\nabla_\perp\phi\right]+\boldsymbol{B}\cdot\nabla\frac{\nabla\times(\nabla\times(\frac{\nabla\psi}{i\omega})_\parallel\boldsymbol{b})}{B}+(\boldsymbol{b}\times\nabla(\frac{\nabla\psi}{i\omega})_\parallel\boldsymbol{b})\cdot\nabla\frac{\mu_0 j_\parallel}{B}$$

$$=-\sum_a\mu_0\int \mathrm{d}^2v\, e_a\{\boldsymbol{v}_\mathrm{d}\cdot\nabla J_0 f\}_a+\sum_a\left[\boldsymbol{b}\times\nabla\left(\frac{\beta_{a\perp}}{2\Omega_a}\right)\right]\cdot\nabla\nabla_\perp^2\phi$$

'pressure' tensor - curvature drift coupling

$$+\sum_a\frac{3v_{th,a}^2}{8v_A^2\Omega_a^2}\nabla_\perp^4\frac{\partial\phi}{\partial t}+\boldsymbol{B}\cdot\nabla\frac{1}{B}\sum_a\frac{\beta_a}{4}\nabla_\perp^2(\frac{\nabla\psi}{i\omega})_\parallel\boldsymbol{b}$$

reduced MHD as limit; various successful benchmarks with ORB5 [Hayward-Schneider, 2021-23]

- quasi neutrality (QN):

$$0=\sum_a e_a\int \mathrm{d}^2v\,\{J_0 f\}_a+\nabla_\perp\cdot\frac{m_i n_i\nabla_\perp\phi}{B^2}$$

- non-adiabatic response for perturbed distribution function:

propagator →resonance

$$\hat{h}=ie\sum_m\int_{-\infty}^{t}dt'\,e^{i[n(\varphi'-\varphi)-m(\theta'-\theta)-\omega(t'-t)]}e^{-im\theta}$$

$$\frac{\partial F_0}{\partial E}[\omega-\hat{\omega}_*]\,J_0^2(k_\perp\varrho_i)\left[\phi_m(r')-(1-\frac{\omega_d(r',\theta')}{\omega})\psi_m(r')\right]$$

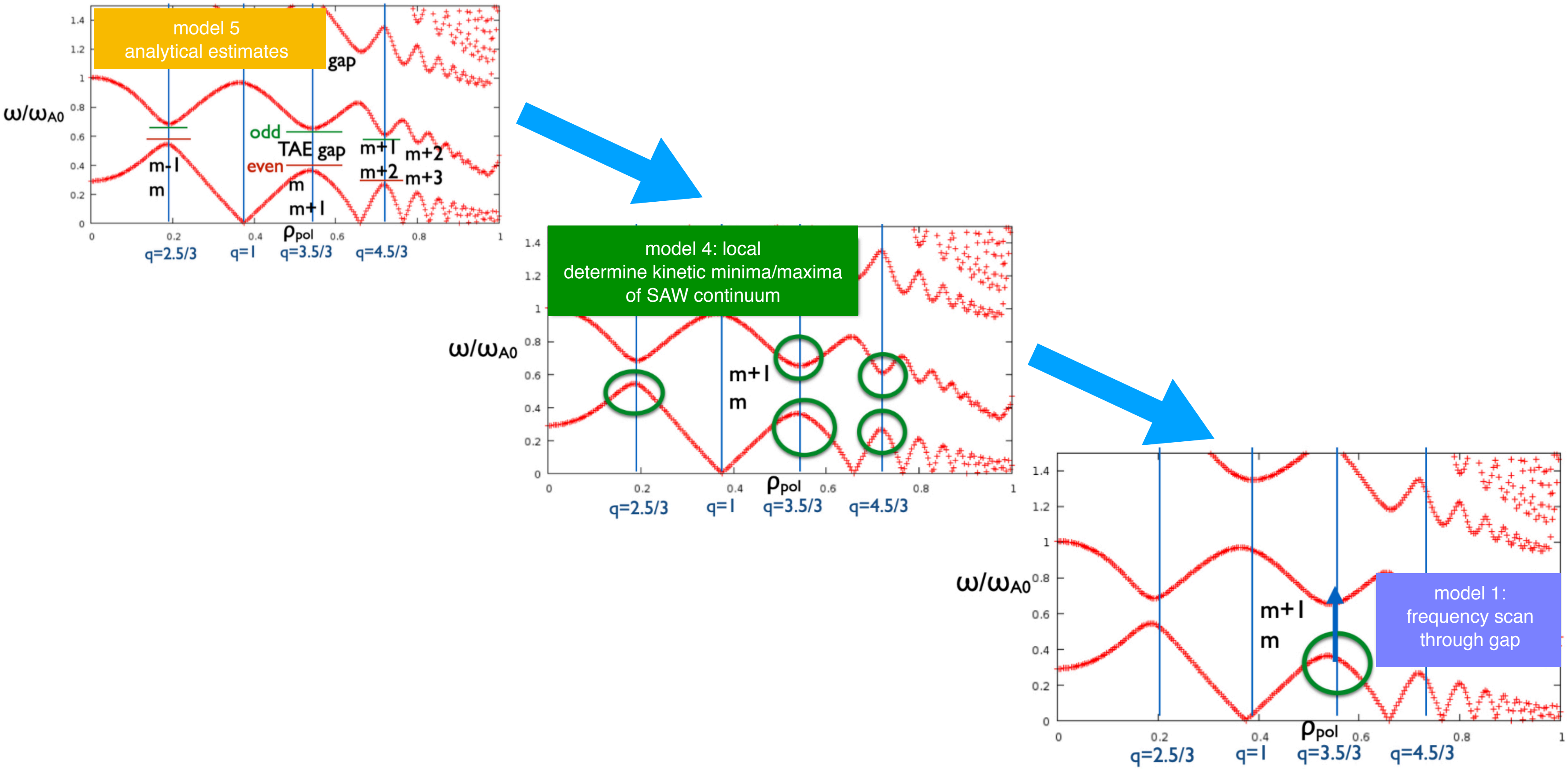
free energy

resonances (circ/trapped):

$$\begin{cases}\omega_{AE}-\omega_{prec}-(nq-m+k)\cdot\omega_t=0\\ \omega_{AE}-\omega_{prec}-k\cdot\omega_b=0\end{cases}$$

for all species , including electrons and energetic particles

Linear mode spectrum: Energetic particle stability workflow (EP-WF)

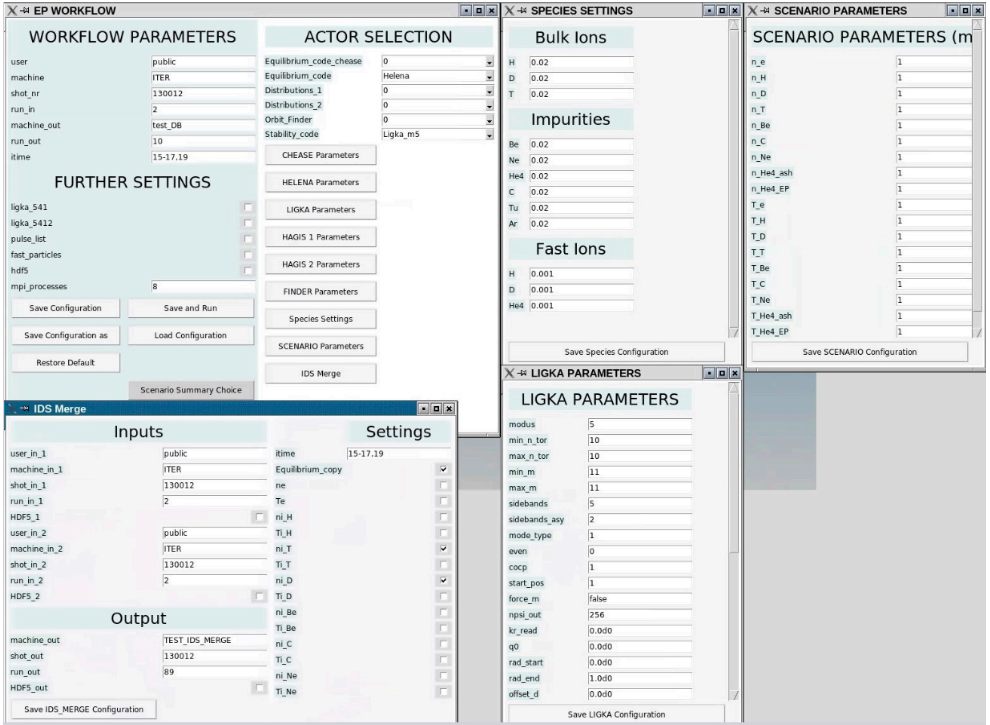


EP-WF: available on Eurofusion Gateway and ITER cluster

[V.-A. Popa et al 2023 Nucl. Fusion 63]

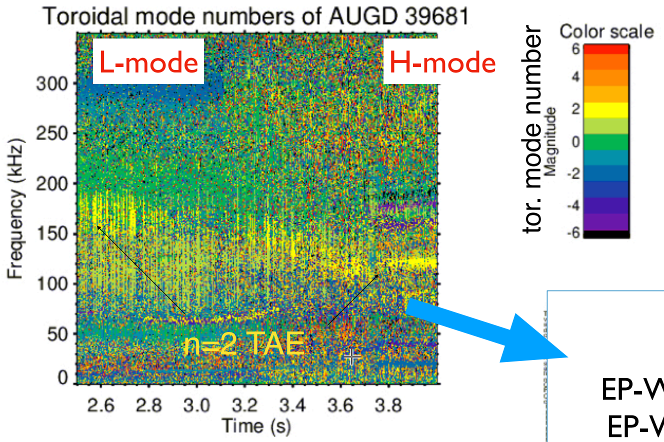
training course & additional material: https://indico.euro-fusion.org/event/2729/

- fully IMAS compatible (python)
- git version control
- module installations available
- gui and non-gui versions
- batch job submission



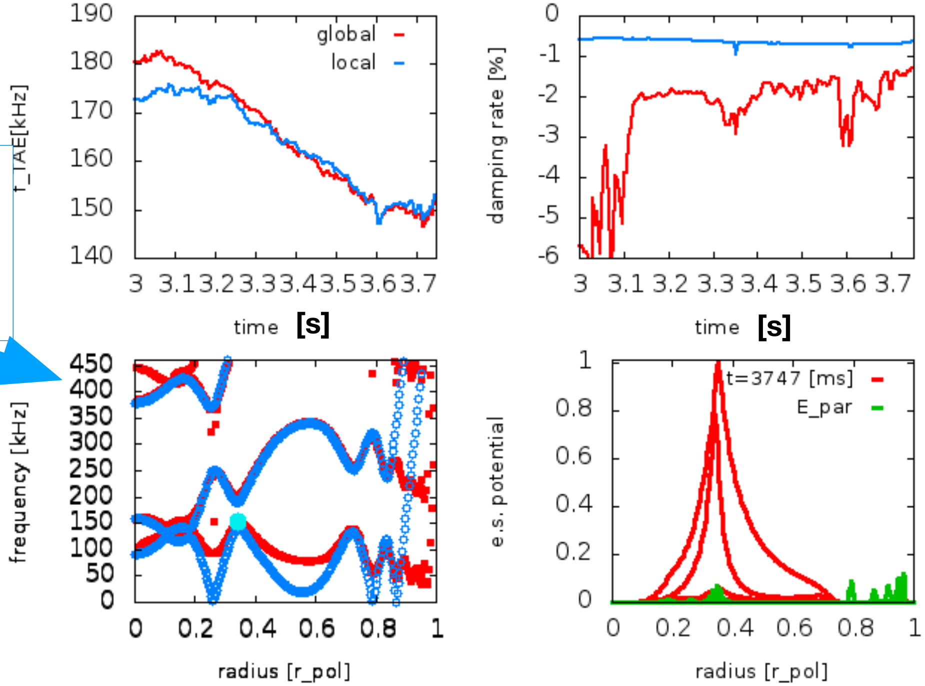
Energetic particle stability workflow: validation at ASDEX Upgrade

AUG EP 'supershot' scenarios: D NBI into D plasma
(further development of NLED AUG benchmark case)



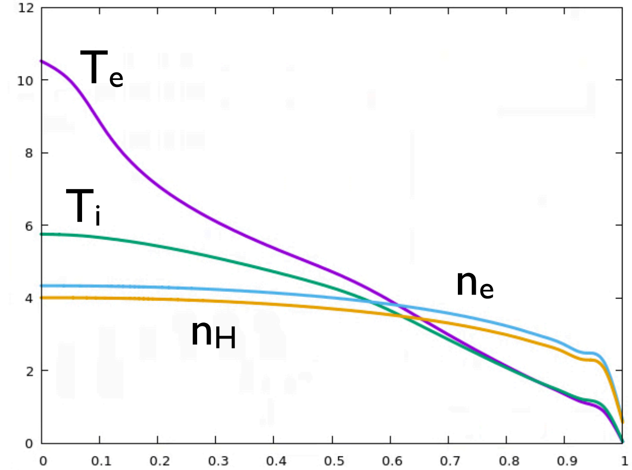
[Lauber, EPS 2022]

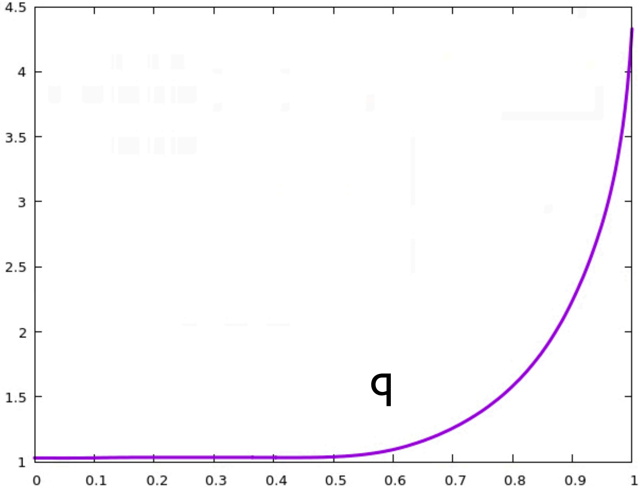
IDA +
TRVIEW +
EP-WF: LIGKA local +
EP-WF: LIGKA global



- analyse L-mode, H-mode and transition phase using
- systematic uncertainty quantification feasible
- bursty and steady-state phases visible, in agreement with damping analysis and drive
- speed up WF using ML methods [V.-A. Popa; in preparation]

ITER pre-fusion H scenario 100015,1 [Metis, M. Schneider NF (2021)]



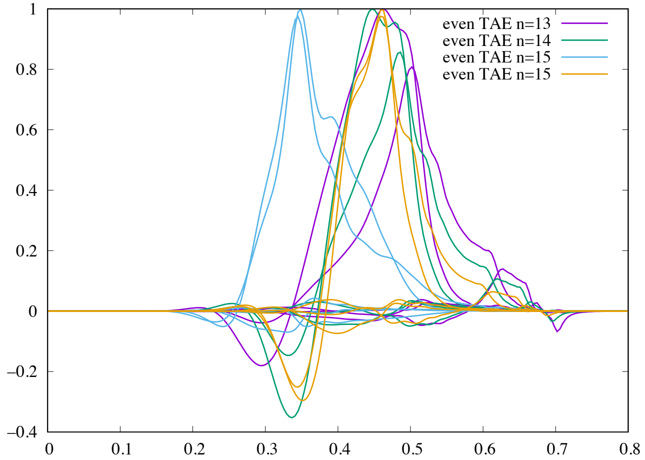


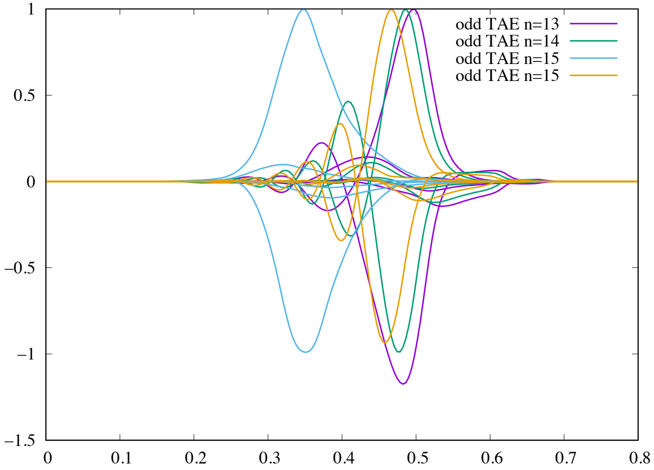
use set of mid-n TAEs as test case (as all data is consistently available in IMAS thx to M. Schneider)

B=-5 T
I= -1.8 MA

small damping rates: 1-5%

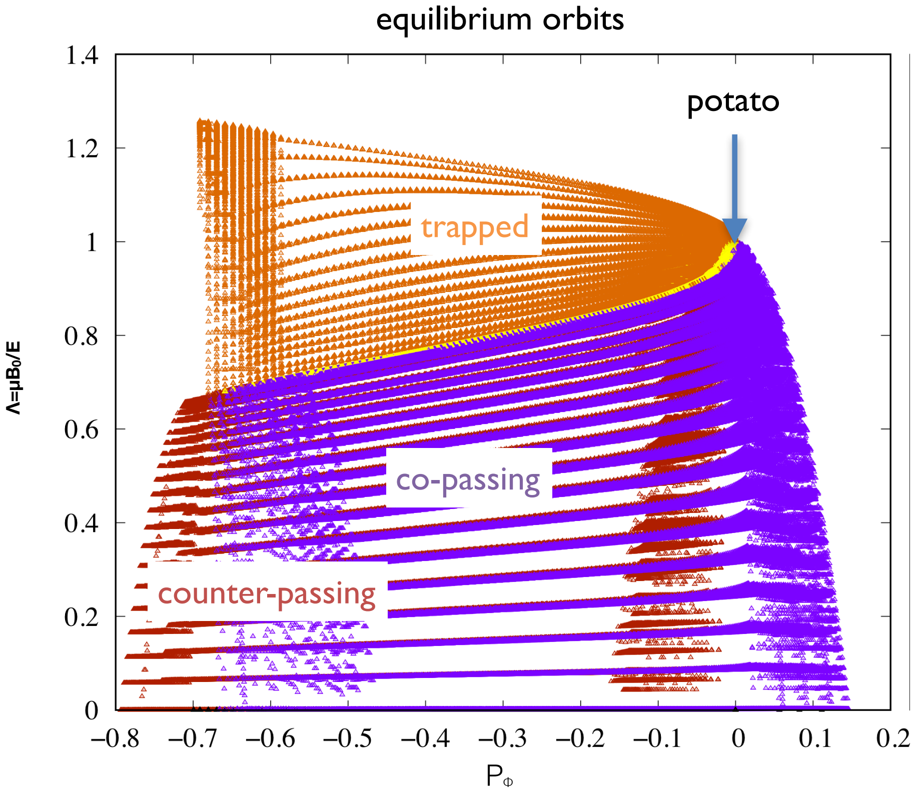
with H beam (870 keV)marginally unstable



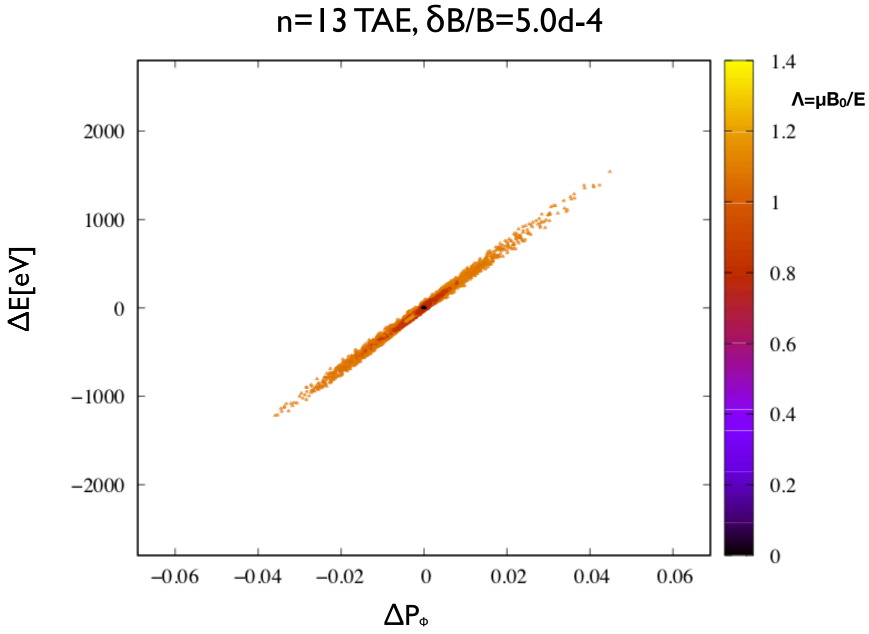


determine phase space transport coefficients

classify particles, calculate orbit properties with and without perturbation(s)



with perturbation: dP/dt and dE/dt of resonant particles in single wave are proportional to each other



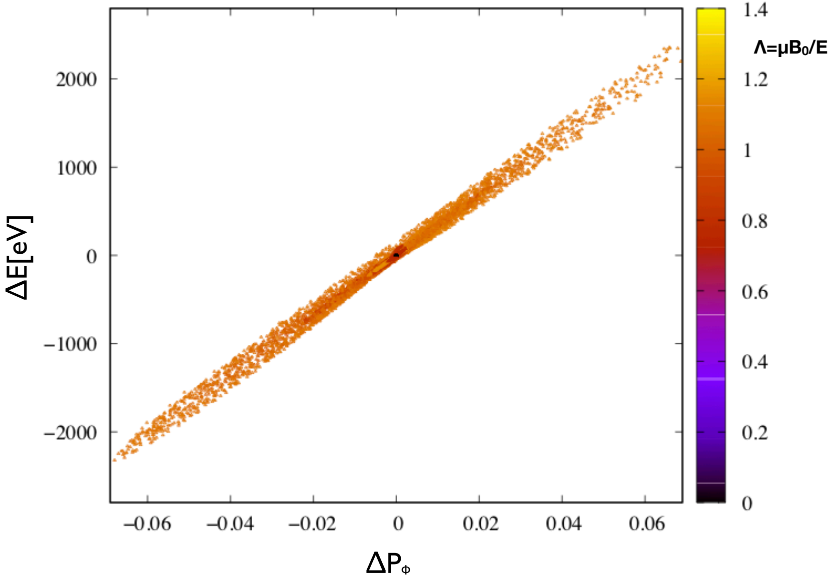
use wrapper ('finder') for HAGIS [S.D. Pinches] to efficiently set up marker space

off-diagonal elements play a role in multi-mode cases, or with $E_{//}$

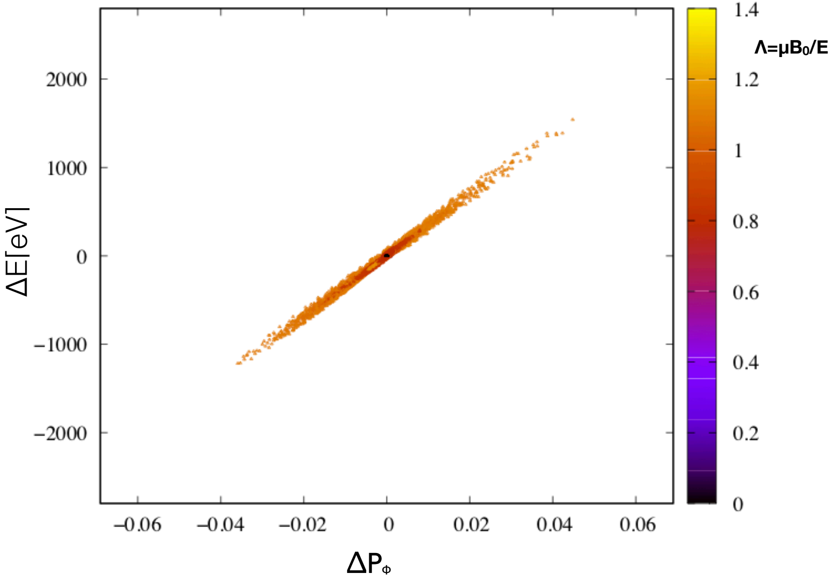
classify particles, calculate orbit properties with and without perturbation(s)

with perturbation: dP/dt and dE/dt of resonant particles in single wave are proportional to each other [Southwood, 1969]

n=13 + n=14 TAE, δB/B=5.0d-4



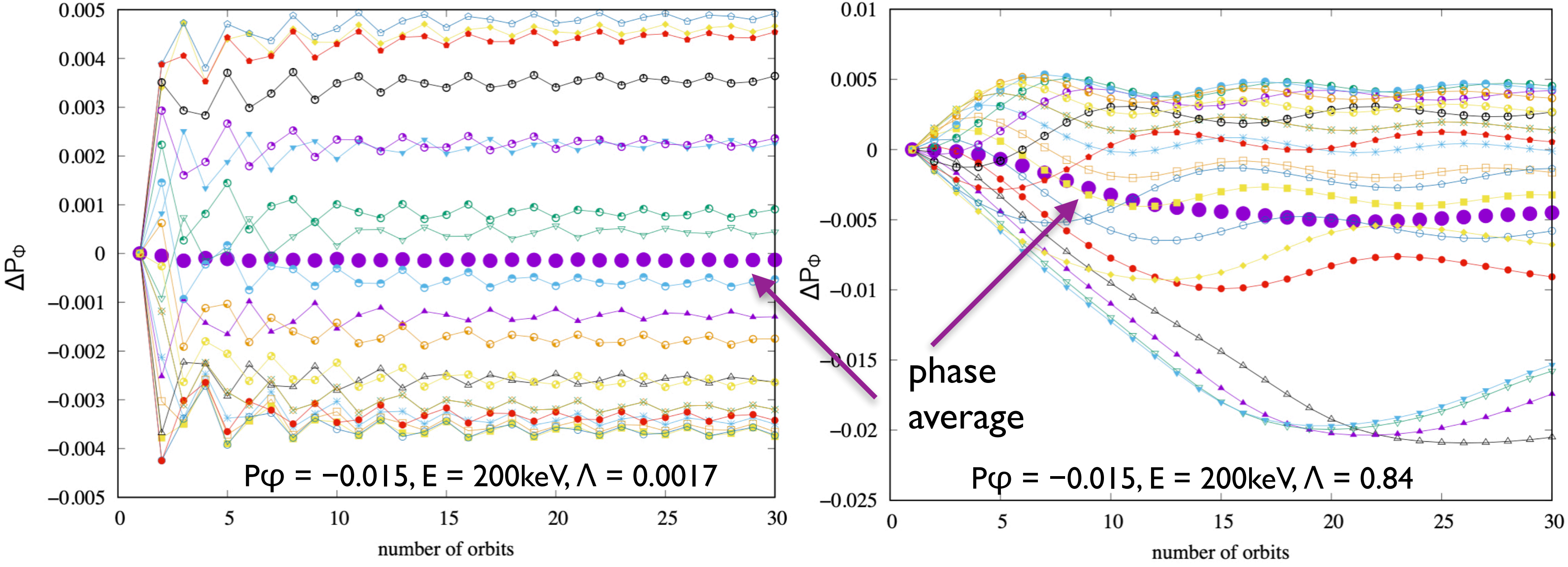
n=13 TAE, δB/B=5.0d-4



off-diagonal elements play a role in multi-mode cases, or with $E_{//}$

zonal and orbit averaging

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)



non-resonant

resonant

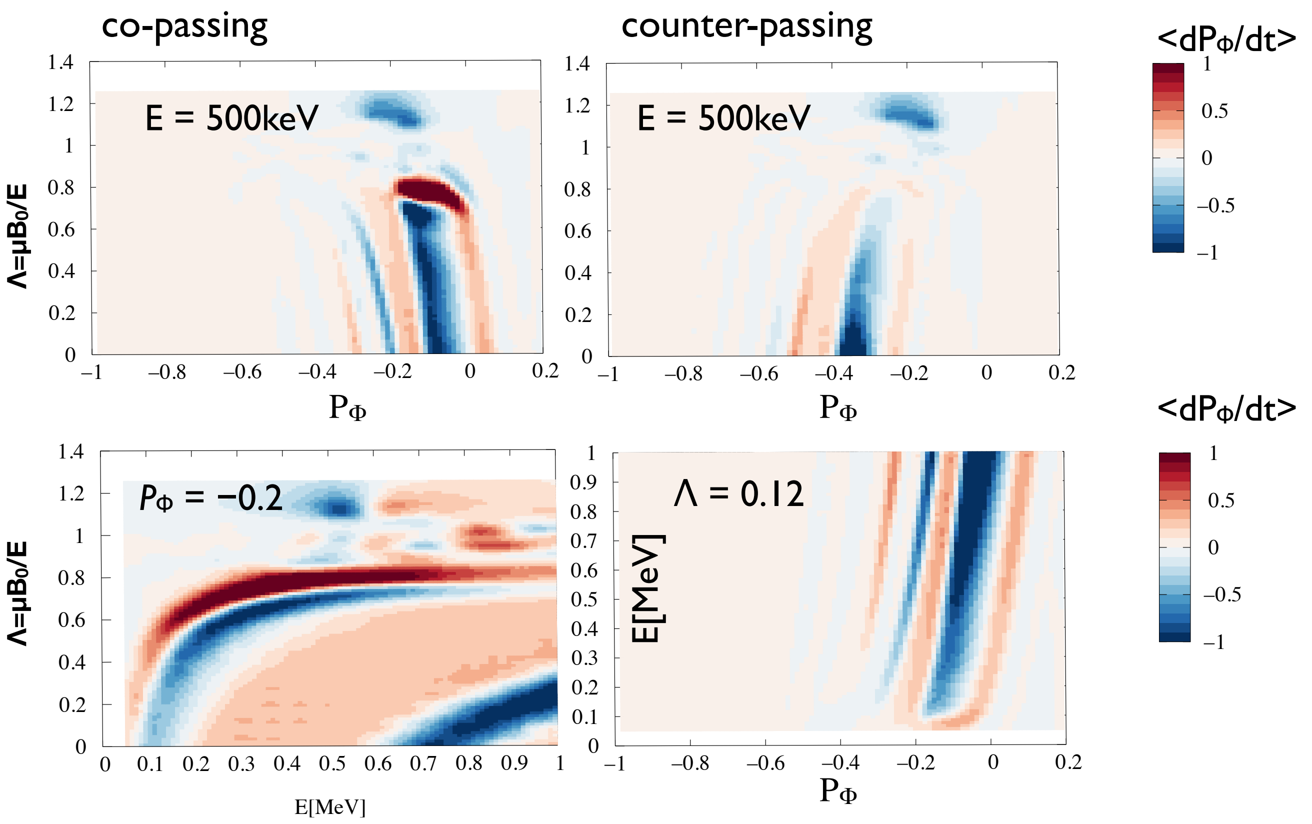
caveat: this procedure is reducing the full dynamics: valid in small-amplitude/QL/limit, transport time scales can be improved, relaxed if needed (ballistic transport cases);

note also close relation to P_Φ grid resolution/Courant criterion; accounts for resonance broadening consistently

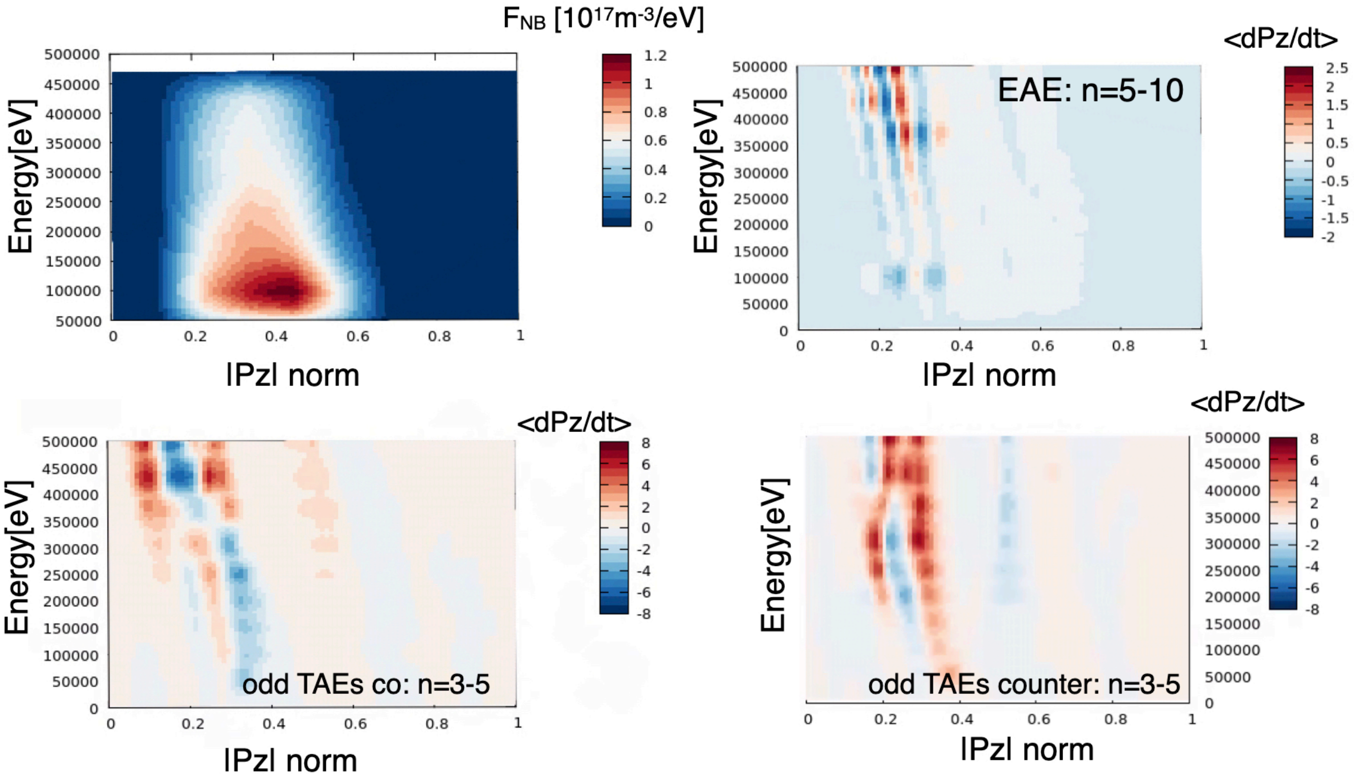
zonal and orbit averaging: <dP_Φ/dt> in CoM representation

$\delta B/B = 5 \cdot 10^{-6}$

- typically follow 128x40x40x4 markers
- store in IDS (distributions)
- use multi-level spline interpolation [Lee 1997]
- use cartesian grid in CoM space (96x96x96)



PSZS for EAEs and odd TAEs



all plots for $\Lambda=\mu B_0/E=0.24$

resonances with both positive and negative gradients of F_{EP} possible

evolve transport equations in kick-model limit

zonal and orbit averaging: <dP$_\Phi$/dt> in CoM representation

$\delta B/B = 5 \cdot 10^{-6}$

- typically follow 128x40x40x4 markers
- store in IDS (distributions)

- use multi-level spline interpolation [Lee 1997]
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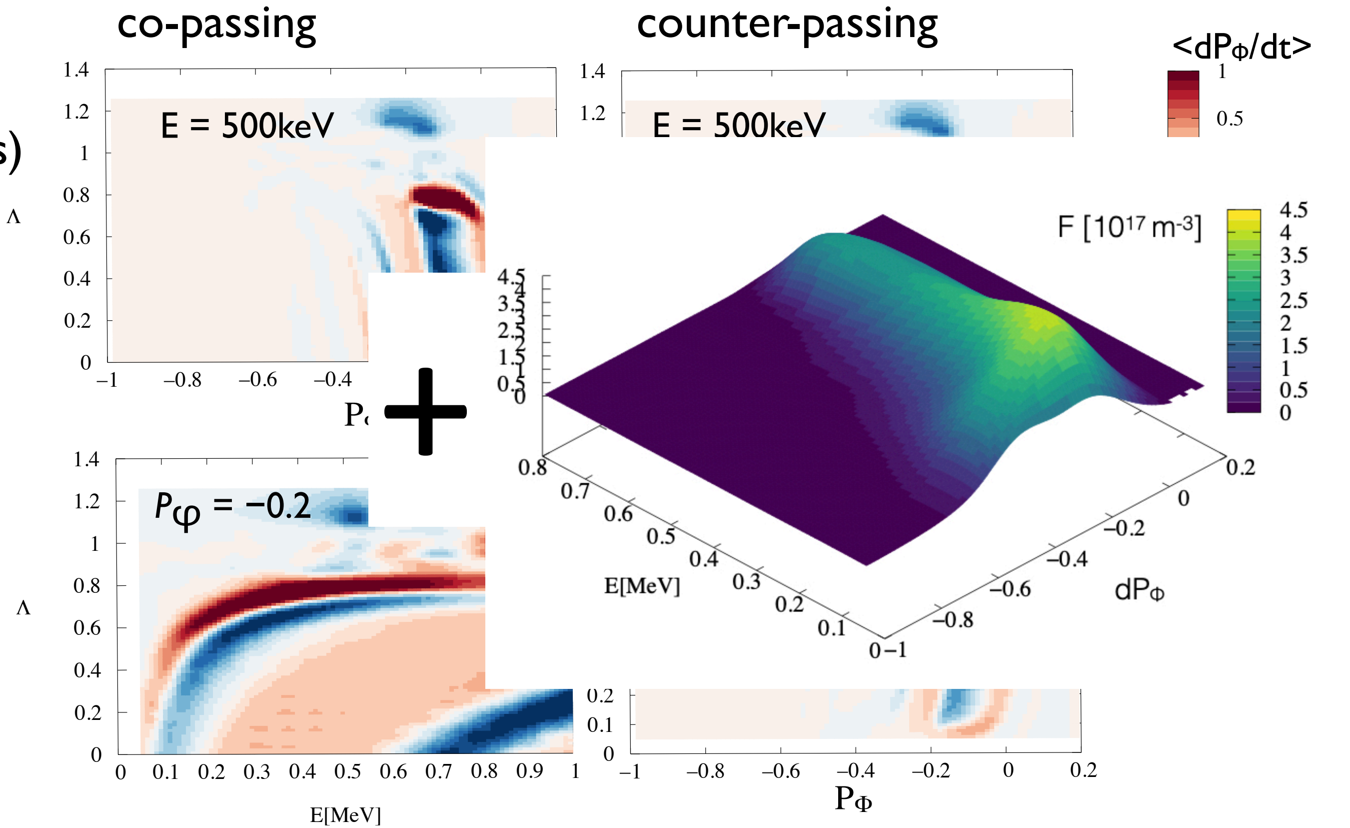
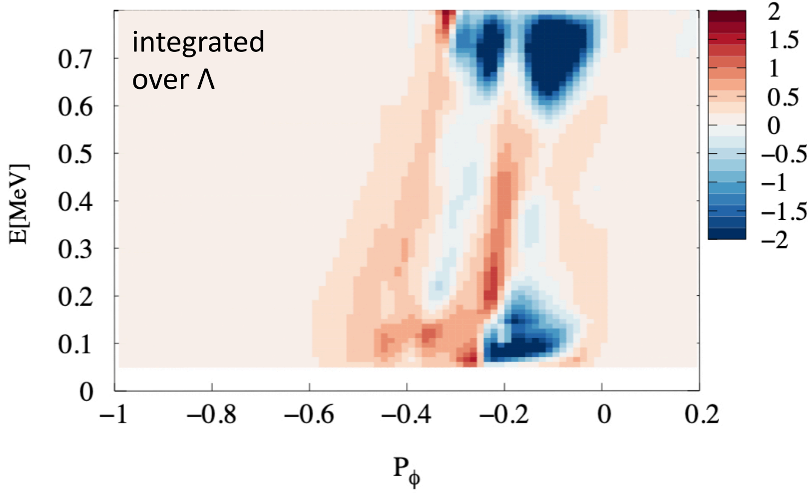


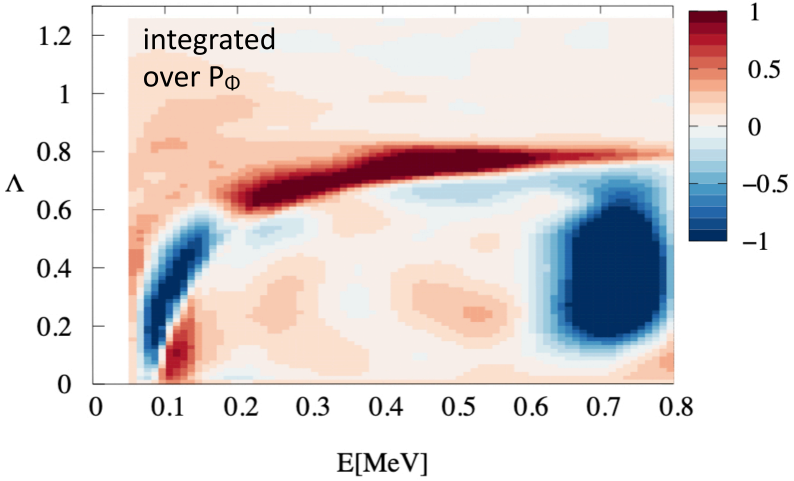
evolve continuity equation for Fz in CoM space

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

advection equation, assuming $\nabla \cdot \mathbf{v}_{P_\phi,E} = 0$ i.e. incompressible phase space flow is evolved with Lax-Wendroff scheme (explicit, adaptive time step - Courant limit)

$\delta F_{EP} = F_{EP}(t = 700ms) - F_{EP}(t = 0)[10^{16} m^{-3}]$ with constant $\delta B(t)/B = 10^{-5}$





evolve continuity equation for Fz in CoM space

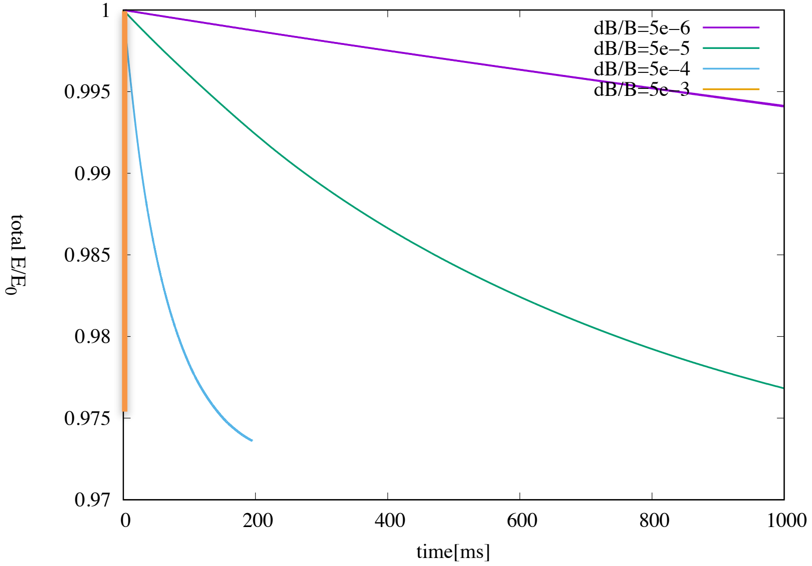
$$\frac{\partial F_z}{\partial t} = -\frac{\partial}{\partial P_\phi}\left(\langle\overline{\frac{dP_\phi}{dt}}\rangle F_z\right) - \frac{\partial}{\partial E}\left(\langle\overline{\frac{dE}{dt}}\rangle F_z\right) \qquad \mathbf{v}_{P_\phi,E} = \left(\langle\overline{\frac{dP_\phi}{dt}}\rangle, \langle\overline{\frac{dE}{dt}}\rangle\right)$$

advection equation, assuming $\nabla \cdot \mathbf{v}_{P_\phi,E} = 0$, i.e. incompressible phase space flow
is evolved with Lax-Wendroff scheme (explicit, adaptive time step - Courant limit)

phase space density is conserved
add energy diagnostic:

$$\mathscr{E}(t) = \int dv_{P_\phi,E,\Lambda} E \cdot F_{EP}(t)/E_0$$

if perturbations are consistently chosen
i.e. as unstable eigenfunctions of the equilibrium,
energy stored in gradients of F_{EP} is depleted



evolve continuity equation for Fz in CoM space

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

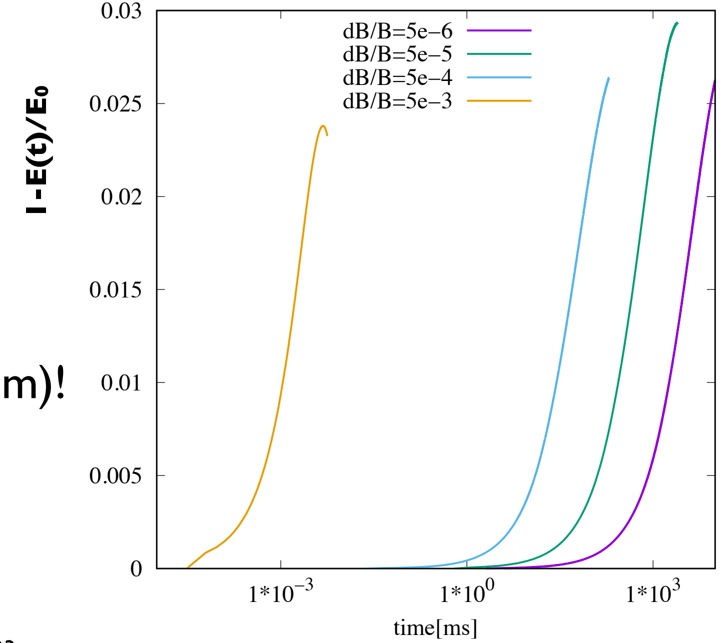
advection equation, assuming $\nabla \cdot \mathbf{v}_{P_\phi,E} = 0$ i.e. incompressible phase space flow is evolved with Lax-Wendroff scheme (explicit, adaptive time step - Courant limit)

phase space density is conserved
add energy diagnostic:

$$\mathscr{E}(t) = \int dv_{P_\phi,E,\Lambda} E \cdot F_{EP}(t)/E_0$$

note that energy can also increase (forced driven system)!

find minimum in energy, defining the maximally relaxed state of F_{EP} in presence of a fixed perturbation



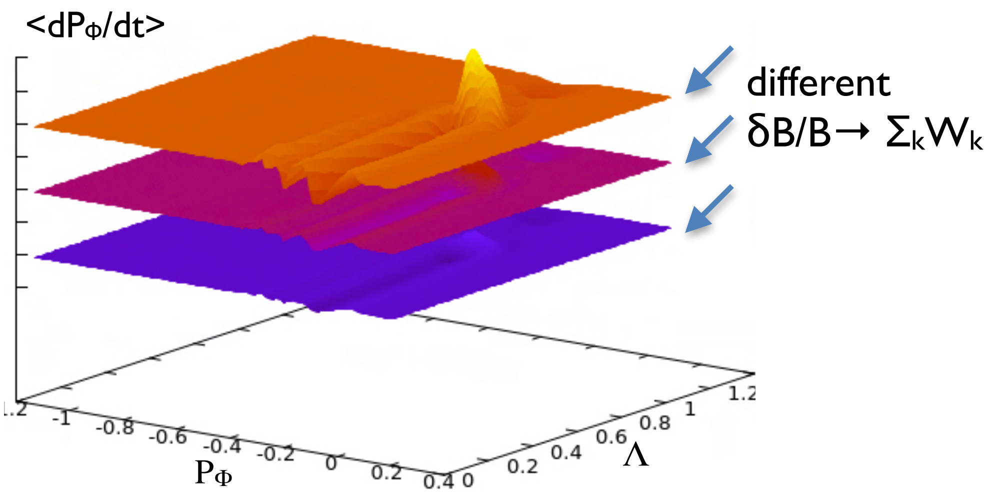
evolve transport equations in quasi-linear limit (QL)

quasi-linear model: add energy conservation equation

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

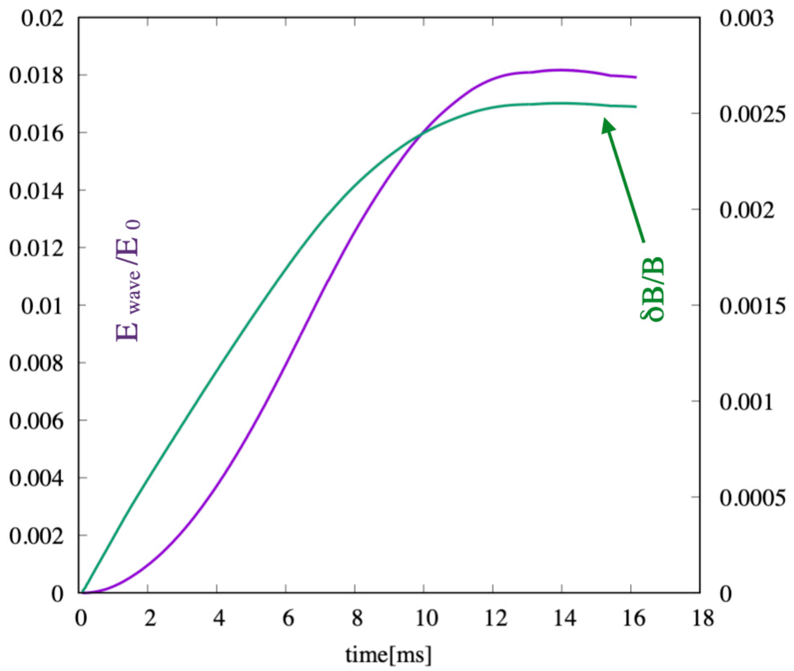
$$\mathcal{E}(t) = \int dv_{P_\phi,E,\Lambda} E \cdot F_{EP}(t)$$

amplitude dependent <dPΦ/dt>, <dE/dt> needed!



- run previously developed WF for calculating PSZS (FINDER/HAGIS) and store in different IDS occurrences
- import into ATEP code (typically 3-5 different amplitudes $\delta B/B = 5 \cdot 10^{-6}, 5 \cdot 10^{-5}, 5 \cdot 10^{-4}, 5 \cdot 10^{-3}$
- interpolate in CoM space, then construct 4D object
- it includes resonance broadening and transitions from isolated to overlapping modes
- it is NOT yet self-consistent, i.e. ratio of mode amplitudes is fixed (radial envelope equation not solved)
- use E-conservation of PSZS transport equation to determine energy transfer to mode and change mode amplitude(s) accordingly

quasi-linear model: δB/B and thus <dP$_\Phi$/dt> change while gradients of F_{EP} flatten



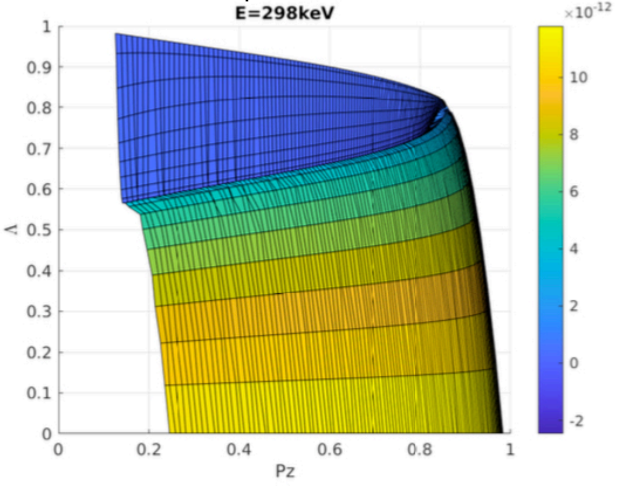
- energy conserving model - energy stored in F_{EP} gradients is converted into wave energy: non-linear hybrid model á la HAGIS (non-linear wave particle interaction Lagrangian)
- relative amplitudes of modes remain fixed, as given by linear growth rates (γ^2~A)
- here, no damping was used yet; mode growth stops after energy of F_{EP} has been exhausted
- for steady state, mode decay has to be balanced by collisions

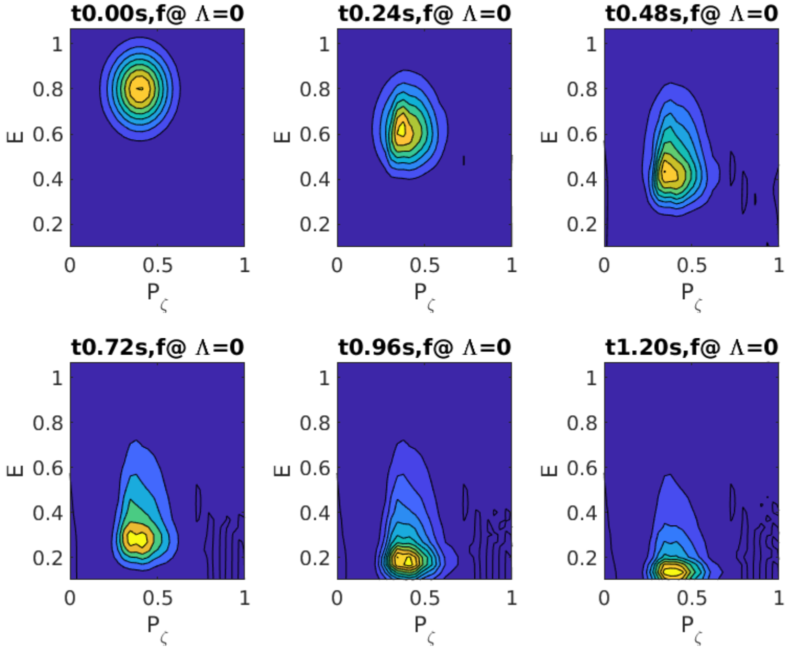
sources+ collisional transport in CoM space: ATEP-3D

[Guo Meng, poster at this conference, FEC 2023]

- collision operators are typically given in E, v// space (explicit pitch angle dependence)
- use framework above (IMAS based wrapper for HAGIS) with neoclassical HAGIS version [A. Bergmann, PoP 2001] to obtain orbit-averaged collision coefficients (linearised collision operator)
- use the same CoM grid as for PSZS part
- general 3D solver (implicit solver)
- details: poster *G. Meng, at this conference*

Collisional transport coefficient DPΦ



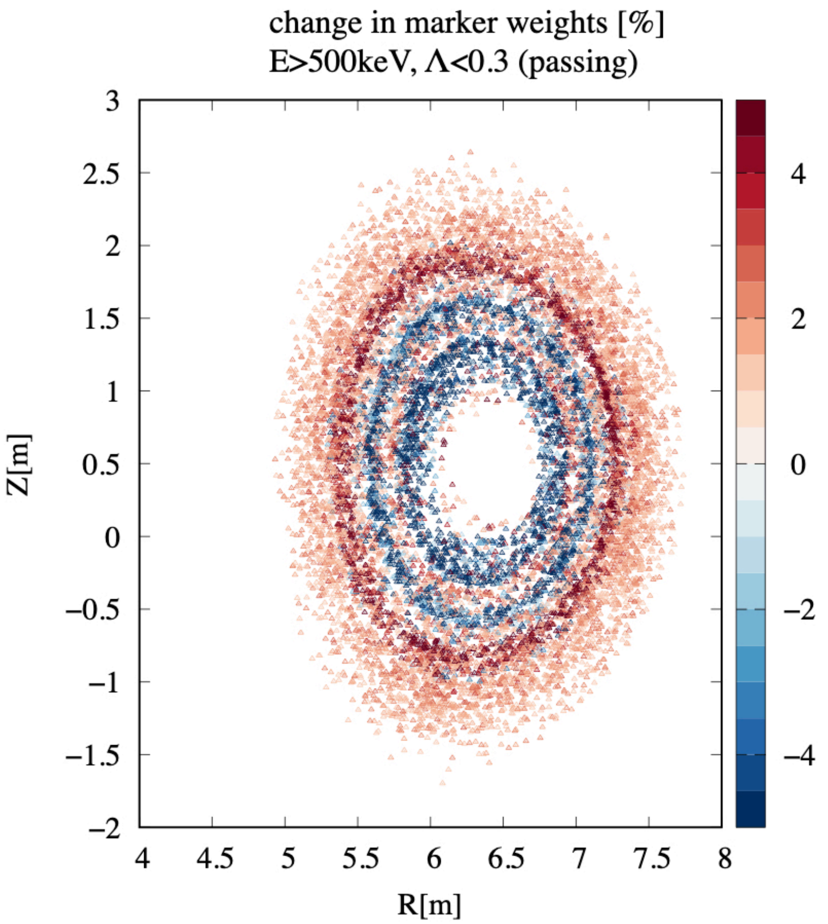


mapping back from CoM space to real space

- use map created for setting up orbits quantities (see above) to assign new weights to markers as given by initial input from heating code or SD model

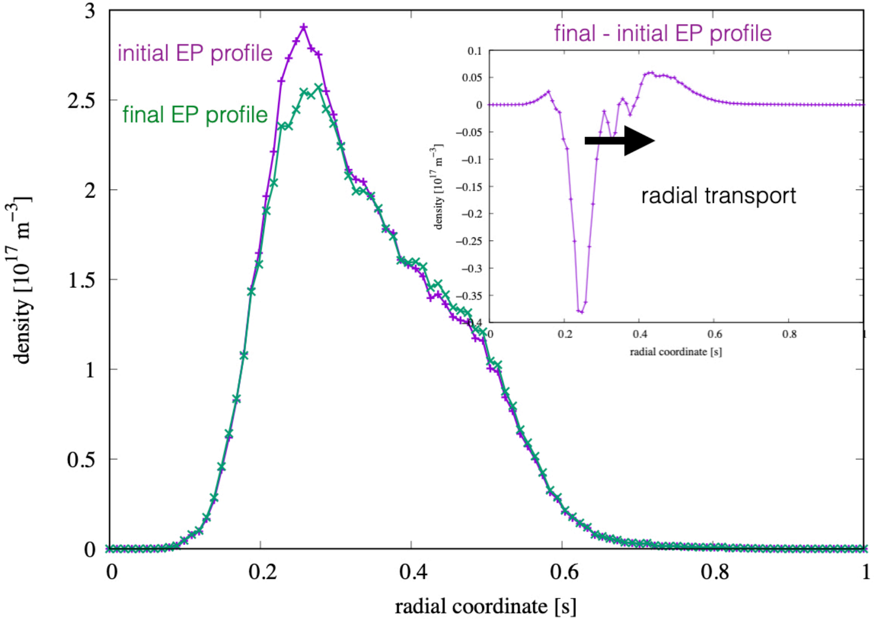
- only 'weights' in CoM are transported, not markers themselves

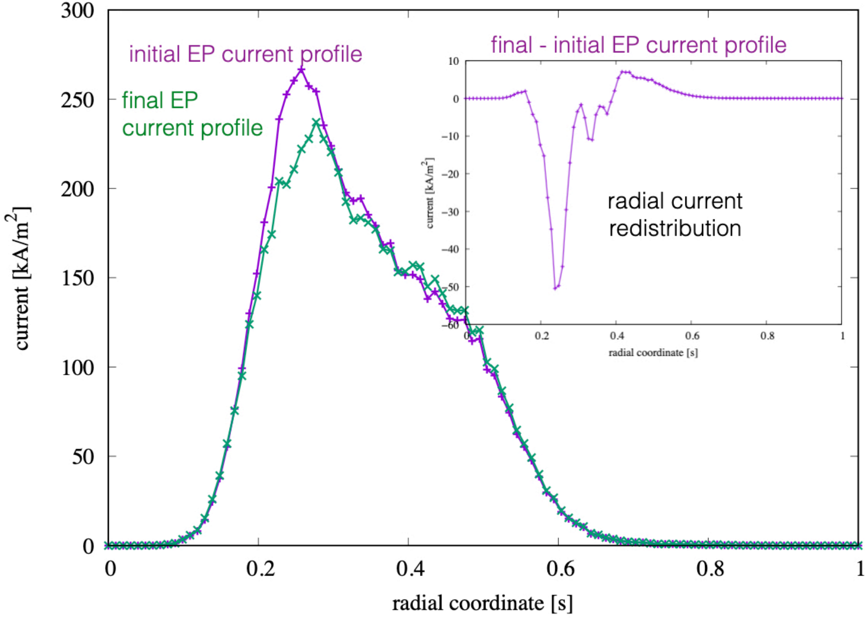
- transport is by construction 'zonal' - taking moments of evolved state allows us to define new non-linear equilibrium:



mapping back from CoM space to real space

back-mapping and calculating moments given EP transport in physical units:

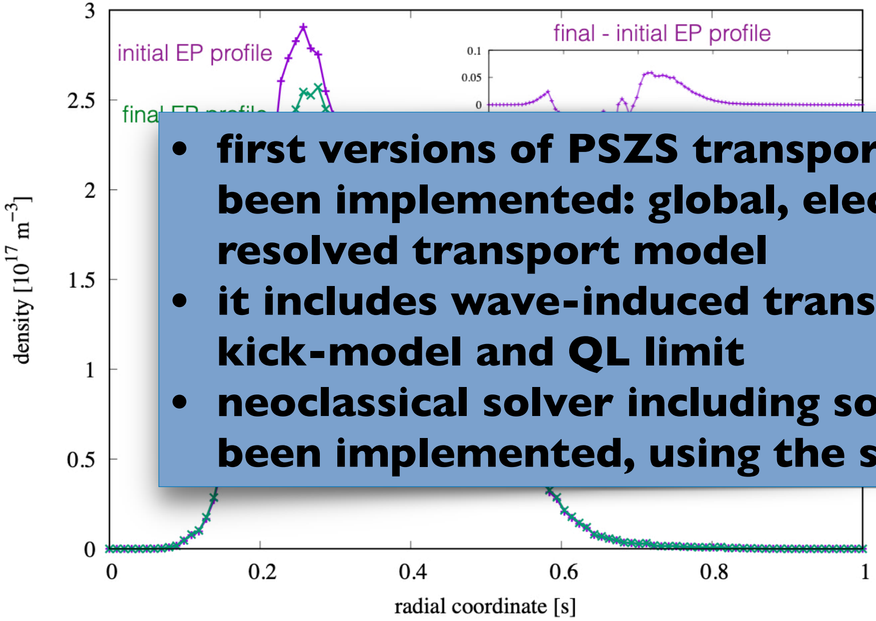


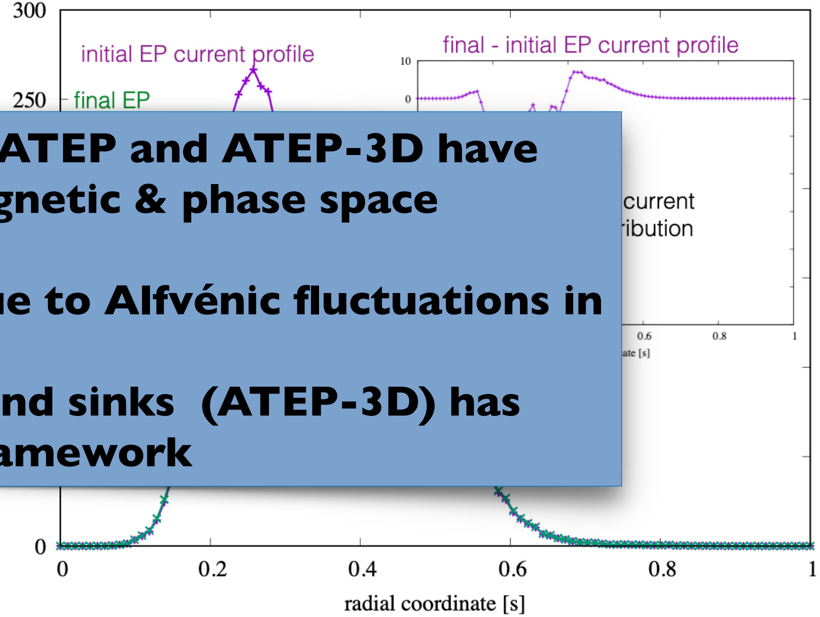


can be passed to transport/equilibrium code to calculate new consistent non-linear equilibrium

mapping back from CoM space to real space

back-mapping and calculating moments given EP transport in physical units:





- **first versions of PSZS transport code ATEP and ATEP-3D have been implemented: global, electromagnetic & phase space resolved transport model**
- **it includes wave-induced transport due to Alfvénic fluctuations in kick-model and QL limit**
- **neoclassical solver including sources and sinks (ATEP-3D) has been implemented, using the same framework**

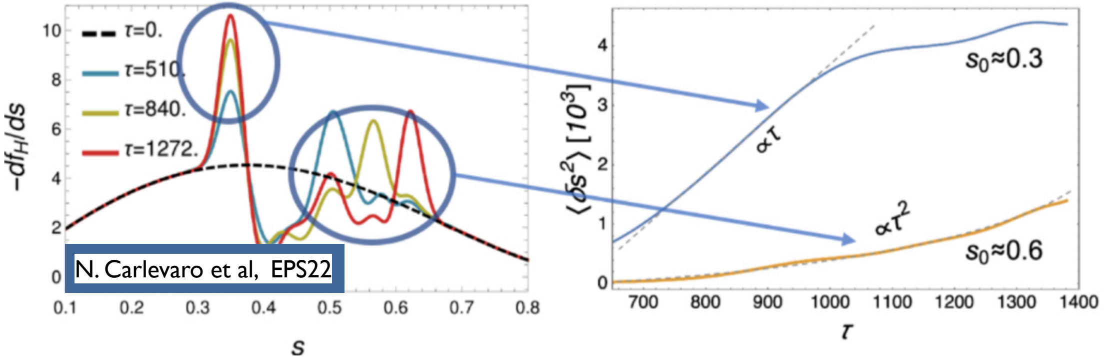
can be passed to transport/equilibrium code to calculate new consistent non-linear equilibrium

verify, validate and evolve models - ENR ATEP team effort

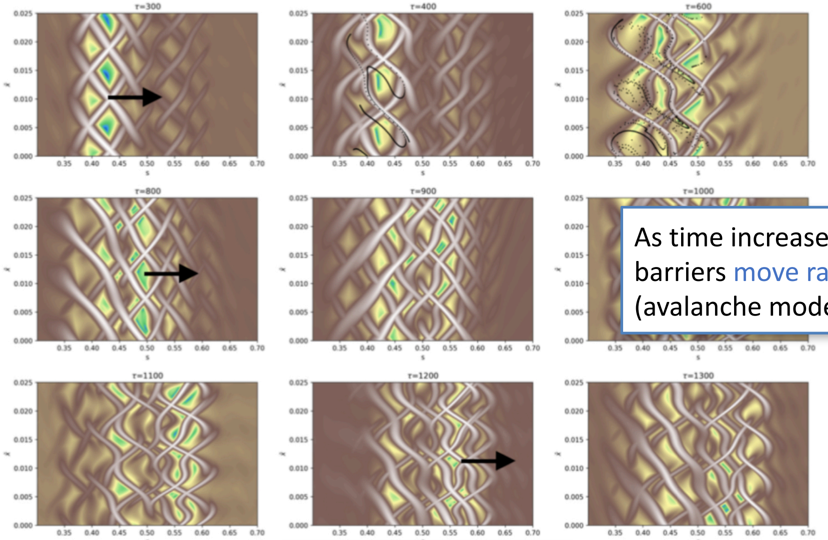
verify, validate and evolve models - ENR ATEP group

- benchmark with original HAGIS model
- benchmark with DAEPS code - calculates fluxes explicitly based on separation of radial and parallel mode structures
- started extension to 3D geometry [A. Zocco, 2023]
- benchmark with 1D beam-plasma system [N. Carlevaro, PPCF 2022]:
    - bump on tail model
    - partition phase space in slides of maximal power exchange
    - use LIGKA linear mode information
    - successful comparison with LIGKA-HAGIS model
- tracers dynamics studied with Lagrangian Coherent structures: relevant structures/barriers change during non-linear evolution: from inner to outer radial transport peak (see ITER case above):

add tracers to system an determine diffusive (τ) vs. convective (τ²) scaling:



N. Carlevaro et al, EPS22



As time increases the more robust barriers move radial outwards (avalanche mode excitation)

verify, validate and evolve models - ENR ATEP group

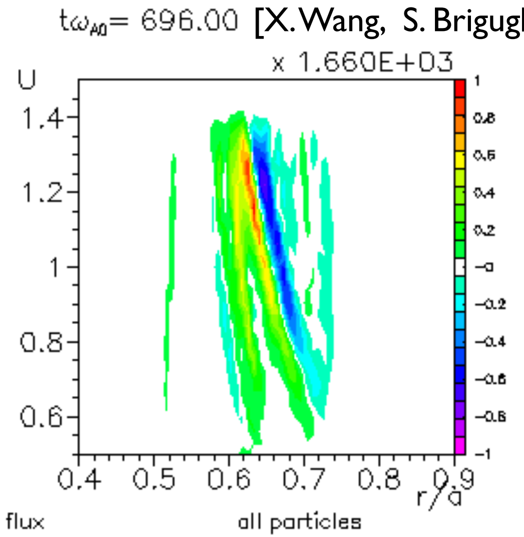
- benchmark with XHMGC calculations, featuring advanced features for transport analysis: Hamiltonian mapping diagnostics & explicit flux 'measurements'
- implemented also in HYMAGYC [G. Vlad, V. Fusco]

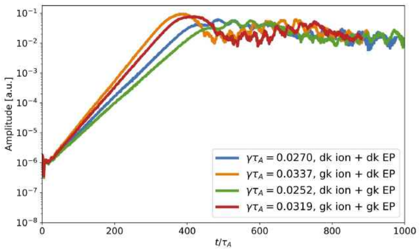
- benchmark with STRUPHY code: MHD-kinetic hybrid code based on new stringent mathematical formulation: structure preserving geometric finite elements + PIC ⇒ improved non-linear stability [F Holderried, S Possanner 2020-2023]

- compare with ORB5 PSZS diagnostics [A. Bottino Varenna 2022] *(see talk M. Falessi)*
  compare to various ORB5 results; e.g. use scaling for chirping modes
  ORB5 runs are available also in presence of turbulence

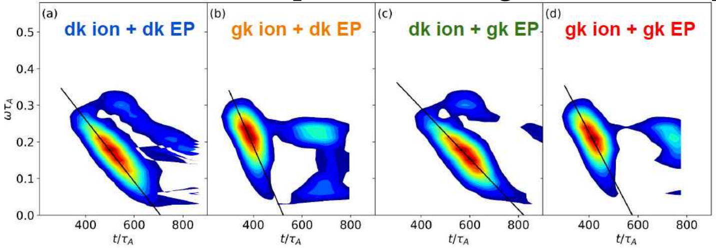
- analyse and plan new experiments based on AUG EP 'Supershots'
  INPA measurements of
  phase space transport !
  [J. R. Rueda, FEC 2023]

[X. Wang, S. Briguglio et al 2021]





[ORB5: X Wang et al, 2022-23]

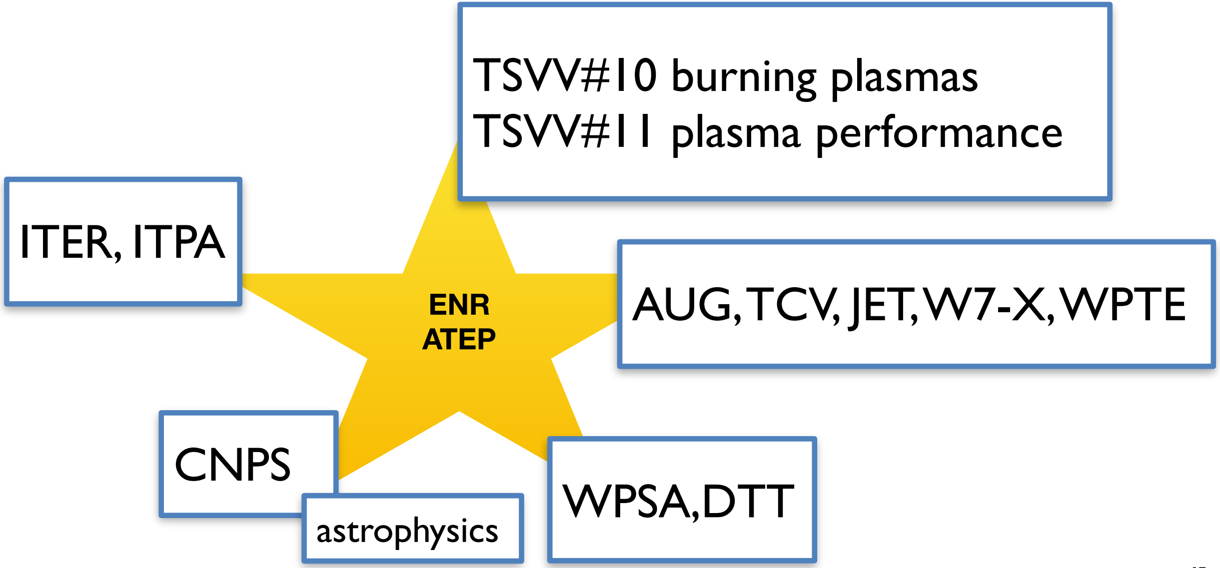


summary

started enable new routes to EP transport analysis and prediction via:

- new theoretical framework
- new common concept of connecting non-linear code results to reduced models (PSZS)
- new common EP transport code developments
- newly implemented analysis methods
- new IMAS based infrastructure

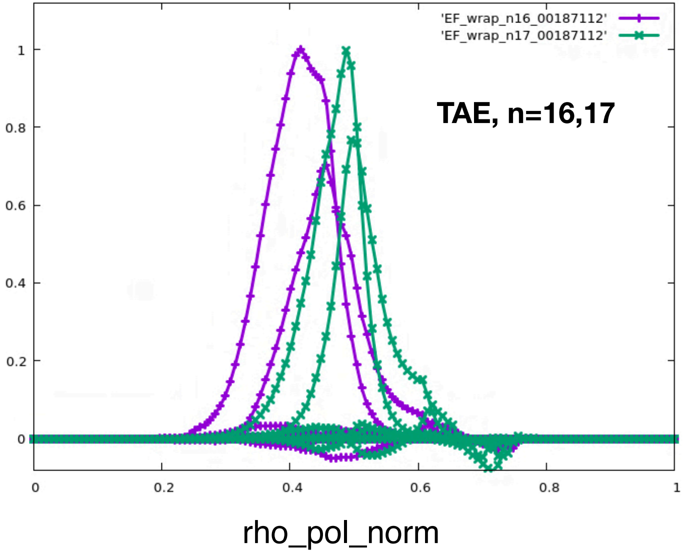
established and growing connections to other groups and experiments

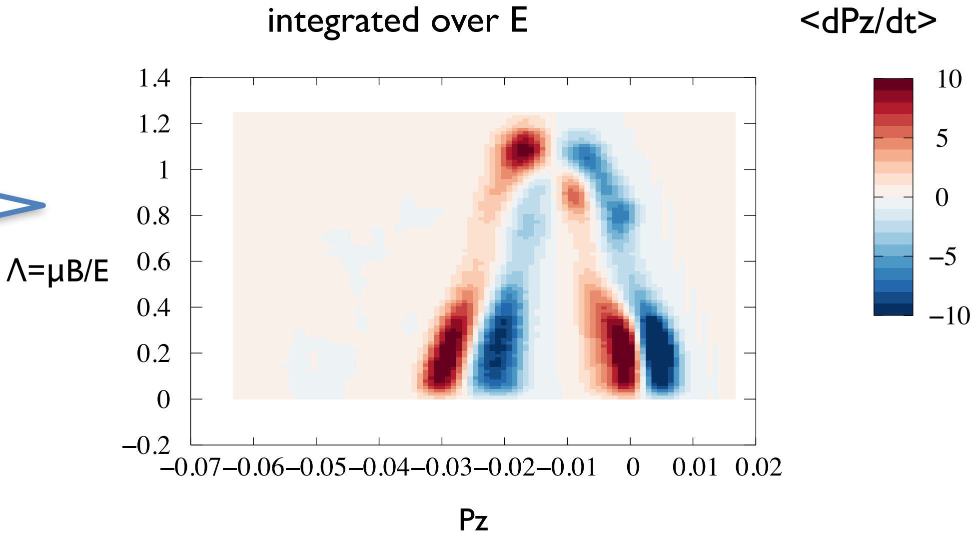


backup

towards multi-mode, QL implementation: investigate two-mode system

- calculate <dPz/dt> , <dE/dt> for given fixed mode structures - here: scan amplitudes in 2 mode system

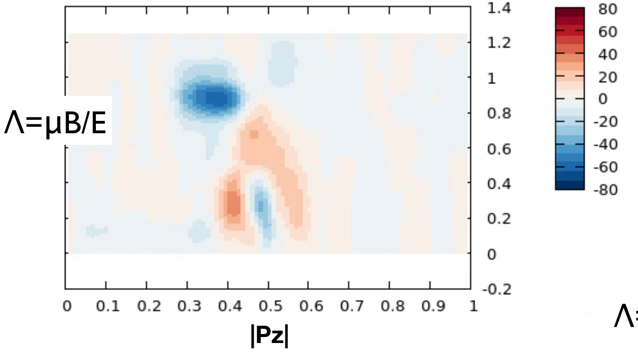




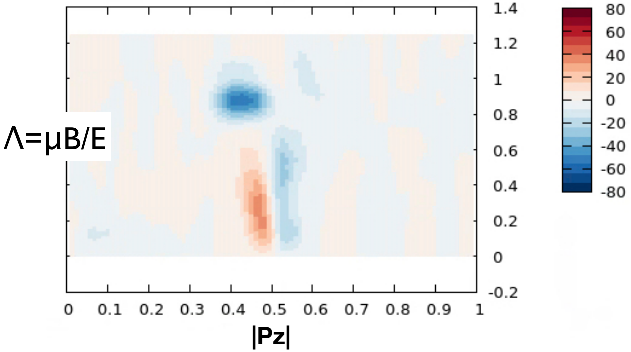
typical grid: (Pz,E,Λ) (128x40x40)

detailed insight into multi-mode cases: amplitude scan: **dB/B=0.5 $*10^{-3}$**

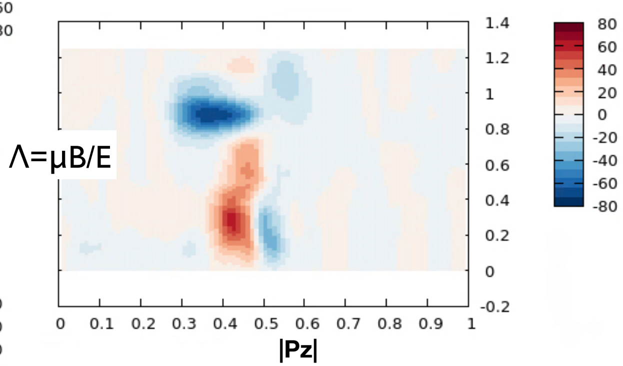
n=16 single



n=17 single

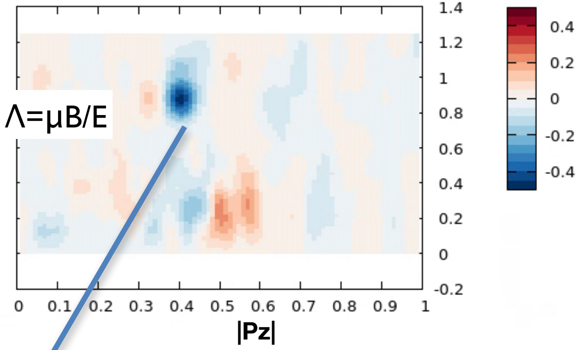


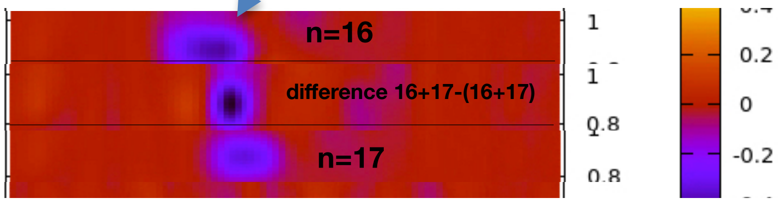
n=16+17 both



relative difference

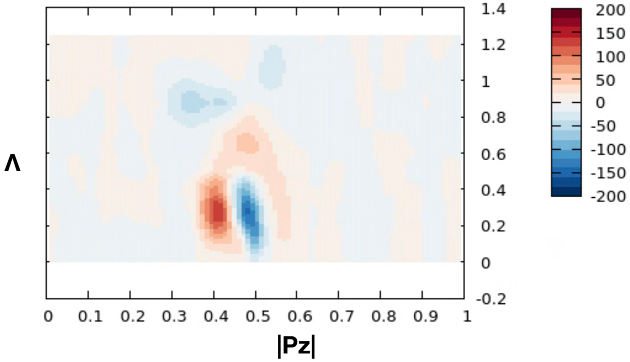
$$\frac{\mathbf{(P16+P17)-P(16+17)}}{\mathbf{P(16+17)max}}$$



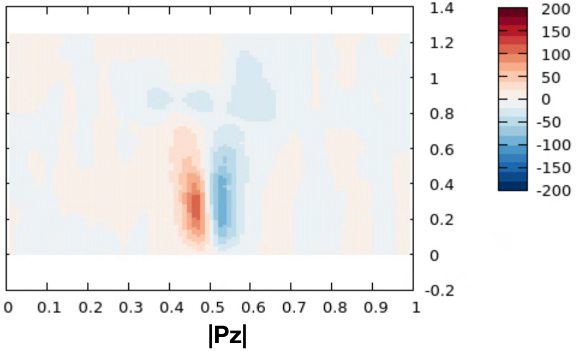


detailed insight into multi-mode cases: amplitude scan: **dB/B=1 *10^{-3}**

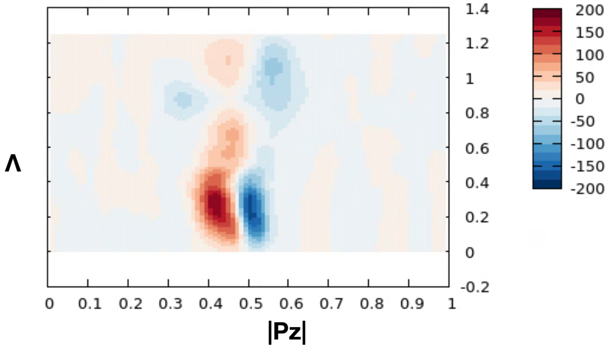
n=16 **single**



n=17 **single**

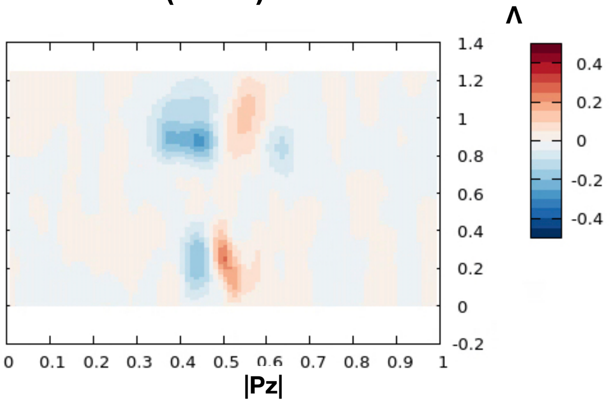


n=16+17 **both**



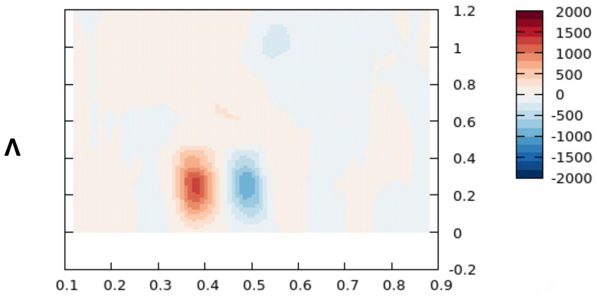
relative difference

$$\frac{P16+P17-P(16+17)}{P(16+17)max}$$

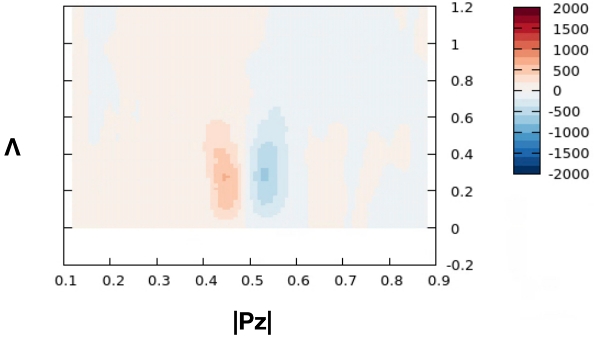


detailed insight into multi-mode cases: amplitude scan: **dB/B=5 *10^{-3}**

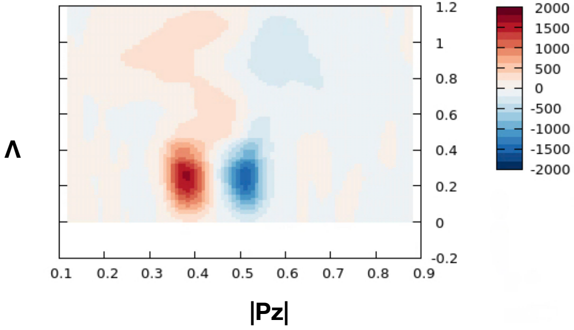
n=16 single



n=17 single

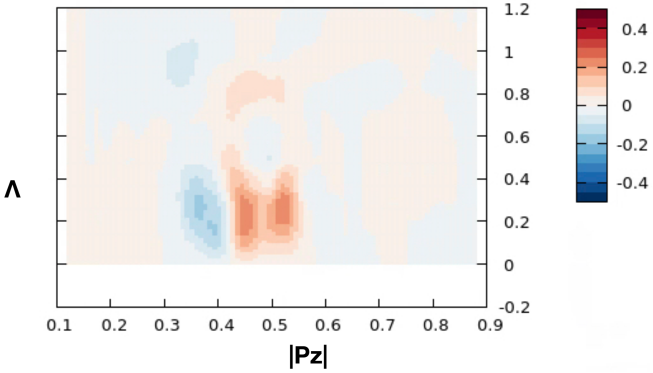


n=16+17 both



relative difference

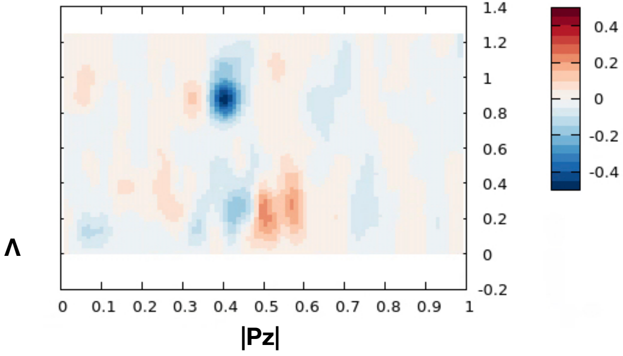
$$\frac{P16+P17-P(16+17)}{P(16+17)max}$$



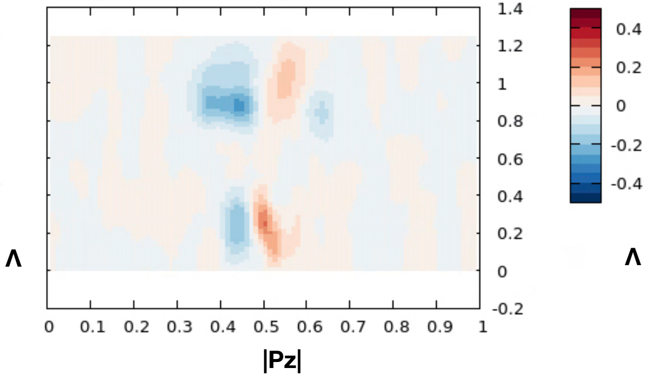
start to investigate multi-mode cases: amplitude scan

relative difference $\frac{(P16+P17)-P(16+17)}{P(16+17)max}$

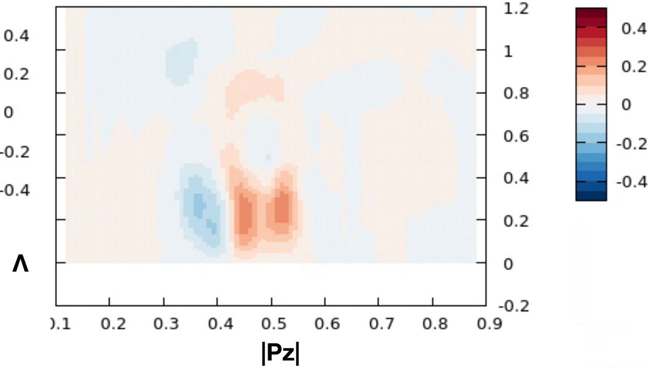
dB/B=0.5 $*10^{-3}$



dB/B=1 $*10^{-3}$

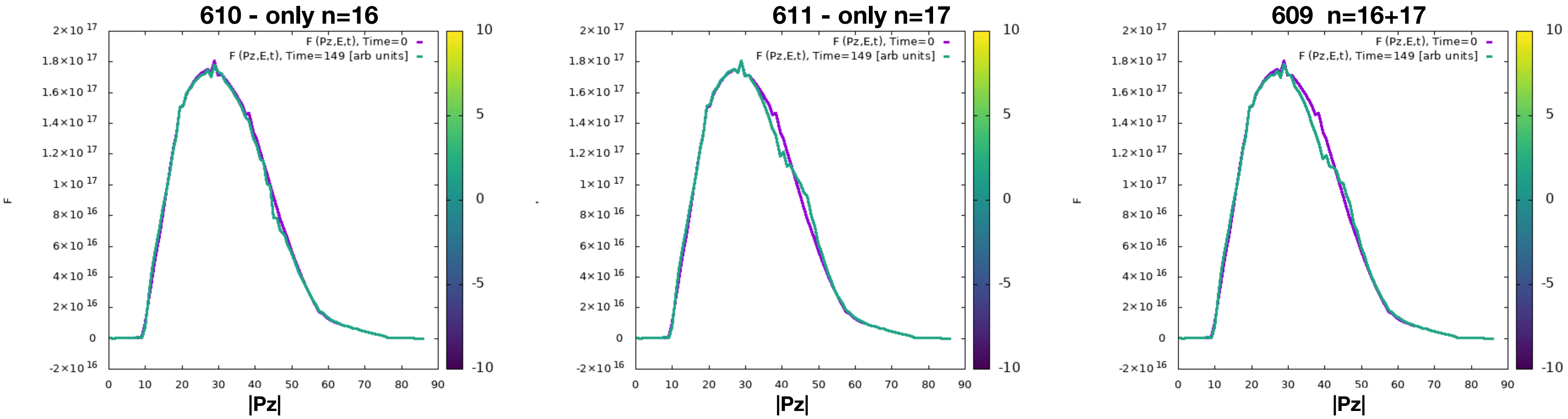


dB/B=5 $*10^{-3}$



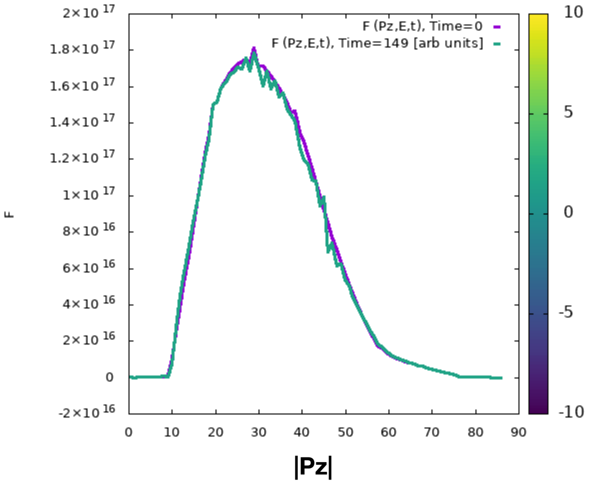
- multi-mode systems need careful treatment when going from isolated mode case to resonance-overlap (diffusive) regime:
- depending on amplitude, trapped and passing particles show different relative importance for causing resonance overlap (FOW vs resonance width) - **consistent treatment of resonance broadening**

two mode system (n=16,17, see above): dB/B=0.5 *10^{-3}

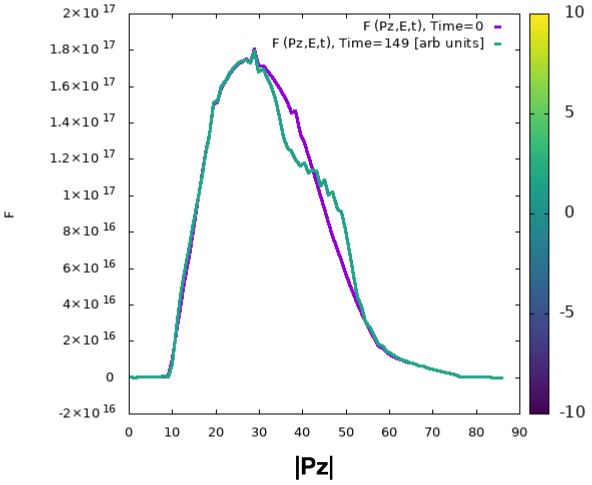


two mode system (n=16,17, see above): dB/B=1 *10^{-3}

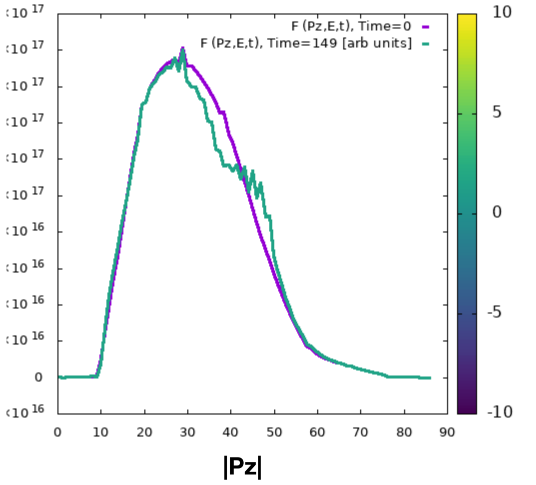
603 - only n=16



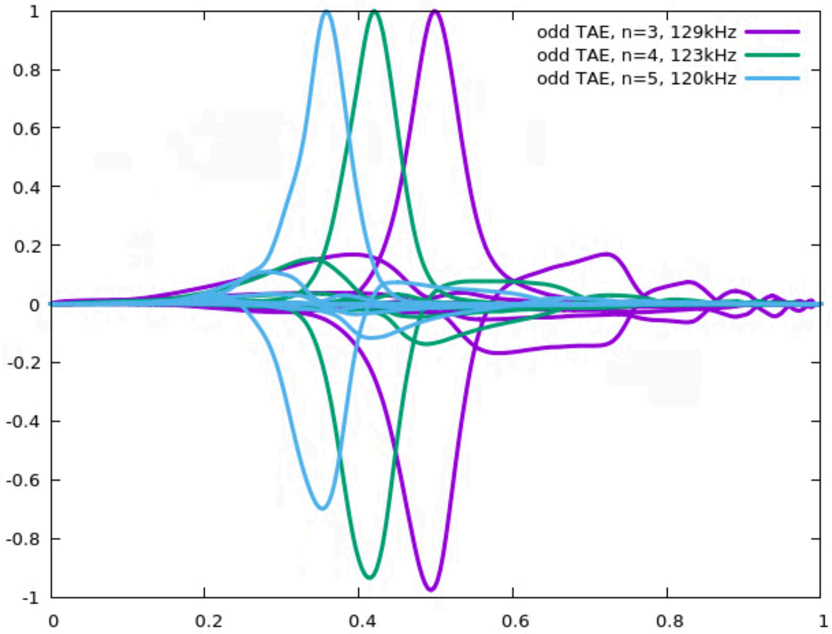
605 - only n=17

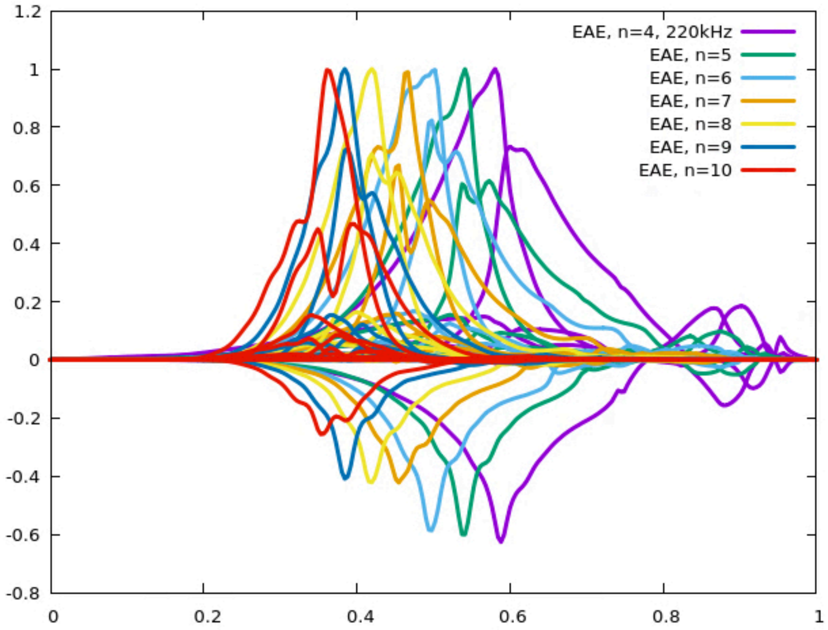


604 n=16+17



JT-60SA - used mode spectrum: odd TAEs and EAEs

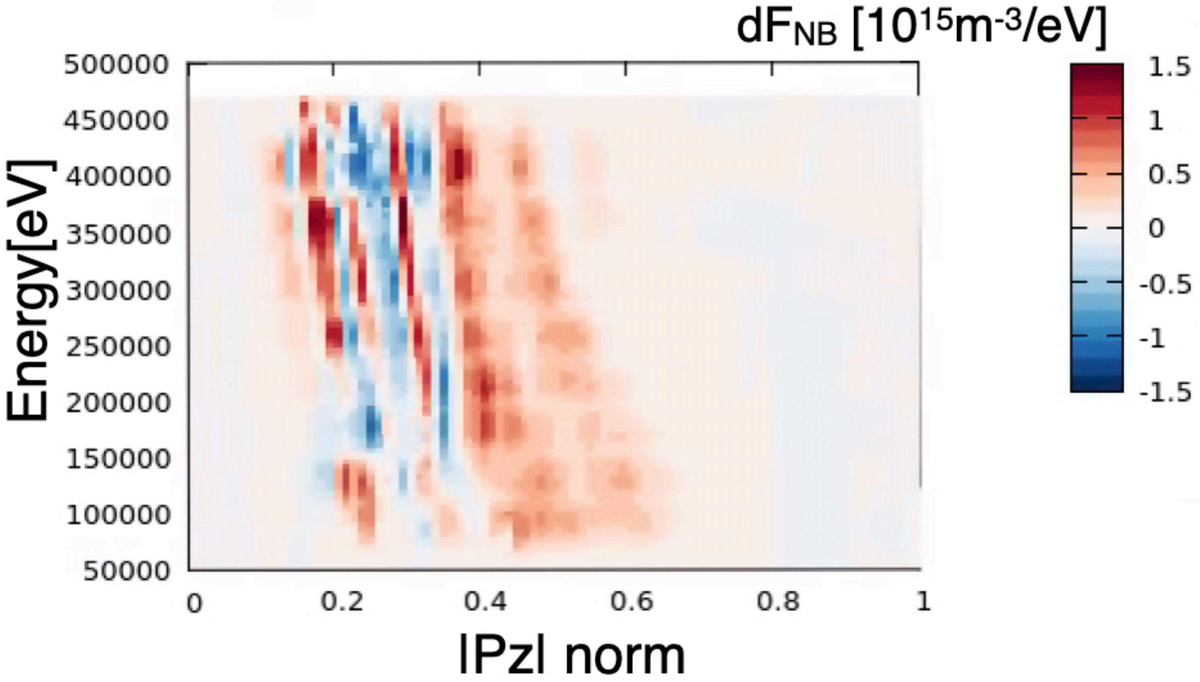


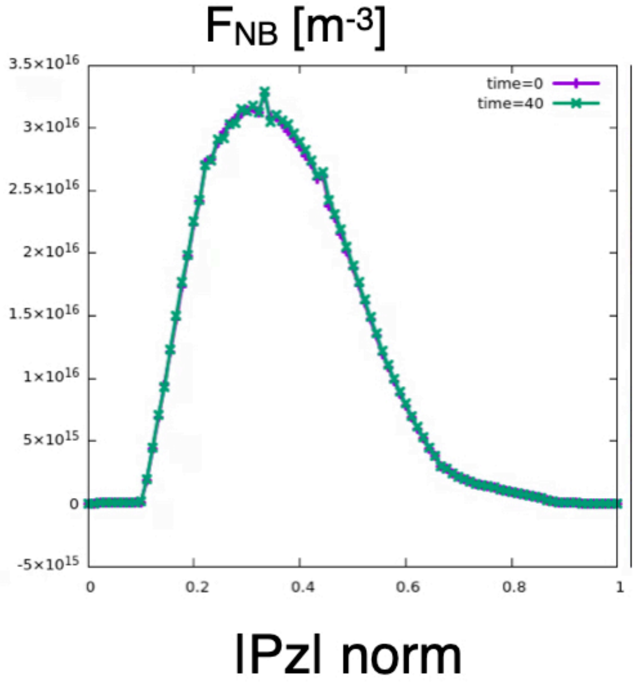


EP-WF has been adopted to cope with co- and counter propagating modes

solving the PSZS equation (kick-model limit): EAEs

$\delta F(t)=F(t=40)-F(t=0)$ in CoM space ($\Lambda=\mu B_0/E=0.24$) for the set of co and counter propagating EAEs



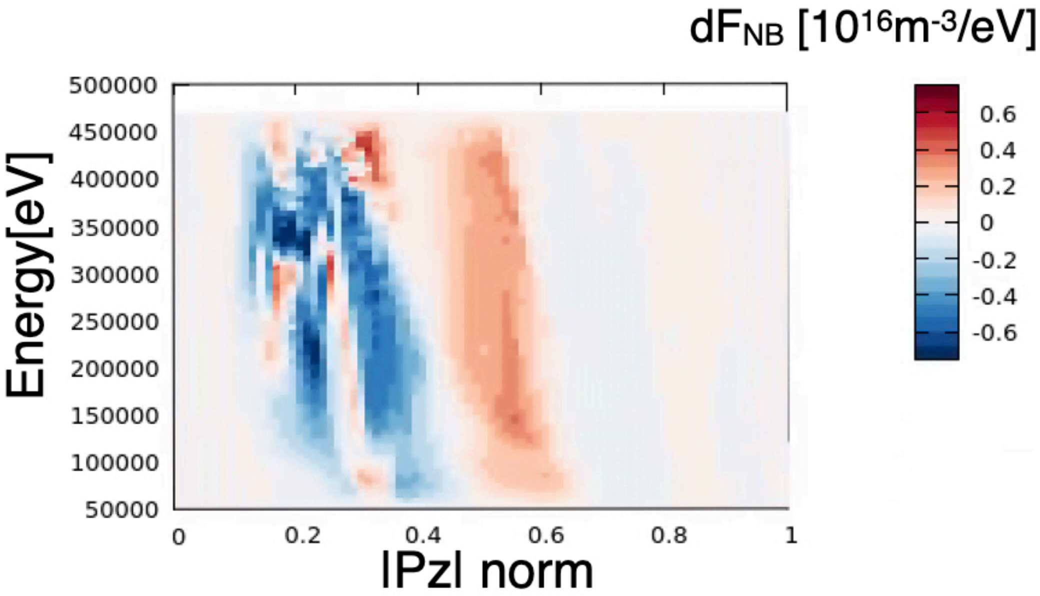


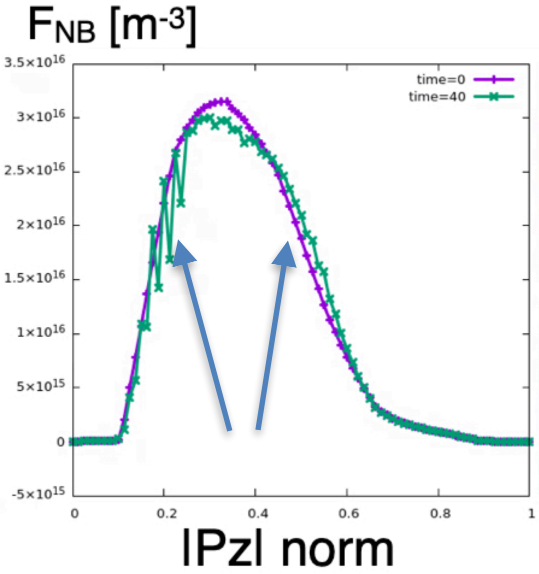
much smaller EP transport (4 times smaller) that odd TAEs (using the same saturation rule $\gamma \sim A^2$)

next: how do these modes affect the current deposition? mapping back and take moments…

solving the PSZS equation (kick-model limit): TAEs

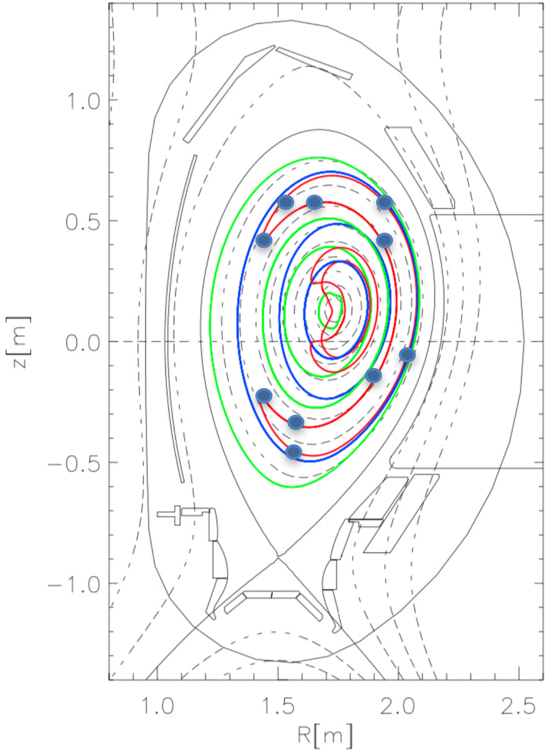
δF(t)=F(t=40)-F(t=0) in COM space (Λ=μB_0/E=0.24) for the set of odd co and counter propagating TAEs





both gradients are depleted

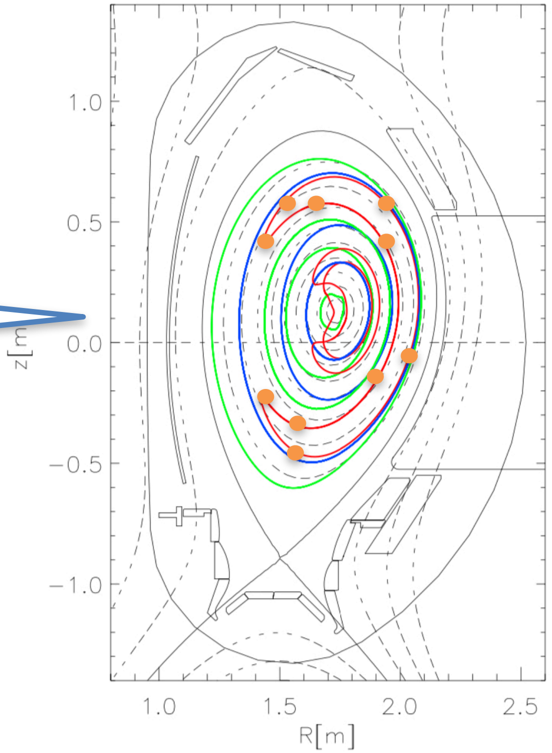
mapping from marker space to COM space and back



bin all markers on same orbit to (Pz,E,Λ)- grid and sum over weights to obtain density in COM space F(Pz,E,Λ)

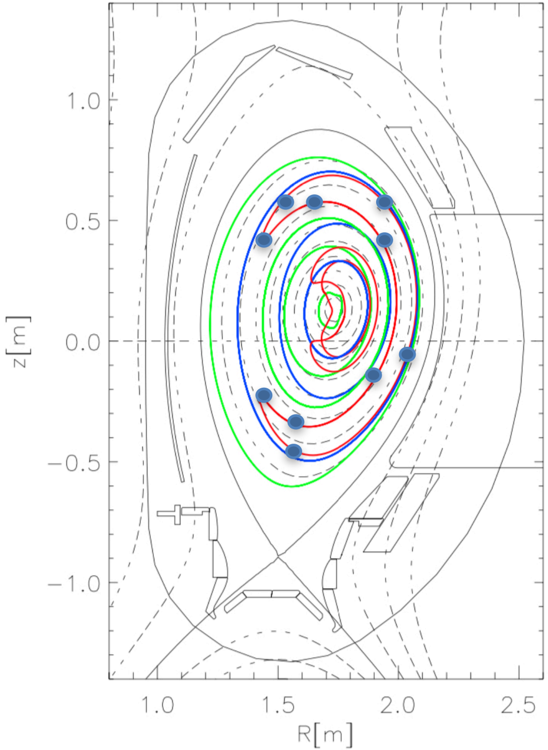
evolve PSZS
transport equation
i.e. update F_u(Pz,E,Λ)

$$\frac{\partial F_{EP}}{\partial t} = \frac{\partial Pz}{\partial t}\frac{\partial F_{EP}}{\partial P_z} + \frac{\partial E}{\partial t}\frac{\partial F_{EP}}{\partial E}$$



distribute new weight proportional to original weights, i.e. scale all marker weights of certain bin by F_u(Pz,E,Λ)/F(Pz,E,Λ)

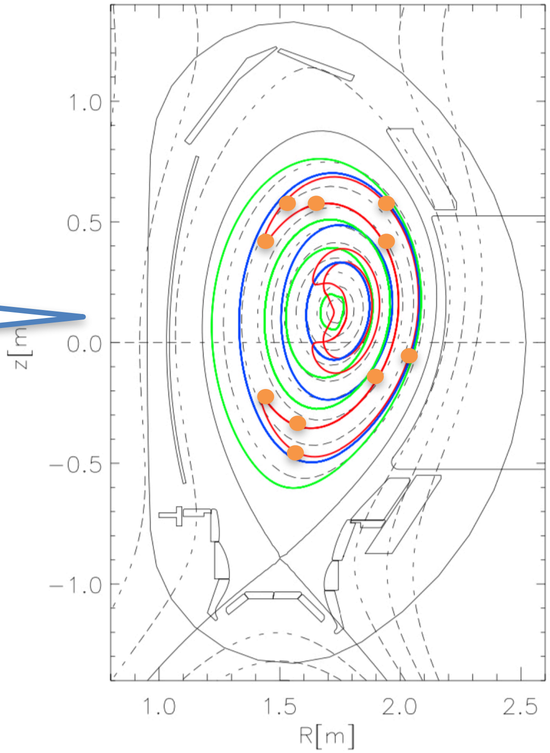
mapping from marker space to COM space and back



bin all markers on same orbit to (Pz,E,Λ)- grid and sum over weights to obtain density in COM space F(Pz,E,Λ)

evolve PSZS
transport equation
i.e. update F_u(Pz,E,Λ)

$$\frac{\partial F_{EP}}{\partial t} = \frac{\partial Pz}{\partial t}\frac{\partial F_{EP}}{\partial P_z} + \frac{\partial E}{\partial t}\frac{\partial F_{EP}}{\partial E}$$



then calculate moments and/or transport coefficients to be used in connected codes

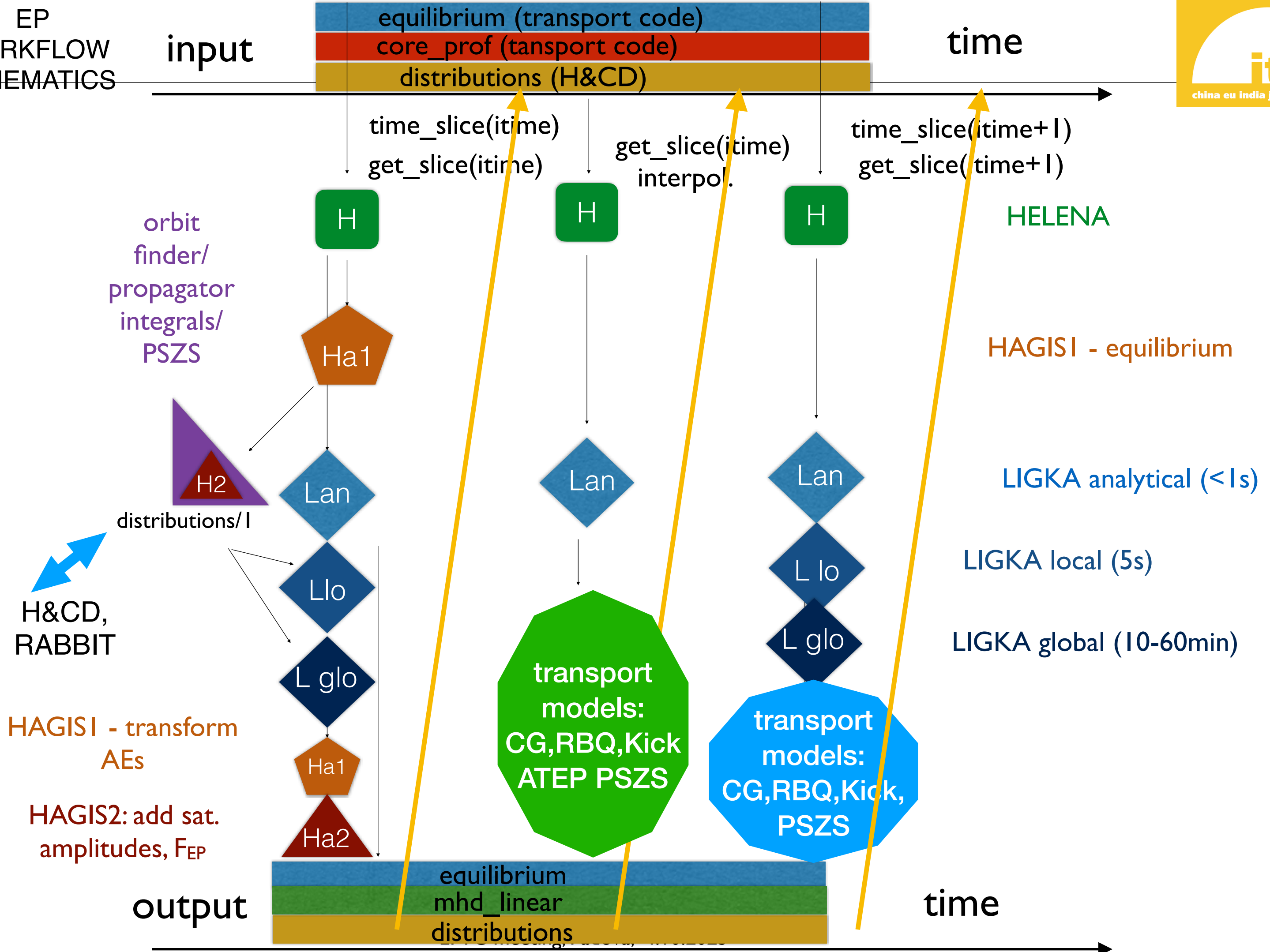
EP WORKFLOW SCHEMATICS

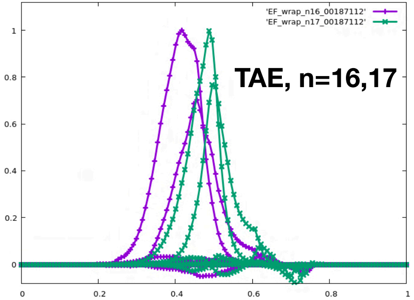
fully IMAS integrated

read ETS,METIS, ASTRA and JINTRAC generated data

read trview generated AUG data,
TCV data
JT-60SA,
ITER,
JET in preparation

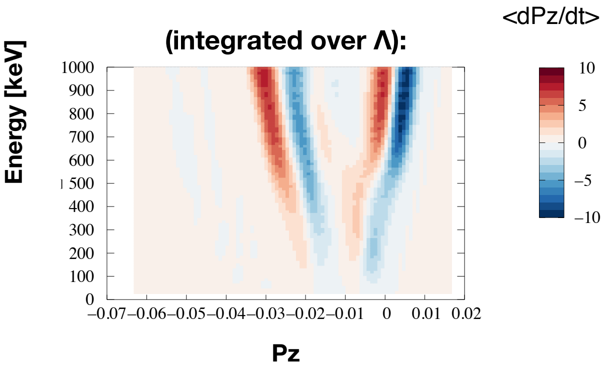
automated tests & installation, gui, nogui, parallelised

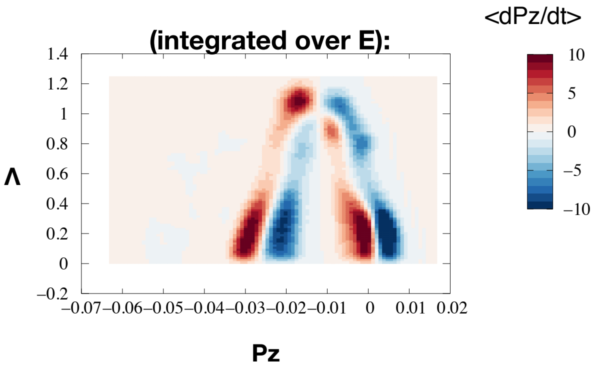


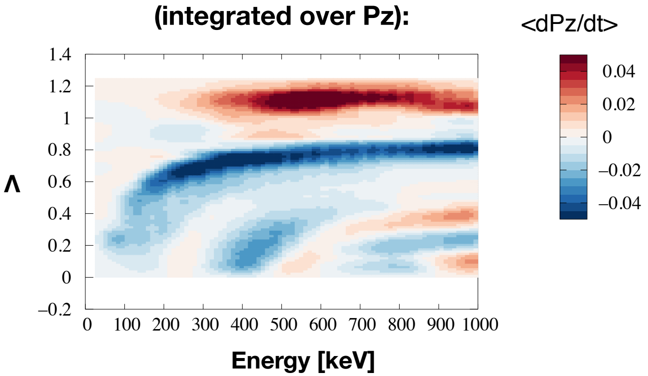


WP3.3-M1 Extend unperturbed orbit integration routines and averaging procedures in order to calculate phase space fluxes in HAGIS mid 2022 (fully)

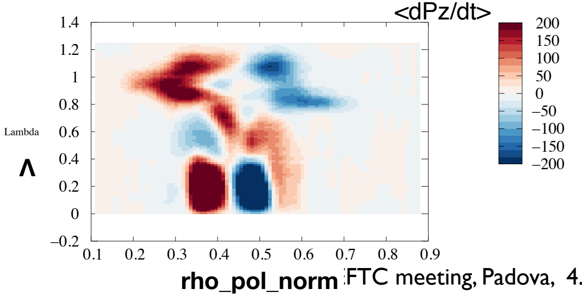
by zonal averaging of a representative particle ensemble, calculate <dPz/dt>, i.e. radial transport for given set of fixed mode structures at fixed amplitudes, write as IDS object in COM Pz,E,Λ [Lauber DTT seminar, 5/2022, Bierwage et al, ID: 30554]

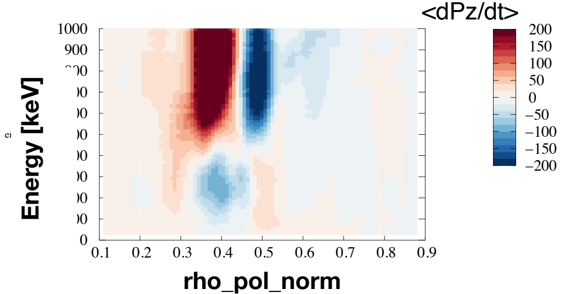




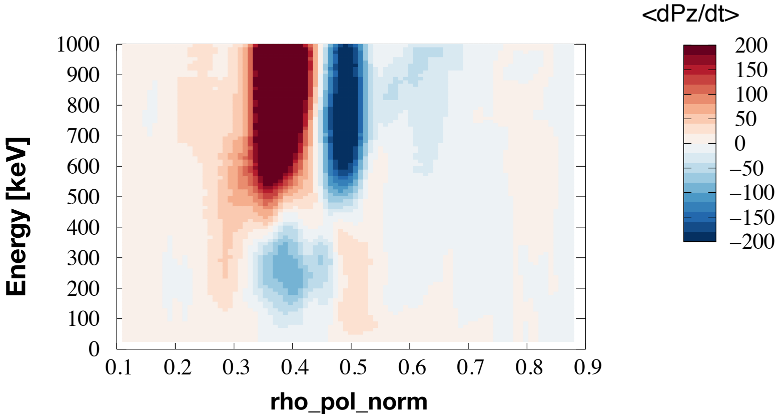


can be easily mapped to <s>:

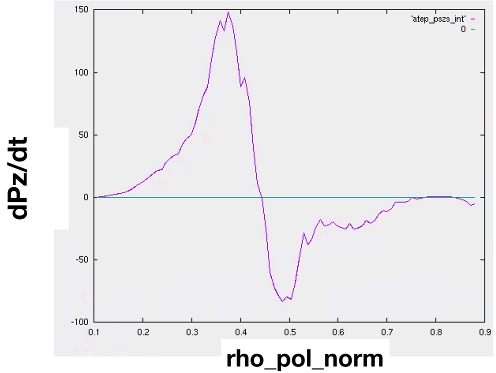




calculation of diffusions coefficients: D(s,E) and D(s)



E integration



to be done: transform from<dPz>²/<dt> to D(s,E)=<ds>²/<dt>

and feed back to transport code

EP properties in various (planned) experiments

scaling of difference machines with respect to energetic particle (EP) ß

α-particle pressure (gradient) has to increase for DEMO: properties of EP confinement?

	B_T[T]	Ti(0)[keV]	$\beta(0)_{back}$ [%]	$\beta(0)_{\alpha,EP}$ [%]	$\beta_\alpha/\beta_{back}$	R[m]	$R_0\nabla\beta_{\alpha,EP}/\beta_{back}$
TFTR-DT	5.0	28	4.6	0.2	0.04	2.5	0.11
JET-DT	3.8	23	5.7	0.4	0.07	3.0	0.21
ITER-15MA	5.3	25	4.8	0.9	0.19	5.2 (2)m	0.50
AUG, off axis	2.2	1.2	0.4	0.4	<1.0	1.65(0.5)m	<3.3
JT-60SA	2.25	6.0	3.8	<2.3	<0.6	2.96(1.2)m	1.48
DEMO PPPT, 2015	5.7	30	7.0	6.0	0.85	9.0 (3)m	2.55

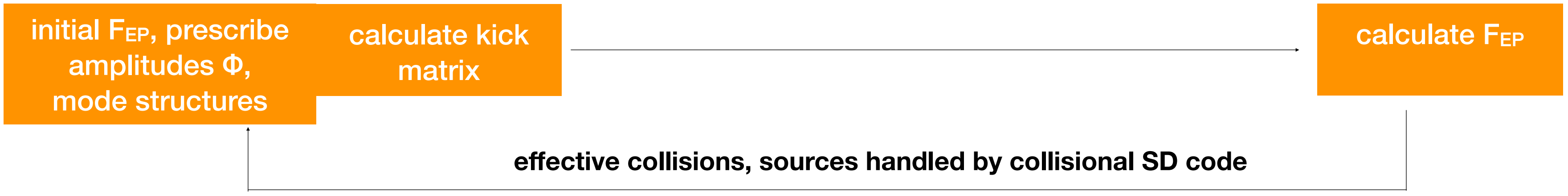
can overcome EPM threshold

known from JT-60U, AUG, spherical tokamaks: EP-driven mode dynamics and transport changes if EPM threshold is reached:

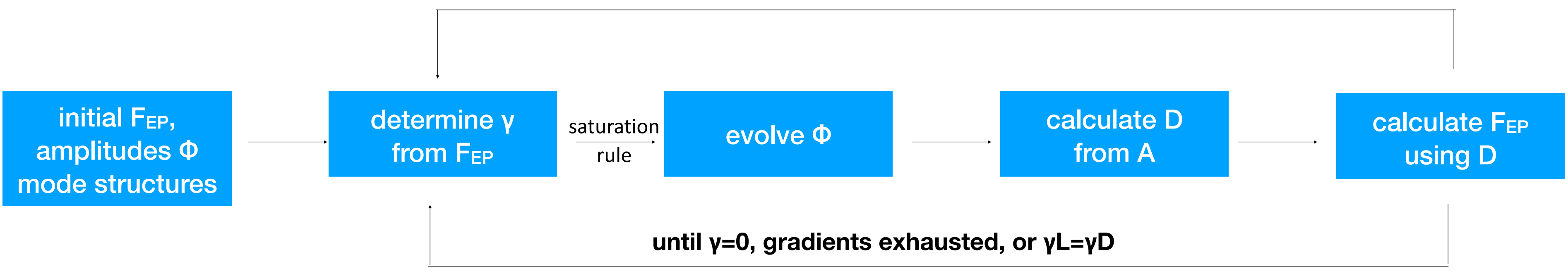
$$q^2 R_0 \nabla \beta_{EP}/\beta_i \; (T_i/T_{EP}) \gg \varepsilon^{3/2}$$ [Zonca et al NF, 45,2005]

kick model/ quasi-linear diffusion model

kick model scheme [Podesta 2014]:



typical quasi-linear scheme [Sagdeev/Galeev 1969, Kaufman 1972, Gorelenkov 2018]:



$$\gamma_n = 2\pi^2 \frac{e^2}{m} \frac{v_n}{|k_n|} \frac{\partial f(v_n)}{\partial v}$$

$$\frac{\partial}{\partial t} W_n = 2\gamma_n W_n$$

$$D(v) = \frac{2\pi e^2}{m^2} \sum_n |k_n \phi_{n0}|^2 \delta(\Omega_n)$$

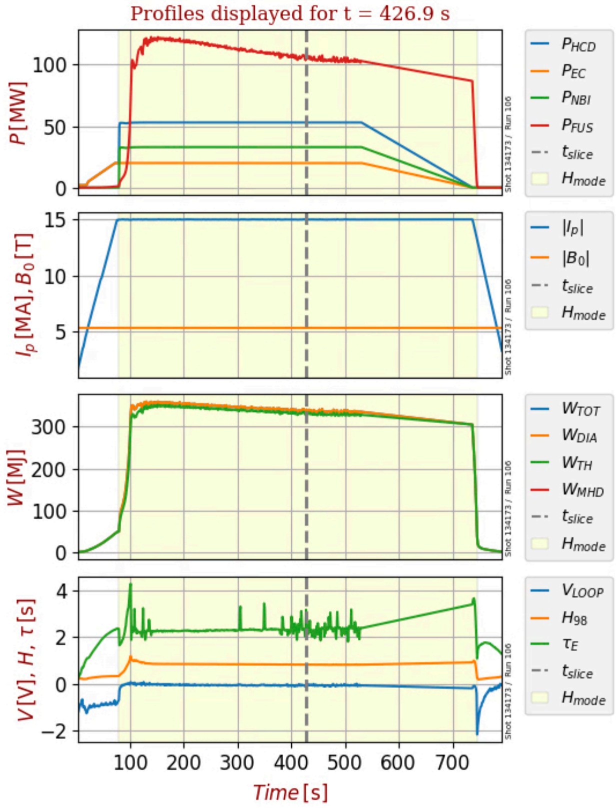
$$W_n = \frac{|k_n \phi_{n0}|^2}{2\pi\, v_n}$$

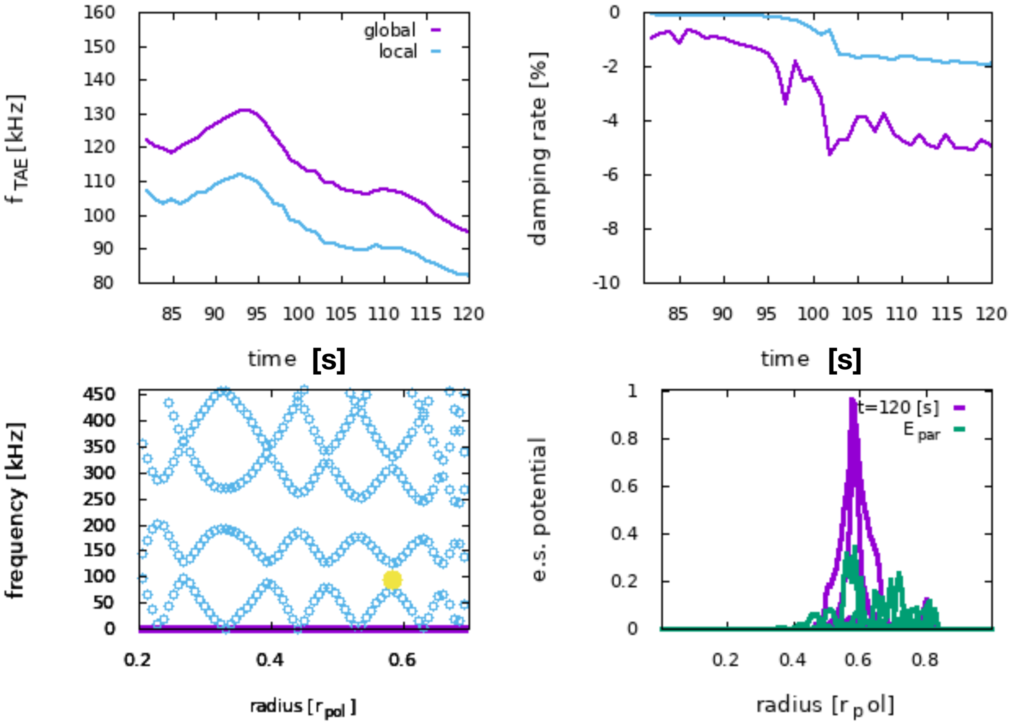
+self consistent resonance broadening

$$\frac{\partial f}{\partial t} = \hat{Q} f \equiv \frac{\partial}{\partial v}\left(D(v) \frac{\partial f}{\partial v}\right)$$

Linear mode spectrum: Energetic particle stability workflow

[S.D. Pinches, plenary EPS 2022] #134173, 106 TAE n=18 [V.-A. Popa, NF accepted 2023]



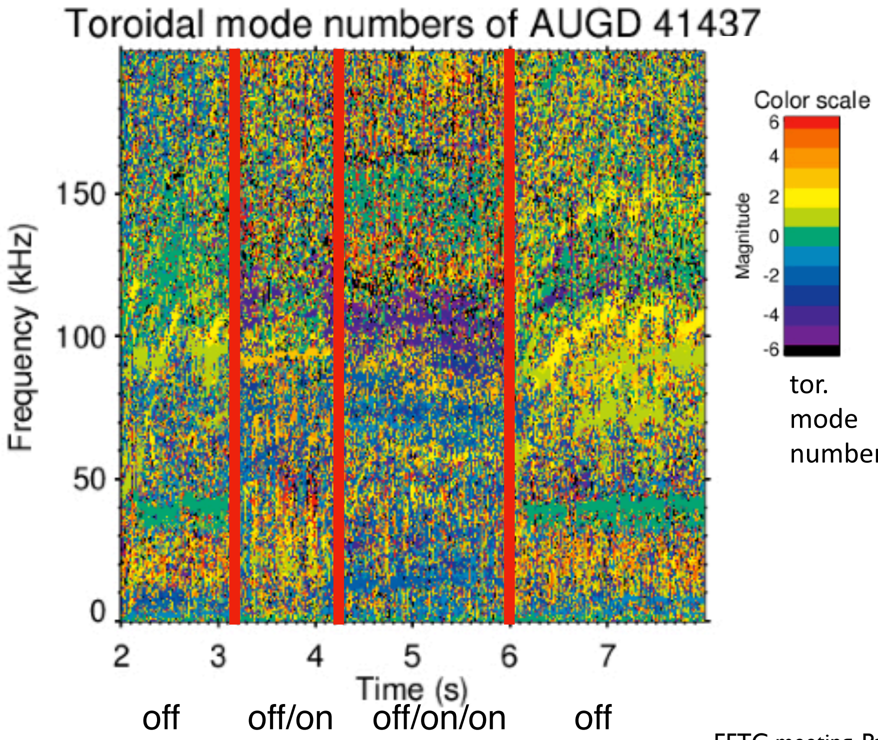


identified end of power ramp-up phases as most critical time points for in-depth EP transport analyses

Energetic particle stability workflow: validation at ASDEX Upgrade

for theory very important: isotope scans (e.g. finite orbit width effects)

- D beam in D plasma
- D beam in H plasma
- H beam in H- plasma
- D beams into He plasma



tor. mode numbers

for some shots: FIDA data available [B. Geiger]