EUROfusion

# Aspects of energetic particle physics at DTT

Philipp Lauber

thanks to Eurofusion ENR ATEP team: Matteo Falessi (Co-PI), Alessandro Biancalani, Sergio Briguglio, Nakia Carlevaro , Valeria Fusco, E. Giovanozzi, Thomas Hayward-Schneider, Florian Holderied, Axel Könies, Yang Li, Yueyan Li, Guo Meng, Alexander Milovanov, V.-Alin Popa, Stefan Possanner, Gregorio Vlad, Xin Wang, Markus Weiland, Alessandro Zocco, Fulvio Zonca

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

Center for Nonlinear Plasma Science
CNPS
Since 2020

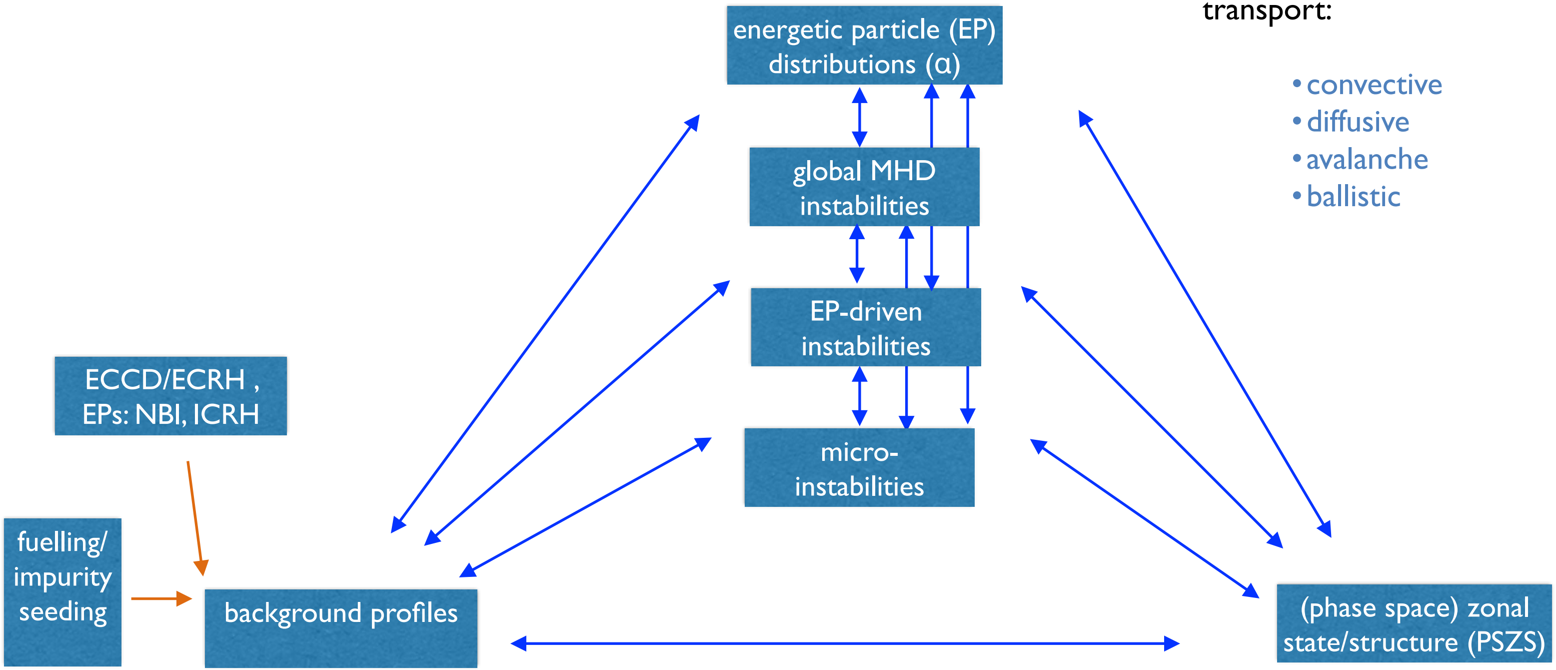
iter
china eu india japan korea russia usa

This work has been carried out within the framework of the EUROfusion Consortium, funded by the European Union via the Euratom Research and Training Programme (Grant Agreement No 101052200 — EUROfusion). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Commission. Neither the European Union nor the European Commission can be held responsible for them.

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

4 types of EP transport:

- convective
- diffusive
- avalanche
- ballistic



energetic particle (EP) distributions (α)

global MHD instabilities

EP-driven instabilities

micro-instabilities

ECCD/ECRH , EPs: NBI, ICRH

fuelling/ impurity seeding

background profiles

(phase space) zonal state/structure (PSZS)

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

# EP transport: selected experimental observations

- 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

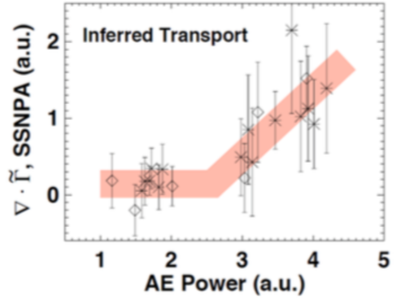
- in JET re-deposition of EPs (ICRH) was observed: core-localised TAEs redistribute EPs, redistributed EPs drive edge-TAE [Nabais et al, PPCF 2019]

- mode chirping and avalanches-type events (‚ALE‘) found in many experiments [Kusama, Shinohara, JT-60U 1999+]

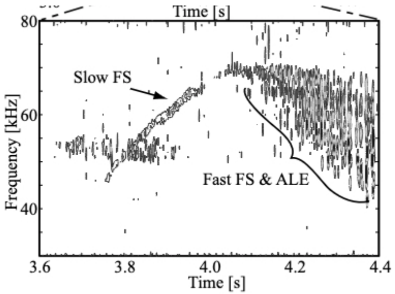
- bursting, non-linear mode-mode couplings and EP transport measured in ASDEX Upgrade EP super-shots [Lauber 2014+], .i.e. further development of AUG NLED benchmarks case [Vlad 2020-2023, Vannini 2019, Rettino 2021-23] : role of impurity control on EP dynamics

- DTT will contribute to bridge present day observations to ITER/DEMO

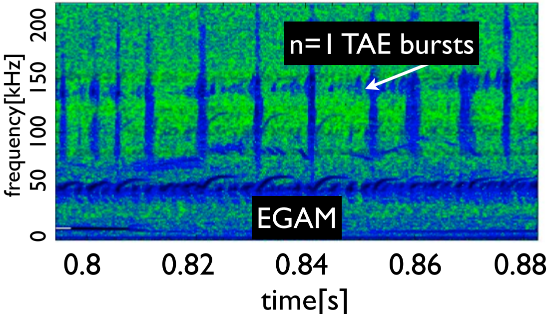
*for a comprehensive review please refer to dedicated review articles, e.g.*
*[NF ITPA special issue 2006, update 2023/24, Heidbrink 2008, Breizman& Sharapov 2011, Lauber 2013, Chen&Zonca RMP 2015, Gorelenkov&PinchesToi 2014, Todo 2019, Qiu 2023,..]*



[Heidbrink, 2015]



[Shinohara 2001]



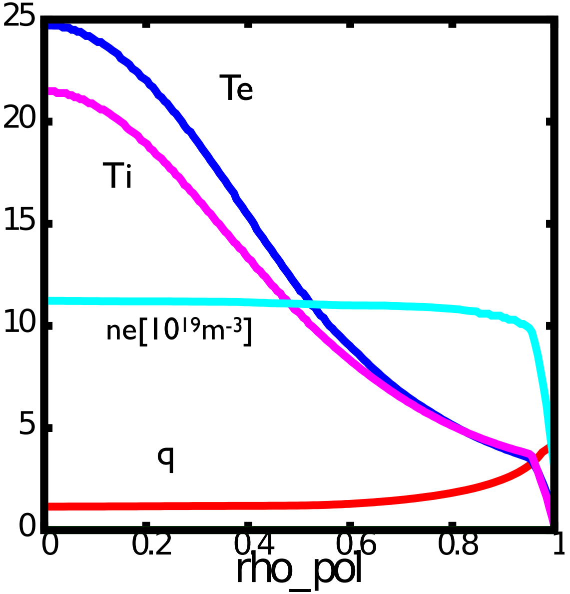
[AUG, Lauber 2014]

# outline

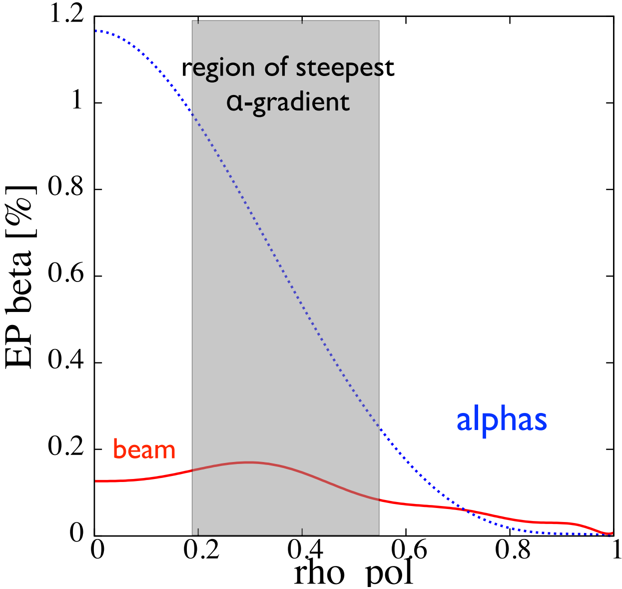
- expected EP transport in ITER
- role of DTT
- available and emerging new tools

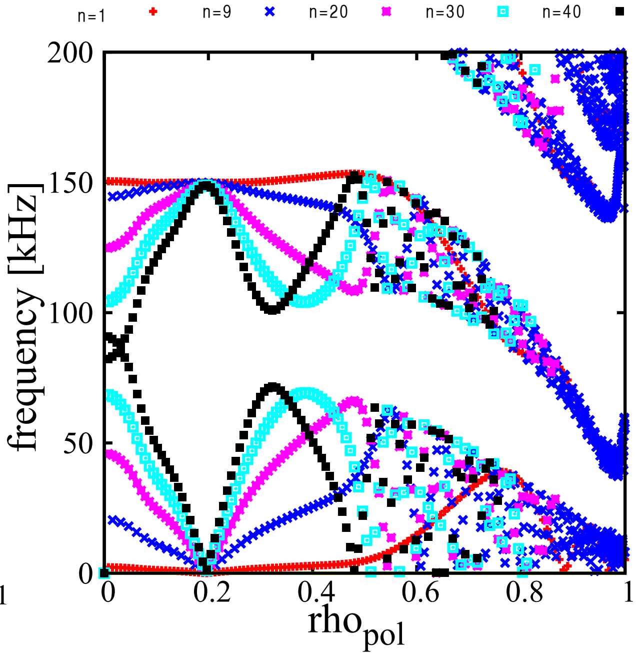
# expectations for ITER 15MA

[A. R. POLEVOI ET AL. J. Plasma Fusion Res., 5 (2002)]



B0=5.3T, R0=6.2m, D,T,He-ash, Be,α,NNBI-D



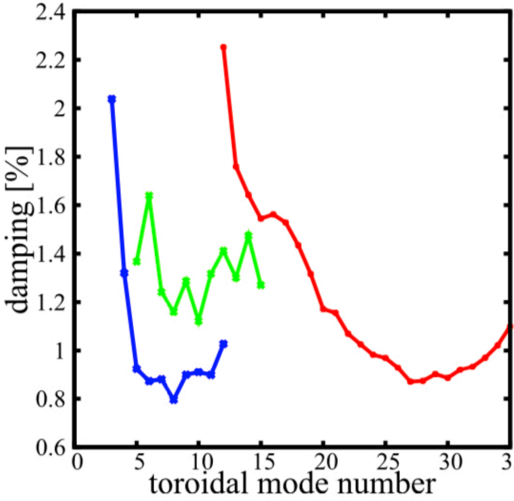


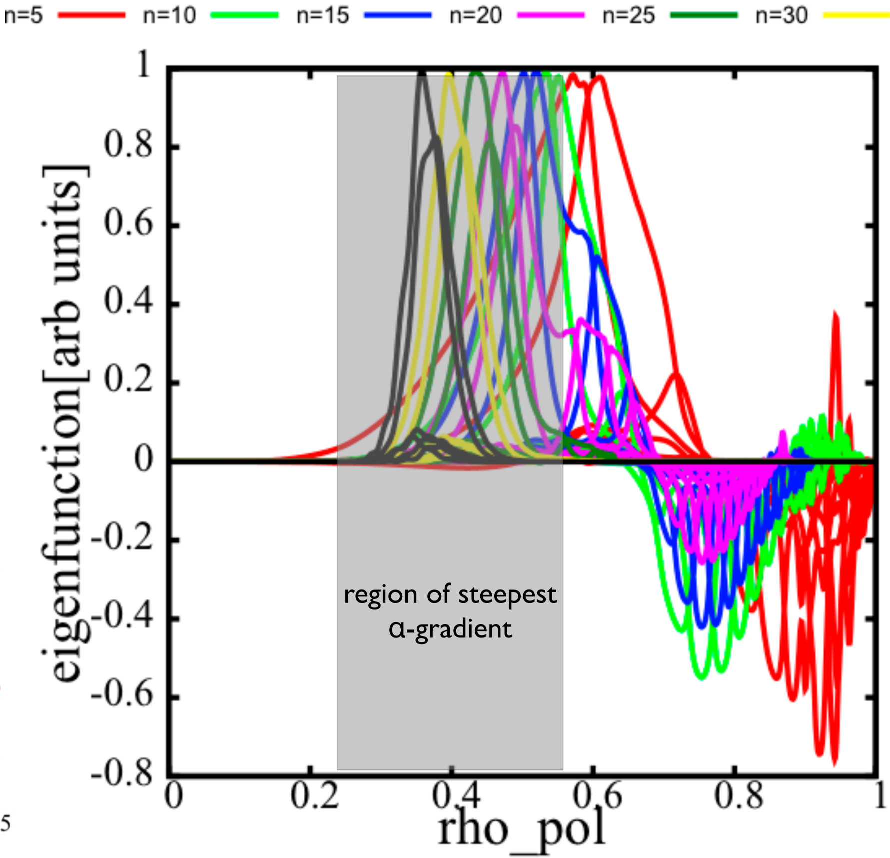
[S.D. Pinches et al PoP , 2015
Ph. Lauber PPCF 2015]

presently these calculations are updated: new baseline, heating mix, density peaking? W transport?

# expectations for ITER 15MA

damping > ~1%
various TAE branches
with same n





qualitatively new situation compared to present-day experiments:

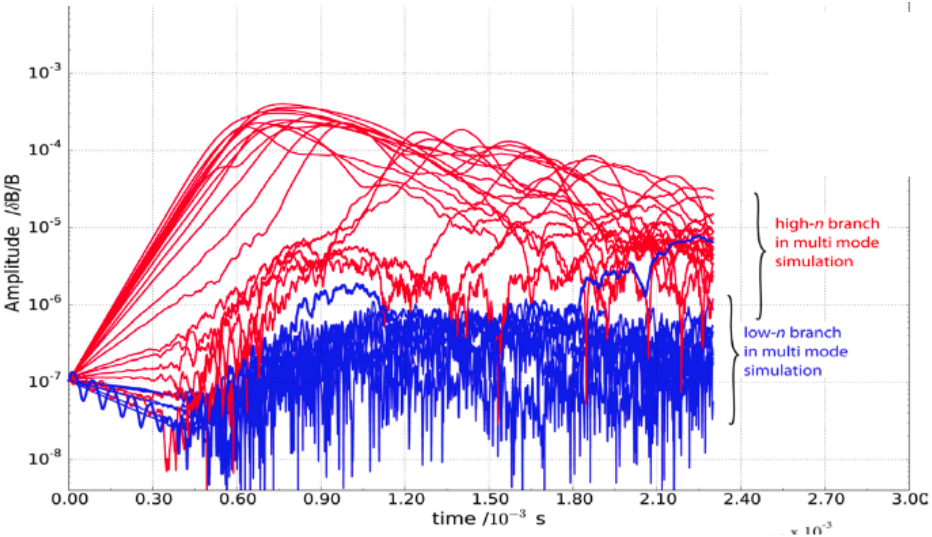
cluster of most unstable modes15<n<25

may destabilise subdominant modes with lower n in outer core

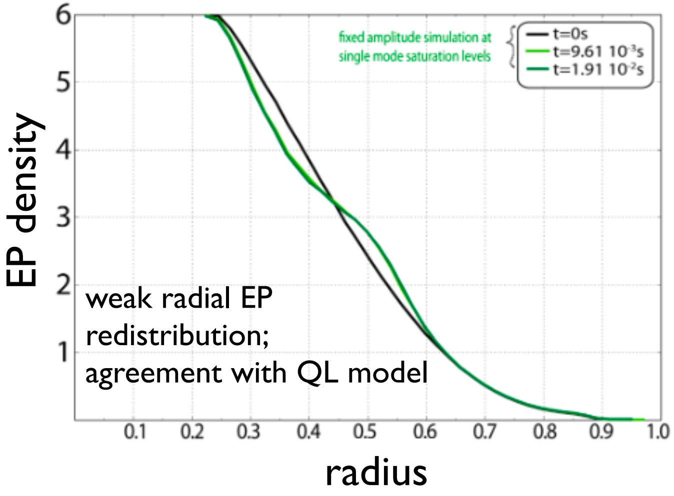
recently confirmed
by JET experiments
[M. Fitzgerald, 2023]

# expectations for ITER 15MA

HAGIS/LIGKA model, ITER 15 MA TAEs [Schneller, 2015]



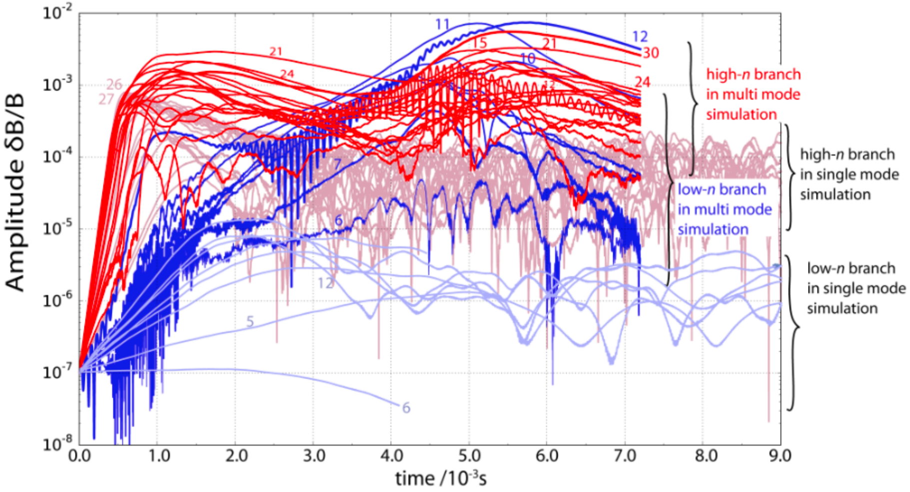
‘sea’ of weakly unstable TAEs expected with small EP transport;
agreement with diffusive/quasi-linear estimates



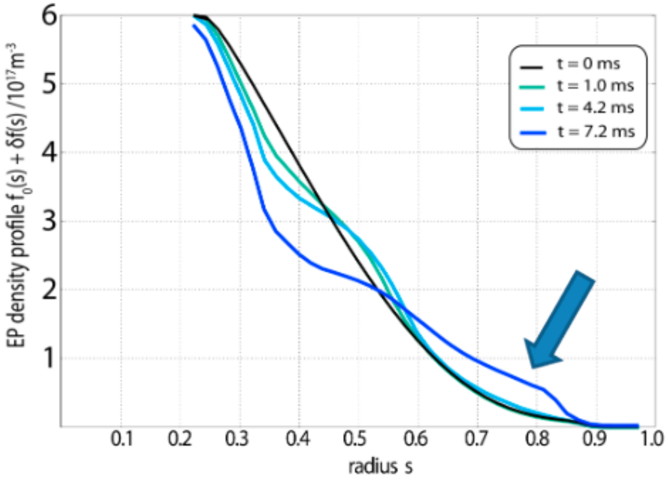
weak radial EP redistribution;
agreement with QL model

# expectations for ITER 15MA : scale $n_{EP}$ by 2

HAGIS/LIGKA model, ITER 15 MA TAEs [Schneller, 2015]



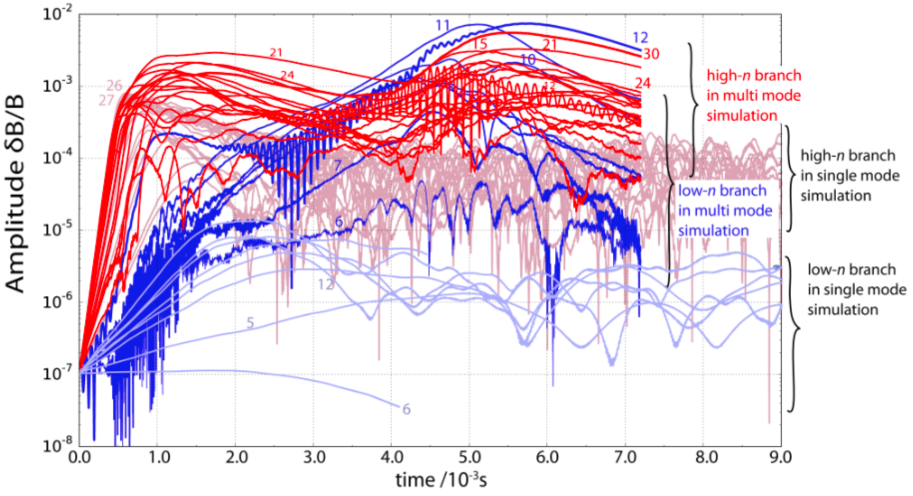
avalanche found, unacceptable EP transport



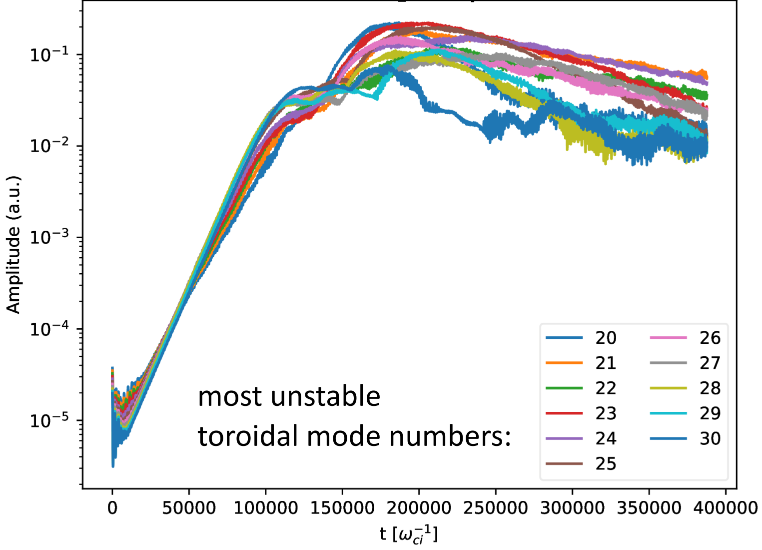
- also found in reduced descriptions: 1d beam plasma model [Carlevaro, 2015-17,2021]
- above simulations do not consider wave-wave non-linearities
- collisions influence saturation level [Slaby 2019]

# expectations for ITER 15MA : scale $n_{EP}$ by 2

HAGIS/LIGKA model, ITER 15 MA TAEs [Schneller, 2015]



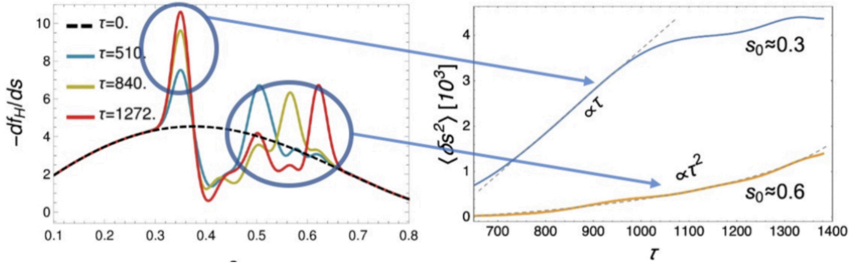
ITER 15 MA case - ORB5 [T Hayward-Schneider NF 2021]



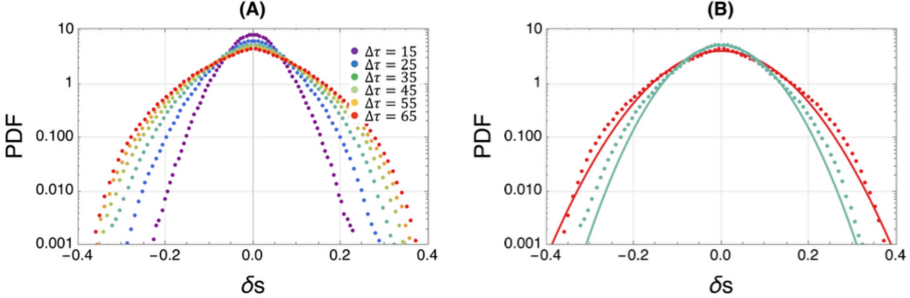
- compare LIGKA/HAGIS model to ORB5: global electromagnetic gyrokinetic code using the PIC approach in toroidal geometry [Lanti CPC 2020, for EP physics: Biancalani, Bottino, Hayward-Schneider, Vannini,… 2012-21]
- Effectively mitigates with the so-called cancellation problem using the pullback scheme (leads to an order of magn. increase of time step) [Mishchenko CPC 2019]
- very similar linear and non-linear properties of ITER 15 MA case were found [T Hayward-Schneider 2021, AAPPS-DPP 2020]

# what kind of EP transport?

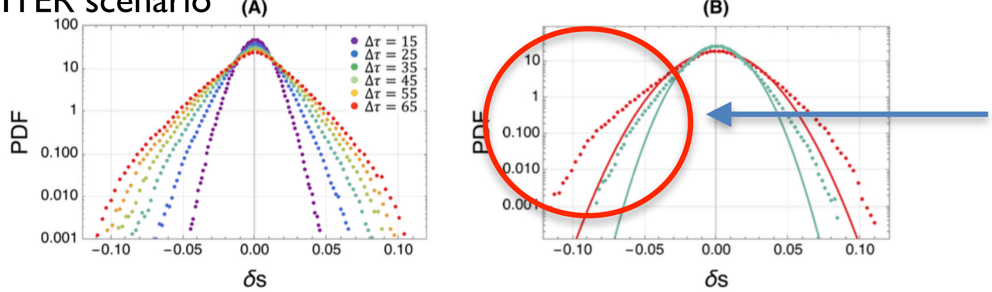
N. Carlevaro, G. Montani, M.V. Falessi, Ph. Lauber, EPS22, P5a.113 ID : 32056



diffusive scenario



ITER scenario



- can we describe the previously studied ITER 15MA case with a diffusive model? [part of ENR ATEP scope]
- using test particle analysis for analysing global transport properties in reduced 1d bump-on tail model
- determined diffusive (τ) vs. convective ($\tau^2$) scalings
- different behaviour of high-n TAE and low-n TAE branch!

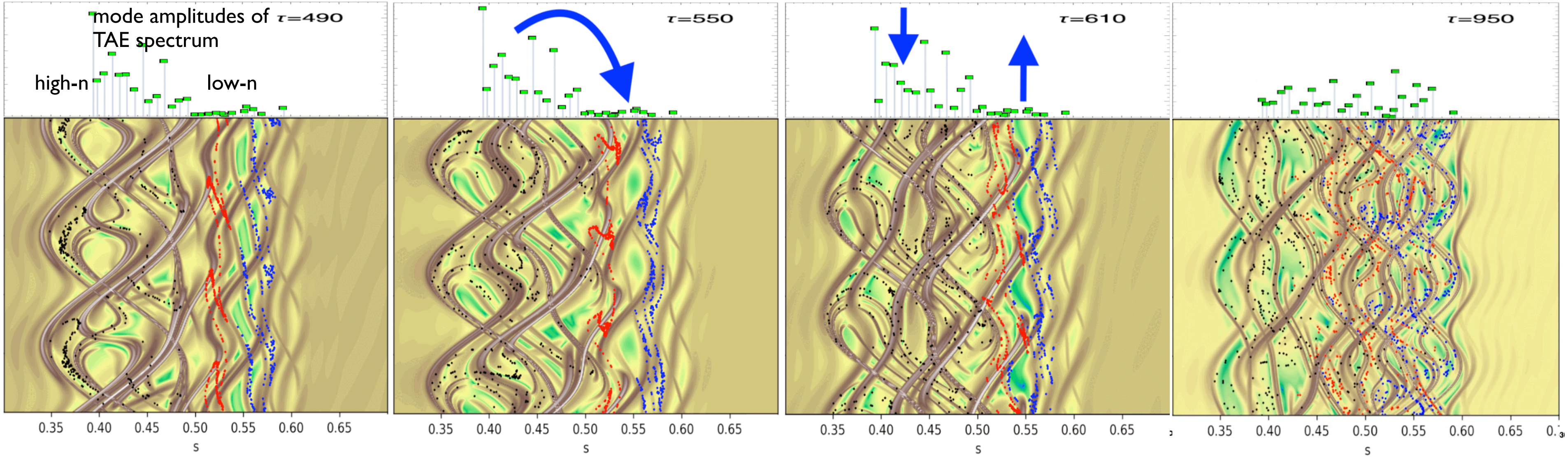
Expectation for a **pure diffusive model:**
trajectories - measured with δs=s(τ-δτ)-s(τ) - defined by random walk
PDF expected to be a **normal distribution**

BUT: asymmetry of the PDF:
**Non diffusive transport!**

# what kind of EP transport?

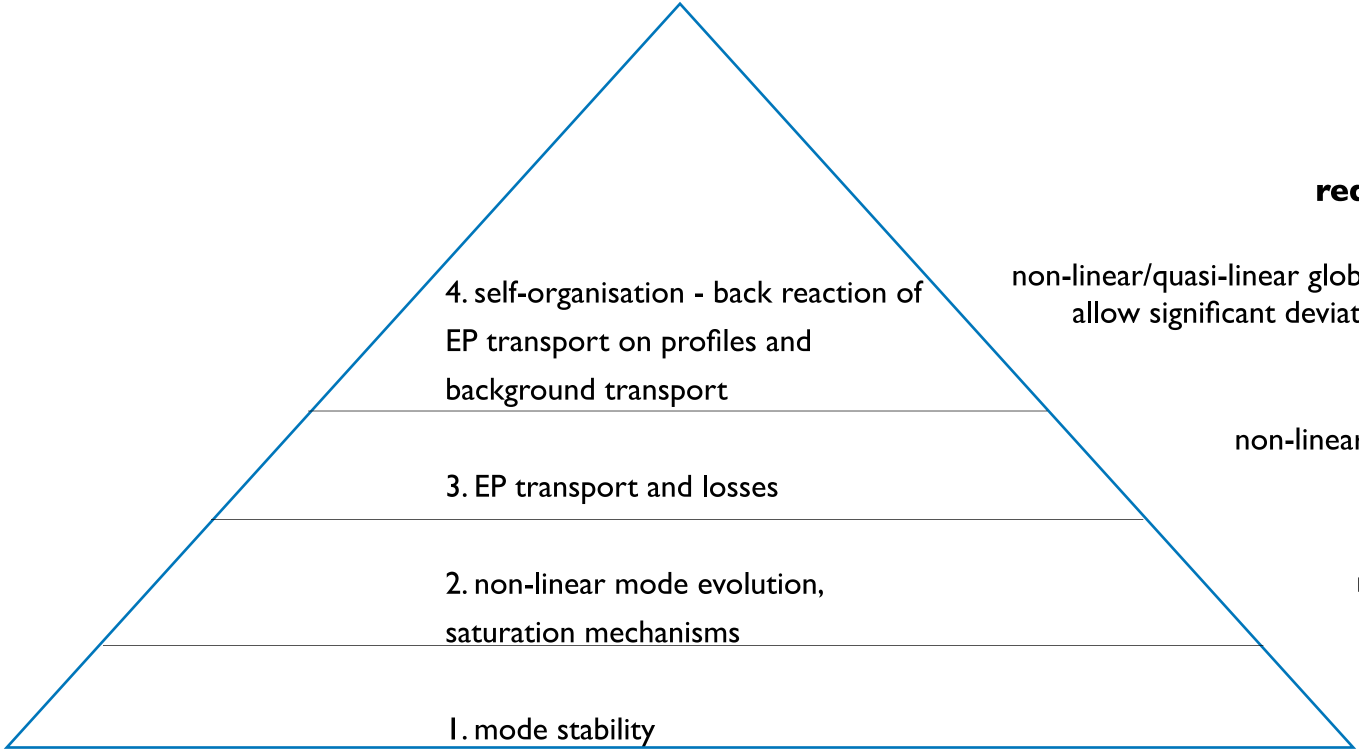
- Lagrangian Coherent Structures: most repulsive or attractive material lines (transport barriers).
- Early times show diffusive behaviour at high-n TAE locations
- Late times show avalanche-like behaviour at low-n branch

[N. Carlevaro et al, to be submitted]



# 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**



4. self-organisation - back reaction of EP transport on profiles and background transport

3. EP transport and losses

2. non-linear mode evolution, saturation mechanisms

1. mode stability

**required models:**

non-linear/quasi-linear global kinetic e.m.+ background transport; allow significant deviations from neoclassical equilibrium

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

non-linear global kinetic e.m.

linear global kinetic e.m.

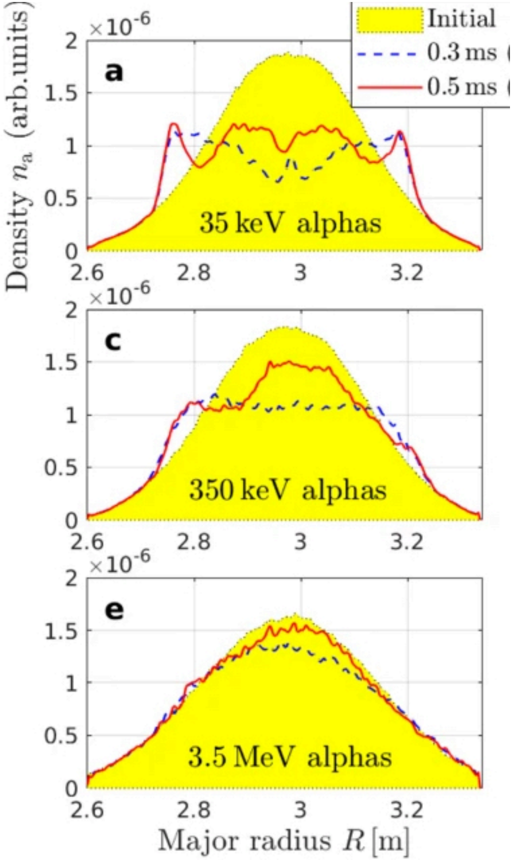
# aspects of self-organisation in a fusion plasma

- in ITER/DEMO, core TAEs can be weakly unstable; edge TAEs are weakly damped and can be driven non-linearly [Pinches, Lauber, Schneller 2014/2015, T Hayward 2019, ORB5]
- let us assume that EPs stabilise background turbulence under ITER/DEMO conditions [Mantica, Citrin et al, 2007-2024] when $\beta_{thermal}$ and $\beta_{EP}$ start to increase during ramp-up; or also density peaking increases reactivity
- $T_{D,T}$ profiles will be more peaked than in [Polevoi 2002] - need to understand exact conditions and time scales for peaking
- peaked $T_{D,T}$ profiles will lead to increased reactivity ~$T^2$ (or density peaking)
- α particle profiles will also peak until significant EP transport sets in (large slowing-down time scales!)
- the nature of this transport determines how large the ‚overshoot' will be - diffusive in the core but large enough to trigger avalanche as in ITER example? ( factor 2 in $\nabla n_\alpha/n_\alpha$ )
- flattened EP profile will negatively impact the EP stabilisation mechanism - additional Ti flattening might set in
- note that this ‚limit cycle oscillation' comprises collisional, transport and EP-transport times - large time scale separation
- in order to avoid large overshoots, mitigation for EP-generated transport barriers may be needed (see ELMs)

# possible control mechanisms

- current profile:  tailor q-profile in order to ensure TAE resonance overlap to stay in diffusive transport regime (difficult under reactor conditions)
- sawtoothing: control sawtooth crashes to tailor energetic α's and He-ash
- D-T fuelling: control D:T mix;  higher D fraction increases ion Landau damping of TAEs; higher T fraction decreases ion LD
- impurities ‚destabilise' AEs and thus may prevent overshoots (central ECRH heating)

[Bierwage Nat.Comm 2022]



# role of DTT for burning plasma physics

DTT:
16MW ECH
4MW ICH
10MW NNBI (~500keV)

$B_T$= 6T
$I_P$=5.5 MA
R=2.2m
a=0.7m

JT-60SA:
7MW ECH
10MW NNBI (~500keV)
24MW PNBI

$B_T$= 2.25T
$I_P$=5.5 MA
R=2.96m
a=1.18m

key opportunity for EP studies:
flexibility of operating at different currents and fields while keeping high heating power [RP, chapter 4]
more space for diagnostics (less PNBI ports)?

# role of DTT for burning plasma physics

- scan unstable AE mode number spectrum - larger capability than other machines, including super-Alfvénic resonances (DTT n~17, ITER n~25; FOW effects - linear physics)

- study overlapping conditions of AEs and characterise nature of transport: as normalised parameters match burning plasmas [chapter 7], this will give indications on EP losses (core-edge integration, linear - quasi-linear/non-linear hybrid)

- study steady-state / chirping transitions, as transport increases significantly when AEs are chirping (non-linear) [X. Wang 2022]

- interaction of EPs with turbulence: wide scan over β-range and EP-distribution function properties (non-linear/ multi-scale) [Di Siena et al, 2021]

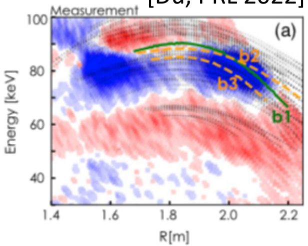
- fusion mock-up experiments: as β and Ti increase (using NNBI + ECRH) - add ICRH to mimic additional drive due to increased reactivity (non-linear/ multi-scale/ neoclassical coupling)

- use current profile and/or impurity control to influence AE stability - exploit W wall and similarity scaling (non-linear/ multi-scale/ neoclassical coupling + control )

- use light impurities to mimic dilution and/or D:T mix scalings (non-linear/ multi-scale/ neoclassical coupling + control)

- use comprehensive diagnostics to measure non-linear zonal state (in particular phase space distortions)

[Du, PRL 2022]



available and emerging new theories/tools

requirements:

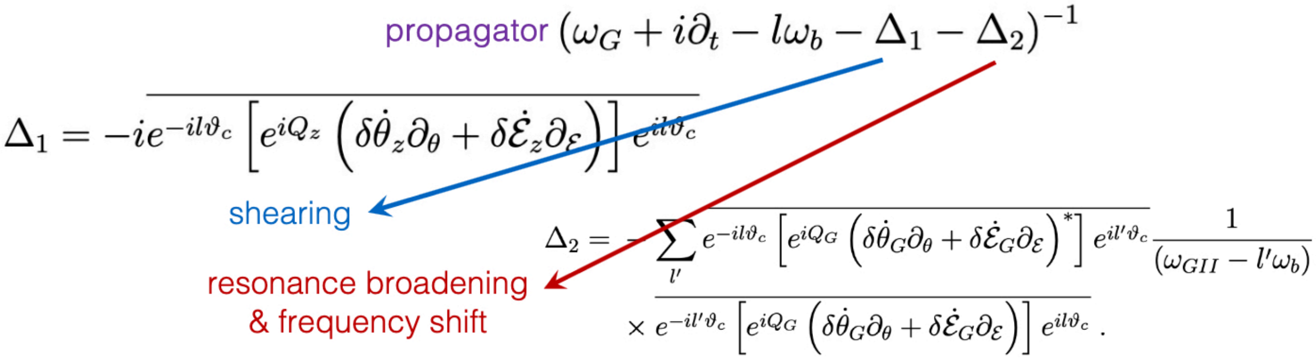
- validation and verification for reactor relevant physics
- special role of EPs and phase space
- able to be eventually integrated in transport codes - aim for IMAS compatibility

# PSZS theoretical framework

- comprehensive PSZS transport theory: include zonal fields as e.m. counterpart of phase space zonal structures - complete description of nonlinear equilibrium
- nonlinear equilibrium connected to (anisotropic) CGL description
- application of theory to EGAMs - explicit equations for non-linear chirping dynamics - ready for comparison with simulations

[M.V. Falessi et al, EPS 2023, invited talk]
[M.V. Falessi et al, EFTC 2023, invited talk]
[M.V. Falessi et al, IAEA FEC 2023]
[M.V. Falessi et al, NJP **25** 123035 2023]

## Self-consistent description of EPM repeated burst dynamics using the PSZS theoretical framework



propagator $(\omega_G + i\partial_t - l\omega_b - \Delta_1 - \Delta_2)^{-1}$

$$\Delta_1 = -i\overline{e^{-il\vartheta_c}\left[e^{iQ_z}\left(\delta\dot{\theta}_z\partial_\theta + \delta\dot{\mathcal{E}}_z\partial_{\mathcal{E}}\right)\right]e^{il\vartheta_c}}$$

shearing

$$\Delta_2 = -\sum_{l'}\overline{e^{-il\vartheta_c}\left[e^{iQ_G}\left(\delta\dot{\theta}_G\partial_\theta + \delta\dot{\mathcal{E}}_G\partial_{\mathcal{E}}\right)^*\right]e^{il'\vartheta_c}}\frac{1}{(\omega_{GII} - l'\omega_b)} \times \overline{e^{-il'\vartheta_c}\left[e^{iQ_G}\left(\delta\dot{\theta}_G\partial_\theta + \delta\dot{\mathcal{E}}_G\partial_{\mathcal{E}}\right)\right]e^{il\vartheta_c}}\,.$$

resonance broadening
& frequency shift

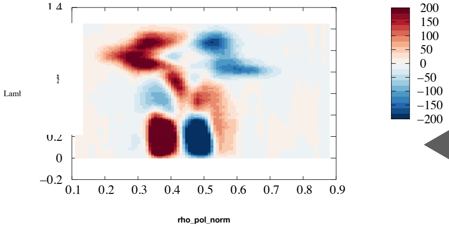
[F. Zonca et al, IAEA FEC 2023]
[F. Zonca et al, AAPPS-DPP 2023]

+beat-driven vs spontaneous excitation of ZFs [Chen/Zonca/Qiu, 2024]

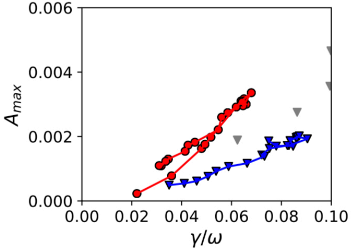
+ 3D version of PSZS equation [A. Zocco et al, 2023]

# ATEP code - physics and structure

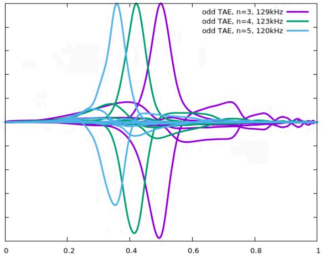
**orbit+zonal averaging**



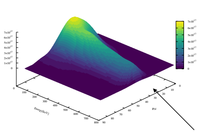
**saturation rule/E**



**EP WF: LIGKA [20]**



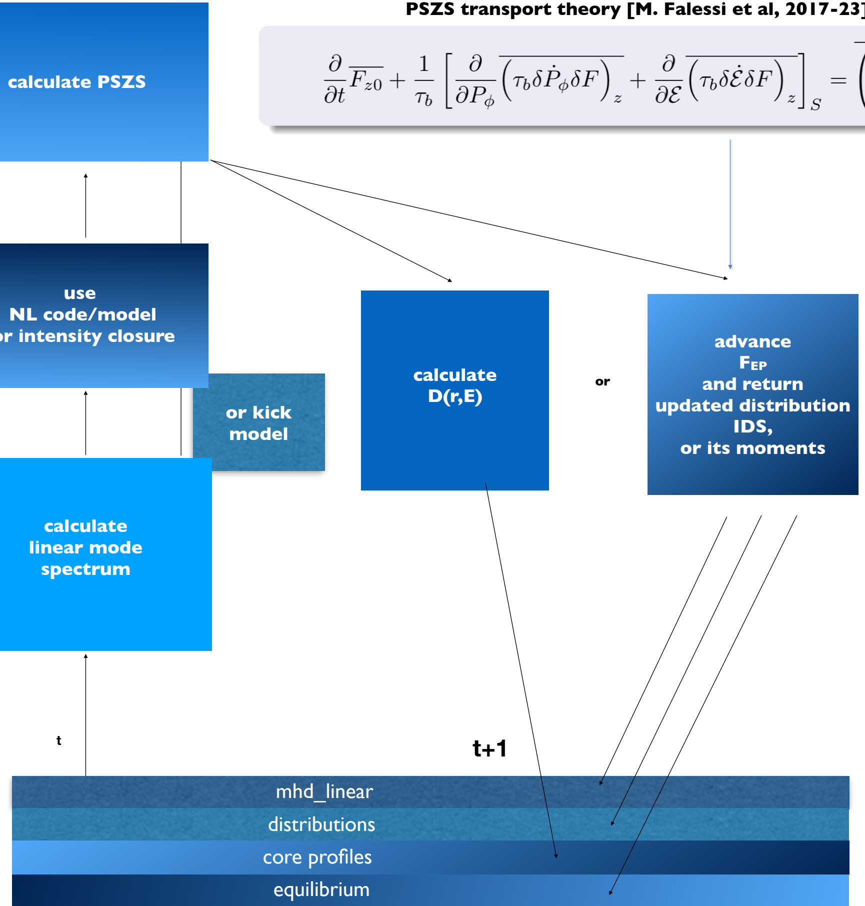
**F$_{EP}$ (CoM)**



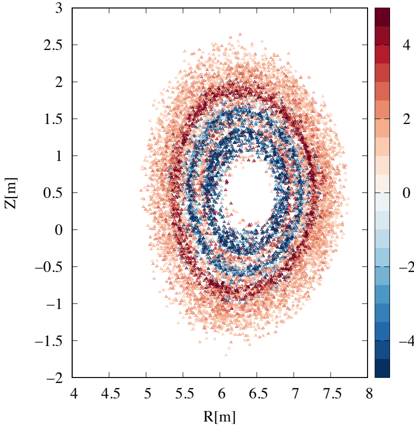
**transport code**

**PSZS transport theory [M. Falessi et al, 2017-23]**

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



**time**



**ATEP code**
**[Ph. Lauber, G. Meng,2022]**

# EP stability workflow, based on linear GK code LIGKA

[Ph. Lauber,
V.-A. Popa,
T. Hayward-Schneider+
ITER support ]

- **automate analysis of stable/unstable Alfvén eigenmodes:**
  - for many equilibrium time slices
  - for many relevant toroidal mode number (Tokamak only, axisymmetry)
  - relevant types of modes
- **use hierarchy:**
  - start with simple, analytical model
  - use local model
  - use global model
- **understand physics and numerical challenges:**
  - determine (kinetic) continuous spectra
  - investigate local vs global damping mechanisms
  - determine resolution requirements for expensive runs
- **determine sensitivity of AEs:** look at series of equilibria, include uncertainties
- **be general:** use IMAS mhd_linear IDS to store results - each model is exchangeable (e.g. spectrum: LIGKA or Falcon)
- **be fast:** use reduced models where possible
- **be robust** enough to use it as fundamental ingredient for transport models

# EP stability WF: design criteria

- **automate analysis of stable/unstable Alfvén eigenmodes:**
  - for many equilibrium time slices
  - for many relevant toroidal mode number (Tokamak only, axisymmetry)
  - relevant types of modes
- **use hierarchy:**

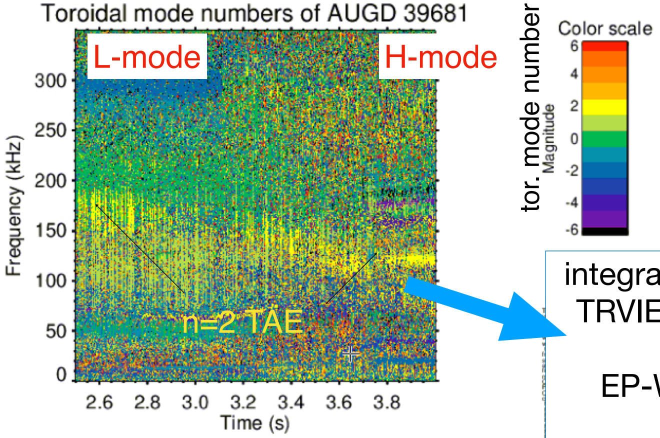
modules available on gateway/ ITER cluster
see training course (July 2023)

https://indico.euro-fusion.org/event/2729/

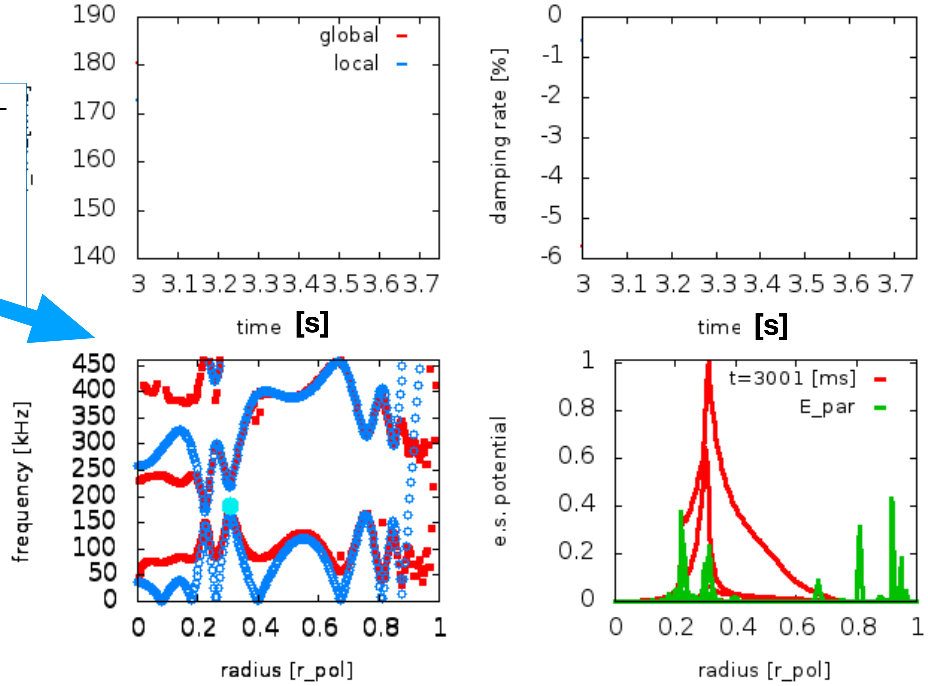
- **unde**
  - investigate local vs global damping mechanisms
  - determine resolution requirements for expensive runs
- **determine sensitivity of AEs:** look at series of equilibria, include uncertainties
- **be general:** use IMAS mhd_linear IDS to store results - each model is exchangeable (e.g. spectrum: LIGKA or Falcon)
- **be fast:** use reduced models where possible
- **be robust** enough to use it as fundamental ingredient for transport models

# application: present-day experiments

- **automated processing of 160 time slices based on IDA equilibria and profiles**
- **fully implemented in IMAS, ensuring reproducibility**



integrated data analysis +
TRVIEW(IMAS interface)
+
EP-WF: LIGKA local
+
EP-WF: LIGKA global



- **analyse L-mode,H-mode and transition phases:**

**beat infamous problem of AE stability sensitivity to profiles**

**- compare trends instead of single time slices**

- **compare local and global models**
- **systematic uncertainty quantification feasible**
- **applied also to TCV, JET, JT-60SA, ITER**

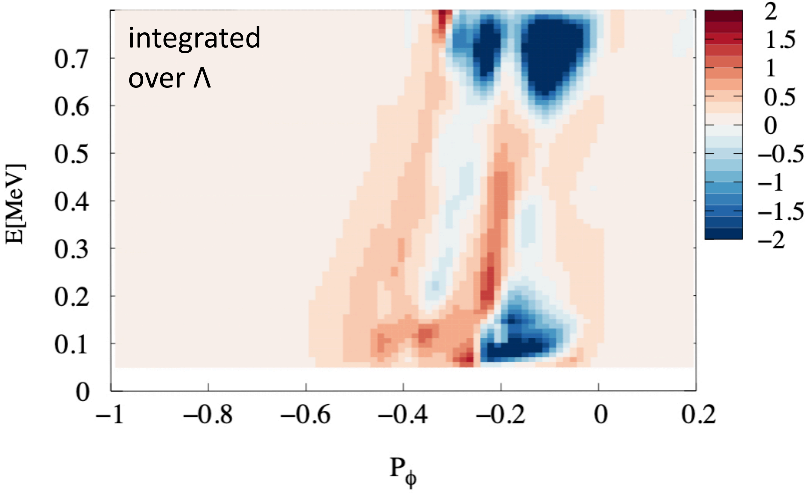
**[Lauber, EPS 2022, Popa 2020-2023]**

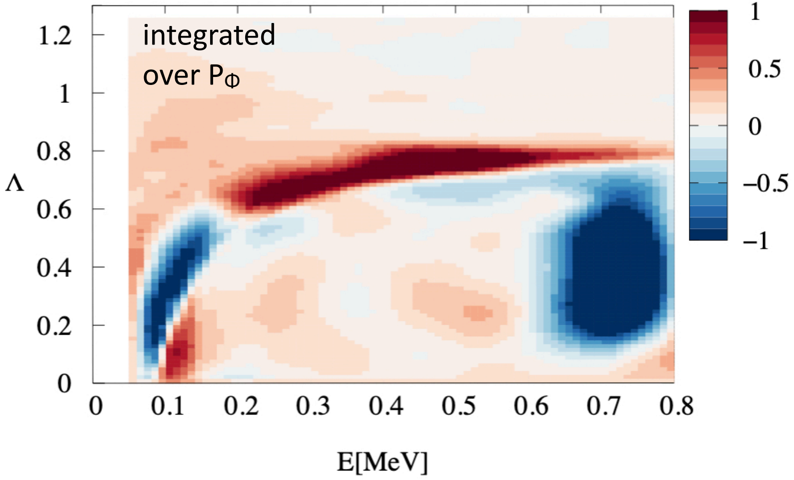
# ATEP code - kick model limit

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

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

with constant $\delta B(t)/B) = 10^{-5}$





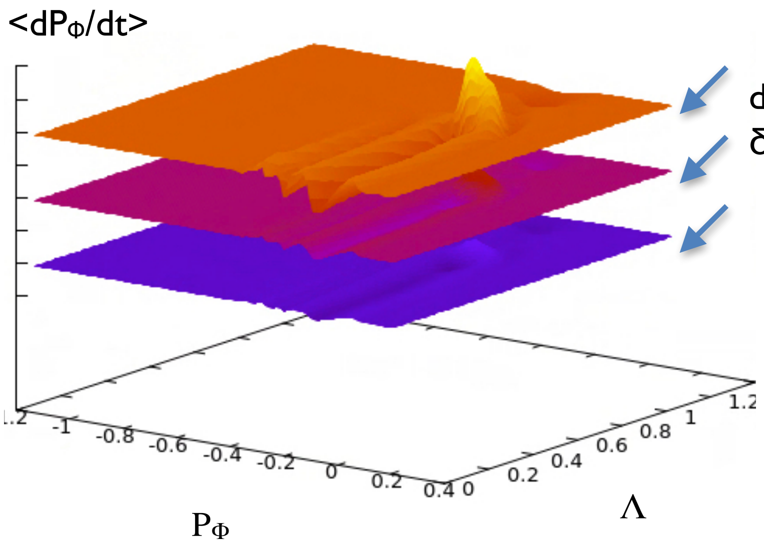
# ATEP code - energy conserving QL model

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

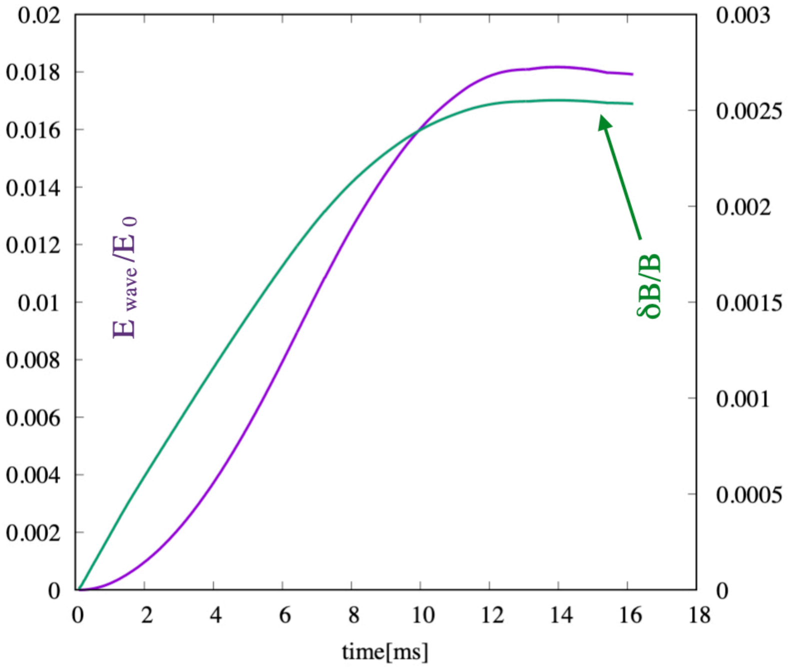
$$\frac{d}{dt}\left(\mathscr{E} + \sum_k W_k\right) = -2\sum_k \gamma_{d,k} W_k$$

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

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

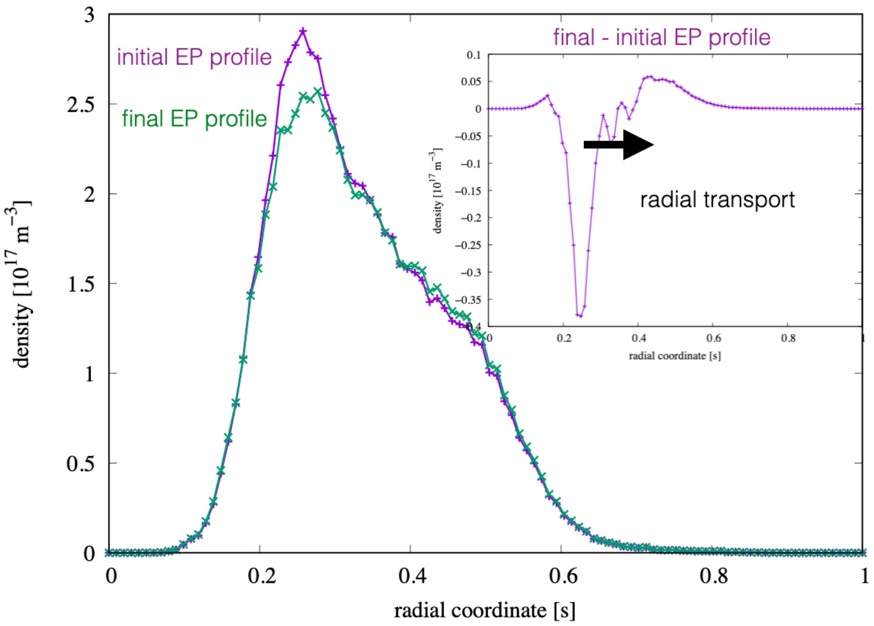


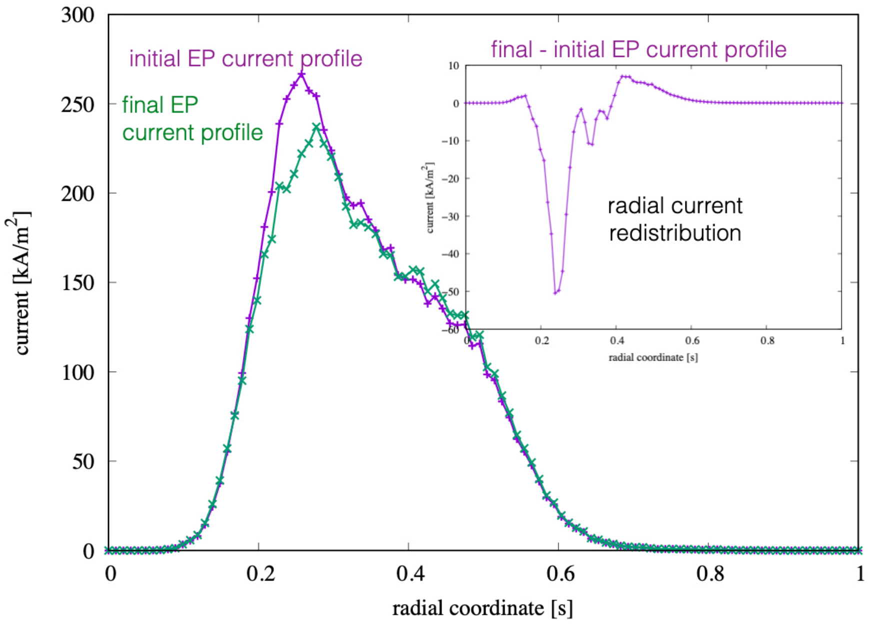
different δB/B



# ATEP code: back-mapping to configuration space

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





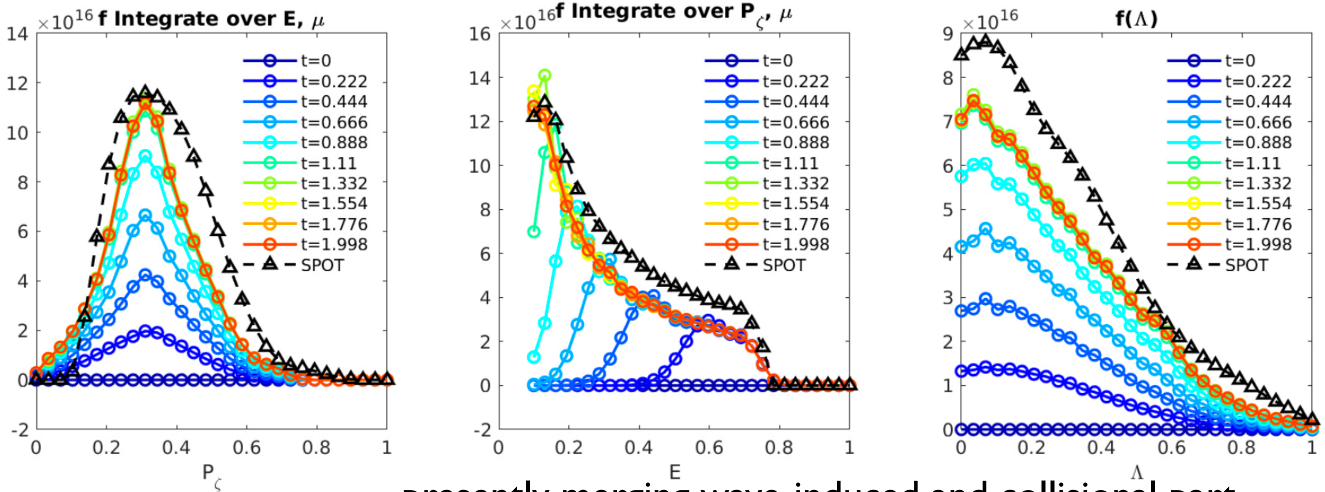
return non-linear EP density, current, pressure to transport code

# new neoclassical building block for ATEP 3D [G Meng, Ph. Lauber, submitted NF 2024]

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

- use collision operator in HAGIS code [A. Bergmann, PoP 2001]
- calculate orbit averaged collision-coefficients in CoM space
- separate co- and counter-passing regions, use IMAS-given n,T profiles

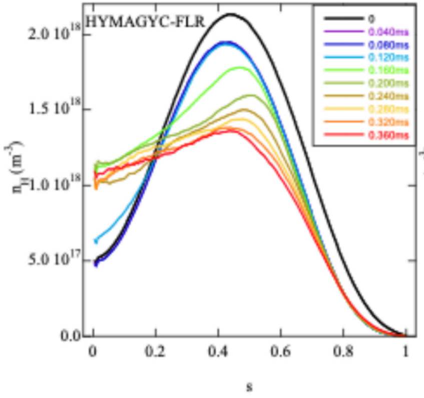
compare to SPOT [M. Schneider]: reasonable agreement

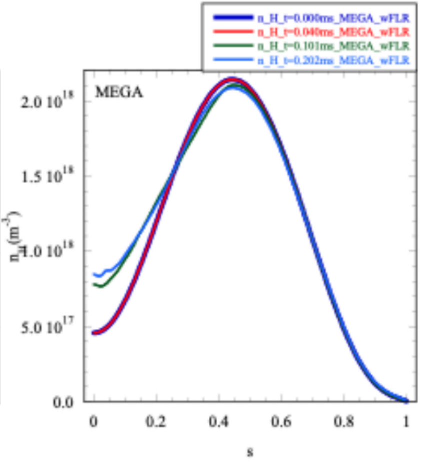


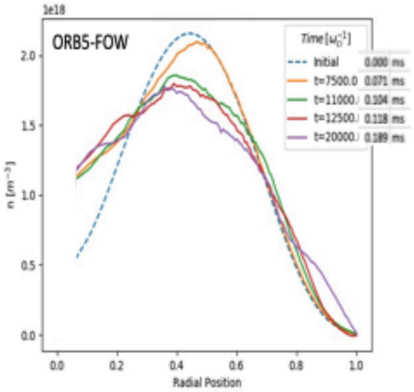
presently merging wave-induced and collisional part

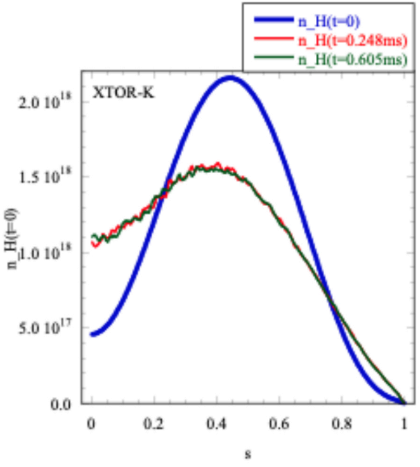
# MHD-kinetic hybrid models deliver benchmarks for reduced models

- together with TSVV10: non-linear benchmark for NLED AUG case has been carried out [G.Vlad, IAEA FEC 2023, submitted NF] - important benchmark for ATEP code suite.
- note large instability-induced EP transport, deviating substantially from neoclassical values



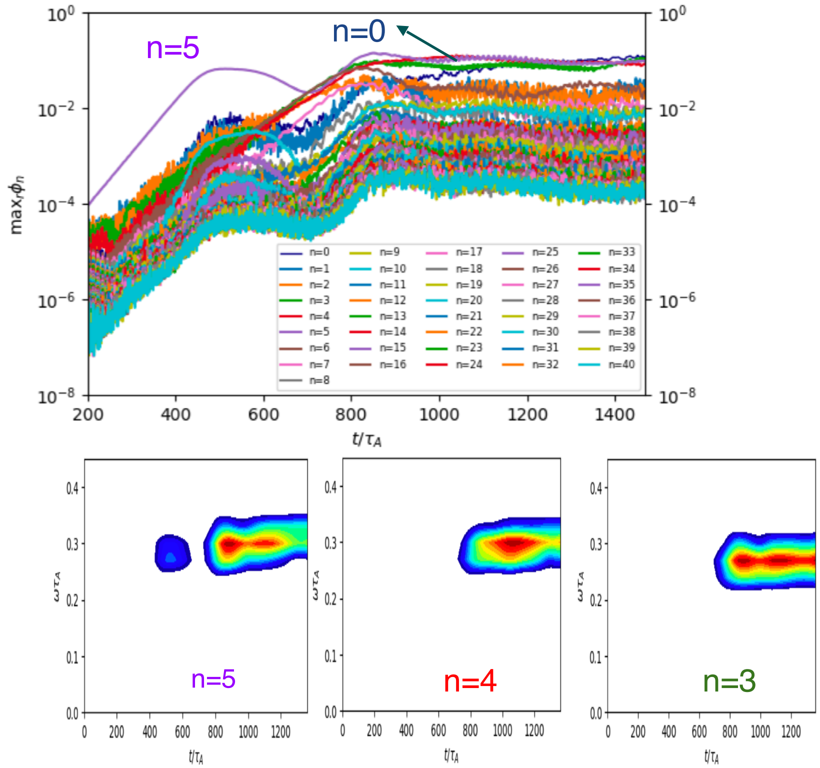






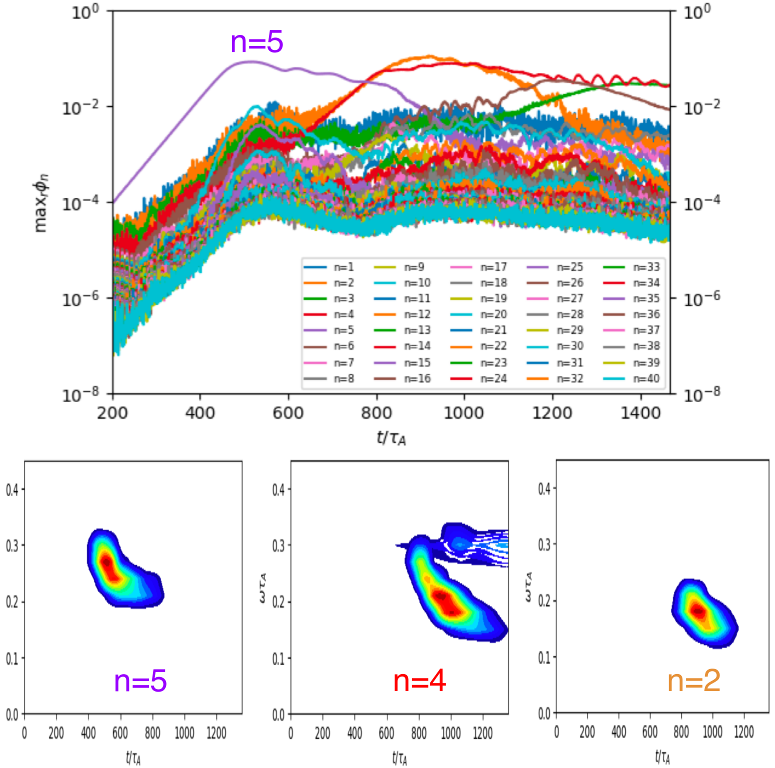
# Fully self-consistent global ORB5 simulations in presence of EPs and turbulence

With Zonal Flow



Without Zonal Flow

[X Wang, ITPA 2022]

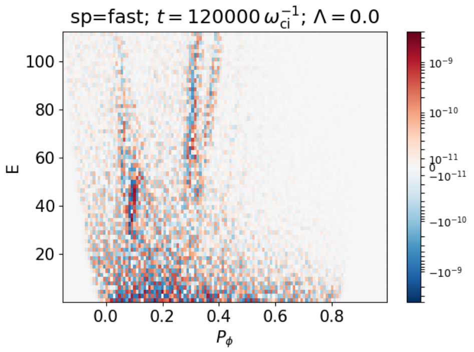


- keep n=[0-40], high-n fluctuation driven by thermal background can develop, EPs drive n=2-5 TAE/EPMs
- result: zonal flows strongly influence the chirping behaviour - typically preventing chirping; turbulence level less important
- in the future: aim for connection to theoretical nonlinear theories and provide input for reduced models

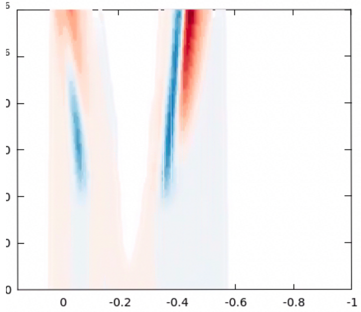
# comparison of reduced models with ORB5

- comparison of PSZS between ATEP and ORB5: n=19 TAE ITER #101006 (ongoing)

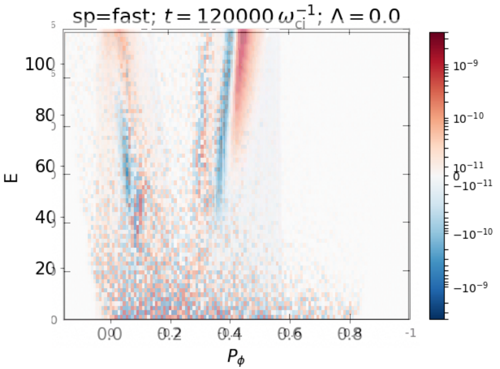
**ORB5: slowing down**
**n=18+19 case, linear phase**



**ATEP: phase space fluxes**
**n=18+19 case**
**hot Maxwellian**



**ORB5 vs ATEP**

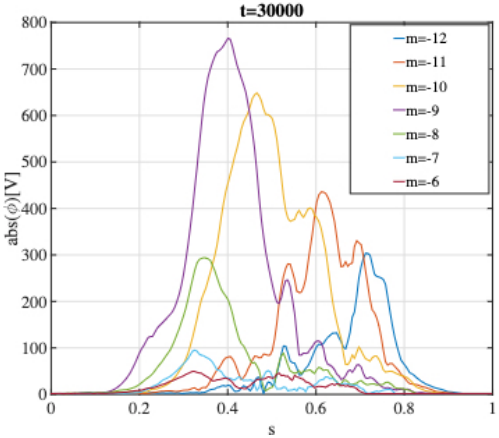


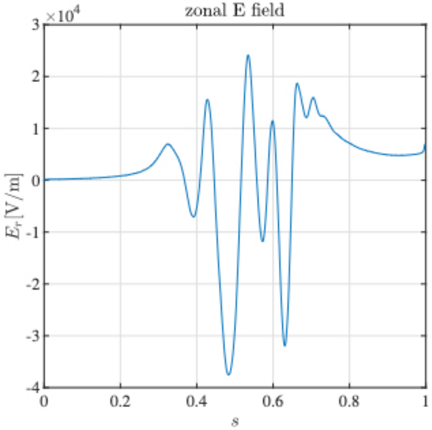
**[T Hayward-Schneider, A. Bottino; TSVV-10]**

- remaining differences: non-perturbative modes in flat-shear scenario
- very challenging, but promising start for comprehensive quantitative match!
- PSZS about to become ‚gold- standard' for comparison of non-linear runs and reduced models
- comparing moments will remain important, but not sufficient for qualifying simulation results

# ORB5 studies of TAE-induced ZF - starting to include ZFs in reduced models

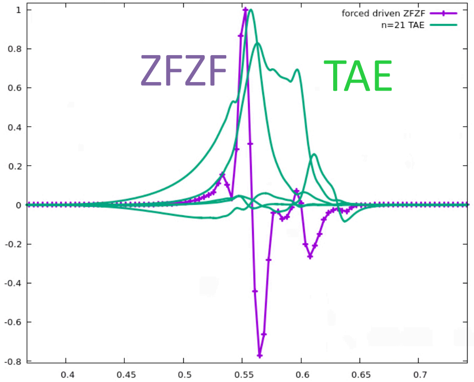
comprehensive AE + ZF studies + turbulence (ORB5/TSVV10)
here: JET case [J. N. Sama, submitted to J. Plasma Phys. (2024)]





- stabilising influence of ZF on ITG spectrum demonstrated
- reasonably large TAE amplitude required for stabilisation
- PSZS diagnostics available as a standard diagnostics in ORB5

EP Stability WF: TAE+ ZFZF
using analytical theory [Qiu, NF 2017]
ITER case



propagator $(\omega_G + i\partial_t - l\omega_b - \Delta_1 - \Delta_2)^{-1}$

$$\Delta_1 = -i\overline{e^{-il\vartheta_c}\left[e^{iQ_z}\left(\delta\dot{\theta}_z\partial_\theta + \delta\dot{\mathcal{E}}_z\partial_{\mathcal{E}}\right)\right]e^{il\vartheta_c}}$$

shearing

$$\Delta_2 = -\sum_{l'}\overline{e^{-il\vartheta_c}\left[e^{iQ_G}\left(\delta\dot{\theta}_G\partial_\theta + \delta\dot{\mathcal{E}}_G\partial_{\mathcal{E}}\right)^*\right]e^{il'\vartheta_c}}\frac{1}{(\omega_{GII} - l'\omega_b)} \times \overline{e^{-il'\vartheta_c}\left[e^{iQ_G}\left(\delta\dot{\theta}_G\partial_\theta + \delta\dot{\mathcal{E}}_G\partial_{\mathcal{E}}\right)\right]e^{il\vartheta_c}}\,.$$

resonance broadening
& frequency shift

building on successful comparison of theory with GTC fishbone simulations [Brochard, accepted 2023]

# summary

- DTT can address very specific and relevant questions concerning burning plasma physics
- core-edge integration as main focus of the machine open opportunities for burn-control studies (impurity control, EP transport control)
- DTT is important opportunity for the validation and verification of reactor relevant physics - special role of EPs and phase space
- developing theories and tools for reduced modelling need to be integrated in transport codes