Collaborazioni EUROfusion: ATEP ENR

M.V. Falessi, G. Vlad, F. Zonca

What is ATEP?

Title	***Advanced Energetic particle transport models (ATEP)***
Topic Area	***3. MHD, disruptions and fast particle physics***
Principal Investigator	***Philipp Lauber (PI), Matteo Falessi (co-PI)***
Beneficiary	***IPP, ENEA***
Project duration	**3 years**

Man power

Manpower: IPP Garching & Greifswald (intended per year for the whole 3yr. project duration):

Philipp Lauber (PI): 6pm;
Xin Wang: 6pm;
Guo Meng: 6pm;
Alessandro Biancalani: 5pm;
Markus Weiland.: 3pm;
Axel Koenies: 3pm;
Alessandro Zocco: 3pm;

IPP: 32pm/y total

At 0 cost: Alin Popa (4pm), Florian Holderied (4pm), S. Possanner (TUM, 3pm)

Manpower ENEA (intended per year for the whole 3yr. project duration):

Matteo Falessi 10pm (co-PI);
Fulvio Zonca 3pm;
Yueyan Li 12pm (post doc);
Valeria Fusco 4pm;
Alexander Milovanov 2.4pm;
Nakia Carlevaro 4pm;
Gregorio Vlad 3pm;

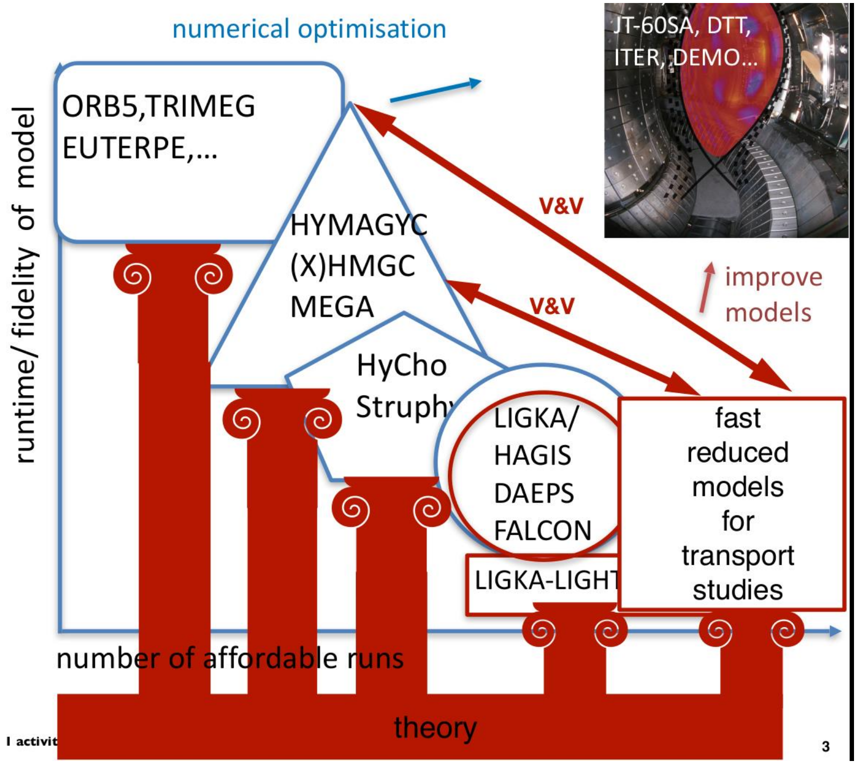
ENEA: 38.4pm/y total

Objectives

- construction and validation of advanced reduced EP transport models;
- go beyond simple models (QL, kick-model) that, however, can be recovered in the appropriate limits;
- transport models will be embedded into the IMAS framework, relying on the stability information given by local and global GK codes;
- the models can be used and integrated into other transport workflows developed outside this ENR project (e.g. in connection with TSVV#10 deliverables), or for experimental modelling.

Scientific Scope

- ATEP follows as a whole a new innovative theoretical framework
- Large analytical component
- The practical implementation(s) of this model relies on recent advances in EP reduced modelling
- V&V with comprehensive codes; investigate statistical properties
- Plan and conduct dedicated experiments for validation in various regimes



Work Packages

WP1:
theoretical framework

WP 2:
Advancing various building blocks according to WP1

WP3:
Implementation, application and verification of reduced EP transport models

WP4:
Preparation of time-dependent reference cases

WP1: What is transport?

- Radial transport requires the study of flux surface averaged equations:

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

- finite contributions only from non-linear terms with vanishing toroidal and poloidal mode-numbers;
- in principle they have arbitrary radial length-scale.

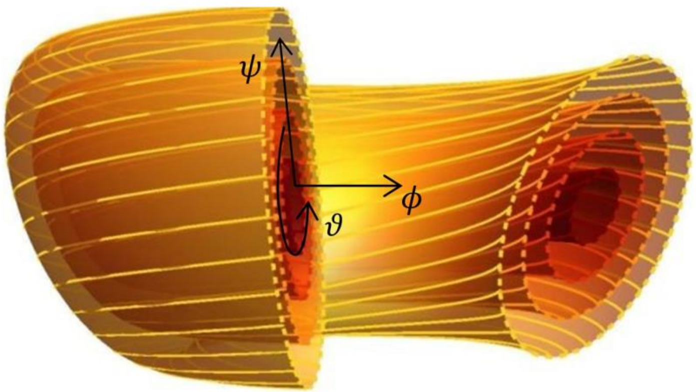
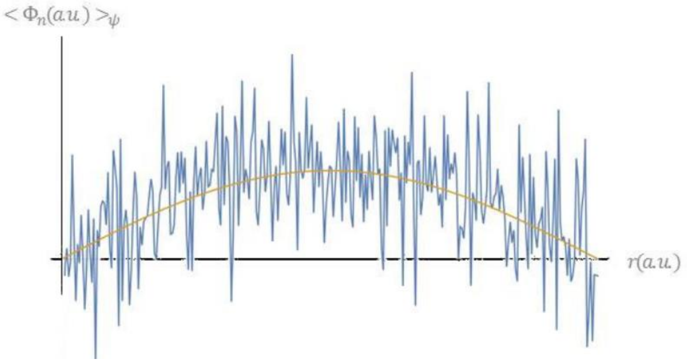


Figure: Courtesy of J. Ball



WP1: theoretical framework

Zonal structures & Zonal field structures

- Mode mode coupling between fluctuating fields can generate toroidal symmetric structures in the density and temperature profiles unaffected by rapid collision-less dissipation, i.e. Landau damping, called zonal structures;
- their counterpart for vector and scalar potentials are called zonal field structures, e.g. $\delta \boldsymbol{E}_r = -\boldsymbol{\nabla}\psi \partial_\psi \delta\phi(\psi)$.

Phase space zonal structures (PSZS)

- fluctuations collision-less undamped in the phase space are called phase space zonal structures and they importantly regulate turbulence saturation level by scattering instability turbulence to shorter radial wavelength stable domain;
- they are coherent micro/meso-scale radial corrugations of the distribution function Chen and Zonca 2016. They are associated to deviations from the local thermodynamic equilibrium and thus they may enhance collisional transport.

WP1: the importance of meso-scales

Meso-scales on ITER . . .

- peculiar feature of ITER: interplay of meso-scale structures with micro-scales generated by energetic particles, e.g. $\rho_{LE} \sim (\rho_L L)^{1/2}$;
- unique role of energetic particles, which act as mediators between the micro- and the macro- scales;

. . . and DTT (Divertor Tokamak Test facility)

- $T_E/T_i \sim (4\rho*)^{-1} \Rightarrow \rho_{LE} \sim (\rho_L L)^{1/2}$ with dimensionless parameters close to ITER;
- using minority heating by ICRH and/or NBI, cross-scale couplings should be similar;

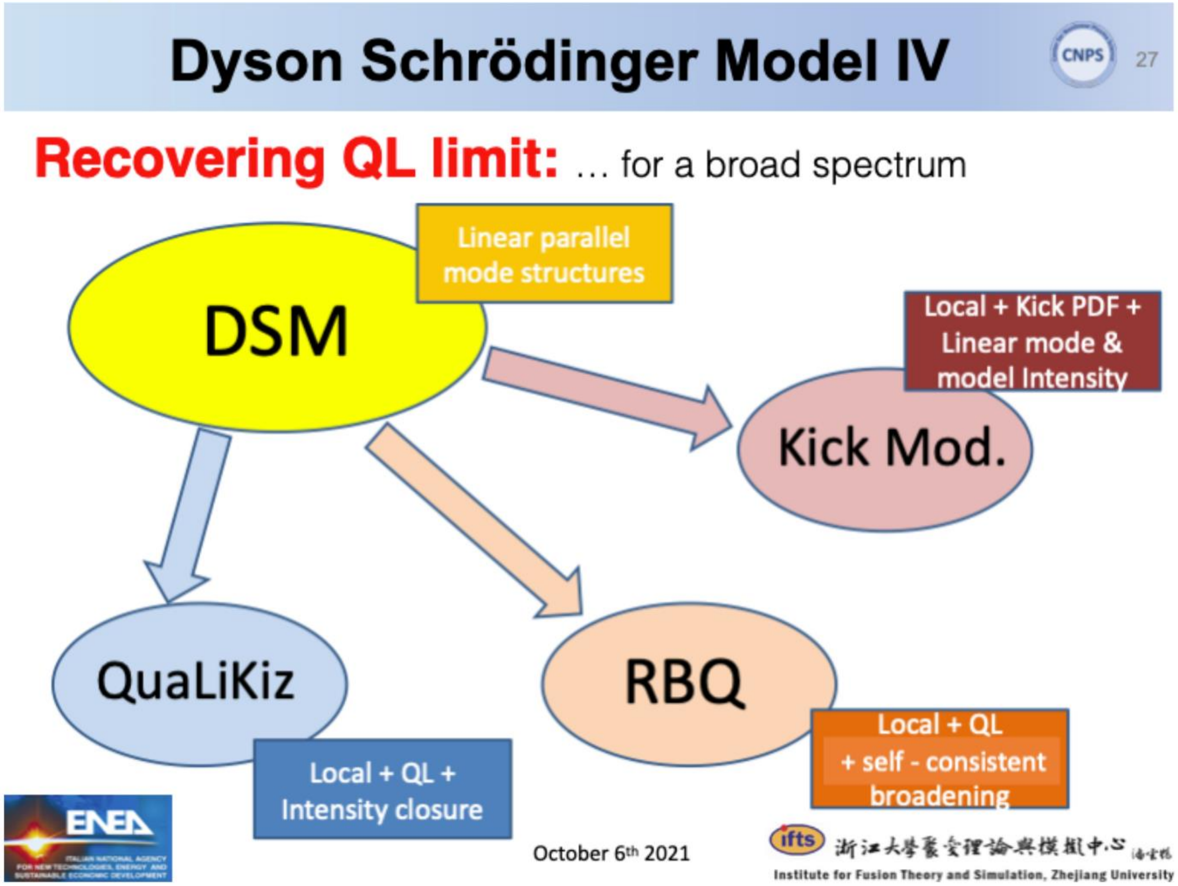
- need for transport equations for the mesoscales extending previous analysis;
- non Maxwellian distribution functions must be taken into account, i.e. phase space transport;
- meso-scales do not emerge only due to EP physics, e.g. ITBs, L-H transitions;
- derivation based on the theory of Phase space zonal structures, see Zonca et al. 2015a; Chen and Zonca 2016; Falessi and Zonca 2019;

WP1: theoretical framework

- 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 $|\omega| \gg \tau_{NL}^{-1} \sim \gamma_L$;
- the second and final level of simplification is the Quasilinear model.

WP1: DSM model



- DSM is 'superset' of various models presently used in community
- describe EP dynamics on transport time scales with general GK transport theory
- applicability beyond local, QL and intensity closure models
- crucial new element [M. Falessi et al, 2016-2020, recent invited talk at Varenna Theory meeting]: introduce concept of long-lived formations in the particle phase space (PSZS); separate from fast fluctuating contributions
- accounting in particular for meso-scales introduced by EPs

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WP2: DAEPS

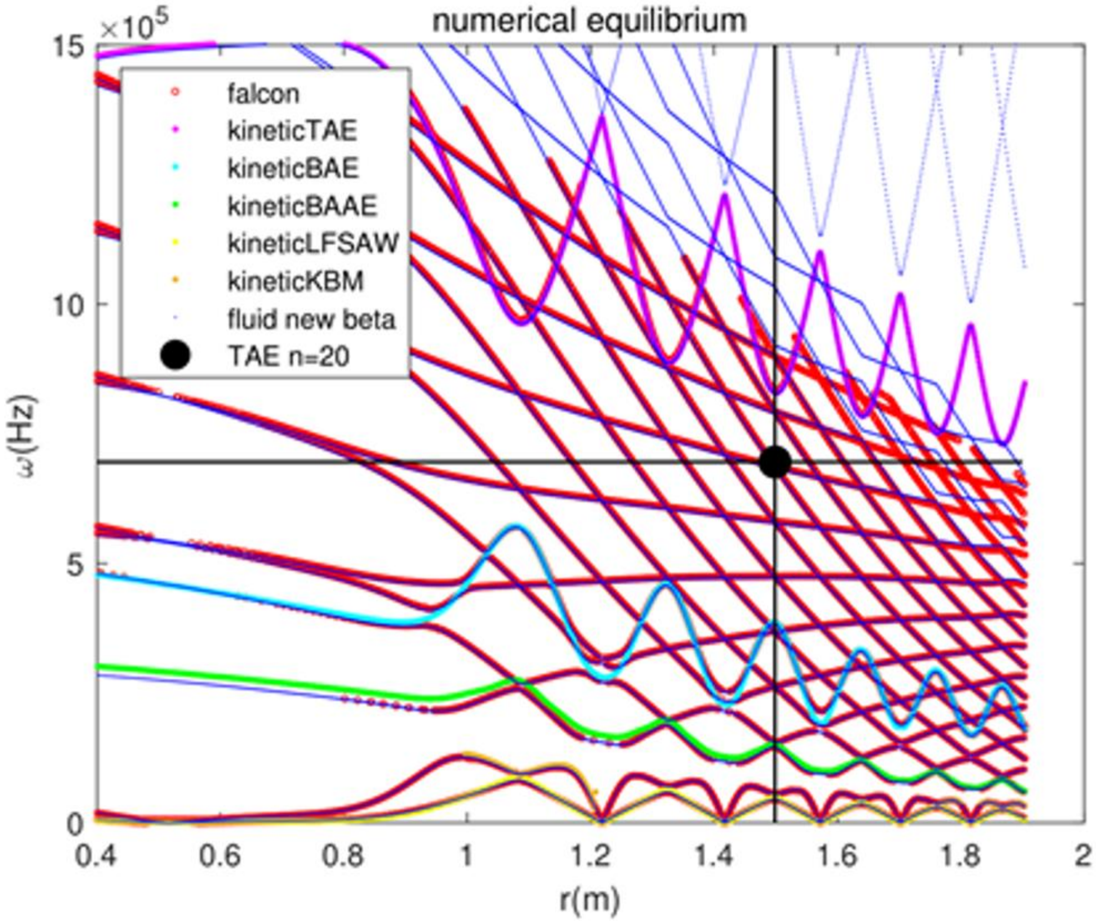
$$\left[\frac{\partial^2}{\partial\vartheta^2} - \left(\frac{\partial_y^2\hat{\kappa}_\perp^2}{2\hat{\kappa}_\perp^2} - \frac{\left(\partial_\vartheta\hat{\kappa}_\perp^2\right)^2}{4\hat{\kappa}_\perp^4}\right) + \frac{\omega^2 J^2 B_0^2}{v_A^2} - 8\pi J^2\frac{\partial P_0}{\partial r}\right.$$

$$\left.\times\left(\frac{rB_0}{q\hat{k}_\perp d\psi/dr}\right)\left(\kappa_g\frac{\hat{\kappa}_\perp\cdot\nabla\psi}{\hat{\kappa}_\perp|\nabla\psi|} - \kappa_n\frac{rB_0}{q\hat{k}_\perp|\nabla\psi|}\right)\right]\hat{\phi}_{s0} = 0$$

$$\hat{\kappa}_\perp = \left[\nabla r(s\vartheta - s\theta_k) + r\nabla\theta - \frac{r}{q}\nabla\zeta\right]$$

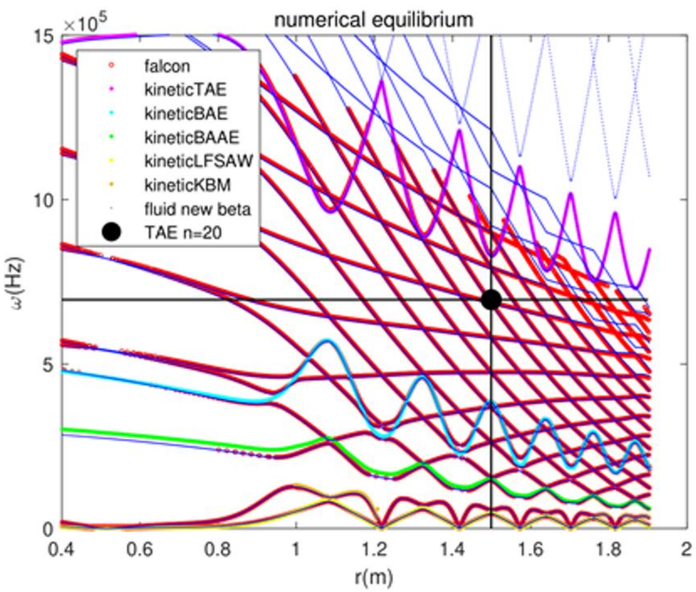
- κ, $|\nabla\psi|^2, J$ can be calculated by EQUIPE consistently with the different level of approximation;
- Possibility of parametric scans, e.g. in triangularity, elongation…
- the resulting TAE frequency will be compared with MARS;
- DAEPS governing equations are similar but more convoluted.

WP2: DAEPS



numerical equilibrium
×10^5
15
10
5
0
ω(Hz)
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
r(m)
falcon
kineticTAE
kineticBAE
kineticBAAE
kineticLFSAW
kineticKBM
fluid new beta
TAE n=20

WP2: DAEPS


numerical equilibrium
×10^5
falcon
kineticTAE
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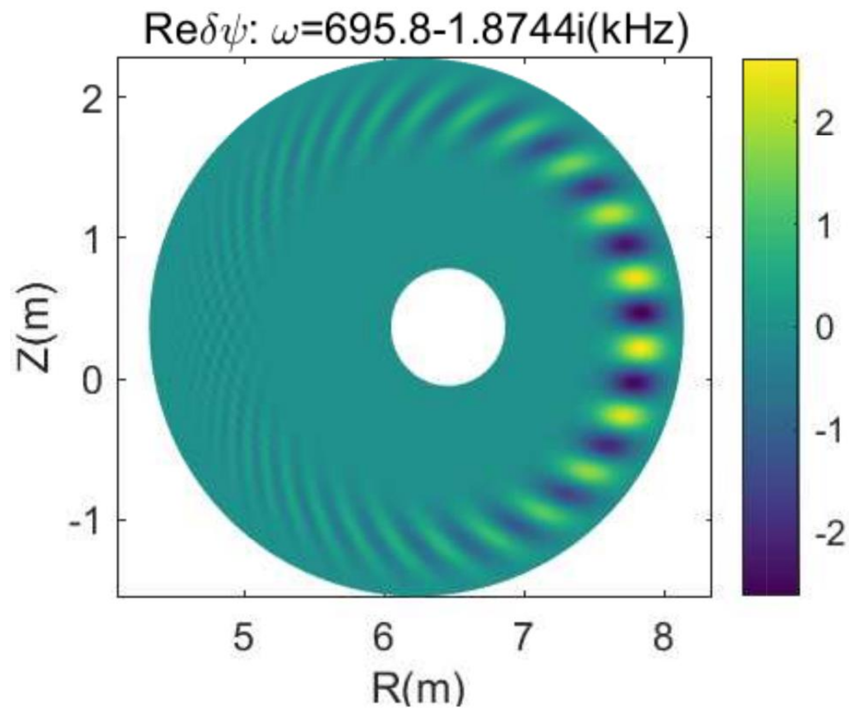
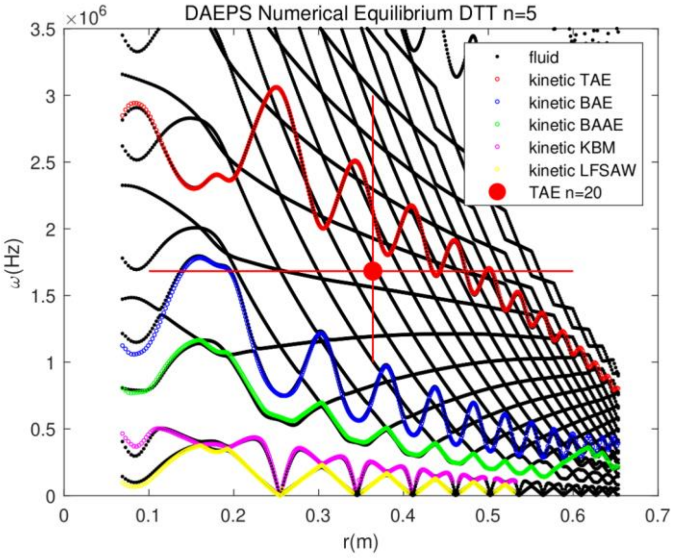
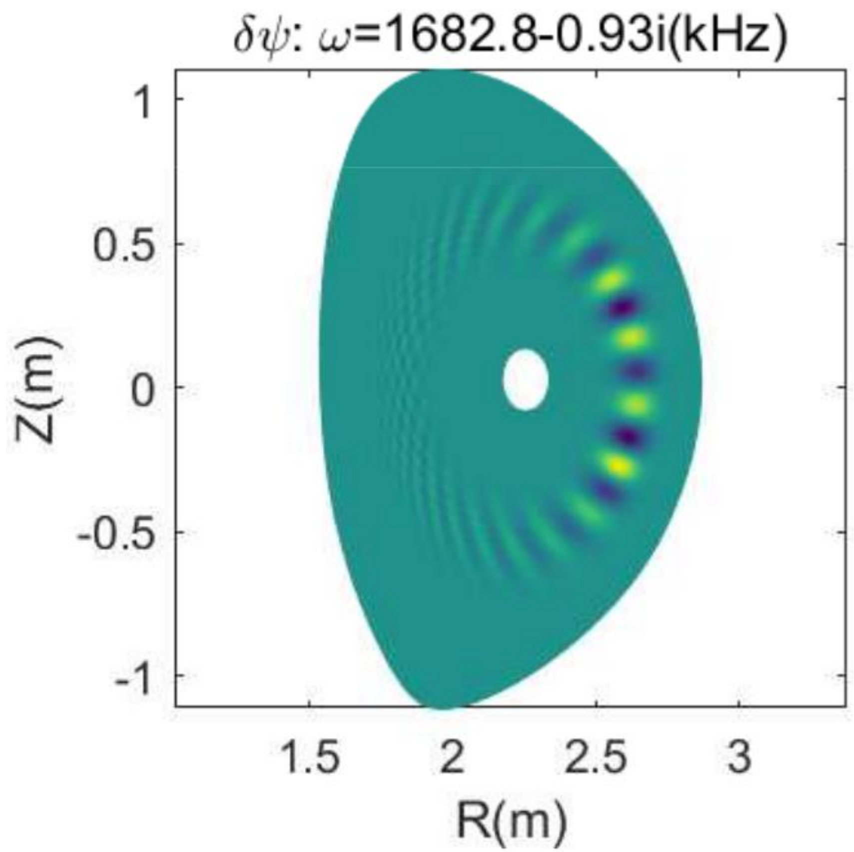
fluid new beta
TAE n=20
ω(Hz)
r(m)


Reδψ: ω=695.8-1.8744i(kHz)
Z(m)
R(m)

WP2: DAEPS


DAEPS Numerical Equilibrium DTT n=5
×10^6
3.5
3
2.5
2
1.5
1
0.5
0
ω(Hz)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
r(m)
fluid
kinetic TAE
kinetic BAE
kinetic BAAE
kinetic KBM
kinetic LFSAW
TAE n=20

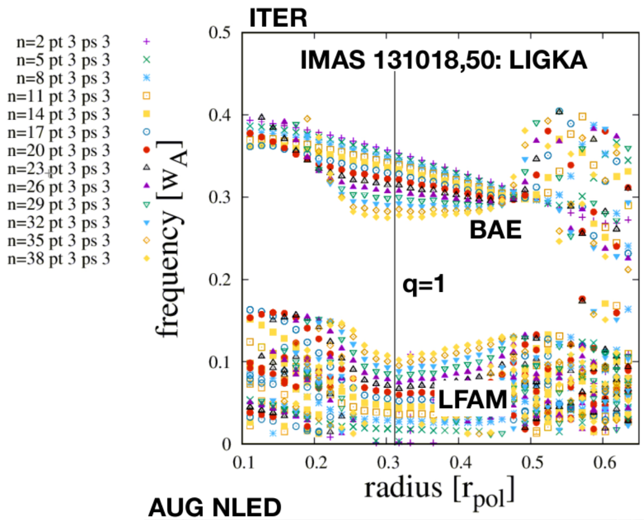

δψ: ω=1682.8-0.93i(kHz)
1
0.5
0
-0.5
-1
Z(m)
1.5
2
2.5
3
R(m)

WP2: DAEPS - LIGKA - FALCON codes

WP2.1-D1 (2021)

DAEPS in general tokamak geometry: **minor possible delay** (3PMs for Y.Y. Liu in 2021); continuum spectrum in realistic geometry ready

due to administration/travel restrictions **to be absorbed in early 2022**

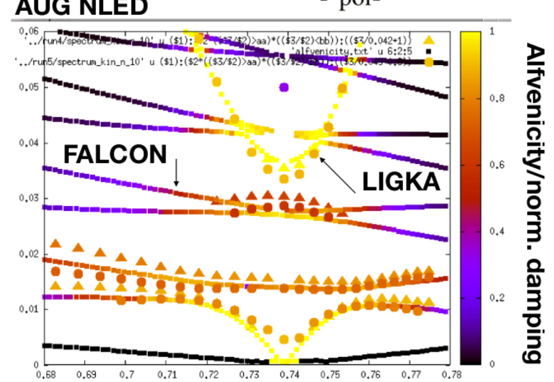


WP2.1-M1 (2022)

Benchmark of DAEPS in general toroidal geometry against reduced local LIGKA analysis

Status:

- 3 cases chosen: AUG NLED, ITER 131018,50 , ITER 131018,50 in circular geometry, equilibria/profiles prepared
- first LIGKA results available, DAEPS runs started
- successful benchmark of LIGKA and FALCON (ENEA) on NLED case
- **trapped particle part in 2022, as expected**



WP2: Linear Codes in 3d geometry

WP 2.3 Extension to 3d geometry/ phase space zonal structures in stellarators
identified new set of action-angle variables for perturbed quasihelically symmetric stellarators and tokamaks
presently investigating how to extend the present analysis to omnigenous stellarators

presentation: Joint CNPS - DTT MHD&Theory series on Friday, October 29th
https://www.afs.enea.it/zonca/CNPS/Activities/meetings.html

local 3d solver: started: checked passing orbits expressions - similar to CAS3D-K,
2022 milestone expected to be reached

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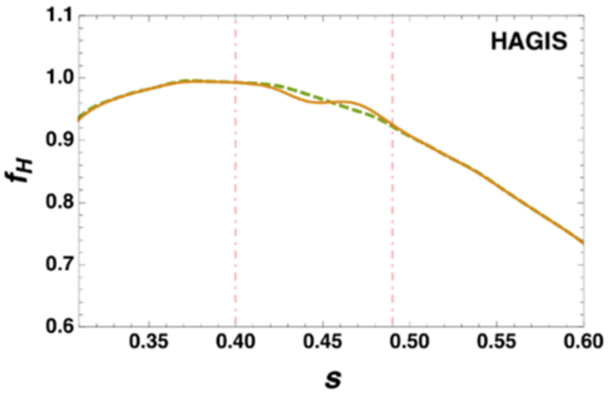
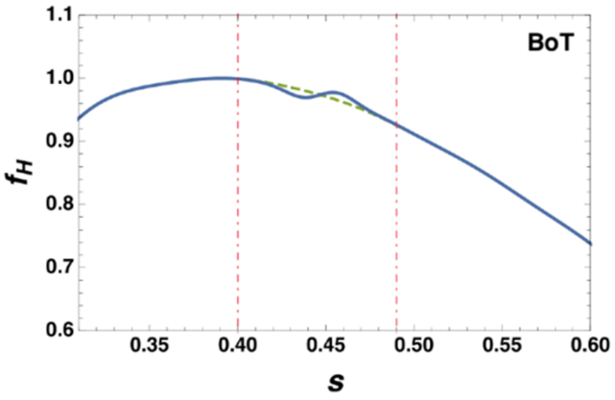
WP3.1: 1d reduced transport model

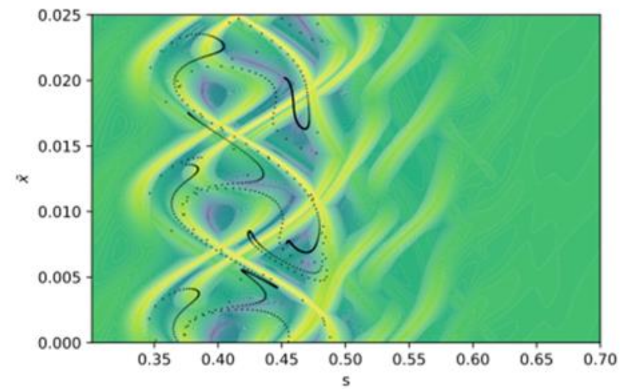
- Partition of phase space into regions of constant μ (magnetic momentum) and $C = \omega P_\varphi - nE$
- Decompose plasma into different slices and estimate the corresponding weight related to the global/reduce wave-particle power exchange: evolution of the most resonant slice (maximization of the power exchange)

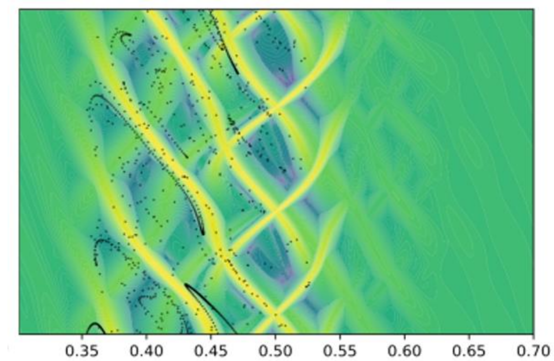




WP3.2: Diffusive transport vs coherent structures

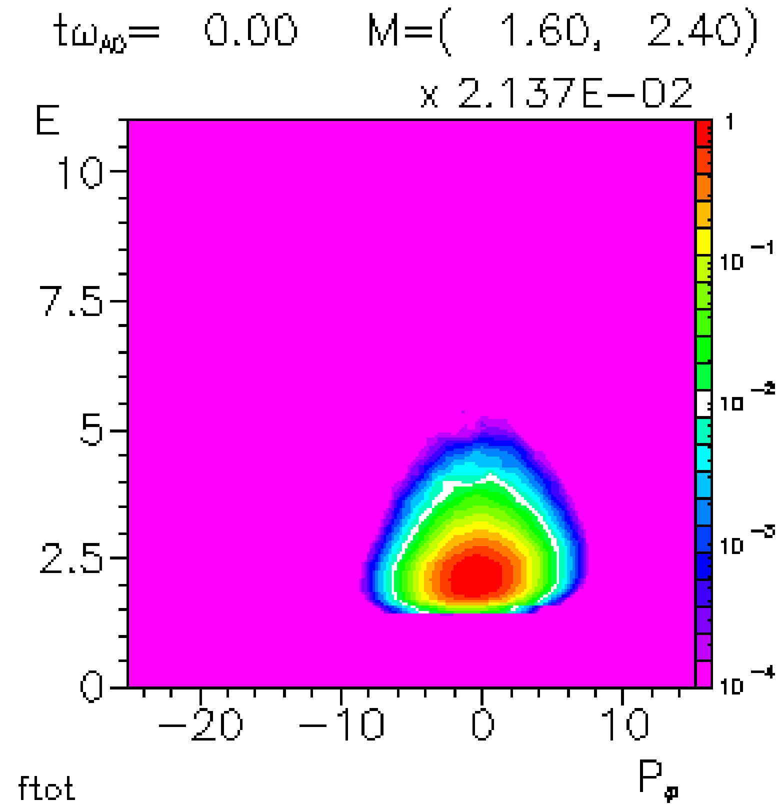
- Tracers' dynamics studied with Lagrangian Coherent structures(Finite Time Lyapunov Exponent): definition of transport barriers. Relevant structures/barriers related to the second peak in the late dynamics
- probability density functions for radial displacements of tracer particles as dictated by the various EP transport models





WP3.3-6: Hybrid kinetic MHD codes for verification and validation

- PSZS have been extracted from an EPM simulation by the HMGC hybrid code, i.e. see Briguglio et al. 1995, and more recently by HYMAGIC;
- the same calculations have been carried out also within HAGIS and ORB5
- realistic NNBI distribution function are calculated by RABBIT code



$$\frac{\partial}{\partial t}\overline{F_{z0}} + \frac{1}{\tau_b}\left[\frac{\partial}{\partial P_\phi}\overline{\left(\tau_b \delta \dot{P}_\phi \delta F\right)} + \frac{\partial}{\partial \mathcal{E}}\overline{\left(\tau_b \delta \dot{\mathcal{E}} \delta F\right)}_z\right]_S = 0$$

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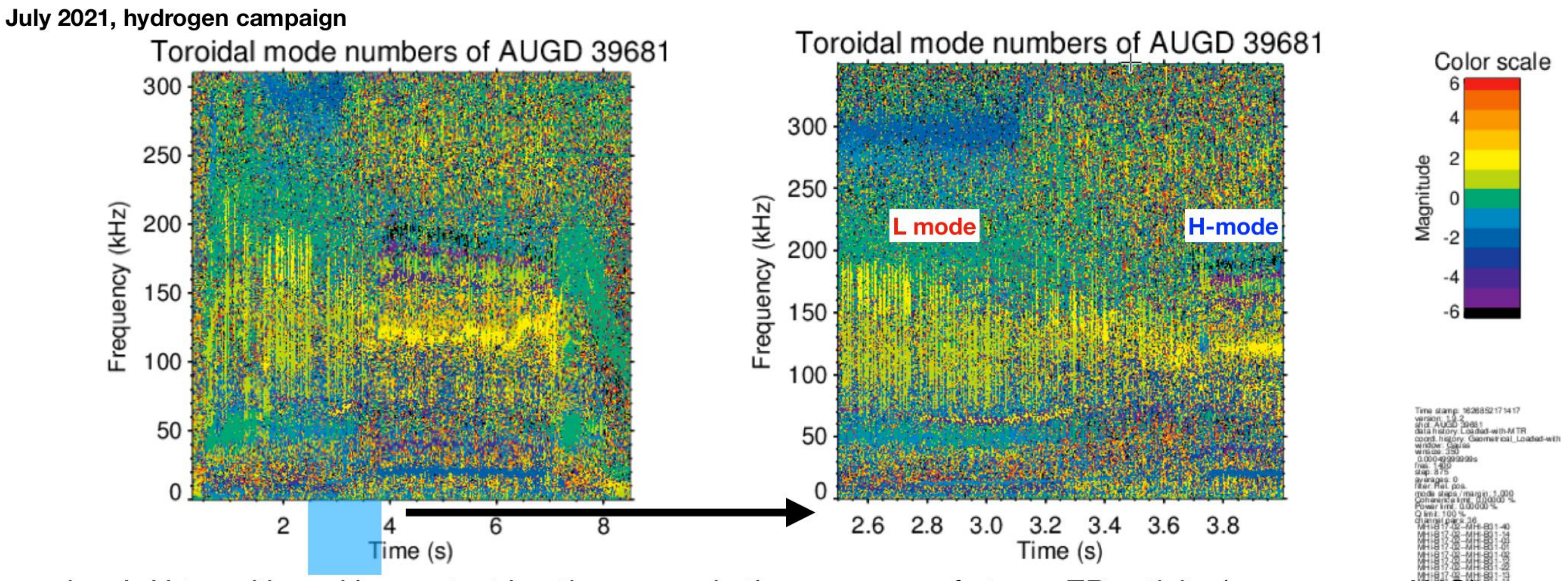
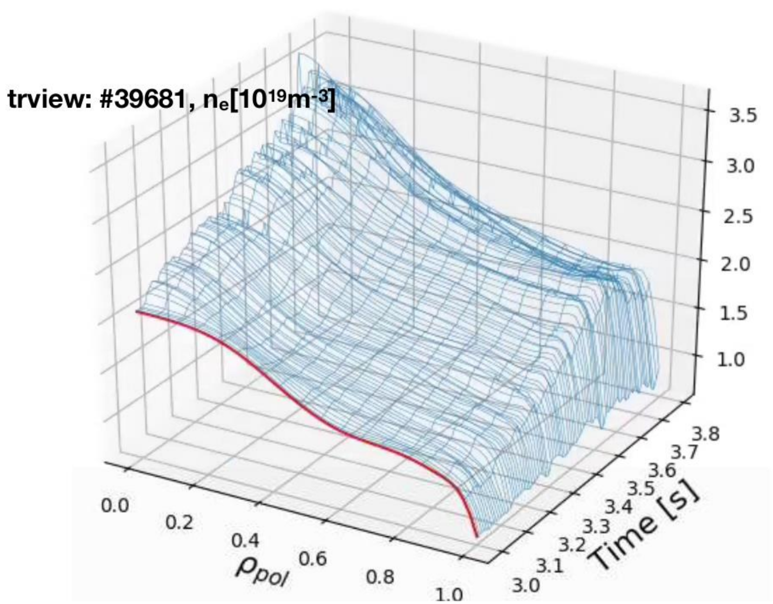
WP 4: Clear transition between EP transport regimes



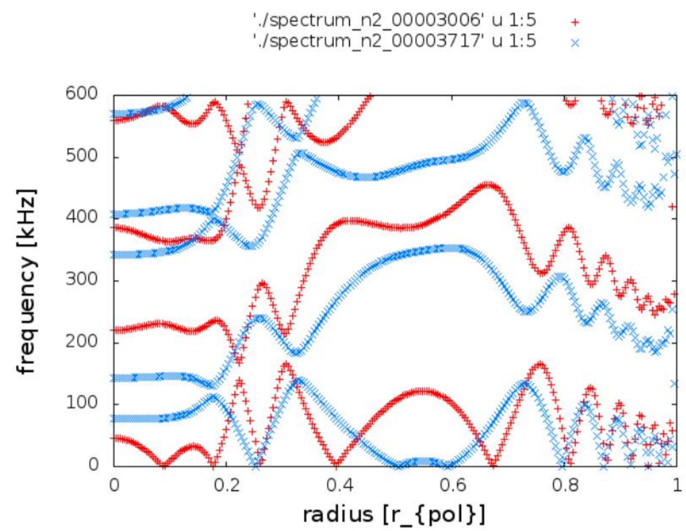
- slow L-H transition with constant heating power in the presence of strong EP activity (very rare on AUG)
- L-mode activity very similar to NLED base case (EGAM/BAE/TAE intermittent crashes, #31213) - but now in flat top phase with transport analysis possible!
- automated analysis on Gateway now working in python (libraries, IMAS versions, AL versions,…)
- new experiments accepted for AUG He campaign in summer 2022

WP 4: Clear transition between EP transport regime

July 2021



using IMAS EP LIGKA/HAGIS workflow on
gateway: trview
AUG->IMAS [G. Tardini]



- slow L-H transition with constant heating power in the presence of strong EP activity (never before on AUG)
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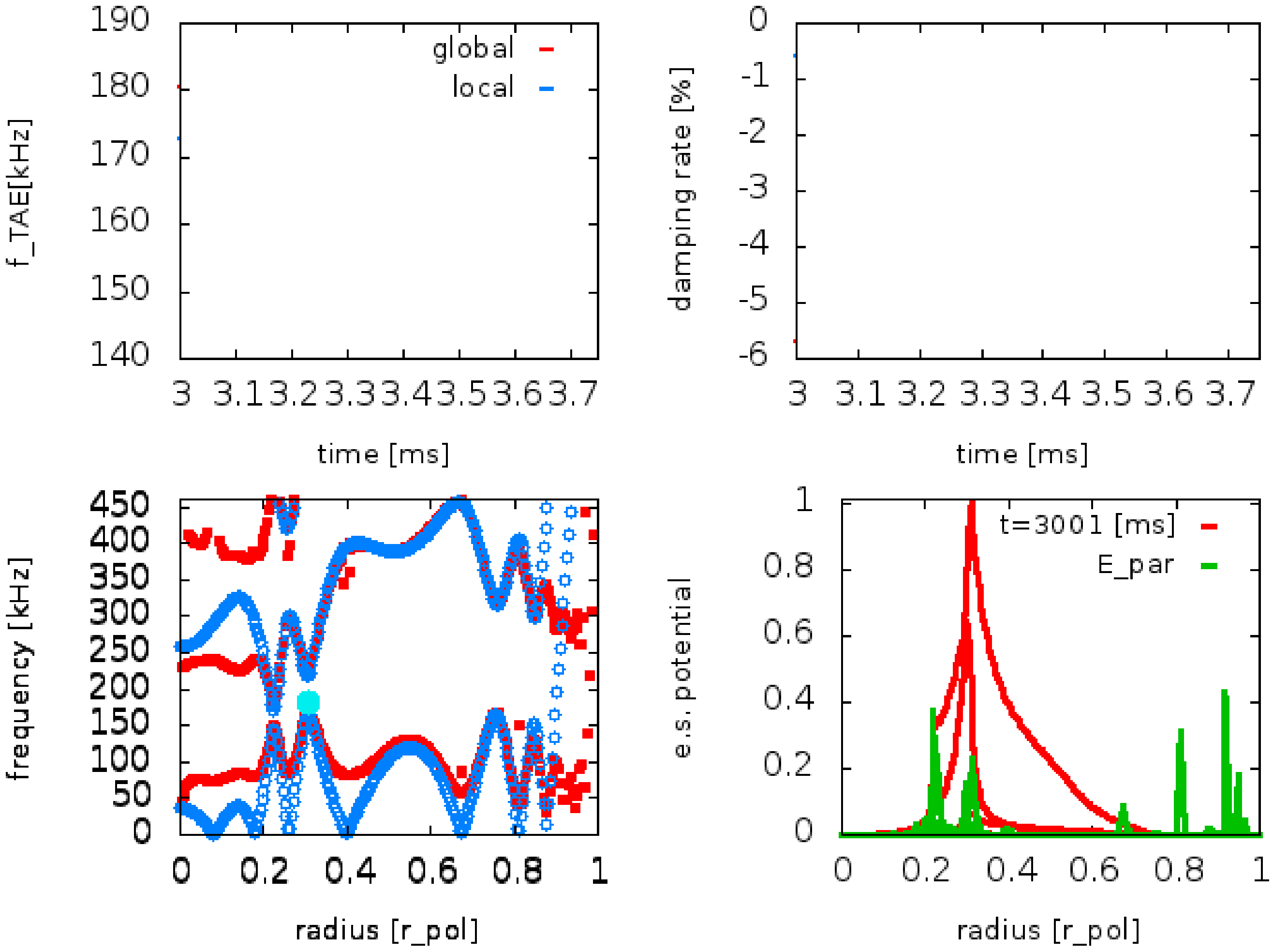
WP4: an example



Thanks for your attention!