EUROfusion

ENR ATEP 2023 review

ATEP team:

Philipp Lauber (PI), Matteo Falessi (Co-PI), Alessandro Biancalani, Sergio Briguglio, Nakia Carlevaro , Valeria Fusco, E. Giovanozzi , Thomas Hayward-Schneider, 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 - special thanks to A. Bottino and A. Mishchenko (TSVV#10)

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

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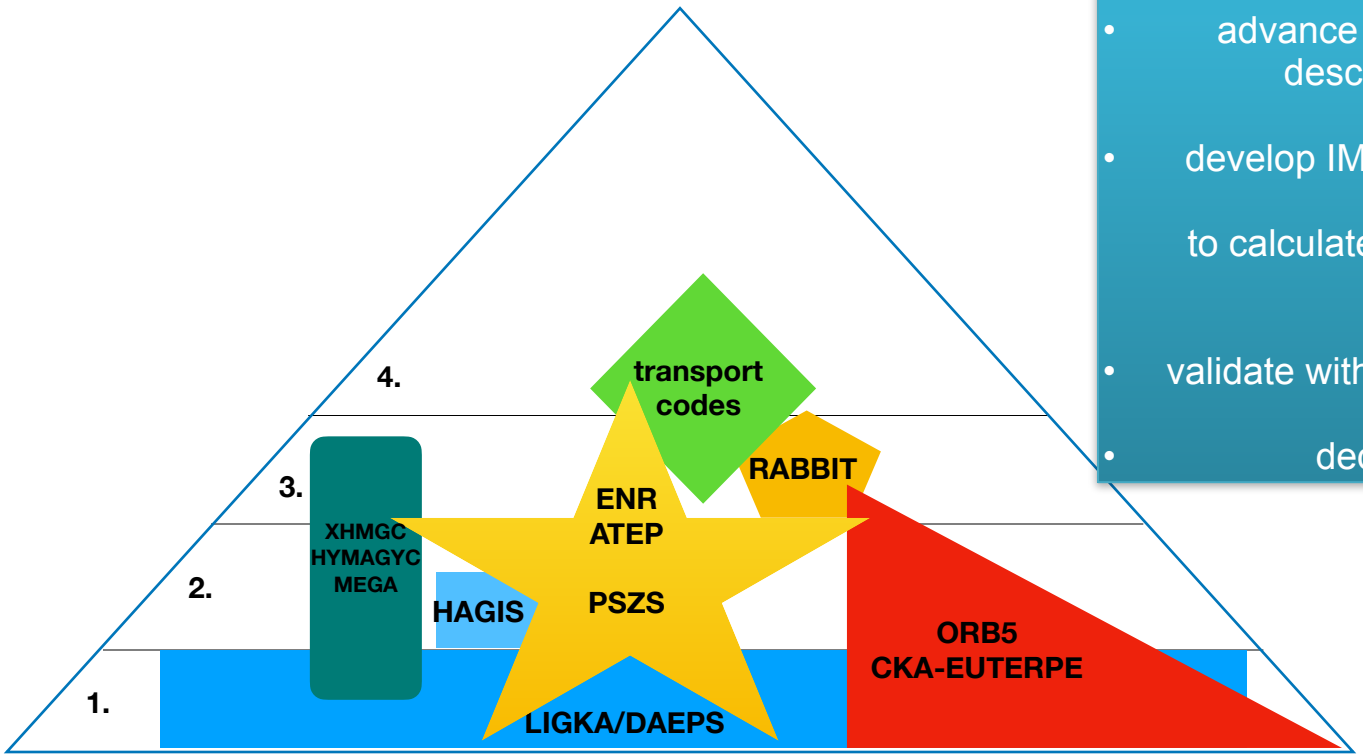
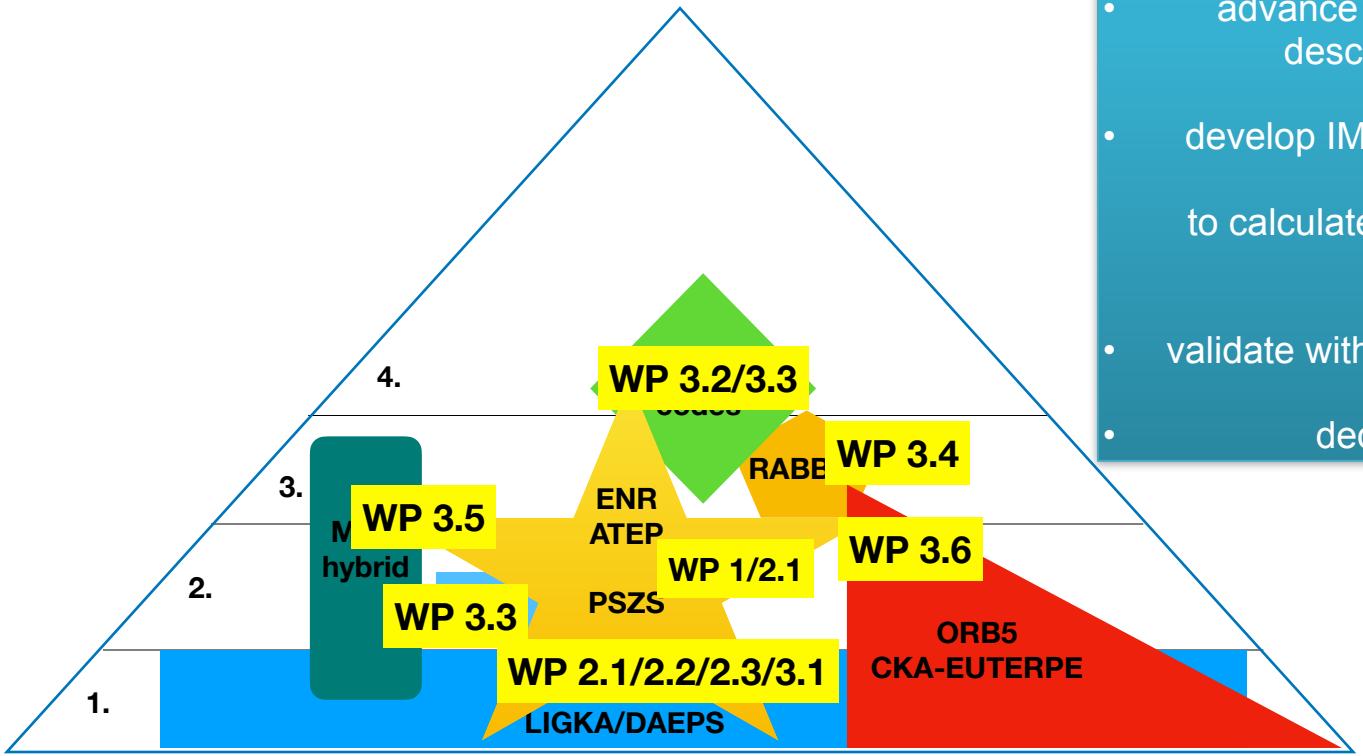
modelling hierarchy for plasmas with significant energetic particle pressure



ENR ATEP aim:

- advance theory for comprehensive description of EP transport
&
- develop IMAS based models of various fidelity and cost to calculate electromagnetic, global EP transport
&
- validate with more comprehensive codes
&
- dedicated experiments

modelling hierarchy for plasmas with significant energetic particle pressure



ENR ATEP aim:

- advance theory for comprehensive description of EP transport **WP 1**
  &
- develop IMAS based models of various fidelity and cost to calculate electromagnetic, global EP transport **WP 2**
  &
- validate with more comprehensive codes **WP 3**
  &
- dedicated experiments **WP4**

2023 Deliverables

Scientific deliverable *(annual scientific deliverables as specified in the Task Agreement)*	**Achieved: Fully/Partly/Not**	**Evidence for achievement, brief reason for partial or non-achievement**
Self-consistent description of EPM repeated burst dynamics using the PSZS theoretical framework	fully	36279, 36126, 36125, 34120, 35683, 34121
Fast analytical LIGKA model including guesses for global mode structures and non-Maxwellian distribution functions	fully	ID: 34971; Master thesis R. Stucchi, TUM Munich, Nov 2023 – to be published 2024; EP-Stability WF training event (July 2023) https://indico.euro-fusion.org/event/2729/
Local eigenvalue code in 3D (LIGKA) including passing particles	Partly/fully	Theory well developed; explicit expressions derived Reduced transport model in stellarator geometry has been developed [Ch. Slaby, see ATEP November meeting, paper in preparation]
Systematic statistical analysis of test particle transport and assessment of diffusive vs. non diffusive behaviours - jointly with WP3.2	fully	ID: 35683 ATEP November meeting, paper in preparation
Practical basic understanding of convective radial transport of energetic particles versus the possible non-local transport regimes	fully	ID: 35683 ATEP November meeting, paper in preparation
Availability of validated reduced phase space transport model (ATEP code) based on LIGKA/HAGIS within IMAS framework	fully	Early achievement – validation still ongoing IDs: 36129, 35459, 35018, 34111, 34092
STRUPHY will deliver long time-scale simulations for V&V purposes (demonstrating conservation properties of advanced coupling scheme) based on the same equilibria as XHMGC, HYMAGYK, MEGA and ORB5	fully	Early achievement: drift kinetic model implemented, successful benchmarks (see ATEP November meeting)

Milestones 1

3 WP2.1-M1 Benchmark of DAEPS/Falcon in general toroidal geometry against reduced local LIGKA analysis for trapped particles, mid 2022

8 WP2.2-M3 Generalise fast analytical LIGKA version to non-Maxwellian distribution functions, in particular slowing down End 2023

6 WP2.2-M1 Develop (semi-)analytical trapped particle model for LIGKA, ongoing

7 WP2.2-M2 Test and tune analytical global mode structure model for LIGKA/HAGIS, ongoing

9 WP2.3-M1 Derive equations for local LIGKA-like version in 3D Mid 2022 (slightly delayed - mid 2024)

5 WP2.1-M3 Benchmark of DAEPS in general stellarator geometry (jointly with WP2.3), mid 2024 delayed

10 WP2.3-M2 Local eigenvalue code in 3D including passing particles mid 2024

fully
ongoing
not started

Milestones 2

17 WP3.3-M3 Finish reduced EP transport workflow based in LIGKA/HAGIS within IMAS combine neoclassical and wave-induced modules mid 2024

18 WP3.4-M1 Develop and implement radial diffusion model to RABBIT End 2022 (canceled)

19 WP3.4-M1 Apply extended RABBIT model to transient events, e.g. EP evolution during sawtooth cycles End 2023

23 WP3.6-M2 Calculate particle and heat transport in the presence of turbulence with ORB5 for validation of the reduced models: upgraded milestone: compare PSZS! mid 2024

fully
partly
not started

publications/conferences 2023

First Author	Initials	Title of work	Journal / Conference	Doc. Type	DOI or status of paper	Pinboard ID
Zonca	F	On the self-consistent evolution of the zonal state	7th Asia-Pacific Conference on Plasma Physics (AAPPS-DPP2023)	Oral 100% ATEP		36279
Falessi	M V	Advanced Energetic Particle Transport Model	27th Joint EU-US Transport Task Force Meeting (TTF 2023), Nancy	Oral 100% ATEP		36126
Falessi	M V	Nonlinear equilibria and phase space transport in burning plasmas.	20th European Fusion Theory Conference (EFTC 2023), Padova, Italy, 2nd October 2023.	Invited 100% ATEP		36125
Zonca	F	ON THE NONLINEAR DYNAMICS OF FISHBONES AND ENERGETIC PARTICLE MODES	29th IAEA Fusion Energy Conference, London, United Kingdom, 16th October 2023	Poster 100% ATEP		34120
Könies	A	Shear Alfvén Waves within Magnetic Islands	Physical Review Letters	25% ATEP	To be submitted	36067
An	Z	Frequency Chirping of Electromagnetic Ion Cyclotron Waves in Earth's Magnetosphere	Geophysical Research Letters	25% ATEP	submitted	36057

First Author	Initials	Title of work	Journal / Conference	Doc. Type	DOI or status of paper	Pinboard ID
Wang	T	Nonlinear dynamics of the reversed shear Alfvén eigenmode in burning plasmas	Plasma Science and Technology	25% ATEP	submitted	36056
Meng	G	A solver for energetic particle transport in constants of motion space with collision and phase space zonal structures in tokamak plasmas	20th European Fusion Theory Conference (EFTC 2023), Padova, Italy	Poster 100% ATEP		36129
Wang	X	First Principle gyrokinetic simulations of frequency chirping Alfvén modes in fusion plasmas	29th IAEA Fusion Energy Conference, London, United Kingdom	Poster 50% ATEP		35987
Bierwage	A	Time-helicity de-resonation (T-H) diagram for energy-selective mixing of charged particles during sawtooth crashes in tokamaks	Nuclear Fusion	10% ATEP	submitted	35882
Falessi	M V	Advanced Energetic Particle Transport Model	49th European Conference on Plasma Physics (EPS 2023), Bordeaux	Invited 100% ATEP		35683
Biancalani	A	Nonlinear interaction of Alfvenic instabilities and turbulence via the modification of the equilibrium profiles	Journal of Plasma Physics	50% ATEP	doi.org/10.1017/S0022377823001137	35587
Lauber	P	Advanced transport models for energetic particles	20th European Fusion Theory Conference (EFTC 2023), Padova	Invited 80% ATEP		35459
Teng	S	Whistler-mode chorus waves at Mars	Nature Communications	25% ATEP	10.1038/s41467-023-38776-z	35215
Meng	G	Energetic particles transport in constants of motion space due to collision in tokamak plasmas	14th International West Lake Symposium on Frontier Progress in Fusion Energy Research and Development, Hangzhou, China	Oral 100% ATEP		35018
Popa	A	An IMAS-integrated workflow for energetic particle stability	Nuclear Fusion	100% ATEP	10.1088/1741-4326/acf056	34971
Chen	L	On Nonlinear Scattering of Drift Wave by Toroidal Alfvén Eigenmode in Tokamak Plasmas	Nuclear Fusion	25% ATEP	10.1088/1741-4326/acf230	34887
Wang	H	Nonlinear excitation of energetic-particle-driven geodesic acoustic mode by resonance overlap with Alfven eigenmode in ASDEX-Upgrade	Nuclear Fusion	25% ATEP	submitted	34717
Mishchenko	A	Numerical tools for burning plasmas	Plasma Physics and Controlled Fusion	10% ATEP	10.1088/1361-6587/acce68	34669
Qiu	Z	Effects of system nonuniformity on toroidal Alfvén eigenmodes nonlinear saturation	29th IAEA Fusion Energy Conference, London, United Kingdom	25% ATEP		34558
Bottino	A	Phase Space Zonal Structures and equilibrium distribution functions in ORB5	49th European Conference on Plasma Physics (EPS 2023), Bordeaux	50% ATEP	EPS proceedings	34535
Wang	X	Nonlinear dynamics of nonadiabatic chirping-frequency Alfvén modes in Tokamak plasmas	Plasma Physics and Controlled Fusion	50% ATEP	10.1088/1361-6587/acd71f	34518
Biancalani	A	EFFECT OF ZONAL STRUCTURES EXCITED BY ALFVEN MODES, ON TURBULENCE	29th IAEA Fusion Energy Conference, London, United Kingdom	50% ATEP		34536

First Author	Initials	Title of work	Journal / Conference	Doc. Type	DOI or status of paper	Pinboard ID
Wang	X	Nonadiabatic frequency chirping Alfvén mode in Fusion plasmas	49th European Conference on Plasma Physics (EPS 2023), Bordeaux	Oral invited 100% ATEP		34512
Wang	H	NONLINEAR EXCITATION OF ENERGETIC PARTICLE DRIVEN GEODESIC ACOUSTIC MODE BY ALFVÉN EIGENMODE IN ASDEX-UPGRADE	29th IAEA Fusion Energy Conference, London, United Kingdom	10% ATEP		34314
Wei	S	Core localized alpha-channeling via low frequency Alfvén mode generation in reversed shear scenarios	49th European Conference on Plasma Physics (EPS 2023), Bordeaux, France	Poster 25% ATEP		34226
Falessi	M V	NONLINEAR EQUILIBRIA AND PHASE SPACE TRANSPORT IN BURNING PLASMAS	29th IAEA Fusion Energy Conference, London, United Kingdom	Poster 100% ATEP		34121
Meng	G	A neoclassical solver for the transport equations of phase space zonal structures of energetic particles	29th IAEA Fusion Energy Conference, London, United Kingdom	Poster 100% ATEP		34111
Lauber	Ph	Advanced transport models for energetic particles	29th IAEA Fusion Energy Conference, London, United Kingdom,	Poster 100% ATEP		34092
Wang	X	First principle gyrokinetic simulations of frequency chirping Alfvén modes in Fusion Plasmas	29th IAEA Fusion Energy Conference, London, United Kingdom	Poster 50% ATEP		34091
Vlad	G	Non-linear benchmark between HYMAGYC, MEGA, ORB5 and XTOR-K codes using the NLED-AUG test case to study Alfvénic modes driven by energetic particles	29th IAEA Fusion Energy Conference, London, United Kingdom	Poster 50% ATEP		34090
Bierwage	A	Energy-Selective Confinement of Alpha Particles during Benign Sawtooth Crashes in a Large Tokamak Plasma	29th IAEA Fusion Energy Conference, London, United Kingdom	Oral 10% ATEP		34015
Mishchenko	A	Towards burning plasmas: theory and simulations	29th IAEA Fusion Energy Conference, London, United Kingdom	Poster, 10% ATEP		33969
Li	Y	Physics of drift Alfvén instabilities and energetic particles in fusion plasmas	Plasma Physics and Controlled Fusion	25% ATEP	10.1088/1361-6587/acda5e	33937
Falessi	M V	Nonlinear equilibria and transport processes in burning plasmas	New Journal of Physics	100% ATEP	10.1088/1367-2630/ad127d	36555
Ma	R R	Low-frequency shear Alfvén waves at DIII-D: theoretical interpretation of experimental observations	Physics of Plasmas	25% ATEP	10.1063/5.0141186	33689
Milovanov	A	Turbulence spreading by the resonant wave-wave interactions: A fractional kinetics approach	Physical Review E	50% ATEP	submitted	36592

2023 highlights and outlook to 2024
(end of ATEP 31.5.2024)

WP1: theoretical framework

- evolved fundamental PSZS transport theory: include zonal fields as e.m. counterpart of phase space zonal structures - comprehensive 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]

WP1-D3 Self-consistent description of EPM repeated burst dynamics using the PSZS theoretical framework

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

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

shearing

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

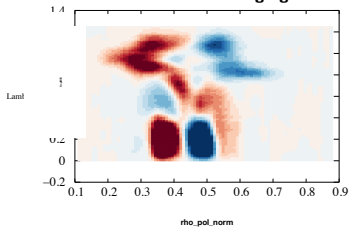
resonance broadening & frequency shift

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

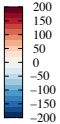
+ 3D version of PSZS equation [A. Zocco et al, 2023]

WP 2/3: ATEP code - physics and structure

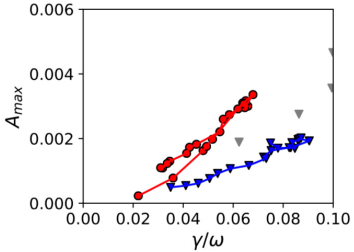
orbit+zonal averaging



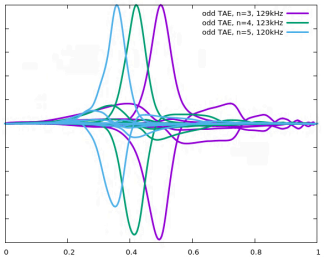
<dP$_\phi$/dt>



saturation rule/E



EP WF: LIGKA [20]



calculate PSZS

use NL code/model for intensity closure

or kick model

calculate linear mode spectrum

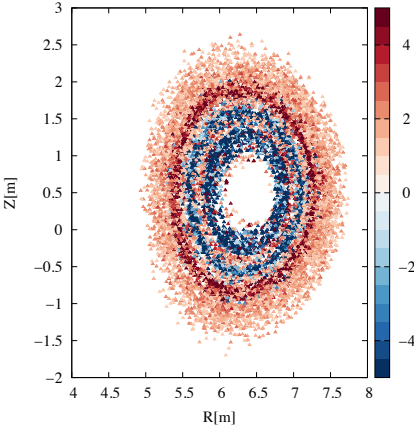
PSZS transport theory [M. Falessi et al, 2017-23]

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

calculate D(r,E)

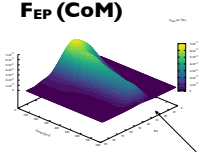
or

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



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

F_{EP} (CoM)



t

t+1

mhd_linear
distributions
core profiles
equilibrium

time

transport code

WP 2/3: ATEP code - added energy conserving QL model

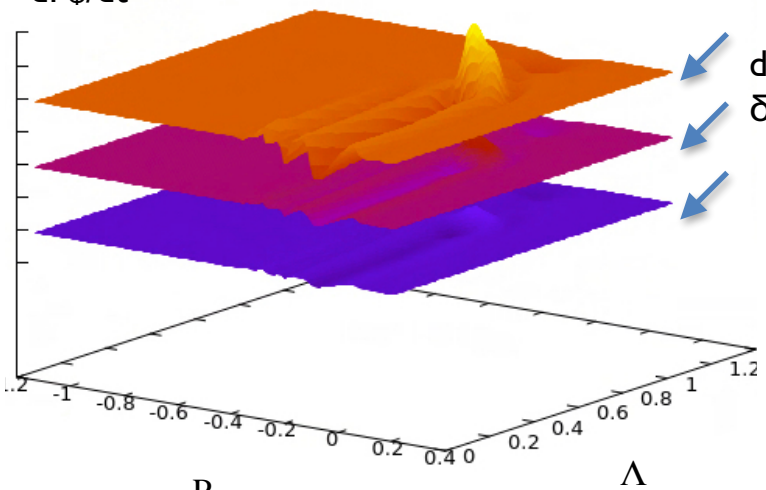
$$\frac{\partial}{\partial t}\overline{F_{z0}} + \frac{1}{\tau_b}\left[\frac{\partial}{\partial P_\phi}\overline{\left(\tau_b \delta \dot{P}_\phi \delta F\right)_z} + \frac{\partial}{\partial \mathcal{E}}\overline{\left(\tau_b \delta \dot{\mathcal{E}} \delta F\right)_z}\right]_S = \overline{\left(\sum_b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

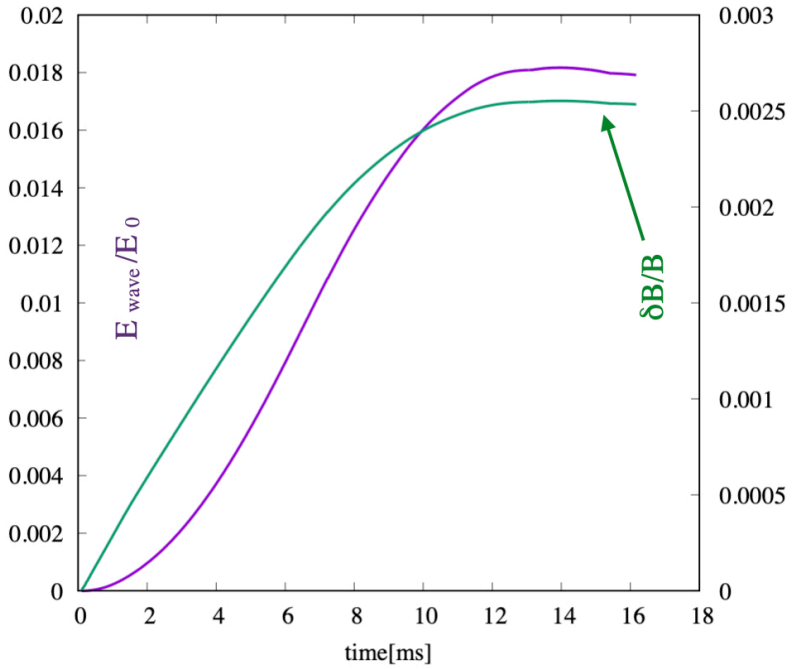
$$\frac{d}{dt}\left(\mathscr{E} + \sum_k W_k\right) = -2\sum_k \gamma_{d,k} W_k$$

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

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

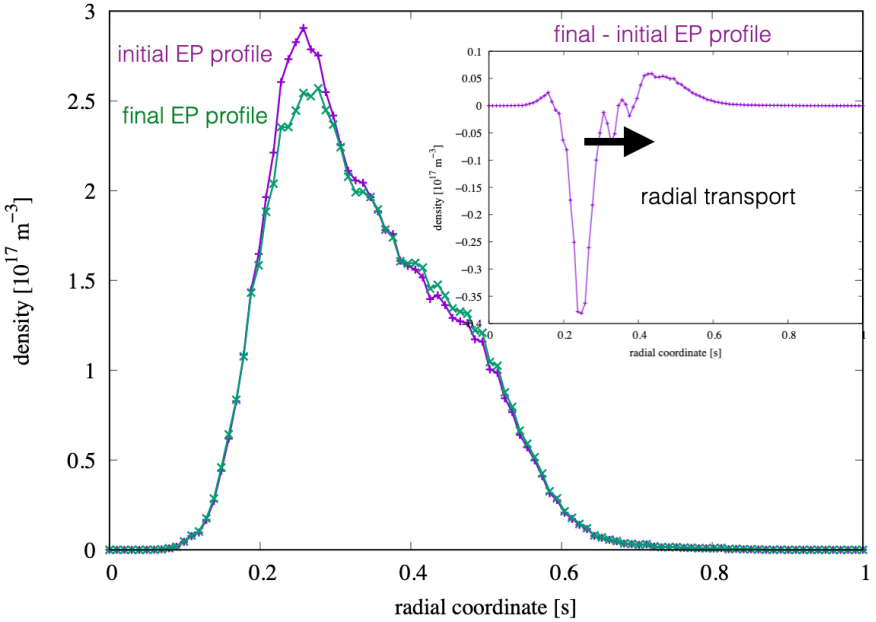
<dPΦ/dt>

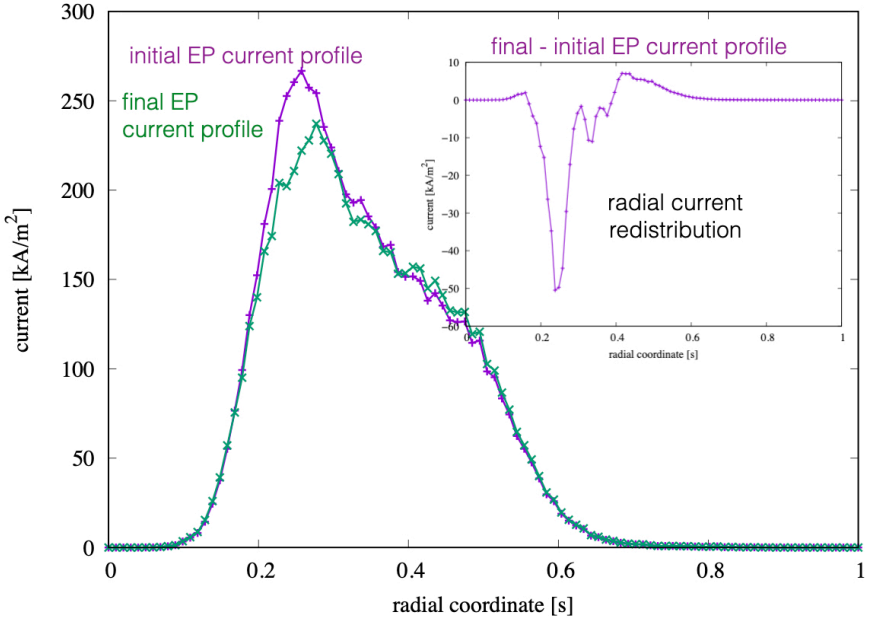




ATEP code: added back-mapping to configuration space

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





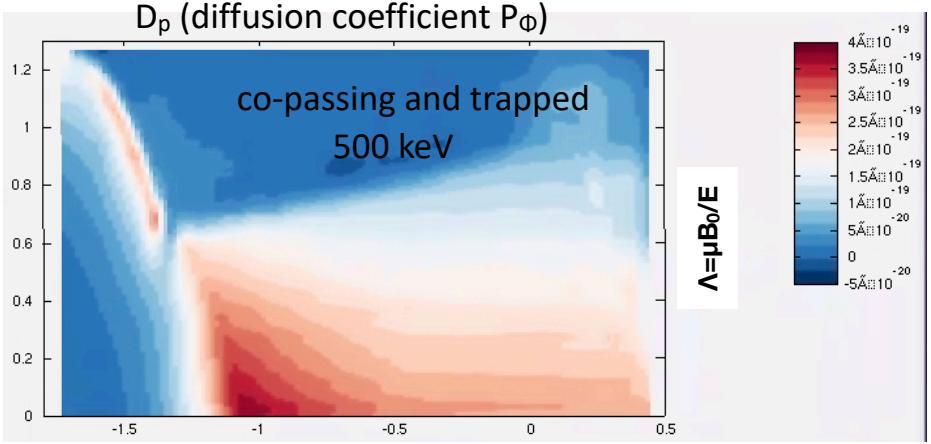
return non-linear EP density, current, pressure to transport code

WP 2/3: new neoclassical building block for ATEP 3D [G Meng, Ph. Lauber, submitted NF 2024]

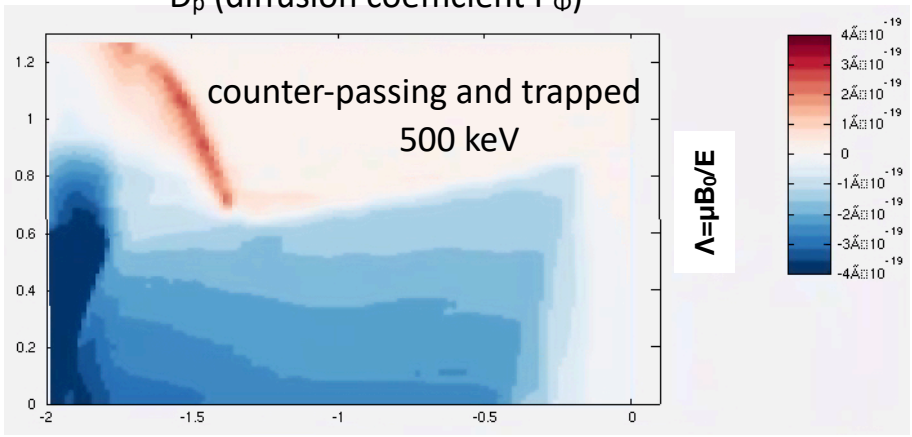
$$\frac{\partial}{\partial t}\overline{F_{z0}} + \frac{1}{\tau_b}\left[\frac{\partial}{\partial P_\phi}\overline{\left(\tau_b \delta \dot{P}_\phi \delta F\right)_z} + \frac{\partial}{\partial \mathcal{E}}\overline{\left(\tau_b \delta \dot{\mathcal{E}} \delta F\right)_z}\right]_S = \overline{\left(\sum_b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

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

D_p (P_Φ diffusion coefficient)



D_p (P_Φ diffusion coefficient)



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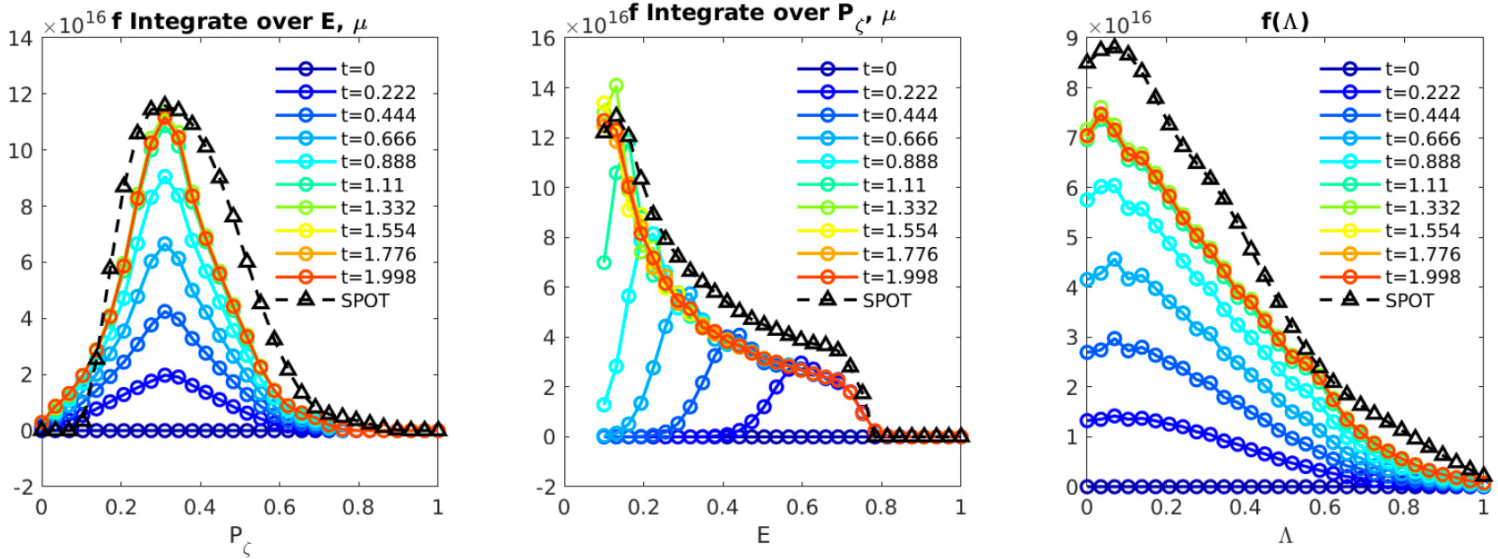
$$\frac{\partial}{\partial t}\overline{F_{z0}} + \frac{1}{\tau_b}\left[\frac{\partial}{\partial P_\phi}\overline{\left(\tau_b \delta\dot{P}_\phi \delta F\right)_z} + \frac{\partial}{\partial \mathcal{E}}\overline{\left(\tau_b \delta\dot{\mathcal{E}} \delta F\right)_z}\right]_S = \overline{\left(\sum_b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

compare to SPOT: reasonable agreement



ready to merge wave-induced and collisional part - early 2024

WP 2: extend LIGKA for non-Maxwellian distributions

master thesis R. Stucchi:

- review and improve numerical algorithm (Hilbert transform) for the integration of general distribution functions with resonance denominator [Xie, 2013]
- in depth analysis of pole structure in the presence of non-analytical features of F - (cut-off velocity, absolute values,…)
- application the EGAM dispersion relation
- implementation of improved algorithm into LIGKA

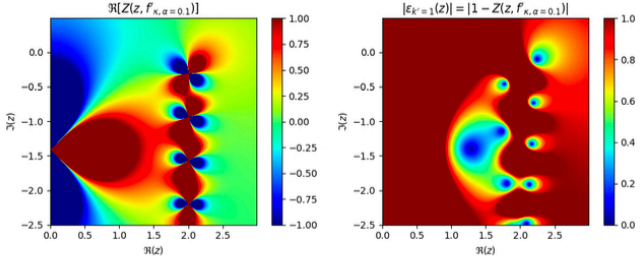


Figure 4.9: 'Strong smoothing': real part of $Z(z, f'_{\kappa=1,\alpha=0.1})$ and absolute value of $\epsilon_{k'}(z)$.

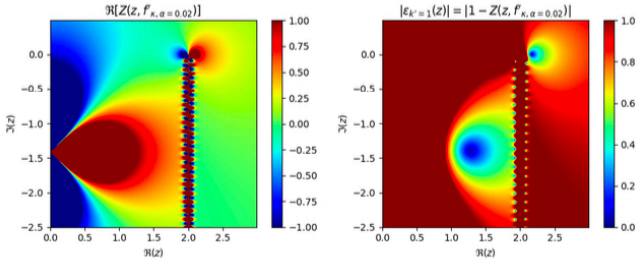
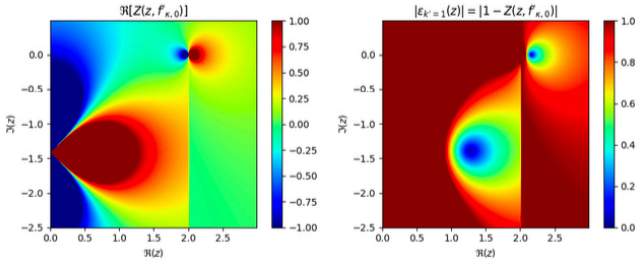
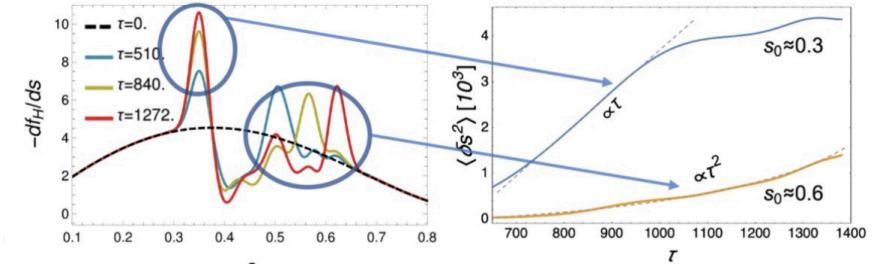


Figure 4.10: 'Weak smoothing': real part of $Z(z, f'_{\kappa=1,\alpha=0.02})$ and absolute value of $\epsilon_{k'}(z)$.

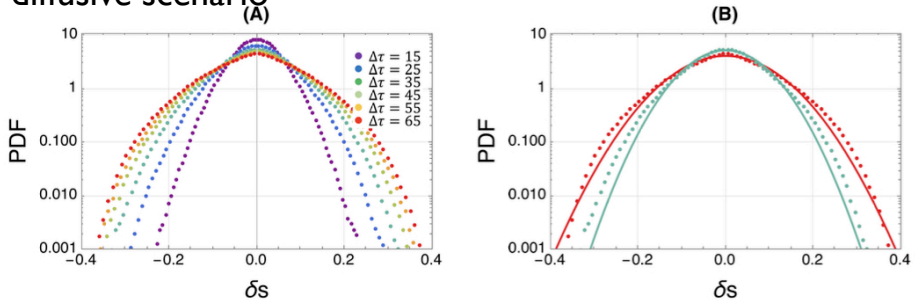


WP3: develop reduced models - 1D bump on tail model

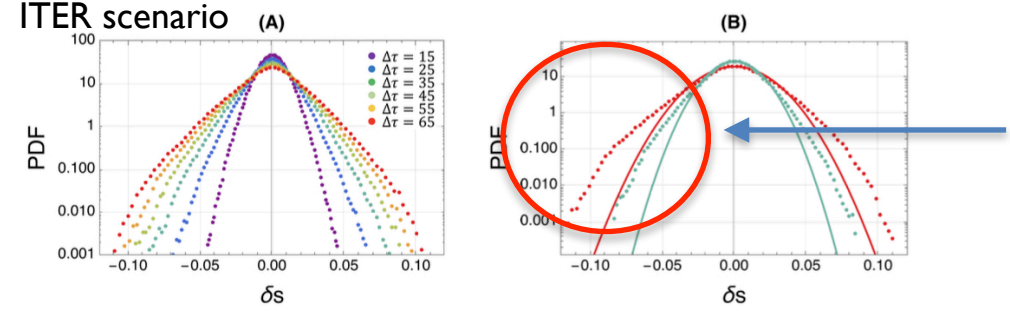
N. Carlevaro, G. Montani, M.V. Falessi, Ph. Lauber, EPS22, P5a.113 ID : 32056



diffusive scenario



ITER scenario



- can we describe the previously studied ITER 15MA case with a diffusive model?
- using test particle analysis for analysing global transport properties
- determined diffusive (τ) vs. convective (τ^2) scalings
- different behaviour of high-n TAE and low-n TAE branch!

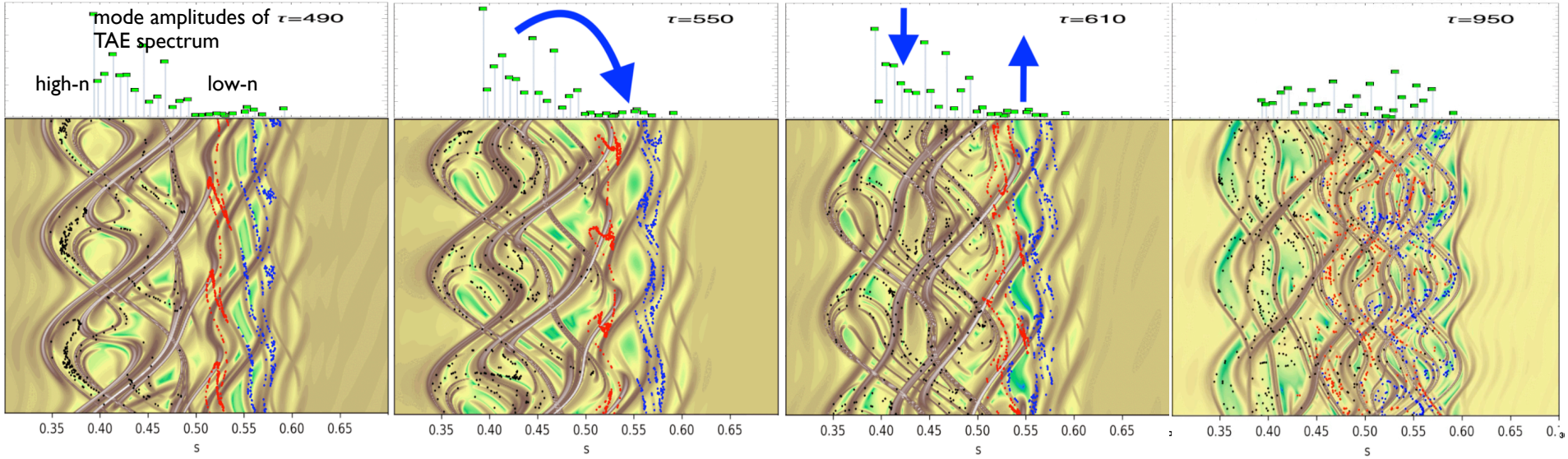
Expectation for a **pure diffusive model (QL):**
trajectories - measured with $\delta s = s(\tau - \delta\tau) - s(\tau)$ - defined by random walk
PDF expected to be a **normal distribution**

BUT: asymmetry of the PDF:
Non diffusive transport!

WP3: 1D bump on tail model - Lagrangian Coherent Structures

- 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]

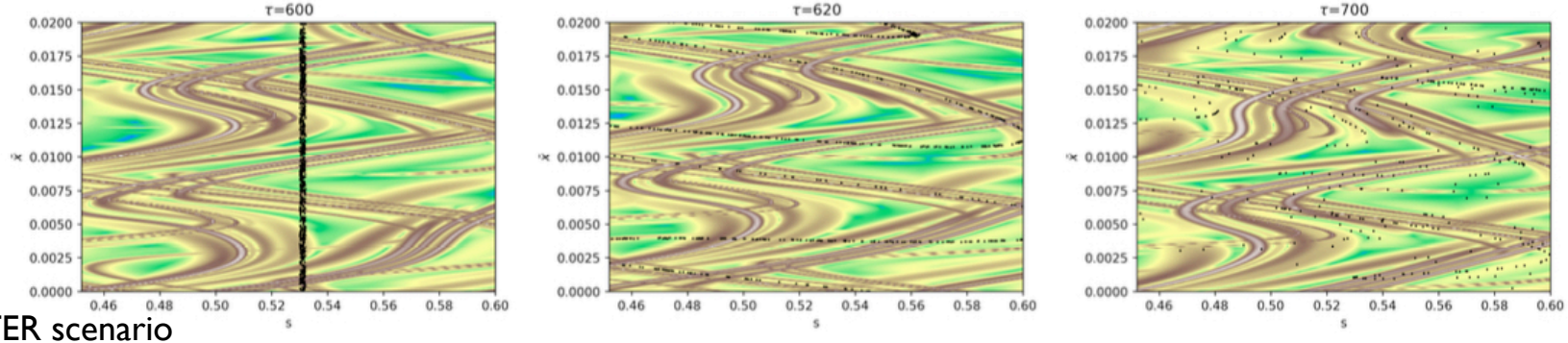


WP3: 1D bump on tail model - Lagrangian Coherent Structures

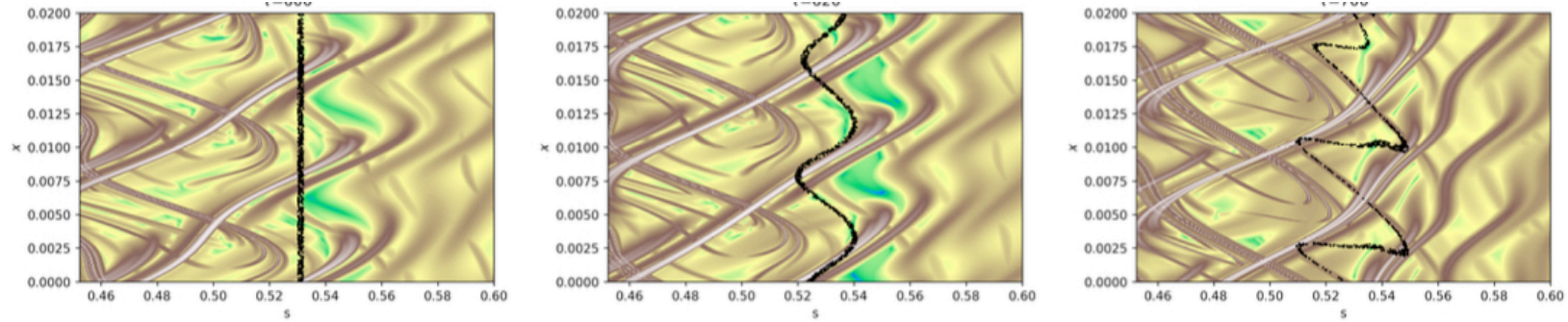
•Lagrangian Coherent Structures: most repulsive or attractive material lines (**transport barriers**). They are associated with **peaked profiles** of the Finite-Time Lyapunov Exponent (FTLE)

[N. Carlevaro et al, to be submitted]

diffusive scenario

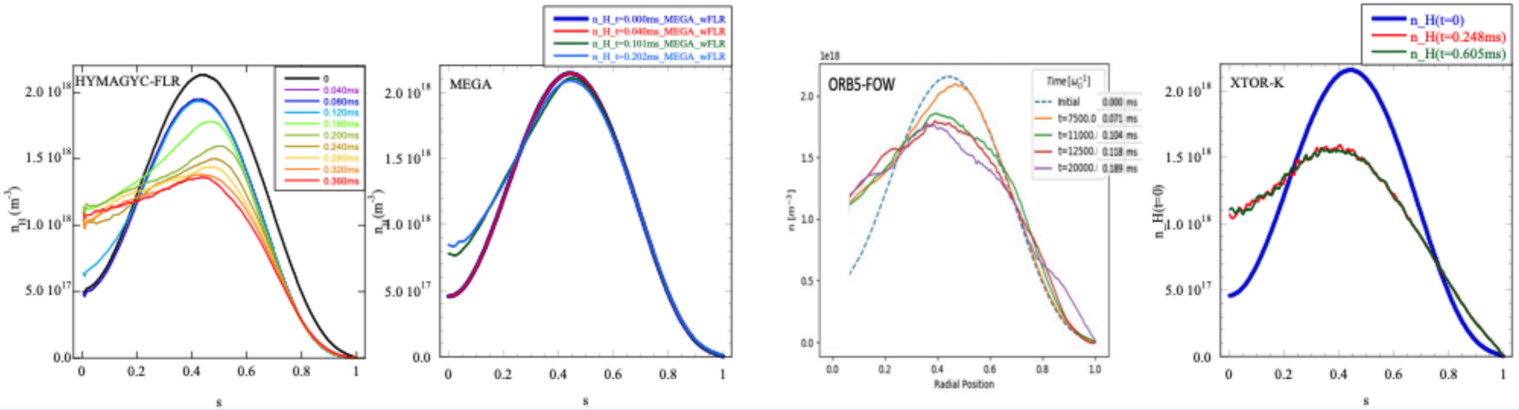


ITER scenario

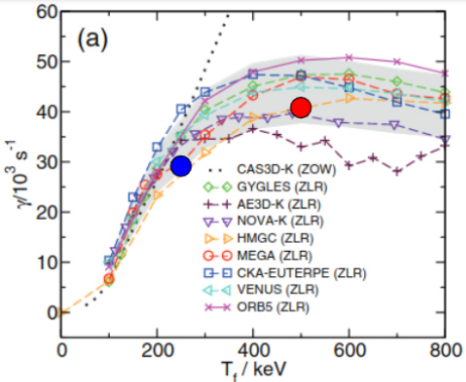


WP3.5: MHD-kinetic hybrid models deliver benchmarks for reduced models

- 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



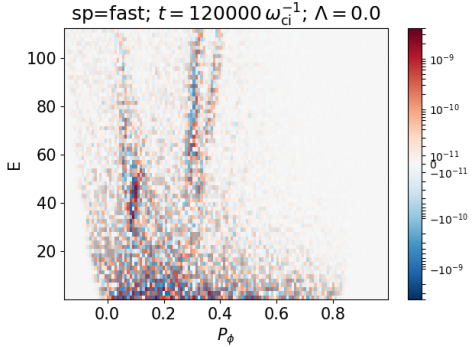
- STRUPHY: implementation of energy-conserving hybrid MHD-drift-kinetic model enabling long-time numerically stable simulations [B.K. Na, 2023]
- coupling to GVEC 3D equilibrium solver for application to tokamaks and stellarators finished
- Parallelisation (MPI, OpenMPI) for PIC and FEEC part
- started discussions about adding LCS, PSZS



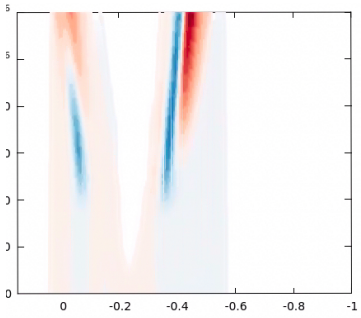
WP3.6: Comparison of reduced models with ORB5

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

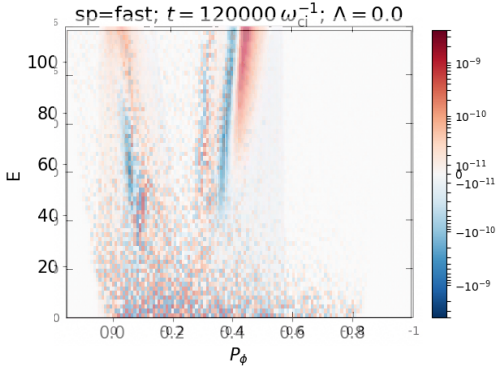
ORB5: slowing down n=18+19 case, linear phase



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



ORB5 vs ATEP

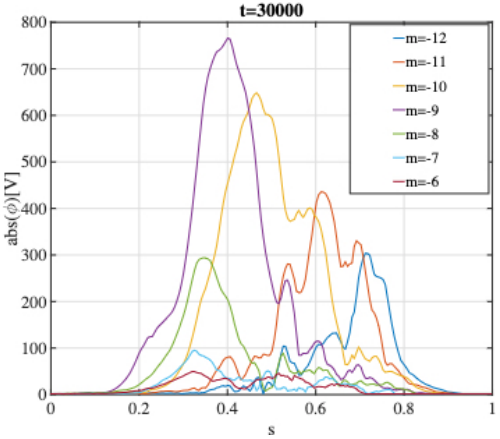


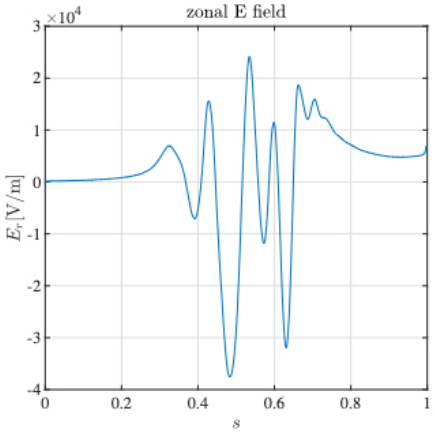
[T Hayward-Schneider, A. Bottino; TSVV-10]

- remaining differences: non-perturbative modes in flat-shear scenario
- very challenging, but promising start for comprehensive quantitative match!

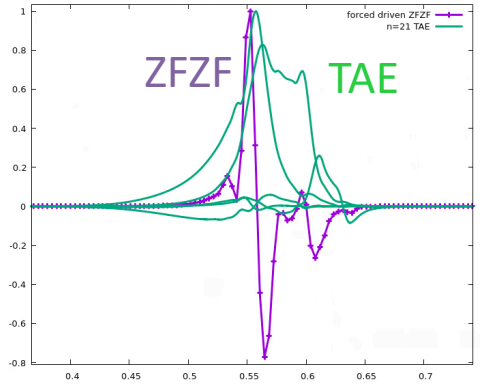
WP3.6: ORB5 studies of TAE-induced ZF - very helpful for including ZFs in reduced models

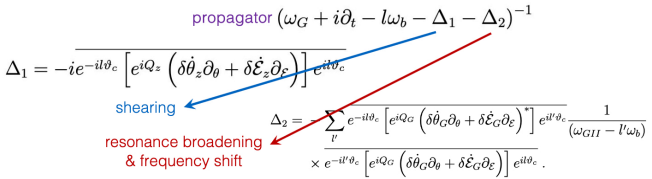
comprehensive AE + ZF studies + turbulence (ORB5/TSVV10)
here: JET case [J. N. Sama, submitted to J. Plasma Phys. (2024)]





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



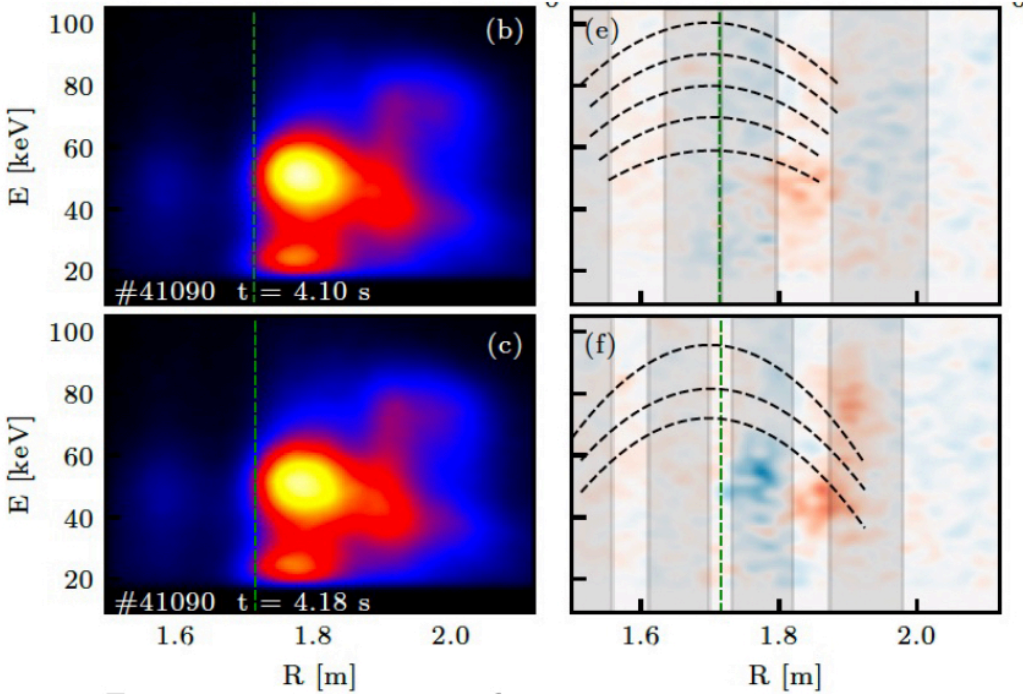


- stabilising influence of ZF on ITG spectrum demonstrated
- reasonably large TAE amplitude required for stabilisation
- PSZS diagnostics available as a standard diagnostics in ORB5

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

WP4: Experimental reference cases

- additional reference cases and scenarios collected and adapted to various WFs in 2023:
- AUG - GAEs, ITER - new HFPS simulation +ASCOT , JET - #99896 (with TSVV10), JT-60SA
- application of EP-Stability WF for interpretation of AUG INPA (Imaging neutral particle analyser) data - PSZS validation ongoing



J. Rueda Rueda [FEC 2023]

summary, outreach

- most deliverables and milestones fully reached in 2023
- deviations/shifts/swaps motivated by personnel changes, decision points after in-depth analysis
- most important ATEP goals have been already reached

- training course has been offered on EP- Stability WF (material + videos)
- ACH help for assessing iWRAP and PAF possibilities - ongoing discussions
- direct outreach to TSVV11 and DEMO (C. Bourdelle), ITER (Brochard, Pinches), JT-60SA, JET (with TSVV10), WPTE (INPA), DTT

- many follow-up plans - ‚enabling' in the best sense
- request from community for fast reduced models needed DEMO studies: this has been started in ENR ATEP - need for follow-up in the next years!