ENR ATEP review (6/2021-5/2024)

ATEP team:

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special thanks to G. Brochard, A. Bottino and A. Mishchenko (TSVV#10) and C. Bourdelle (TSVV#11)

MAX-PLANCK-INSTITUT FÜR PLASMAPHYSIK

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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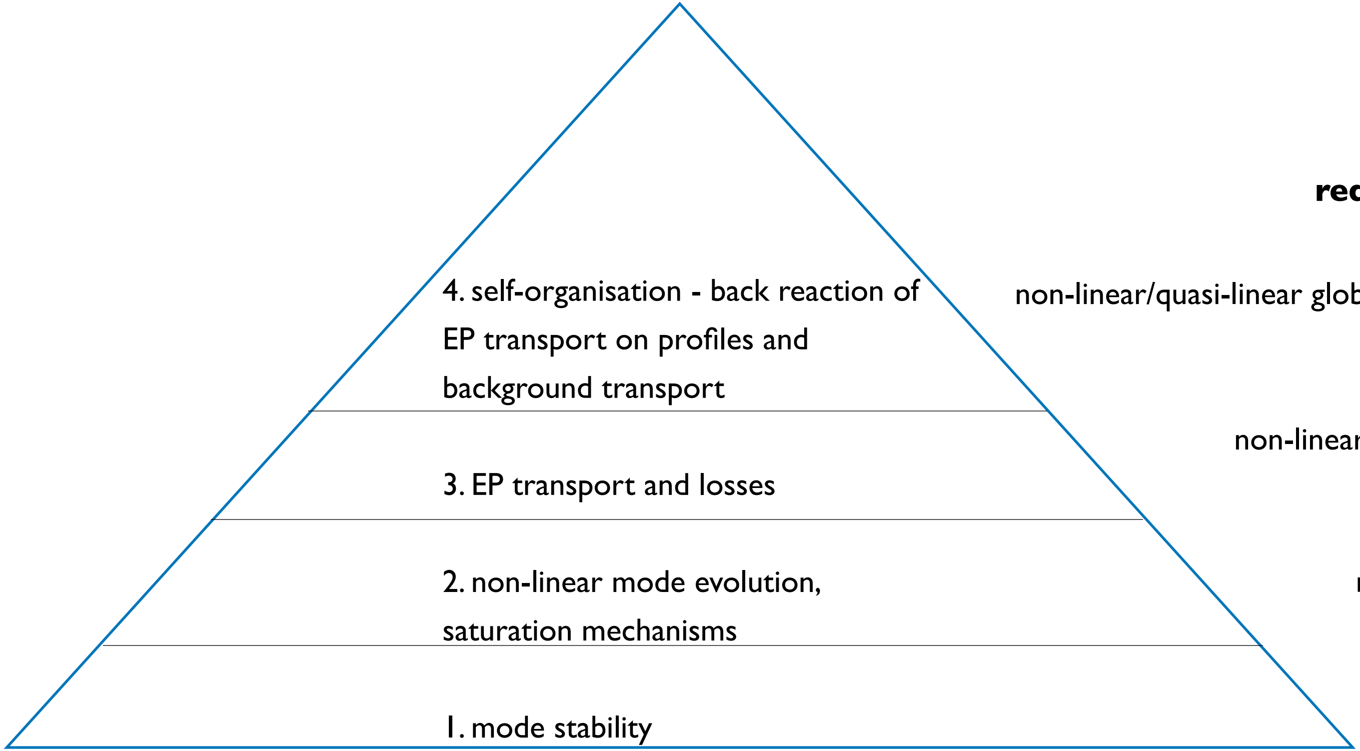
ENR ATEP goal: develop hierarchy of reduced models for EP transport

needed for scaling from TCV-AUG-JET, W7X etc to JT-60SA-DTT-ITER-DEMO, in particular to burning plasmas addressing gap in Eurofusion programme



required models:

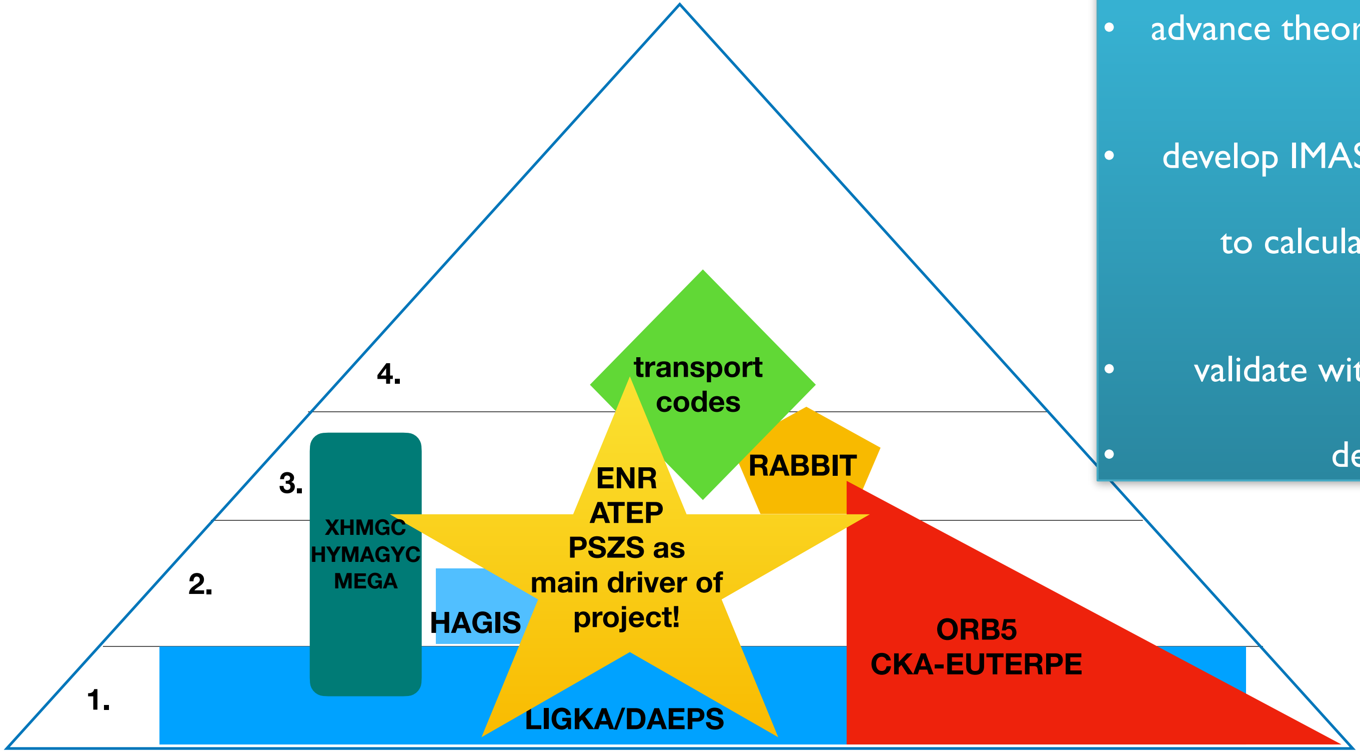
non-linear/quasi-linear global kinetic e.m.+ background transport

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

non-linear global kinetic e.m.

linear global kinetic e.m.

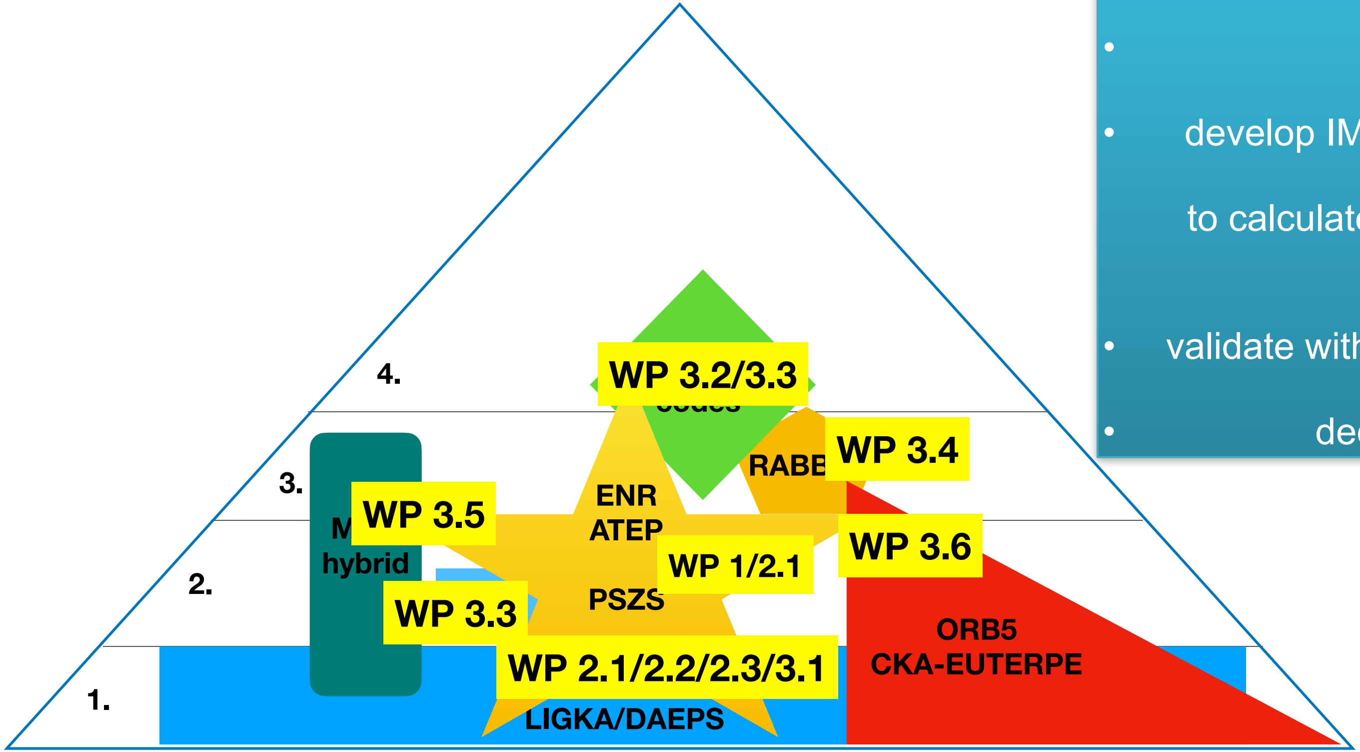
modelling hierarchy for plasmas with significant energetic particle pressure



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

Deliverables 1

- End 2021 WP1-D1 Complete transport theory of Phase Space Zonal Structures and Zonal State separating its microscale structures from macro-/meso- scale components
- End 2022 WP1-D2 Explicit expressions of phase space fluxes as input for WP2
- mid 2024 WP1-D3 Self-consistent description of EPM repeated burst dynamics using the PSZS theoretical framework

- End 2021 WP2.1-D1 DAEPS in general tokamak geometry
- mid 2023 WP2.1-D2 Reduced EP transport model in tokamaks
- mid 2024 WP2.1-D3 DAEPS in general stellarator geometry

fully
partly
not started

- End 2022 WP2.2-D1 Fast analytical LIGKA version including trapped particles
- End 2023 WP2.2-D2 Fast analytical LIGKA model including guesses for global mode structures and non-Maxwellian distribution functions
- Mid 2022 WP2.3-D1 Explicit expressions for local eigenvalue code in 3D
- mid 2024 WP2.3-D2 Local eigenvalue code in 3D including passing particles

- End 2022 WP3.1-D1 Validated 1D reduced model for EP transport in ITER/DTT
- mid 2024 WP3.1-D2 Systematic statistical analysis of test particle transport and assessment of diffusive vs. non diffusive behaviours - jointly with WP3.2

Deliverables 2

- End 2022 WP3.2-D1 Insights into short- and long-time relaxation dynamics of a non- thermal plasma with intense energetic particle component
- mid 2024 WP3.2-D2 Practical basic understanding of convective radial transport of energetic particles versus the possible non-local transport regimes
- Mid 2024 WP3.3-D1 Availability of validated reduced phase space transport model based on LIGKA/HAGIS within IMAS framework (ATEP 3D)

- End 2022 WP3.4-D1 Validated version of RABBIT including model for fluctuation-induced radial transport of EPs (replaced by collisional ATEP-3D)

- End 2022/23 WP3.5-D1 Hybrid kinetic-MHD results for V&V of transport models: with generalized distributions functions and collisions for AUG, ITER, DDT.
- mid 2024 WP3.5-D2 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, HYMAGYC, MEGA and ORB5

- End 2022/23 WP3.6-D1 Deliver quantitative criteria for transitions between different transport regimes w/o turbulence and ZF/ZSs using experimentally relevant parameters
- End 2022 WP4-D1 Availability of reference scenarios (ITER, AUG, DTT) for application of transport models

publications/conferences 2021

First Author	Initials	Title of work	Journal / Conference	Doc. Type	DOI or status of paper	Pinboard ID
Zonca	F.	A theoretical framework of chorus wave excitation	Reviews of Modern Plasma Physics 5, 8 (2021	Paper	https://doi.org/10.1007/s41614-021-00057-x	29812
Zonca	F.	Nonlinear dynamics of phase space transport by chorus emission	JGR	Paper	To be published	30076
Lauber	Ph.	Kinetic Alfven Waves in Tokamaks	5th AAPPS-DPP 26th Sept 2021	Topical plenary	N/A	30323
Carlevaro	N.	Hierarchical approach for energetic particle transport in 1-dimensional uniform plasmas	47th EPS Conference on Plasma Physics 2021, Vol. 45A, P3.1067	Poster	published	28666
Carlevaro	N.	One dimensional reduced model for ITER relevant energetic particle transport	Plasma Physics and Controlled Fusion	paper	published	30899
Wang	X.	Analysis of the nonlinear dynamics of a chirping-frequency Alfvén mode in a Tokamak equilibrium	N/A	paper	submitted	30841
Holderied	F.	Magneto-hydrodynamic eigenvalue solver based on smooth polar splines	JCP	paper	submitted	30814
Wang	X.	Nonlinear dynamics of frequency chirping energetic particle driven modes in fusion plasmas	5th AAPPS-DPP 26th Sept 2021	invited	N/A	30204
Meng	G.	Mode structure symmetry breaking of reversed shear Alfvén eigenmodes and its impact on the generation of parallel velocity asymmetries in energetic particle distribution	PST	paper	accepted	30199
Bierwage	A.	Representation and modeling of charged particle distributions in tokamaks	CPC	paper	submitted	30554
Popa	V. –A.	IMAS - INTEGRATED WORKFLOW FOR ENERGETIC PARTICLE STABILITY	4th IAEA TM on Fusion Data Processing, Validation and Analysis, Chengdu, China, 30th November 2021.	oral	N/A	31086
Qiu	Z.	Evidence of 'two plasmon' decay of energetic particle induced geodesic acoustic mode	NJP		published	29280

First Author	Initials	Title of work	Journal / Conference	Doc. Type	DOI or status of paper	Pinboard ID
Falessi	M. V.	Nonlinear equilibria and transport processes in burning plasmas	28th IAEA Fusion Energy Conference (FEC2020)		N/A	29490

13 (7 papers, 6 invited/contributed)

publications/conferences 2022

First Author	Initials	Title of work	Journal / Conference	Doc. Type	DOI or status of paper	Pinboard ID
Lauber	Ph.	Energetic particle driven instabilities during the L-H transition in ASDEX Upgrade	Proceedings 48th EPS Conference on Plasma Physics (EPS), Maastricht, Netherlands, 2022	Poster, paper	published	31591
Pinches	S.D.	Role of Energetic Ions in the ITER Research Plan	Plenary talk at 48th EPS Conference on Plasma Physics (EPS), Maastricht, Netherlands, 2022	Plenary talk	N/A	N/A
Wang	X.		THEORY OF FUSION PLASMAS JOINT VARENNA - LAUSANNE INTERNATIONAL WORKSHOP, Varenna, Italy, 12th September 2022.	Invited talk		
Wang	X.	Nonlinear dynamics of nonadiabatic chirping-frequency energetic particle mode in Tokamak plasmas	28th ITPA Topical Group Meeting on Energetic Particle Physics, Caradache, France, 21st November 2022.	talk	N/A	33267
Wang	T.	Excitation of toroidal Alfvén eigenmode by barely circulating energetic electrons in low density plasmas	Plasma Physics and Controlled Fusion	paper	submitted	33536
Hayward-Schneider	T.	Global electromagnetic gyrokinetic simulations of Energetic Particle driven instabilities in ITER and ASDEX Upgrade	6th Asia Pacific Conference on Plasma Physics (AAPPS-DPP2022), online , 9th October 2022.	invited	N/A	33120
Carlevaro	N.	Energetic particle transport: diffusion vs convection and phase-space barriers	48th EPS Conference on Plasma Physics (EPS), Maastricht, Netherlands, 27th June 2022.	poster	published	32056
Biancalani	A.	Interaction of Alfvénic modes and turbulence via the nonlinear modification of the equilibrium profiles	48th EPS Conference on Plasma Physics (EPS), Maastricht, Netherlands, 27th June 2022.	Poster/paper	published	31903
Sama	J.N	Effect of temperature anisotropy on the dynamics of geodesic acoustic modes	Journal of Plasma Physics, 2022	paper	submitted	33147
Zocco	A.	Nonlinear drift-wave and energetic-particle transport in stellarators: solution of the kinetic problem.	Journal of Plasma Physics,2022	paper	submitted	33166
Koenies	A.	A numerical	Physics of Plasmas	paper	10.1063/5.01	32404

First Author	Initials	Title of work	Journal / Conference	Doc. Type	DOI or status of paper	Pinboard ID
		approach to the calculation of the Alfven continuum in the presence of magnetic islands			02239	
Falessi	M. V.	Energetic particle nonlinear equilibria and transport processes in burning plasmas	6th Asia Pacific Conference on Plasma Physics (AAPPS-DPP2022), online , 9th October 2022.	invited	N/A	33199
Wei	S.	Core localized alpha-channeling via low frequency Alfvén mode generation in reversed shear scenarios	Nuclear Fusion	paper	10.1088/1741-4326/ac968f	33016
Chen	L.	On scattering and damping of Toroidal Alfvén eigenmode by drift wave turbulence	Nuclear Fusion	paper	10.1088/1741-4326/ac7cf9	32705
Bottino	A.	Time evolution and finite element representation of phase space zonal structures in ORB5	THEORY OF FUSION PLASMAS JOINT VARENNA - LAUSANNE INTERNATIONAL WORKSHOP, Varenna, Italy, 12th September 2022.	poster, paper	accepted	32694
Wu	Y.	Nonlinear electron phase-space dynamics in spontaneous excitation of falling-tone chorus	:Geophysical Research Letters	paper	10.1029/2022GL100046	32688
Chen	L.	Parity-breaking parametric decay instability of kinetic Alfvén waves in a nonuniform plasma	Physics of Plasmas	paper	10.1063/5.0091057	32397
Li	Y.Y.	Kinetic Structure of Low Frequency Continuous Spectrum in General Tokamak Geometry	48th EPS Conference on Plasma Physics (EPS), Maastricht, Netherlands, 27th June 2022.	Poster/paper	published	31816
Falessi	M. V.	Energetic particle nonlinear equilibria and transport processes in burning plasmas	48th EPS Conference on Plasma Physics (EPS), Maastricht, Netherlands, 27th June 2022.	Poster/paper	published	31766
Ma	R.R.	Theoretical studies of low-frequency Alfvén modes in tokamak plasmas	Plasma Physics and Controlled Fusion	paper	10.1088/1361-6587/ac434a	31657
Li	Y.Y.	Physics of drift Alfvén instabilities and energetic particles in fusion plasmas	THEORY OF FUSION PLASMAS JOINT VARENNA - LAUSANNE INTERNATIONAL WORKSHOP, Varenna, Italy, 12th September 2022.	Invited/paper	To be submitted	33607

21 (9 papers, 12 invited/contributed)

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

27 (15 papers, 12 invited/ contributed)

publications/conferences 2024

N Chen et al : 16th September 2024 | DocumentID : 38814
: Drift wave solitons and zonal flows: implication on staircase formation
Journal : SCIENCE CHINA Physics, Mechanics & Astronomy, . Co-authors : L. Chen, F. Zonca and Z. Qiu
L Chen et al : 12th September 2024 | DocumentID : 38789
: Effects of Zonal Fields on Energetic-Particle Excitations of Reversed Shear Alfv´en Eigenmode: Simulation and Theory
Journal : Nuclear Fusion, . Co-authors : P. Liu, R. Ma, Z. Lin, Z. Qiu, W. Wang and F. Zonca
T Hayward-Schneider et al : 4th September 2024 | DocumentID : 38754
: Global gyrokinetic instabilities going to high plasma beta
Conference : Joint Varenna-Lausanne International Workshop, Varenna, Italy, 2nd September 2024.
A Koenies et al : 14th August 2024 | DocumentID : 38553
: Calculation of Alfvén eigenmodes within Magnetic Islands
Conference : 24th International Stellarator/Heliotron Workshop (ISHW), Hiroshima, Japan, 9th September 2024.
F Zonca et al : 2nd August 2024 | DocumentID : 38486
: Universal behaviour of frequency chirping fluctuations in magnetized plasmas
Conference : Joint Varenna-Lausanne International Workshop, Varenna, Italy, 2nd September 2024.
Co-authors : L. Chen, M. V. Falessi, X. Tao, and Z. Qiu
T Hayward-Schneider et al : 14th June 2024 | DocumentID : 38084
: Global gyrokinetic instabilities going to high plasma beta
Conference : Joint Varenna-Lausanne International Workshop, Varenna, Italy, 2nd September 2024.
G Wei et al : 9th April 2024 | DocumentID : 37679
: Calculation of toroidal Alfvén eigenmode mode structure in general axisymmetric toroidal geometry
Journal : Physics of Plasmas, .
Co-authors : M.V. Falessi, T. Wang, F. Zonca, Z. Qiu
Published Title : Calculation of toroidal Alfvén eigenmode mode structure in general axisymmetric toroidal geometry
DOI : 10.1063/5.0213242
L Chen et al : 10th February 2024 | DocumentID : 37161
: On beat-driven and spontaneous excitations of zonal flows by drift waves
Journal : Physics of Plasmas, .
Co-authors : Z. Qiu, F. Zonca
Published Title : On beat-driven and spontaneous excitations of zonal flows by drift waves
DOI : 10.1063/5.0203053
P Lauber et al : 2nd February 2024 | DocumentID : 36991
: ATEP: A phase space resolved transport model for energetic particles
Conference : 50th EPS Conference on Plasma Physics (EPS 2024), Salamanca, Spain, 8th July 2024.
Co-authors : M. V. Falessi, G. Meng, T. Hayward-Schneider, V.-A. Popa, F. Zonca, M. Schneider
G Meng et al : 2nd February 2024 | DocumentID : 36970
: Theoretical, Numerical, and Experimental Studies of Advanced Transport Models for Energetic Particles
Conference : 50th EPS Conference on Plasma Physics (EPS 2024), Salamanca, Spain, 8th July 2024.
Co-authors : P. Lauber, Z. Lu, M. Falessi, J. Bao, F. Zonca
N Chen et al : 31st January 2024 | DocumentID : 36920
: Drift wave soliton formation via forced-driven zonal flow and implication on plasma confinement
Journal : Physics of Plasmas, .
Co-authors : L. Chen, F. Zonca and Z. Qiu
Published Title : Drift wave soliton formation via forced-driven zonal flow and implication on plasma confinement
DOI : 10.1063/5.0201169

P Lauber et al : 3rd October 2024 |
: ATEP - a reduced model for EP transport in CoM space
Conference : 32nd ITPA EP meeting (online)

P Lauber et al : 11th October 2024 |
: ATEP - a reduced model for EP transport in CoM space
Conference : CNPS seminar (online)

13(7 papers, 5 invited/contributed)

∑ 74 (38 papers, 36 invited/contributed)

ATEP highlights and outlook

time: 25 +15 mins

WP1:

theoretical framework

WP 2:

Implementation and advancing various building blocks according to WP1

PSZS

WP3:

Application, verification and validation of reduced EP transport models

WP4:

Preparation and analysis of time-dependent reference cases: experiment, predictions for future machines

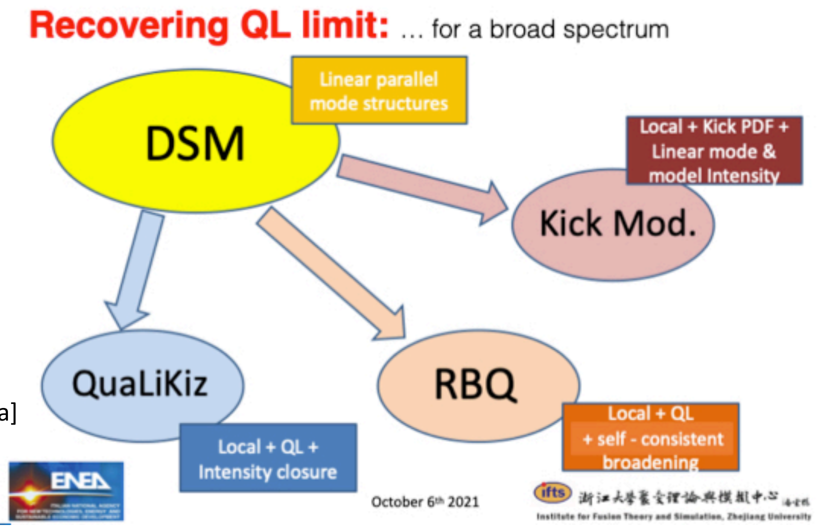
WP1: theoretical framework - PSZS transport theory

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

$\nabla_z \cdot \Gamma$
wave-induced phase space flux

collisions + source

[Zonca & Chen, NJP15 Zonca & Chen et al. NJP 17, NJP 21]
[Zonca et al, JPCS 2021]
[F. Zonca et al, IAEA FEC 2023]
[F. Zonca et al, AAPPS-DPP 2023]
[F. Zonca JPP Colloquium, Jul 2024]
[M-V. Falessi, PoP 2018, PoP 2019]
[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]



[F. Zonca]

- without approximations: solving nl - GK full-F equations
- crucial new element: introduce concept of long-lived formations in the particle phase space (PSZS); separate from fast fluctuating contributions
- nonlinear envelope equations for the self-consistent evolution of the SAW fluctuation spectrum driven by EPs and the PSZS transport equations can be cast in form of a Dyson-Schrödinger equation (='DSM')
- Dyson Schrödinger model is superset of various models presently used in community
- other limits can be obtained: kick model, QL, RBQ, Qualikiz,…

WP1: theoretical framework - PSZS transport theory

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

- include zonal fields as e.m. counterpart of phase space zonal structures -comprehensive description of nonlinear equilibrium
- nonlinear equilibrium connected to (anisotropic) CGL description
- accounting in particular for meso-scales introduced by EPs, but also background transport has phase space features [S.J. Wang et al. PRL 2024, ITB by ITG]
- Self-consistent description of EPM repeated burst dynamics using the PSZS theoretical framework : application of theory to EGAM; ready for comparison with simulations

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

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

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]

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

WP1:

theoretical framework

WP 2:

Implementation and advancing various building blocks according to WP1

PSZS

WP3:

Application, verification and validation of reduced EP transport models

WP4:

Preparation and analysis of time-dependent reference cases: experiment, predictions for future machines

WP2: implementation of reduced models

'more analytical'

DAEPS/Falcon

- use mode decomposition methodology to separate radial envelope and parallel mode structures
- solve general fishbone-like dispersion relation
- calculate non-linear fluxes

benchmarks diagnostics

'more numerical'

ATEP (LIGKA-HAGIS)

- local and global solver
- solve linear GK equations
- use IMAS-coupled EP stability WF (HAGIS/ LIGKA) to calculate orbit+zonal averaged fluxes
- use sources from models or ITER H&CD
- evolve transport equations
- collision operator in CoM

benchmarks diagnostics

'fastest'

1d beam plasma model

- 1d beam-plasma system: bump on tail
- partition phase space in slides of maximal power exchange
- use LIGKA linear mode information
- can directly run on long time scales

[Y. Li, PoP 2020, EPS 2022 ID: 31816, Invited talk at Varenna Theory meeting 2022, M.V. Falessi NJP 2023 (ID 36555)]

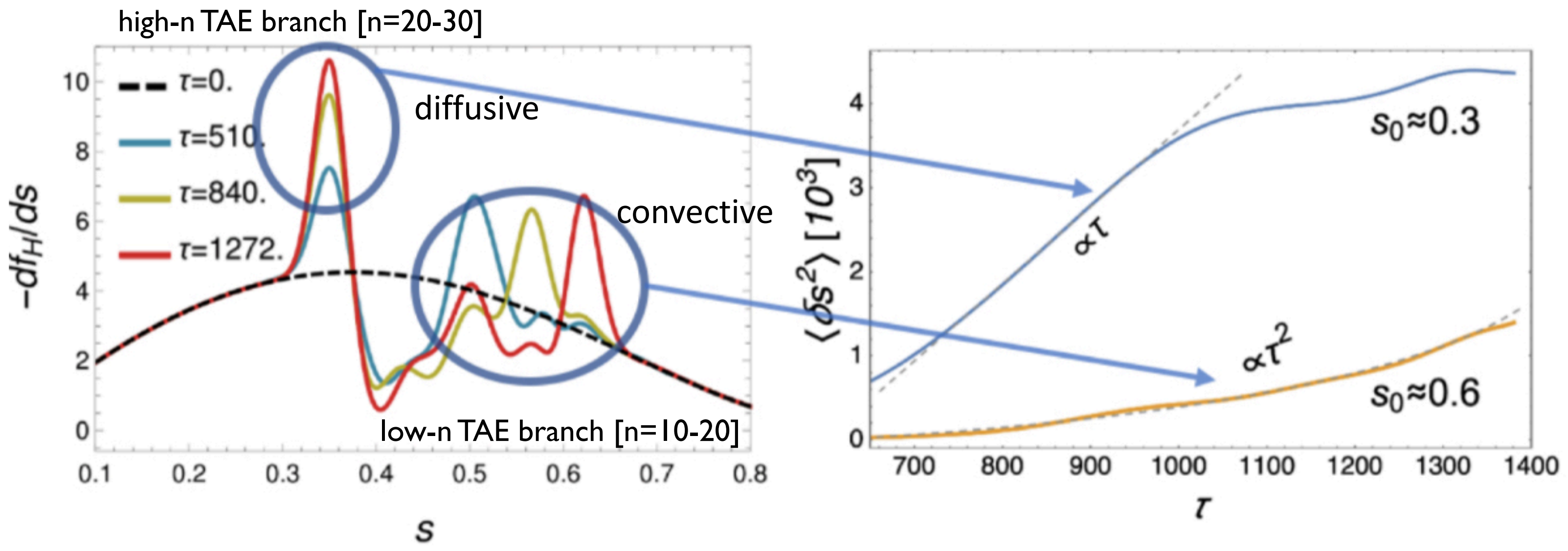
[Ph. Lauber, EPS 2022,(ID 31591), Ph Lauber et al NF 2024 (ID 36991), G. Meng, NF 2024 (ID 36970)]

[N. Carlevaro et al PPCF 2022 (ID 30899)
N. Carlevaro et al EPS22, P5a.113 (ID 32056)
N. Carlevaro JPP subm. 2024 (ID 38909)]

WP2: 1D beam plasma model

N. Carlevaro, G. Montani, M.V. Falessi, Ph. Lauber, EPS22, P5a.113 ID: 32056
N. Carlevaro, M.V. Falessi, G. Montani, Ph. Lauber, submitted to JPP (Sept. 2024) ID: 38909

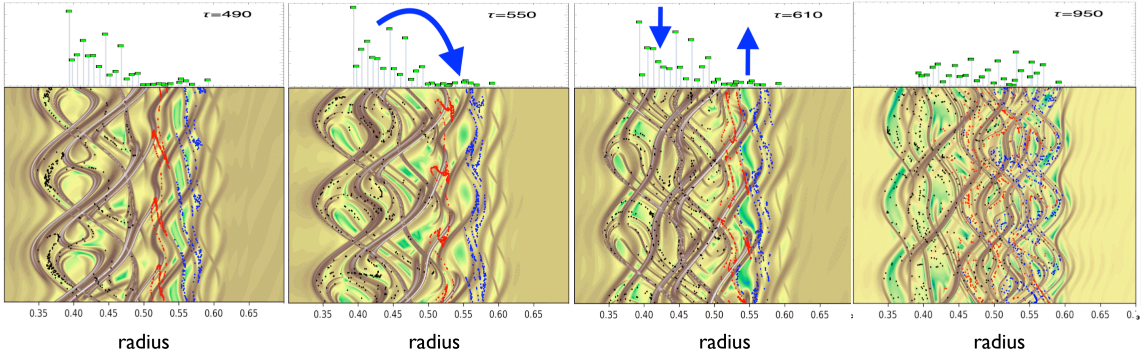
- previously: successful benchmark with HAGIS for ITER 15 MA case, 2x EP density, [Schneller, NF 2016]
- add tracers to system an determine diffusive (τ) vs. convective (τ²) scaling:



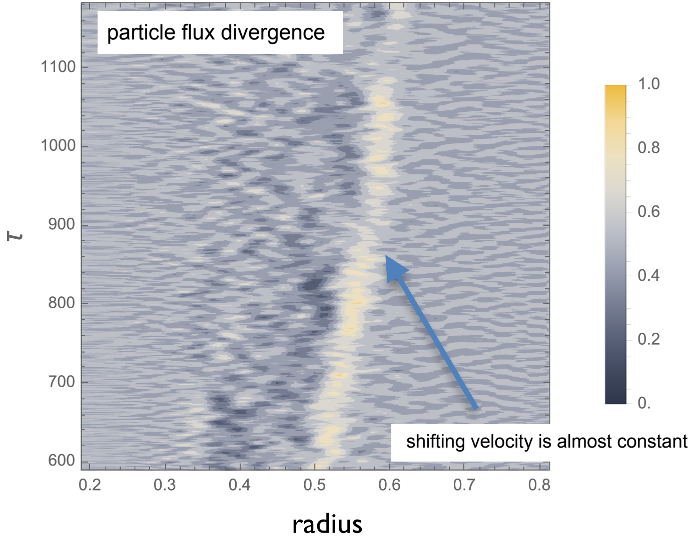
WP2: 1D beam plasma model

N. Carlevaro, G. Montani, M.V. Falessi, Ph. Lauber, EPS22, P5a.113 ID: 32056
N. Carlevaro, M.V. Falessi, G. Montani, Ph. Lauber, submitted to JPP (Sept. 2024) ID: 38909

- tracers dynamics studied with Lagrangian Coherent structures: relevant structures/ barriers change during non-linear evolution: from inner to outer radial transport peak
- different behaviour of high-n TAE and low-n TAE branch (super-diffusive)!



peaked structure with ballistic-like motion consistent with non-diffusive transport

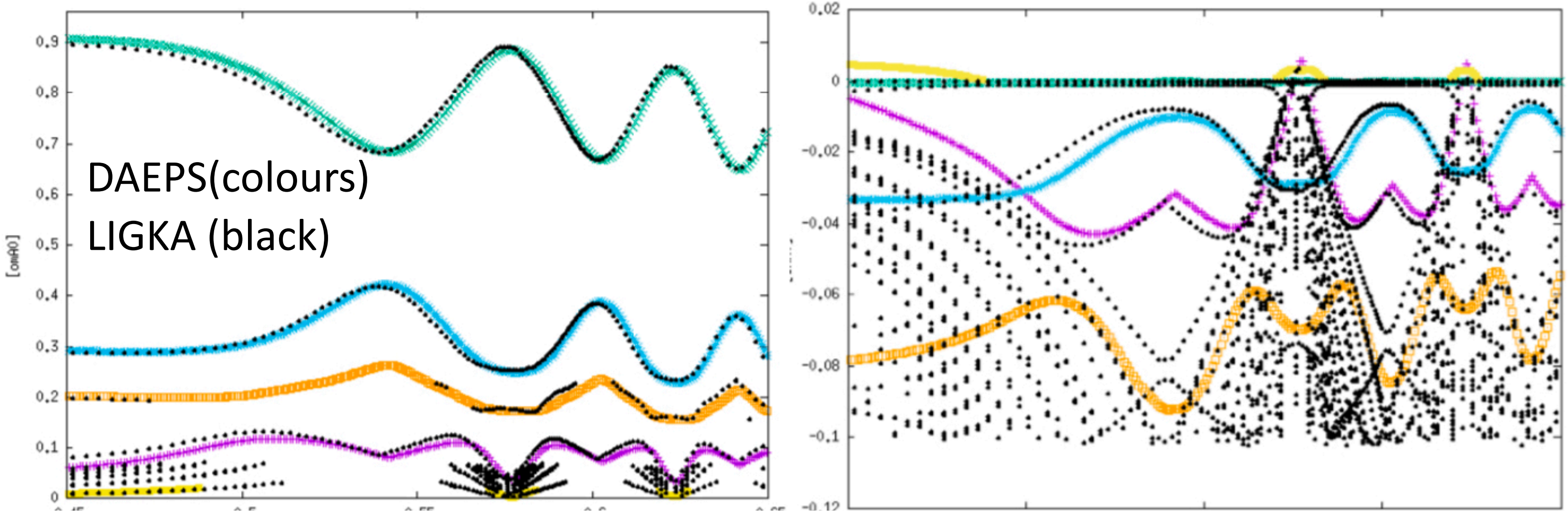


- investigate convective EPM transport analytically: in force-free limit it was confirmed that Lévy flights do not influence the dynamics of EPMs [A. Milovanov et al PHYSICAL REVIEW E (2021)]
- no "heavy" power-law tails with regard to the long-time distribution of EPs have been found in simulations. Explanation: dissipative nonlinearity and continuum damping of EPM can effectively stabilise the nonlocal features typical of Lévy flights (Milovanov in preparation 2023).

WP2: DAEPS/FALCON - LIGKA/ATEP comparison

frequency

damping

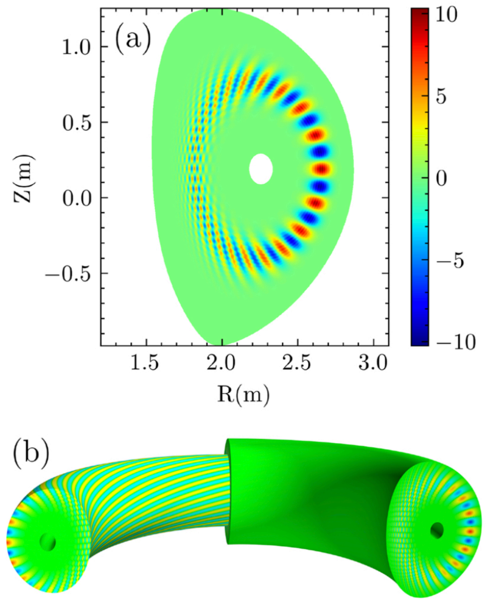


[Y. Li, EPS 2022 ID: 31816]

- successful benchmark of continua with LIGKA

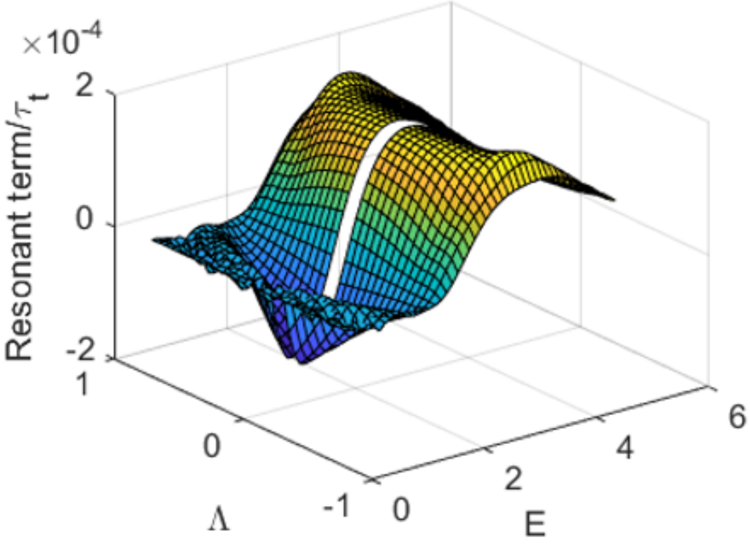
WP2: DAEPS/FALCON/PEANUT

TAE in DTT [Wei, PoP 2024 ID 37679]



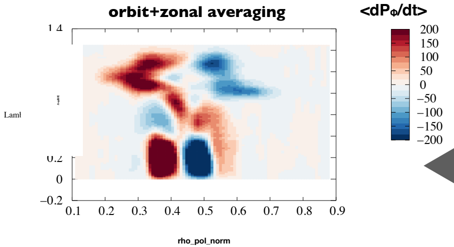
TAE induced fluxes

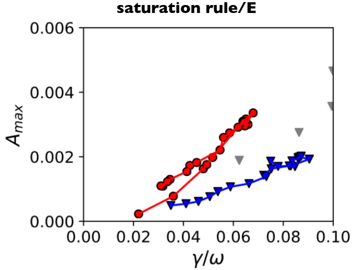
$$\left[\tau_b e^{iQ_z} \overline{\delta\dot{\psi}\delta F}\right]_z$$

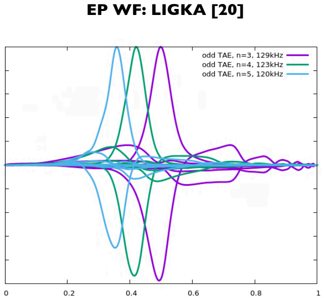


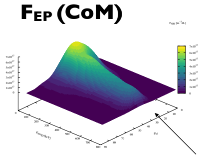
- successful benchmark of continua with LIGKA
- global modes, expressed in extended ballooning space
- explicit expressions for EP fluxes derived
- ongoing benchmarks on EP fluxes

WP2: ATEP code - physics and structure









transport code

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

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

calculate PSZS fluxes

use NL code/model for intensity closure

or kick model

calculate linear mode spectrum

calculate D(r,E)

or

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

t

t+1

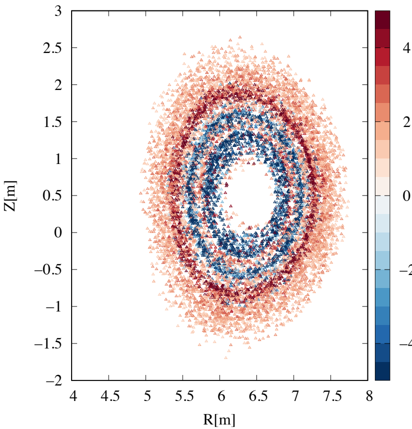
mhd_linear

distributions

core profiles

equilibrium

time



ATEP code [Ph. Lauber , NF 2024

ATEP-3D [G. Meng, NF2024]

WP2: extended LIGKA for non-Maxwellian distributions

- 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

[master thesis R. Stucchi,2023]

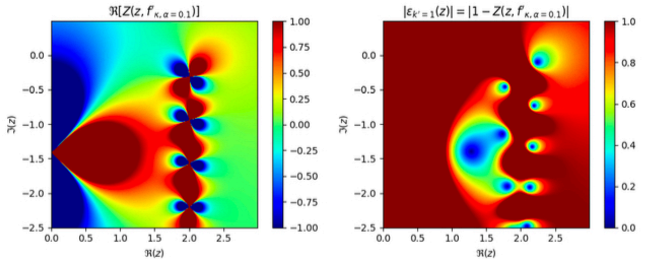


Figure 4.9: 'Strong smoothing': real part of $Z(z, f'_{\kappa=1,\alpha=0.1})$ and absolute value of $\epsilon_{k'}(z)$.

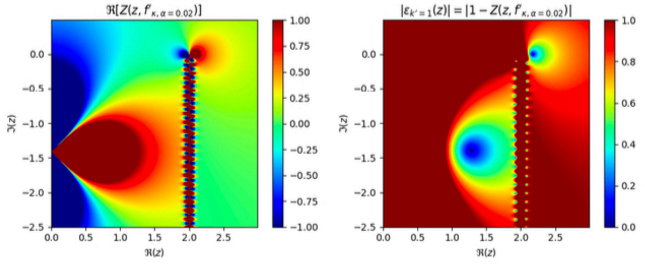
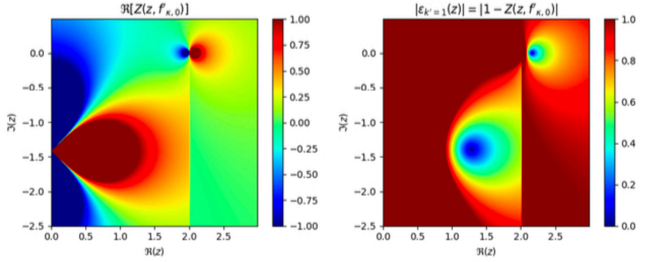
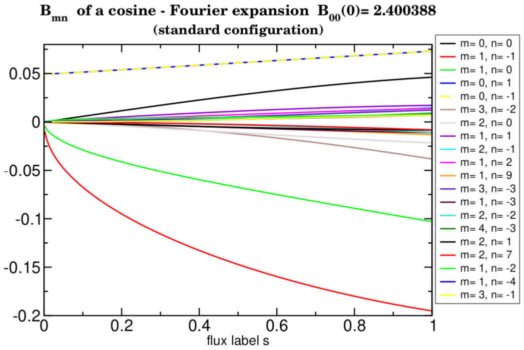


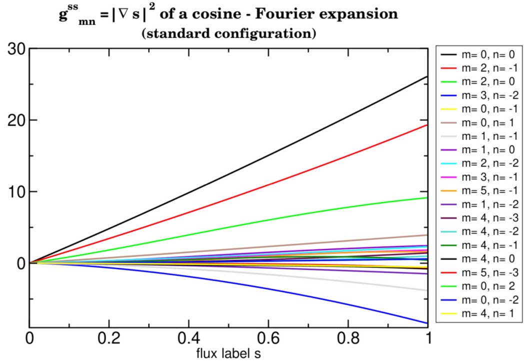
Figure 4.10: 'Weak smoothing': real part of $Z(z, f'_{\kappa=1,\alpha=0.02})$ and absolute value of $\epsilon_{k'}(z)$.



WP 2: first steps towards a 3-d version

- in analogy to the local version two-dimensional gyro-kinetic code LIGKA, develop a three-dimensional extension -> stellarator equilibria calculated with VMEC.
- kinetic part: drift kinetic code CAS3D-K, benchmark against analytical model of Kolesnichenko et al. and EUTERPE/ STAE-K code.
- 1d QL mixing length model implemented [Ch. Slaby, 2023]





Stellarator specific modifications

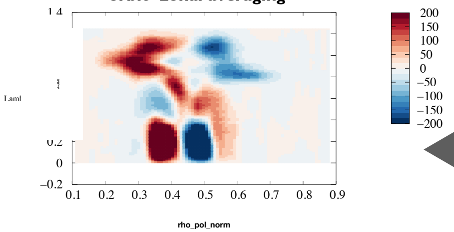
$$B(r,\vartheta,\varphi) = B_0\left(\epsilon_{00}(r) + \epsilon_t(r)\cos\vartheta + \epsilon_h(r)\cos(m_h\vartheta + n_h\varphi) + \epsilon_m(r)cos\varphi\right)$$

$$g^{ss}(r,\vartheta,\varphi) = \sum_{i=1}^{n_g} \epsilon_i^g(r)\cos(m_i\vartheta + n_i\varphi)$$

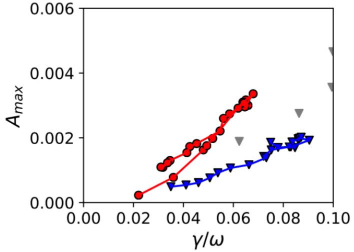
- ☑ large aspect ratio in Boozer coordinates to keep the integrals tractable
- ☑ decomposition of the particle motion
- ☑ quasi-neutrality, Ampère's law
- ☑ kinetic equation
- ☐ compose terms (tedious, but straight-forward)
- ☐ decide upon approximation on the left hand side of Eq. (1) (MHD coupling in W7-X is strong $\Rightarrow n_g$ must have a certain size otherwise the quantitative agreement in the MHD limit is not sufficient)

WP2: ATEP code - physics and structure

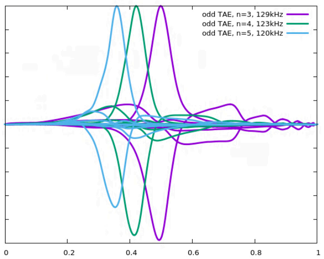
orbit+zonal averaging



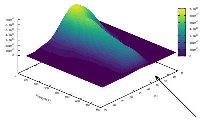
saturation rule/E



EP WF: LIGKA [20]



F_{EP} (CoM)



transport code

calculate PSZS fluxes

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

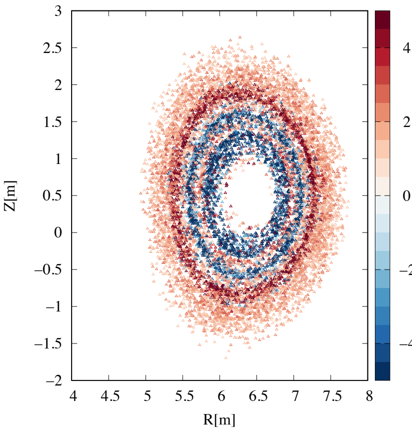
advance F_{EP} and return updated distribution IDS, or its moments

t

t+1

- mhd_linear
- distributions
- core profiles
- equilibrium

time



ATEP code
[Ph. Lauber , NF 2024
ATEP-3D
[G. Meng, NF2024]

WP2: ATEP code - fluxes in CoM space

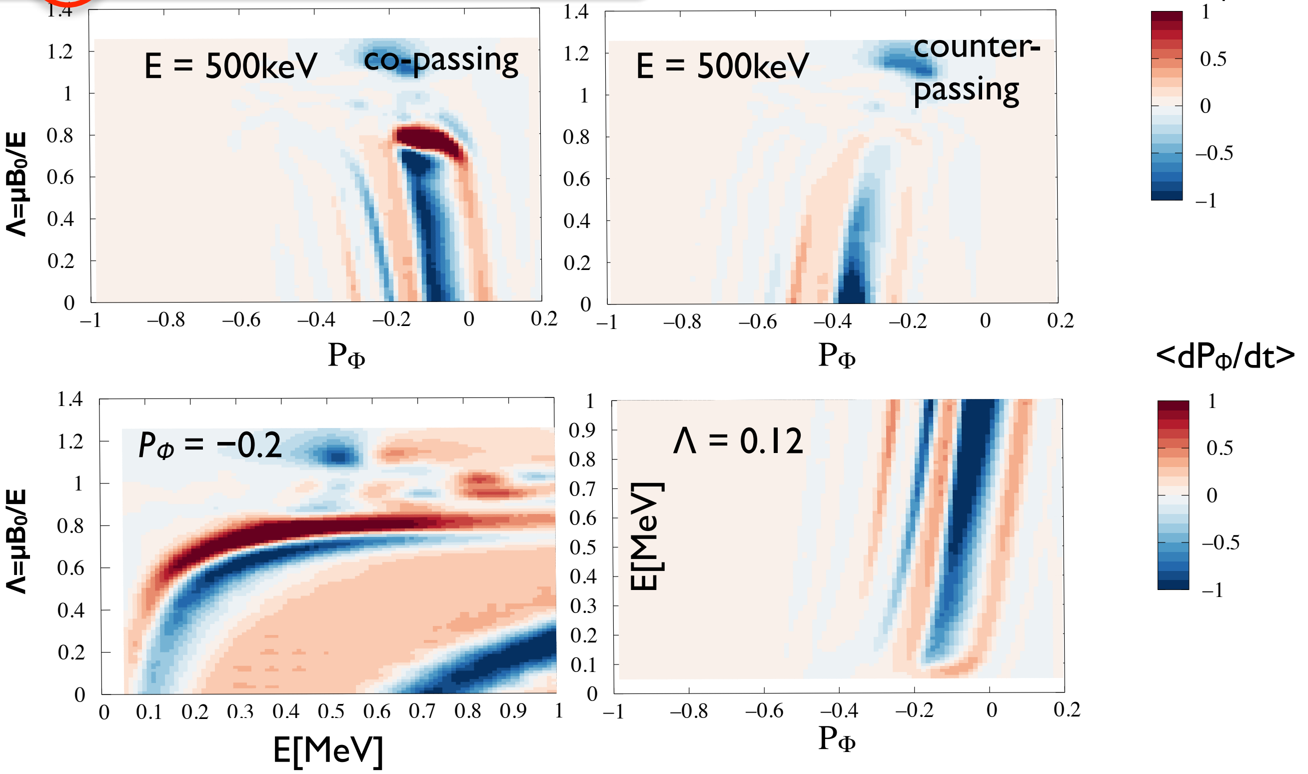
$$\frac{\partial}{\partial t}\overline{F_{z0}} + \frac{1}{\tau_b}\left[\frac{\partial}{\partial P_\phi}\overline{\left(\tau_b \delta \dot{P}_\phi \delta F\right)}_z + \frac{\partial}{\partial \mathcal{E}}\overline{\left(\tau_b \delta \dot{\mathcal{E}} \delta F\right)}_z\right]_S = \overline{\left(\sum_b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

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

typical resolution (P_Φ,E,Λ): 128/20/20 -256/40/40

use multi-level b-splining to project to high-res grid in CoM space [Lee,1997]

use fixed amplitude from experiment or nl-codes to determine transport in CoM space



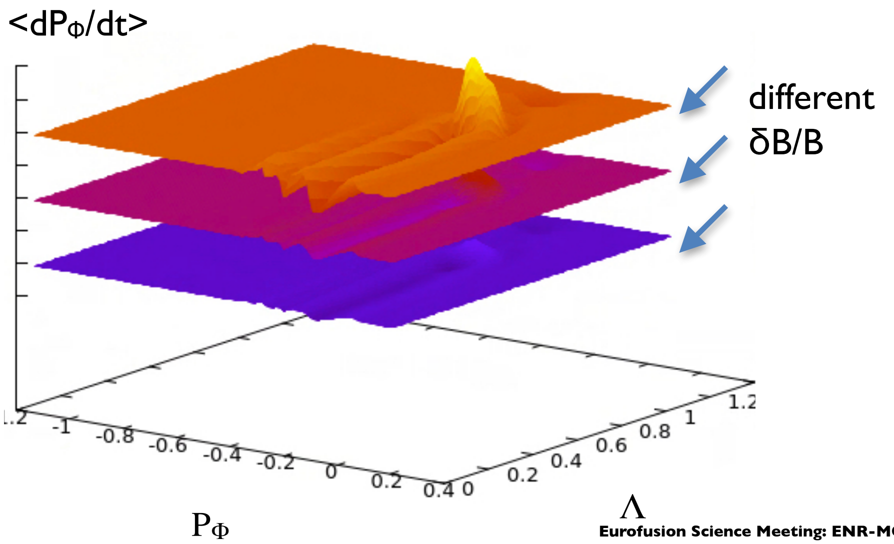
WP 2: ATEP code - energy conserving QL model

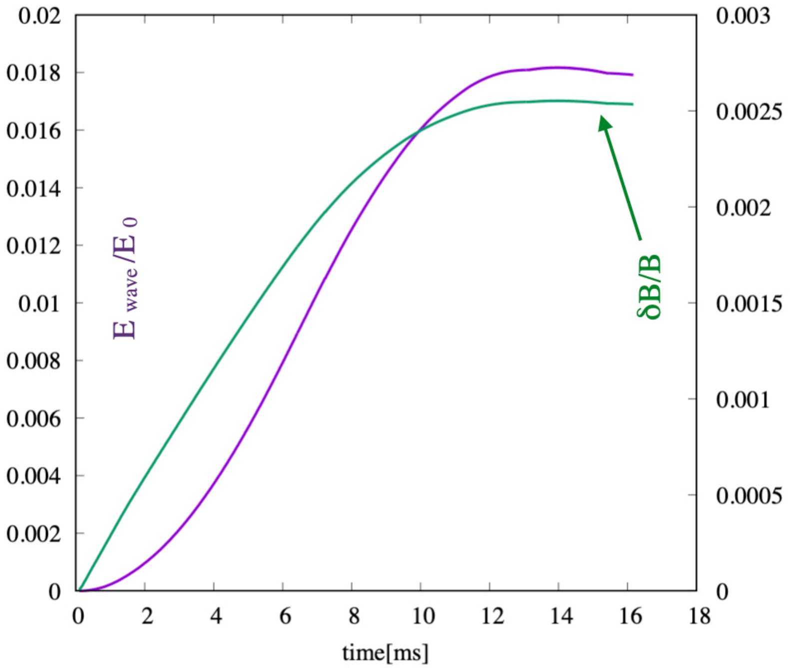
$$\frac{\partial}{\partial t}\overline{F_{z0}} + \frac{1}{\tau_b}\left[\frac{\partial}{\partial P_\phi}\overline{\left(\tau_b \delta \dot{P}_\phi \delta F\right)}_z + \frac{\partial}{\partial \mathcal{E}}\overline{\left(\tau_b \delta \dot{\mathcal{E}} \delta F\right)}_z\right]_S = \overline{\left(\sum_b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

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

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

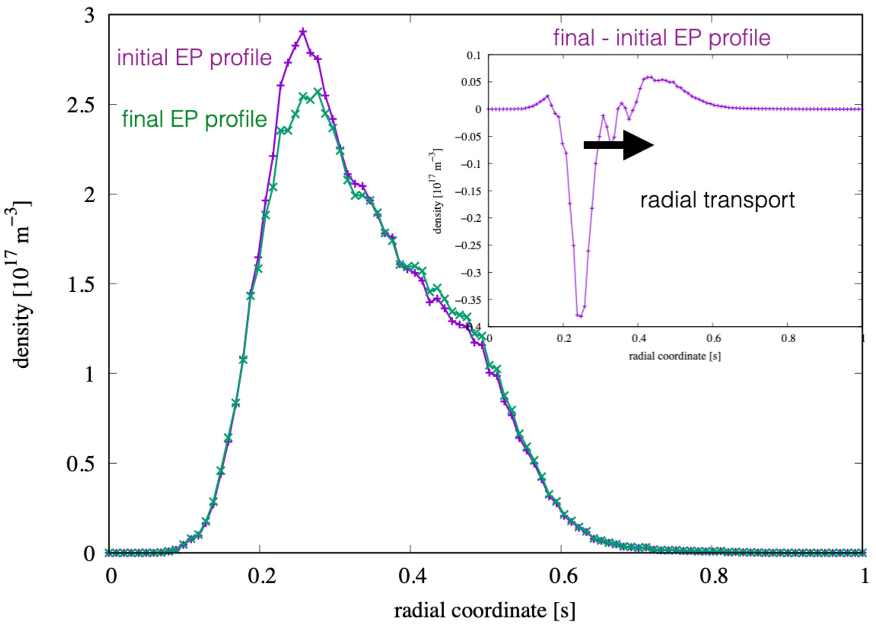
amplitude dependent <dPΦ/dt>, <dE/dt> needed!

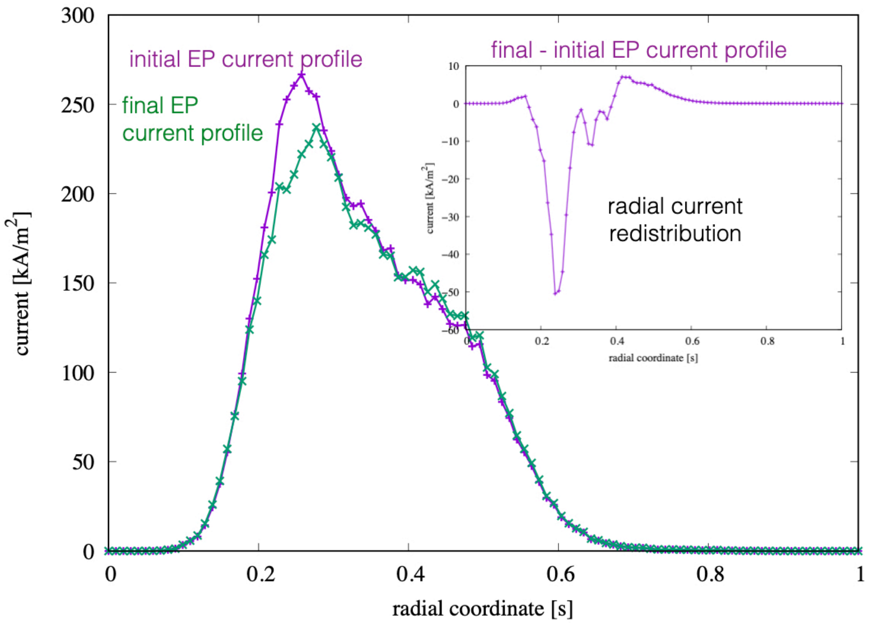




WP 2: ATEP code: back-mapping to configuration space

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





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

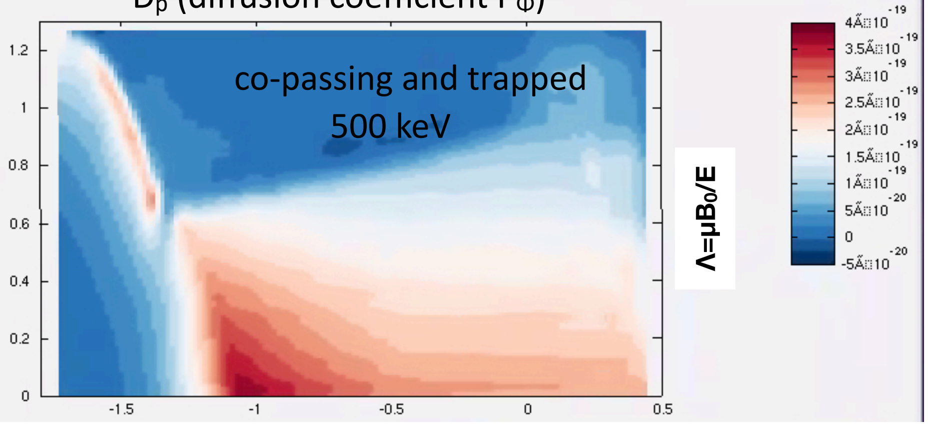
WP 2: collisional ATEP-3D

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

[G Meng, et al, NF 2024]

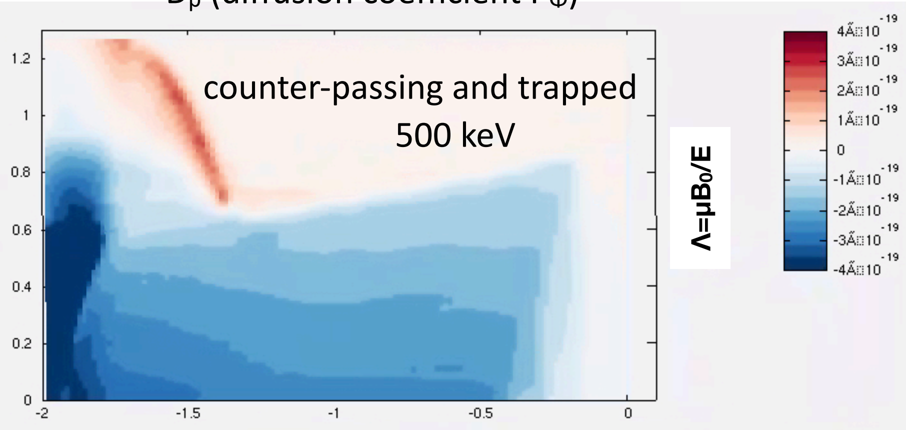
- use collision operator in HAGIS code [A. Bergmann, PoP 2001]
- calculate orbit averaged collision-coefficients in CoM space, Λ- scattering needs to be included
- separate co- and counter-passing regions, use IMAS-given n,T profiles, parallel implicit 3-D solver

D_p (diffusion coefficient P_Φ)



P_Φ

D_p (diffusion coefficient P_Φ)

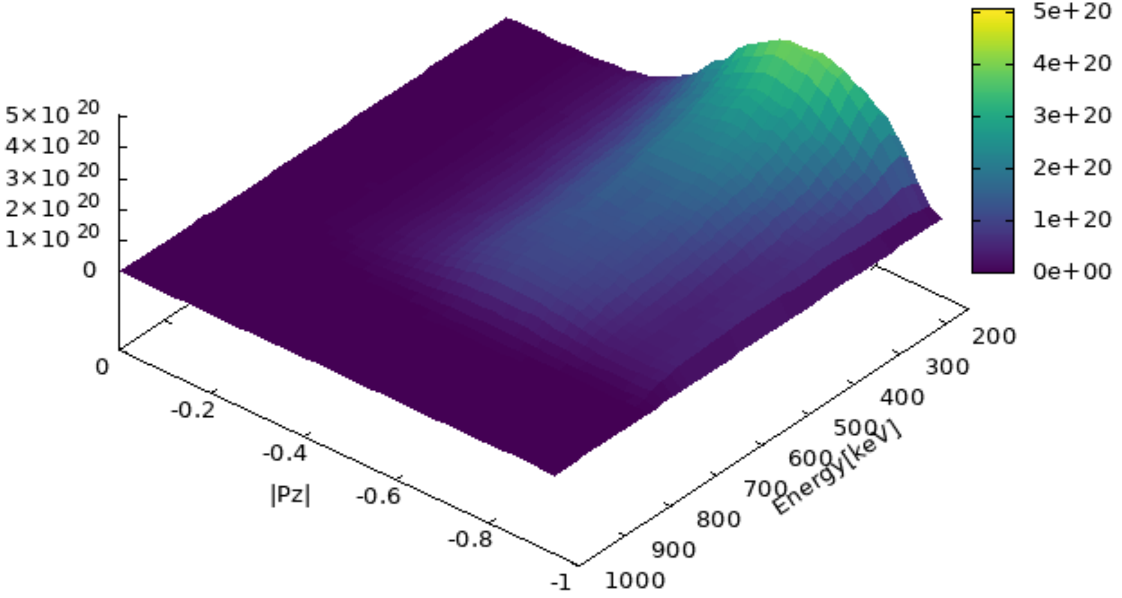


P_Φ

WP 2: collisional ATEP 3D

Gaussian source at 1MeV, ITER case
realistic sources to be implemented

F (Pz,E,t), Time=920 [ms]



due to averaging,
code is much faster (~30 times)
than full orbit following codes

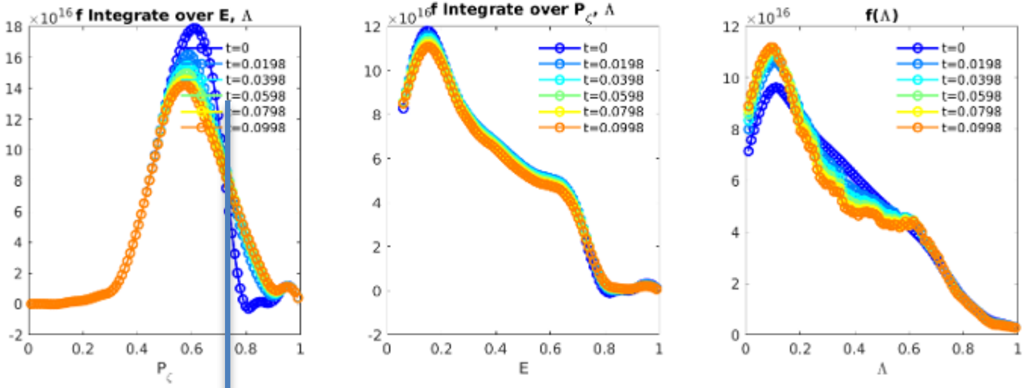
here: no waves

WP2: preliminary results ATEP-3D: TAE and collisions

[G. Meng Invited EPS 2024]

TAE only

test case: 100 ms, fixed $dB/B=10^{-3}$



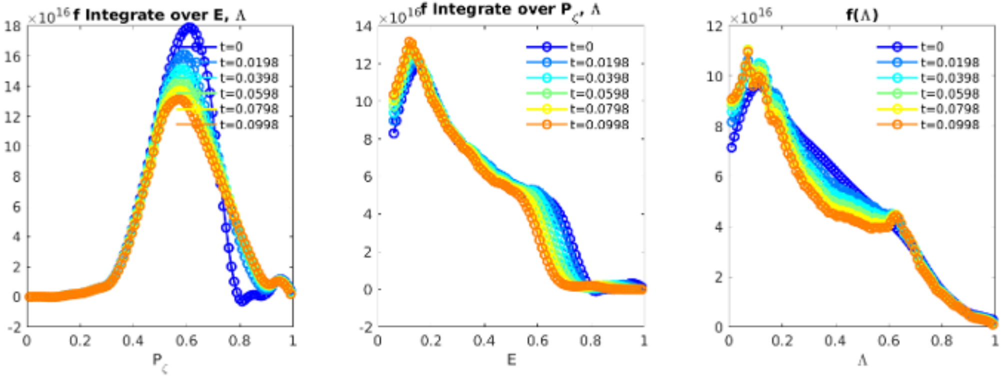
mode position

TAE + collisions

with collisions:

considerable energy relaxation

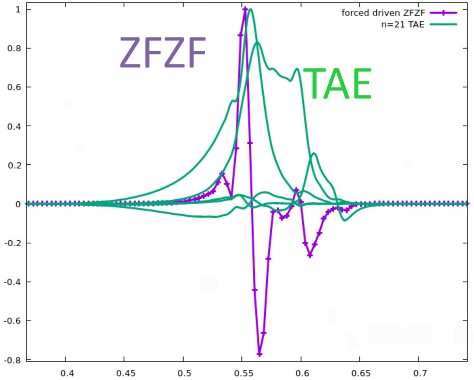
pitch angle scattering smoothes resonances



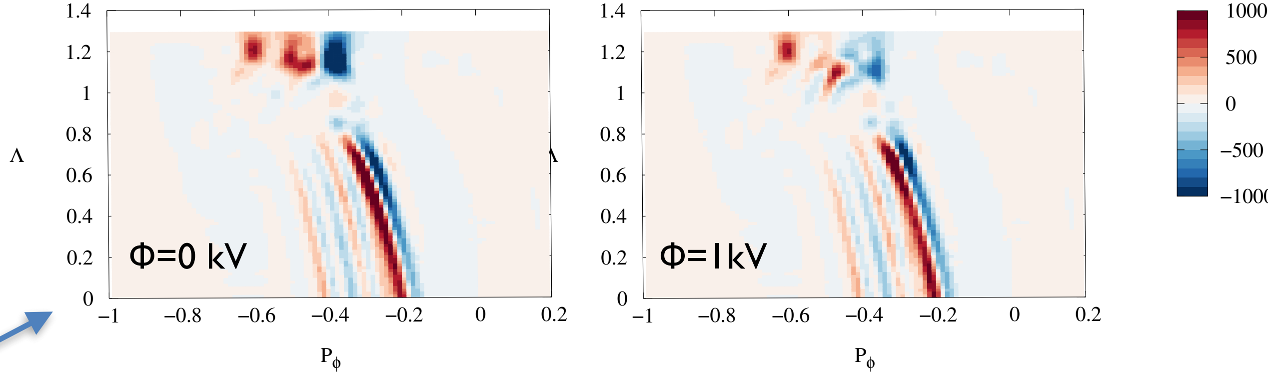
WP2: zonal field model included in ATEP

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

$$\delta\psi_Z = -\frac{1}{B_0}\frac{k_{\theta,0}}{\omega_0}\frac{\partial}{\partial r}\left(|\hat{A}_0|^2 \sum_m |\Phi_0|^2\right).$$



using ad hoc scaling for ZF saturation: PSZS influenced by shearing and resonance broadening effects, as expected by theory:



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

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

resonance broadening
& frequency shift

[Zonca, FEC 2023]

- comparison with comprehensive AE + ZF studies + turbulence ongoing (ORB5/TSVV10) [J. N. Sama, PoP (2024)]
- study saturation scaling
- explore coupling to reduced turbulent transport models

WP1:

theoretical framework

WP 2:

Implementation and advancing various building blocks according to WP1

PSZS

WP3:

Application, verification and validation of reduced EP transport models

WP4:

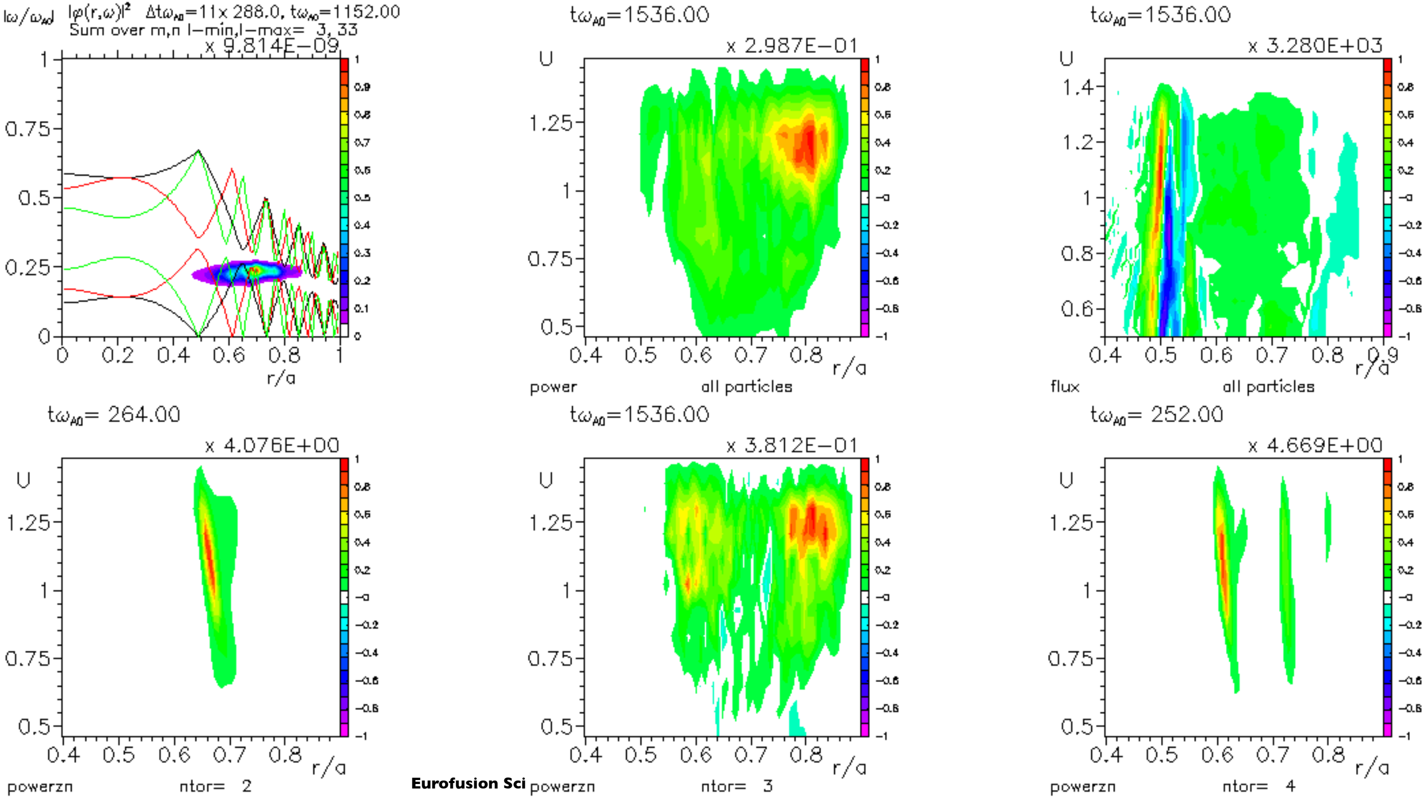
Preparation and analysis of time-dependent reference cases: experiment, predictions for future machines

WP3: develop diagnostics in non-linear codes for comparison

(X)HMGC: pioneering calculations of PSZS

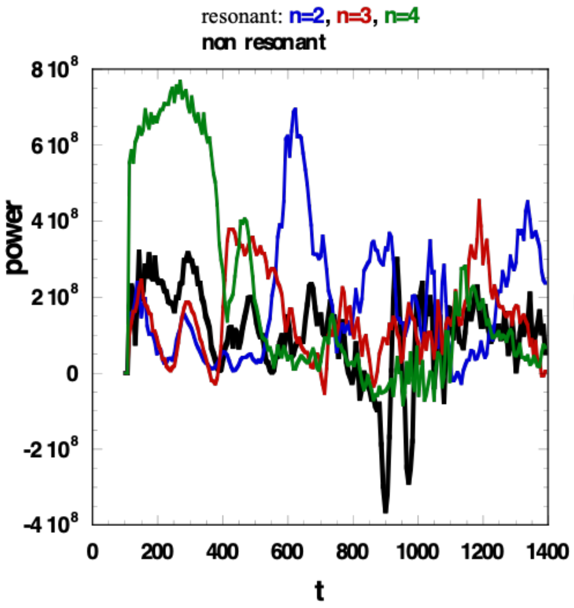
in addition: power exchange and radial flux for multi-n chirping modes n=2, 3, 4

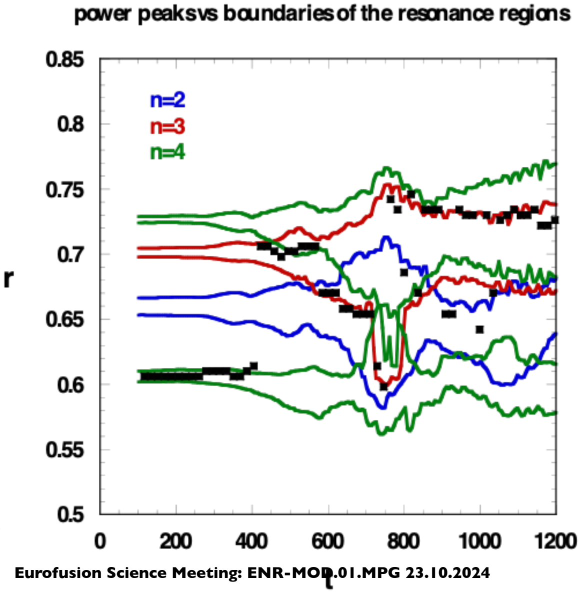
μ-average of power, flux and power(n)

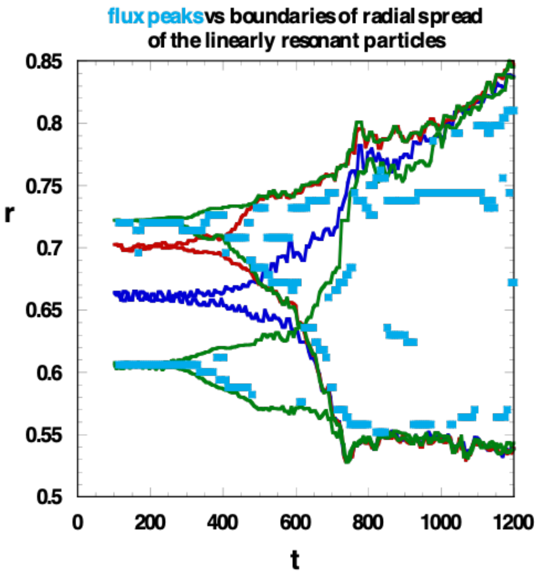


WP3: develop diagnostics in non-linear codes for comparison

- each mode yields an "island"; islands overlap allowing for larger radial excursion of linearly resonant particles
- density-gradient and flux peaks are tightly related to the radial boundaries of such overlapping region; power peaks are not
- power peaks are instead related to the boundaries of the resonance regions
- thus, power transfer is mainly resonant
- important insight for multi-mode treatment in reduced models!



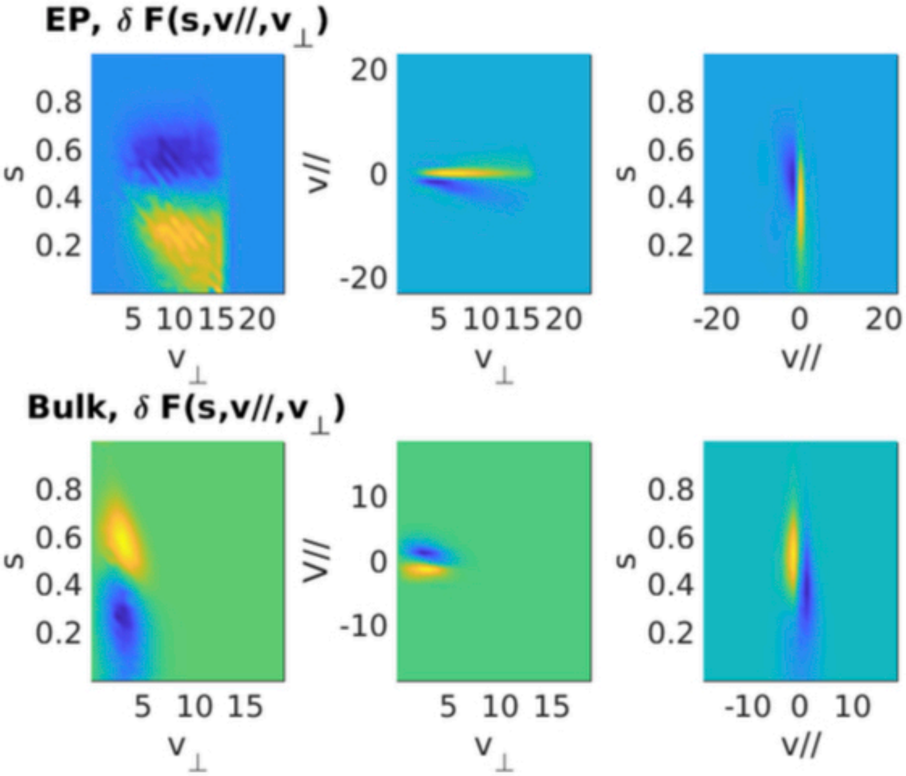


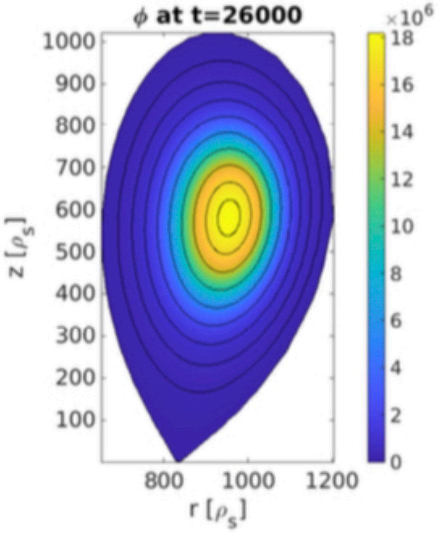


WP3: develop diagnostics in non-linear codes for comparison

- PSZS are not only very useful quantity when comparing the results of non-linear codes and transport models
- possibility to restart simulations consistently

EGAM ORB5, A Bottino, Varenna 2022, JCPS 2022

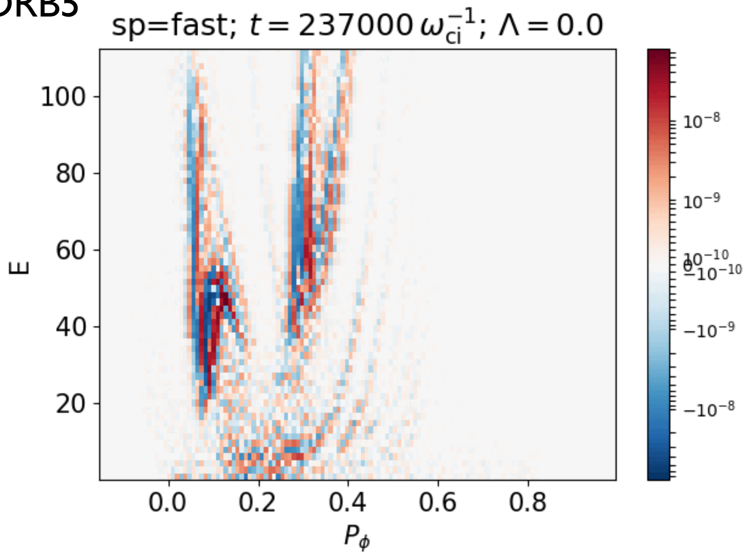




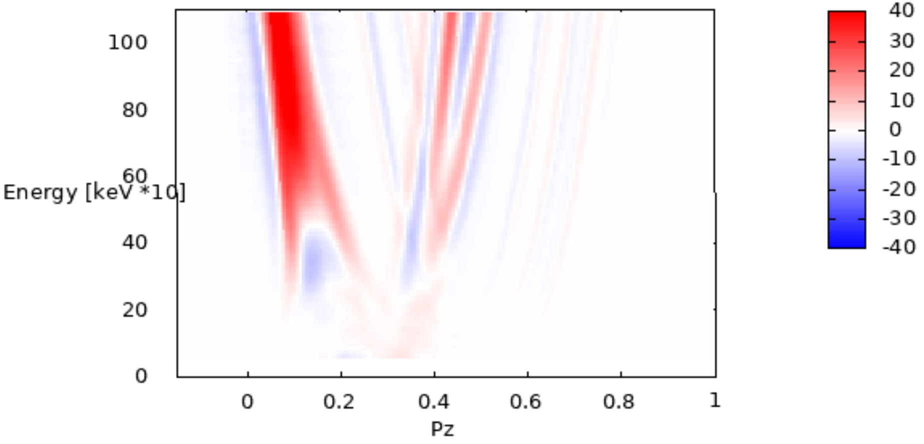
WP 3: comparison ORB5 - ATEP

- based on pioneering work in HMGC [S. Briguglio], PSZS diagnostic has been implemented in ORB5 [Bottino, JPC 2022]
- non-linear phase: ITER (101006) TAE n=18,19 with comparable amplitudes

ORB5



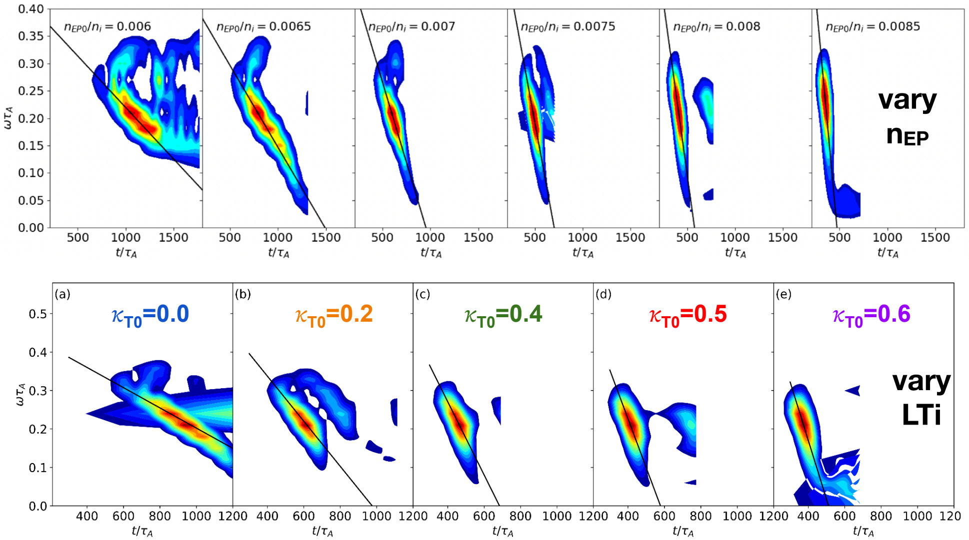
ATEP



remaining differences mostly understood (equilibrium, mode structure, SD vs hot Maxwellian)

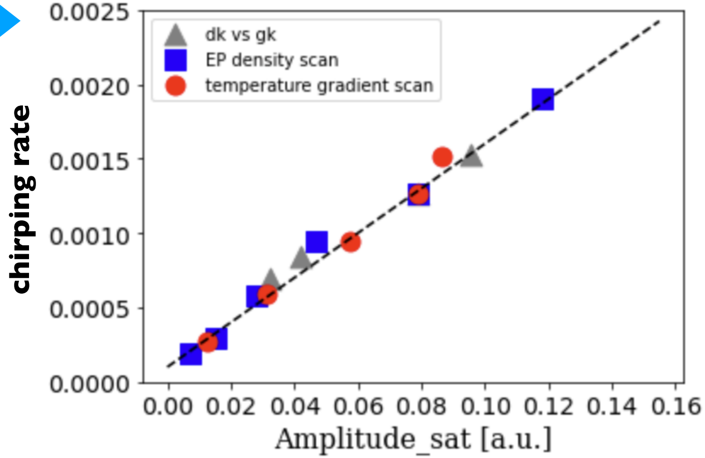
WP3: Connect non-linear GK simulations to theory

scaling of chirping rate obtained with comprehensive AE + ZF studies + turbulence (ORB5)



from analytical theory:

$$(\Delta\omega/\Delta t)_{sat} \sim (\omega_{res}') \ A_{sat}$$



non-adiabatic evolution: $\dot{\omega} \sim \omega_B^2 \sim A$

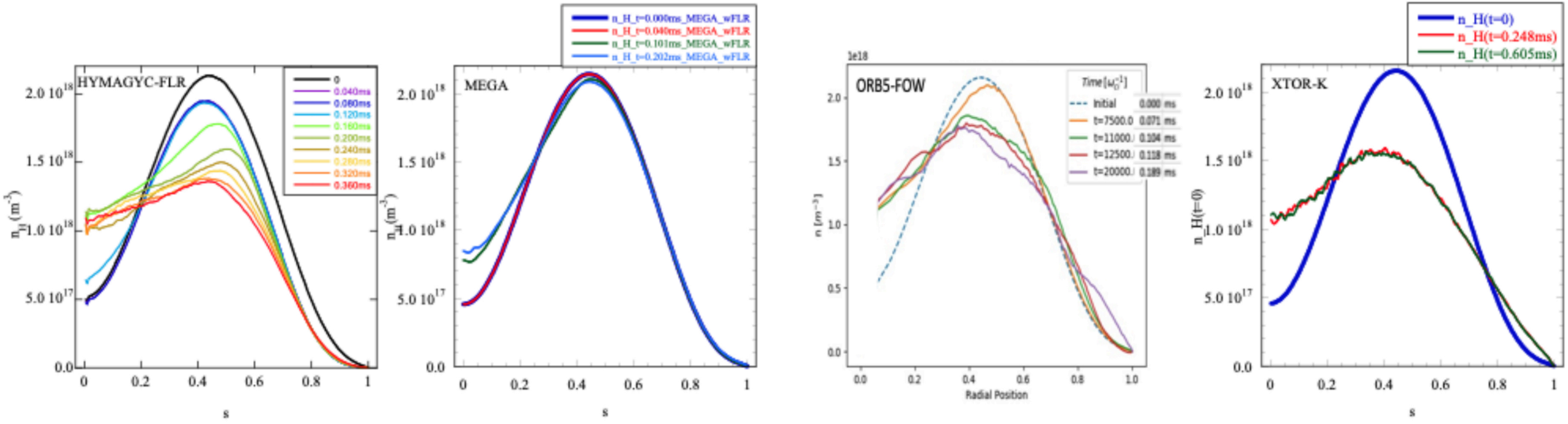
phase locking [Zonca et al NJP 2015]

[X. Wang EPS invited talk 2023, PPCF 2023]

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

- in TSVV10: non-linear benchmark for NLED AUG case has been carried out [G.Vlad, IAEA FEC 2023] - important benchmark for ATEP code suite

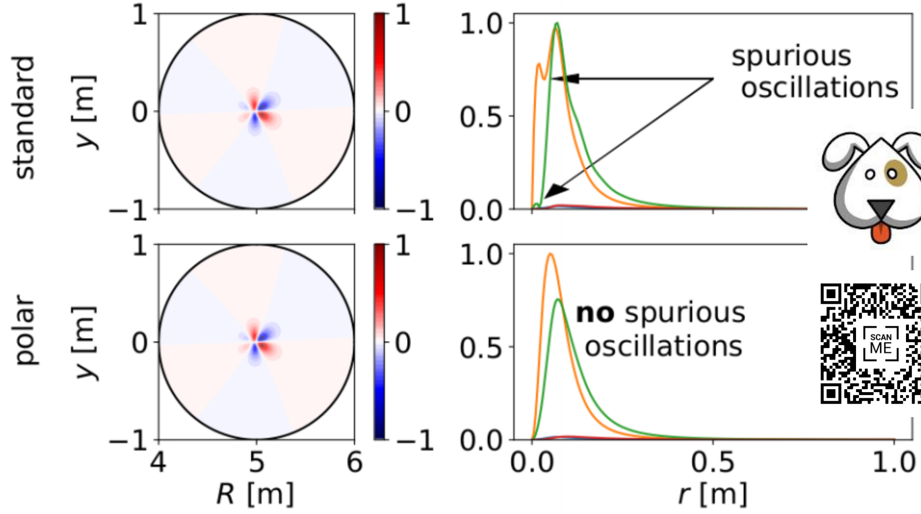
- note large instability-induced EP transport, deviating substantially from neoclassical values



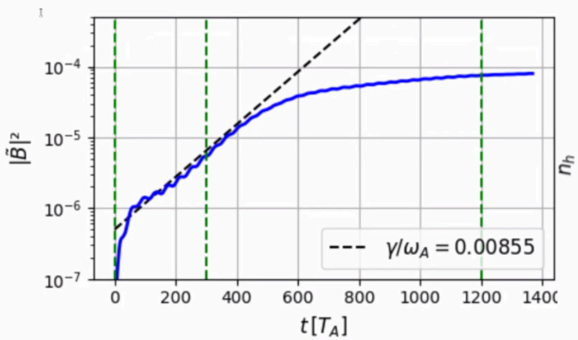
WP3: MHD-kinetic hybrid models deliver benchmarks for reduced models

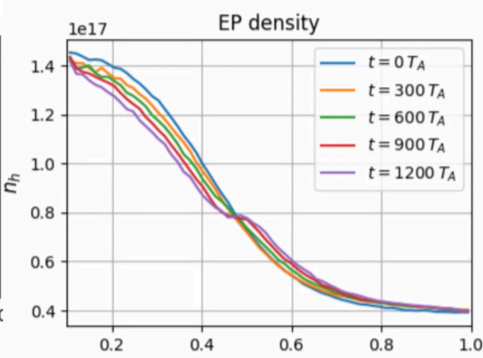
STRUPHY: [S. Possanner et al]

- follows stringent mathematical formulation: geometric finite elements + PIC ⇒ **improved non-linear stability**
- trustworthy long-time simulations
- modular python package, contains a collection of mappings, equilibria, initial conditions, dispersion relations
- open source
- several successful benchmarks (ITPA TAE)
- 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
- addition of canonical Maxwellians (no need for initial relaxation)
- addition of Fourier and binomial filters (noise reduction)
- simulation of TAEs (using filters) into the nonlinear regime



F. Holderied, PhD thesis 2022, JCP 2021 & 2022





WP1:

theoretical framework

WP 2:

Implementation and advancing various building blocks according to WP1

PSZS

WP3:

Application, verification and validation of reduced EP transport models

WP4:

Preparation and analysis of time-dependent reference cases: experiment, predictions for future machines

WP 4: connecting to the experiments

presently the following scenarios are available on ITER/Gateway (IMAS) and have been investigated with the EP stability WF:

AUG*
TCV* [M. Vallar, NF 2023, ID 33003]
JT-60SA
DTT
ITER*: 15MA (various), waiting for re-baselining
JET*: 99896 (ongoing, 3 EP species)
DEMO

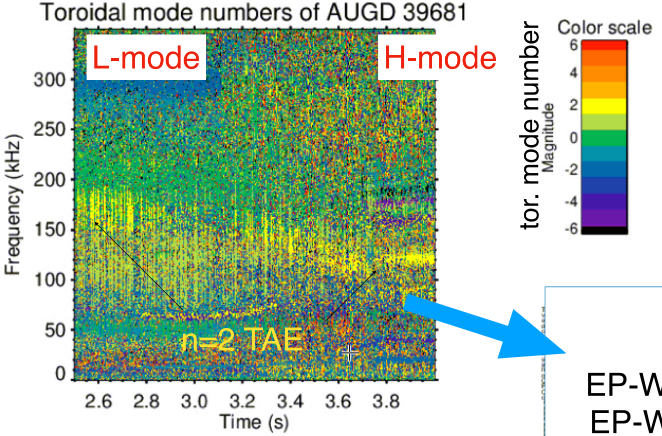
*time dependent [JET thanks to J. Ferreira]

further needs:

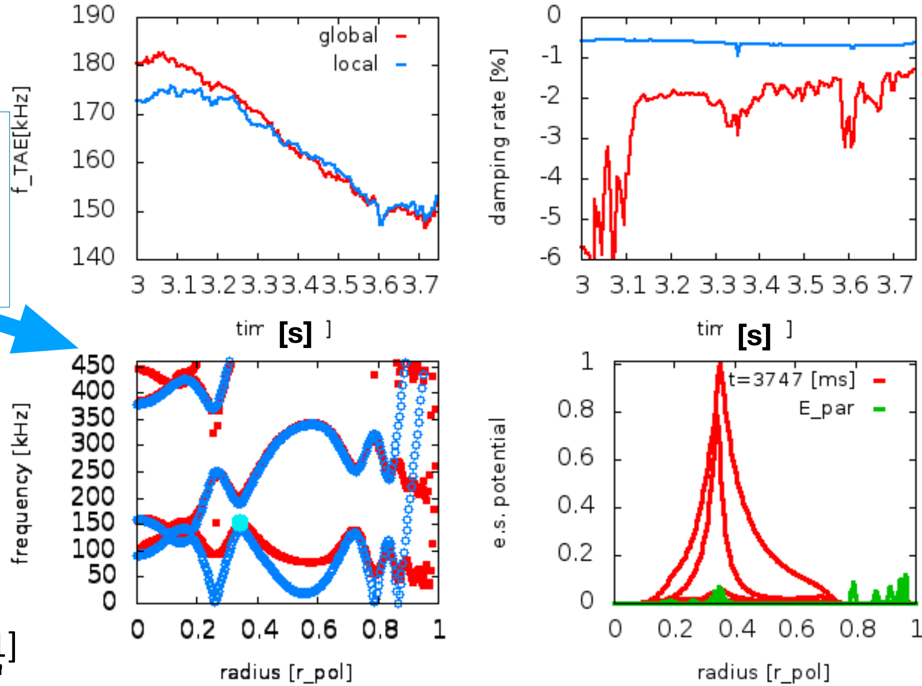
- location for publicly available IMAS database validated by WPTE for sharing on gateway with standard for 'mandatory fields' in IDS
- IMAS input from heating codes - EPCoM development at ITER [Brochard]

WP 4: AUG reference case: L-H transition in presence of TAEs

AUG EP 'supershot' scenarios: D NBI into D plasmas, D -> H and H-> H



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

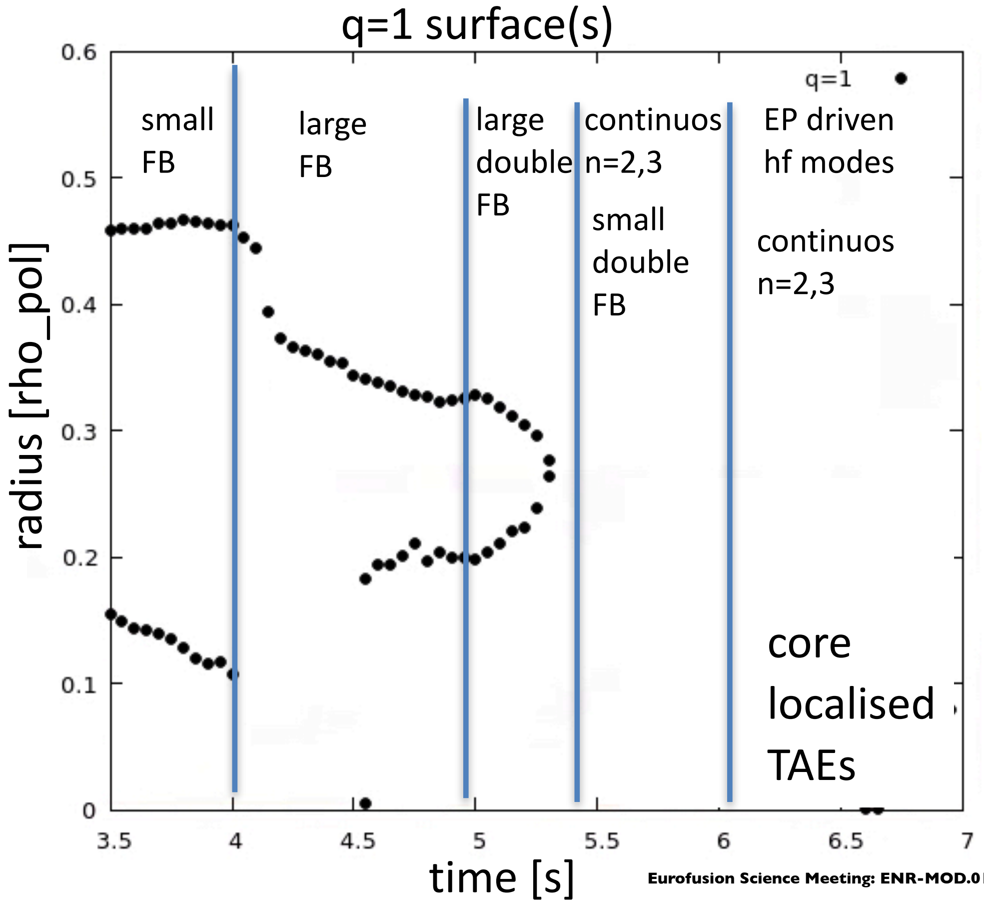


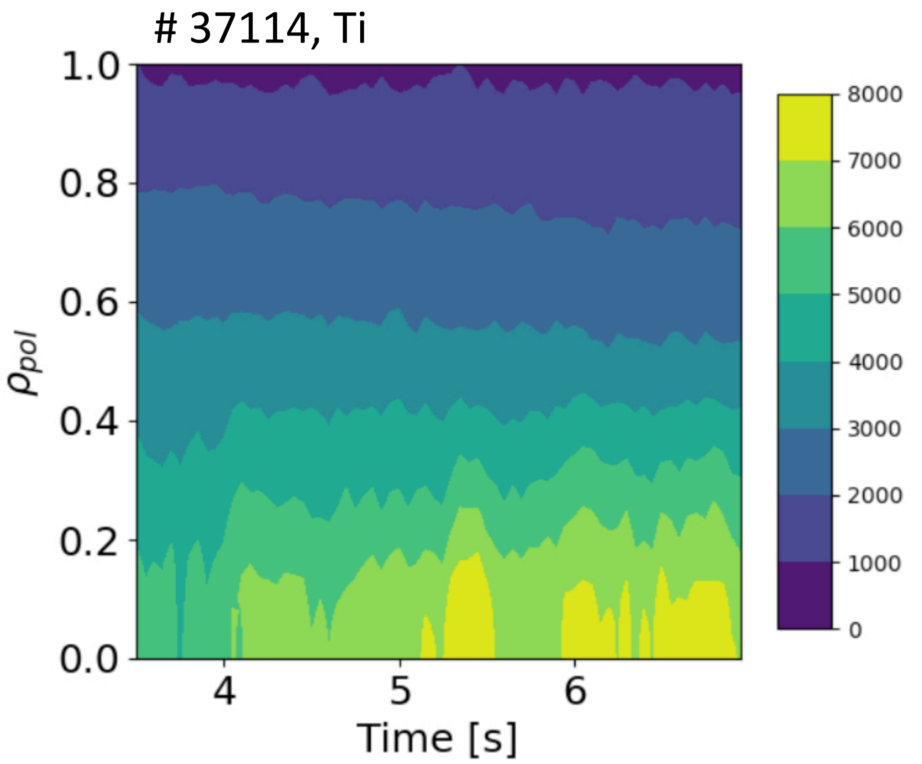
- analyse L-mode,H-mode and transition phase using
- systematic uncertainty quantification feasible
- bursty and steady-state phases visible, in agreement with damping analysis and drive - EP transport?
- speed up WF using ML methods [V.-A. Popa]

[Lauber, EPS 2022,ID 31591]

WP 4: AUG advanced scenarios

interplay of low frequency mode activity, core localised TAEs, shear reversal and T_i peaking



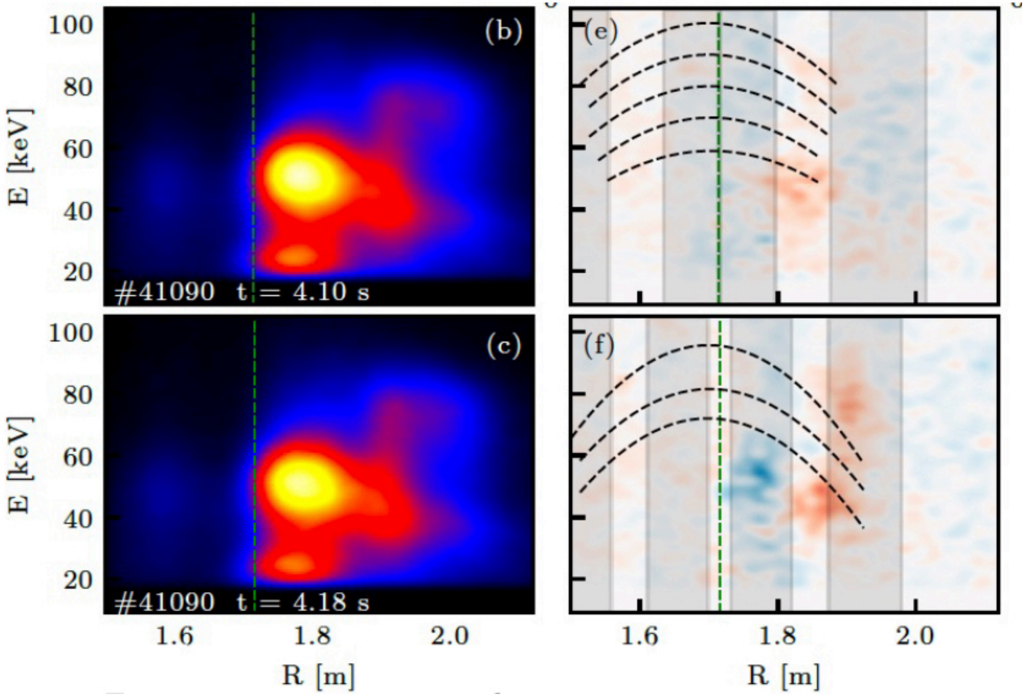


started to include fishbones in EP-WF and ATEP

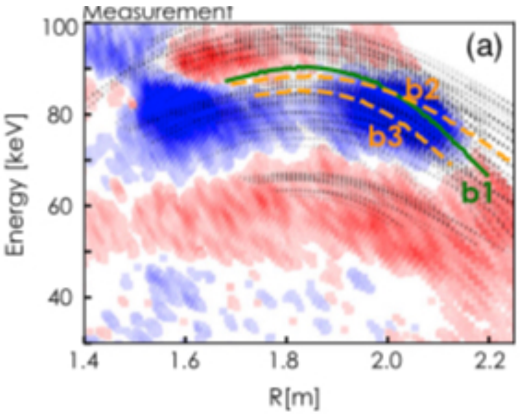
WP4: Experimental reference cases

- PSZS and phase space flows can be measured!
- application of EP-Stability WF for interpretation of AUG INPA (Imaging neutral particle analyser) data

J. Rueda Rueda [FEC, NF 2023/24]



DIII-D, INPA [Du et al PRL 2021]

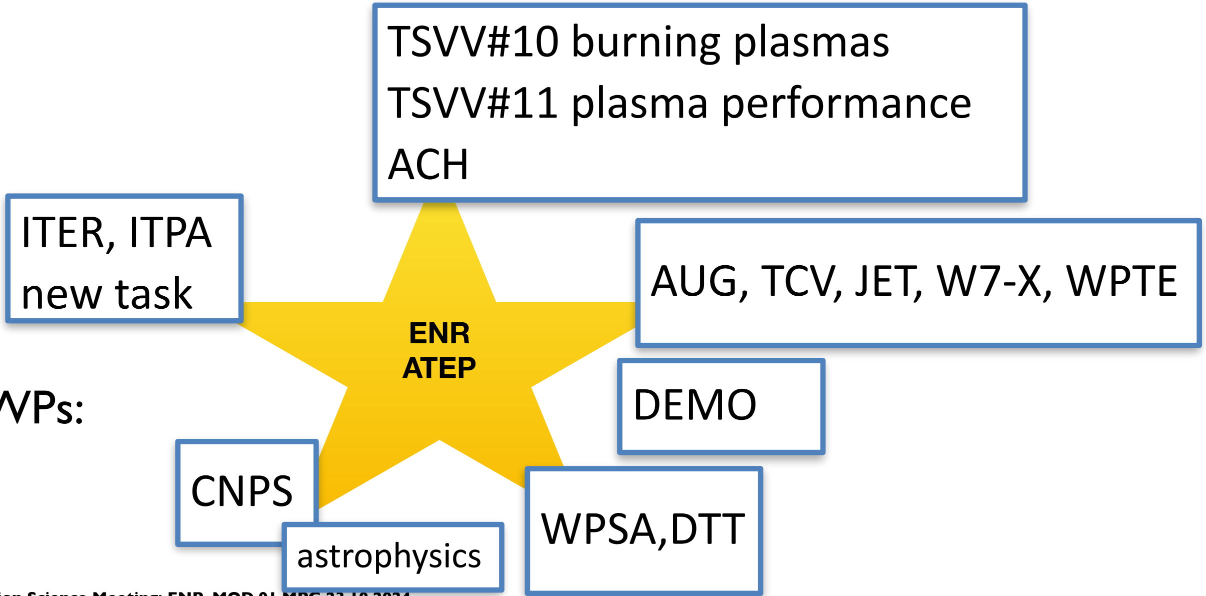


summary, outlook, dissemination of results

ATEP enabled 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
- new analysis methods
- new IMAS based infrastructure

established connections to other WPs:



impact on other Eurofusion WPs, outreach, further plans

impact:
- close collaboration with TSVV#10 on various levels of physics and simulation
- emerging collaboration with TSVV#11 - challenging but vital route for predictive reduced models
- EP-Stability WF ready to use in WPTE (example TCV)
- coupling of ATEP/DAEPS/1d models to transport codes needs to be done

support and infrastructure:
- training course has been offered on EP- Stability WF (material + videos)
- easy access via ITER/Gateway to (FALCON/PEANUT, EP-WF)
- open source STRUPHY
- significant overhead to move all tools to new AL, IMAS versions, clusters (libraries)
- ACH help for assessing PAF possibilities

further needs and recommendations:
- need for ENR type work: basic theory is main driver! developing models, try new approaches both conceptually and numerically, especially for coupling to turbulent transport models
- dedicated effort needed to couple, to expand and to speed up building blocks for the use in transport solvers
- dedicated experiments: PSZS/INPA measurements in discharges with various EP transport regimes/ fusion mock-up experiments/control of EP transport via DEMO relevant actuators (fuelling/impurities)

backup

Milestones1

1 WP1-M1 2D and 3D formulation of Phase Space Zonal Structures transport equations, and definition of Zonal State with corresponding equations for Zonal Field Structures governing equations with separated dependences from nonlinear radial envelope and parallel mode structures,   end 2021

2 WP1-M2 study of EPM dynamics in the presence of linearized collision integral and source terms, end 2022

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

4 WP2.1-M2 Computation of nonlinear coupling coefficients in the nonlinear envelope equation and of EP fluxes in phase space,   end 2022

5 WP2.1-M3 Benchmark of DAEPS in general stellarator geometry (jointly with WP2.3), end 2023

6 WP2.2-M1 Develop (semi-)analytical trapped particle model for LIGKA, mid 2022

7 WP2.2-M2 Test and tune analytical global mode structure model for LIGKA/HAGIS, end 2022

fully
partly
not started

Milestones 2

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

9 WP2.3-M1 Derive equations for local LIGKA-like version in 3D Mid 2023

10 WP2.3-M2 Local eigenvalue code in 3D (LIGKA) including passing particles

11 WP3.1-M1 Implementation of the 1D “mapping” in general geometry End 2021

12 WP3.1-M2 Interface of the 1D “mapping” in the ITER/IMAS workflow; Investigation of the influence of turbulence on the 1D "mapping"

13 WP3.2-M1 Probability density function of the radial displacements of tracer particles deduced from EP transport models Mid 2022

14 WP3.2-M2 The hypothesis of super-diffusive spreading of tracer particles on Lévy flights tested in simulations, hybrid flight- convective model complete mid 2023

fully
partly
not started

Milestones 3

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

16 WP3.3-M2 Explore methodology and possibly implement RABBIT as EP source into HAGIS End 2023 (replaced by collisional ATEP 3D)

17 WP3.3-M3 Finish reduced EP transport workflow based in LIGKA/HAGIS within IMAS mid 2024

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

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

fully
partly
not started

Milestones 4

20 WP3.5-M1 Flux calculations for frequency-chirping modes, compared to fixed frequency modes; add magnetic axis to STRUPHY End 2021

21 WP3.5-M2 Implementation of generic EP distributions into XHMGC, HYMAGYC and MEGA; add drift-kinetic model to STRUPHY; couple to GVEC 3D equilibrium solver for application to tokamaks and stellarators

22 WP3.6-M1 Calculate zonal structures in the presence of turbulence with ORB5 for validation of the reduced models End 2021

23 WP3.6-M2 Calculate particle and heat transport in the presence of turbulence with ORB5 for validation of the reduced models End 2022

fully
partly
not started

24 WP4-M1 Plan and conduct AUG experiments in the view of clear and well-diagnosed transitions between EP transport regimes End 2021/22