project time line; changes/update concerning ATEP team

- project start: 1.6.2021, kick-off meeting 9.6.2021; some milestones/deliverables have been shifted to 2022 due to late start; half of the resources for 2021 were shifted to 2024 (see TA)

- 8/2021: A. Biancalani moved from IPP to Universitaire Leonard de Vinci, Paris; 2021: MPG; from 2022 CEA/ESILV (planned)

- Guo Meng - parental leave from Aug 2021-fall 2022 - replaced by T. Hayward-Schneider (MPG)

- fall 2021: Y. Li has been hired: PostDoc contract by CREATE: 3pm foreseen in 2021 are secured and work on WP1&2 is in progress as expected

- Oct 19th: 2nd general ATEP progress meeting, various rehearsals for AAPPS-DPP, IAEA TCM EPPI, Fusion Data Processing, Validation and Analysis

- Nov-Dec 2021, preparation of annual report, update wiki with all papers and presentations

ATEP wiki and meetings:
https://wiki.euro-fusion.org/wiki/Project_No10
https://indico.euro-fusion.org/category/309/

scope

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

effort with large analytical/semi-analytical component

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

Milestones

No	Title	Description	Expected date
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

Deliverables

Year	Title	Description
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
End 2023	WP1-D3	Self-consistent description of EPM repeated burst dynamics using the PSZS theoretical framework

papers:

2 manuscripts on Chorus: simple paradigmatic application of general PSZS theoretical framework **WP1-D1**

- A theoretical framework of chorus wave excitation (FZ, XT, LC); RMPP to be published ID 29812
- Nonlinear dynamics of phase space transport by chorus emission (FZ, XT, LC); JGR submitted ID 30076

2 manuscripts in preparation:

- Nonlinear equilibria and transport processes in burning plasmas (MF, LC, ZQ, FZ); NJP to be submitted
- Section for NF Chapter 5 update (MF, LC, ZQ, FZ); NF to be submitted

Draft in preparation (A. Zocco et al.): 3D generalization of PSZS theoretical framework **WP1-D1/WP2.3**

presentations:

2 invited presentations: general PSZS theoretical framework **WP1-D1**

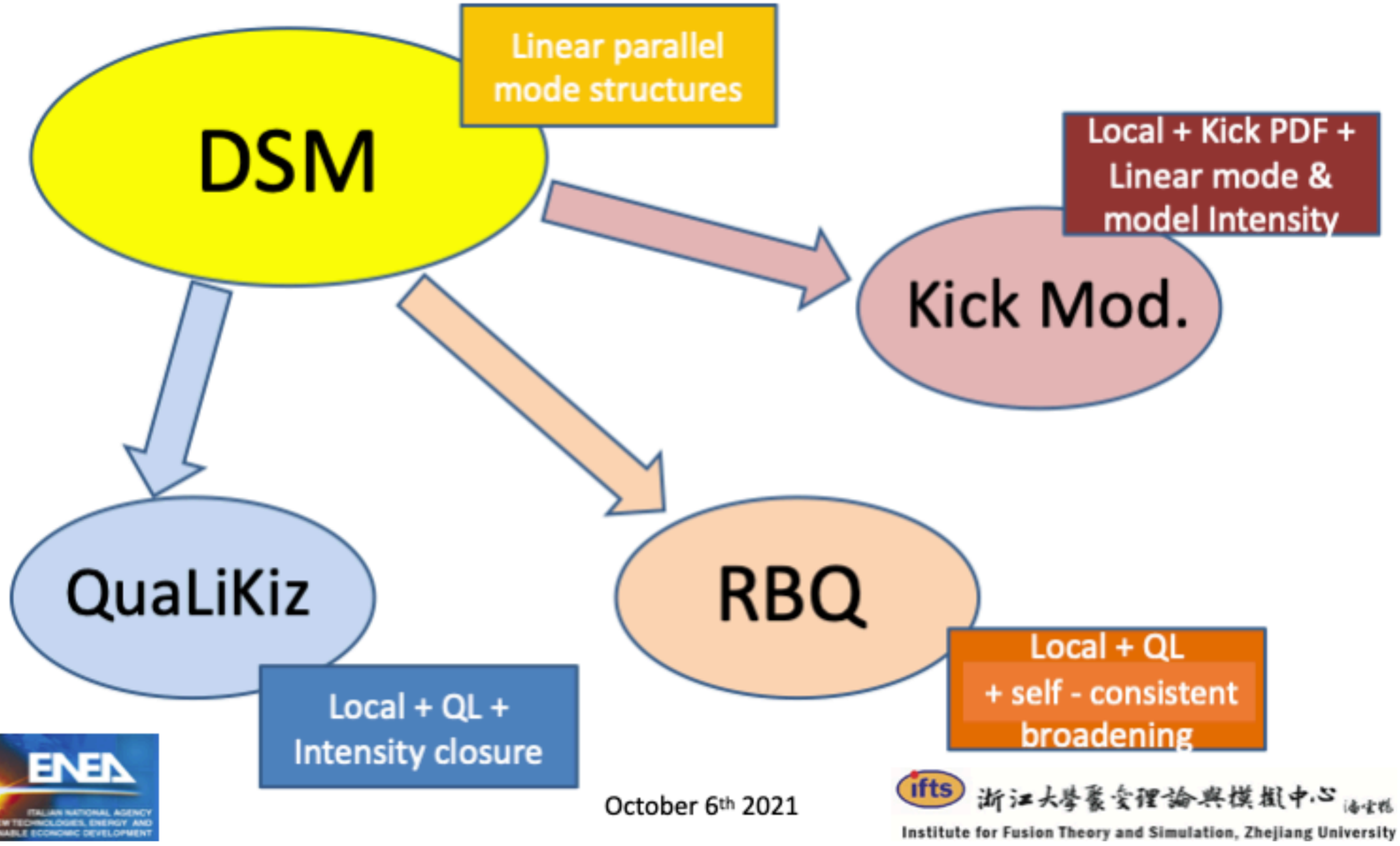
- Numerical study of kinetic low frequency electromagnetic continuous spectrum with DAEPS code (YL, LC, RM, FZ); AAPPS invited (explaining recent DIIID results; consistent with LIGKA see Philipp's presentation) **WP2.1**
- Nonlinear gyrokinetic theory of Alfvénic fluctuations and energetic particle transport (FZ, LC, MF, ZQ); ISEP invited

Joint CNPS-DTT seminar:

- Canonical particle motion in quasisymmetric toroidal magnetic fusion devices: applications to turbulent transport. A. Zocco (connection with draft in preparation on 3D extension of PSZS transport theory) **WP2.3**

Dyson Schrödinger Model IV

Recovering QL limit: … for a broad spectrum



October 6th 2021

Institute for Fusion Theory and Simulation, Zhejiang University

- 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

WP1:

theoretical framework

WP 2:

Advancing various building blocks according to WP1

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Implementation, application and verification of reduced EP transport models

WP4:

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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

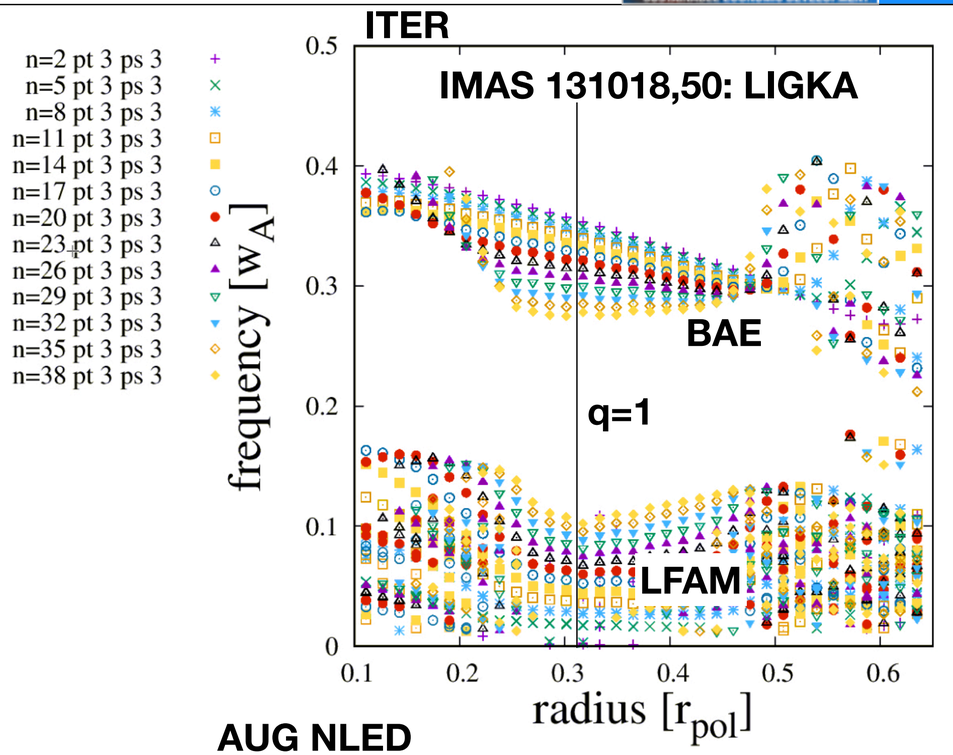
due to administration/travel restrictions **to be absorbed in early 2022**

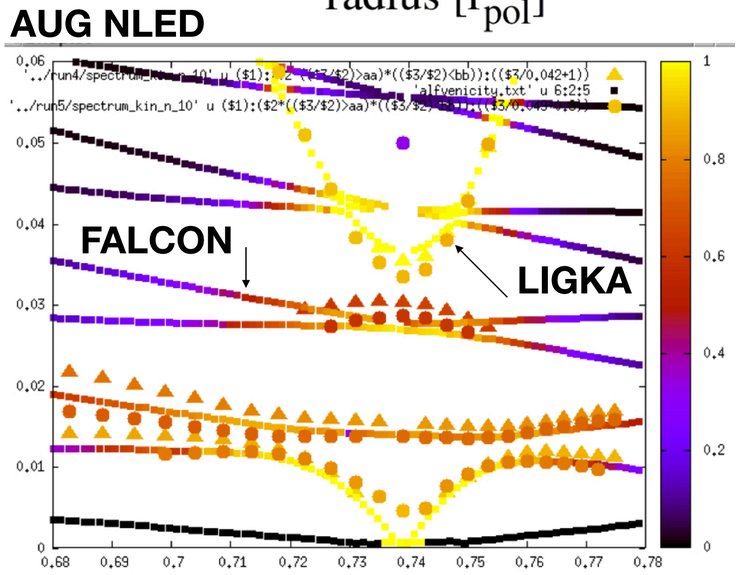
WP2.1-M1 (2022)

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**





WP 2.2 analytical extension of LIGKA

started

identified/analysed good test case for isolating trapped particle contribution; do far fully kinetic analysis performed (JET n=5 case, based on M. Fitzgerald 2021)

presentations/paper

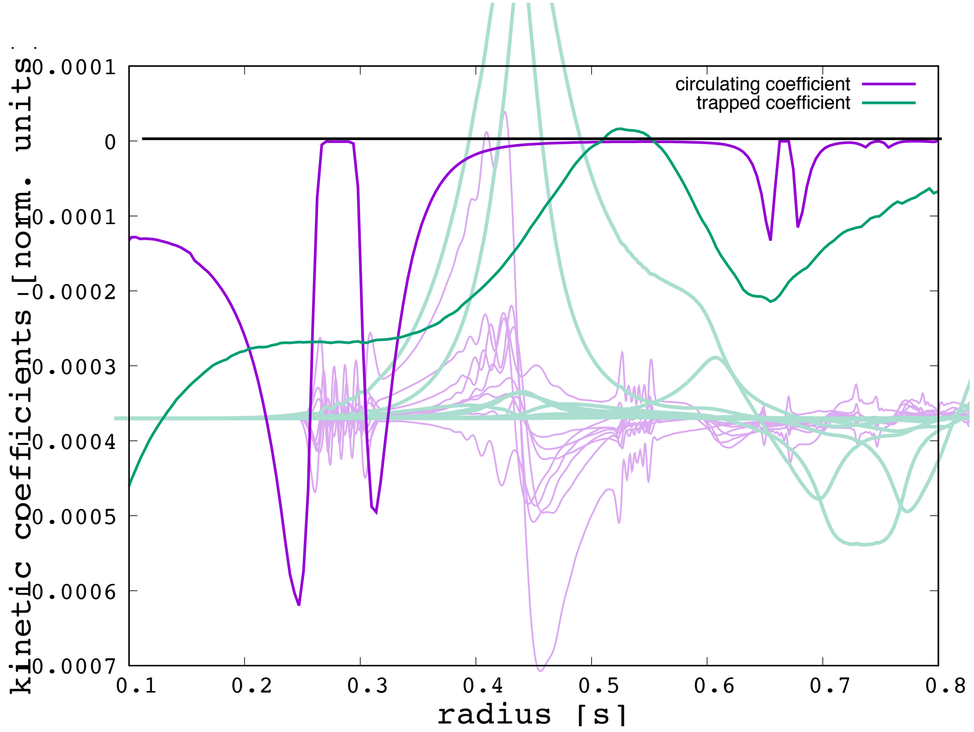
Ph. Lauber: plenary topical talk AAPPS-DPP 2021 (ID 30323)

Ph. Lauber: presentation at JET TF meeting, 5.10.2021

Ph. Lauber: invited presentation at ISEP meeting, 17.11.2021

Ph. Lauber: chapter 7/8 NF EP chapter update (ITPA group)

Im[circ. el response coefficient]
Im[trapped el response coefficient]



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

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

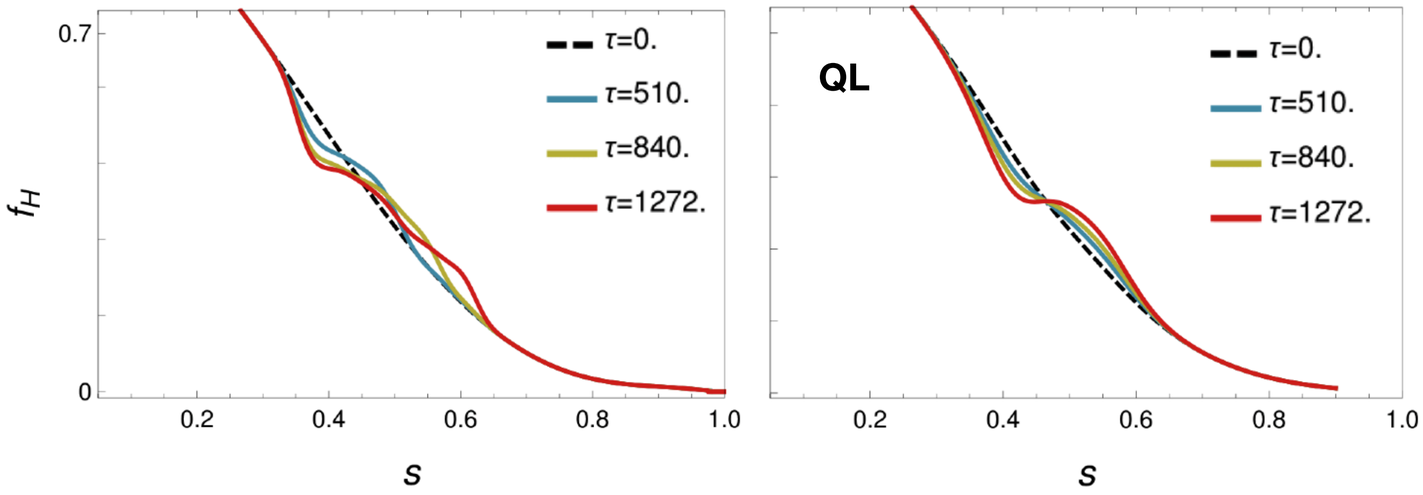
WP3.1-M1 Implementation of the 1D "mapping" in general geometry : fully achieved

N. Carlevaro, F. Cianfrani, G. Montani, F. Zonca, "*Hierarchical approach for energetic particle transport in 1-dimensional uniform plasmas*", in **47th EPS** Conference on Plasma Physics 2021, Vol. 45A, P3.1067 ID : 28666

N. Carlevaro, G. Meng, G. Montani, F. Zonca, T. Hayward-Schneider, Ph. Lauber, Z. Lu, X. Wang, "*One dimensional reduced model for ITER relevant energetic particle transport*", **Plasma Phys. Control. Fusion,** in press (2021) ID : 30899

- **1D Reduced Model**: mapping procedure between EP radial redistribution in tokamaks and velocity space of the bump-on-tail paradigm
- Reduced computational effort + capability to capture/predict phenomena beyond QL theory
- Analysis and prediction of avalanches (non-diffusive transport) triggered by EP

ITER 15MA baseline Scenario

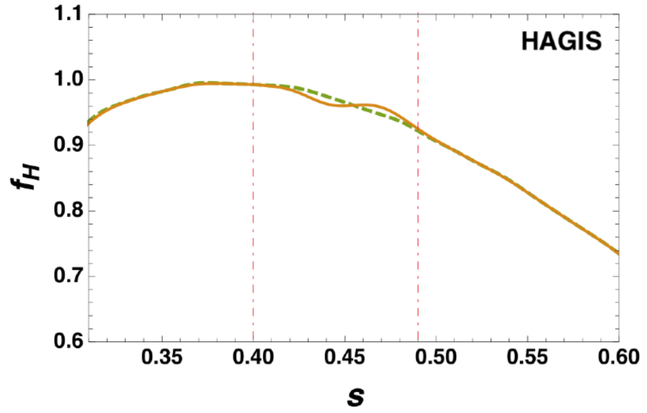


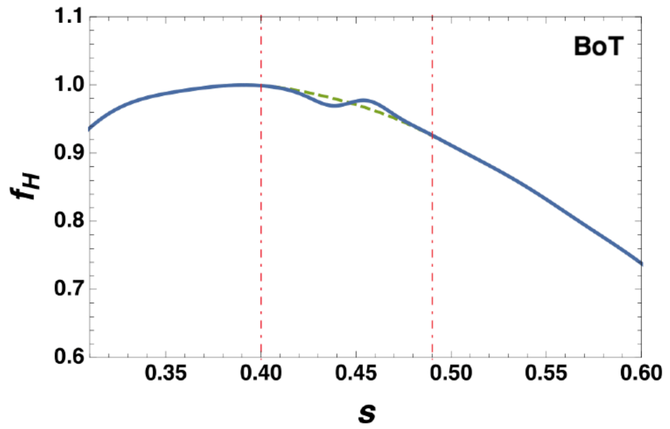
WP3.1 and 3.2

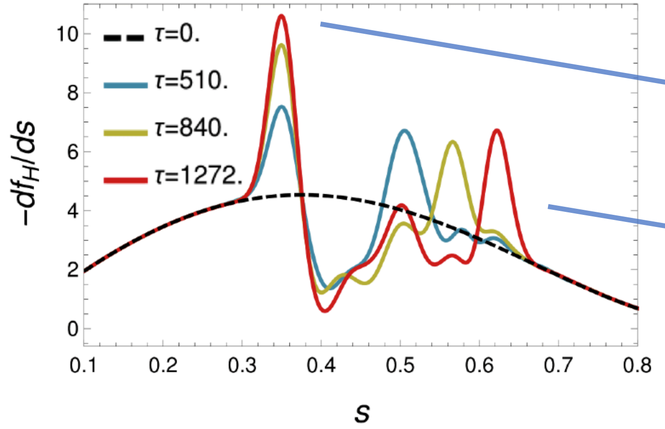
Extension of the mapping procedure in view of a more quantitative prediction of the EP redistribution

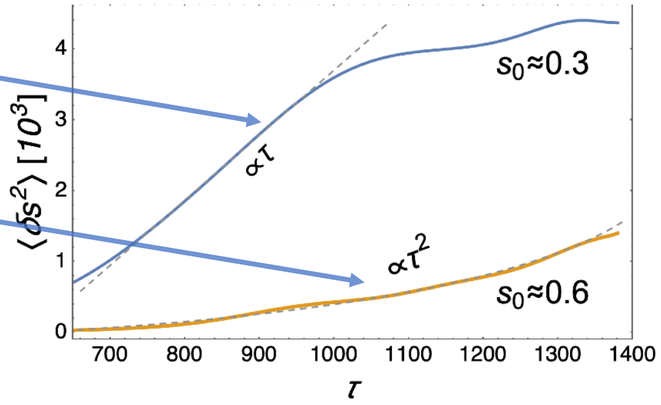
- Partition of phase space into regions of constant μ (magnetic momentum) and $C=\omega P_\varphi - nE$
- Decompose plasma into different slices and estimate the corresponding weight related to the global/reduced wave-particle power exchange: evolution of **the most resonant slice** (maximization of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

Analysis of mean square path of test particles: **characterization of diffusive vs. convective transport**. Second peak profile not modelled by the QL treatment: avalanches



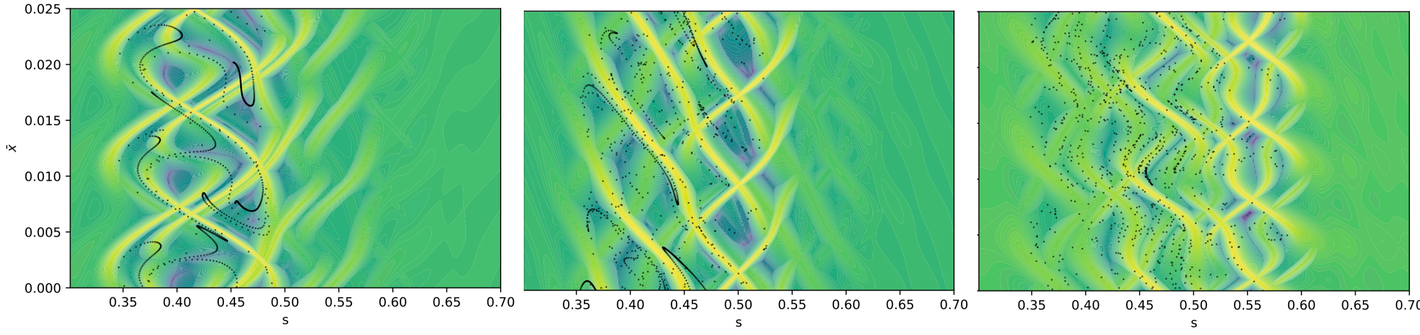






WP3.2:

- 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
- investigate convective EP transport analytically (applicability of Klein-Kramers equations possible?)
- next goal: probability density functions for radial displacements of tracer particles as dictated by the various EP transport models

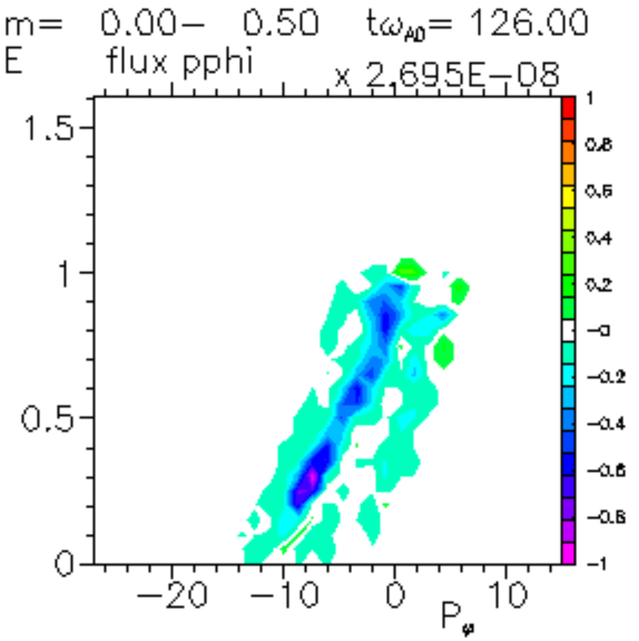


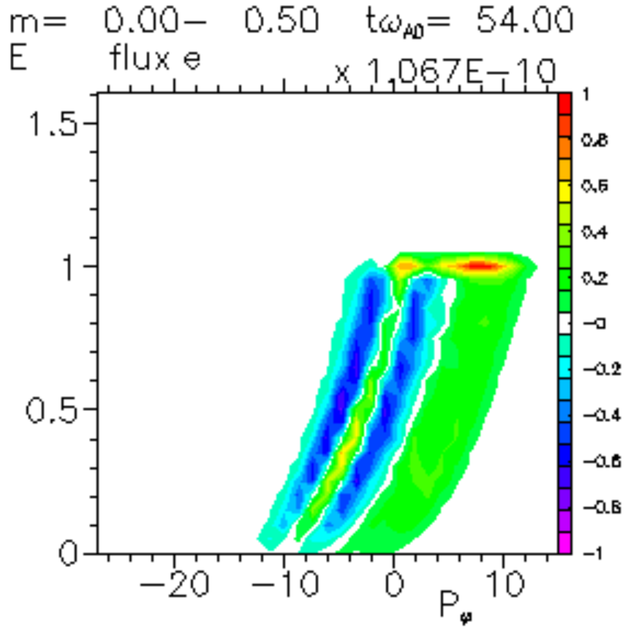
WP3.5 Hybrid kinetic MHD codes for verification and validation

- Diagnostics for zonal averages leading to the explicit extraction of phase space fluxes have been already applied to different cases comprising different type of EP-driven modes. An example with fluxes calculation for a chirping EPM mode are shown in the figure. Recipe was extensively discussed and is presently ported to various other codes: ORB5, HAGIS,…

- Linear AUG NLED Benchmark has been successfully performed among HYMAGYC, MEGA and Orb5. Currently nonlinear benchmark activities are in progress. Ready for 'transition' studies - see below (WP4)
- Realistic EP distribution given by TRANSP is used for full-f simulation of AUG NLED case in MEGA. Meanwhile, progress in using HYMAGYC with IMAS-IDSs and Kepler with batch execution has been achieved. Ready for 'transition' studies - see below (WP4)

- Extension of finite element exterior calculus framework (used in STRUPHY) to polar domains using so-called polar splines around the magnetic axis.
- Application to MHD eigenvalue problem yields eigenfunctions which are continuously differentiable across the axis





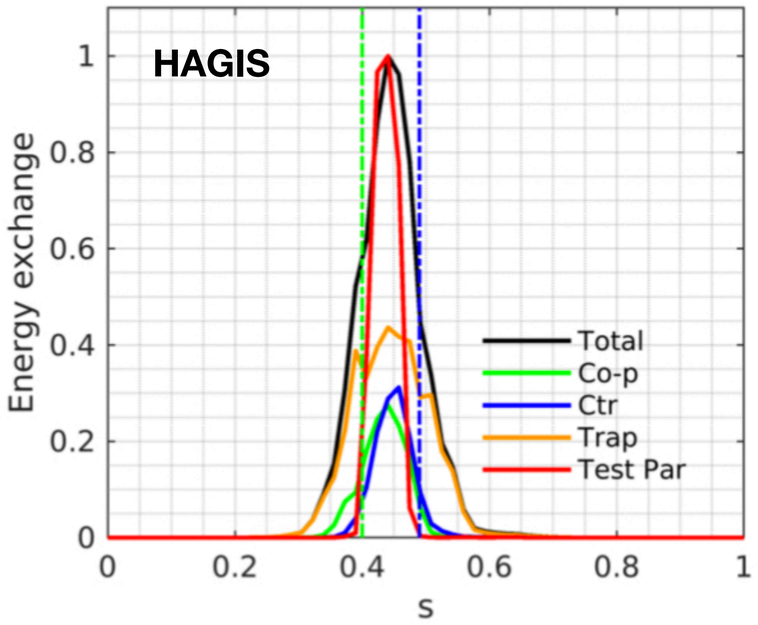
[1] G. Vlad, X. Wang, F. Vannini, S. Briguglio, N. Carlevaro, M. Falessi, G. Fogaccia, V. Fusco, F. Zonca, A. Biancalani, A. Bottino, T. Hayward-Schneider, and Ph. Lauber. A linear benchmark between HYMAGYC, MEGA and ORB5 codes using the NLED-AUG test case to study Alfvénic modes driven by energetic particles. Nuclear Fusion, 61:116026, 2021. ID : 29680
[2] X. Wang, S. Briguglio, C. Di Troia, M. Falessi, G. Fogaccia, V. Fusco, G. Vlad and F. Zonca, " Analysis of the nonlinear dynamics of a chirping-frequency Alfvén mode in a Tokamak equilibrium", Ready for submission. ID : 30841
[3] F. Holderied and S. Possanner, "Magneto-hydrodynamic eigenvalue solver based on smooth polar splines", submitted to Journal of Computational Physics ID : 30814
[4] X. Wang, S. Briguglio, " Nonlinear dynamics of frequency chirping energetic particle driven modes in fusion plasmas", invited, 5th Asia-Pacific Conference on Plasma Physics (AAPPS-DPP2021) Sep. 26 - Oct. 1 as e-Conference. ID : 30204

WP 3.3 Extend HAGIS/LIGKA framework to calculate EP fluxes

HAGIS: detailed energy exchange diagnostics for all species implemented (non-IMAS version finished) - will be straightforwardly extended to calculate radial fluxes
(G. Meng in [Carelvaro, PPCF in press 2021 ID : 30899] and G. Meng et al: Mode structure symmetry breaking of reversed shear Alfvén eigenmodes and its impact on the generation of parallel velocity asymmetries in energetic particle distribution, PST accepted 2021; ID 30199)

calculation of PSZS in preparation - before finish IMAS based orbit data base as described in:
[A. Bierwage, Ph. Lauber et al: "Representation and modeling of charged particle distributions in tokamaks" submitted 2021, ID:30554]

[Carlevaro, PPCF in press 2021]



WP 3.4 Fast ion transport model for RABBIT

RABBIT framework provides source and collision terms needed for reduced transport models

difficulty of coordinate mapping (canonical coordinates - (E-$v_{//}$/v)) and mapping to orbit database (see above) to be further investigated

simple diffusion model should be straightforward to implement (milestone in 2022);

build on experience coupling ORB5 and Rabbit (TSVV#10) [T. Hayward- Schneider, B. Rettino, A. Bottino]

WP 3.6 Fully gyrokinetic simulations for verification and validation: ORB5

- calculation of PSZS started - input from WP 3.5 (shared recipe by S. Briguglio)
- previously, the role of ZSs by means of first-principles gyrokinetic simulations, the mechanisms of the excitation of zonal flows by turbulence and by Alfven modes have been compared with ORB5 for the simplified configuration used in [Biancalani-JPP-2020] and[Biancalani-PPCF-2021] (high-aspect-ratio, low-beta).
- for the same configuration, the zonal current has also been evaluated, and consequently the nonlinear modification of the equilibrium safety factor profile.

WP1:

theoretical framework

WP 2:

Advancing various building blocks according to WP1

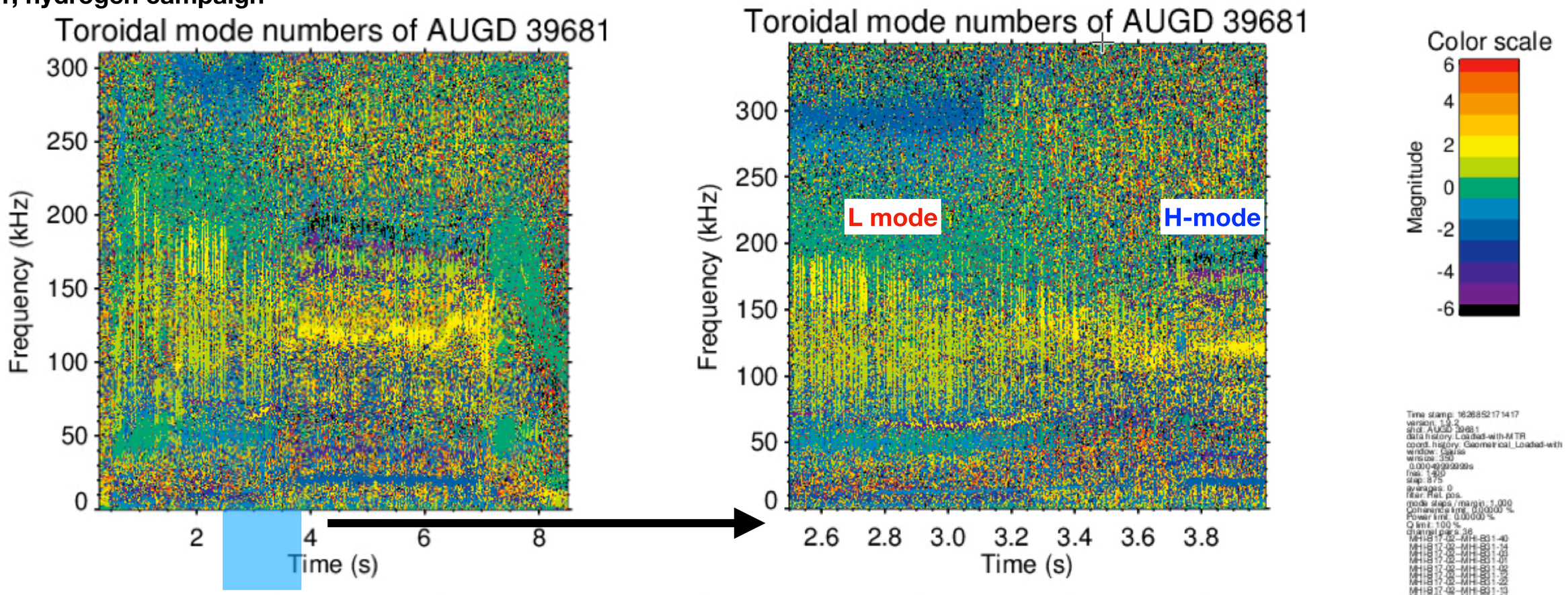
WP3:

Implementation, application and verification of reduced EP transport models

WP4:

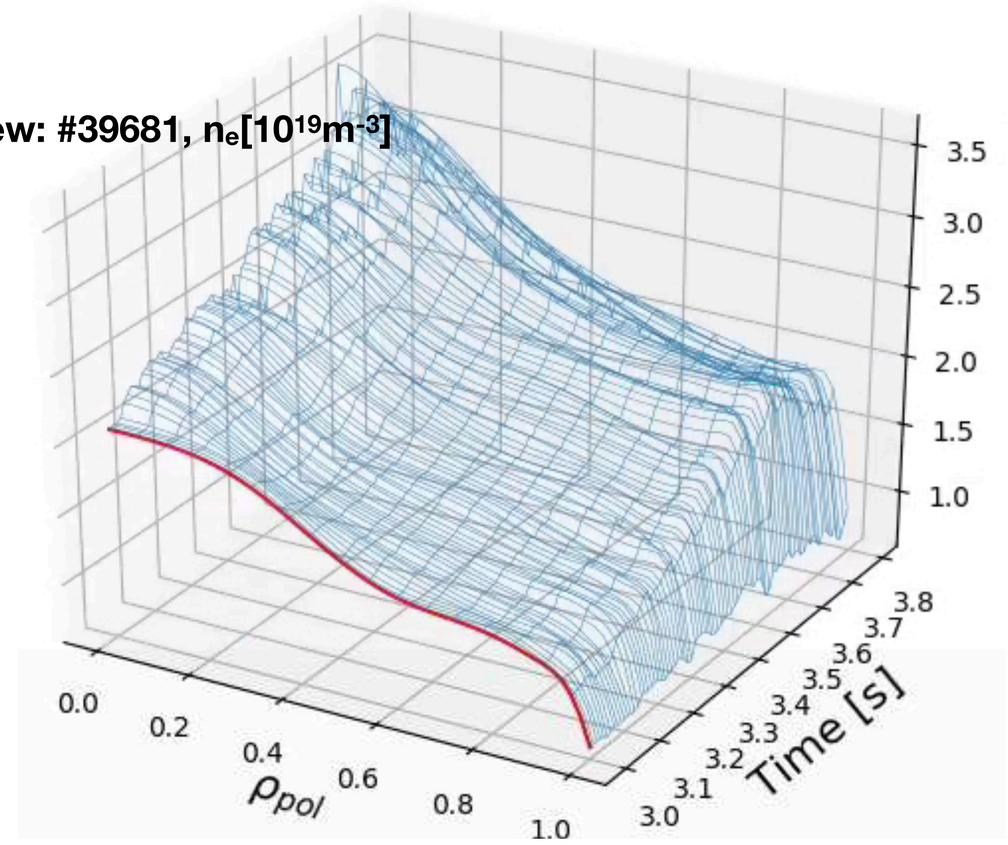
Preparation of time-dependent reference cases

July 2021, hydrogen campaign

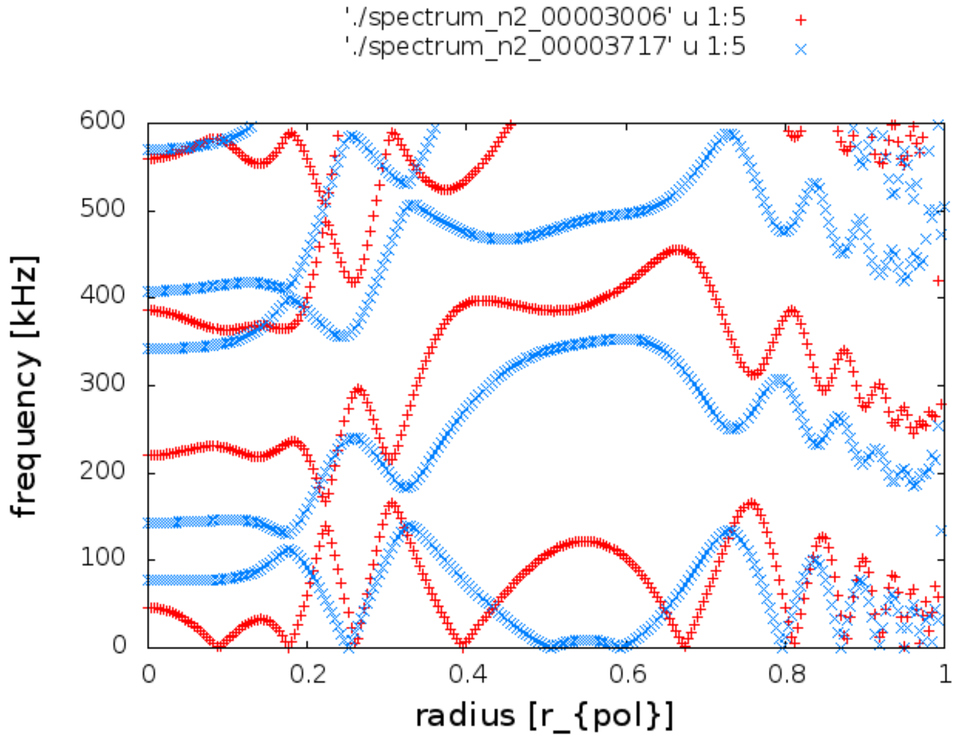


- slow L-H transition with constant heating power in the presence of strong EP activity (very rare on AUG)
- L-mode activity very similar to NLED base case (EGAM/BAE/TAE intermittent crashes, #31213) - but now in flat top phase with transport analysis possible!
- automated analysis on Gateway now working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

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)
- L-mode activity very similar to NLED base case (EGAM/BAE/TAE intermittent crashes, #31213) - but now in flat top phase - 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

summary

2021:

WP1-M1 fully
WP3.1-M1 fully
WP4-M1: fully

WP1-D1 fully
WP2.1-D1 partly, will be finished early 2022

2022:

many challenging milestones and deliverables ahead - but already considerable progress on various parts in 2021

Milestones

No	Title	Description	Expected date
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	End 2021
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
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 version in 3D	Mid 2022
10	WP2.3-M2	Local eigenvalue code in 3D (LIGKA) including passing particles	End 2023
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"	End 2022
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	Early 2023
15	WP3.3-M1	Extend unperturbed orbit integration routines and averaging procedures in order to calculate phase space fluxes in HAGIS	End 2021
16	WP3.3-M2	Explore methodology and possibly implement RABBIT as EP source into HAGIS	End 2022
17	WP3.3-M3	Finish reduced EP transport workflow based in LIGKA/HAGIS within IMAS	Mid 2023
18	WP3.4-M1	Develop and implement radial diffusion model to RABBIT	End 2022
19	WP3.4-M1	Apply extended RABBIT model to transient events, e.g. EP evolution during sawtooth cycles	End 2023
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, HYMAGYK and MEGA; add drift-kinetic model to STRUPHY; couple to GVEC 3D equilibrium solver for application to tokamaks and stellarators	End 2022
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
24	WP4-M1	Plan and conduct AUG experiments in the view of clear and well-diagnosed transitions between EP transport regimes	End 2021/22

Deliverables

Year	Title	Description
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
End 2023	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
End 2022	WP2.1-D2	Reduced EP transport model in tokamaks
End 2023	WP2.1-D3	DAEPS in general stellarator geometry
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
End 2023	WP2.3-D2	Local eigenvalue code in 3D (LIGKA) including passing particles
End 2022	WP3.1-D1	Validated 1D reduced model for EP transport in ITER/DTT
End 2023	WP3.1-D2	Systematic statistical analysis of test particle transport and assessment of diffusive vs. non diffusive behaviours - jointly with WP3.2
End 2022	WP3.2-D1	Insights into short- and long-time relaxation dynamics of a non-thermal plasma with intense energetic particle component
End 2023	WP3.2-D2	Practical basic understanding of convective radial transport of energetic particles versus the possible non-local transport regimes
End 2023	WP3.3-D1	Availability of validated reduced phase space transport model based on LIGKA/HAGIS/RABBIT within IMAS framework
End 2022	WP3.4-D1	Validated version of RABBIT including model for fluctuation-induced radial transport of EPs
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.
End 2023	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, HYMAGYK, MEGA and ORB5
End 2022/23	WP3.6-D1	Deliver quantitative criteria for transitions between different transport regimes w/o turbulence and ZF/ZSs in experimentally relevant regimes
End 2022	WP4-D1	Availability of reference scenarios (ITER, AUG, DTT) for application of transport models