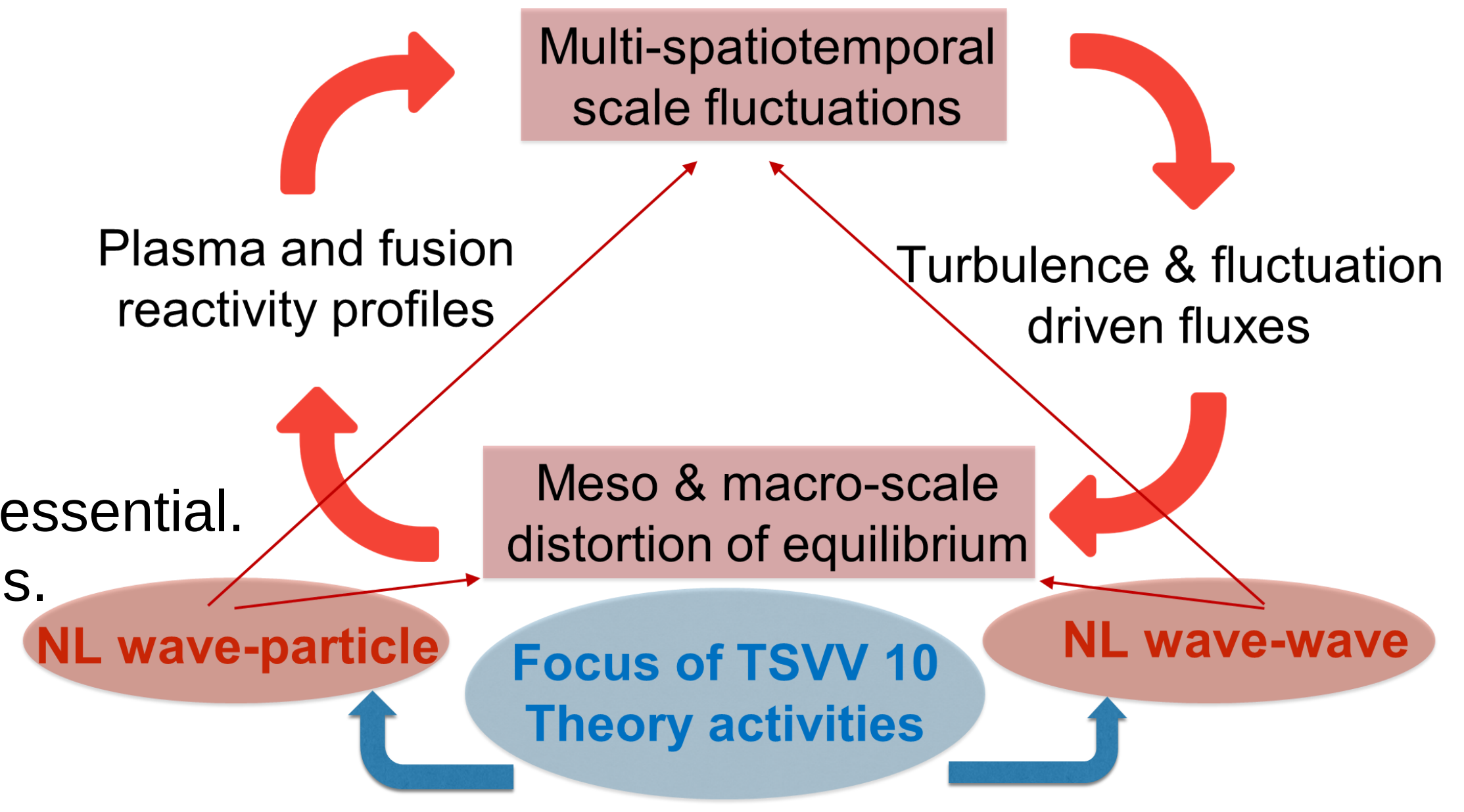
Towards burning plasmas: theory and simulations

A. Mishchenko for TSVV Task-10

- Plasma heating in Q = 10 ITER baseline scenario will be dominated by fusion-born α particles. DEMO will operate close to ignition, employing auxiliary power only for control purposes.
- Understanding of burning plasma physics is an urgent point to be addressed. Significant rate of α particle generation is inaccessible to present devices. Theory and modelling are of particular importance.
- Energetic particles in reactor-relevant plasmas have a unique and crucial role as mediators of cross-scale couplings making transport in fusion devices a nonlinear multi-spatiotemporal-scale process.
- Predictive analyses based on first principles computations is challenging. Developing a deep understanding (high-fidelity and reduced models) of the nonlinear self-organizing dynamics in burning plasmas is essential.
- Aim of the project: develop a self-consistent description and simulation tools for interaction of energetic particles with MHD modes, turbulence, and kinetic plasma profiles in tokamak and stellarator geometries.

Burning plasmas as complex self-organized systems:



Multi-spatiotemporal scale fluctuations

Plasma and fusion reactivity profiles

Turbulence & fluctuation driven fluxes

Meso & macro-scale distortion of equilibrium

NL wave-particle

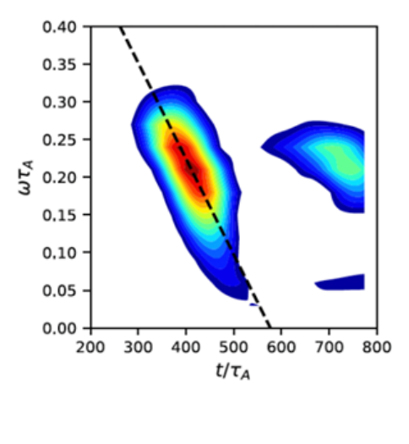
Focus of TSVV 10 Theory activities

NL wave-wave

Gyrokinetic simulations of chiriping instabilities: wave-particle nonlinearity *(ORB5)*

1. Theory compared to simulations (verification): chirping modes in presence of energetic particles.
Chirping rate from simulations is proportional to saturation amplitude (as predicted theoretically, [Zonca et al., Varenna Conf. 2024])
Plasma Phys. Control. Fusion **65** 074001

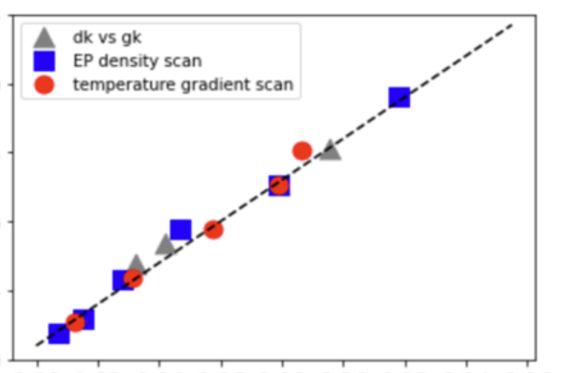
- Comprehensive studies on the nonlinear frequency chirping of energetic particle driven Alfvén modes with the fully gyrokinetic code **ORB5**.
- Aim to understand the likelihood of a mode to oscillate at a constant frequency or to evolve to nonlinear chirping oscillations, as well as its consequences on the type of energetic particle induced transport.



various parameter scans to map chirping rate vs saturation amplitude

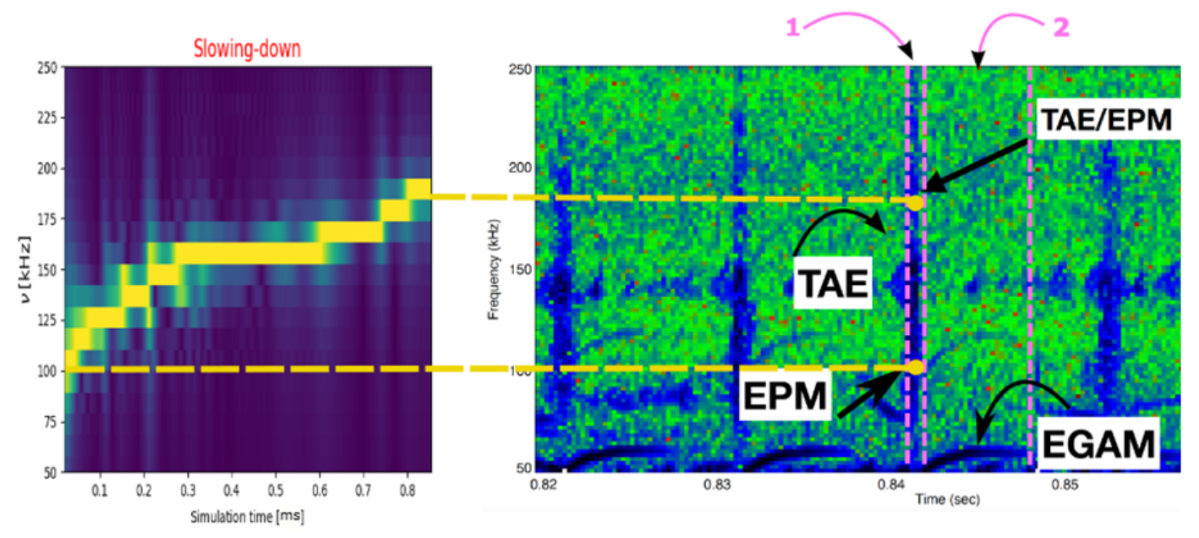
Energetic particle density, energy, …

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



2. Simulations compared to experiment (validation):
ASDEX Upgrade discharge #312213@0.84s
Same chirping range in simulations as in experiment
Nucl. Fusion **62** 126042

Time evolution of the mode



Requires a comprehensive theoretical framework for the self-consistent description of drift Alfvén wave excitation and phase space energetic particle transport in fusion plasmas [Chen&Zonca RMP16].

Nonlinear gyrokinetic formulation of fluctuation spectrum evolution and energetic particle transport.

JET #92416: TAE simulations, beat-driven zonal flows *(ORB5)*

Table 1: Simulation parameters

T_f/T_e	Frac_ep	Betta	ntor	R[m]	a[m]
25	10%	0.9%	0, 5	2.88	0.95

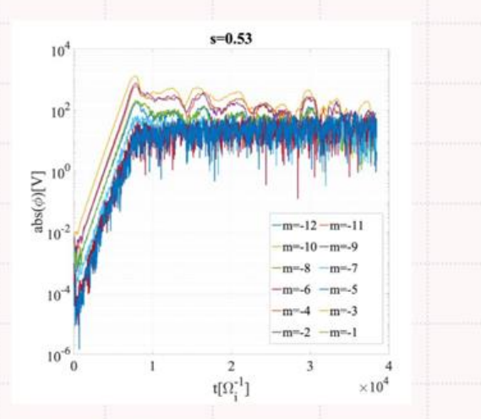


FIG 5: Time evolution of scalar potential

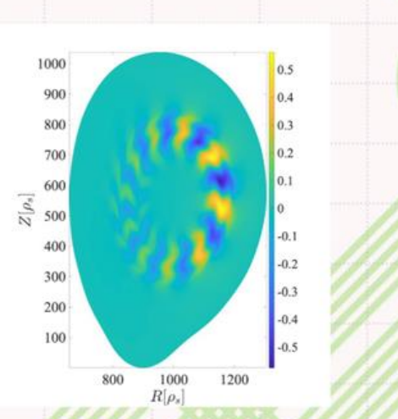


FIG 6: Mode structure in linear phase

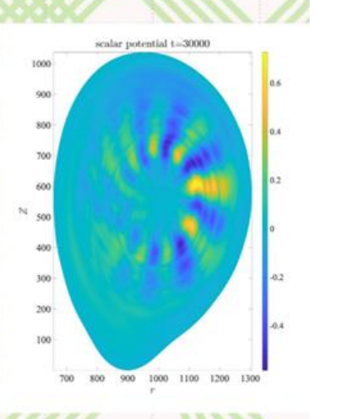


FIG 6: Mode structure in nonlinear phase

- The excited mode is an n=5, m=10, TAE

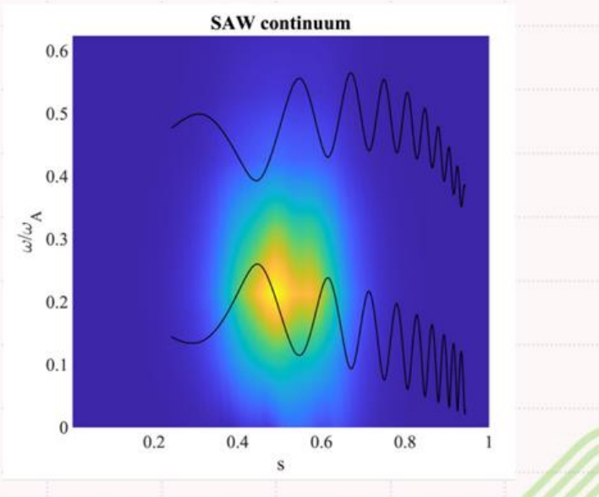


FIG 7: Frequency spectrum. Black line are the SAW continuum spectrum from FAICON

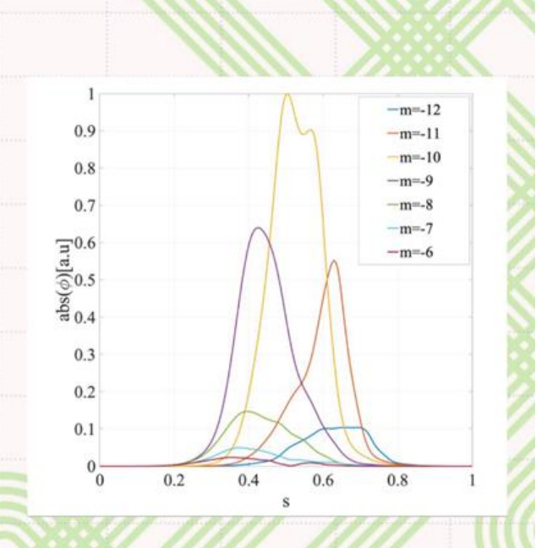


FIG 8: Radial mode structure

- Excitation of zonal flows by TAE
- Force Driven excitation of zonal flows

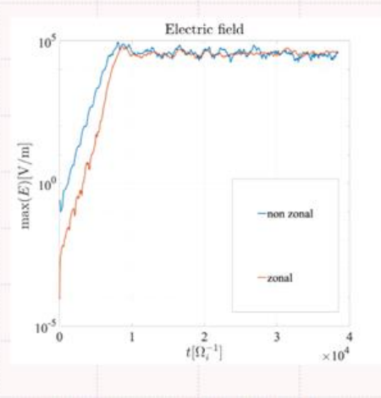


FIG 9 : Time evolution of TAE field and zonal flow

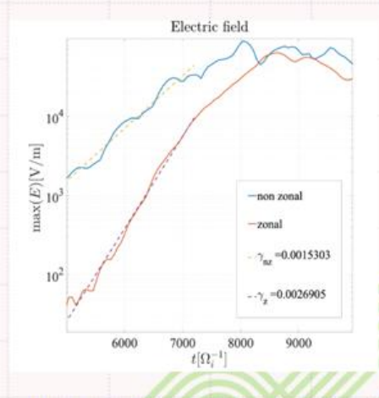


FIG 10 :Zoom showing growth rate doubling

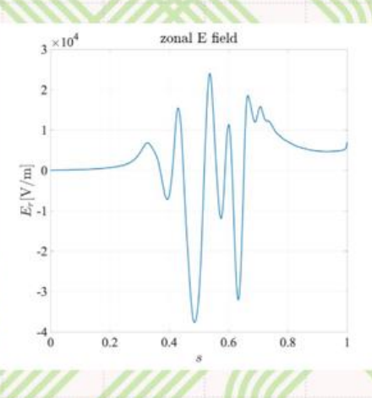


FIG 11: Radial structure of the excited zonal flow

- ITG mitigation by forced-driven zonal flows

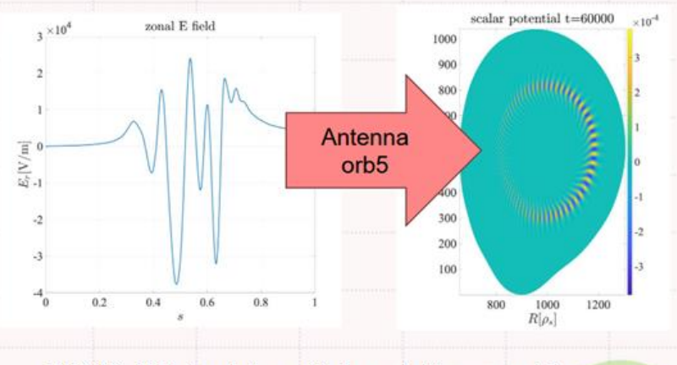


FIG 12: ITG simulation with forced driven zonal flows emulated by the orb5 antenna module

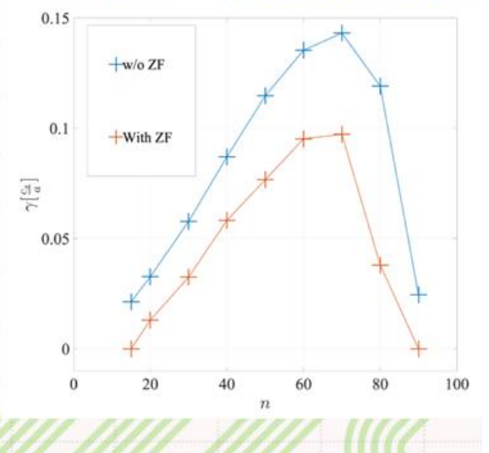
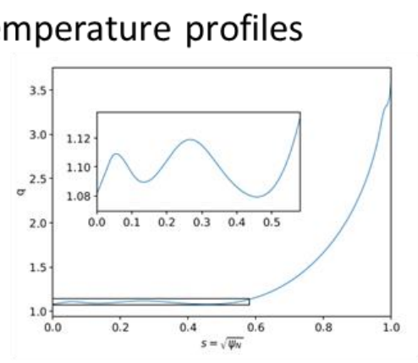
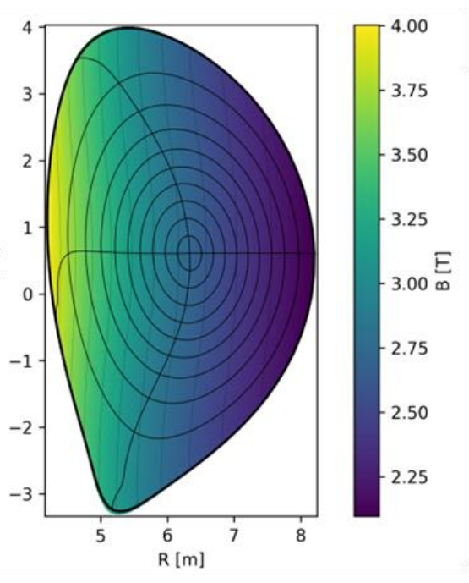


FIG 13: ITG mitigation by forced driven zonal flows

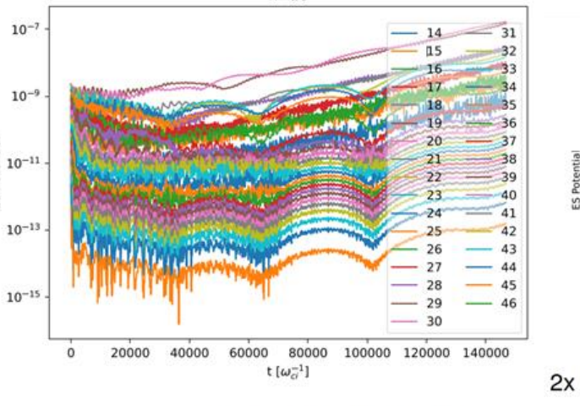
ITER 7.5MA (IMAS #101006) Pre-fusion-power-operation-2 case *(ORB5)*

- H-plasma, 1/2 fields, 1/2 current, NBI-heated
- Low shear, (multi-) reversed q-profile due to off-axis beams
- Flat density, peaked temperature profiles

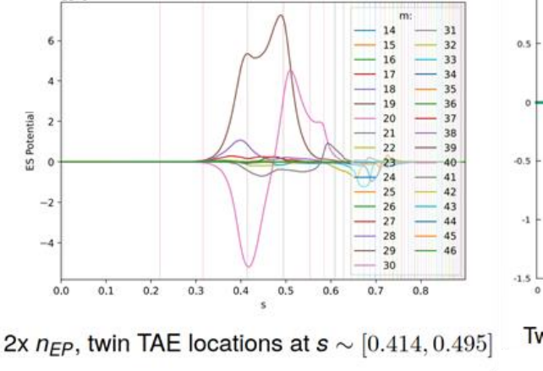




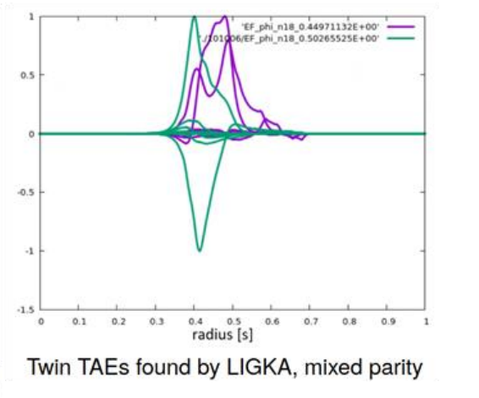
ITER 7.5MA (with EP)



2x n_{EP}, growing beating mode(s)

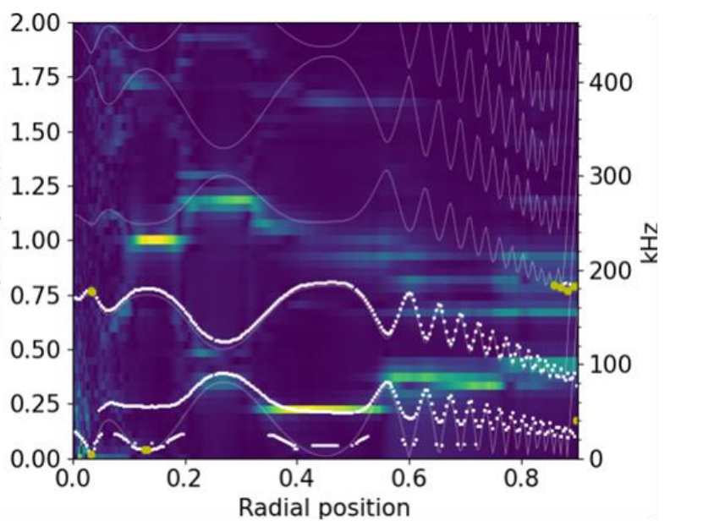


2x n_{EP}, twin TAE locations at $s \sim [0.414, 0.495]$



Twin TAEs found by LIGKA, mixed parity

ITER 7.5MA (without EPs): stable TAEs, EAEs, RSAEs; weakly-damped n=12 BAEs (minimum of dispersion)



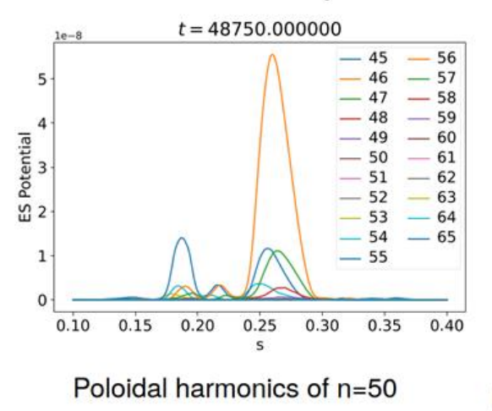
Higher-n core BAEs/AITGs (Alfvénic ITG) in the absence of EPs (driven **unstable** by **bulk** plasma[2])
– flute-like structure

Low frequency: in range $40 < n < 70$ (γ depends on distance between rational and q-extrema)

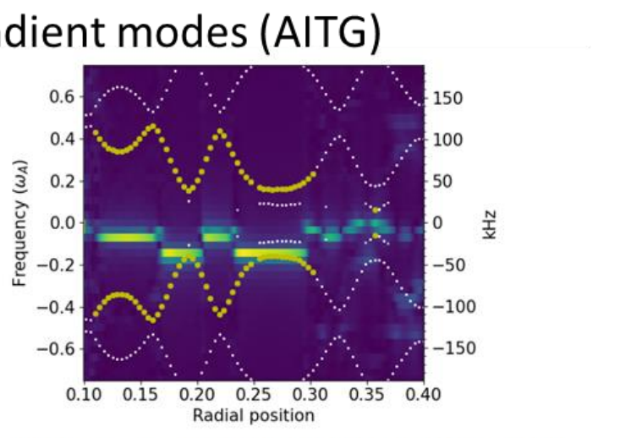
n=50, frequency: -37.4 kHz
γ/ω = 5.5%

ITER 7.5MA (without EPs): other instabilities
- ITG – Unstable electrostatc modes found in range of n ≈ 180 – 200
- Unexpected electromagnetic modes found in range of n ≈ 50 – 80

Alfvénic Ion Temperature Gradient modes (AITG)



Poloidal harmonics of n=50



n=50, w/ kinetic spectrum from ligka in white/yellow dots (Im(ω)$< 0, > 0$)

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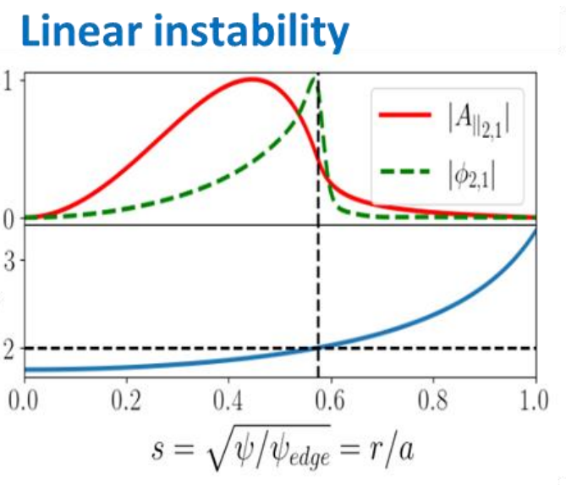
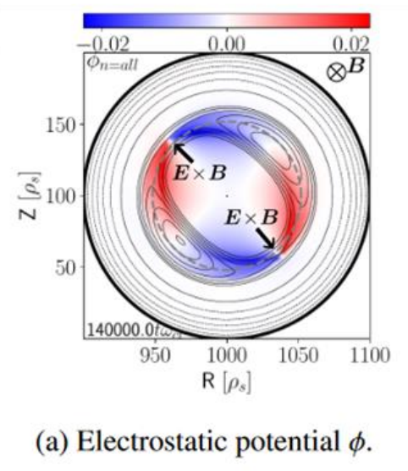
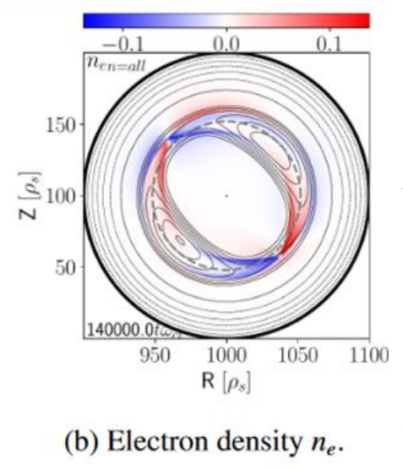
[2] Zonca+ 1996; 1998

Gyrokinetic simulations of collisionless tearing modes *(ORB5)*

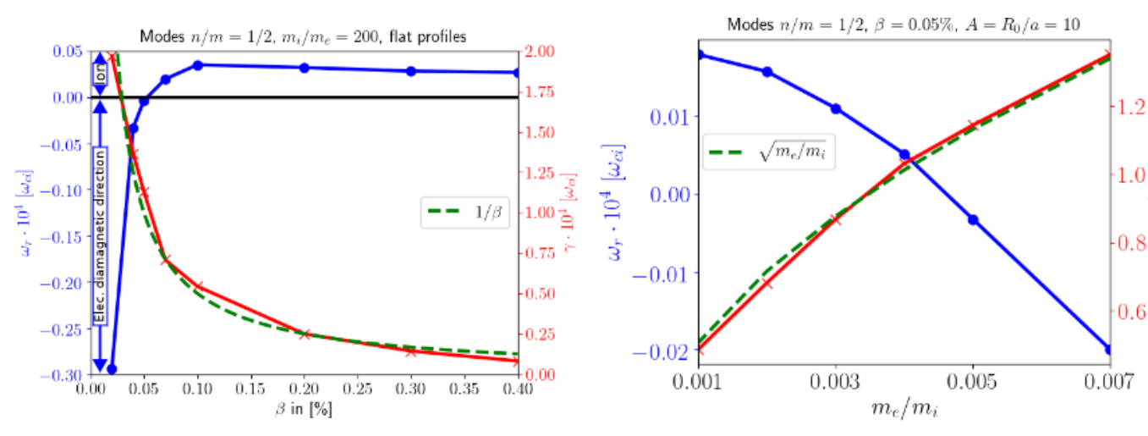




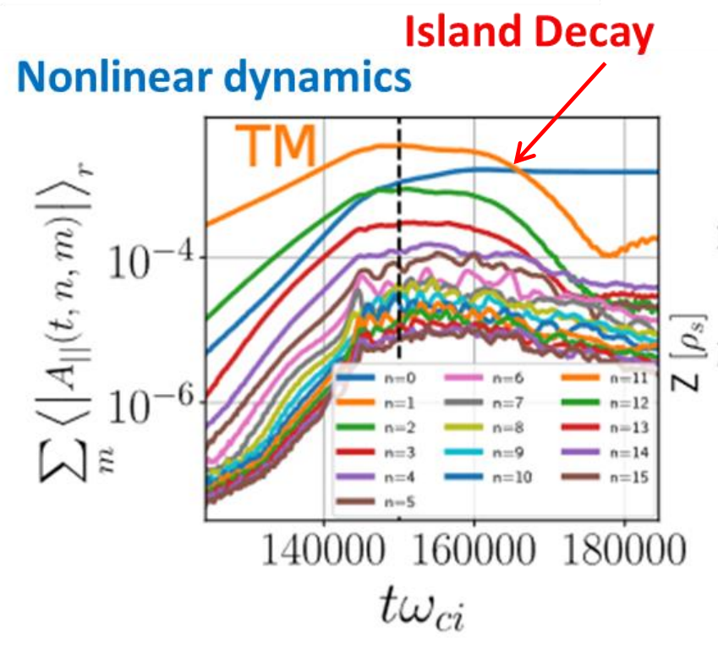
(a) Electrostatic potential ϕ.



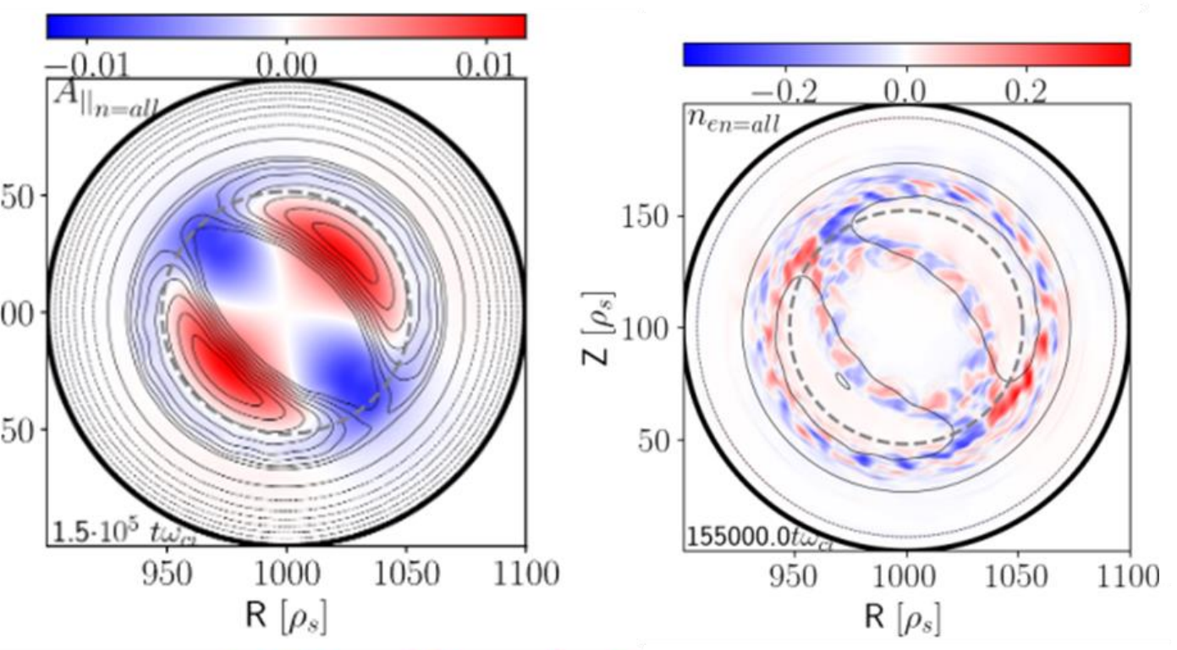
(b) Electron density n_e.



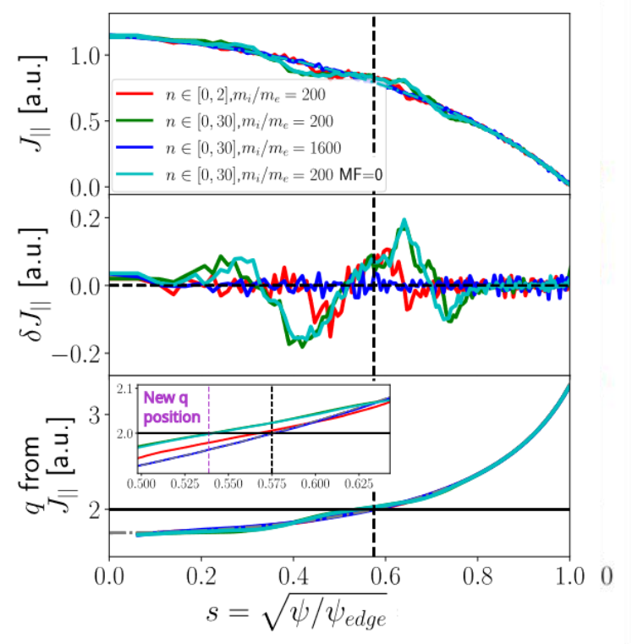
Linear growth rate scales as expected



Island saturation and healing

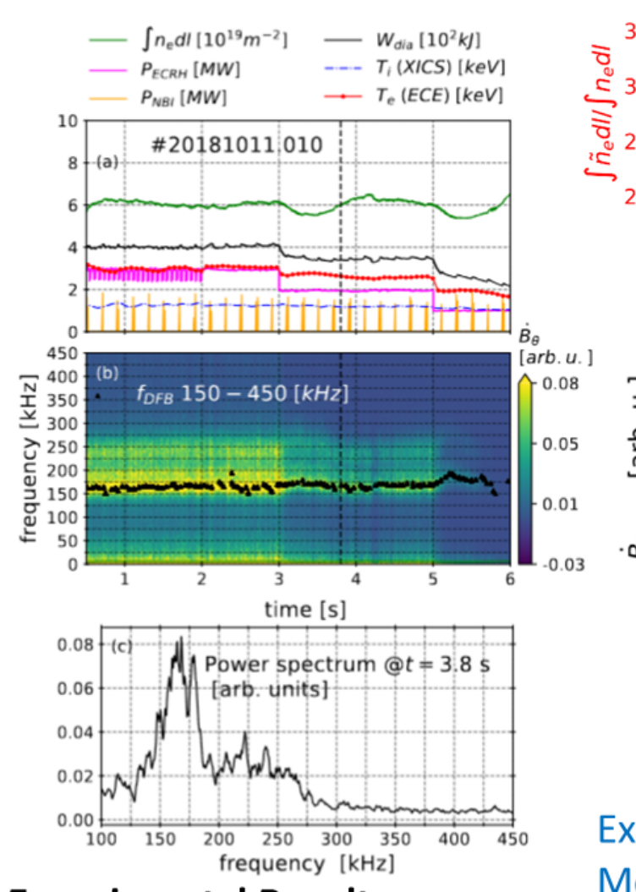


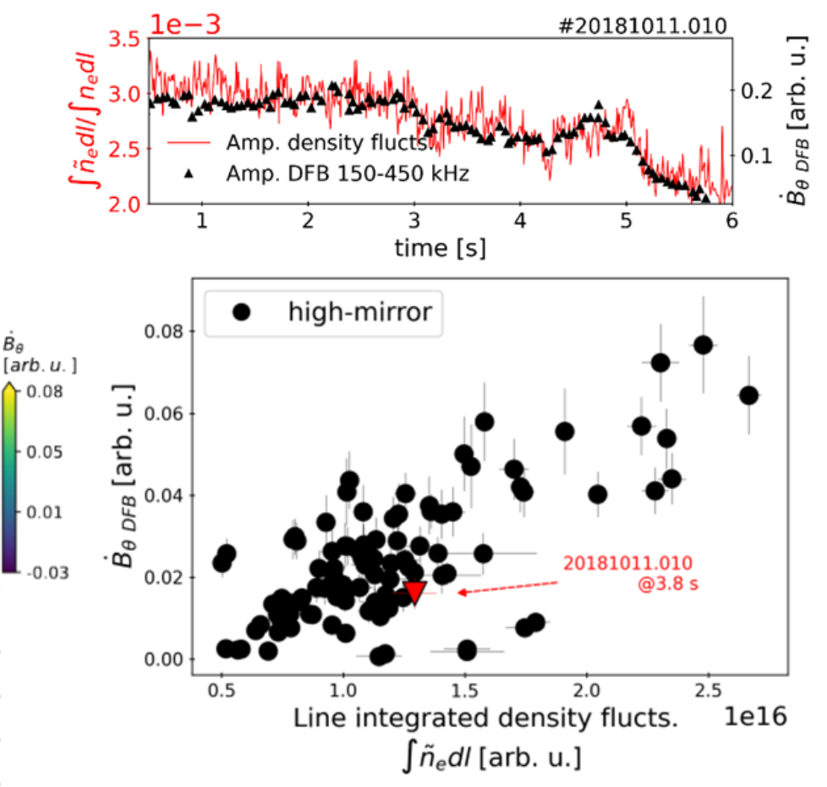
1. KH Instability at beginning of island decay



2. Zonal fields impact islands modifying background current and safety factor profile

Excitation of Alfvénic Modes via Electromagnetic Turbulence in Wendelstein 7-X *(EUTERPE)*

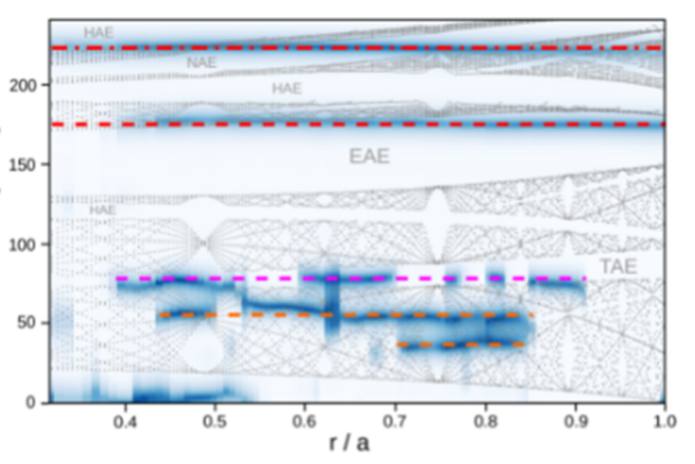




Experimental W7-X data
Mendes et al., NF 63 (2023)

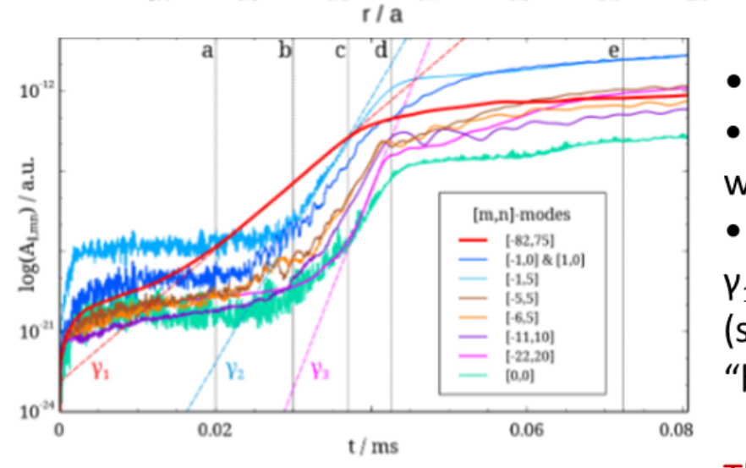
Experimental Results:
- predominant ITG turbulence observed in W7-X (density fluctuations)
- dominant Alfvénic frequency band is seen in many experiments
- temporal evolution of turbulence (PCI) and magnetic fluctuations (Mirnov) is found very similar over entire discharges, **no fast ions!**
- Alfvénic fluctuation amplitudes and turbulence level are correlated

Hypothesis: Alfvénic fluctuations in W7-X are driven by ITG turbulence.



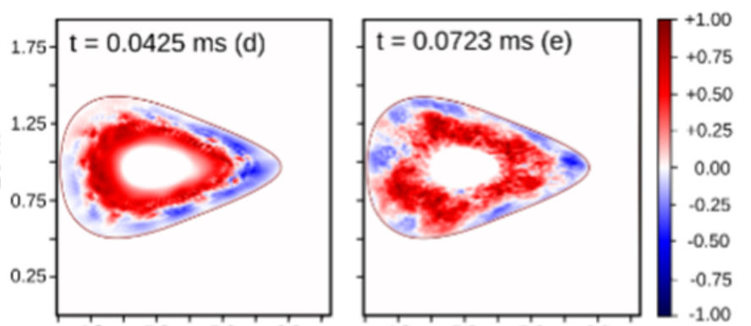
Gyrokinetic simulations recover experimental result:

freqs & [m,n]-modes:
175 kHz → [±1,0] EAE
225 kHz → [−1,5] NAE
77 kHz → [−5,5], [−6,5] TAE



- early ITG (high-m) activity
- Zonal Flow & Alfvénic modes when ITG has passed threshold
- growth rate cascade

$\gamma_1 : \gamma_2 : \gamma_3 = \gamma : 2\gamma : 3\gamma$
(similar to 2γ observed in "beat-driven" ZFs)

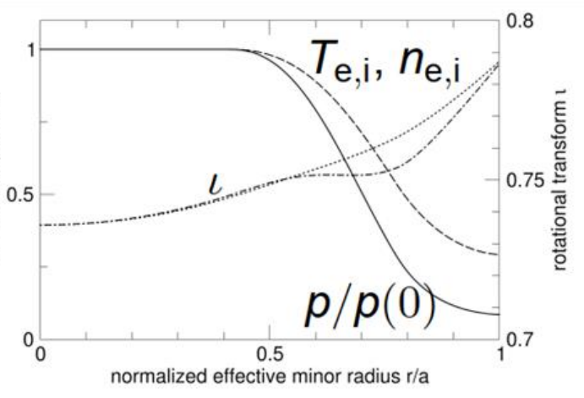


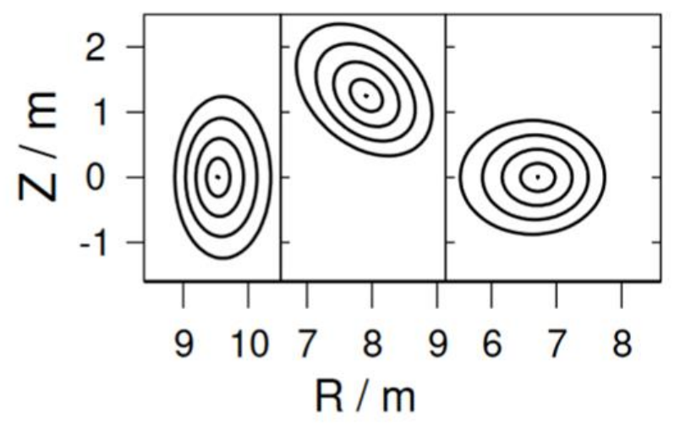
early and late NL phase

The role of ITG activity.
1. ITG modes included in Fourier filter → low-m modes follow ITG growth
2. ITG modes excluded from Fourier filter→ low-m modes are stable

Synergy with TSVV13 and TSVV12

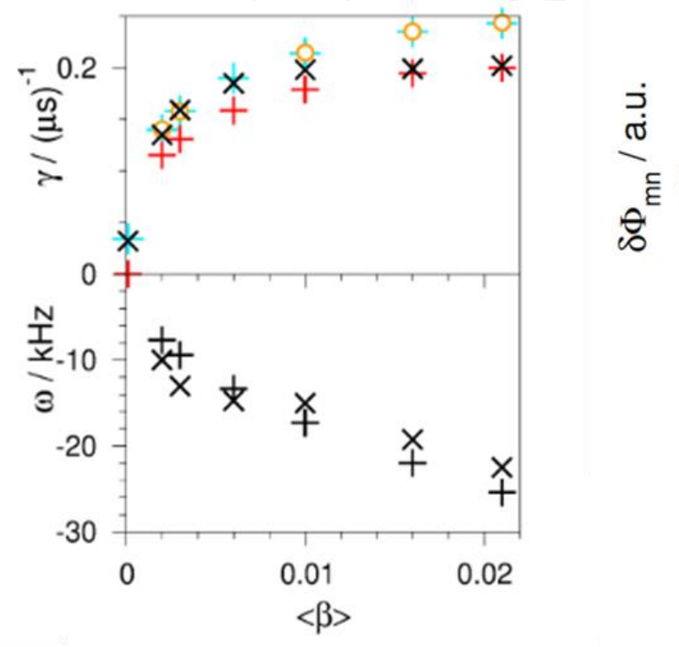
Gyrokinetic simulations of MHD-unstable stellarator configurations *(EUTERPE)*

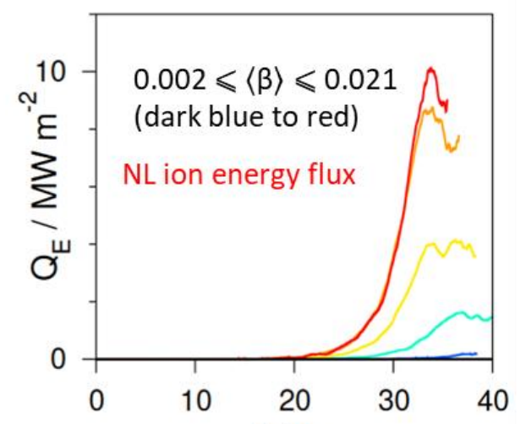




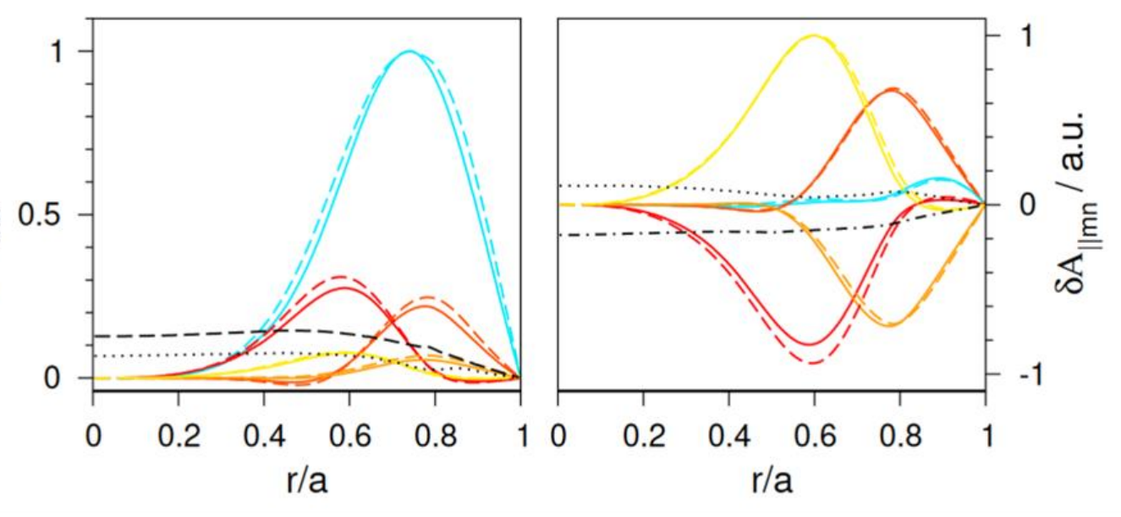
4-period HELIAS [5] stellarator
Mercier-unstable at finite β!
(not a reactor candidate)
Perform full-torus GK simulations
Compare to MHD (CAS3D, CKA)

Linear instability: comparison GK (x), ideal-MHD (+), reduced-MHD (o)
Bottom: GK frequency vs. omega_star

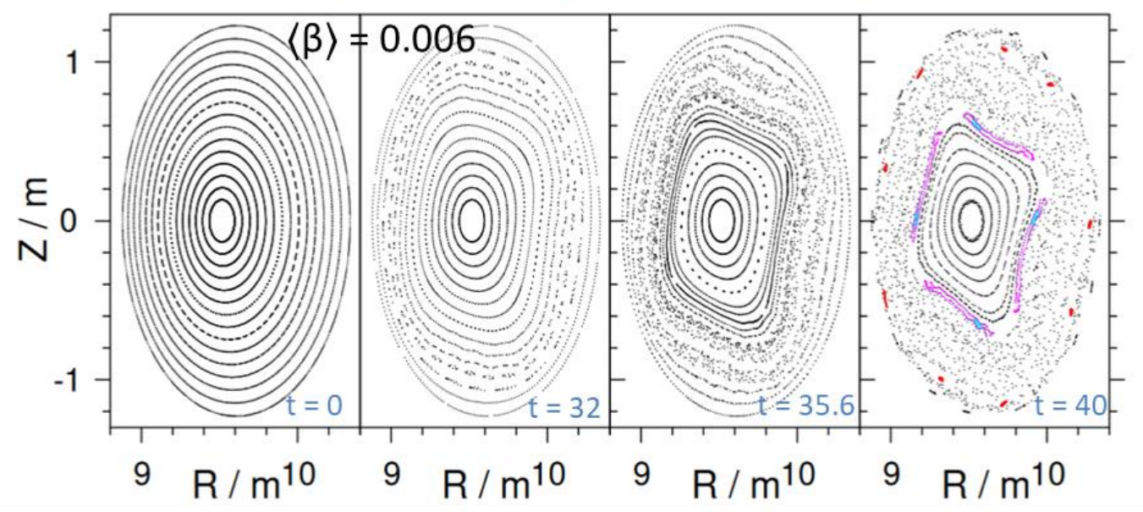




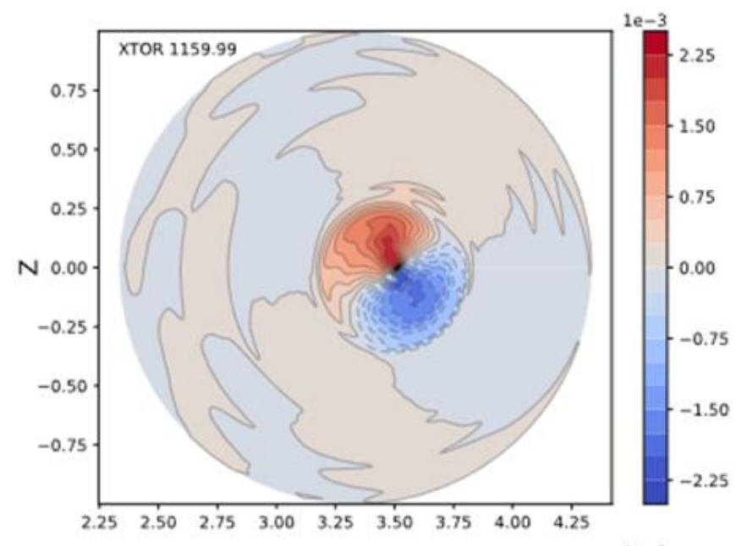
Dominant Fourier harmonics: ideal-MHD (solid) vs. GK (dashed). Very good agreement!



Perturbed field-line tracing for GK magnetic field: nonlinear growth of magnetic islands, ergodization



Internal kink instability. Hybrid simulations with 2 MeV fusion alphas. Nonlinear stationary helical state.



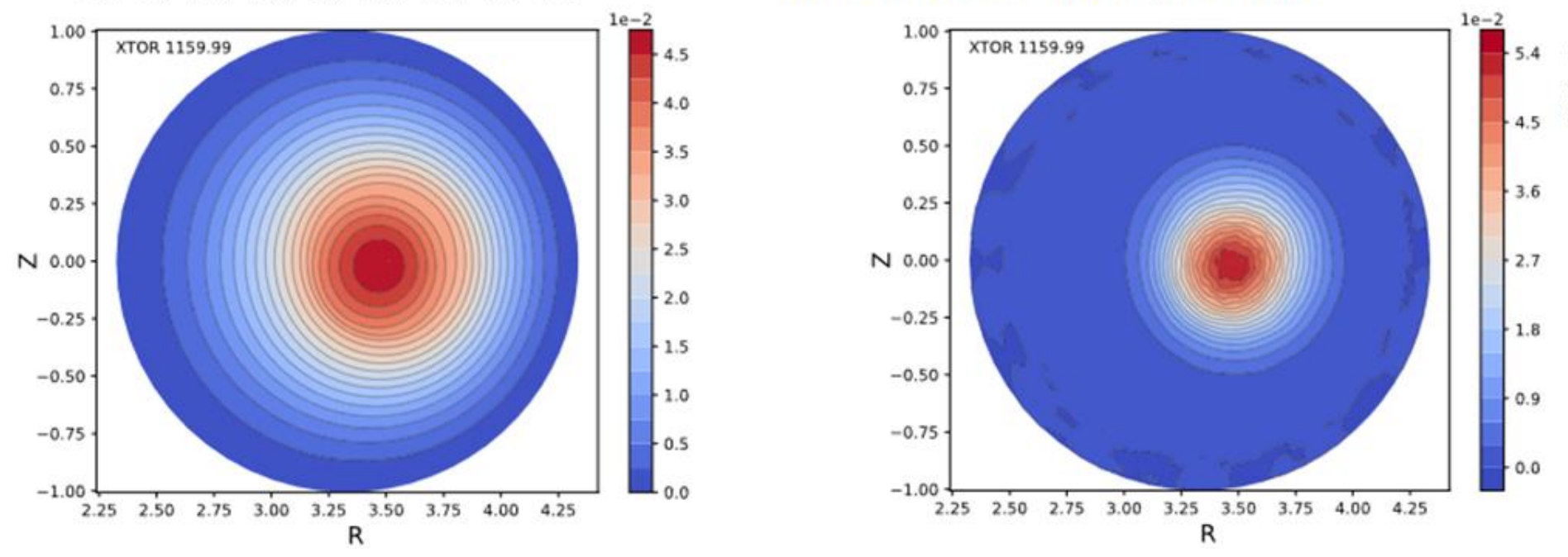
V_r(phi=0)

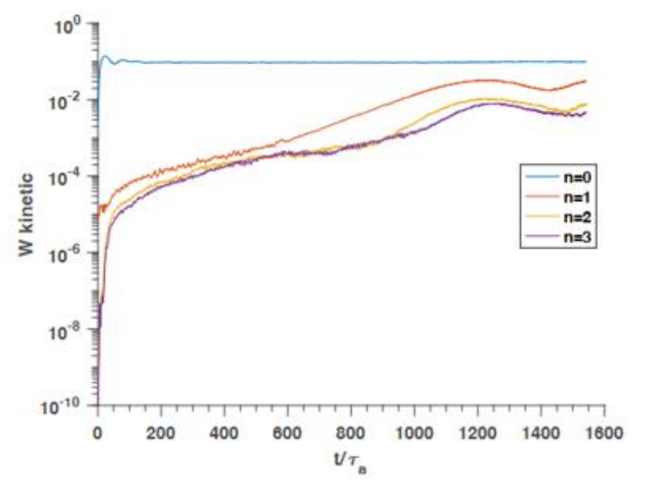
(XTOR-K)

Ni0=ne0=2 10^19 m-3
Ti0=Te0=30KeV
Nf0=4.10^17 m-3
Beta_pol=0.78;
r(q=1)=0.45
S=3.e6
Chi//=1., Chi_perp=1.e-6

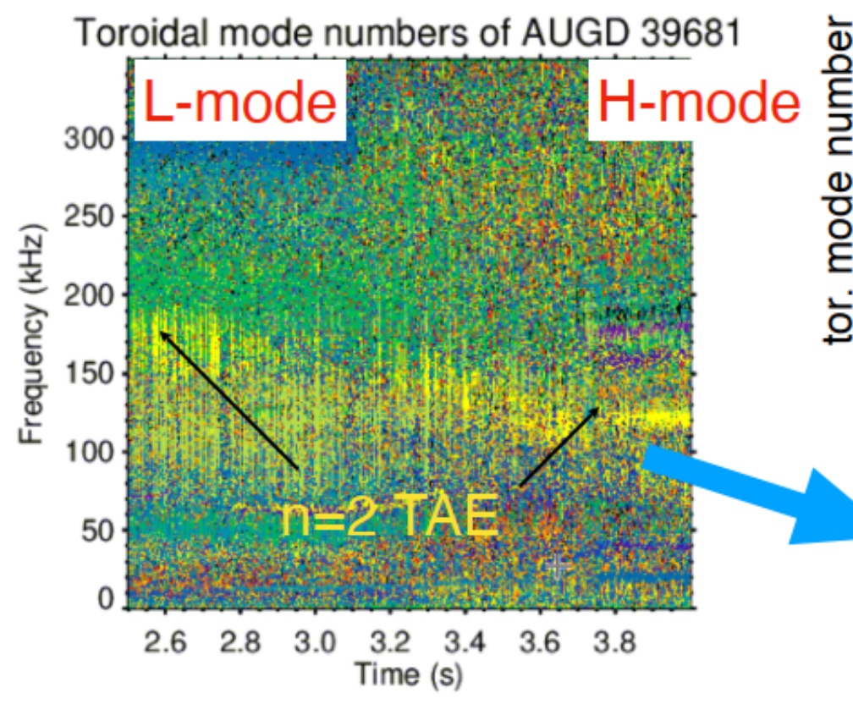
Evolution of fluctuation spectrum and EP transport suggest two possible routes to nonlinear physics: nonlinear wave-wave interactions and nonlinear wave-particle interactions.

Fluid and kinetic ion pressures



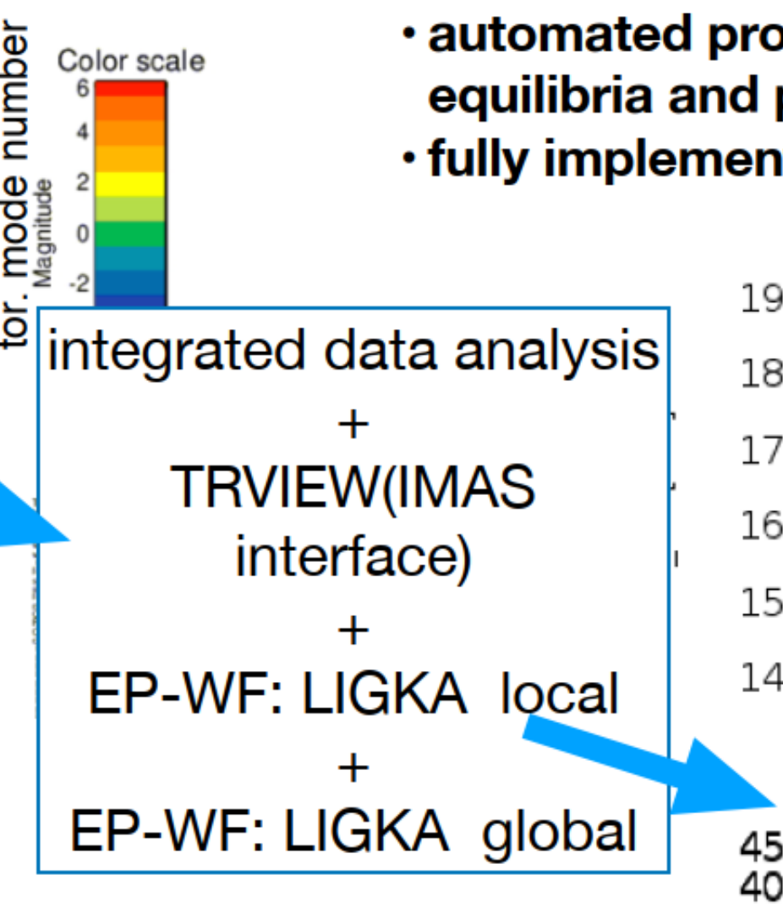


Integral modelling (Energetic-particle Workflow)

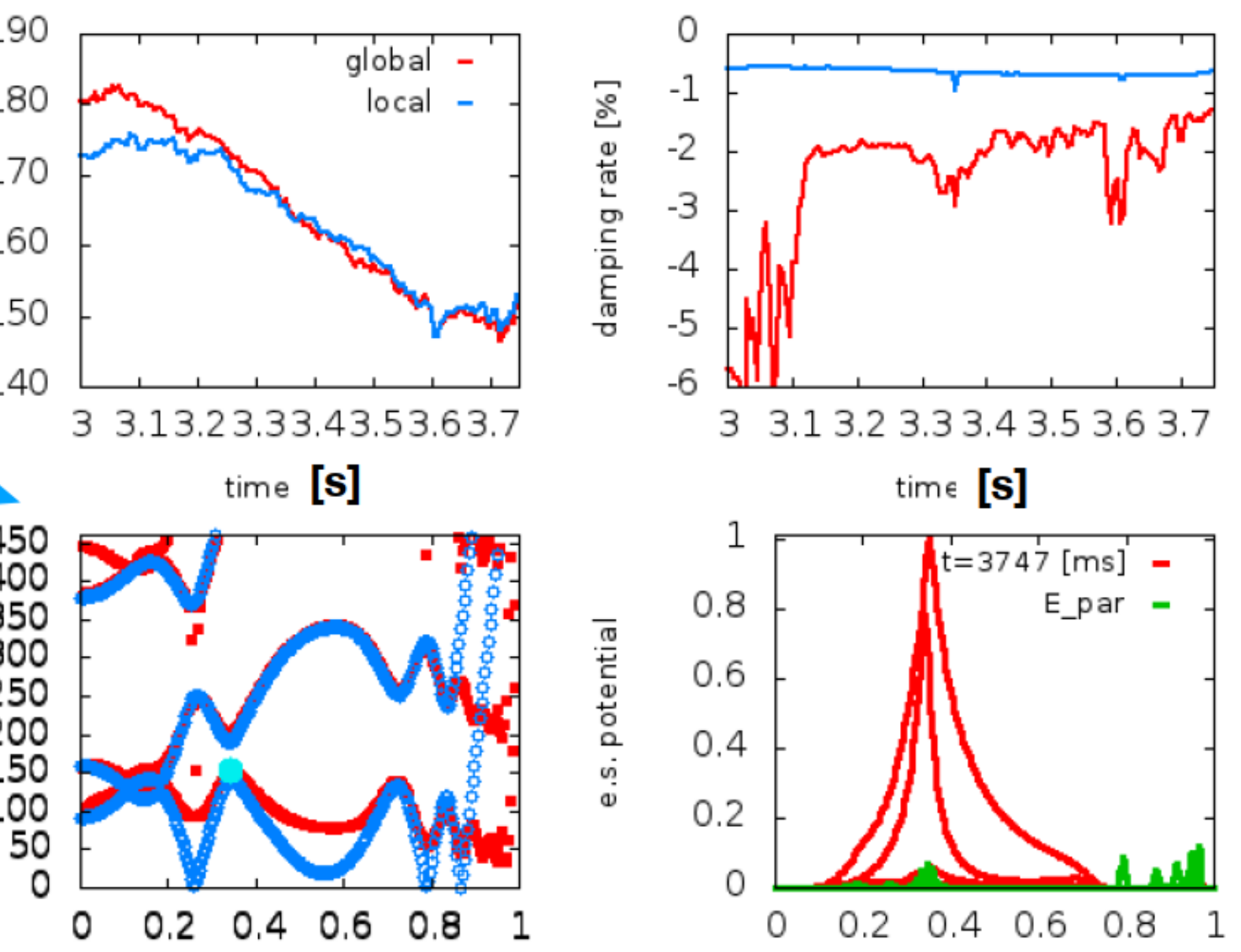


- **automated processing of 160 time slices based on IDA equilibria and profiles**
- **fully implemented in IMAS, ensuring reproducibility**

(LIGKA)



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



- **analyse L-mode,H-mode and transition phases: beat infamous problem of AE stability sensitivity to profiles - compare trends instead of single time slices**
- **compare local and global models**
- **systematic uncertainty quantification feasible**
- **applied also to TCV, JET, JT-60SA, ITER, DEMO**

EP-Stability WF training course, July 2023

[Lauber, EPS 2022, Popa 2020-2023]

CONCLUSIONS:

- Theory and software stack are developed for burning plasma applications: gyrokinetic codes, hybrid-MHD codes, integrated modelling
- GPU-enabling and IMASification of the key tools (assisted by ACHs)
- Both tokamak and stellarator plasmas addressed; simulations of complex physics and in realistic geometries
- Cross-code verification and comparisons to theory carried out
- Validation on ASDEX-Upgrade, JET, TCV, W7-X are ongoing
- Dissemination via publications (wiki, indico), EUROfusion‘s Gitlab (including code documentation), and training (Energetic-particle Workflow)

MAX-PLANCK-INSTITUT FÜR PLASMAPHYSIK

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