Turbulence, zonal flows, and global modes in burning plasmas: code development and simulations

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(E-TASC TSVV-10 team, ORB5 and EUTERPE groups)

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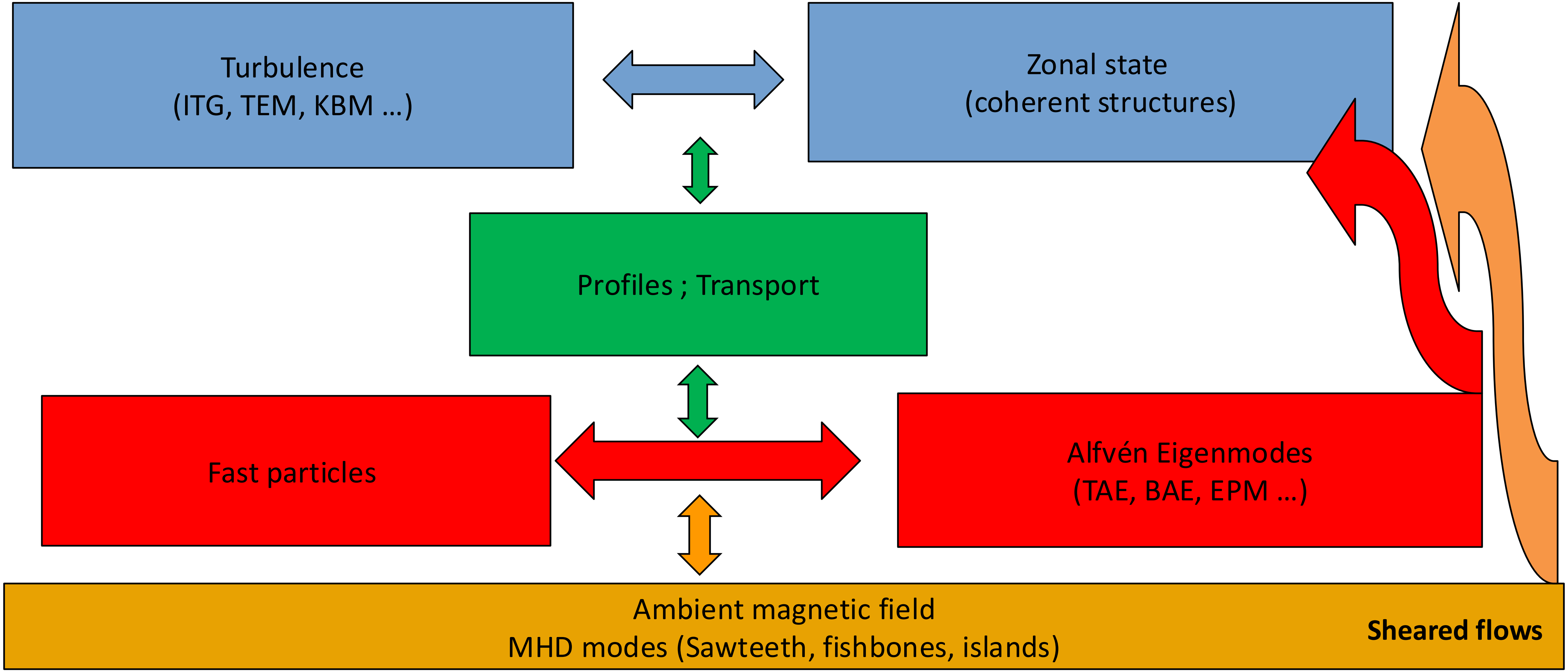
Introduction

- Several experiments worldwide will produce burning plasmas.
- Energetic particles will be important for cross-couplings between micro- and macro-scales.
- Fine-scale turbulence and zonal structures cannot be considered separately from fast particles and Alfvénic modes.
- MHD-type instabilities will also affect the plasma dynamics, turbulence, and transport in phase space.
- Plasma profile evolution becomes a multi-scale nonlinear problem with global and kinetic contributions.
- Global nonlinear gyrokinetics is a minimal inclusive description addressing this problem within a single framework.
- This talk: global gyrokinetic simulations of multiscale fusion plasma dynamics in tokamaks and stellarators.

Synergies and couplings



Global NL gyrokinetic theory is a minimal inclusive description

ORB5 and EUTERPE codes

- Effects of turbulence on flux surfaces in W7-X
- ITG and KBM turbulence in tokamak plasmas
- tearing instabilities and island generation in a tokamak
- Chirping Alfvenic modes (TAE, EPM) in TCV
- EP-destabilized TAE, beat driven zonal flows and ITG modes in JET
- Nonlinear Alfven modes driven by ITG turbulence in W7-X
- Nonlinear gyrokinetic MHD modes in stellarator plasmas

The equations include the gyrokinetic Vlasov equation:

$$\frac{\partial f_{1s}}{\partial t} + \dot{\boldsymbol{R}} \cdot \frac{\partial f_{1s}}{\partial \boldsymbol{R}} + \dot{v}_\parallel \frac{\partial f_{1s}}{\partial v_\parallel} = -\dot{\boldsymbol{R}}^{(1)} \cdot \frac{\partial F_{0s}}{\partial \boldsymbol{R}} - \dot{v}_\parallel^{(1)} \frac{\partial F_{0s}}{\partial v_\parallel} , \quad (1)$$

the equations for the gyro-center orbits:

Collision operators available

$$\dot{\boldsymbol{R}} = \dot{\boldsymbol{R}}^{(0)} + \dot{\boldsymbol{R}}^{(1)} , \quad \dot{v}_\parallel = \dot{v}_\parallel^{(0)} + \dot{v}_\parallel^{(1)} \quad (2)$$

$$\dot{\boldsymbol{R}}^{(0)} = v_\parallel \boldsymbol{b}_0^* + \frac{1}{q B_\parallel^*} \boldsymbol{b} \times \mu \nabla B , \quad \dot{v}_\parallel^{(0)} = -\frac{\mu}{m} \boldsymbol{b}_0^* \cdot \nabla B \quad (3)$$

Reduced models available

$$\dot{\boldsymbol{R}}^{(1)} = \frac{\boldsymbol{b}}{B_\parallel^*} \times \nabla \langle \phi - v_\parallel A_\parallel^{(\mathrm{s})} - v_\parallel A_\parallel^{(\mathrm{h})} \rangle - \frac{q}{m} \langle A_\parallel^{(\mathrm{h})} \rangle \boldsymbol{b}_0^* \quad (4)$$

$$\dot{v}_\parallel^{(1)} = -\frac{q}{m} \left[\boldsymbol{b}^* \cdot \nabla \langle \phi - v_\parallel A_\parallel^{(\mathrm{h})} \rangle + \frac{\partial}{\partial t} \langle A_\parallel^{(\mathrm{s})} \rangle \right] - \frac{\mu}{m} \frac{\boldsymbol{b} \times \nabla B}{B_\parallel^*} \cdot \nabla \langle A_\parallel^{(\mathrm{s})} \rangle \quad (5)$$

$$\boldsymbol{b}^* = \boldsymbol{b}_0^* + \frac{\nabla \langle A_\parallel^{(\mathrm{s})} \rangle \times \boldsymbol{b}}{B_\parallel^*} , \quad \boldsymbol{b}_0^* = \boldsymbol{b} + \frac{m v_\parallel}{q B_\parallel^*} \nabla \times \boldsymbol{b} \quad (6)$$

Model for $\delta B_{||}$ available

$$B_\parallel^* = B + \frac{m v_\parallel}{q} \boldsymbol{b} \cdot \nabla \times \boldsymbol{b} , \quad (7)$$

Exact polarization density available

$$\frac{\partial}{\partial t} A_\parallel^{(\mathrm{s})} + \boldsymbol{b} \cdot \nabla \phi = 0 ,$$

$$-\nabla \cdot \left(\frac{n_0}{B \omega_{ci}} \nabla_\perp \phi \right) = \bar{n}_{1i} - \bar{n}_{1e}$$

$$\sum_{s=i,e} \frac{\beta_s}{\rho_s^2} A_\parallel^{(\mathrm{h})} - \nabla_\perp^2 A_\parallel^{(\mathrm{h})} = \mu_0 \sum_{s=i,e} \bar{j}_{\parallel 1s} + \nabla_\perp^2 A_\parallel^{(\mathrm{s})}$$

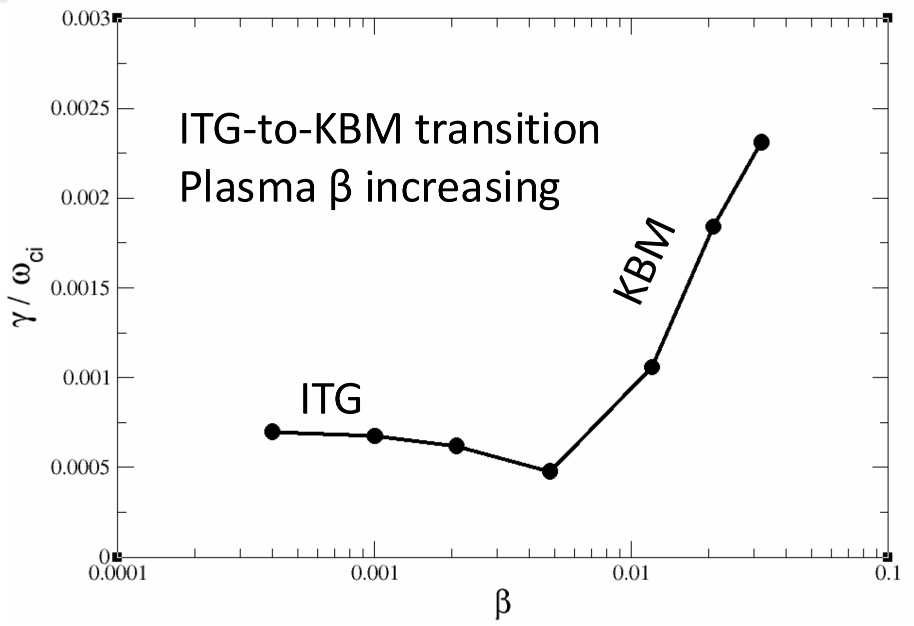
Mixed-variable GK

A Mishchenko *et al* 2021 *Plasma Phys. Control. Fusion* **63** 084007

ORB5: E. Lanti et al. Computer Physics Communications 251 (2020) 107072
EUTERPE: R. Kleiber et al. Computer Physics Communications 295 (2024) 109013

EM turbulence in tokamak: no divergence in global simulations

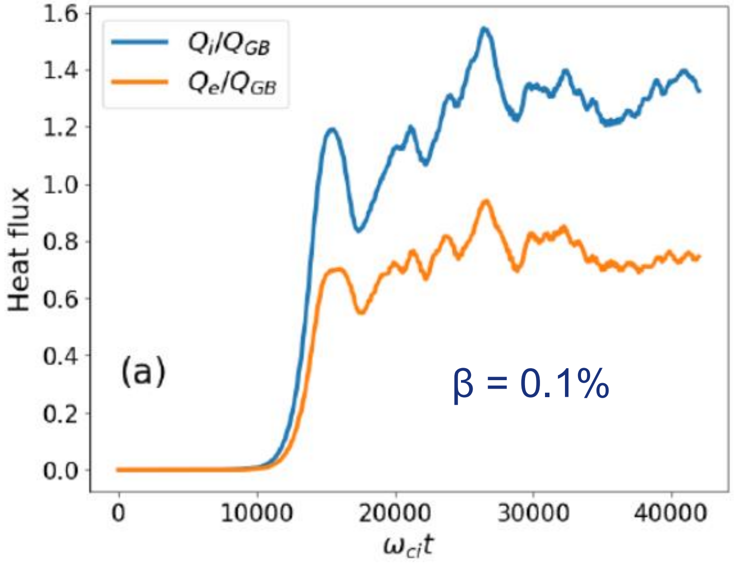
ORB5

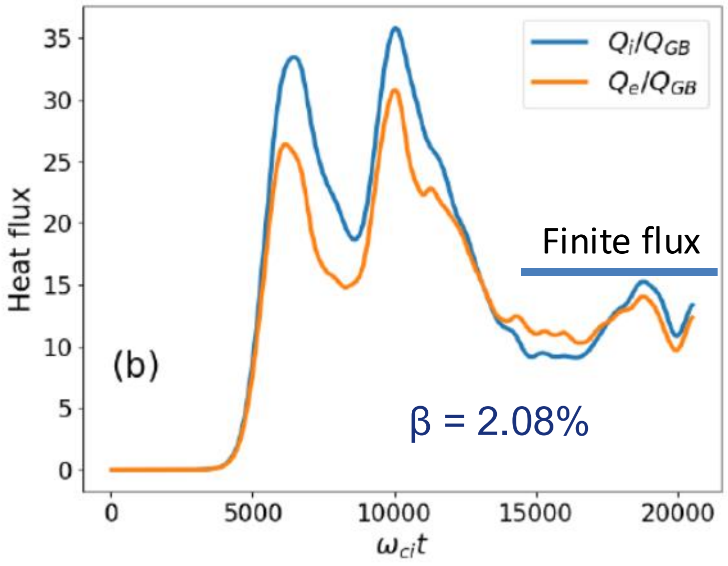


Linear growth rate in circular-shaped tokamak for different safety factor profiles: electromagnetic ITG-to-KBM transition.

Heat flux in the gyro-Bohm units for
a) β = 0.1% (electromagnetic ITG)
(b) β = 2.08% (KBM regime).
The heat flux is larger in KBM regime.

No "electromagnetic run-away" in global tokamak simulations.





Profiles are evolving.

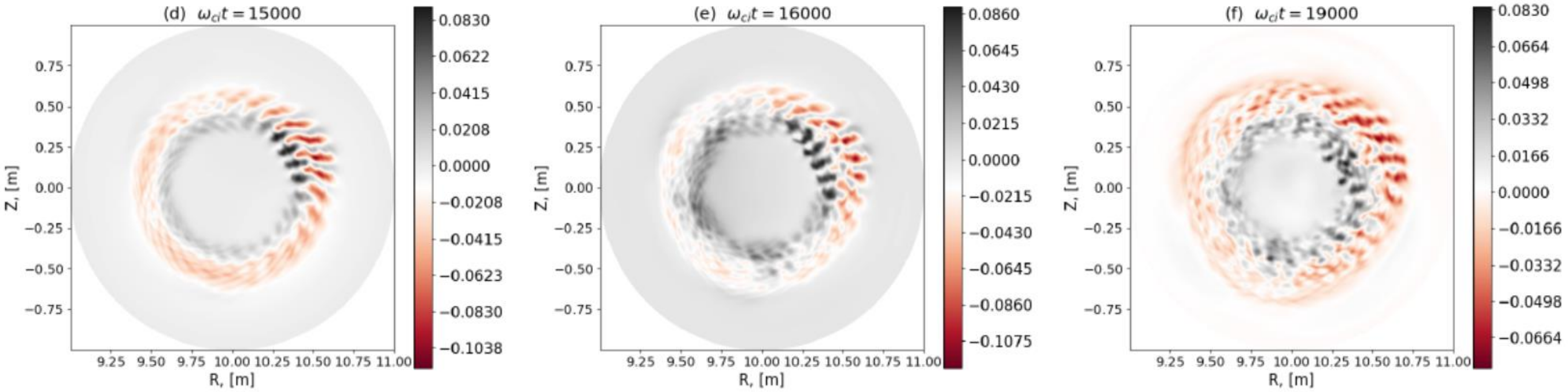
Adaptive Maxwellian is used for very long simulations.

EM turbulence in tokamak

ORB5

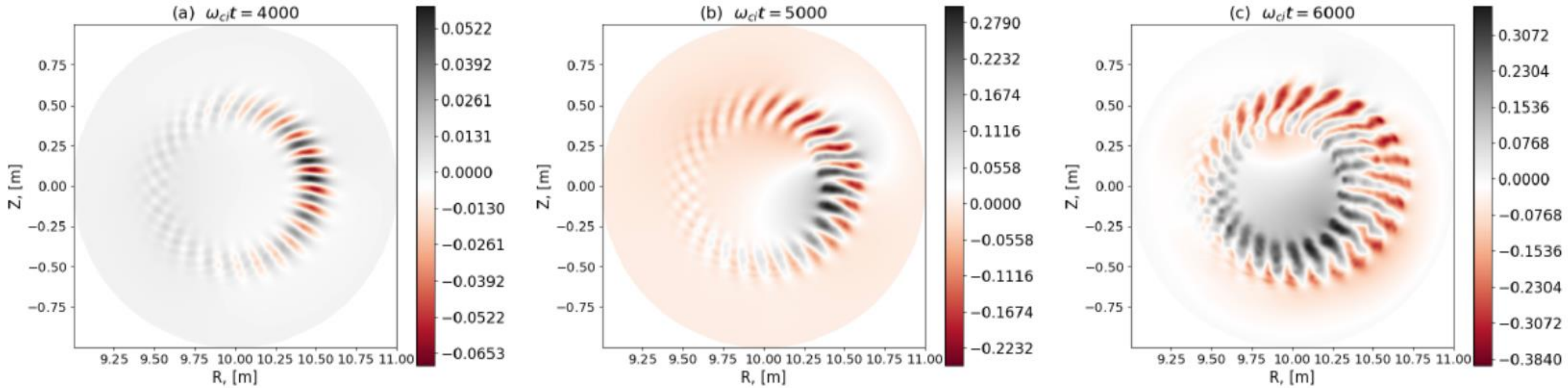
<u>Zonal</u> “eddy shearing” in EM-ITG regime

Low beta →



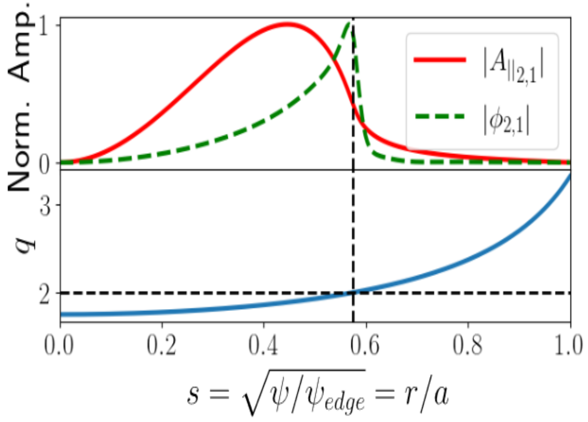
<u>Non-zonal</u> finger-like structures are developed and expelled out of “unstable region” in KBM regime

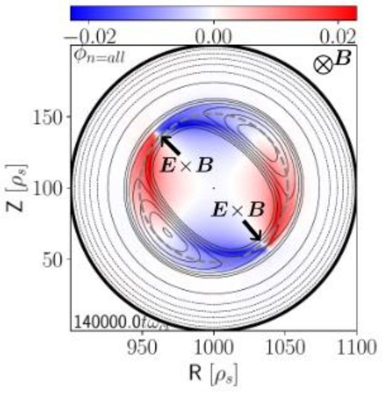
High beta →



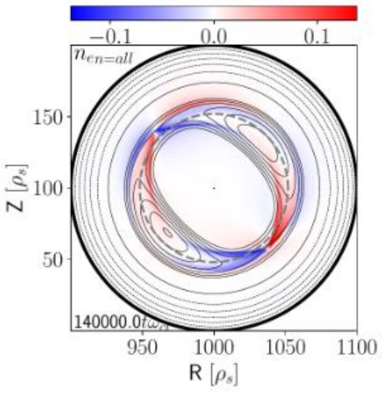
Gyrokinetic simulations of collisionless tearing modes

Linear instability

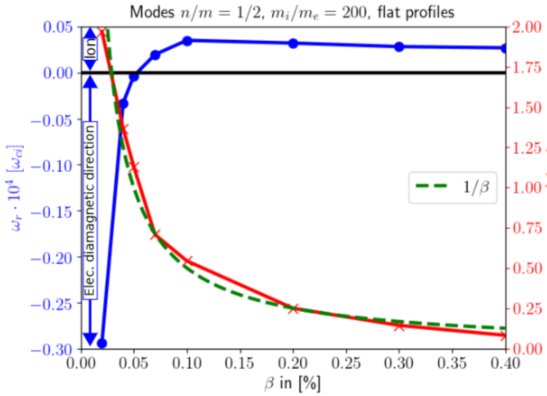


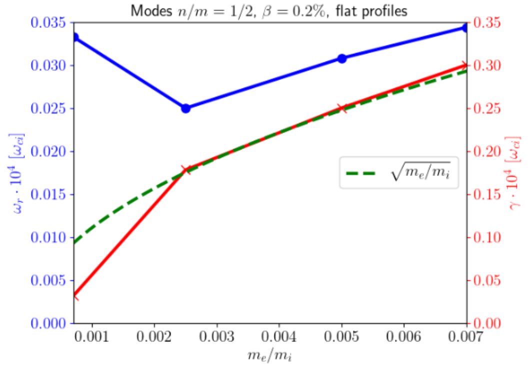


(a) Electrostatic potential ϕ.



(b) Electron density n_e.

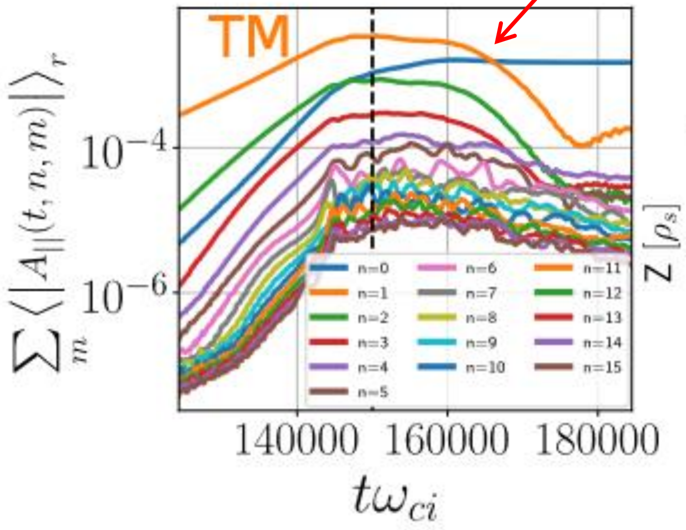




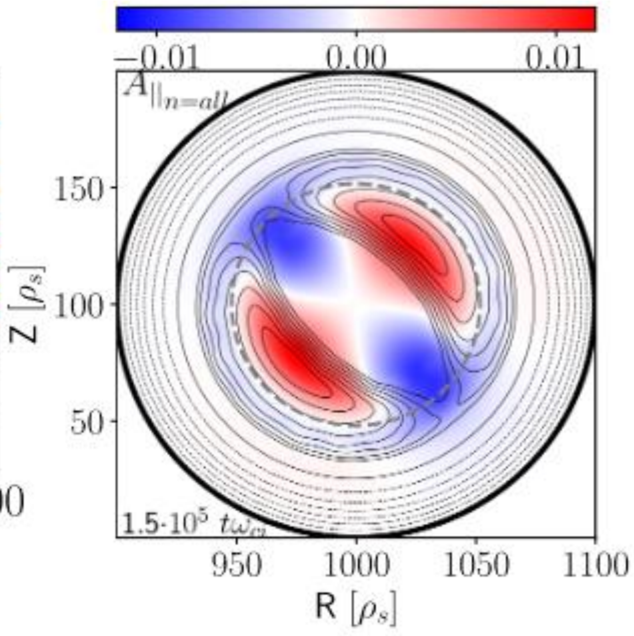
Linear growth rate scales as expected

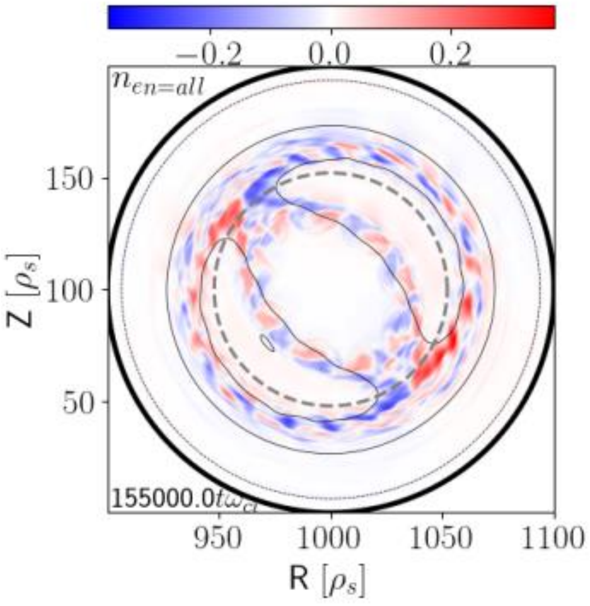
Nonlinear dynamics

Island Decay

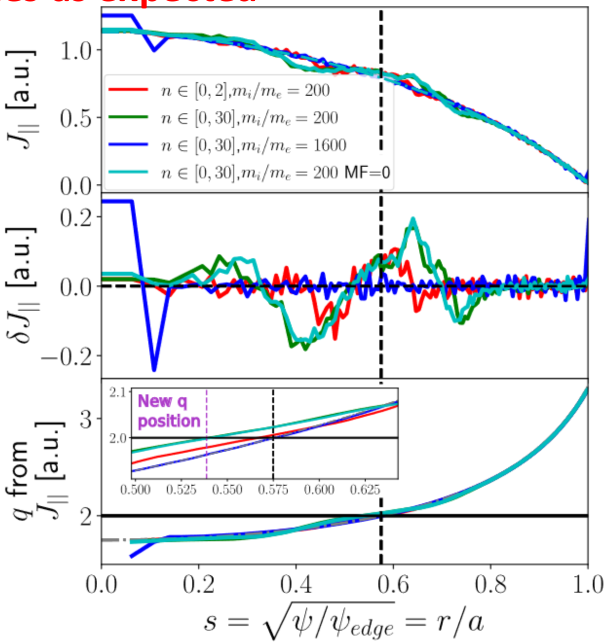


Island saturation and healing





1. KH Instability at beginning of island decay

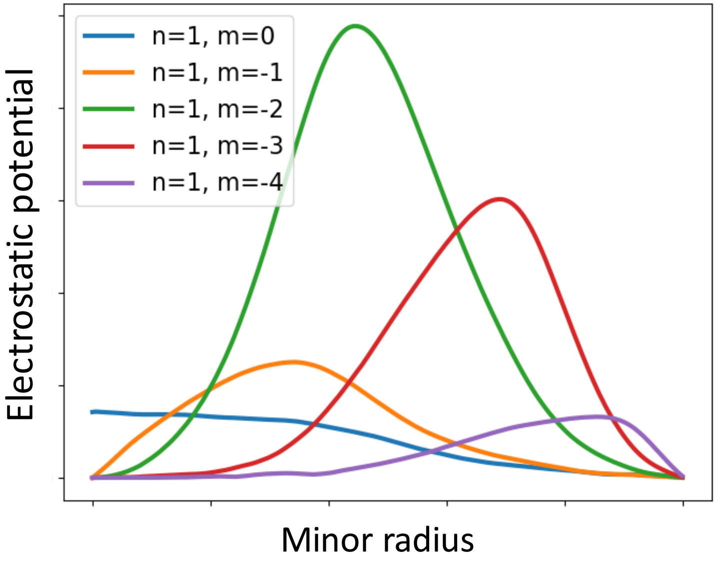


2. Zonal fields impact islands modifying background current and safety factor profile

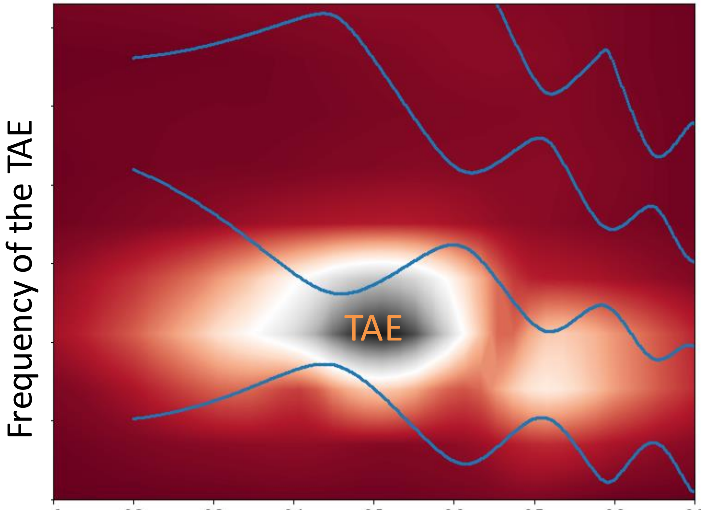
Gyrokinetic simulations of chirping instabilities: wave-particle nonlinearity

ORB5

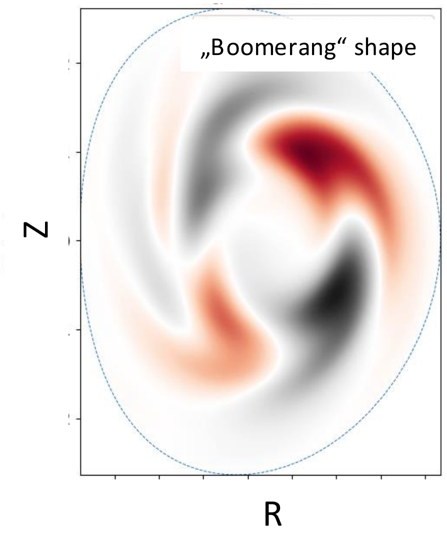
Poloidal harmonics (TAE mode)

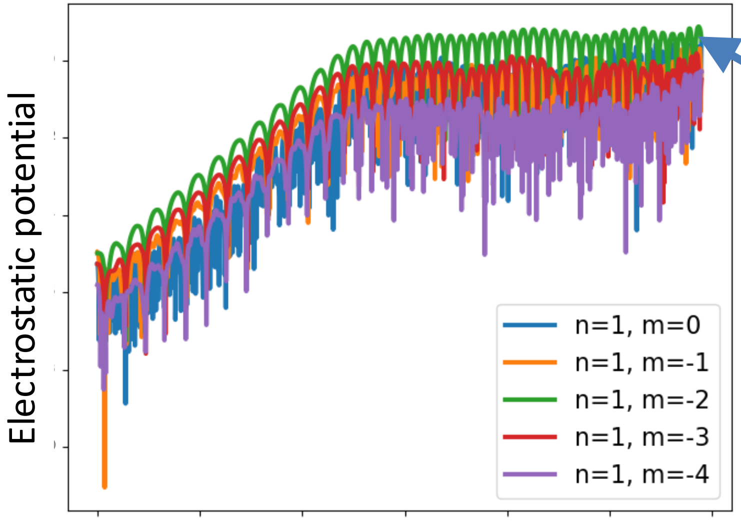


FFT of electrostatic potential



Electrostatic potential





Energetic-particle driven TAE/EPM instabilities in TCV-shaped tokamak.

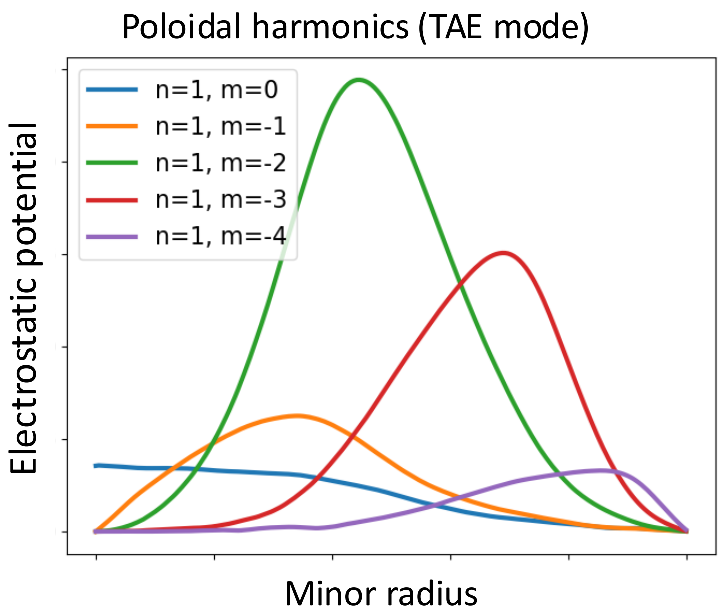
Coupled poloidal harmonics m = -2 and m = -3. Eigenmode frequency in the toroidal gap.

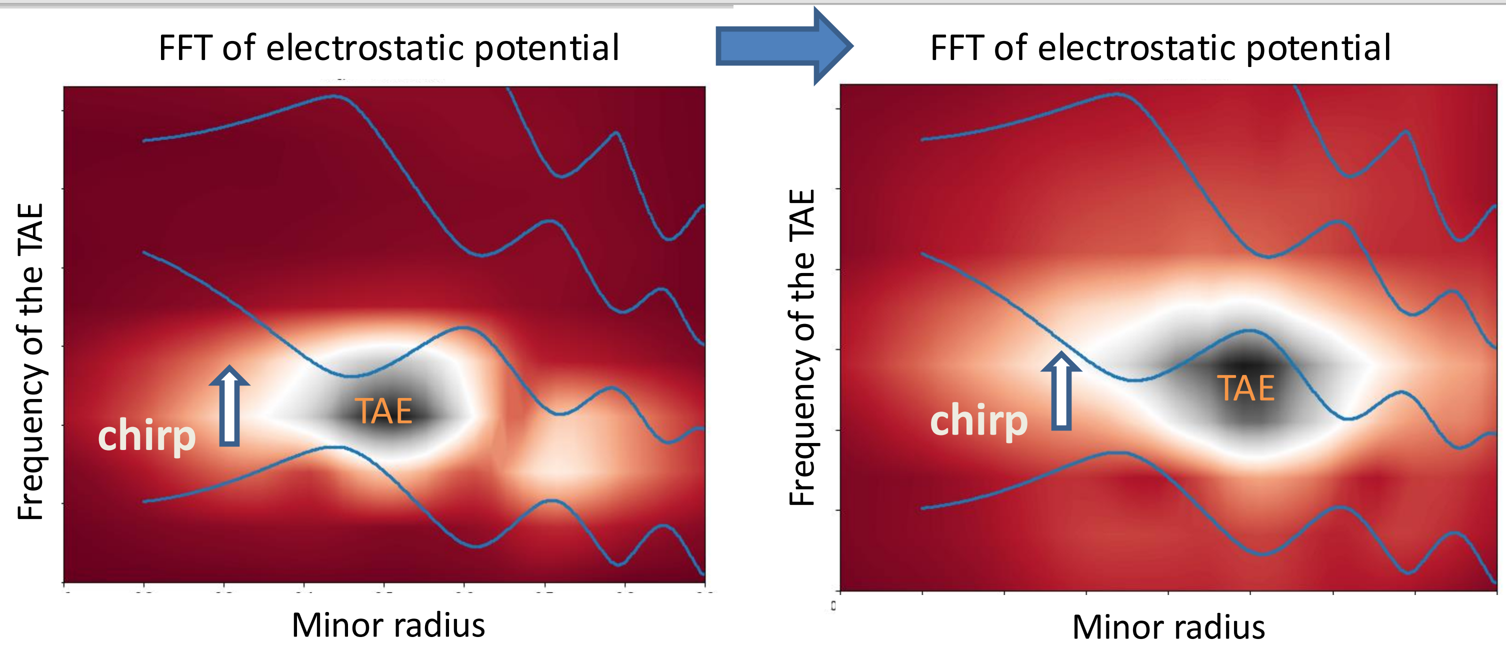
“Boomerang” shape of 2D mode structure caused by energetic-particle resonant response.

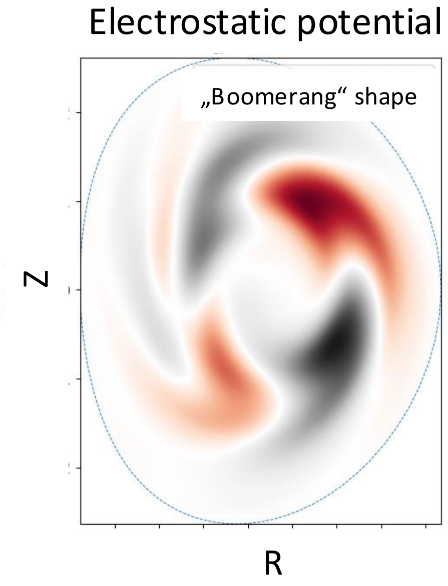
Saturation amplitude of the instability determines energetic-particle transport.

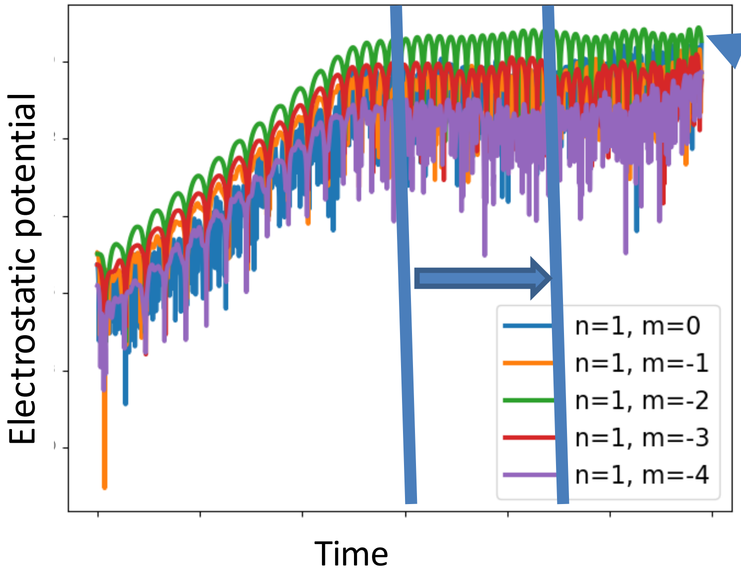
Gyrokinetic simulations of chirping instabilities: wave-particle nonlinearity

ORB5









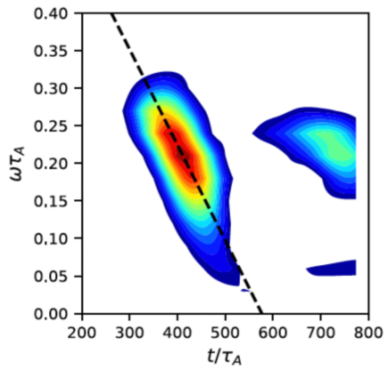
Saturation amplitude of the instability determines energetic-particle transport.

Chirping dynamics is observed for mode frequency: phase-space structures.

Gyrokinetic simulations of chiriping instabilities: wave-particle nonlinearity

1. Theory compared to simulations (<u>verification</u>):
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.

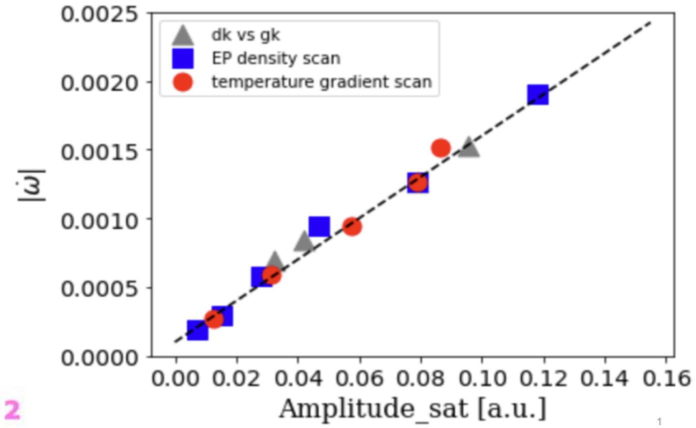


Time evolution of the mode

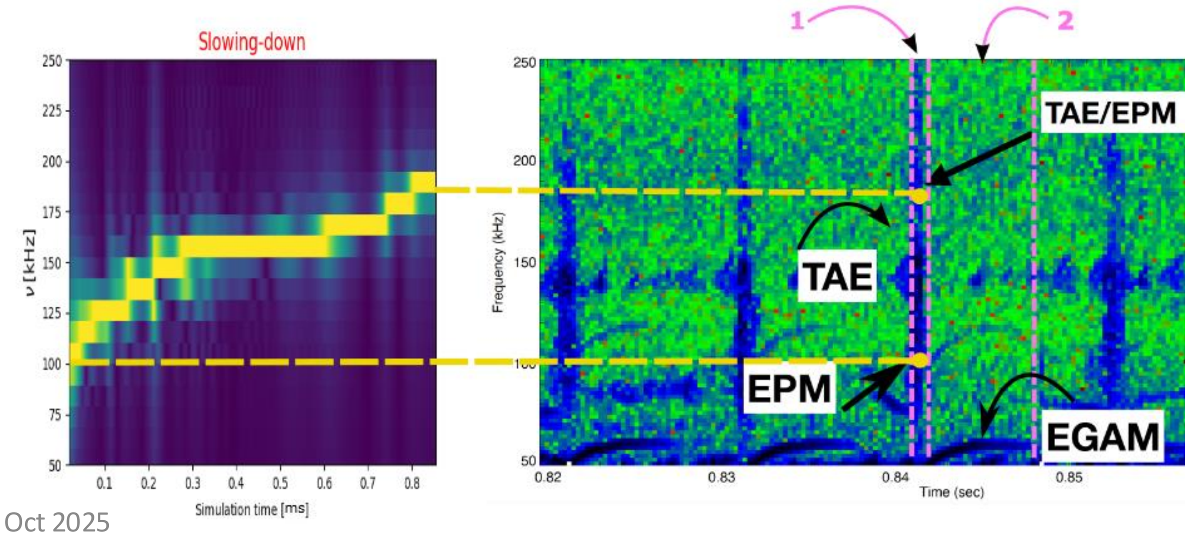
various parameter scans to map chirping rate vs saturation amplitude

Energetic particle density, energy, …

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

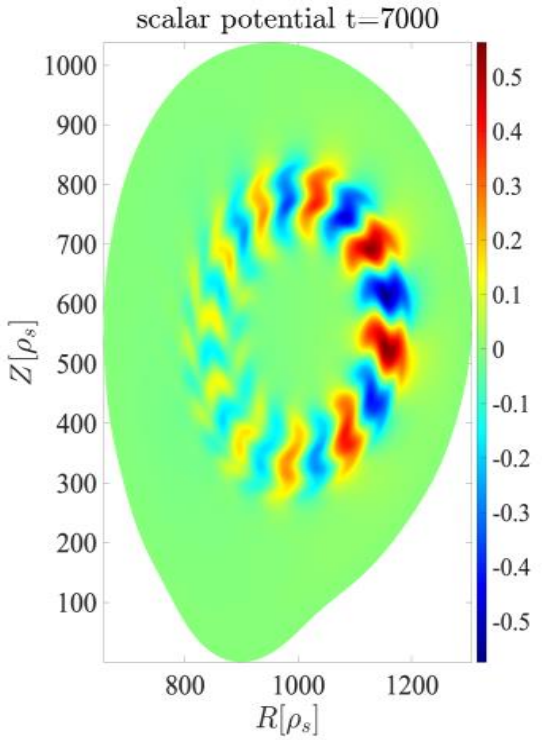


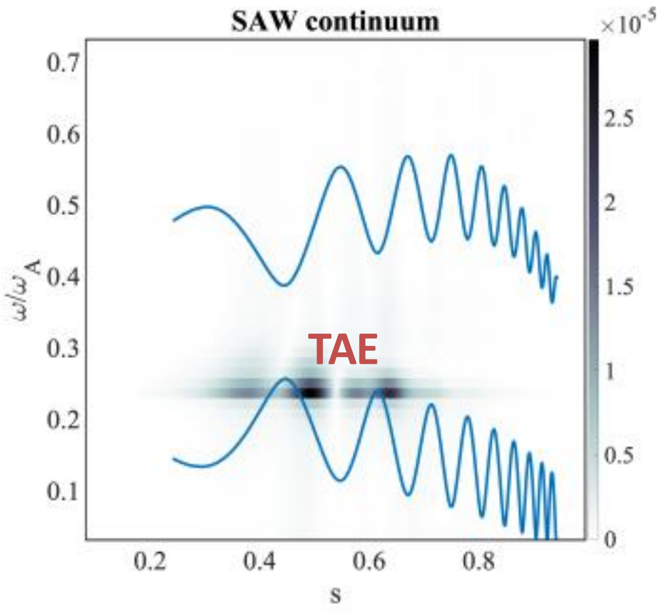
2. Simulations compared to experiment (<u>validation</u>):
ASDEX Upgrade discharge #312213@0.84s
Same chirping range in simulations as in experiment
Nucl. Fusion **62** 126042

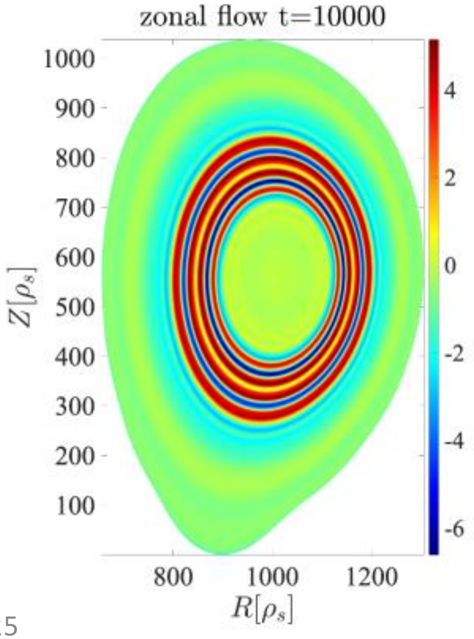


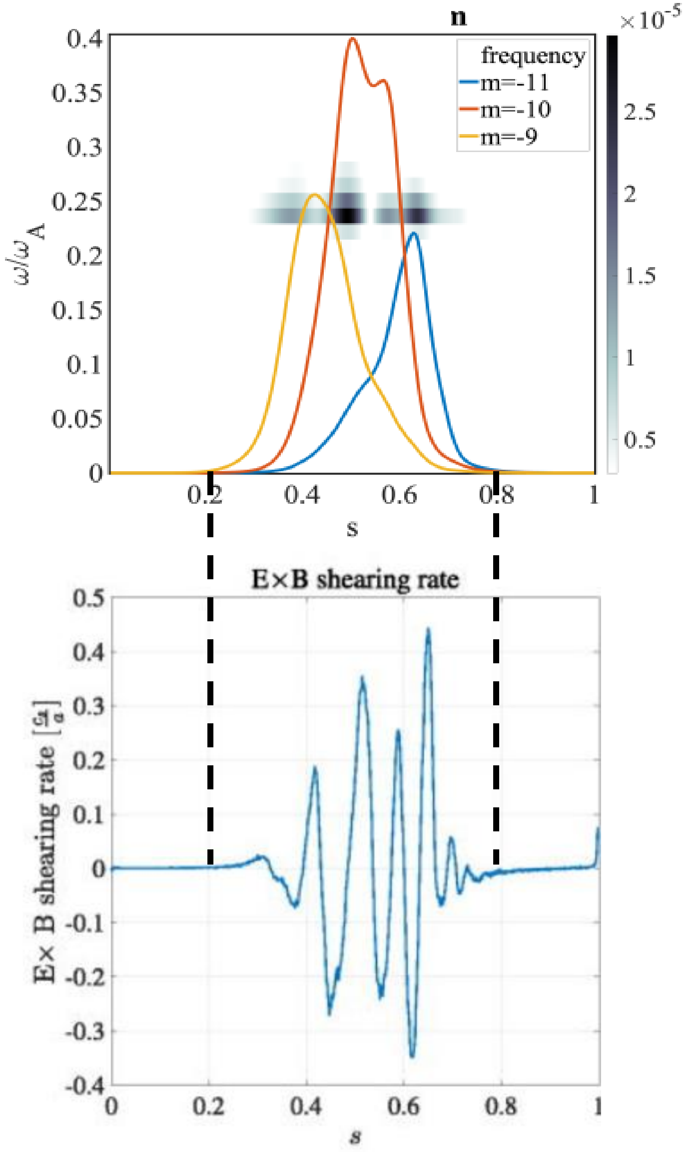
JET #92416: TAE simulations, beat-driven zonal flows

ORB5







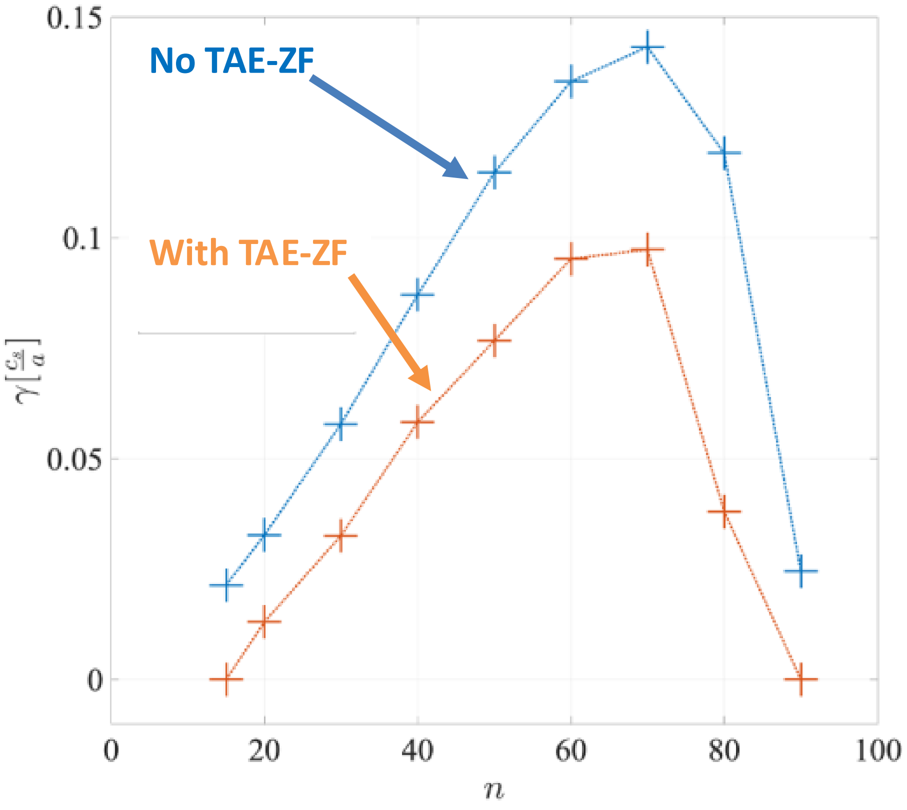


Fast-ion destabilized TAE generates beat-driven zonal flow (double growth rate of TAE).

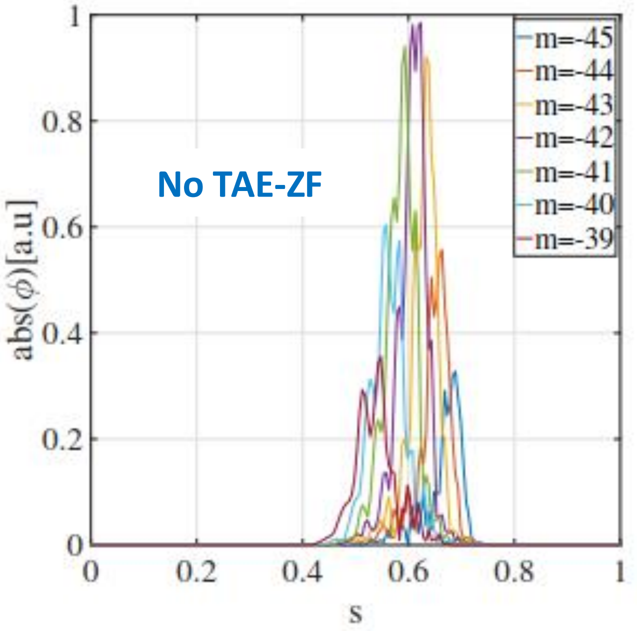
Radial location of zonal flow is determined by the TAE structure.

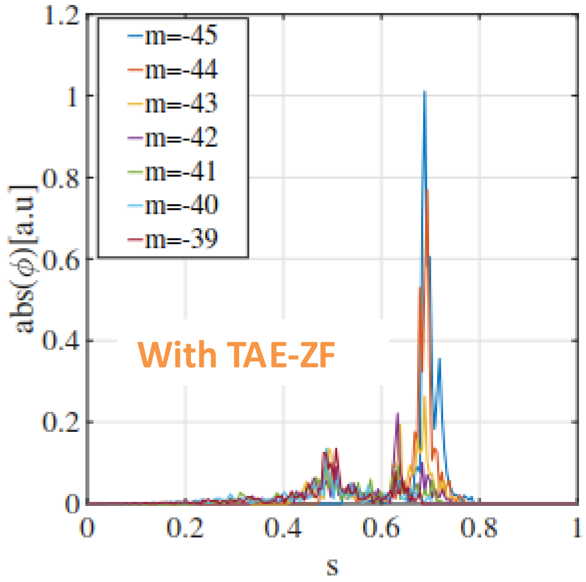
JET #92416: ITG simulations, TAE-driven zonal flows suppresses ITG (mode structure)

ORB5



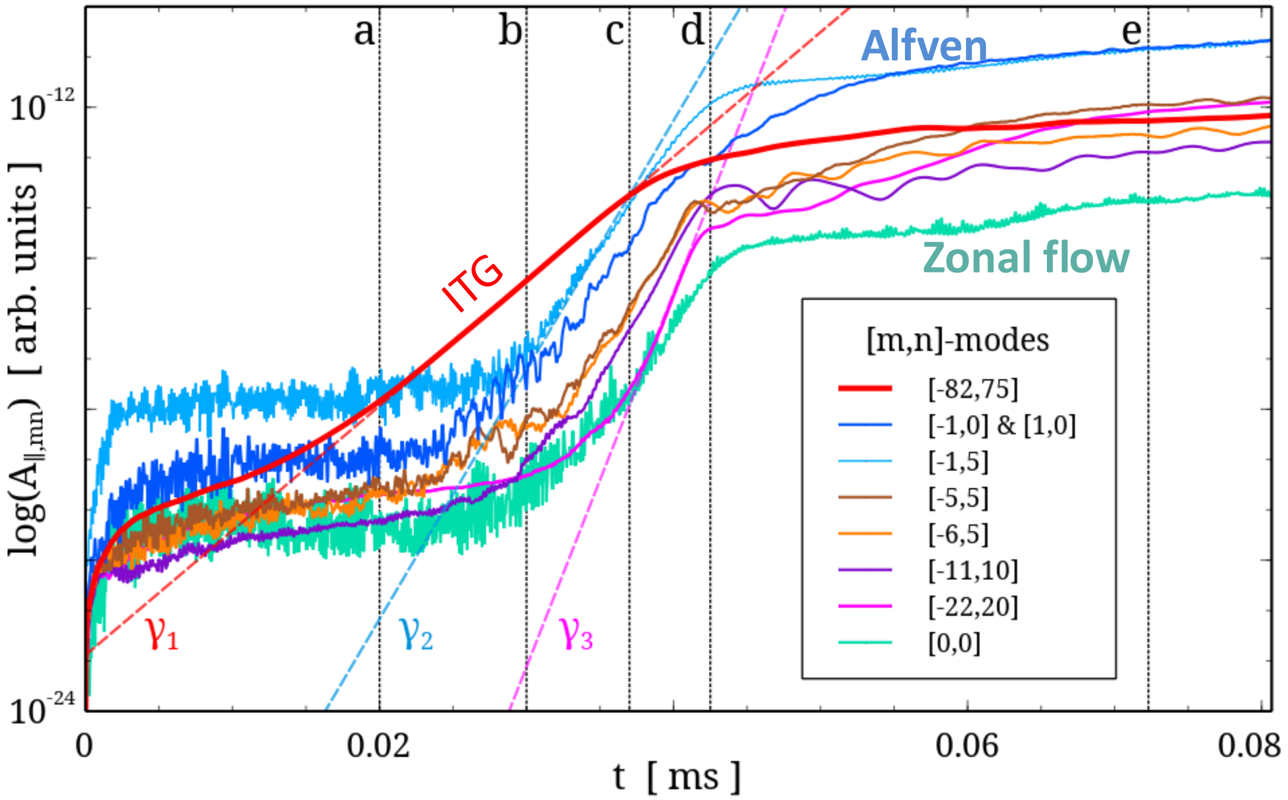
Beat-driven zonal flow mitigates ITG instability (antenna-emulated ZF)





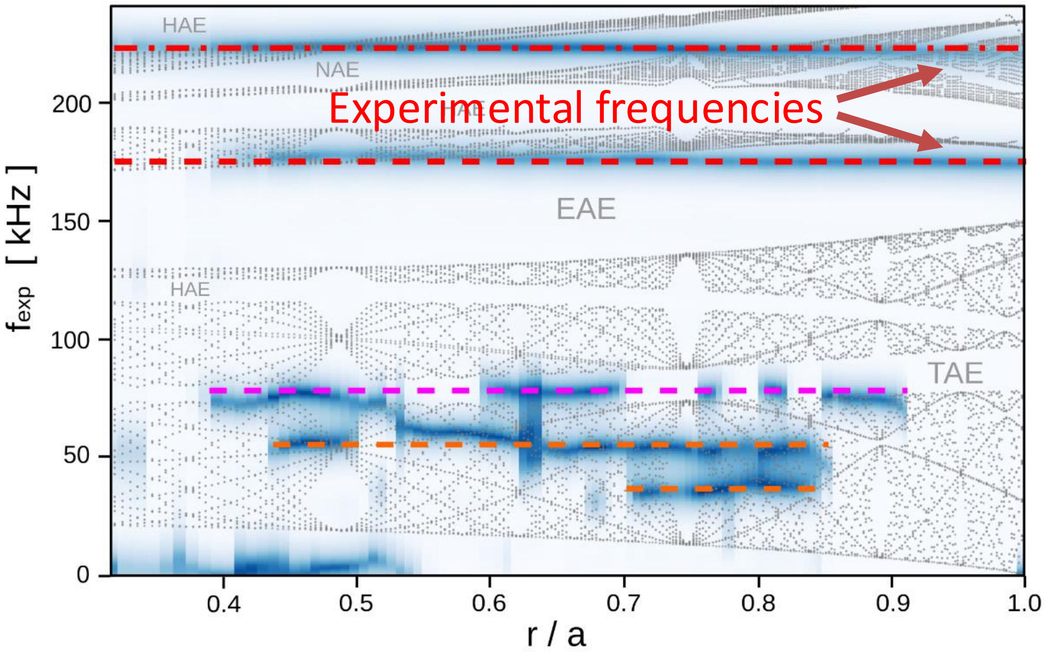
TAE-driven zonal flows strongly affect mode structure of ITGs

Simulations: Alfvénic Modes and Electromagnetic Turbulence in Wendelstein 7-X



EUTERPE

Simulation results:



- early ITG (high-m) activity
- Zonal Flow & Alfvénic modes when ITG amplitude has passed threshold
- growth rate cascade $\gamma_1 : \gamma_2 : \gamma_3 = \gamma : 2\gamma : 3\gamma$ (similar to "beat-driven" ZFs)

The role of ITG activity:
1. ITG modes included in simulations → low-m Alfvénic modes nonlinearly excited
2. ITG modes excluded from simulations → low-m modes remain stable

Gyrokinetic simulations recover experimental frequencies

J. Riemann, S. Vaz Mendes, et al., *Phys. Rev. Lett.* **134**, 025103 (2025)

Gyrokinetic simulations of MHD-unstable stellarator configurations

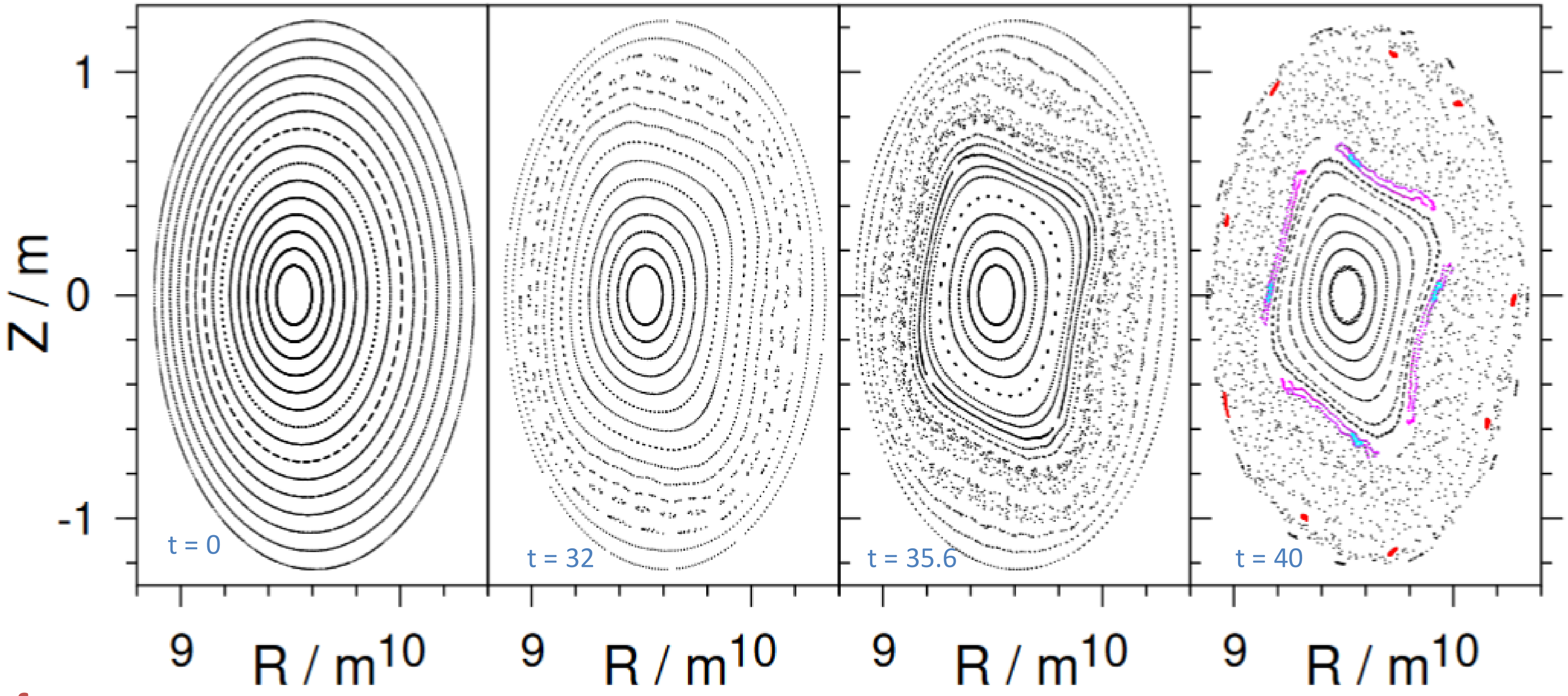
- Consider 4-period stellarator
- Choice: Mercier-unstable at finite β (not a reactor candidate)
- Perform full-torus GK simulations
- Find good agreement with MHD (CAS3D, CKA) in linear phase.

First-ever benchmark of global MHD with global gyrokinetics in stellartors!

EUTERPE

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

⟨β⟩ = 0.006



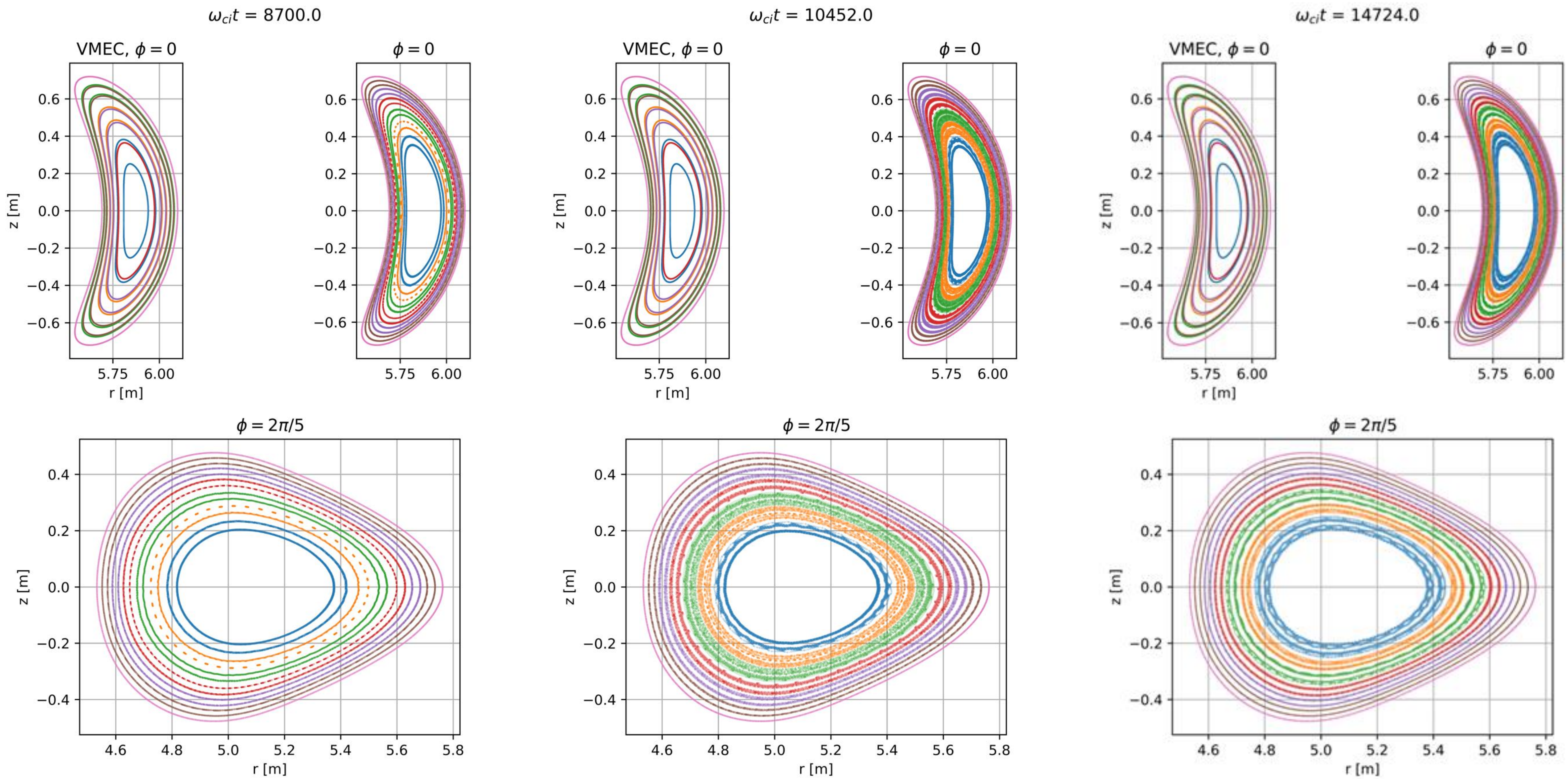
Soft decay of magnetic surfaces.
No disruptive dynamics!
Soft beta limit in stellarators.

MHD instabilities in stellarator destroy flux surfaces. Magnetic configuration is affected.

C. Nührenberg et al. *Journal of Plasma Physics.* **91**(4):E93 (2025)

First-ever fully gyrokinetic simulations of nonlinear MHD in stellarator plasmas!

EM turbulence in W7-X UFM (<β>=4.16%) configuration (Y. Narbutt)



Conclusions

- Turbulence, zonal flows, Alfvénic modes, energetic particles, MHD-like perturbations coexist and affect each other
- Global nonlinear gyrokinetics is a minimal inclusive approach for this system
- ORB5 and EUTERPE codes provide such a framework; enabled by numerous improvements in algorithms
- First-in-kind simulations of nonlinear plasma evolution shown in tokamak and stellarator geometries
- Our work is done in the scope of EUROfusion‘s E-TASC program (TSVV Task 10 „Burning plasmas“)
- Availability of E-TASC software ecosystem will make a qualitative difference for future fusion reactor projects
- This ecosystem will benefit both public and private sectors of future fusion industry

References

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- J. Riemann, S. Vaz Mendes, et al., *Phys. Rev. Lett.* **134**, 025103 (2025)
- C. Nührenberg et al. *Journal of Plasma Physics*. **91**(4):E93 (2025)