Overview of simulations conducted by TSVV-10 on Marconi's (CPU and GPU)

A. Mishchenko on behalf of TSVV10

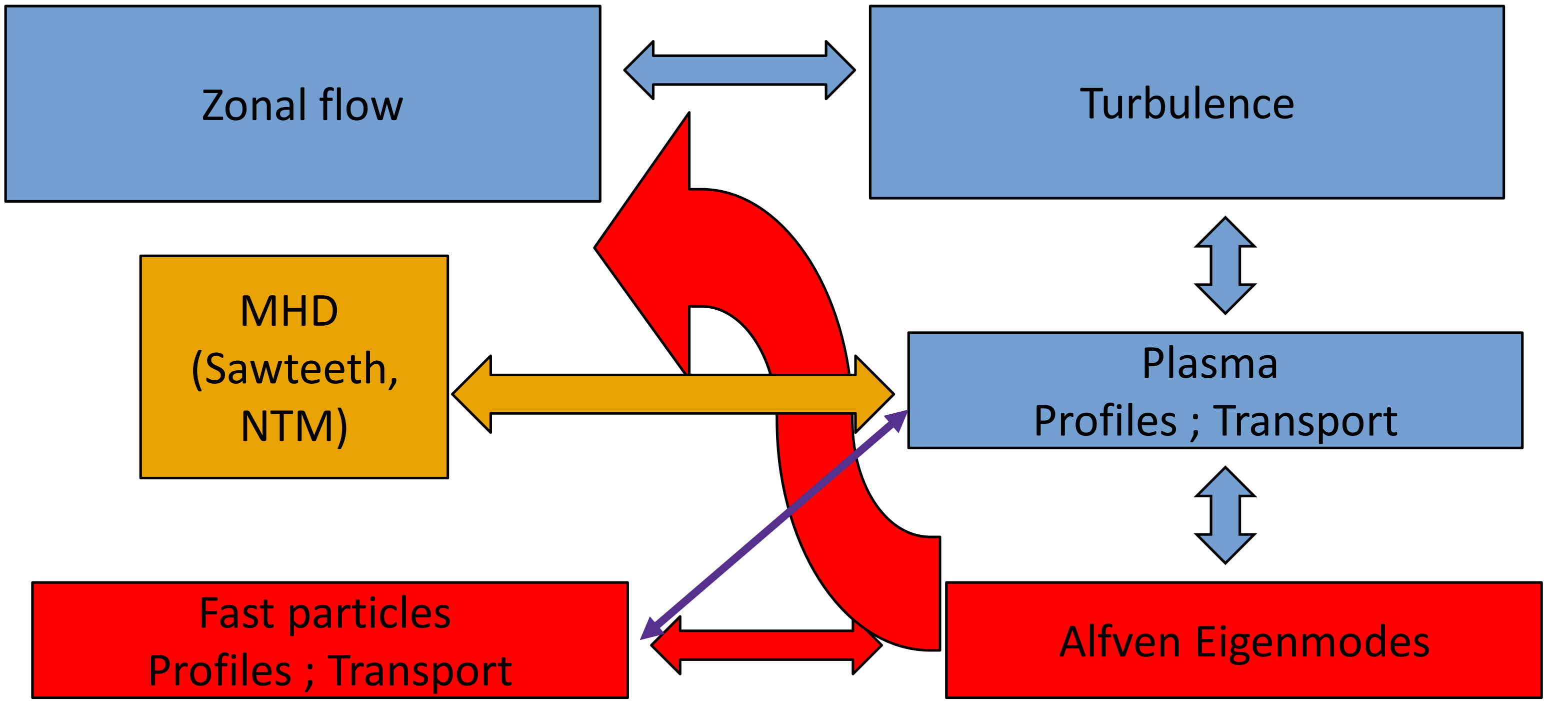
This work was supported in part by the Swiss National Science Foundation. Simulations presented in this work were performed on the MARCONI FUSION HPC system at CINECA. We acknowledge PRACE for awarding us access to Marconi100 at CINECA, Italy. We acknowledge PRACE for awarding us access to Joliot-Curie at GENCI@CEA, France.

MAX-PLANCK-INSTITUT FÜR PLASMAPHYSIK

This work has been carried out within the framework of the EUROfusion Consortium, funded by the European Union via the Euratom Research and Training Programme (Grant Agreement No 101052200 — EUROfusion). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Commission. Neither the European Union nor the European Commission can be held responsible for them.

System couplings in burning plasmas

- Energetic Particles (EP) are abundant in burning plasmas
- “Meso-scale” EP dynamics introduces couplings across scales



Single framework

- Burning plasmas will have high beta and include energetic particles
- Presence of energetic particles creates complex coupled system
- Single framework including all parts consistently is needed
- Many parts of the problem are kinetic and global
- Many connections between the parts are kinetic and global
- Global gyrokinetic theory is a minimal inclusive description
- Global gyrokinetics requires intensive computation (exa-scale)

Energetic particle orbits, global Alfvénic and MHD modes, shear Alfvén continuum, avalanches, profile corrugations, phase-space structures (holes/clumps), reconnection/turbulence, Alfvén Eigenmodes-zonal flows-turbulence, …

Gyrokinetic equations (mixed variables)

https://doi.org/10.1088/1361-6587/ac0bcb

The equations include the gyrokinetic Vlasov equation:

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

the equations for the gyro-center orbits:

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

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

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

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

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

$$B_\|^* = B + \frac{m v_\|}{q} \boldsymbol{b} \cdot \nabla \times \boldsymbol{b} \;, \tag{7}$$

Field equations:

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

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

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

Gyrokinetic particle-in-cell codes

- "Klimontovich" representation for perturbed distribution function:

$$\delta f_s(\boldsymbol{R}, v_\|, \mu, t) = \sum_{\nu=1}^{N_p} w_{s\nu}(t)\delta(\boldsymbol{R} - \boldsymbol{R}_\nu)\delta(v_\| - v_{\nu\|})\delta(\mu - \mu_\nu) \ ,$$

- Maxwellian distribution for all species:

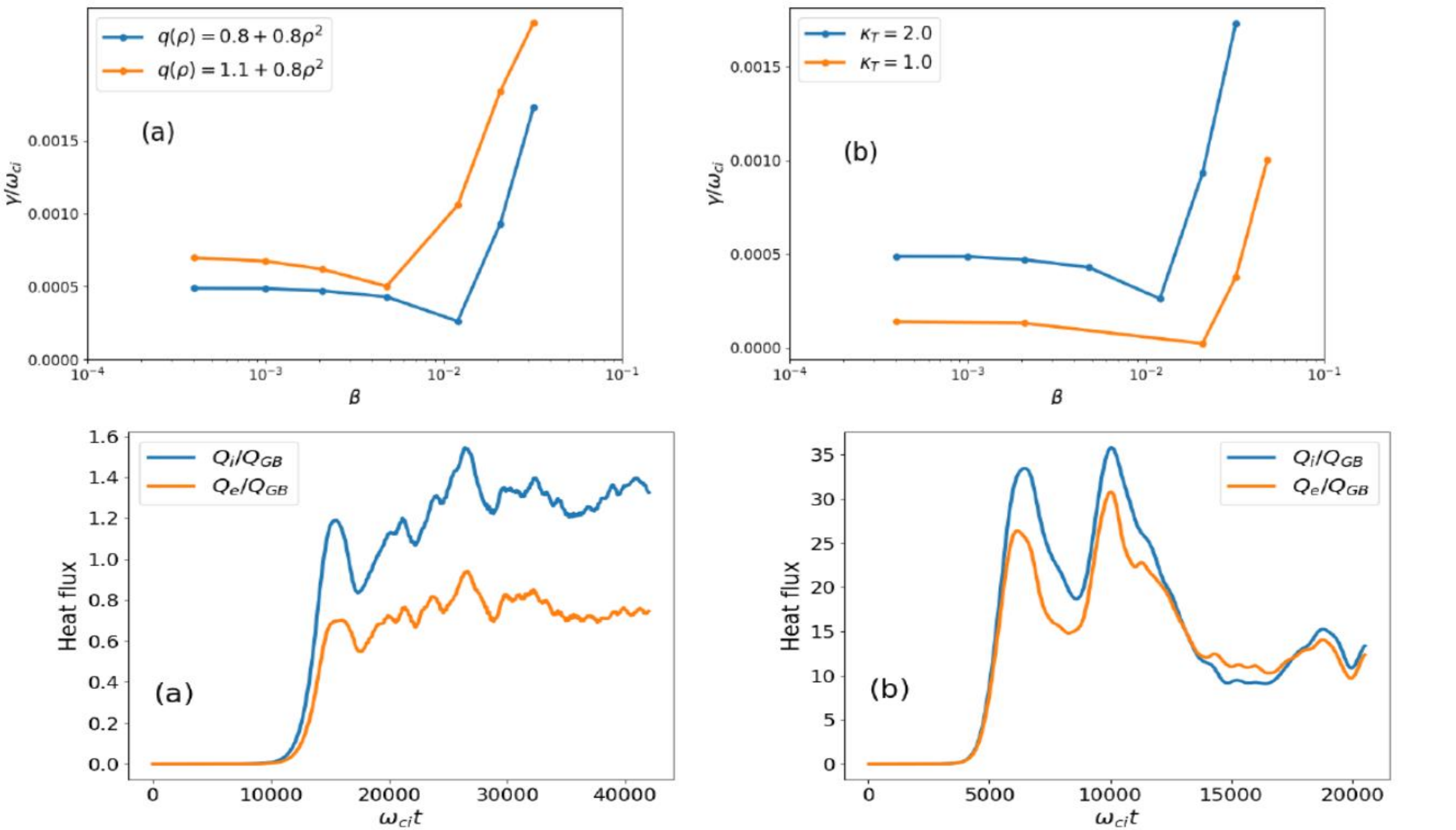
$$F_{0s} = n_0 \left(\frac{m}{2\pi T_s}\right)^{3/2} \exp\left[-\frac{m_s v_\|^2}{2T_s}\right] \exp\left[-\frac{m_s v_\perp^2}{2T_s}\right]$$

- Finite-element discretization for fields:

$$\phi(\boldsymbol{x}) = \sum_{l=1}^{N_s} \phi_l(t)\Lambda_l(\boldsymbol{x}) \ , \quad A_\|(\boldsymbol{x}) = \sum_{l=1}^{N_s} a_l(t)\Lambda_l(\boldsymbol{x}) \ ,$$

- Larmor structure for GPU-enabling in ORB5; openacc
- GPU-enabling of EUTERPE: separate routines for different particle species;
- openacc, now transitioning to openmp 5.x (wider support, more architectures)
- Replacing „globals“ (global data) with Fortran abstract types
- Gradual transition of the code base (EUTERPE) to C++
- Following general trends in HPC (abstract types, C++, accelerated hardware)
- Better access to accelerator frameworks (such as Kokkos)

Electromagnetic turbulence in tokamak plasmas



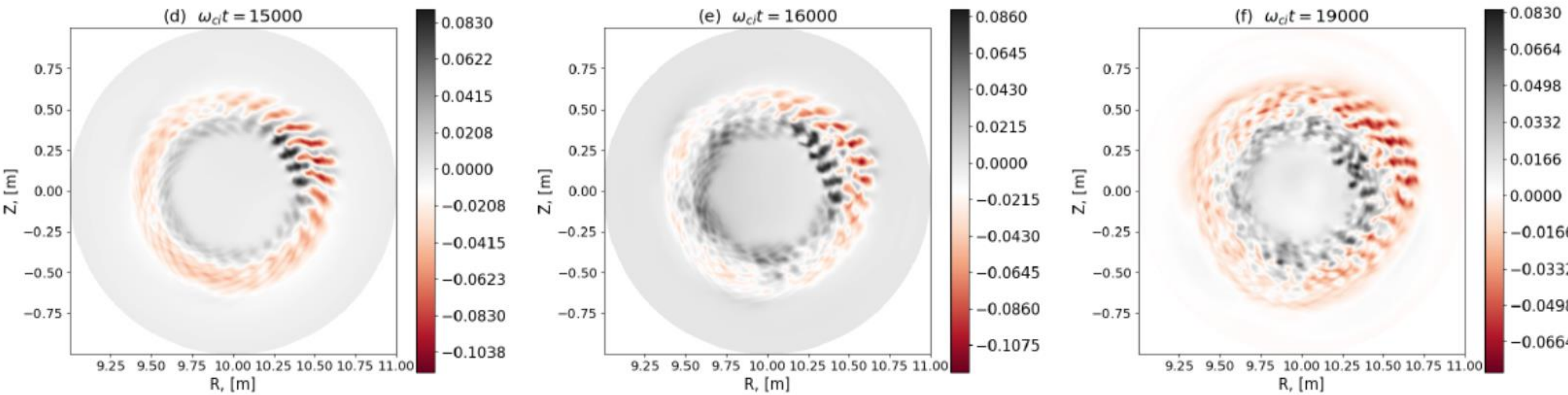
(1) Linear growth rate in circular-shaped tokamak for different safety factor profiles and temperature gradients showing electromagnetic ITG-to-KBM transition (ORB5 simulations on Marconi100, CINECA). Heat flux in the gyro-Bohm units for (a) β = 0.1% (electromagnetic ITG) and (b) β = 2.08% (KBM regime). The heat flux is considerably larger in KBM regime.

No “electromagnetic run-away” in global tokamak simulations.

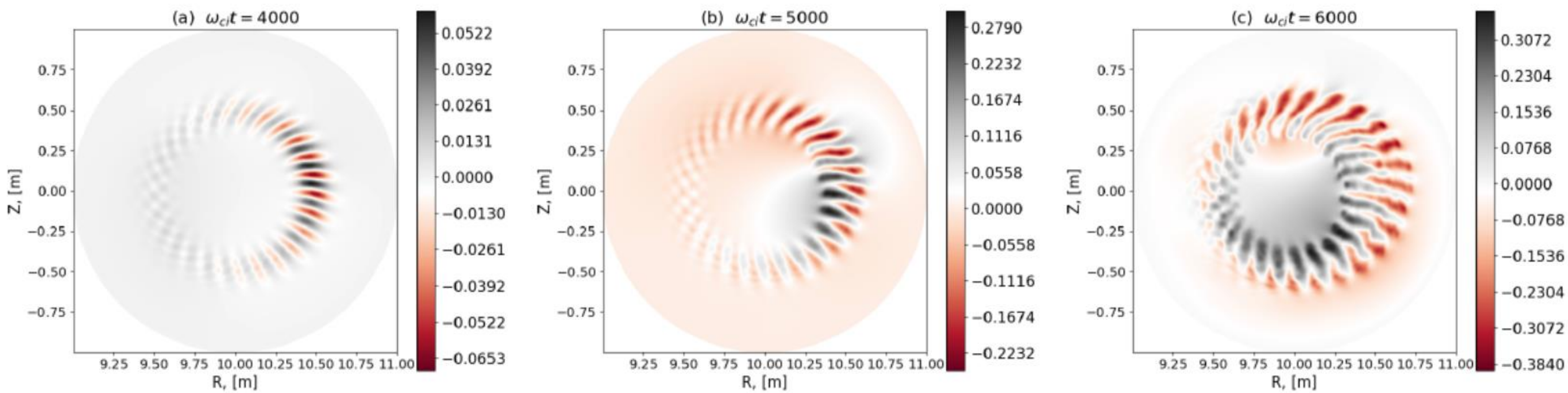
MAX-PLANCK-INSTITUT FÜR PLASMAPHYSIK

EUROfusion

EM turbulence in circular cross-section tokamak

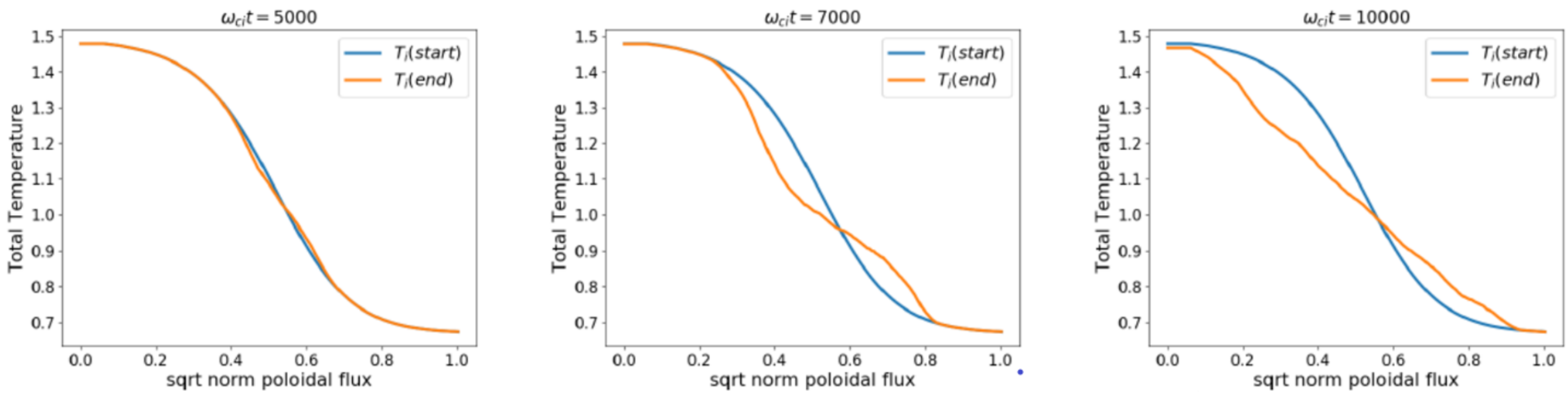


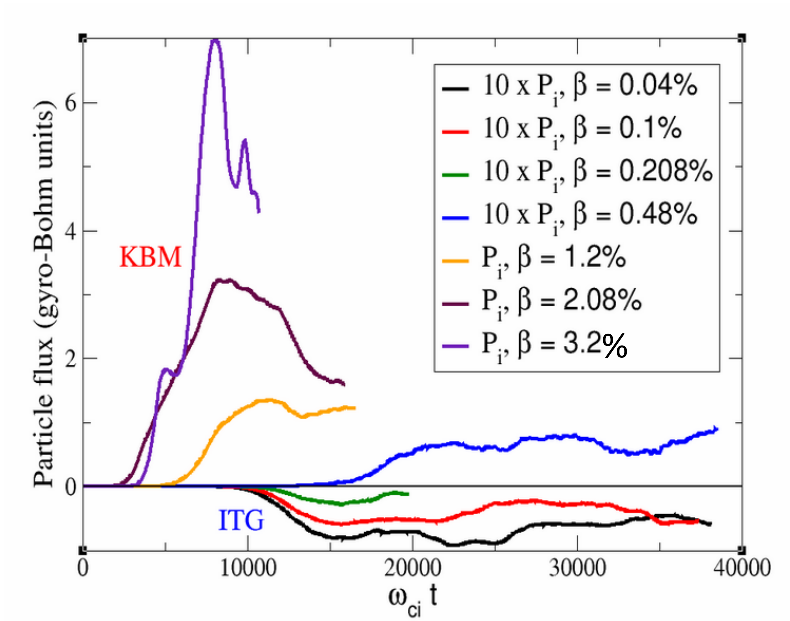
“Eddy shearing”in EM-ITG regime



Finger-like structures expelled out of “drive region” in KBM regime

EM turbulence in circular cross-section tokamak



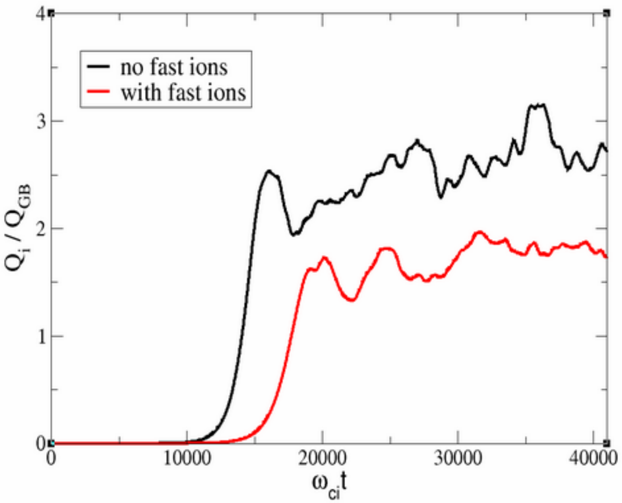


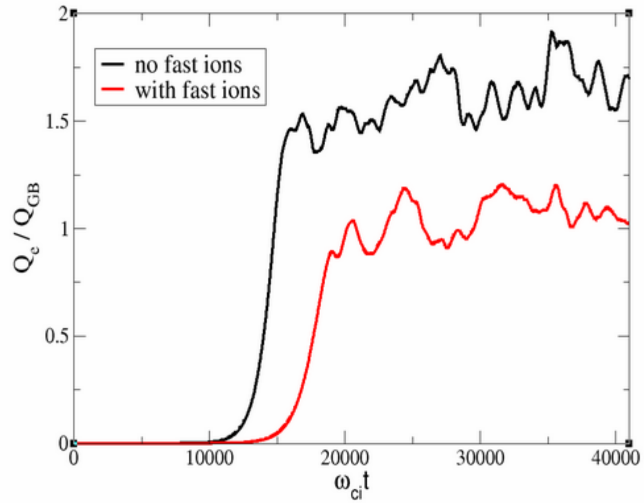
Evolution of KBM finger-like structures is accompanied by strong avalance-like relaxation of temperature profile

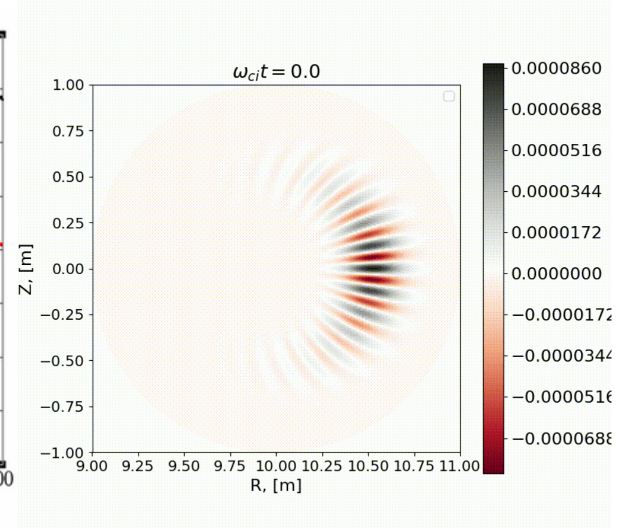
Particle flux is inward for ITGs and outward for KBMs

Density peaking in the ITG regime

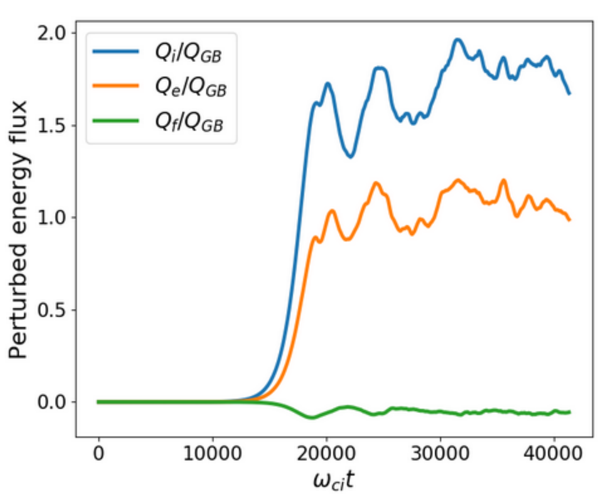
Fast ion stabilization of EM turbulence

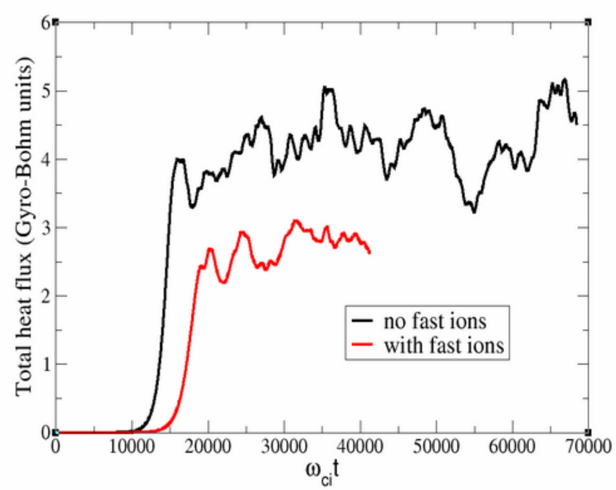


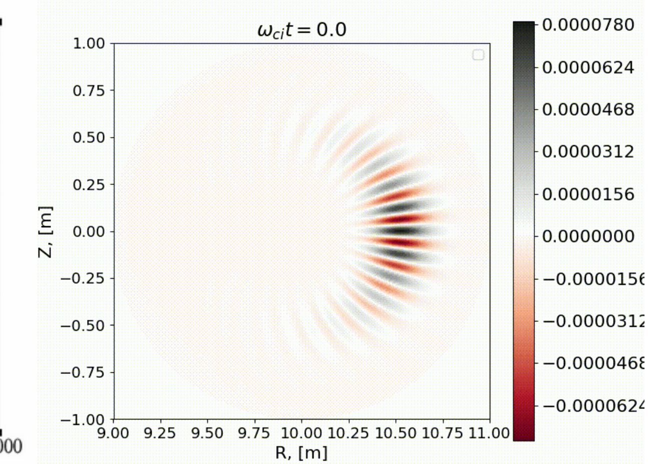




One observes a clear reduction in the heat flux for both the bulk ions and the electrons!

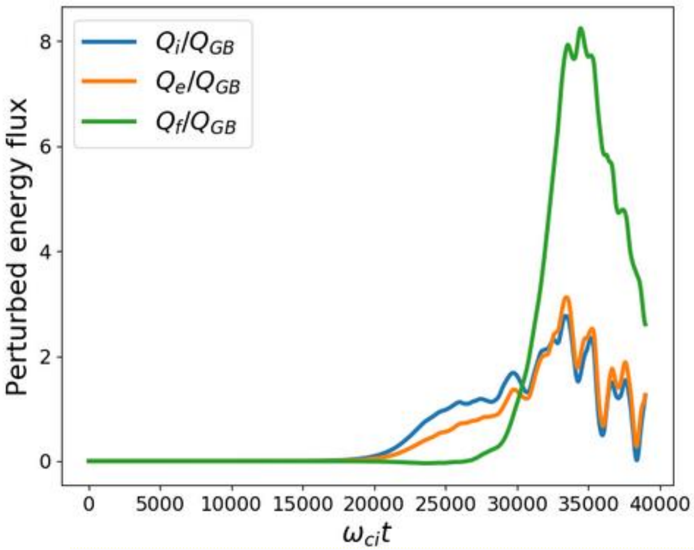


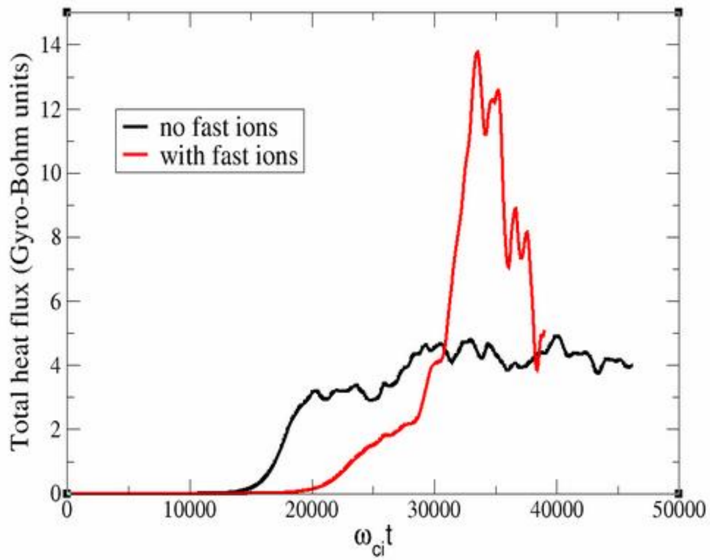




Fast ion do not transport much of energy. Total heat flux reduced by the fast ions! $\boldsymbol{\beta_e = 0.1\%}$

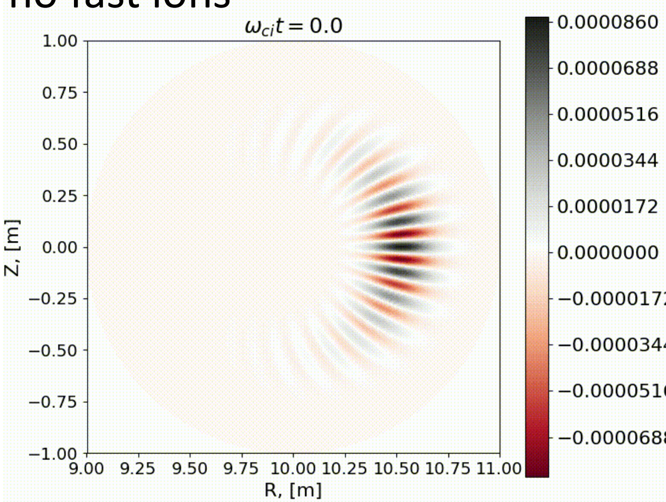
Fast ion stabilization of EM turbulence



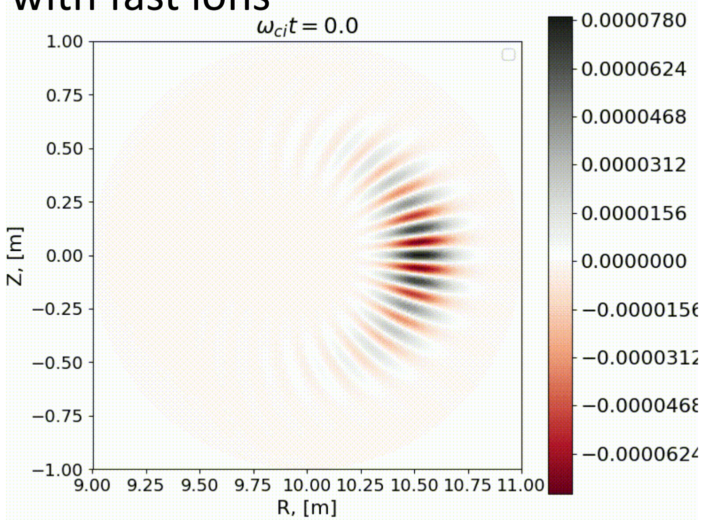


For $\boldsymbol{\beta_e = 0.24\%}$, the dynamics is different. Fast ion heat flux is substantial. Total heat flux is not reduced!

no fast ions

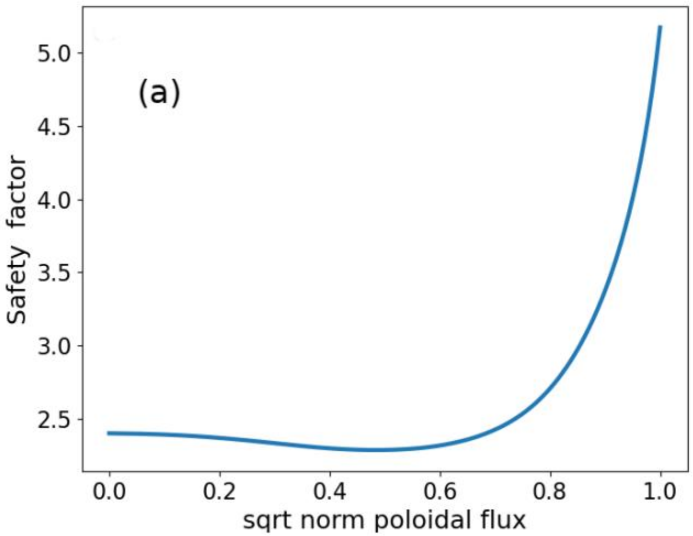


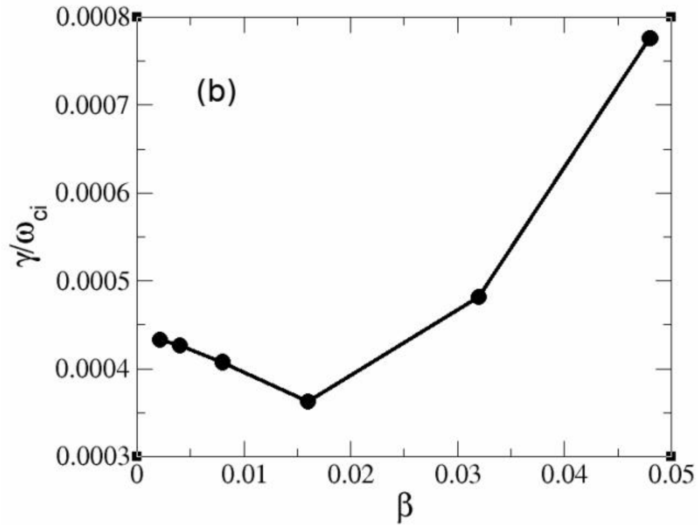
with fast ions



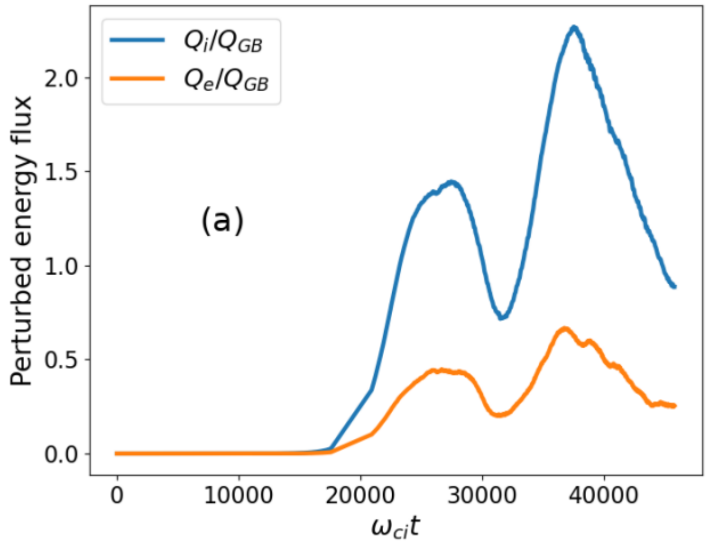
Global Alfvenic mode (a BAE?) develops driving fast ion energy flux. Work in progress!

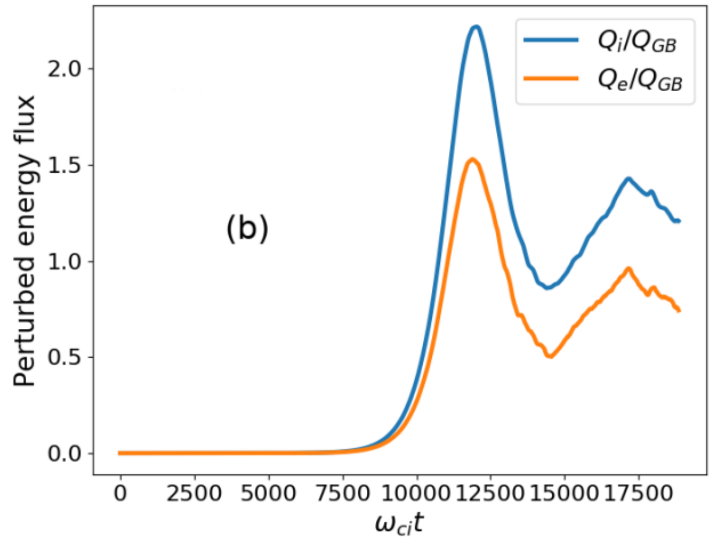
EM Turbulence simulations in ASDEX-Upgrade





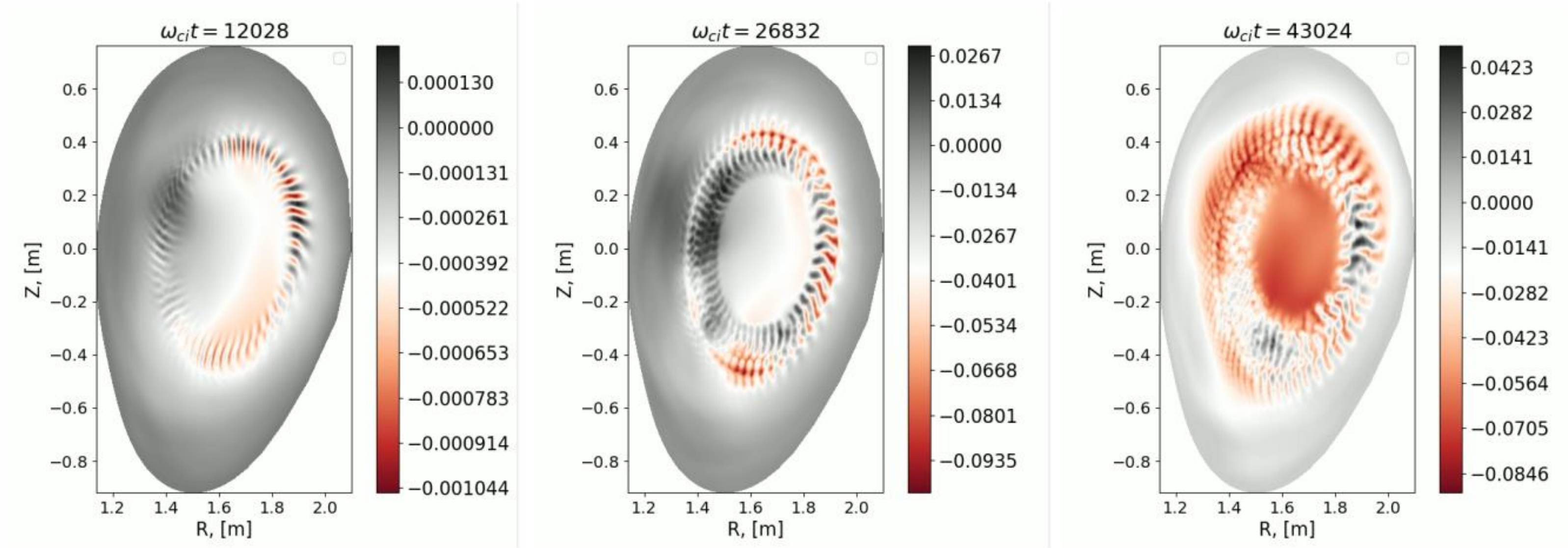
NLED-AUG case



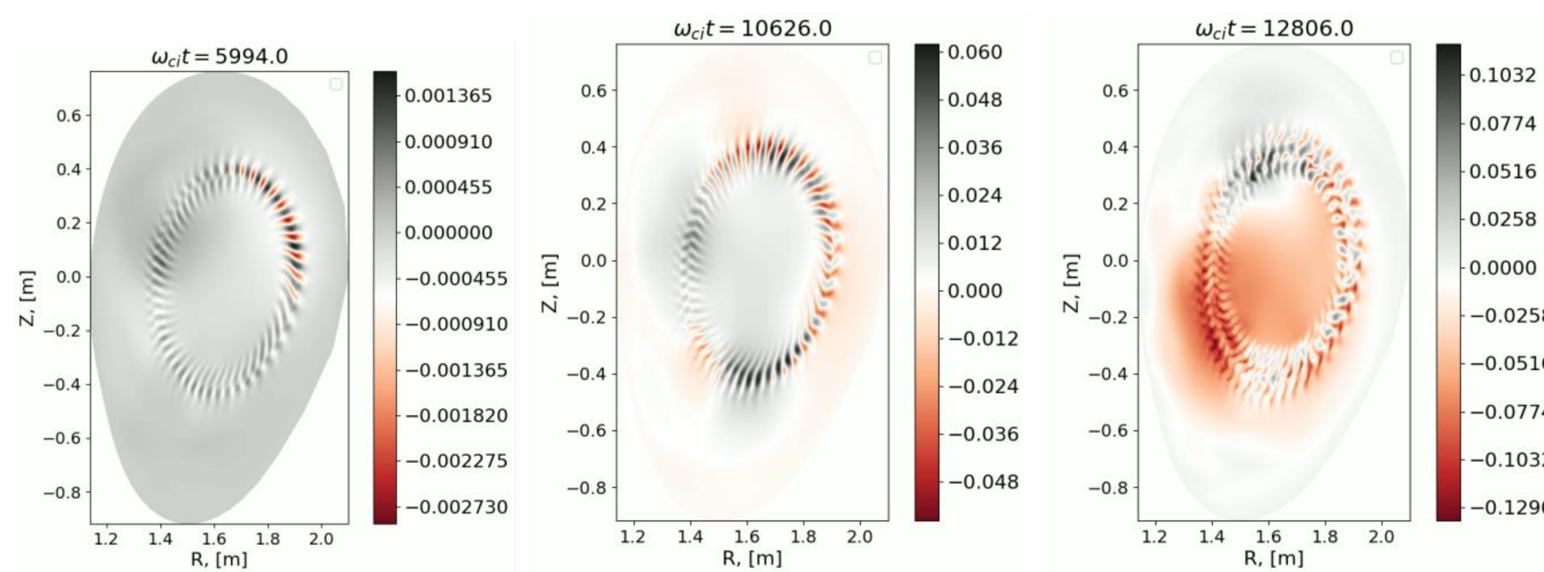


Oscillating fluxes may be caused by radial motion of max. gradient

Real-space mode structure in ASDEX-Upgrade

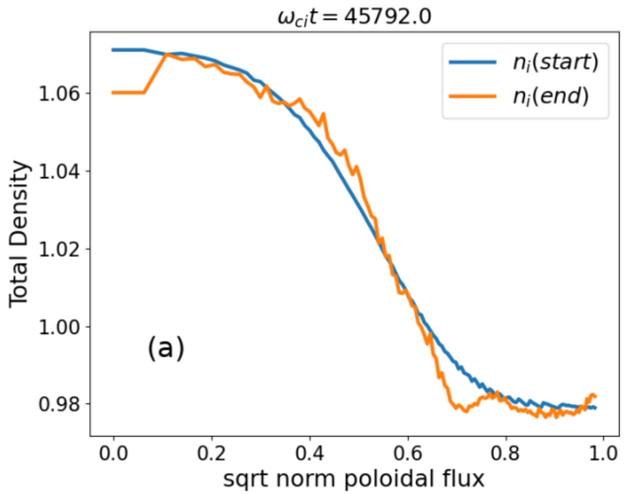


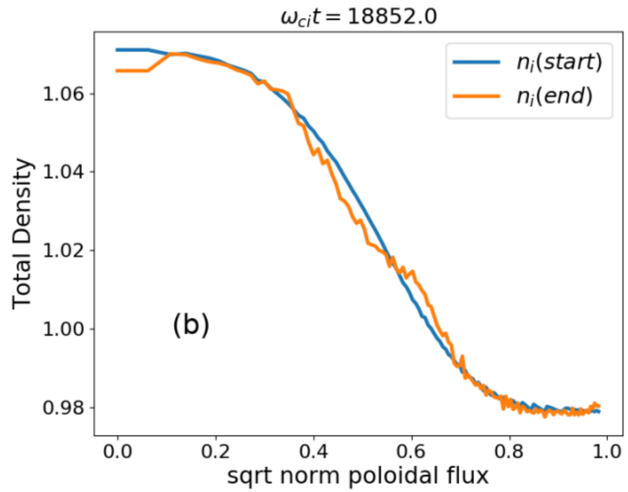
EM ITG, β = 0.4%



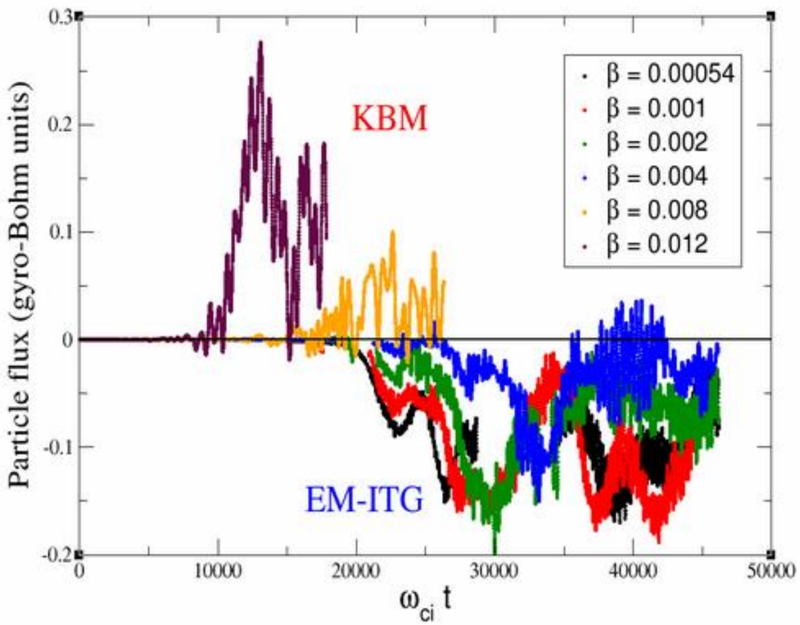
KBM, β = 4.8%

EM particle flux in ASDEX-Upgrade



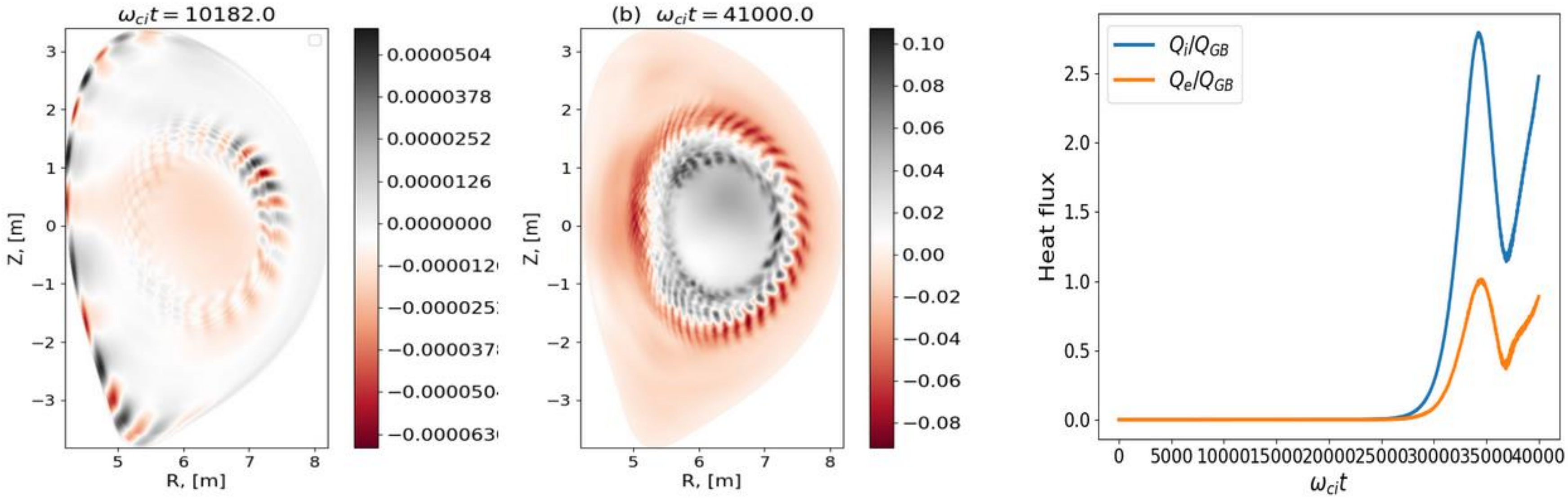


(a) β = 0.4% (EM-ITG)
(b) β = 4.8% (KBM)



- Inward particle flux is observed for ITGS
- For KBMs, particle flux changes sign (outward)
- Density peaking in ITG regime

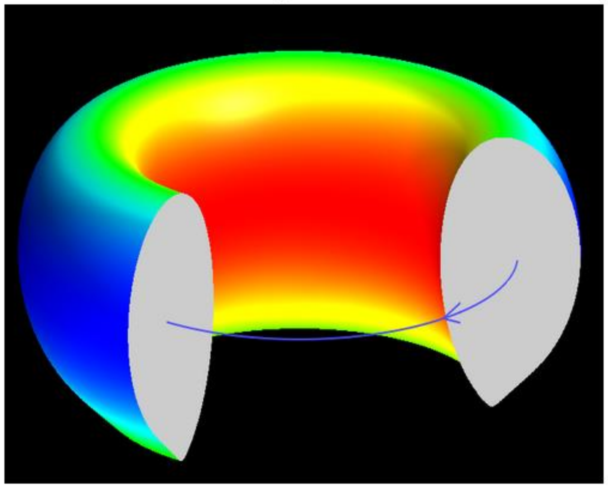
EM simulations in ITER geometry

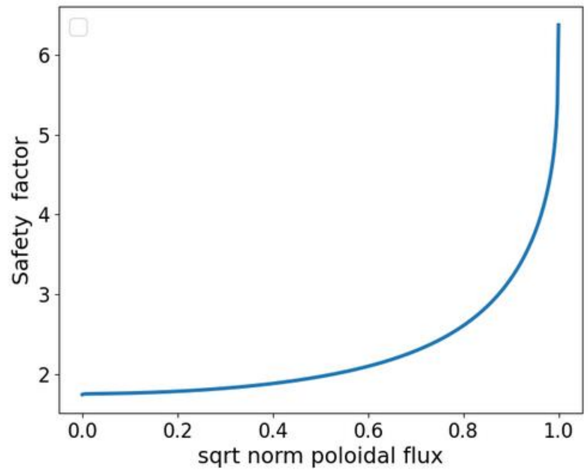


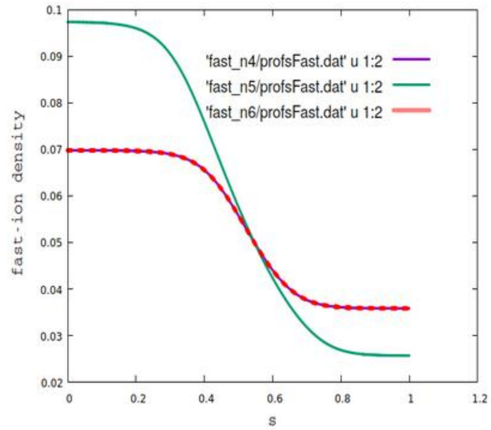
Simulation crashes for radial resolution 288 grid points (left)
but works fine for 512 points (middle and right)

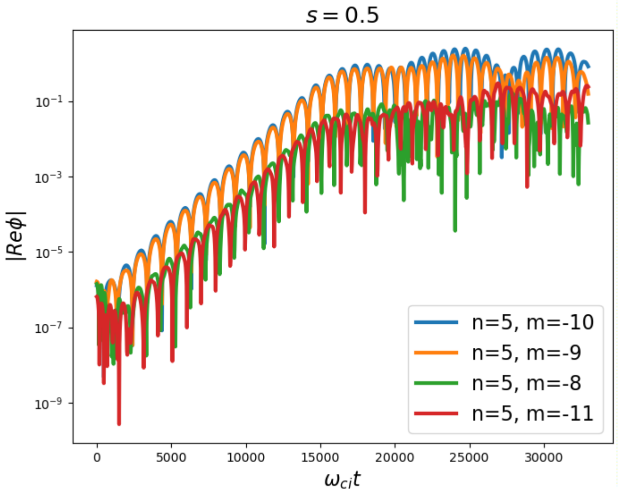
Here again: oscillations in the radial flux
Consequence of non-local profile relaxation?

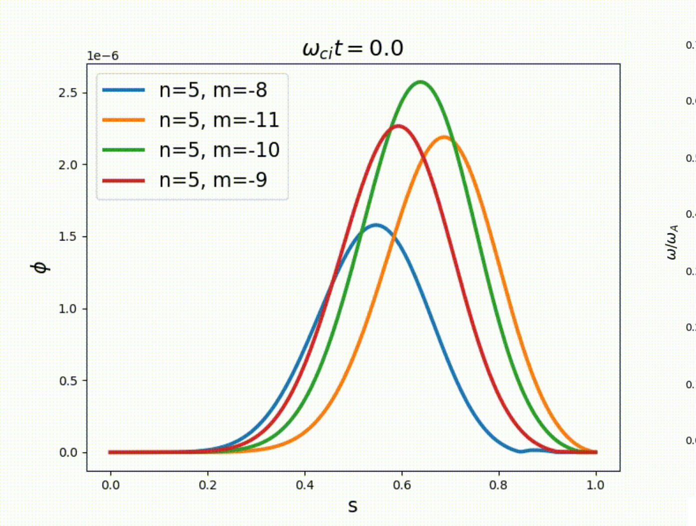
EM simulations in JET geometry

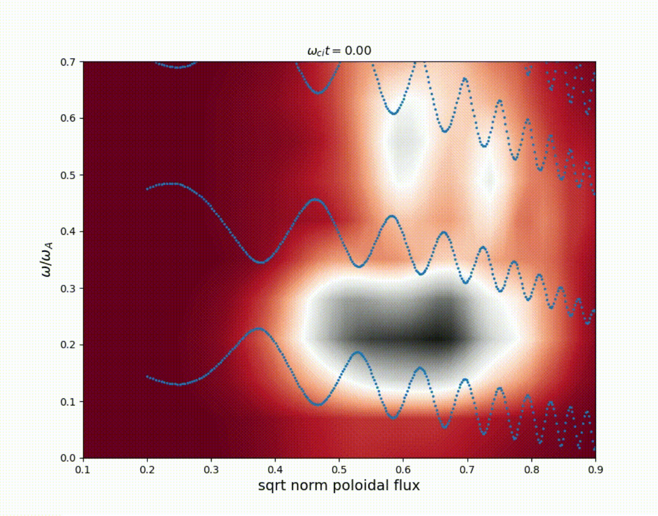






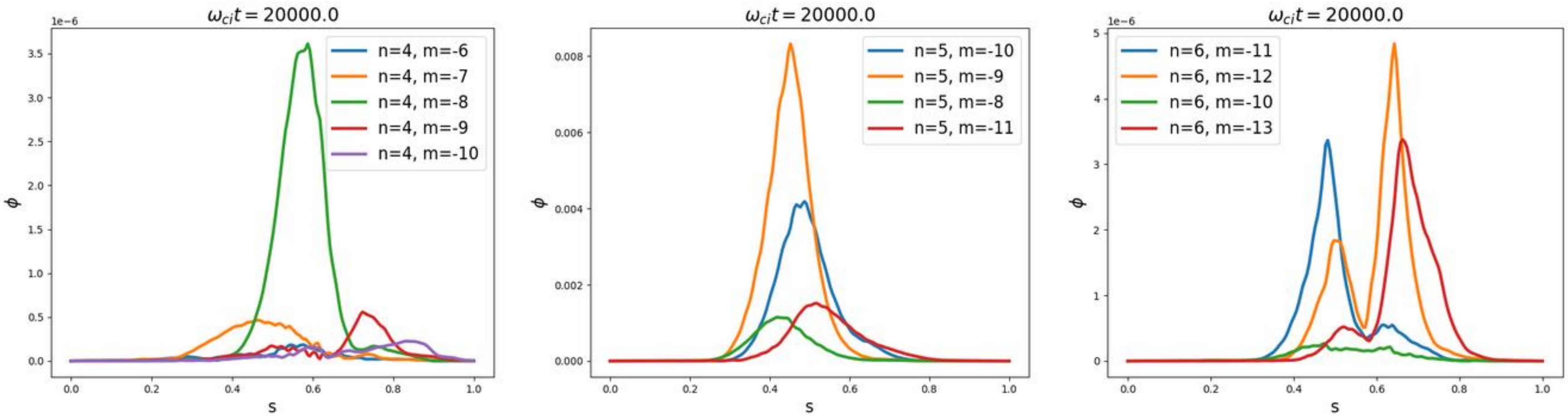




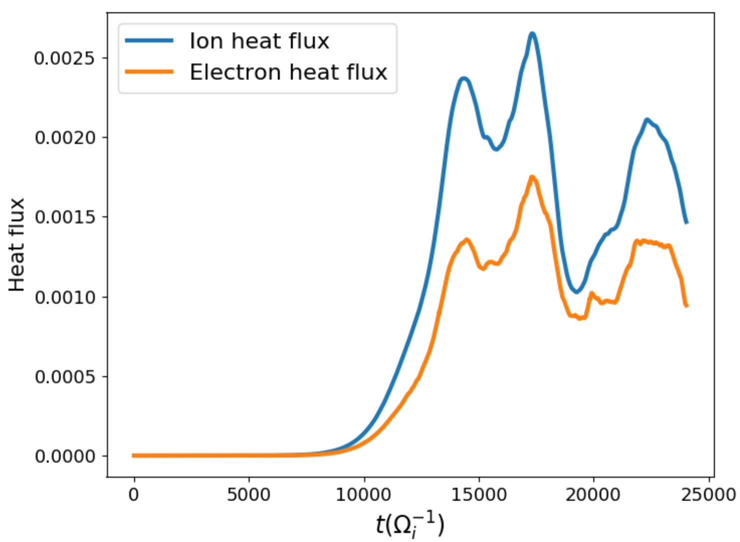


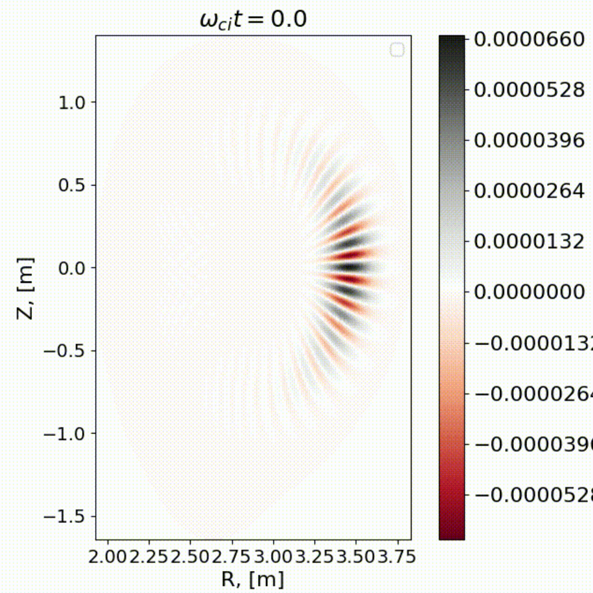
TAE and EPM instabilities in JET; frequency for n=5 TAE similar to LIGKA

TAE/EPM instabilities in JET and turbulence

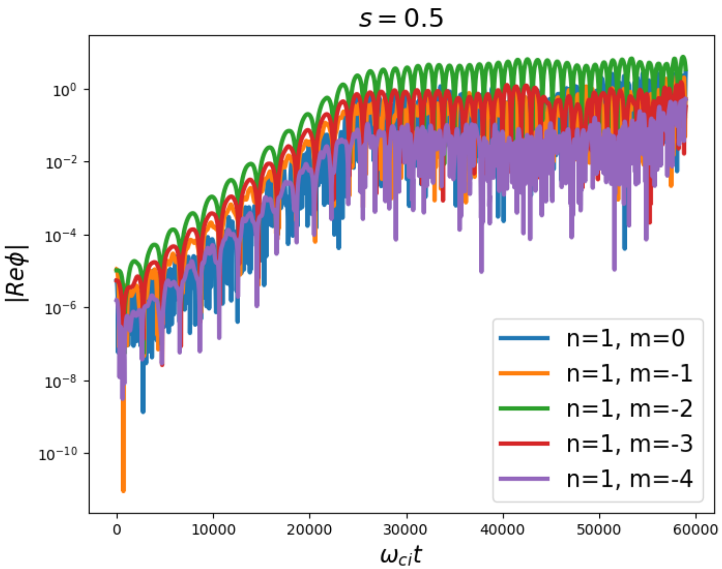


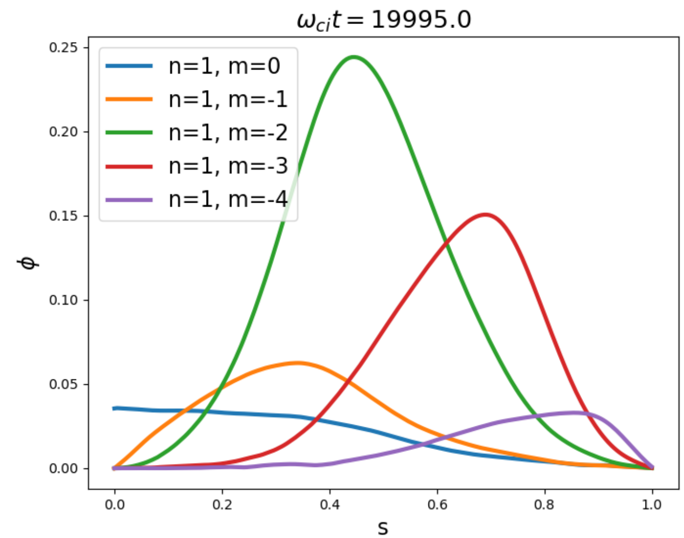
Mode structure: $n = 4$, $n = 5$, $n = 6$

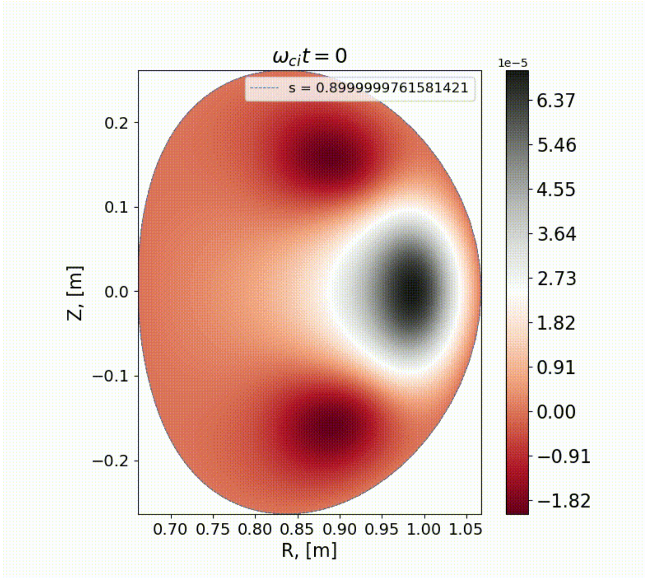


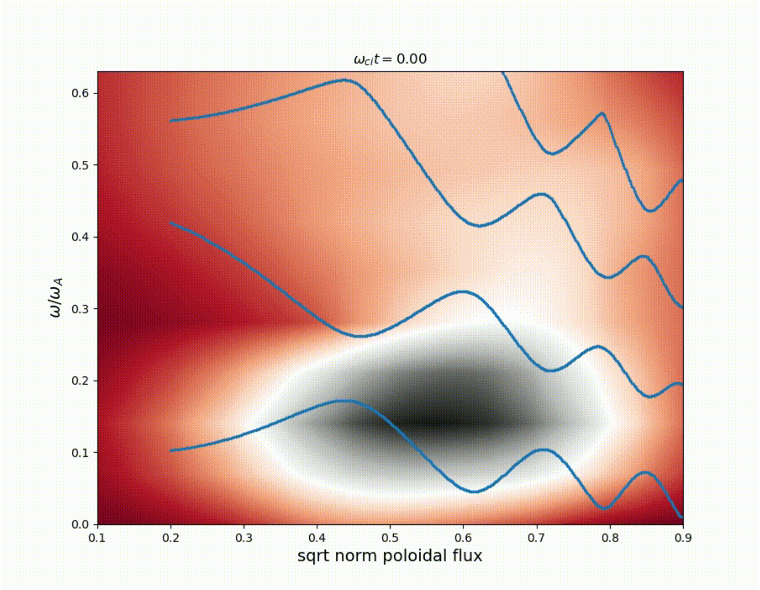


Chirping TAE/EPM instabilities in TCV





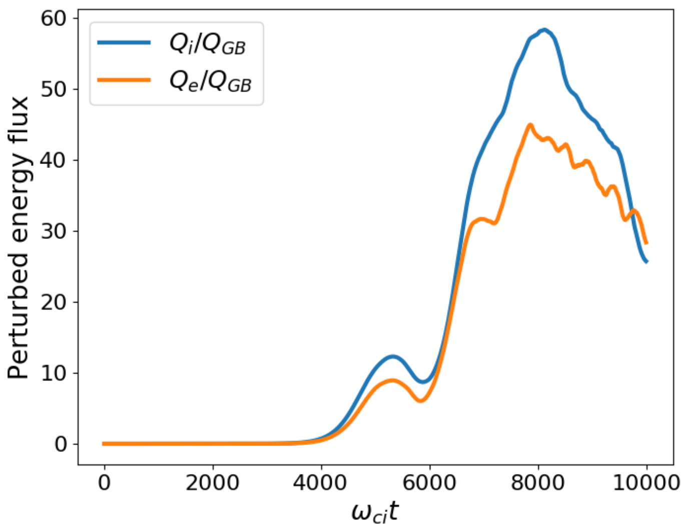


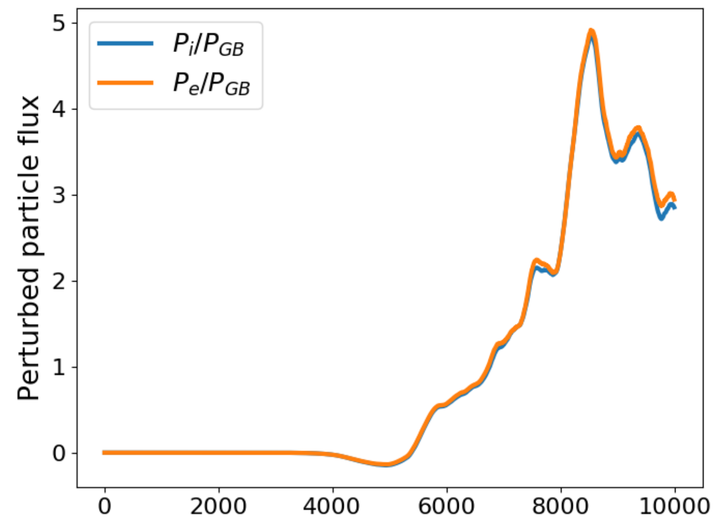


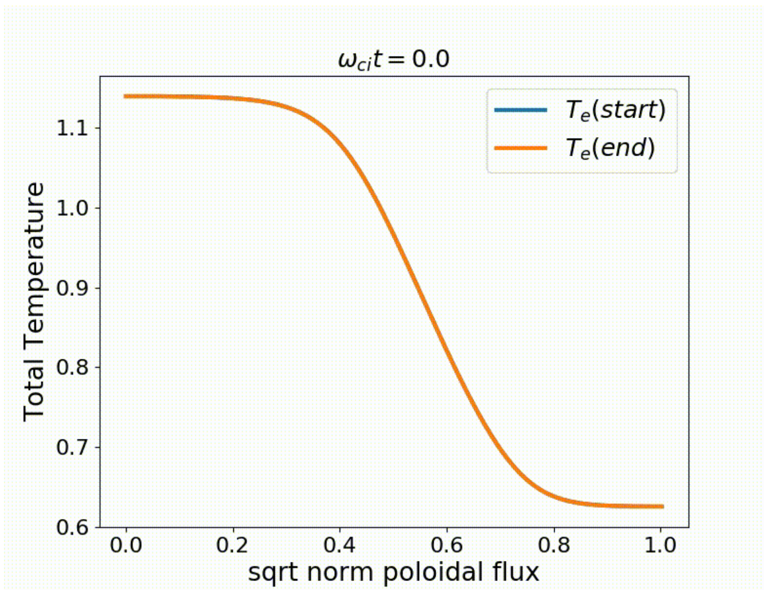
MAX-PLANCK-INSTITUT FÜR PLASMAPHYSIK

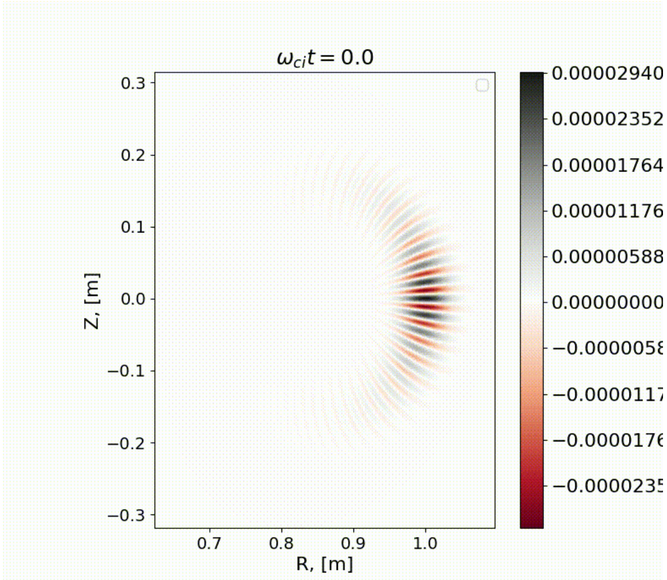
EUROfusion

Electromagnetic turbulence in TCV

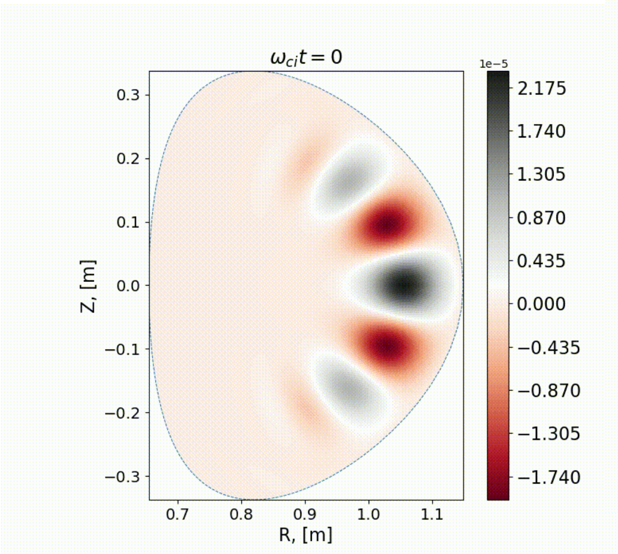


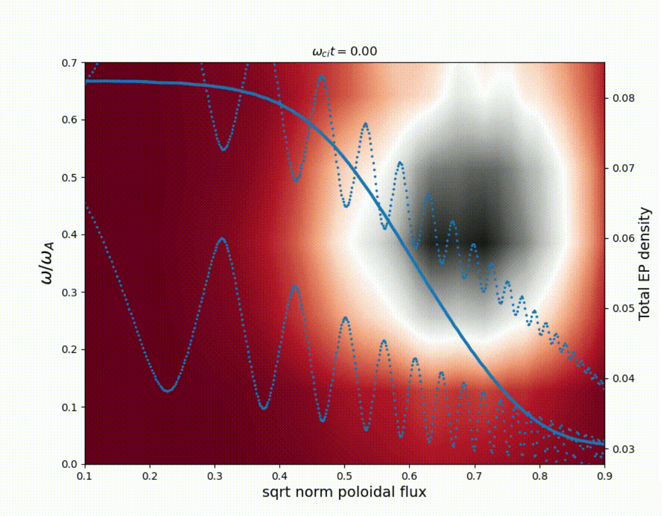


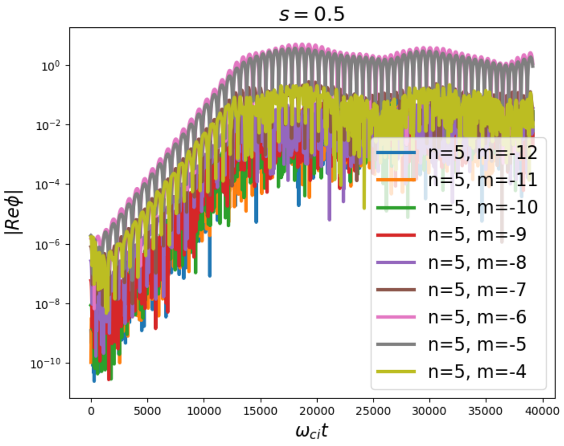


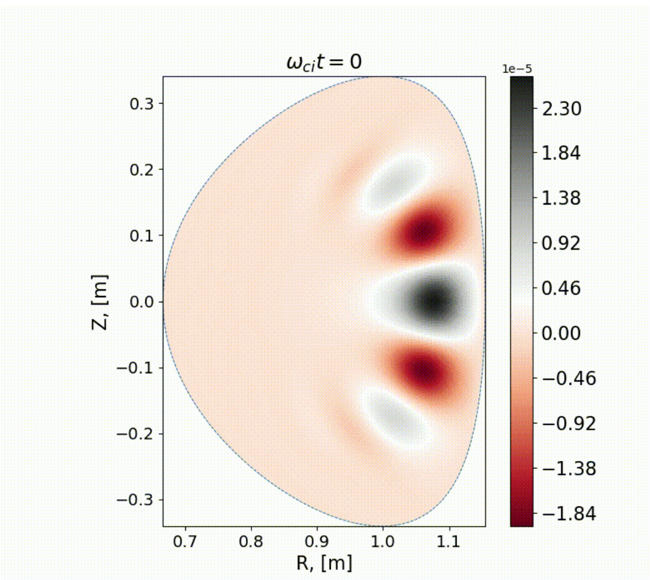


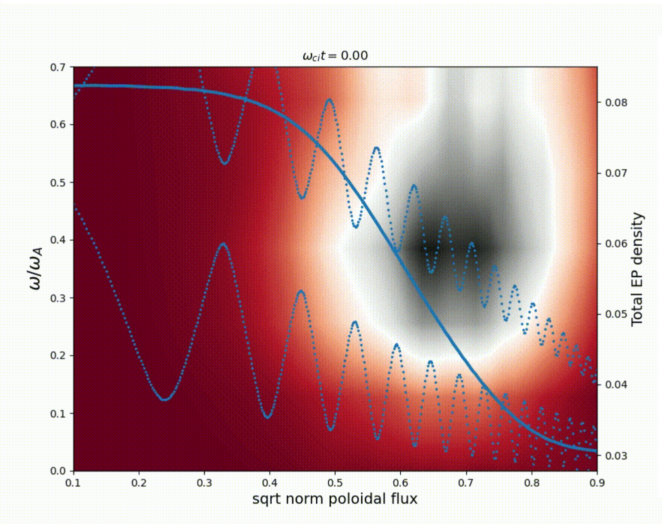
TAE/EPM: negative/positive triangularity TCV

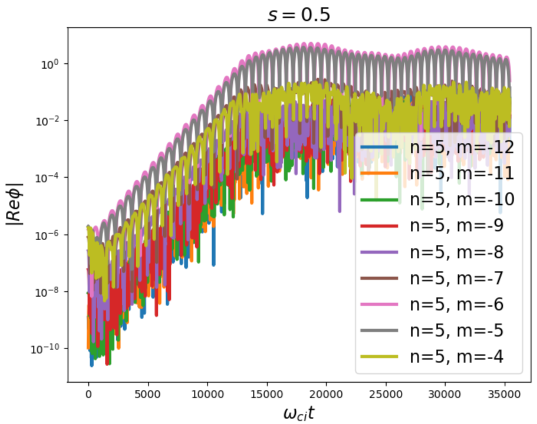




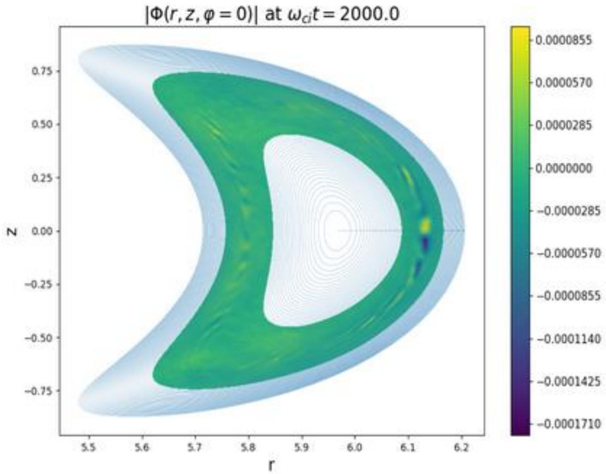


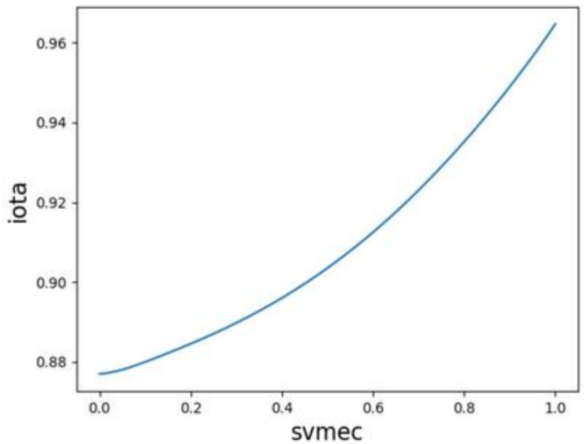






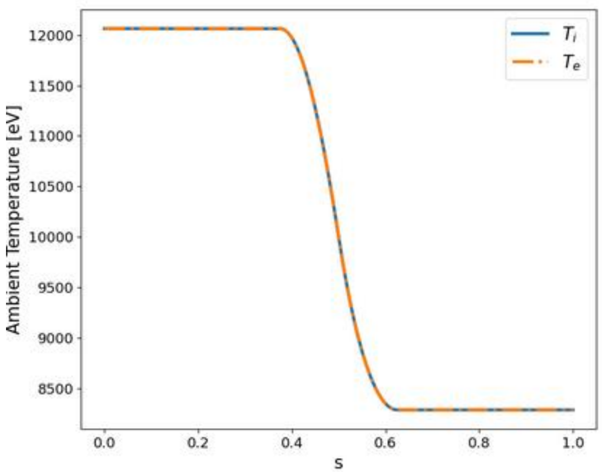
EM simulations in stellarators

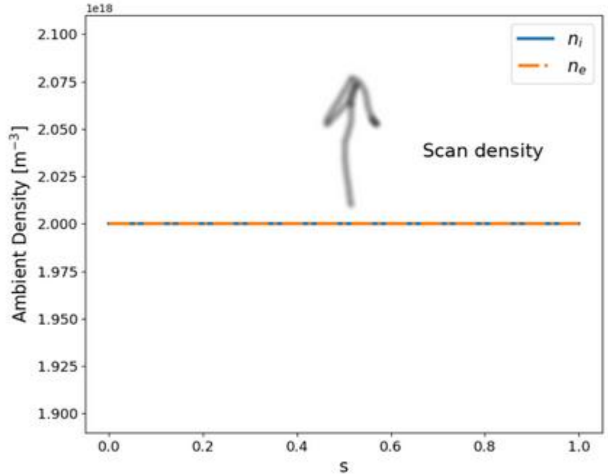


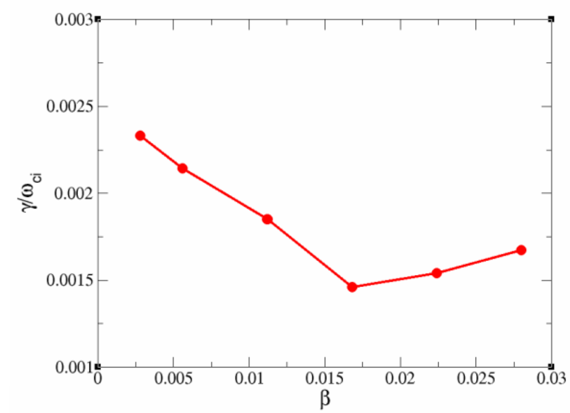


Larger temperature implies larger ρ_*

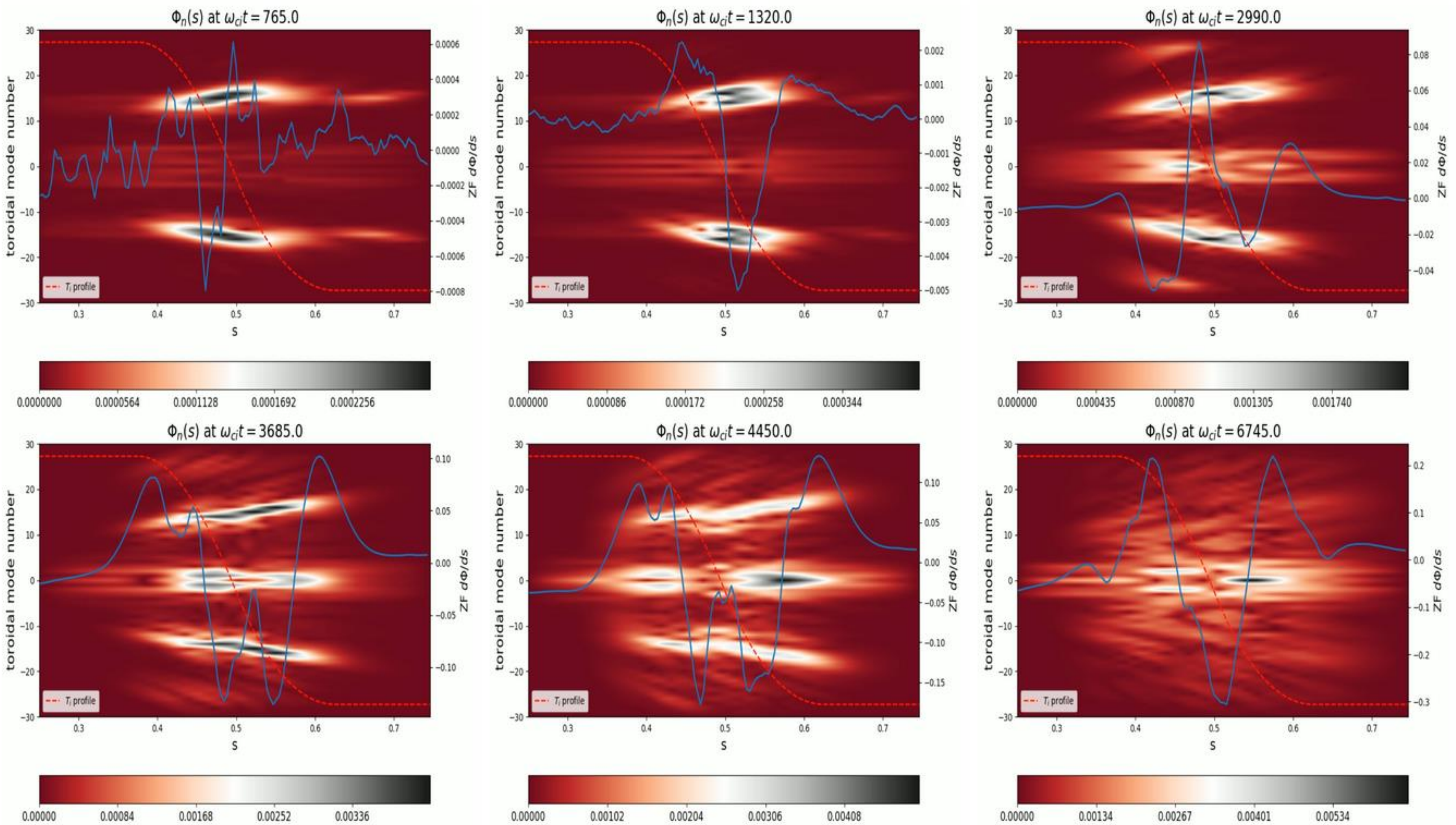
Larger ρ_* need less Fourier harmonics (to resolve the same $k\,\rho_i \sim 1$)







Toroidal spectrum: ZF and KBMs



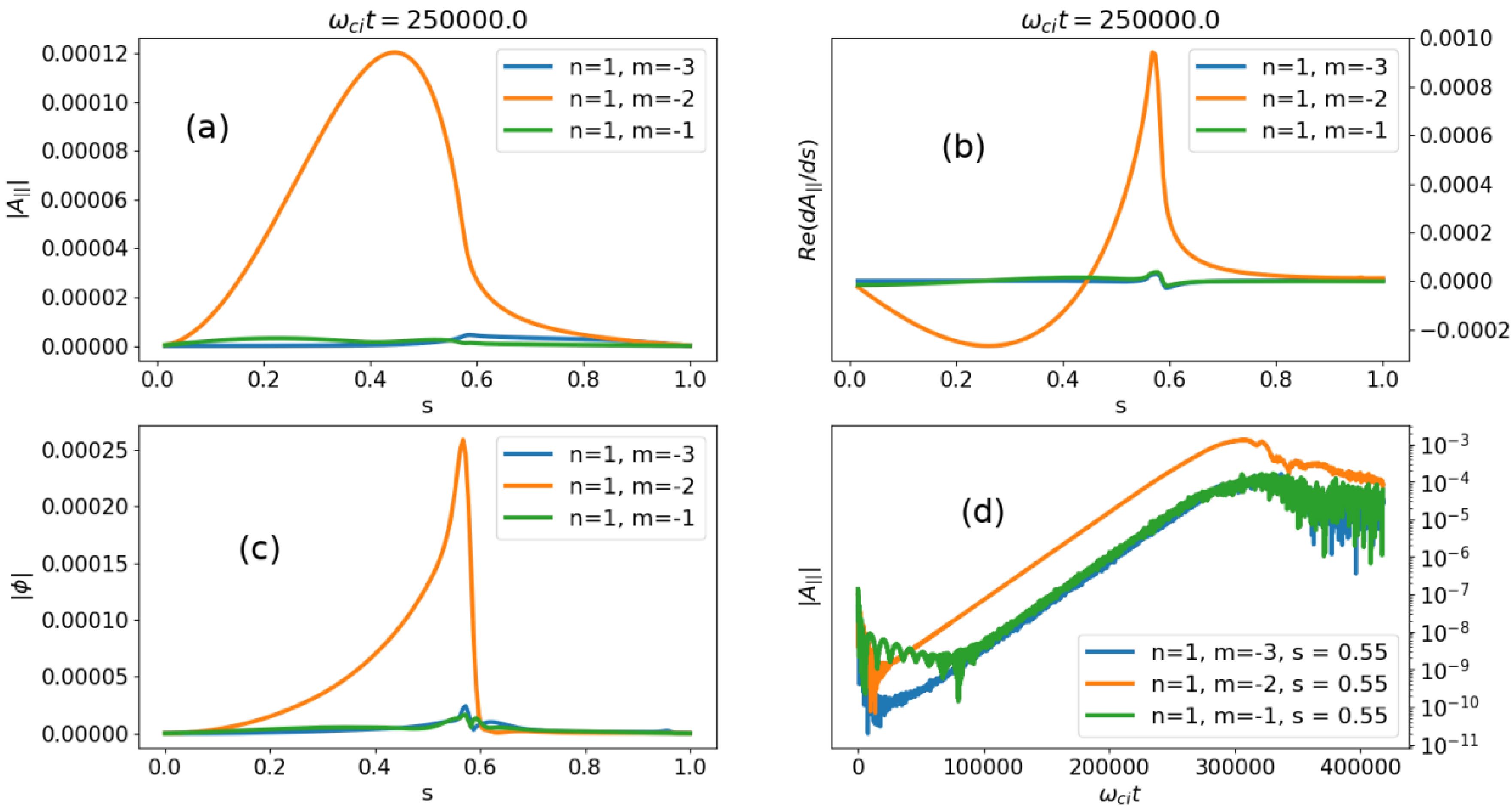
Toroidal spectrum and zonal flow evolution for $\beta = 2.8\%$

Zonal electric field (blue line) is driven self-consistently by stellarator turbulence

MAX-PLANCK-INSTITUT FÜR PLASMAPHYSIK

EUROfusion

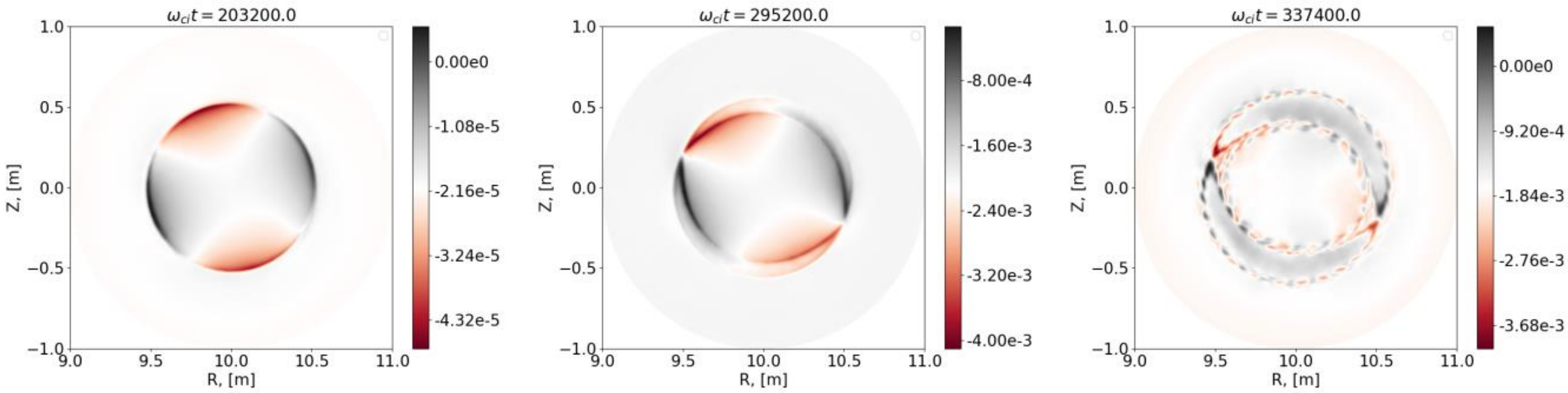
Tearing mode simulations



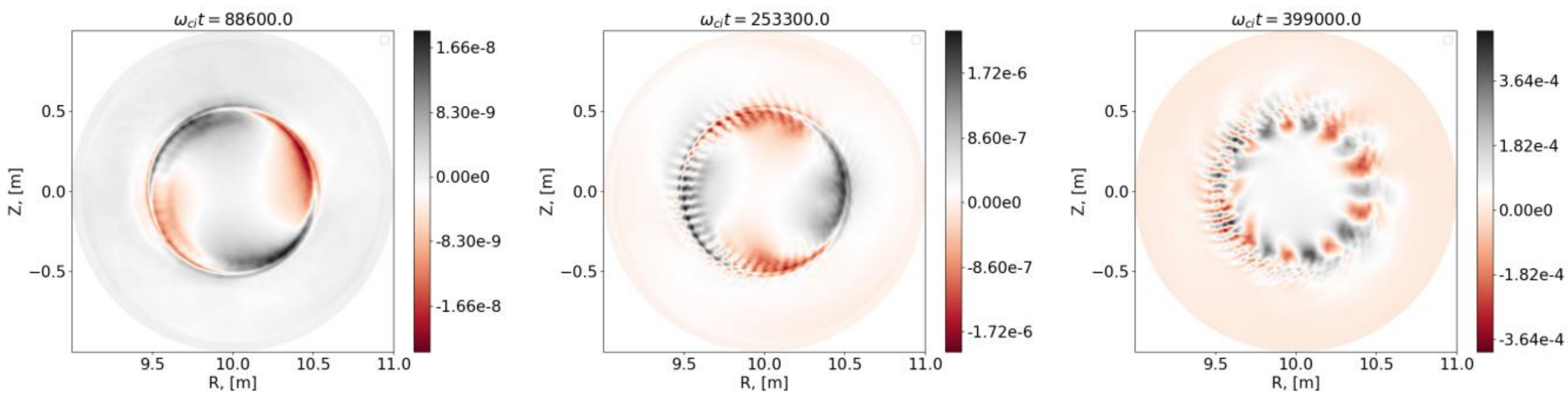
Safety factor profile with q=2 resonance; shifted Maxwellian for electrons
Tearing instability develops; peaked structures at resonant flux surface

MAX-PLANCK-INSTITUT FÜR PLASMAPHYSIK EUROfusion

Tearing mode simulations

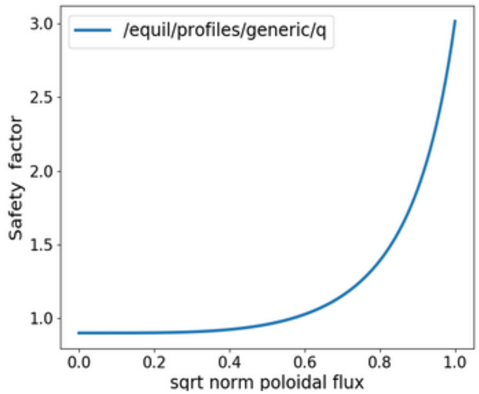


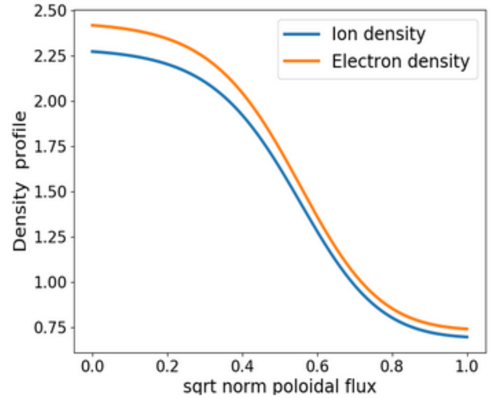
An island growth (X-points can be clearly seen); flat plasma profiles

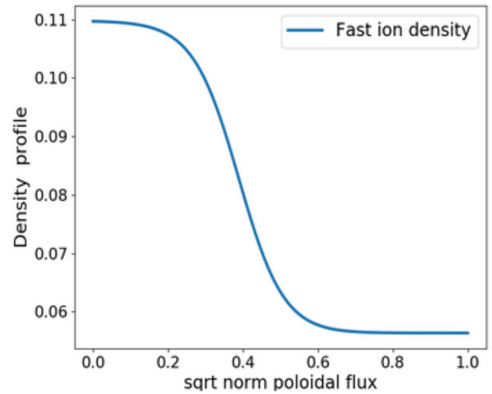


More complex physics for plasma with non-flat profile (turbulence)
It includes tearing, AEs, EM turbulence, and ZFs

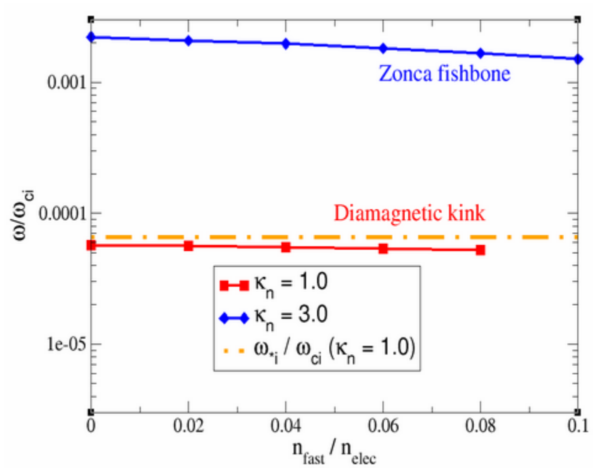
Internal kink and fishbone instabilities

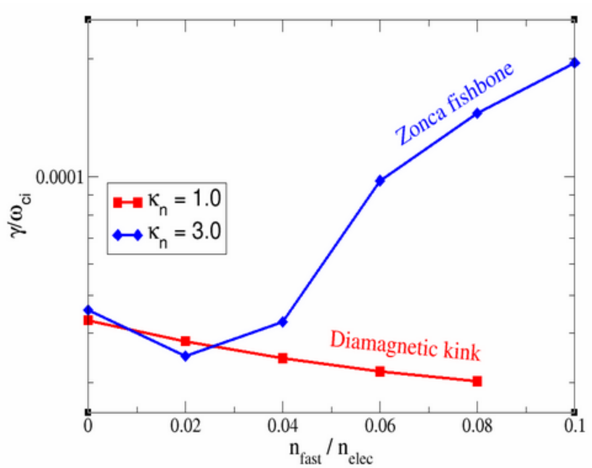




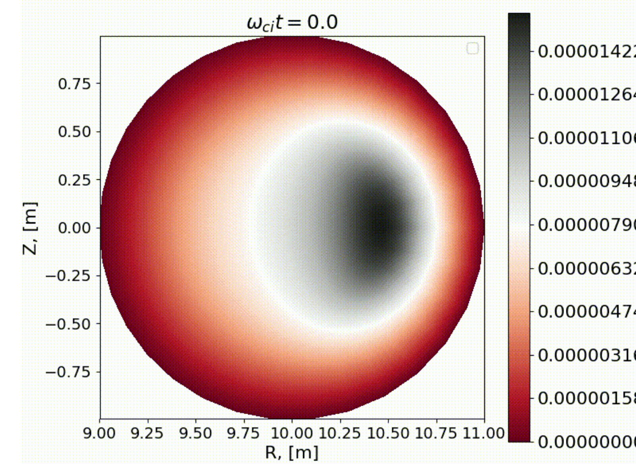


Large-aspect-ratio tokamak (A=10) with circular cross-sections. Safety factor (q=1 at s=0.57). Finite gradients for bulk-plasma density and EP density. Temperatures are flat for all species. Maxwellian fast ions; shifted Maxwellian for electrons.





Precessional FB



Chirping TAEs

Electromagnetic turbulence and global modes 9

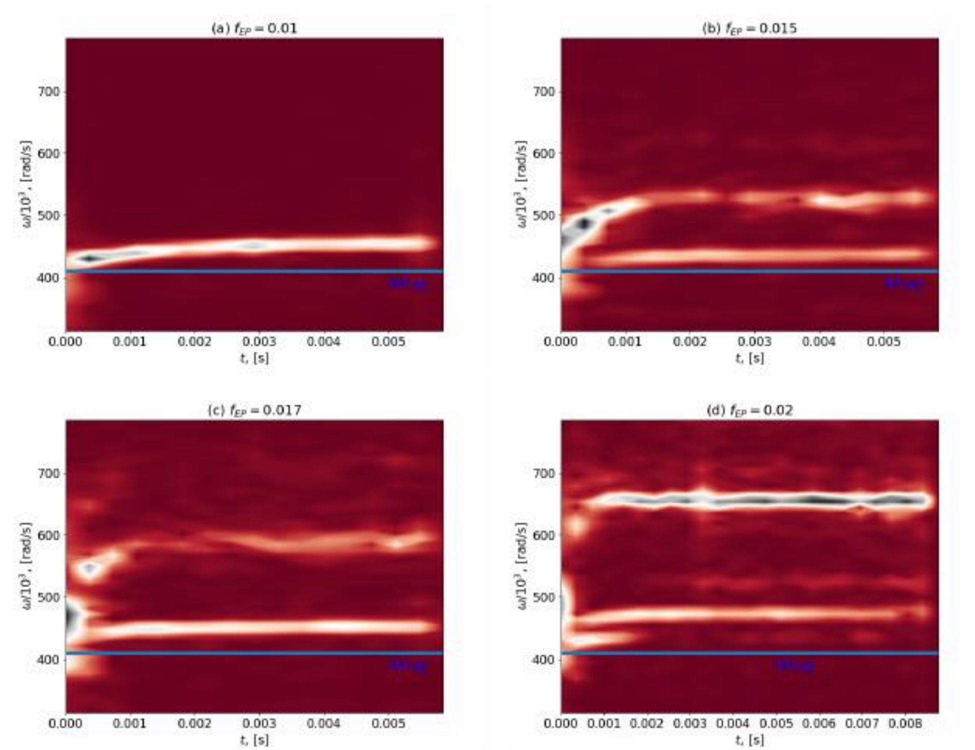
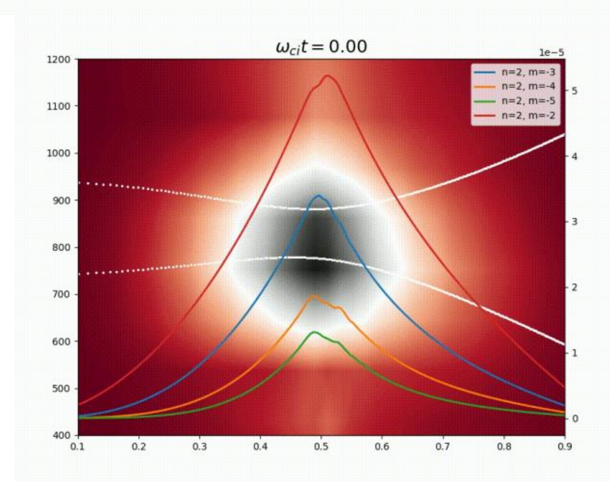
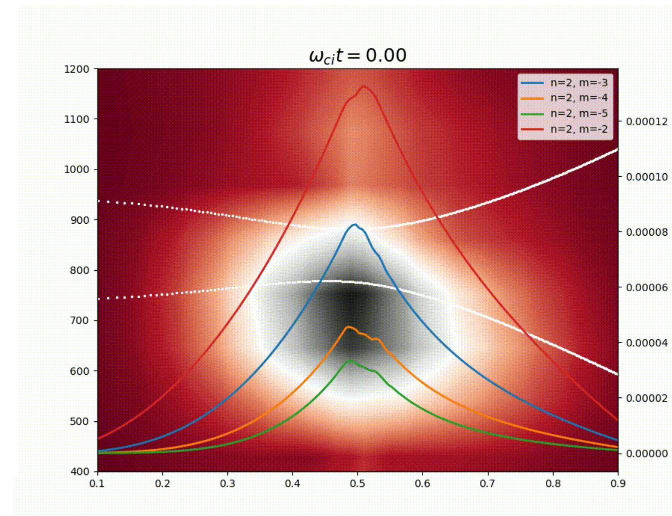


Figure 13. Energetic-particle nonlinearity only (flat bulk-plasma profiles). Frequency as a function of time for the fast-particle fraction: (a) $f_{EP} = 0.01$, (b) $f_{EP} = 0.015$, (c) $f_{EP} = 0.017$, (d) $f_{EP} = 0.02$. One sees how the nonlinear frequency evolution increases with the number of the fast particles.



No turbulence: mode stays at the TAE gap



In presence of turbulence (bulk-plasma dT/dr): frequency changes along continuum branch

MAX-PLANCK-INSTITUT FÜR PLASMAPHYSIK

EUROfusion

Conclusions

- The creation and control of burning plasmas is an ultimate goal of magnetic fusion world-wide efforts. Tokamak and stellarator geometries are considered.
- One of the characteristic features of such plasmas is the intrinsic richness of their physics featuring complex couplings and interactions of microscopic turbulence with macroscopic MHD and Alfvén modes.
- In burning plasmas, such couplings may become especially strong since fast particles are abundant and can drive the macroscopic modes unstable.
- A global approach is needed to assess the physics combining the macroscopic modes, fast ions, Alfvénic instabilities, zonal flows, and turbulence.
- The global gyrokinetic particle-in-cell codes ORB5 and EUTERPE have been used to simulate the electromagnetic turbulence in the toroidal geometries of axisymmetric tokamaks and the more general stellarators.
- The so-called ITG-KBM transition has been identified and the relaxation of the profiles has been observed in a circular cross-section tokamak plasma and in the ASDEX-Upgrade geometry. First results from ITER, JET, and TCV.
- The multiscale physics has been addressed, showing the coupling of electromagnetic turbulence to the collisionless tearing instability and Alfvén modes destabilized by fast ions (including JET and TCV).
- Electromagnetic turbulence has also been addressed in the stellarator Wendelstein 7-X geometry. Turbulence spreading and generation of low-mode-number components.
- It has been demonstrated that such simulations are possible using existing global gyrokinetic particle-in-cell codes on the HPC systems already available for EUROfusion.