Overview of work done by TSVV-10

A. Mishchenko on behalf of TSVV10

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MAX-PLANCK-INSTITUT FÜR PLASMAPHYSIK

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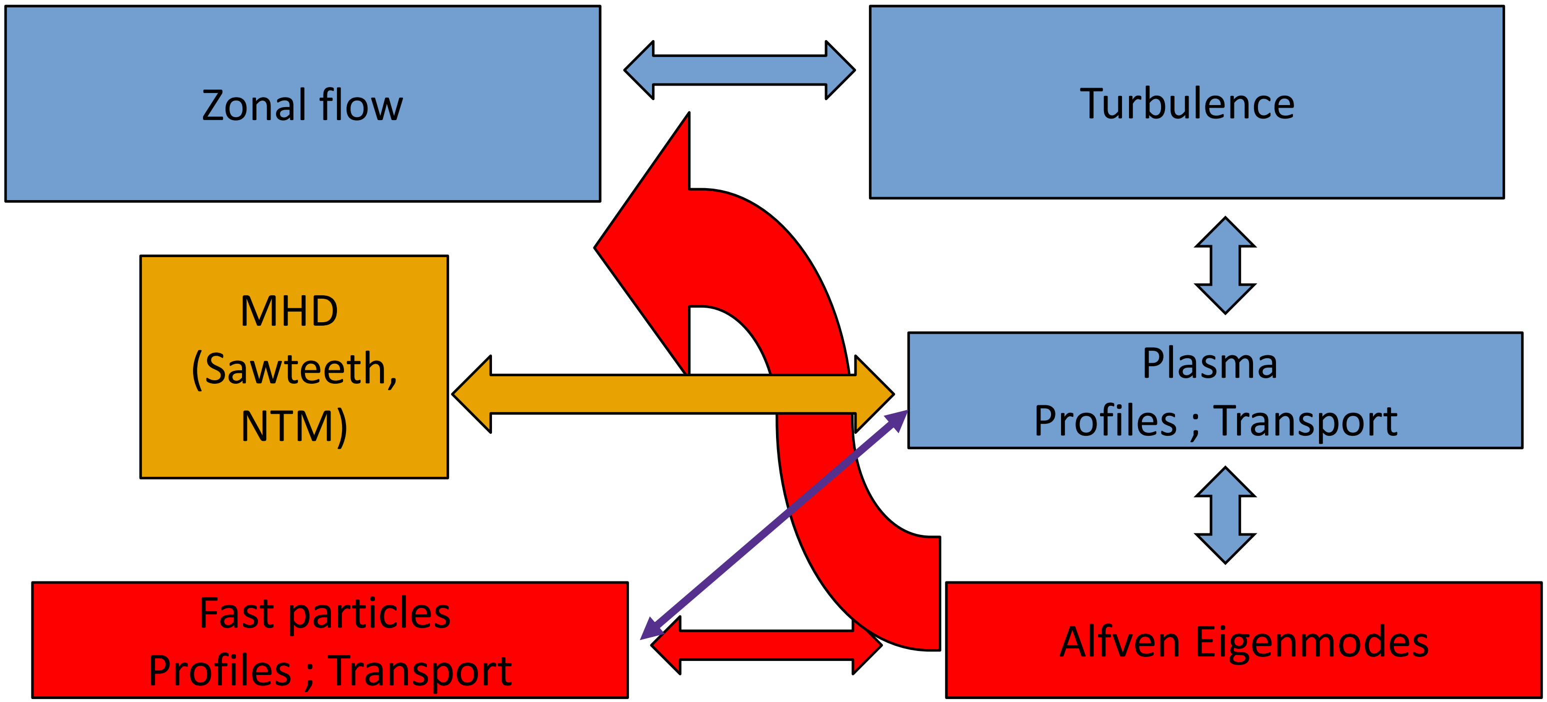
System couplings in burning plasmas

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



Burning plasmas: modelling

- 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)
- Multi-fidelity approach is essential in practice

TSVV10 code stack:

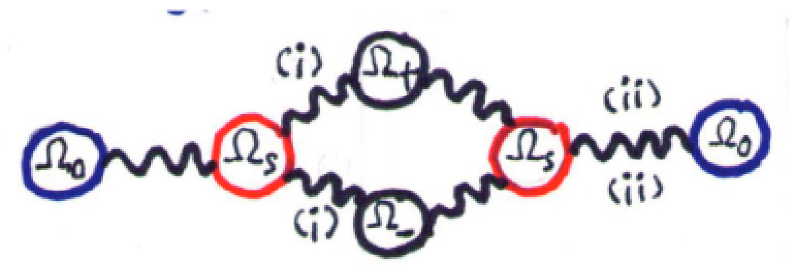
- Global gyrokinetic: ORB5, EUTERPE, LIGKA
- Global kinetic MHD: XTOR, HYMAGYK, HMGC
- Integrated modelling: LIGKA, HAGIS, ETS

TSVV10 Theory:

Phase space zonal structures
Generalized fishbone disp. rel.
Dyson-Schrödinger model

Theory

Scattering of TAE by ambient stationary DW: symbolically



Generalized fishbone dispersion relation; phase space zonal structures and transport theory, Dyson-Schrödinger model.

(i) Generation of KAWs by TAE Ω_0 and DW Ω_s coupling

$$\epsilon_{A\pm}\delta\phi_\pm = \beta_\pm\delta\phi_s \left\{ \begin{array}{c} \delta\phi_0 \\ \delta\phi_0^* \end{array} \right\} \tag{1}$$

(ii) Feedback of KAW to test TAE Ω_0

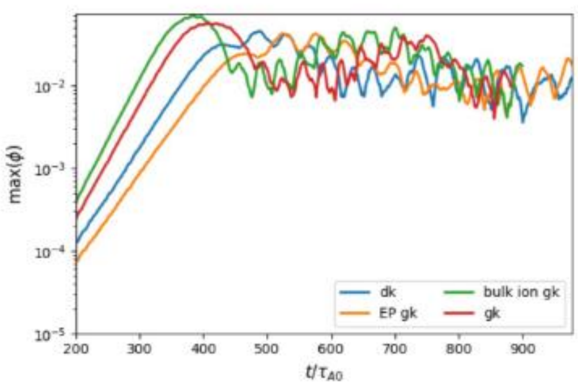
$$\left[\epsilon_{A0} + \alpha_0|\delta\phi_s|^2\right]\delta\phi_0 = \left[\beta_0^+\delta\phi_s^*\delta\phi_+ + \beta_0^-\delta\phi_s\delta\phi_-^*\right] \tag{2}$$

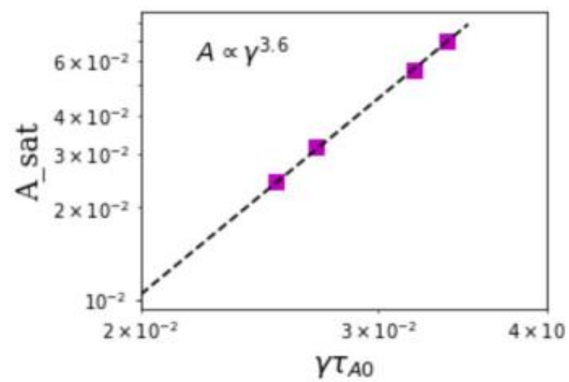
$\Rightarrow$ test TAE evolution due to DW scattering to short wavelength KAW $\Omega_\pm$

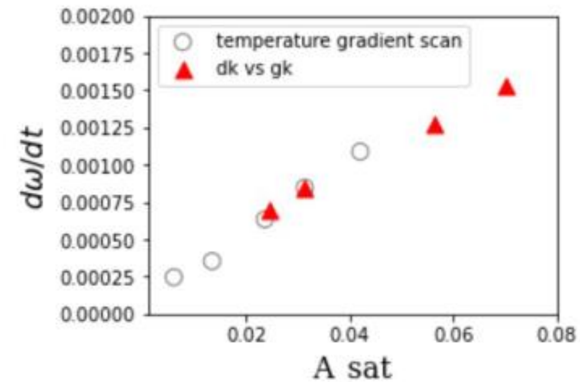
$$\left[\epsilon_{A0} + \alpha_0|\delta\phi_s|^2\right]\delta\phi_0 = \left[\beta_0^+\delta\phi_s^*\frac{\beta_+\delta\phi_s}{\epsilon_{A+}} + \beta_0^-\delta\phi_s\frac{\beta_-\delta\phi_s^*}{\epsilon_{A-}}\right]\delta\phi_0 \tag{3}$$

Theory compared to simulations

Dynamics of the Alfvén modes in single n=5 simulations: from drift kinetic to gyrokinetic I

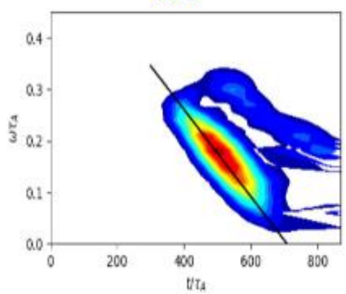




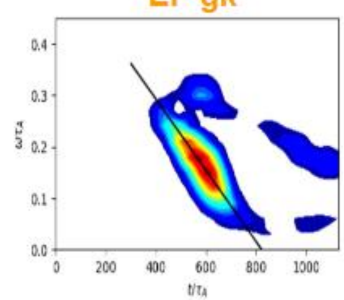


Amplitude and chirping rate scale as predicted by the theory

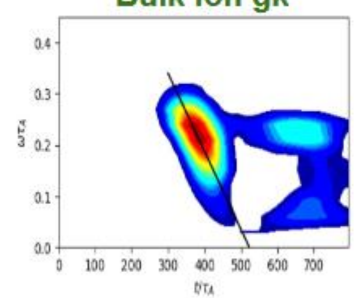
dk



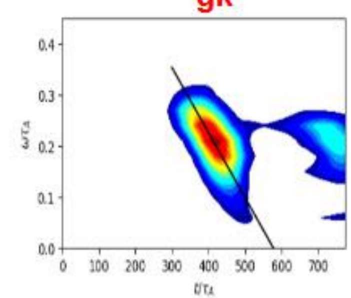
EP gk



Bulk ion gk



gk



Simulations compared to simulations

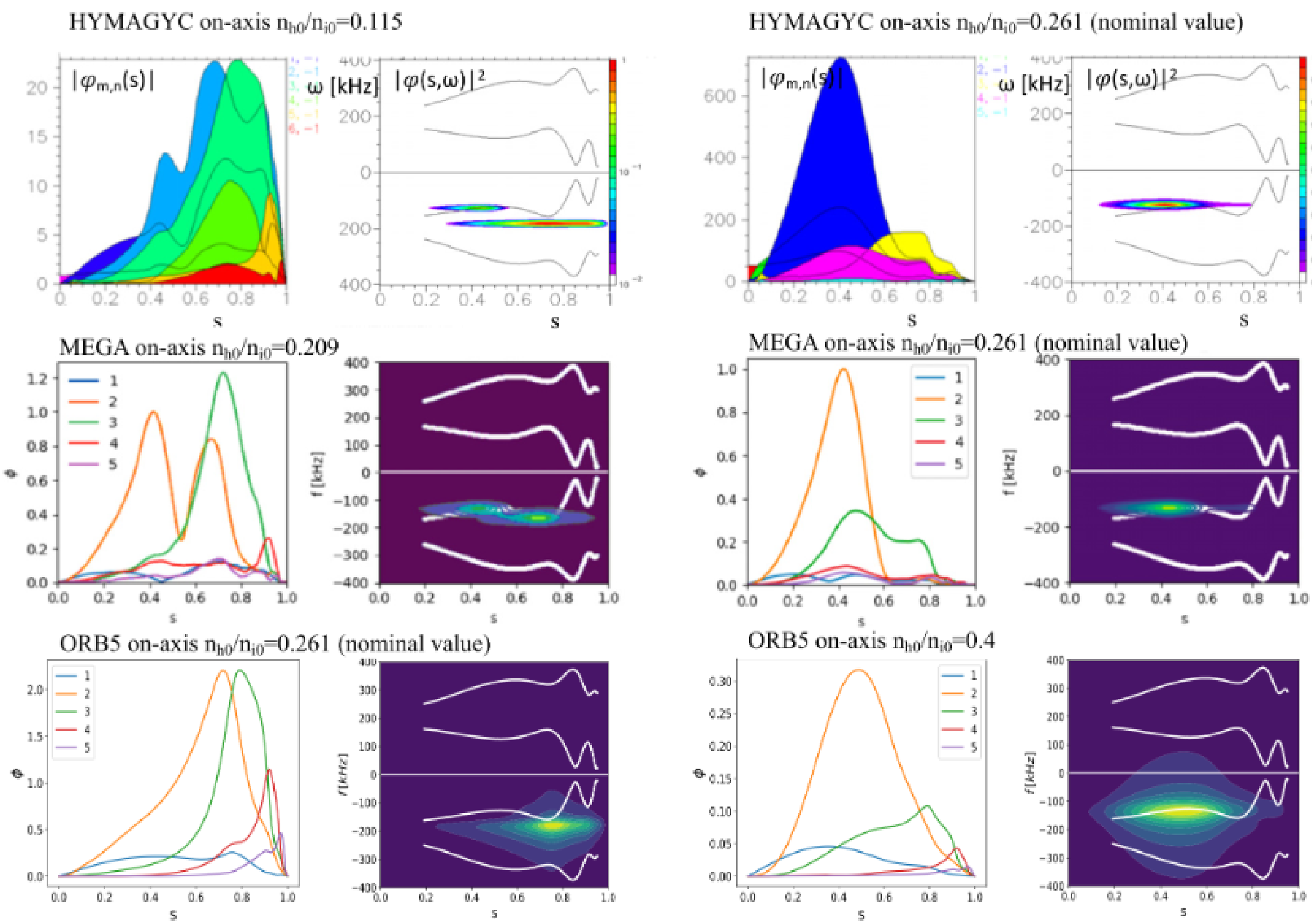
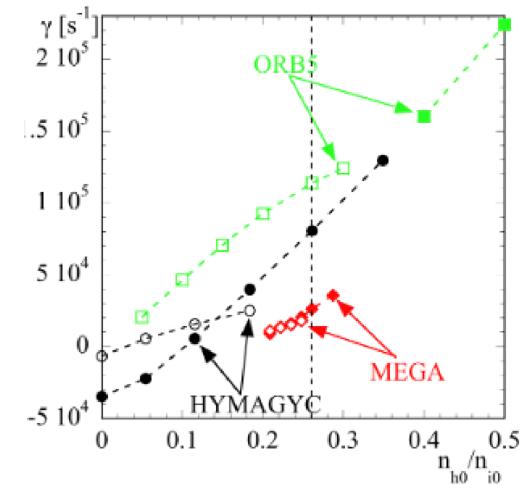
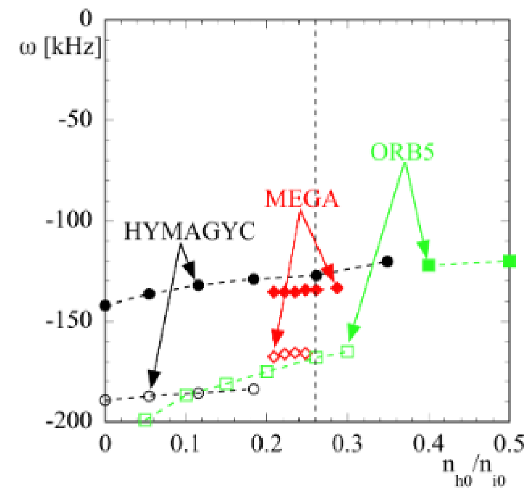


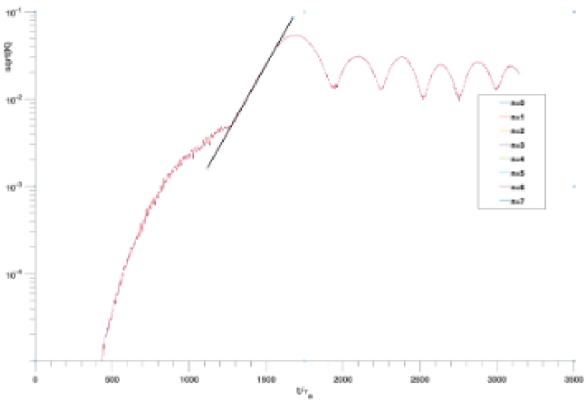
Figure 11. TAE solution (left) and RSAE solution (right) as obtained by HYMAGYC (top), MEGA (middle), and ORB5 (bottom) at 'low' values of EP density (left column), and 'high' density (right column). Note that the values of n_{h0}/n_{i0} varies for each plot; note also that some of the plots shown in this Figure are the same of figure 8 and are reported here for the ease of the reader.

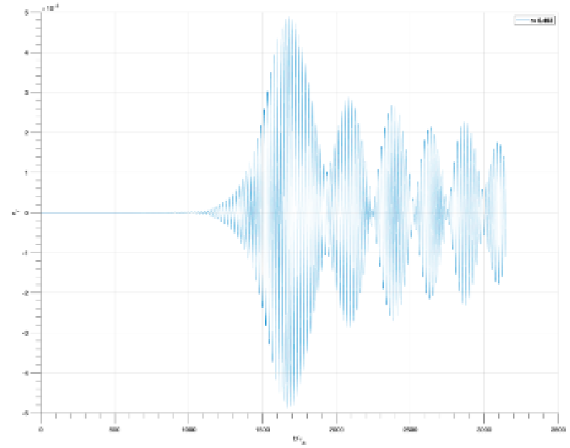




NLED-AUG case

XTOR-K: verification (ITPA benchmark)

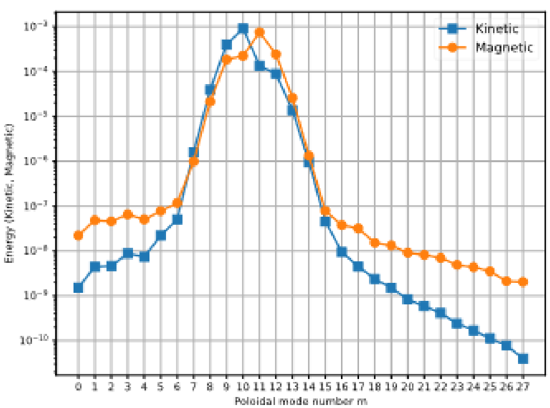


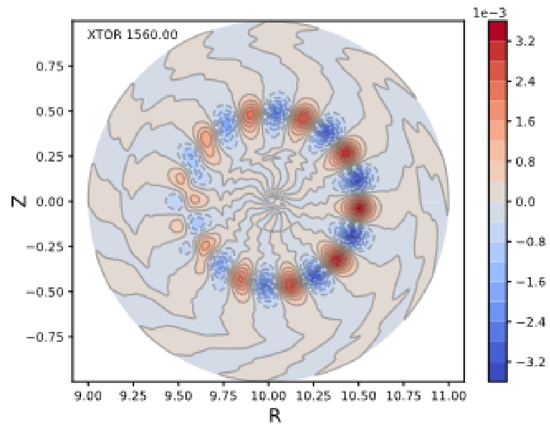


n=6 TAE evolution:

Gamma = 2.18 x 10^4 s^{-1}
Omega = 0.399 x 10^6 rad/s

Compares well with
[Mishchenko 2009, Könies 2018]:



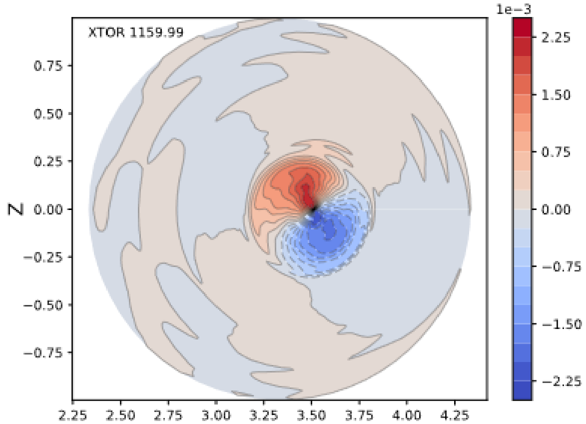


Gamma = 2.3 x 10^4 +/-10% s^{-1}
Omega = 0.42 x 10^6 rad/s

Omega ideal MHD eigenvalue code (CAS3D):
Omega = 0.401 x 10^6 rad/s

XTOR-K: kink + EPs

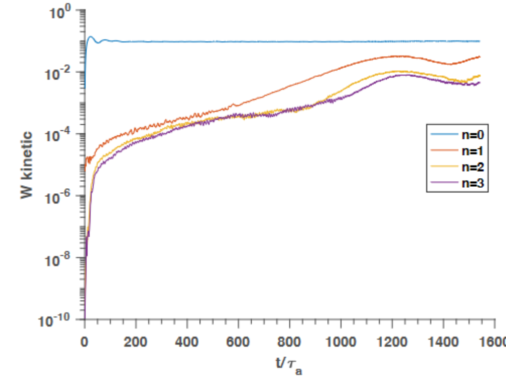
Internal kinKink simulations (2) : Hybrid simulation with 2Mev Fusion alphas



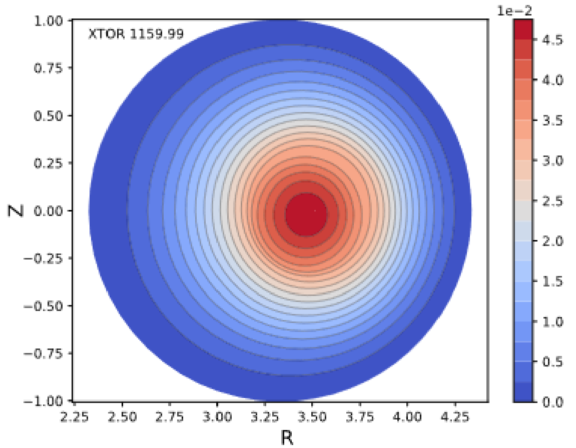
V_r(phi=0)

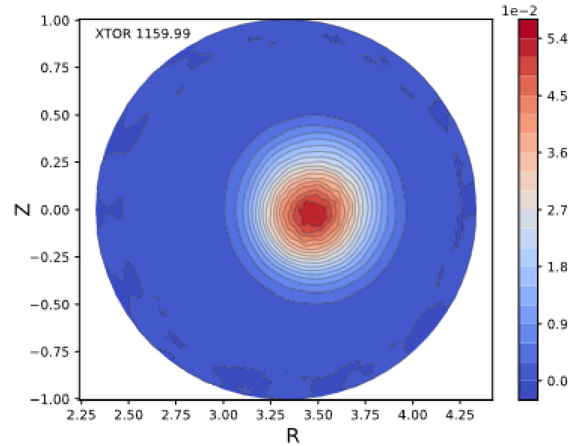
Ni0=ne0=2 10^19 m-3
Ti0=Te0=30KeV
Nf0=4.10^17 m-3
Beta_pol=0.78;
r(q=1)=0.45
S=3.e6
Chi//=1., Chi_perp=1.e-6

saturated helical equilibrium state



Fluid and kinetic ion pressures





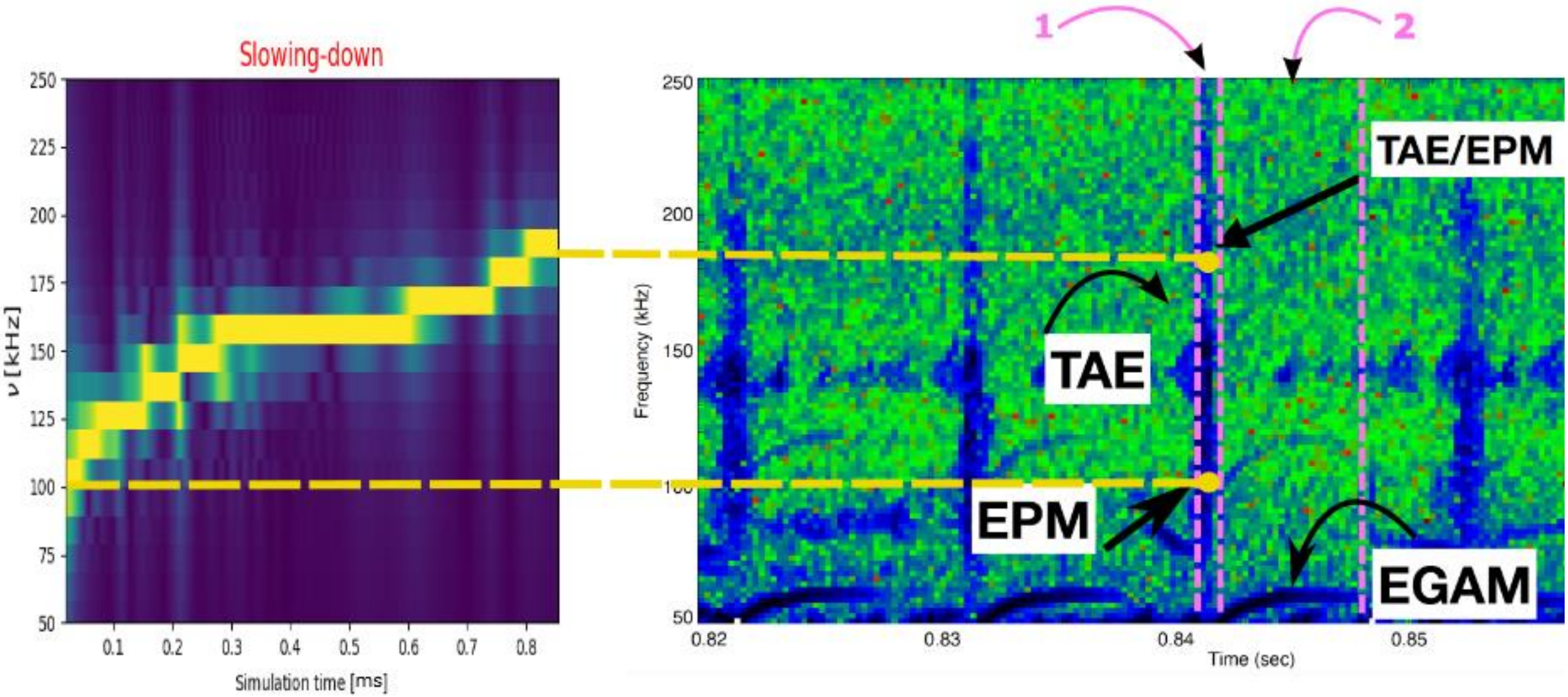
In progress: kink + fast ions + AEs

Simulations compared to experiment

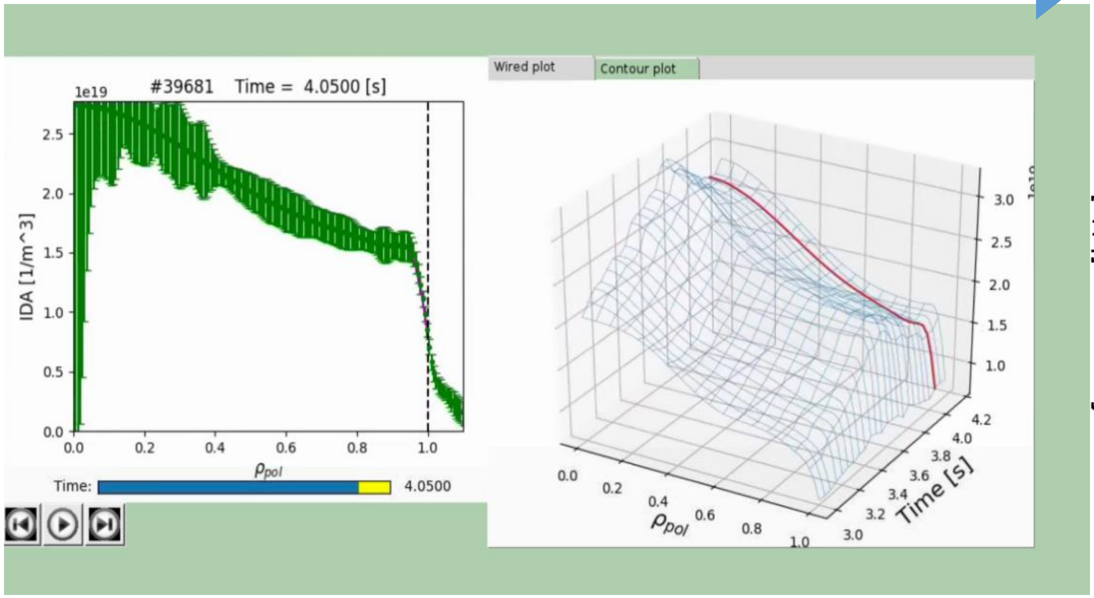
NLED-AUG case

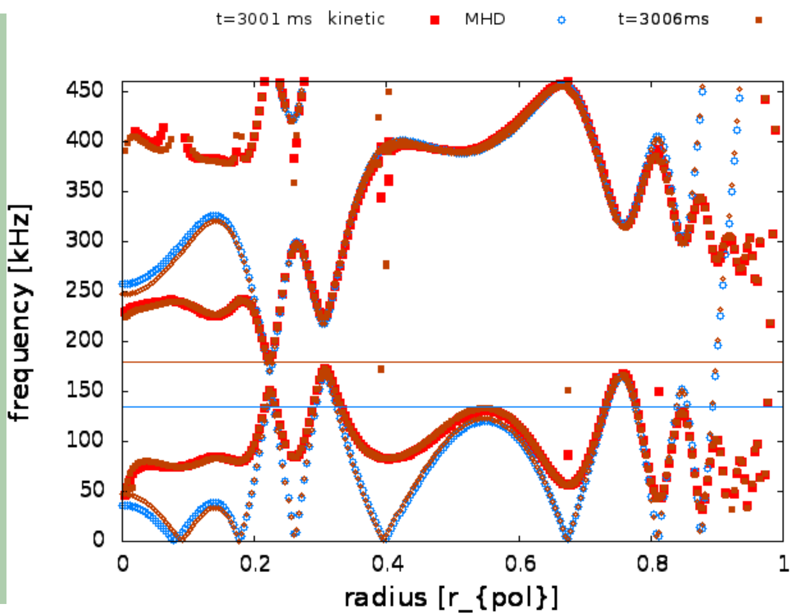
ASDEX Upgrade discharge #31213@0.84s

P. Lauber et al., proceedings of the 27th IAEA Fusion energy, 2018.



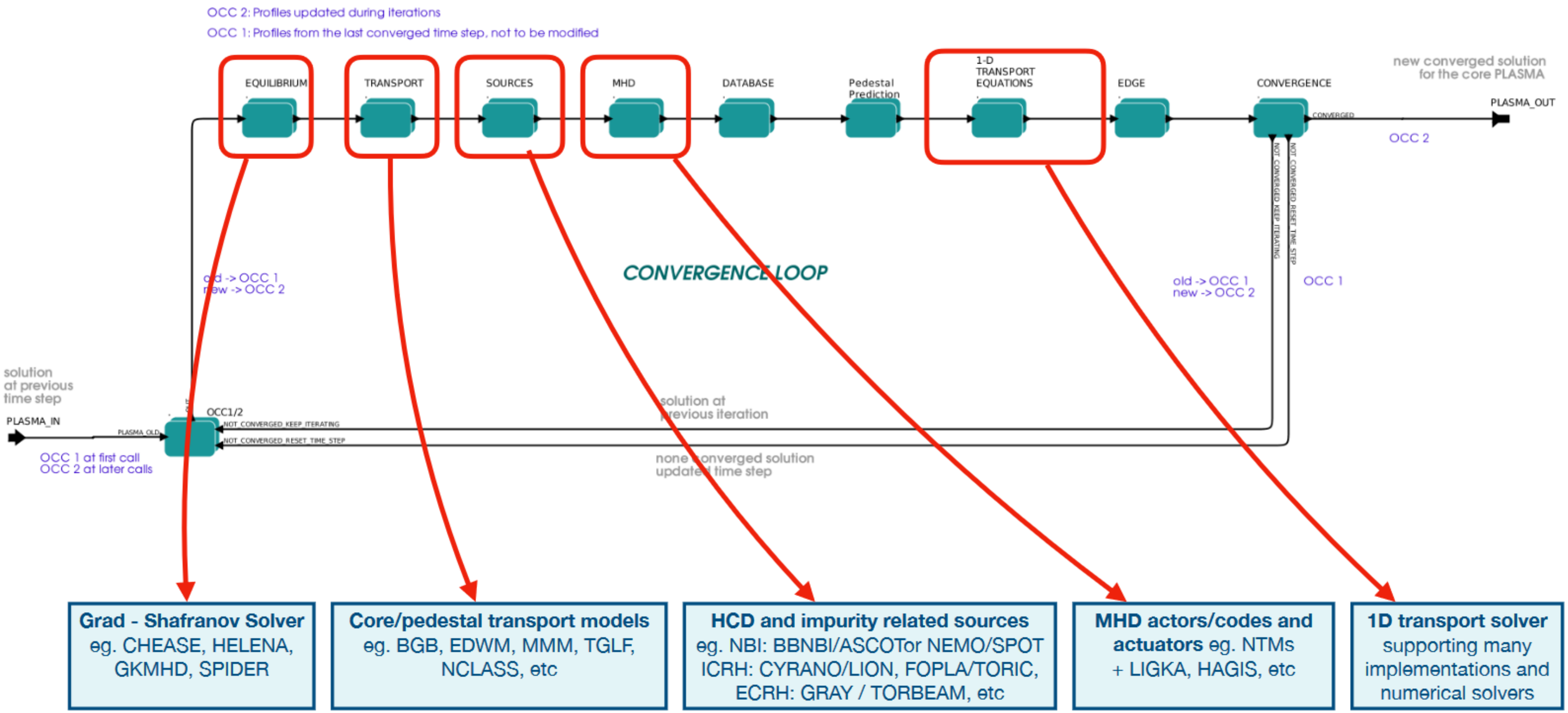
Integrated modelling via IMAS (IDA, LIGKA, ETS)





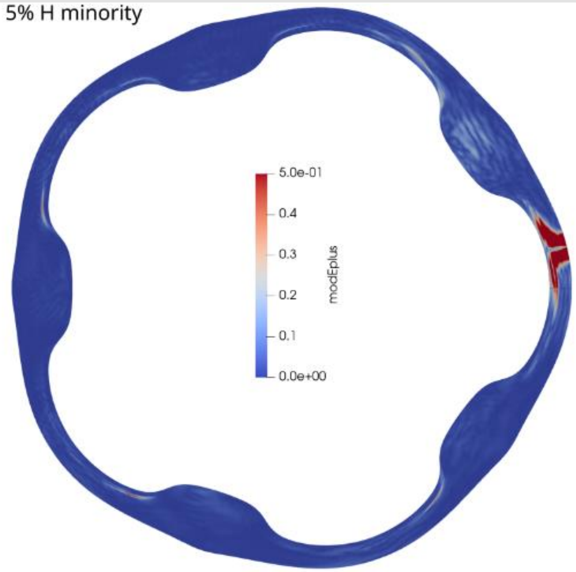
- slow L-H transition with constant heating power in the presence of strong EP activity
- L-mode activity very similar to NLED base case (EGAM/BAE/TAE intermittent crashes, #31213) - but now in flat top phase with transport analysis possible!
- automated analysis on Gateway now working using python EP-WF
- Using time evolving experimental profiles (e.g. density) for LIGKA EP simulations
- Hierarchy of models of varying fidelity available (from local models to full GK)

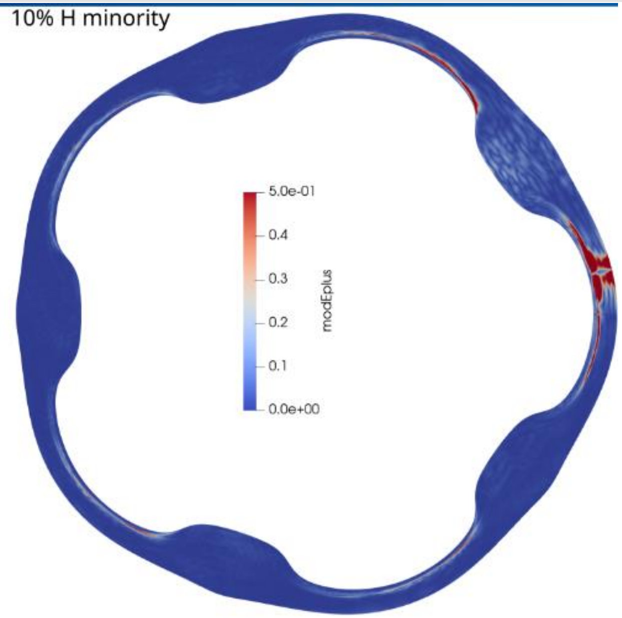
IMAS: coupling EP actors to ETS

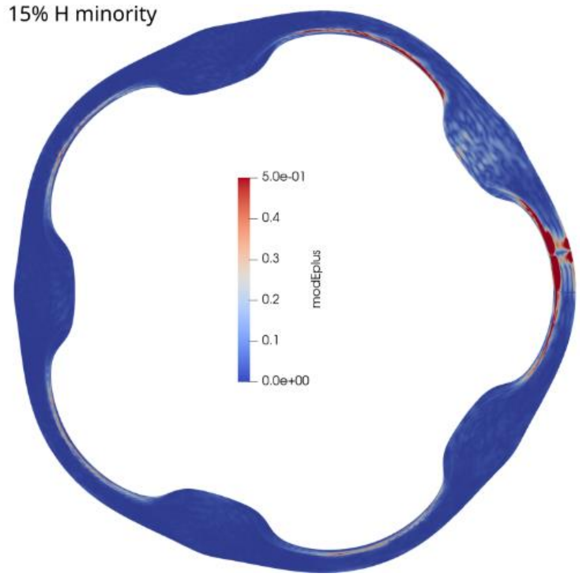


Further details at the EP Stability WF training course on July 18-19th 2023
https://indico.euro-fusion.org/event/2729/

Stellarators: ICRH modelling

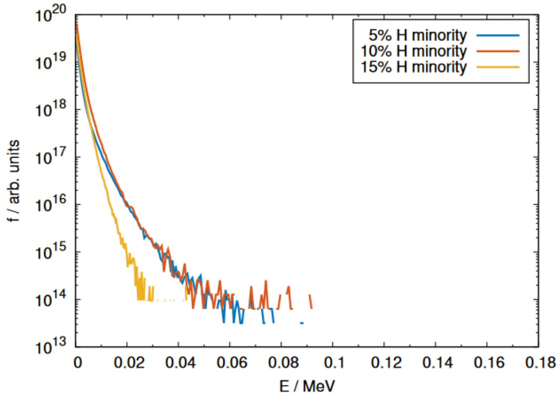






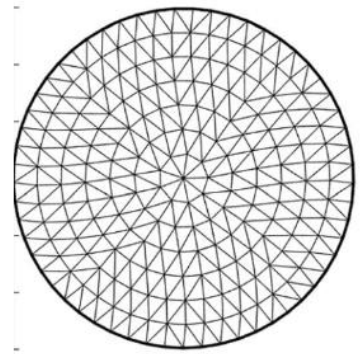
Comparison of the ICRH wave field ($|E_+|$)

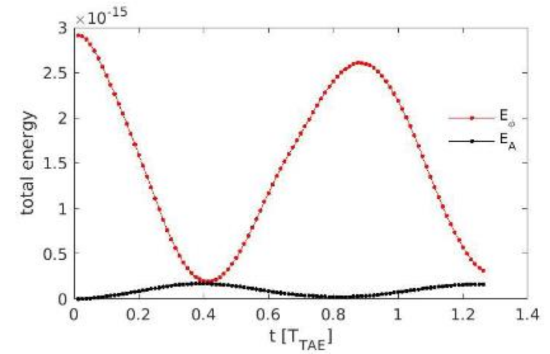
- overall shape of the wave field looks similar
- resonance only in the bean-shaped cross section and absent in triangular cross section
- depends on equilibrium (mirror ratio)

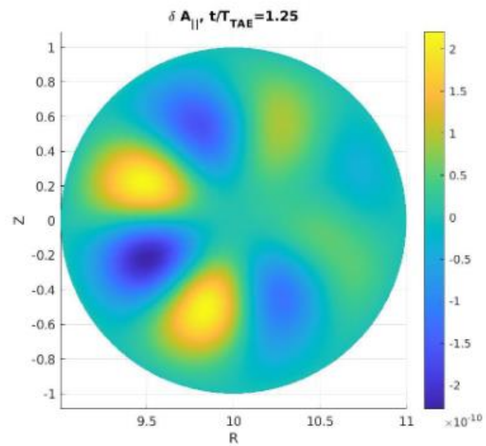


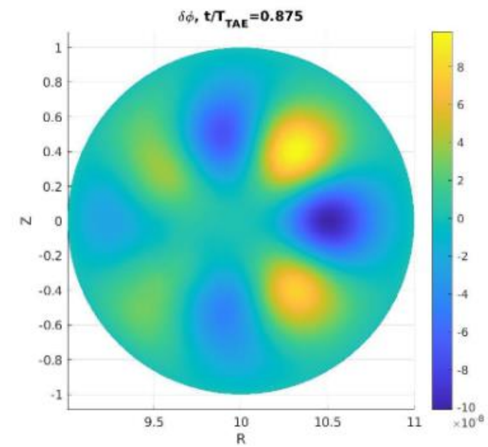
Unstructed meshes: TAEs with TRIMEG-C1

- Unstructured meshes are generated for circular geometry
- TAE oscillation simulated using the modified ITPA-TAE parameters
  - $n = 2, \beta = \frac{10^{-4}}{9}, \frac{m_e}{m_p} = \frac{1}{200}$
  - nominal: $n = 6, \beta = 9 \times 10^{-4}, \frac{m_e}{m_p} = \frac{1}{1836}$
- Magnetic axis is included
- Two species; pure $p_{\parallel}$ form
- 18 radial grids, 8 grids/per toroidal wave length
- Ongoing: simulations with smaller electron skin depth (d_e), longer time scale, higher resolution.



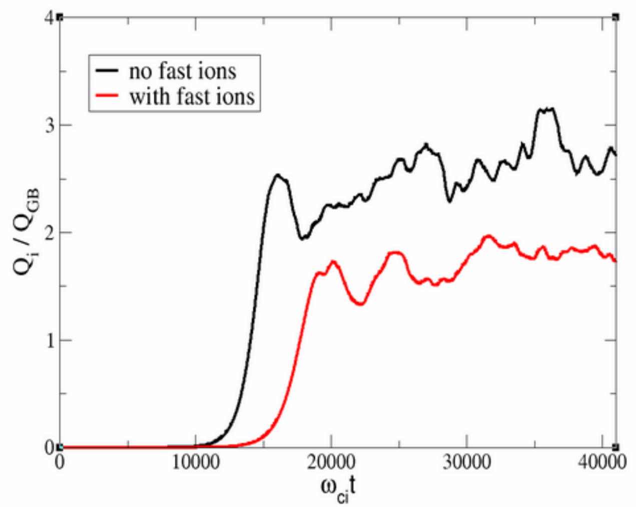


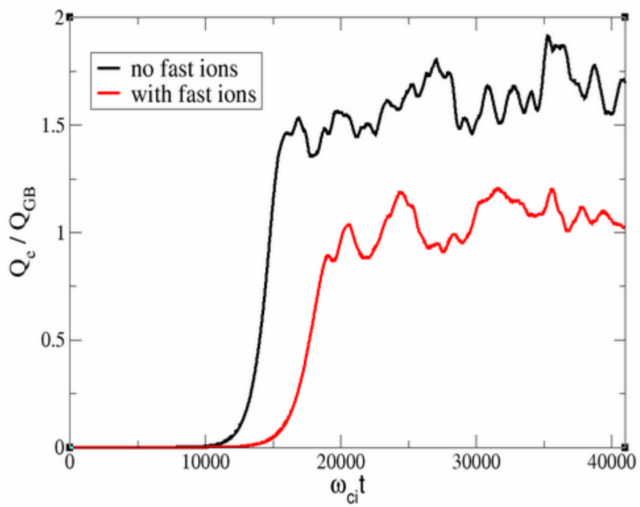


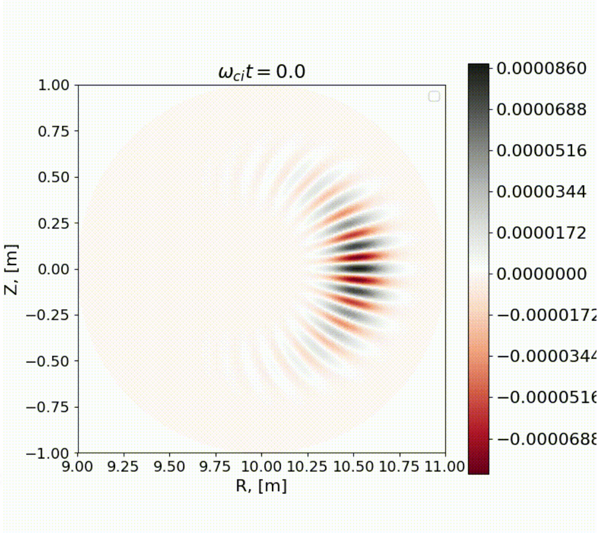


- Aiming for physics studies with X point, EM and kinetic electrons
- Field aligned coordinate in parallel direction, unstructured mesh in (R, Z): merit more effort
- Application to EP/AE studies in AUG experiments merits more effort
- Implementation of the EM GK model in JOREK can lead to a powerful tool
- Full f collision might reveal interesting physics (NC-instability synergy, edge coupling etc.)

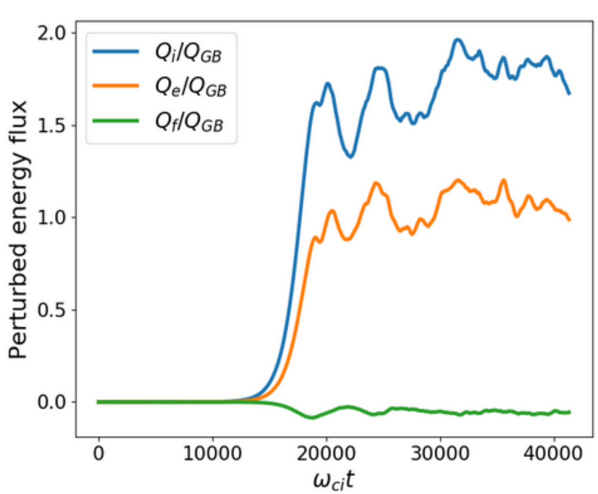
Fast ion stabilization of EM turbulence

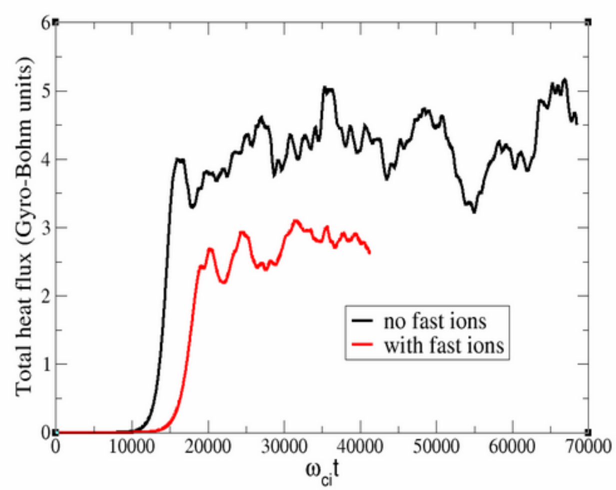


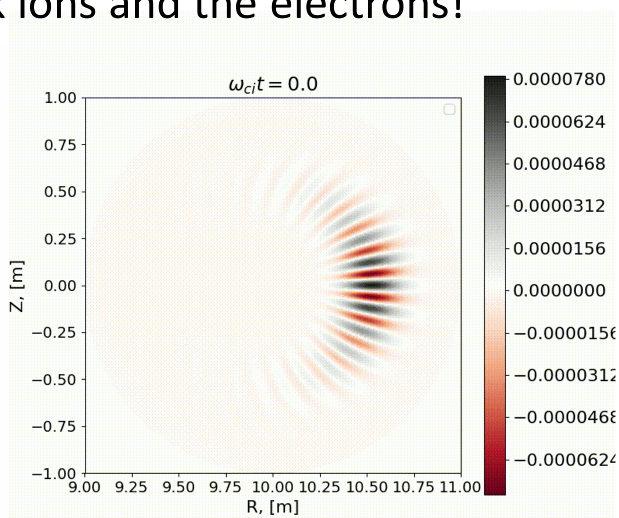




One observes a clear reduction in the heat flux for both the bulk ions and the electrons!

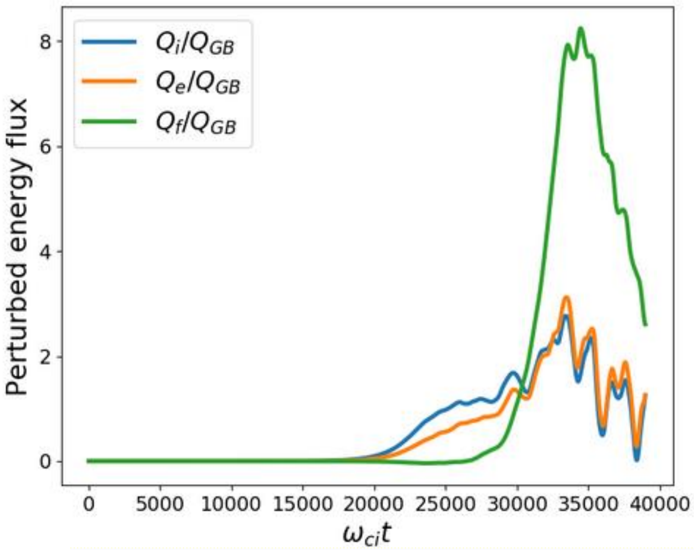


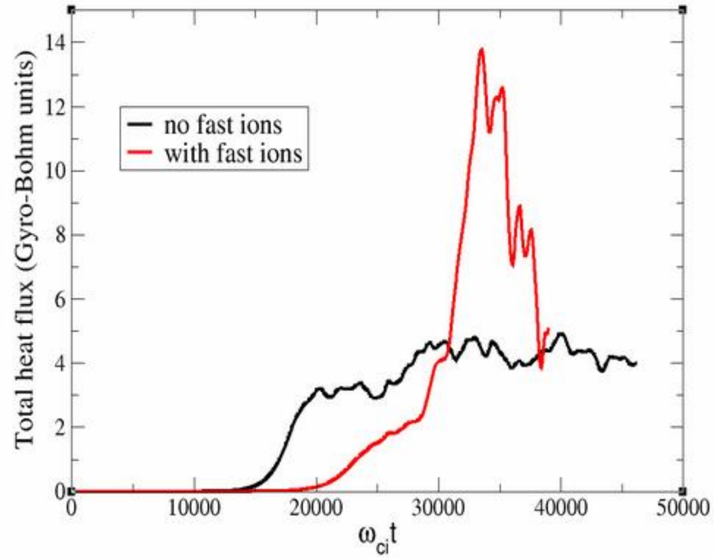




Fast ion do not transport much of energy. Total heat flux reduced by the fast ions! $\boldsymbol{\beta_e = 0.1\%}$

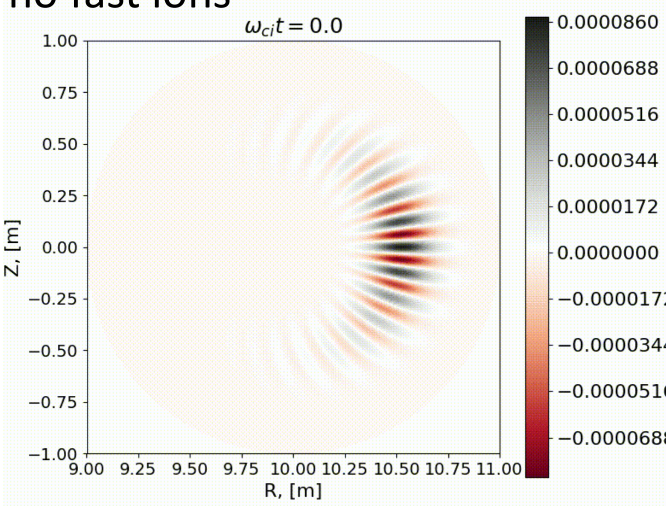
Fast ion stabilization of EM turbulence



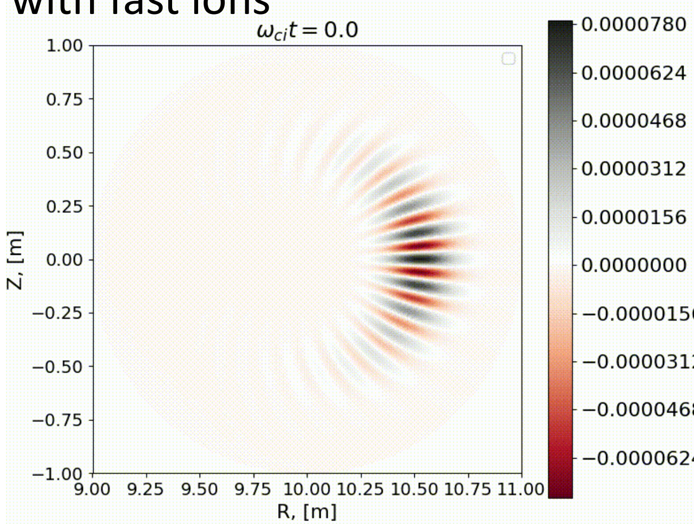


For $\boldsymbol{\beta_e = 0.24\%}$, the dynamics is different. Fast ion heat flux is substantial. Total heat flux is not reduced!

no fast ions

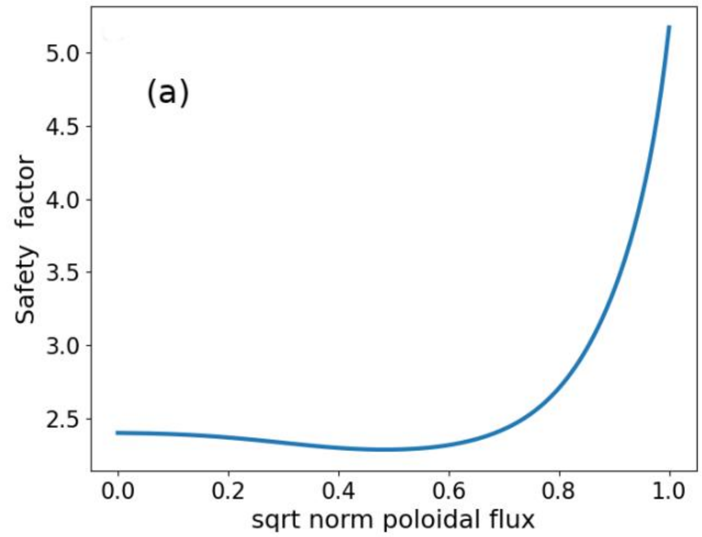


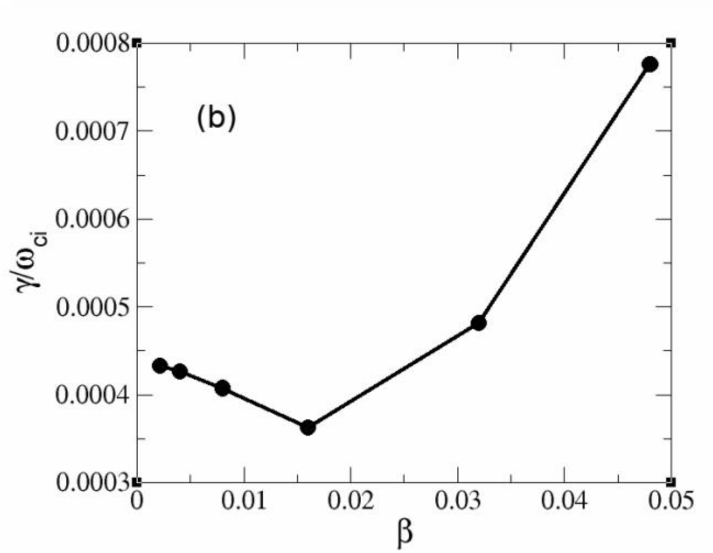
with fast ions



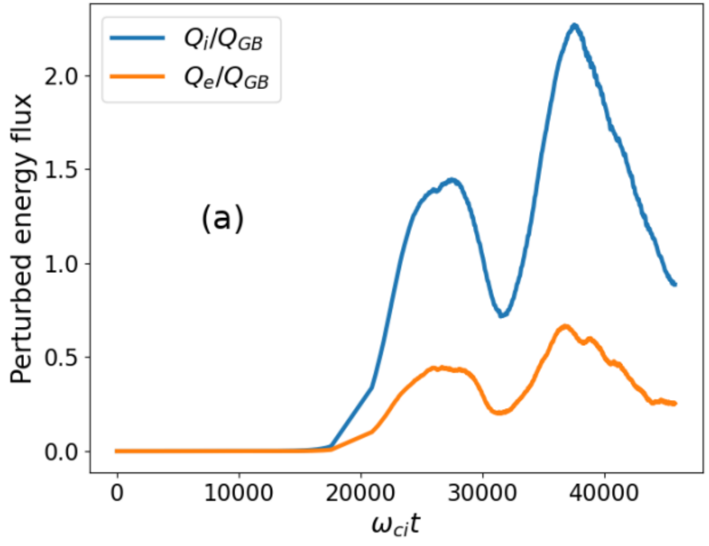
Global Alfvenic mode (a BAE?) develops driving fast ion energy flux. Work in progress!

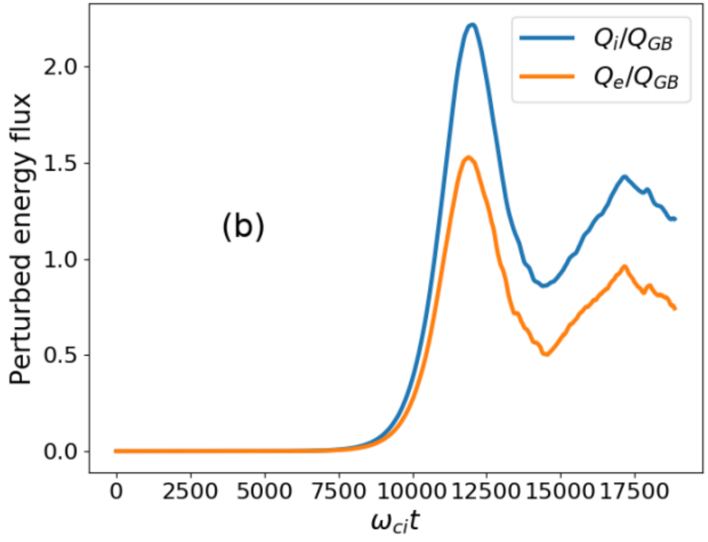
EM Turbulence simulations in ASDEX-Upgrade





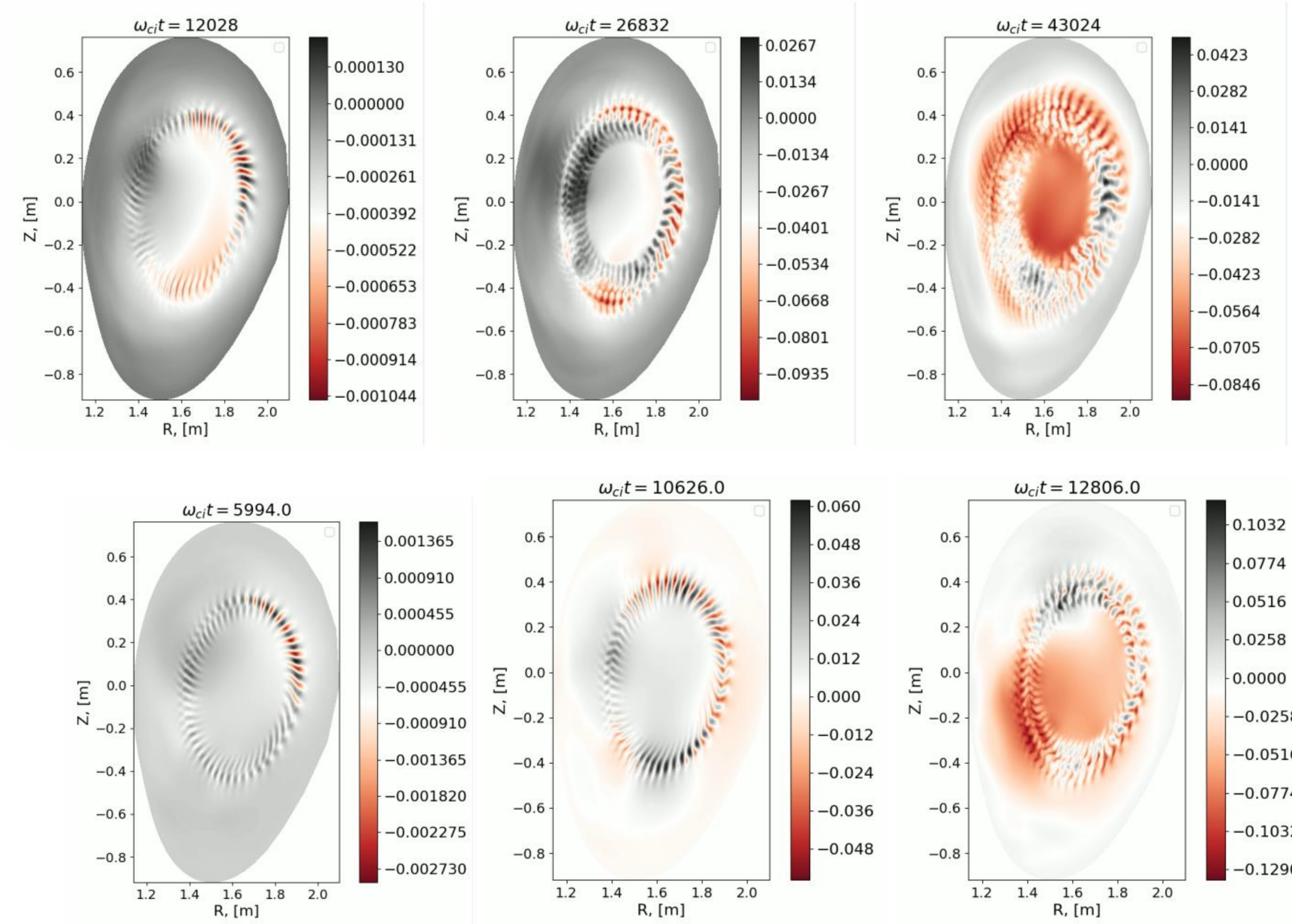
NLED-AUG case





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

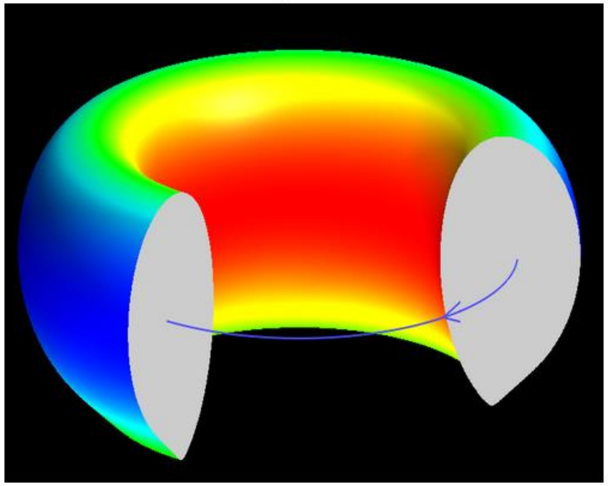
Real-space mode structure in ASDEX-Upgrade

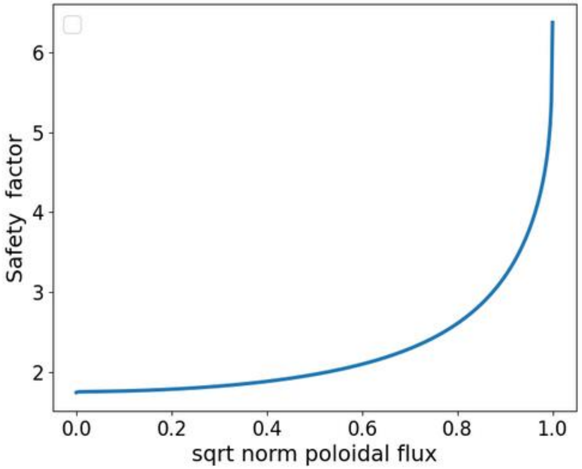


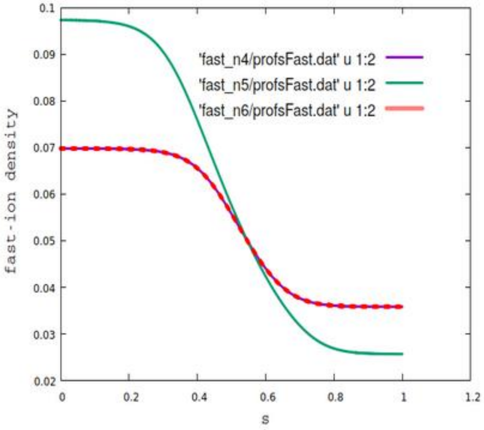
EM ITG, β = 0.4%

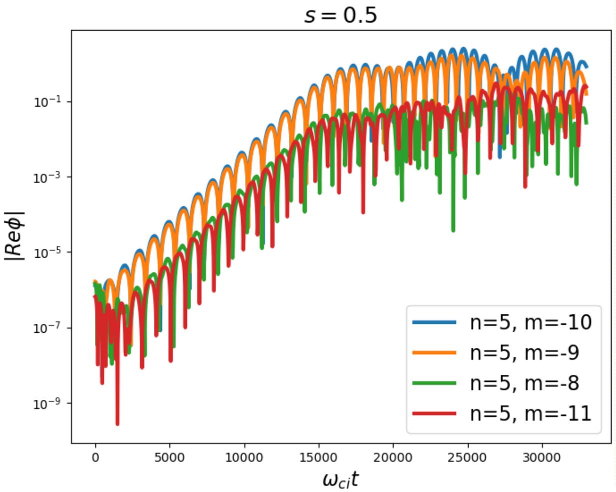
KBM, β = 4.8%

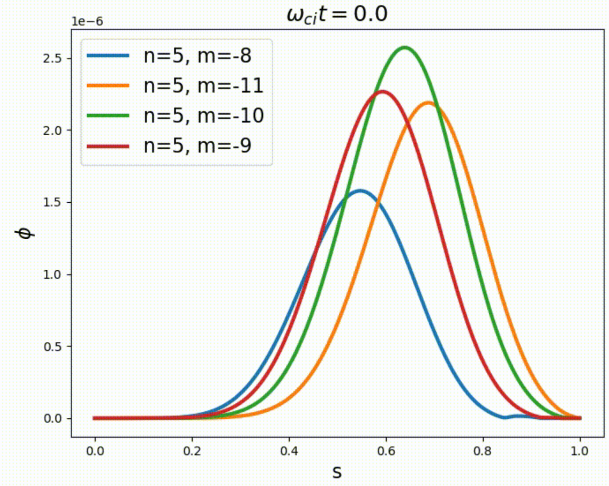
EM simulations in JET geometry

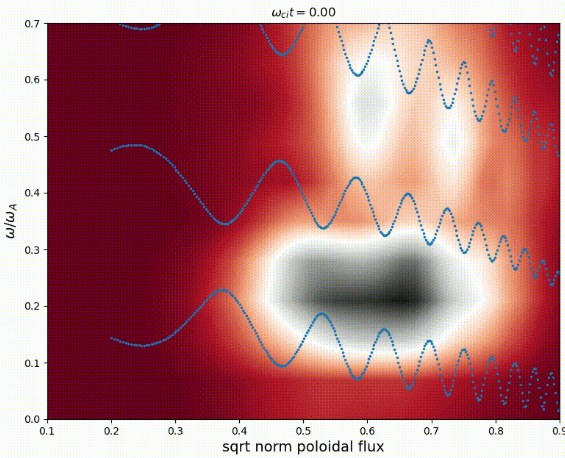






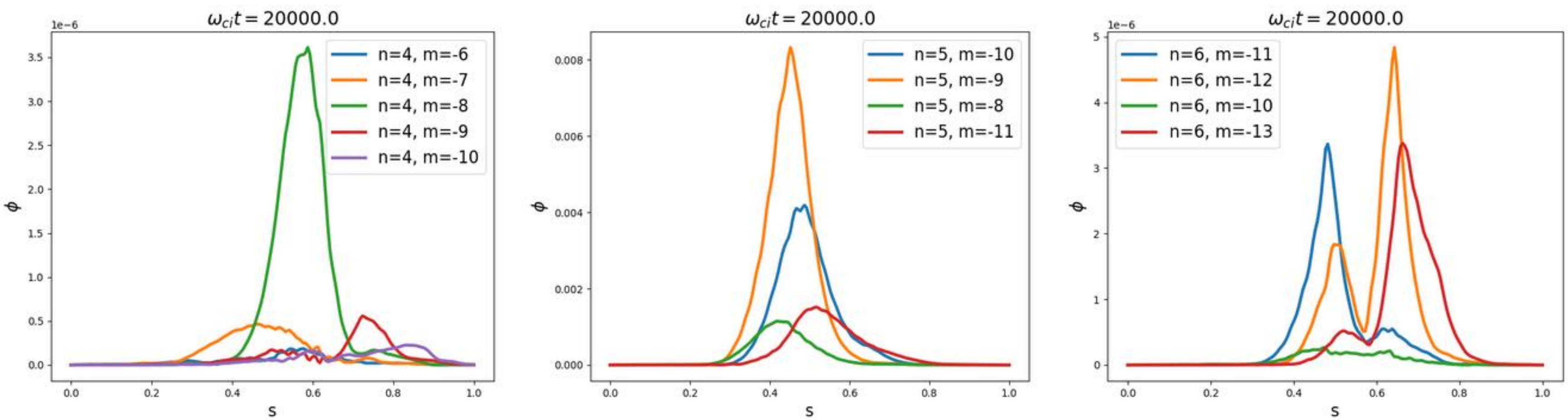




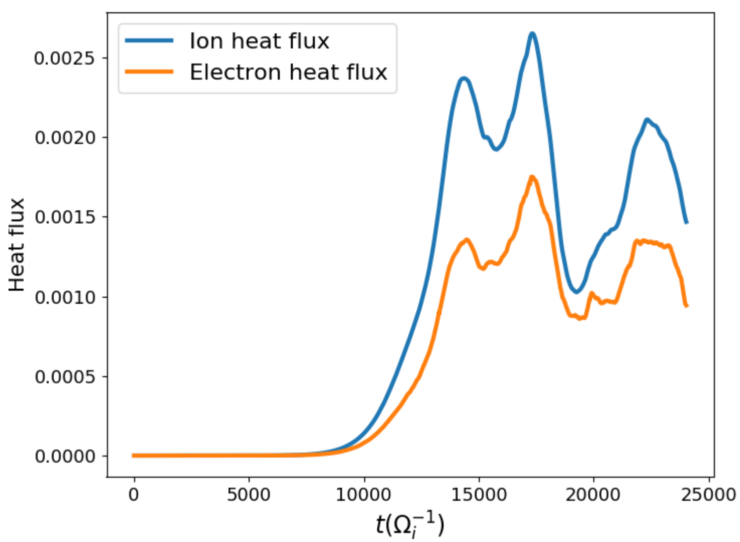


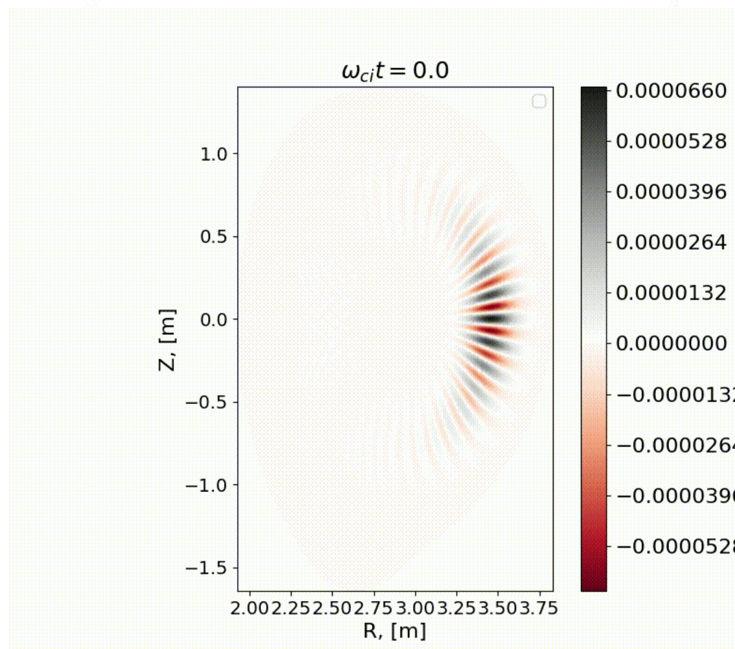
TAE and EPM instabilities in JET; frequency for n=5 TAE similar to LIGKA

TAE/EPM instabilities in JET and turbulence

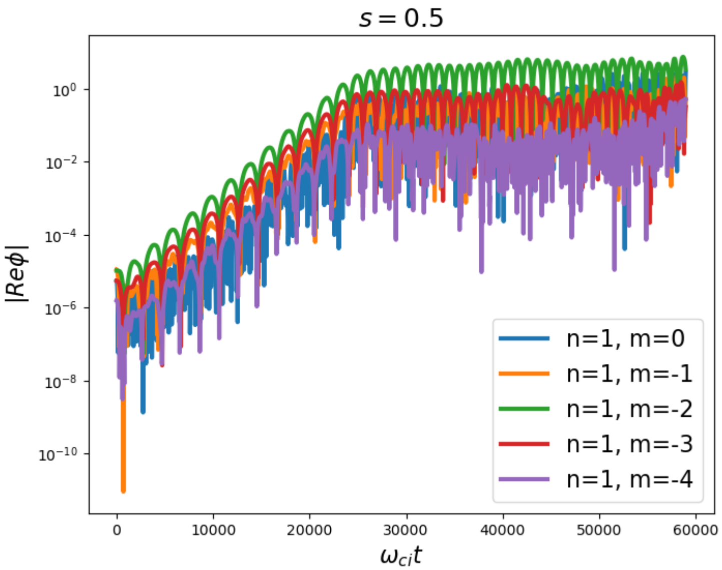


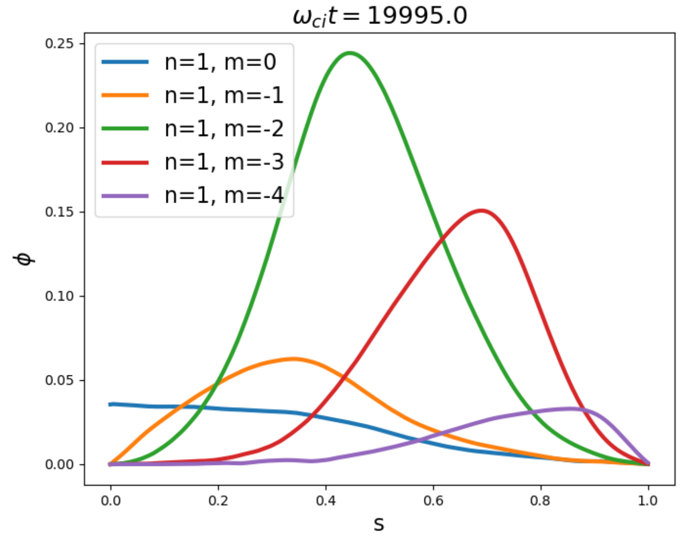
Mode structure: $n = 4$, $n = 5$, $n = 6$

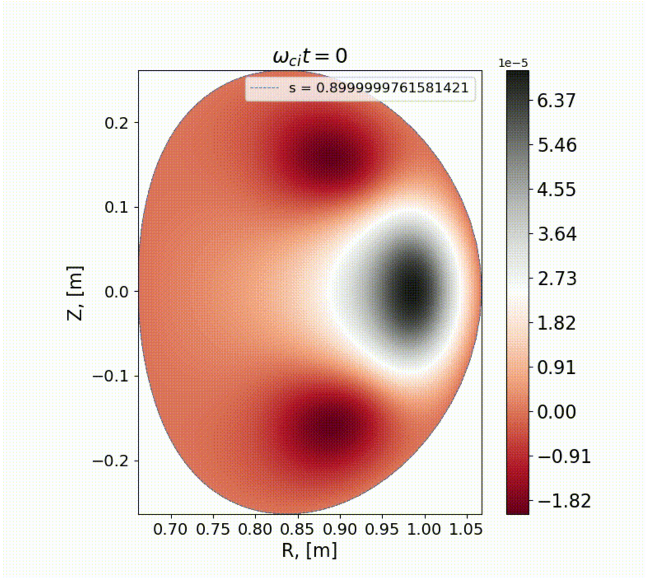


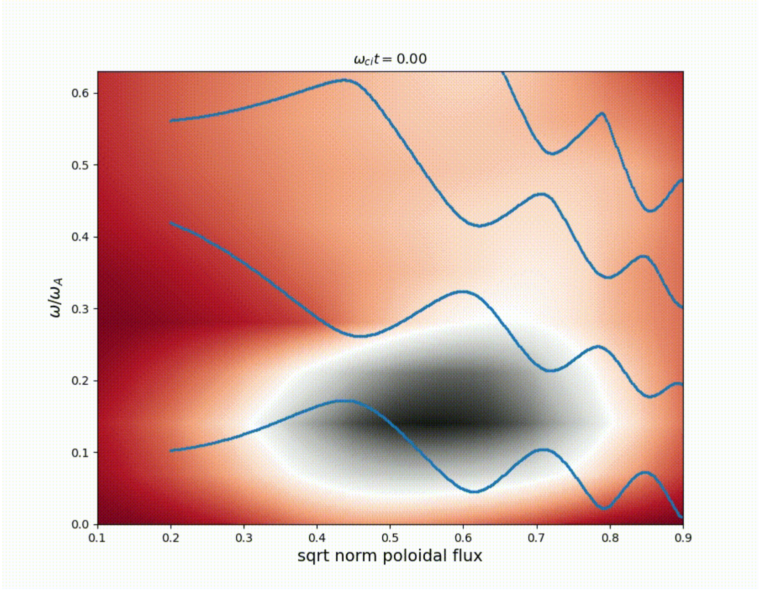


Chirping TAE/EPM instabilities in TCV

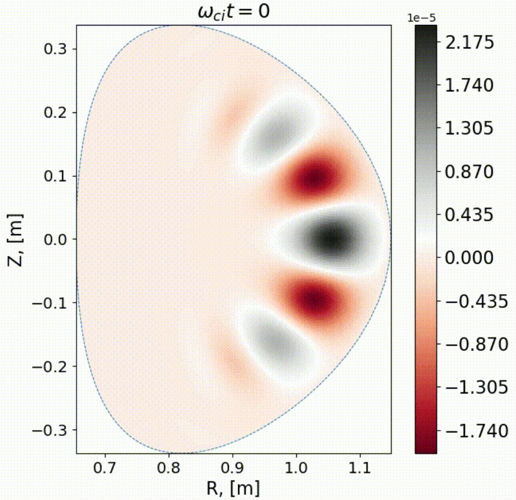


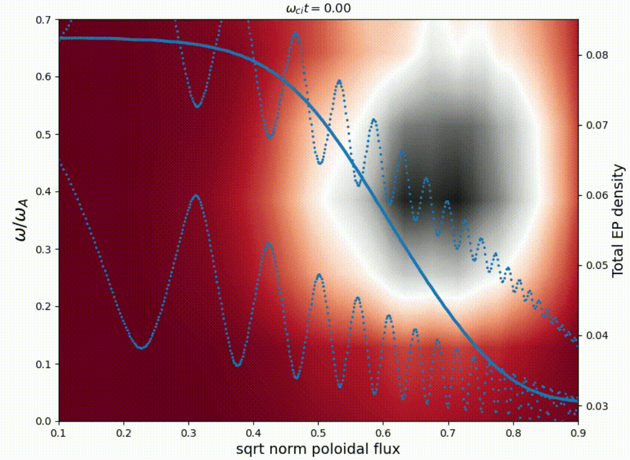


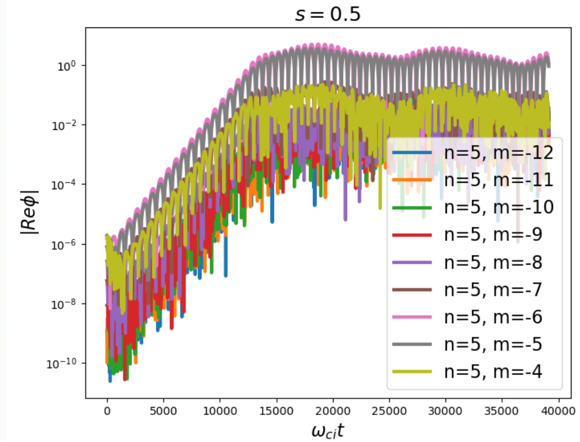


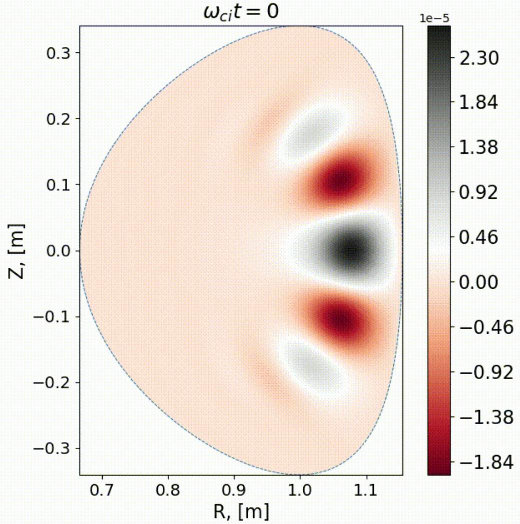


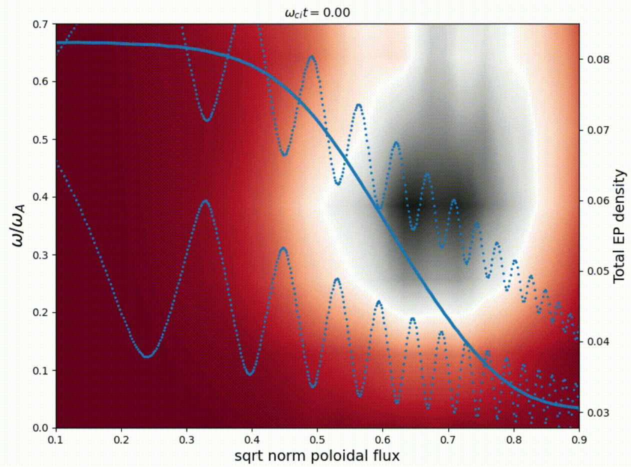
TAE/EPM: negative/positive triangularity TCV

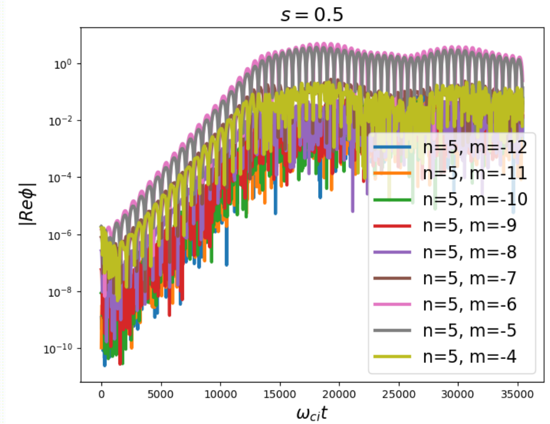




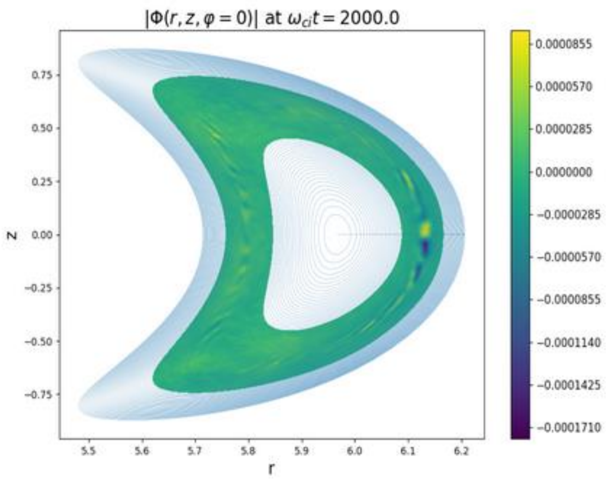


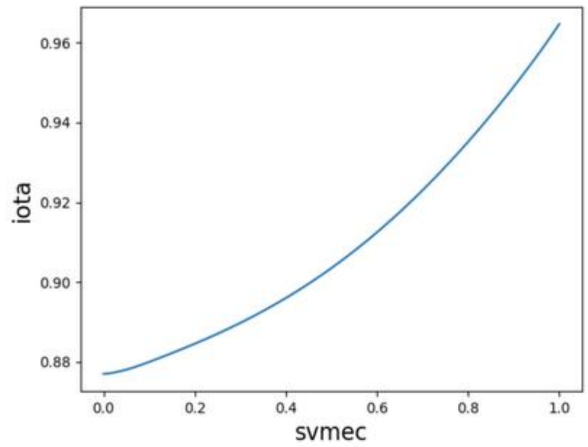






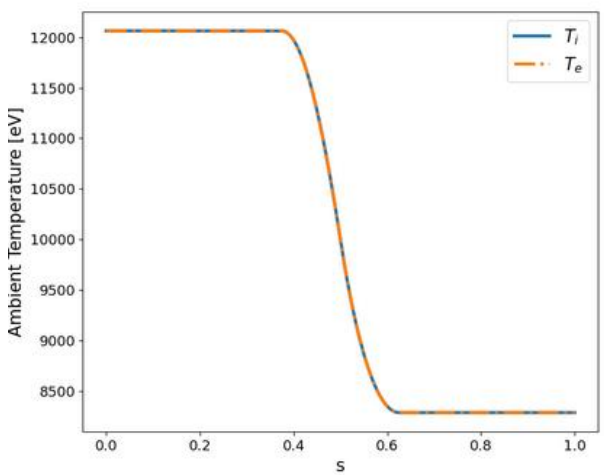
EM simulations in stellarators

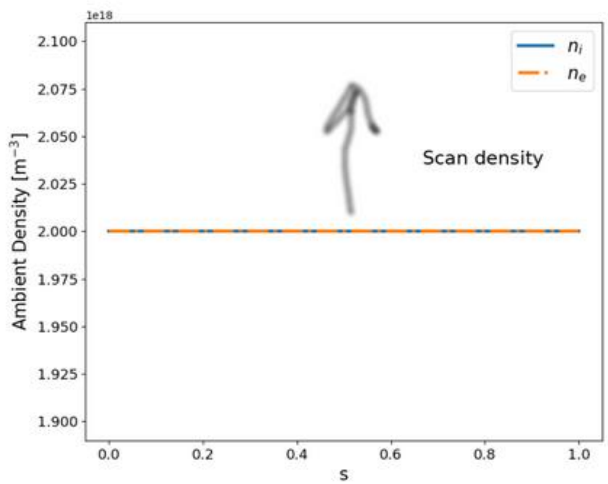


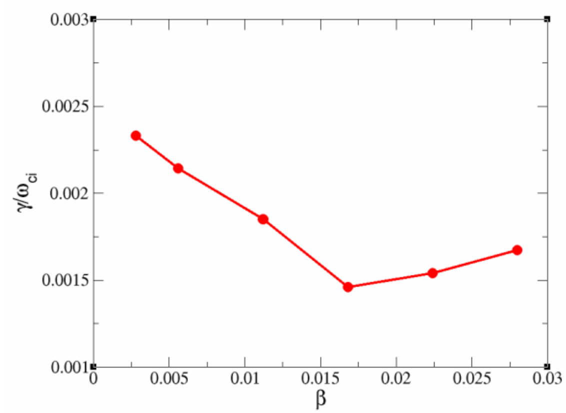


Larger temperature implies larger ρ_*

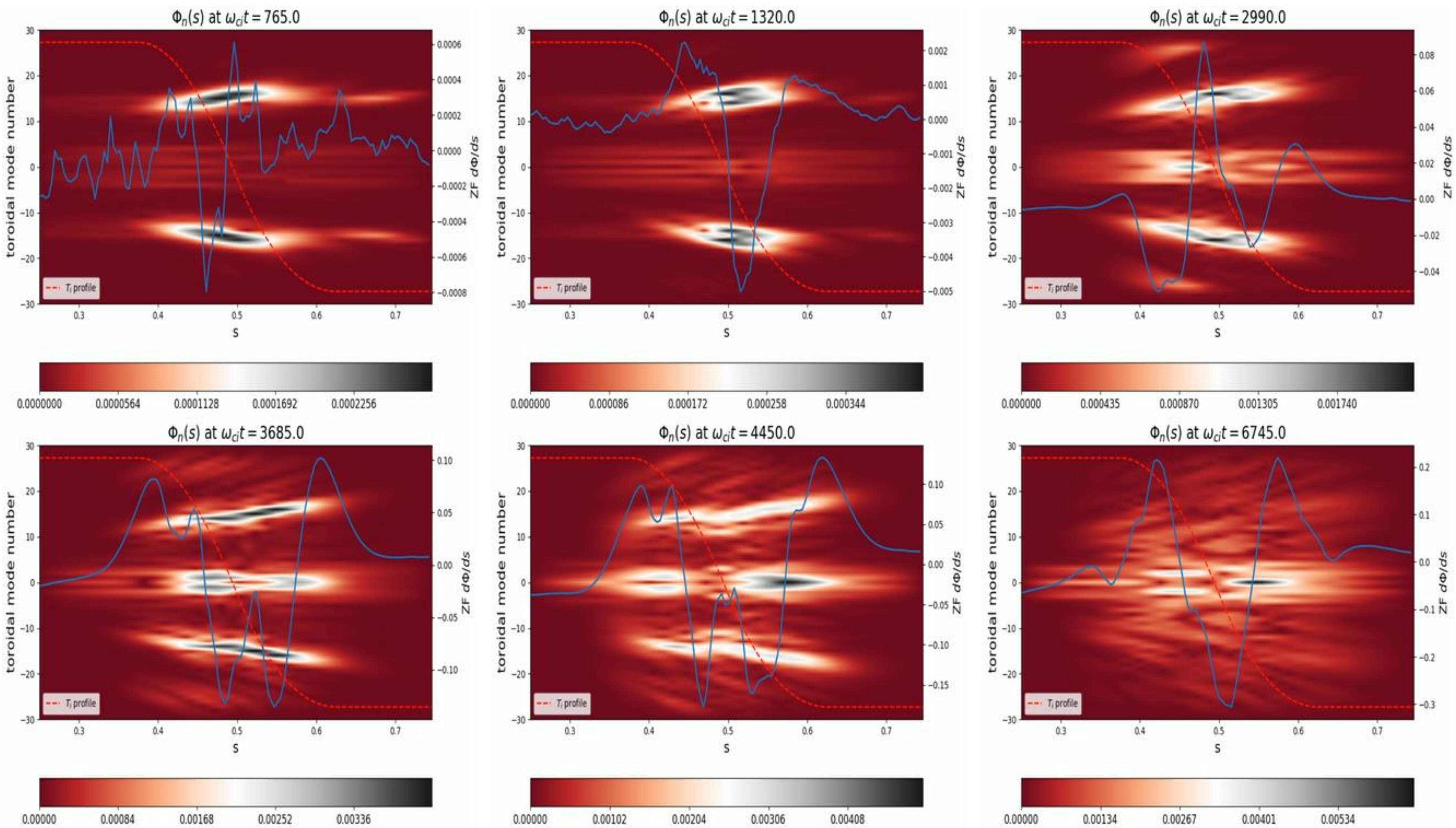
Larger ρ_* need less Fourier harmonics (to resolve the same $k\,\rho_i \sim 1$)







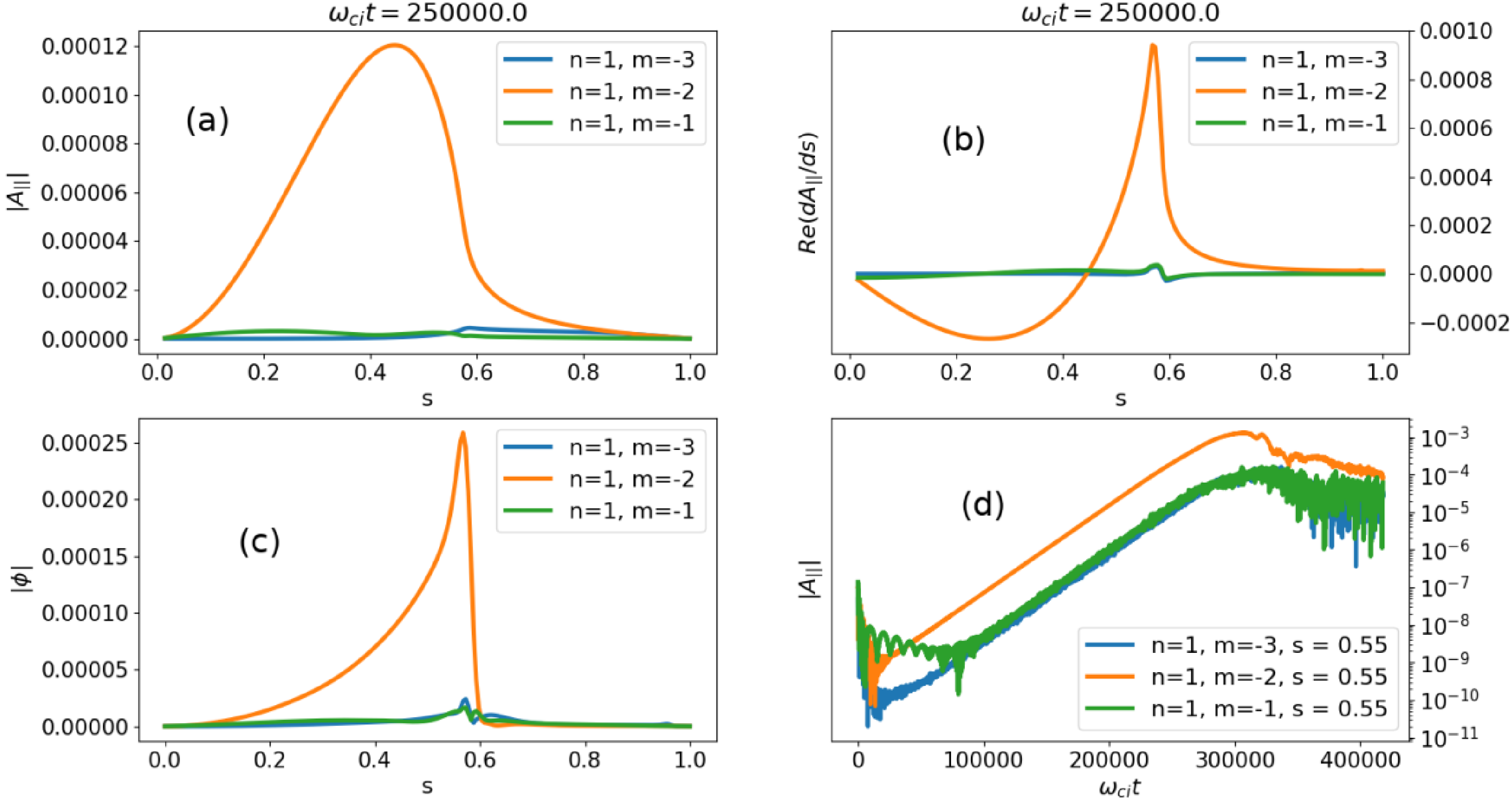
Toroidal spectrum: ZF and KBMs



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

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

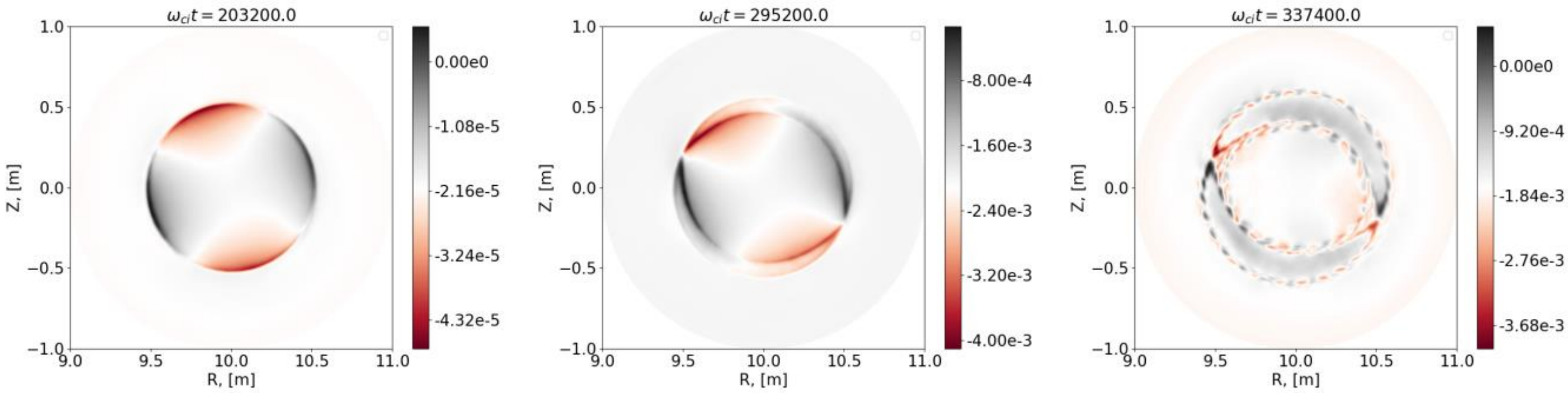
Tearing mode simulations



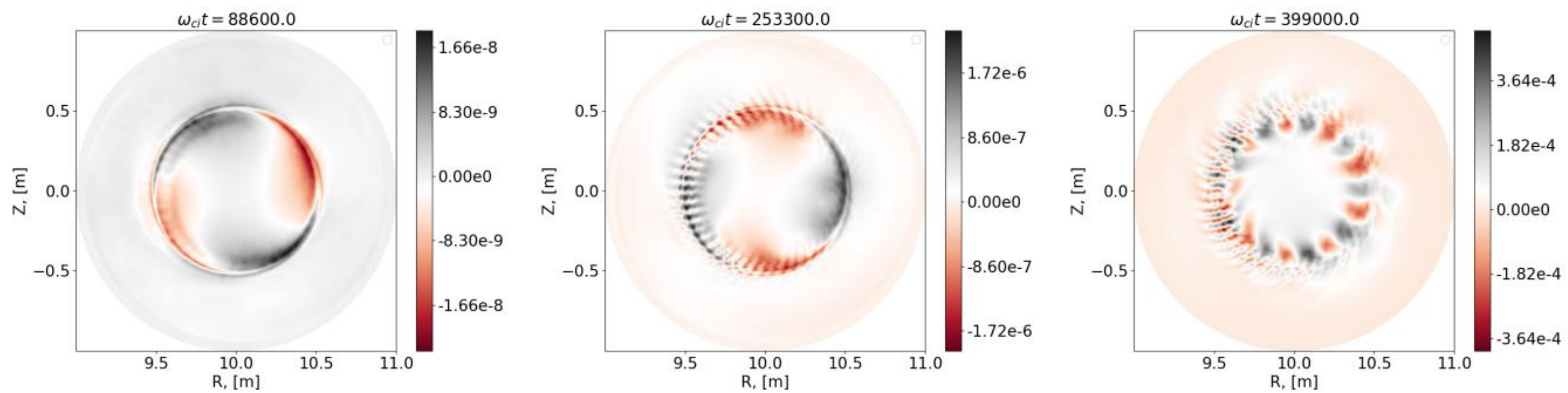
Safety factor profile with q=2 resonance; shifted Maxwellian for electrons

Tearing instability develops; peaked structures at resonant flux surface

Tearing mode simulations

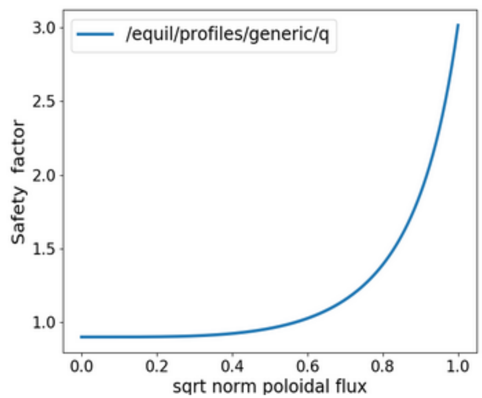


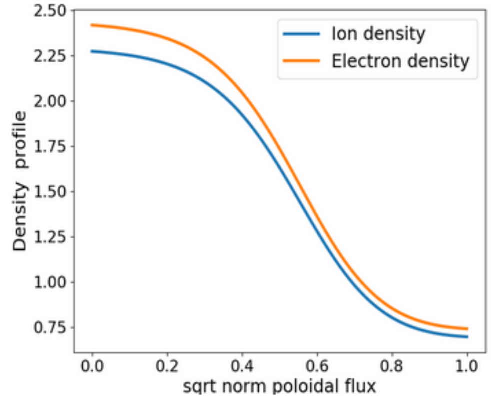
An island growth (X-points can be clearly seen); flat plasma profiles

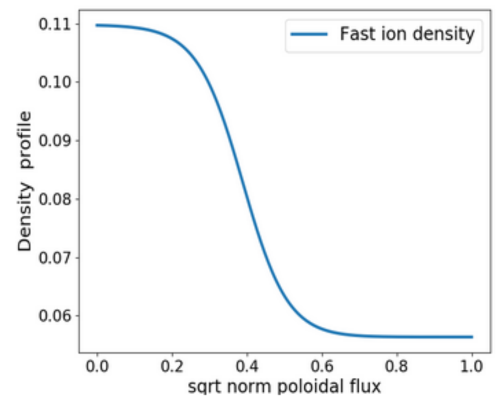


More complex physics for plasma with non-flat profile (turbulence)
It includes tearing, AEs, EM turbulence, and ZFs

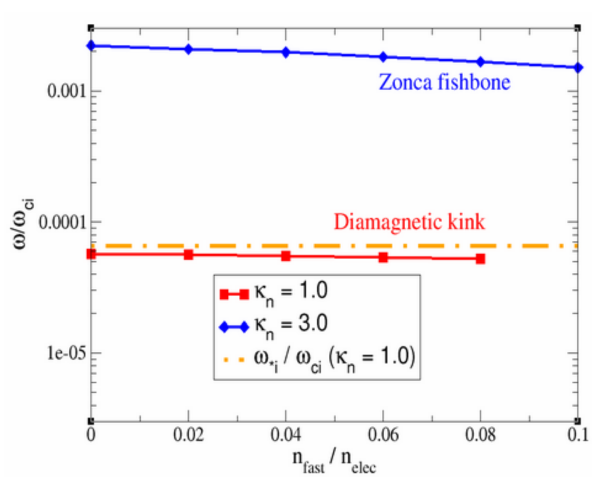
Internal kink and fishbone instabilities

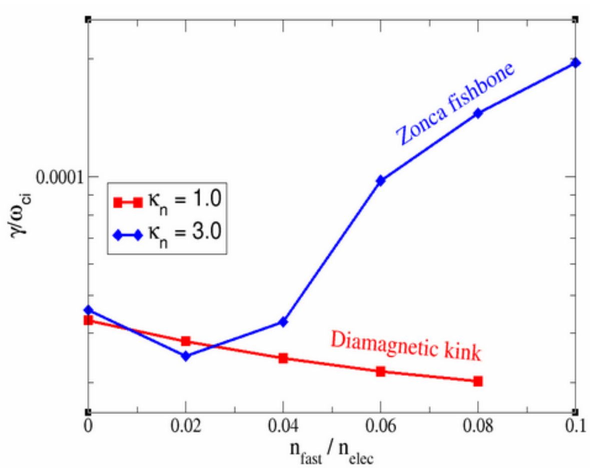


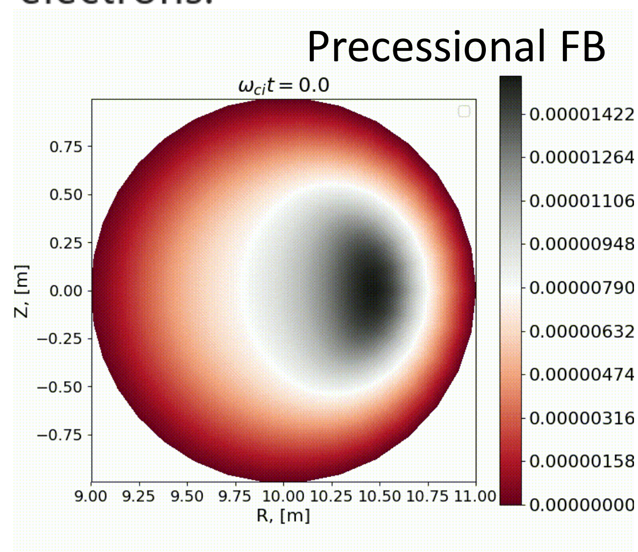




Large-aspect-ratio tokamak (A=10) with circular cross-sections. Safety factor (q=1 at s=0.57). Finite gradients for bulk-plasma density and EP density. Temperatures are flat for all species. Maxwellian fast ions; shifted Maxwellian for electrons.







Chirping TAEs

Electromagnetic turbulence and global modes 9

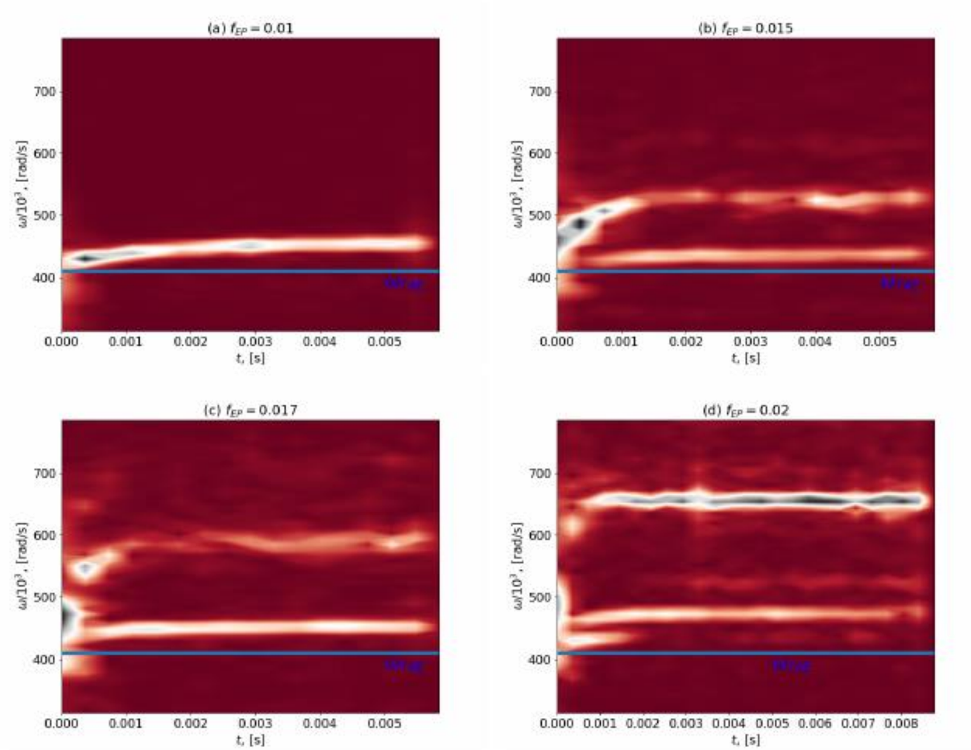
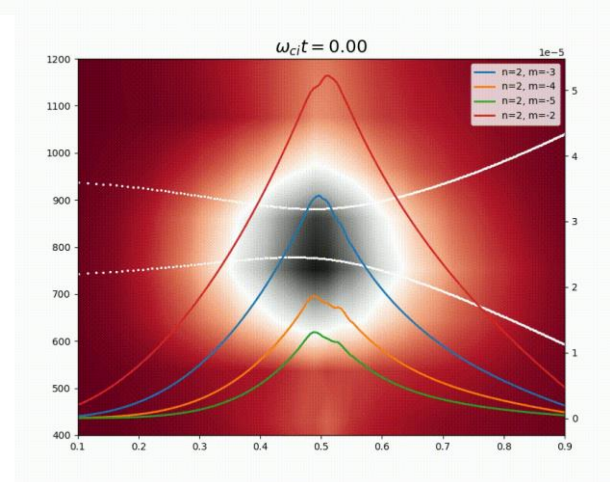
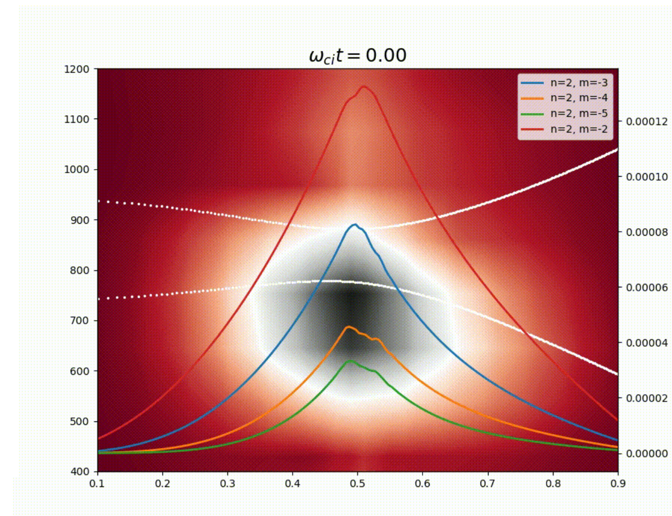


Figure 13. Energetic-particle nonlinearity only (flat bulk-plasma profiles). Frequency as a function of time for the fast-particle fraction: (a) $f_{EP} = 0.01$, (b) $f_{EP} = 0.015$, (c) $f_{EP} = 0.017$, (d) $f_{EP} = 0.02$. One sees how the nonlinear frequency evolution increases with the number of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



No turbulence: mode stays at the TAE gap



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

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EUROfusion

Conclusions

- TSVV10 succesfully started its work in 2021
- Regular team meetings (indico)
- Publications and conference presentations (pinboard)
- Cooperation with ACHs and other TSVVs
- Extensive usage of EUROfusion‘s HPC (including GPUs)

- Interactions with EUROfusion‘s Work Packages
  - Implementation of IMAS-integrated energetic-particle Workflow to TCV, AUG-U, JT60-SA
  - Participation in analysis and planning of W7-X experiments

- Broad cooperations within code-developer teams