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Non-linear gyro-kinetic Ion Temperature Gradient (ITG) and Trapped Electron Modes (TEM) turbulence modelling in X-point geometry with 3D fields, Edge Localized Modes and at negative and positive triangularity shapes

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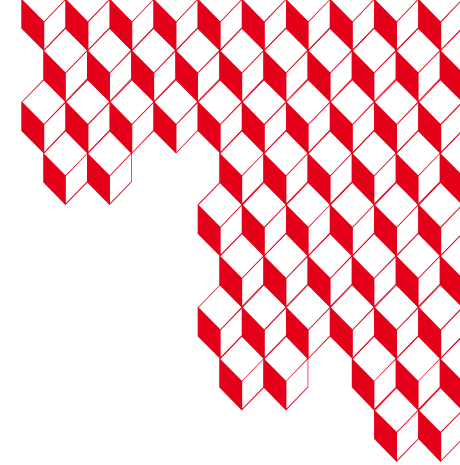
Submitted on 19 Mar 2024

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Non-linear gyro-kinetic Ion Temperature Gradient (ITG) and Trapped Electron Modes (TEM) turbulence modelling in X-point geometry with 3D fields, Edge Localized Modes and at negative and positive triangularity shapes.

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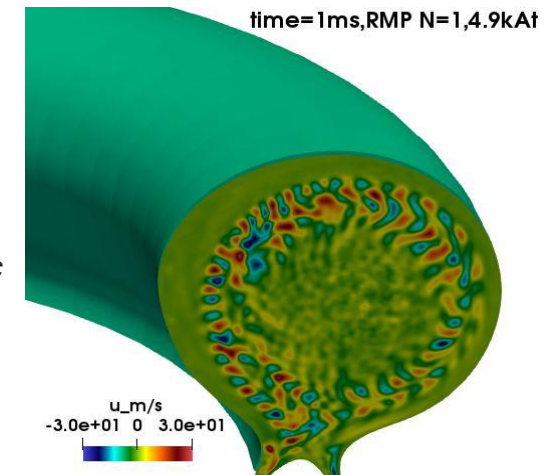
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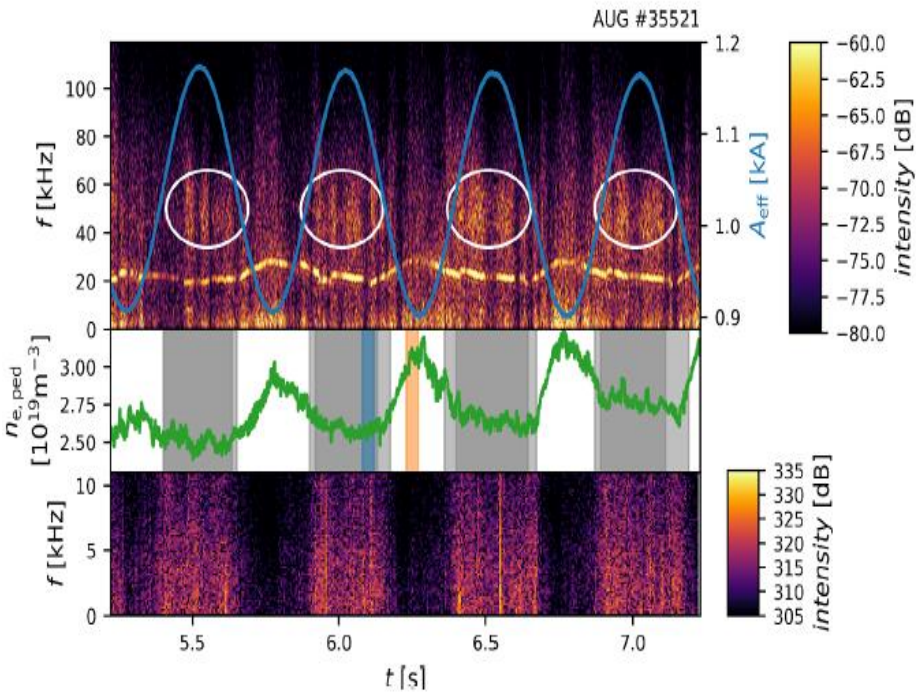
⁶Faculty of Mathematics and Physics, Charles University, Prague, Czech Republic

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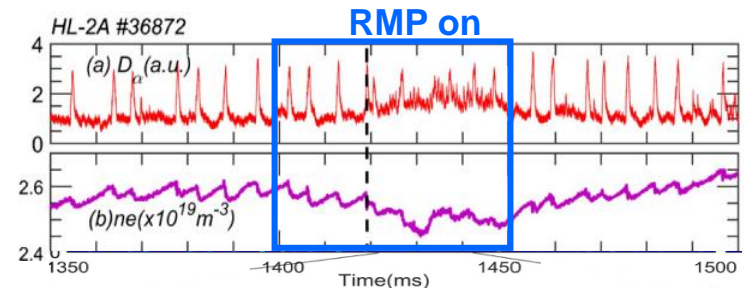


Motivation. Experimental observation : turbulence increases with RMPs. Why? What kind of turbulence? Reason for density pump-out?

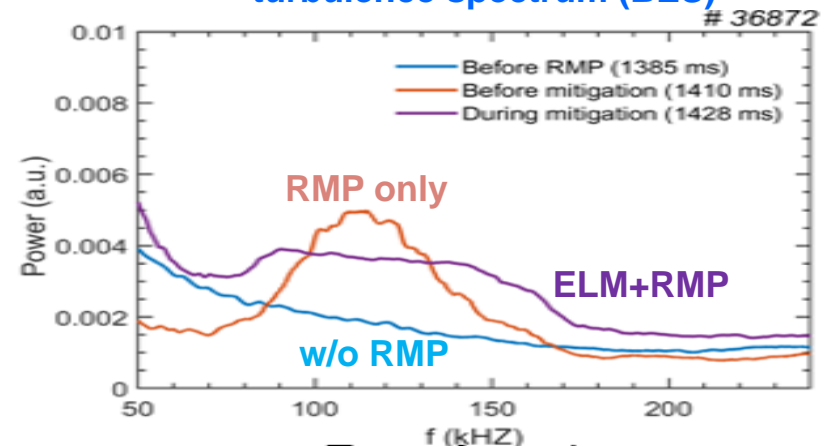
[AUG, N Leuthold, NF2023]:
Turbulence increases during ELM suppression by RMP N=2, density pump-out.



[HL2A, T F Sun, NF2021]:
Turbulence increases during ELM mitigation by RMP N=1, density pump-out.



turbulence spectrum (BES)

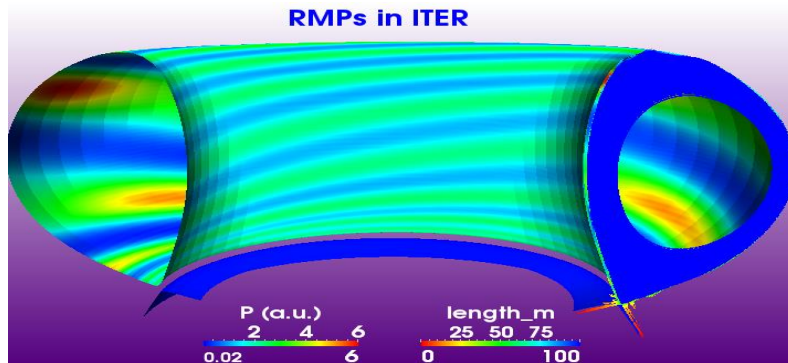


JOREK code.

[G Huysmans, NF 2007, PPCF 2009, M Hoelzl NF2021, <https://www.jorek.eu/>].

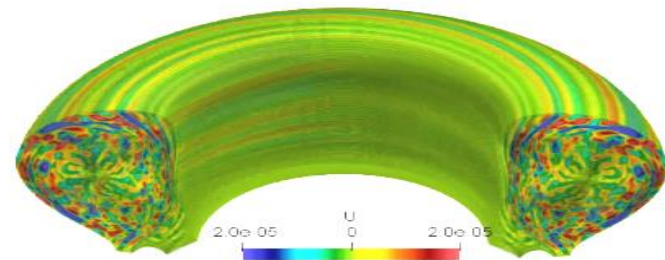
Fluid MHD model:

- Non-linear resistive MHD.
- Two fluid diamagnetic effects, rotation.
- Realistic geometry: SOL, divertor, walls, RMP coils.
- Bohm sheath boundary conditions.
- Flux-aligned grid, C^1 cubic Bezier finite elements in poloidal plane + toroidal Fourier harmonics.
- Parallelization: MPI/OpenMP, GPU.
- Fully implicit.
- Applications: ELMs, RMPs with plasma response, disruptions, pellets, runaways, etc



Kinetic particles for electrostatic ITG/TEMs:

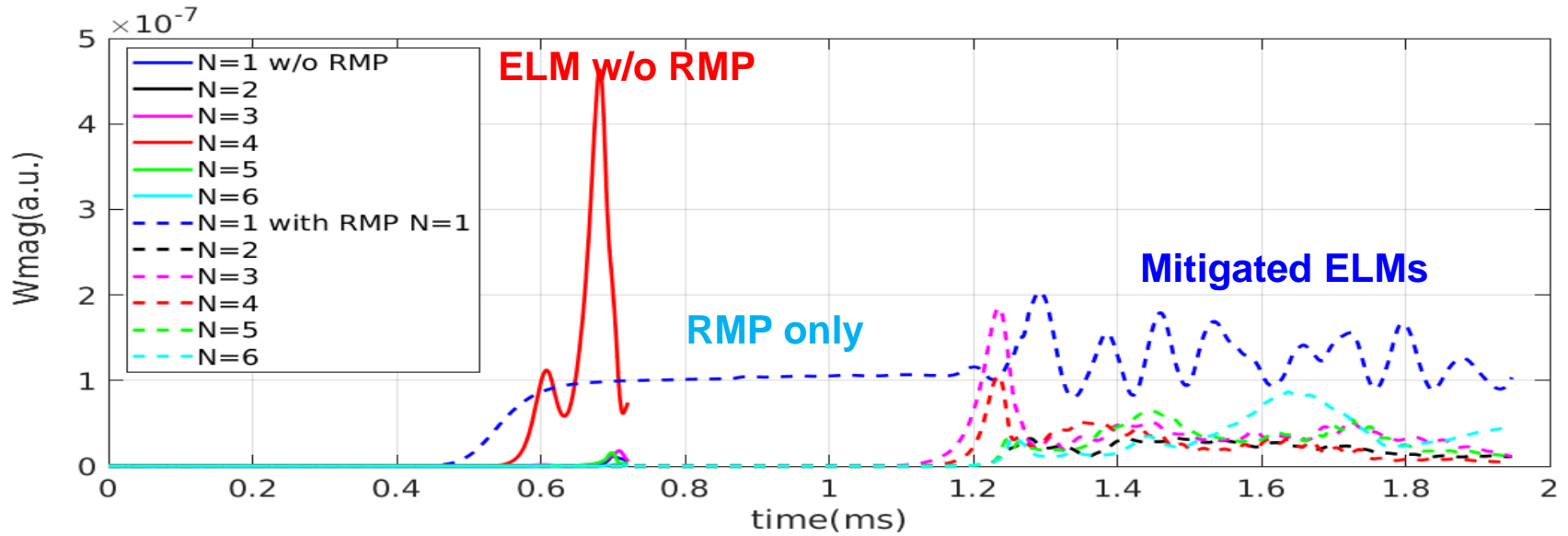
- Particles are initialized on the grid, plasma profiles and magnetic field from MHD.
- Non-linear full-f. Particles are advanced in time evolving electric field and static magnetic field (3D ergodic if RMPs!).
- Ions: // and ExB motion of gyro-centers in gyro-averaged electric field.
- Electrons: adiabatic or kinetic electrons.
- Projection and solution in weak form using the same basis functions as in fluid MHD.



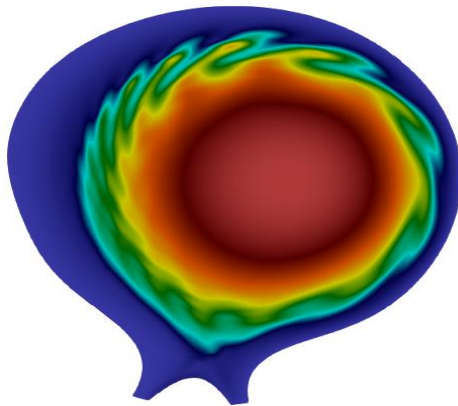
ITG/TEM in COMPASS with RMPs

Fluid non-linear MHD modelling of ELMs mitigation by RMPs (N=1, 4.9kAt, odd) in H-mode (HL2A#36872)

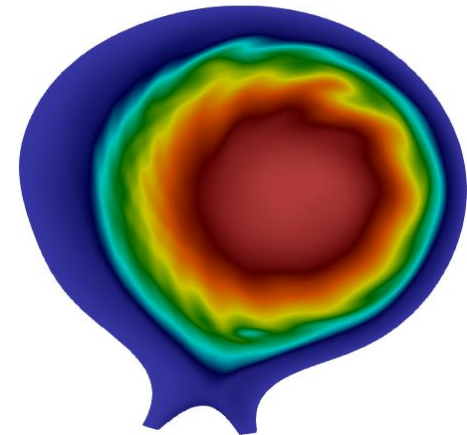
Data from [HL2A, T F Sun, NF2021]



Density in ELM crash w/o RMP



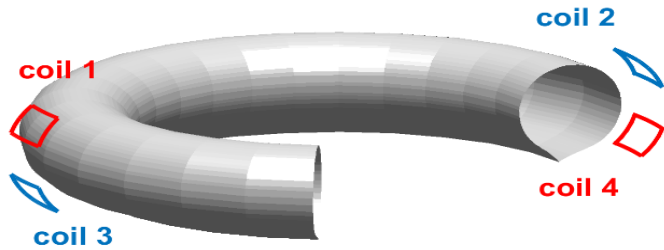
Density in mitigated by RMP ELMs



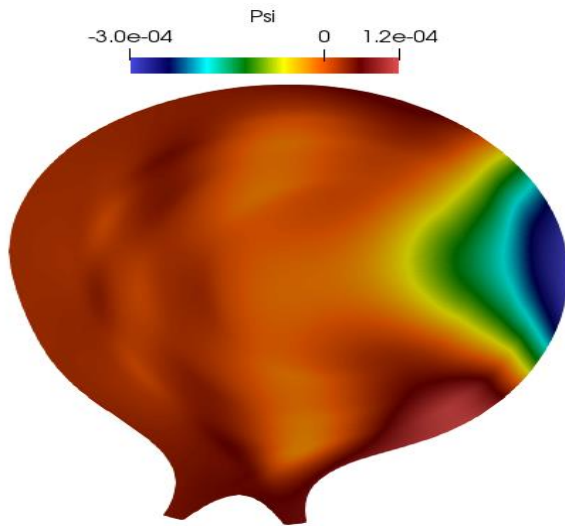
Equilibrium (3D with RMPs) and plasma profiles used for kinetic particles initialisation.

RMPs => 1) edge 3D ergodic field; 2) decreased pedestal gradients 3) decrease E_r "well". How they influence turbulence?

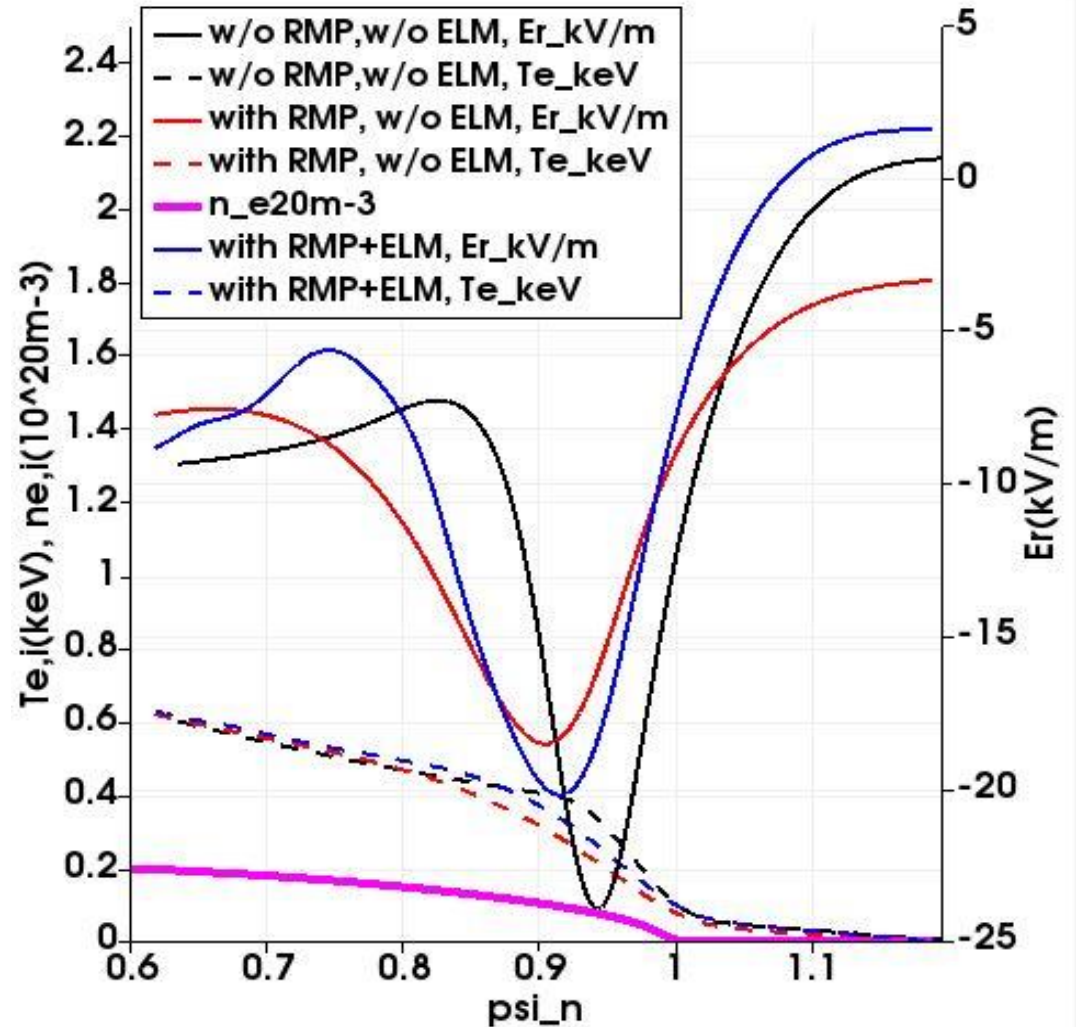
RMP coils in HL2A



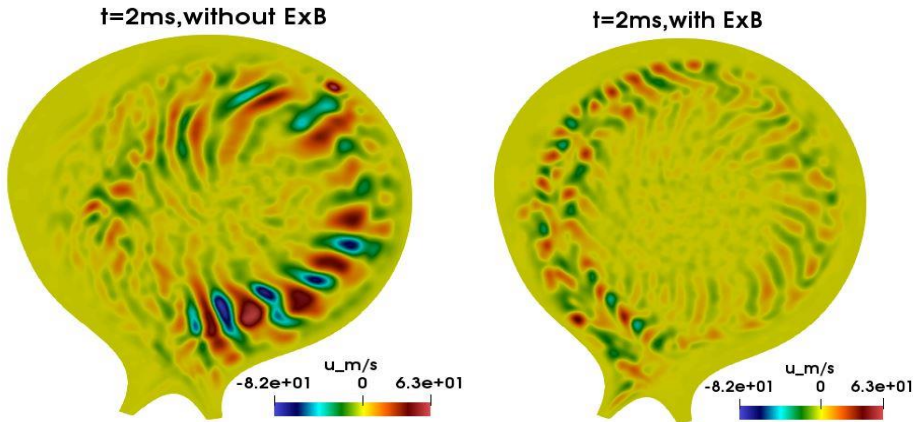
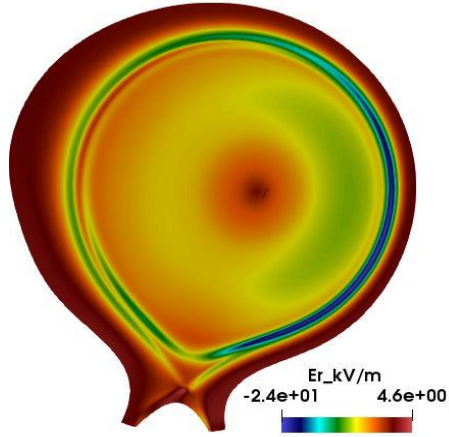
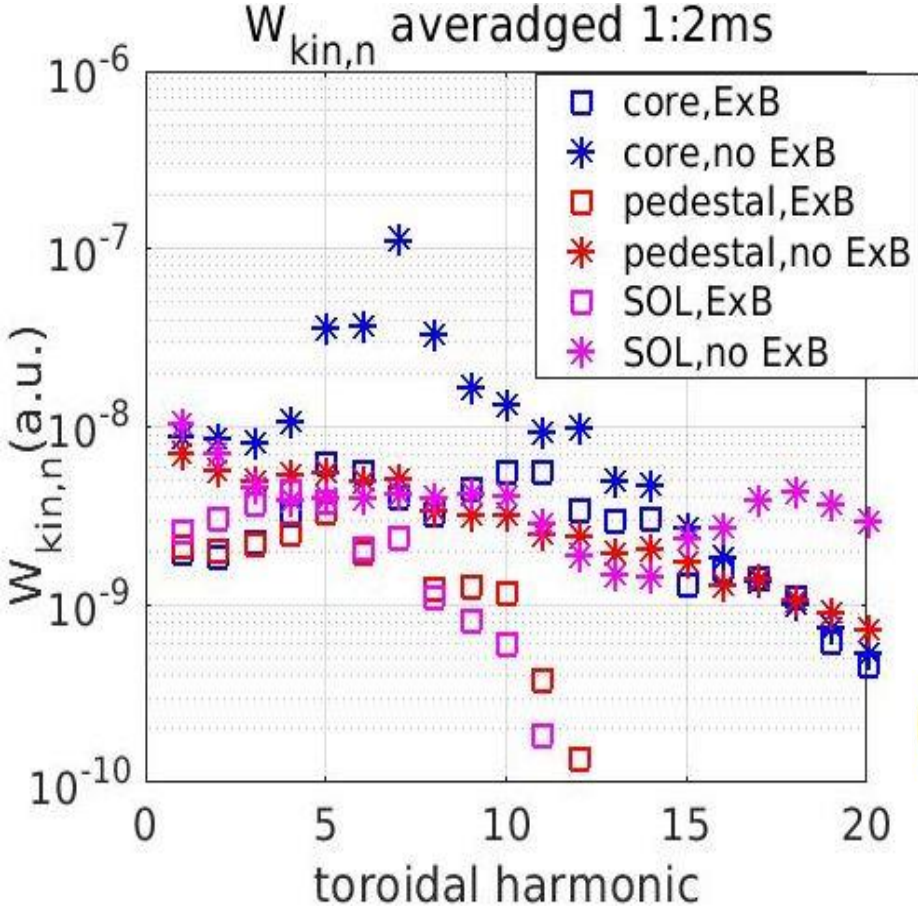
pol flux perturbation by RMP $N=1$, 4.9kAt, odd parity



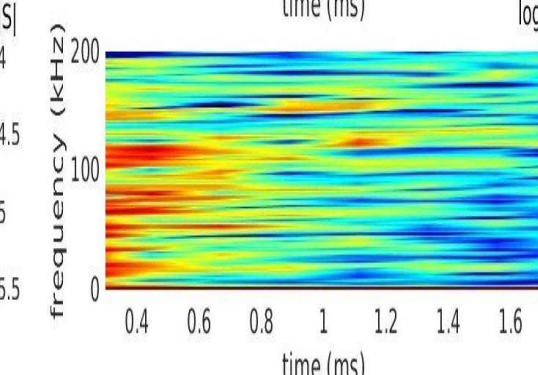
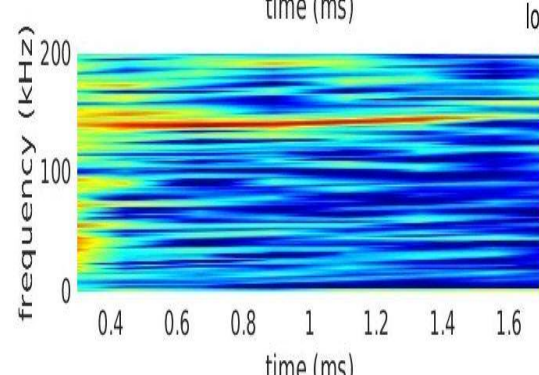
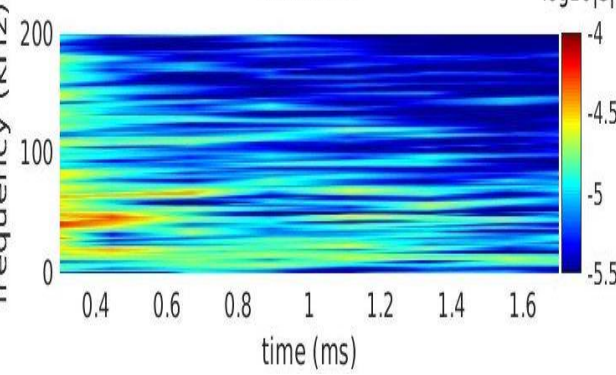
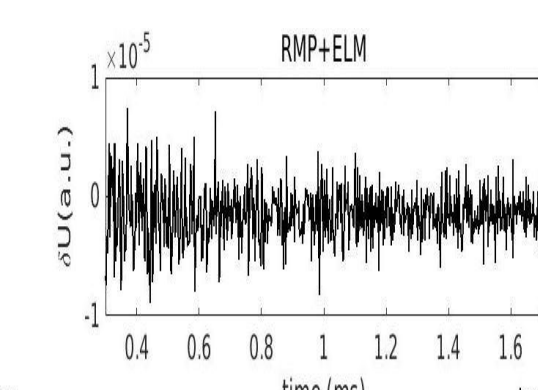
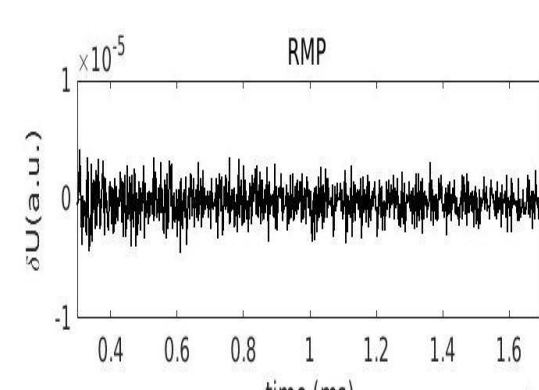
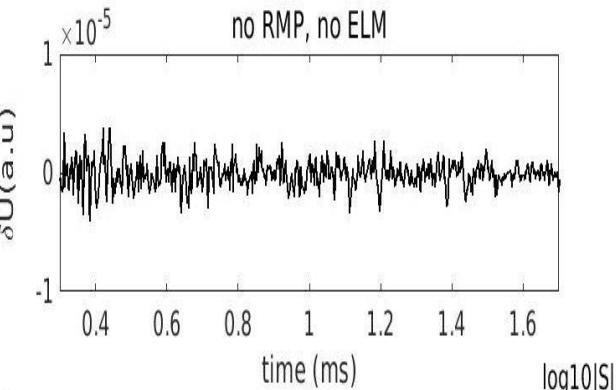
profiles



Non-linear gyro-kinetic modelling of ITGs with adiabatic electrons for H-mode (HL2A#36872). Stabilising effect of mean poloidal ExB flow in the pedestal.



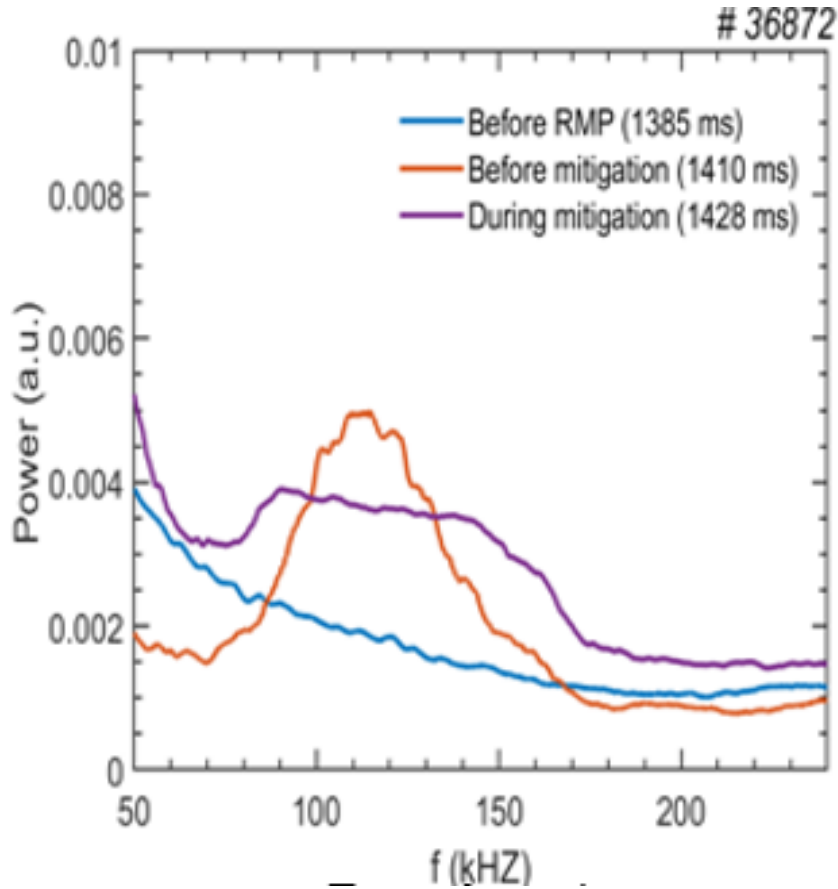
Potential fluctuations signal (upper rows) frequency spectra (low rows) in the pedestal w/o ELMs ,RMP; RMP only and mitigated ELMs in modelling of ITGs(N=1:1:20) with adiabatic electrons for HL2A #36872.



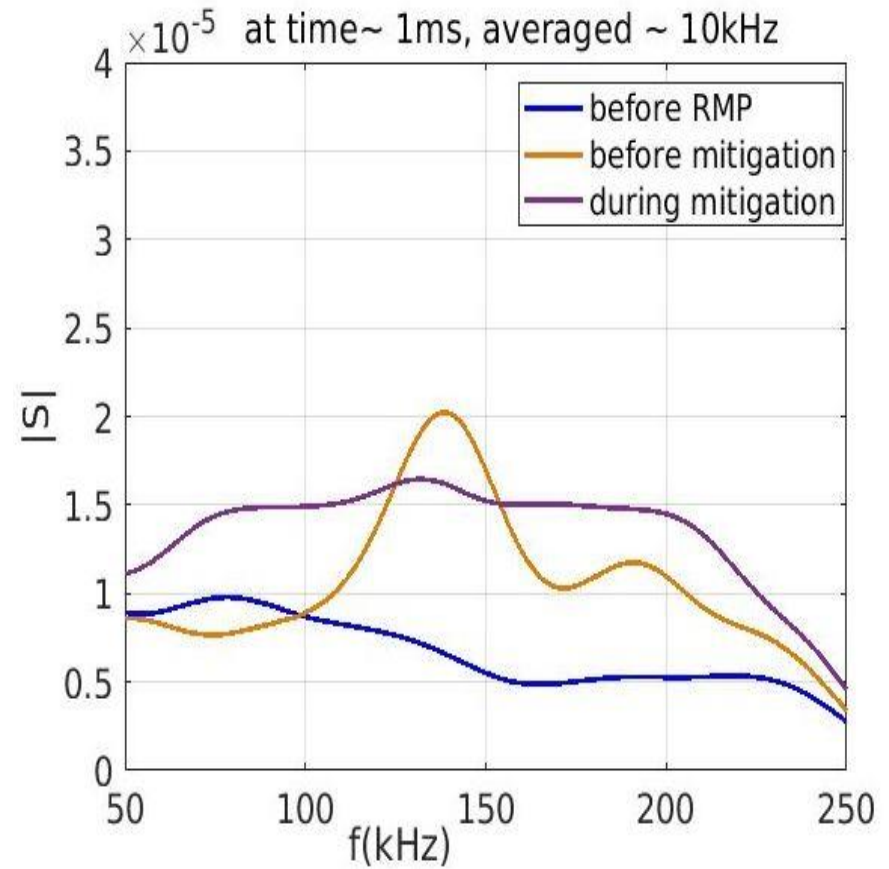
Frequency range and spectrum shape in modelling is similar to experimental

Experiment

[HL2A, T F Sun, NF2021]



JOREK

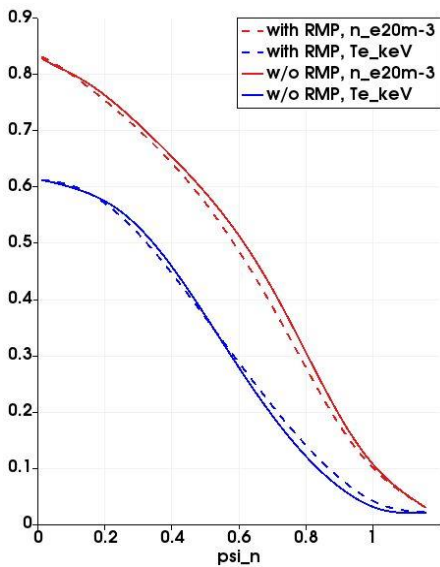


Modelling of ITG/TEM turbulence for COMPASS# 8078 L-mode

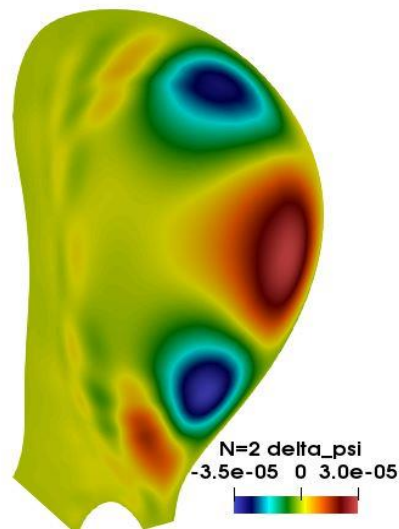
Data from [T Markovic NF2006]

JOREK as non-linear fluid MHD code => 3D fields and profiles with plasma response to RMP (N=2, 1.5kAt) are used for particles initialization.

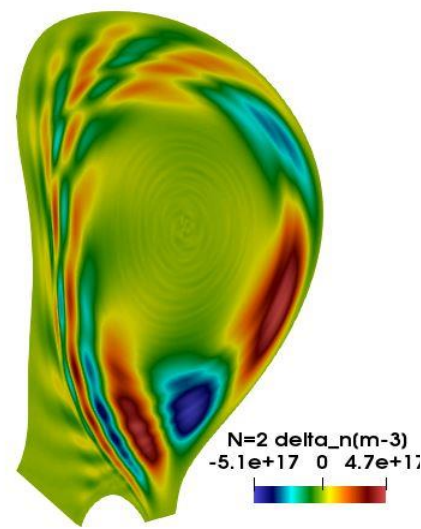
Density, temperature (Te=Ti) mid-plane profiles



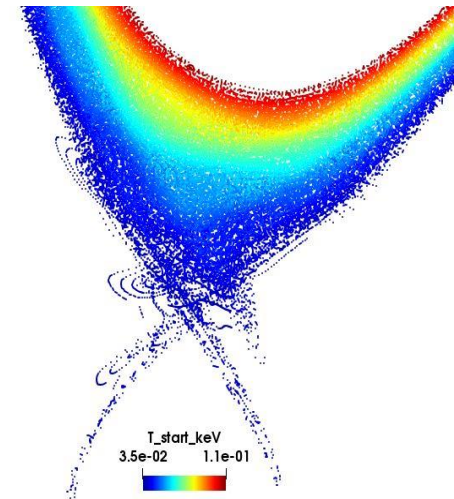
Magnetic flux perturbation with RMP



Density perturbation with RMP



Edge magnetic topology with RMP. Ergodic 3D field.



Increased turbulence with RMPs. Larger TEM/ITG with kinetic electrons compared to ITG with adiabatic electrons

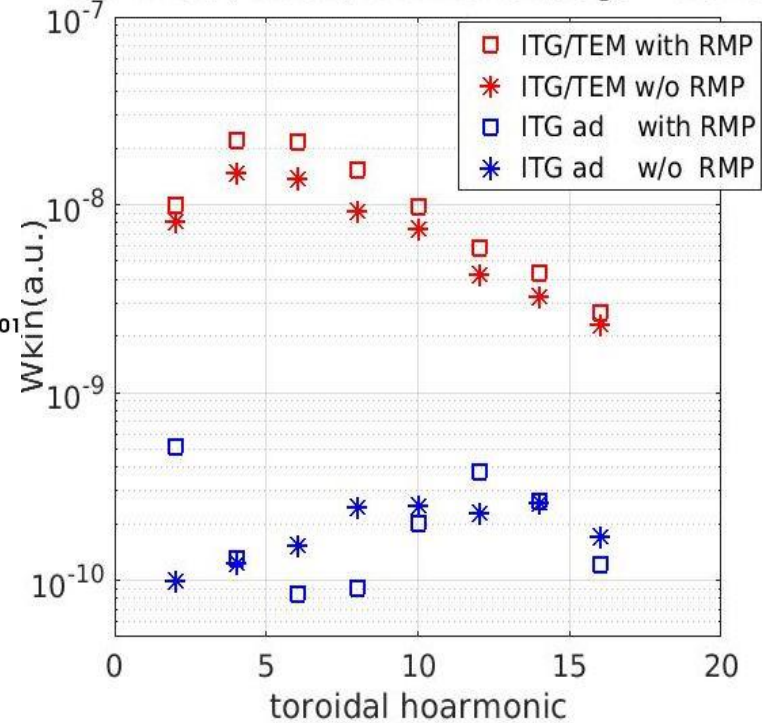
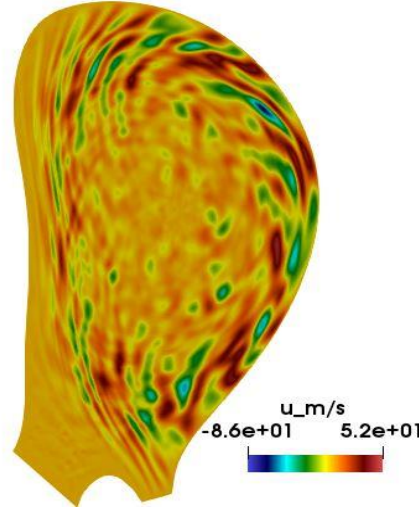
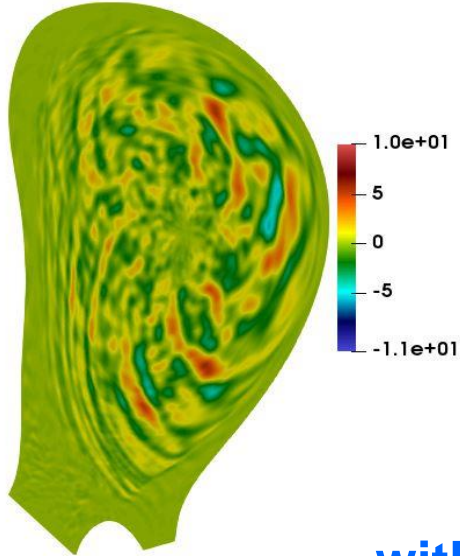
w/o RMP

time=1ms, TEM/ITG w/o RMP

COMPASS , ini 3D, Wkin tot average ~0.5ms

ITG,adiabatic

ITG+TEM, kinetic el, zonal

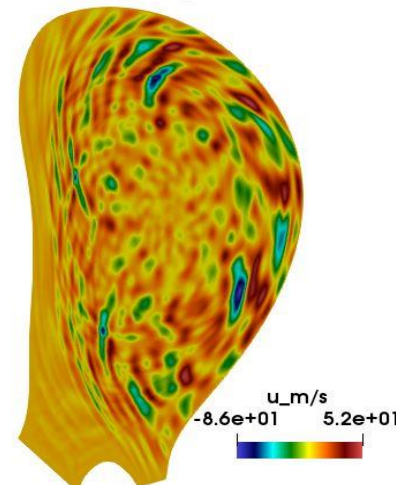
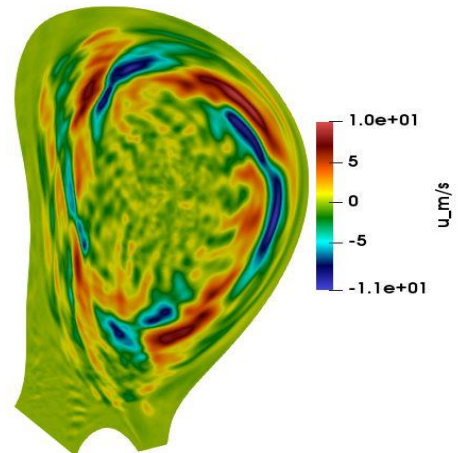


with RMP

time=1ms, TEM/ITG with RMP

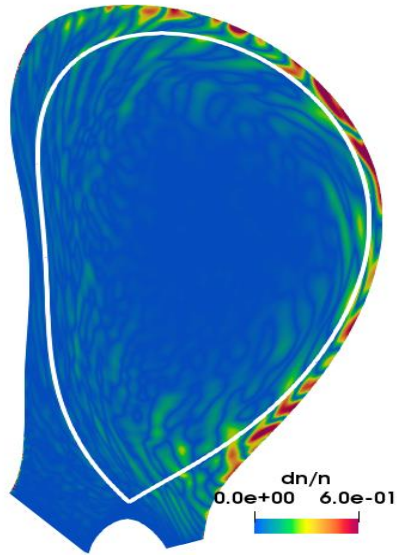
ITG,adiabatic

ITG+TEM, kinetic el, zonal

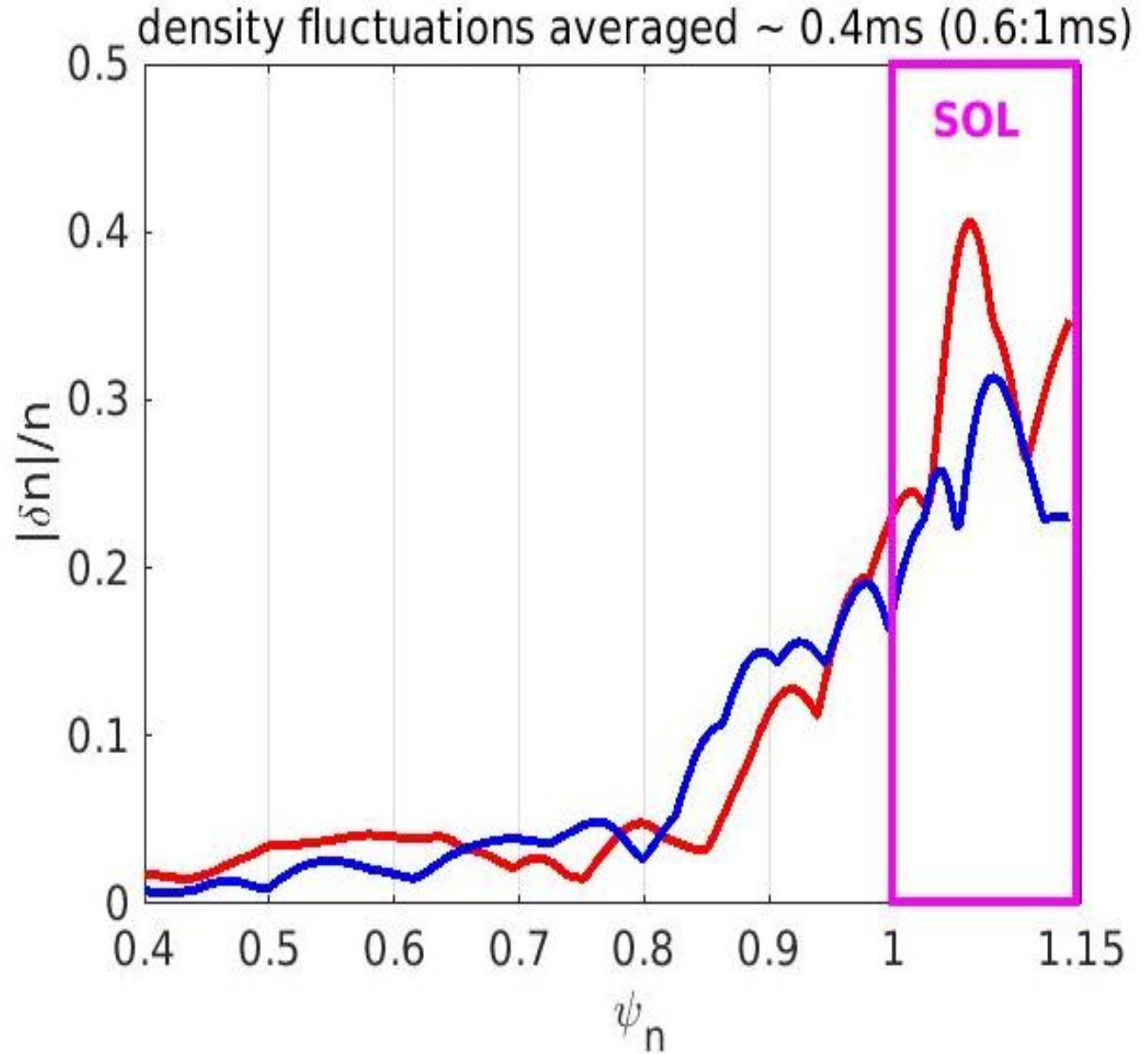
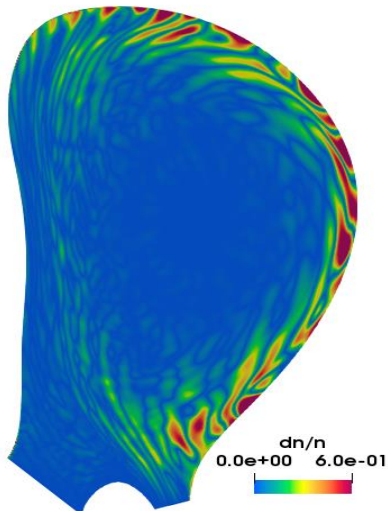


With RMPs density fluctuations are increased (especially in the SOL)

$t=0.6\text{ms}$, w/o RMP



$t=0.6\text{ms}$, with RMP N=2, 1.5kAt

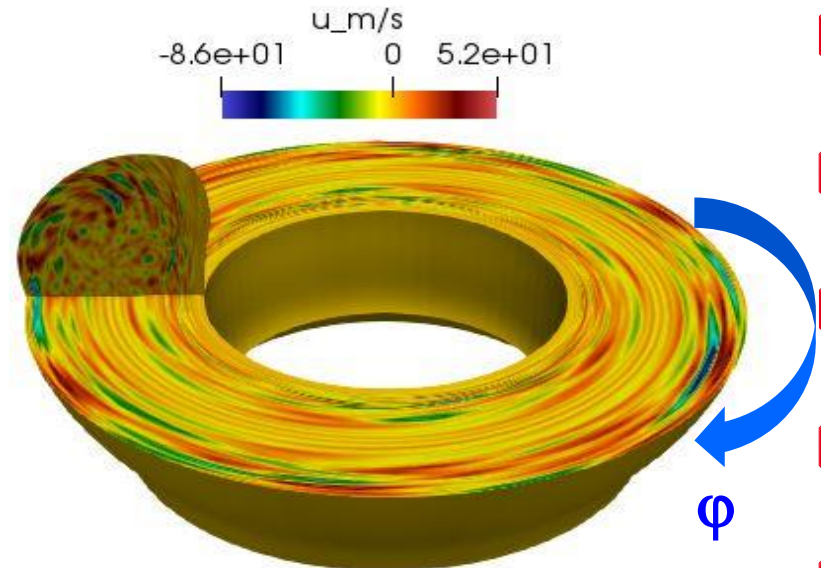
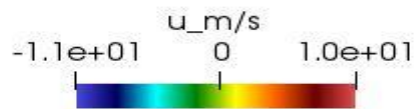
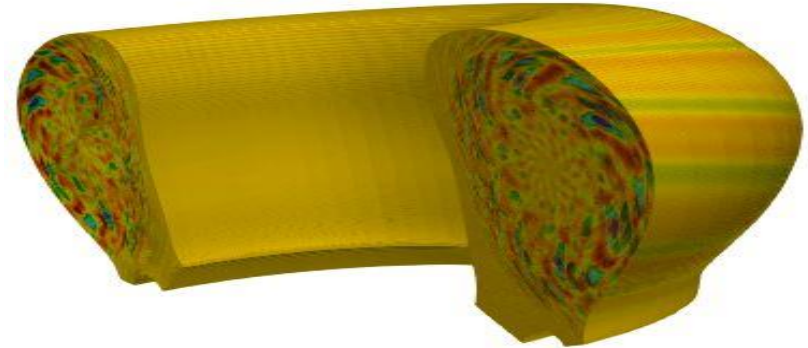
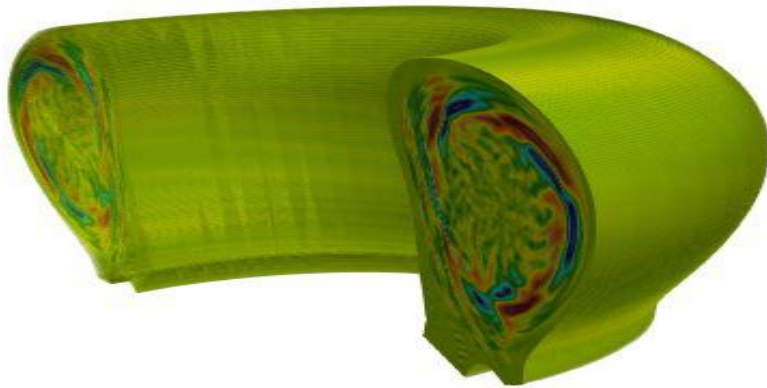
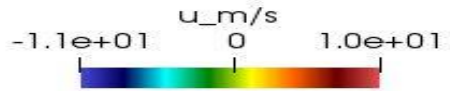


Toroidal asymmetry of turbulence with RMPs.

Seen in some experiments [AUG: N. Leuthold et al Nucl Fusion 63(2023)]

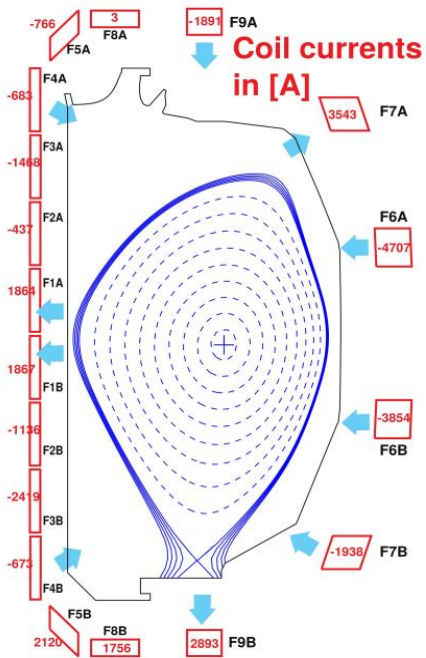
ITG, ad el

ITG/TEM, kinetic el

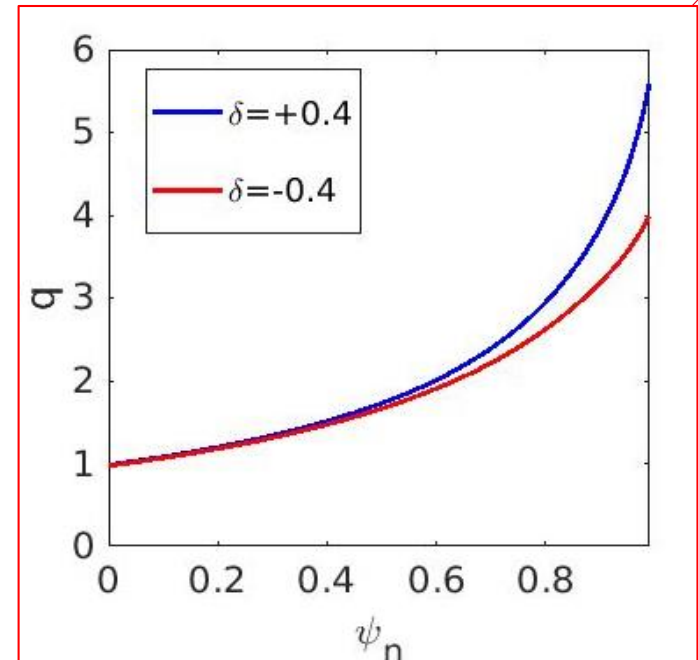
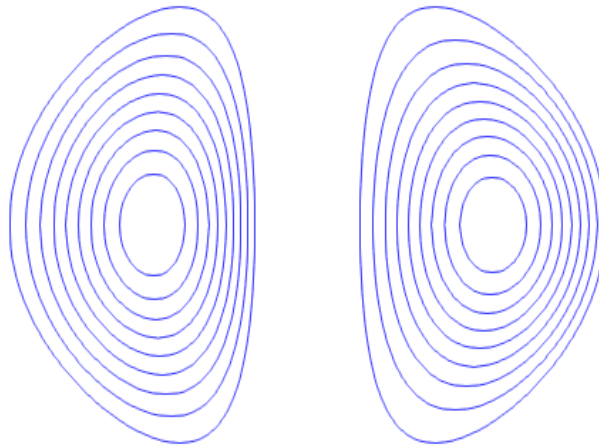


ITG/TEM (with kinetic electrons) and ITG (with adiabatic electrons) turbulence in plasmas with positive/negative triangularity.

DIII-D-like L-mode parameters [A Marinoni et al., Nucl Fus 61(2021)].

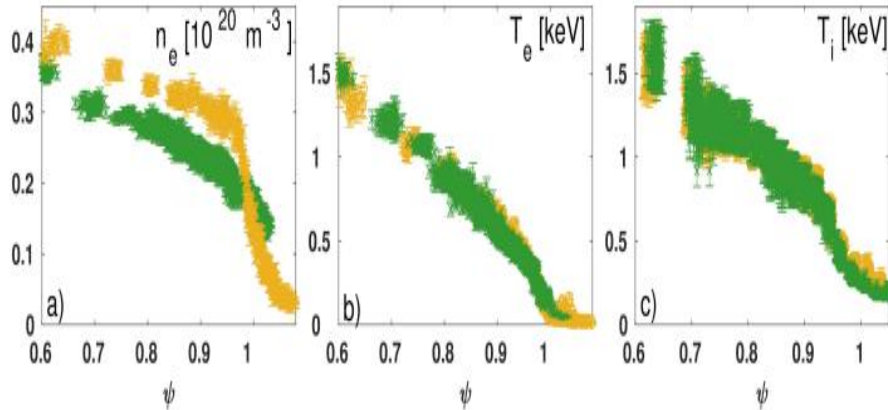


note that with the same profiles $q_{95_NT}=4.5$ $q_{95_PT}=3.6$ for PT)



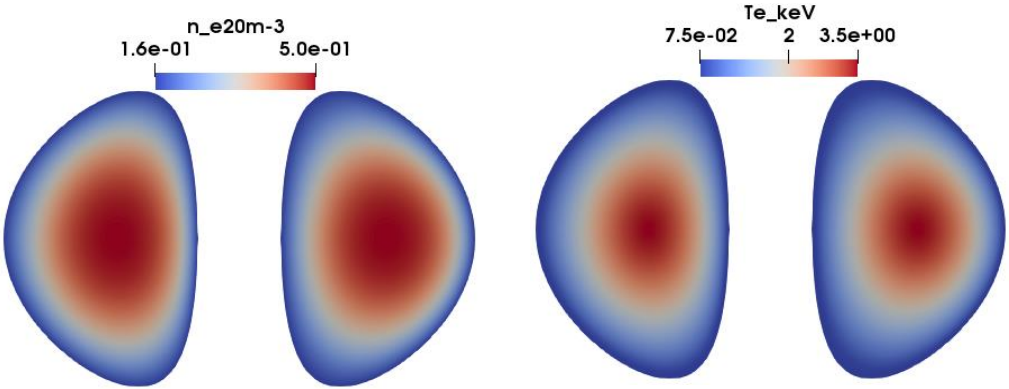
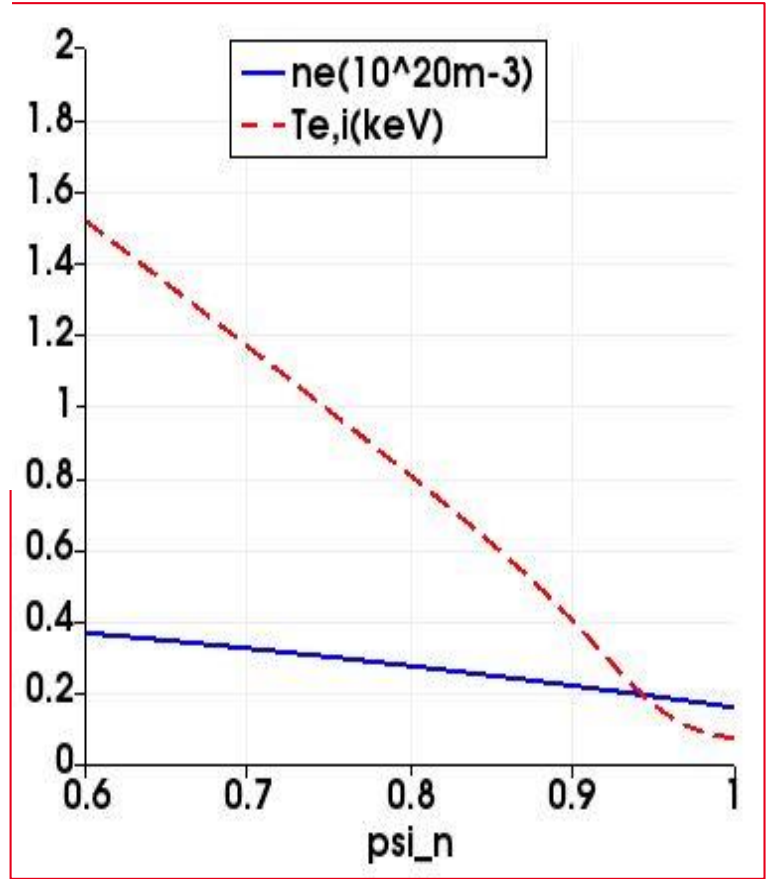
**$R=1.74m$, $B_0=2T$, $q_{95}\sim 4.2$,
 elongation = 1.6, triangularity (up=low)=+ - 0.4,
 $T_e=T_i$. Limiter configuration in JOREK modelling for simplicity**

Initial profiles (n_e , $T_e=T_i$, ff') as a function of normalized poloidal flux are the same (L-mode) for negative and positive triangularity shapes

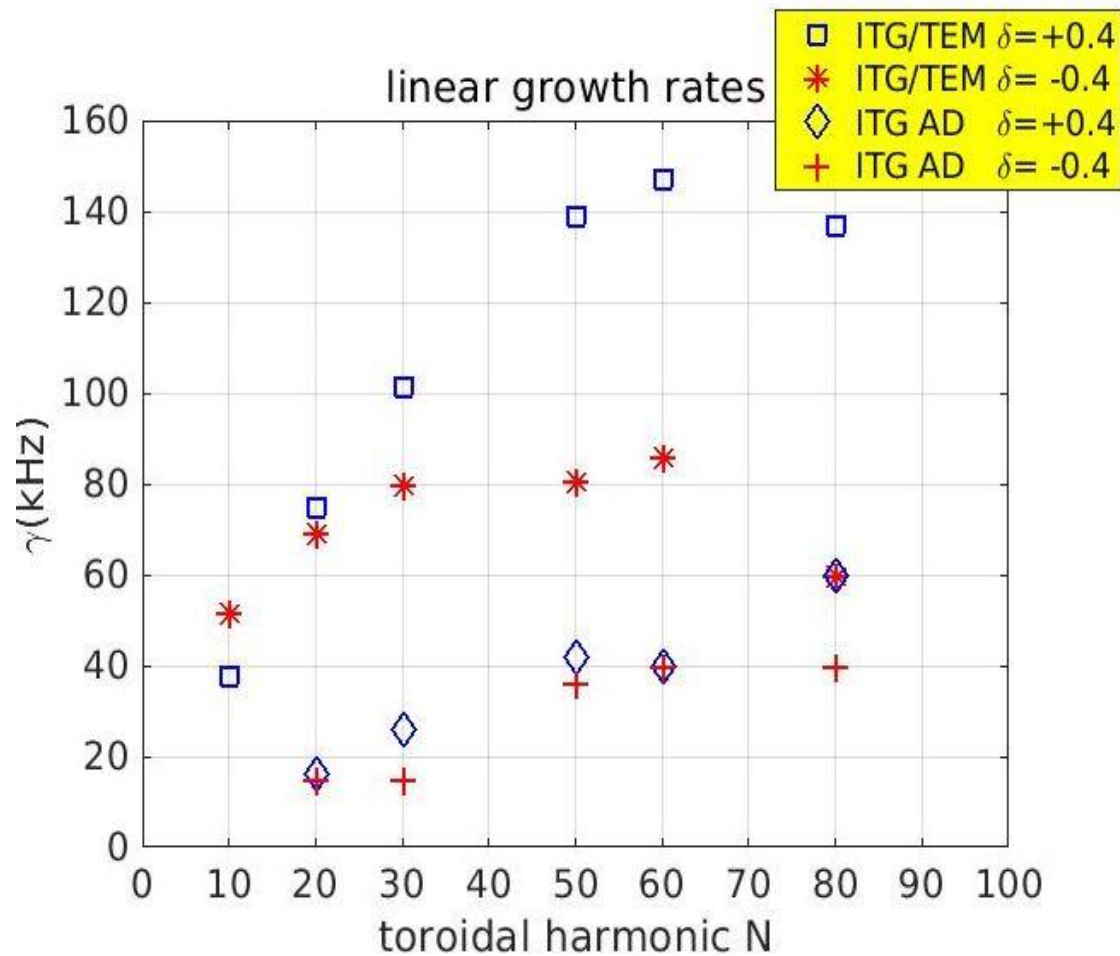


[A Marinoni et al., Nucl Fus 61(2021)]

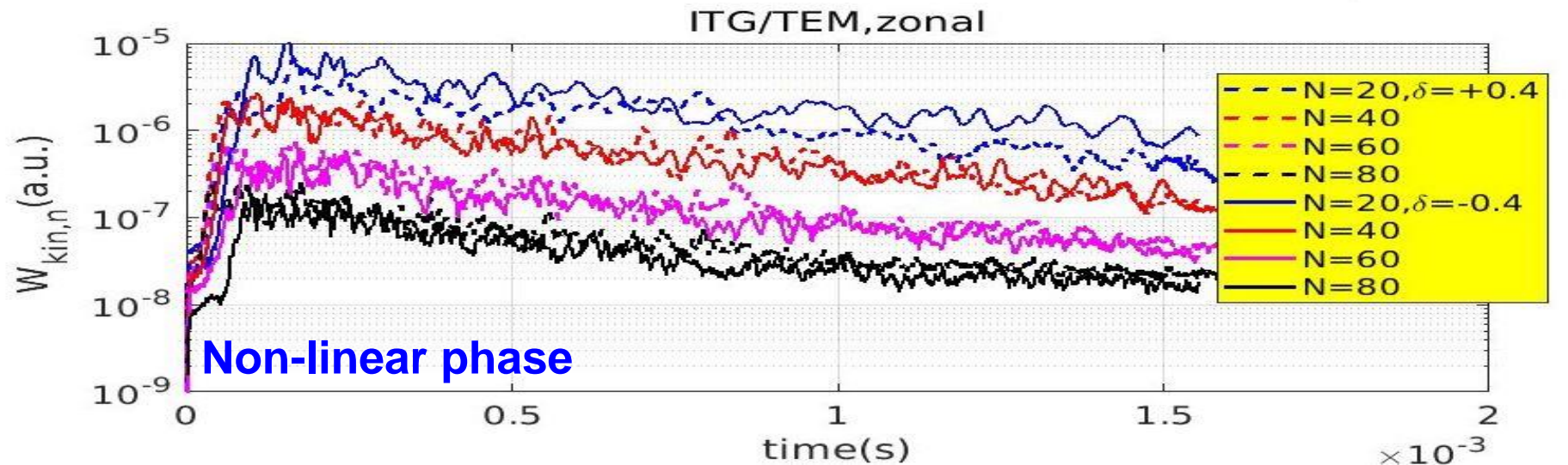
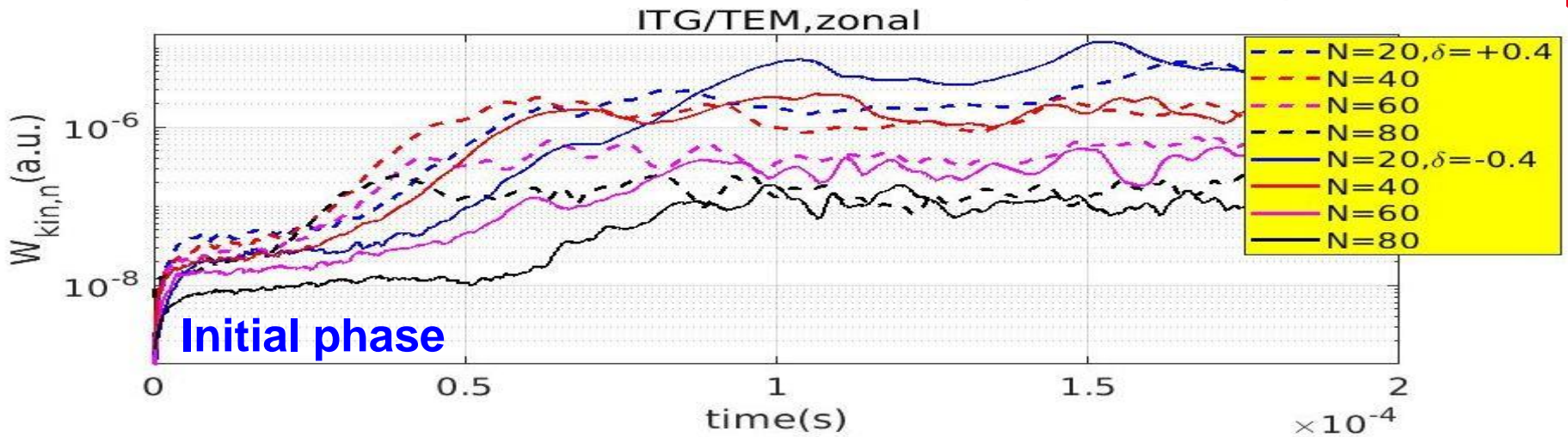
Figure 3. Comparison between profiles of discharges 180520 (H-mode, ●) and 180533 (L-mode, ●). Electron density (a) and temperature (b) along with C^{6+} temperature (c) as a function of the normalized poloidal flux.



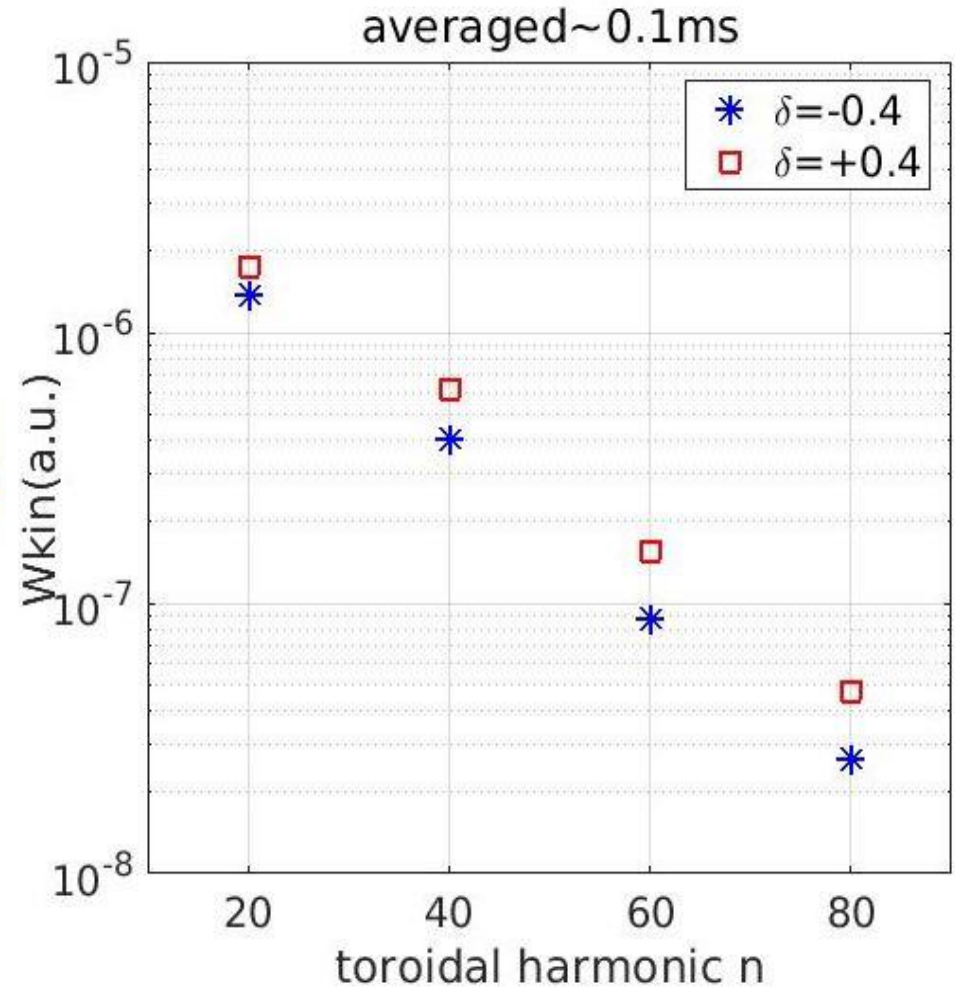
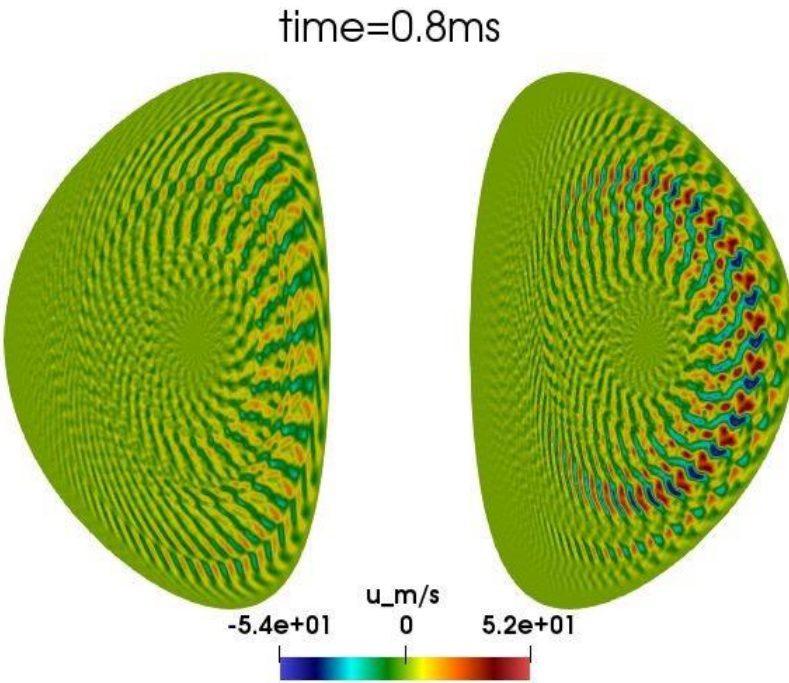
Linear growth rates of ITG/TEM single modes with kinetic electrons at NT ($\delta=-0.4$) are smaller than in PT ($\delta=+0.4$) for $N>20$. Smaller effect (if any) on ITGs with adiabatic electrons.



**Multi-harmonics N=20:80 ITG/TEM non-linear modelling.
Initial phase (time<0.2ms) integrated $W_{kin,n,NT} < W_{kin,n,PT}$.
But similar in non-linear phase (time>0.2ms)**

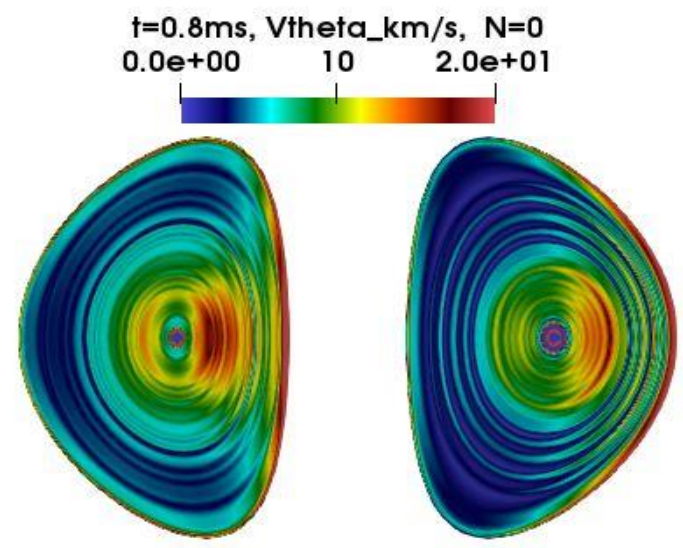
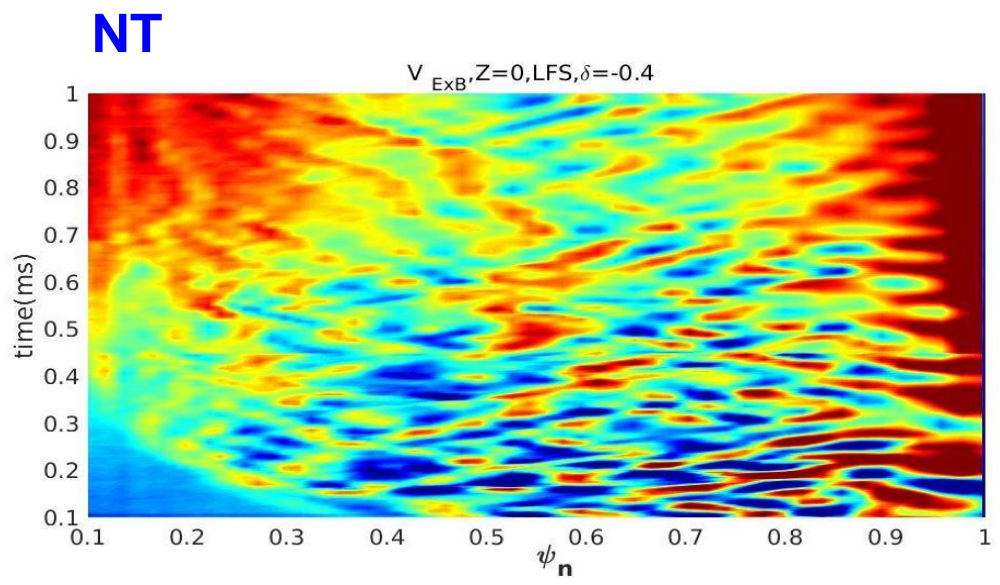
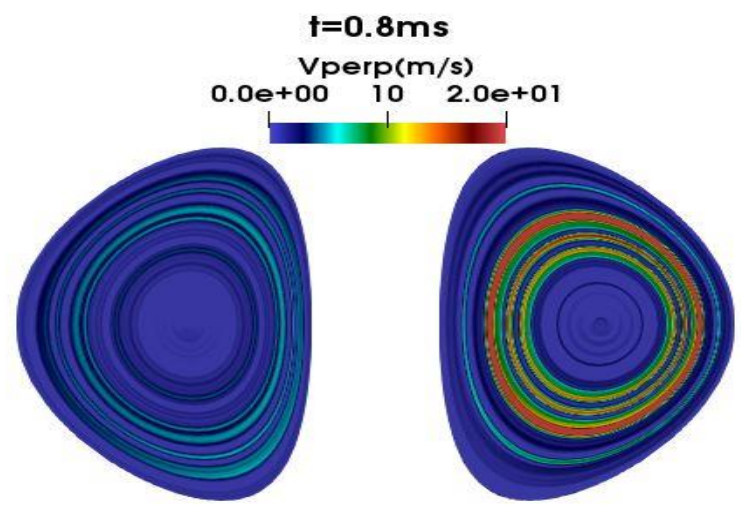
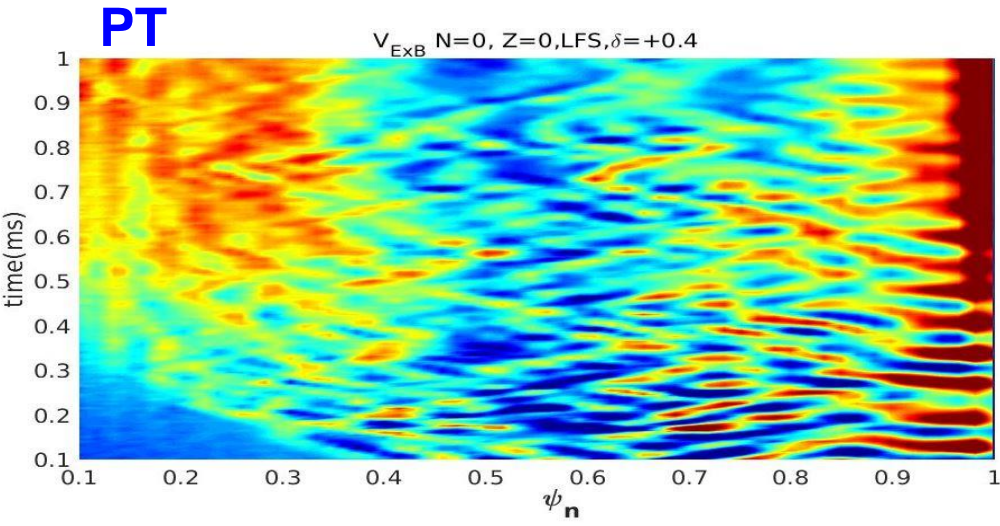


Small beneficial effect of NT&PT is seen on the integrated over volume kinetic energy for harmonics in TEM/ITG turbulence.





BUT! Poloidal zonal flow ($V_{\text{ExB}, \theta, N=0}$) in NT is larger compared to PT and perpendicular velocity ($V_{\text{ExB}, r, N=0}$) is smaller.



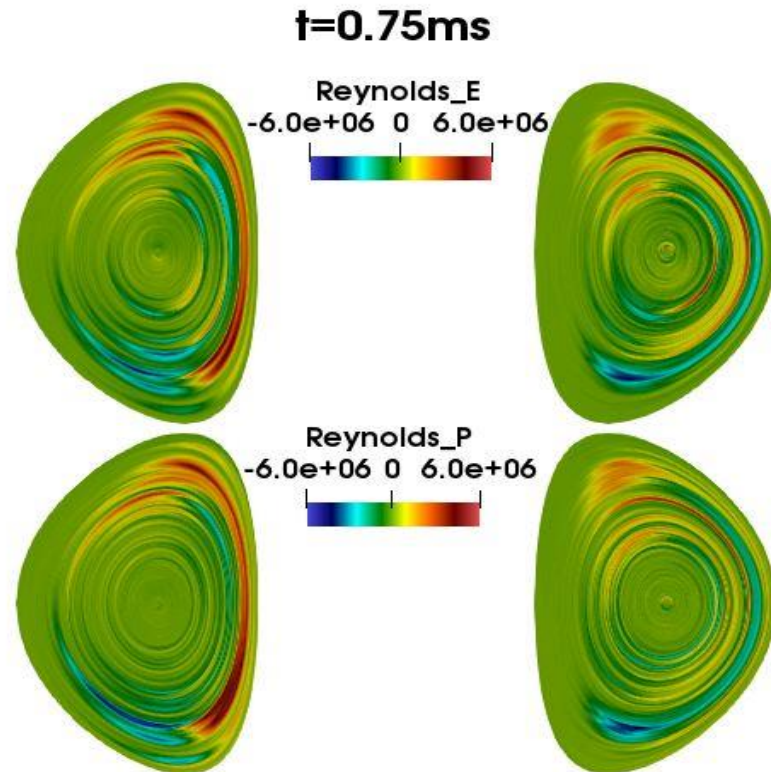
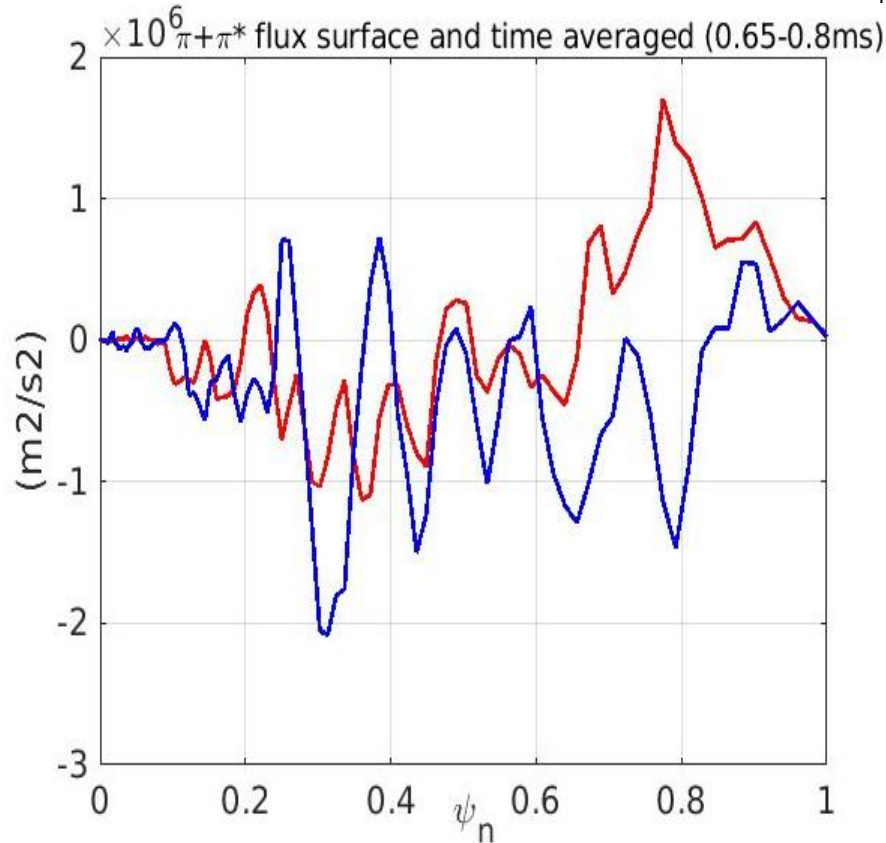
Reynolds stress tensor = source of zonal flows ? => not clear if NT is better

$$\bar{\bar{R}} = (\bar{\vec{V}} \otimes \bar{\vec{V}}) \approx \pi + \pi^*$$

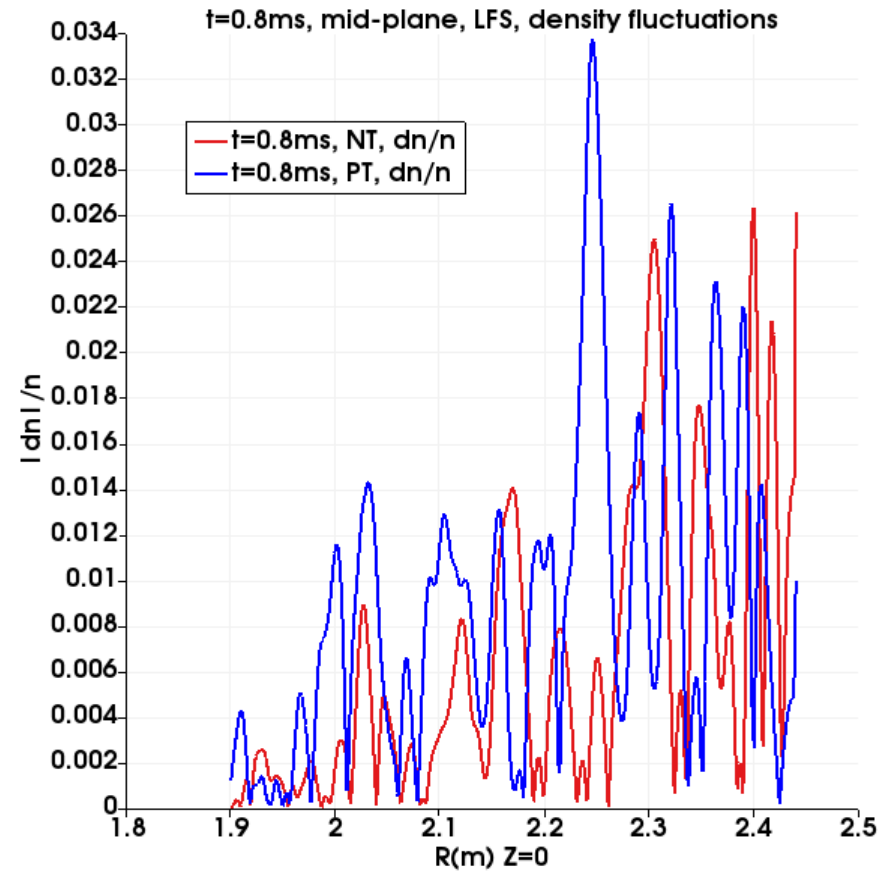
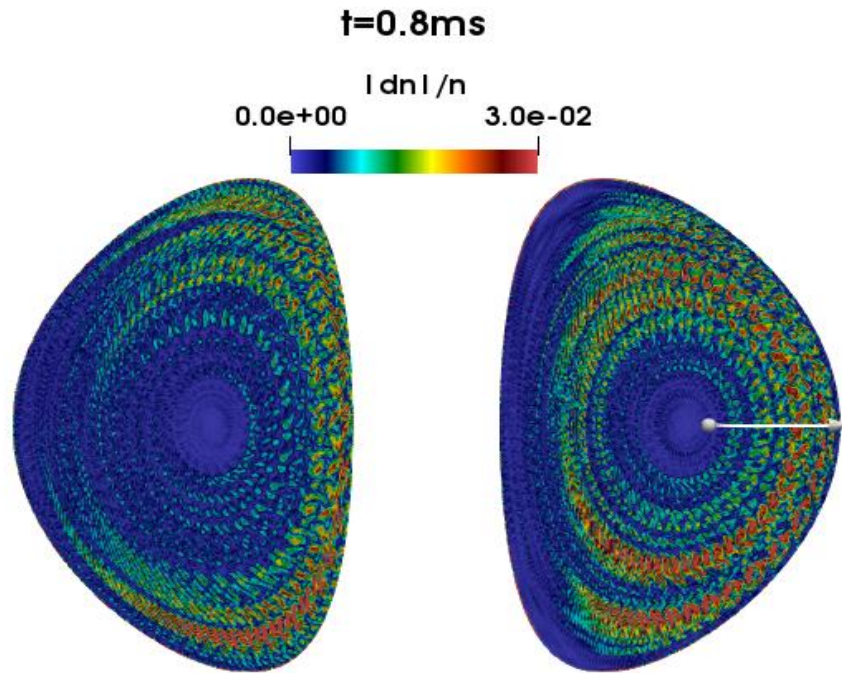
$$\pi = \langle \tilde{V}_{r,E} \tilde{V}_{\theta,E} \rangle; \quad \pi^* = \langle \tilde{V}_r^* \tilde{V}_{\theta,E} \rangle$$

$$\vec{V}_{i_{\perp}} = \vec{V}_E + \vec{V}_i^* \approx -(R^2 / F_0) (\nabla U \times \nabla \phi) - \delta^* (R^2 / \rho) (\nabla P_i \times \nabla \phi)$$

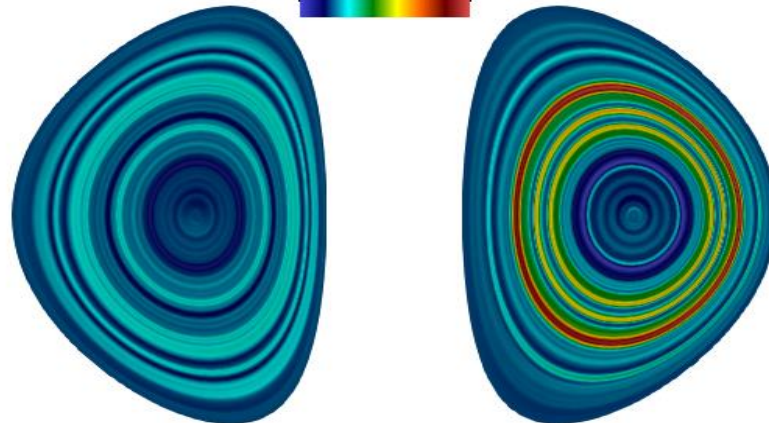
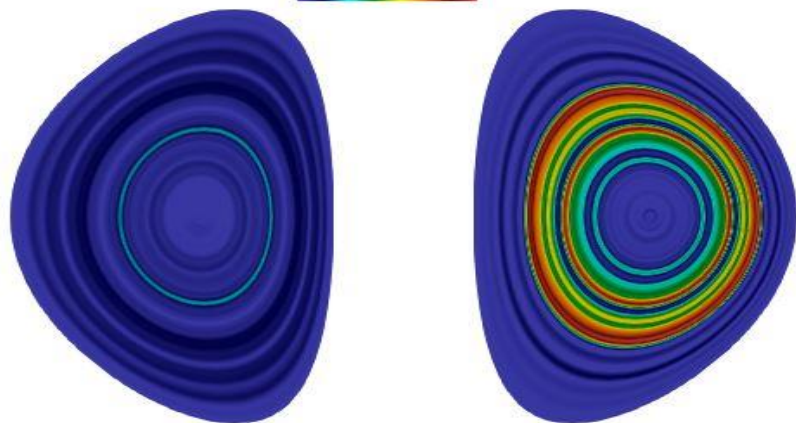
$$\hat{e}_r = \frac{\nabla \psi}{|\nabla \psi|} \quad \hat{e}_{\theta} = \frac{1}{|\nabla \psi| |\nabla \phi|} \nabla \psi \times \nabla \phi = \frac{R}{|\nabla \psi|} \nabla \psi \times \nabla \phi; \quad |\nabla \phi| = \frac{1}{R};$$



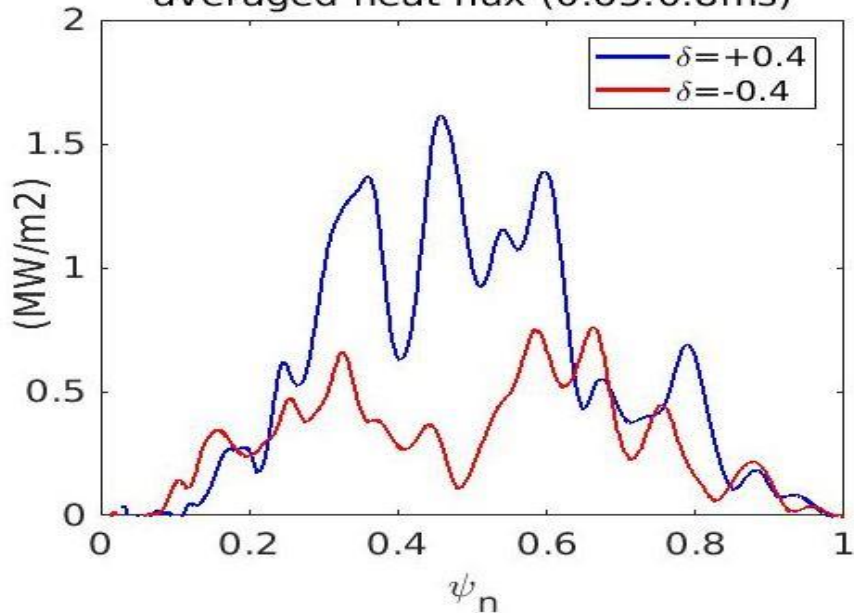
Density fluctuations are reduced in NT compared to PT.



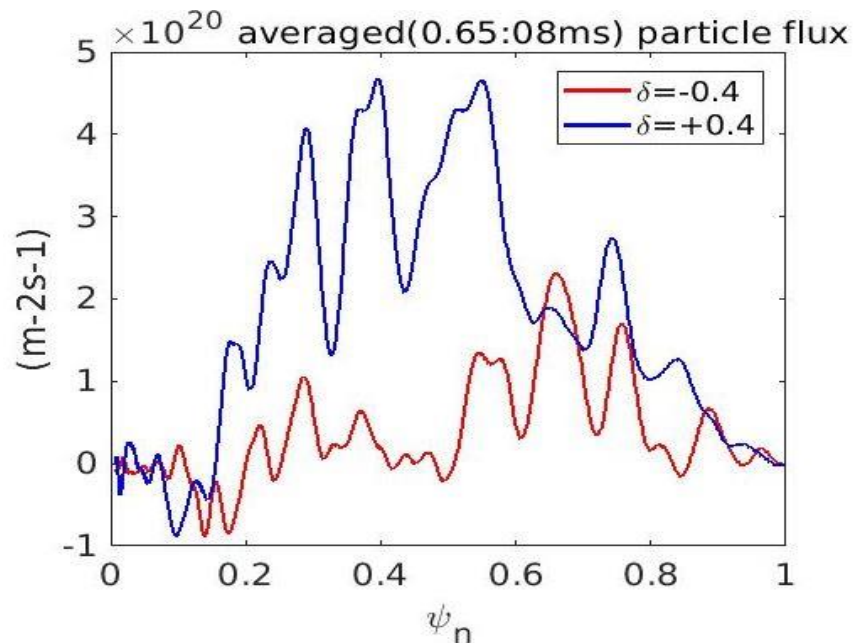
Perpendicular heat and particle fluxes are (up to factor ~2) smaller for NT than for PT.



averaged heat flux (0.65:0.8ms)



averaged(0.65:08ms) particle flux



Conclusions

- 1. Particles in JOREK code for global non-linear turbulence modelling in realistic X-point geometry: gyro-kinetic ions+ adiabatic or kinetic electrons. ITGs, ITG/TEMs were modelled in 3D ergodic fields with RMPs and at negative/positive triangularity shaping.**
- 2. ITGs with adiabatic electrons in H-mode (HL2A#36872) with RMPs. Comparison with experiment : frequency range and shape of spectra are similar in JOREK gyro-kinetic modelling. Stabilizing effect of mean ExB flow in pedestal.**
- 3. ITG and ITG/TEMs in L-mode (COMPASS #8078) with RMPs. Larger turbulence ITG/TEMs with kinetic electrons than only ITGs with adiabatic electrons. Increased turbulence with RMPs. Toroidal asymmetry of turbulence with RMP.**
- 4. Smaller (up to factor ~ 2) perpendicular heat and particle fluxes due to TEM/ITG turbulence in negative triangularity plasma shape compared to positive triangularity.**