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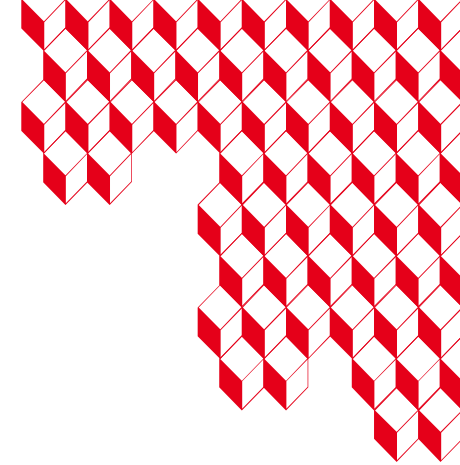
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# Non-linear gyro-kinetic Ion Temperature Gradient (ITG) and Trapped Electron Modes (TEM) turbulence modelling in X-point geometry with 3D fields, Edge Localized Modes and at negative and positive triangularity shapes.

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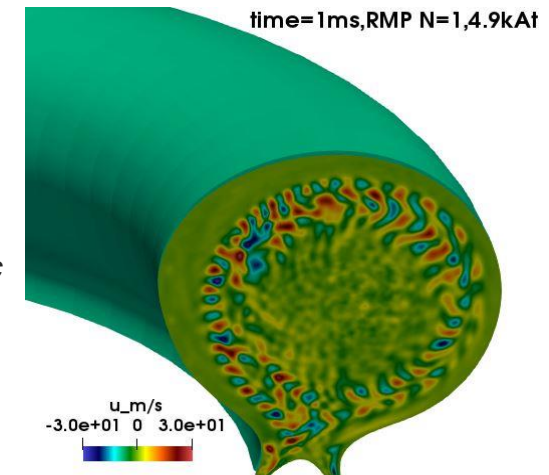
<sup>3</sup>Southwestern Institute of Physics, P. O. Box 432, Chengdu 610041, China

<sup>4</sup>Jacobs School of Engineering, University of California San Diego, CA 92093-0403, USA

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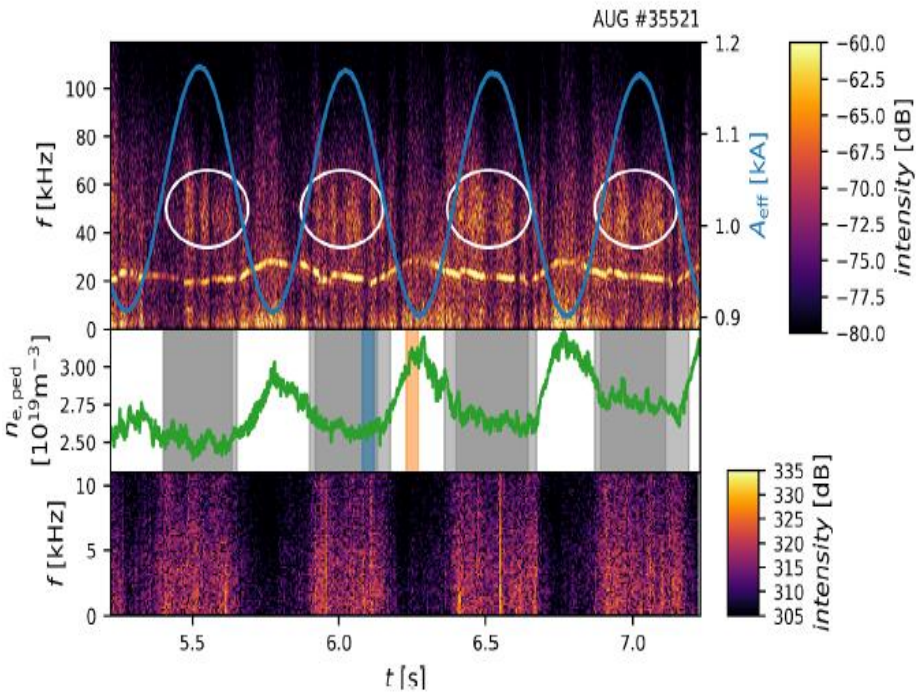
<sup>6</sup>Faculty of Mathematics and Physics, Charles University, Prague, Czech Republic

[marina.becoulet@cea.fr](mailto:marina.becoulet@cea.fr)

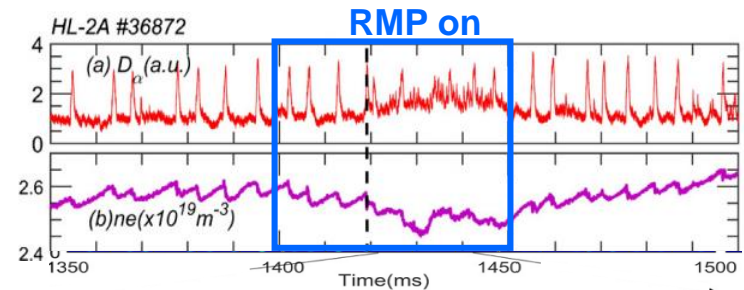


# Motivation. Experimental observation : turbulence increases with RMPs. Why? What kind of turbulence? Reason for density pump-out?

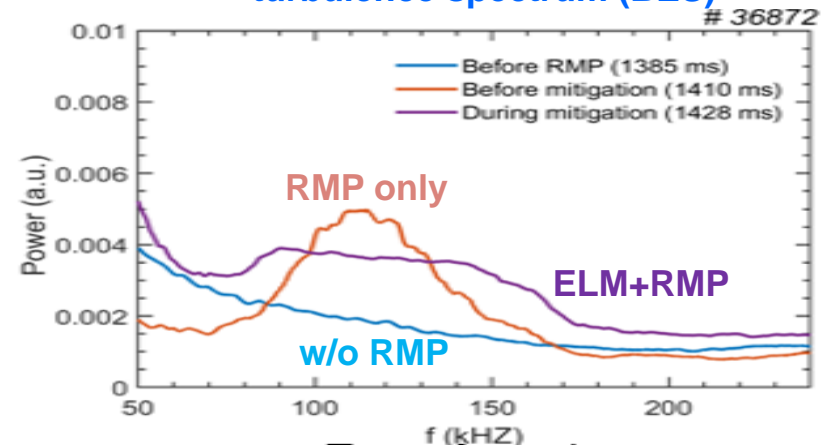
[AUG, N Leuthold, NF2023]:  
**Turbulence increases** during ELM suppression by RMP N=2, density pump-out.



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



turbulence spectrum (BES)

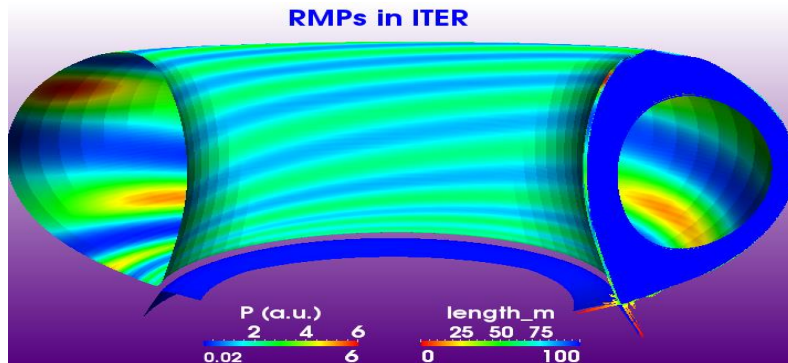


# JOREK code.

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

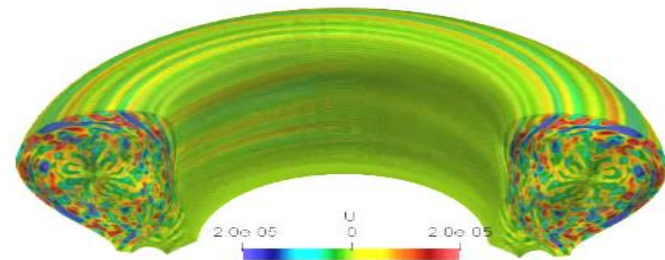
## Fluid MHD model:

- 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:

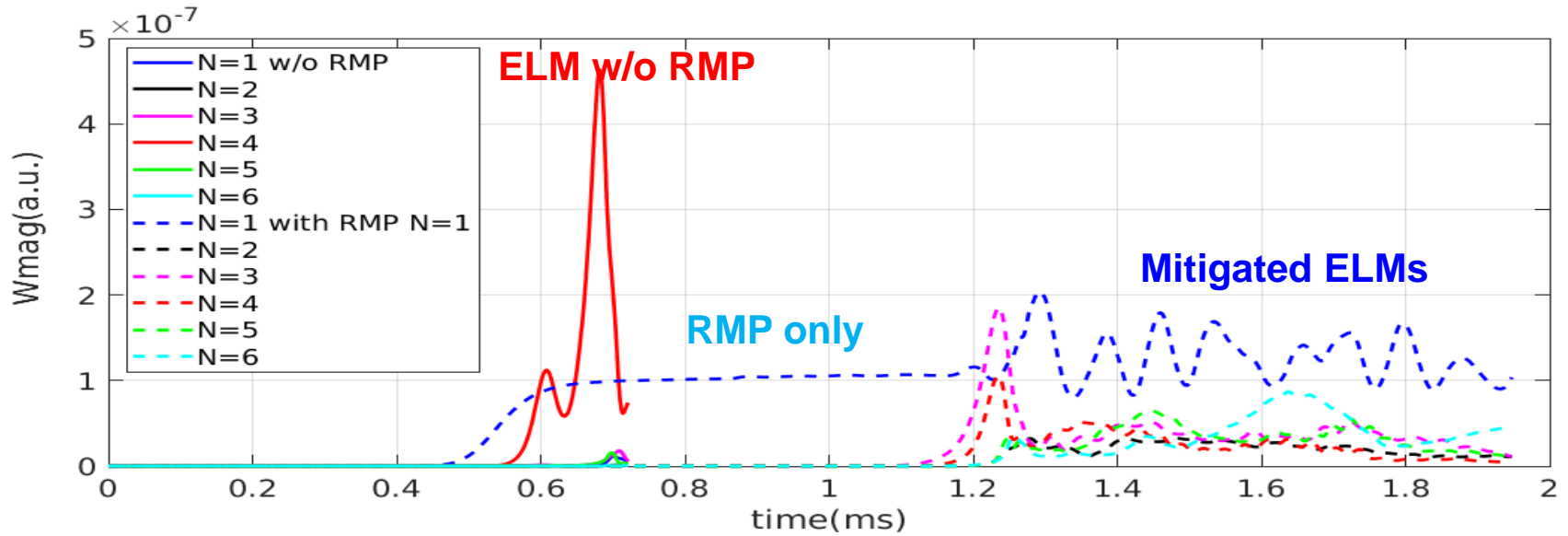
- Particles are initialized on the grid, plasma profiles and magnetic field from MHD.
- Non-linear full-f. Particles are advanced in time evolving electric field and static magnetic field (3D ergodic if RMPs!).
- Ions: // and ExB motion of gyro-centers in gyro-averaged electric field.
- Electrons: adiabatic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



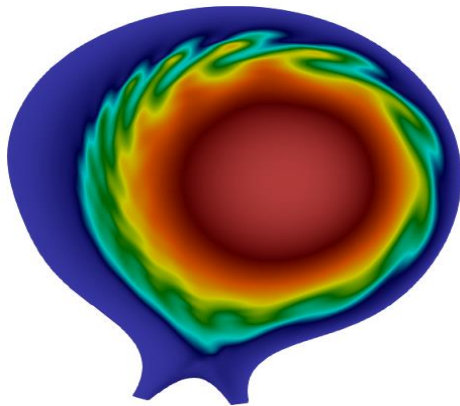
ITG/TEM in COMPASS with RMPs

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

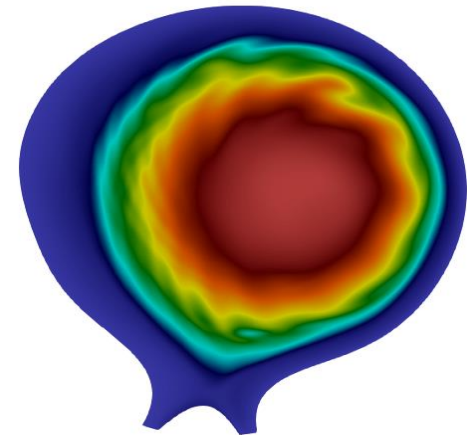
Data from [HL2A, T F Sun, NF2021]



Density in ELM crash w/o RMP



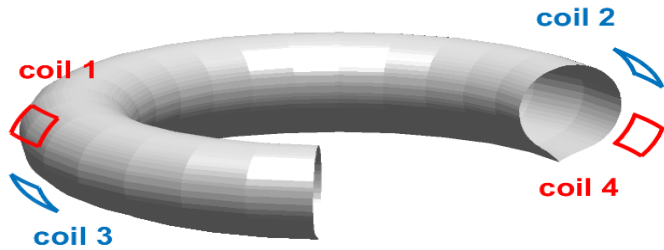
Density in mitigated by RMP ELMs



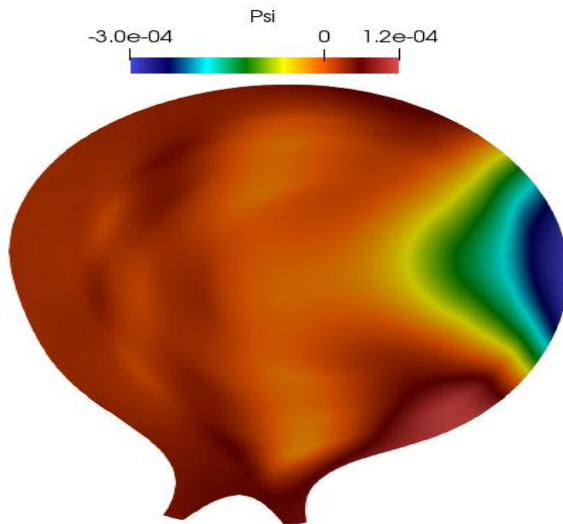
# Equilibrium (3D with RMPs) and plasma profiles used for kinetic particles initialisation.

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

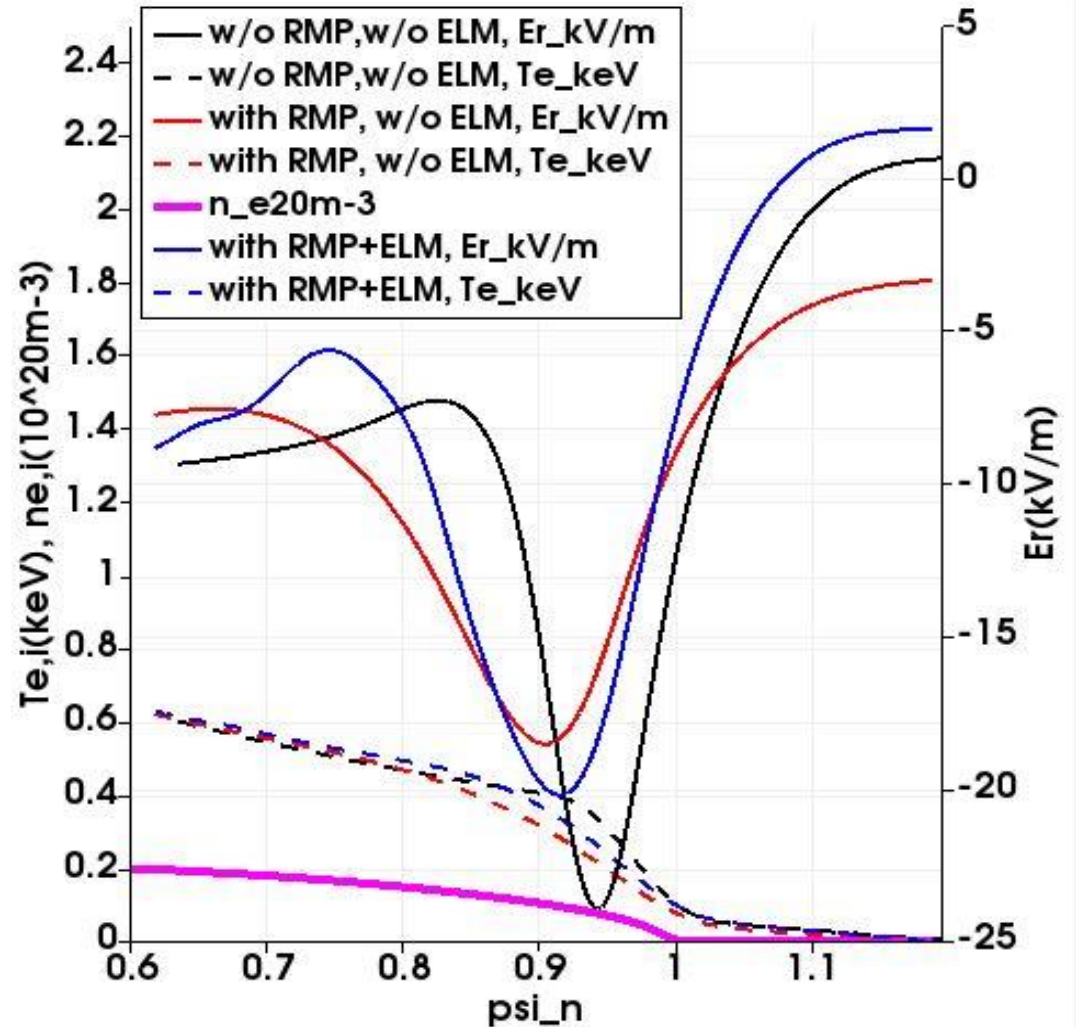
## RMP coils in HL2A



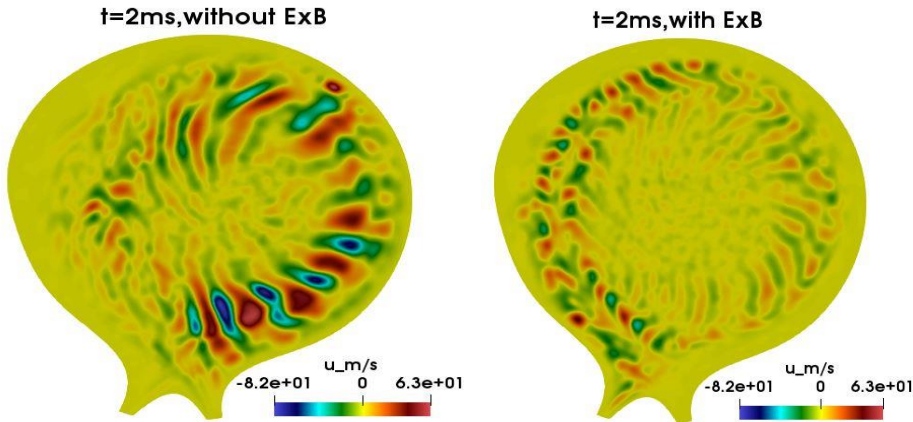
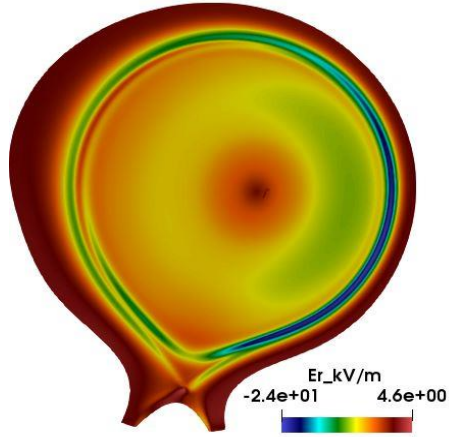
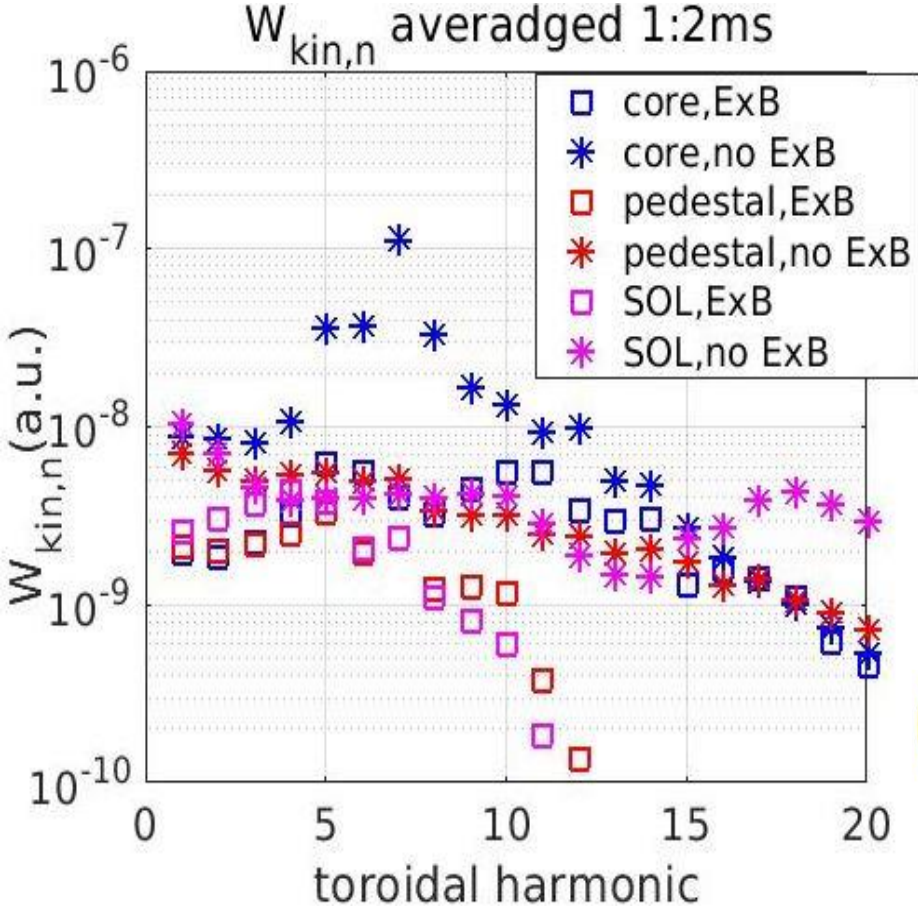
## pol flux perturbation by RMP $N=1$ , 4.9kAt, odd parity



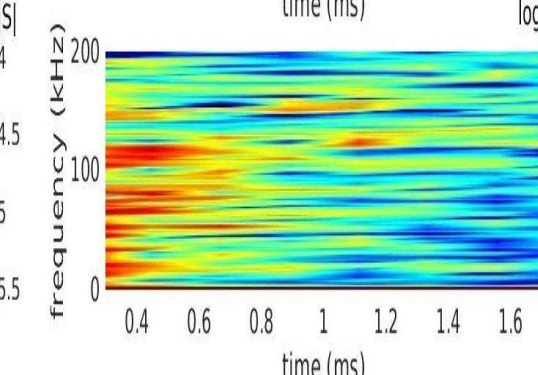
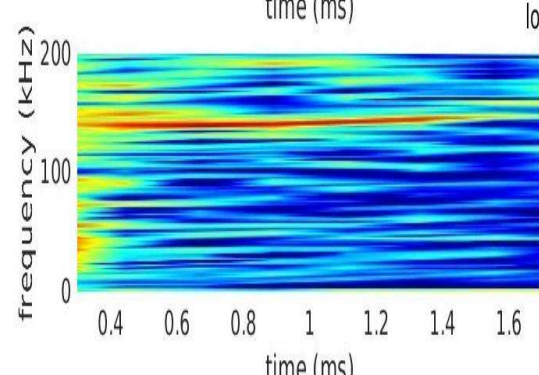
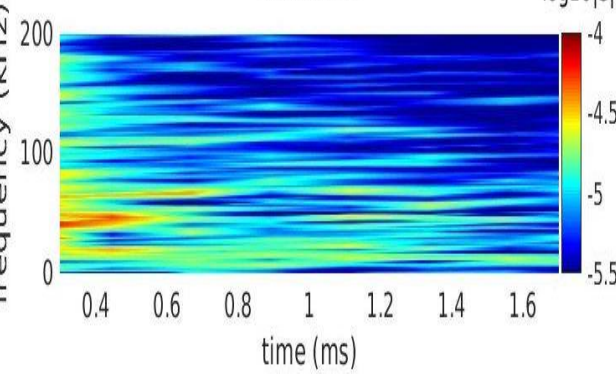
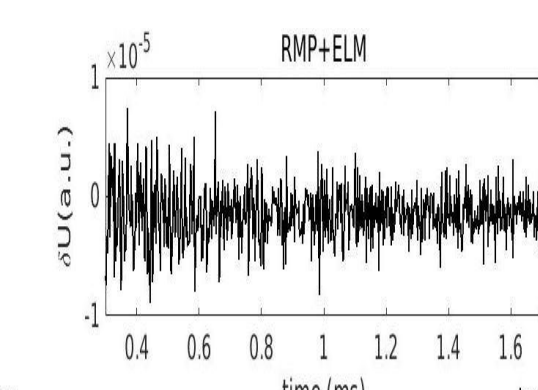
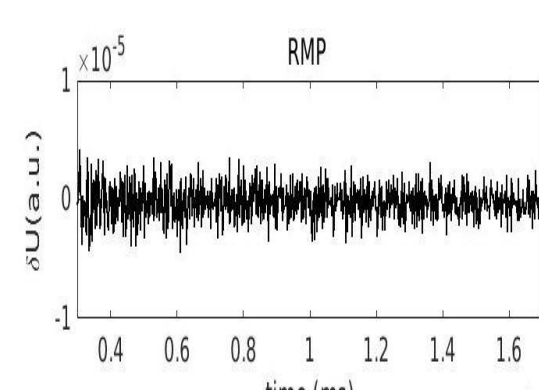
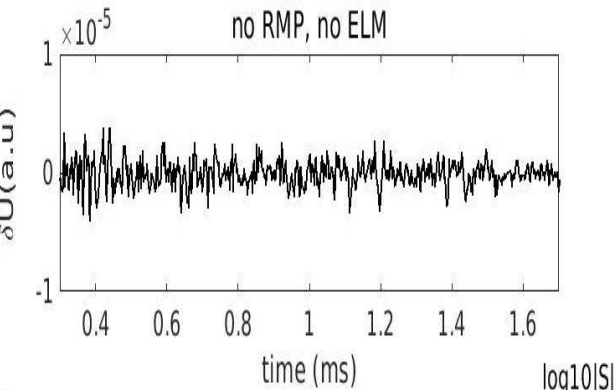
## profiles



# 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.**

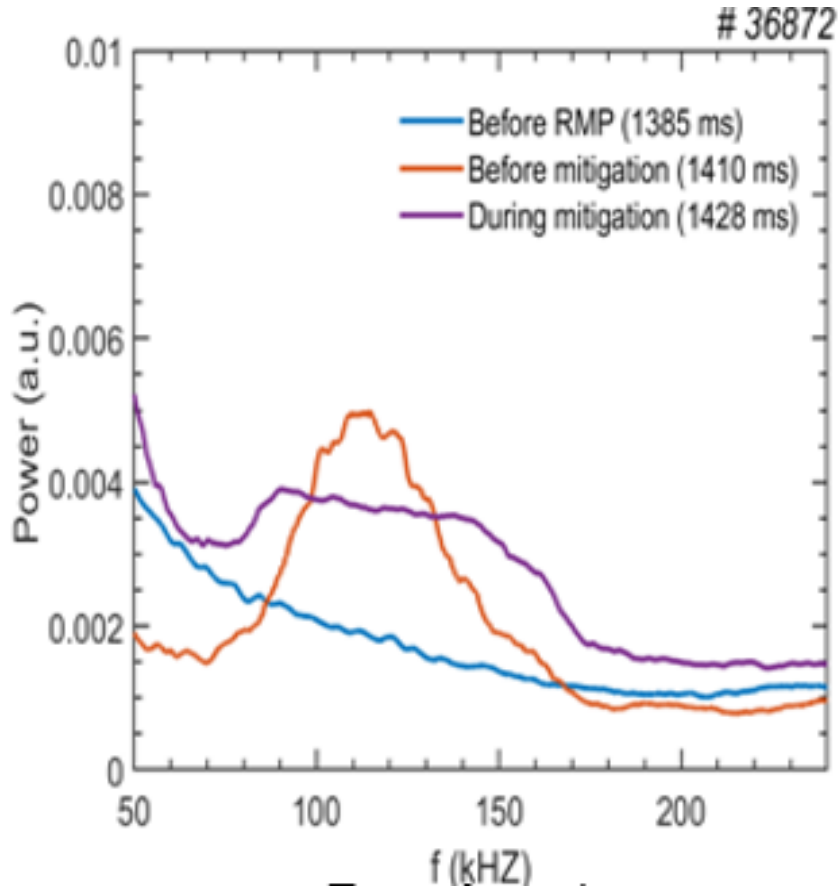




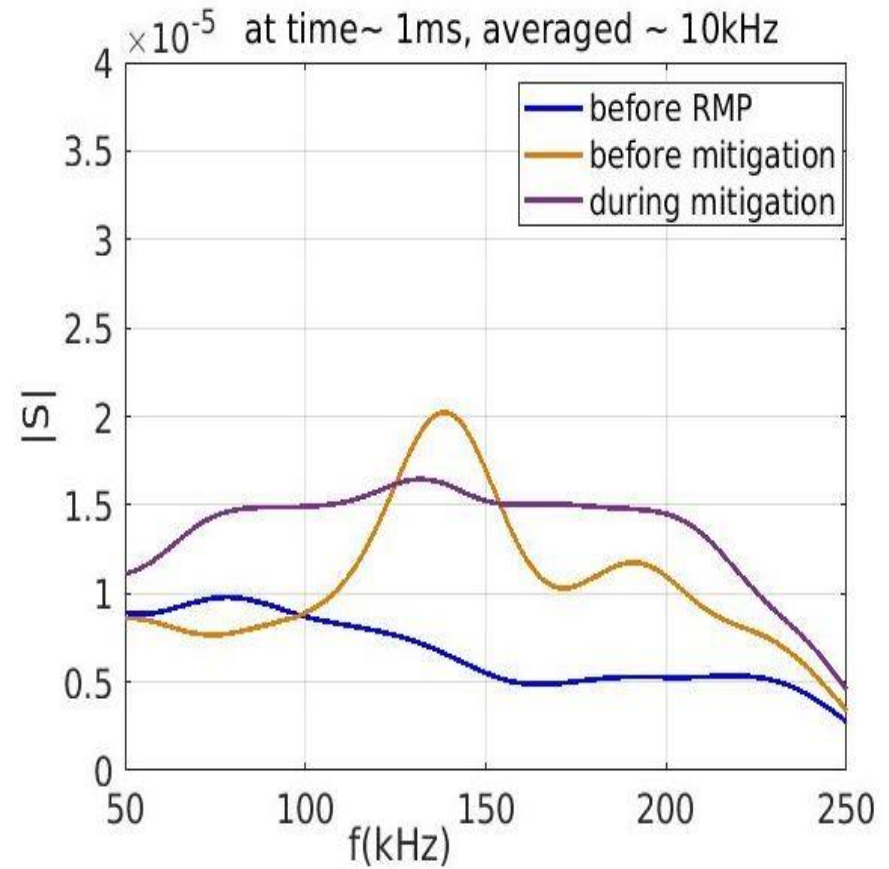
# Frequency range and spectrum shape in modelling is similar to experimental

## Experiment

[HL2A, T F Sun, NF2021]



## JOREK

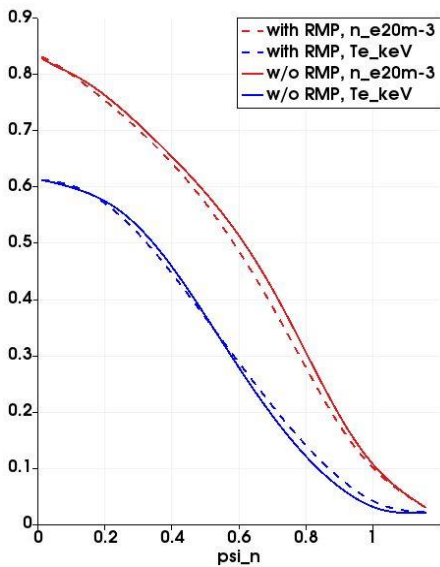


# Modelling of ITG/TEM turbulence for COMPASS# 8078 L-mode

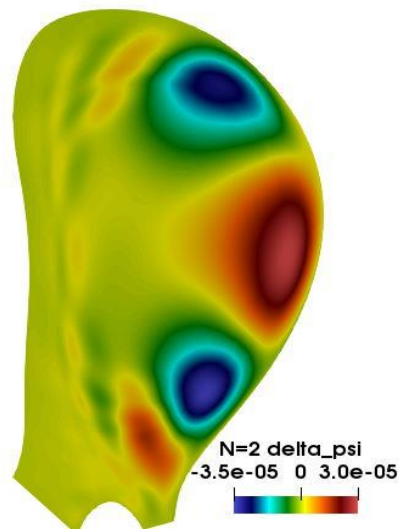
Data from [T Markovic NF2006]

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.

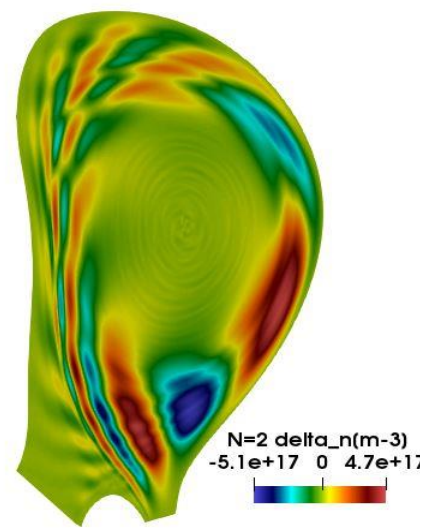
Density, temperature (Te=Ti) mid-plane profiles



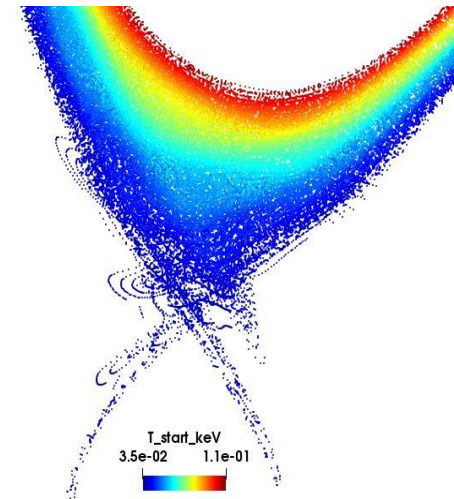
Magnetic flux perturbation with RMP



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

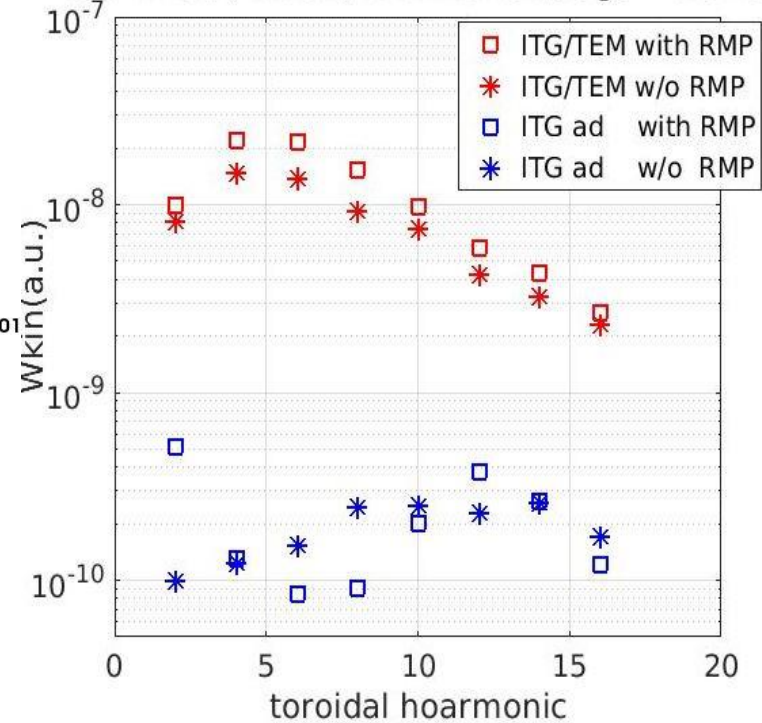
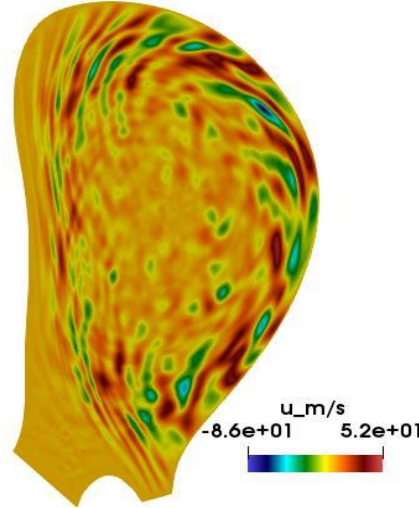
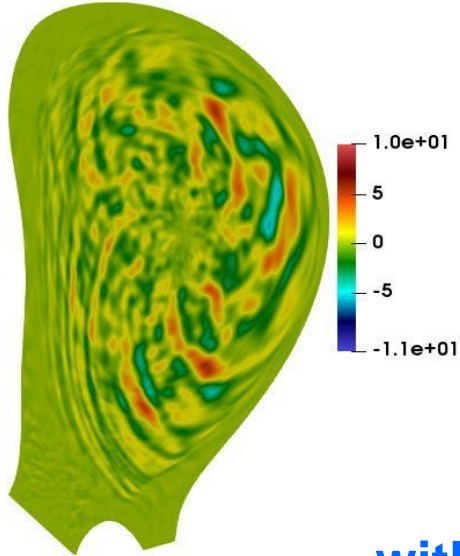
w/o RMP

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

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

ITG,adiabatic

ITG+TEM, kinetic el, zonal

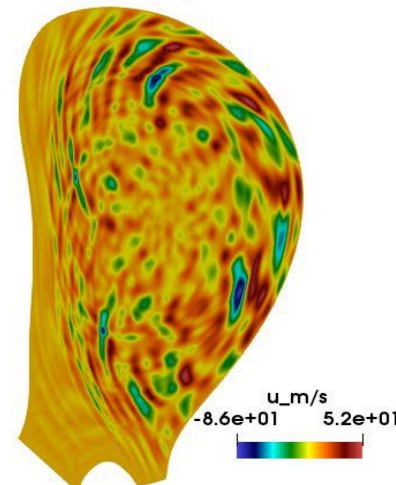
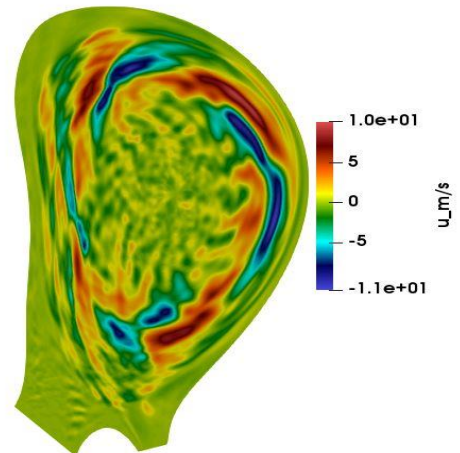


with RMP

time=1ms, TEM/ITG with RMP

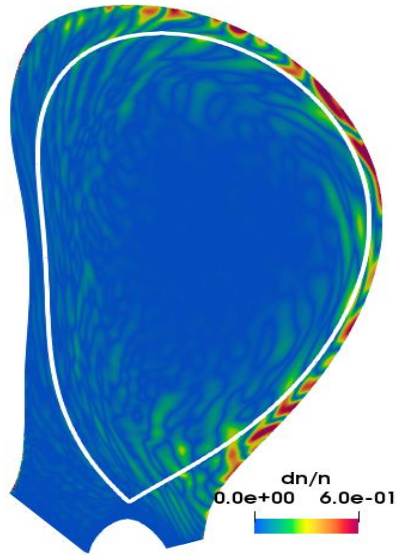
ITG,adiabatic

ITG+TEM, kinetic el, zonal

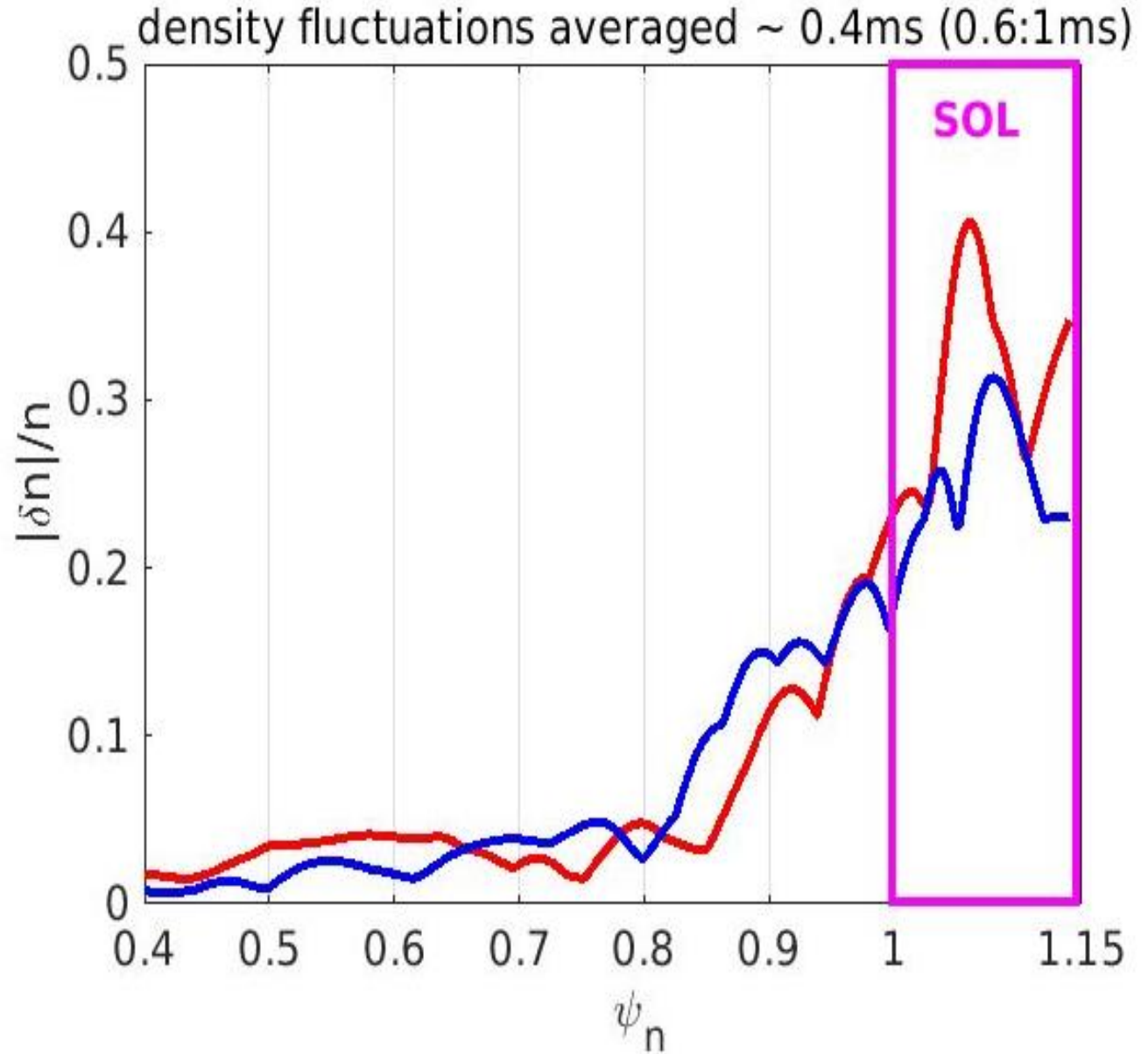
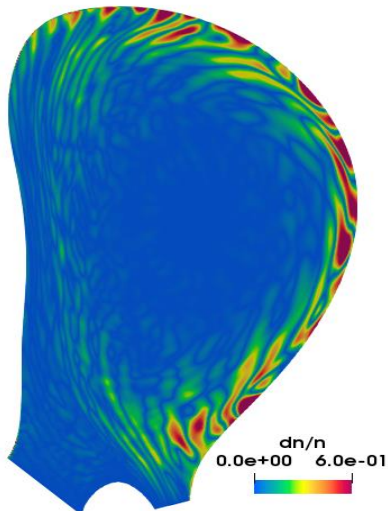


# With RMPs density fluctuations are increased (especially in the SOL)

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



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

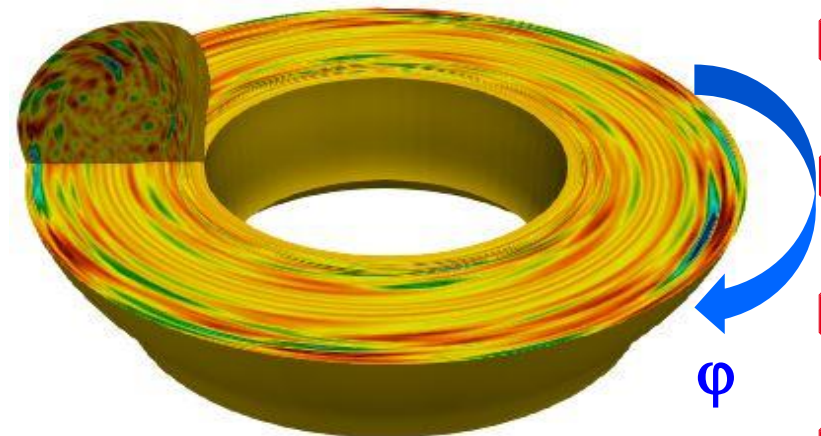
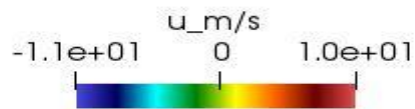
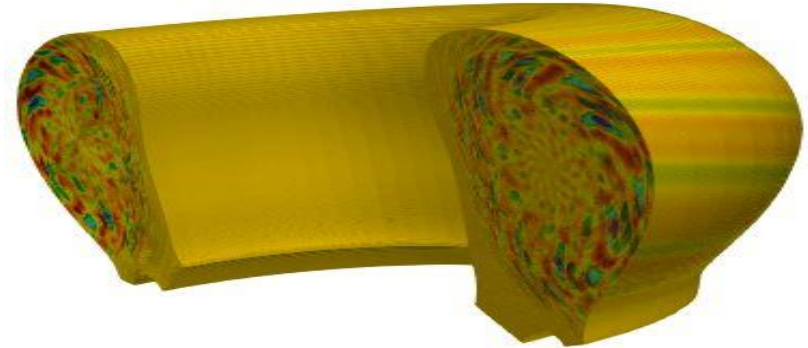
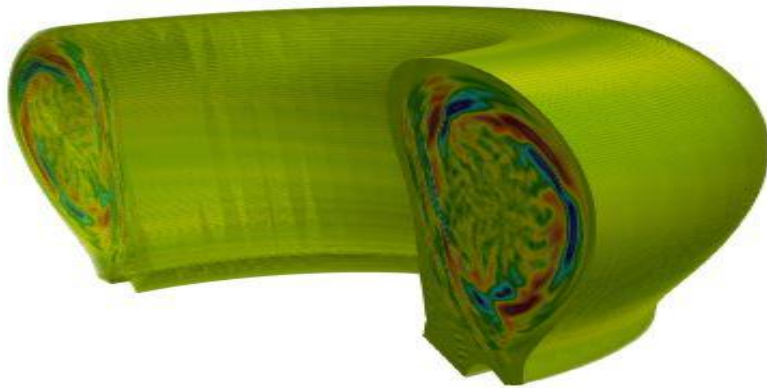
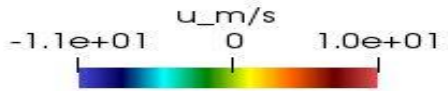


# Toroidal asymmetry of turbulence with RMPs.

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

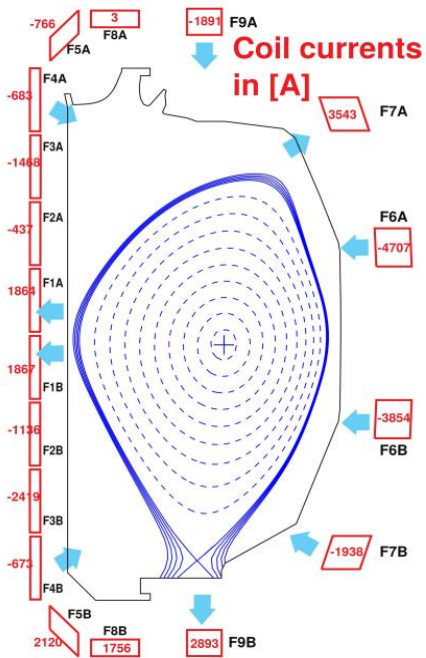
ITG, ad el

ITG/TEM, kinetic el

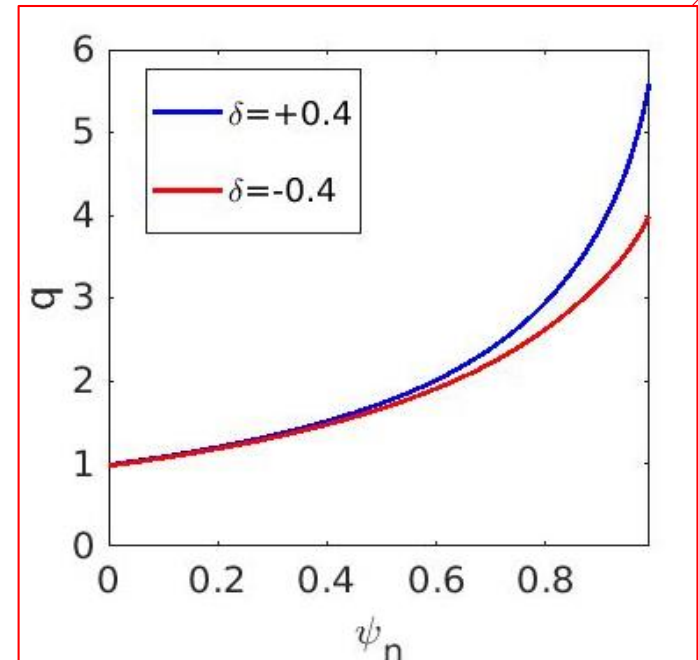
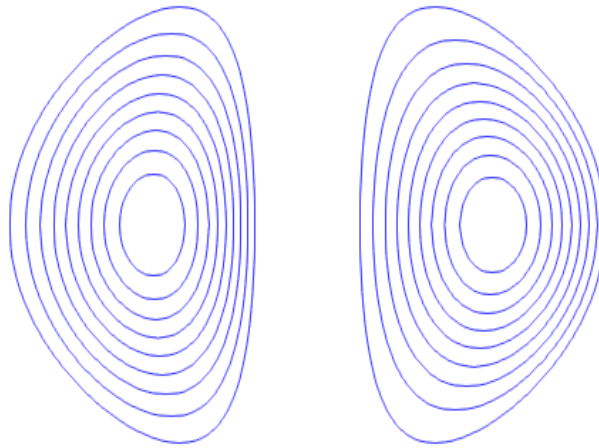


# ITG/TEM (with kinetic electrons) and ITG (with adiabatic electrons) turbulence in plasmas with positive/negative triangularity.

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

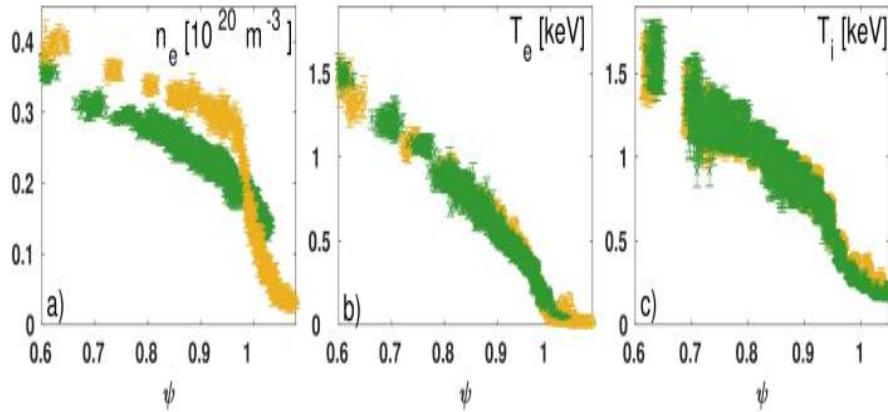


*note that with the same profiles  $q_{95\_NT}=4.5$   $q_{95\_PT}=3.6$  for PT)*



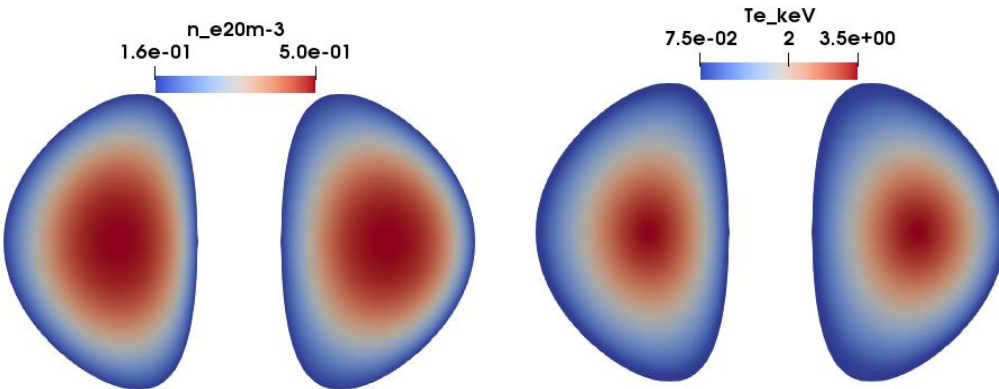
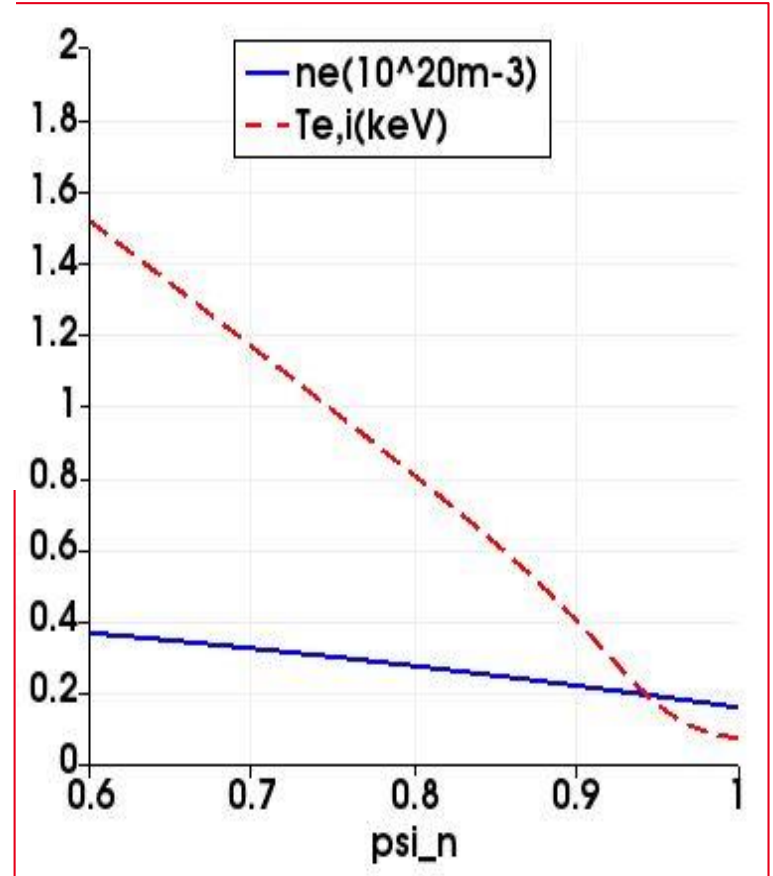
**$R=1.74m$ ,  $B_0=2T$ ,  $q_{95}\sim 4.2$ ,  
 elongation = 1.6, triangularity (up=low)=+ - 0.4,  
 $T_e=T_i$ . Limiter configuration in JOREK modelling for simplicity**

# 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

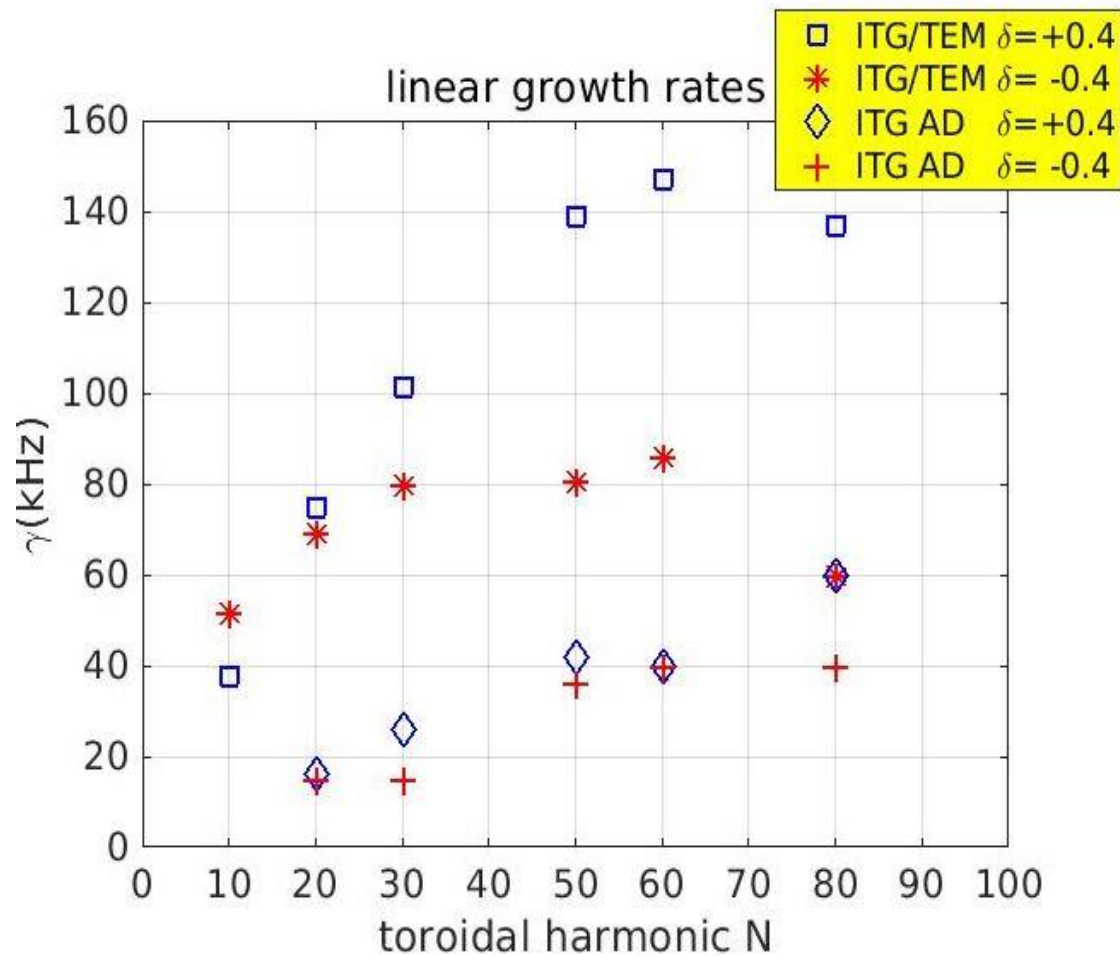


[A Marinoni et al., Nucl Fus 61(2021)]

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.

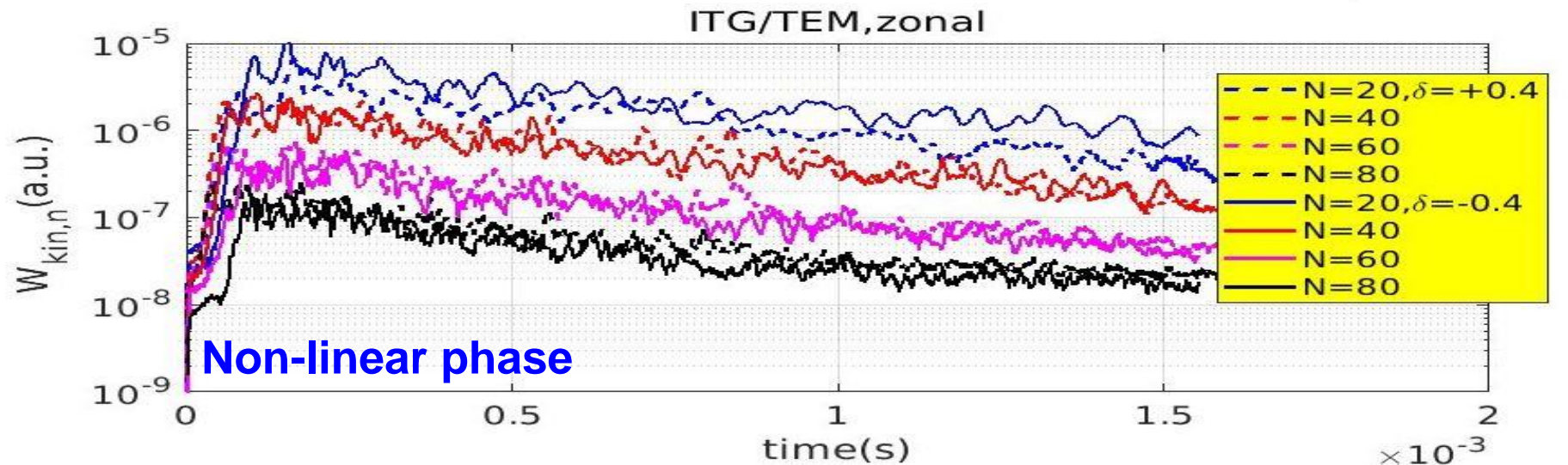
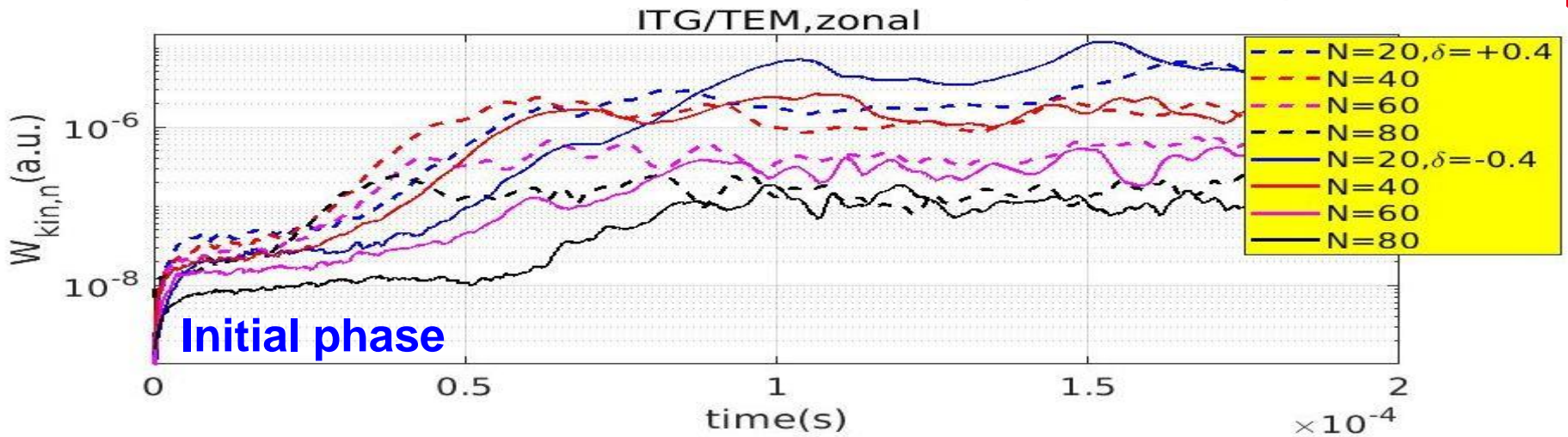


**Linear growth rates of ITG/TEM single modes with kinetic electrons at NT ( $\delta=-0.4$ ) are smaller than in PT ( $\delta=+0.4$ ) for  $N>20$ .  
Smaller effect (if any) on ITGs with adiabatic electrons.**

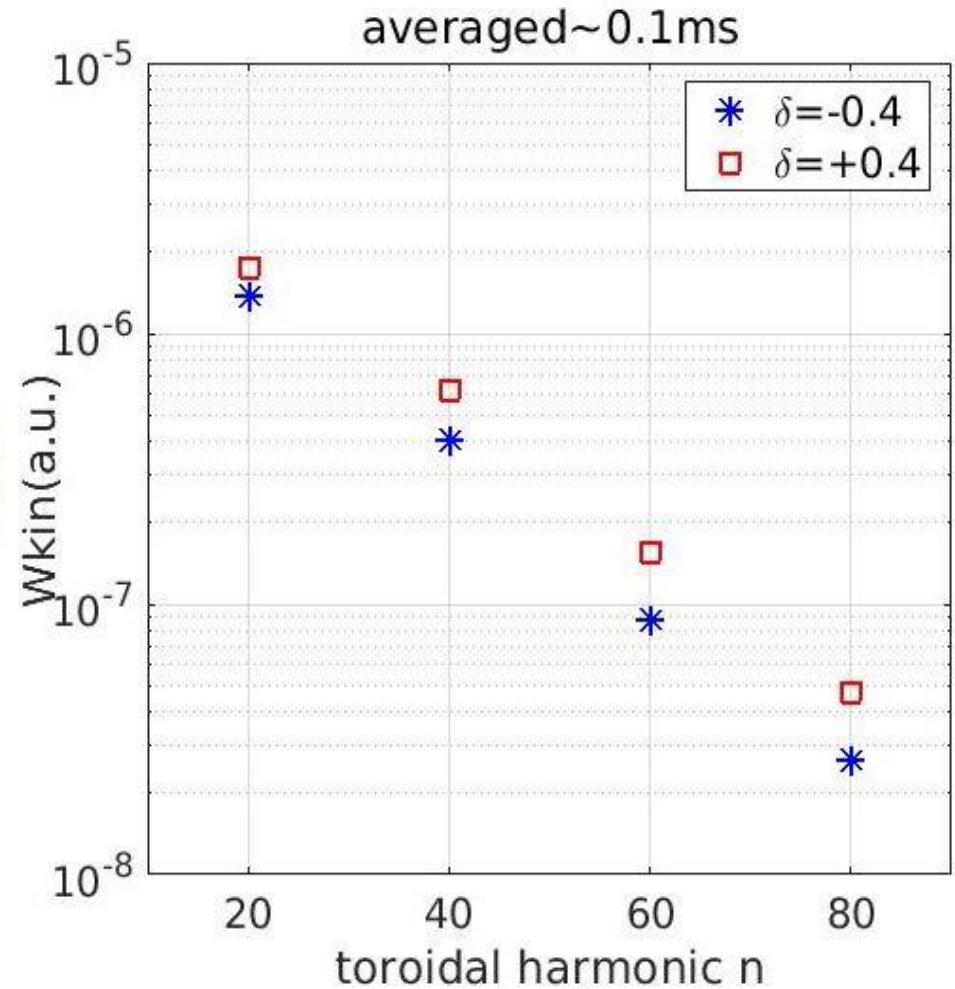
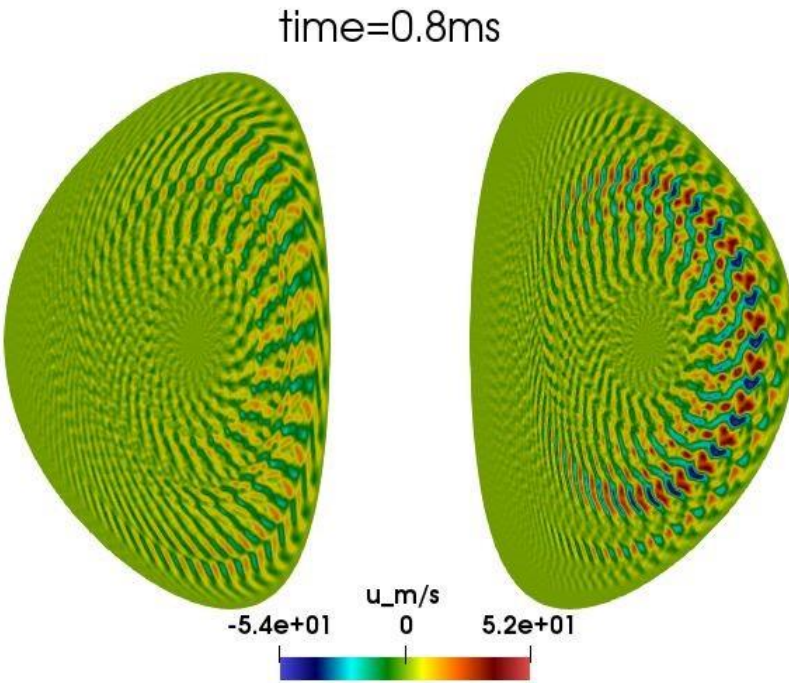




**Multi-harmonics N=20:80 ITG/TEM non-linear modelling.  
Initial phase (time<0.2ms) integrated  $W_{kin,n,NT} < W_{kin,n,PT}$ .  
But similar in non-linear phase (time>0.2ms)**



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

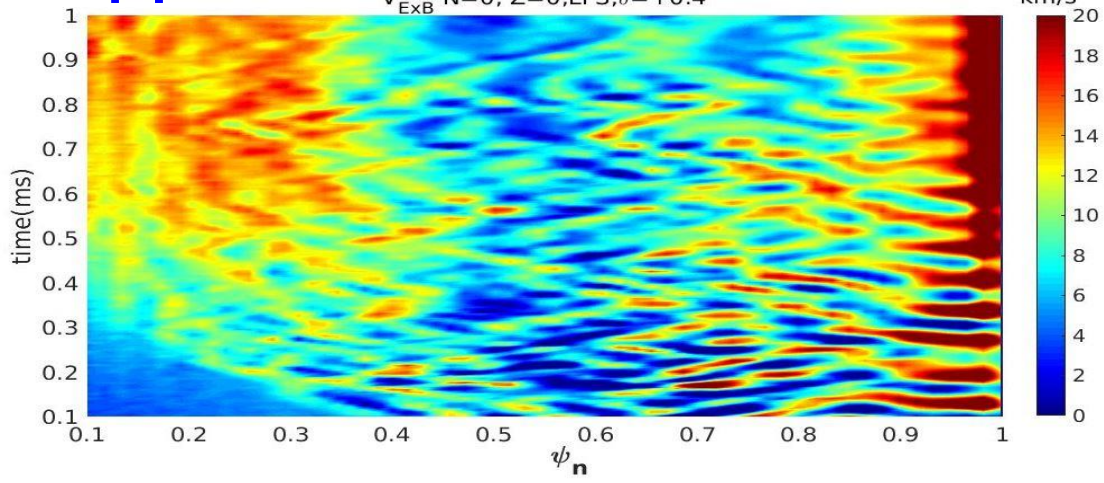




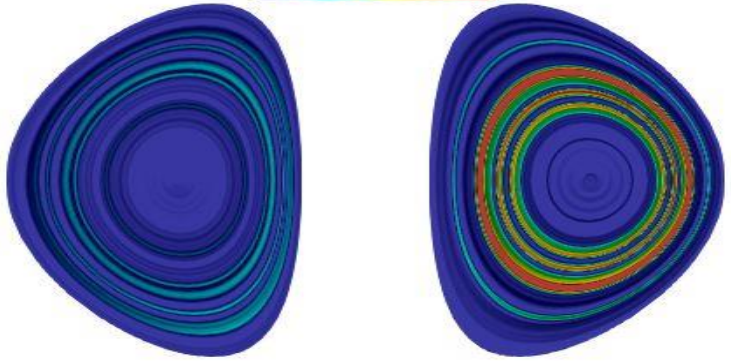
# BUT! Poloidal zonal flow ( $V_{\text{ExB}, \theta, N=0}$ ) in NT is larger compared to PT and perpendicular velocity ( $V_{\text{ExB}, r, N=0}$ ) is smaller.

PT

$V_{\text{ExB}} N=0, Z=0, \text{LFS}, \delta=+0.4$

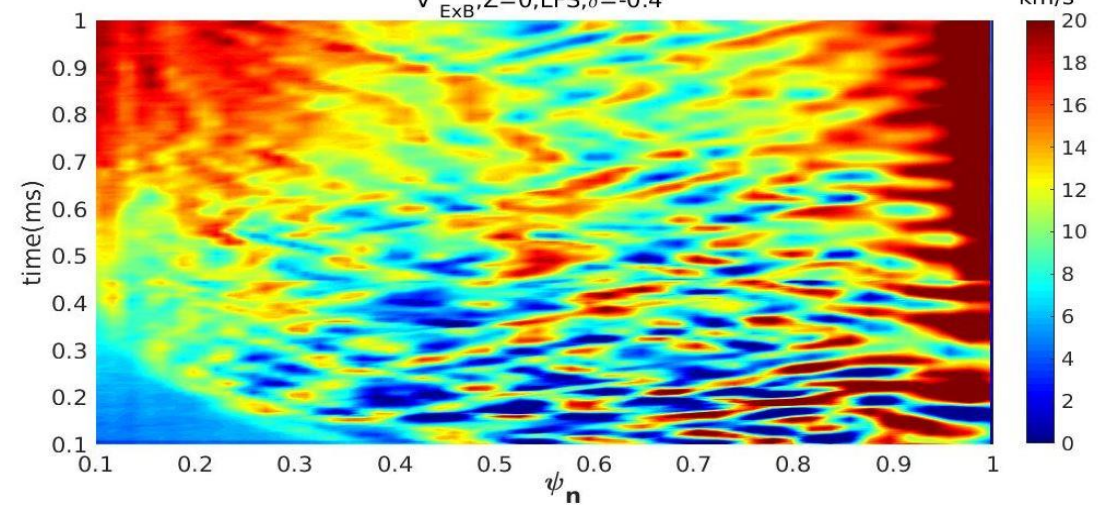


$t=0.8\text{ms}$   
 $V_{\text{perp}}(\text{m/s})$   
0.0e+00 10 2.0e+01

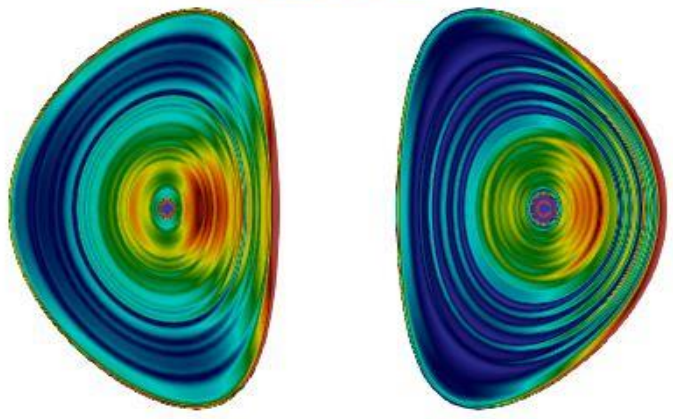


NT

$V_{\text{ExB}}, Z=0, \text{LFS}, \delta=-0.4$



$t=0.8\text{ms}, V_{\theta}(\text{km/s}), N=0$   
0.0e+00 10 2.0e+01



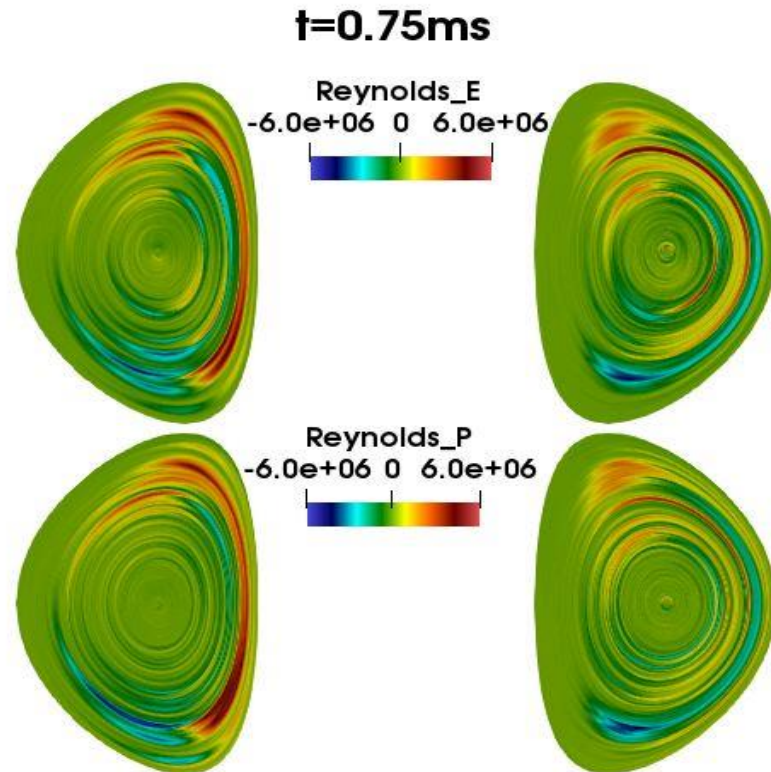
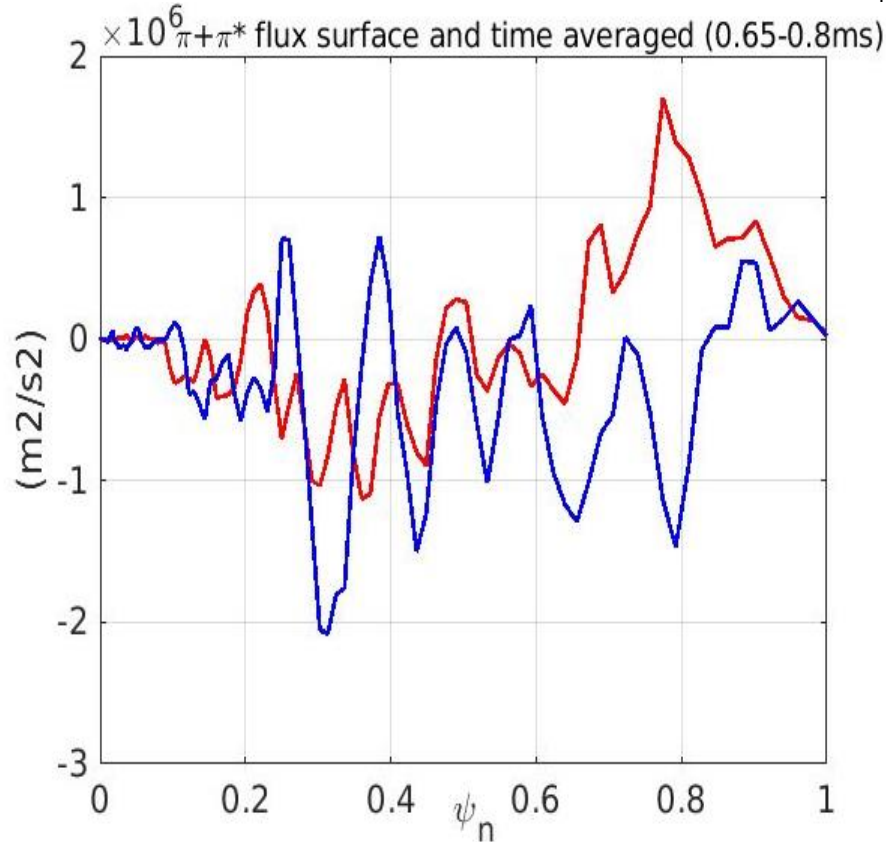
# Reynolds stress tensor = source of zonal flows ? => not clear if NT is better

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

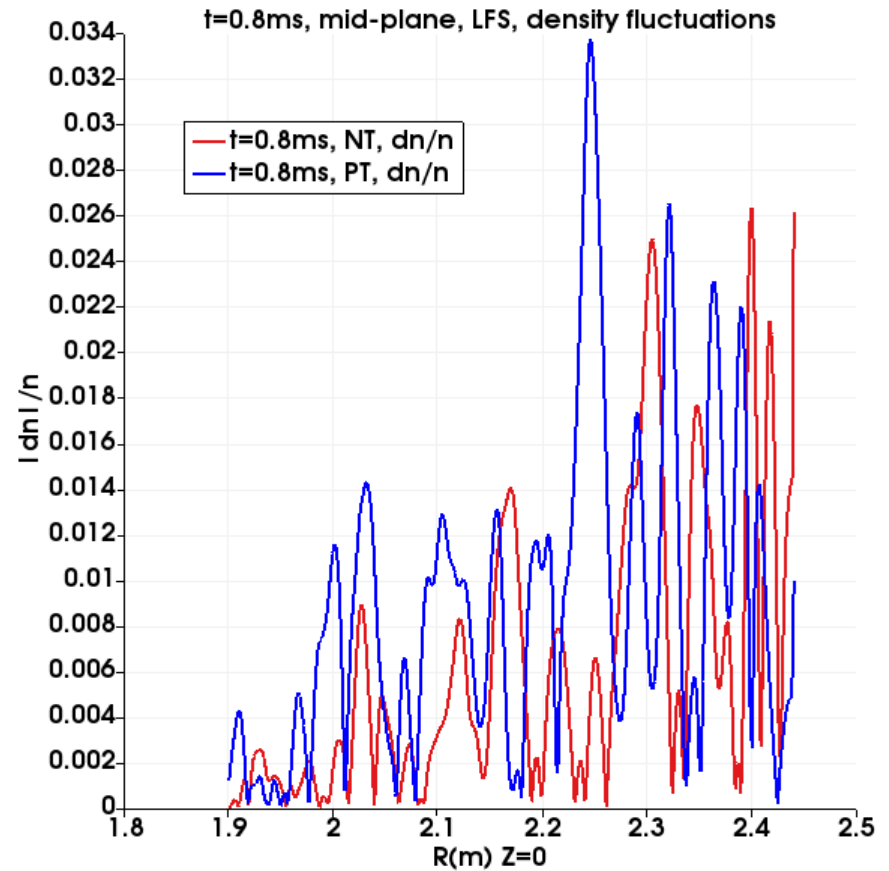
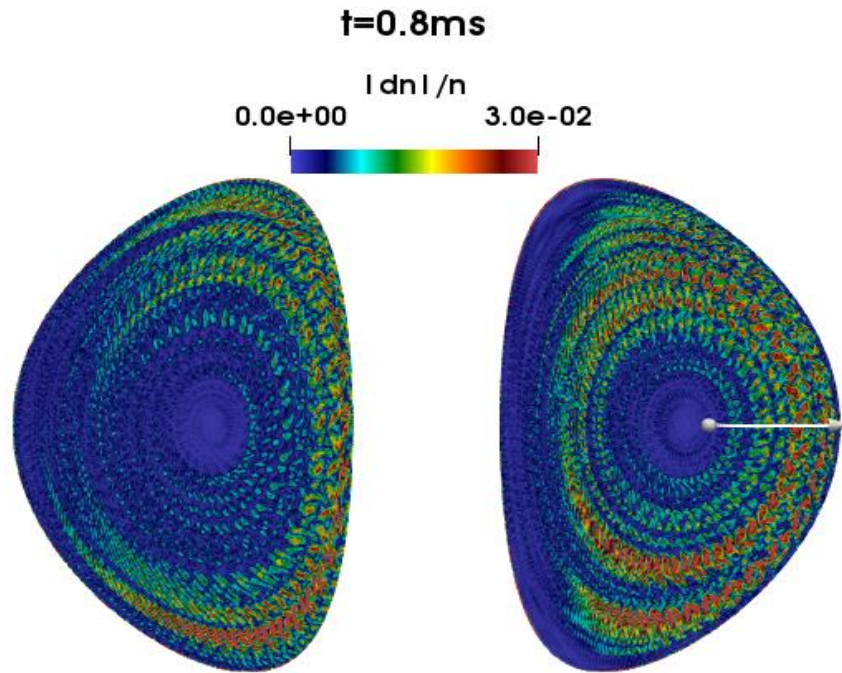
$$\pi = \langle \tilde{V}_{r,E} \tilde{V}_{\theta,E} \rangle; \quad \pi^* = \langle \tilde{V}_r^* \tilde{V}_{\theta,E} \rangle$$

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

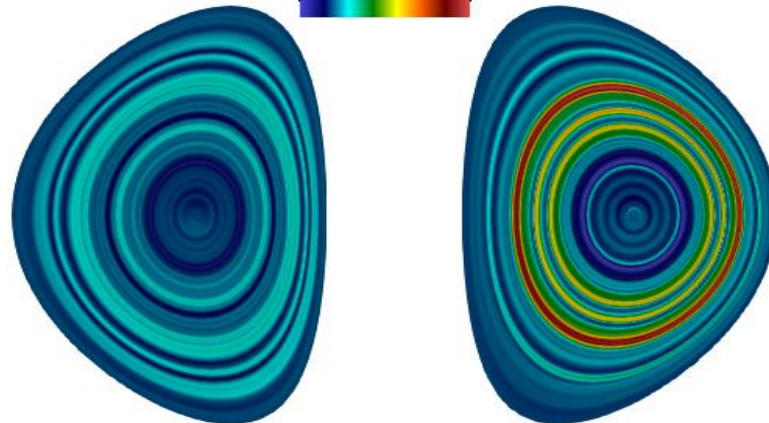
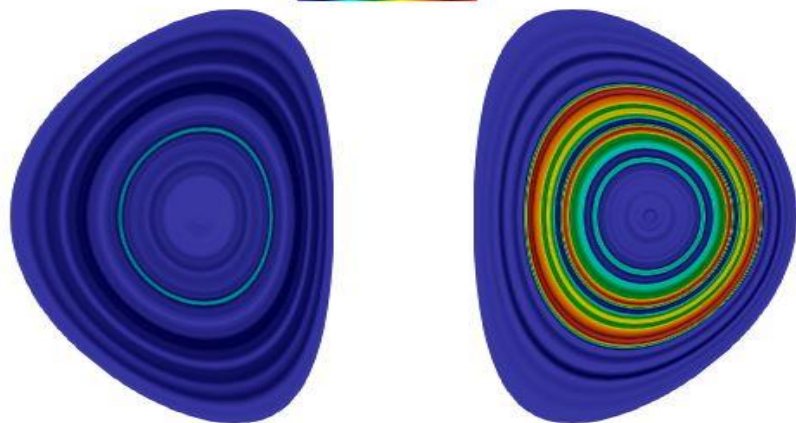
$$\hat{e}_r = \frac{\nabla \psi}{|\nabla \psi|} \quad \hat{e}_\theta = \frac{1}{|\nabla \psi| |\nabla \phi|} \nabla \psi \times \nabla \phi = \frac{R}{|\nabla \psi|} \nabla \psi \times \nabla \phi; \quad |\nabla \phi| = \frac{1}{R}$$



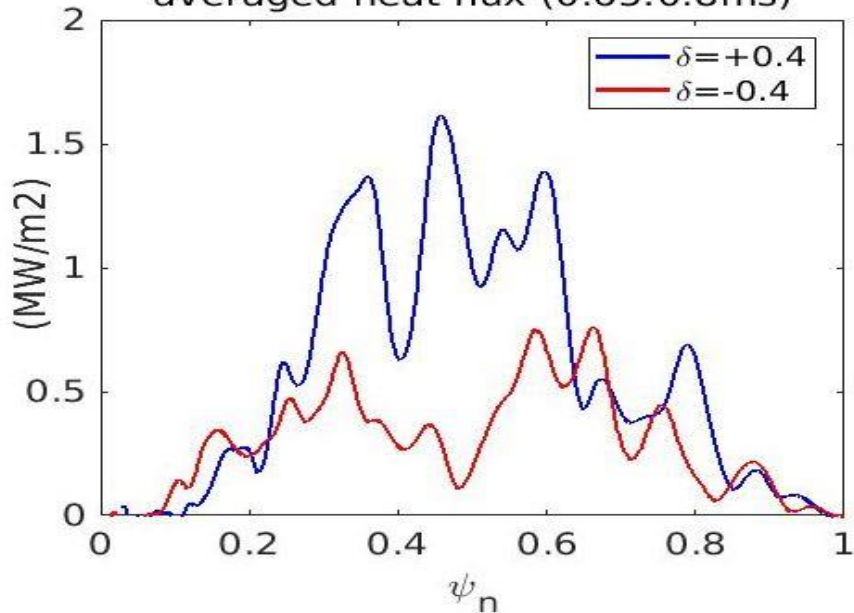
# Density fluctuations are reduced in NT compared to PT.



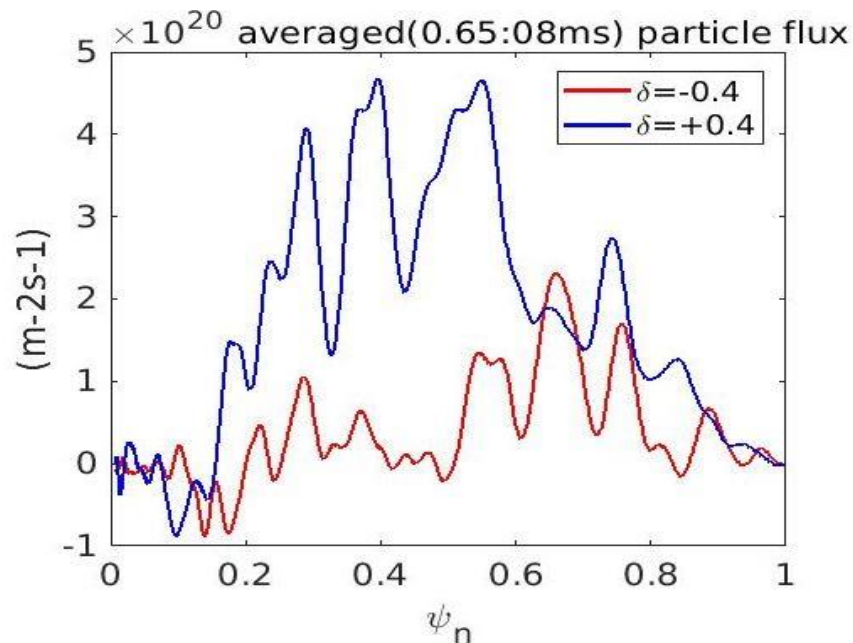
# Perpendicular heat and particle fluxes are ( up to factor ~2) smaller for NT than for PT.



averaged heat flux (0.65:0.8ms)



averaged(0.65:08ms) particle flux



## Conclusions

- 1. Particles in JOEREK 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 JOEREK 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.**