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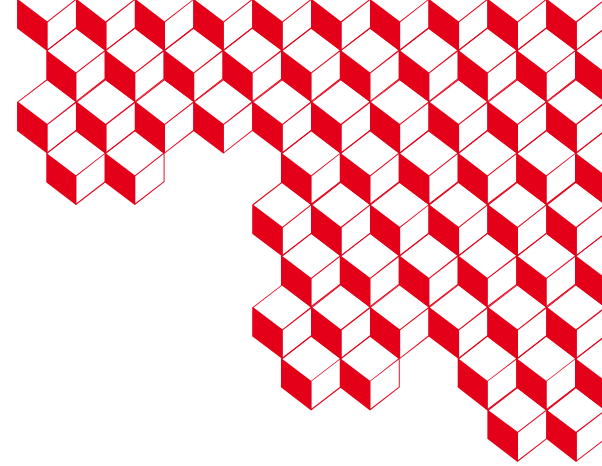
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Non-linear gyro-kinetic Ion Temperature Gradient (ITG) and Trapped Electron Modes(TEM) turbulence modelling in X-point geometry with Resonant Magnetic Perturbations(RMPs).

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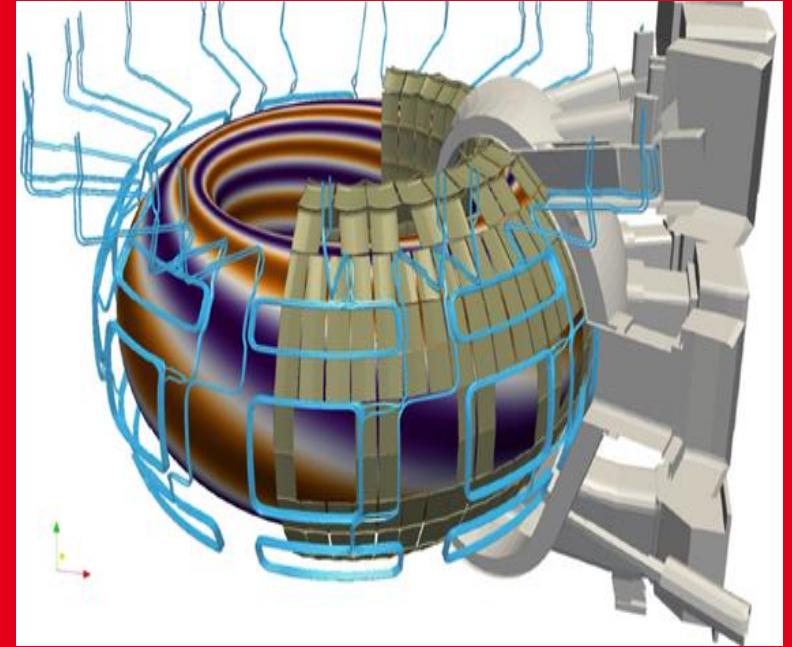
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⁵Faculty of Mathematics and Physics, Charles University, Prague, Czech Republic

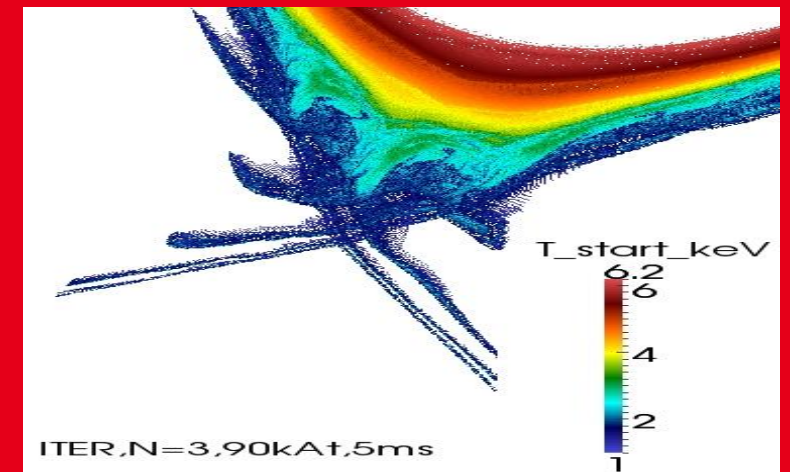
Outline:

1. **Motivation: study of turbulence during RMPs which are used for Edge Localized Modes (ELMs) suppression in existing tokamaks and foreseen for ELMs control in ITER.**
2. **Particles in JOREK code for ITGs + TEMs turbulence modelling in X-point geometry: gyro-kinetic ions+ adiabatic or kinetic electrons**
3. **ITGs/TEMs with RMPs in L-mode (COMPASS#8078).**
4. **ITGs with RMPs in H-mode (HL2A#36872), comparison with experiment.**
5. **Conclusions.**

RMP ELM control coils in ITER



Edge 3D ergodic fields with RMP



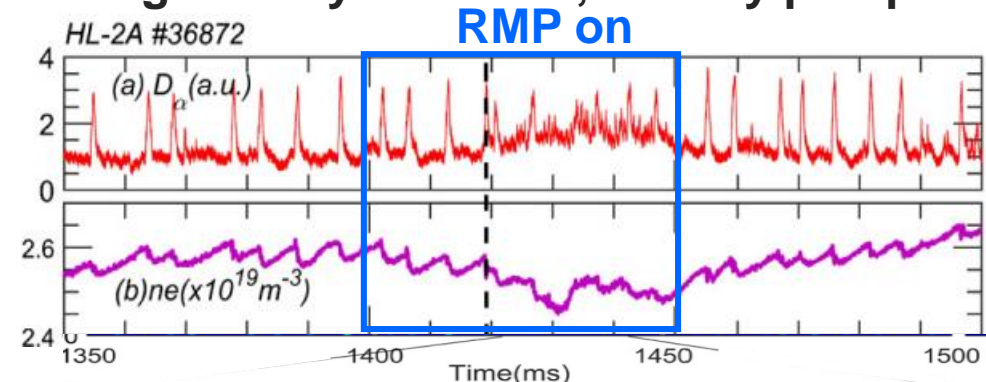
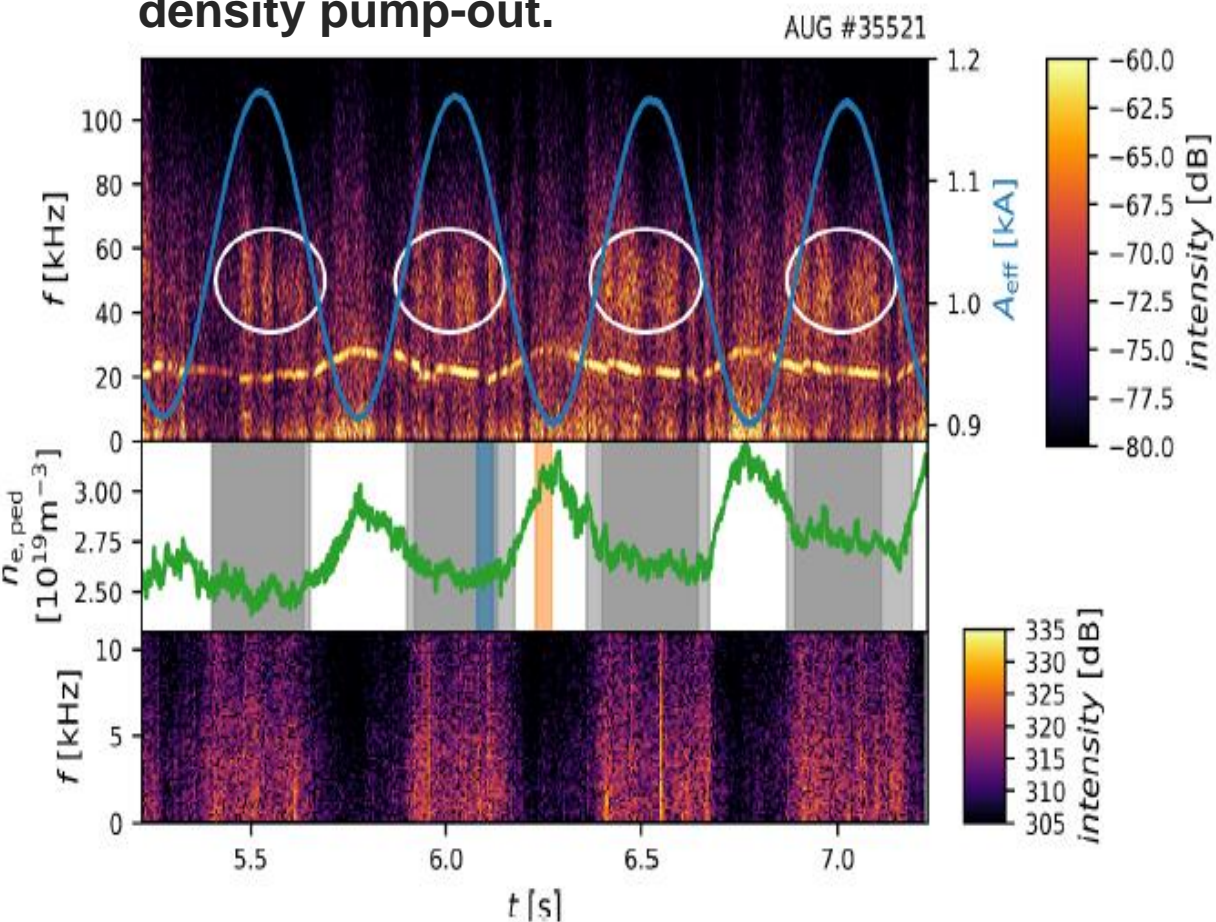
1. Motivation. Experimental observation : turbulence increases with RMPs. Why? What kind of turbulence? Reason for density pump-out?

[AUG, N Leuthold, NF2023]:

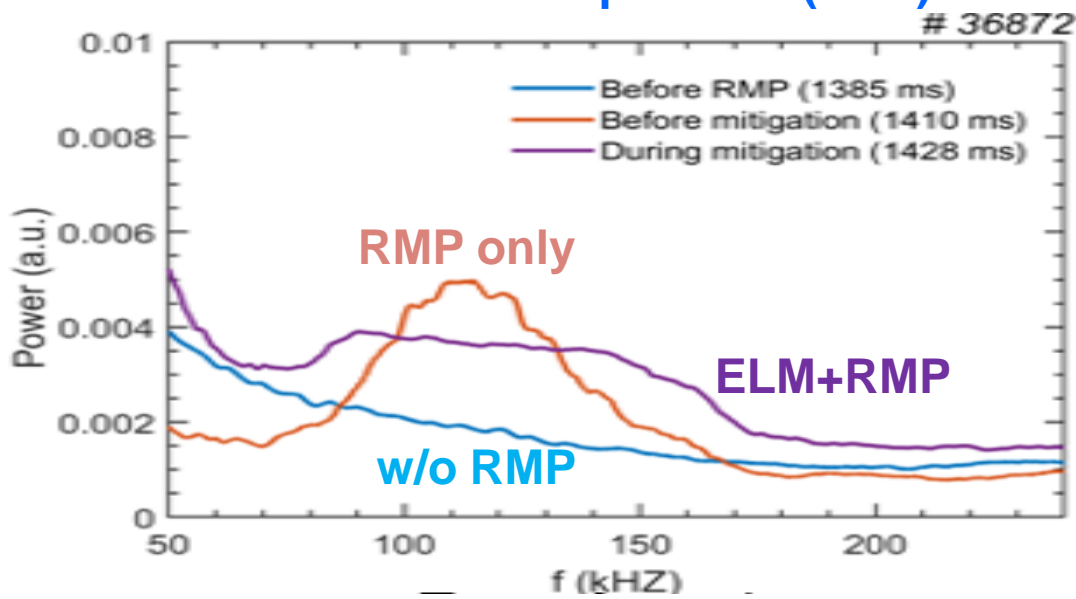
Turbulence is increased during ELM suppression by RMP (N=2), pedestal density pump-out.

[HL2A, T F Sun, NF2021]:

Turbulence is increased during ELM mitigation by RMP N=1, density pump-out.



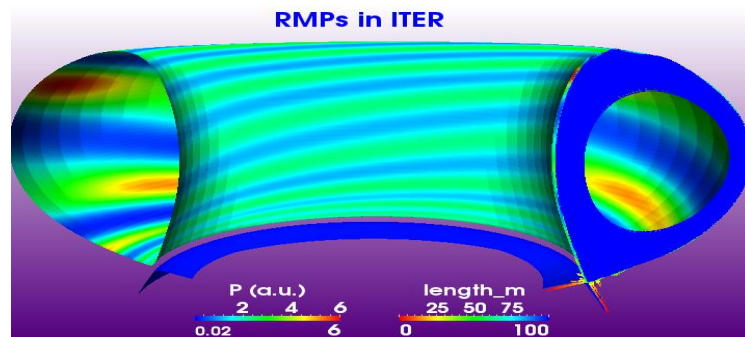
turbulence spectrum (BES)



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

Fluid MHD model:

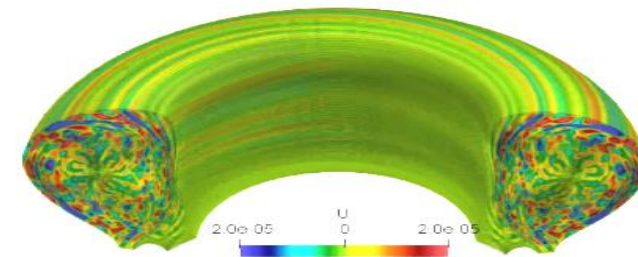
- Non-linear resistive (full or reduced) MHD. Magnetic flux, density, temperatures, velocities equations.
- Two fluid diamagnetic effects, rotation.
- Realistic geometry: SOL, divertor, walls, RMP coils.
- Bohm sheath boundary conditions on divertor and walls (if crossing field lines).
- Flux-aligned grid, high order Bezier finite elements, C1 in poloidal cross-section + toroidal harmonics.
- Parallelization: MPI/OpenMP, GPU.
- Fully implicit.
- Applications: ELMs, RMPs with plasma response, disruptions, pellets, runaways, QH mode etc



Kinetic particles model for ITG/TEMs: See poster P... G T A Huijsmans

- Particles with Maxwell distribution are initialized on the grid, plasma profiles and magnetic topology resulting from fluid MHD.
- Particles are advanced in time evolving electric field and static magnetic field (3D ergodic if RMPs).
- Ions: parallel and ExB motion of gyrocenters in gyro-averaged electric field.
- Electrons: adiabatic or “heavy” kinetic electrons $m_i/m_e=100$, guiding center orbits.
- Projection and solution in weak form using the same basis functions as in fluid MHD

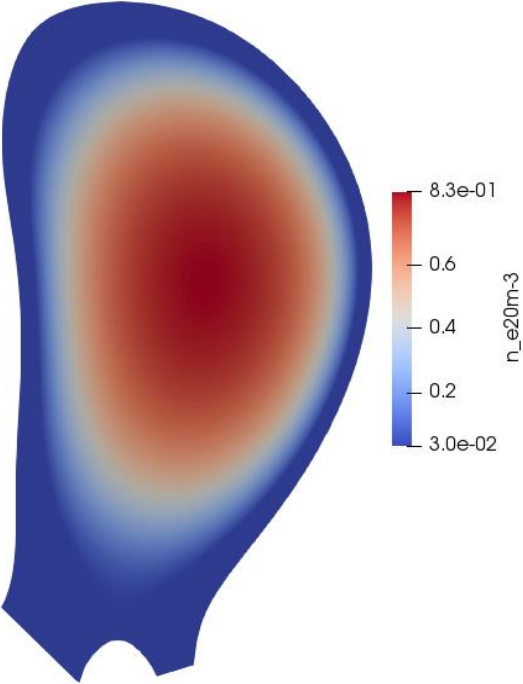
ITG/TEM turbulence in COMPASS with RMPs



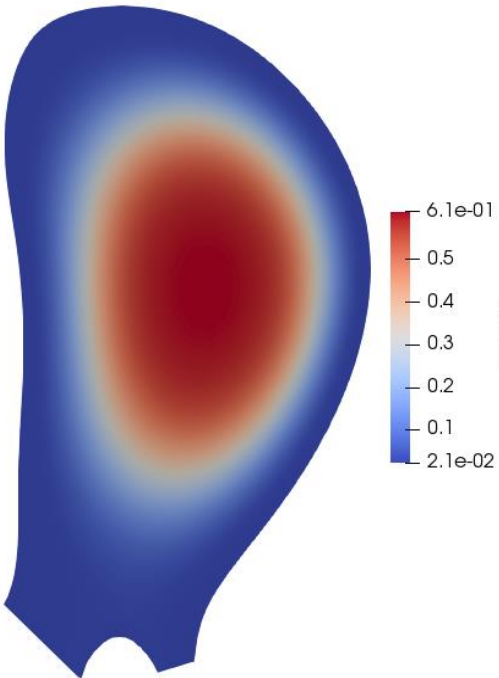
3. Modelling of RMPs N=2, 1.5kAt in L-mode COMPASS #8078. [T Markovic NF2006]

First we model RMPs with plasma response with JOEREK as non-linear fluid MHD code:

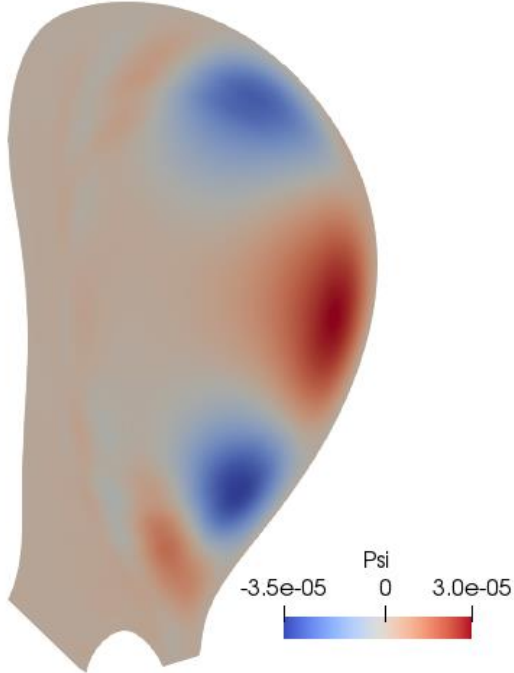
Density



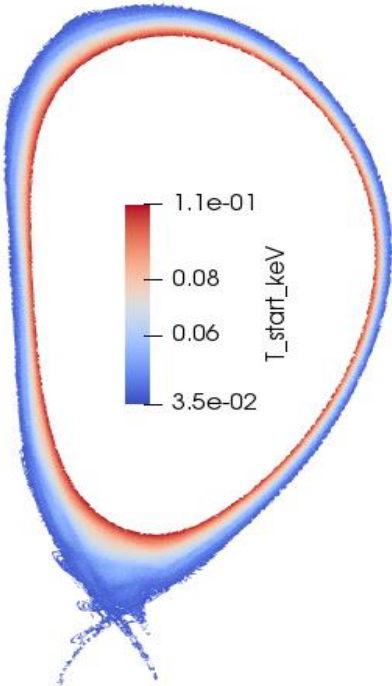
Temperature



Magnetic flux perturbation with RMP

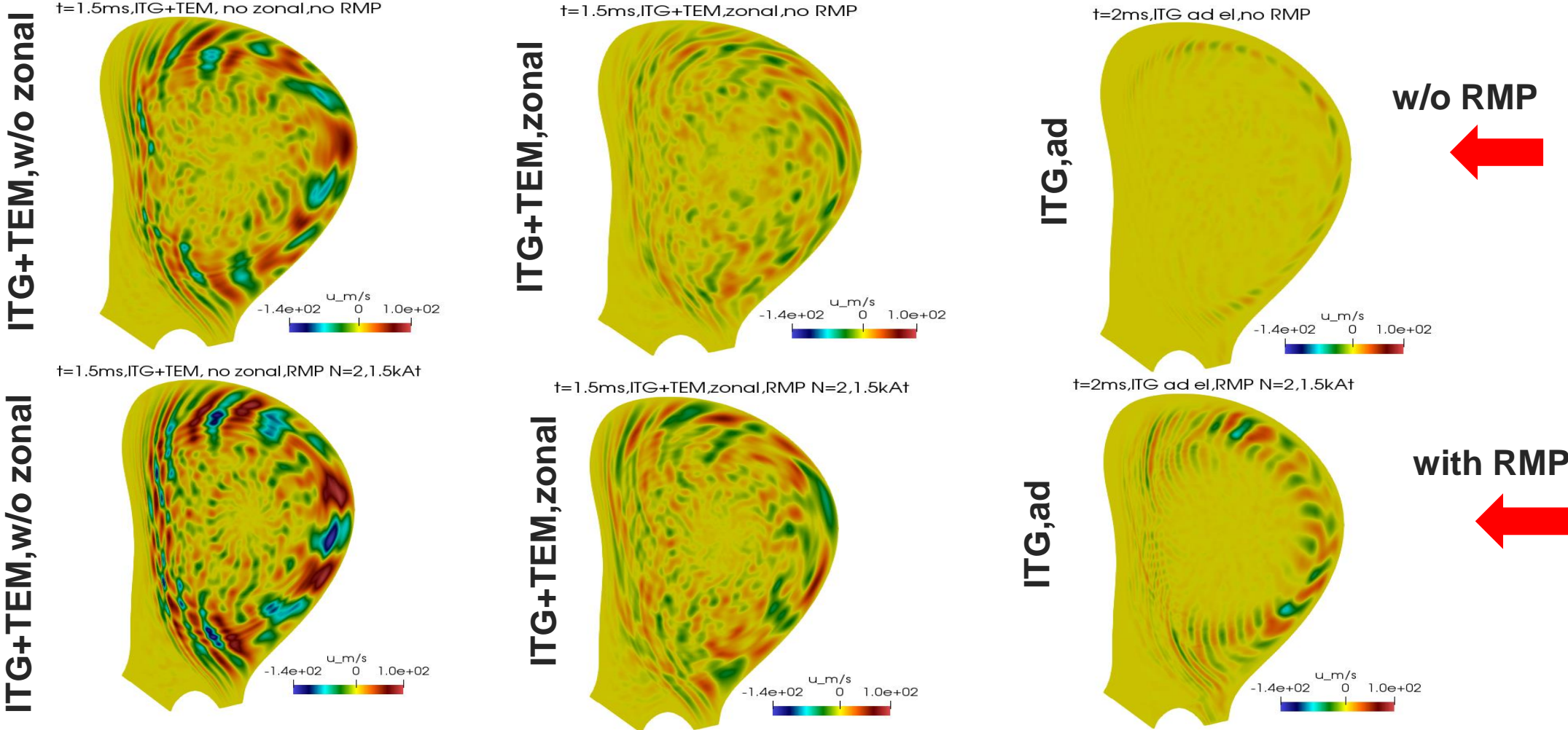


Edge magnetic topology with RMP. Ergodic 3D field.



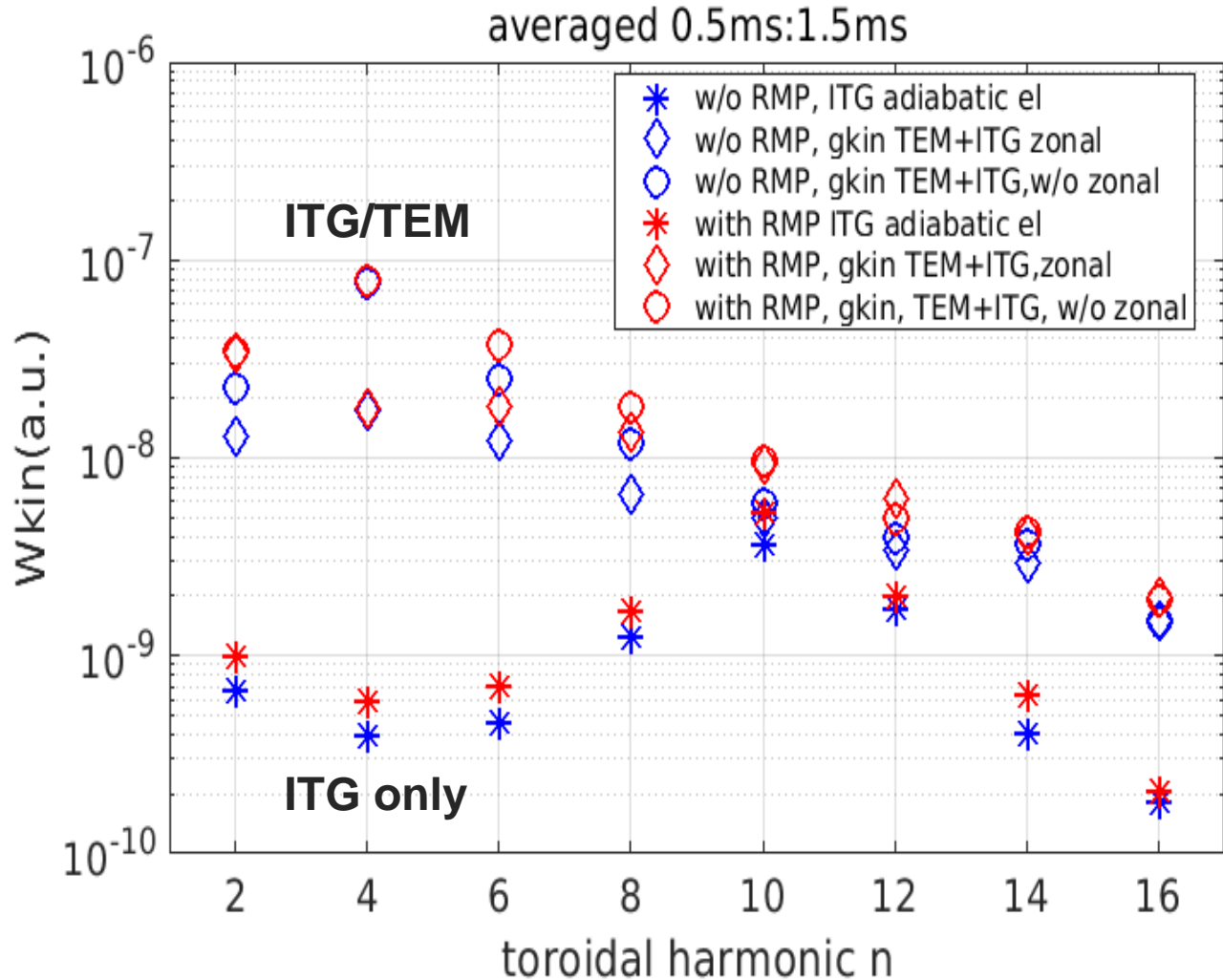
3. ITG and ITG/TEM modelling in L-mode COMPASS #8078.

Particles are initialized on grid and profiles obtained in fluid MHD. Toroidal harmonics N=2:2:16 are evolving in time from noise level to saturated turbulence state ~2ms.

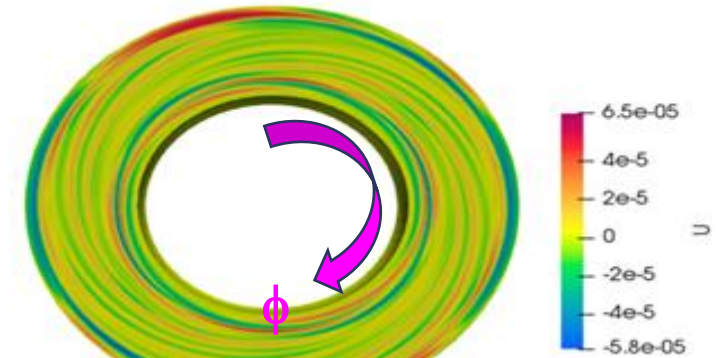


3. ITG and ITG/TEM modelling in L-mode COMPASS #8078.

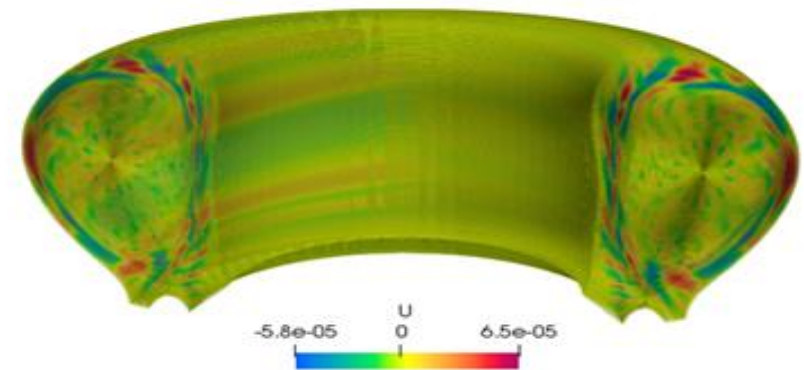
TEM+ITG turbulence is larger compared to ITG only. Stabilizing effect of zonal flows. Larger turbulence with RMPs. Toroidal asymmetry N=2 of ITG/TEMs with zonal flows: similar observation in AUG! [N. Leuthold, NF2023]



t=0.943ms, ITG+TEM with RMP N=2, 1.5kAt



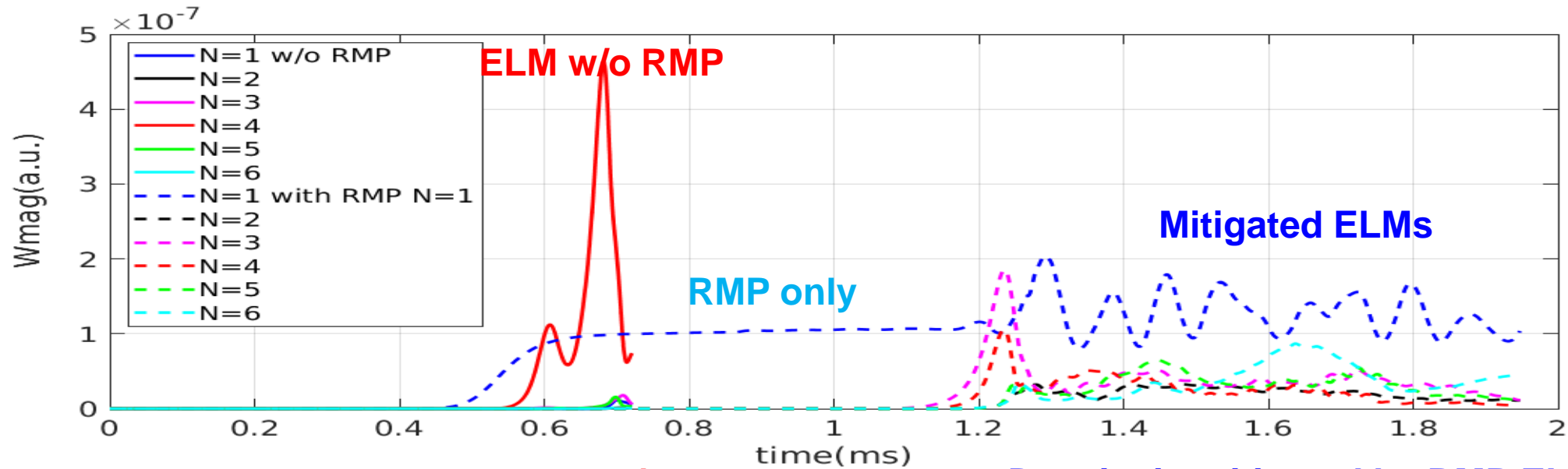
t=0.943ms, ITG+TEM with RMP N=2, 1.5kAt



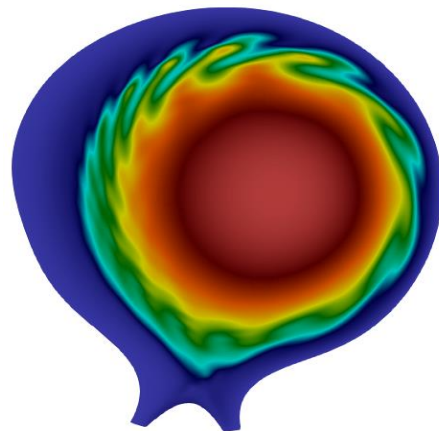
4. ELMs mitigation by RMPs (N=1, 4.9kAt) in H-mode (HL2A#36872)

[HL2A, T F Sun, NF2021]:

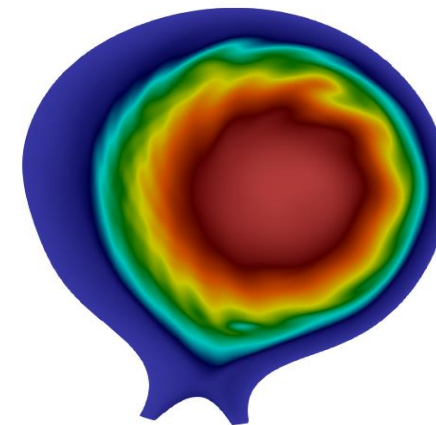
As a first step we model ELM mitigation by RMPs (N=1, 4.9kAt) using fluid MHD :



Density filaments in ELM crash w/o RMP

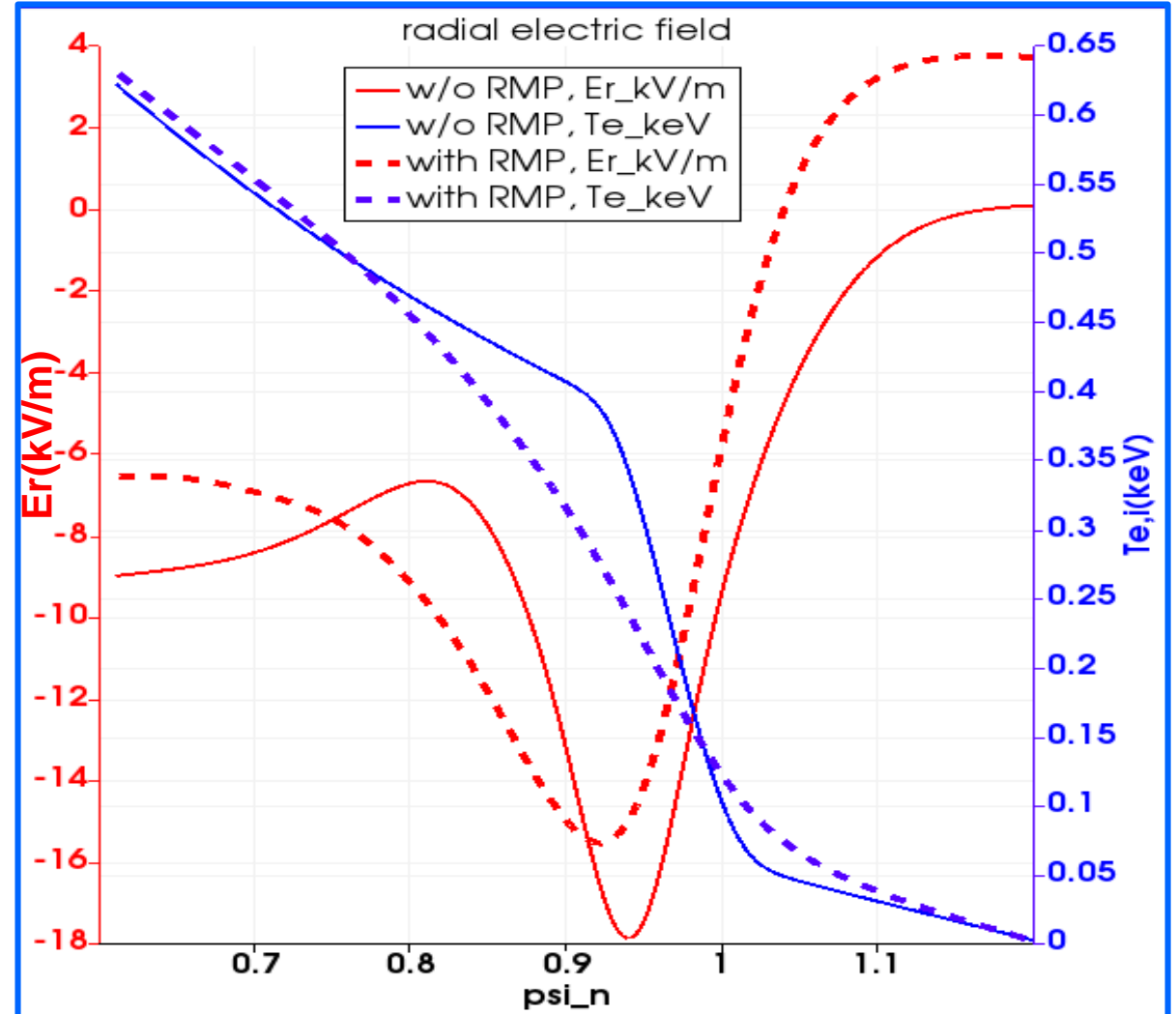
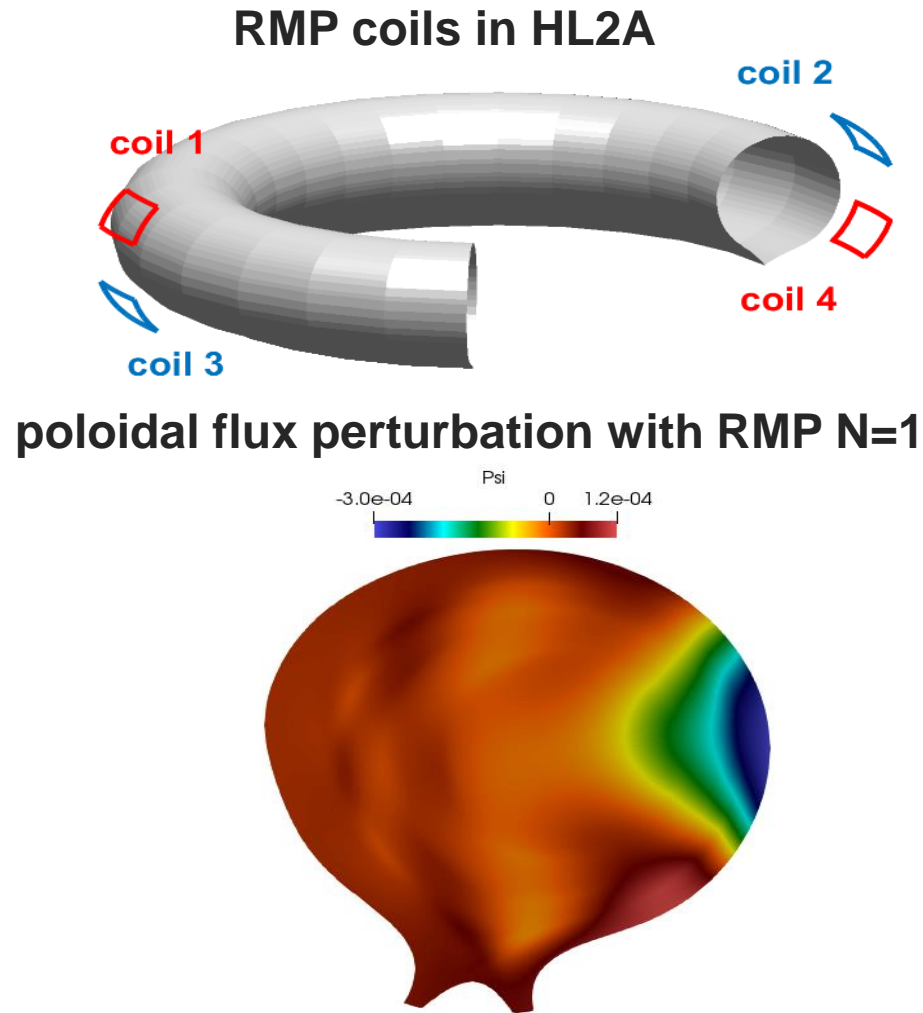


Density in mitigated by RMP ELMs



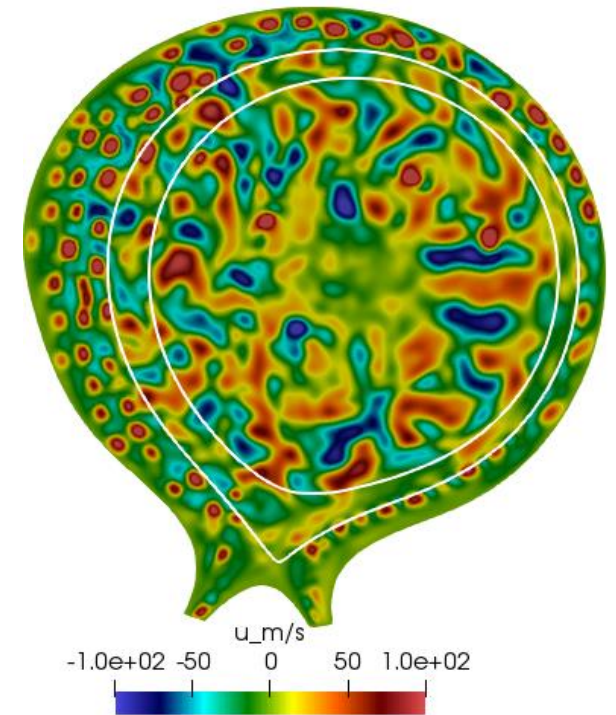
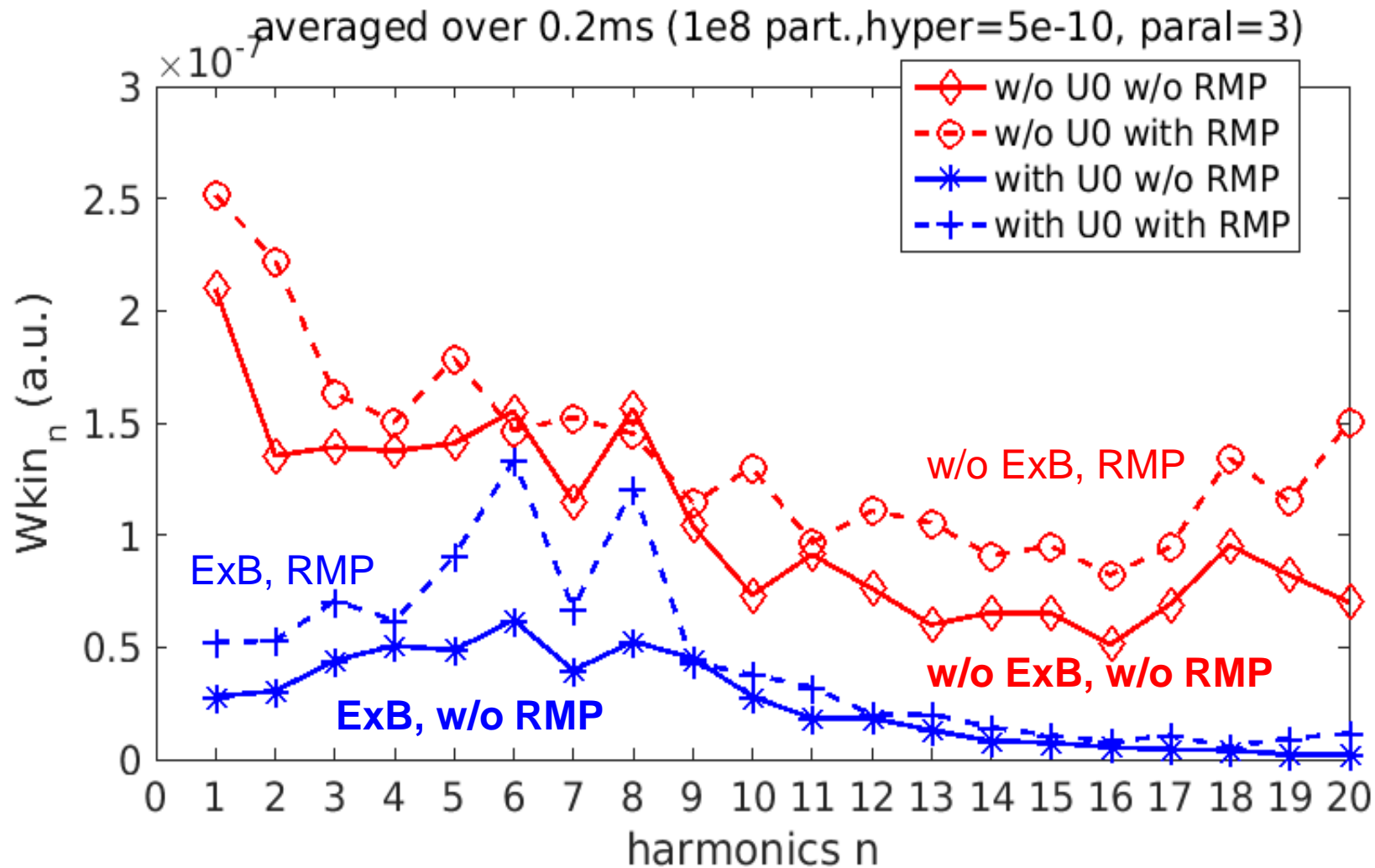
4. RMPs with plasma response in H-mode (HL2A#36872).

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



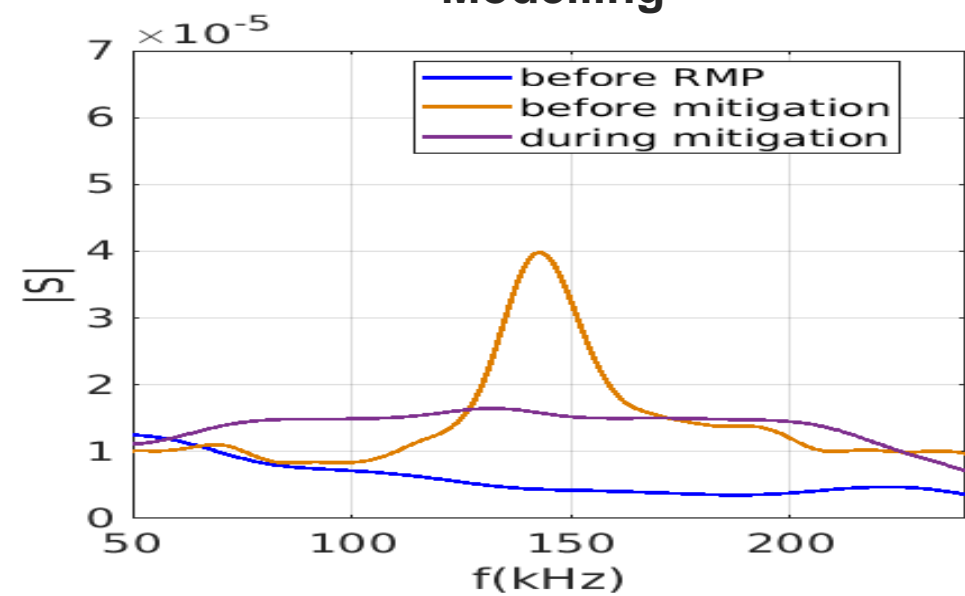
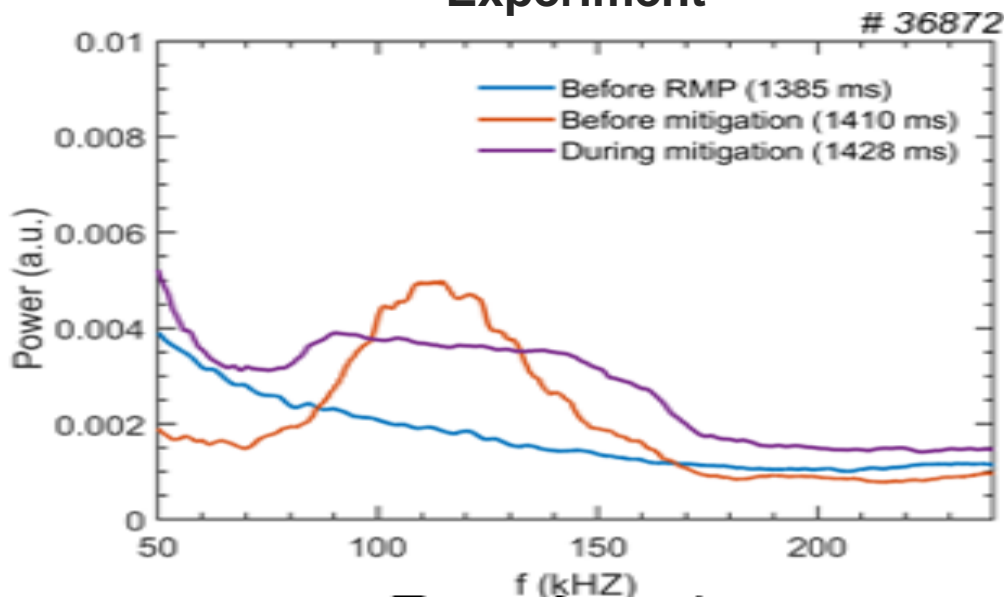
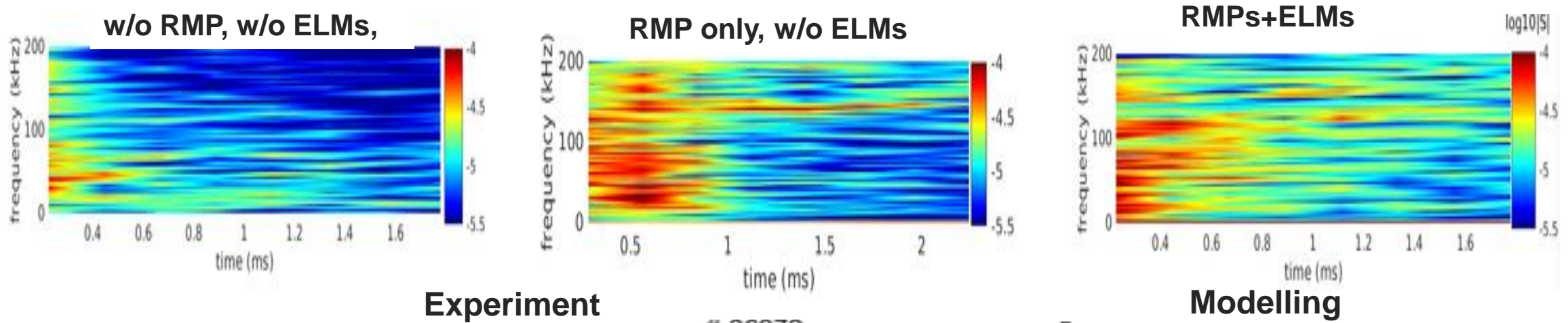
4. ITGs with adiabatic electrons in H-mode (HL2A#36872).

With equilibrium E_r field without RMPs ITG are suppressed in the pedestal due to $E \times B$ rotation. With RMP ITGs are increased because: 1) ergodic field 2) $E \times B$ is reduced.



4. ITGs with adiabatic electrons in HL2A#36872, comparison with experiment.

Frequency range and shape of the spectra are very similar to experimental. Increase of ITG turbulence with RMP+ELMs in spite of the fact that temperature gradient is smaller (less drive), but 3D ergodic field + smaller Er well (less stabilization by ExB) are dominant factors.



[HL2A, T F Sun, NF2021]

Conclusions

1. Particles in JOREK code for 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.

2. ITG and ITG/TEMs in L-mode (COMPASS #8078) with RMPs.

- 1) Larger turbulence ITG/TEM with kinetic electrons than ITG with adiabatic electrons.**
- 2) Increased turbulence with RMPs**
- 3) Stabilizing effect of zonal flows as expected.**
- 4) Toroidal asymmetry of turbulence with RMP**

3. ITGs with adiabatic electrons in H-mode (HL2A#36872) with RMPs.

- 1) Increase of edge ITG turbulence with RMPs in spite of the fact that edge profiles are relaxed (=>less drive for ITGs). 3D ergodic fields and decreased ExB (=>less stabilization of ITGs) are dominant factors in the increase of the turbulence.**
- 2) Shape and frequency range of ITG spectra are in good agreement with the experiment.**

Kinetic particles in JOREK

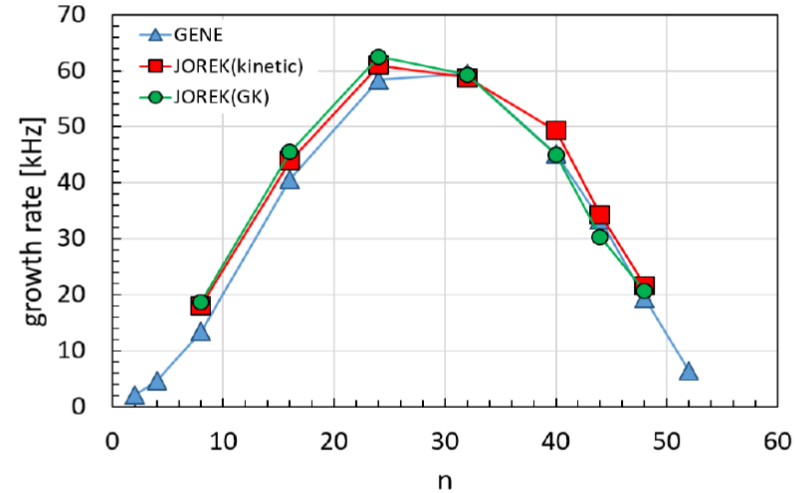


Parallel and ExB motion of gyro-centers in gyro-averaged electric field for ions.

$$\frac{d\vec{x}}{dt} = \frac{\vec{B}^*}{B_{\parallel}^*} u - \frac{\vec{b} \times \vec{E}^*}{\vec{b} \cdot \vec{B}^*} \quad u = \vec{b} \cdot \frac{d\vec{x}}{dt}$$

$$\frac{du}{dt} = \frac{\vec{B}^* \cdot \vec{E}^*}{B_{\parallel}^*} \quad \vec{B}^* = \nabla \times \vec{A}^* = \nabla \times (\vec{A} + u\vec{b})$$

$$\vec{E}^* = \langle \vec{E} \rangle - \mu \nabla B$$



Benchmarking ITGs
 GENE, XGC, ORB5
 (Merlo 2018), 10^9
 particles,
 filter_perp = $3 \cdot 10^{-11}$,
 filter_par = 0.3

Poisson equation: $n_i = n_e$

Adiabatic electrons => ITGs only

$$\nabla \cdot \frac{m_i n_0}{q_i B^2} \nabla_{\perp} \phi - \frac{e n_0}{T_e} (\phi - \langle \phi \rangle) = n_i$$

Projection and solution in weak form on the same basis functions as in fluid MHD JOREK:

$$\int -\nabla \left(\frac{T_e}{e n_0} v^*(\vec{x}) \right) \cdot \frac{m_i n_0}{q_i B^2} \nabla_{\perp} \phi - v^* (\phi - \langle \phi \rangle) dV = \int \frac{T_e}{e n_0} v^*(\vec{x}) \sum_{i=1}^N w_i \delta(\vec{x} - \vec{x}_i) dV$$

Adiabatic electrons

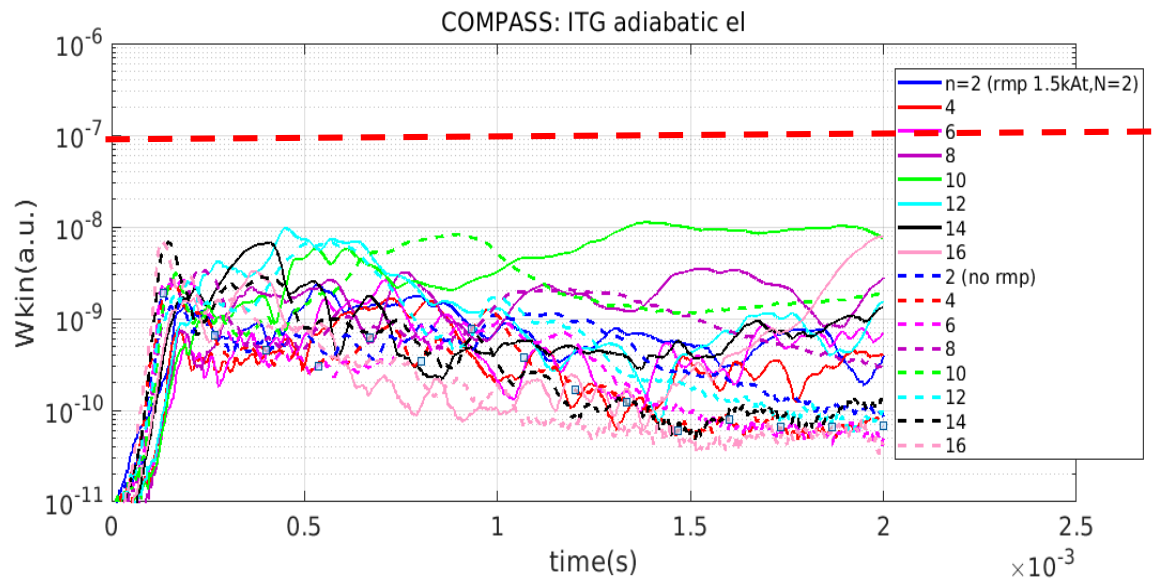
$$\int -\nabla \left(\frac{T_e}{e n_0} v^*(\vec{x}) \right) \cdot \frac{m_i n_0}{q_i B^2} \nabla_{\perp} \phi - v^* \phi dV = \int \frac{T_e}{e n_0} v^*(\vec{x}) \sum_{i=1}^{2N} \frac{q_i}{e} w_i \delta(\vec{x} - \vec{x}_i) dV$$

Kinetic electrons

Kinetic electrons => ITGs/TEMs

Time traces of the kinetic energy of ITGs only and ITG/TEM with/without RMP. COMPASS L-mode. RMP N=2, 1.5kAt.

ITG, adiabatic electrons



ITG/TEM, kinetic electrons, zonal flows

