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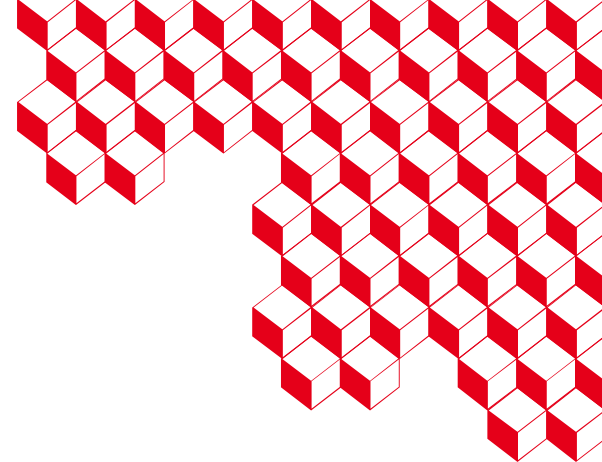
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Non-linear gyro-kinetic Ion Temperature Gradient (ITG) and Trapped Electron Modes(TEM) turbulence modelling in X-point geometry with Resonant Magnetic Perturbations(RMPs).

M.Bécoulet¹, G.T.A.Huijsmans^{1,2}, X.Garbet¹, P. Donnel¹, Lian Wang³, Guangzhou Hao³, L.Kripner^{4,5}

¹CEA, IRFM, 13108 Saint-Paul-Lez-Durance, France

²Eindhoven University of Technology, 5600MB Eindhoven, The Netherlands

³Southwestern Institute of Physics, P. O. Box 432, Chengdu 610041, China

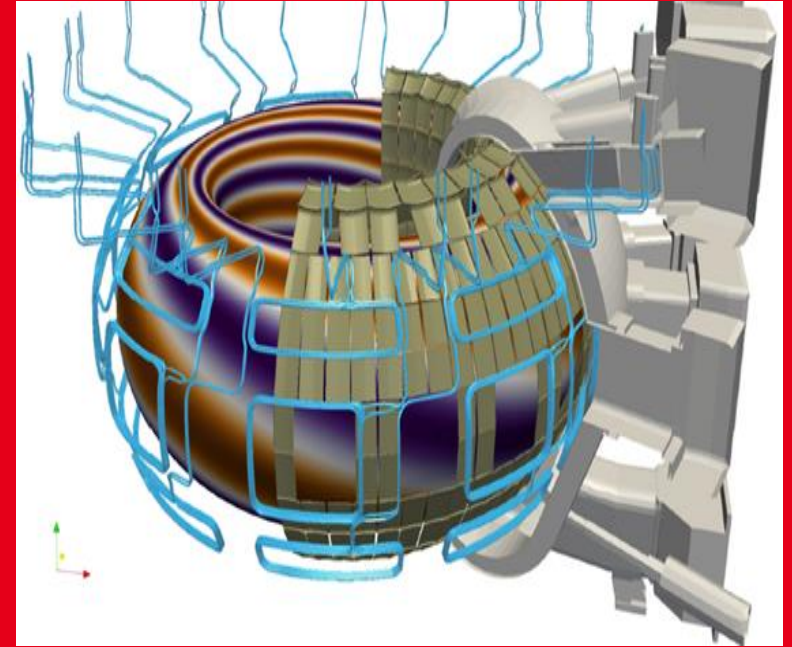
⁴Institute of Plasma Physics of the CAS, Za Slovankou 3, 182 00 Prague 8, Czech Republic

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

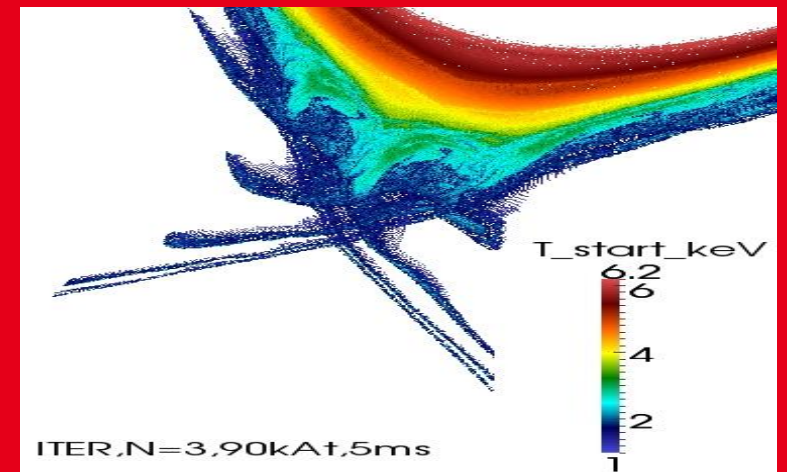
Outline:

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 JOEREK 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



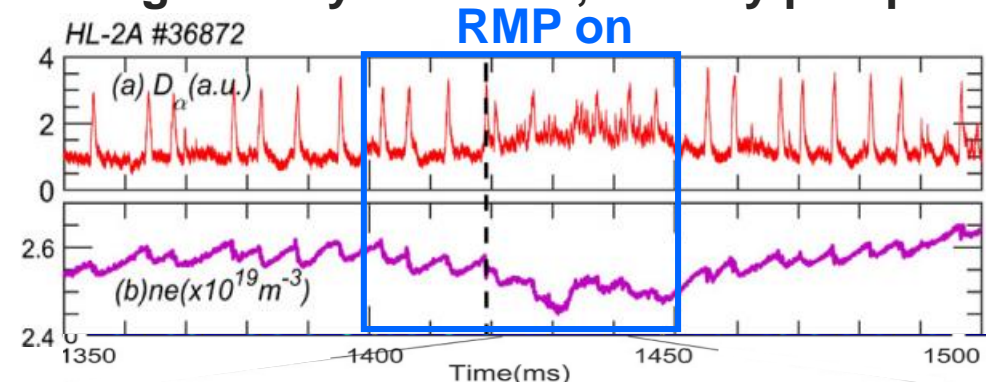
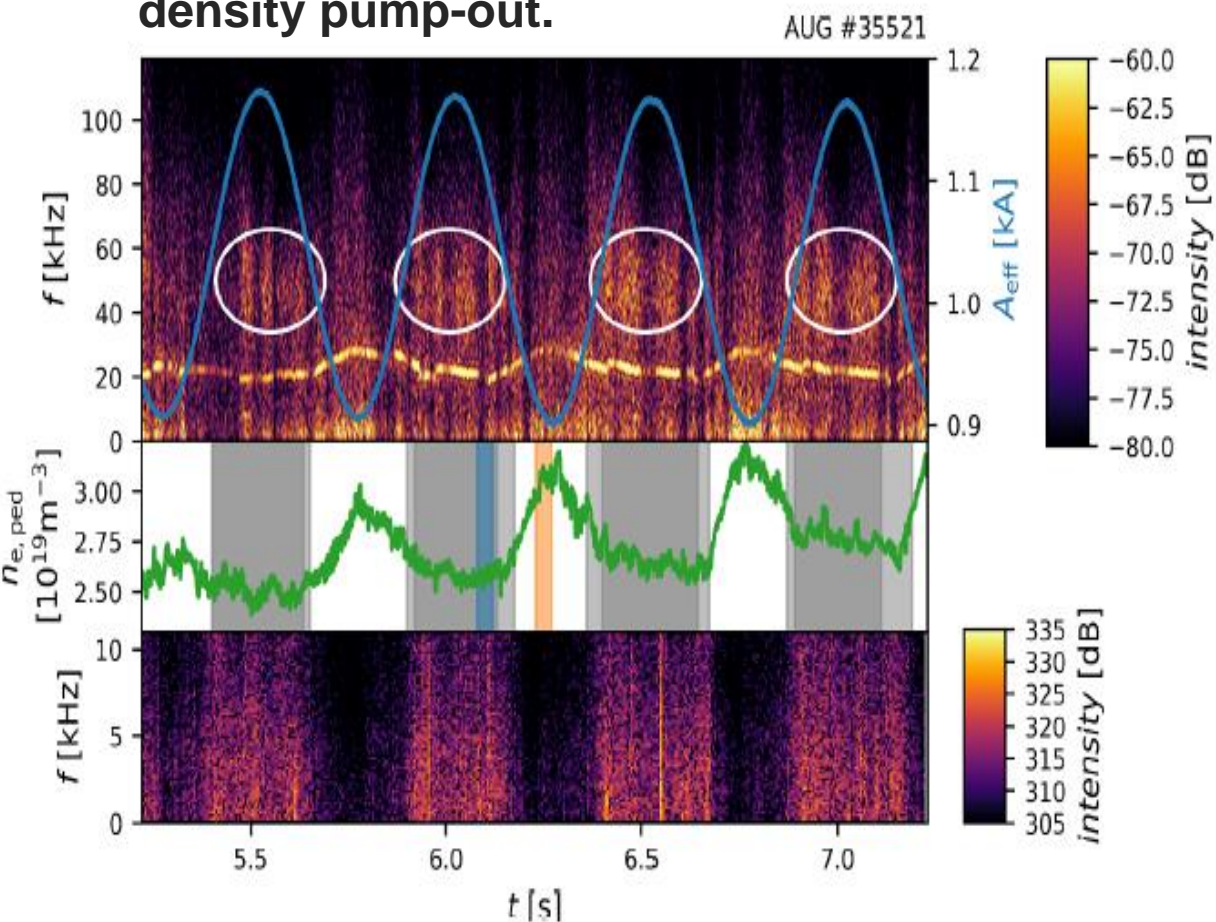
1. Motivation. Experimental observation : turbulence increases with RMPs. Why? What kind of turbulence? Reason for density pump-out?

[AUG, N Leuthold, NF2023]:

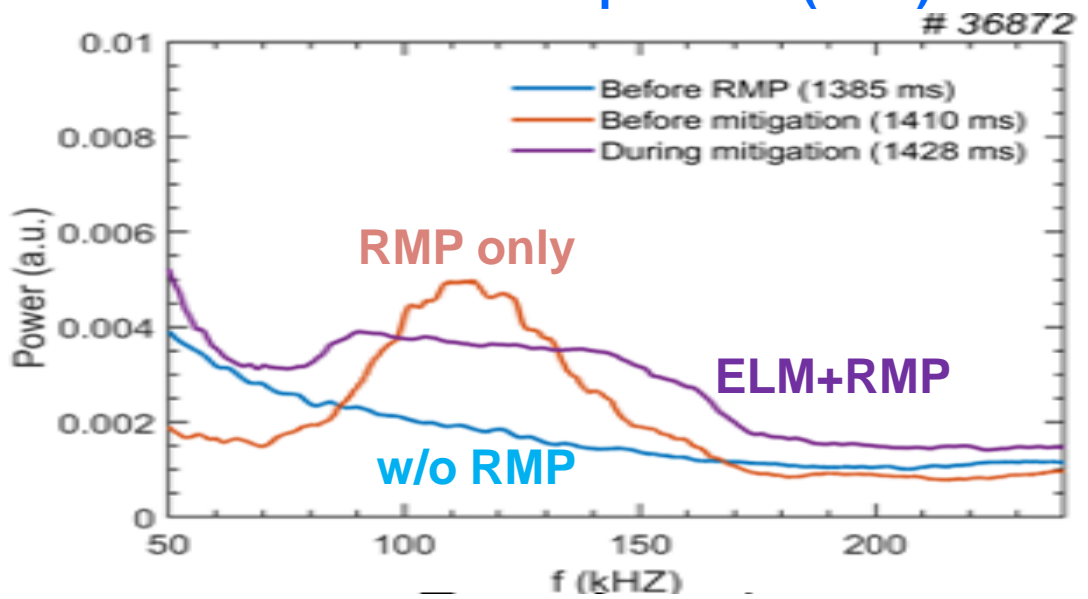
Turbulence is increased during ELM suppression by RMP (N=2), pedestal density pump-out.

[HL2A, T F Sun, NF2021]:

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



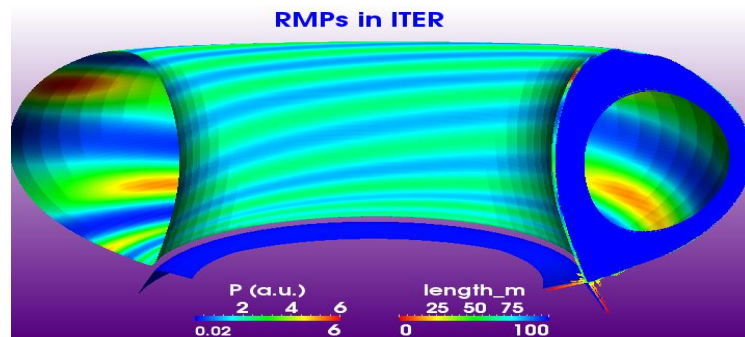
turbulence spectrum (BES)



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

Fluid MHD model:

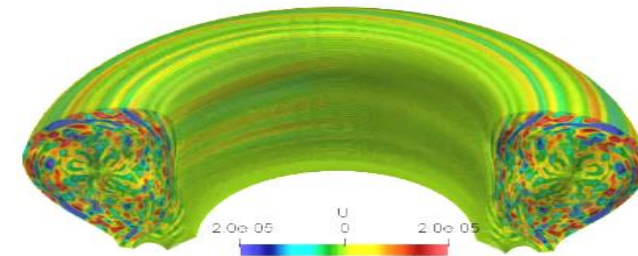
- Non-linear resistive (full or reduced) MHD. Magnetic flux, density, temperatures, velocities equations.
- Two fluid diamagnetic effects, rotation.
- Realistic geometry: SOL, divertor, walls, RMP coils.
- Bohm sheath boundary conditions on divertor and walls (if crossing field lines).
- Flux-aligned 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

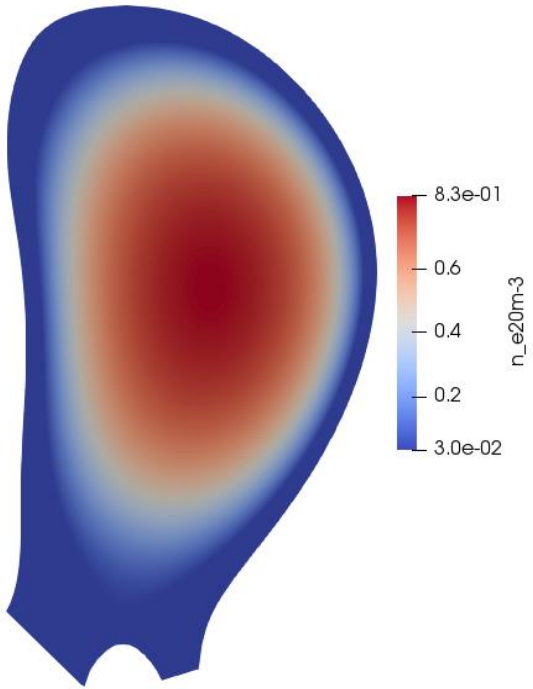
ITG/TEM turbulence in COMPASS with RMPs



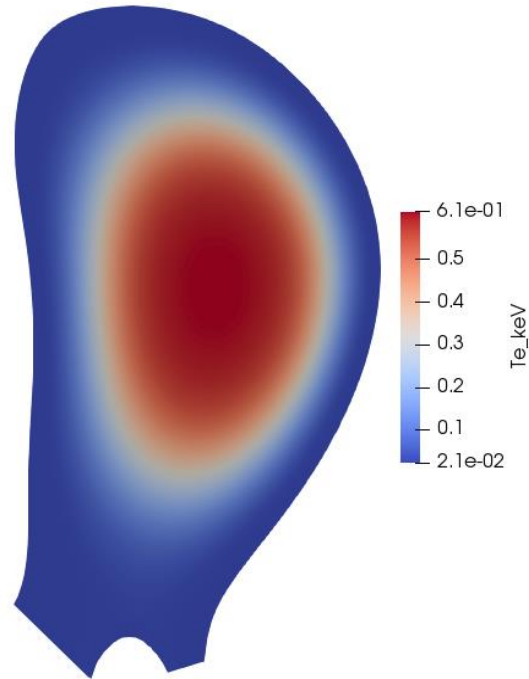
3. Modelling of RMPs N=2, 1.5kAt in L-mode COMPASS #8078. [T Markovic NF2006]

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

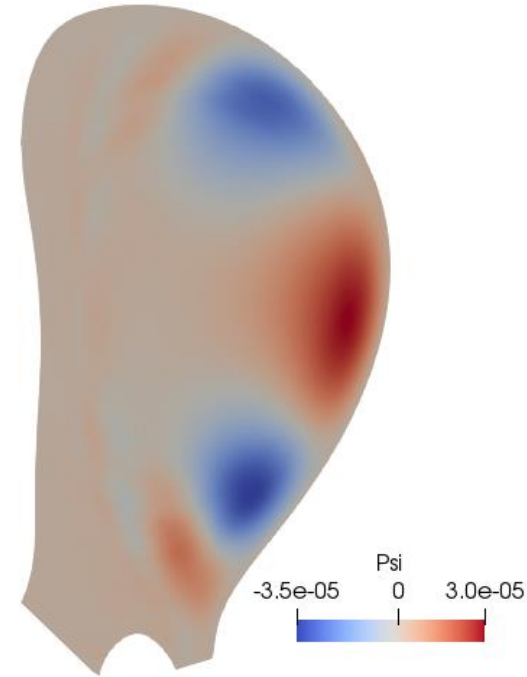
Density



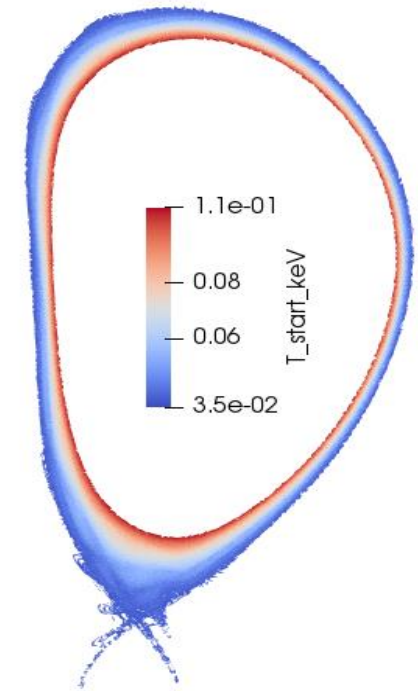
Temperature



Magnetic flux perturbation with RMP

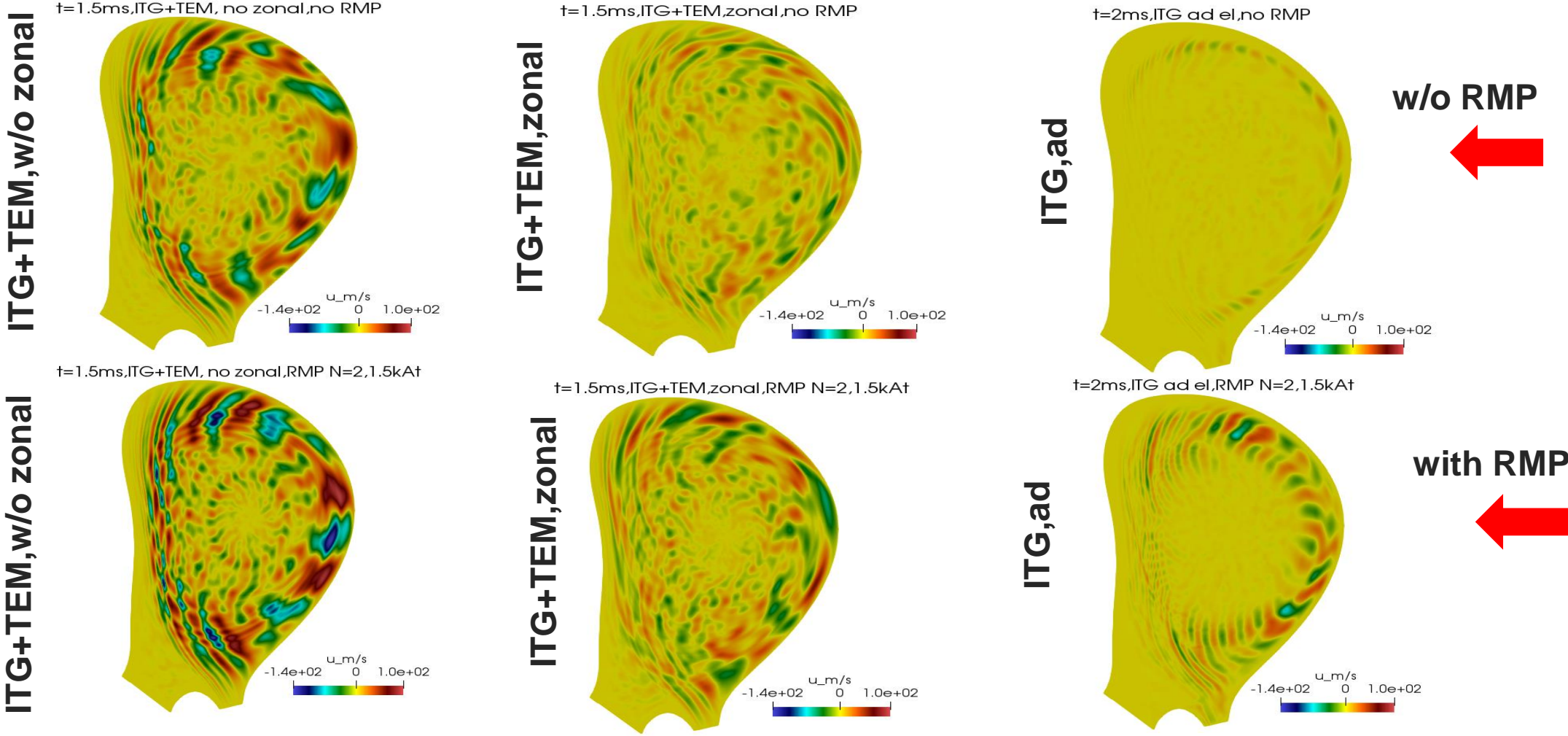


Edge magnetic topology with RMP. Ergodic 3D field.



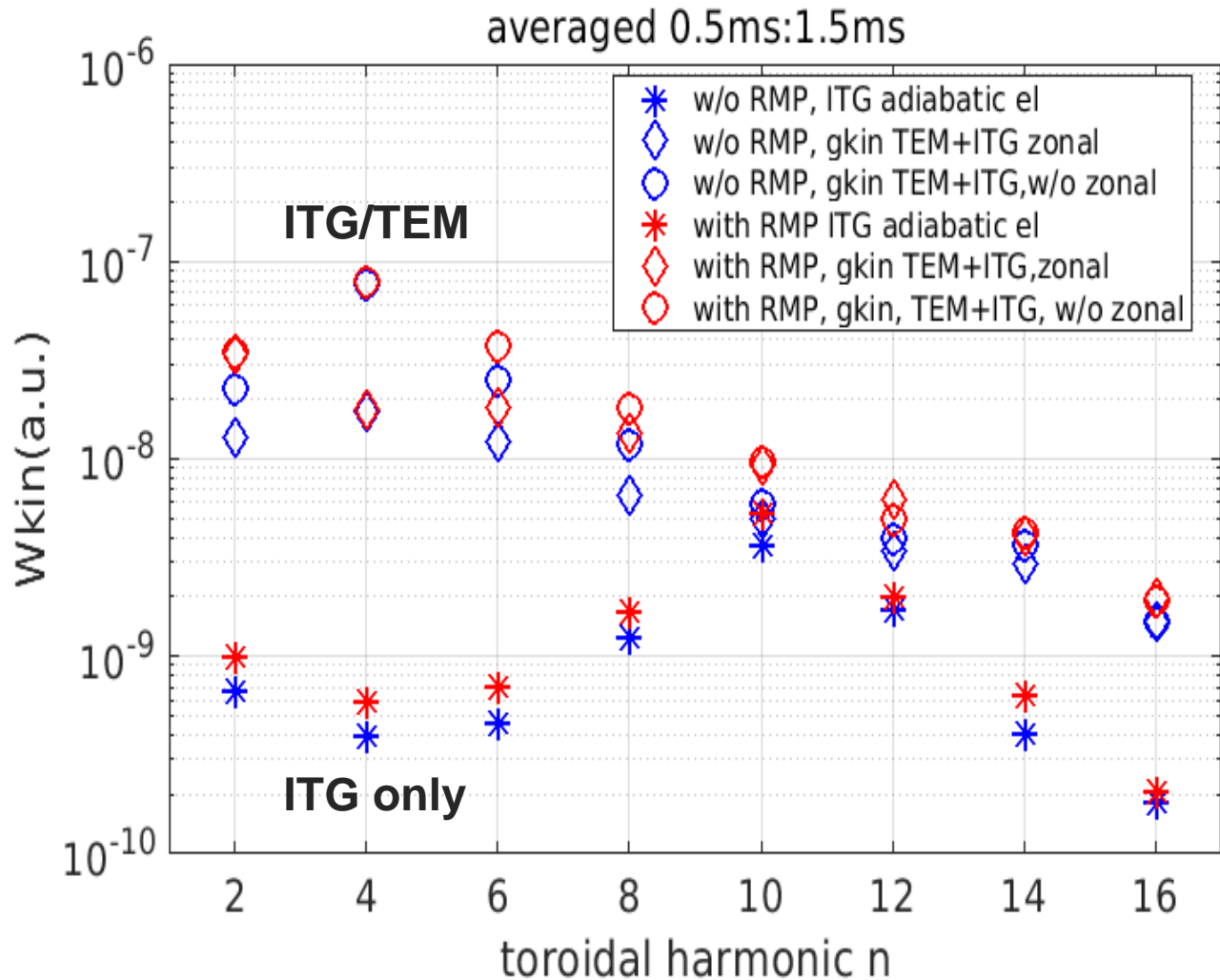
3. ITG and ITG/TEM modelling in L-mode COMPASS #8078.

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.

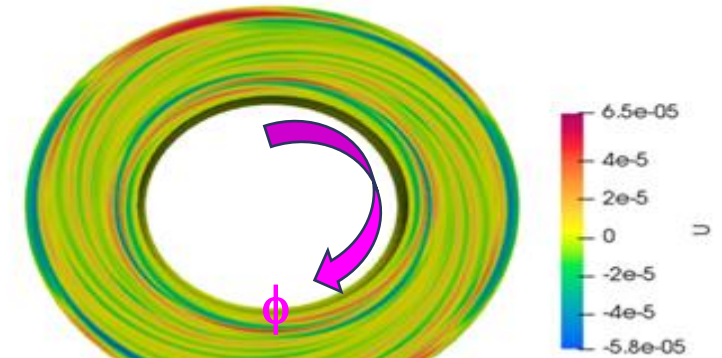


3. ITG and ITG/TEM modelling in L-mode COMPASS #8078.

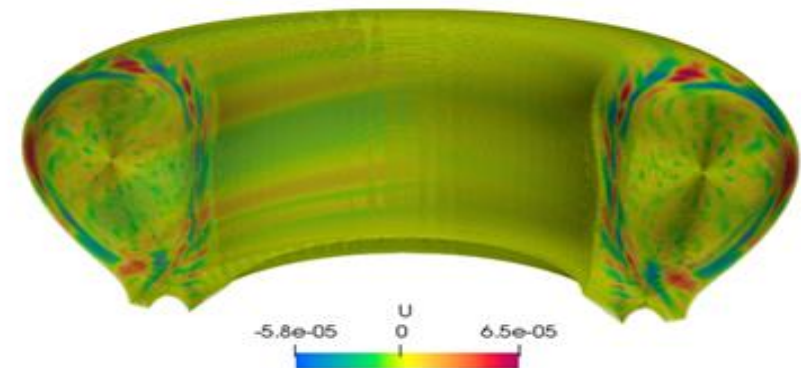
TEM+ITG turbulence is larger compared to ITG only. Stabilizing effect of zonal flows. Larger turbulence with RMPs. Toroidal asymmetry N=2 of ITG/TEMs with zonal flows: similar observation in AUG! [N. Leuthold, NF2023]



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



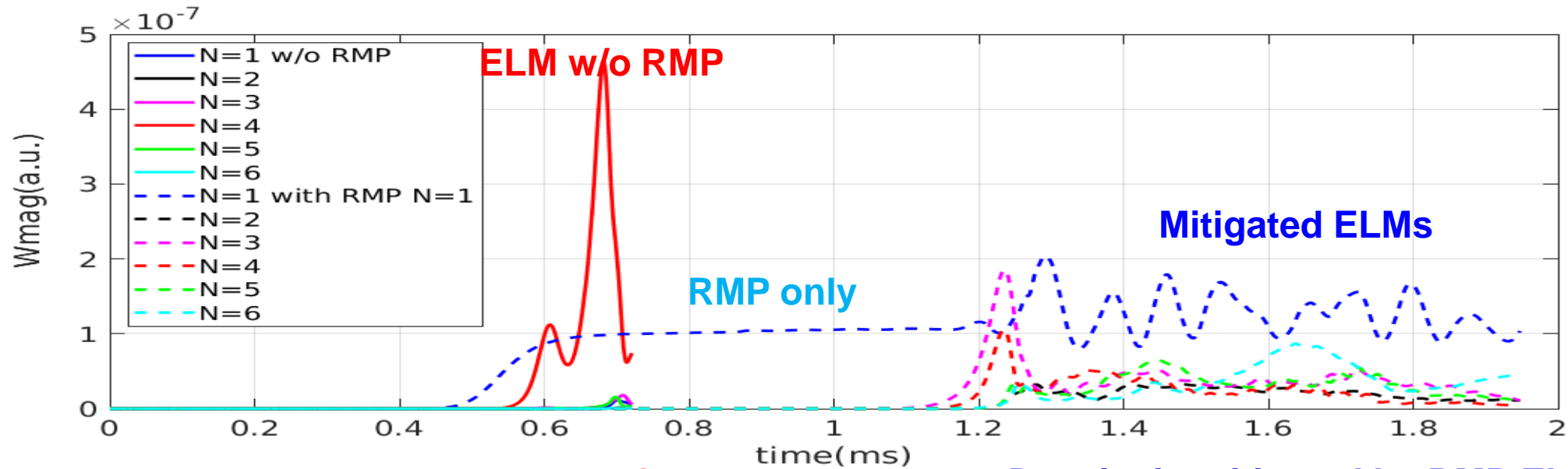
t=0.943ms, ITG+TEM with RMP N=2, 1.5kAt



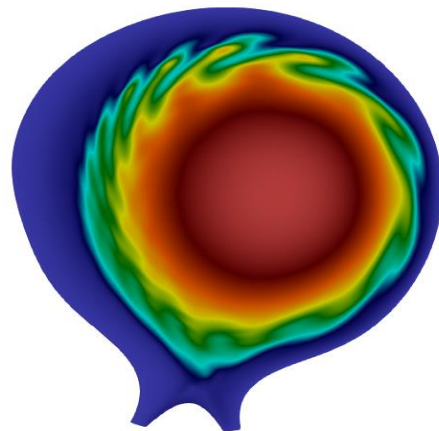
4. ELMs mitigation by RMPs (N=1, 4.9kAt) in H-mode (HL2A#36872)

[HL2A, T F Sun, NF2021]:

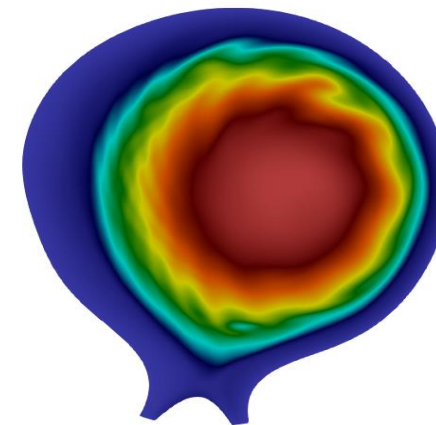
As a first step we model ELM mitigation by RMPs (N=1, 4.9kAt) using fluid MHD :



Density filaments in ELM crash w/o RMP

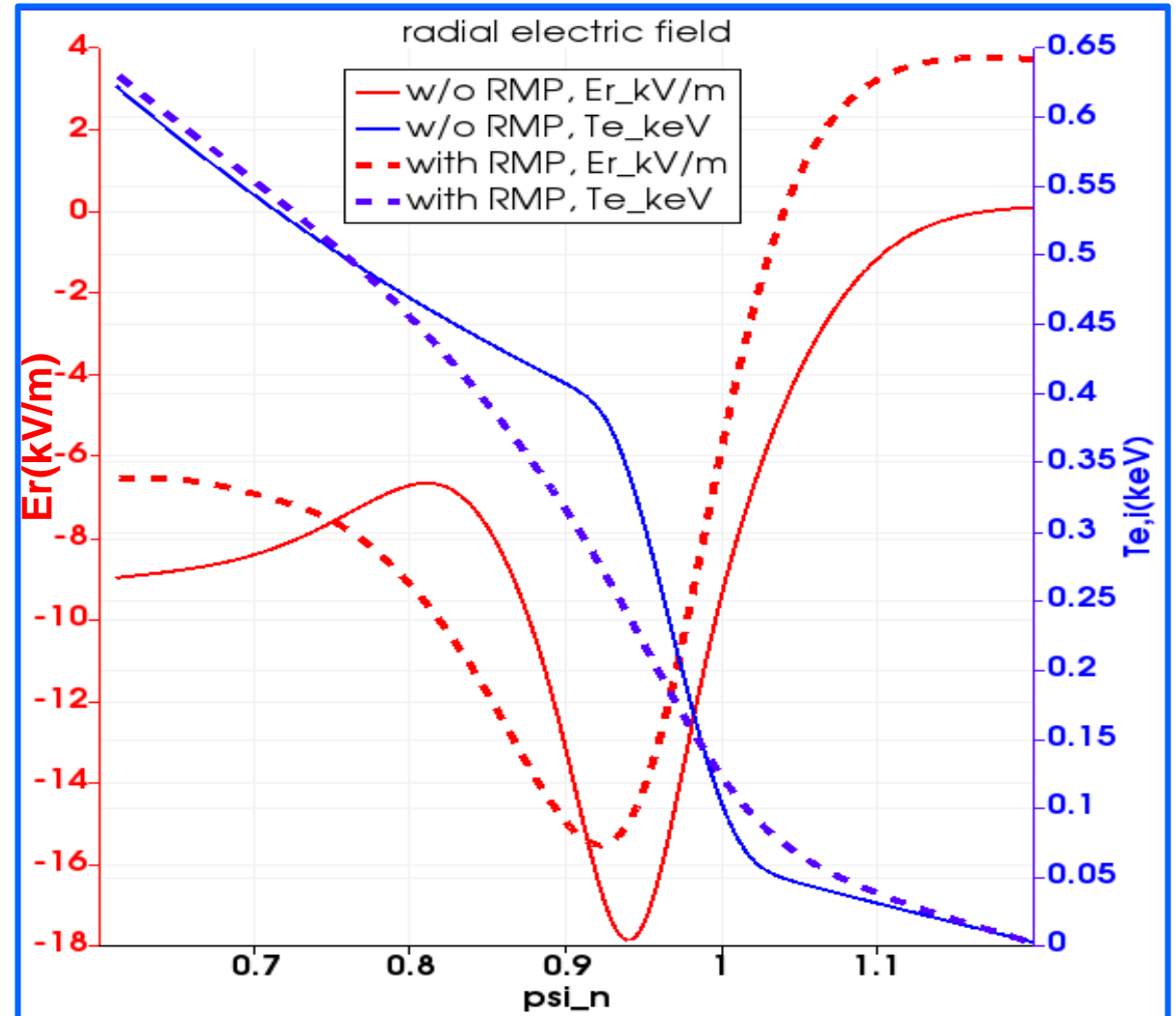
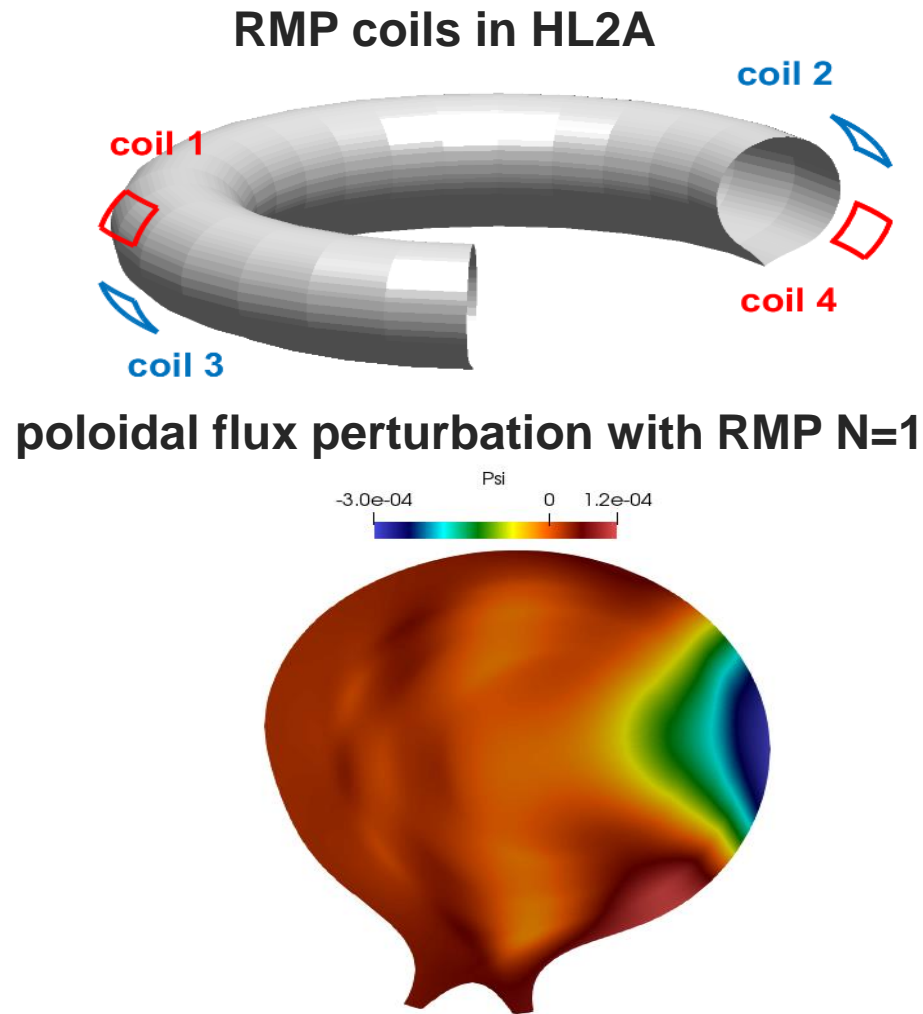


Density in mitigated by RMP ELMs



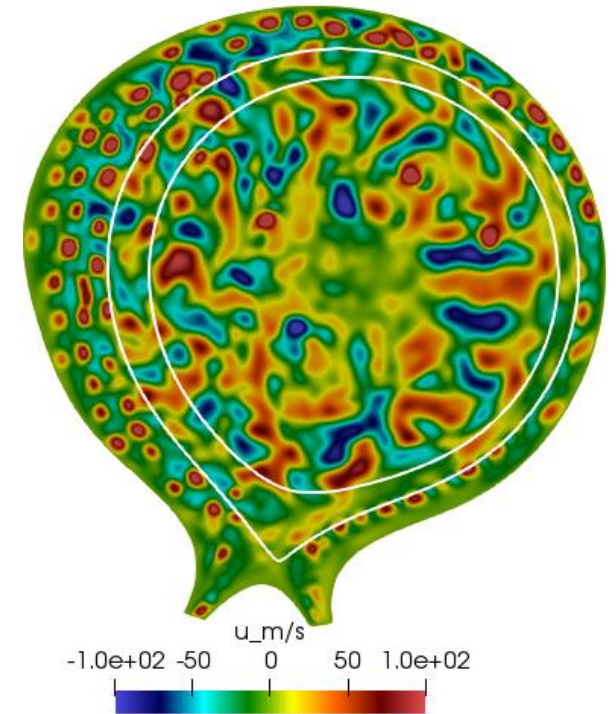
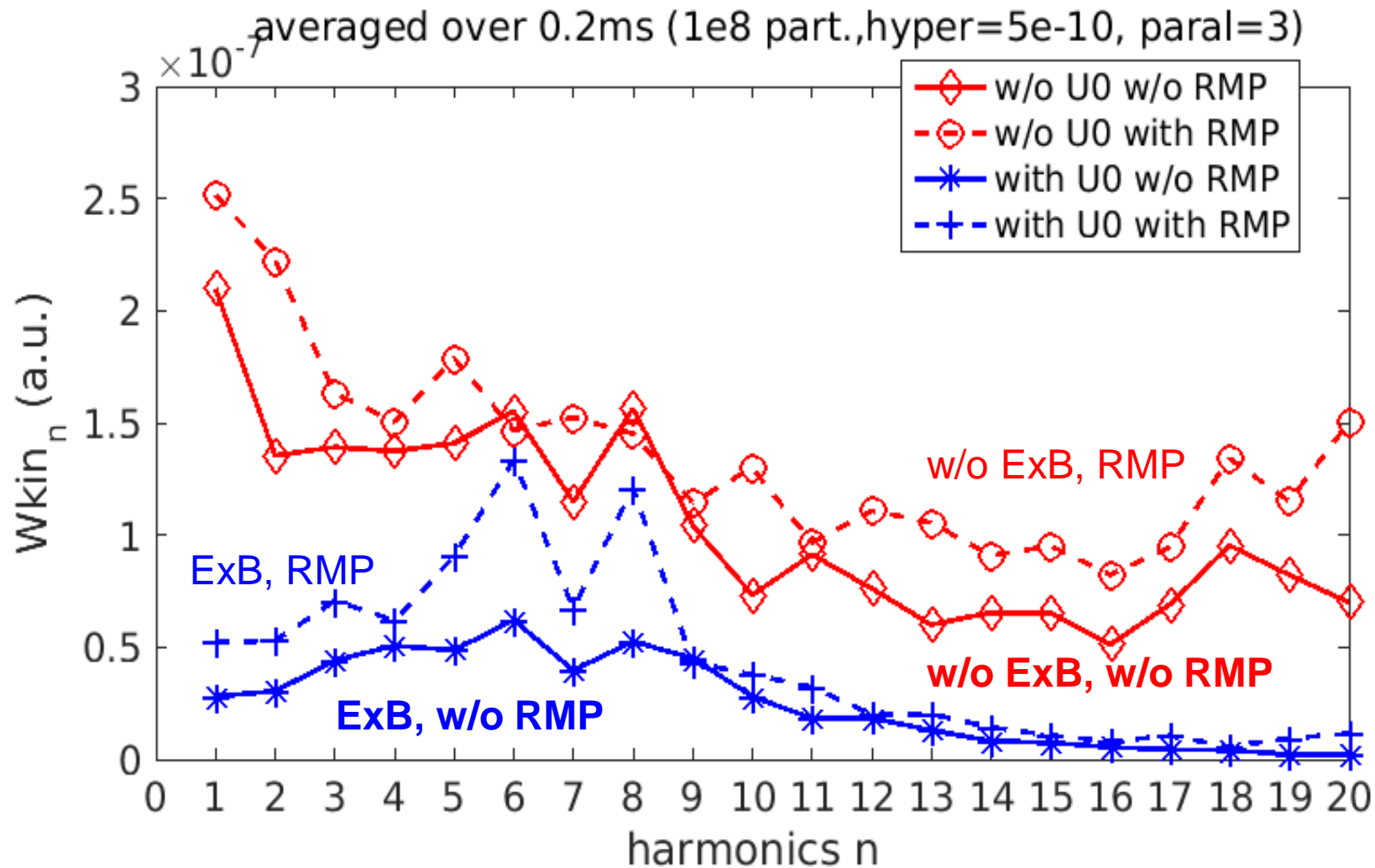
4. RMPs with plasma response in H-mode (HL2A#36872).

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



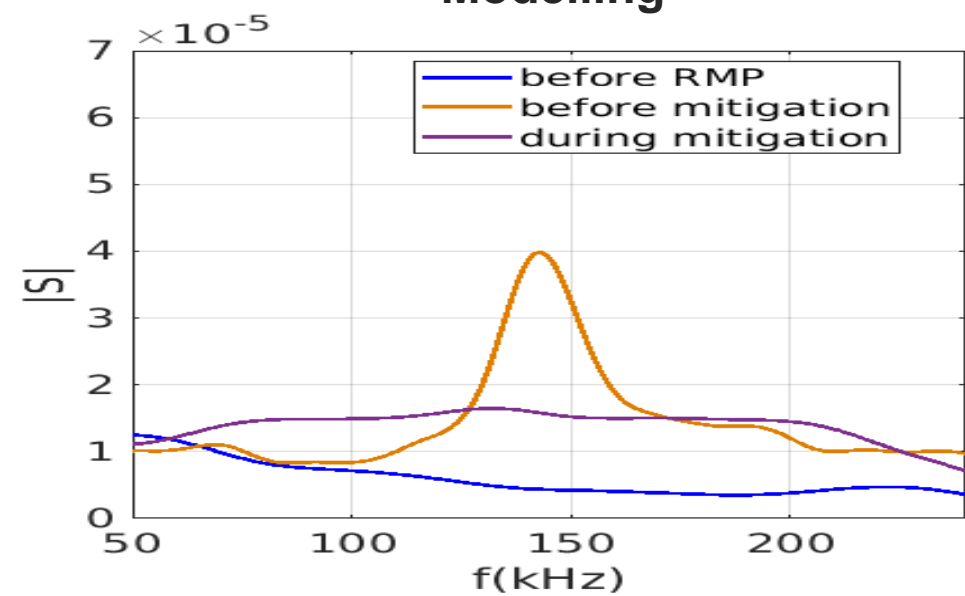
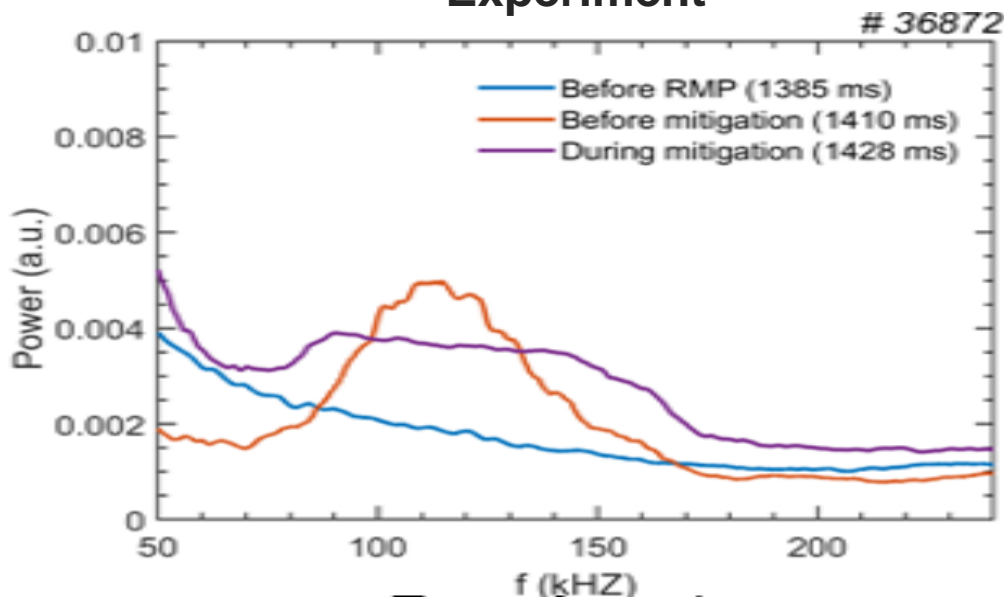
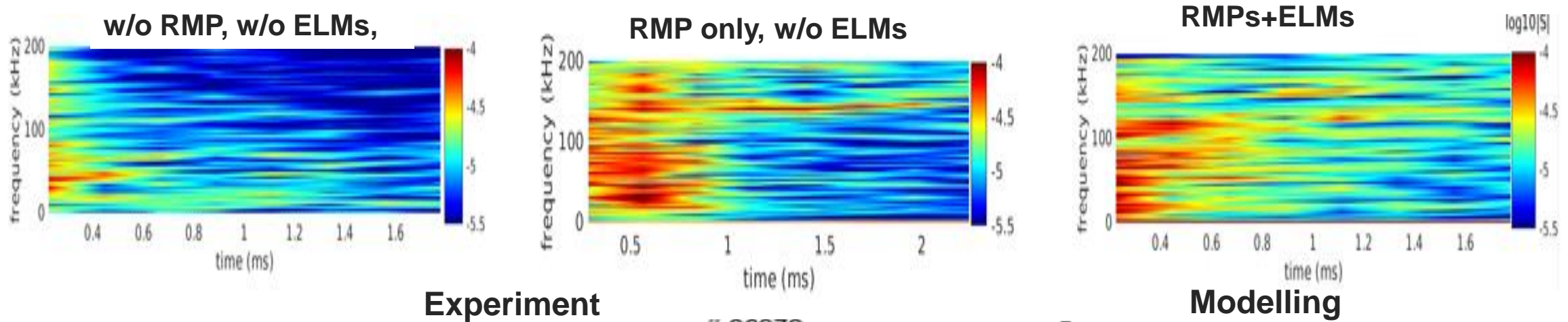
4. ITGs with adiabatic electrons in H-mode (HL2A#36872).

With equilibrium Er field without RMPs ITG are suppressed in the pedestal due to ExB rotation. With RMP ITGs are increased because: 1) ergodic field 2) ExB 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 E_r well (less stabilization by $E \times B$) are dominant factors.



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

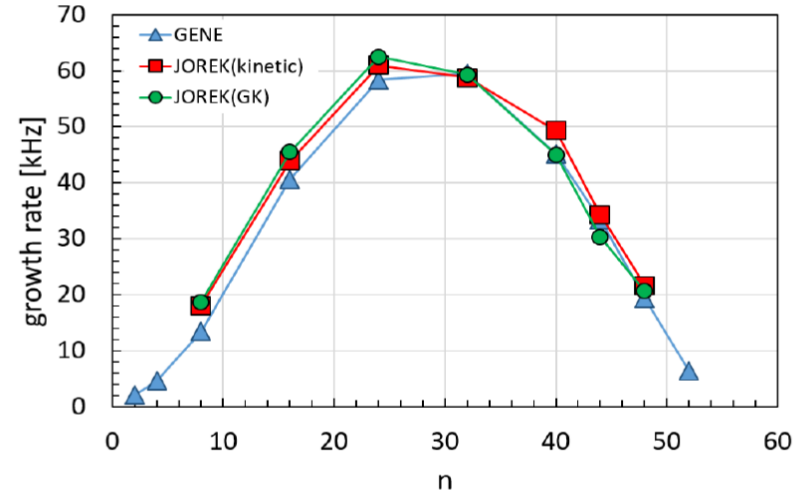


Parallel and ExB motion of gyro-centers in gyro-averaged electric field for ions.

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

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

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



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

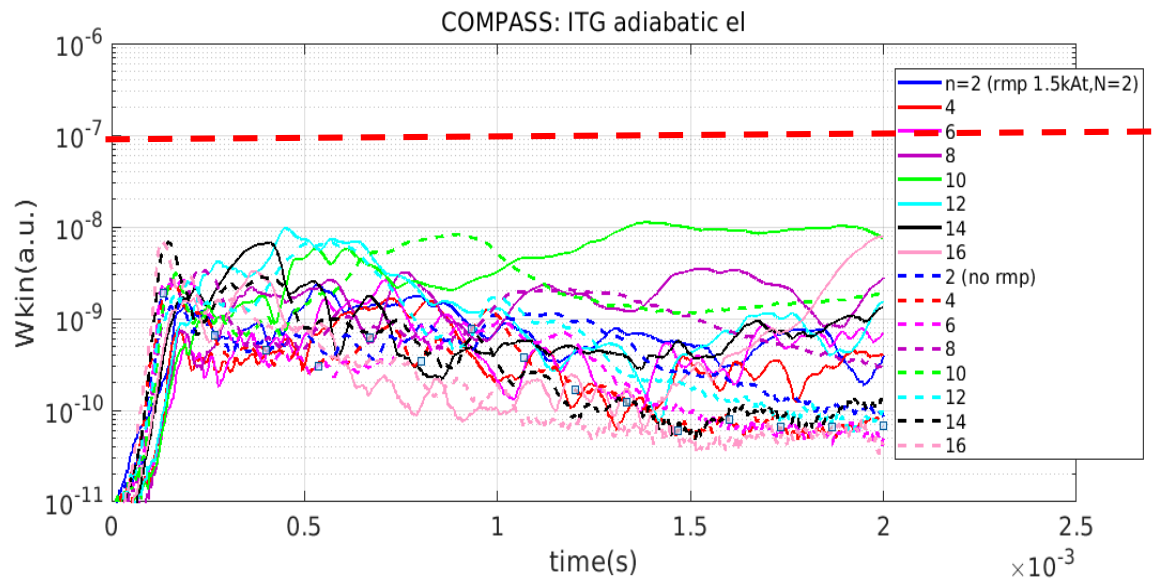
$$\int -\nabla \left(\frac{T_e}{e n_0} v^*(\vec{x}) \right) \cdot \frac{m_i n_0}{q_i B^2} \nabla_{\perp} \phi - v^* \phi dV = \int \frac{T_e}{e n_0} v^*(\vec{x}) \sum_{i=1}^{2N} \frac{q_i}{e} w_i \delta(\vec{x} - \vec{x}_i) dV$$

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

