Interaction of Alfvénic modes and turbulence, investigated in a self-consistent gyrokinetic framework

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In the framework of the EUROfusion projects on
Multi-scale Energetic particle Transport in fusion devices

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Outline

- **1. Introduction and motivation**
- **2. Model and equilibrium**
- **3. ZSs excited by turbulence**
- **4. ZSs excited by Alfvén modes**
- **5. Alfvén modes and turbulence**
- **6. Conclusions and outlook**

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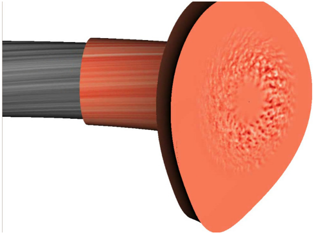
[1] Turbulence in tokamak plasmas

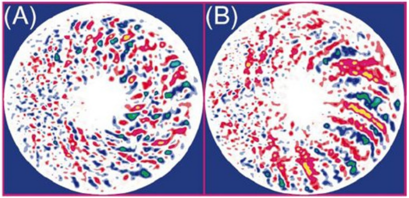
- Radial temperature and density gradients in tokamaks drive various types of microinstabilities.
- Nonlinear effects lead to quasistationary turbulent states, associated with radial transport of particles, momentum, and energy.



- **Turbulence** in tokamak core relatively well understood: gyrokinetic (GK) simulations have made remarkable progress, including collisions, impurities, EM, global, etc (edge still challenging)
- GK model typically used to study either turbulence or energetic-particle (EP) modes
- In this paper: combined effects of EP, turbulence and EP-mode excitation, with focus on the zonal structures.

[1] Zonal structures (ZS)

- **Zonal flows** (ZF) are zonal (i.e. axisymmetric) radial perturbations of the electric field, breaking the turbulence vortices, and consequently modifying the transport.

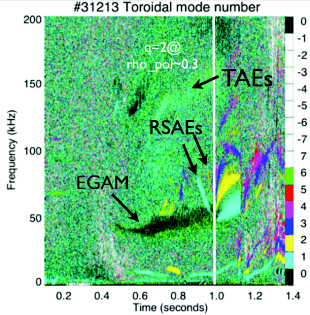


[Lin-98]

- Two types of ZFs are observed: zero-frequency ZFs (ZFZF) [Hasegawa-79, Diamond-05] and **geodesic acoustic modes** (GAM) with characteristic sound frequency $\omega \sim c_s/R$ [Winsor-68, Conway-05, Zonca-08].
- Both ZFZFs and GAMs are excited by turbulence via nonlinear modulational instability
- ZFZFs are mainly damped by collisional damping, whereas GAMs are mainly damped by ion or electron Landau damping

[1] Energetic-particle driven modes

- **Energetic particles** (EP) in the MeV range are present in ignited plasmas, either as fusion products or because they are produced by auxiliary heating / current drive systems.
- Plasma oscillations can exchange energy with the EP population, via (inverse) Landau damping.



[NLED-AUG case, Lauber-14]

- Alfvén Eigenmodes (AE), transverse electromagnetic perturbations which propagate parallel to the equilibrium magnetic field with the characteristic Alfvén velocity [Cheng-85, Chen-16]
- AE can also nonlin. excite ZS [Spong-94, Todo-10, Chen-12, Zhang-13, Qiu-16, Biancalani-16] → possible mediators of EPs and turbulence
- Ultimate goal of the numerical approach: self-consistent nonlinear simulations of global modes (like ZFs), turbulence, and EPs.

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[2] Theoretical models: from fluid to kinetic

The need for a kinetic model

- A kinetic treatment is known to be necessary due to [Chen-16]:

  1) the low frequencies ($\sim \omega_{ti}$), where resonances with bulk ions substantially modify the MHD predictions

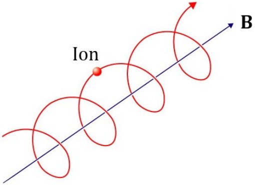
  2) wave-particle interaction responsible for the EP drive / transport

  3) kinetic modific. to wave-wave inter. (especially for $k_\perp \rho_i \sim 1$)

- Simulations show strong electron Landau damping for GAMs in AUG [Novikau-17] → kin. ele. crucial for comparison with experiments.

- The frequency of the modes is much lower than the cyclotron frequency → the gyro-motion can be averaged out

- **Gyrokinetics**: dimension of phase-space reduced, 6D → 5D



[Frieman-82, Littlejohn-83, Hahm-88, Brizard-07]

[2] Theoretical models: the numerical tool

ORB5: global GK particle-in-cell electro-magnetic code [Jolliet-07, Bottino-11, Tronko-18, Lanti-19]

- Gyrocenter trajectories:

$$
\begin{aligned}
\dot{\mathbf{R}} &= \frac{1}{m}\left(p_\parallel - \frac{e}{c}J_0 A_\parallel\right)\frac{\mathbf{B}^*}{B^*_\parallel} + \frac{c}{eB^*_\parallel}\mathbf{b}\times\left[\mu\nabla B + e\nabla J_0\big(\phi - \frac{p_\parallel}{mc}A_\parallel\big)\right] \\
\dot{p}_\parallel &= -\frac{\mathbf{B}^*}{B^*_\parallel}\cdot\left[\mu\nabla B + e\nabla J_0\big(\phi - \frac{p_\parallel}{mc}A_\parallel\big)\right]
\end{aligned}
$$

- GK Poisson equation:

$$-\nabla\cdot\frac{n_0 mc^2}{B^2}\nabla_\perp\phi = \Sigma_{\mathrm{sp}}\, e\int \mathrm{d}W J_0 f$$

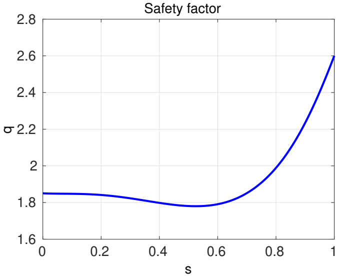
- Ampère equation ($J_0 = 1$ here for simplicity):

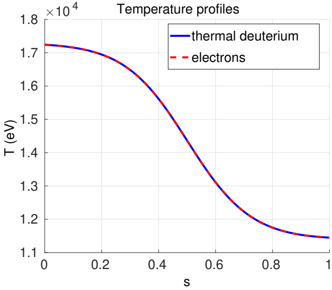
$$\Sigma_{\mathrm{sp}}\int \mathrm{d}W\left(\frac{ep_\parallel}{mc}f - \frac{e^2}{mc^2}A_\parallel f_M\right) + \frac{1}{4\pi}\nabla^2_\perp A_\parallel = 0$$

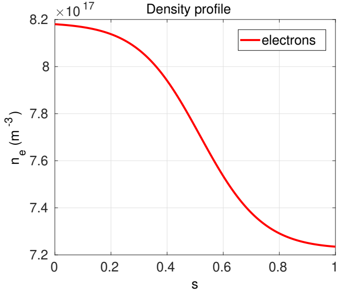
Pull-back scheme strongly mitigates cancellation problem [Mishchenko-19].

[2] Selected case: equilbrium and profiles

- Circular concentric flux surfaces
- High aspect ratio: $\epsilon = 0.1$
- Reversed shear
- Typical temperature of medium size tokamaks: $\rho * = 1/175$
- $\beta = 1 \cdot 10^{-3}$
- On-axis energetic ions with Maxwellian distr. funct.







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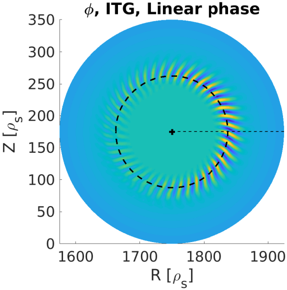
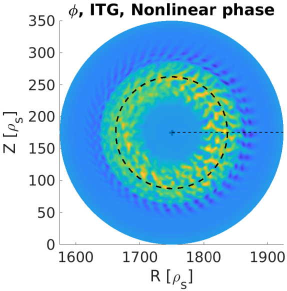
[3] Turbulence characterisation

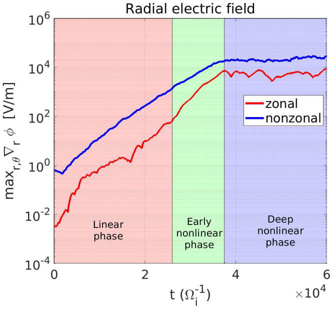
- Electrostatic simulations, adiabatic electrons
- Ion temperature gradient driven turbulence
- No energetic particles here
- Linear growth rate spectrum peaked at n=26, with
  $\omega_{ITG} = 5.7 \cdot 10^{-4}\,\Omega_i = 0.55\,c_s/R$
  $\gamma_{ITG} = 2.5 \cdot 10^{-4}\,\Omega_i = 0.24\,c_s/R$
- Radial structure centered at s=0.5
- Zonal flows developing in the nonlinear phase

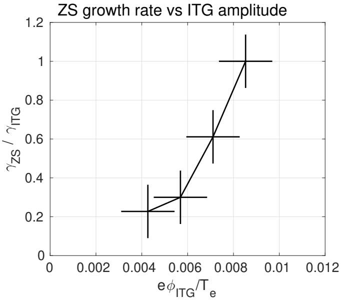




[3] Excitation by modulational instability

- Interaction of ZSs and ITG starts in early nonlinear phase
- Saturated zonal and nonzonal fields comparable with GENE flux tube simulations
- Numerical experiment: restart with additional artificial damping to keep ITG amplitude constant
- ZS growth rate depends on ITG amplitude → **modulational instability** [Chen-00]
- Part of the ZS energy goes into GAM oscillations → Landau damping also acts as sink





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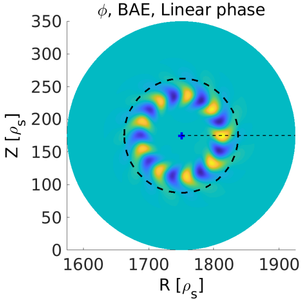
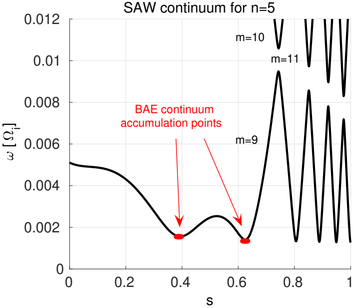
[4] Alfvén mode characterisation

- Electromagnetic simulations (kinetic electrons with $m_i/m_e = 200$)
- EP population with $k_n = 10$, $k_T = 0$, $\langle n_{EP}\rangle/\langle n_e\rangle = 0.01$, $T_{EP}/T_e(0.5) = 10$.
- Dominant mode: **beta-induced AE (BAE)** [Chu-92, Heidbrink-99] with n=5, m=9
- $\omega_{BAE} = 2.4 \cdot 10^{-3}\,\Omega_i = 2.3\, c_s/R$
$\gamma_{BAE} = 0.58 \cdot 10^{-3}\,\Omega_i = 0.56\, c_s/R$
- Radial structure centered at s=0.4, near inner continuum accumulation point

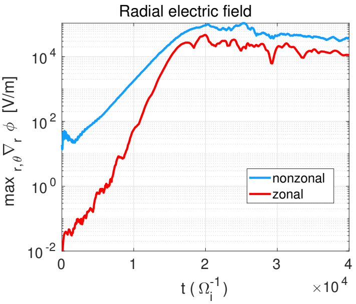


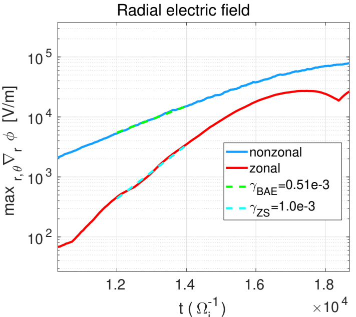


[4] Force-driven excitation (a)

Wave-particle NL + wave-wave NL
(all species follow perturbed orbits)

- BAE with n=5 initialized at t=0
- Toroidal filter allows $0 \leq n \leq 9$
- Nonzonal electric field saturates at $\tilde{E}_{r,max} = 1 \cdot 10^5$ V/m
- Interaction of ZSs and BAEs starts in the early nonlinear phase.
- ZS growth rate found to be twice the BAE growth rate $\rightarrow$ signature of **force-driven excitation** [Qiu-16]



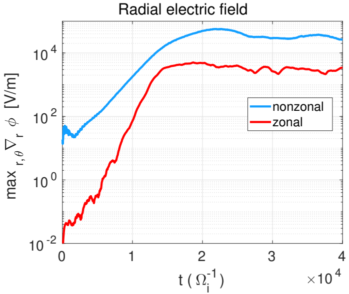


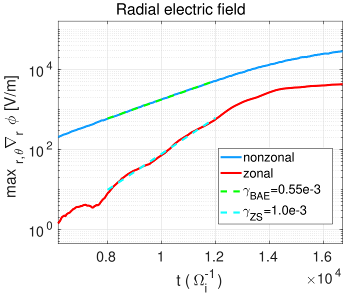
[4] Force-driven excitation (b)

Wave-particle NL only

(thermal species treated linearly)

- Only EP allowed to redistribute in time here
- Toroidal filter allows $0 \leq n \leq 9$
- Different value of BAE saturation: $\tilde{E}_{r,max} = 0.6 \cdot 10^5$ V/m $\rightarrow$ wave-wave coupling important for predicting BAE saturation
- ZS growth rate still found to be twice the BAE growth rate $\rightarrow$ force-driven excitation **mediated by the EPs** via curvature term [Qiu-16]


Radial electric field


Radial electric field

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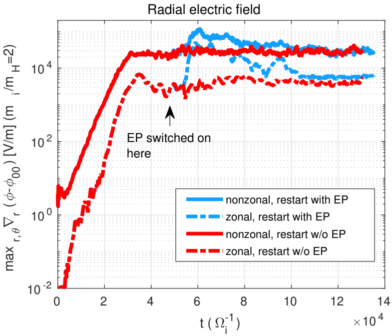
[5] Definition of the numerical experiment

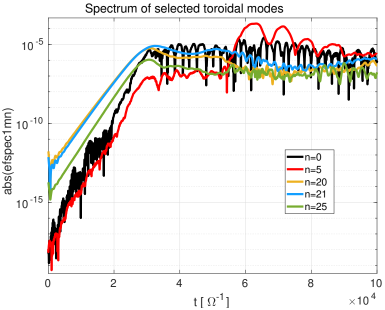
- Zonal electric field excited first by turbulence, then by AMs
- Fully NL electromagnetic simulation: WP-NL + WW-NL (all species follow perturbed orbits)
- Noise initialized at t=0
- Toroidal filter allows $0 \leq n \leq 40$
- EP switched on at $t = 4.9 \cdot 10^4 \, \Omega_i^{-1}$

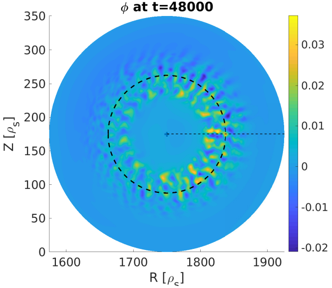


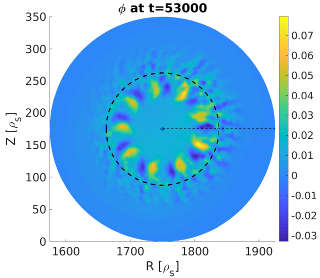
- Krook operator, conserving zonal fields, applied to thermal species: → source restoring thermal profiles, no sources for EPs
- Numerically demanding → 72 hours on 1920 CPUs in Marconi

[5] Coexistence of BAEs, ZSs and turbulence

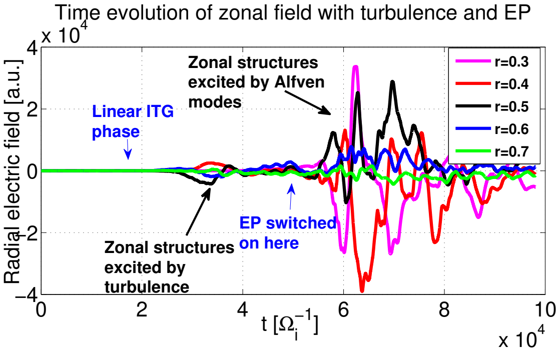
- BAE with n=5, m=9 develops after EP are switched on
- Nonzonal radial electric field grows after EPs are switched on, then saturates at $\tilde{E}_{r,max} = 1 \cdot 10^5$ V/m
- ZS oscillates with GAM frequency







[5] Force-driven excitation efficient in driving ZSs

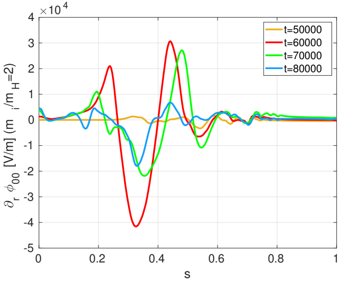


- Zonal structures excited before and after EPs are switched on
- **Zonal electric field excited by force-driven excitation of BAE higher than ZSs excited by turbulence** → 1 order of magnitude higher, for this case with $\langle n_{EP}\rangle/\langle n_e\rangle = 0.01,\ T_{EP}/T_e(0.5) = 10$

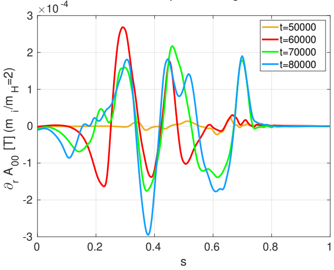
[5] Zonal fields observed with fine radial structures

- Zonal radial electric field observed around the location of the most unstable BAE (s=0.4)
- Zonal poloidal magnetic field also observed to develop
- Fine radial eigenmode structures found
- Location of zonal poloidal magnetic field found near the inner and outer SAW continuum accumulation points → excited by primary and secondary BAEs

Structure of the zonal radial electric field

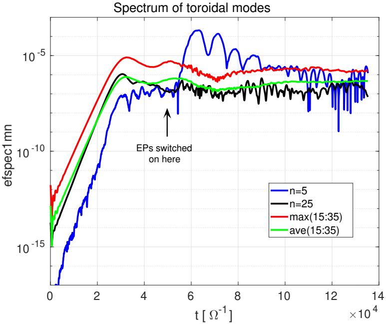


Structure of the zonal poloidal magnetic field



[5] Turbulence stabilization by EPs

- Spectrum of modes with high-toroidal mode number ($15 \leq n \leq 35$) observed to decrease in amplitude when EPs are switched on
- Correlation with increase of modes with low toroidal mode number (BAE, n=5)


Spectrum of toroidal modes

EPs switched on here

- Stabilizing effect of EPs on turbulence. Possible reasons:
  1) Direct modification of the ITG disp. rel. in the presence of EPs
  2) Dilution effect
  3) Electromagnetic effects
  4) Nonlinear interaction of BAEs and ITG modes
  5) Effect of Zonal Structures on turbulence

  → in progress (see also [Di-Siena-19])

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[5] Conclusions and outlook

- Electromagnetic global simulations of Alfvén modes and turbulence performed
- Zonal structures excited via modulational instability by turbulence
- Zonal structures excited by force-driven excitation by BAEs
- Zonal radial electric field force-driven by BAE reaches levels one order of magnitude higher than those excited by turbulence for this case
- Strong wave-wave coupling of BAE and ZS found: important for predictions of saturation levels
- Direct interaction of AM and ITG not efficient in this case: BAE saturation level found to be not sensibly modified by turbulence
- Turbulence stabilization when EPs are switched on → effect of ZS ?

Acknowledgements

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List of contributions within the same projects, at this conference:
N. Carlevaro, et al, *Beam-plasma system as reduced model for energetic particle ITER relevant transport*, P5.1014.
M. V. Falessi, et al, *Hierarchical approach to first principle based reduced transport models*, P2.1074
G. Fogaccia, et al, *Full exploitation of the HYMAGYC code for a shaped cross section scenario*, P1.1092
Z. Qiu, et al, *Gyrokinetic theory of toroidal Alfvén eigenmodes nonlinear saturation*, P1.1039