Gyrokinetic investigation of the nonlinear interplay of Alfvén instabilities and energetic particles in tokamaks

Alessandro Biancalani

@ Max-Planck Institute for Plasma Physics, Germany

with M. Cole, A. Bottino, A. Könies, Ph. Lauber, A. Mishchenko, Z. Qiu, B. Scott, F. Zonca.

in the framework of the:

"Nonlinear Energetic-Particle Dynamics" European Enabling Research Project

IAEA Fusion Energy Conference 2016, Kyoto (TH/4-2).

October 20, 2016

EUROfusion

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

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[1.1] Motivation (a)

- Alfvén Eigenmodes (AE) are oscillations of perpendicular magnetic field, [Cheng-AnPh-85, Chen-RMP-16], important for interaction with energetic particle (EP) population.
- EP population is consequently redistributed in phase space if wave-particle nonlinearity is effective
  $\rightarrow$ plasma heating is less effective and EP losses occur.
- A kinetic treatment is known to be necessary due to:

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

  2) the wave-particle interaction responsible for the EP drive.

  3) kinetic modific. to wave-wave inter. (expecially for $k_\perp \rho_i <\sim 1$)
- Dynamics slower than gyrofrequencies $\rightarrow$ GK ordering valid.

[1.1] Motivation (b)

- EP redistribution depends on AE saturation levels.
- Several saturation mechanisms should be investigated theoretically and compared with experiments:
  ↪ wave-particle trapping
  ↪ EP radial redistribution
  ↪ resonance overlapping
  ↪ mode-mode coupling
- Global GK theoretical investigation needed, taking into account all these nonlinear effects on the same footing.
  ↪ The strategy is to implement in the code ORB5 an intrinsically selfconsistent nonlinear electromagnetic model (NEMORB project).
  ↪ treatment valid for investigating EP dynamics embedded in self-consistent background turbulence
- Comparisons with other GK codes, like EUTERPE [Kornilov-PoP-04, Cole-PPCF-15] important for benchmark purposes.

[1.2] ORB5 model equations

- Gyrocenter trajectories: [Jolliet-Comput.Phys-07, Bottino-PPCF-11]

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

$$\dot{p}_\parallel = -\frac{\mathbf{B}^*}{B^*_\parallel}\cdot\left[\mu\nabla B + e\nabla J_0\left(\phi - \frac{p_\parallel}{mc}A_\parallel\right)\right]$$

- GK Poisson equation:

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

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

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

- Cancellation problem in Ampère eq. fixed via control-variate scheme ([HatzkyJCP07]'s scheme implemented, pull-back [MishchenkoPoP14] in progr.)

[1.2] The discretization

• Construct a set of discrete electromagnetic gyrokinetic equations, suited for PIC simulations if

1) preserve symmetries: conserve energy, momentum [Scott-PoP-10]

2) contain (only) relevant physics: approximations are needed, but must not break self-consistency.

Tool: Gyrokinetic field theory.

Our model:

• Establish a GK Lagrangian.
• Discretise the Lagrangian.
• Construct discrete equations from the discrete Lagrangian.
• The resulting discrete Vlasov-Maxwell equations will keep the nice symmetry properties of the discrete Lagrangian.

[Bottino-JPP-15]

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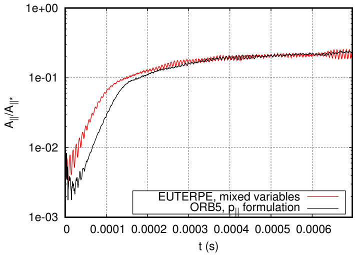
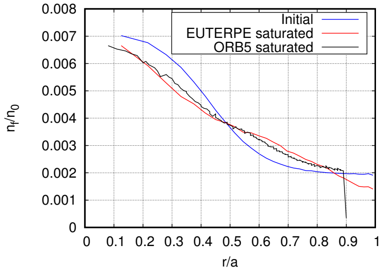
[2.1] Comparison of GK codes shows good agreement

- Toroidicity-induced Alfvén Eigenmode of ITPA benchmark
- Wave-particle nonlin. retained.
- Good agreement of ORB5 and EUTERPE on saturation levels.
- Good agreement of ORB5 and EUTERPE on EP saturated profile.
- Nonlinear structure modific. observed (due to EP redistrib. in phase-space).

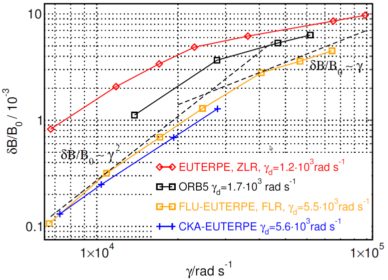
[Cole-PoP-16, Biancalani-PPCF-16]

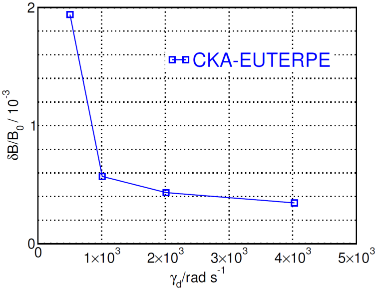




[2.2] Hybrid codes need tuning of damping rate

- Saturation due to wave-particle nonlinearity depends on drive.
- Fully GK and hybrid MHD-GK codes compared.
- Transition from weakly driven TAE to strongly driven EPM recovered with all models (see also Briguglio-PoP-14, Chen-RMP-16, Wang TH/P4-19)
- Part of the difference due to equilibrium loading
- Electron Landau damping determines the saturation level → tuning of γ_d necessary for hybrid codes [Cole-PoP-16]
  ↪ kinetic electrons required for selfconsistent simulations





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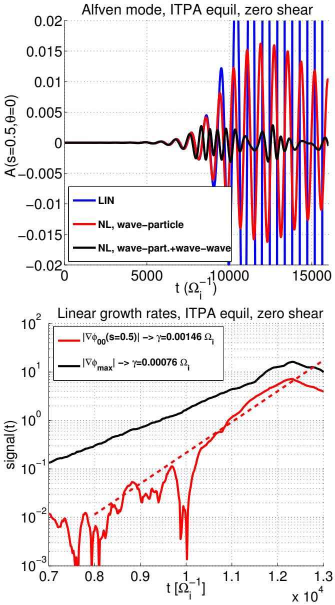
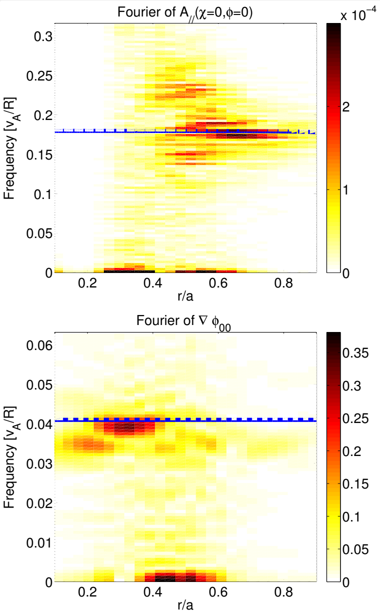
[3.1] Alfvén mode saturation due to zonal structure

- Modes with n=6 and n=0, ITPA case, rev-shear prof.
- Wave-particle and wave-wave nonlinearities.
- Alfvén modes saturate earlier if ZS is excited (like in global hybrid codes [Todo-NuFu-10, Zhang-PST-13], and local GK codes [Bass-PoP-10]).
- Ratio of linear growth rates agrees with anal. prediction $\gamma_{ZF} = 2\gamma_{AE}$
  $\hookrightarrow$ force-driven excitation [Qiu TH/P4-21].



[3.1] Geod. acoustic mode and zonal flow detected

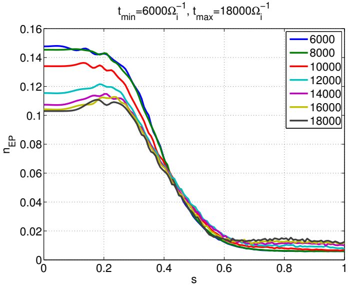
- Fourier transform in time of $A_{\parallel}(s,\chi=0)$ shows m=11 EPM, and a zero frequency signal.
- $\rightarrow$ nonlinear modifications create some noise in Fourier signal of $A_{\parallel}$.
- Fourier transform in time of $E_r(s)$ shows Geodesic Acoustic Mode (GAM) and Zonal Flow.
- $\rightarrow$ kinetic electron effects important for GAM dynamics.

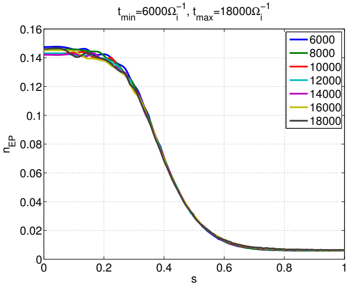


[3.2] No EP relaxation when zonal structure is excited

- EP radial redistribution strong for saturation due to wave-particle nonlinearity (large-T_{EP} case)
- EP radial redistribution absent when zonal structure is excited
- NL coupling with GAM $\rightarrow$ stronger damping than Alfvén mode (q=1.78).
- $\Rightarrow$ EPM satur. amplitude one order of magnitude lower than with one with only wave-part. NL.

(Main limitations here: 1) only 3-waves coupling; 2) zero shear.)





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[4] Conclusions and next steps

- Global electromagnetic GK PIC codes ORB5 and EUTERPE offer now capability of investigating selfconsistently NL Alfvén dynamics
- Bulk ions, electrons and energ. ions treated fully gyrokinetically
- The GK codes agree on wave-particle NL saturation levels (determined by electron Landau damping)
- MHD-GK hybrid codes need tuning of damping rate
- Zonal structures (GAMs and ZFs) are force-driven by Alfvén mode (electron compressibility and kin. electron effects must be retained)
- No EP redistribution found when AE saturates due to coupling to zonal struct (2 modes only, for ITPA equil. with zero-shear profile)
- Ready for global modes with energetic particles and turbulence

THANK YOU FOR YOUR ATTENTION.