WP 3.6 - Fully GK simulations for verification and validation with the PIC code ORB5

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Motivation: from fluid to kinetic

The need for a kinetic model for EP transport studies

- 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

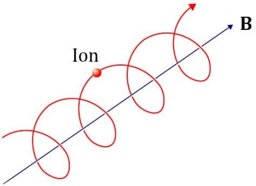
  3) kinetic modific. to wave-wave inter. (especially for $k_\perp \rho_i \sim 1$)

- Electron Landau damping important in AUG [Novikau-17, Vannini-20] $\rightarrow$ kin. ele. crucial for comparison with experiments

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

- **Gyrokinetics**: dimension of phase-space reduced, 6D $\rightarrow$ 5D

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



The gyrokinetic code ORB5

ORB5: global GK particle-in-cell electro-magnetic code [Lanti-19]

- Gyrocenter trajectories:

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

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

- GK Poisson equation:

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

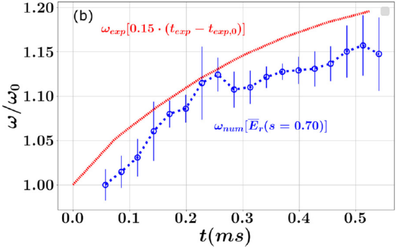
- Ampère equation ($J_0 = 1$ here for simplicity):

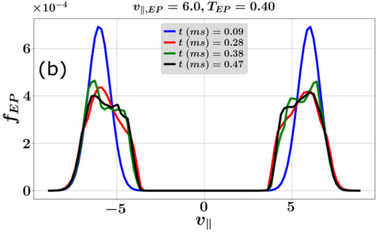
$$\Sigma_{\rm sp}\int \mathrm{d}W\left(\frac{ep_\parallel}{mc}f - \frac{e^2}{mc^2}A_\parallel f_M\right) + \frac{1}{4\pi}\nabla^2_\perp A_\parallel = 0$$

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

EGAMs in AUG, fully nonlinear

- Experimental magnetic equil. (NLED-AUG case)
- GK ions, DK ele., and GK EPs, with EPs modelled with bump-on-tail
- Fully NL sims of mode with $n = 0$
- Despite approximations, relative EGAM frequency chirping analog to experiment
- Redistribution of EP in velocity space studied (see also talk by N. Carlevaro for results of ORB5 in simplified configurations)
- Next step: comparison with reduced models with and w/o turbulence

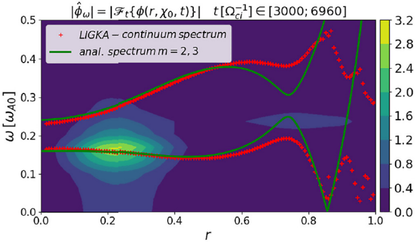




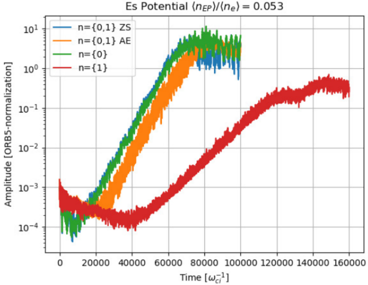
[Novikau-20]

EPM/TAE in AUG, with wave-EP nonlinearity

- Experimental magnetic equil. (NLED-AUG case)
- GK ions, DK ele., and GK EPs, with EPs modelled with maxwellian and bump-on-tail
- EPM and TAE identified with $n = 1$ (see also [Vlad-21])
- Nonlinear simulations show pumping of AM by EGAM at low EP concentrations.
- Next step 1: investigation of EP redistribution for sim with $n = 1$, with and $n = 0, 1$



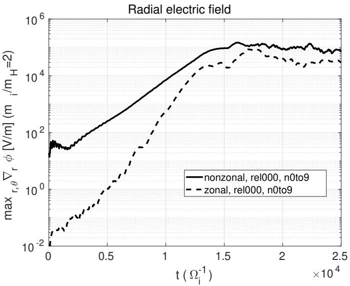
[Vannini-20]

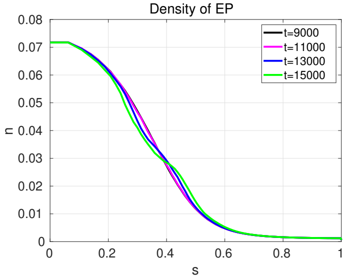


[Vannini-21]

BAE and zonal structures, fully nonlinear

- Simplified magnetic equilibrium: circular flux surfaces, $\epsilon = 0.1$
- Fully nonlinear simulation of modes with $0 \leq n \leq 9$.
- BAE Saturation due to EP redistribution and ZS excitation
- Redistribution of thermal species (especially electrons) also crucial for nonlinear dynamics [Biancalani-20]
- Zonal structures excited by forced-driven excitation [Spong-94, Todo-10, Chen-12, Zhang-13, Qiu-16]

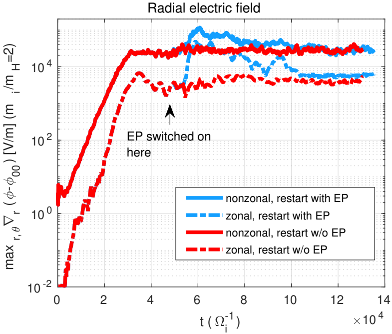




BAE, turbulence and zonal structures (fully NL)

- 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 $t = 4.9 \cdot 10^4 \, \Omega_i^{-1}$



[Biancalani-21]

- Krook operator, conserving zonal fields, applied to thermal species:
  $\rightarrow$ source restoring thermal profiles, no sources for EPs
- Next step: EP redistribution in the presence of turbulence

Summary - state of the art

- Gyrokinetic model needed for comparison of NL dynamics of EP-driven instabilities and experiments, especially at low frequencies
- GK PIC code ORB5 verified and benchmarked for EGAMs and AMs in the absence of turbulence
- ORB5 validation in progress for AUG experimental data
- ORB5 also applied to DIIID [Taimourzadeh-19] and ITER [Hayward-Schneider-21] for AM studies
- Electromagnetic global simulations of Alfvén modes (BAEs) and turbulence also performed in simplified configurations at low beta [Biancalani-21] and higher beta [Mishchenko-21]

Outlook: GK simulations and reduced models

Goal: get data from NL ORB5 sims to help writing reduced models

- Simplified configurations (circular equilibria, friendly profiles) help the comparison with analytical theory and reduced models, which should then be validated in more experimental configurations.
- Nonlinear interaction of EPs and EGAMs/AMs can be studied with phase space diagnostics $\rightarrow$ derive simplified analytical models where only the region near the resonances are considered
- GK sims can investigate the regimes where the effect of turbulence on the EP dynamics is important $\rightarrow$ combine resonant and non-resonant EP dynamics in reduced models
- Long time behavior: the measurement of phase space zonal structure in ORB5 (in analogy with what done in HMGC and HYMAGIC) can help comparing predictions of reduced models with results GK turbulence simulations