Progress in AE and EGAM simulations for the NLED-AUG case

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MET Project Mid-Term Workshop
March 25th 2020

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

Outline

1. Gyrokinetic code ORB5.

2. Experimental profiles from the **NLED-AUG case**:
   - Study of the damping mechanisms in linear simulations.
     - Only $n = 1$
     - Linear simulations
     - All species have Maxwellian distribution functions.
   - Study of the interaction between Egams and Alfvén waves.
     - $n = 0, 1$
     - Nonlinear simulations.
     - EPs have two bumps-on-tail distribution function.

3. Implementation of Slowing down distribution function in ORB5 and initial tests.

ORB5

- **ORB5**[1] is a global, nonliner, gyrokinetic, electromagnetic, PIC code which can take into account collisions and sources.
- The Vlasov-Maxwell gyrokinetic equations are derived through variational principles from a gyrokinetic Lagrangian. Field equations are derived via functional derivatives.
- The distribution function is discretized through numerical particles (markers). The fields are discretized through cubic B-splines.
- The gyrokinetic model of ORB5 contains the reduced MHD as subset[2].

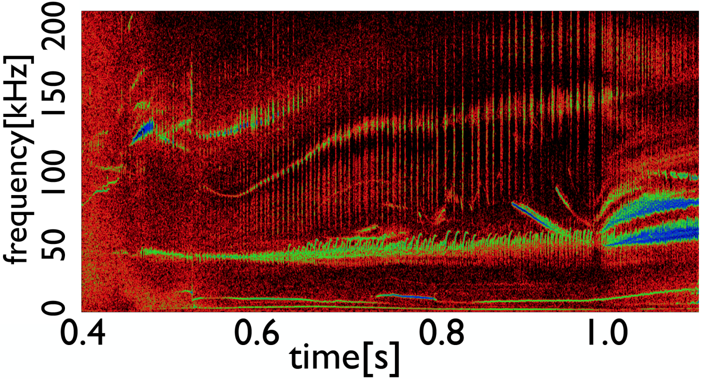
[1] E. Lanti et al. "Orb5: A global electromagnetic gyrokinetic code using the PIC approach in toroidal geometry". In: *Computer Physics Communications* (2019).

[2] Naoaki Miyato et al. "A Modification of the Guiding-Centre Fundamental 1-Form with Strong ExB Flow". In: *Journal of the Physical Society of Japan* (2009).

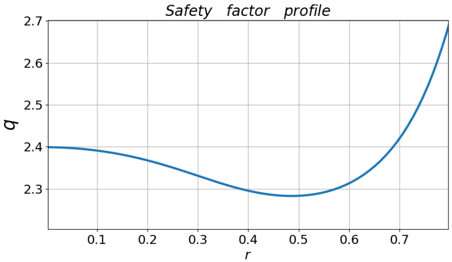
NLED-AUG case

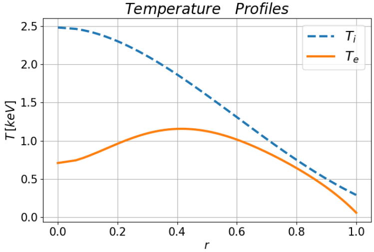
- The shot number $\#31213$ of ASDEX-Upgrade (**AUG**) has been selected within the Non-Linear Energetic-particle Dynamics (**NLED**) Eurofusion enabling research project.

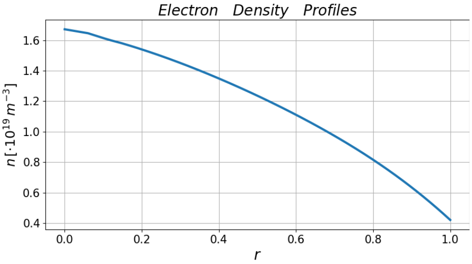
- Here an early off-axis NBI (Injection energy$\sim 93\,keV$)



Equilibrium







- Density profiles involved satisfy quasi-neutrality condition.
- EPs when considered have flat temperature profile.

Study of the damping

- Linear simulations and nonlinear simulations, $n = 1$.
- Equilibrium distribution function for all the species: **Maxwellian**
- Different shape for the EPs density involved:

[3] F. Vannini et al. "Gyrokinetic Investigation of the damping channels of Alfvén modes in ASDEX Upgrade". In: *Physics of Plasmas* (2020, accepted).

Study of the damping

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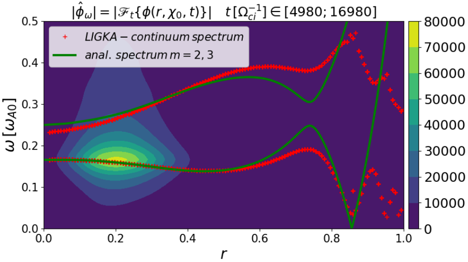
1. Off-axis profile



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Study of the damping

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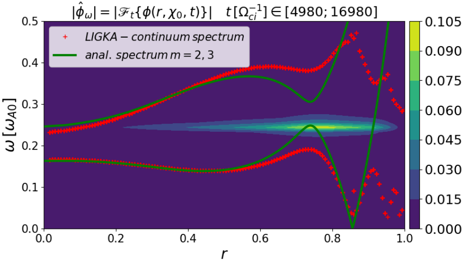
2. On-axis profile



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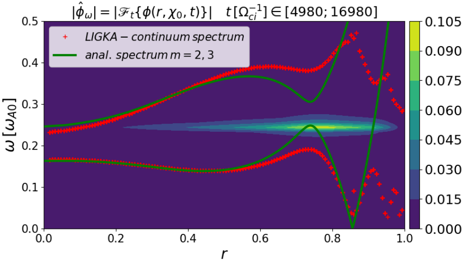

- Electron Landau damping dominant for a TAE in this regime[3].

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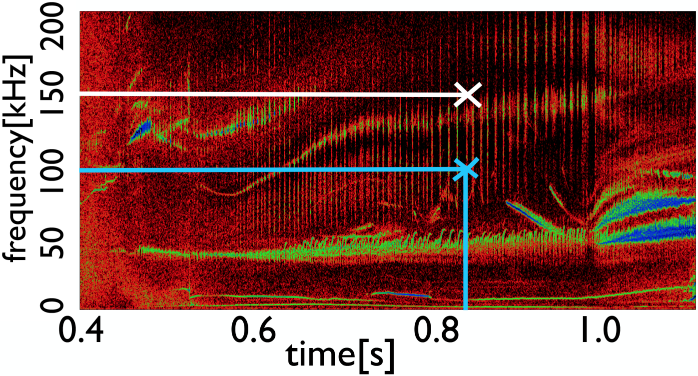
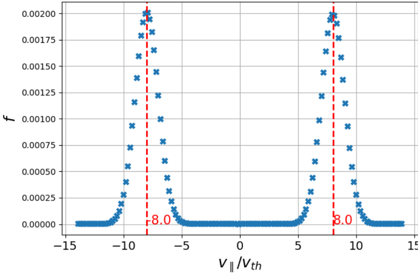


Two Bumps-on-tail

$$f_j = \frac{n_j(\psi)}{(2\pi v_{th,j}^2\, tval_j)^{3/2}} e^{\frac{-\epsilon\, m_j}{tval_j}} e^{-\frac{vpar_j^2}{2\, tval_j}} cosh(u_\parallel \frac{vpar_j}{tval_j}) \tag{1}$$

1. $tval = 1$
2. $vpar = 8$



- Keeping only $n = 0$, EGAMS have been studied with ORB5 in[4].

[4] Ivan Novikau et al. "Implementation of energy transfer technique in ORB5 to study collisionless wave-particle interactions in phase-space". In: *Computer Physics Communications* (2019 accepted).

Interaction Egams and Alfvén waves

- Retained both $n = 0, 1$.
- Nonlinear simulations.
- Two bumps-on-tail distribution function for the EPs.

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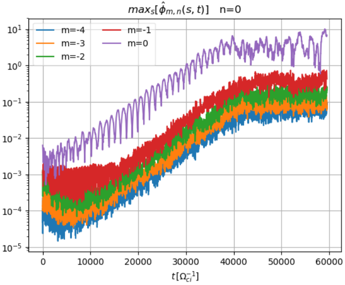

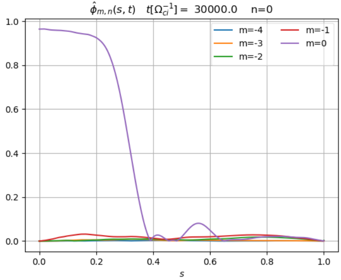

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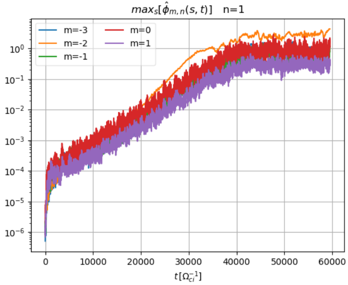

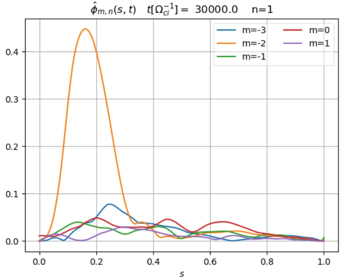

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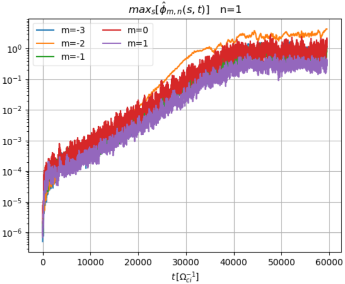
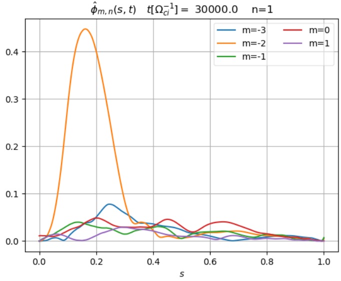




$$f = \phi e^{-\gamma t} \quad f_1 = \mathscr{F}(f/max_r(f)) \quad f_2 = f_1/max_r(f_1)$$

Frequency Spectra

n=1 m=-2

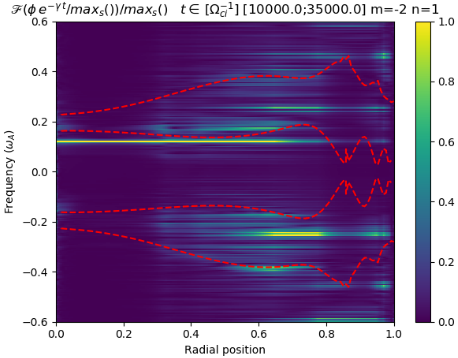


Figure: Linear phase

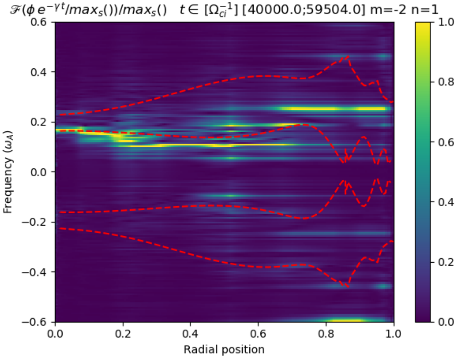


Figure: Nonlinear Phase

Frequency Spectra

n=1 m=-3

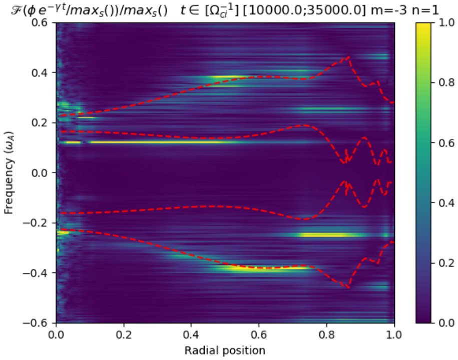


Figure: Linear phase

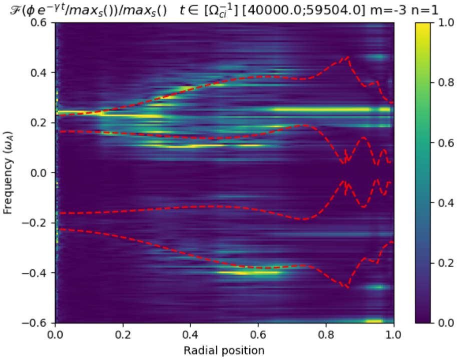
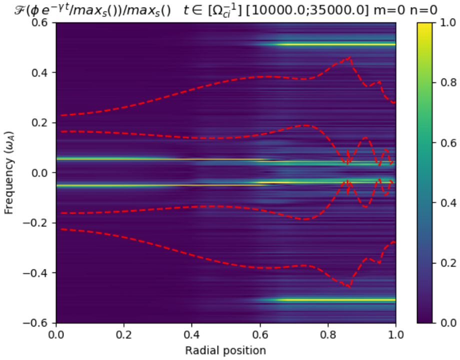


Figure: Nonlinear Phase

Frequency Spectra

n=0 m=0



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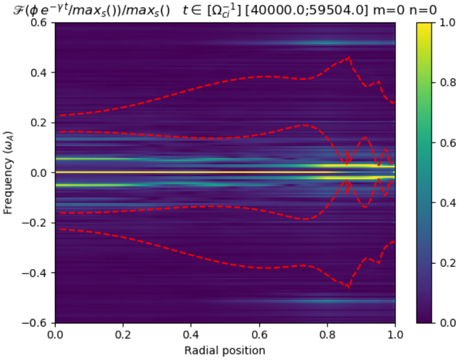


Figure: Nonlinear Phase

Slowing down distribution function

- Solution of the Fokker-Planck equation in high-speed limit for an isotropic source.

$$f_j = \frac{n_j(\psi)}{\frac{4\pi}{3}} \frac{\theta(v_\alpha - v)}{log\left[1 + (\frac{v_\alpha}{v_c})^3\right](v_c^3 + v^3)}$$

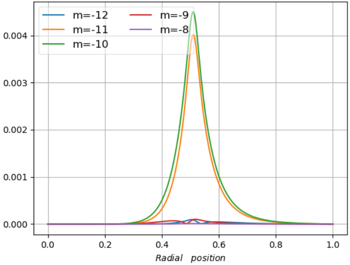
- v_c is the speed above which the electron drag dominates over the ion drag.

$$v_c = v_{th,e}\left(\frac{3\sqrt{\pi}}{4}\frac{m_e}{n_e}\sum_j \frac{n_j z_j^2}{m_j}\right)^{\frac{1}{3}}$$

Slowing down distribution function

- Initial tests considering magnetic equilibrium and profiles taken from the ITPA-TAE international benchmark case[5]:

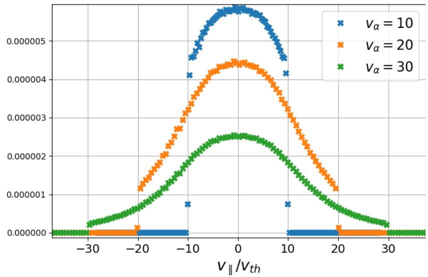
- Flat densities and temperature profiles, $\epsilon = 0.1$.
- $a = 1\,m,\ R_0 = 10\,m,\ B_0 = 3\,T$
- $q = 1.71 + 0.16 \cdot (r/a)^2$
- With Maxwellian, most unstable mode $n = 6,\ m = -10, -11$

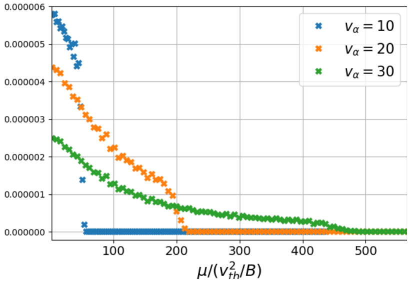


[5] A. Könies et al. “Benchmark of gyrokinetic, kinetic MHD and gyrofluid codes for the linear calculation of fast particle driven TAE dynamics”. In: *Nuclear Fusion* (Oct. 2018), p. 126027.

Slowing down distribution function

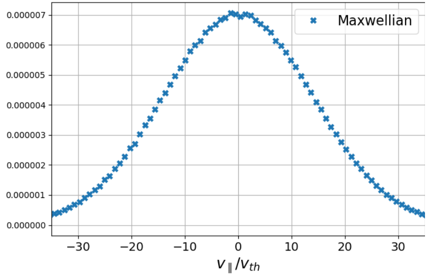
$$f_j = \frac{n_j(\psi)}{\frac{4\pi}{3}} \frac{\theta(v_\alpha - v)}{log\left[1 + (\frac{v_\alpha}{v_c})^3\right](v_c^3 + v^3)} \qquad v_c = v_{th,e}\left(\frac{3\sqrt{\pi}}{4}\frac{m_e}{n_e}\sum_j \frac{n_j z_j^2}{m_j}\right)^{\frac{1}{3}} \tag{2}$$





Slowing down distribution function

ITPA-TAE benchmark case



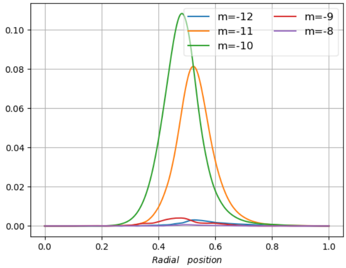


Figure: $f(v_\parallel, \mu = 0)$

$r = 0.5$	$\gamma\ [\omega_{A0}]$	$\omega\ [\omega_{A0}]$
Maxwellian	0.0317	-0.285

Slowing down distribution function

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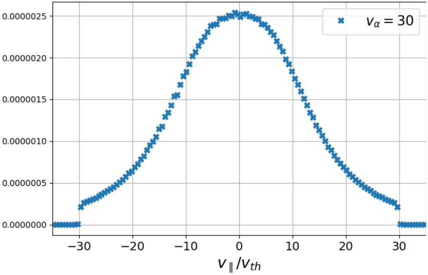

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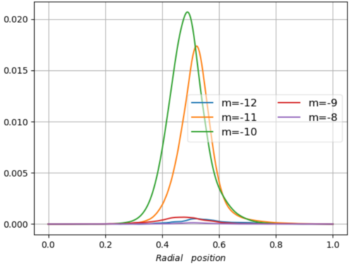

Figure: Mode structure

$r = 0.5$	$\gamma\ [\omega_{A0}]$	$\omega\ [\omega_{A0}]$
Maxwellian	0.0317	-0.285
$v_\alpha = 30\, v_{th,EP}$	0.0156	-0.276

Conclusions

- Alfvén modes in **AUG** investigated for the first time with **ORB5** with experimental magnetic equilibrium and experimental profiles.
- Study of the damping mechanisms affecting Alfvén waves ([Vannini-2020], accepted in Physics of Plasmas).
- Study of the interaction between Egams and Alfvén waves (collaboration I. Novikau).
- Slowing down distribution function implemented in ORB5. Initial test started.

Next Steps:

- Benchmark with HYMAGYC and MEGA (see talk of G. Vlad)
- Comparison with GFLDR (general fishbone-like dispersion relation).