Nonlinear dynamics of zonal structures with ORB5 in the framework of the OrbZONE project

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based on material from
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A. Biancalani, et al, Plasma Phys. Control. Fusion 63, 065009 (2021)

obtained in the framework of the Eurofusion projects on:
- NL energetic particle dynamics (F. Zonca)
- NL interaction of Alfvénic and turb. fluctuations in burning plasmas (P. Lauber)
- Multi-scale energetic particle transport in fusion devices (F. Zonca)

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Outline

- **1. Introduction and motivation**
- **2. Model**
- **3. Problem A: EP redistribution by EGAMs**
- **4. Problem B: Zonal structures, AMs and turbulence**
- **5. Conclusions**

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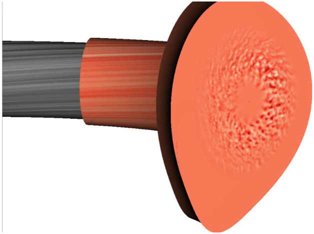
[1] Turbulence in tokamak plasmas

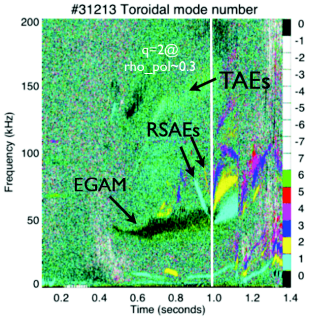
- Radial temperature and density gradients in tokamaks drive microinstabilities.
- Nonlinear coupling leads to **turbulence** states, in the presence of **zonal flows** (ZFs) [Hasegawa-79].
- Turbulence carries heat fluxes, modifying the equilibrium temperature profiles → bad for confinement



- 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 in the past to study either turbulence or global instabilities separately, due to technological limits

[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 Modes** (AM), transverse global electromagnetic perturbations excited by EPs [Cheng-85, Chen-16]
- **EP-driven Geodesic Acoustic Modes** (EGAMs) are electrostatic oscillating zonal flows excited by EPs [Fu-08, Qiu-10]
- Ultimate goal of the numerical approach: self-consistent simulations of global modes (like AMs, ZFs), turbulence, and EPs.

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[2] Theoretical models: from fluid to kinetic

The need for a kinetic model

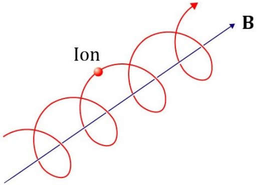
- A kinetic treatment is known to be necessary due to [Chen-16]:

  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 $k_\perp \rho_i \sim 1$)

- 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]

- Numerical simulations numerically demanding in comparison to fluid models or hybrid fluid-kinetic models $\rightarrow$ need for smart numerical schemes and parallelization to simulate experimental configurations

[2] Theoretical models: the numerical tool

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

- Gyrocenter trajectories:

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

- 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):

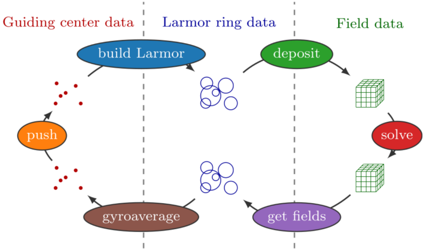
$$\Sigma_{\mathrm{sp}}\int \mathrm{d}W\left(\frac{ep_\parallel}{mc}f - \frac{e^2}{mc^2}A_\parallel f_M\right) + \frac{1}{4\pi}\nabla_\perp^2 A_\parallel = 0$$

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

[2] ORB5 enabled for GPUs (a)

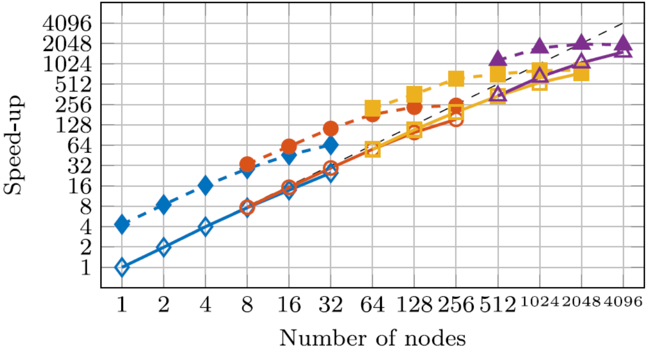
- ORB5 enabled for GPUs in 2019 [Ohana-CPC-21]. Other GPU-enabled GK codes include GENE, GTC, CGYRO and XGC...
- Tests succesfull on Piz Daint and Summit [Ohana-CPC-21]. Now ported to M100 [Hayward-Schneider-IFERC-workshop-20].
- Originally pure MPI based on domain decomposition (efficient in toroidal direction in axysymmetric geometries) and domain cloning, now uses hybrid MPI/OpenMP and MPI/OpenACC.

- All the computations involving the markers now offloaded to the GPUs
- Communication between GPU and CPU minimized by keeping marker data on GPU only



[2] ORB5 enabled for GPUs (b)

- ORB5 shows very good scaling of EM simulations on Summit up to 4096 nodes



[Ohana-CPC-21]

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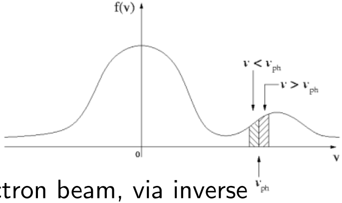
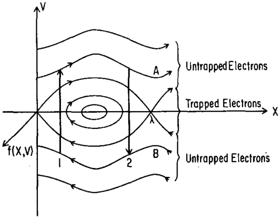
Interaction with the EP: the beam-plasma paradigm

- Langmuir waves: longitudinal perturbations of the electron pressure, with the characteristic plasma frequency $\omega_p = \sqrt{4\pi n e^2/m_e}$
- They are affected by Landau damping:

$$\gamma_L = \frac{\pi}{2}\frac{\omega_p^3}{k^2}\frac{\partial f_0}{\partial v}\Big|_{\omega/k} \qquad (1)$$



- They can be driven unstable by an electron beam, via inverse Landau damping, if $v_{ph} = \omega/k$ falls where $\partial f_0/\partial v > 0$ [O'Neil-65]
- Due to the nonlinear wave-particle interaction, the passing electrons (with $v > v_{ph}$) can lose energy, become trapped in the potential well created by the wave, and stop exchanging energy with the mode



[3] EP redistribution by EGAMs: saturation (a)

EGAMs studied extensively in the past [Nazikian-08, Fu-08, Qiu-10, Zarzoso-12, Wang-13, Miki-15, Horvath-16, Sasaki-17, Novikau-20].

COMPARISON WITH BEAM-PLASMA INSTABILITY
EP squared bounce frequency proportional to radial electric field [Qiu-PST-11]:

$$\omega_b^2 = \alpha_1 \, \delta \bar{E}_r \, , \quad \text{with } \alpha_1 \equiv \frac{e \hat{V}_{dc}}{2 m_{EP} v_{\parallel 0} q R_0} \tag{2}$$

and $\delta \bar{E}_r = \alpha_2 \gamma_L^2$ found in ORB5 simulations. We obtain, like for the beam-plasma instability:

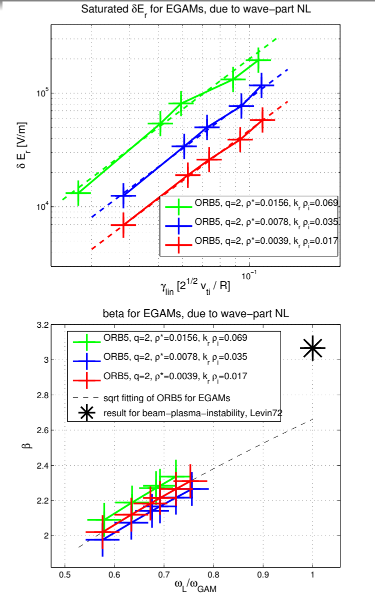
$$\omega_b = \beta \, \gamma_L \tag{3}$$

where β is calculated as $\beta = (\alpha_1 \alpha_2)^{1/2} / \omega_s$, which yields:

$$\beta = \beta_0 \left(\frac{\omega_L}{\omega_{GAM}} \right)^{1/2}, \quad \text{with} \quad \beta_0 = \frac{1}{\omega_s} \left(\frac{\omega_{GAM} \, \alpha_2}{2RB} \right)^{1/2} \tag{4}$$

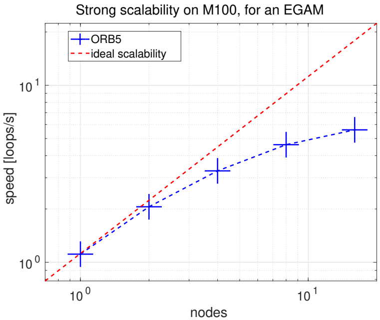
[3] EP redistribution by EGAMs: saturation (b)

- Quadratic scaling of the saturated electric field on the linear growth rate found (kin. ele. effects neglected).
- Saturated level depends on bulk temperature.
- β does not depend on bulk temperature
- $\beta \rightarrow 2.66$ for $\omega_L \rightarrow \omega_{GAM}$ [Biancalani-JPP-17].



[3] EP redistribution by EGAMs: CPU vs GPU

- One typical EGAM simulation is at convergence with the following space resolution, time resolution, and number of markers: (ns, nchi, nphi) $=$ (256, 32, 4), $\mathrm{dt} = 20\ \Omega_i^{-1}$, $\mathrm{nptot} = 8 \cdot 10^6$ $\Rightarrow$ 244 markers/cell
- The nonlinear saturation is achieved in 1500 time steps (loops).
- The original simulation runs in 28 minutes on 4 nodes (of 48 CPUs) in Marconi
- It now runs in 7 minutes on 4 nodes in M100 (3.3 loops/s).
- 4 nodes is a good compromise of speed and scalability, for a sim with $\mathrm{nptot} = 8 \cdot 10^6$ and 1 toroidal mode only.



- ORB5 weak-scales with respect to markers.

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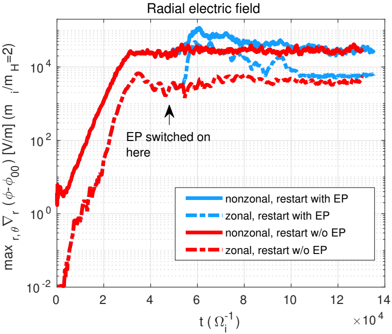
[4] Definition of the numerical experiment

Interaction of turb. and EPs studied with reduced models [White-89, Angioni-09, Zhang-10, Citrin-13, Zonca-15, Garcia-15, Chen-16, DiSiena-19].

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

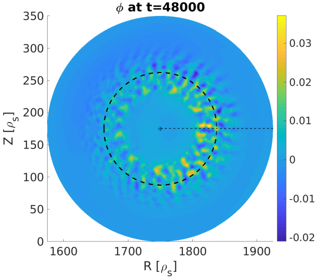


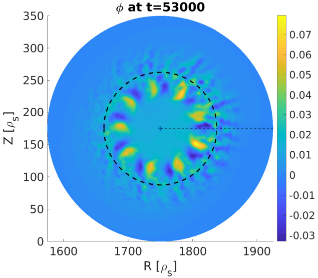
[Biancalani, PPCF 2021]

- Krook operator, conserving zonal fields, applied to thermal species: → source restoring thermal profiles, no sources for EPs

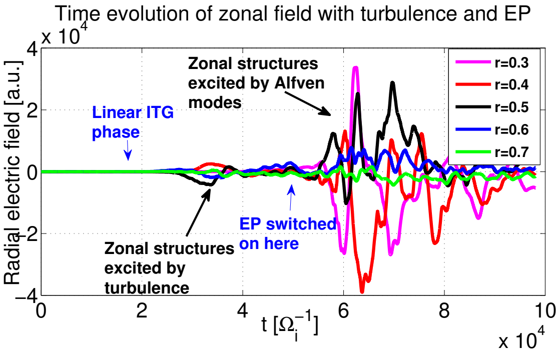
[4] Coexistence of BAEs, ZSs and turbulence

- BAE with n=5, m=9 develops after EP are switched on
- BAE radial electric field grows after EPs are switched on, then saturates at same levels as w/o turbulence
- BAE saturation mechanism: mainly EP redistribution
- BAE electric field higher than ITG field for this EP concentration





[4] Force-driven excitation efficient in driving ZSs

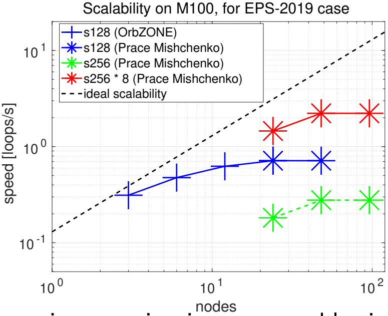


[Biancalani, EPS 2019, I5.J602]

- 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** $\rightarrow$ 1 order of magnitude higher, for this case with $\langle n_{EP}\rangle/\langle n_e\rangle = 0.01,\ T_{EP}/T_e(0.5) = 10$
- Role of ZSs strongly depend on localization $\rightarrow$ global problem under investigation (addressed locally in [DiSiena NuFu19])

[4] Alfvén modes and turbulence : CPU vs GPU

- One typical simulation of AMs, turb. and ZFs has the following space resolution, time resolution, and number of markers: (ns, nchi, nphi) = (128, 192, 96), $\mathrm{dt} = 5\ \Omega_i^{-1}$, $\mathrm{nptot} = 1.75 \cdot 10^8$ $\Rightarrow$ 74 markers/cell
- The saturation of all modes is achieved in 26000 time steps (loops).
- This simulation runs in 3 days on 12 nodes in M100
- It runs in 12 days in 10 nodes in Marconi.
- For this simulation there is no gain in going to larger number of nodes in M100.



- OrbZONE in M100 allows to have sims running in a reasonable time.
- For a higher resolution, sims were done with OrbZONE and Prace.

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[5] Conclusions

- Gyrokinetic PIC code ORB5 enabled for GPUs in 2019 [Ohana-CPC-21] and ported to M100 [Hayward-Schneider].
- Two physics production cases chosen here to study efficiency.
- A) Single toroidal mode (n=0) EGAM.
  - The study of many simulations with different equilibria helped the formulation of a reduced model obtaining a simple analytical formula for the prediction of the saturation amplitudes.
  → Simulations in M100 are 4 times faster than in Marconi.
- B) Alfvén modes, zonal flows and turbulence with broad spectrum of toroidal modes (n=0,40).
  - One single simulation needs many markers for studying the excitation of zonal flows by Alfvén modes and by a saturated turbulence
  → Simulations in M100 are 3 times faster than in Marconi, which helps a lot for such long simulations. For optimal resolution, Prace is needed (A. Mishchenko's project)

Acknowledgements

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Numerical simulations were performed on the CINECA **Marconi** and **Marconi100** supercomputers within the framework of the OrbZONE and ORBFAST projects.