Verification of GK codes on linear collisionless dynamics of axisymmetric modes in tokamaks: Current status of verification on GAMs.

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Outline

- **Introduction and motivation, and models.**
- **Verification on circular flux-surfaces.**
- **Effect of elongation (due 2015).**
- **Finite-orbit-width effects (in progress, due 2016).**
- **Conclusions and next steps**

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Introduction and motivation

- Geodesic acoustic modes (GAMs) and Zonal Flows (ZF) are oscillations of radial electric field observed in the tokamak plasmas, with characteristic frequencies respectively of the order of the sound frequency and zero, m=0 n=0 potential pert. and m=1 n=0 density pert. e.g. [Winsor-68]
- GAM and ZF can interact with turbulence in tokamaks, modifying the transport. e.g. [Conway-11]
- Ultimate goal of burning plasma modeling: nonlinear global electromagnetic simulations of global instabilities and turbulence and fast particles.

Intermediate step → verification with GAM, ZF and SAW.

The GK codes

ORB5

- Global nonlinear GK full-f PIC code.
- Gyrokinetic Vlasov equation for ions, drift-kinetic for electrons.
- Linearized Poisson equation and parallel Ampère's law.
- Ideal MHD equilibria (CHEASE code).

[Jolliet-Comp.Phys-2007, Bottino-JPP-2015]

GENE

- Global nonlinear GK Eulerian code.
- Multi-species kinetic dynamics.
- Local, global or full surface (for non-axisymmetric eq.)
- Ideal MHD equilibria (CHEASE code).

[Jenko-PoP-2000, Görler-JCP-2011]

GYSELA

- Global nonlinear GK full-f, flux-driven semi-Lagrangian code.
- Multi-species transport (kinetic electrons under development).
- Synergy between neoclassical and turbulent transport
- Circular magnetic configuration.

[Sarazin-NuFu-2010, Grandgirard-CPC-2016]

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Analytical dispersion relation for GAMs

- Explicit formula derived in the limit of large values of q, with small dependences on FLR/FOW neglected for frequency (but important for damping rates), and for circular flux-surfaces. Example for frequency:

$$\omega_{GAM}^2 = \frac{v_{thi}^2}{R_0^2}\left[\frac{7}{4}+\tau\right]\left[1+\frac{2(23+16\tau+4\tau^2)}{q^2(7+4\tau)^2}\right] \qquad (1)$$

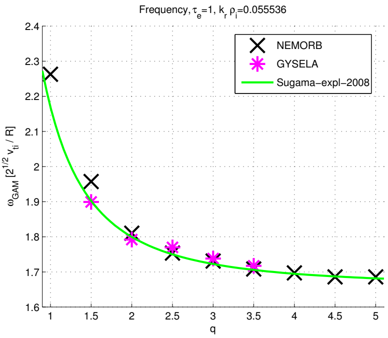
  [Sugama-Watanabe-06, Sugama-Watanabe-08]

- It can be recovered in the framework of the generalized fishbone-like disp. rel. (GFLDR), due to the degeneracy BAE/GAM at the shear Alfvén wave continuum accum. point
  $\hookrightarrow$ ion FLR/FOW effects retained.
  [Zonca-ppcf-96, Zonca-ppcf-98, Chen-RMP-16]

Verification of GAM frequency, small $k_r \rho_i$.

FREQUENCY:

- Linear electrostatic simulations with *adiabatic* electrons: $\delta n_e = (e n_{e0}/T_e)(\delta\phi - \delta\bar{\phi})$
- Circular flux surfaces, with $\rho^* = 1/160$
- Flat q-profiles $\rightarrow$ local limit

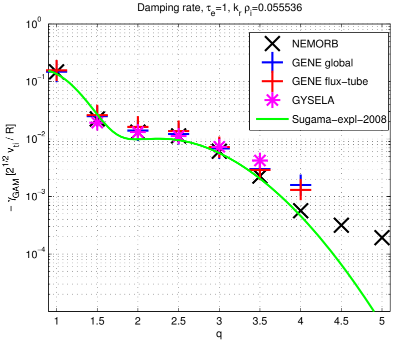


- Good agreement with analytical theory of Sugama-2006-2008, where no FOW effects are retained for the frequency.

Verification of GAM damping rate, small $k_r \rho_i$

DAMPING RATES:

- Collisionless damping rate measured (ion Landau damping)
- Cross-code benchmark succesfull
- Comparison with Sugama breaks down at large q.



- First-order FOW effects, contained in Sugama-08, are not sufficient to describe the damping at large values of q.

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Effect of elongation, GAM, analytical theory.

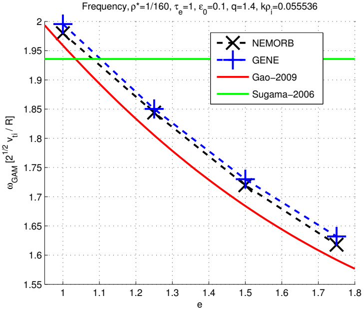
Concentric flux surfaces with constant elongation e.

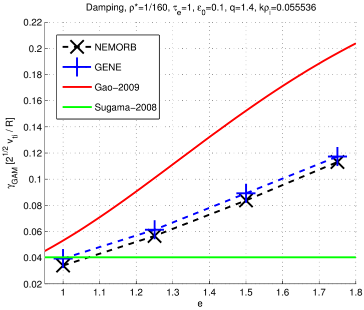
$$\omega_{GAM} = \frac{v_{thi}}{R}\sqrt{\frac{7}{4}+\tau} * \sqrt{\frac{2}{e^2+1}} * \left[1+\frac{23+16\tau+4\tau^2}{q^2(7+4\tau)^2}+\frac{(e^2-1)}{2}\frac{23+16\tau+4\tau^2}{q^2(7+4\tau)^2}\right] \quad (2)$$

- Resulting from the balance of the toroidal drift polarization ($\propto 1/e^2$) and the classical polarization ($\propto (1+e^2)/2e^2$).
- Sugama-Watanabe-2006 recovered for circ. flux surf. ($e=1$).

[Gao, NuFu (2009)]

Effect of elongation, GAM, q=1.4, $\rho^* = 1/160$.





- Frequency well approximated by analytical formula (verification successful).
- Good qualitative match for damping rates, with Gao-2009,
- Quantitative match of γ with theory not ready (in progress).

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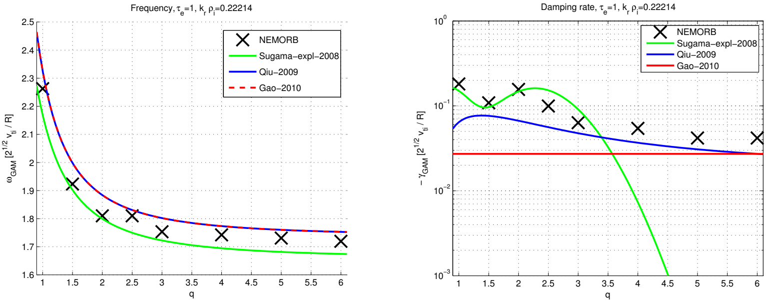
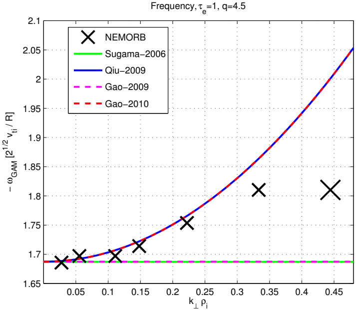
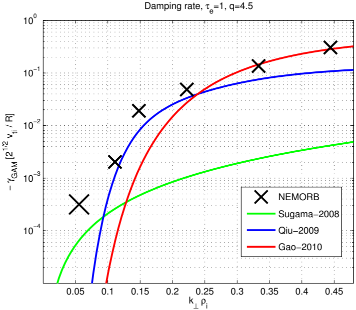
Verification of GAM freq. and damping, $k_r \rho_i = 0.22$



- Circular flux surface, adiabatic electrons.
- FOW effects do not sensibly affect frequency.
- Analytical theory of Sugama, with only first-order FOW effects included, breaks down at large q.
- Analytical theories with higher-order FOW effects (Qiu-09, Gao-10) necessary for estimating the damping rate at large q.

Verification of GAM freq. and damping, scan in k_r





- Qualitative dependence of ω on FOW effects correctly taken into account by Qiu-09.
- Analytical theory of Sugama for γ, with only first-order FOW effects included, breaks down at large k_r.
- Analytical theories with higher-order FOW effects (Qiu-09, Gao-10) necessary for estimating the damping rate at large k_r (the key parameter is $k_r \rho_i q^2$).

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Conclusions and outlook

- GAM frequency found to be the simplest test of axisymmetric oscillations for GK codes, with no FLR/FOW effects required to leading order.
- GAM collisionless damping rate (ion Landau damping) found to be a good test case for ion FLR/FOW effects.
- FOW found to dominate the damping rates at large $k_r \rho_i q^2$.
- Verification of ORB5 succesfull for FOW effects.
- Benchmark of ORB5 and GENE and GYSELA in progress.
  $\hookrightarrow$ see also talks by Asahi and Ehrlacher for GYSELA.
- Other codes are welcome to join the project.