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Electrostatic gyrokinetic simulations in Wendelstein 7-X geometry: benchmark between the codes `stella` and GENE

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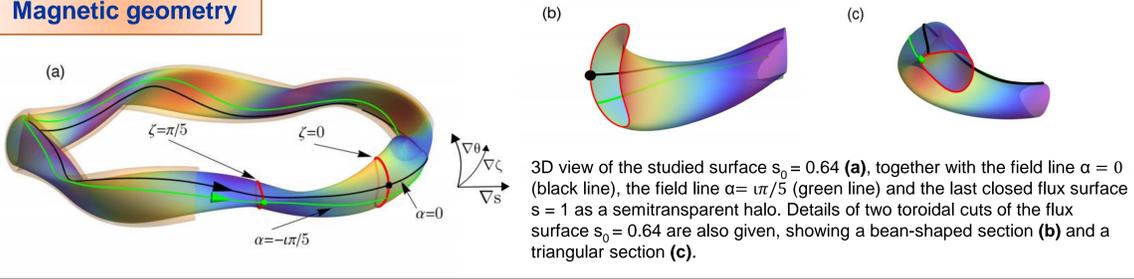[2]Max-Planck Institut für Plasmaphysik, 17491 Greifswald, Germany
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Motivation

W7-X first experimental campaigns *[Wolf, NF, 2017]* ; *[Kingler, NF, 2019]* have shown the importance of turbulent transport in neoclassically optimized stellarators.

The goal of this work is to provide a sufficiently complete, documented and verified set of gyrokinetic simulations in W7-X geometry against which new codes or upgrades of existing codes can be tested and benchmarked.

Much work on gyrokinetic modelling to understand its first available experimental results and to prepare the next experimental campaigns.

Linear and nonlinear collisionless electrostatic flux-tube simulations carried out with the codes `stella` *[M. Barnes, JCP, 2019]* and GENE *[F. Jenko, PoP, 2000]* in the so-called bean ($\alpha = 0$) and triangular ($\alpha = \pi/5$) flux tubes of W7-X are given.

Magnetic geometry

3D view of the studied surface $s_0 = 0.64$ (a), together with the field line $\alpha = 0$ (black line), the field line $\alpha = \pi/5$ (green line) and the last closed flux surface $s = 1$ as a semitransparent halo. Details of two toroidal cuts of the flux surface $s_0 = 0.64$ are also given, showing a bean-shaped section (b) and a triangular section (c).

Comparing linear growth rates in both flux tubes
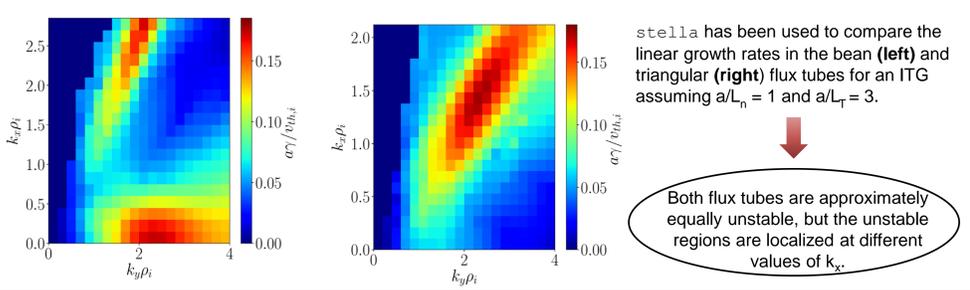
`stella` has been used to compare the linear growth rates in the bean (left) and triangular (right) flux tubes for an ITG assuming $a/L_n = 1$ and $a/L_T = 3$.

Both flux tubes are approximately equally unstable, but the unstable regions are localized at different values of k_x.

## Comparing nonlinear saturated ITG-driven heat flux in both flux tubes
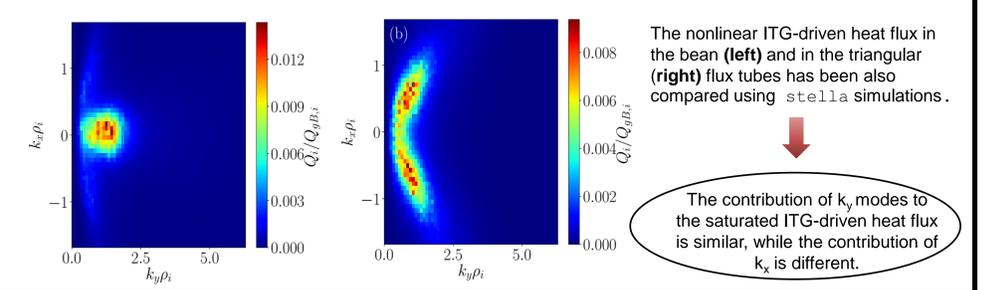
The nonlinear ITG-driven heat flux in the bean (left) and in the triangular (right) flux tubes has been also compared using `stella` simulations.

The contribution of k_y modes to the saturated ITG-driven heat flux is similar, while the contribution of k_x is different.

TESTS

Test 1. Linear ITG in the bean flux tube assuming $a/L_n = 1$ and $a/L_T = 3$
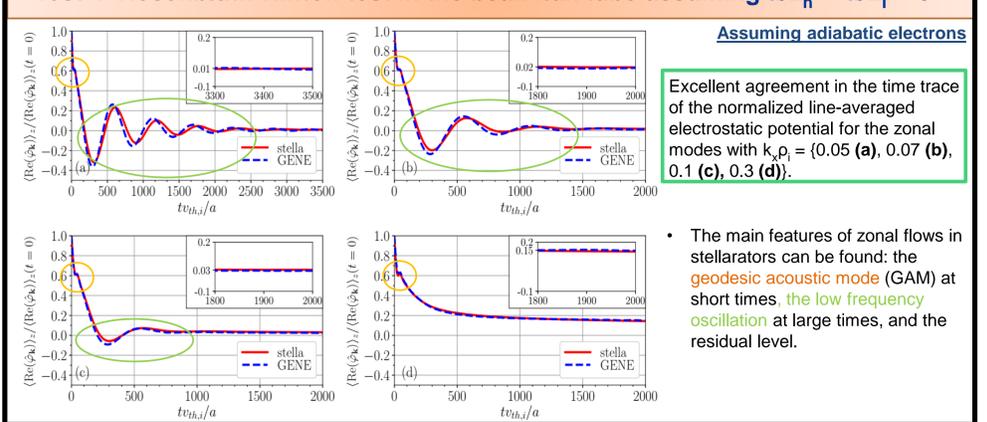
Assuming adiabatic electrons
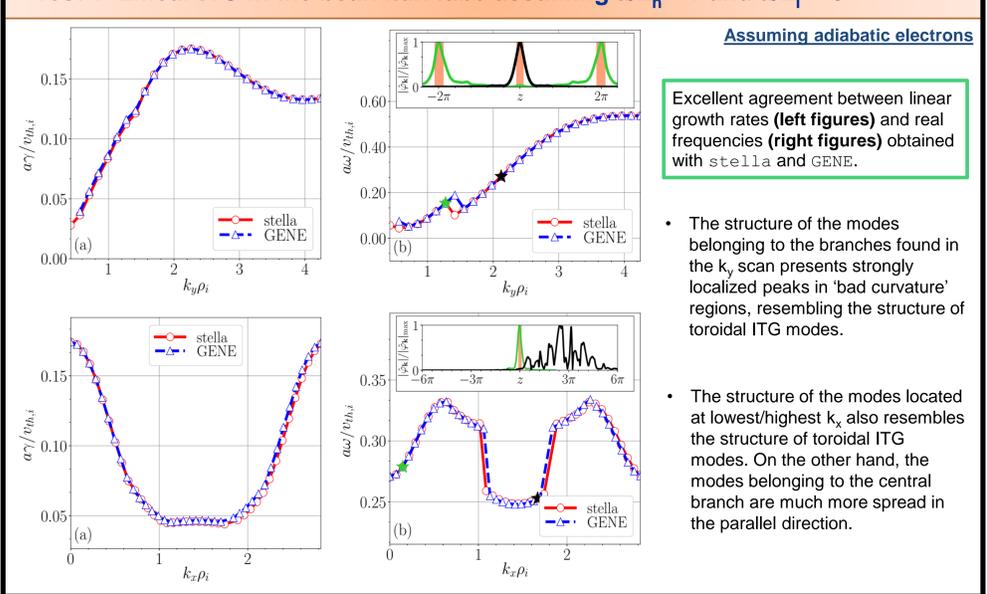
Excellent agreement between linear growth rates (left figures) and real frequencies (right figures) obtained with `stella` and GENE.

- The structure of the modes belonging to the branches found in the k_y scan presents strongly localized peaks in 'bad curvature' regions, resembling the structure of toroidal ITG modes.

- The structure of the modes located at lowest/highest k_x also resembles the structure of toroidal ITG modes. On the other hand, the modes belonging to the central branch are much more spread in the parallel direction.

Test 2. Linear ITG in the triangular flux tube assuming $a/L_n = 1$ and $a/L_T = 3$

Assuming adiabatic electrons
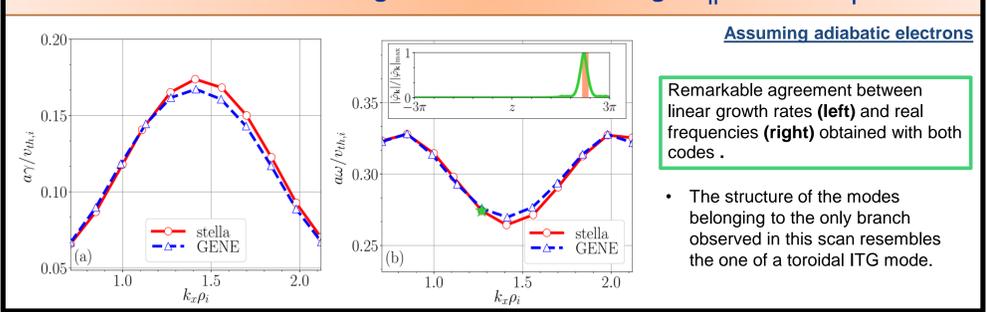
Remarkable agreement between linear growth rates (left) and real frequencies (right) obtained with both codes .

- The structure of the modes belonging to the only branch observed in this scan resembles the one of a toroidal ITG mode.

Test 3. Linear density-gradient-driven TEM in the bean flux tube assuming $a/L_n = 3$ and $a/L_T = 0$

Assuming kinetic electrons
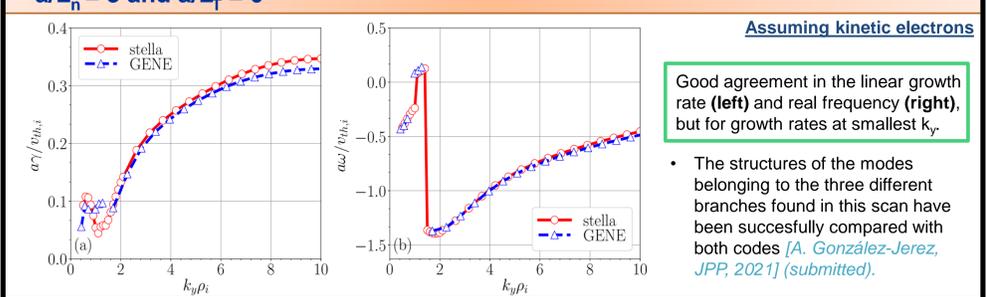
Good agreement in the linear growth rate (left) and real frequency (right), but for growth rates at smallest k_y.

- The structures of the modes belonging to the three different branches found in this scan have been successfully compared with both codes *[A. González-Jerez, JPP, 2021] (submitted)*.

Test 4. Rosenbluth-Hinton test in the bean flux tube assuming $a/L_n = a/L_T = 0$
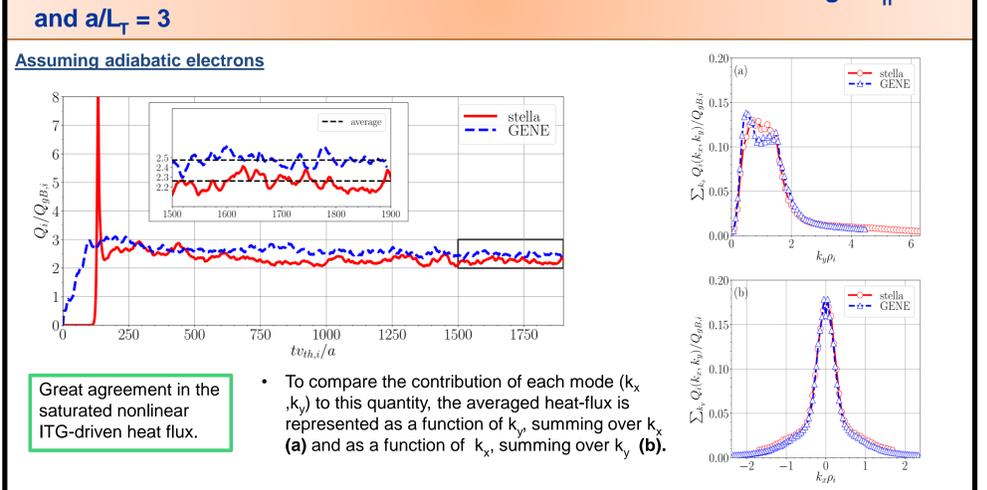
Assuming adiabatic electrons

Excellent agreement in the time trace of the normalized line-averaged electrostatic potential for the zonal modes with $k_x\rho_i = \{0.05$ (a), 0.07 (b), 0.1 (c), 0.3 (d)$\}$.

- The main features of zonal flows in stellarators can be found: the geodesic acoustic mode (GAM) at short times, the low frequency oscillation at large times, and the residual level.

Test 5. Nonlinear ITG-driven heat flux in the bean flux tube assuming $a/L_n = 1$ and $a/L_T = 3$

Assuming adiabatic electrons

Great agreement in the saturated nonlinear ITG-driven heat flux.

- To compare the contribution of each mode (k_x, k_y) to this quantity, the averaged heat-flux is represented as a function of k_y, summing over k_x (a) and as a function of k_x, summing over k_y (b).

Conclusions

- Successful benchmark of `stella` against GENE in W7-X geometry including collisionless, electrostatic linear and nonlinear simulations in two flux tubes through comparing:
  - Linear ITG spectra along k_x and k_y in the bean flux tube (test 1).
  - Linear ITG spectra along k_x in the triangular flux tube (test 2).
  - Linear TEM spectra along k_y in the bean flux tube (test 3).
  - Linear evolution of zonal potential perturbations in the bean flux tube (test 4).
  - Nonlinear ITG-driven heat flux in the bean flux tube (test 5).

- Linear and nonlinear simulations in both flux tubes draw the same conclusions:
  - Both flux tubes are equally unstable.
  - The differences between both flux tubes are found in the contribution to the instability of different wavenumbers.

- The comprehensive and well-documented set of simulations included in this study can be used to benchmark and test other stellarator gyrokinetic codes.