Gyrokinetic simulations in stellarators using different computational domains

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ABSTRACT

In this work, we compare gyrokinetic simulations in stellarators using different computational domains, namely, flux tube, full-flux-surface, and radially global domains. Two problems are studied: the linear relaxation of zonal flows and the linear stability of ion temperature gradient (ITG) modes. Simulations are carried out with the codes EUTERPE, GENE, GENE-3D, and stella in magnetic configurations of LHD and W7-X using adiabatic electrons. The zonal flow relaxation properties obtained in different flux tubes are found to differ with each other and with the radially global result, except for sufficiently long flux tubes. The flux tube length required for convergence is configuration-dependent. Similarly, for ITG instabilities, different flux tubes provide different results, but the discrepancy between them diminishes with increasing tube length. Full-flux-surface and flux tube simulations show good agreement in the calculation of the growth rate and frequency of the most unstable modes in LHD, while for W7-X smaller growth rates are found in the full surface domain. Radially global simulations provide results close to, but not the same as, the full-flux-surface ones.

BACKGROUND AND GOALS

- Gyrokinetics is the appropriate theoretical framework to study turbulence in magnetized plasmas. Gyrokinetic (GK) codes are based on this formalism.
- Flux tube computational domain is commonly used in tokamaks and also in stellarators [1,2]. However, the lack of axisymmetry in stellarators makes the application of the flux tube domain questionable.
- In this work we study gyrokinetic simulations in LHD (standard) and W7-X (KJM) configurations using different computational domains.
- Two linear problems are studied: the linear collisionless relaxation of zonal flows (ZF) [3,4,5,6,7] and the Ion Temperature Gradient (ITG) instability [8].
- We use four gyrokinetic codes: EUTERPE, stella, GENE and GENE-3D.

GYROKINETIC CODES AND COMPUTATIONAL DOMAINS

EUTERPE. Particle-in-cell δf GK code [9,10]. Global in radius. Can simulate the entire confined plasma or a radial annulus. Includes phase factor extraction and Fourier filtering of modes.

Stella. Eulerian δf GK code using the flux tube approximation [11]. Field aligned coordinates.

GENE. Eulerian δf GK code that can be run in full flux surface or flux tube simulation domains in stellarators [12]. Field aligned coordinates.

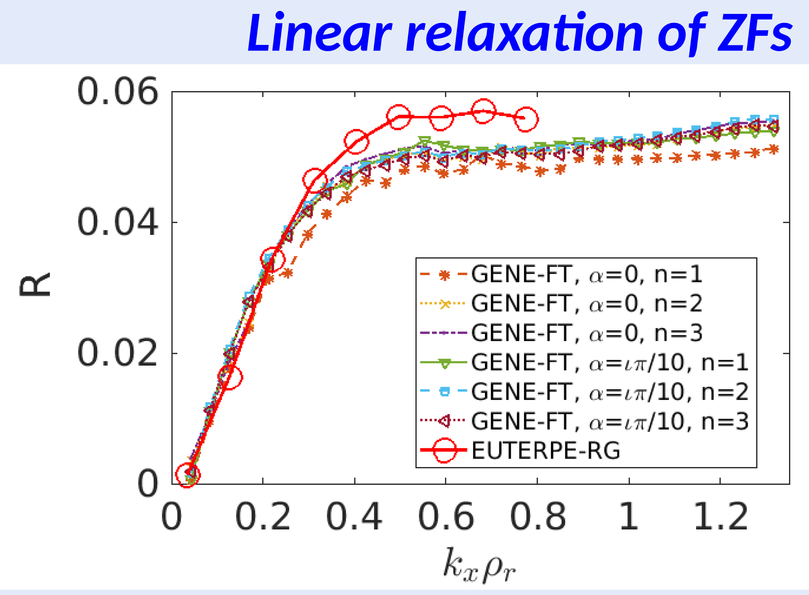
GENE-3D. New version of the code GENE supporting stellarator geometries [13]. Eulerian code. Can be used in either flux tube, full flux surface and radially global domains.

The equilibrium magnetic field for all codes is obtained with the code VMEC [14].

Computational domains: flux tube (**FT**), full flux surface (**FFS**) and radially global (**RG**). Stellarator symmetric FTs (α=0 and $\alpha=\pi/N$; with N the device periodicity) with different number of poloidal turns (n) are considered.

Linear relaxation of ZFs (GENE-FT vs EUTERPE-RG)

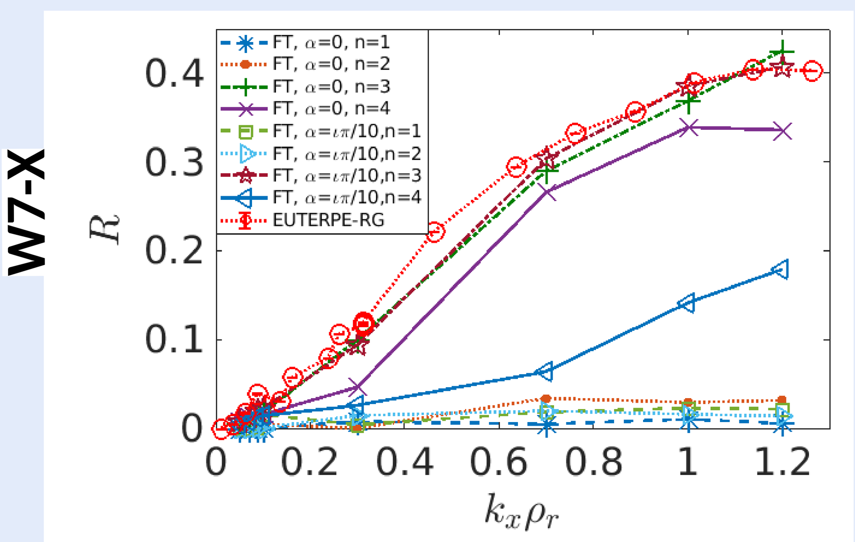
LHD

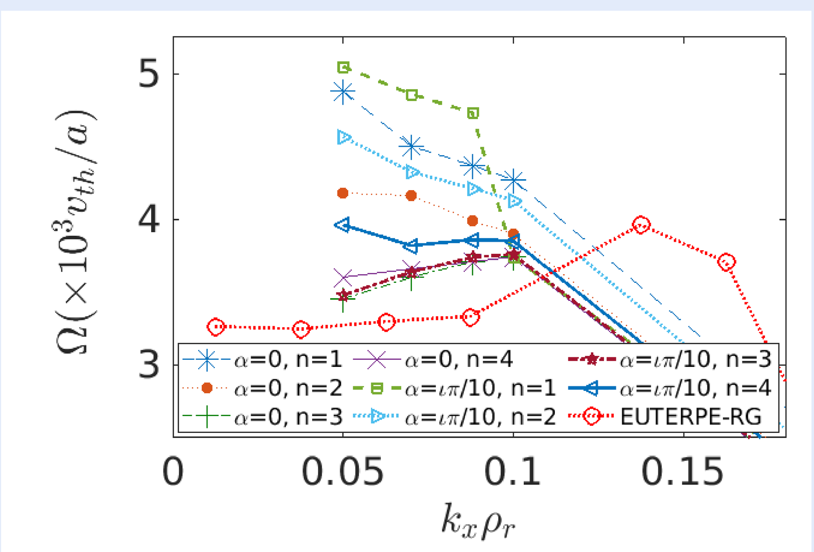


- Residual level **R** and ZF oscillation frequency **Ω** are obtained from a fit of the potential/electric field time trace to a model.

$$\frac{\varphi'(t)}{\varphi'(0)} = A\cos(\Omega t)e^{-\gamma_{ZF}t} + \frac{c}{1+dt^e} + R$$

W7-X

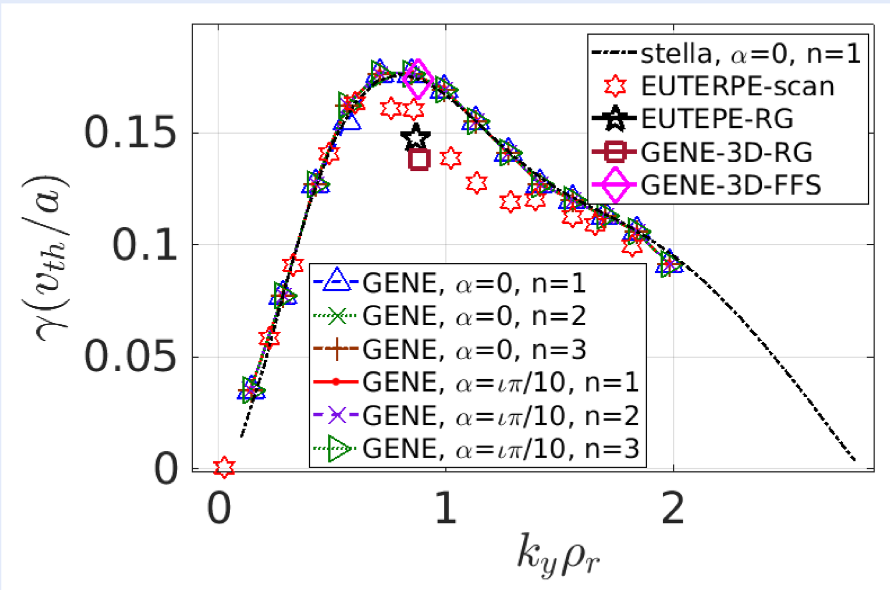


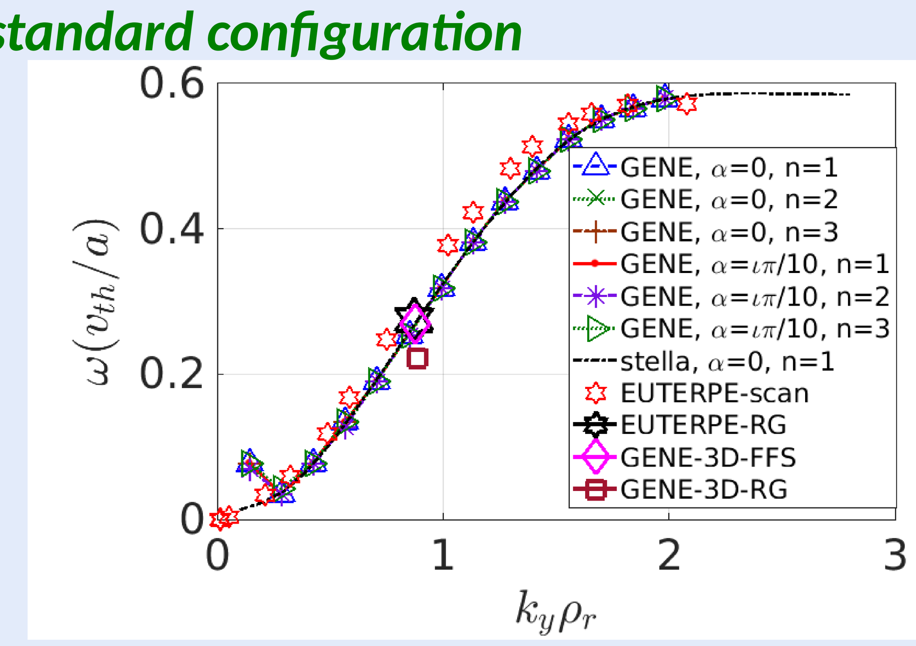


ITG instability

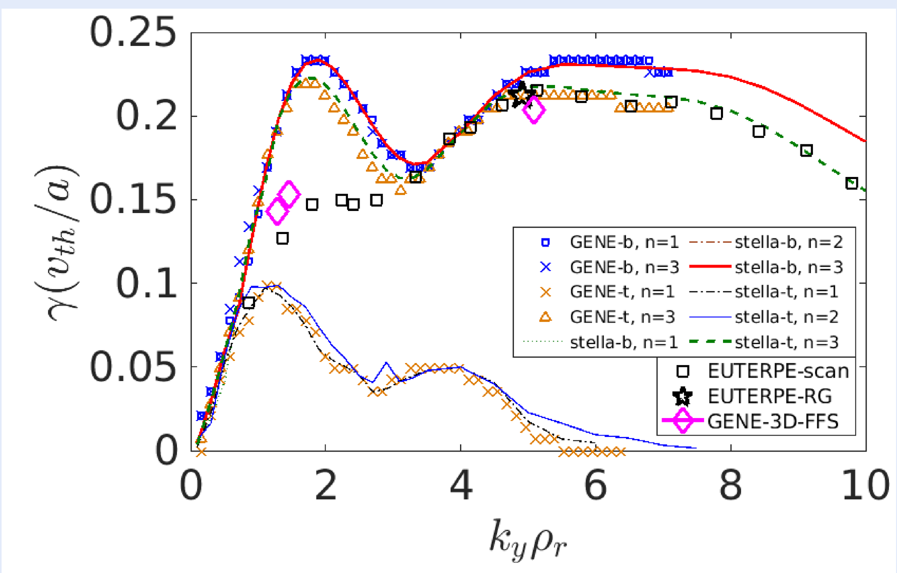
- The linear growth rate γ and frequency ω of ITG modes are obtained for different wavenumbers (k_y).
  - FT codes can scan different k_y separately.
  - In RG and FFS simulations, γ and ω of the most unstable mode is obtained.
  - EUTERPE can make a scan in k_y using phase factor and Fourier filtering.

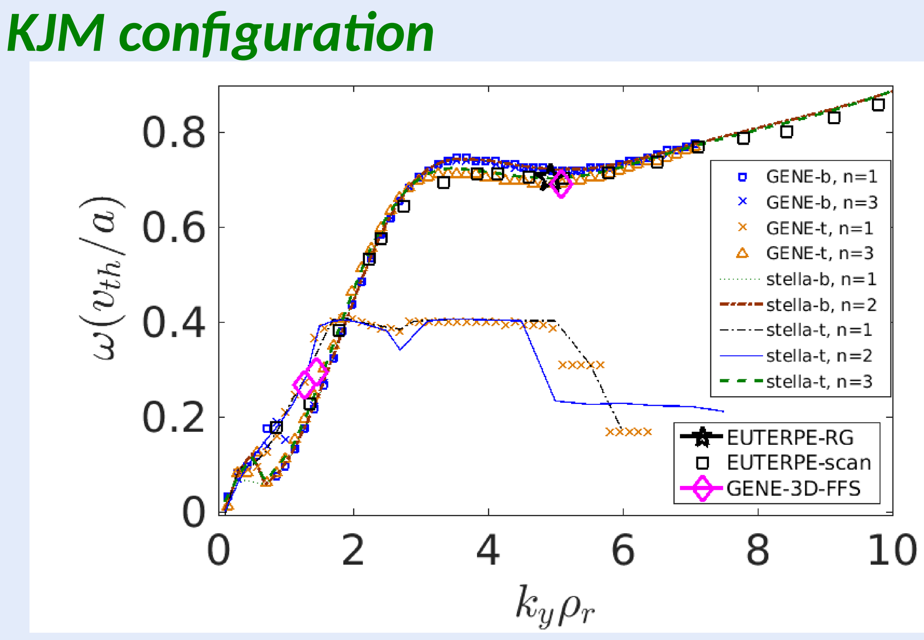
Linear ITGs in LHD standard configuration





Linear ITGs in W7-X KJM configuration





CONCLUSION

- **In the LHD configuration, different FTs provide similar results:**
  - For the ZF properties, different FTs provide very similar results, independently of the length of the FT. ZF residual is slightly smaller in FTs in RG simulations.
  - The ITG γ and ω are also similar in different FTs and very close to FFS. RG calculations give very similar ω and slightly smaller γ than FTs.
- **In W7-X, different FTs provide different results:**
  - Different FTs give different results for ZF properties R and Ω, and the results approach the RG ones as the length of the FTs increases.
  - Short FTs (n=1,2) give different values for γ and ω, and results of bean and triangular FTs approach (without full convergence) as the length increases.
  - FFS and RG results are close to each other, and are close to FT ones for $k_y\rho$>3, while for $k_y\rho$<3, FFS and RG growth rates are smaller than those of FTs.
  - FFS and RG results show small differences between them.
- **Different FTs provide different results, in general.**
  - FT results converge and approach FFS and RG results as the FT length increases.
  - The degree of convergence and the required length is configuration-dependent, in agreement with previous works [15].
- **FFS can be considered the minimum computational domain appropriate for stellarator geometries, in general.**

REFERENCES:

[1] BEER, M. A. et al. Phys. Plasmas 2 (1995).
[2] MARTIN, M. F. et al. Plasma Phys. Control. Fusion 60 (2018).
[3] MISHCHENKO, A. et al. Physics of Plasmas, 15(7) (2008).
[4] HELANDER, P. et al. Plasma Phys. Control. Fusion 53 (2011).
[5] MONREAL, P. et al. Plasma Phys. Control. Fusion 58 (2016).
[6] MONREAL, P. et al. Plasma Phys. Control. Fusion 118 (2017).
[7] SUGAMA, H. et al. Phys. Rev. Lett. 94 (2005).
[8] COPPI et al. Physics of Fluids 10, 582 (1967).
[9] JOST, G. et al. Physics of Plasmas, 8(7) (2001).
[10] KORNILOV, V. et al. Phys. Plasmas 3196 (6) (2004).
[11] BARNES, M. et al. J. Comput. Phys. 391 (2019).
[12] JENKO, F. et al. Phys. Plasmas 7 (2000).
[13] MAURER, M. et al. J. Comput. Phys. 420, 1 (2019).
[14]HIRSHMAN, S. P. et al. Phys. Fluids 26 (1983).
[15] SMONIEWSKI. J. et al. Phys. Plasmas 28 (2021).

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