Linear gyrokinetic studies in W7-AS and W7-X stellarators with the GS2 code

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Abstract

The GS2 gyrokinetic code is being used to study microinstabilities and turbulence in non-axisymmetric flux-tube geometries. Non-axisymmetric systems, such as stellarators, have a number of interesting features, like natural reversed magnetic shear and a large number of shaping parameters. These offer possibilities for reducing microturbulence and improving performance. The W7-AS and W7-X designs were partially optimized for neoclassical transport, and significant comparisons have been made between experimental data and neoclassical expectations. However, the turbulent transport has not been studied in detail. We will present initial studies of gyrokinetic instabilities in W7-AS and W7-X equilibria.
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Goal: to study of the effects of stellarator geometry on gyrokinetic drift-wave turbulence

- Conduct first 3D benchmark of GS2 with GENE, using NCSX geometry
- Create viable simulation grids for GS2 of W7AS and W7X equilibria
- Modify GS2 trapped particle treatment to handle W7AS and W7X geometries
- Study the linear stability of W7AS and W7X plasmas
- Investigate nonlinear instabilities in stellarator geometry
- Compare with experiment

Previous work:

- Reproduced benchmarks of GS2 with FULL using NCSX design QAS3-C82
- Studied the linear stability of the kinetic ballooning mode in QAS3-C82

GS2

- Is an initial-value gyrokinetic turbulence code which uses flux-tube geometry.
- Uses Eulerian finite difference and spectral methods in real space and spectral methods in velocity space.
- Returns growth rates, real frequencies, heat and particle fluxes, and eigenfunctions.
- Has been benchmarked with FULL[a] and GENE.[b]

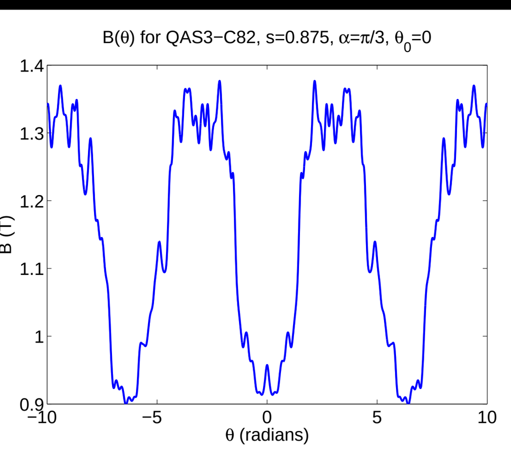
[a]G. Rewoldt Phys. Plasmas **6**, 12 (1999)
[b]F. Jenko et. al. Phys. Plasmas **7**, 1904 (2000)

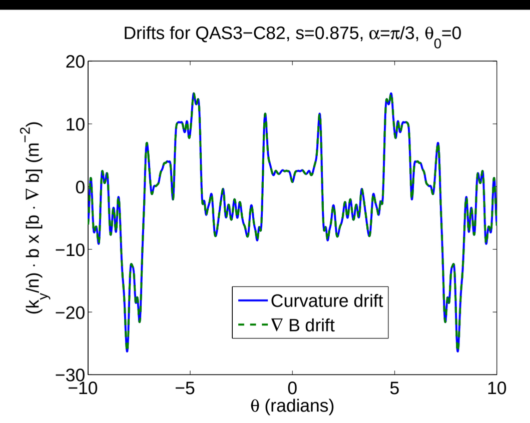
Creating Stellarator Equilibria for GS2

- VMEC: calculates 3D MHD equilibrium [a]
- TERPSICHORE: transforms to Boozer coordinates [b]
- VVBAL: calculates field line data[c]
- GS2's rungridgen: creates equilibrium grid
- GIST packages TERPSICHORE, VVBAL, and TRACER to create input grid files for GS2 and GENE[d]

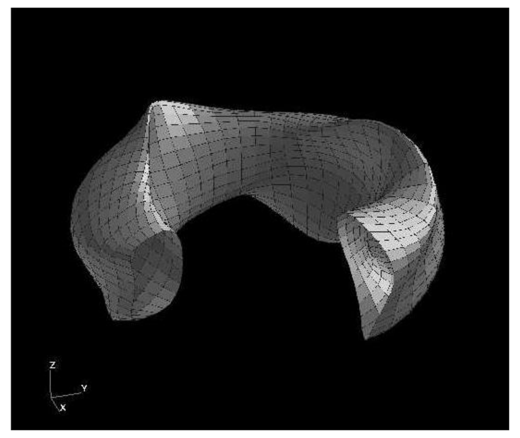
[a]S. P. Hirshman, U. Schwenn, and J. Nuehrenberg, J. Comput. Phys. 87, 396 (1990)
[b]D. V. Anderson, et al. Int. J. Supercomput. Appl. 4, 34 (1990)
[c]A Cooper, Plasma Phys. Control. Fusion 34 1011-1036 (1992)
[d]Xanthopoulos et al., Phys. Plasmas 16 082303 (2009)

Example NCSX Geometry Input





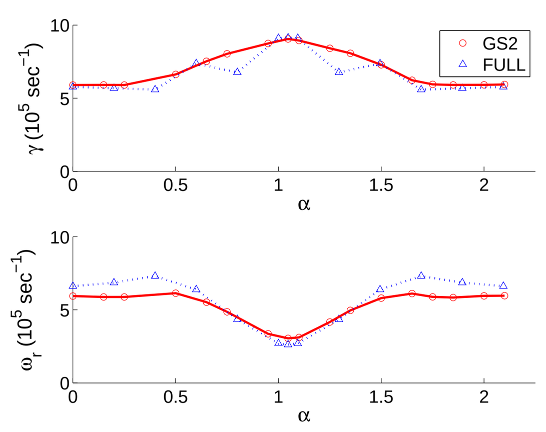
I. GS2 and FULL benchmark: NCSX



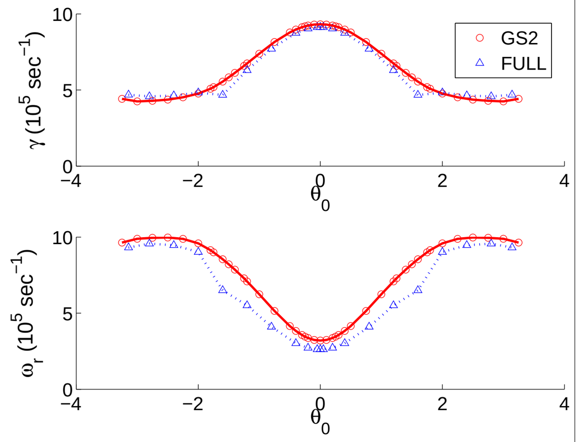
- Kinetic Electrons

- Electrostatic
- $\nu = 0$
- $s = 0.875$
- $\alpha = \zeta - q/\theta = \pi/3$
- $\theta_0 = 0$
- $q = 2.118$
- $<\beta>= 0.01\%$
- $k_y\rho_i(\theta = 0) = 0.3983 (n = 25)$
- $T_i = T_e = 1keV$
- $\frac{a}{L_{ni}} = \frac{a}{L_{ne}} \approx 13.096$
- $\frac{a}{L_{Ti}} = \frac{a}{L_{Te}} \approx 39.288$

Maximum Growth Rates occur at $\alpha = \pi/3$ and $\theta_0 = 0$



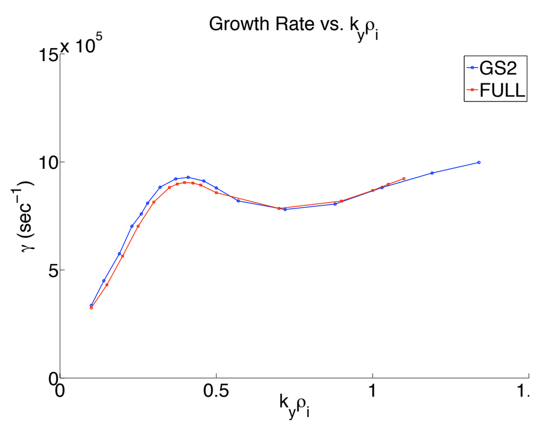
Variation of growth rate with α



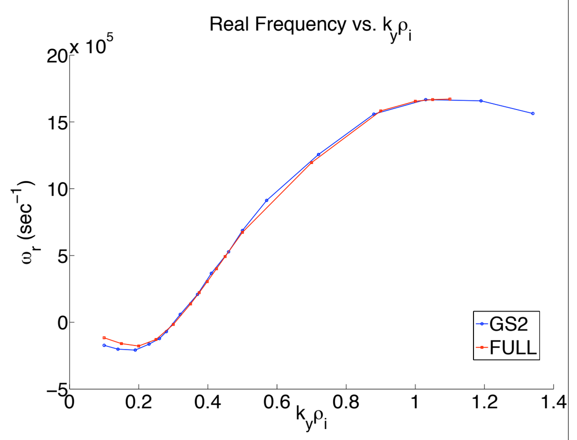
Variation of growth rate with θ_0

- E. Belli, to be published

3D GS2 and FULL benchmark successful



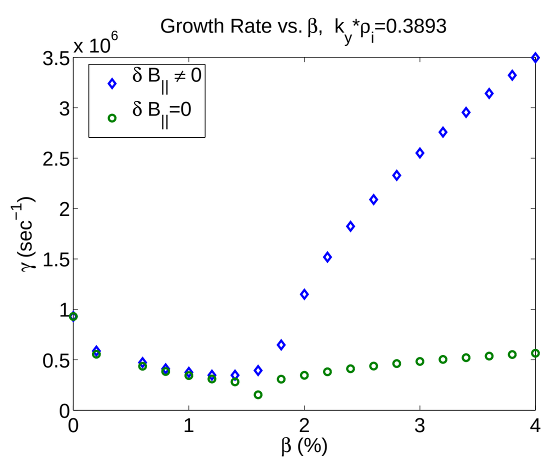
Local maximum at $k_y\rho_i \approx 0.4$; another maximum at higher $k_y\rho_i$



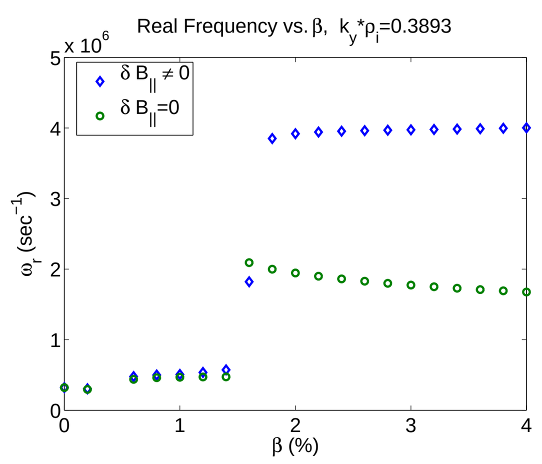
Variation of frequency with $k_y\rho_i$

II. $\delta B_{||}$ Greatly Affects Growth Rate for Large Beta

- $\delta \mathbf{B}_\perp = \nabla A_{||} \times \hat{z} \neq 0$
- $\delta B_{||}\hat{z} = \nabla_\perp \times \mathbf{A}_\perp$



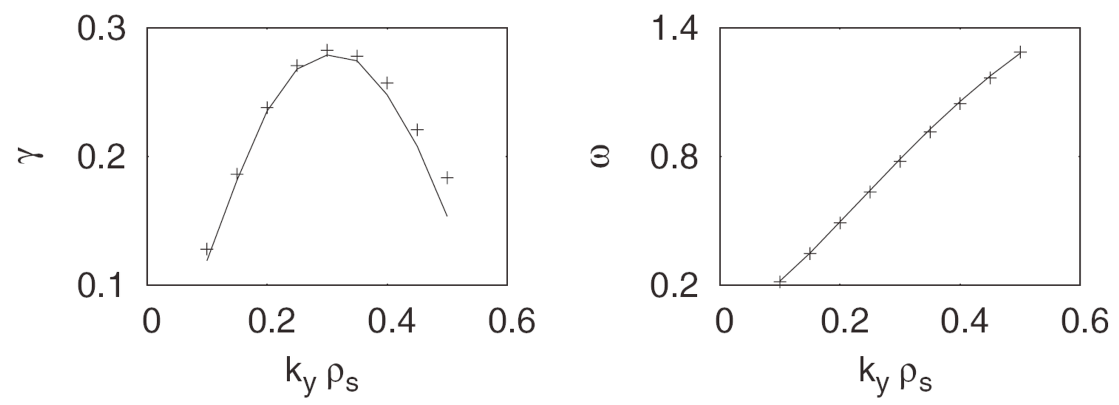
Variation of growth rate for beta.



Variation of frequency for beta.

- For high beta, $\delta B_{||} = 0$ growth rates are approximately zero, while they grow quickly when $\delta B_{||}$ is included

III. GS2 and GENE benchmark: Tokamak



k_y scan for $\hat{s} - \alpha$ geometry from GS2 (line) and GENE (crosses). Units are in c_s/R, where c_s is the sound speed and R is the major radius

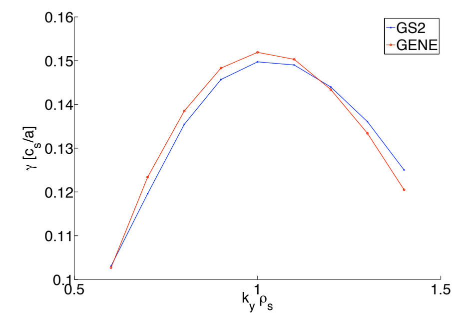
- P. Xanthopoulos et. al. PoP 15, 122108

VI. GS2 and GENE benchmark: NCSX

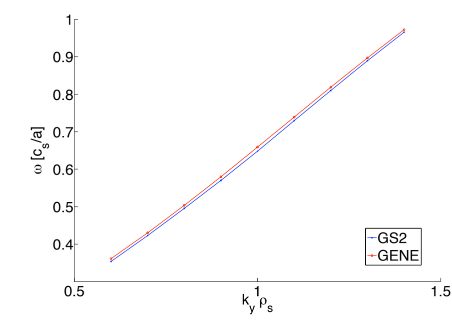
- Adiabatic Electrons
- Electrostatic, collisionless
- $s = 0.5$
- $\alpha = \zeta - q/\theta = 0$
- $\theta_0 = 0$

- $\nu = 0$
- $<\beta>= 0.01\%$
- $T_i = T_e = 1keV$
- $\frac{a}{L_{ni}} = \frac{a}{L_{ne}} \approx 0$
- $\frac{a}{L_{Ti}} = \frac{a}{L_{Te}} \approx 3$

First 3D GS2 and GENE benchmark successful

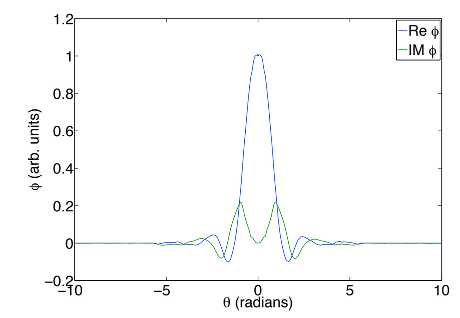


Maximum at $k_y\rho_i \approx 1$, agreement approximately as good as tokamak benchmark.



Excellent agreement in frequency spectrum.

Eigenfunctions balloon about $\theta = 0$

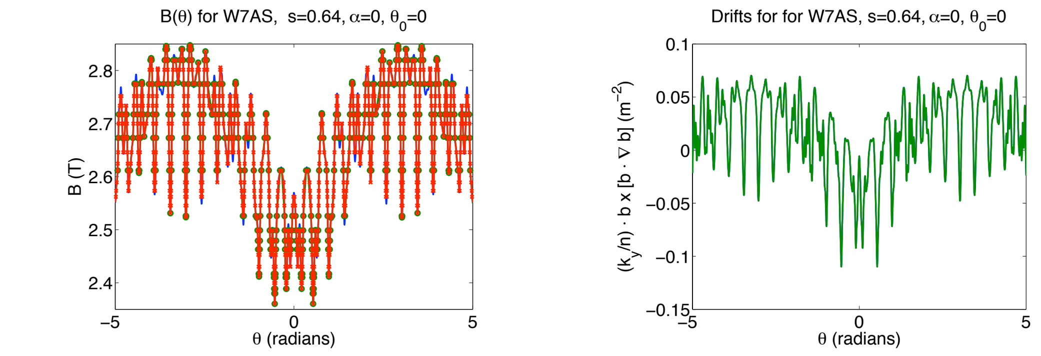


Variation of ϕ with θ.

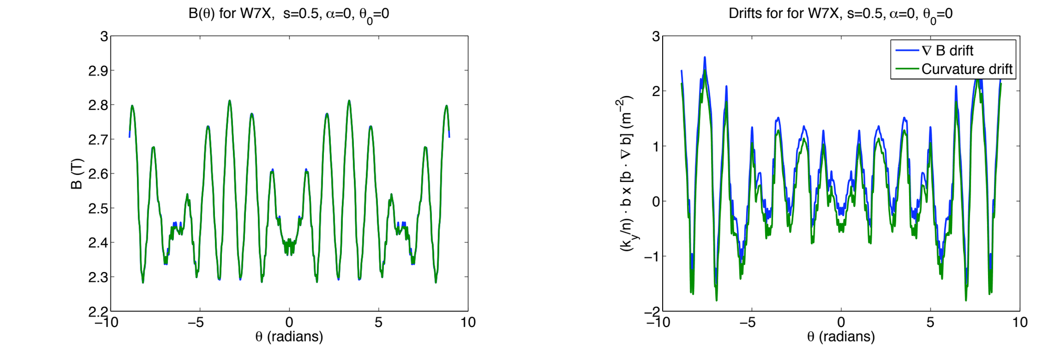
V. GS2 and GENE benchmark: W7AS and W7X

- In Progress
- Issues due to complicated geometry:
  - need for high θ resolution
  - restrictive trapped particle treatment: now more flexible

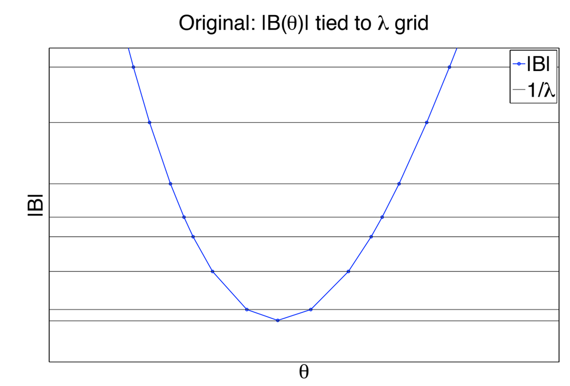
W7-AS Geometry Requires High θ Resolution



W7-X Geometry



VI. GS2 Trapped Particle Treatment Now More Flexible



- No longer requires particles to reflect exactly at a θ grid point ($B(\theta) = 1/\lambda$)
- Consistently treats all particles which reflect at some θ grid point

- Allows for multiple totally-trapped particles at each θ grid point.

Thus, θ and $\lambda = \mu/E$ grids can be independent.

Conclusions

- Benchmarked GS2 stellarator simulations with FULL
- Observed that including $\delta B_{||}$ is important for larger β
- Benchmarked GS2 stellarator simulations with GENE
- Created W7AS and W7X geometry input for GS2
- Improved GS2's trapped particle treatment

Future Work

- Conduct W7AS and W7X linear benchmark with GENE
- Extend NCSX, W7AS, and W7X results to nonlinear studies
- Benchmark nonlinear results with other gyrokinetic codes
- Conduct detailed TEM study in 3D geometries
- Study ETG stabilization in reversed magnetic shear
- Compare W7AS nonlinear fluxes to experimental values

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