Improved algorithms for the GS2 code and application to gyrokinetic studies in the NCSX and W7-X Stellarators

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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 NCSX and W7-X designs were partially optimized for neoclassical transport; however, the turbulent transport has not been studied in detail. We will present studies of gyrokinetic instabilities in NCSX and W7-X equilibria, including important geometry and linear benchmarks between GS2 and GENE, a gyrokinetic code from IPP. We will also discuss improvements to the GS2 trapped particle treatment and a new computational grid generator for GS2. Within the grid generator, we experiment with various averages over geometric parameters (such as the curvature drift terms) in order to improve convergence and reduce required grid resolution. This work was supported by the SciDAC Center for the Study of Plasma Microturbulence and Department of Energy Contract DE-AC02-09CH11466.

Goal: to study of the effects of stellarator geometry on gyrokinetic drift-wave turbulence

- Benchmark GS2 with FULL using NCSX design QAS3-C82
- Conduct first 3D benchmark of GS2 with GENE, using NCSX and W7-X geometry
- Modify GS2 trapped particle treatment to handle W7AS and W7X geometries
- Write more flexible grid generator for GS2 input geometry

GS2

- Is an initial-value gyrokinetic turbulence code that uses flux-tube geometry.
- Uses Eulerian finite difference and spectral methods in position 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]

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[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]
- Original Method:
  - TERPSICHORE: transforms to Boozer coordinates [b]
  - VVBAL: calculates field line data[c]
  - GS2's Rungridgen: creates computation grid
- New Method:
  - GIST packages TERPSICHORE, VVBAL, and TRACER to create input grid files for GS2 and GENE[d]
  - FIGG: creates computation grid (see Section VI)

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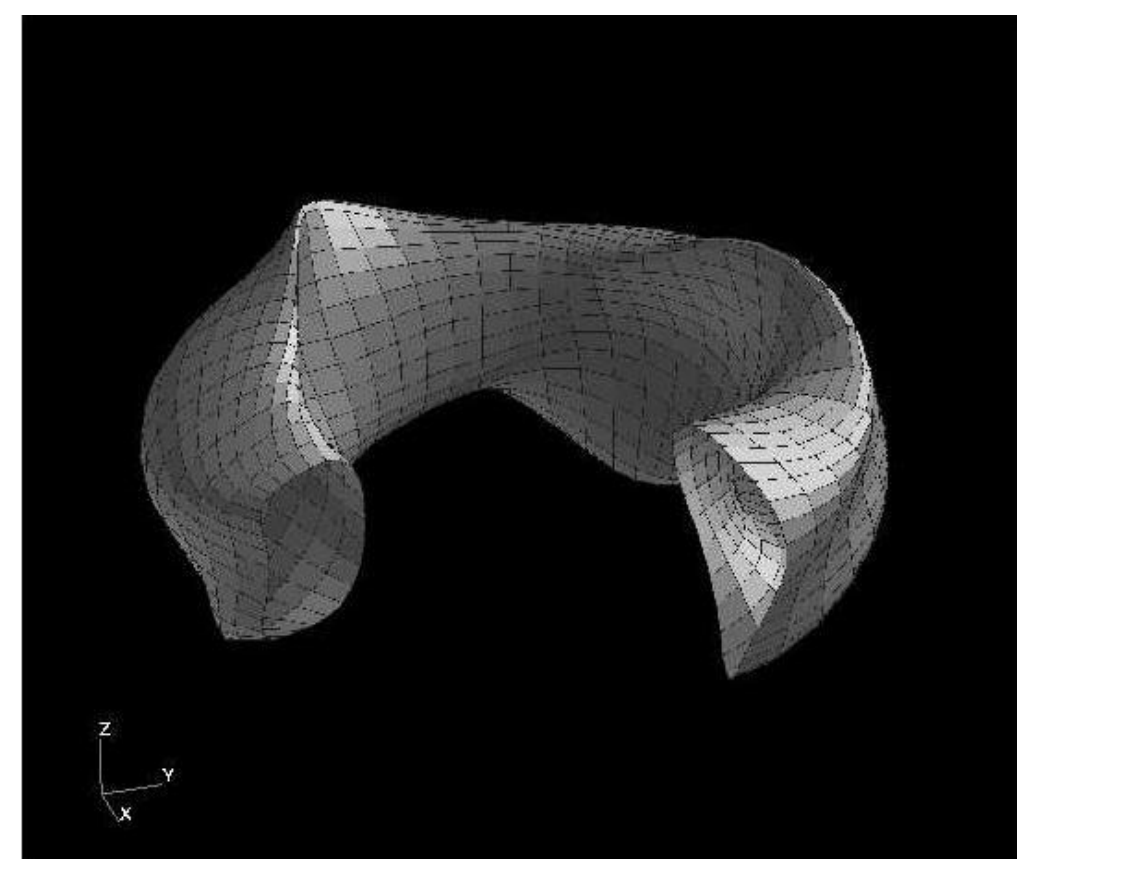
[a] S. P. Hirshman, U. Schwenn, and J. Nuehrenberg, J. Comput. Phys. 87, 396 (1990)

[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] Xanthopolous et al., Phys. Plasmas 16 082303 (2009)

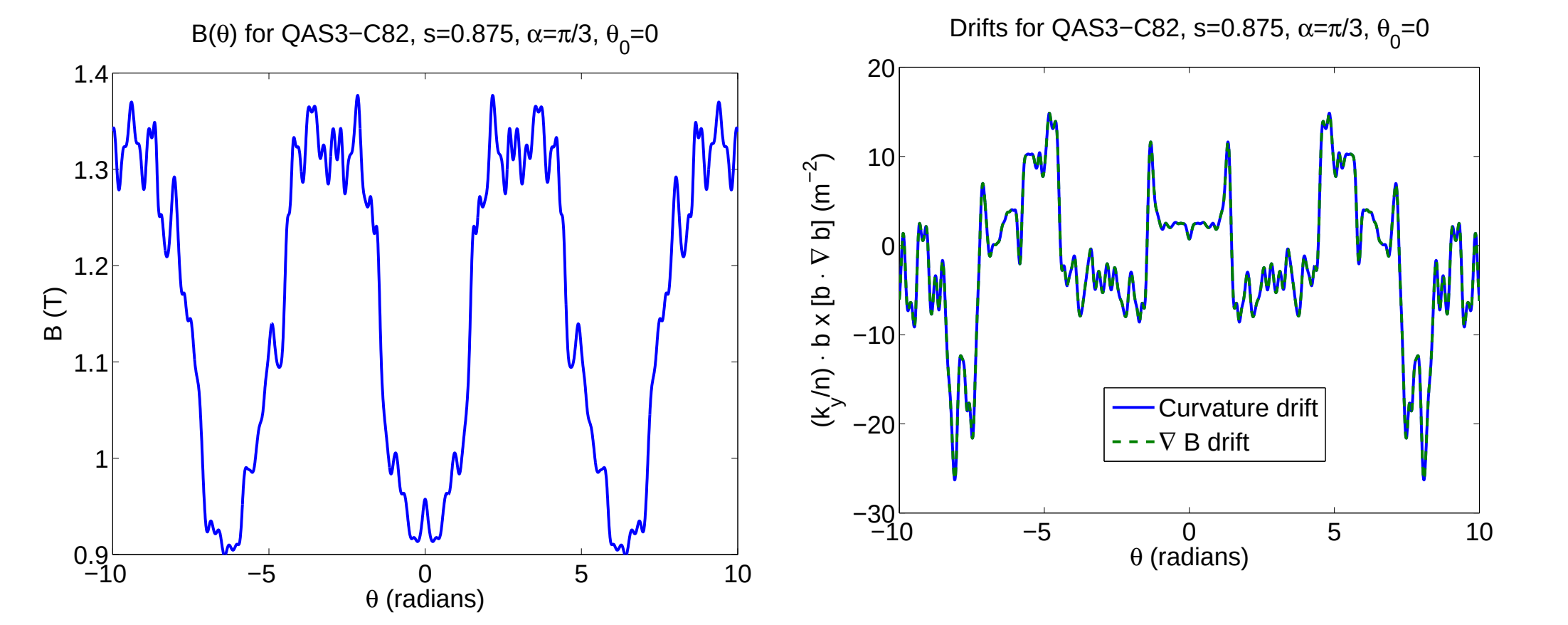
I. GS2 and FULL benchmark: NCSX



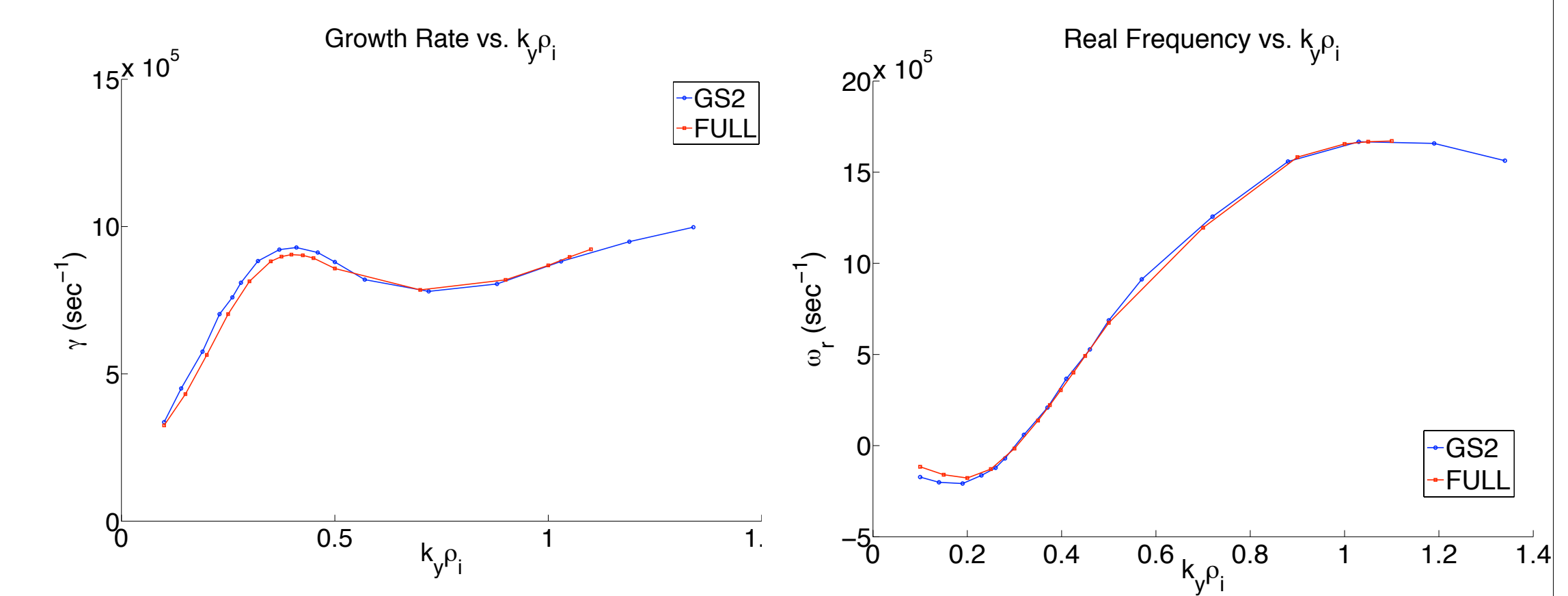
- Drift Kinetic Electrons
- Electrostatic

- $\nu = 0$
- $s = 0.875$
- $\alpha = \zeta - q/\theta = \pi/3$
- $\theta_0 = 0$
- $q = 2.118$
- $< \beta >= 0.01\%$
- $k_y\rho_i(\theta = 0) = 0.3983(n = 25)$
- $T_i = T_e = 1keV$
- $\frac{a_N}{L_{ni}} = \frac{a}{L_{ne}} \approx 13.096$
- $\frac{a_N}{L_{Ti}} = \frac{a}{L_{Te}} \approx 39.288$
- normalizing length $a_N \approx 0.35m$

NCSX Geometry



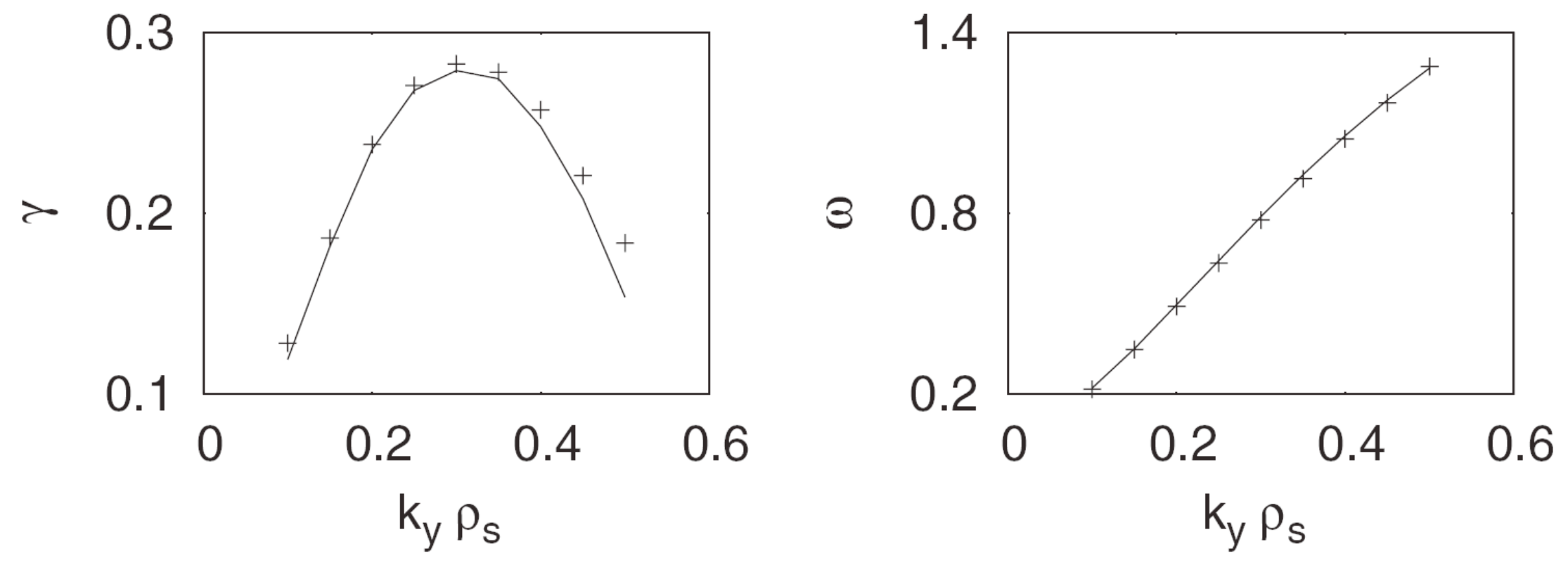
3D GS2 and FULL benchmark successful



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

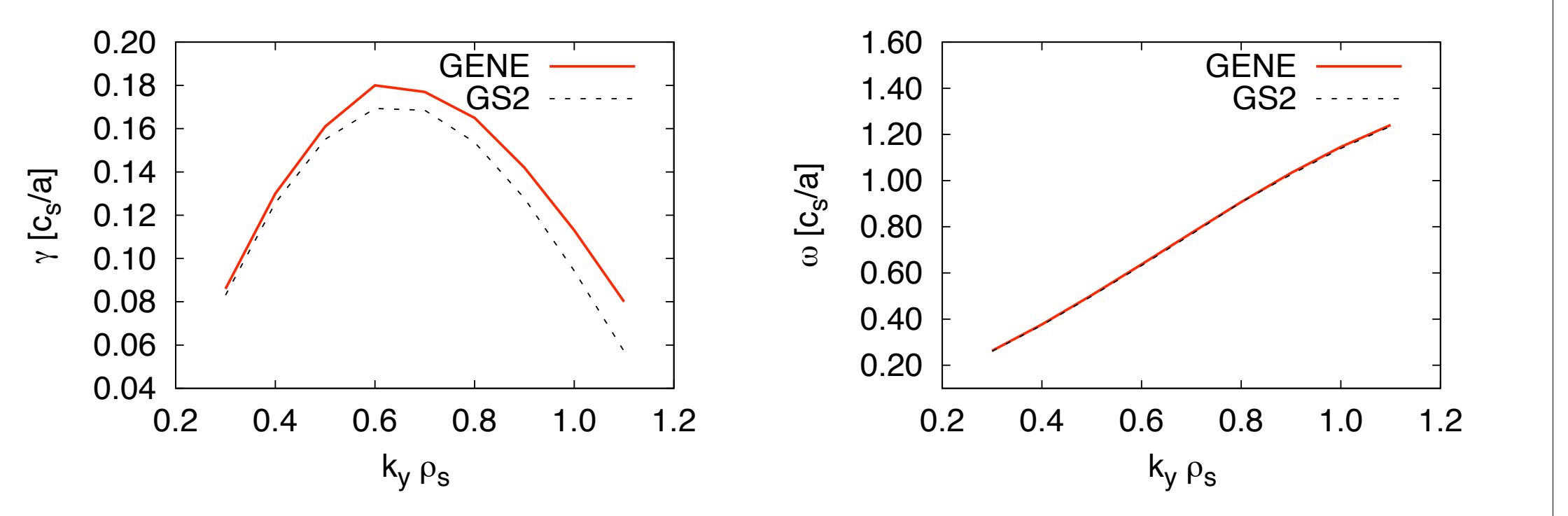
Variation of frequency with $k_y\rho_i$

II. 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. Xanthopolous et. al. PoP 15, 122108

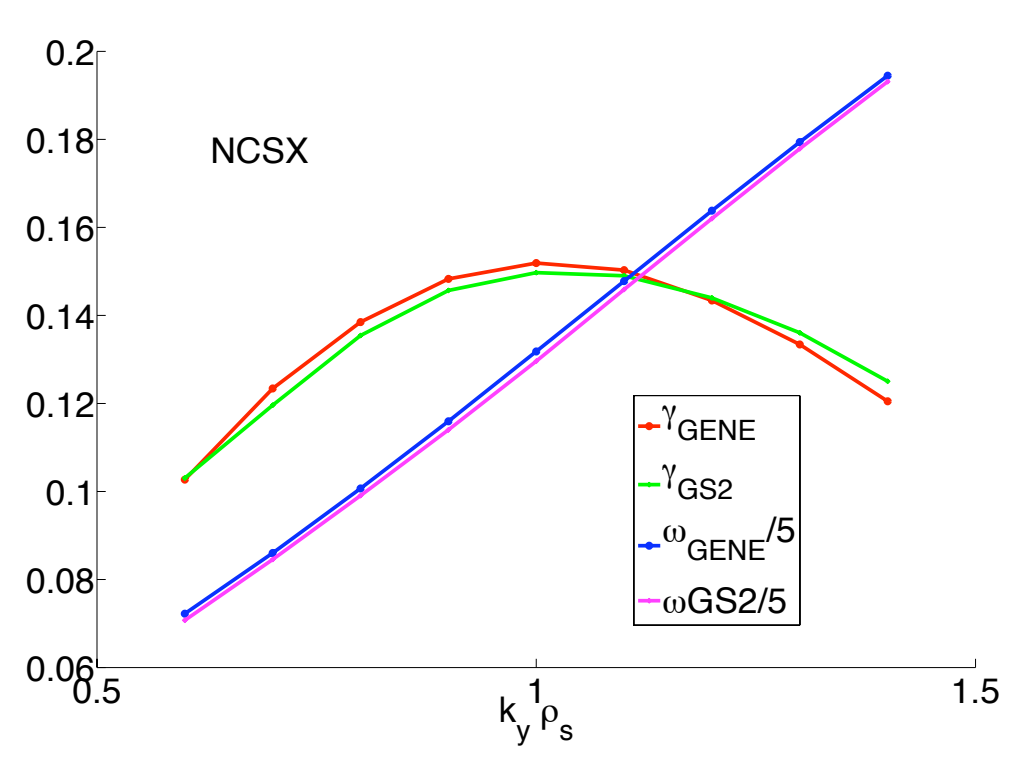


k_y scan for Symmetric NCSX tests 3-D geometry codes.

III. GS2 and GENE benchmark: NCSX

- Adiabatic Electrons
- Electrostatic, collisionless
- Radial variable: $\sqrt{s}$
- $s = \Phi_T/\Phi_{Ta} = 0.5$
- $\alpha = \zeta - q/\theta = 0$
- $\theta_0 = 0$
- $< \beta >= 0.01\%$
- $T_i = T_e = 1keV$
- $\frac{a_N}{L_{ni}} = \frac{a}{L_{ne}} \approx 0$
- $\frac{a_N}{L_{Ti}} = \frac{a}{L_{Te}} \approx 3$
- normalizing length $a_N \approx 0.35m$

First 3D GS2 and GENE benchmark successful

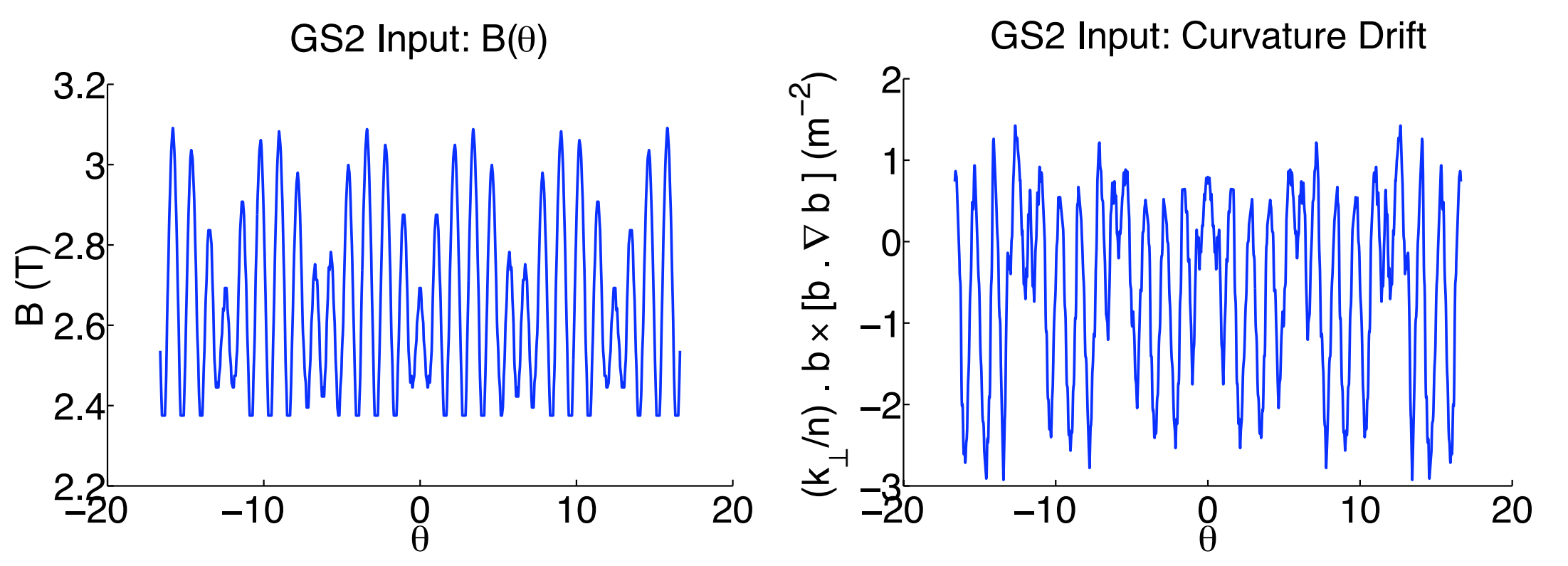


Frequency units normalized by v_t/a_N.

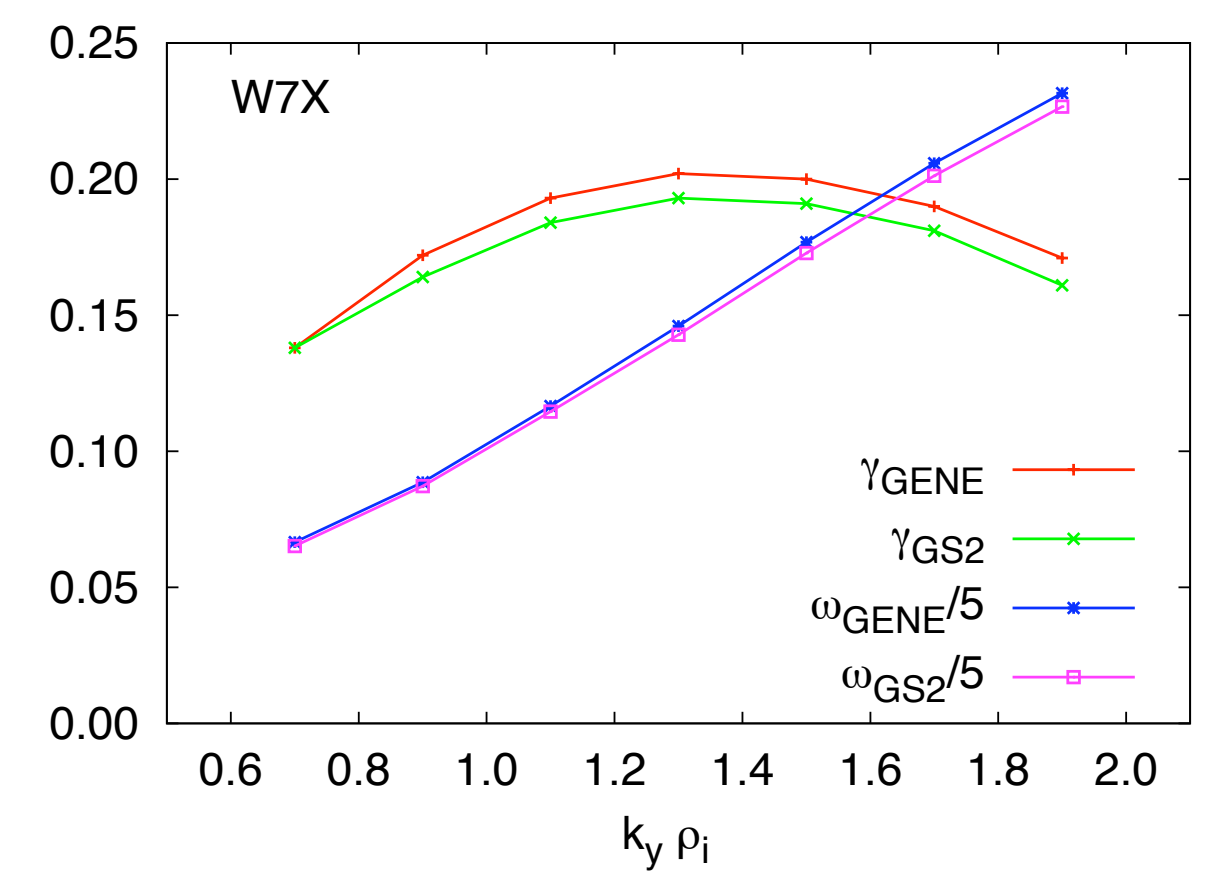
IV. GS2 and GENE benchmark: W7-X

- Adiabatic Electrons
- Electrostatic, collisionless
- Radial variable: $\sqrt{s}$
- $s = \Phi_T/\Phi_{Ta} = 0.2$
- $\alpha = \zeta - q/\theta = 0$
- $\theta_0 = 0$
- $T_i = T_e = 1keV$
- $\frac{a_N}{L_{ni}} = \frac{a}{L_{ne}} = 0$
- $\frac{a_N}{L_{Ti}} = \frac{a}{L_{Te}} = 3$
- normalizing length $a_N \approx 0.5m$

W7-X Geometry

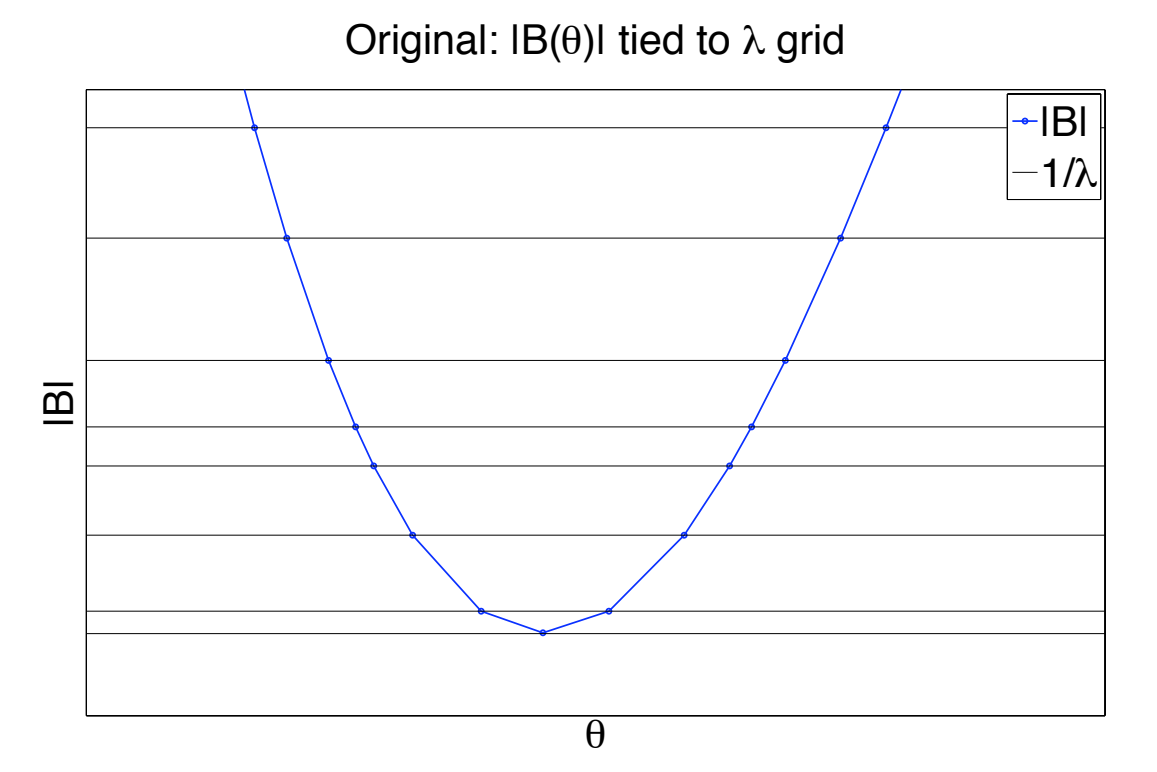


3D GS2 and GENE W7-X benchmark successful



Frequency units normalized by v_t/a_N.

V. GS2 Trapped Particle Treatment Now More Flexible



- For complicated geometry, Rungridgen wouldn't satisfy constraint of tied θ/λ grids
- GS2 would give unphysical results on such grids
- New GS2 modifications allow θ and $\lambda = \mu/E$ grids to be independent.
- 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.

VI. FIGG: Flexible Improved Grid Generator

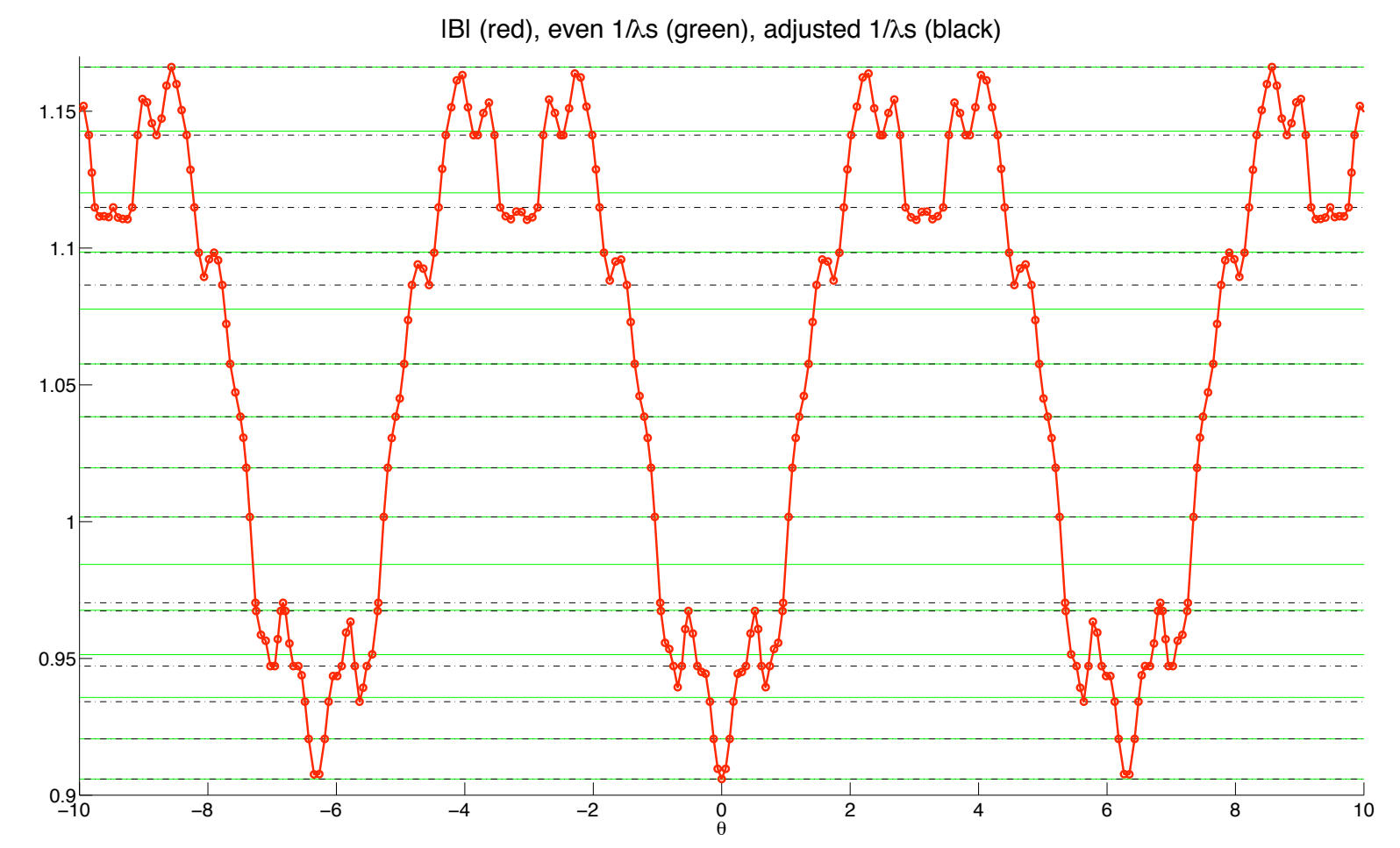
FIGG

- Input: from VVBAL or GIST
- Output: GS2 computational grid
- Allows independent θ and λ grids.
- λs: evenly-spaced or adjusted
- Can create grids with low ntheta
- Written in Matlab
- Seconds to run

Rungridgen

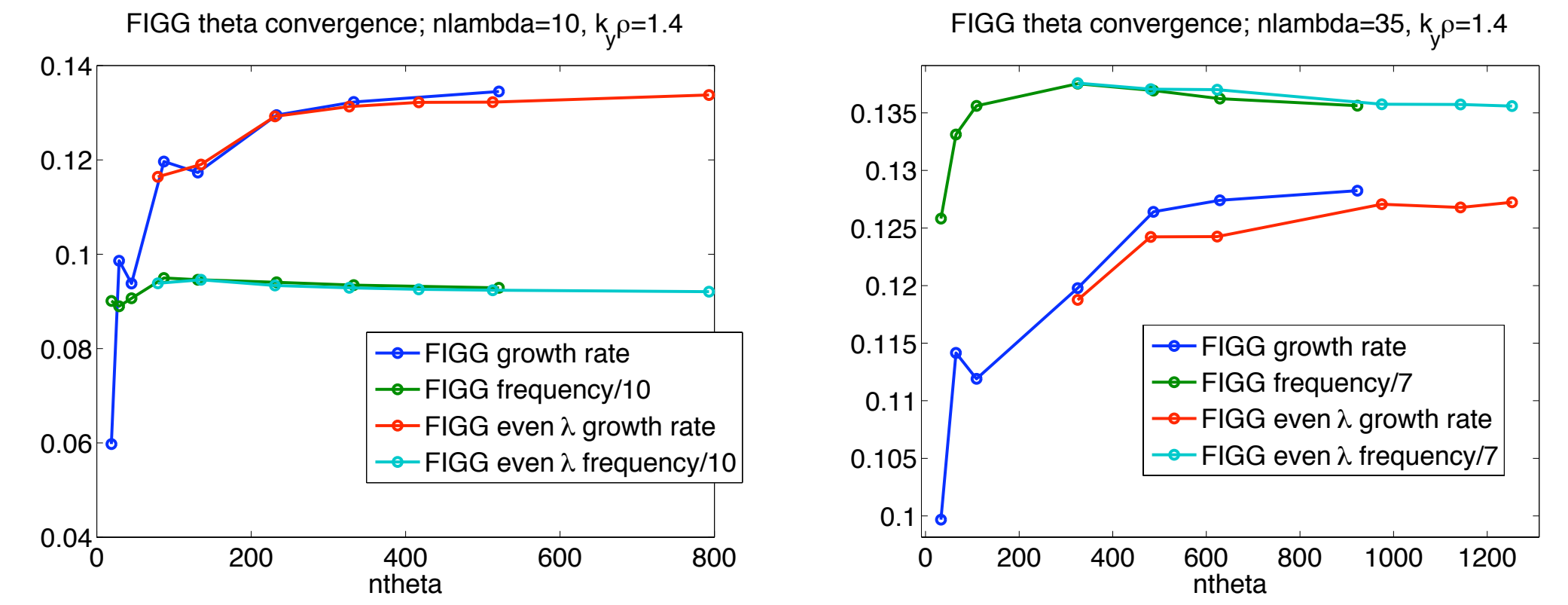
- Input: from VVBAL or GIST
- Output: GS2 computational grid
- Ties θ and λ grids
- λ grid fixed by θ grid
- Has difficulty with low ntheta
- Written in FORTRAN
- Minutes to run

Two Ways of Computing FIGG λ grid



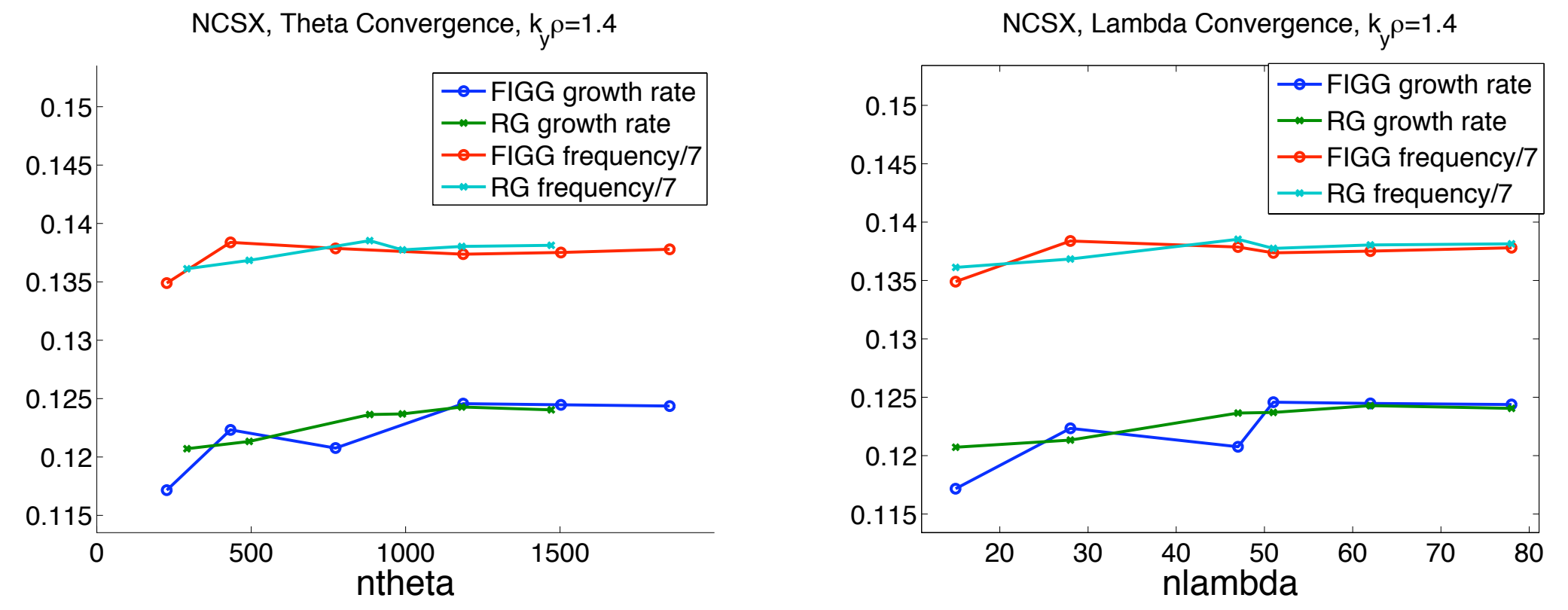
- Evenly-spaced λs
- Adjust even λs to match local extrema

FIGG Convergence: NCSX



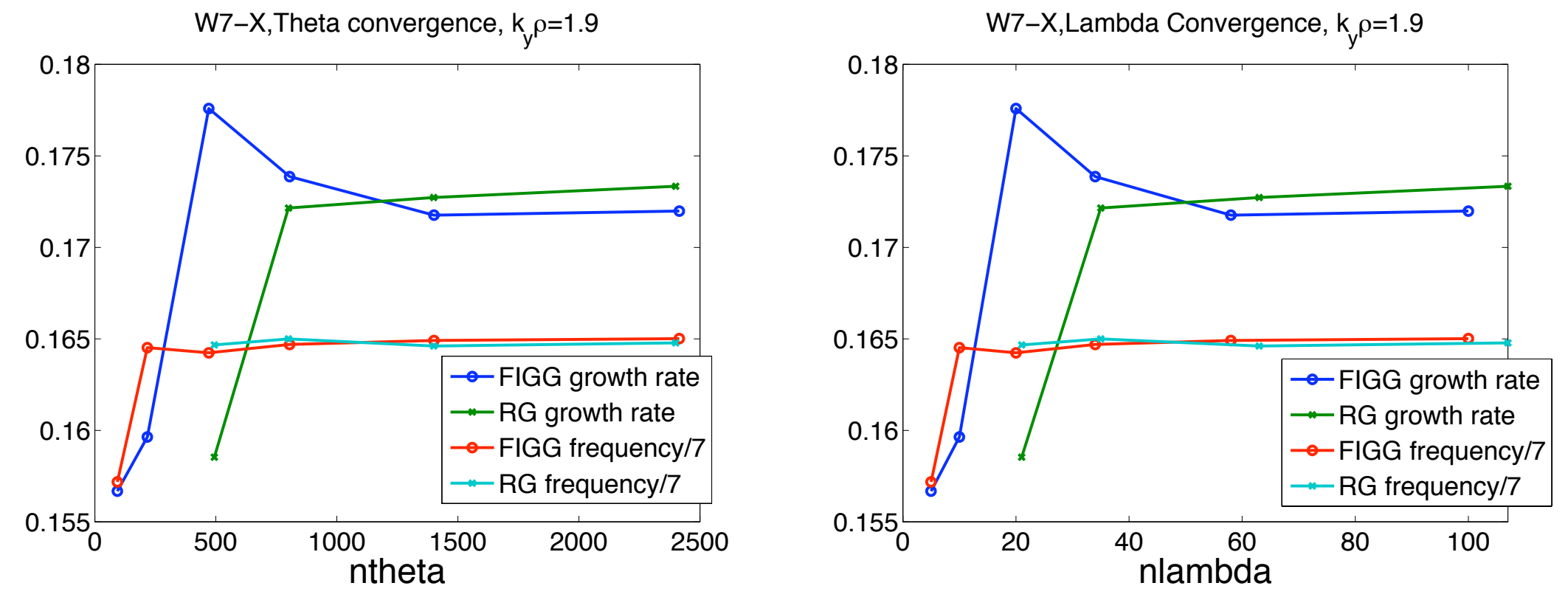
$ntheta$ from $[-3\pi, 3\pi]$.

FIGG vs. Rungridgen Convergence: NCSX



$ntheta$ from $[-5\pi, 5\pi]$.

FIGG vs. Rungridgen Convergence: W7-X



$ntheta$ from $[-3\pi, 3\pi]$.

Conclusions

- Benchmarked GS2 NCSX simulations with FULL
- Benchmarked GS2 Symmetric, NCSX, and W7-X simulations with GENE
- Improved GS2's trapped particle treatment
- Wrote FIGG: Flexible Improved Grid Generator for GS2 geometry input

Future Work

- Add drift-averaging capability to FIGG in order to reduce required resolution
- Conduct LHD, W7-AS, W7-X linear benchmarks with GENE
- Conduct detailed TEM study in 3D geometries
- Investigate stability dependence on β and ν in 3D geometries

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