Upgrades of GS2 for stellarators and initial gyrokinetic results

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Outline

1. Motivation and Background
2. Upgrades to GS2
   - Trapped Particle Treatment
   - Geometry Input
3. Benchmarks
   - GS2 vs. FULL Benchmark
   - GS2 vs. GENE benchmark
4. Other Studies
   - Electromagnetic
   - Nonlinear
   - How do we compare different devices?
5. Conclusions
   - Summary
   - Future Work

Turbulence should be studied in stellarators

- Modern stellarators are optimized for neoclassical transport
- Turbulence could become more important
- Stellarators have large parameter space of configurations
    - opportunity for optimizing for turbulence

Gyrokinetics in stellarators is an active area of research

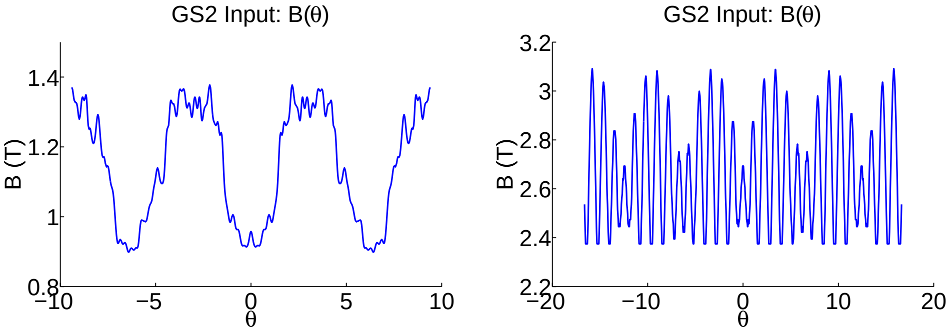
- FULL: Linear eigenvalue code
  - G. Rewoldt compared nine configurations for linear stability (PoP 12, 102512 (2005))
  - Also simulated studied ITG and TEM stability in an equilibrium produced as part of the NCSX design: QAS3-C82 (PoP 6, 4705 (1999))
- GENE: Nonlinear code
  - F. Jenko and P. Xanthopoulos have linearly and nonlinearly studied the ITG mode in W7-X plasmas (PoP 14, 042501 (2007), PRL 99, 035002 (2007))
  - H. Mynick and P. Xanthopoulos are using GENE to investigate optimization of stellarators for turbulent transport (PRL 105, 095004 (2010))
- GKV-X: nonlinear code, adiabatic electrons
  - Watanabe, Nunami, Sugama, Tanaka simulating LHD plasmas (Plasma and Fusion Research 6, 1403001 (2011))

GS2 was briefly used for stellarators a few years ago

- Original studies by Belli/Dorland: FULL/GS2 NCSX benchmark
  - needed reproduction to resolve questions of geometry normalizations
  - my initial thesis research
- Guttenfelder: HSX linear studies

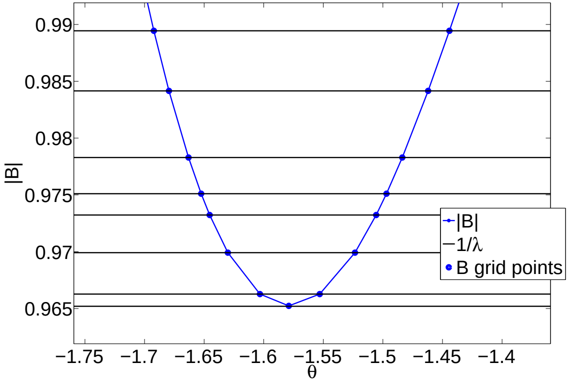
Outline

Initial W7-X studies revealed numerical instability/bug related to complicated |B| structure

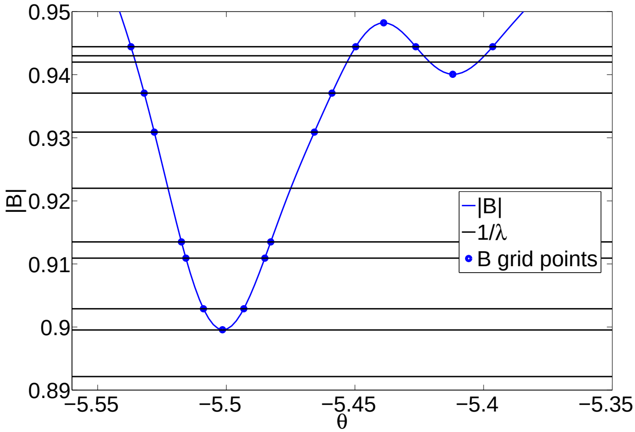


The grid generator should require coupled θ and λ grids

- Original velocity integral required a $v_{||}/v = \sqrt{1 - \lambda B(\theta)} = 0$ at each theta point (where $\lambda = \mu/E = 1/B_{tp}$).



GS2 grid generator improperly handles pitch angles for complicated geometries



Trapped particle treatment now allows for these more flexible grids

- Allows for multiple "totally trapped pitch angles" in a single well
- Treats barely passing or barely trapped particles consistently
- Fixed bugs in handling the boundary conditions for trapped particles at turning points.
- **Now allows the pitch angle grid to be independent of the spatial theta grid.**
  - $v_{||}/v = 0$ grid point not required at each theta grid point.
- All of these changes are buried in GS2's implicit solver
- Currently writing a replacement for rungridgen to be more robust.

Outline

New 3D geometry builder chain for GS2

- Starting from a VMEC 3D MHD equilibrium. . .
- Historically:
  - Terpsichore
    - Boozer coordinate transformation
  - VVBAL
    - Single flux tube ballooning coefficients
    - Radial coordinate: normalized poloidal flux
- New:
  - GIST[2]
    - Used for GENE 3D geometry
    - Radial coordinate: either poloidal or toroidal flux
    - Tested: reproduces VVBAL geometry

[2] PoP 16 082303 (2009)

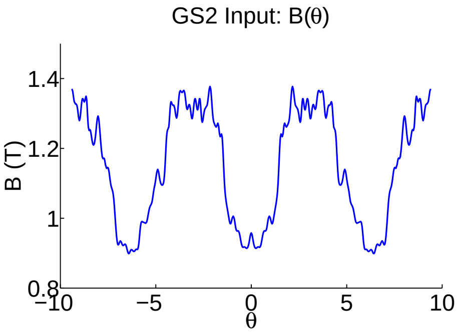
Outline

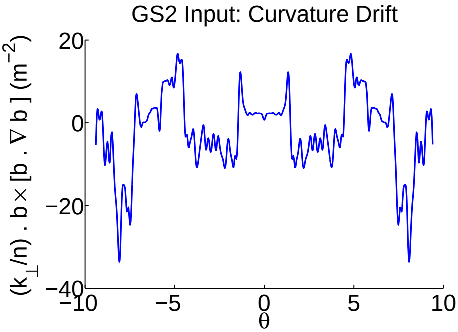
GS2 vs. FULL

- In 2000, E. Belli and W. Dorland conducted the first linear GS2 studies with non-axisymmetric geometries (NCSX QAS3-C82)
- My initial thesis research was redoing the study
  - troubleshooting geometry chain, reproducing geometry input
    - bug fixes (Guttenfelder)
    - clarifying definitions of parameters
  - re-benchmarking with the modern GS2
    - newer energy grid
    - my trapped particle modifications
- Still matches!
  - results will be published soon

NCSX QAS3-C82: 990 θ and 90 λ points

- $s = 0.875$, $\alpha = \pi/3$, $\theta_0 = 0$

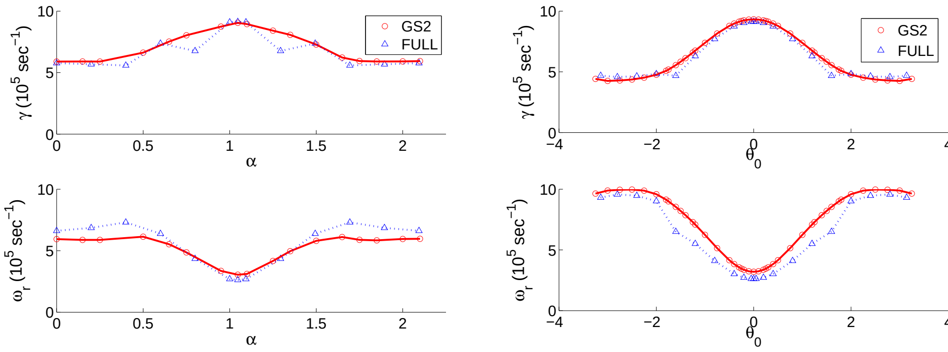




Test case: ITG with kinetic electrons

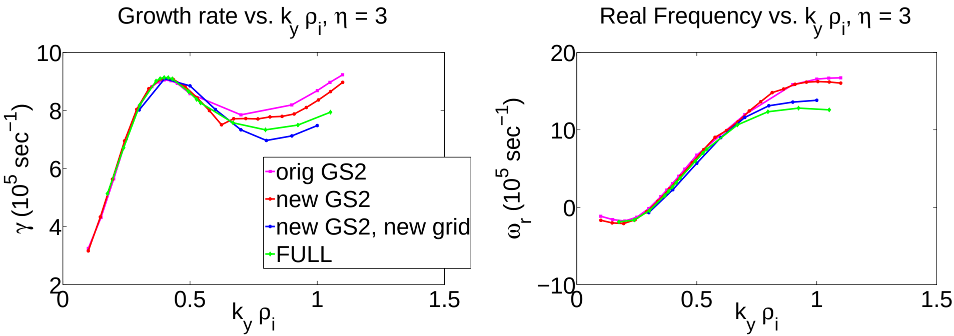
- Radial variable: Ψ_n
- $s = \Phi_T/\Phi_0 = 0.875$: very near the edge
- $q = 2.118$
- $T_i/T_e = 1.0$
- $a/L_T = 39.288$
- $a/L_n = 13.096$
- $a = 0.352m$
- $delt = 0.005$
- Time: linear run with 1 k_y about 7 minutes with 24 processors

GS2 and FULL agree well in α and θ_0 scan

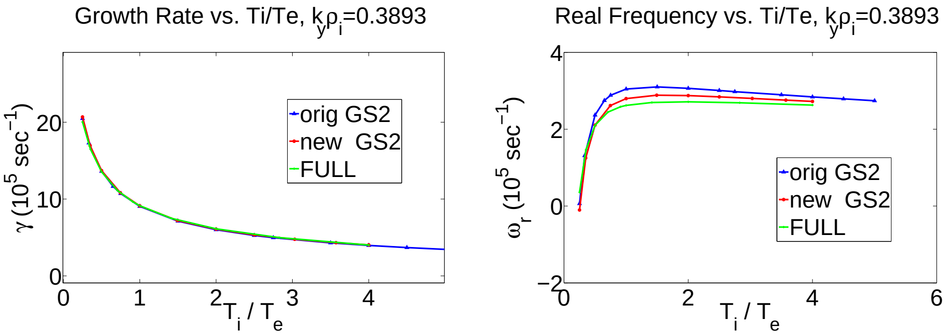


- $\alpha = \zeta - q\theta$ scan held $\theta_0 = 0$
- θ_0 scan held $\alpha = 0$

GS2 and FULL agree well in $k_y\rho_i$ scan



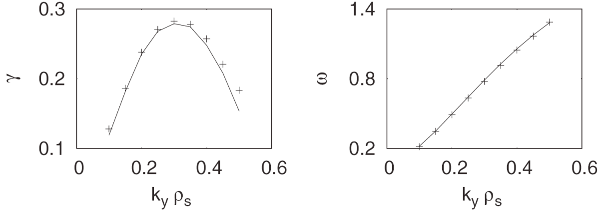
Ti/Te agreement improved with modern GS2



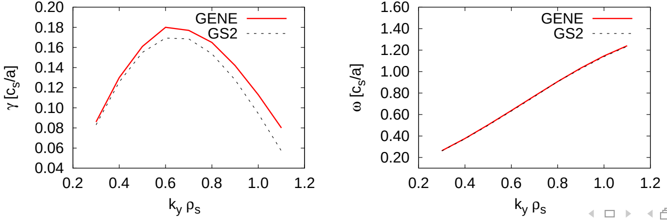
Outline

GS2/GENE NCSX-Sym matches with tokamak precision

Tokamak (PoP 15, 122108 (2008)):

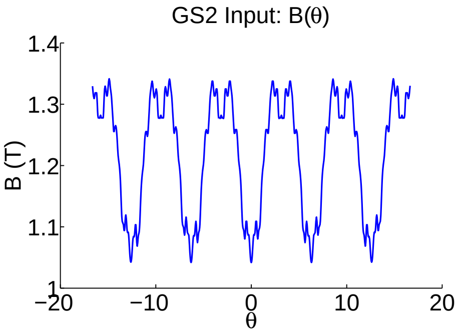


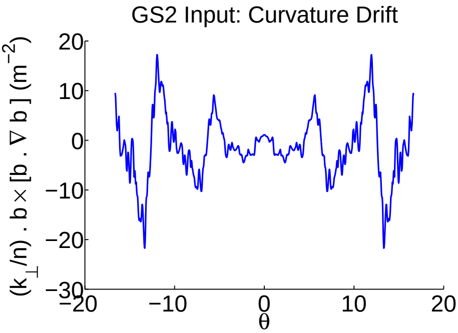
NCSX-Sym benchmark tests 3D geometry chain



NCSX-3D Geometry Coefficients: 990 θ and 51 λ points

- Future work: reduce θ resolution by bounce/orbit averaging coefficients over θ and/or λ grid?

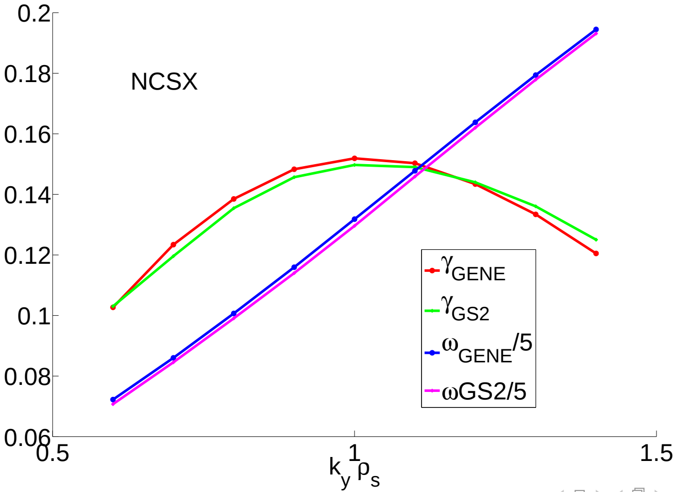




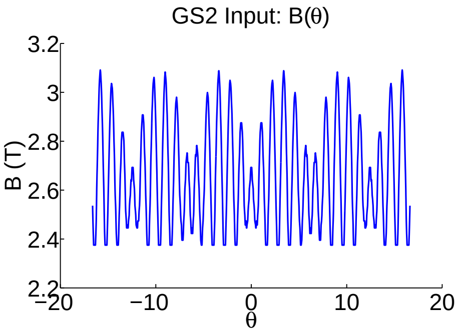
Test case: ITG with adiabatic electrons

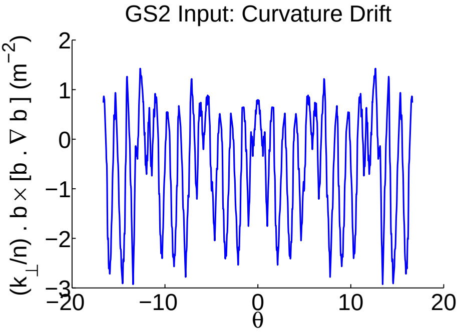
- Radial variable: $\sqrt{s}$
- $s = \Phi_T/\Phi_{Ta} = 0.515$
- $q = 2.162$
- $a = 0.345m$
- $T_i/T_e = 1.0$
- $a/L_T = 3.0$
- $a/L_n = 0.0$
- $delt = 0.005$
- Time: linear run with 9 k_ys, about 4 minutes with 48 processors

GS2 and GENE agree well for NCSX-3D $k_y\rho_i$ spectrum



W7-X Geometry: 1464 θ and 33 λ points

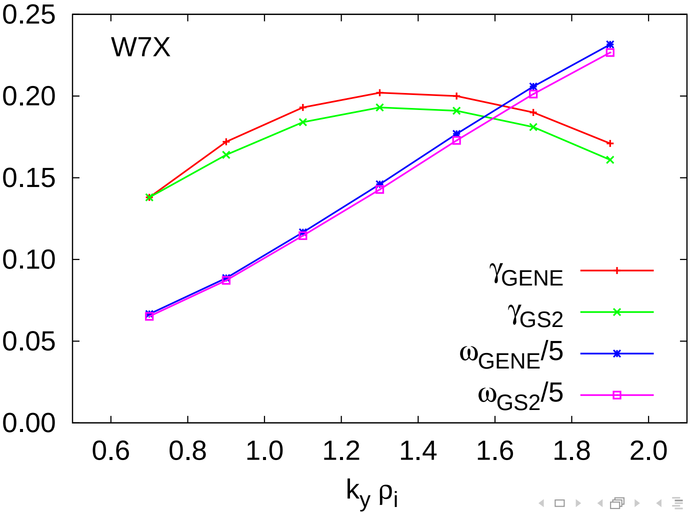




Test case: ITG with adiabatic electrons

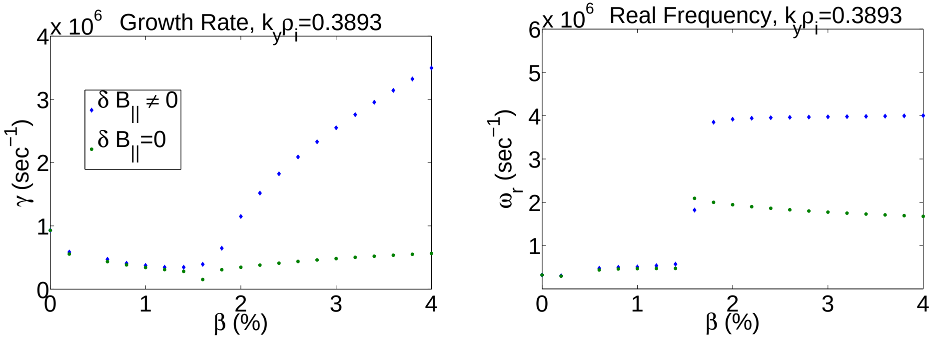
- Radial variable: $\sqrt{s}$
- $s = \Phi_T / \Phi_{Ta} = 0.2$
- averaged minor radius $a = 0.5m$
- $T_i / T_e = 1.0$
- $a / L_T = 3.0$
- $a / L_n = 0.0$
- $delt = 0.005$
- Time: linear run with 7 k_ys, about 20 minutes with 48 processors

GS2 and GENE agree well for W7-X $k_y \rho_i$ spectrum



Outline

Initial EM results

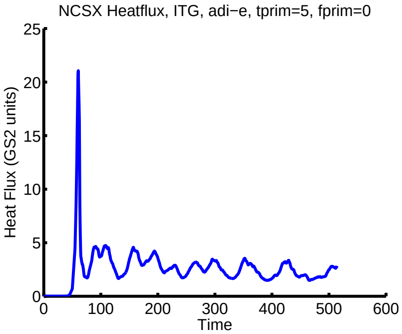


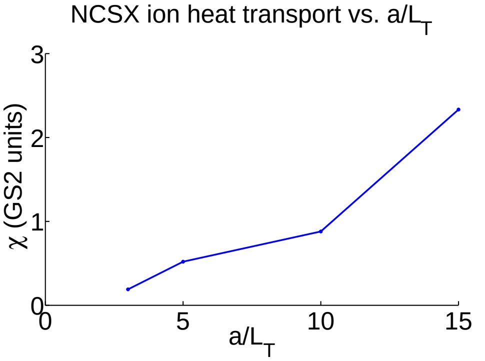
Outline

Parameters

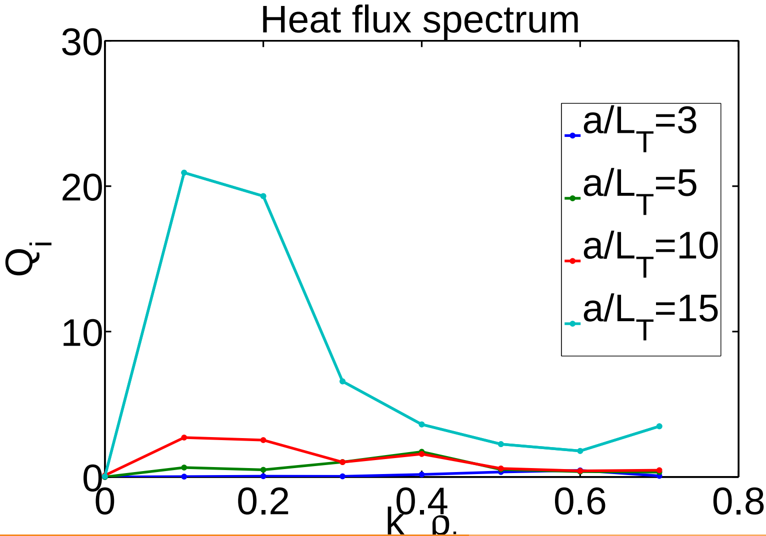
- NCSX eqs3.01.01: same geometry as GS2/GENE linear study
- 292 theta gridpoints
- 15 trapped pitch angles
- 8 k_y, 21 k_x
- Time: $\sim$27 hours on 48 processors

First GS2 nonlinear stellarator results





First GS2 nonlinear stellarator results

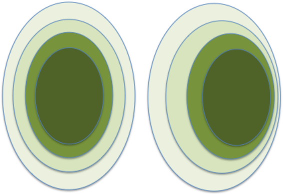


Outline

Appropriate metric of comparison between devices: χ_{ITER}?

- χ_{ITER} is invariant to $\rho = F(\rho')$ with the ITER standard definition:
- $\frac{3}{2}\frac{\partial}{\partial t}(nT) = \frac{1}{V'}\frac{\partial}{\partial \rho}[V'\langle|\nabla\rho|^2\rangle \chi_{ITER} n \frac{\partial T}{\partial \rho}] + P$

Better metric of comparison between devices: $\langle|\nabla\rho|^2\rangle\chi_{ITER}$?

- Because $\frac{1}{\tau_E} \sim \langle|\nabla\rho|^2\rangle\chi$, a better metric is $\langle|\nabla\rho|^2\rangle\chi$:
- 
- ∇T increases locally, $|\nabla\rho|^2$ increases, decreasing τ_E.
- This isn't invariant to ρ, so should use same definition: $\rho = \sqrt{\Phi_T/\Phi_{Ta}}$ (GENE standard, GS2 able), $\rho \in [0, 1]$.

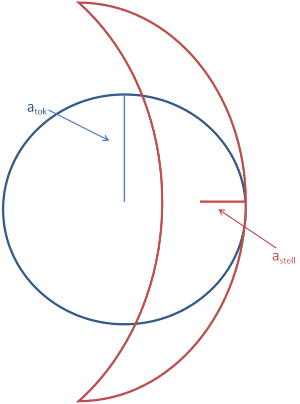
Even better metric of comparison between devices: $R\langle a\kappa\rangle\langle|\nabla\rho|^2\rangle\chi_{ITER}$?

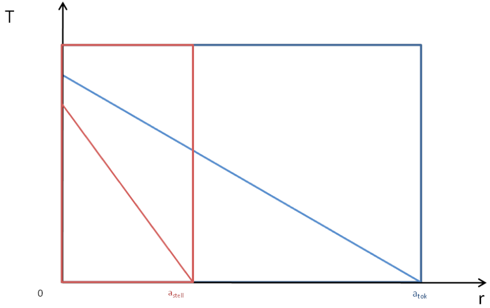
- Smaller $\langle|\nabla\rho|^2\rangle\chi$ may mean much larger device, which could be undesirable due to cost.
- $\frac{\$}{Q} \sim \frac{S}{nT\tau_E} \sim \frac{R\langle a\kappa\rangle\langle|\nabla\rho|^2\rangle\chi_{ITER}}{\beta}$: roughly compensates for size and cost (inverse of bang per buck)
  - S =surface area
  - assume fixed β (for now)

R/L_{Tcrit} preferred in tokamak comparisons

- $R/L_{Tcrit-TOK} \approx 2(1 + \frac{T_i}{T_e}) \approx 4$
- $T_0 = T_a e^{\int_0^a dr/L_T} \approx T_a e^{a/L_T} = T_a e^{\frac{a}{R}\frac{R}{L_T}} \approx T_a e^{4\frac{a}{R}}$
    - Smaller aspect ratio increases T_0
    - Higher R/L_{Tcrit} would also improve T_0
    - Stability is determined by R/L_T, but performance depends on a/L_T.
    - $\frac{a}{L_T} \equiv -\frac{1}{T}\frac{\partial T}{\partial \rho}$

Higher R/L_{Tcrit} might be offset by narrower plasma





- This stellarator has a higher R/L_{Tcrit} than the tokamak but a smaller T_0.
- R isn't as meaningful in stellarators

One could use: $R\langle a\kappa\rangle\langle|\nabla\rho|^2\rangle\chi_{ITER}$ vs. a/L_T instead

- $R\langle a\kappa\rangle\langle|\nabla\rho|^2\rangle\chi_{ITER}$ captures heat transport and approximate cost for size and complexity
- $\frac{a}{L_T} \equiv -\frac{1}{T}\frac{\partial T}{\partial\rho}$ determines performance

Outline

Summary

- GS2 has been upgraded to allow for more flexible grids
- New geometry framework for 3D GS2 simulations (GIST) was initially tested
- Linear benchmark with FULL was reproduced with modern GS2
- Successfully linearly benchmarked GS2 and GENE on initial ITG, adiabatic electron NCSX and W7-X cases
- Demonstrated the need to include $\delta B_{||}$ in high β studies
- Initial nonlinear NCSX studies are promising
- We discussed best comparison metrics between fusion devices

Outline

Goals

- Complete new grid generator
- Further benchmarks with GENE in NCSX and W7-X geometries (ITG kinetic electron, collisions, EM, nonlinear)
- Extend nonlinear turbulence studies: reverse shear and shaping effects on ITG/TEM/ETG