A Comprehensive Study of the Parametric Dependencies of Transport Using Gyrokinetic Simulations

Presented by
J. Kinsey, R. Waltz, J. Candy

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Over 320 Nonlinear Gyrokinetic Simulations Have Been Performed Using The GYRO Code

- A nonlinear simulation database has been created for benchmarking and transport model development

  http://fusion.gat.com/comp/parallel

- Scans in $R/a$, $r/a$, $q$, $s$, $\hat{s}$, $\alpha$, $\alpha/L_n$, $\alpha/L_T$, $\nu$, $\beta$, $T_i/T_e$, $\kappa$, $\delta$, dilution, and ExB shear with and without kinetic electrons (most runs w/ kinetic electrons)

- Simulations around several reference cases assuming $s$-$\alpha$ geometry, electrostatic (except for $\beta$ scan), and flat profiles across annulus, zero boundary conditions
  - GA Standard Case (STD): $R/a=3$, $r/a=0.5$, $q=2$, $\hat{s}=1$, $\alpha=0$, $\alpha/L_T=3$, $\alpha/L_n=1$, $T_i/T_e=1$, $\nu=0$, $\beta=0$
  - TEM1 Case: STD w/ $\alpha/L_n=2$, $\alpha/L_T=2$
  - TEM2 Case: STD w/ $\alpha/L_n=3$, $\alpha/L_T=1$

- Miller geometry used for $\kappa$ and $\delta$ scans

- Diffusivities shown are time-averaged values and are normalized to the gyro-Bohm diffusivity, $\chi_{GB} = c_s \rho_s^2 / a$
Nonlinear Database Comprised of Parameter Scans

• Temperature and density gradient scans: 25 kinetic electron simulations (plus 6 kinetic electron Cyclone simulations, J. Candy)
• Aspect ratio and minor radius scans: 12 kinetic electron simulations
• Collisionality and Ti/Te scans: 10 kinetic electron simulations
• Elongation and triangularity scans: 5 adia. electron + 34 kinetic electron simulations
Temperature Gradient Scan for STD Case Including Kinetic Electrons

- STD case scans in $a/L_T$ w/ $a/L_n=0.5$, $1.0$, and $1.5$
- Transport not as stiff at low gradients for peaked density ($a/L_n=1.5$)

* Flat Density
* Peaked Density

* Note: error bars on plots are a measure of intermittency and NOT uncertainty

$\chi_{GB} = c_s \rho_s^2 / \alpha$
Density Gradient Scan for STD Case

• STD case $a/L_n$ scan with $a/L_T=1.0$
  – Ion and electron density gradient varied together

• Particle diffusivity changes from negative (inward) to positive (outward) as density gradient is increased
  – $D=D_e=D_i$ due to ambipolarity

• Electron energy and particle transport show stronger dependence on $a/L_n$ than ion energy transport
Temperature Ratio Scan for STD Case

- STD case $T_i/T_e$ scan at fixed $a/L_T$
- Ion energy diffusivity modestly reduced going from $T_i/T_e = 1$ to $T_i/T_e = 2$
- Electron energy transport fairly insensitive to $T_i/T_e$
- Particle pinch somewhat reduced as $T_i/T_e$ is increased
- Linear stability of spectrum for $T_i/T_e = 2$ shows ITG modes below $k_\theta \rho_s = 0.3$ and TEM modes above $k_\theta \rho_s = 0.3$
Aspect Ratio and Minor Radius Scans for STD Case

- Scans in R/a and r/a for STD parameters with kinetic electrons
- Strong reduction in transport below A=2 which is consistent with previous linear gyrokinetic studies (e.g. Rewoldt)
- Nearly linear increase in transport with increasing r/a at fixed R/a
Shorter Wavelength Modes Drive Outward Flow at High Aspect Ratio

- Particle pinch predicted at low-medium aspect ratio
  - At $A = R/a = 3.0$, all modes in spectrum drive a pinch

- Null flow point near $A = 5.0$
  - Modes above $k_{\theta \rho_s} = 0.15$ drive an outward flow
Particle Pinch Strongly Impacted By Collisions

- Particle pinch predicted for STD case w/o collisions
- Addition of collisions increasingly eliminates particle pinch driven by low $k_y$ modes
- Electron energy transport insensitive to collisions

\[ \nu = 0.02 \]

\[ \nu = 0.10 \]
Ion and Electron Transport Exhibits Linear \( q \) Dependence in STD Case Kinetic Electron Simulations

- Energy transport exhibits linear \( q \) dependence for both positive and negative shear
  - \( D \) also follows linear \( q \) dependence if \( D \) is positive
  - Spectral downshift w/ decreasing \( q \) is evident
  - Small contribution to \( \chi_e \) from higher \( k_0 \rho_s \) modes

- Particle transport insensitive to \( q \) for \( s=1.0 \) case where \( D \) is negative
  - Passing electron contribution to \( D \) changes sign near \( q=2 \)
  - \( D_{\text{pass}}/D_{\text{total}} \) small (0.1-0.2) but large enough to impact \( q \) scaling
TEM Cases Also Exhibit Linear $q$ Dependence

- **TEM1**: STD parameters with $a/L_T=2$, $a/L_n=2$
  (half of modes in ion direction, others in electron direction)

- **TEM2**: STD parameters with $a/L_T=3$, $a/L_n=1$
  (All modes in electron direction)
GAM Amplitude Increases With Increasing q

- Geodesic Acoustic Modes evident at n=0 at
  \( \omega(a/c_s) = \pm 0.75 \)

- Amplitude in simulations is consistent with q scaling of
  GAM damping rate:

  \[ \gamma_G = -\omega_G \exp(-q^2) \]

  where \( \omega_G \) is the GAM frequency (Hinton, 1999)

- Fluctuations ITG dominated in q=4 case with 1 peak at negative
  \( \omega(a/c_s) \)

- Spectrum shows both ITG and TEM peaks for q=1.25 case
At Low $q$, $n=0$ Amplitude Larger Than Neighboring $n > 0$ Mode Amplitudes

- Time-averaged RMS spectral intensity of the potential fluctuations compared for STD case w/ $q=1.25$ and $q=4.0$

- Spectral intensity shown in $(k_x, k_y)$ plane where $k_x = k_r \rho_s$ and $k_y = k_\theta \rho_s$

- Also evident that higher $k_y$ modes contribute more to transport at low $q$ compared to high $q$
Particle Diffusivity Can Change Sign As Magnetic Shear Is Varied

- Magnetic shear $\hat{s}$ varied at fixed $q$ for $\alpha=0$ and $\alpha=1$
- For STD case, null flow point found at $\hat{s}=0.5$ for $\alpha=0$
  - $D$ negative for $\hat{s} > 0.5$
  - $D$ positive for $\hat{s} < 0.5$
- Alignment of null point with maximum in $\chi$ particular to STD parameters
- Alpha stabilizing for negative shear (e.g. $\hat{s}=-0.5$), and destabilizing for positive shear (e.g. $\hat{s}=2$)
Spectral Analysis at Null Point Shows Some Modes Drive A Negative Flow With Other Modes Drive A Positive Flow

- Spectrum includes 16 toroidal mode numbers with a maximum \( k_{\theta \rho_s} = 0.75 \)
- Null flow point at \( s = 0.5 \)
  - Linear stability shows transition from ITG to TEM above \( k_{\theta \rho_s} = 0.65 \)
- Time-average particle diffusivity is negative for \( s = 1.5 \) and positive for \( s = -0.5 \)
  - Linear stability shows TEM above \( k_{\theta \rho_s} = 0.50 \) for \( s = 1.5 \)
  - Linear stability shows TEM above \( k_{\theta \rho_s} = 0.65 \) for \( s = -0.5 \)
Ratio Of Ion to Electron Energy Transport Changes Dramatically With Magnetic Shear

- For STD case, ratio of $\chi_i/\chi_e$ changes significantly with shear
  - At $s=2$, $\chi_i/\chi_e = 9.7$
  - At $s=1$, $\chi_i/\chi_e = 3.4$
  - At $s=-1$, $\chi_i/\chi_e = 1.6$
The Effects Of Elongation and Triangularity On Turbulent Transport Have Been Investigated Using The Miller Equilibrium Model

- Nine parameters are required to describe the local equilibrium using Miller geometry:\(^1\): \(\kappa\) (elongation), \(\delta\) (triangularity), \(q\), \(s\) (magnetic shear), \(\alpha\) (normalized pressure gradient)\(^1\), \(A=R_0/r\), \(\partial_r R_0\), along with gradient factors of \(\kappa\) and \(\delta\) (\(s_\kappa\) and \(s_\delta\))

- For D-shaped plasmas, the shape of a flux surface is specified in terms of the major radius \(R\) and height \(Z\) as a function of the poloidal angle \(\theta\):
  \[
  R = R_0 + r \cos[\theta + (\sin^{-1}\delta)\sin \theta]
  \]
  \[
  Z = \kappa r \sin \theta
  \]

- Systematic nonlinear scans in \(\kappa\) and \(\delta\) were performed for the STD case with \(\partial_r R_0=0\), \(\alpha=0\), \(\beta=0\)
  - For \(\kappa\) scans, we also varied \(s_\kappa = (r/\kappa)\partial_r \kappa \approx (\kappa-1)/\kappa\)
  - For \(\delta\) scans, we also varied \(s_\delta = (r/(1-\delta^2)^{0.5})\partial_r \delta \approx \delta/(1-\delta^2)^{0.5}\)

Adiabatic Electron Simulations Show The Ion Energy Transport Decreasing Linearly With Increasing Elongation

- $\kappa$ varied from 1 to 2 for STD case using Miller geometry
  - kappa gradient factor $s_\kappa$ varied along with $\kappa$
  - GYRO results for $\chi_{\text{natural}}$ where
    \[ \chi_{\text{natural}} = \langle |\nabla r|^2 \rangle \chi_{\text{ITER}} \]
    For concentric ellipses where "r" is the midplane minor radius:
    \[ \langle |\nabla r|^2 \rangle = (1+\kappa^2)/(2\kappa^2) \]
    \[ B_{\text{unit}} = (\rho/r)(d\rho/dr)B_0 \approx \kappa^2 B_0, \text{ so} \]
    \[ \chi_{\text{ITER}} \approx 2/(1+\kappa^2) \chi_{\text{natural}} \]

- Previous NL gyrofluid simulations by Waltz\(^1\) showed no $\kappa$ dependence for $\chi_{\text{natural}}$ at $q=2$ (and $q=3$)

\(^1\) R. E. Waltz, and R.L. Miller, Phys. Plasmas 6, 4265 (1999).
Kinetic Electron Simulations Also Shows Energy Transport Decreases Linearly With Increasing Elongation

- Linear decrease in both $\chi_e$ and $\chi_i$ valid for $\kappa$ scans at different safety factors
  - $\kappa$ varied from 1.0 to 2.0 for different $q$ values and for different shear values using STD parameters with $s=1.0$
  - Miller geometry with $\delta=0$; kappa gradient factor $s_\kappa=(\kappa-1)/\kappa$ varied along with $\kappa$
  - Offset linear gives best fit to NL results. Growth rate at $k_\theta\rho_s=0.3$ shows same dependence
  - Particle transport shows little or no $\kappa$ dependence
    Caveat: D is small and negative
    -> follows $\kappa^{-1}$ dependence if D is positive (see shear scan)
Dependence of Transport on Triangularity Weak For Circular Plasmas, Stronger For Elongated Plasmas

- $\delta$ varied for $\kappa=1.0$, 1.5, and 2.0 using STD parameters
  - Miller geometry, delta gradient factor $s_\delta$ varied along with $\delta$
- Stronger $\delta$ dependence for $\kappa=1.5$, 2.0 cases compared to $\kappa=1.0$ case
  - $\delta$ destabilizing, especially for $\chi_e$ and D, going from $\delta=0.0$ to $\delta=0.5$
Triangularity Strongly Impacts Particle Transport Spectrum For Elongated Plasmas

- $\delta$ varied from 0.0 to 0.5 for STD case with $\kappa=2.0$
- Particle transport changes from $D/D_{GB}=-1.73$ to $D/D_{GB}=+0.51$
  - Transport from low $k$ modes changes sign
  - Less of an effect at $\kappa=1.0$ ($D/D_{GB}=-0.8 \rightarrow D/D_{GB}=-0.1$ when $\delta=0.0 \rightarrow 0.5$)
Nonlinear Gyrokinetic Simulations With Adiabatic Electrons Show Higher ExB Shear Quench Point Compared to Gyrofluid Simulations

- ExB shear quench rule originally developed from gyrofluid ITG simulations which showed a quench point at $\gamma_E = \gamma_{\text{max}}$
- Using GYRO with no parallel velocity shear ($\gamma_p = 0$), two quench points can be found depending on how the ExB shear is applied in the simulations
  - ITG transport quenches at $\gamma_E = 1.6 \gamma_{\text{max}}$ when $\gamma_E$ applied at onset of simulation
  - Quench point higher near $\gamma_E = 2 \gamma_{\text{max}}$ when $\gamma_E$ applied in a restart from simulation without $\gamma_E$ included
- Purely toroidal rotation case with $\gamma_p = (Rq/r) \gamma_E = 12 \gamma_E$ shows that transport not quenched by any level of $\gamma_E$
ExB Shear Quench Rule Remains Valid With Addition Of Kinetic Electrons In Nonlinear Gyrokinetic Simulations

- ExB shear quench point near \( \gamma_E = 2\gamma_{\text{max}} \) for ions and electrons
  - Same quench point found for the adiabatic electron case
  - Also valid for TEM cases (e.g. STD case w/ \( a/L_n=3, a/L_T=1 \)) and for negative shear (e.g. STD case w/ \( s=-0.5 \))

- Gradual reduction to zero transport near quench point
  - Sharp drop in \( \chi \) near quench point seen in adiabatic runs NOT seen with kinetic electrons

- Transport not quenched when parallel velocity shear included (assuming purely toroidal rotation with \( \gamma_p = (Rq/r)\gamma_E = 12\gamma_E \))

16 modes
\( k_\theta \rho_s \leq 0.75 \)
\( \gamma_{\text{max0}} = 0.27 \)
Summary

- A large database of over 320 nonlinear GYRO gyrokinetic simulations has been created comprising of various parameter scans around several reference cases
  - Scans in R/a, r/a, q, s, α, a/Lₙ, a/Lₜ, ν, β, Tᵢ/Tₑ, κ, δ, dilution, and ExB shear with and without kinetic electrons (most runs w/ kinetic electrons)

- Aspect ratio scan shows strong reduction in transport below A=2, weak reduction going from A=3 to A=5
  - Strong particle pinch near A=2
  - At high A, low-k modes drive a pinch while higher-k modes drive an outward flow

- Safety factor scans show that the ion and energy transport exhibits linear q dependence for both ITG and TEM dominated cases
  - Spectral downshift with increasing q which contributes to most of q⁻¹ dependence of transport
  - D also exhibits linear q dependence if D is positive. If D is negative (pinch), then overall q dependence weak due to change in sign of passing electron contribution as q is varied
  - GAM amplitude increases with increasing q; amplitude and frequency consistent with analytic calculations by Hinton, et al.
  - n=0 amplitude greater than neighboring n>0 amplitudes at low q, comparable amplitudes at higher q values
Summary (cont.)

• Magnetic shear scans show that particle diffusivity can change sign as shear is varied
  - At null flow point, some modes drive a pinch while other modes drive an outward flow
  - Ratio of ion to electron transport changes dramatically with shear ($\chi_i/\chi_e$ largest for large positive shear, smallest for negative shear)

• Adiabatic and kinetic electron simulations robustly show that $\chi_{\text{natural}}$ exhibits an inverse linear dependence on elongation
  - Unlike previous gyrofluid ITG simulations by Waltz, we find $\kappa^{-1}$ regardless of q and s values
  - Particle transport also exhibits $\kappa^{-1}$ dependence if D is positive

• Dependence on triangularity strongest for highly elongated plasmas, weak effect for circular shaped plasmas
  - Triangularity destabilizing for both energy and particle transport
  - Triangularity has significant impact on particle transport spectrum at high elongation; transport from low-k modes can change sign as $\delta$ is varied

• ExB shear quench rule remains valid in the presence of kinetic electrons with a quench point at $\gamma_E=2\gamma_{\text{max}}$ for ions and electrons
  - Quench rule valid for both ITG and TEM cases
  - Transport may not be quenched at higher q values if parallel velocity shear included in simulations