Plasma Shaping Effects on Driftwave Transport and ExB Shear Quenching in GYRO Simulations

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

- **Over 350 nonlinear gyrokinetic simulations have been performed using the GYRO code**

  http://fusion.gat.com/theory/gyro

- **Systematic scans in R/a, r/a, q, $\hat{s}$, α, a/L_n, a/L_T, ν, β, T_i/T_e, κ, δ, dilution, and ExB shear with and without kinetic electrons (most runs w/ kinetic electrons)**
- **Simulations around several reference cases: most with $\hat{s}$-α geometry, electrostatic (except for β scan), and flat profiles across annulus, zero boundary conditions**
  - **GA Standard Case (STD):** $R/a=3$, $r/a=0.5$, $q=2$, $\hat{s}=1$, $\alpha=0$, $a/L_T=3$, $a/L_n=1$, $T_i/T_e=1$, $\nu=0$, $\beta=0$
  - **TEM1 Case:** STD w/ $a/L_n=2$, $a/L_T=2$
  - **TEM2 Case:** STD w/ $a/L_n=3$, $a/L_T=1$
- **Miller equilibrium model used for κ and δ scans**
- **Diffusivities shown are time-averaged values and are normalized to the gyro-Bohm diffusivity, $\chi_{GB}=c_s\rho_s^2/a$**

The effects of elongation and triangularity on turbulent transport have been investigated using the Miller equilibrium model in the GYRO code

- **Nine parameters are required to describe the local equilibrium using Miller geometry[1]: κ (elongation), δ (triangularity), q, $\hat{s}$ (magnetic shear), α (normalized pressure gradient) , $A=R_0/r$, $\partial_r R_0$, along with gradient factors of κ and δ (s_κ and s_δ)**

- **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 θ:**

$$R = R_0 + r\cos[\theta + (\sin^{-1}\delta)\sin\theta]$$
$$Z = \kappa\, r \sin\theta$$

- **Systematic nonlinear scans in κ and δ were performed for the STD case with $\partial_r R_0=0$, $\alpha=0$, $\beta=0$**
  - For κ scans, we also varied $s_\kappa=(r/\kappa)\partial_r\kappa \approx (\kappa-1)/\kappa$
  - For δ scans, we also varied $s_\delta=(r/(1-\delta^2)^{0.5})\partial_r\delta \approx \delta/(1-\delta^2)^{0.5}$
  - All other quantities held fixed, including **r**, within κ and δ scans

[1] R. L. Miller, et al, Phys. Plasmas 5, 973 (1998)

Scaling with shape and aspect ratio requires a clear definition of the diffusivity and what is held constant

- **Elongation scans performed at fixed midplane minor radius, r, and gradient scale lengths (defined in terms of r)**
- **Translation of $\hat{\chi}_{GYRO}$ to $\hat{\chi}_{ITER}$ where $\hat{\chi} = \chi / \chi_{GB} = \chi / (c_s \rho_s^2/a)$**

$\chi_{GYRO} = <|\nabla r|^2> \chi_{ITER}$

For concentric ellipses where "r" is the midplane minor radius:

$$<|\nabla r|^2> = (1+\kappa^2)/(2\kappa^2)$$

So, we have $\hat{\chi}_{ITER} = [2\kappa^2/(1+\kappa^2)]\ \hat{\chi}_{GYRO}\ \chi_{GB\_Bunit} / \chi_{GB\_B0}$

$$= [2\kappa^2/(1+\kappa^2)]\ \hat{\chi}_{GYRO}\ (B_0/B_{unit})^2$$

Where χ_{GB_B0} and χ_{GB_Bunit} are the GB χ's at fixed B_0 and B_{unit}

We have a κ dependence that enters thru B_{unit} in ρ_s

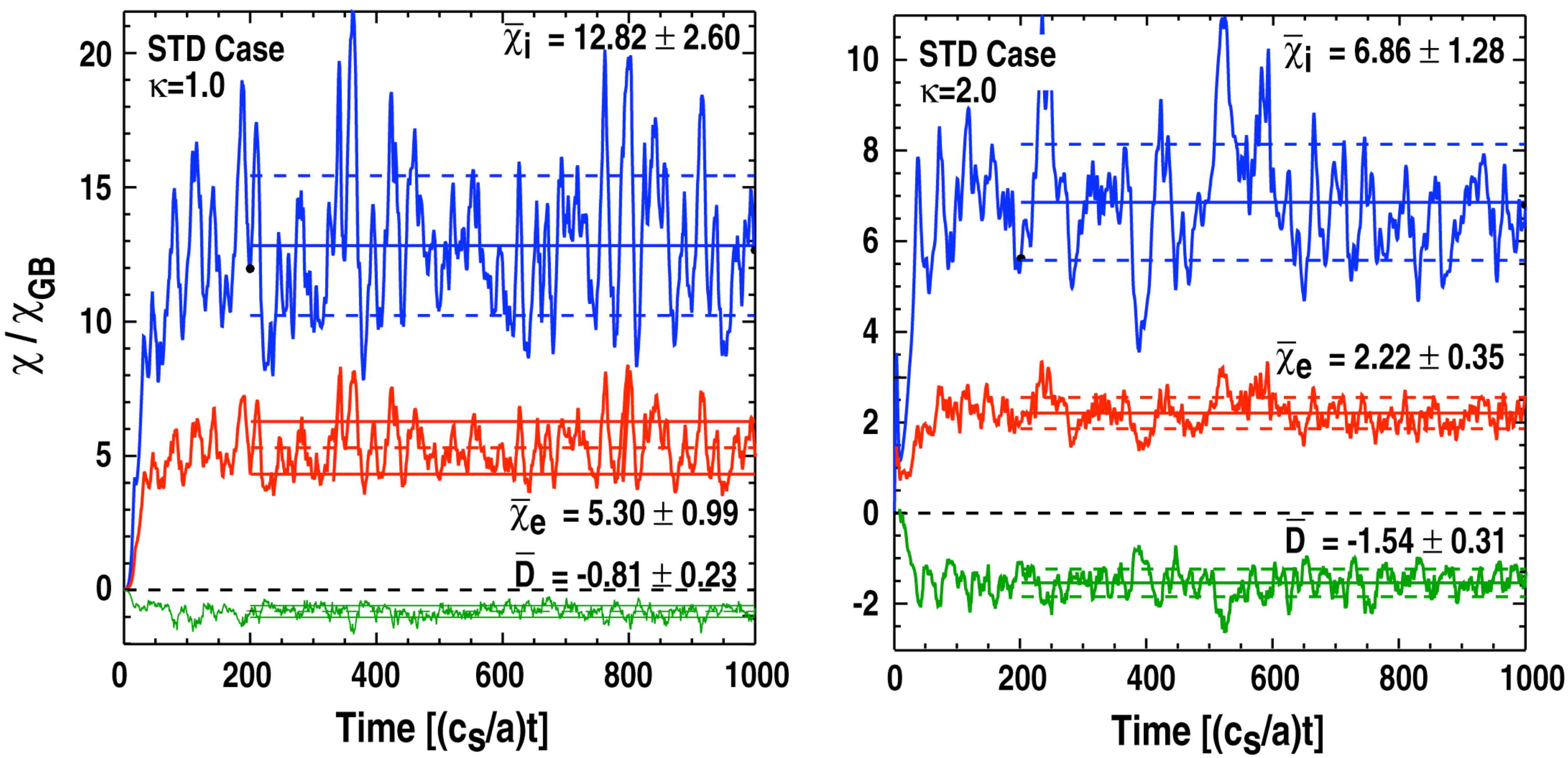
$$B_{unit} = (\rho/r)(d\rho/dr) B_0 \approx \kappa B_0 \text{ since } \rho \approx (\kappa)^{0.5}\, r$$

Finally, we have

$$\hat{\chi}_{ITER}\ (@\text{fixed } B_0) \approx 2/(1+\kappa^2)\ \hat{\chi}_{GYRO}\ (@\text{fixed } B_{unit})$$

GYRO simulations show elongation stabilizes transport

- **Elongation and elongation gradient factor varied around GA STD case**
  - Miller geometry w/ kinetic electrons, collisionless, electrostatic



GYRO simulations show the normalized energy diffusivities decreasing linearly with increasing elongation for the STD case

- **Linear decrease in transport for κ scan around STD case**
  - At fixed power, we can write

    $$\tau_E \propto a^2/\hat{\chi}_{GYRO} \propto a^2\left[B_o^2 a\kappa^2/\hat{\chi}_{GYRO}\right]^{2/5}\left[\kappa n R/P\right]^{3/5}$$

    So, going from κ=1.0 to 1.5 w/

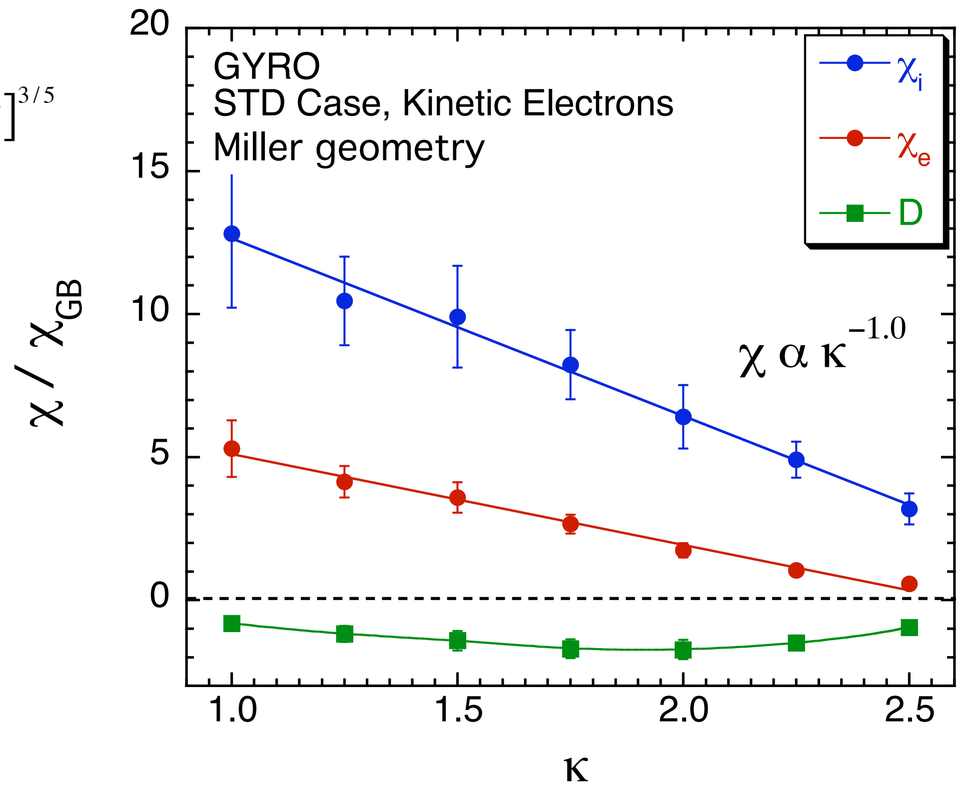
    $\hat{\chi}_{GYRO} \propto \kappa^{-1}$ yields an increase in τ_E of $(1.5^{6/5})(1.5^{3/5})=2.08$

    ITER 98(y,2) with $I \propto \left(a^2 B_o/(Rq)\right)\kappa$ yields

    $$\tau_E \propto I^{0.93} B^{0.15} P^{-0.69} n^{0.41} M^{0.19} R^{1.97} \varepsilon^{0.58} \kappa^{0.46}$$

    $$\propto \kappa^{1.71} q^{-0.93} B^{1.08} P^{-0.69} n^{0.41} a^{1.08} R^{0.46}$$

    which yields $(1.5)^{1.71}=2.0$!
  - D shows little or no κ dependence when negative
    - -> D has same dependence as χ if D is positive (e.g. s=0.5)



* Offset linear fit shown for χ_i and χ_e

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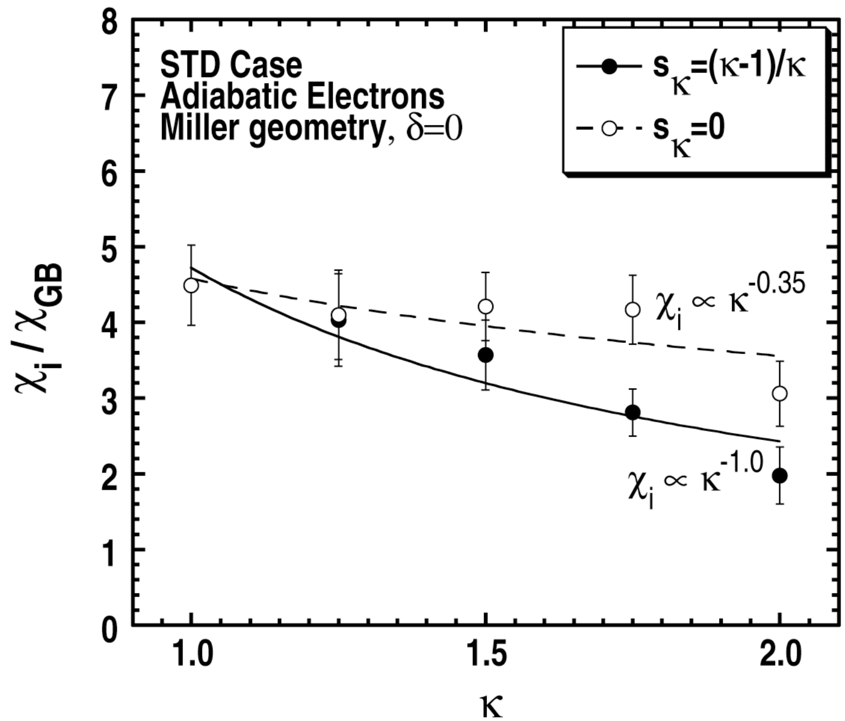
Most of elongation scaling in GYRO simulations is from elongation shear rather than local value of elongation

- **Elongation varied in GYRO simulations around STD parameters holding all other quantities fixed**
- **Elongation scan varying κ but with no elongation gradient (s_κ) shows that changing the local κ only result in a weak effect on transport**
  - Normalized χ_i scales like κ^{-1} if s_κ is varied along with κ

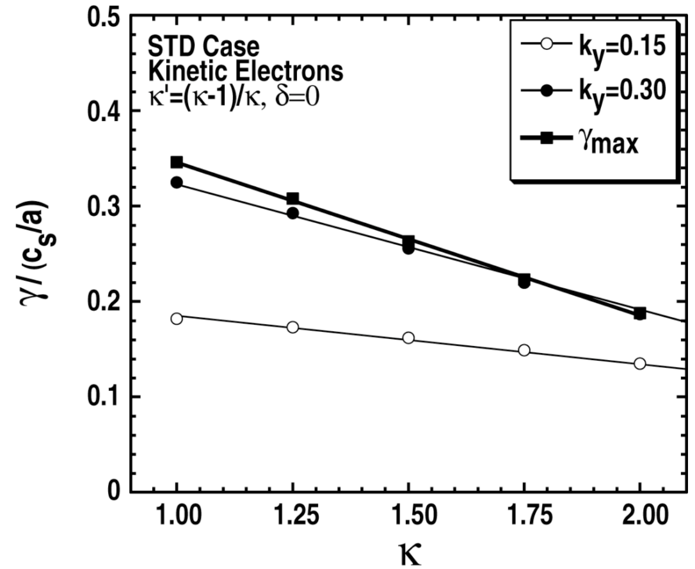


Elongation scaling of the energy transport can vary and depends on the wavenumber where the transport peaks

- **Elongation scans performed for a variety of safety factors, magnetic shears, and temperature gradients**
- **Elongation scaling for χ_e changes more than χ_i**
  - Scaling is weaker if χ peaks at low $k_\theta\rho_s$ (high drive cases)
  - Scaling stronger when the peak occurs at high $k_\theta\rho_s$ (low drive cases)
- **Low k modes less sensitive to elongation than higher k modes**
- **Higher k modes more sensitive to κ and contribute more to χ_e**

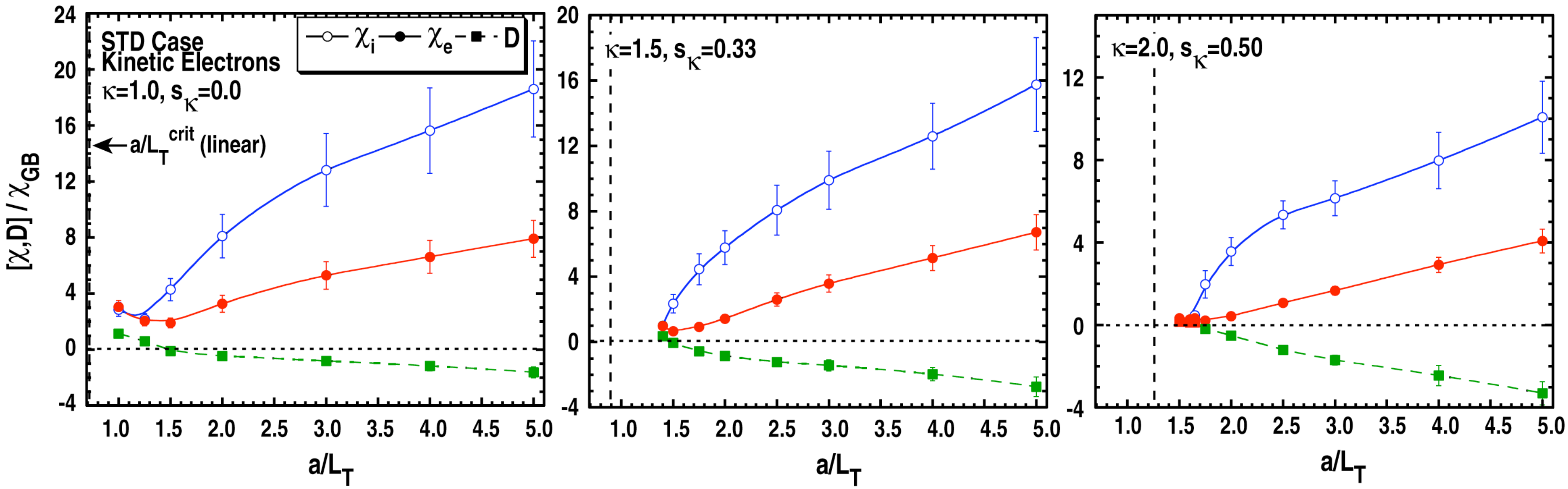
$$\chi_i \propto \kappa^{-1.0+0.14(q-2)+0.33(s-1)+0.14(a/L_T-3)}$$

$$\chi_e \propto \kappa^{-1.4+0.14(q-2)+0.33(s-1)+0.54(a/L_T-3)}$$



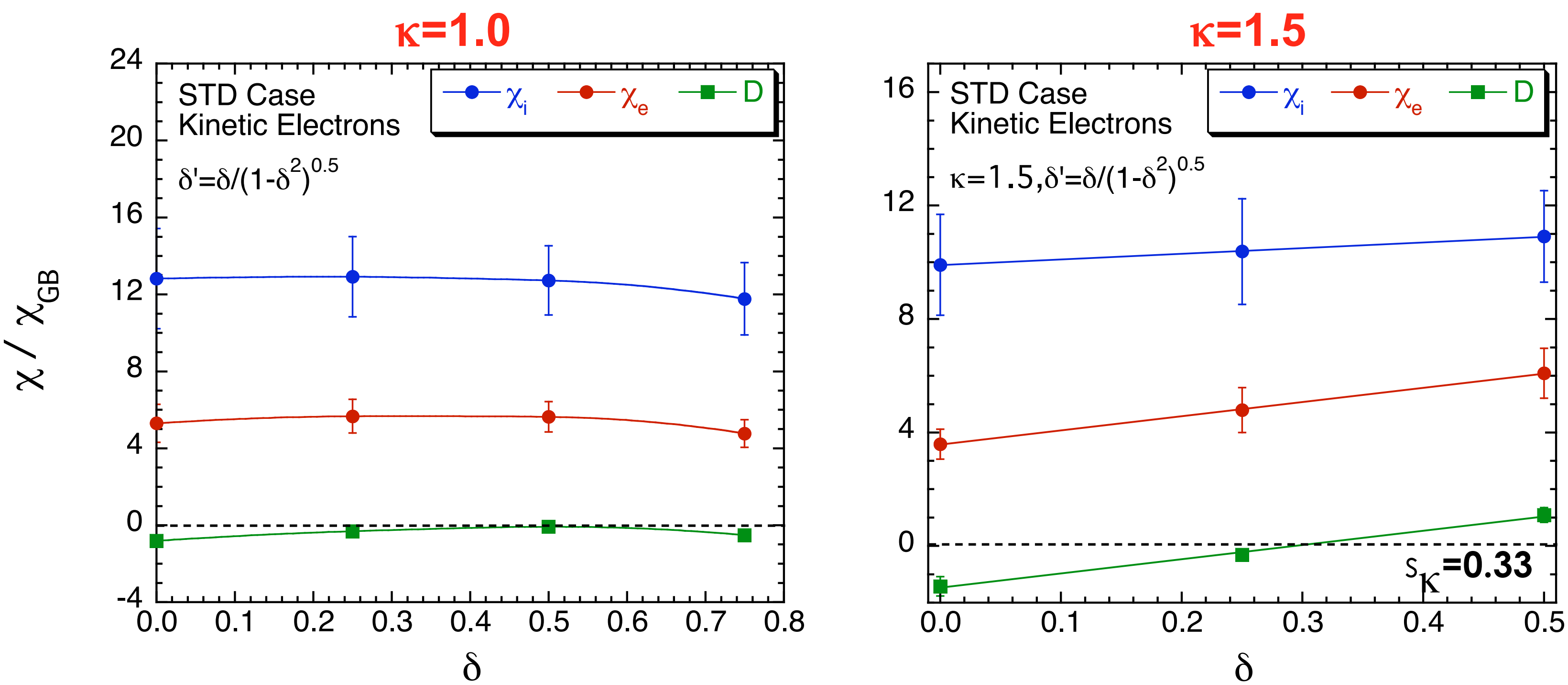
GYRO simulations show an upshift in the nonlinear temperature gradient that is insensitive to elongation

- **Linear (L) a/L_T^{crit} increases with elongation**
- **Nonlinear (NL) a/L_T^{crit} also increases with elongation**
  - For κ=1.0, can't identify a threshold at low a/L_T due to transition from ITG to TEM as a/L_T decreases
  - For κ > 1.0, a NL threshold is evident but can't discern any change in ($a/L_t^{crit,L}$ - $a/L_t^{crit,NL}$)



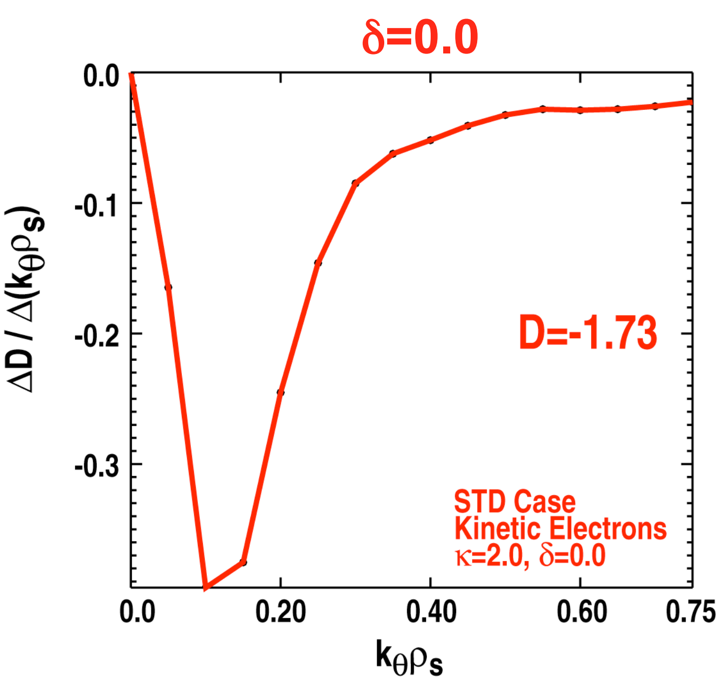
Dependence of transport on triangularity weak for κ=1 plasmas, somewhat stronger for elongated plasmas

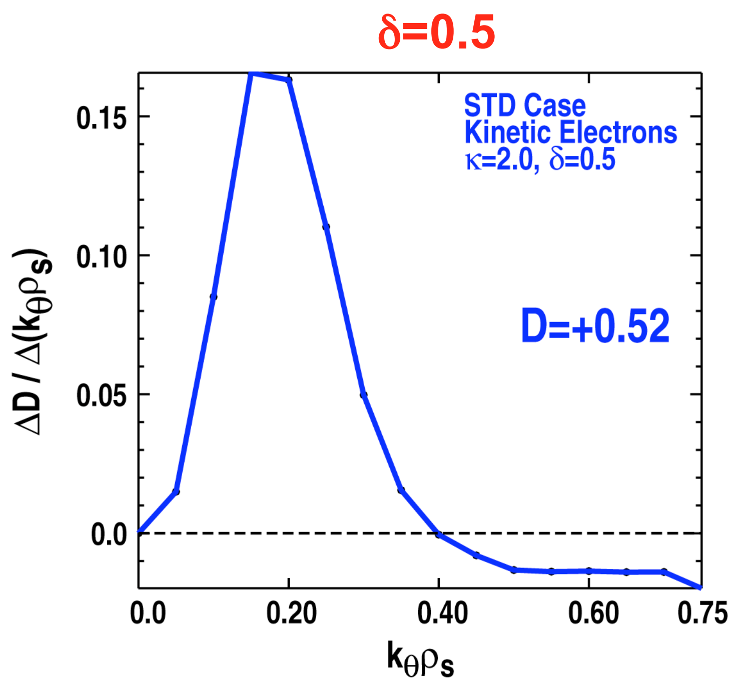
- **δ varied for κ=1.0, 1.5, and 2.0 using STD parameters**
  - Miller geometry, delta gradient factor s_δ varied along with δ
- **Transport increases with δ for high elongation**
  - Stronger dependence for κ=1.5, 2.0 cases compared to κ=1.0 case



Triangularity strongly impacts particle transport spectrum for elongated plasmas near a null flow point

- **δ varied from 0.0 to 0.5 for STD case w/ κ=2.0**
- **Particle transport changes from D/D_{GB}=-1.73 to D/D_{GB}=+0.52**
  - Transport from low k modes changes sign
  - Less of an effect at κ=1.0 (D/D_{GB}=-0.8 -> D/D_{GB}=-0.1 when δ=0.0 -> 0.5)





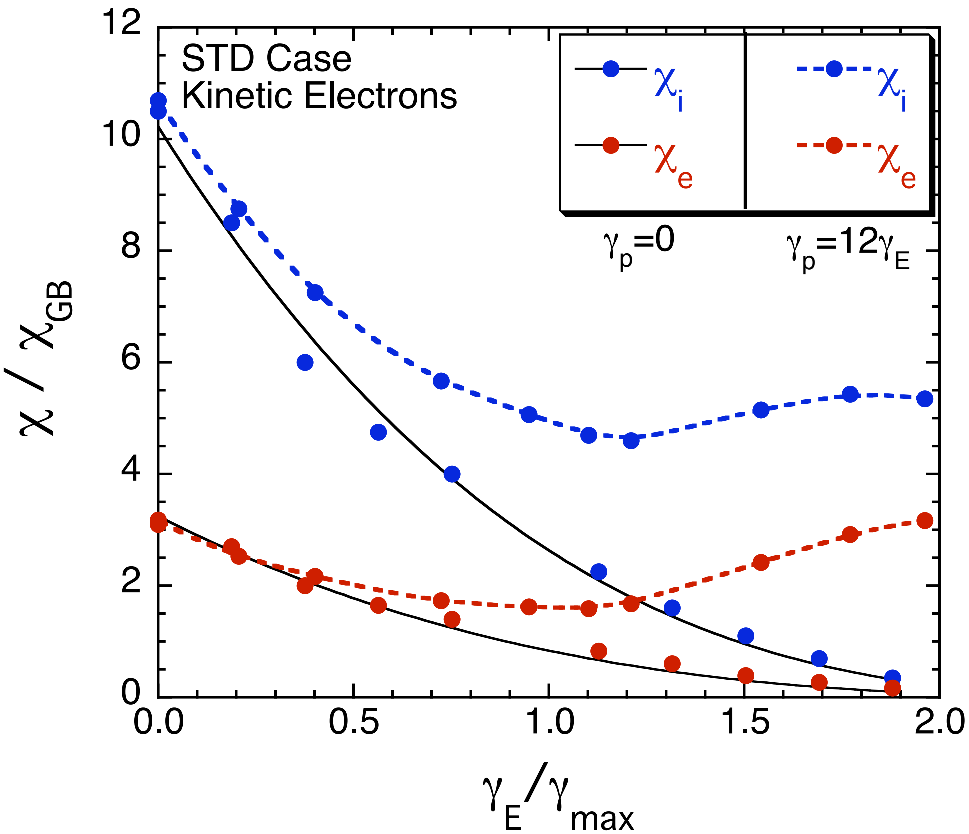
ExB shear quench rule

- **Effect of ExB flow shear on ITG/TEM transport implemented in GLF23 model is originally based on adiabatic electron simulations**
- **Quench rule:**
  - $\chi \propto [1 - \alpha_E (\gamma_E/\gamma_{max})]$

    where γ_E = ExB shear rate, γ_{max} = max linear growth rate, and $\alpha_E = 1.0 \pm 0.5$
- **Gyrofluid simulations by Waltz, et al found that driftwave transport was quenched when $\gamma_E = \gamma_{max}$, Dimits later found $\gamma_E \approx 1.3\gamma_{max}$ in his gyrokinetic simulations (IAEA,2000)**
- **Since then, there has been uncertainty in the validity of the quench rule when kinetic electrons are included and for cases where the modes are rotating in electron direction**

ExB shear quench rule remains valid with addition of kinetic electrons in nonlinear gyrokinetic simulations

- **ExB shear quench point near $\gamma_E=2\gamma_{max}$ 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)
- **Kelvin-Helmholtz drive (γ_p) outruns γ_E stabilization for large Rq/r**
  - Transport not quenched when parallel velocity shear included in STD case (assuming purely toroidal rotation gives $\gamma_p / \gamma_E =(Rq/r)=12$)
- **Transport is not quenched for $\gamma_p=4\,\gamma_E$ with quench pt near 2.4**

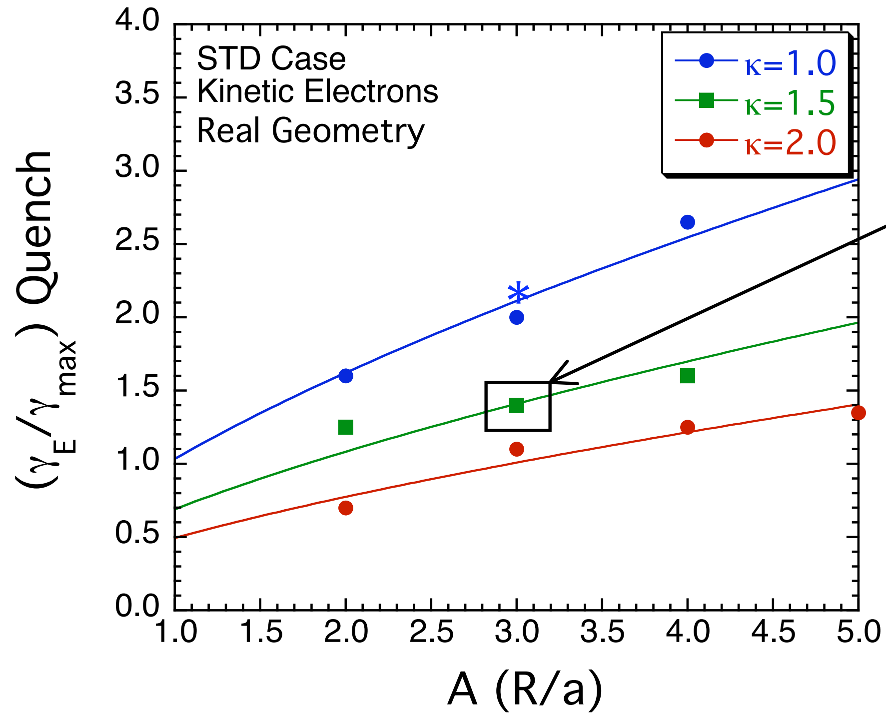


s-α geometry
16 modes

$k_\theta \rho_s$ <= 0.75
γ_{max} w/ γ_p

Real geometry simulations show the ExB shear quench point varies systematically with elongation & aspect ratio

- **Quench point scales approximately like $\gamma_E / \gamma_{max} \propto (1/\kappa)A^{0.65}$ over the range of $1 < \kappa < 2$ and $2 < A < 5$**
- **Systematic nonlinear scans in κ and δ were performed for the STD case with $\partial_r R_0$=0, α=0, β=0 using the Miller equilibrium model in GYRO**
  - Gradient factors s_κ and s_δ varied as κ and δ are varied



Relevant DIII-D and JET parameters

81 GYRO simulations

*** s-α and Miller geometry with κ=1 give same γ_E=2γ_{max}**

Extension of ExB shear quench rule for real geometry

- **A fit to the GYRO results for χ vs γ_E/γ_{max} over the range of $1 < \kappa < 2$ and $2 < A < 5$ yields**

$$\chi \propto [1 - \alpha_E(\kappa,A)\,(\gamma_E/\gamma_{max})]$$

with

$\alpha_E(\kappa,A) = 0.71[\kappa/1.5][A/3]^{-0.6}$ **for flux-surface-constant Waltz γ_E**

$\alpha_E(\kappa,A) = 0.38[\kappa/1.5]^{-0.25}[A/3]^{-0.5}$ **for outboard Hahm-Burrell γ_E**

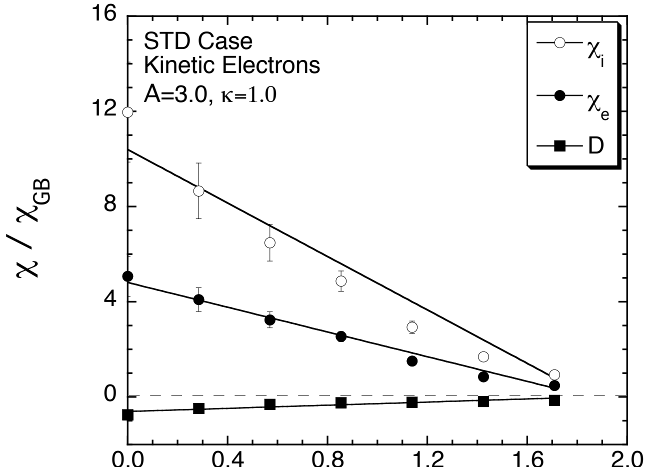
* **For $A=3$, $\kappa=1.5$:** α_E (Waltz) = 0.71, α_E (HB) = 0.38

* **Effect of triangularity on quench pt looks weak (< 10%) based on STD case runs w/ $A=3$, $\kappa=1.5$, further investigation needed**

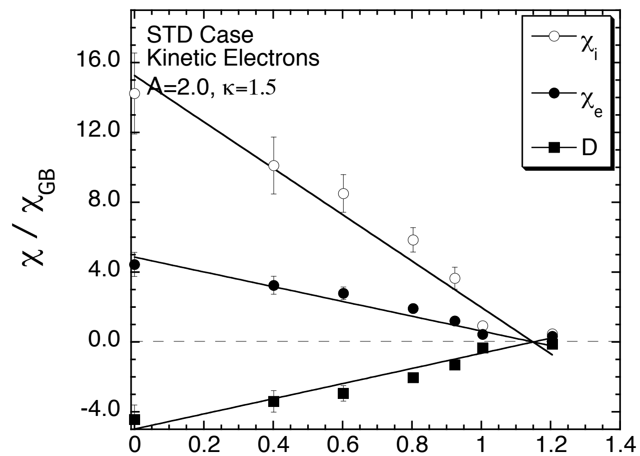
* **Quench rule ONLY valid for low-k turbulence. Transport not actually quenched when unstable ETG modes included in the simulations**

Comparison beween ExB shear fit for α_E and GYRO results

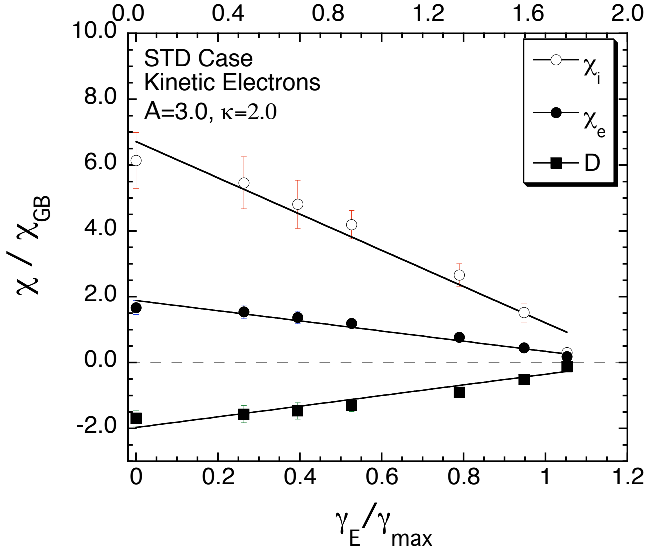
$\alpha_E(\kappa, A)$ = **$0.71[\kappa/1.5][A/3]^{-0.6}$ for Waltz γ_E**



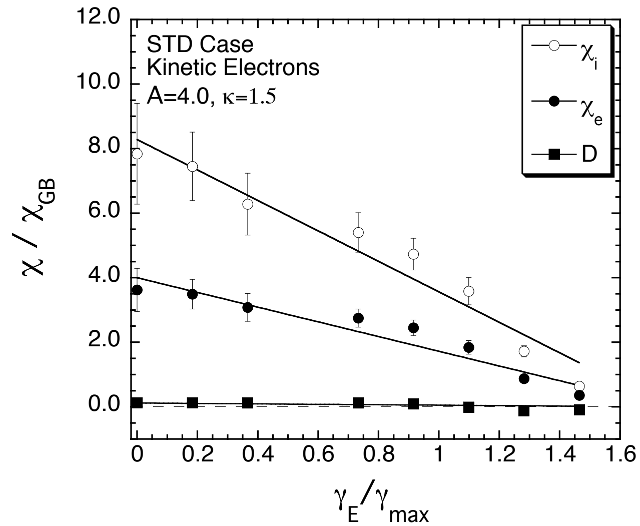
κ=1.0
A=3



A=2
κ=1.5



κ=2.0
A=3



A=4
κ=1.5

Summary

- **The GYRO ion energy diffusivity, in gyro-Bohm units, exhibits a κ^{-1} scaling at fixed minor radius using Miller geometry. This result is in good agreement with the ITER 98(y,2) scaling.**
- **Most of the elongation scaling in the simulations is due to the shear in elongation with a relatively weaker contribution from kappa itself.**
- **The κ scaling of the energy transport (especially χ_e) can vary and depends on where the transport peaks in $k_\theta\rho_s$ space.**
  - Scaling is weaker if χ peaks at low $k_\theta\rho_s$ (high drive cases)
  - Scaling stronger when the peak occurs at high $k_\theta\rho_s$ (low drive cases)
- **Fits to the κ exponents can be summarized as**

$$\chi_i \propto \kappa^{-1.0+0.14(q-2)+0.33(s-1)+0.14(a/L_T-3)}$$

$$\chi_e \propto \kappa^{-1.4+0.14(q-2)+0.33(s-1)+0.54(a/L_T-3)}$$

Summary (cont.)

- **GYRO simulations show an upshift in the nonlinear critical temperature gradient with no discernable change with elongation relative to the linear threshold**
- **Effect of triangularity is destabilizing for highly elongated plasmas, weak effect for circular shaped plasmas**
- **For shifted circle geometry, ExB shear quench rule remains valid in the presence of kinetic electrons with the quench point at $\gamma_E=2\gamma_{max}$ for ions and electrons**
  - Quench rule equally valid for both ITG and TEM cases
  - Transport may not be quenched if parallel velocity shear is included or if ETG transport is included
- **Linear quench rule has been extended to real geometry with the ExB shear multiplier α_E varying with elongation and aspect ratio**
  - Extended rule found for flux surface constant (Waltz), Hahm-Burrell versions
  - Less ExB shear needed for high elongation and for low aspect ratio