Neutral Recycling Effect on Edge ITG Turbulence and Transport*

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Abstract

The effects of recycled neutral atoms on tokamak ion temperature gradient (ITG) turbulence have been investigated in a steep edge pedestal, magnetic separatrix configuration with the full-f edge gryokinetic code XGC1. ITG turbulence is the most fundamental and robust instability, having a long radial correlation length and an ability to impact other forms of pedestal turbulence. The charge exchange interactions of the atoms with the plasma ions enhance the ITG turbulence, first, by increasing the ion temperature gradient in the pedestal region and, second, by reducing the $E \times B$ shearing rate.

Summary

- Full-f edge gyrokinetic code XGC1 with adiabatic electron option,
  - $\Rightarrow$ neoclassical $+$ turbulence $+$ MC neutrals.

- 2 simulations of DIII-D-like H-mode plasma:
  - One without neutral recycling $\Rightarrow$ lower edge turbulence,
  - One with 99% recycling $\Rightarrow$ higher edge turbulence.

- Charge exchange of atoms with ions enhances turbulence intensity by:
  - Increasing pedestal ∇T_i,
    - Nonlocal banana mixing spreads ∇T_i from localized CX cooling all the way to pedestal top,
  - Reduced $E \times B$ shearing rate.

Introduction

- ITER & other burning plasma devices expected to operate in H-mode,
  - Yet, L-H transition not well understood,
  - Nor are mechanisms for suppressing H-mode turbulence or maintaining steep gradients.

- Effects of neutral recycling on core fueling frequently discussed,
  - But, impact on turbulence, L-H transition, & H-mode are open areas of investigation.
  - Previously, first-principles based simulation has been difficult, requiring full-f in edge geometry.

- Expect electron impact ionization & charge exchange to be dominant processes,
  - CX cools ions & enhances neutral penetration,
  - Note that ionization is a local power *source* for ions.
  - Molecules dissociate close to walls & do not penetrate into closed surfaces.
  - Recombination confined to divertor.

XGC1: Full-f Gyrokinetic PIC Code

- XGC family: kinetic full-f (total-f) parallelized PIC codes,
  - Realistic separatrix geometry specified by EFIT EQDSK.
  - Can simulate entire plasma from magnetic axis to material walls.
  - Self-consistent electrostatic potential.

Code (TH/#)	ES / EM Turbulence?	Field Solver	Impurities?	Neutrals?	Collision Operator	CPU Hours
XGC1 (2-1,P6-16)	✓	$\Phi(\psi, \theta, \zeta)$	Under development	Monte Carlo neutrals	Fully nonlinear	$\sim 10^6$
XGCa (P2-27,P6-10)	✘	$\Phi(\psi, \theta)$	Under development	Monte Carlo neutrals	Fully nonlinear	$\sim 10^4$
XGC0 (P2-27)	✘	$\Phi(\psi)$	✓	DEGAS 2	Linear	$\sim 10^4$

Neutral Transport Model

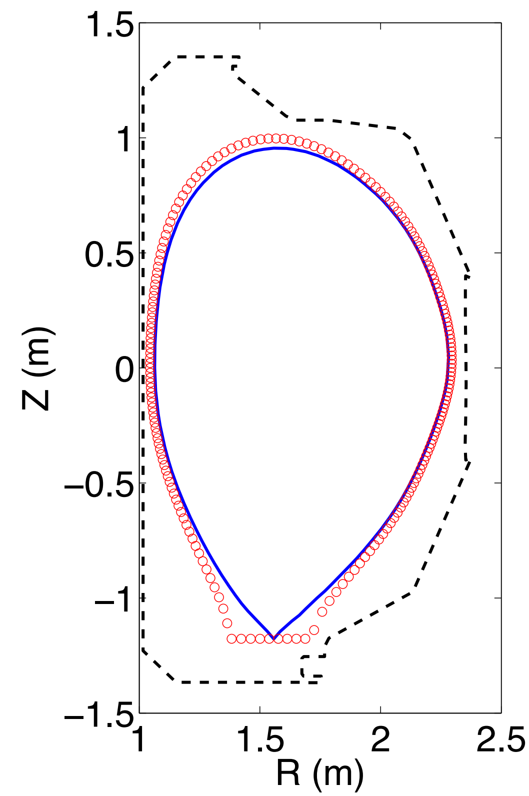
- Two "test particle" Monte Carlo models available:
  - DEGAS 2 $\Rightarrow$ comprehensive treatment,
  - Built-in 2-D Monte Carlo $\Leftarrow$ suffices given focus on confined plasma.
- Atoms undergo ionization:

$$S_{\text{ion}} = 8 \times 10^{-15} \frac{\sqrt{T_e}\, e^{\frac{-13.56}{T_e}}}{(1.0 + 0.01 T_e)} \text{ m}^3/\text{s}$$

- And charge exchange:

$$S_{\text{cx}} = 1.1 \times 10^{-14} (E_i^{0.3}/\sqrt{M_i}) \text{ m}^3/\text{s}.$$

- Neutral density in "kinetic plasma" collision routine scaled to enforce 99% recycling rate.

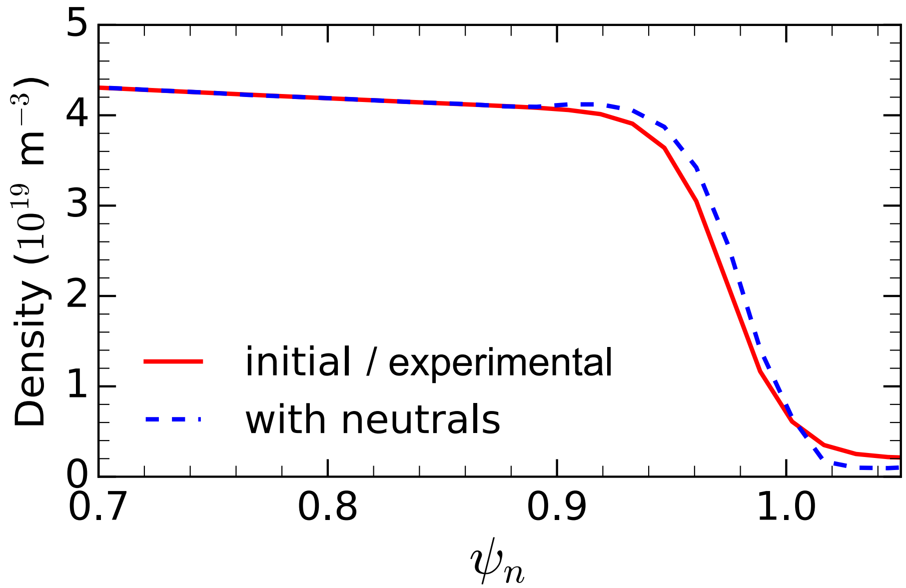


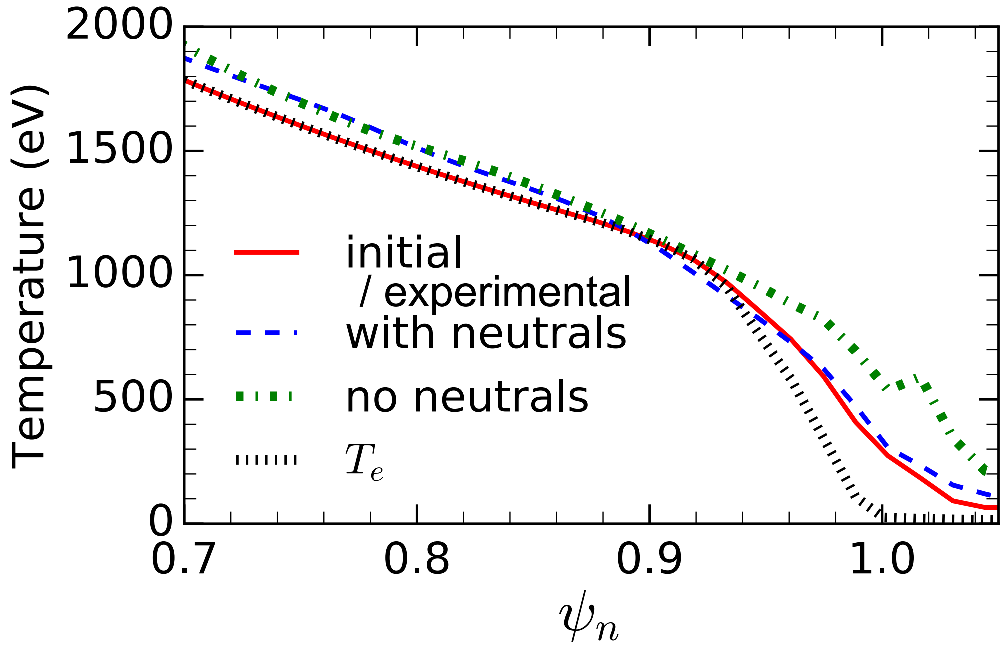
- Molecules implicitly incorporated in kinetic neutral routine via SOL birth surface.
- 3 eV (Franck-Condon), isotropic atoms,
- Distribution peaked around X-point.

Two Simulations Based on DIII-D H-mode 96333

- 2 MW core heating,
- Initial profiles are fits resembling profiles in EFIT equilibrium.
- Do not have detailed edge profiles $\Rightarrow$ assume T_e pedestal steeper than T_i.
- XGC1 quickly evolves ion profiles to consistent GK equilibrium.
- Focus is on ITG $\Rightarrow$ treat electrons adiabatically,
  - $\Rightarrow$ turbulence does not drive particle transport, only changes due to sources & sinks.
  - T_e fixed.
- 99% recycling $\rightarrow$ "with neutrals",
  - Run until turbulence reaches quasi-steady state, $\sim$ 4 ms.
- 0% recycling $\rightarrow$ "no neutrals",
  - Run for 3.4 ms,
  - T_i still evolving at end with turbulence dropping,
  - SOL density being depleted.

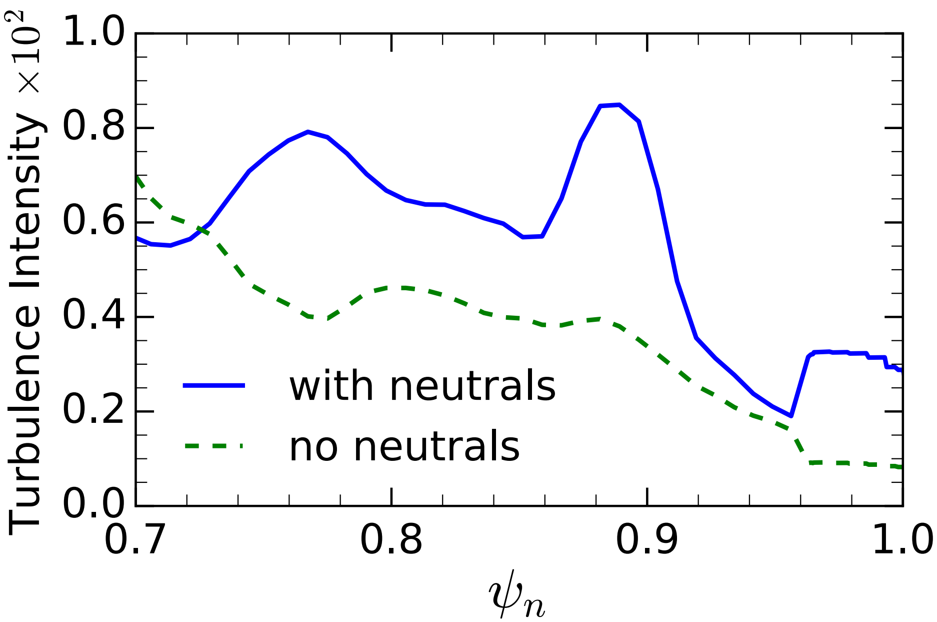
Density & T_i Profile Evolution





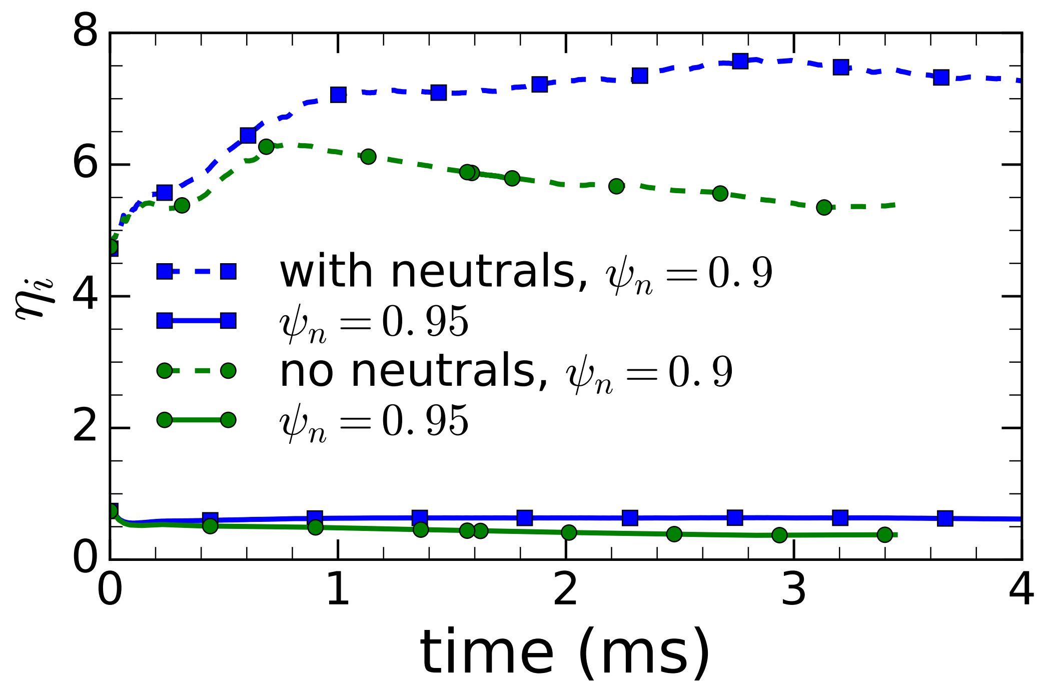
Saturated Edge ITG Turbulence Larger with Neutrals

- Turbulence intensity $\equiv e\sqrt{\langle\delta\phi^2\rangle}/T_e$,
- "with neutrals" ITG linear drive at top of density pedestal, $\psi_n < 0.92$, where ∇T_i finite, ∇n small.
  - Nonlocal spreading into steep density gradient region.
- Turbulence in "no neutrals" run decreases with ψ_n.



Due to Increased ∇T_i "with neutrals"

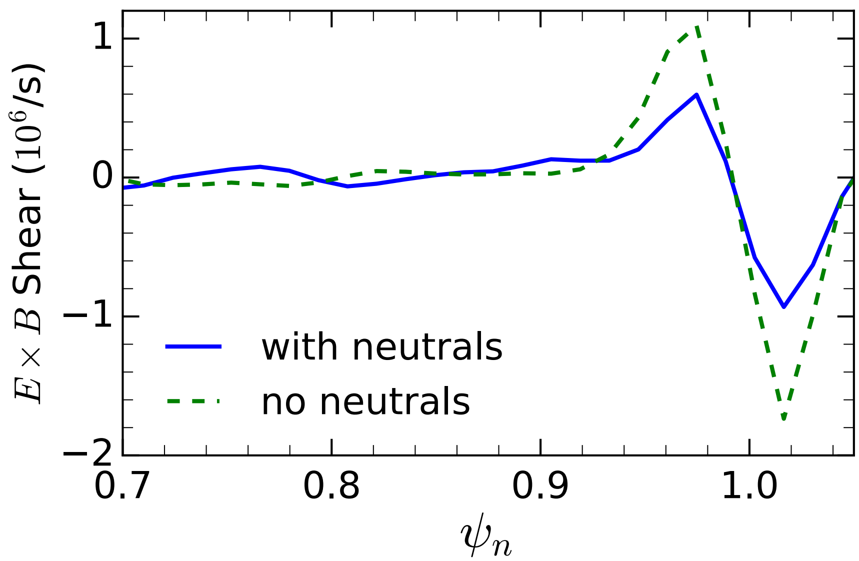
- . . . for $\psi_n = 0.85 \rightarrow 1$.
- "with neutrals" T_i similar to initial,
- "no neutrals" T_i increases & flattens.
- Only difference is neutral recycling $\Rightarrow$ due to CX cooling of ions.
- Effects propagate inward due to banana orbit mixing, neoclassical & turbulent transport.



$\eta_i \approx (d \ln T_i/d\psi)/(d \ln n_{e0}/d\psi)$

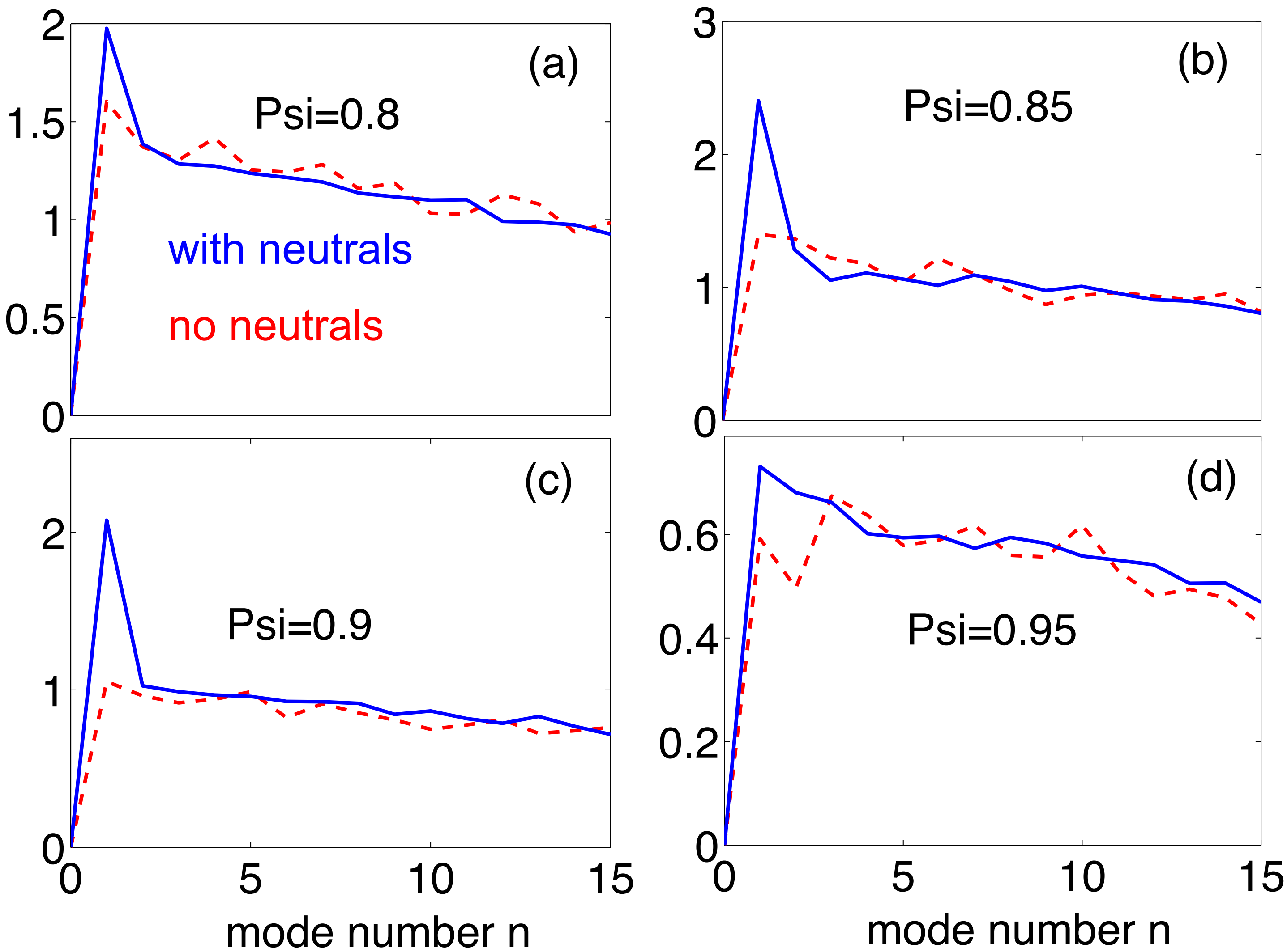
And Reduction of $E \times B$ Shearing by Neutrals

- . . . in steep gradient region,
- Consistent with enhancement of nonlocal edge turbulence.
- This is also neutral penetration zone,
  - Damping of zonal flow rate by CX predicted theoretically.

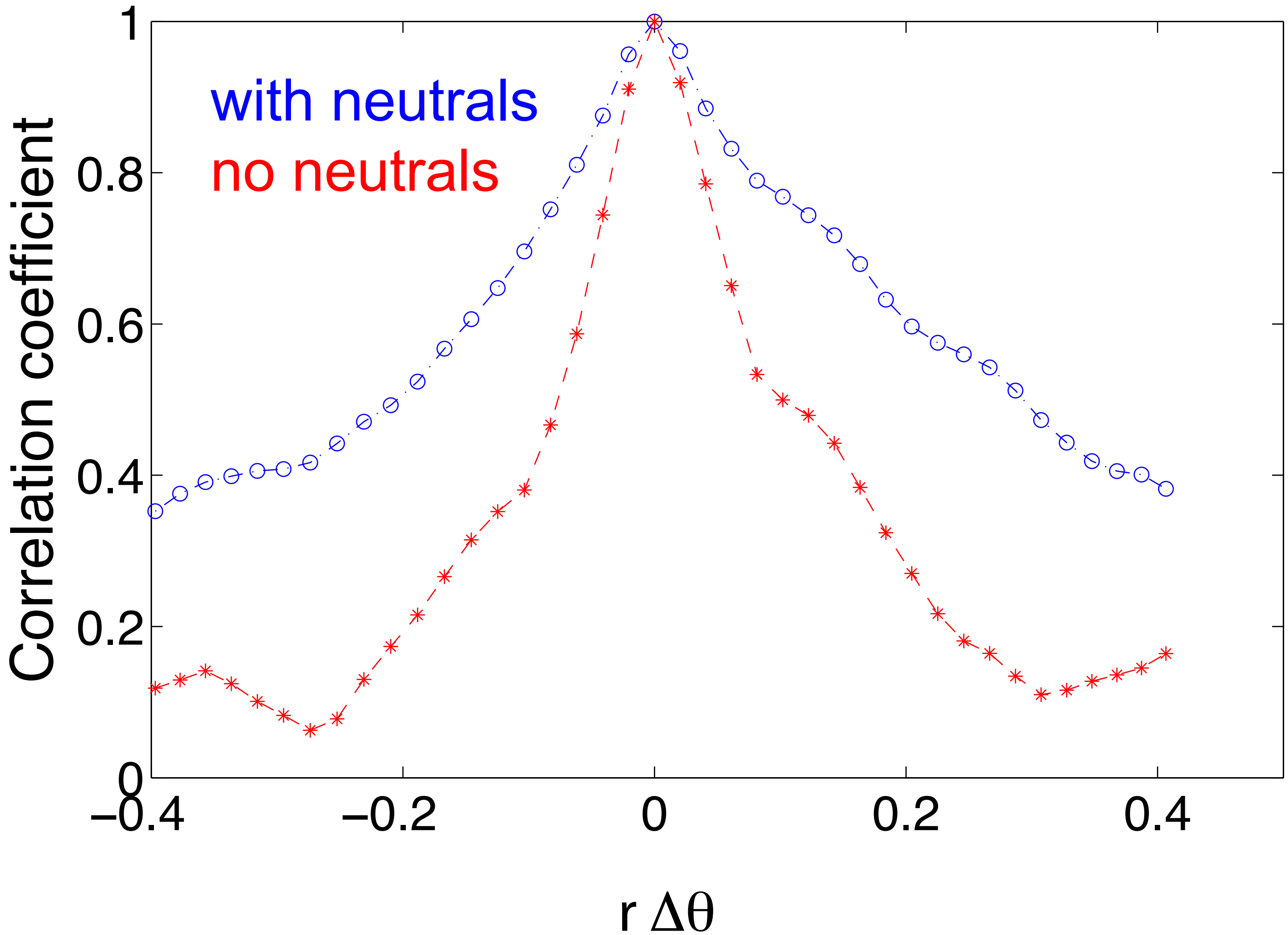


$E \times B$ shear $\equiv dv_{E\times B}/dR$

Neutrals Increase Turbulence at Long Wavelengths



And Increase Spatial Correlation Length



Conclusions

- Recycled atoms enhance ITG turbulence:
  - By increasing ∇T_i,
  - & reducing $E \times B$ shearing rate.

- 3 eV atoms can reach bottom of H-mode pedestal,
  - Ionization & CX alter ion distribution,
  - $\Rightarrow$ impacts ITG turbulence.
  - Only with full-f GK code can neoclassical, neutral, and turbulence effects be rendered consistently in realistic separatrix geometry.

- Comparison with experiment will require more complete simulations,
  - Include kinetic electrons $\Rightarrow T_e, n_e$ evolve.
  - Use DEGAS 2 $\Rightarrow$ consistent neutral source profile & molecular processes.