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Gyrokinetic particle simulation of CTEM turbulence and transport dynamics

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Introduction

- Electron heat transport is important for burning plasma
- Collisionless trapped electron mode (CTEM) is a prominent candidate for electron anomalous transport in tokamak core plasma
- What is saturation mechanism in CTEM?
- What is transport mechanism in CTEM?
- Does any transport scaling law exist in CTEM?
- Global gyrokinetic particle simulation (GTC) is applied to address these key issues

Lin, et al Science, 1998

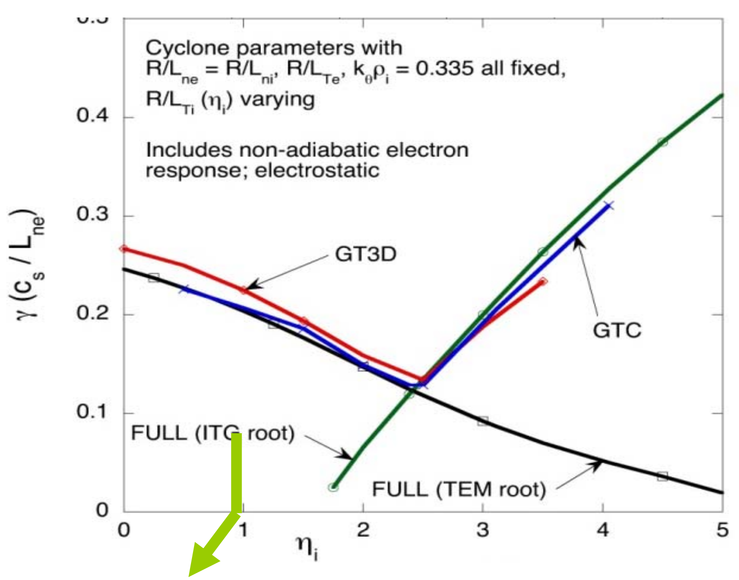
R_0/L_{Te}=6.9, R_0/L_{Ti}=2.2

R_0/L_n=2.2, T_e/T_i=1

m_i/m_e=1837, q=1.4, s=0.78

15 Billion particles

29,000 procs for 42 hours

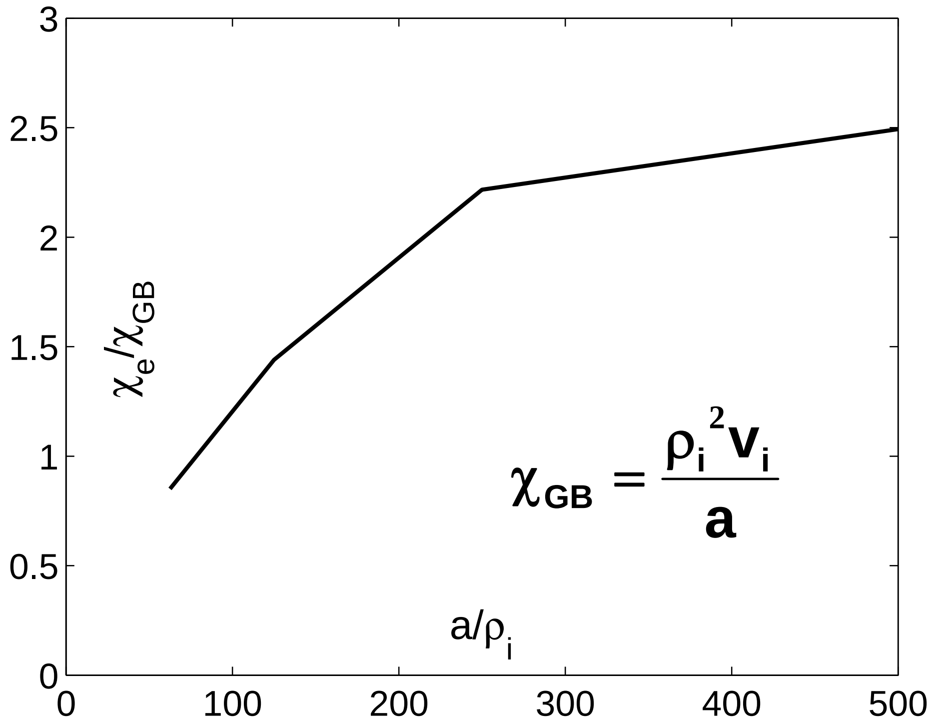


CTEM

Rewoldt/Lin/Idomura CPC 2007

Part 1---Transport Scaling

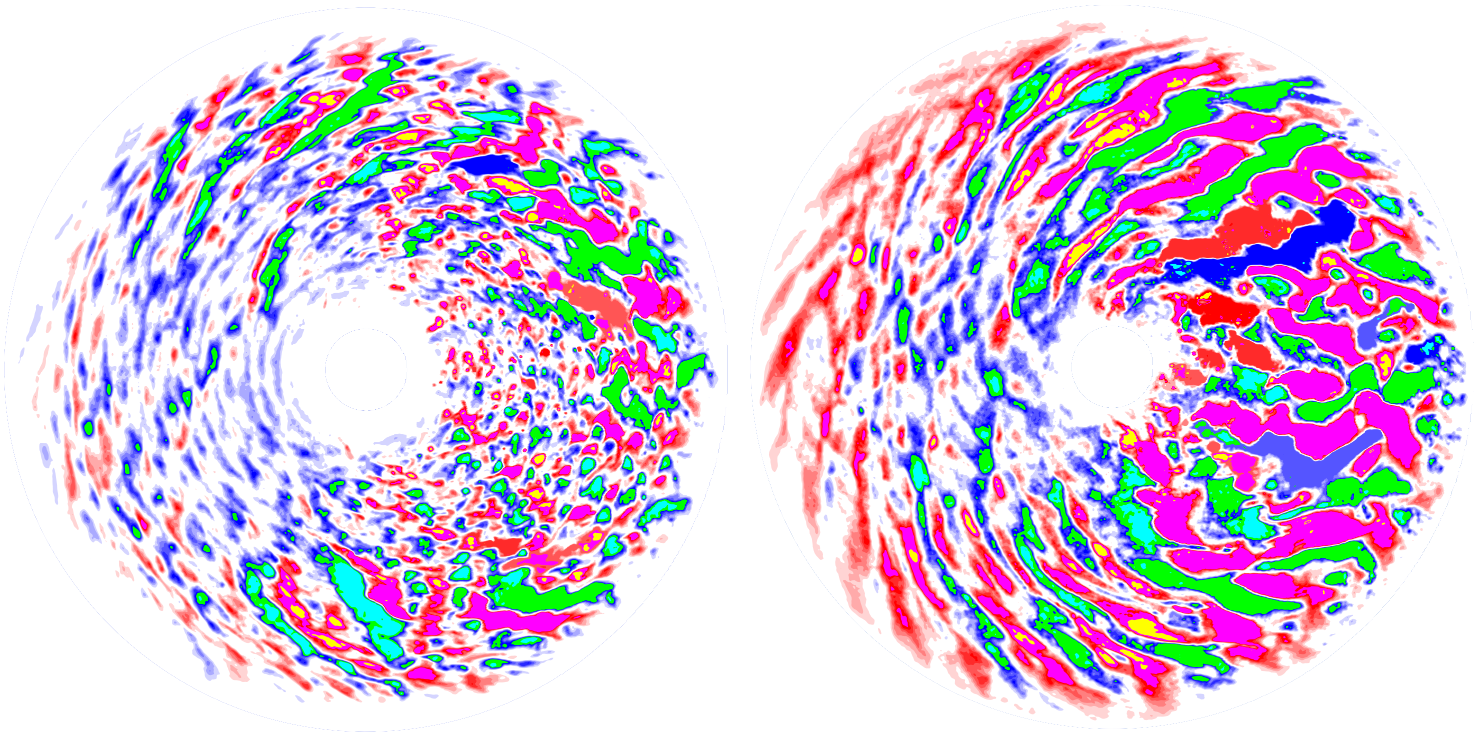
Transport Scaling



- Electron heat transport in CTEM: Bohm → GyroBohm scaling when increasing the system size
- Eddies are mostly microscopic due to the zonal flow shear
- ITER: a/ρ_i>1000, should follow the GyroBohm scaling
- Simulation keeps all the dimensionless parameters unchanged except for $\rho^* = \rho_i/a$

Part 2---Saturation Mechanism

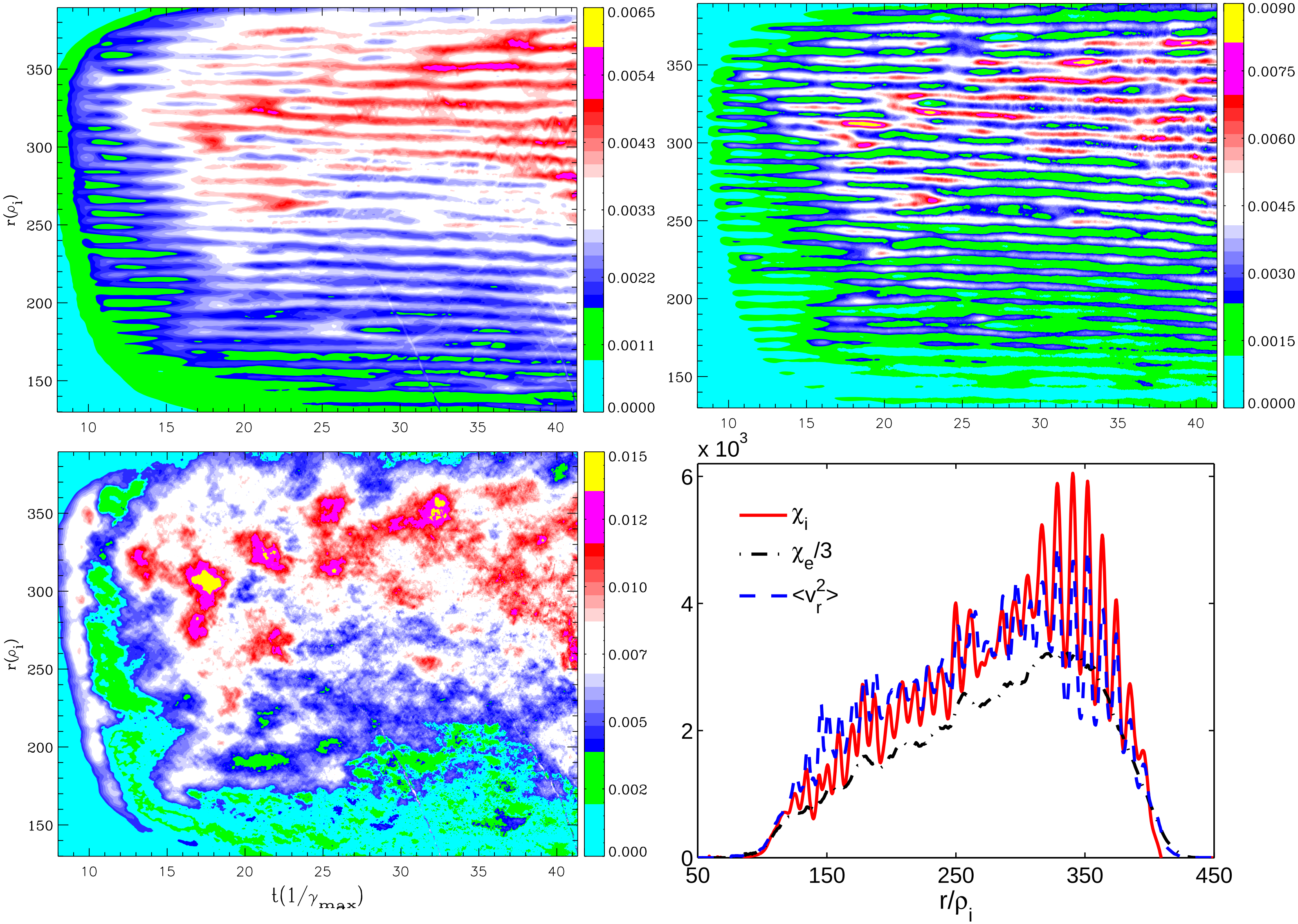
Zonal Flow Effect



- Radial streamers break and merge: dynamic system
- When removing the zonal flow:
  - Strong radial streamer forms
  - Transport level increases about 5 times
- Zonal flow is the dominant saturation mechanism for CTEM

Part 3---Transport Mechanism

Transport Feature



- χ_i: diffusive, proportional to local EXB intensity

ITG: Lin PRL 2002

- χ_e: track global profile of intensity; but contain nondiffusive, ballistic features

CTEM Characteristic Time Scales

$[L_{ne}/v_i]$	$\tau_{wp} = \frac{4\chi}{3\langle\delta v_r\rangle^2}$	$\tau_{\parallel}$	$\tau_{\perp}$	τ_{rb}	τ_{eddy}	τ_{au}	τ_s	$\frac{1}{\gamma_{max}}$
ITG ion	1.7	1.8	2.0	21	4.9	7.2	1.4	9.1
CTEM e	0.65		54,000	4.8	1.6	11.1	0.66	4.0

Table 1: Characteristic time scales for trapped electrons in CTEM turbulences and ions in ITG turbulence

- CTEM Instability is kinetic --- driven by toroidal precessional resonance
- Given turbulence intensity, e heat transport can be understood as a fluid process due to weak detuning of precessional resonance
- In ITG, kinetic and fluid processes can both regulate turbulence

Effective Wave particle decorrelation time $\tau_{wp} = \frac{2D}{\langle \delta V_r^2 \rangle} \rightarrow \frac{4}{3}\frac{\chi_e}{\langle \delta V_r^2 \rangle}$

Parallel decorrelation time $\tau_{\parallel} = \frac{1}{\Delta k_{\parallel} v_i}$

Perpendicular diffusion time

for ions : $\tau_{\perp} = \frac{3}{4 s^2 \bar{\theta}^2 \bar{k}_{\theta}^2 \chi_e}$, for electrons : $\tau_{\perp} = \frac{3a^2}{4\chi_e}$

Diffusion time across the radial streamers $\tau_{rb} = \frac{3L_r^2}{4\chi_e}$

Eddy turnover time $\tau_{eddy} = \frac{L_r}{\delta V_r}$

Turbulence autocorrelation time τ_{auto}

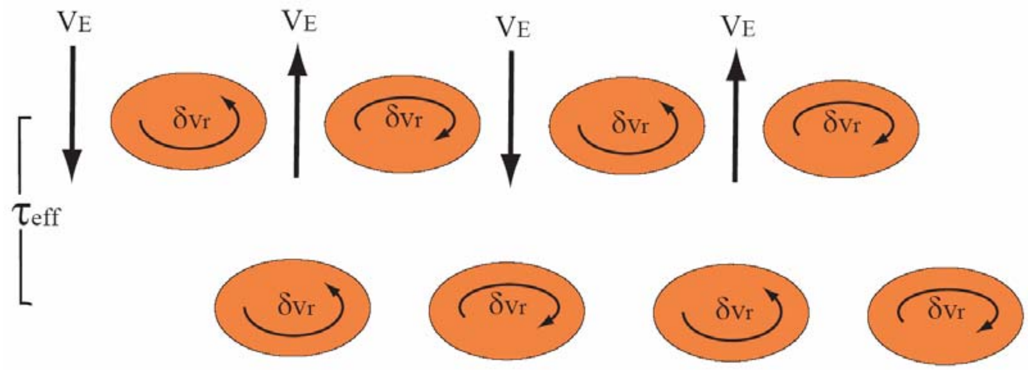
Zonal flow shearing time $\tau_s = \left[\frac{Lr}{L_{\zeta}} \frac{\partial}{\partial r}\left(\frac{q v_E}{r} \right) \right]^{-1}$

Lin et al, 2007 PRL

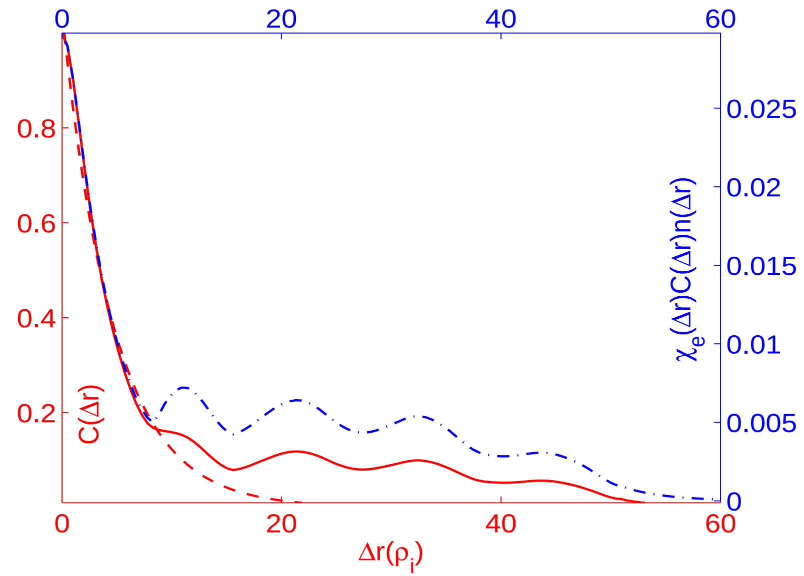
Transport Mechanism

Mixing Length Estimate:

δn_e, δT_e move with eddy as fluid element



$$v_{eff} = \delta v_r + V_E$$
$$\frac{1}{\tau_{eff}} = \frac{1}{\tau_{eddy}} + \frac{1}{\tau_s} \rightarrow \tau_{eff} = 0.46$$
$$\chi_e = f_s \delta v_r^{\,2} \tau_{eff} + f_L \delta v_r^{\,2} \tau_c f_{res}$$
$$\rightarrow f_{res} \tau_c = 0.84$$
$$\mathbf{s: small\ eddy, L: large\ eddy}$$



- Large eddies contribute significantly to e transport since electron can travel long distance --- this is essential to produce smooth radial profile of e heat transport

- Ion can’t move freely in the large eddies due to kinetic decorrelation

Conclusion

- Electron heat transport transits from Bohm to GyroBohm scaling when increasing system size.

- Zonal flow is important in regulating TEM turbulence for the applied parameters. The shearing time is much smaller than other kinetic and fluid time scales and provides effective shielding.

- Two kinds of eddies coexist and both contribute to transport.

- Elongated radial streamers enable electrons travels tens of gyroradii in the radial direction and thus smooth out the local feature of electron transport– due to weak toroidal precession detuning. Ion transport in CTEM is driven by local intensity of EXB drift.

Other GTC presentations:

Energetic particles: W. Zhang (NO3.00010), Z. Lin (GP6.00098)

Momentum transport: I. Holod (BO3.00005)