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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

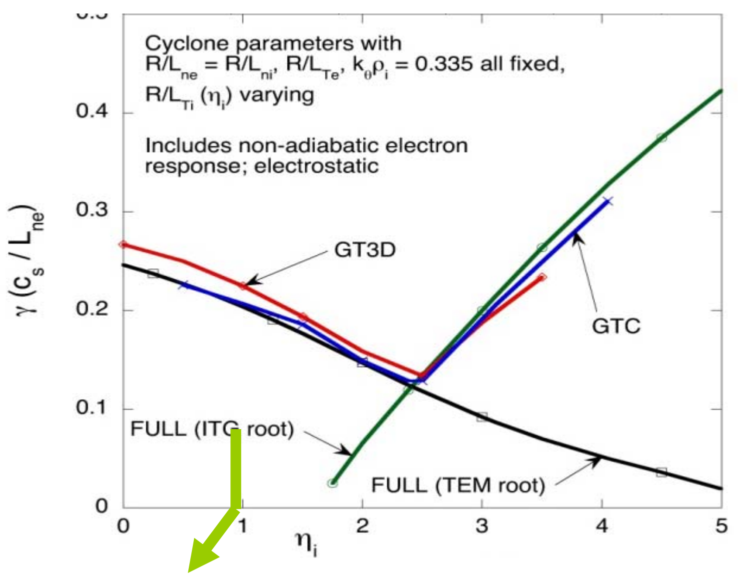
R_0/L_{Te}=6.9, R_0/L_{Ti}=2.2

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

Fluid-Kinetic Hybrid Electron Model in GTC

- Ion is gyrokinetic and electron drift kinetic in GTC
- Challenges in electron particle simulation:
  - Fast parallel electron motion requires much smaller time step.
  - Numerical particle noise is enhanced due to electrons.
- Fluid-Kinetic Hybrid Model[1,2] circumvents these difficulties by considering the fact:
  - Electrons respond to non-zonal component of electrostatic potential nearly adiabatically, but almost don't respond to zonal component.

$$\phi = \langle \phi \rangle + \delta\phi, \text{ with } \delta\phi = \delta\phi^{(0)} + \delta\phi^{(1)} \qquad \text{expansion parameter } \varepsilon \sim \sqrt{m_e / m_i}$$

$$f_e = f_0 e^{e\delta\phi/T} + \delta g_e^{(1)}, \text{ with } \delta g_e^{(1)} \sim \varepsilon \frac{\delta\phi}{T_e} f_0 \sim \frac{\delta\phi^{(1)}}{T_e} f_0$$

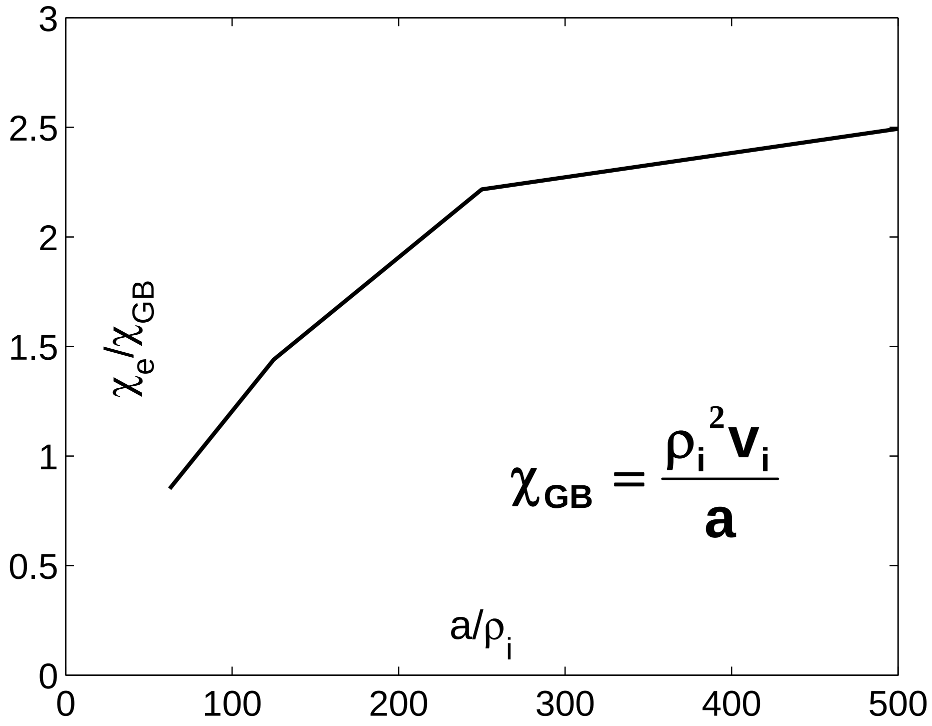
- Hybrid Model retains wave-electron resonance and trapped electron effect

1. Maluilskiy/Lee POP (2000), Chen/Parker POP (2001)

2. Lin/Chen POP (2001)

Part 1---Transport Scaling

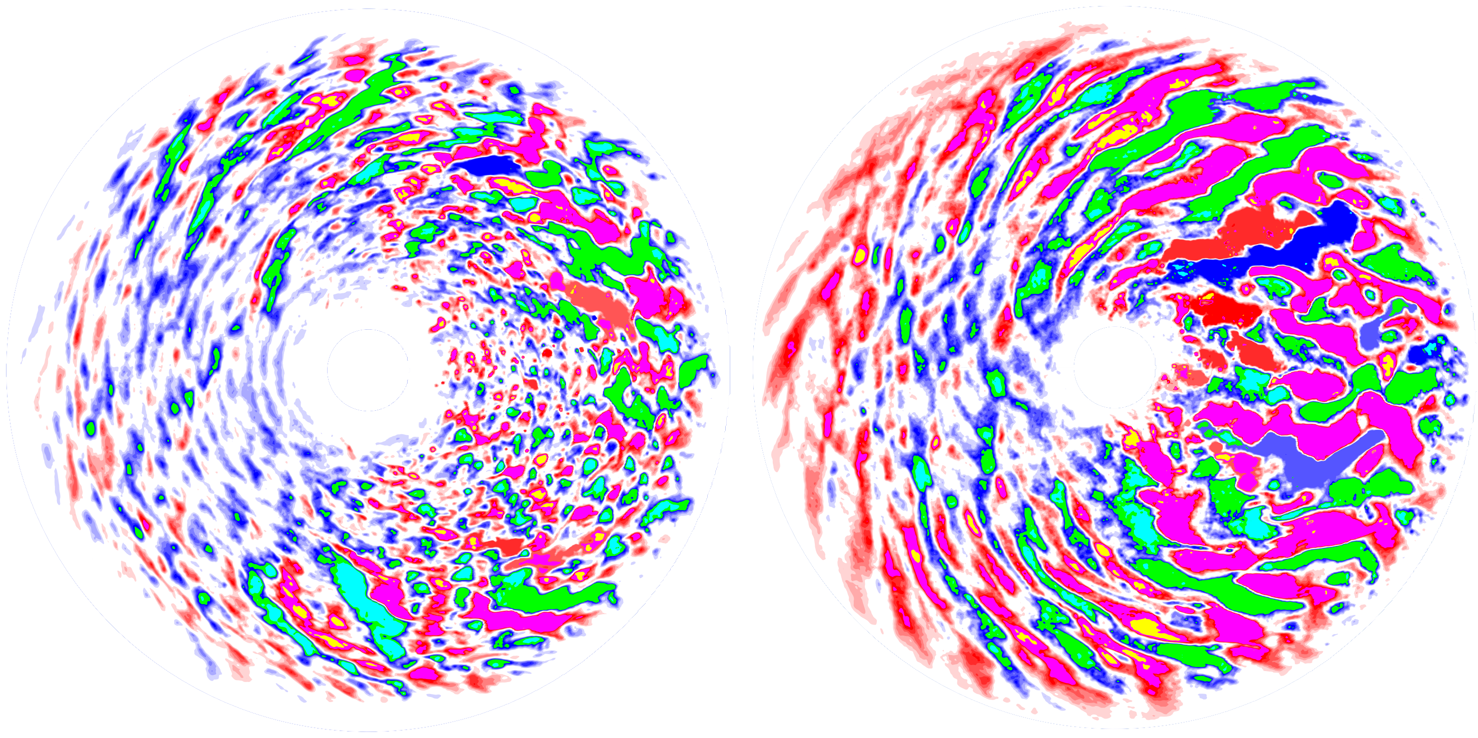
Transport Scaling



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

Part 2---Saturation Mechanism

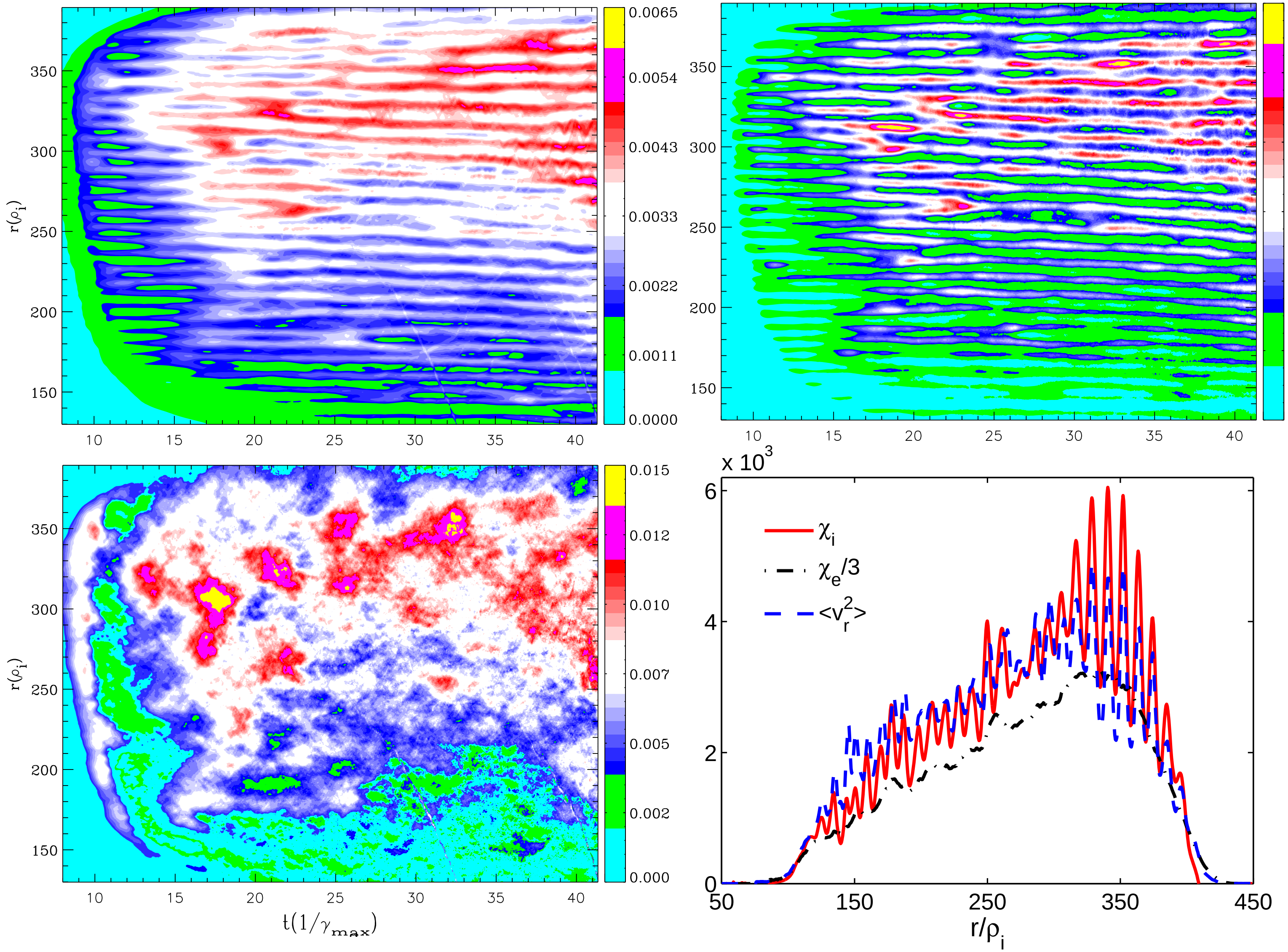
Zonal Flow Effect



- 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 $\tau_{rb} = \frac{3L_r^2}{4\chi_e}$

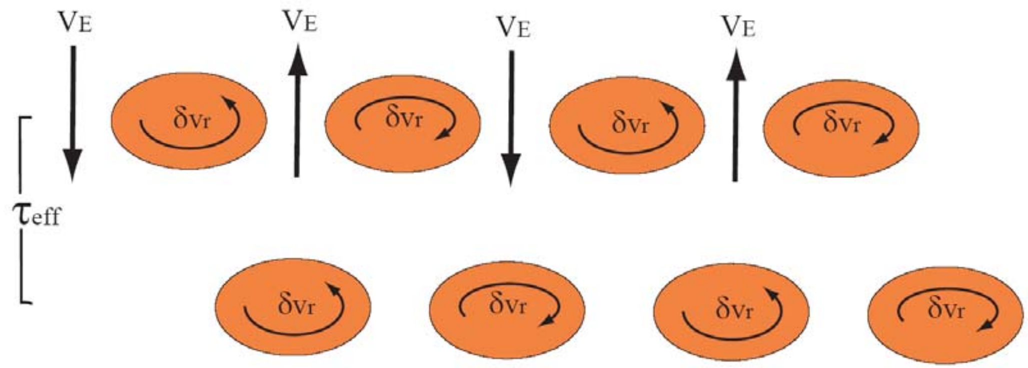
Eddy turnover time $\tau_{eddy} = \frac{L_r}{\delta V_r}$

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

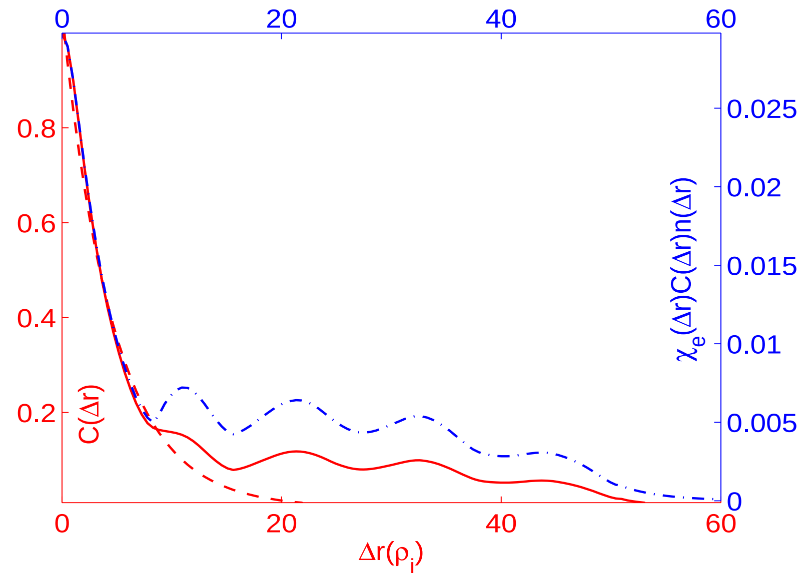
$$\mathbf{v}_{\mathrm{eff}} = \delta \mathbf{v}_r + \mathbf{V}_E$$

$$\frac{1}{\tau_{\mathrm{eff}}} = \frac{1}{\tau_{\mathrm{eddy}}} + \frac{1}{\tau_s} \rightarrow \tau_{\mathrm{eff}} = 0.46$$

$$\chi_e = f_s \delta v_r^2 \tau_{\mathrm{eff}} + f_L \delta v_r^2 \tau_c f_{\mathrm{res}}$$

$$\rightarrow f_{\mathrm{res}} \tau_c = 0.84$$

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

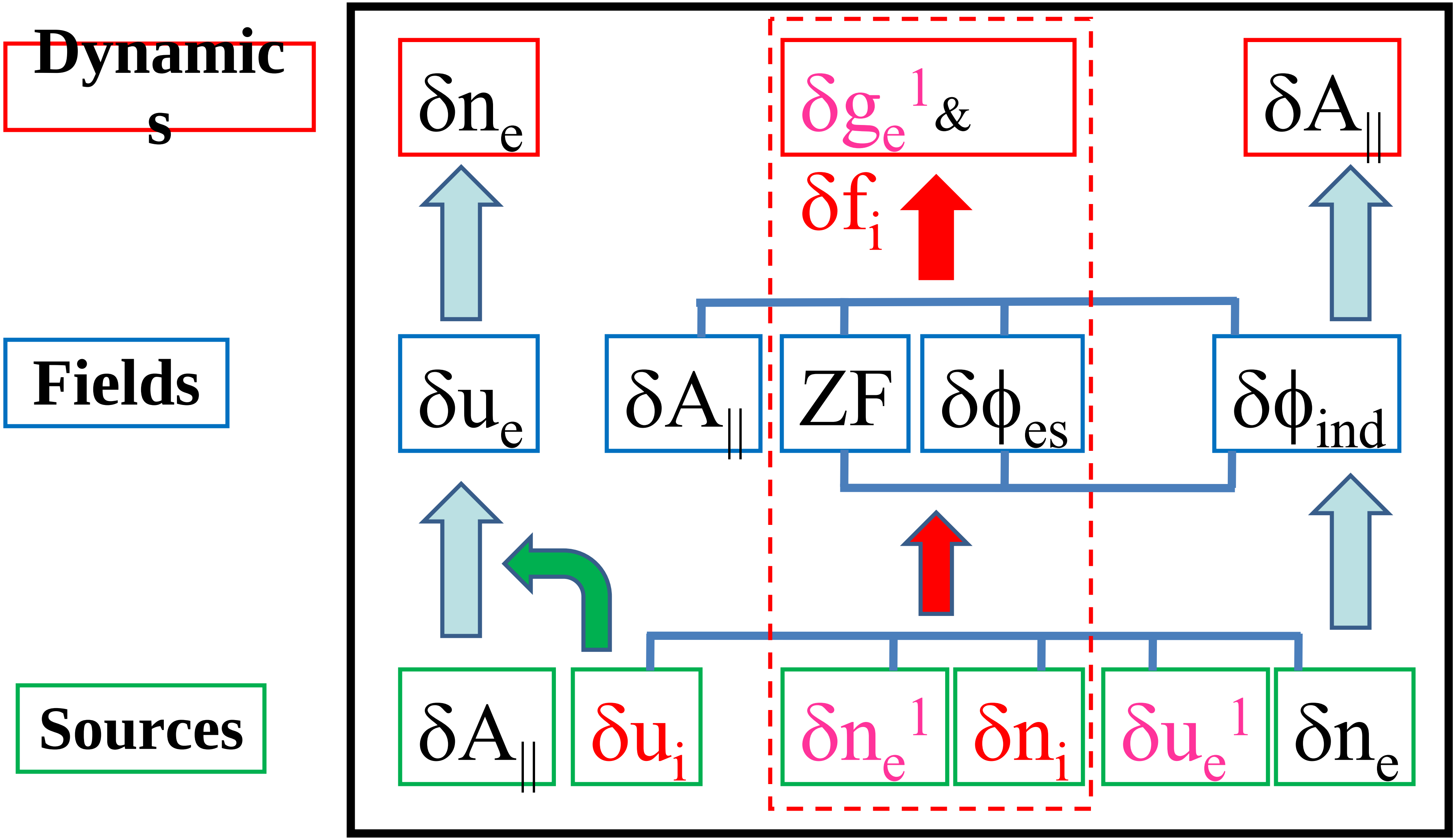
Part II

- GTC --- Status and Plan
  - Code development
  - Physical applications:
    - CTEM
    - Energetic particle transport
    - Momentum transport

GTC Status and Plan

- IIntegration of key capabilities in a single GTC version: done
  - Kinetic electrons via fluid-kinetic hybrid electron model
  - Electromagnetic solver using PETSc
  - General geometry MHD equilibrium and plasma profiles using spline
  - Global field-aligned mesh using magnetic coordinates
  - Multi-level parallelism using mixed mode of MPI/OpenMP
  - Advanced I/O using ADIOS
- PPlan for GTC upgrades: full-f ion simulation & neoclassical physics
- GGTC is part of benchmark suites for DOE OASCR, NERSC, and Cray; pioneering applications of ORNL LCF computers; INCITE FUS017; SciDAC GPS, GSEP, & CPES
- Kkey active developers: Z. Lin, I. Holod, W. Zhang, Y. Xiao (UCI), S. Klasky (ORNL), S. Ethier (PPPL). Supported by SciDAC GPS, GSEP, & CPES

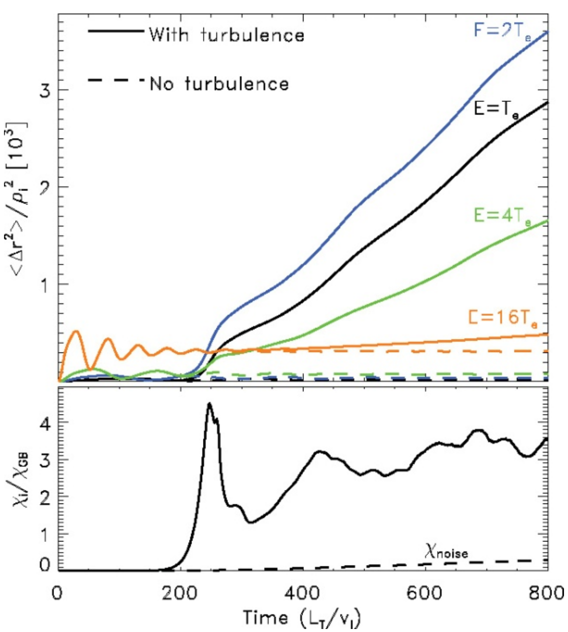
Electromagnetic GTC via Fluid-Kinetic Electron

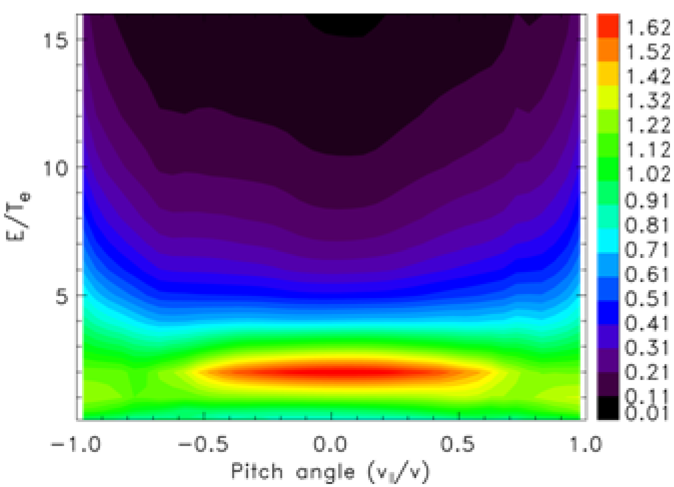


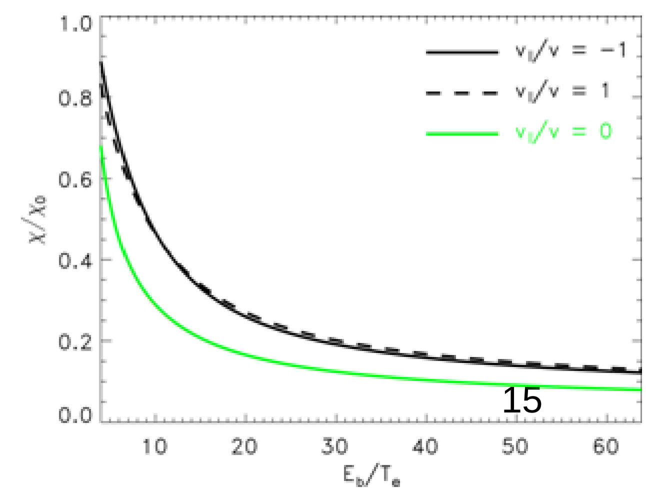
GTC Simulation of Energetic Particle Transport

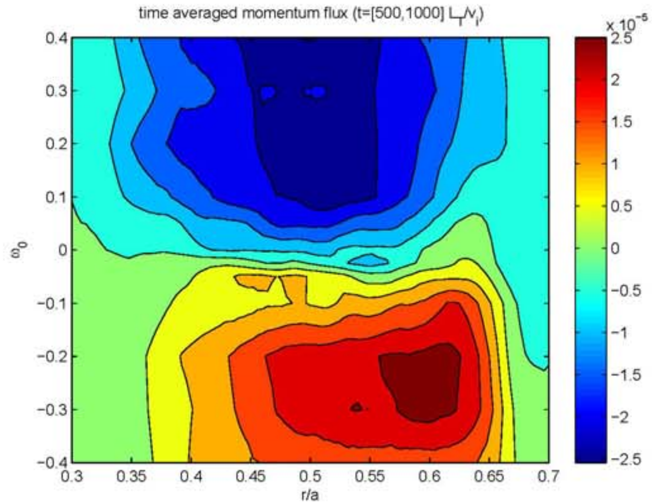
- Recent tokamak experiments revive interest of fast ions transport induced by microturbulence *[Heidbrink & Sadler, NF94; Estrada-Mila et al, PoP06; Gunter et al, NF07]*
- Radial excursion of test particles found to be diffusive in GTC global simulation of ion temperature gradient (ITG) turbulence
- Detailed studies of diffusivity in energy-pitch angle phase space
  - Diffusivity drops quickly at higher particle energy due to averaging effects of larger Larmor radius/orbit width, and faster wave-particle decorrelation
- NBI ions: lower diffusivity for higher born energy

Transport of Energetic Particles by Microturbulence in Magnetized Plasmas, W. Zhang, Z. Lin, and L. Chen, *Phys. Rev. Lett.* **101**, 095001 (2008).







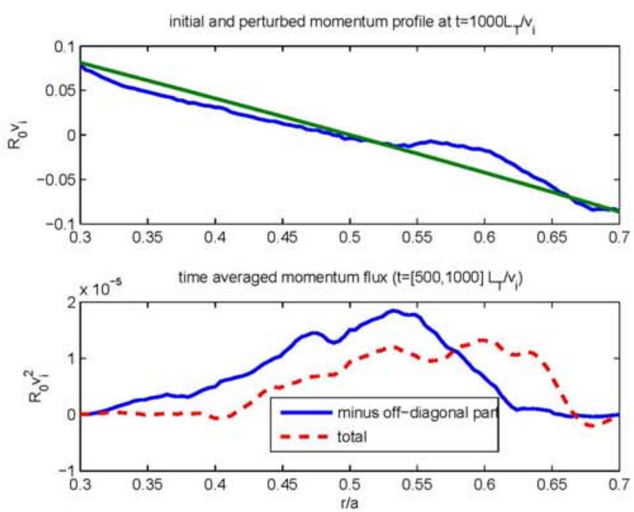


Momentum flux for various rigid rotation cases
Angular velocity: $\omega_\phi=(\omega_0+\omega_1 r/a)v_i/R_0$

Constant angular velocity (rigid rotation case):

- inward momentum flux (pinch);
- redistribution of momentum (spinning up towards the center)

Gyrokinetic particle simulations of toroidal momentum transport, I. Holod and Z. Lin, *Phys. Plasmas* 15, 092302 (2008).



Sheared angular velocity case with
$\omega_\phi=(0.2\text{-}0.4r/a)R_0/v_i$

Sheared rotation case

Flux separation: subtracting pinch contribution from the total flux gives diffusive flux

$$\mathrm{Pr} \equiv \chi_\phi^{\mathrm{diff}} / \chi_\mathrm{i} \approx 0.2 \sim 0.7$$

GTC Simulation results consistent with a quasilinear theory, which shows that Pr<1 if the ratio of particle's resonant energy to the thermal energy >1.

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.

- Elongated radial streamers enable electrons travels tens of gyroradii (mesoscale) 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.

- Two kinds of eddies coexist and both contribute to transport. The existence of mesoscale eddies leads to GyroBohm → Bohm for small size device.

- Energetic particle transport --- High energy particle has less diffusivity due to large orbit width averaging effects, and faster wave-particle decorrelation

- Momentum transport has an inward pinch flux, and the measured Pt number consistent with qusilinear theory estimates

ES Fluid-Kinetic Hybrid Model (II)

- Electron drift electron equation

2

$$L\{\delta g_e\} = -f_{Me} e^{e\delta\phi / T_e} \{ \frac{e}{T_e} \frac{\partial \delta\phi^{(0)}}{\partial t} + (\mathbf{v}_d + \mathbf{v}_E) \cdot \nabla \ln f_{Me} - (\mathbf{v}_d + \delta \mathbf{v}_E) \cdot \nabla \frac{e\langle\phi\rangle}{T_e} \}$$

$$\text{where} \quad L = \frac{\partial}{\partial t} + (v_{\parallel} \mathbf{b} + \mathbf{v}_d + \mathbf{v}_E) \cdot \nabla - \mathbf{b}^* \cdot \nabla(\mu B - e\phi) \frac{\partial}{m_e \partial v_{\parallel}}$$

- Gyrokinetic poisson equation

$$\frac{\tau}{\lambda_D{}^2}\left(\langle\phi\rangle - \langle\bar{\phi}\rangle\right) = 4\pi e\left(\langle\delta n_i\rangle - \langle\delta n_e\rangle\right) = 4\pi e\left(\langle\delta n_i\rangle - \langle\delta n_e{}^{(1)}\rangle\right)$$

$$\frac{\tau}{\lambda_D{}^2}\left(\delta\phi - \delta\tilde{\phi}\right) = 4\pi e\left(\delta n_i - \langle\delta n_i\rangle - \delta n_e + \langle\delta n_e\rangle\right)$$

- Expansion

1

$$(\tau + 1)\frac{e\delta\phi^{(0)}}{T_e} - \frac{e\delta\tilde{\phi}^{(0)}}{T_e} = \frac{\left(\delta n_i - \langle\delta n_i\rangle\right)}{n_0}$$

3

$$(\tau + 1)\frac{e\delta\phi}{T_e} - \frac{e\delta\tilde{\phi}}{T_e} = \frac{\left(\delta n_i - \langle\delta n_i\rangle - \delta n_e{}^{(1)} + \langle\delta n_e{}^{(1)}\rangle\right)}{n_0}$$

$$\text{with} \quad \delta n_e{}^{(1)} = \int d^3 v \, \delta g_e{}^{(1)}$$