CTEM Simulation and Transport Dynamics

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Linear Growth Rate Benchmark

- GTC has the capability to simulate kinetic electrons

1. Rewoldt/Lin/Idomura
   CPC 2007
Outline

- Convergence study
- Heat transport and zonal flow in CTEM
- Features of CTEM turbulences
- CTEM characteristic time scales
- Summary and Future Work
Convergence of CTEM (NC)

The images show graphs with various parameters:
- Ion transport
- Electron transport
- Zonal flow

The graphs are labeled with different time steps and number of cells (NC).

- Top left: $\Delta t = 0.05$, $NC = 20$
- Top right: $\Delta t = 0.05$, $NC = 40$
- Bottom left: $\Delta t = 0.05$, $NC = 100$
- Bottom right: $\Delta t = 0.05$, $NC = 200$
Particle convergence study shows 100 particle per cell is sufficient to simulate CTEM.

Reducing the time step numerically stabilizes the zonal flow.
CTEM/ITG Heat Transport and Zonal Flow

Turbulence transport is strongly correlated with the shearing of zonal flow.

Zonal flow shows a regulation effect in both CTEM and ITG.

\[ \omega_s = \frac{L_r}{L_\zeta} \frac{\partial}{\partial r} \left( \frac{q}{r} V_E \right) \]

Hahm POP 95
Zonal Flow Pattern of CTEM

- Zonal flow initially is excited by turbulence in the linear phase, when the spectrum cascades to short wavelength.
- In the nonlinear phase, zonal flow spectrum inversely cascades to long wavelength.
Spectral Cascade of Three Turbulences

CTEM has an inverse perpendicular spectral cascade, and ITG has a normal parallel spectral cascade.
Ballooning Structure and Radial Correlation

CTEM has a smaller ballooning angle than ITG, corresponding a stronger ballooning structure.

CTEM has a shorter radial correlation length.
Wave Propagation and Autocorrelation Time

Wave propagate in electron diamagnetic direction for CTEM, in ion diamagnetic direction for ITG.

Two time---two point correlation can be applied to calculate the autocorrelation time of the turbulence eddy.

\[ C_{t\zeta}(\Delta t, \Delta \zeta) = \frac{\langle \phi(t + \Delta t, \zeta + \Delta \zeta) \phi(t, \zeta) \rangle}{\sqrt{\langle \phi^2(t + \Delta t, \zeta + \Delta \zeta) \rangle \langle \phi^2(t, \zeta) \rangle}} \]
Nonlinear Transport Mechanism

- Effective wave-particle decorrelation time

\[ \tau_{wp} = \frac{2D}{\left\langle \delta V_r^2 \right\rangle} \rightarrow \frac{4}{3} \frac{\chi_e}{\left\langle \delta V_r^2 \right\rangle} \]
The similarity between the radial profile of heat transport and EXB velocity intensity in ITG indicated a quasi-linear theory may be sufficient to model ITG turbulence.

Modeling CTEM seems more difficult.
Other Characteristic Time Scales

- Parallel decorrelation time
  \[ \tau_{||} = \frac{1}{\Delta k_{\parallel} v_i} \]

- Diffusion time across mode rational surface
  \[ \tau_{\text{eddy}} = \frac{L_r}{\delta V_r} \]

- Diffusion time across radial streamer
  \[ \tau_{\perp} = \frac{3}{4s^2\theta^2k^2\chi_e} \]

- Eddy turn over time
  \[ \tau_{rb} = \frac{3L^2_r}{4\chi_e} \]

- Turbulence autocorrelation time
  \[ \tau_{au} \]
Characterize Turbulence Spectrum

| \( \frac{L_{\perp}}{v_{\parallel}} \) | \( \tau_{wp} = \frac{4x}{3\Delta v_{\parallel}} \) | \( \tau_{||} = \frac{1}{\Delta k_{||}} \frac{1}{v_{\parallel}} \) | \( \tau_{f} \) | \( \tau_{edd} \) | \( \tau_{rh} \) | \( \tau_{nn} \) | \( \tau_{s} \) | \( \frac{1}{\gamma} \) |
|-----------------|-----------------|-----------------|----------|----------|----------|----------|----------|----------|
| ETG 500         | 1.3             | 1.7             | 2.5      | 13.4     | 139      | 110      |           | 11       |
| ITG(A) 500      | 1.7             | 1.8             | 2.0      | 4.9      | 21       | 7.2      |           | 9.1      |
| ITG(A) 250      | 1.6             | 1.7             | 2.2      | 4.9      | 23       | 15       | 1.4      | 9.1      |
| ITG(k) 250\( i \) | 1.6             | 1.8             | 1.64     | 3.6      | 12.6     | 6.6      | 0.87     | 5.0      |
| ITG(k)_250\( e \) | 0.7             | 8.8             | 67       | 5.0      | 5.0      |          |          |          |
| CTEM 250\( i \) | 0.26            | 1.91            | 7.7      | 1.82     | 19.3     | 9.27     | 0.65     | 4.0      |
| CTEM 250\( e \) | 0.61            | 7.8             | 19.6     | 4.0      |          |          |          |          |
| CTEM_125\( i \) | 0.25            | 1.96            | 13.0     | 1.96     | 29.7     | 13.7     | 0.98     | 4.0      |
| CTEM_125\( e \) | 0.61            | 13.8            | 31.6     | 4.0      |          |          |          |          |
| CTEM_62.5\( i \) | 0.17            | 1.90            | 4.43     | 4.89     | 44.8     | 22.5     | 0.95     | 4.0      |
| CTEM_62.5\( e \) | 0.33            | 5.33            | 54.0     | 4.0      |          |          |          |          |

- ETG/ITG(A), fluid time scales are quite separate from kinetic scales. Parallel wave-particle decorrelation is the main transport mechanism for thermal transport in ITG(A) and ETG, which provides a basis for the validity of quasilinear description of these turbulences.

- Kinetic time scale are mixed with fluid time scale, which will make TEM turbulence more difficult to model.

- Nonlinear transport mechanism of TEM is still under investigation Lin et al PRL 2007
Summary and Future Work

- Short wavelength CTEM mode could drive electron heat transport comparable ion heat transport (ITB physics)

- In the nonlinear phase CTEM cascade normally to long wavelength range.

- Current studies show that the shearing of zonal flow has a strong correlation with heat transport, which may suggest the regulation effect of zonal flow.

- Characterization of CTEM turbulence shows that the nonlinear heat transport may be closely related the shearing of the zonal flow.

- Future work includes
  
  - Further study the nonlinear heat transport and turbulence saturation of CTEM: zonal flow physics and precession resonance detuning
  
  - CTEM parameter scanning -> CTEM modeling -> predictive power
Convergence Study of ITG(K)

- Increase NC → increase velocity space resolution → more clear GAM oscillation
- Heat transport not influenced by the fine velocity space structure
- Zonal flow becomes more numerically stable by reducing the time step