First-Principle Simulation of Particle Transport in the inversed-density-gradient profile

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• Summary
Inversed-density-gradient appears in fueling operations.

- Hollow density profile due pellet or gas-puff injection
  ⇒ inversed density gradient appears in the edge region.
- Relevant to
  - What mechanism of the particle flux (pinch?)

(Note: in this work, profile relaxation is out of our target, due to local approach.)

- Fueling physics contributes ITER/DEMO development.
- Works on validation of particle transport physics. [Angioni ‘09][Wan ‘10][Tangared ‘16]

We here undergo the first-principle simulation on the particle transport in the inversed-density gradient region.
dFEFI: delta-\(f\) gyrokinetic solver for ions and electrons. [B. Scott, PoP (2010)]

- delta-f Electromagnetic GK equation

\[
\frac{\partial g}{\partial t} + \frac{c}{B_0} [(J_0 \psi_c), h]_{xy} - \frac{m z^2 + wB}{2e} K(h) + \frac{B^s}{mB} [H_0, h]_{zs} = 0
\]

\[
g = \delta f + \frac{F^M}{T} e \frac{z}{c} J_0 A_{z} \quad h = \delta f + \frac{F^M}{T} e J_0 \phi \quad H_0 = m \frac{z^2}{2} + wB,
\]

\[
\psi_c = J_0 \left( \phi - \frac{z}{c} A_{z} \right)
\]

Polarization equation:

\[
\sum_{sp} \int d\mathcal{W} \left[ e J_0 g + e^2 \frac{F^M}{T} (J_0^2 - 1) \phi \right] = 0
\]

Induction equation:

\[
\nabla^2 A_{z} + \sum_{sp} \frac{4\pi}{c} \int d\mathcal{W} \left[ e z J_0 g - \frac{e^2}{c} z^2 \frac{F^M}{T} J_0^2 A_{z} \right] = 0
\]

- Field-aligned coordinate
- Shifted metric
- Fixed boundary on radius
- Local code, but remains globality on the boundary conditions.
(x: radial, y: binormal, s: magnetic field line)
Benchmark on cyclone-base case (CBC) parameter

core plasma:

\[ \frac{a}{R} = 0.184, \quad \frac{L_{\perp}}{R} = 0.145, \quad \min(k_y \rho_s) = 0.025. \quad \frac{T_i}{T_e} = 1, \quad \frac{qR}{L_{\perp}} = 9.67, \]

\[ \beta_e (qR/L_{\perp})^2 = 1 \times 10^{-3}, \quad \frac{r q'}{q} = 1.14, \quad \frac{L_{\perp}}{L_n} = 0.321, \quad \frac{L_{\perp}}{L_{Te}} = \frac{L_{\perp}}{L_{Ti}} = 1.0 \]

\[ \frac{L_y}{L_x} = 4.0, \quad (nx, ny, ns, nz, nw) = (128, 128, 32, 48, 16) \]

- \( R/L_{Ti} = 6.9 \)
- \( R/L_{Te} = 6.9 \)
- \( R/L_n = 2.2 \)
Linear calculation exhibits two modes with ion and electron direction rotation

Edge plasma parameters:
\[ R_0 = 165 \text{cm}, \ n_e = 2.0 \times 10^{13} \text{ cm}^{-3}, \ Te = 100 \text{ eV}, \ L_n = -7 \text{cm}, \ L_{ni} = L_{te} = 3.5 \text{cm}, \ B = 2.5 \text{ T}, \ T_i/T_e = 1, \ a/R = 0.303, \ L_{\perp}/R = 0.0212, \ q = 3.5, \ \text{Normalized beta} = 6.44 \times 10^{-5}, \ \nu_i(L_{\perp}/c_s) = 0.00956, \ \nu_e(L_{\perp}/c_s) = 0.823 \]
\( (nx, ny, ns, nz, nw) = (32, 128, 32, 32, 16), \ L_x/L_y = 1.0, \ \Delta t = 0.005 \)

Power spectra in linear phase

We observe ITG-like and TEM-like modes growing.
Time evolution of Particle Flux

⇒ Inward, with phase-shifted

For the inversed-density-gradient case, we expect larger phase shifts in the density-potentials.
Spectral analyses on electrostatic potential and particle flux.

- In the nonlinear phase, the lower wave number mode survives.
- Both peaks contributes to inward particle fluxes. In the nonlinear phase, modes with $0.1 < k_y \rho_s < 0.8$ contributes the inward flux.
Candidate? Ion-Mixing-Mode\textsuperscript{[Coppi '78 PRL]}

- Slab fluid Model
- Mode dispersion
\[ 1 + iA + k_{\parallel}^2 \frac{T_e}{m_i} \frac{\omega_{Ti}}{\omega^3} - \frac{\omega_{*e}}{\omega} = 0 \]
- Non-trivial mode:
\[ \omega = -\left[ (k_{\parallel}^2 \frac{T_e}{m_i}) \frac{\omega_{Ti}}{(1 + A^2)} \right]^{1/3} (1 - iA)^{1/3} \]

Electron adiabaticity is affected by the electron thermal force.

\[ \frac{\tilde{n}_e}{n} = \frac{e\tilde{\phi}}{T_e} \left[ 1 + (1 + \alpha_T) \frac{i}{\omega} (\omega - \omega_{*e} + \frac{3}{2} \eta_e \omega_{*e}) \right] \quad \omega_{\chi} \equiv \hat{\chi} e k_{\parallel}^2 T_e / (m_e v_e) \]

Assumption: \( \omega \sim \omega_{*e} < \omega_{\chi} \)  
- Diagonal effects (prop. to grad n) are cancelled, remaining off-diagonal (prop. to grad Te) term.

Particle Flux: \( \Gamma = \langle \tilde{n} \tilde{v}_{Ex} \rangle = -(2c / B) \text{Im} \left( \sum_k k_y \tilde{\phi}_k \tilde{n}_k \right) \)
\[ = 3(1 + \alpha_T) D_B^4 \eta \sum_k k_y^2 \left| \frac{e\tilde{\phi}}{T_i} \right|^2 \frac{1}{\omega_{\chi}} cT_i \frac{d \ln T_e}{dx} \]

However, Is this assumption correct? \[ \text{Estimate from simulation results} \sim -0.73 \]
Validation of Ion-Mixing-Mode

\[ \omega \sim \omega_{*e} < \omega \chi \]

Is correct?

\[ \frac{\tilde{n}_e}{n} = \frac{e\tilde{\phi}}{T_e} \left[ 1 + (1 + \alpha_T) \frac{i}{\omega \chi} (\omega - \omega_{*e} + \frac{3}{2} \eta_e \omega_{*e}) \right] \]

\[ \omega(k_y = 0.1) \sim -0.063(c_s / L_-) \]

\[ \omega_{*e} = \frac{k_y c T_e}{e B} \frac{d \ln n}{dr} \sim -0.1 (c_s / L_-) \]

\[ \omega \chi = \hat{\chi}_e k_{||}^2 T_e / m_e v_e \sim 0.7(c_s / L_-) > \omega_{*e} \]

\[ A = \frac{3}{2} \frac{\eta_e \omega_{*e}}{\omega \chi} (1 + \alpha_T) \sim 0.73 > \sqrt{\frac{m_e}{m_i}} \]

This mode is enough large compared with collisional effects.

Measures degree of the cancellation.

dTe/dr dependency
Parameter Scan(1) n scan

- $\nabla n$ scan on saturated particle flux is almost similar within fluctuations.
- Diffusive part is not significant
- Higher $\nabla n$ gives (slightly) higher growth rate.

In the IMM theory, a diffusive part on particle flux is not significant, since $\omega \sim \omega_{*e}$ is satisfied.
Parameter scan(2) Grad Ti Scan

$\Gamma(n_0c_s)$ Grad Ti scan (x1.0, x0.9, x0.8)

- Higher $\nabla T_i$ gives higher saturated inward particle flux.
- Higher $\nabla T_i$ gives higher growth rates, related to ITG mode.
- Higher $\nabla T_i$ gives drastically higher phase shift ($\delta = \Gamma / \langle \phi^2 \rangle$).

Higher $\nabla T_i$ => higher Inward flux, originated from phase shift, as well as increase of growth rates.
summary

• We have simulated the turbulence in case that density gradient inversed. In linear phase, two modes appear; one is ITG-like, and the other is TEM-like modes.

• The TEM-like modes disappears in the nonlinear phase.

• The ITG-like mode may be identified as the ion-mixing-mode. Note that the IMM is unique to the inversed-density-gradient case.

• In future work, toroidal IMM model should be derived for further understanding of the simulation results.

Implications:

• Further physics should enter in hollow density profile.

• Electron temperature is a key for the case, in that electron thermal fluctuation can modulate the phase shift.