Analysis of Different Responses of Ion and Electron in Six-Field Landau-Fluid ELM Simulations

C. H. Ma$^{1, 2}$, X. Q. Xu$^{2}$, P. W. Xi$^{1, 2}$, T. Y. Xia$^{3}$, A. Dimits$^{2}$, M. V. Umansky$^{2}$

$^1$Fusion Simulation Center, School of Physics, Peking University, Beijing, China
$^2$Lawrence Livermore National Laboratory, Livermore, CA 94550, USA
$^3$Institute of Plasma Physics, Chinese Academy of Sciences, Hefei, China

Presented at 2013 BOUT++ Workshop
Livermore, CA, September/2013

This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Security, LLC, Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344, and is supported by the China Scholarship Committee under contract NO.201206010101, as well as supported by the China Natural Science Foundation under Contract No.10721505.

LLNL-PRES-643194
1. Introduction
2. Physics Model
3. Simulation Result
   1) Effect of different parallel heat flux closures
   2) $L_n/L_t$ scan
   3) Different response of ion and electron
   4) Effect of thermal force
4. Summary
Background

• H-mode
  ➢ Better power confinement for plasmas
  ➢ Edge transport barrier and pedestal region

• ELMs
  ➢ Periodic MHD events at H-mode pedestal;
  ➢ Damage to PFC;
  ➢ Affect confinement;

• Peeling-ballooning model
  ➢ Driven by combination of high pressure gradient and current
  ➢ Different linear instabilities, different types of ELMs.

P.B. Snyder, et.al Nucl. Fusion 47 (2007) 961
Landau fluid model can fill the gap between hot and cold boundary plasma.

**Core region**
- Temperature: high
- Collision: weak
- Model: gyro-kinetic

**Boundary region**
- Temperature: low
- Collision: strong
- Model: two fluid

Landau fluid model
- Two fluid model for ideal peeling-ballooning mode
- Using non-local transport closure to simulate kinetic effect on hot, collisionless region
6-field includes the effect of thermal conductivity and temperature profile

<table>
<thead>
<tr>
<th>Model</th>
<th>Variables</th>
<th>Physics</th>
</tr>
</thead>
<tbody>
<tr>
<td>3-field</td>
<td>$\varpi, A_\parallel, P$</td>
<td>Peeling-balloonning model</td>
</tr>
<tr>
<td>6-field</td>
<td>$\varpi, A_\parallel, n_i, V_\parallel, T_i, T_e$</td>
<td>+Thermal conductivity</td>
</tr>
</tbody>
</table>

• 3-field:
  • Only peeling-balloonning model

• 6-field:
  • Thermal conductivity
    - Landau closure: collisionless wave-particle resonances
    - Flux limited heat flux: collisional transport and flux streaming
  • Effect of temperature profile $\rightarrow \eta_i = L_n / L_T$ scan
6-field Landau fluid model with parallel heat flux

Vorticity:
\[
\frac{\partial}{\partial t} \omega = -\left( \frac{1}{B_0} b \times \nabla_{\perp} \phi + V_{||} b \right) \cdot \nabla \omega + B^2 \nabla \left( \frac{J_{||}}{B} \right) + 2b \times \kappa \cdot \nabla P
\]
\[
- \frac{1}{2\Omega_i} \left[ \frac{1}{B} b \times \nabla P_i \cdot \nabla \left( \nabla_{\perp}^2 \phi \right) - Z_i e B b \times \nabla n_i \cdot \nabla \left( \nabla_{\perp}^2 \phi \right)^2 \right]
\]
\[
+ \frac{1}{2\Omega_i} \left[ \frac{1}{B} b \times \nabla \phi \cdot \nabla \left( \nabla_{\perp}^2 P_i \right) - \nabla_{\perp}^2 \left( \frac{1}{B} b \times \nabla \phi \cdot \nabla P_i \right) \right] + \mu_i \nabla_{||}^2 \omega
\]

Ion density:
\[
\frac{\partial}{\partial t} n_i = -\left( \frac{1}{B_0} b \times \nabla_{\perp} \phi + V_{||} b \right) \cdot \nabla n_i - \frac{2n_i}{B_0} b \times \kappa \cdot \nabla \phi - \frac{2}{Z_i e B} b \times \kappa \cdot \nabla P - n_i B \nabla_{||} \left( \frac{V_{||}}{B} \right)
\]

Ion parallel velocity:
\[
\frac{\partial}{\partial t} V_{||} = -\left( \frac{1}{B_0} b \times \nabla_{\perp} \phi \right) \cdot \nabla n_i - \frac{1}{m_i n_i} b \cdot \nabla P
\]

Ohm’s law:
\[
\frac{\partial}{\partial t} A_{||} = -\nabla_{||} \phi + \frac{\eta}{\mu_0} \nabla_{\perp}^2 A_{||} + \frac{1}{en_i} \nabla_{||} P_e + \frac{\epsilon B}{2Z_e} \nabla_{||} T_e - \frac{\eta_H}{\mu_0} \nabla_{||}^4 A_{||}
\]

Electron temperature:
\[
\frac{\partial}{\partial t} T_e = -\frac{2}{3} T_e \left[ \left( \frac{2}{B} b \times \kappa \right) \cdot \left( \nabla \phi + \frac{1}{en_e} \nabla P_e + \frac{5k_B}{2e} \nabla T_e \right) + B \nabla \left( \frac{V_{||}}{B} \right) \right]
\]
\[
- \left( \frac{1}{B_0} b \times \nabla_{\perp} \phi + V_{||} b \right) \cdot \nabla T_e - \frac{2}{3n_i k_B} \frac{Z_i}{m_i} \left( T_e - T_i \right)
\]

Parallel heat flux

Parallel heat flux
Different balance pressure profile

- Simulations are based on the shifted circular cross-section toroidal equilibria (cbm18_den6) generated by the TOQ code*.

Landau damping closure

\[ q_{\parallel i} = -n_0 \sqrt{\frac{8}{\pi}} v_{T_{\parallel i}} \frac{ik_{\parallel} k_B T_i}{|k_{\parallel}|} \]
\[ q_{\parallel e} = -n_0 \sqrt{\frac{8}{\pi}} v_{T_{\parallel e}} \frac{ik_{\parallel} k_B T_e}{|k_{\parallel}|} \]

✓ Non-local thermal transport

classical thermal conductivities

\[ q_{\parallel i} = -\kappa_{\parallel i} \nabla_{\parallel} k_B T_i \]
\[ q_{\parallel e} = -\kappa_{\parallel e} \nabla_{\parallel} k_B T_e \]

Where

\[ \kappa_{\parallel i} = \left( \kappa_{\parallel i}^{SH} + \kappa_{\parallel i}^{FS} \right)^{-1} \]
\[ \kappa_{\parallel e} = \left( \kappa_{\parallel e}^{SH} + \kappa_{\parallel e}^{FS} \right)^{-1} \]

\[ \kappa_{\parallel i} = 3.9n_i v_{th,i}^2 / \nu_i \]
\[ \kappa_{\parallel e} = 3.2n_e v_{th,e}^2 / \nu_e \]

✓ Classical heat flux

Spitzer-Harm

Flux streaming

Classical heat flux

Non-local thermal transport
Landau closure has more damping effect on linear growth rate, but not very strong

- Both Landau closure and flux limited thermal conductivity has stabilizing effect on peeling-ballooning modes;
- Landau closure has stronger stabilizing effect;
- Thermal conductivity doesn’t change the unstable island of modes.

Why the stabilizing effect from local/nonlocal parallel thermal conductive is not that strong?
• For ideal ballooning mode, dispersion relation is
\[ \omega \left( \omega - i \chi_\parallel k_\parallel^2 \right) + \gamma_i^2 = 0 \]

• We get growth rate
\[ \gamma = \frac{1}{2} \left( -\chi_\parallel k_\parallel^2 + \sqrt{\chi_\parallel^2 k_\parallel^4 + 4 \gamma_i^2} \right) \]

• Parallel conductivity has a stabilizing effect on peeling ballooning mode

• Parallel conductivity should have no effect on rational surface which \( k_\parallel = 0 \) \( \Rightarrow \) Radial structure
Our simulations show consistent radial structure with theoretic expectation!

- Radial mode structure
  - Without parallel diffusion: smooth;
  - With Landau damping for flux limited thermal conductivity: peaked at rational surface.

<table>
<thead>
<tr>
<th></th>
<th>Rational surface</th>
<th>Irrational surface</th>
</tr>
</thead>
<tbody>
<tr>
<td>Instability</td>
<td>Strong</td>
<td>Weak</td>
</tr>
<tr>
<td>Parallel damping</td>
<td>Weak</td>
<td>Strong</td>
</tr>
</tbody>
</table>

- The mismatch between instability and parallel diffusion reduces the damping effect on peeling ballooning modes.
Landau damping leads to smaller ELM size in nonlinear simulations than flux limited expression.

- Nonlinear result is similar as linear result;
- Landau damping closure has more damping effect on the turbulence transport phase of elm crash;
- Elm size with Landau closure is smaller than Elm size with flux limited heat flux;
Effect on rational surface during linear phase

- Electron temperature contour of nonlinear run
- Parallel heat flux has no effect on rational surface
- Trace of rational surface disappear in the turbulence state
Different $L_n/L_t$

- Keep the same pressure profile, change density and temperature;
- $L_n/L_t$ scan:

<table>
<thead>
<tr>
<th>$L_n/L_t$</th>
<th>Height</th>
<th>tail</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>0.800</td>
<td>0.000</td>
</tr>
<tr>
<td>2</td>
<td>0.400</td>
<td>0.200</td>
</tr>
<tr>
<td>4</td>
<td>0.240</td>
<td>0.280</td>
</tr>
<tr>
<td>6</td>
<td>0.171</td>
<td>0.316</td>
</tr>
<tr>
<td>8</td>
<td>0.133</td>
<td>0.333</td>
</tr>
<tr>
<td>10</td>
<td>0.109</td>
<td>0.345</td>
</tr>
</tbody>
</table>
Damping effect is strong when $Ln/L_T$ is large

- Keep pressure profile and local density and temperature profile fixed, change $Ln/L_T$
- $Ln/L_T$ has small effect on peeling ballooning mode
- Parallel conductivity has small effect when $Ln/L_T$ is small
\( L_n/L_T \) has little effect on growth rate spectrum

- \( L_n/L_T \) has small effect on the growth rate and spectrum;
- Small effect from diamagnetic term because of different density gradient profile.
Spreading is strong when $L_n/L_T$ is large

- $L_n/L_T$ has small effect on initial crash phase.
- Speed in spreading phase is large when $L_n/L_T$ is large.
- When $L_n/L_T$ is small, result with Landau closure has more damping effect on ELM size. When $L_n/L_T$ is large, ELM size with Landau closure has faster spreading speed than flux limited case.
ELM has fast crash phase and slow perturbation spreading phase

- Ion perturbation has larger initial crash
- Electron provides the spreading
Ion perturbation has a large initial crash and electron perturbation only has spreading.
Dominant mode number changed in different phases
Electron has a positive phase shift with \( \phi \).
ExB drift term in electron temperature equation cause the spreading

- Drift velocity in electron equation is similar with spreading speed
- Drift wave instability cause the spreading
- Dissipation effect, (Landau damping, parallel thermal conductivity), destabilize the instability.

\[ \frac{\partial \langle T_e \rangle}{\partial t} = - \frac{1}{B_0} \langle b \times \nabla \perp \phi \cdot \nabla T_e \rangle \]
Larger conductivity leads to the spreading for electron perturbation

$q_i = -\kappa_e \nabla_{||} T_i$

- With larger thermal conductivity, ion perturbation has same ELM size as electron perturbation.
Thermal force, when coupled with parallel heat flux, can destabilizes modes

- With Landau closure or flux limited diffusion: Thermal force has an unstable effect on modes;
- Without parallel diffusion: Thermal force has small effect on the linear growth rate of modes.
Summary

• Parallel conductivity term has stabilize effect on peeling-ballooning mode and can reduce elm size.

• Landau closure has more damping effect for the linear growth rate of peeling-ballooning mode.

• Spreading is caused by drift wave instability. Speed for electron perturbation is determined by ExB drift velocity which is large when $\nabla T_e$ is large.

• Different response of ion and electron in nonlinear ELM simulation is compared.