Spontaneous ITB formation in gyrokinetic flux-driven ITG/TEM turbulence

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Internal Transport barrier (ITB) has a crucial key to achieve a high-performance plasma confinement.

Some possible mechanism for ITB formation are proposed [Ida, PPCF-2018] as:

1. Positive feedback loop via $E \times B$ mean flow [Sakamoto, NF-2004] [Yu, NF-2016]
2. Positive feedback loop via safety factor profile (BS current) [Eriksson, PRL-2002]
3. Positive feedback loop via Shafranov shift + EM stabilization [Staebler, NF-2018]
By our full-$f$ gyrokinetic code *GKNET*, we found that momentum injection can change mean $E \times B$ flow through the radial force balance, which can break the ballooning symmetry of turbulence, leading to ITB formation. [Imadera, IAEA-2016]

Such a mechanism can also benefit the ITB formation around $q_{min}$ surface in reversed magnetic shear plasma.

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**Pressure gradient**

- **Mean $E \times B$ flow**
  - Recover the symmetry
  - $\rightarrow$ weak stabilization

**Momentum injection**

- **Turbulence**
  - Trigger
- **Flow generation**
  - Steepening
  - Mean $E \times B$ flow
  - Break the symmetry
  - $\rightarrow$ strong stabilization

**Pressure gradient**

- **Heat & momentum source region**
- $q_{min}$
Motivation of This Research

✓ However, in our previous study based on the original GKNET with adiabatic electron, enough large co-momentum injection is required for ITB formation in flux-driven ITG turbulence. In addition, some experiments indicate the importance of counter-intrinsic rotation. [Sakamoto, NF-2001]

✓ In this study, we have introduced hybrid kinetic electron model [Lanti, JP-2018] and investigated spontaneous ITB formation in flux-driven ITG/TEM turbulence.

\[
\begin{align*}
&\text{GKNET} \\
&\text{Toroidal} \\
&\text{Electrostatic} \\
&\text{Adiabatic Electron} \\
&\text{full-f} \\
\end{align*}
\]

\[
\begin{align*}
&\text{GKNET-KE} \\
&\text{Toroidal} \\
&\text{Electrostatic} \\
&\text{Kinetic Electron} \\
&\text{global delta-f} \\
\end{align*}
\]

\[
\begin{align*}
&\text{GKNET-KE-EM} \\
&\text{Toroidal} \\
&\text{Electromagnetic} \\
&\text{Kinetic Electron} \\
&\text{global delta-f} \\
\end{align*}
\]

\[
\begin{align*}
&\text{GKNET-shaped} \\
&\text{Magnetic flux} \\
&\text{Electrostatic} \\
&\text{Adiabatic Electron} \\
&\text{full-f} \\
\end{align*}
\]

\[
\begin{align*}
&\text{GKNET-HE} \\
&\text{Toroidal} \\
&\text{Electrostatic} \\
&\text{Hybrid Electron} \\
&\text{full-f} \\
\end{align*}
\]

[Imadera, IAEA-2014]

[Imadera, PFR-2020]

[Ishizawa, PoP-2019]

[Ishizawa, this conference, TH/4-2]
GK Vlasov equation

\[
\frac{\partial}{\partial t} (\mathcal{J} f_s) + \mathcal{J} \frac{d\mathbf{R}}{dt} \cdot \frac{\partial f_s}{\partial \mathbf{R}} + \mathcal{J} \frac{d\mathbf{v}_\parallel}{dt} \frac{\partial f_s}{\partial \mathbf{v}_\parallel} = \mathcal{J} C_{s,s} + \mathcal{J} S_{src} + \mathcal{J} S_{snk}
\]

\[
\frac{d\mathbf{R}}{dt} = \frac{1}{B_i^*} \left[ \mathbf{v}_\parallel (\mathbf{V} \times \mathbf{A}) + \frac{B_0}{\Omega_s} \mathbf{v}_\parallel^2 (\mathbf{V} \times \mathbf{b}) + \frac{c}{e_s} \mathbf{H} \mathbf{V} \times \mathbf{b} - \frac{c}{e_s} \mathbf{V} \times (\mathbf{H} \mathbf{b}) \right]
\]

\[
\frac{d\mathbf{v}_\parallel}{dt} = -\frac{1}{m_s B_i^*} \left[ (\mathbf{V} \times \mathbf{A}) \cdot \mathbf{V} \mathbf{H} + \frac{B_0}{\Omega_s} \mathbf{v}_\parallel \mathbf{V} \cdot (H \mathbf{V} \times \mathbf{b}) \right]
\]

GK quasi-neutrality condition

\[
\int \langle \delta f_i \rangle_{\alpha,i} \frac{B_i^*}{m_i} d\mathbf{v}_\parallel d\mu + \frac{1}{4\pi e_i} \frac{\rho_{ti}^2}{\lambda_{Di}^2} \mathbf{V} \cdot \mathbf{V} \phi = \delta n_e
\]

\( f_s \): full-f distribution function for species \( s = i, e \)

\( C_{s,s} \): self-collision operator for species \( s \)

\( S_{src} \): Heat source operator

\( S_{snk} \): Krook-type sink operator

Physical model

- **GKNET-HE** is based on full-f gyrokinetic model, which trace turbulence and background profiles self-consistently.
- External heat source and sink are introduced so that the turbulence is not decayed but sustained over the confinement time (flux-driven simulation).
- To study flux-driven ITG/TEM turbulence, we have introduced the following hybrid kinetic electron model [Lanti, JP-2018].

<table>
<thead>
<tr>
<th>( \delta n_{e,\text{pass}} )</th>
<th>( \delta n_{e,\text{trap}} )</th>
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<tbody>
<tr>
<td>Kinetic response</td>
<td>Kinetic response</td>
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<tr>
<td>Kinetic response</td>
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</table>

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To study flux-driven ITG/TEM turbulence, we have introduced the following hybrid kinetic electron model [Lanti, JP-2018].
**Full-f Gyrokinetic Code GKNET - 2**

**GK Vlasov equation**

\[
\frac{\partial}{\partial t} (\mathcal{J} f_s) + J \frac{dR}{dt} \cdot \frac{\partial f_s}{\partial R} + J \frac{dv}{dt} \frac{\partial f_s}{\partial v} = \mathcal{J} C_{s,s} + JS_{src} + JS_{snk}
\]

\[
\frac{dR}{dt} = \frac{1}{B^*_||} \left[ v_{||}(\nabla \times A) + \frac{B_0}{\Omega_s} v_{||}^2 (\nabla \times b) + \frac{c}{e_s} \cdot H \nabla \times b - \frac{c}{e_s} \nabla \times (Hb) \right]
\]

\[
\frac{dv_{||}}{dt} = -\frac{1}{m_s B^*_||} \left[ (\nabla \times A) \cdot \nabla H + \frac{B_0}{\Omega_s} v_{||} \nabla \cdot (H \nabla \times b) \right]
\]

**GK quasi-neutrality condition**

\[
\int \langle \delta f_i \rangle_{\alpha,i} \frac{B^*_{||}}{m_i} dv \, d\mu + \frac{1}{4\pi e_i} \nabla \cdot \frac{\rho_{ti}^2}{\lambda_{Di}^2} \nabla \phi = \delta n_e
\]

- \( f_s \): full-f distribution function for species \( s = i, e \)
- \( C_{s,s} \): self-collision operator for species \( s \)
- \( S_{src} \): Heat source operator
- \( S_{snk} \): Krook-type sink operator

**Numerical model**

- We discretize the Vlasov equation by using Morinishi scheme, which was developed for fluid simulation and introduced to rectangular gyrokinetic code, [Morinishi, JCP-2004, Idomura, JCP-2007] to polar coordinate with new flux-conservative scheme.

- Field equation is solved in real space (not k-space) and full-order FLR effect is taken into account by using 20 point average on gyro-ring.

- 3D MPI decomposition is introduced by utilizing 1D FFT and MPI_ALLtoALL transpose technique.
Simulation condition

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$a_0/\rho_i$</td>
<td>150</td>
</tr>
<tr>
<td>$a_0/R_0$</td>
<td>0.36</td>
</tr>
<tr>
<td>$(R_0/L_n)_{r=a_0/2}$</td>
<td>2.22</td>
</tr>
<tr>
<td>$(R_0/L_{Ti})_{r=a_0/2}$</td>
<td>10</td>
</tr>
<tr>
<td>$(R_0/L_{Te})_{r=a_0/2}$</td>
<td>(A) 6.92 (B) 10</td>
</tr>
<tr>
<td>$\Delta_r$</td>
<td>45</td>
</tr>
<tr>
<td>$\sqrt{m_i/m_e}$</td>
<td>10</td>
</tr>
</tbody>
</table>

Parameter Value

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\nu_i^*$</td>
<td>0.1</td>
</tr>
<tr>
<td>$\nu_e^*$</td>
<td>0.1</td>
</tr>
<tr>
<td>$\tau_{src,i}^{-1}$</td>
<td>0.02 -&gt; 4 [MW]</td>
</tr>
<tr>
<td>$\tau_{src,e}^{-1}$</td>
<td>(A) 0 -&gt; 0 [MW] (B) 0.02 -&gt; 4 [MW]</td>
</tr>
<tr>
<td>$\tau_{snk}^{-1}$</td>
<td>0.1/0.36</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_r$</td>
<td>96</td>
</tr>
<tr>
<td>$N_\theta$</td>
<td>240</td>
</tr>
<tr>
<td>$N_\varphi$</td>
<td>48</td>
</tr>
<tr>
<td>$N_{v</td>
<td></td>
</tr>
<tr>
<td>$N_\mu$</td>
<td>16</td>
</tr>
<tr>
<td>$\Delta t$</td>
<td>$3.125 \times 10^{-4}$</td>
</tr>
</tbody>
</table>

We consider (A) ITG dominant and (B) ITG/TEM dominant cases.

Safety factor profile is reversed, which local minimum is located at $r = 0.6a_0$.

Only heat source is applied, which does not provide particle and momentum.
Stable local maximum of mean $E_r$ are formed near $q_{min}$ surface only in kinetic electron cases.
Large co-rotation is driven around $q_{min}$ surface in case (A-2) and (B).

According to the momentum transport theory, $\langle \Pi_{RS} \rangle_{\theta \phi} = \alpha I'_{E_r} + \beta I' + \gamma \langle k_{\theta} k_{\phi} \Phi_k^2 \rangle_{\theta \phi}$ [Kwon, NF-2012], the first and second terms can reduce momentum diffusion in this case, which can keep the stable local maximum of mean $E_r$ through the radial force balance.

Counter-rotation is also observed in negative magnetic shear region in case (B).
What is the Origin of Co-/Counter-Rotation?

- The finite ballooning angle of the global mode structure arising from the profile shearing effect [Kishimoto, PPCF-1998] induces the residual stress part of momentum flux [Camenen, NF-2011].

- The sign of the ballooning angle between ITG and TEM turbulence is opposite (left figures) so that the direction of intrinsic rotation is reversed.

- The steep electron temperature gradient is considered to destabilize TEM in the negative magnetic shear region.
In flux-driven ITG turbulence with kinetic electrons, the co-current toroidal rotation can balance with $E_r$, of which shear becomes strong just inside of $q_{min}$ surface.

On the other hand, in ITG/TEM turbulence with kinetic electrons, $E_r$ is reversed in negative magnetic shear region, which makes its shear stronger and pressure gradient steeper.
As the result, ion turbulent thermal diffusivity in flux-driven ITG/TEM case spontaneously decreases to the neoclassical transport level among $0.4a_0 < r < 0.6a_0$, where $E_r$ shear becomes steep.

These results indicate that the co-existence of different modes can trigger the discontinuity near $q_{min}$, leading to the spontaneous ITB formation.
Summary & Future Plans

Summary
✓ We have performed the flux-driven ITG/TEM simulation in reversed magnetic shear configuration by using hybrid kinetic electron model.

✓ In the presence of both ion and electron heating, a counter-intrinsic rotation by TEM turbulence is driven in negative magnetic shear region, leading to steeper $E_x$ shear and the resultant spontaneous larger reduction of ion turbulent thermal diffusivity.

Discussion
✓ An increase of counter intrinsic rotation in the narrow region of the ITB located just inside of $q_{min}$ is also observed in JT-60U reversed magnetic shear discharge with balanced momentum injection [Sakamoto, NF-2001]. -> Qualitative agreement!

✓ It can conclude that counter intrinsic rotation is a possible candidate to trigger the positive feedback loop via $E \times B$ mean flow, leading to spontaneous ITB formation.

Future Plans
✓ By reflecting bootstrap current and shafranov shift effects to the analytical magnetic equilibrium [Imadera, PFR-2020] in time, we can take them into account, which can help us to understand the other positive feedback loop.