Gyrokinetic analysis of turbulent transport in helical systems with different magnetic shear

A. Ishizawa
Kyoto University
Motivation

– Approximate degrees of deviation from axisymmetry
  • 3D tokamak ($\delta B_{n\neq0}/\delta B_{n=0} = 10^{-3}$ to $10^{-2}$)
  • Helical reversed field pinch state ($\delta B_{n\neq0}/\delta B_{n=0} = 0.03$ to 0.05)
  • Stellarator ($\delta B_{n\neq0}/\delta B_{n=0} = 0.1$ to 0.3)
Outline

• Introduction
• Large Helical Device (LHD)
• Heliotron J (HJ)
• Comparison
• Summary
LHD discharge #88343

- $B=2.75T$, $R=3.6m$ (shifted to $3.75m$)
- Low-Ti phase: $Ti=1.6keV$ $t=1.8s$
- High-Ti phase: $Ti=3.9keV$ $t=2.2s$
  - Beta($r/a=0.65$)=0.3%
  - Collision: $1/\nu$

Tanaka, PFR 2010
Linear analysis of LHD

- Ion temperature gradient (ITG) modes are unstable.
- Kinetic electron effects enhance the instability.
• ITG and ETG modes are unstable.
Turbulent energy flux of LHD

Ion and electron energy fluxes due to turbulence, \( Q_i \) and \( Q_e \).

- The transition of the energy flux from the low-Ti phase (\( t=1.8, \ Ti=1.6\text{keV} \)) to the high-Ti phase (\( t=2.2\text{s}, \ Ti=3.9\text{keV} \)) in the experiment is reproduced.

- There is no short-fall problem, which suffers the GK analysis of some tokamaks.
Prediction of profile by flux matching

- The predicted temperature gradient length deviates from experimental observation about 20%.

$\frac{L_T}{L_{T,\text{exp}}}$ : Temperature gradient length

$Q_s$ : Heat flux of “s” species

$Q_s(L_{T,\text{exp}})$ : Experimental observation of Qs

- High-Ti phase
- LHD 88343 t=2.2 $\rho=0.65$

![Graph showing predicted and experimental temperature gradient lengths, with annotations for $L_T$, $L_{T,\text{exp}}$, $Q_s$, and $Q_s(L_{T,\text{exp}})$.]
Turbulent particle flux

- The turbulent particle flux directs to the magnetic axis, and its direction is opposite to the neo-classical particle flux.

\[ \Gamma = \Gamma_{\text{neo-classical}} + \Gamma_{\text{turbulence}} \]
Profiles of HJ plasma

- Density profile
- Temperature profiles

HJ-ST: standard configuration
HJ-HB: High-toroidal ripple configuration

Nishioka, PFR 2014
Simulation results

- The ITG mode is unstable
  - The LHD is the inner shifted configuration, so it is magnetic hill with a moderate shear.
  - The HJ is magnetic well with a very weak shear.
  - The LHD has an advantage compared with HJ from the linear aspect of drift wave instability.

<table>
<thead>
<tr>
<th>$R_0/a$</th>
<th>LHD-L</th>
<th>HJ-ST</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\rho = r/a$</td>
<td>0.68</td>
<td>0.5</td>
</tr>
<tr>
<td>$q$</td>
<td>1.5</td>
<td>1.7</td>
</tr>
<tr>
<td>$\rho_s [10^{-3}]$</td>
<td>2.</td>
<td>4.5</td>
</tr>
<tr>
<td>$v_i^*$</td>
<td>0.083</td>
<td>3.2</td>
</tr>
<tr>
<td>$\beta [%]$</td>
<td>0.2</td>
<td>0.05</td>
</tr>
<tr>
<td>$T_e / T_i$</td>
<td>0.96</td>
<td>1.3</td>
</tr>
<tr>
<td>$R_0 / L_n$</td>
<td>2.7</td>
<td>9.3</td>
</tr>
<tr>
<td>$R_0 / L_T i$</td>
<td>8.7</td>
<td>13.</td>
</tr>
<tr>
<td>$R_0 / L_T e$</td>
<td>9.1</td>
<td>17.</td>
</tr>
<tr>
<td>$s$</td>
<td>1.2</td>
<td>0.023</td>
</tr>
<tr>
<td>$D_{well}$</td>
<td>-0.01</td>
<td>0.74</td>
</tr>
</tbody>
</table>

- Instability
  - $\gamma [v_{Ti} / R_0]$ | ITG | ITG |
  - $R_0 / L_T - R_0 / L_{T\text{crit}}$ | 2.6 | 5.2 |
  - $\chi_i [v_{Ti} \rho_{T_i}^2 / R_0]$ | 11. | 5.9 |
  - $\chi_e [v_{Ti} \rho_{T_i}^2 / R_0]$ | 4.8 | 2.4 |
  - $E_{ZF} / (E_{ZF} + E_{ITG})$ | 0.14 | 0.72 |

Eigen function of the ITG mode
Comparisons in (s_hat, Dwell) space

- The stabilizing effect of the magnetic shear is confirmed by the reduction of the growth rate by increasing the shear.
- The neoclassical optimization improves turbulent transport in HJ.
- Weak magnetic shear of HJ does not lead to high turbulent transport because of nonlinear interactions including zonal flow production.
Summary

• Comparisons of turbulent transport in helical systems including the LHD and the Heliotron J

• LHD analysis
  – The simulations reproduce the temperature gradients before and after the additional NBI within 20% error.
  – There is no short-fall problem.

• HJ analysis
  – The neoclassical optimization (high-toroidal ripple) suppresses the turbulent heat transport.

• Comparison reveals that the regulation of turbulence by zonal flows is more efficient in HJ which has very weak magnetic shear.