Turbulence Spreading as a Non-local Mechanism of Tokamak Confinement Degradation

Sumin Yi[1], J.M. Kwon[1], and P. H. Diamond[2]

[1] Advanced Physics Research Division, NFRI, Korea
[2] CMTFO and CASS, UCSD, USA

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Outline

1. Introduction
   - Dependence of core confinement on magnetic shear and toroidal rotation shear
   - Conventional understanding: Local paradigm
   - Another possible mechanism: Turbulence spreading
   - Quick summary of this work

2. Numerical experiments

3. Results
   - Synergy of magnetic shear and toroidal rotation shear in turbulence spreading
   - Increase of transport by turbulence spreading
   - Dependence of spreading-induced transport on magnetic shear and rotation shear

4. Conclusion and discussion
Parametric Dependence of Core Confinement

- Degradation of heating efficiency
  \[ \tau_{Th}^{IPB98} \sim 1/P^{0.69} \]
  Profile stiffness: the sharp increase of transport as profile gradients exceed thresholds for micro-instabilities
  \[ \Rightarrow \] A serious limitation of \( T_i(0) \)

- The level of turbulent transport depends on various parameters.
  - Both weak or negative magnetic shear \( s \) and high toroidal rotation shear \( U_0' \) facilitate improvement of core confinement.

Energy confinement time versus heating power in ASDEX-Upgrade

Results of JET experiments
(P. Mantica et al, PRL 2011)
Conventional Understanding

- Interpretations of the dependence of core confinement on $s$ and $U_0'$ based on local properties of turbulence
  - $E\times B$ shear stabilization of local turbulence:
    \[ \chi_{tur} \sim \chi_{L-mode}/\left[1 + \alpha \left(\frac{\omega_E}{\gamma_{Lin}}\right)^\beta\right] \]

- Underestimation of the level of turbulent transport as compared to the experimental results
  - Other mechanisms increasing turbulent transport ?!

Validation of a local model against DIII-D plasmas
(C. Holland et al, PoP 2011)
Results of fluctuation measurements during ITB:

- Before ITB formation, correlation length $\gg$ typical $\ell_{local}$ of local theories
- As the level of transport decreases with ITB, correlation length $\sim$ typical $\ell_{local}$

$\Rightarrow$ Turbulence penetration into the ITB region degrades the core confinement.

Radial correlation measured by a reflectometry in JT-60U plasmas (R. Nazikian, et al, PRL 2005)
A Prime Candidate: Turbulence Spreading

- Fluctuation energy can be transferred to distant regions by nonlinear mode-mode coupling
  \( (\text{Garbet NF 1994, Hahm PPCF 2004, Gürcan PoP2005}) \)

- Turbulence intensity evolution = spreading process + local processes

  \[
  \frac{\partial I}{\partial t} + \frac{\partial \Gamma_I}{\partial r} = \gamma [\nabla T] I - \gamma_{NL} I^2 - \alpha_0 V_{ZF} I + \cdots,
  \]

  coupled to evolution of zonal flow, …

  \textbf{Flux of turbulence intensity}

  \[
  \Gamma_I = -D_0 I \frac{\partial I}{\partial r}.
  \]

- Fluctuation from a strongly driven region can increase turbulent transport in a marginally stable or weakly turbulent region.
Quick Summary of Results

- Turbulence spreading into a marginally stable zone can increase turbulent transport to a level exceeding predictions of local theories.

- We present the first quantification of the parametric dependence of turbulence spreading on toroidal rotation shear $u'_0$ and magnetic shear $s$.
  - Spreading is significant at high $s > 0.2$, but slows down at low $s$.
  - Rotation shear inhibits spreading only at low $s$.

- The parametric dependence of spreading-induced transport on $s$ and $u'_0$ is consistent with the experiments of improved core confinement, which is facilitated by low or negative magnetic shear and toroidal rotation shear.
Gyrokinetic Simulation of ITG Turbulence

- Global $\delta f$ PIC gyrokinetic simulation code $gKPSP$ (Kwon, et al., Nucl. Fusion 2012)
  - Decaying ITG turbulence due $T_i$ profile relaxation (No profile control)
  - Turbulence spreading processes are faster than turbulence decay.

\[
\frac{T_{\text{spreading}}}{T_{\text{decay}}} = 0.1 - 0.4
\]

- An inner core and the outer region with linearly unstable and marginally stable $T_i$ profiles, respectively

⇒ Separation of local physics and non-local spreading

- External toroidal rotation shear on the outside of the unstable region of

\[
U_0' \equiv -\frac{a}{v_{T_0}} \frac{dV \varphi_0}{dr} = 0, 0.4, 0.8
\]

(comparable with experimental values)

⇒ Control only the spreading

- Equilibrium $E_{r0} = \frac{\partial p_i}{en_0 \partial r} - V_{\theta,neo} B\varphi + V_{\phi_0} B_{\theta}$ is added to self-consistently calculated $E_r$. 

![Graph showing $R_0/L_{Ti}$ and $\eta_i$ vs. $r/a$ with $V_{\phi_0}$ values at 0.4, 0.6, 0.8]
Various Magnetic Shear $s$ Profiles

- Same $s$-profile in the linearly unstable region
  \[ \Rightarrow \text{Identical linear instability} \]
- Different $s$-profile in the region of marginal stability
  \[ \Rightarrow \text{Changes of the nonlinear turbulence spreading?} \]
- The $s$-profiles are labeled by the magnetic shear at a reference position $r/a = 0.7$ in the stable region.
  \[ \Rightarrow \text{A concentric circular equilibrium of } a/\rho_{i0} \sim 170. \]
Results
Different Dynamics of Turbulence Spreading

- External E×B flow shear can hinder turbulence spreading (W.X. Wang PoP 2007).
- The suppression of spreading by rotation shear depends strongly on $s$.
- For $U'_0 = 0$:
  - **at high $s = 0.5$, prompt propagation**
  - **at low $s = 0.1$, much slower propagation**
  \[ \Rightarrow \text{A slowing down of spreading processes and easier control of the spreading} \]
- For $U'_0 = 0.8$:
  - **at high $s = 0.5$, turbulence spreading persists.**
  - **at low $s = 0.1$, suppression of turbulence spreading.**
Penetration Depth $x_0$ for Different $s$ and $U_0'$

- Turbulence spreading is promoted by positive magnetic shear and maximized around $s = 0.5$.
- The suppression of spreading is only effective when $s < 0.2$.
  (The rotation shear is ineffective at high magnetic shear.)

Penetration depth $x_0$:
the penetration distance of the front from the boundary at $r/a = 0.5$. 
Heat Transport induced by Spreading

- As expected from $Q_i \approx \chi \frac{\partial T_i}{\partial r} \sim I \frac{\partial T_i}{\partial r}$,

- When spreading is large ($s = 0.5$ and $U_0' = 0$), turbulence spreading causes turbulent transport in the linearly stable region, which dominates the neoclassical transport.

⇒ **Transport in a weakly turbulent region can increase by turbulence from strongly driven regions.**

- The rotation shear combined with low $s$ prevents the degradation of local confinement by the spreading in the stable region.

⇒ **Preservation of local confinement to the level set by local mechanisms.**
Physics of the Dependence on $s$ and $U_0'$

- Estimation of a time scale required for spreading $\tau_N \equiv <r_c>^2/D$
  - $D$: diffusivity of spreading
  - $<r_c>$: radial correlation length of fluctuations in the linearly stable region
- Comparison with an $E \times B$ decorrelation time scale $\tau_{E \times B} \equiv 1/\max(|\omega_{E \times B}|)$

- At low or negative magnetic shear ($s<0.2$),
  - Divergent behavior of the spreading time
    - $\Rightarrow$ Turbulence spreading slowing down
  - $\tau_N$ longer than $\tau_{E \times B}$
    - $\Rightarrow$ Effectiveness of rotation shear in spreading suppression
s- and $U_0'$-Dependence of Spreading-induced Transport

$\langle Q_i \rangle_{SPR} \sim \frac{1}{1 + (\tau_N/\tau_{E \times B})^2}$

Results of JET experiments
(P. Mantica et al, PRL 2011)

<table>
<thead>
<tr>
<th>$U_0'$ and s</th>
<th>$\tau_N/\tau_{E \times B}$</th>
<th>$\langle Q_i \rangle_{SPR}$</th>
<th>Transport level in Exp.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$U_0' = 0$ irrespective s</td>
<td>$&lt;1$</td>
<td>Large</td>
<td>Large</td>
</tr>
<tr>
<td>$U_0' &gt; 0$ at high s</td>
<td>$\leq 1$</td>
<td>Intermediate</td>
<td>Intermediate</td>
</tr>
<tr>
<td>$U_0' &gt; 0$ at low s</td>
<td>$&gt;1$</td>
<td>Small</td>
<td>Small</td>
</tr>
</tbody>
</table>

* Qualitative agreement with the dependence of transport experiments in JET.*
In practice, local physics and non-local spreading are mixed.

A direct measure of turbulence spreading by non-local bicoherence of radially distant modes

\[
\bar{b}^2(r, r + \delta r) = \frac{1}{N} \sum_{n_1,n_2,m_1,m_2} \left| \frac{\langle \phi_{m_1,n_1}(r) \phi_{m_2,n_2}(r) \phi_{m_1+m_2,n_1+n_2}^*(r+\delta r) \rangle^2}{\langle \phi_{m_2,n_2}(r) \phi_{m_2,n_2}(r) \rangle^2 \langle \phi_{m_1+m_2,n_1+n_2}(r+\delta r) \rangle^2} \right|
\]

When spreading is significant at high \( s \) ⇒ Larger bicoherence at longer distance

Applicable to fluctuations from experiments
Conclusion and Discussion

- Core confinement can be degraded by turbulence spreading.
- The parametric dependence of spreading-induced transport on $s$ and $U'_0$ is consistent with the experimental confinement scaling.

- We propose that omission of spreading from local transport models will lead to underestimation of the level of turbulent transport and inferior understanding of plasma confinement scaling on rotation and magnetic shear.

- We propose to measure the bicoherence of fluctuation spectra in different radii. If turbulence spreading degrades core confinement, the non-local bicoherence will change as the level of turbulent transport varies.
Supplements
Estimation of Diffusivity of Turbulence Spreading

- A fluctuation intensity transport analysis by adapting a minimalist model of turbulence intensity evolution (T. S. Hahm, et al., PPCF 2004)

\[
\frac{\partial I}{\partial t} - \frac{\partial}{\partial x} D \frac{\partial I}{\partial x} = \gamma I - \gamma_{NL} I^2,
\]

\[D = D_0 I\]

- An expression for \(x_0\) (Gürcan, et al., PoP 2005)

\[x_0 = \sqrt{\frac{2D_0}{\gamma_{NL}}} F \left( \frac{\gamma_g}{\gamma_d} \right)\]

**Contribution of local linear physics**

- Evaluation of spreading (i.e. \(D\)) after measuring \(x_0\) and the various \(\gamma\)'s from simulation data.

Deeper penetration for higher q-values

Effect on linear damping rate: $\gamma_d \sim k_{||}R_0 \sim 1/q$

The change of the penetration depth is well described by a single value of $D_0$.

The increased penetration depth for higher q-values results from the decrease of linear damping rate.

The value of safety factor itself does not affect the efficiency of turbulence spreading much.

Behavior of the Total $E \times B$ Flow Shear

- Total $E \times B$ shear
  \[ \omega_{E \times B} \equiv \omega_{E \times B}^{(0)} + \omega_{E \times B}^{(ZF)} \]
- $\omega_{E \times B}$ increases with the amplitude of $\omega_{E \times B}^{(0)}$.
- But, the amplitude of $\omega_{E \times B}$ is dominated by the zonal component.
- Suppression of spreading does not result from the direct effect of the external rotation shear.
  \[ \Rightarrow \text{a self-organized process} \]