Intrinsic Rotation and Dynamics of Internal Transport Barriers with Reversed Magnetic Shear in Tokamaks

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Outline

- Motivating issues

- Methodology: Global flux-driven gyrofluid simulations

- Intrinsic rotation in ITB
  - Characteristics
  - Scaling
  - Phenomenology: Hysteresis

- Formation and back transition of internal transport barrier (ITB)
  - Role of intrinsic rotation & parallel shear flow instability (PSFI) in ITB dynamics
  - Cross interactions
Motivating issues and questions

● Intrinsic rotation (self-acceleration) in ITB:
  - ITER:
    - Low-torque environment
    - Advanced steady state operation will require ITB plasmas
    - Limited power available to access H-mode
  - Characteristics of intrinsic rotation in ITBs? Scaling?
  - Hysteresis happens?
  - Both interesting and useful

● ITB dynamics:
  - Intrinsic rotation closely coupled in ITB evolution
  - Mean flow shear & Reynolds stress are key players in ITB dynamics.
  - Questions:
    - What drives the Reynolds stress change? Parallel flow shear instability (PSFI)?
    - What is the role of momentum transport/transfer in ITB dynamics?
Tokamak: a leading candidate for magnetic fusion

- Tokamak plasma confinement is realized by the JXB force (gravitational force in the Sun) against pressure → Plasma current required

\[ q = \frac{rB_{tor}}{RB_{pol}} \]

\[ q = \text{field line pitch} = \frac{\Delta \phi}{2\pi} \]
Tokamak Turbulence and Transport

- Strongly magnetized quasi-2D ($k_\parallel \ll k_\perp$) turbulence as in geostrophic flow (Lorentz ↔ Coriolis)
- Transport by fluctuating electric and magnetic fields → Directly connected to reactor size
- Mixing length/system size $\sim \rho_i/a \sim \rho_*$ ($\sim 10^{-3}$ ITER)
  - Mean transport flux is diffusive $D = D_{GB} = D_B \rho_*$
- Meso-scale structure formation → Self-regulation by ZF, ExB staircase, …
- Scale invariant extended, transport events happen as in SOC.
Numerical model

- Three-field gyrofluid equations with electrostatic ion temperature gradient (ITG) turbulence

\[
\begin{align*}
(d_t^E - D_c - D_{\text{neo}})\Omega &= -n\nabla \parallel V_\parallel + n(V_E + V_p) \cdot (\kappa + \nabla \ln B) + nV_p \cdot \nabla \left(\frac{n_1 - \Omega}{n}\right) - d_t^E n_{eq} \\
(d_t^E - D_c)\dot{V}_\parallel &= -\frac{e}{m} \nabla \parallel \varphi - \frac{1}{mn} \nabla \parallel p \\
(d_t^E - D_c - D_{\text{glf}})p &= \frac{5}{3} pV_T \cdot (\kappa + \nabla \ln B) + \frac{5}{3} Td_t^E n + S_p
\end{align*}
\]

Vorticity

Parallel flow

Pressure

\[
\begin{align*}
d_t^E &= \frac{\partial}{\partial t} + V_E \cdot \nabla, \quad V_T = \frac{1}{m\omega_c} b \times \nabla T, \quad \Omega = n_1 - \frac{nc}{\omega_c B} \nabla^2 \phi, \quad n_i = n_{eq} \frac{e\phi}{T_e} \\
D_{\text{neo}}\Omega &= -\mu_{\text{neo}} \left(\Omega_{\text{eq}} - \Omega_{\text{neo}}\right), \quad \Omega_{\text{neo}} = \frac{n_{eq}c}{B\omega_c r} \frac{1}{\sigma} \left[\alpha_{\text{neo}} \frac{T_{eq}}{en_{eq}} \frac{\partial n_{eq}}{\partial r} + \left(1 - \alpha_{\text{neo}}\right) \frac{1}{en_{eq}} \frac{\partial p_{eq}}{\partial r} + \frac{B}{c qR} V_{\parallel eq}\right] \\
D_c F &= \mu_1 \nabla^2 \parallel F + \mu_2 \nabla^4 \parallel F + \mu_3 \nabla^2 \parallel^2 F, \quad D_{\text{glf}} p = -\frac{8T_{eq}}{\pi m} \nabla \parallel p_1
\end{align*}
\]
Simulation features

- **Global gyrofluid simulations** using the TRB code [Garbet et. al. PoP’01, Kim et. al. NF’11]
  
  - **Electrostatic ITG turbulence** with heat and momentum sources
  - **Global, flux-driven, self-consistently evolving ion temperature/flow profiles**
  - Fix q-profile & electron density/temperature profiles
  - **Only resonant modes are retained**
  - **No-slip** boundary condition on $V_{\parallel}$

[Graphs and data plots showing heat flux vs. $-\nabla T_i$.]
Intrinsic rotation (self-acceleration) happens

- Strong ($M_{th} \sim 0.1-0.2$, $|V_{ITB}| >> |V_L|$) co-current rotation is generated in heat flux driven ITB plasmas with reversed magnetic shear.
- The flow is intrinsic rotation generated via residual stress.

**Ion temperature vs. r/a**

**$V_\parallel$ vs. r/a**
Formation of intrinsic rotation

- Intrinsic rotation is generated near **ITB head** and, initially, propagates into the core.
- Reynolds stress $\left\langle \tilde{v}_r \tilde{v}_\parallel \right\rangle < 0$, because of large **inward** residual stress.

![Diagram showing $V_{\parallel}$ evolution during initial phase](image)

\[ V_{\parallel} \text{ evolution during initial phase} \]

- Diffusive part
- Reynolds stress
- Residual stress

![Graph showing $r/a$ vs. $V_{\parallel}$](image)

Graph showing $r/a$ vs. $\langle \tilde{v}_r \tilde{v}_\parallel \rangle$ and $\rho_{\parallel} c_{\parallel 0}^2$ with dips indicating:
- Diffusive part
- Reynolds stress
- Residual stress
Intrinsic rotation correlates with \[ \left< V_E' \frac{\partial |\tilde{\phi}|^2}{\partial r} \right> \]

- The position of **maximum intrinsic rotation** coincides with the position of maximal \[ \left< V_E' \frac{\partial |\tilde{\phi}|^2}{\partial r} \right> \]

\[ \Pi^{RS}_{r||} \sim V_E' |\tilde{\phi}|^2 \Rightarrow \nabla \cdot \Pi^{RS}_{r||} = \tau_{\text{int}} \sim V_E' \frac{\partial |\tilde{\phi}|^2}{\partial r} \]

~ position of maximal intrinsic torque
New regime of $V_{||}(0)$ vs $\nabla T_i$ scaling is found

- Linear $V_{||}(0)$ vs. $-\nabla T_i$ enters roll-over for $\chi_{i,turb} \lesssim \chi_{i,neo}$ (strong turbulence suppression in ITB) → Ultimate limitation on intrinsic rotation?

- Why? There are intermediate states between “active” and “fully suppressed” turbulent states determined by residual heat and momentum transport in barrier

$$Pr_{neo} = \frac{\chi_{\phi,neo}}{\chi_{i,neo}}$$

$$\nabla V_{\phi} \sim \frac{I \gamma_E^\alpha}{Q_i} \left( \frac{Q_i}{\chi_{i,t} 1 + \hat{\chi}_i} \right)^\beta \frac{\chi_{i,t} 1 + \hat{\chi}_i}{\chi_{\phi,t} 1 + \hat{\chi}_\phi}$$
Power ramp simulations reveal ITB dynamics

- Long time power ramp simulations show
  - Both heat and momentum transport barriers are self-organized
  - **Hysteresis** happens first-order phase transition
  - Reynolds stress generated **intrinsic rotation** is crucial to ITB dynamics.
Relative hysteresis between $\nabla T_i$ & $\nabla V_\parallel$

- Relatively stronger hysteresis of intrinsic rotation over temperature gradient is observed → **Recovers** features of recent experimental observation in LHD [K. Ida et. al., NF 50 (2010) 064007]

- **Predict** that residual transport ($Pr_{neo}$) governs strength of relative hysteresis → $\Delta(\nabla V_\parallel)$ decreases as $Pr_{neo}$ increases.
ExB shearing rate closely tracks $\nabla V_{||}$ at $q_{\text{min}}$ position → similar trend observed at Alcator C-Mod [Fiore et.al. Nucl. Fusion 2010]

- Forward transition occurs when mean flow shear develops.
Several positions important in ITB dynamics

- **Four radial positions** are found to be important in ITB dynamics:
  - $r=0.57$ (ITB shoulder), $r=0.6$ ($q_{min}$), $r=0.61$ (ITB foot), $r=0.63$ (most unstable)
- Physical quantities at these positions are **coupled** to each other.
Parallel shear flow instability & momentum redistribution

- Several peaks in $<\delta V_{||}^2>$ observed when $\gamma_E < \gamma_{\text{lin}} \rightarrow$ excitation of PSFI
- PSFI onset is followed by Reynolds stress change $\rightarrow$ momentum redistribution.
- Forward transition occurs during $\nabla V_{||}$ relaxation induced by PSFI.
Cross interactions important at $q_{\text{min}}$ position

- **Resonant modes with same rational $q$ appear in pairs.** Cross interactions between them may play an important role in ITB dynamics near $q_{\text{min}}$.

$$Q = \frac{3}{2} \langle \tilde{p}_l \tilde{V}_r \rangle = \frac{3}{2} \left[ \langle \tilde{p}_{li} \tilde{V}_{ri} \rangle + \langle \tilde{p}_{r2} \tilde{V}_{r2} \rangle \right]$$

- **Cross phases** between them are down-shifted along with growth of $\gamma_E$ during forward transition while reverse process prevails in back transition.
Negative feedback in back transition

- ExB shearing rate causes negative feedback in cross phase,
  \[ \alpha = \frac{\langle \tilde{v}_r \tilde{T}_i \rangle}{\sqrt{\langle \tilde{v}_r^2 \rangle \langle \tilde{T}_r^2 \rangle}} \]
- \( V_{\text{ExB}} \) shear collapse starts from the ITB foot position and propagates into the ITB head

**Spatio-temporal evolution** of \( \left( \frac{c_{s0}}{a} \right) \)

**E×B shearing rate and cross phase**

Back transition
Splitting of $\nabla V_\parallel$ observed

- At back transition, $\nabla V_\parallel$ splits into two sections → local flattening of $\nabla V_\parallel$ within ITB region
- Flow evolution simultaneous with ExB shear

**Spatio-temporal evolution of $-\nabla V_\parallel / a$**

**$V_\parallel$ before and after back transition**
Reynolds stress bursts & back transition

- Reynolds stress bursts (RSBs) appear after PSFI onset.
- During RSBs prior to back transition, momentum flux changes its direction from inward to outward, accompanied with axial flow decrease. \(\rightarrow\) similar to MTE [Osborne et.al. NF’95]
- Outward RSBs \(\rightarrow\) local flattening of \(V_\parallel\) at \(q_{\text{min}}\) \(\rightarrow\) triggers back transition
**ITB dynamics**

- A detailed analysis reveals mechanisms for **ITB formation** and **back transition**:
  - **Intrinsic rotation** dynamics are strongly coupled to ITB evolution.
  - **Parallel shear flow instability** is a hidden player governing intrinsic rotation.
Conclusions

- Robust intrinsic co-rotation with \( 0.1 < M_{th} < 0.2 \) found in RS ITB from global gyrofluid simulations of ITG turbulence.

- \( V_{||}(0) \) vs \( \nabla T_i \) shows a roll-over at the point of strong turbulence suppression → Indication of saturation in the Rice scaling trend and of limit on intrinsic rotation

- Open-loop hysteresis in \( Q \) vs. \( \nabla T_i \) discovered and correlated with Nusselt number. Relative hysteresis between \( \nabla T_i \) and \( \nabla V_{||} \) noted to correlate with \( Pr_{neo} \)

- Intrinsic rotation dynamics is strongly coupled to ITB evolution.

- Onset of parallel shear flow instability (PSFI) and resulting momentum redistribution is a hidden player in ITB dynamics.

- Cross interactions between inner and outer modes at \( q_{min} \) position may be important in dynamics of ITB with reversed magnetic shear → Role of non-resonant modes are under study.

- Outward Reynolds stress burst (RSB) appears during PSFI and results in the reduction of both mean and zonal flow shears, which triggers back transition.