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

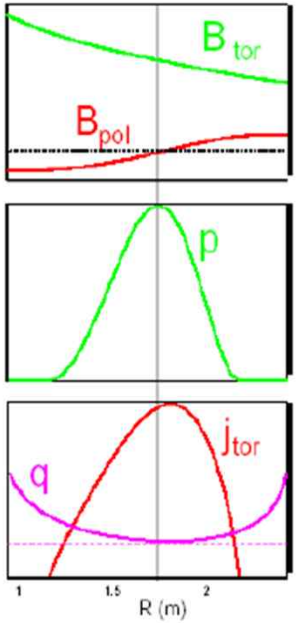
Motivating issues and questions

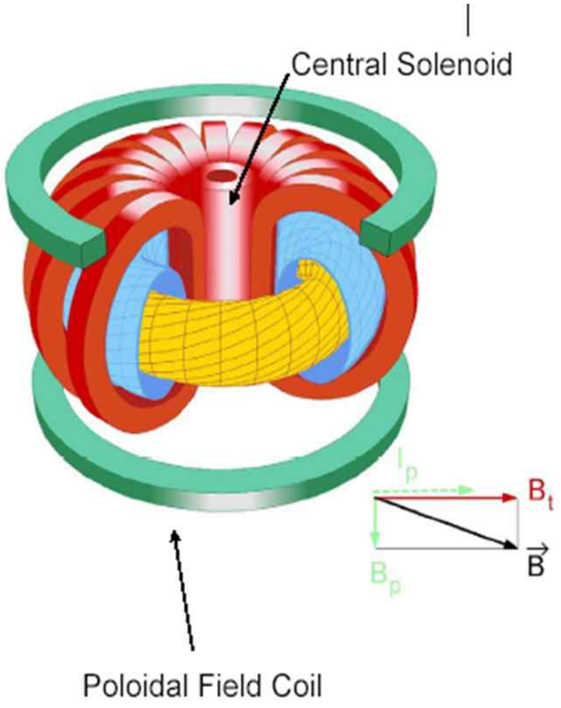
- **Intrinsic rotation (self-acceleration) in ITB:**
  - ITER:
    - Low-torque environment
    - Advanced steady state operation will require ITB plasmas
    - Limited power available to access H-mode
  - Characteristics of intrinsic rotation in ITBs? Scaling?
  - Hysteresis happens?
  - Both **interesting**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

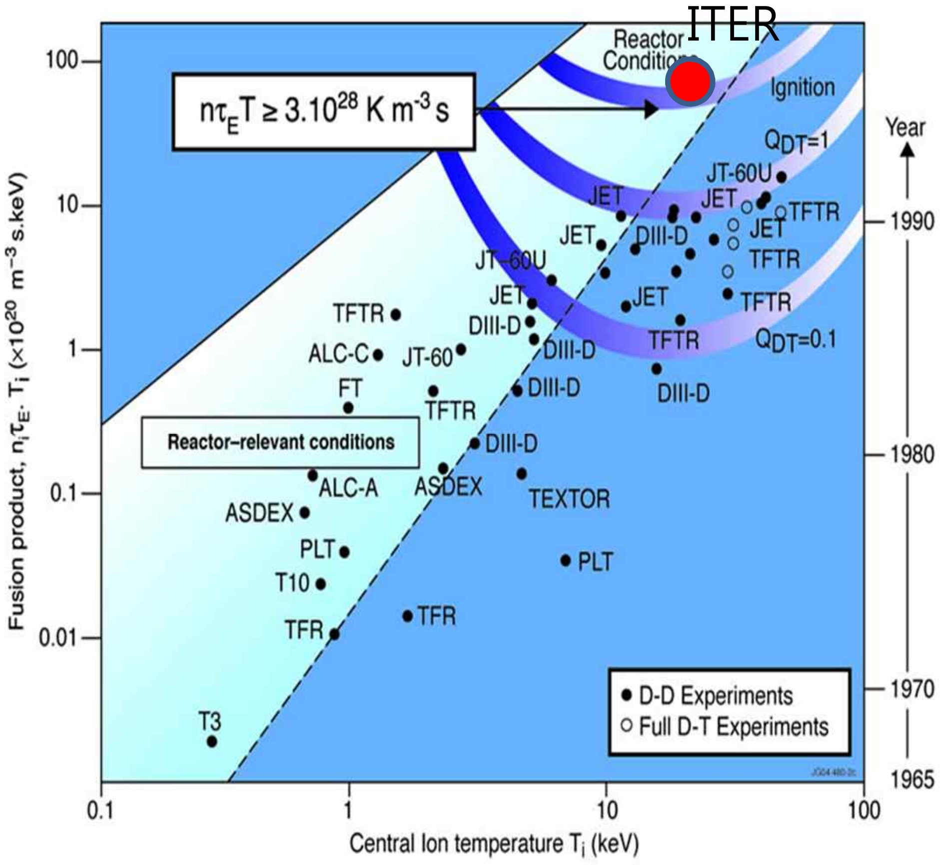
- **ITB dynamics:**
  - Intrinsic rotation closely coupled in ITB evolution
  - Mean flow shear & Reynolds stress are key players in ITB dynamics.
  - **Questions**:
    - What drives the Reynolds stress change? Parallel flow shear instability (PSFI)?
    - What is the role of momentum transport/transfer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





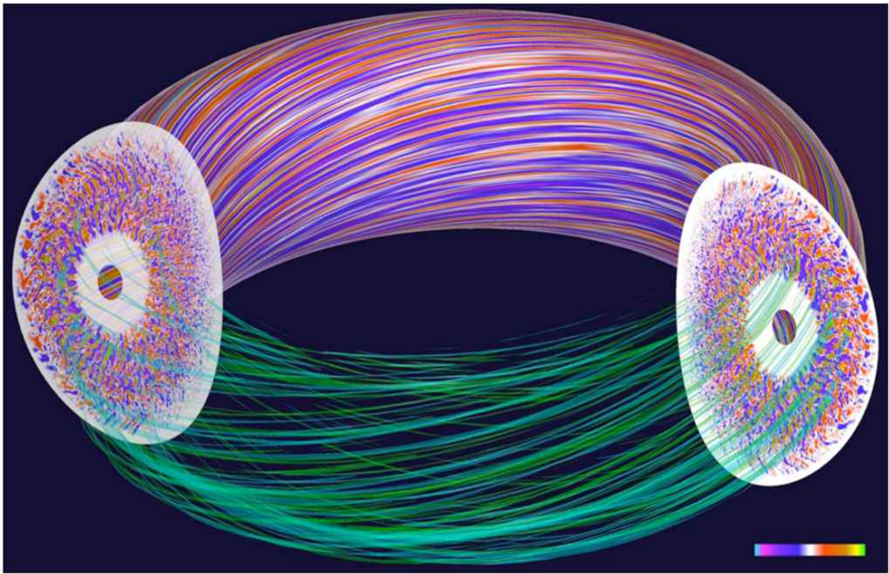


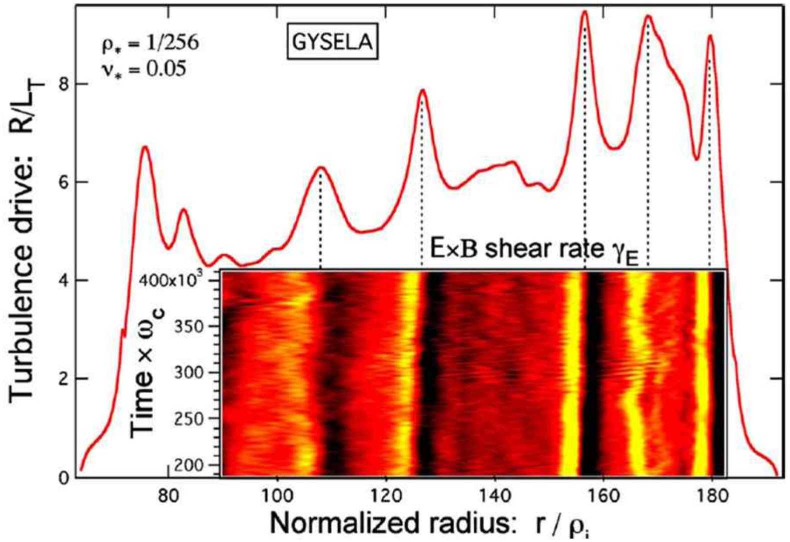
Safety factor: $q = \frac{rB_{tor}}{RB_{pol}}$

q =field line pitch =$\Delta\phi/2\pi$

Tokamak Turbulence and Transport

- Strongly magnetized quasi-2D ($k_{||} << k_{\perp}$) turbulence as in geostrophic flow (Lorentz ↔ Coriolis)
- Transport by fluctuating electric and magnetic fields → Directly connected to reactor size
- Mixing length/system size ~ ρ_i / a ~ ρ_* (~ 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**

$$\left(d_t^E - D_c - D_{neo}\right)\Omega = -n\nabla_\parallel V_\parallel + n\left(\mathbf{V}_E + \mathbf{V}_p\right)\cdot\left(\boldsymbol{\kappa} + \nabla \ln B\right) + n\mathbf{V}_p\cdot\nabla\left(\frac{n_1 - \Omega}{n}\right) - d_t^E n_{eq}$$

Vorticity

$$\left(d_t^E - D_c\right)V_\parallel = -\frac{e}{m}\nabla_\parallel\varphi - \frac{1}{mn}\nabla_\parallel p$$

Parallel flow

$$\left(d_t^E - D_c - D_{glf}\right)p = \frac{5}{3}p\mathbf{V}_T\cdot\left(\boldsymbol{\kappa} + \nabla \ln B\right) + \frac{5}{3}T d_t^E n + S_p$$

Pressure

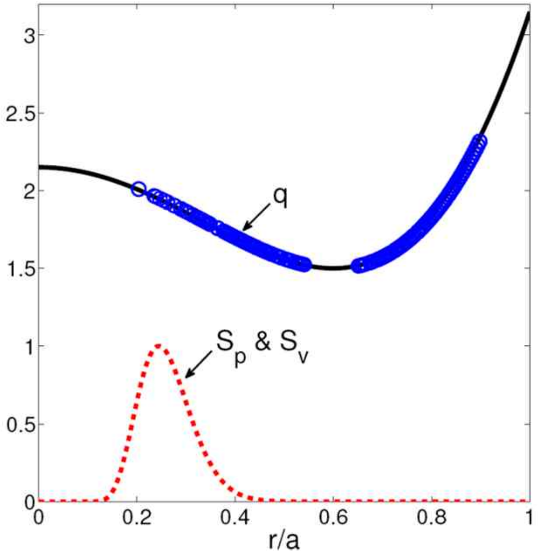
$$d_t^E = \frac{\partial}{\partial t} + \mathbf{V}_E\cdot\nabla, \quad \mathbf{V}_T = \frac{1}{m\omega_c}\mathbf{b}\times\nabla T, \quad \Omega = n_1 - \frac{nc}{\omega_c B}\nabla_\perp^2\phi\,, \quad n_1 = n_{eq}\frac{e\phi_1}{T_e}$$

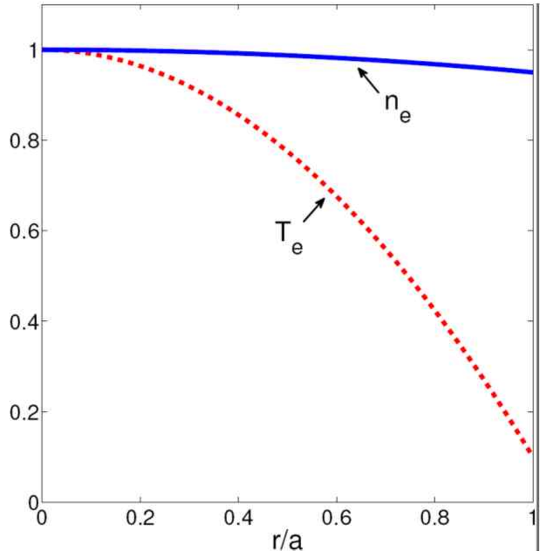
$$D_{neo}\Omega = -\mu_{neo}\left(\Omega_{eq} - \Omega_{neo}\right), \; \Omega_{neo} = \frac{n_{eq}c}{B\omega_c}\frac{1}{r}\frac{\partial}{\partial r}r\left[\alpha_{neo}\frac{T_{eq}}{en_{eq}}\frac{\partial n_{eq}}{\partial r} + \left(1 - \alpha_{neo}\right)\frac{1}{en_{eq}}\frac{\partial p_{eq}}{\partial r} + \frac{B}{c}\frac{r}{qR}V_{\parallel eq}\right]$$

$$D_c F = \mu_1\nabla_\perp^2 F + \mu_2\nabla_\perp^4 F + \mu_3\nabla_\parallel^2 F, \quad D_{glf}\,p = -\sqrt{\frac{8T_{eq}}{\pi m}}\left|\nabla_\parallel\right| p_1$$

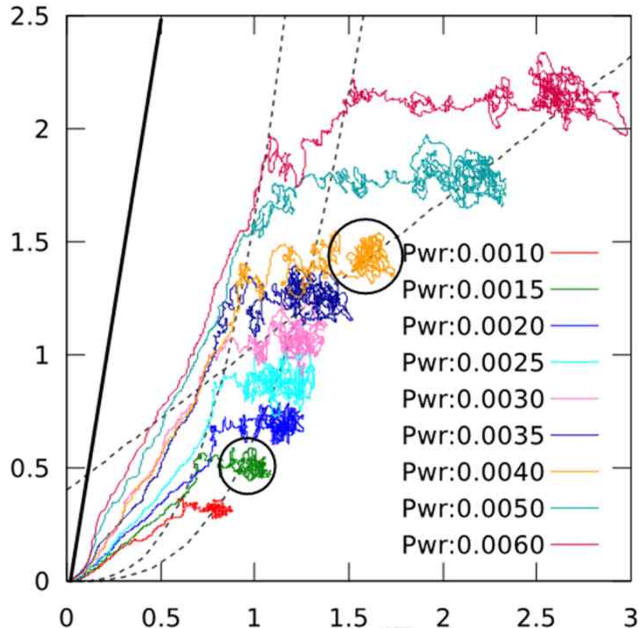
Simulation features

- **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 $V_{||}$





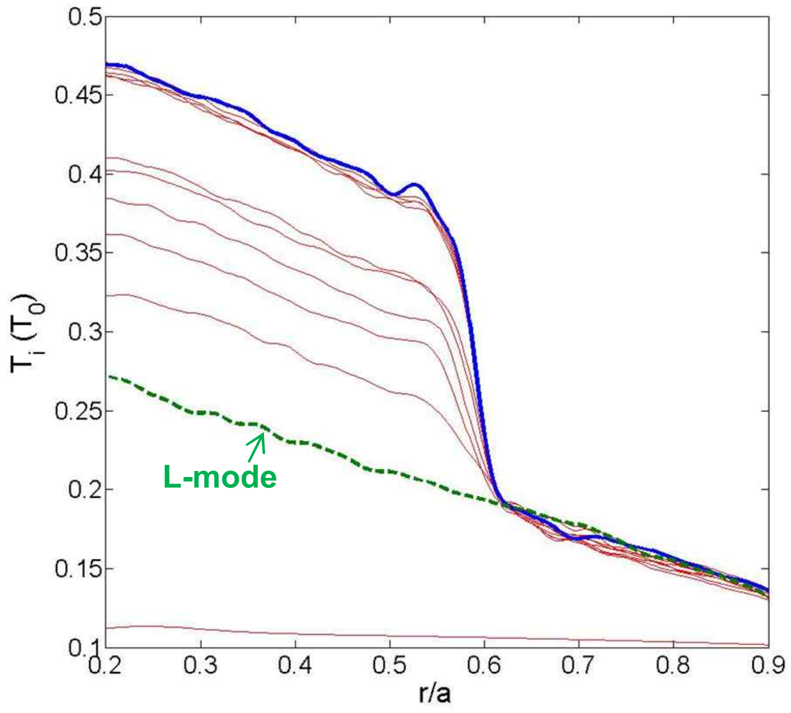
Heat flux vs. -∇T_i



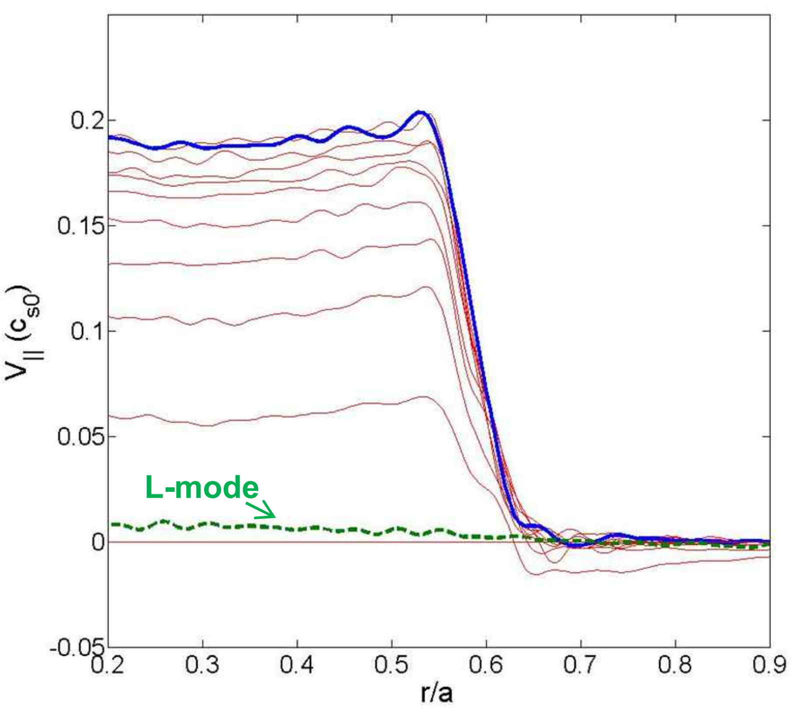
Intrinsic rotation (self-acceleration) happens

- Strong (M_{th} ~ 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

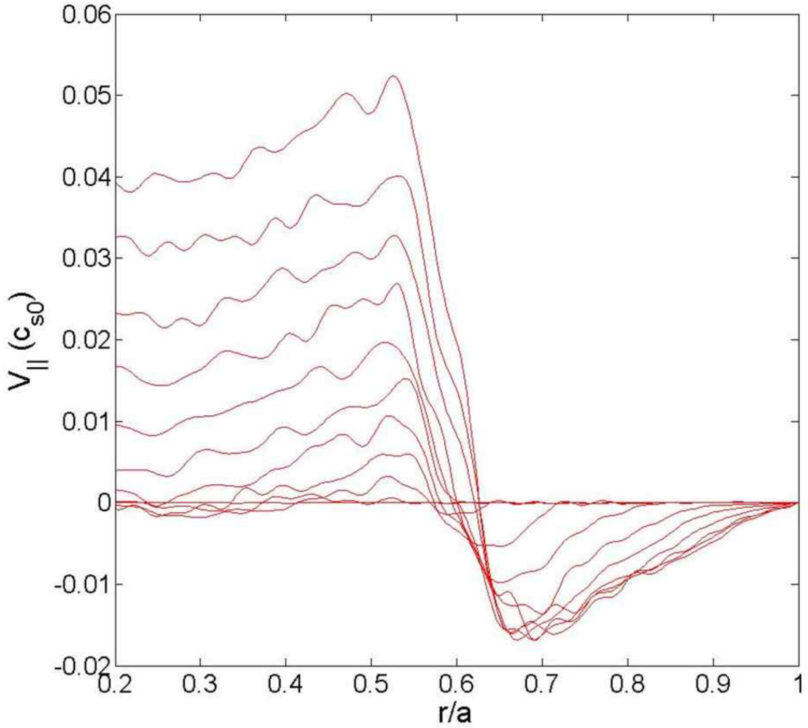


$V_{||}$ vs. r/a

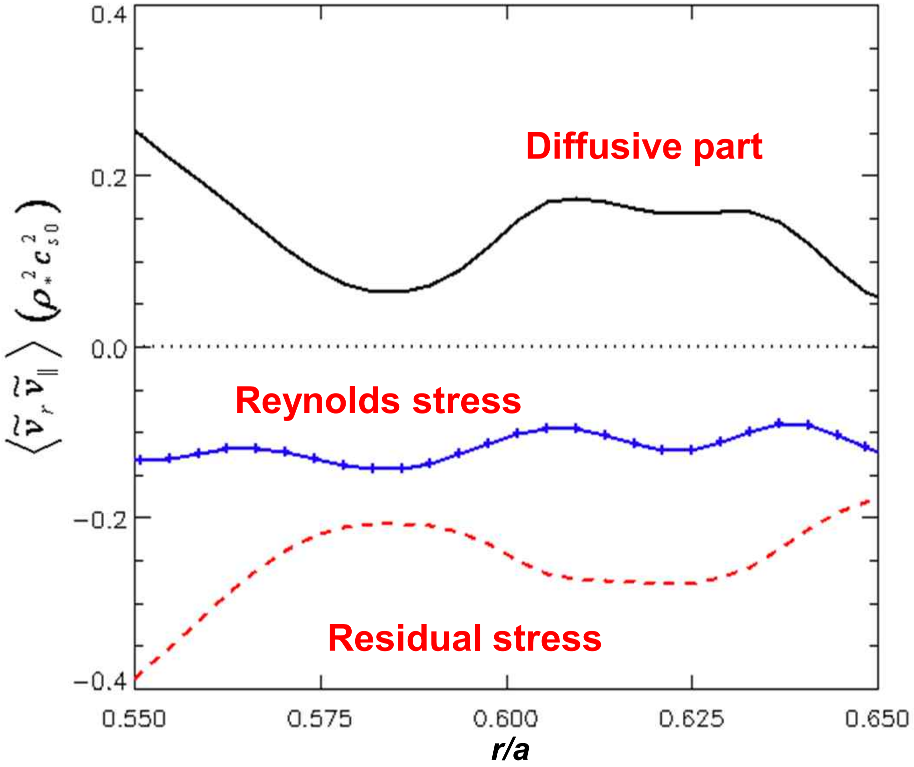


Formation of intrinsic rotation

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



$V_{\|}$ evolution during initial phase

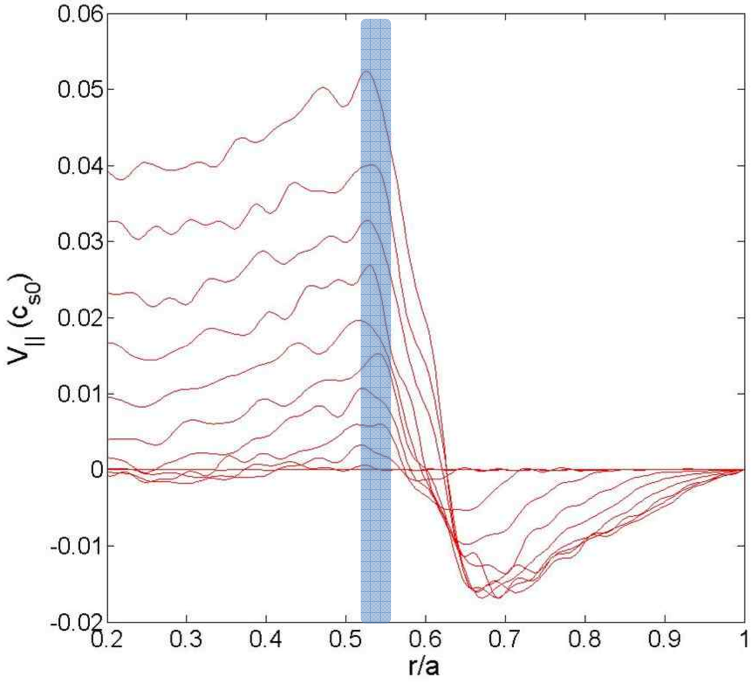


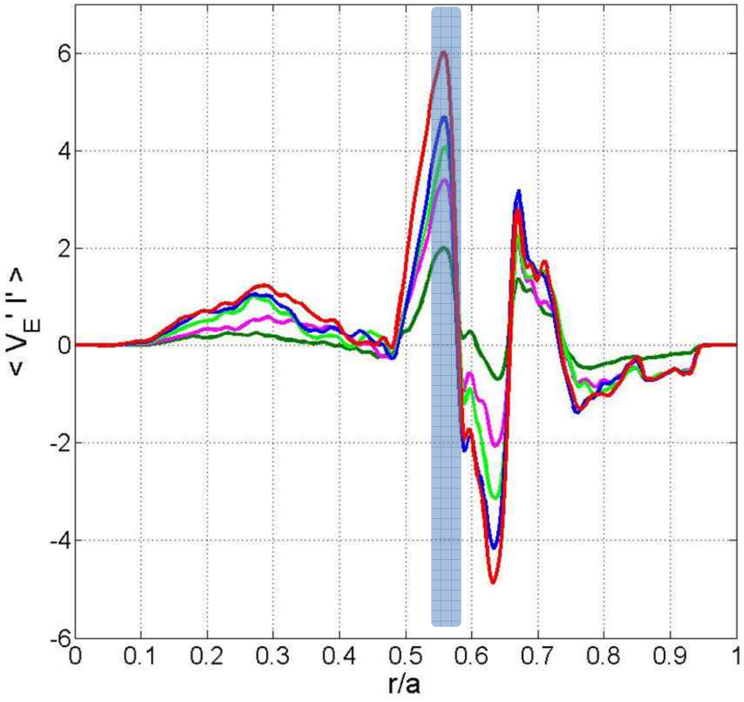
Intrinsic rotation correlates with $\left\langle V_E' \frac{\partial|\tilde{\varphi}|^2}{\partial r} \right\rangle$

- The position of **maximum intrinsic rotation** coincides with the position of **maximal** $\left\langle V_E' \frac{\partial|\tilde{\varphi}|^2}{\partial r} \right\rangle$

$$\Pi_{r\|}^{RS} \sim V_E' |\tilde{\varphi}|^2 \Rightarrow \nabla \cdot \Pi_{r\|}^{RS} = \tau_{\text{int}} \sim V_E' \frac{\partial|\tilde{\varphi}|^2}{\partial r}$$

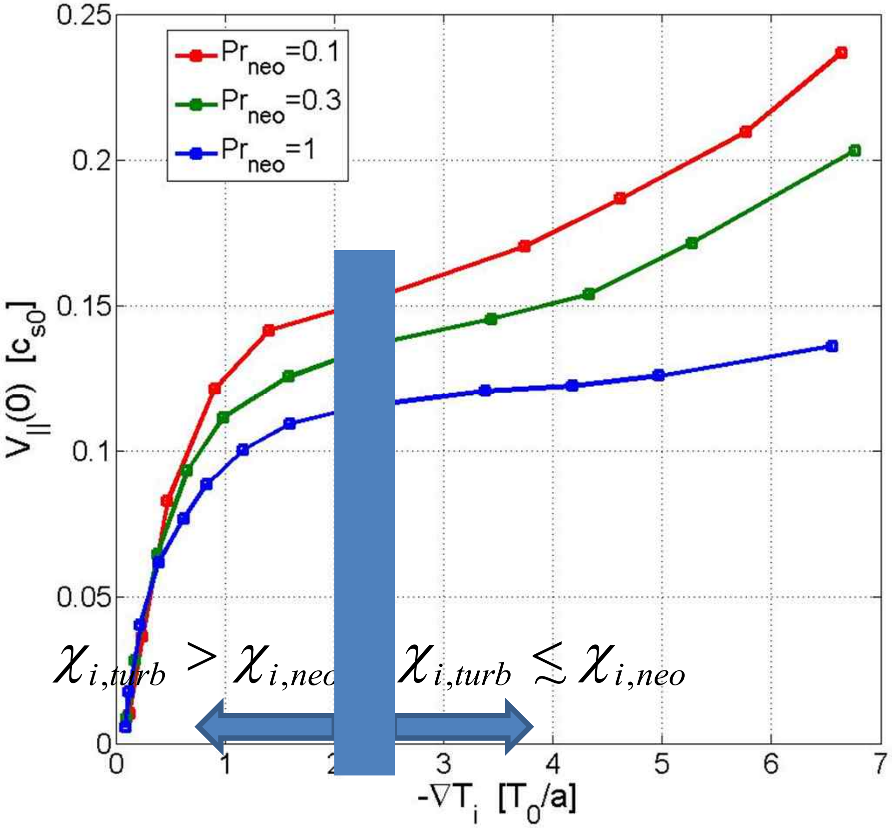
➡ ~ position of maximal intrinsic torque





New regime of $V_{||}(0)$ vs ∇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?**



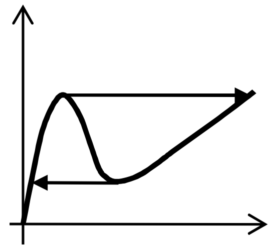
- Why? There are intermediate states between **“active”** and **“fully suppressed”** turbulent states ➡ determined by residual heat and momentum transport in barrier

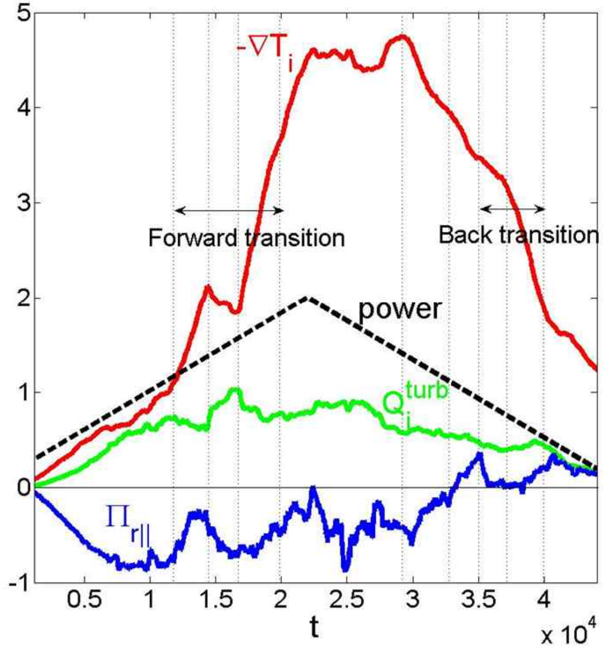
$Pr_{neo} = \chi_{\phi,neo}/\chi_{i,neo}$

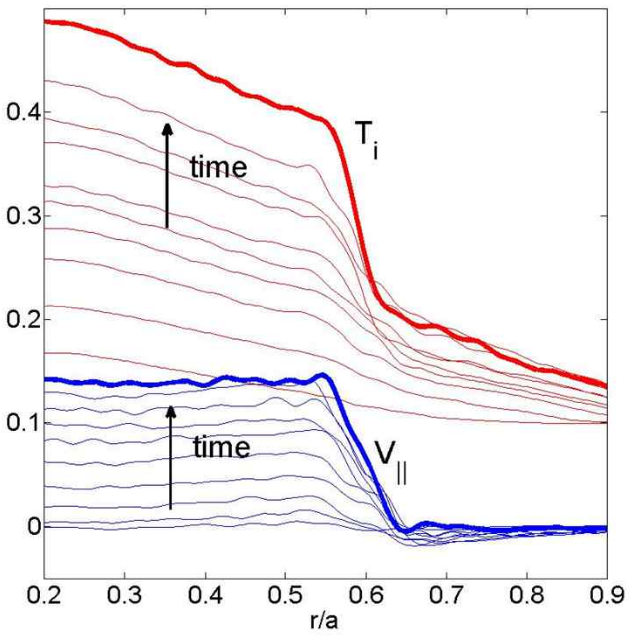
$$\frac{\nabla V_\phi}{\nabla T_i} \sim \frac{I\gamma_E^\alpha}{Q_i}\left(\frac{Q_i}{\chi_{i,t}}\frac{1}{1+\hat{\chi}_i}\right)^\beta \frac{\chi_{i,t}}{\chi_{\phi,t}}\frac{1+\hat{\chi}_i}{1+\hat{\chi}_\phi},$$

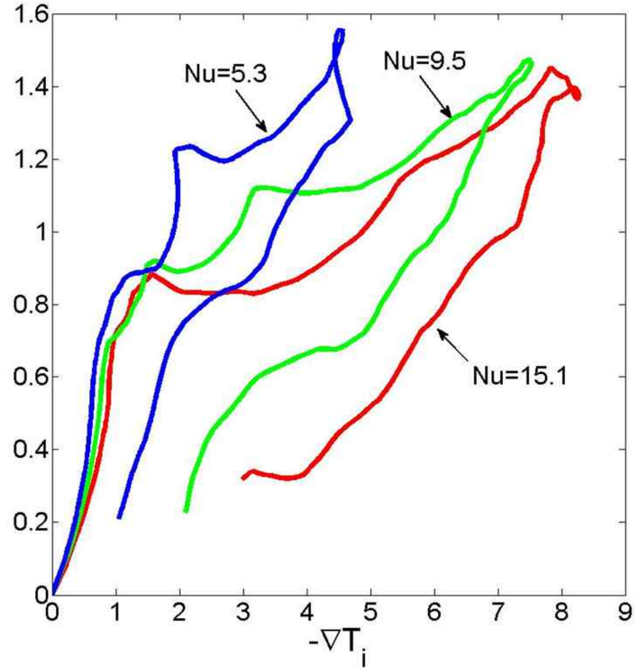
Power ramp simulations reveal ITB dynamics

- **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.

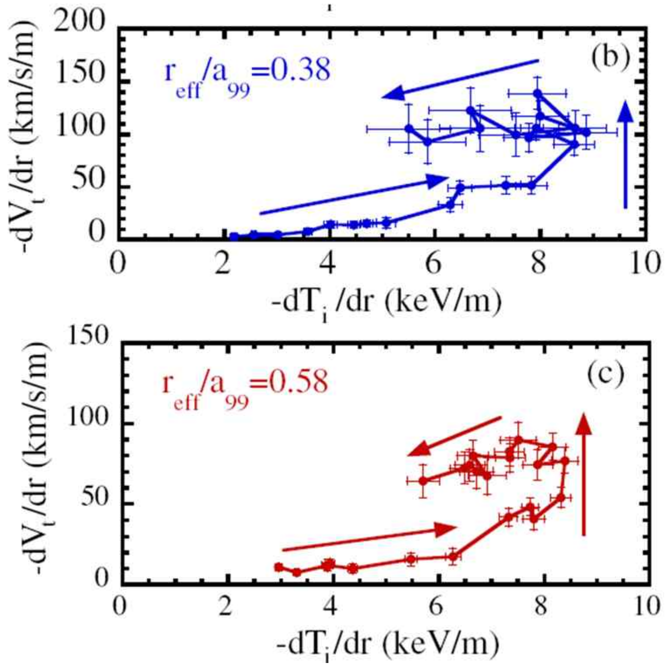


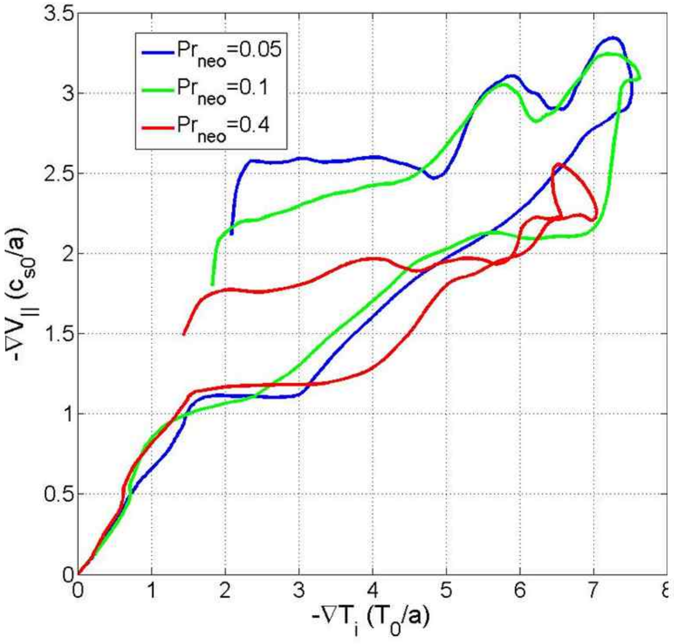


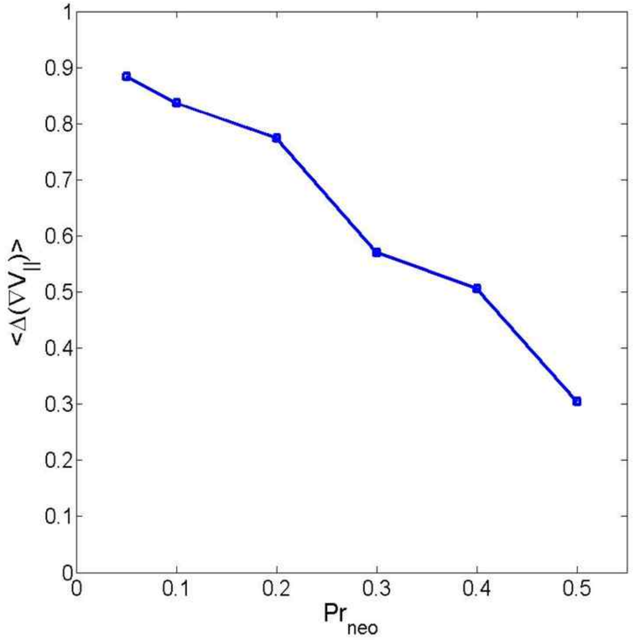




Relative hysteresis between ∇T_i & $\nabla V_{||}$



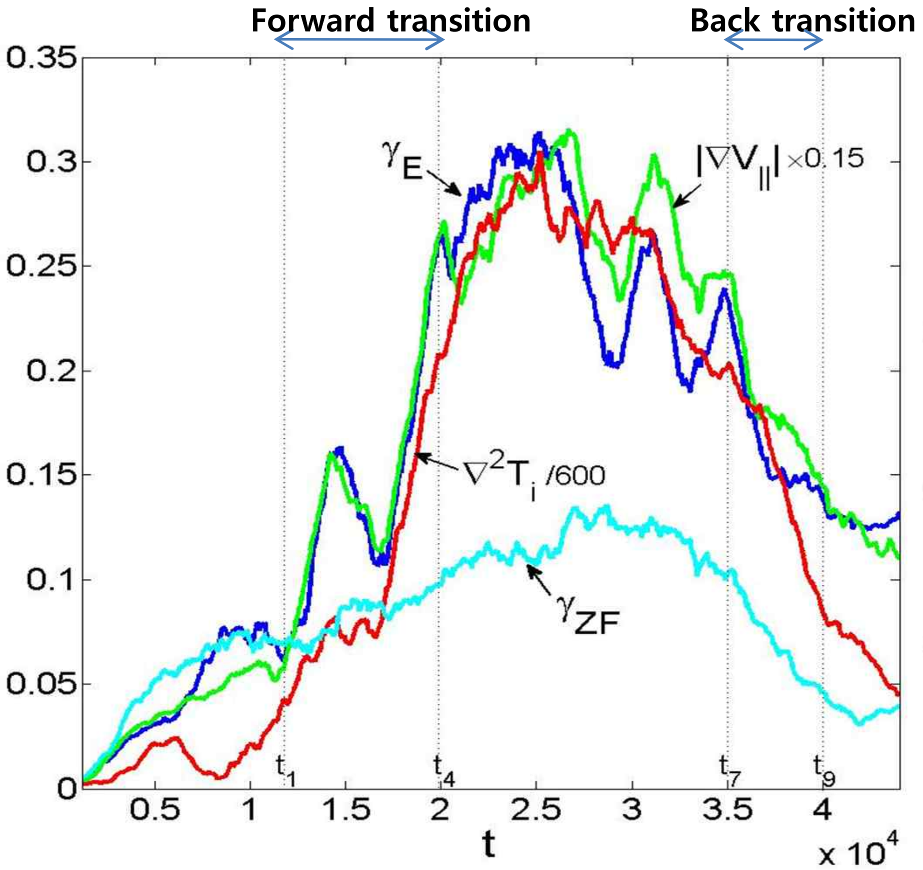


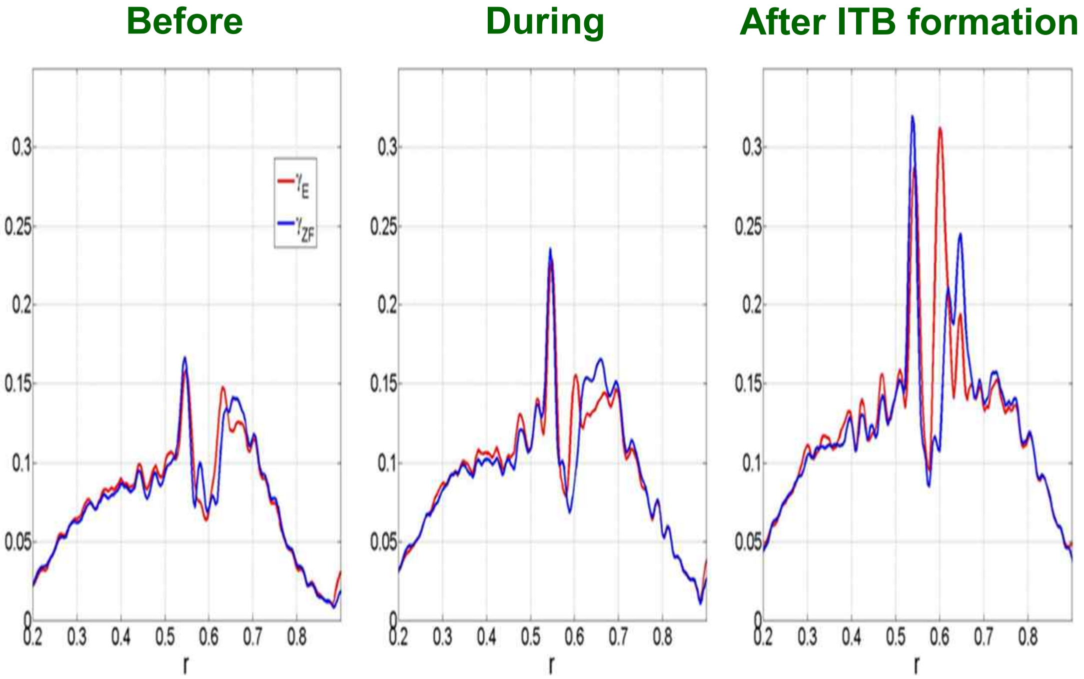


- Relatively stronger hysteresis of intrinsic rotation over temperature gradient is observed → **Recovers** features of recent experimental observation in LHD [K. Ida et. al., NF 50 (2010) 064007]
- **Predict** that residual transport (Pr_{neo}) governs strength of relative hysteresis → $\Delta(\nabla V_{||})$ decreases as Pr_{neo} increases.

Coupling of intrinsic rotation to ITB dynamics

- ExB shearing rate **closely tracks $\nabla V_{||}$** at q_{min} position → similar trend observed at Alcator C-Mod [Fiore et.al. Nucl. Fusion 2010]
- Forward transition occurs when mean flow shear develops.

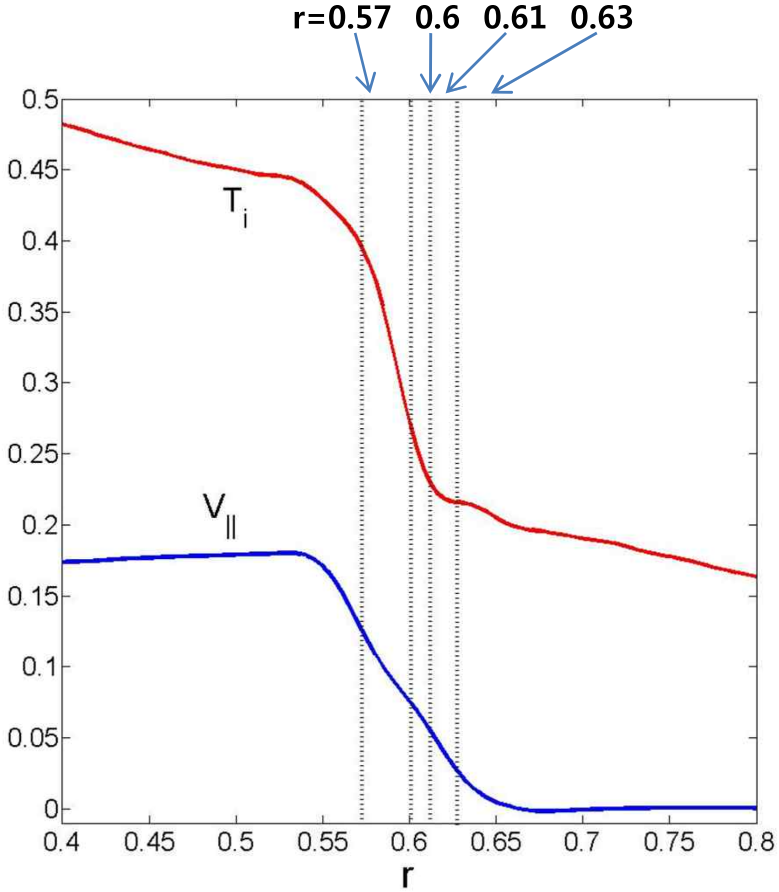


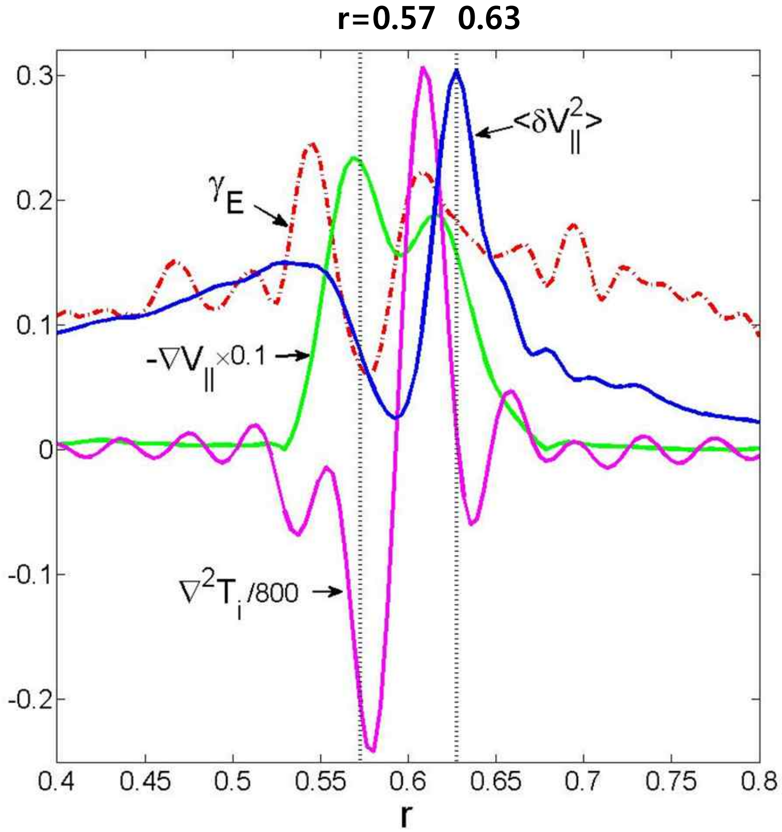


NFRI National Fusion Research Institute

Several positions important in ITB dynamics

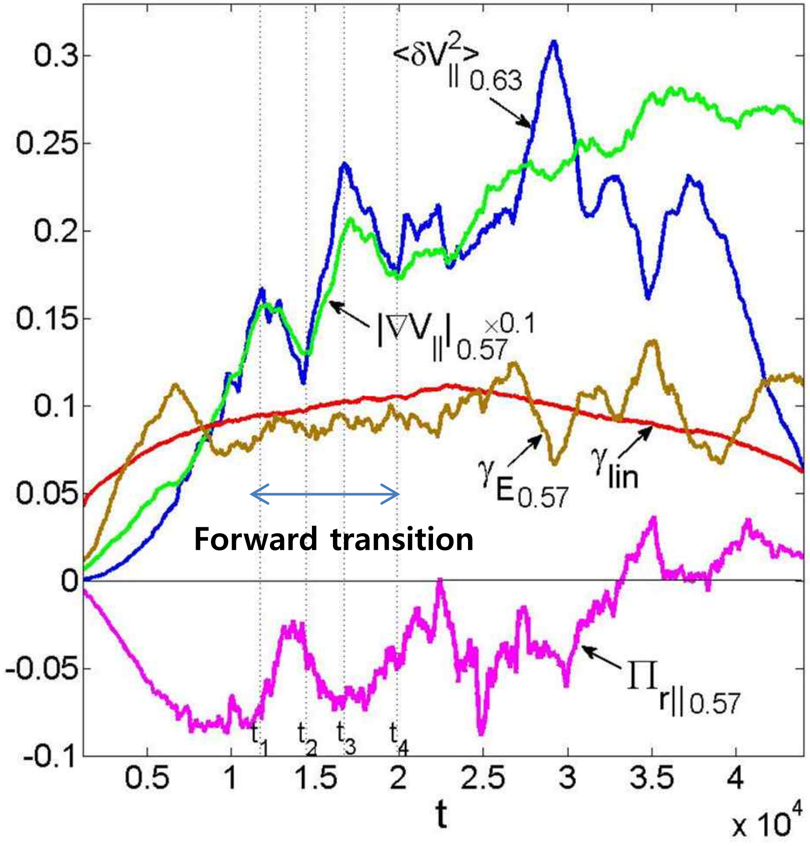
- **Four radial positions** are found to be important in ITB dynamics:
  r=0.57 (ITB shoulder),   r=0.6 (q_{min}),   r=0.61 (ITB foot),   r=0.63 (most unstable)
- Physical quantities at these positions are **coupled** to each other.

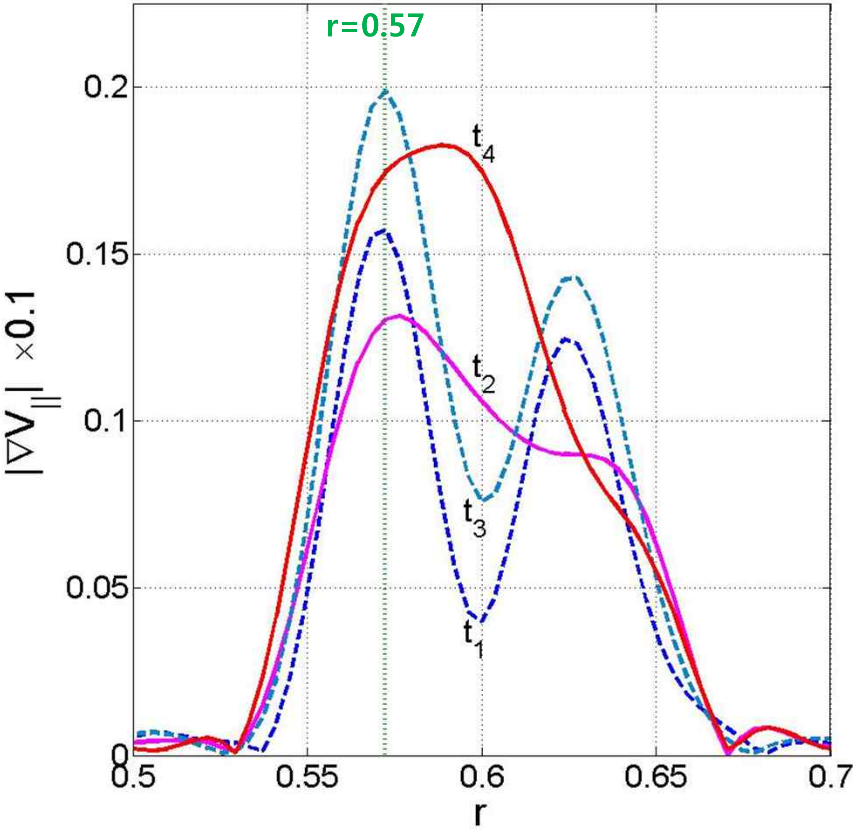




Parallel shear flow instability & momentum redistribution

- Several **peaks in $<\delta V_{||}^2>$** observed when $\gamma_E < \gamma_{lin} \longrightarrow$ excitation **of PSFI**
- **PSFI** onset is followed by Reynolds stress change → momentum redistribution.
- Forward transition occurs during **$\nabla V_{||}$ relaxation** induced by **PSFI.**



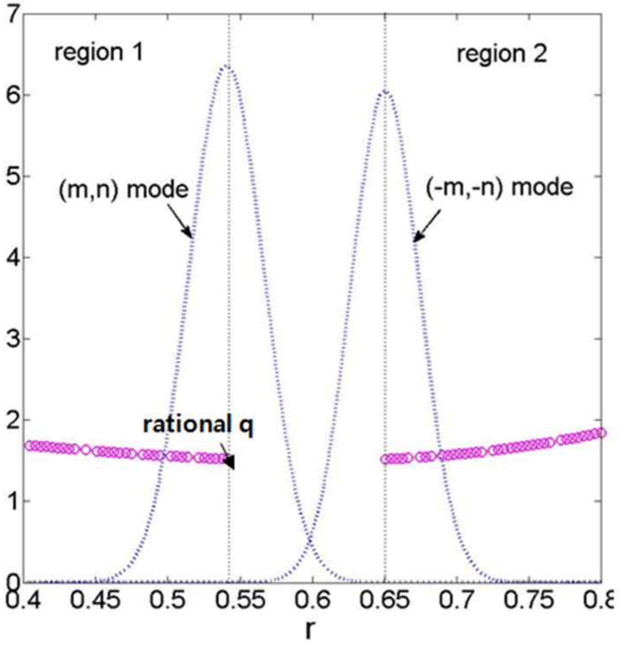


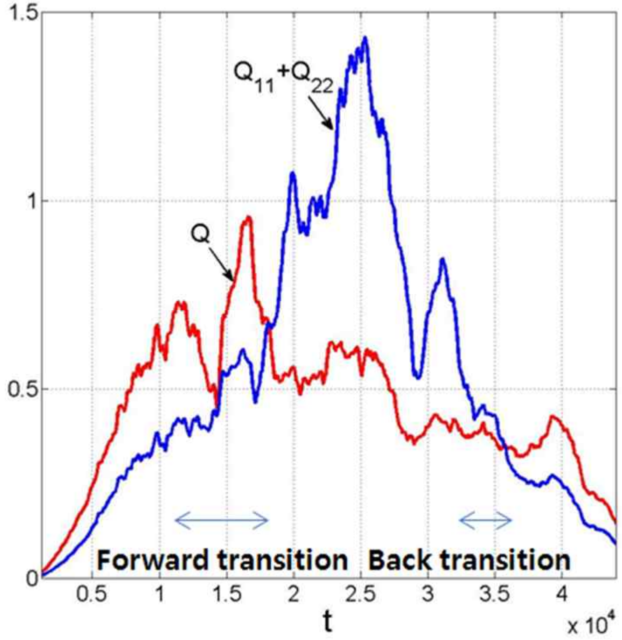
Cross interactions important at q_{min} position

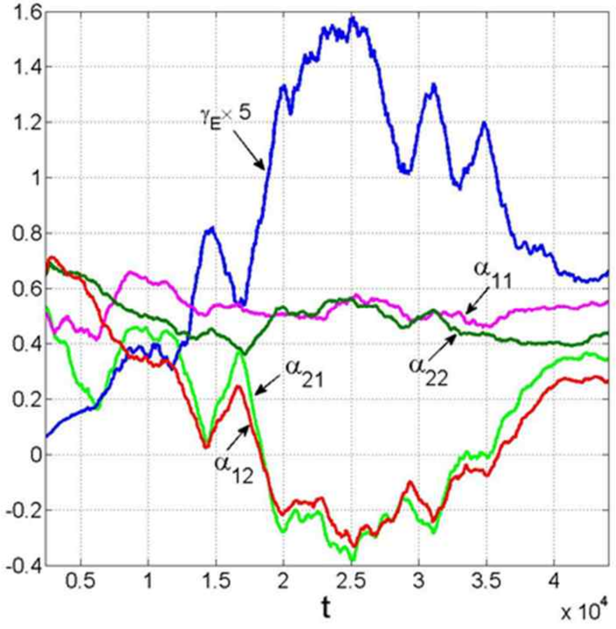
- **Resonant modes with same rational q appear in pairs**. Cross interactions between them may play an important role in ITB dynamics near q_{min} .

$$Q = \frac{3}{2}\left\langle \tilde{p}_i \tilde{V}_r \right\rangle = \frac{3}{2}\left[\left\langle \tilde{p}_{i1} \tilde{V}_{r1} \right\rangle + \left\langle \tilde{p}_{i2} \tilde{V}_{r2} \right\rangle + \right.$$

- **Cross phases** between them are down-shifted along with growth of γ_E during forward transition while reverse process prevails in back transition.



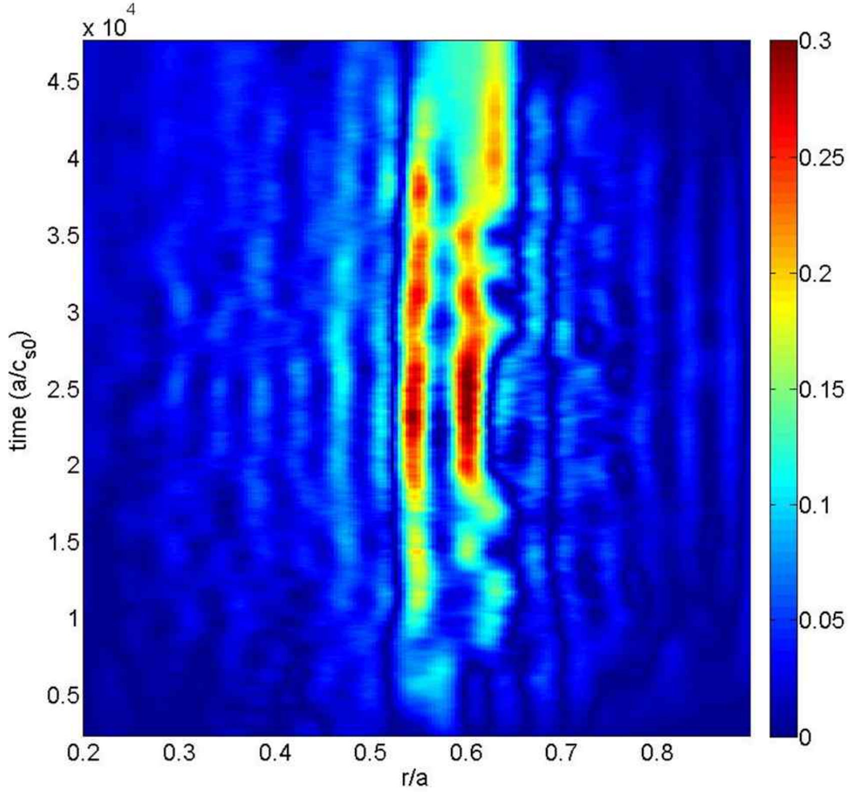




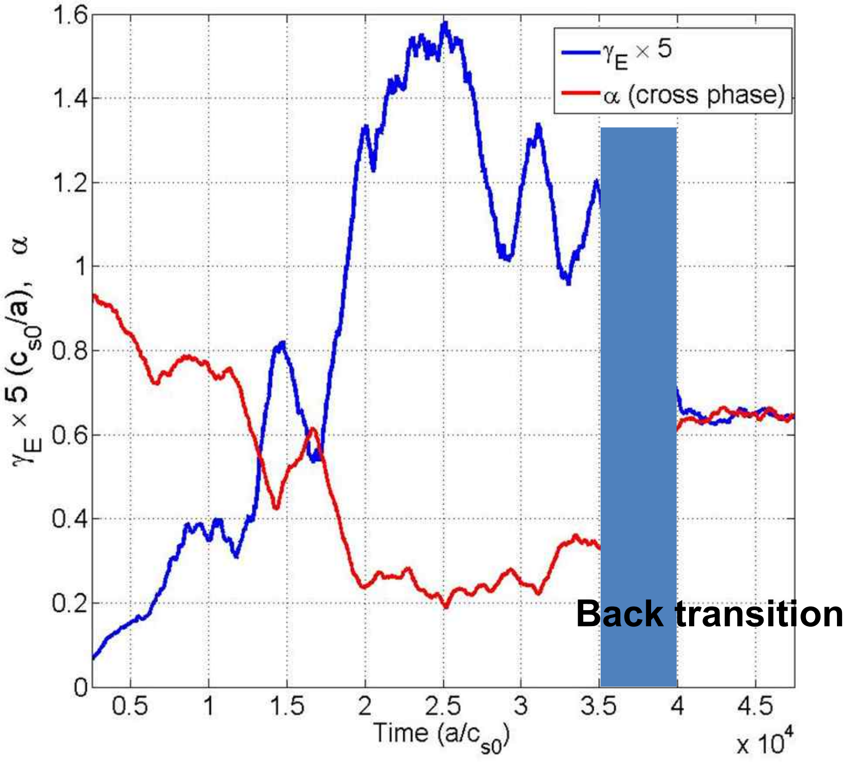
Negative feedback in back transition

- ExB shearing rate causes negative feedback in cross phase, $\alpha = <\tilde{v}_r \tilde{T}_i> \Big/ \sqrt{<\tilde{v}_r^2><\tilde{T}_r^2>}$
- V_{ExB} shear collapse starts from the ITB foot position and propagates into the ITB head

Spatio-temporal evolution of $\gamma_E\,(c_{s0}/a)$



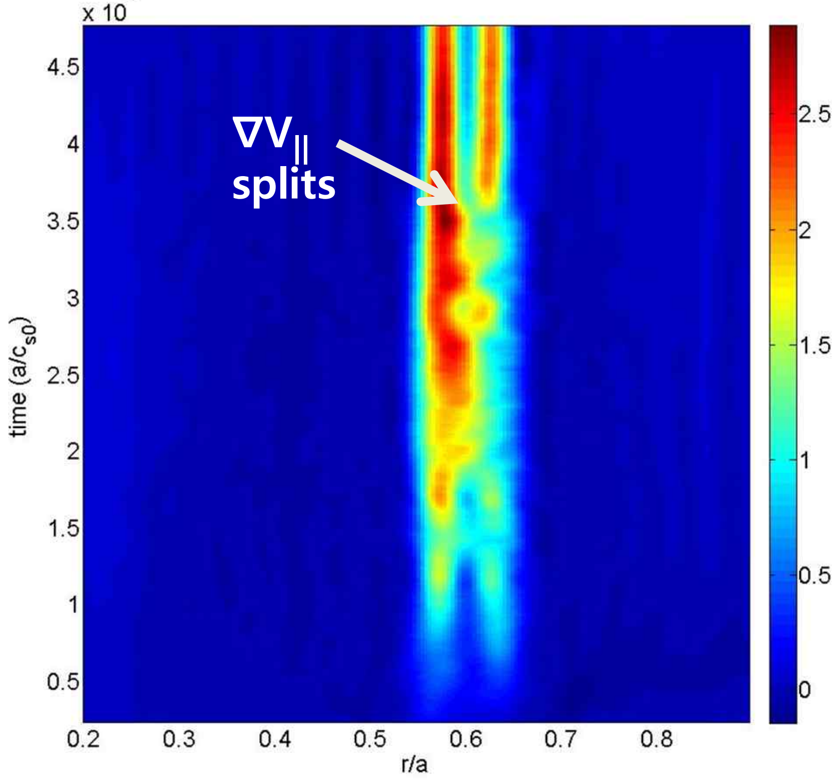
E×B shearing rate and cross phase



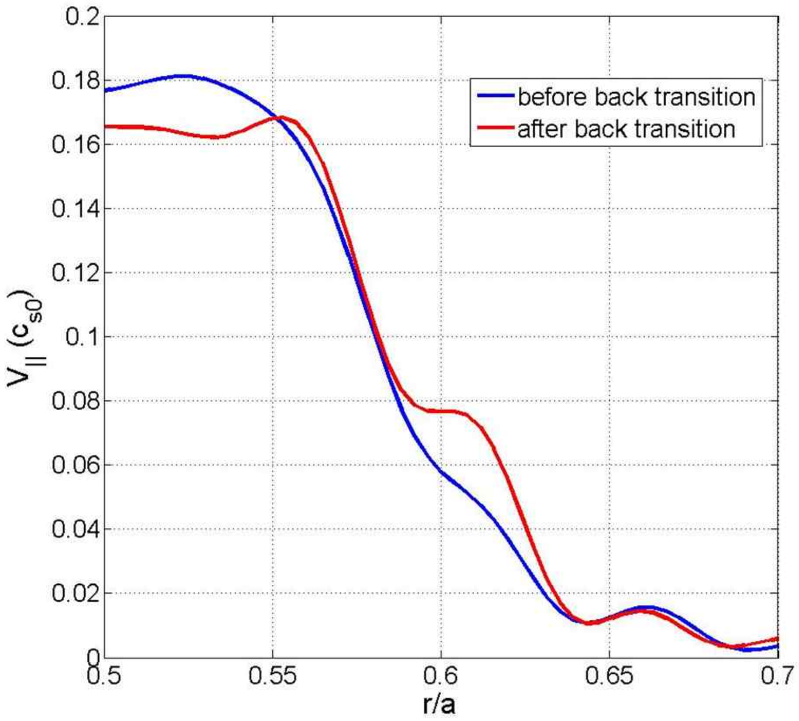
Splitting of $\nabla V_{||}$ observed

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

Spatio-temporal evolution of $-\nabla V_{||}\ (c_{sp}/a)$

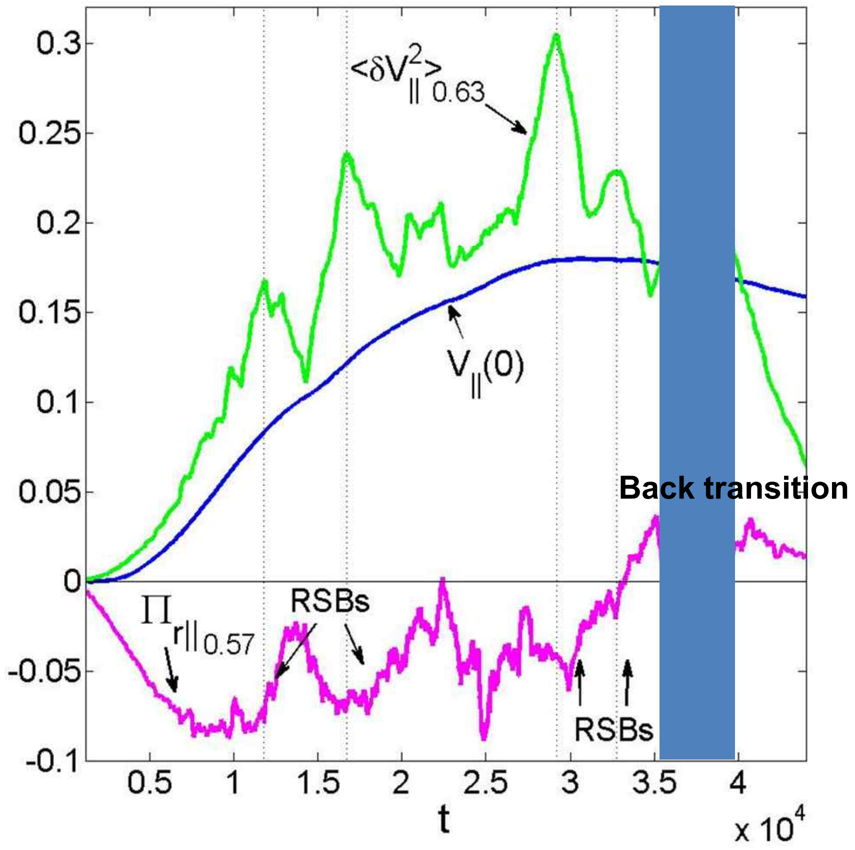


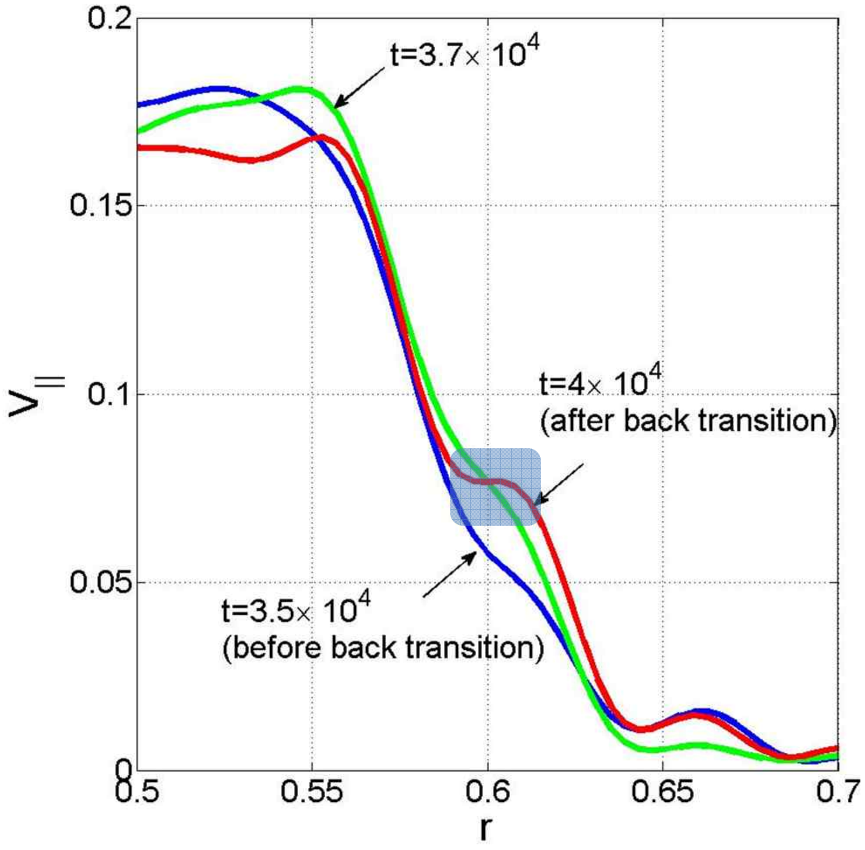
$V_{||}$ before and after back transition



Reynolds stress bursts & back transition

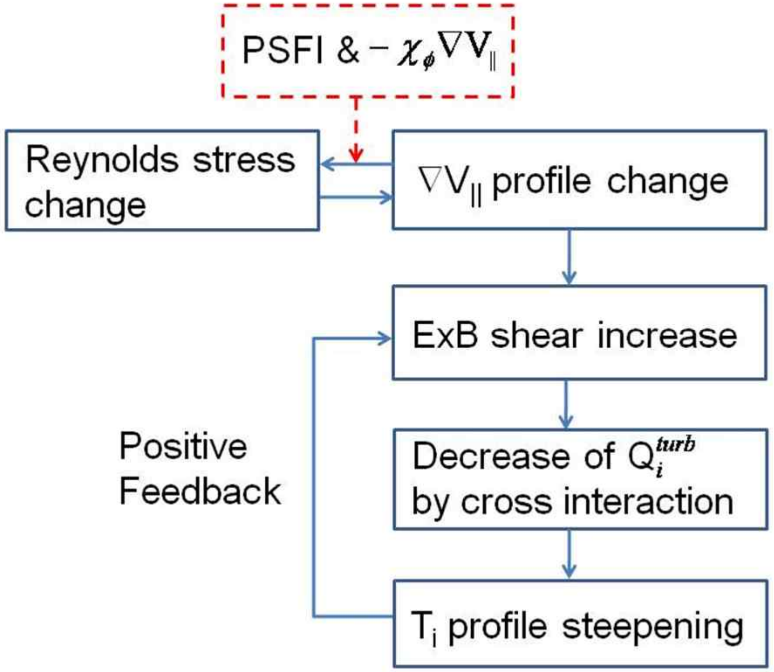
- **Reynolds stress bursts** (**RSBs**) appear **after PSFI onset.**
- During **RSBs** prior to **back transition**, momentum flux changes its direction from inward to outward, accompanied with axial flow decrease. → similar to MTE [Osborne et.al. NF'95]
- Outward RSBs → local flattening of $V_{||}$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



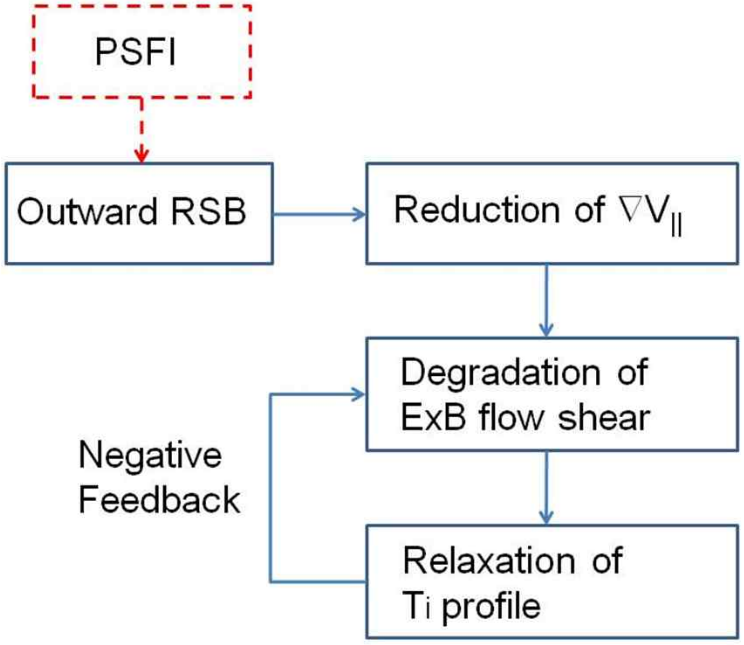


ITB dynamics

- 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.



ITB formation mechanism



ITB back transition mechanism

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. ∇T_i discovered and correlated with Nusselt number. Relative hysteresis between ∇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**.