25th IAEA Fusion Energy Conference, 13-18 Oct. 2014, Saint Petersburg, Russia

L→H Transition Criterion: A 3D Nonlinear Simulation Study

G.Y. Park[1], S.S. Kim[1], T. Rhee[1], H.G. Jhang[1], P.H. Diamond[1,2], I. Cziegler[2], G. Tynan[2], and X.Q. Xu[3]

[1]National Fusion Research Institute, Korea
[2]CMTFO and CASS, UCSD, USA
[3]Lawrence Livermore National Laboratory, USA

국가핵융합연구소
National Fusion Research Institute

Introduction

- L-H transition phenomenology
  - Sudden bifurcation to high confinement (H-mode)
  - Studied for ~32 years
  - Theory perspective-based on **transport bifurcation** and **profile self-organization** via predator-prey dynamics
  - **Main paradigm: ExB flow shear(ω_{ExB}) suppression of the turbulence**
    - ✓ $\omega_{ExB} > \gamma_{lin} \rightarrow$ **turbulence suppressed and H-mode sustained**
  - Unknown
    - ✓ Trigger mechanism
    - ✓ **Transition criterion based on microphysics** (need predictive capability)

- Main questions
  - **What triggers the transition?**
  - **How the transition evolves?**

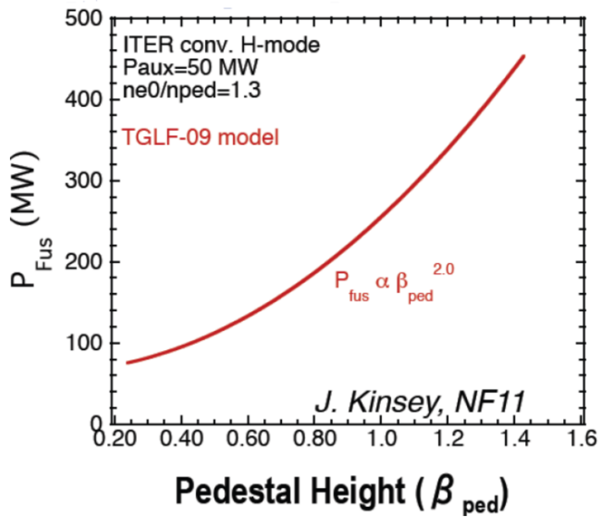
  → **To be explained in the present talk**
  - **How predict transition, and power threshold?**

H-mode and L-H transition

- H-mode: enhanced plasma confinement with edge transport barrier (ETB)

- H-mode history/phenomenology (1982-2014)
  - ✓ Wagner (1982): first discovered at ASDEX-U
  - ✓ Er shear layer at edge, fluctuation decrease, existence of power threshold (P_{th})
  - ✓ Predator-Prey paradigm [Diamond, PRL, 1994; Kim & Diamond, PRL 2003]
    - Zonal flow (ZF): predator, turbulence: prey, mean flow: another predator
    - ZF triggers the transition, while mean flow sustains the barrier

- Why H-mode is important for fusion?
  - ✓ Practical reason: can reduce reactor size
  - ✓ H-mode driven high pedestal height
    → high fusion performance



Experimental evidence of a role of turbulence-driven (ZF) flow in triggering L-H transition

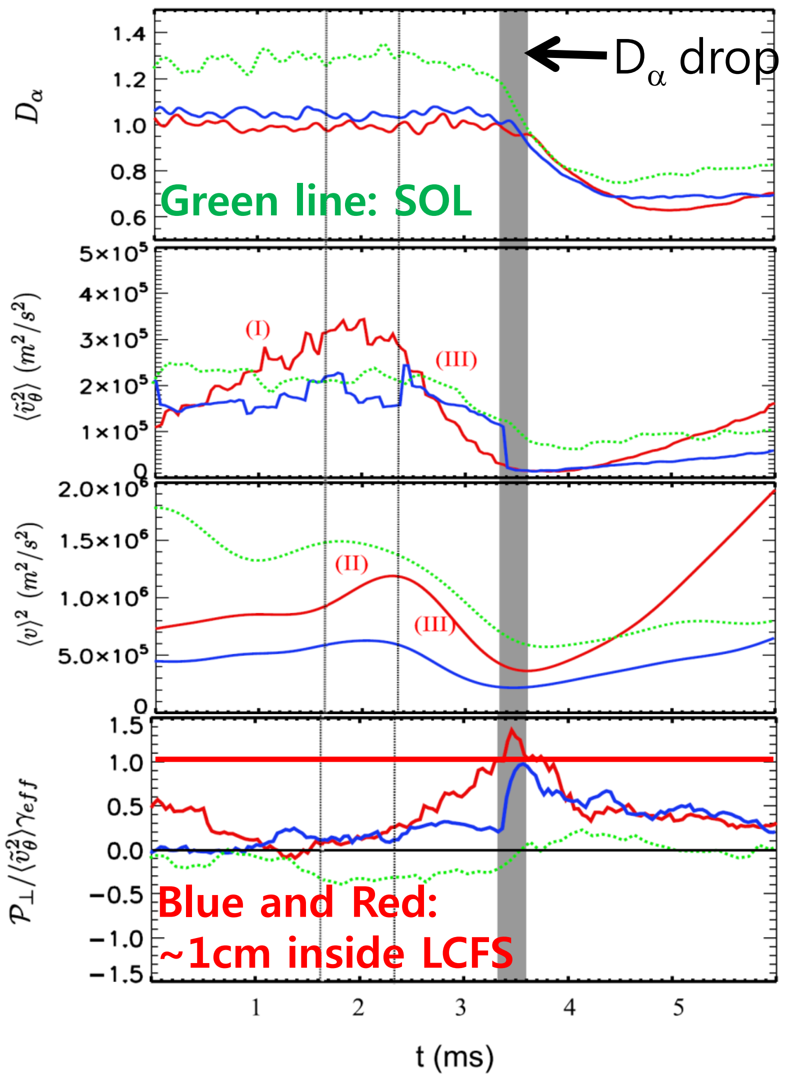
- Tynan (2013) and Manz (2012)
  - ✓ Normalized Reynolds power

$$R_T = \frac{\langle \tilde{v}_r \tilde{v}_\theta \rangle \langle V_{E\times B}^{LF} \rangle'}{\gamma_{eff} \langle \tilde{v}_\perp^2 \rangle}$$

    meaning a ratio of kinetic energy transfer from turbulence into ZF to the turbulence input power

  - ✓ **Turbulence collapse condition $R_T > 1$**
  - ✓ Experimental results show that L-H transition occurs when $R_T > 1$
- Yan (2014) reported a similar finding at DIII-D

- Tynan (2013)



Main results

- **3D flux-driven simulation of edge transport barrier (ETB) formation** shows that

1. **ETB forms once input power exceeds a threshold value**
   - ✓ Steep pressure pedestal , deep Er well appear when $P_{in} > P_{th}$
   - ✓ Q versus $-\nabla P$ curve shows a feature of first-order phase transition

2. **ETB transition is triggered by turbulence-driven flow shear**
   - ✓ **$R_T > 1$: criterion for the trigger of the transition**
   - ✓ Burst of the turbulence-driven flow shear appears just prior to the transition point

3. **Time sequence of the transition is clear**
   1) **Peaking of the normalized Reynolds power ($R_T > 1$):**
   2) Turbulence suppressed and pressure gradients increased
   3) Mean flow shear ($\langle V_E \rangle'$ from ∇P) rises: **sustain H-mode**

➡ **Microphysics (R_T) may govern L→H transition!**

3D model using BOUT++

- **Electrostatic model with resistive ballooning (RBM) turbulence**
  - ✓ **Two field (vorticity, pressure) reduced MHD equations (constant density)**
  - ✓ **Flux driven**, self-consistently evolving pressure profile

- **Vorticity (U)**

Neoclassical poloidal flow damping accounting for self-consistent flow

$$\frac{\partial U}{\partial t} = -\vec{V}_E \cdot \nabla U - B^2 \nabla_{\parallel} \frac{J_{\parallel}}{B} + \vec{b} \times \vec{\kappa} \cdot \nabla P + \mu_{\perp} \nabla_{\perp}^2 U - \mu_{neo} (U_{0,0} - U_P),$$

$U = \nabla_{\perp}^2 \Phi, \quad J_{\parallel} = S \nabla_{\parallel} \Phi, \quad S = \mu_0 \bar{L} V_A / \eta,$: Lundquist number ($=10^5$)

$U_P = -\delta(1 - k_{neo}) \nabla_{\perp}^2 P_{0,0},$ $\quad k_{neo}(\nu_{i,*}), \mu_{neo}(\nu_{i,*})$: Neoclassical flow/friction coefficients

Since $\nu_{i,*} \sim nT_i^{-2} \sim P^{-2}, \quad k_{neo}(\nu_{i,*}) \to k_{neo}(P), \mu_{neo}(\nu_{i,*}) \to \mu_{neo}(P)$

- **Pressure (P)**

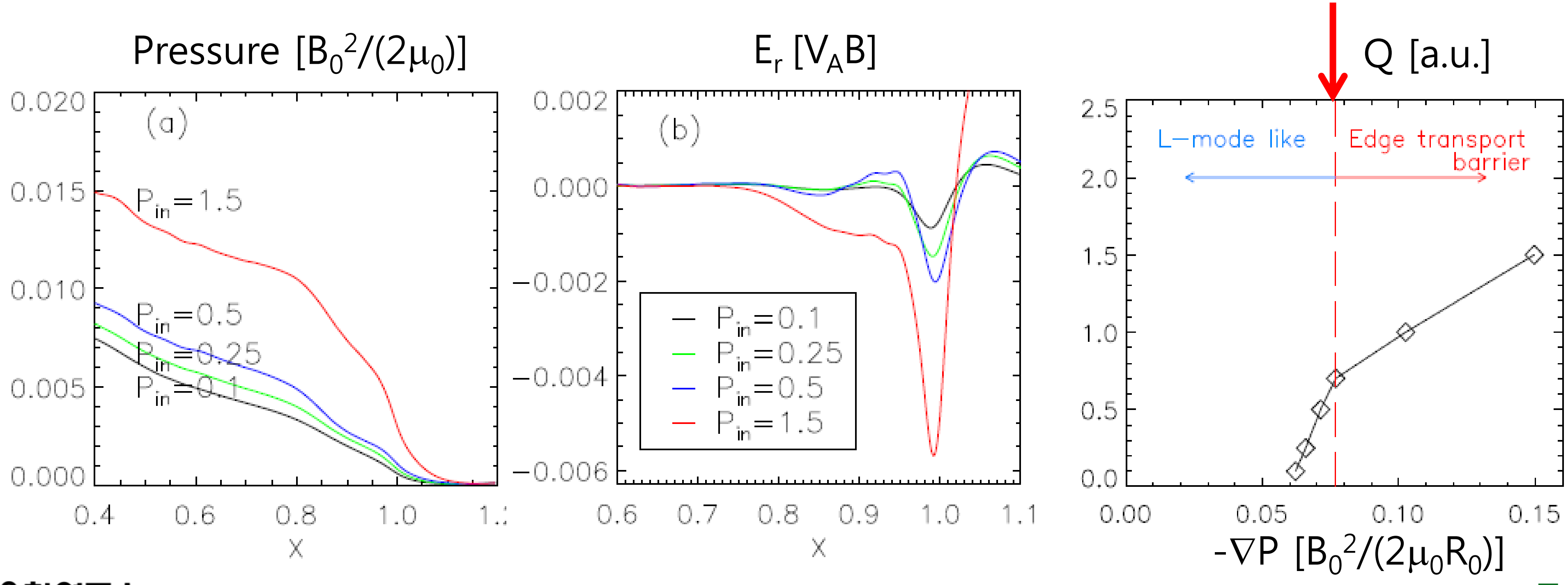
Heat source   Sink → models SOL loss

$$\frac{\partial P}{\partial t} = -\vec{V}_E \cdot \nabla P + \chi_{\parallel} \partial_{\parallel 0}^2 P + \chi_{neo} \nabla_{\perp}^2 P + S_0(r) - S_1 P_{0,0}$$

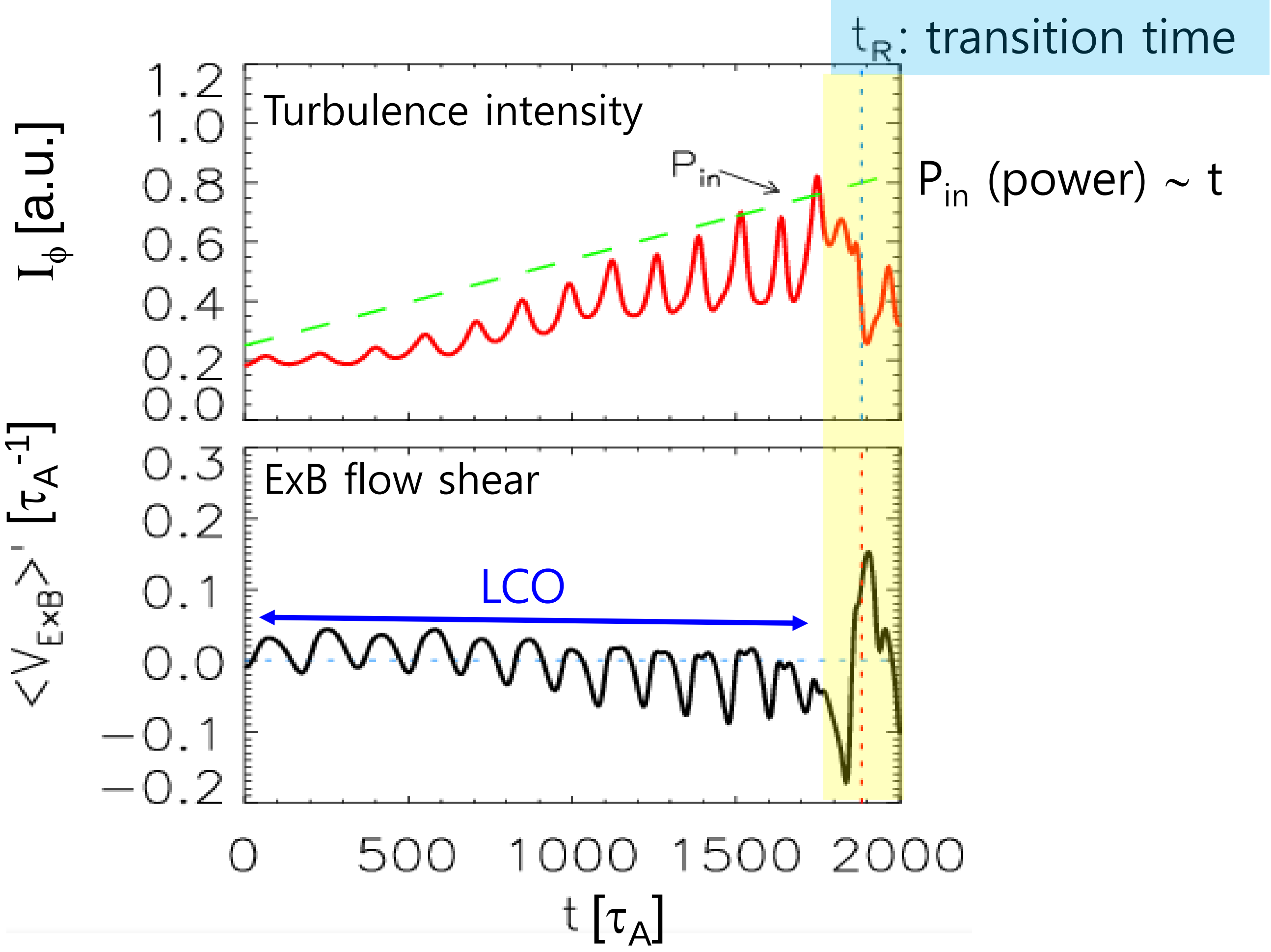
- Overall results are independent of the particular source and sink profiles
- For transport coefficients, we use $\chi_{\parallel}=0.1$, $\chi_{neo}=\mu_{\perp}=3.0\times10^{-6}$

Edge transport barrier (ETB) forms when $P_{in} > P_{th}$

- **ETB forms at x~0.95 for $P_{in} > P_{th}$** [Park, H-mode Workshop, 2013]
  – Steep pressure pedestal
  – Deep Er well
  – Discontinuity in slope of Q versus -∇P graph
    → A feature of first-order phase transition
  – Similar simulation result of ETB formation has been reported [Chone, PoP, 2014]



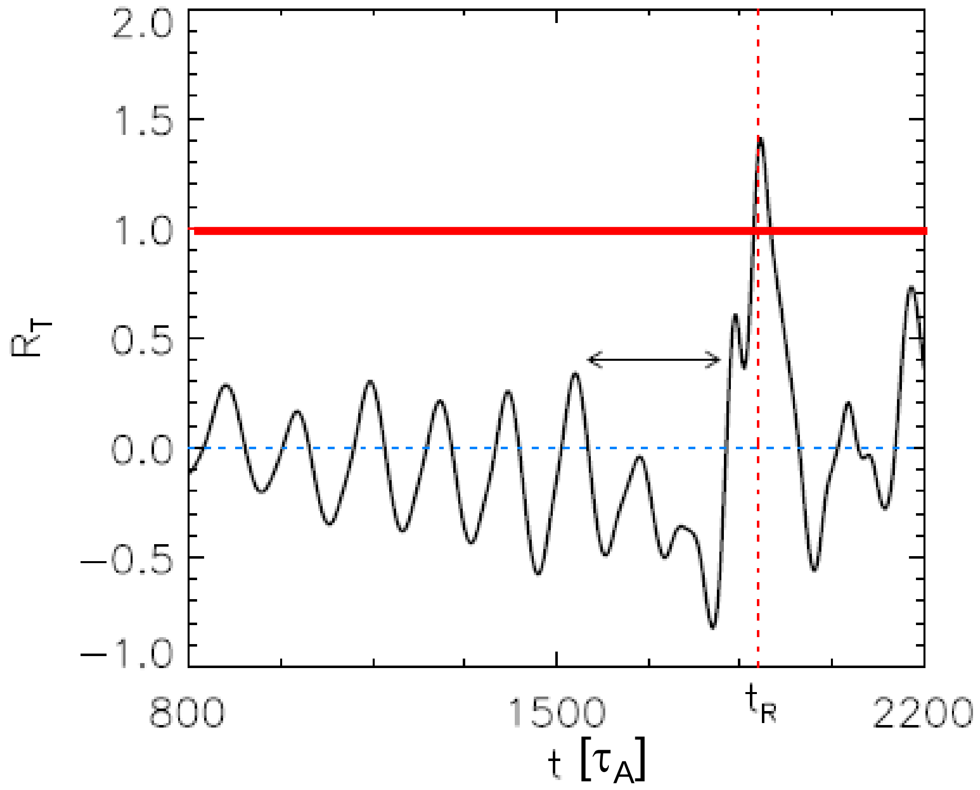
Power ramp up simulation shows the turbulence collapse at $t=t_R$ via an intermediate phase



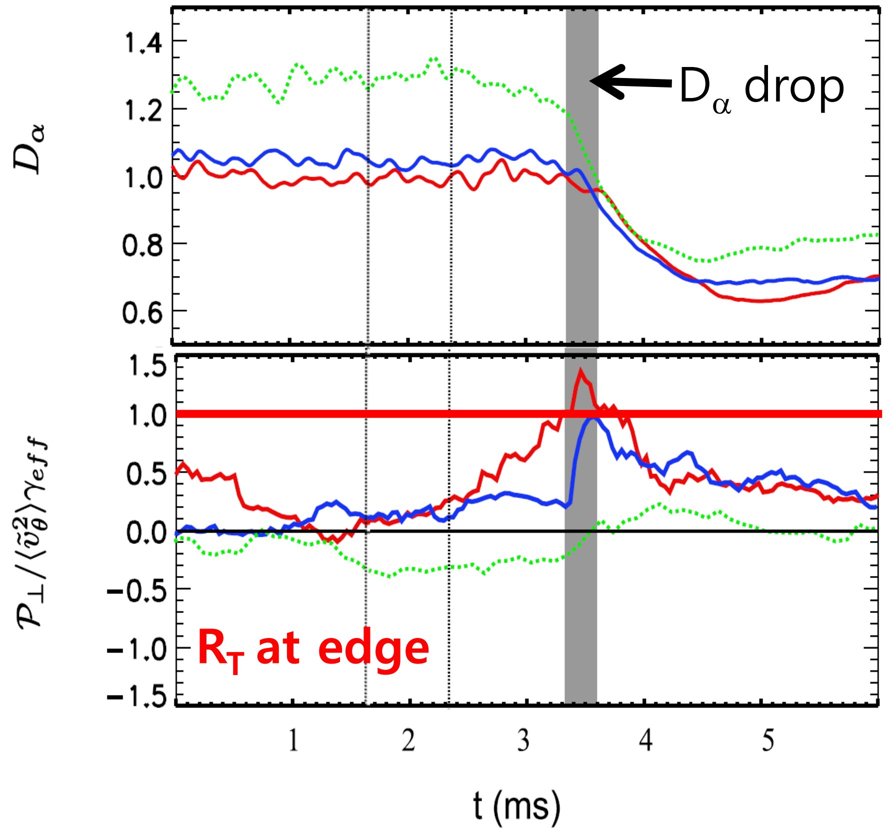
- Limit-cycle oscillation (LCO) appears prior to the transition
- Turbulence is continuously growing and peaks just before the transition
- ExB flow shear changes abruptly near the transition (yellow shaded area)

R_T > 1 for the trigger of the transition at $t=t_R$: fluctuation energy → flow (m=n=0) energy

Reynolds work (simulation)

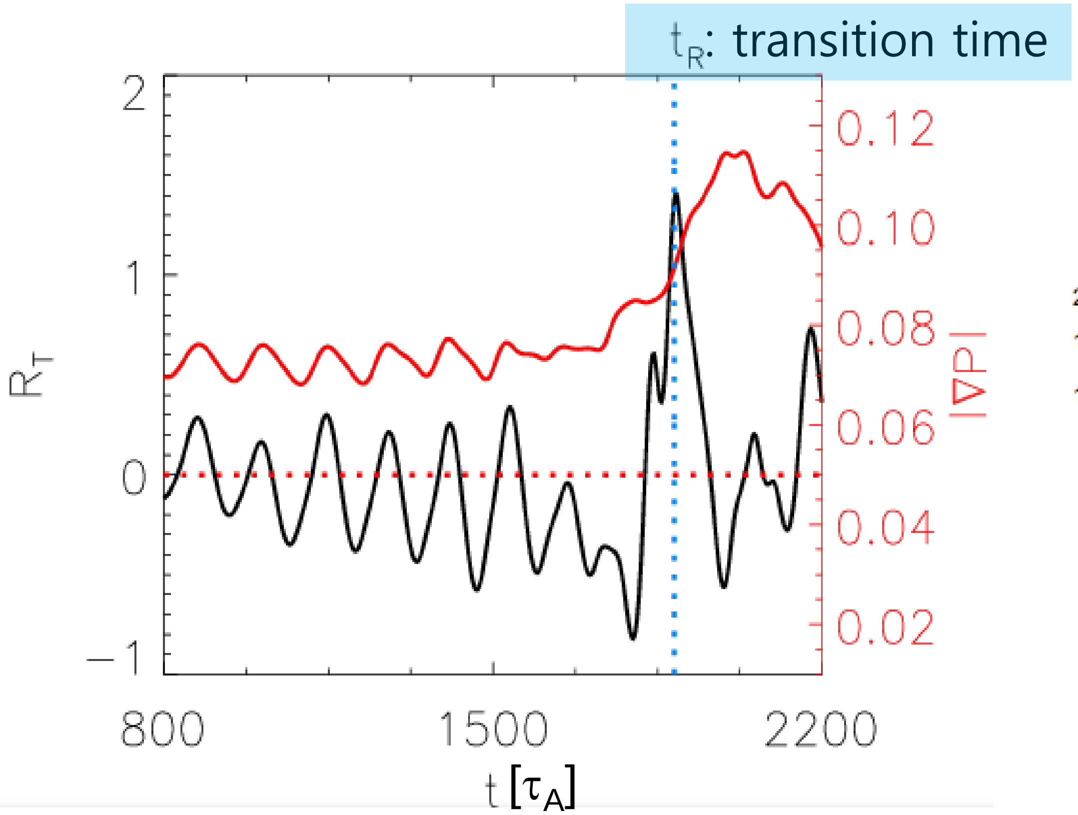


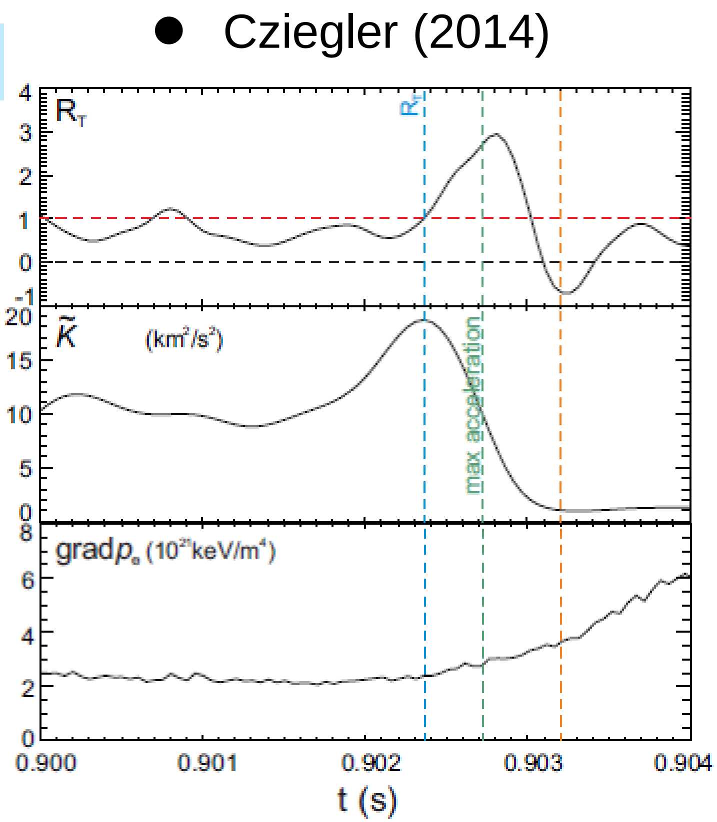
- Tynan (2013)



- Turbulence collapse condition ($\partial \tilde{V}_\perp^2 / \partial t \leq 0$) → **$R_T \geq 1$**
- **R_T > 1 means the conversion of fluctuation energy into flow energy faster than turbulence energy increase**

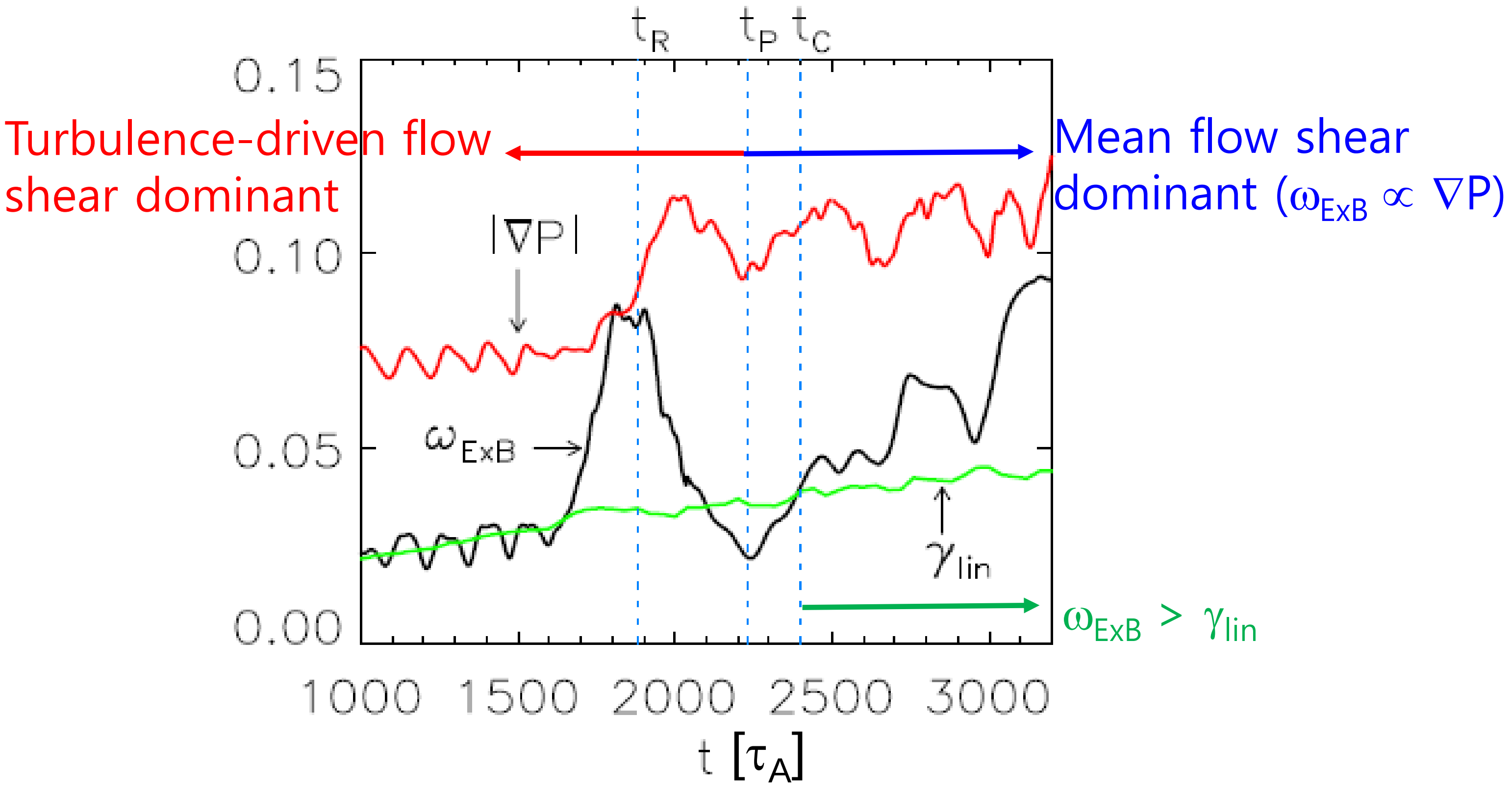
Simulation shows a similar sequence of the transition to that observed on C-Mod (Cziegler, 2014)





- **R_T >1 at $t=t_R$ → an increase of pressure gradient.**
  - ✓ R_T >1 at $t=t_R$ triggers the transition
  - ✓ Turbulence collapse → an increase of ▽P

Microscopic time sequence of the transition: ∇P, ExB flow shear (ω_{ExB}), and linear growth rate (γ_{lin})



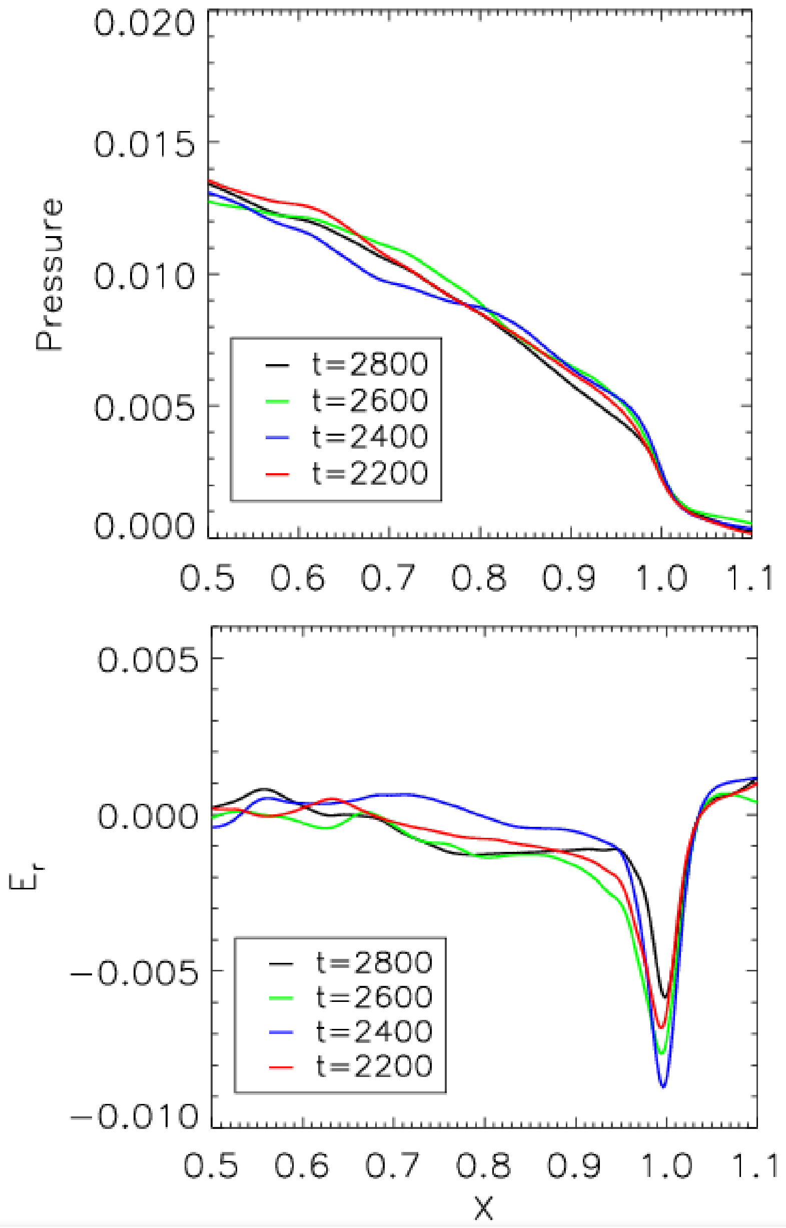
- **$R_T > 1$ causes the surge of the turbulence-driven flow shear at $t=t_R$**
- **Increase of pressure gradient precedes mean flow shear development**
- Positive feedback between ∇P and ω_{ExB} begins at $t=t_P$
- Mean shear criterion ($\omega_{ExB} > \gamma_{lin}$) is satisfied later, at $t=t_C$ → H-mode sustained afterward

Preliminary electromagnetic three-field results

- Simulation of ETB formation using three-field model
  - ✓ Two-field model + Ohm's law for perturbed vector potential (ψ)

$$\frac{\partial \psi}{\partial t} = -\nabla_{\parallel}\Phi + \frac{1}{S}\nabla_{\perp}^{2}\psi,$$

  - ✓ Profiles of μ_{neo} and k_{neo} are fixed in time in this simulation
  - ✓ ETB occurs for P_{in} = 2.0 as seen in right figures
  - ✓ Suggests that the transition physics as found in electrostatic case may also apply for the electromagnetic case (Work is in progress)



Conclusions and discussions

- First 3D turbulence simulation to explicitly show
  - ✓ ETB formation for $P_{in} > P_{th}$
  - ✓ **The criteria $R_T > 1$ is the trigger of the L→H transition**

    ⟶ **Microphysics (R_T) may govern L→H transition process**
  - ✓ **Detailed time sequence of the L-H transition**
    - **$R_T > 1$ → the surge of the turbulence-driven flow shear**
    - **An increase of pressure gradient → mean flow shear development via positive feedback**
    - **$\omega_{ExB} > \gamma_{lin}$ → steady H-mode sustained**

- Future works
  - ✓ **Microscopic parameter trends in R_T and their relation to L→H transition power threshold scaling**
  - ✓ Formation of sudden deep (in time) R_T just prior to the transition
  - ✓ H→L back transition and hysteresis
  - ✓ Electromagnetic case