Dynamics of Pedestal Rotation and Ion Temperature Profile Evolution in KSTAR H-mode Discharge with RMP

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Outline

1. Motivation and Basic Profile Structure
2. Profile Evolution through L→H Transition
3. Profile Evolution through H→L Back Transition, with and without RMP
4. Profile Evolution during ELM cycle
5. Transport Analysis
6. Conclusions and Future Plans

1. Motivation and Basic Profile Structure

Motivation

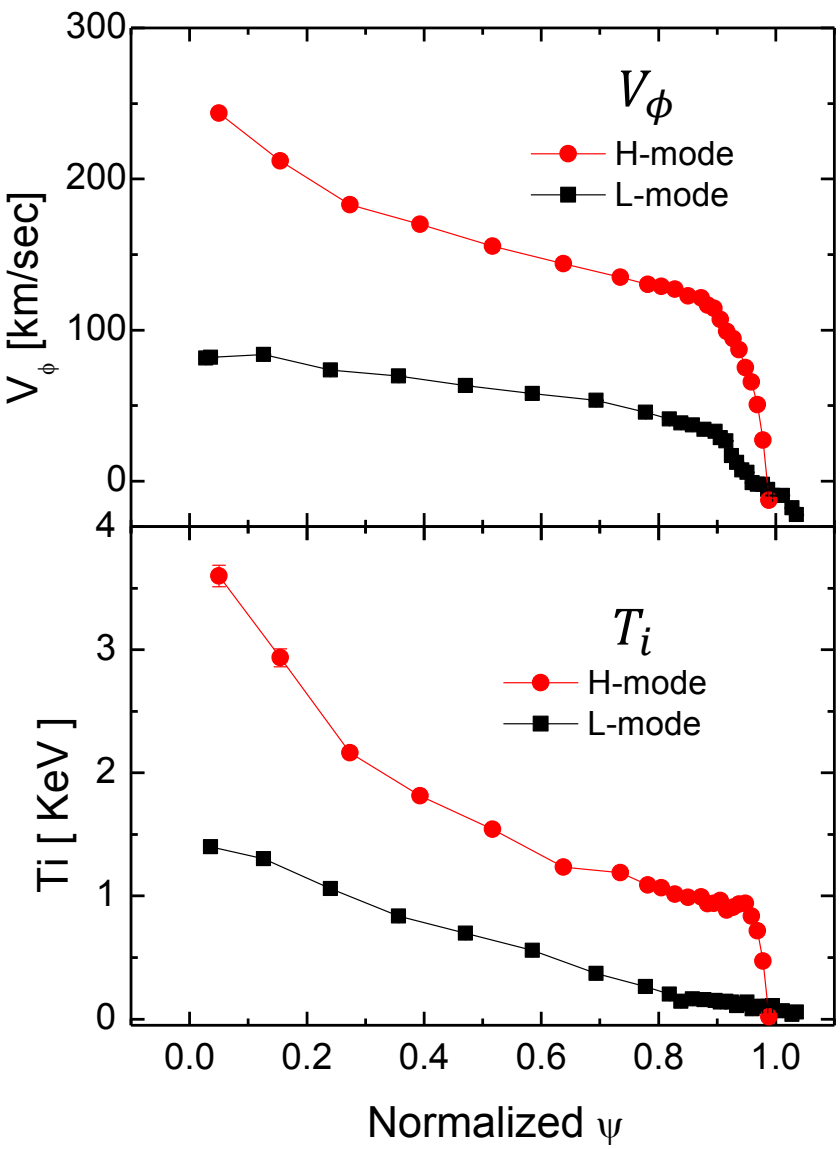
- Pedestal rotation profiles are important for ITER in the multiple contexts of enhanced confinement, the source of intrinsic torque in H-mode, and their response to ELMs and to ELM mitigation techniques.

- We present Charge Exchange Spectroscopy(CES) studies of T_i and V_ϕ (CVI) pedestal profile structure and evolution at the L→H and H→L transitions and during ELMs.

- The evident disparity between the width of the V_ϕ pedestal and that of the Ti pedestal is striking! This is interesting, since the conventional wisdom says the Ti pedestal should be broader, since we usually expect the neoclassical ion thermal diffusivity in the pedestal to exceed the turbulent viscosity.

- Pedestal rotation profiles have been measured during ELM suppression experiments on KSTAR using an n=1 RMP using the segmented in-vessel control coil (IVCC) system of KSTAR.

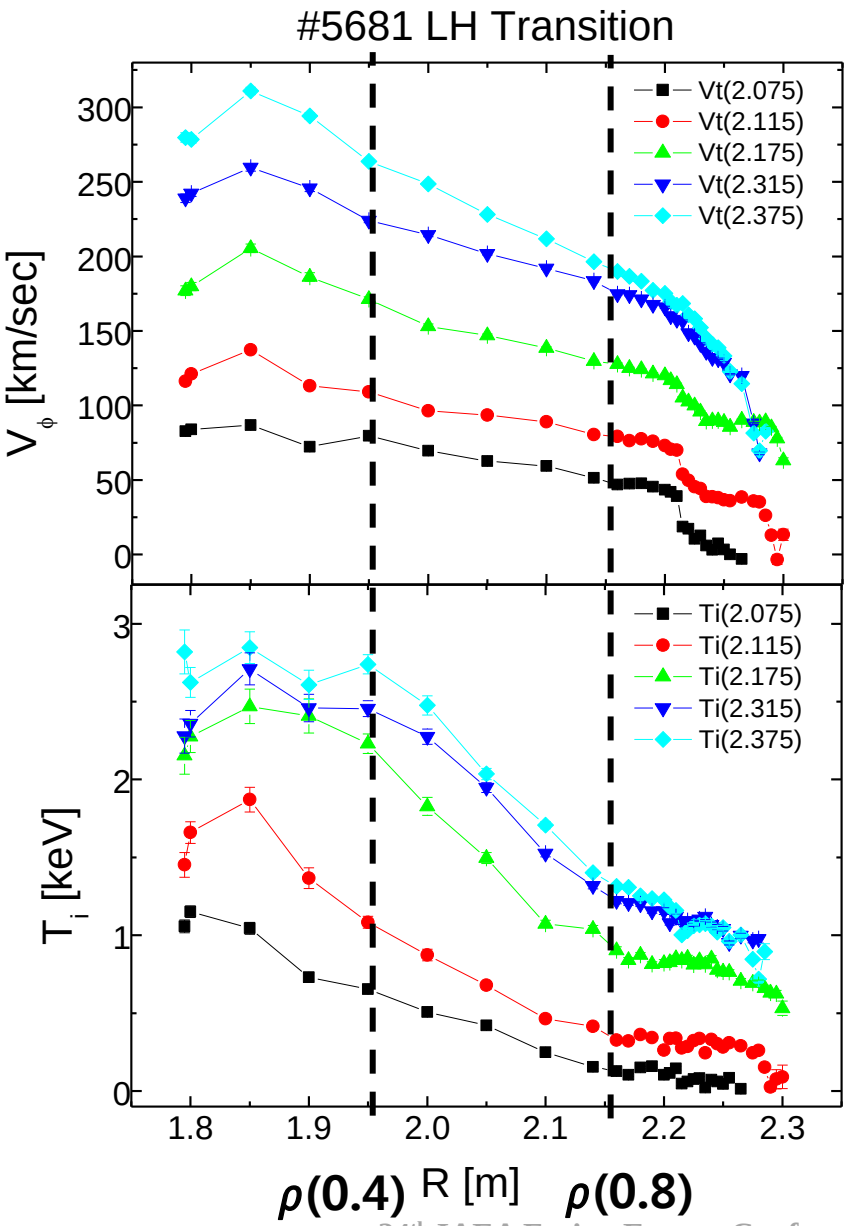
T_i and V_ϕ Profiles in H-mode

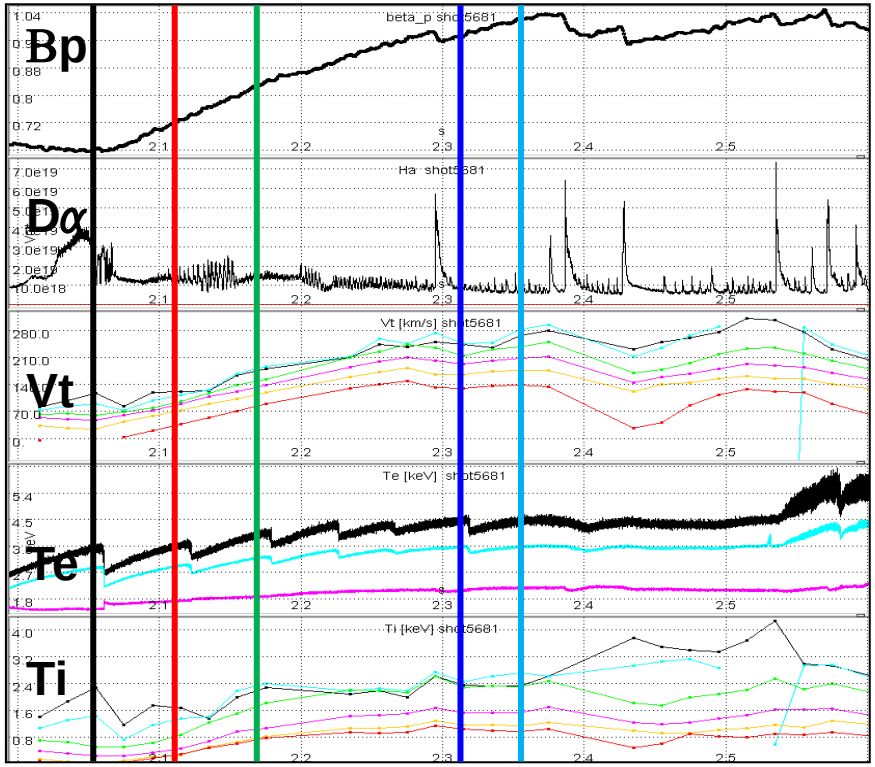


- CES measures Carbon impurity (VI) lines.
- Core gradients of both rotation and ion temperature profile in H-mode are significantly steeper than in L-mode. Toroidal rotation has clear L-mode pedestal. Ion temperature pedestal appears only in H-mode.
- It is interesting to note the sharp and wide observe rotation pedestal structure (V_ϕ^{ped}) in H-mode. It is natural to expect broader T_i pedestal as compared to V_ϕ (i.e. $\Delta_i^{ped} > \Delta_\phi^{ped}$). However, V_ϕ pedestal is broader than T_i (i.e.$\Delta_\phi^{ped} > \Delta_i^{ped}$) in KSTAR.

2. Profile Evolution through L→H Transition

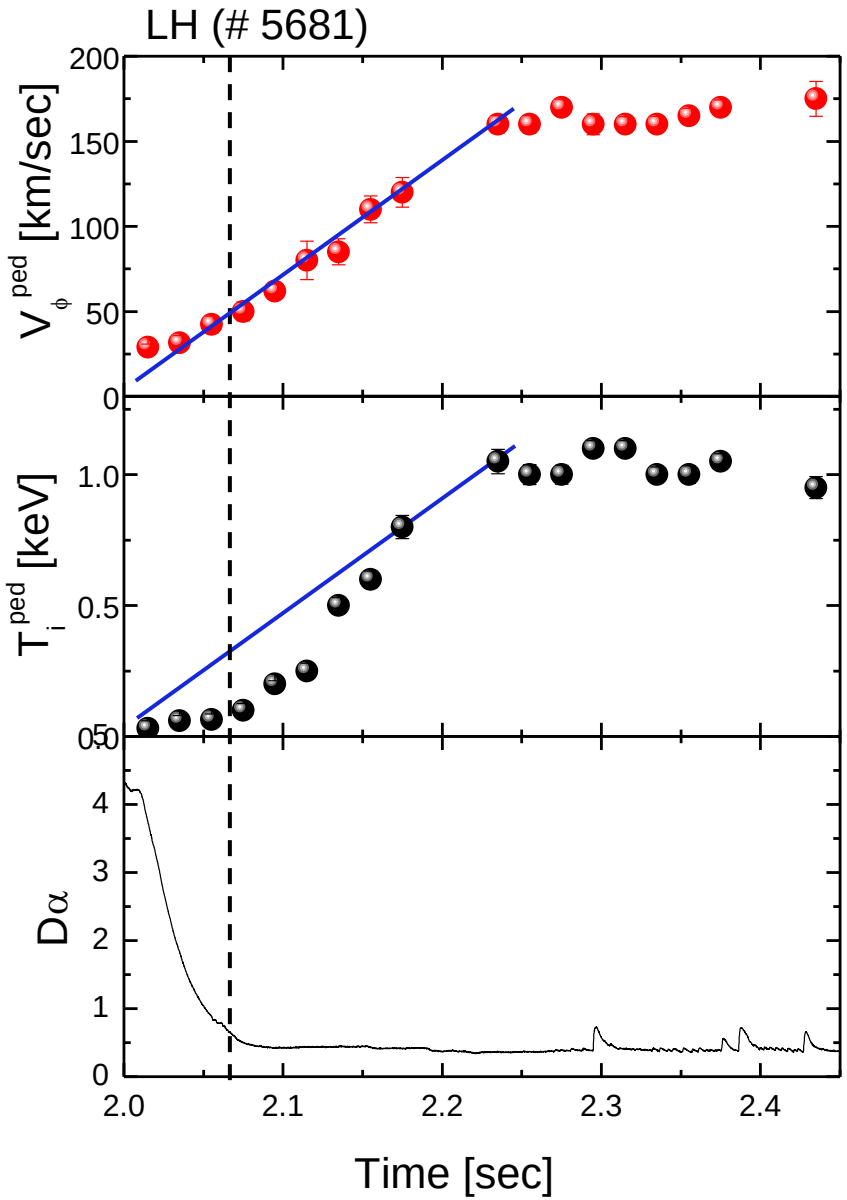
Time Evolution of V_ϕ and T_i during L→H Transition





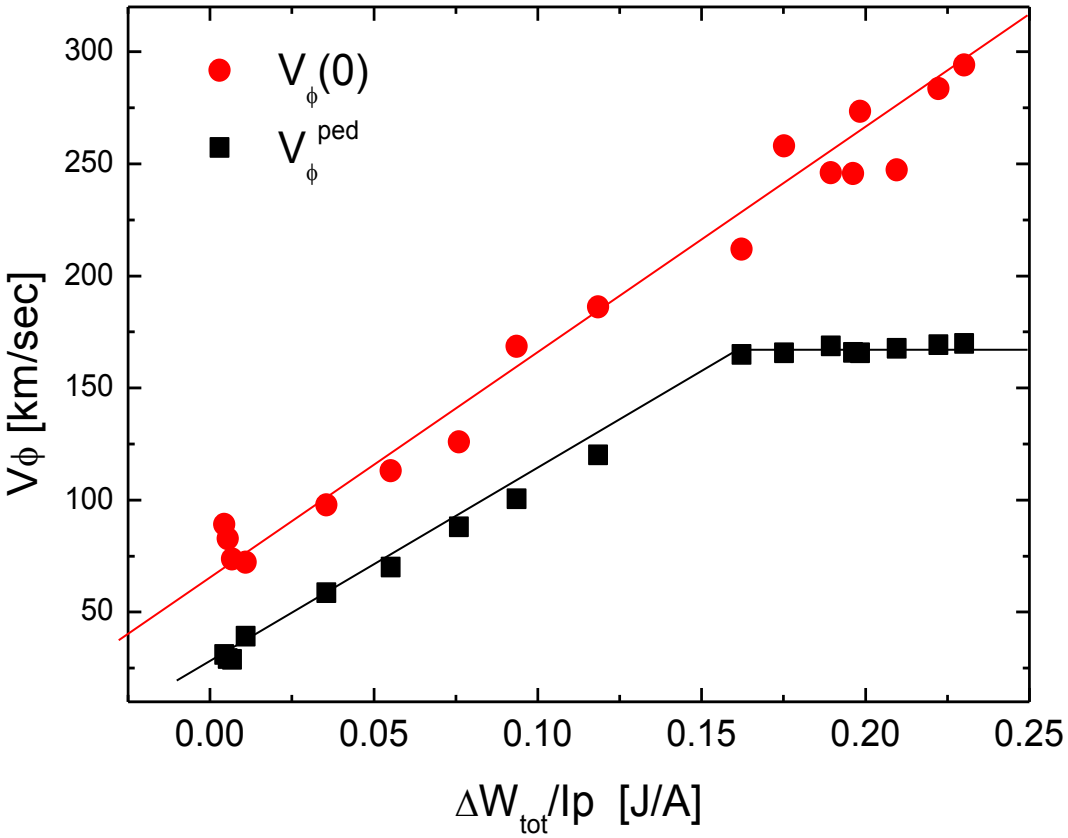
- Detailed profiles of V_ϕ and T_i have been obtained during the L→H transition and during ELMs. Time resolution is 10 msec.
- During the L→H transition, V_ϕ pedestal formation leads T_i pedestal formation, and builds inward from the separatrix.

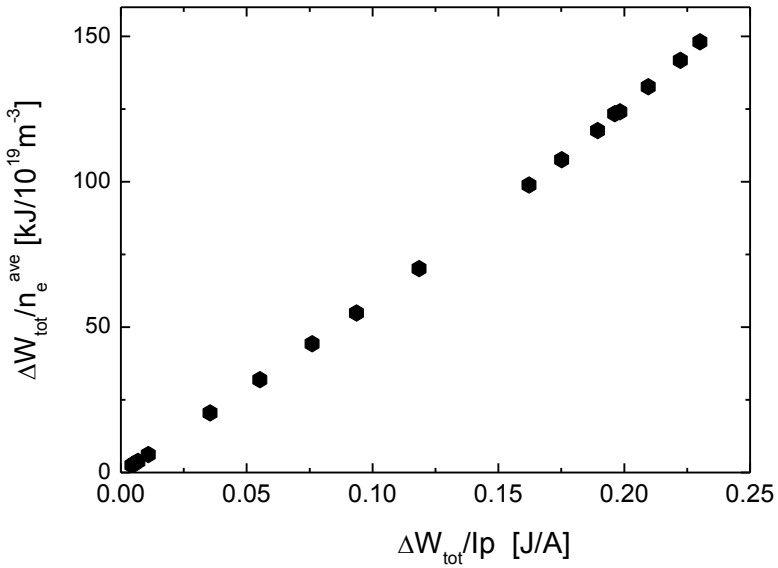
Evolution of Pedestal Top Through L→H Transition



- V_ϕ pedestal formation leads T_i formation i.e. V_ϕ increases faster than T_i.
- This observation is consistent with the expectation that toroidal momentum transport is effectively governed by turbulence only, while neoclassical ion thermal transport plays a significant role in T_i profile evolution. Thus V_ϕ can react more rapidly to the suppression of turbulence at the L→H transition than T_i can.
- In a related and consistent vein, we observe that V_ϕ also responds faster and more strongly to the ELM than T_i does.

Stored Energy and Rotation During L→H Transition





- $V_\phi(0)$ exhibits "Rice Scaling" trend, though with NBI (?!) → see next
- V_ϕ(ped. top) saturates at $\Delta W/I_p \sim 0.15$

∴ Momentum pinch active in core?

- $\Delta W/I_p$ well correlated with $\Delta W/n_e$

Stored Energy and Rotation During L→H Transition

- How can "Rice Scaling" appear for co-NBI H-mode
- Simple 0D model:

$$\partial_t \bar{V}_\phi + \frac{\bar{V}_\phi}{\tau_\phi} = T_b + T_{intr}$$

intrinsic torque

beam torque

momentum confinement time

$$T_{intr} \cong -\partial_r \langle \tilde{V}_r \tilde{V}_\phi \rangle^{resid} \cong -\partial_r \left(\frac{\chi_\phi V_{th}}{L_{sym}} \right) \cong \frac{\chi_\phi V_{th}}{L_{ped} L_{sym}}$$

$$\Pi_{resid} \cong \chi_\phi V_{th} / L_{sym}$$

- Key point:
  - At transition 2 effects enter:
    - ① Enhanced confinement → τ_ϕ increases
    - ② Pedestal intrinsic torque enters → τ_{intr} rises

$$\Delta \bar{V}_\phi \cong \left(\tau_\phi \Big|_H - \tau_\phi \Big|_L \right) T_b + \left(\tau_\phi T_{intr} \right) \Big|_H - \left(\tau_\phi T_{intr} \right) \Big|_L$$

$$\tau_\phi^{-1}|_L \sim \frac{\chi_\phi}{a^2}, \quad \tau_\phi^{-1}|_H \sim \frac{\chi_\phi}{a^2} F\left(\frac{V'_E}{\omega_0}\right)$$

An Example

$$F\left(\frac{V'_E}{\omega_0}\right) \sim \frac{1}{1 + V'^2_E / \omega_0^2}$$

Stored Energy and Rotation During L→H Transition

$$\Delta\bar{V}_\phi \cong \tau_\phi^L T_b \left(\frac{V_E'^2}{\omega_0^2}\right) + \tau_\phi^L \left(\frac{V_{thi}}{L_{ped}}\frac{\chi_\phi^L}{L_{sym}}\right)$$

N.B. $\frac{V_{thi}\chi_\phi^L}{L_{ped}L_{sym}} \sim \frac{V_{thi}}{T_i}\frac{QL_{Ti}}{L_{ped}^2}$

① Increase in $\bar{V}_\phi$ due enhanced confinement

② Pedestal intrinsic torque

- For pedestal torque

$$L_{sym} \sim L_{V_E'} \sim L_{ped}$$

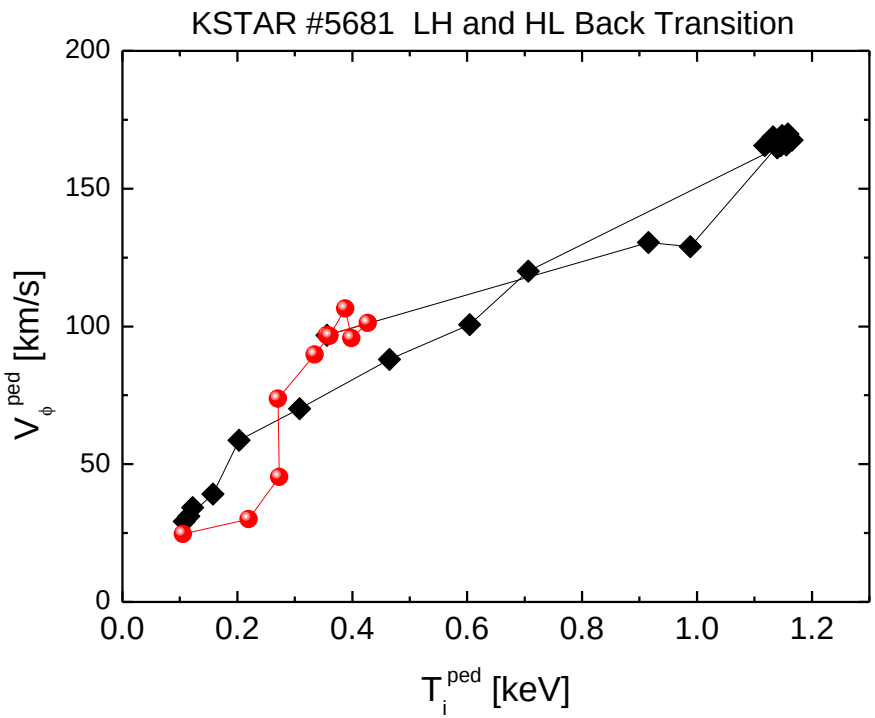
$$\frac{\partial}{\partial r} \sim \frac{1}{L_{ped}}$$

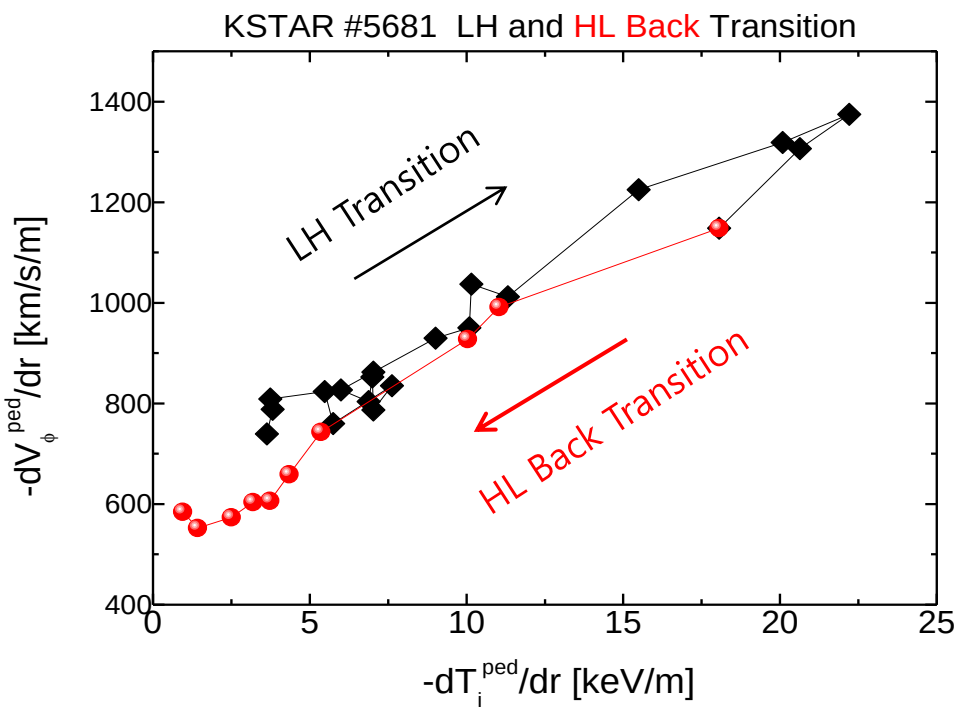
Key point: both ①, ② scale ~ $1/L_{ped}^2$

$$\Delta\bar{V}_\phi \sim \left(\frac{\tau_\phi^L}{L_{ped}^2}\right)\left[\left(\frac{V_E'}{\omega_0}\right)^2 T_b + \frac{V_{thi}}{T_i}(QL_{Ti})\right]$$

- Common length scale dependence and Q ↔ T_b proportionality (all co-NBI heated) of ①, ② allows "Rice Scaling" form
- Need scan of cntr NBI anticipated in 2012 campaign, P_{NBI}/T_b, NBI direction to unravel relative contributions

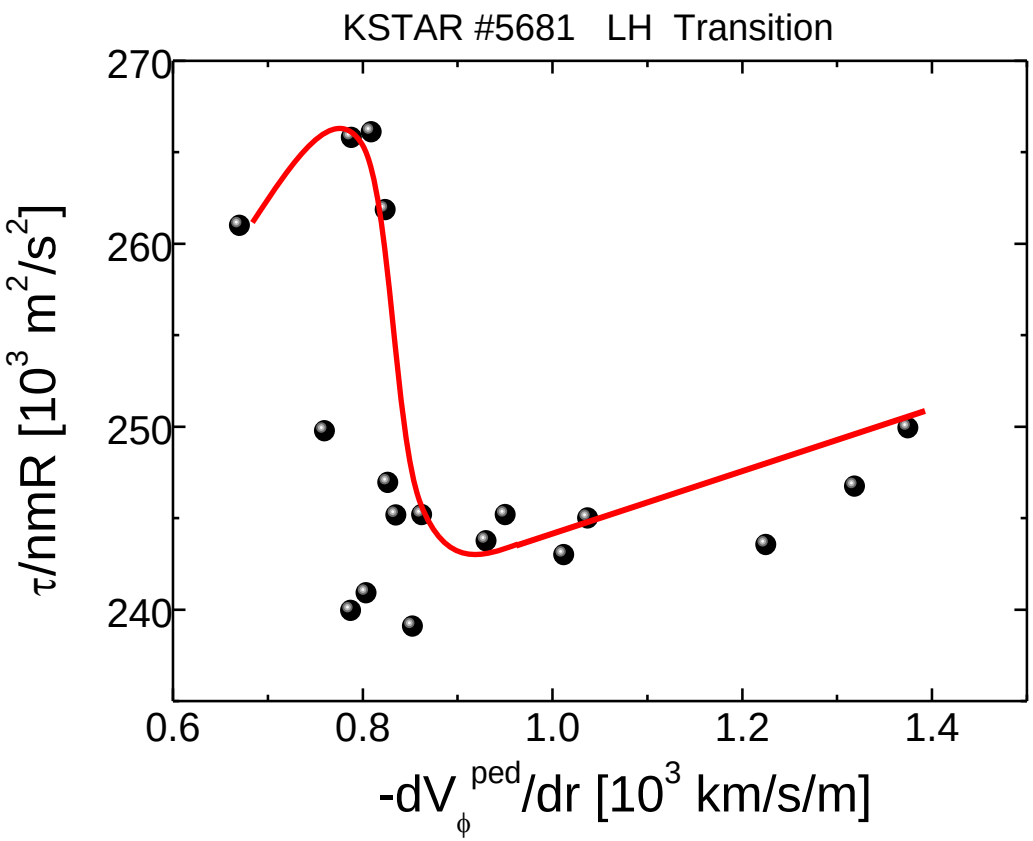
Correlation between pedestal ∇T_i and ∇V_ϕ

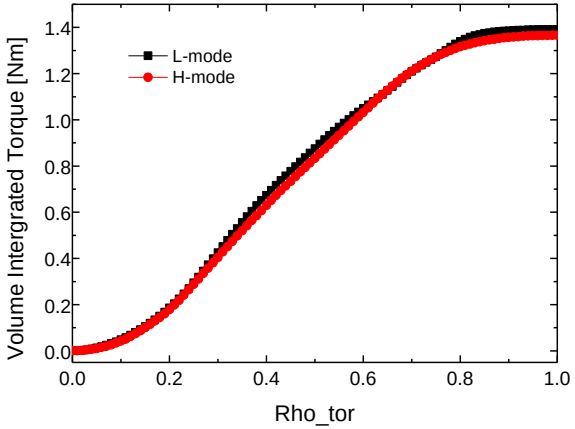


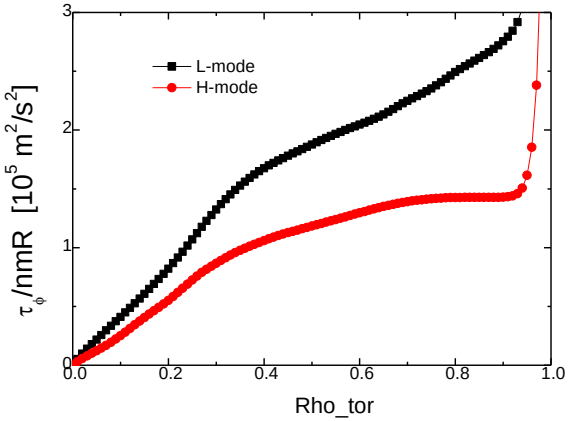


- There is a close correlation between pedestal top values of toroidal rotation and ion temperature during L→H and H→L back transition.
- Close correlation and weak relative hysteresis between pedestal ▽Vϕ and ▽Ti exists during both L→H and H→L transitions. This suggests that single transport process controls both channels during the transitions.
- The correlation in quantity gradients (i.e. ▽Vϕ, ▽Ti — directly related to the driving fluxes!) is more fundamental than the correlation in the quantities.

Torque vs ∇V_ϕ S-curve for rotation bifurcation







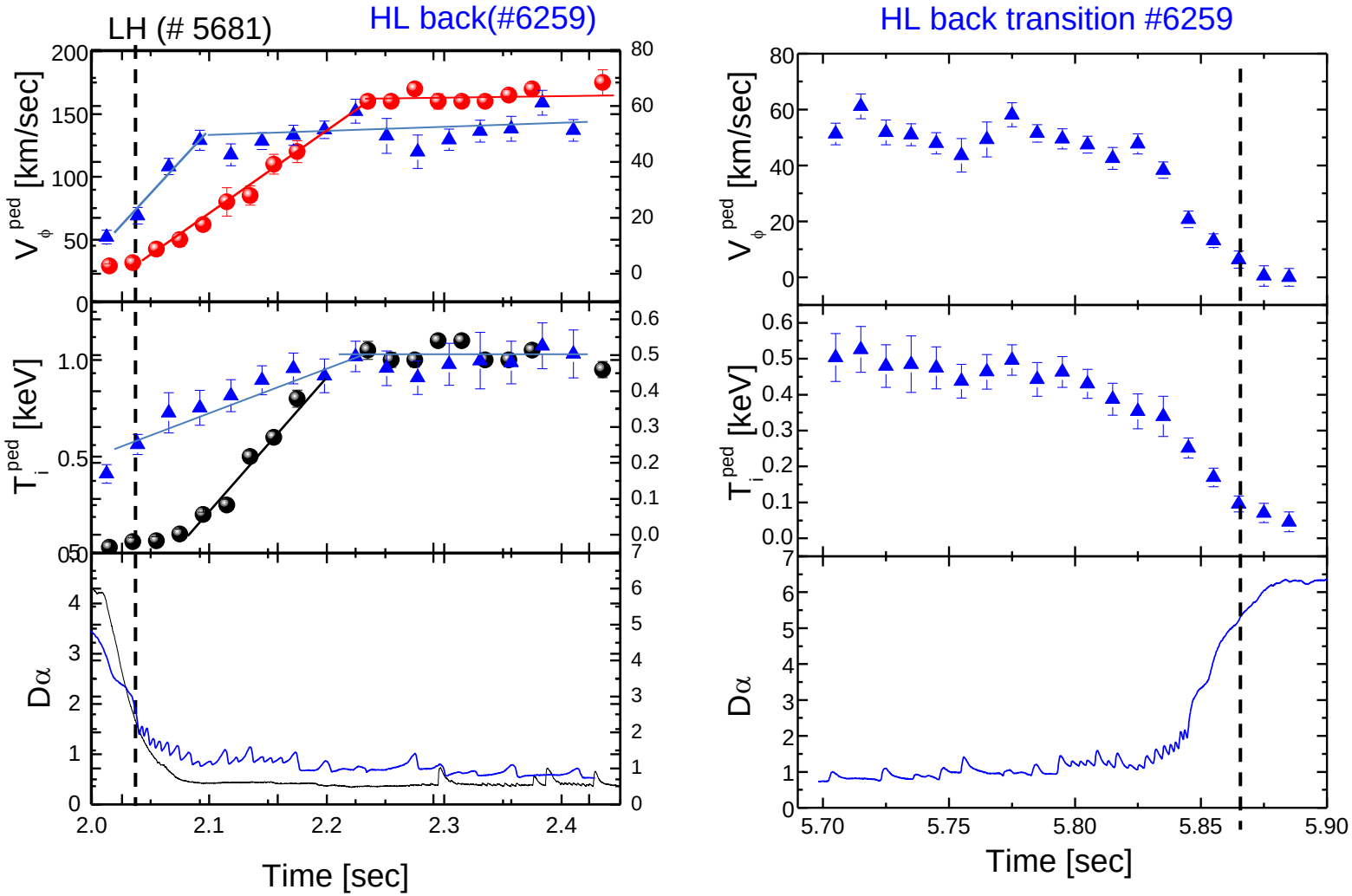
- Bifurcation studies reconstruct a torque(τ) vs ∇V_ϕ S-curve from CES data for the L→H transition.
- Related Qi vs ∇Ti plot is under construction.

3. Profile Evolution

through H→L Back Transition,

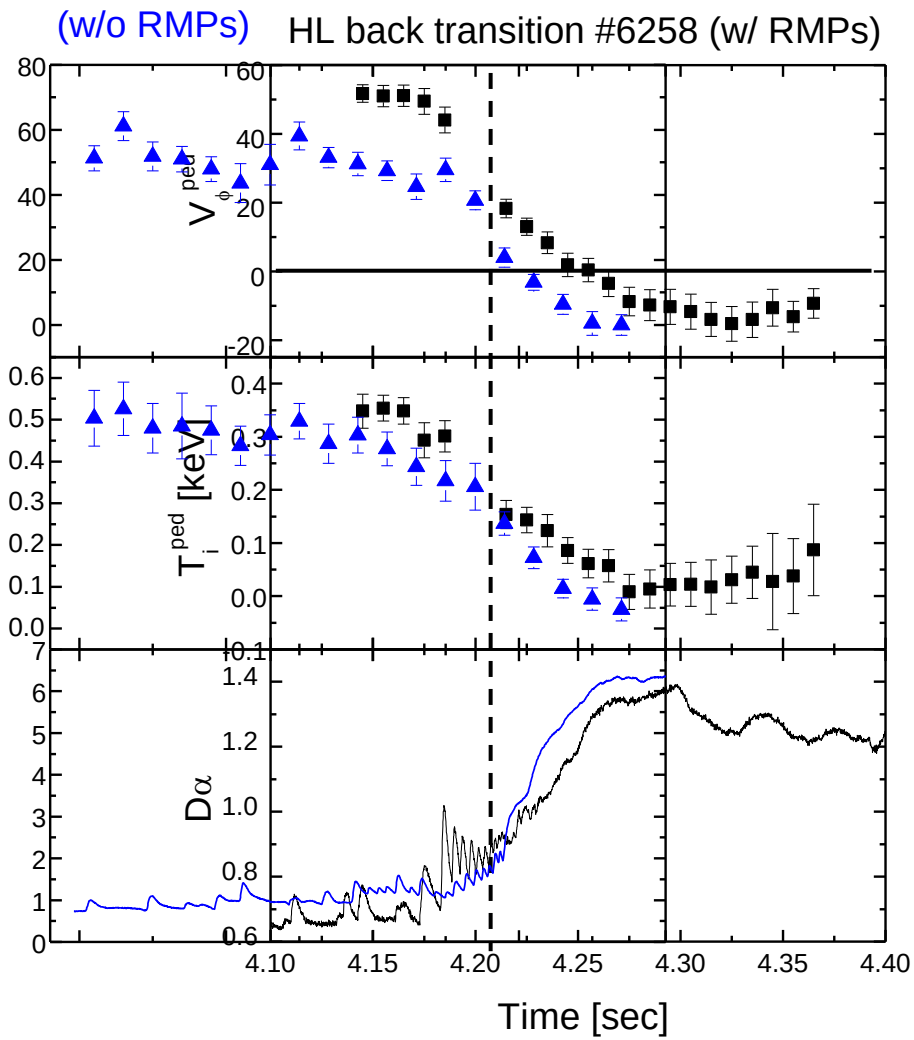
with and without RMP

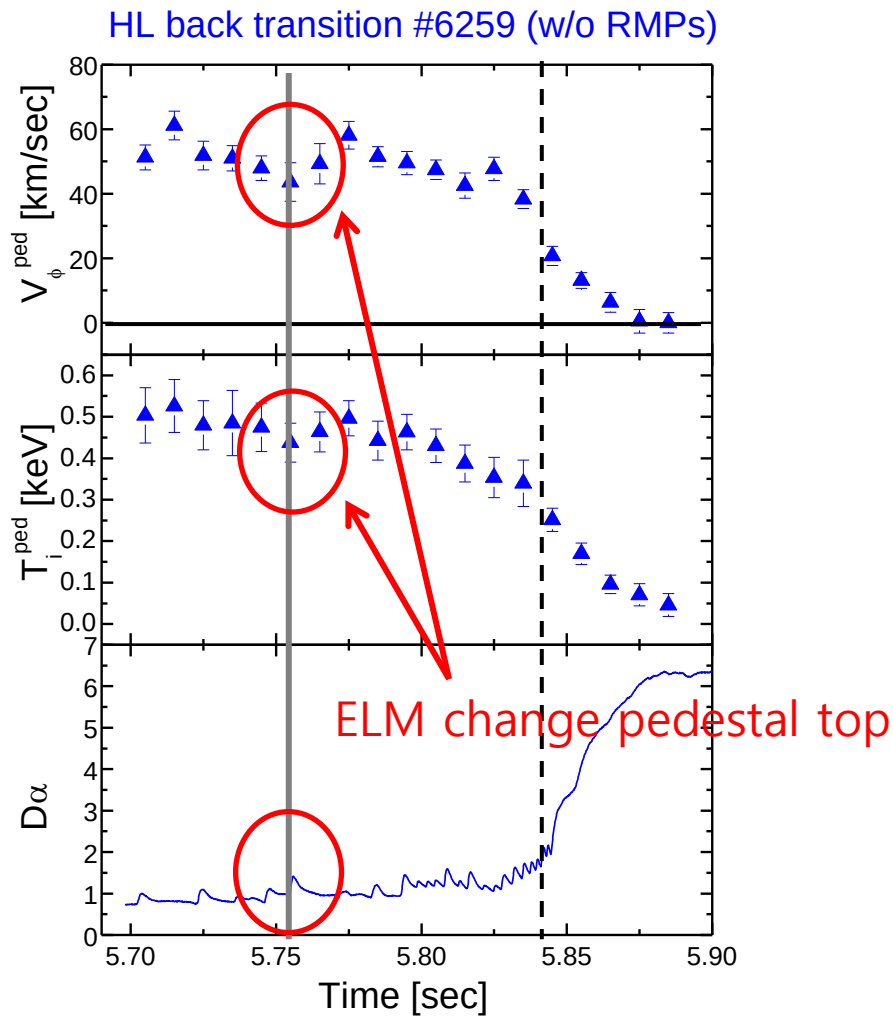
Pedestal Evolution in L→H and H→L Transition



- Time evolution of pedestal V_ϕ and T_i for L→H and H→L back transition.
- Both pedestal V_ϕ and T_i exhibit hysteresis in H→L back transition as compared to L→H transition. Quantitative study underway.

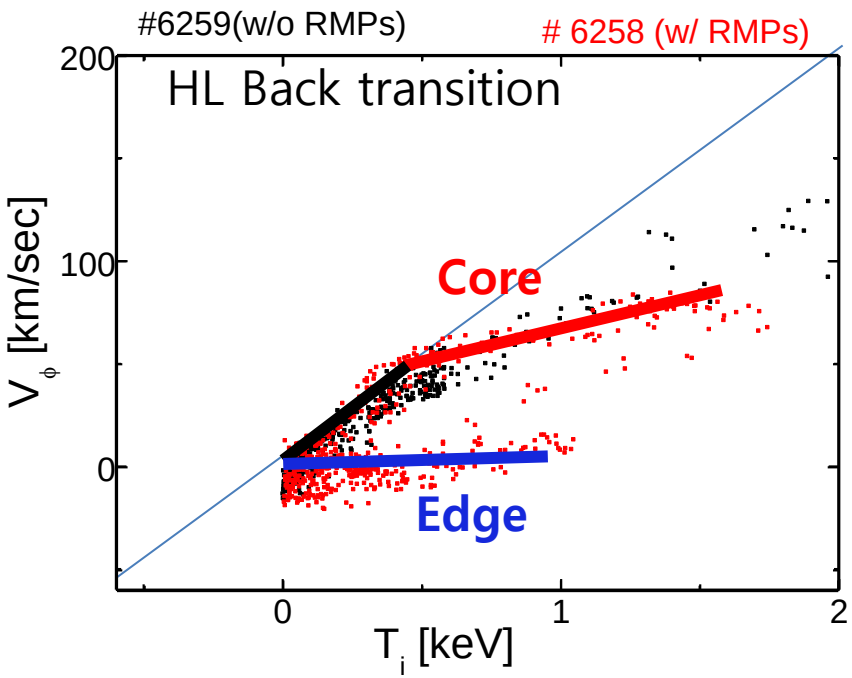
H→L Back Transition with and w/o RMPs

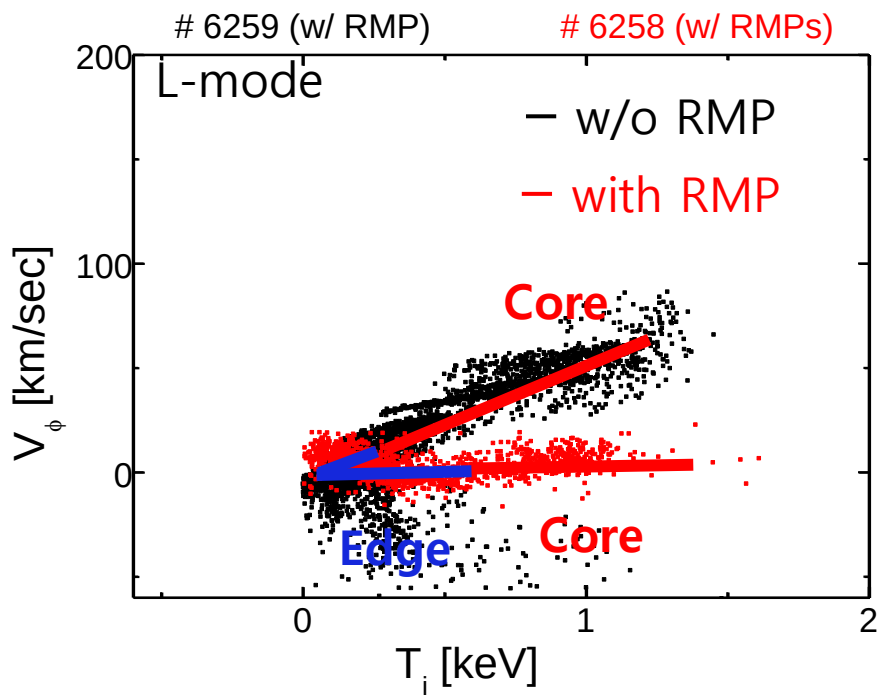




- Time evolution of pedestal V_ϕ and T_i for H→L back transition both with and without RMP. Pedestal V_ϕ and T_i show similar trend in both cases.
- Rotation damping appears in H→L transition when RMP is applied.

H→L Back Transition with and w/o RMPs

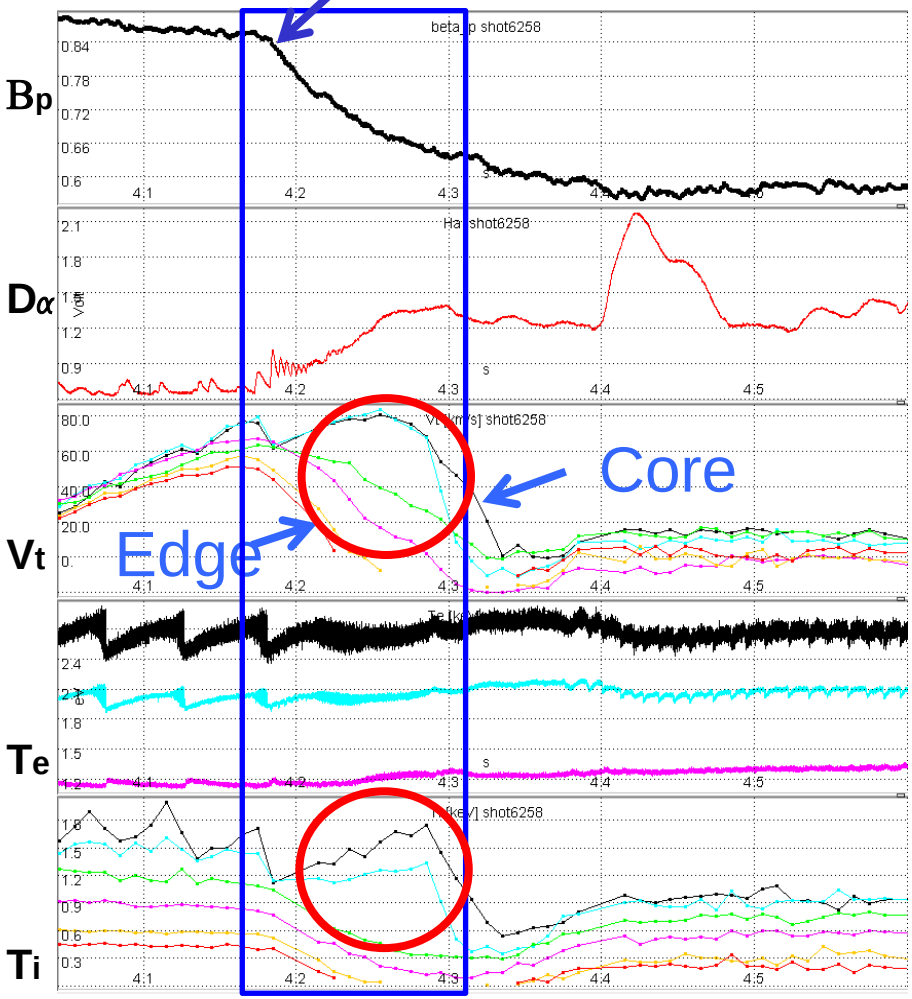


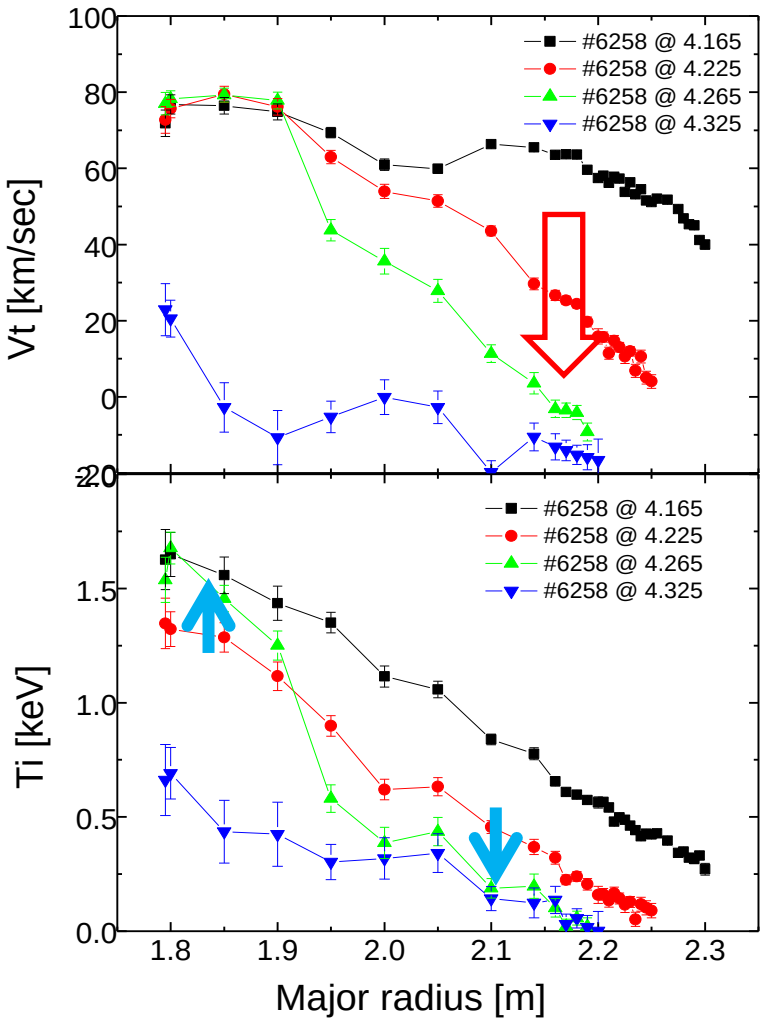


- Core V_ϕ and T_i show similar correlation both with and without RMP.
- Edge V_ϕ and T_i show different trends with and without RMP.

  With RMP, V_ϕ damping enters during H→L back transition.
- With RMP, V_ϕ damping continues in L-mode after H→L back transition.

HL back transition with n=1 RMPs



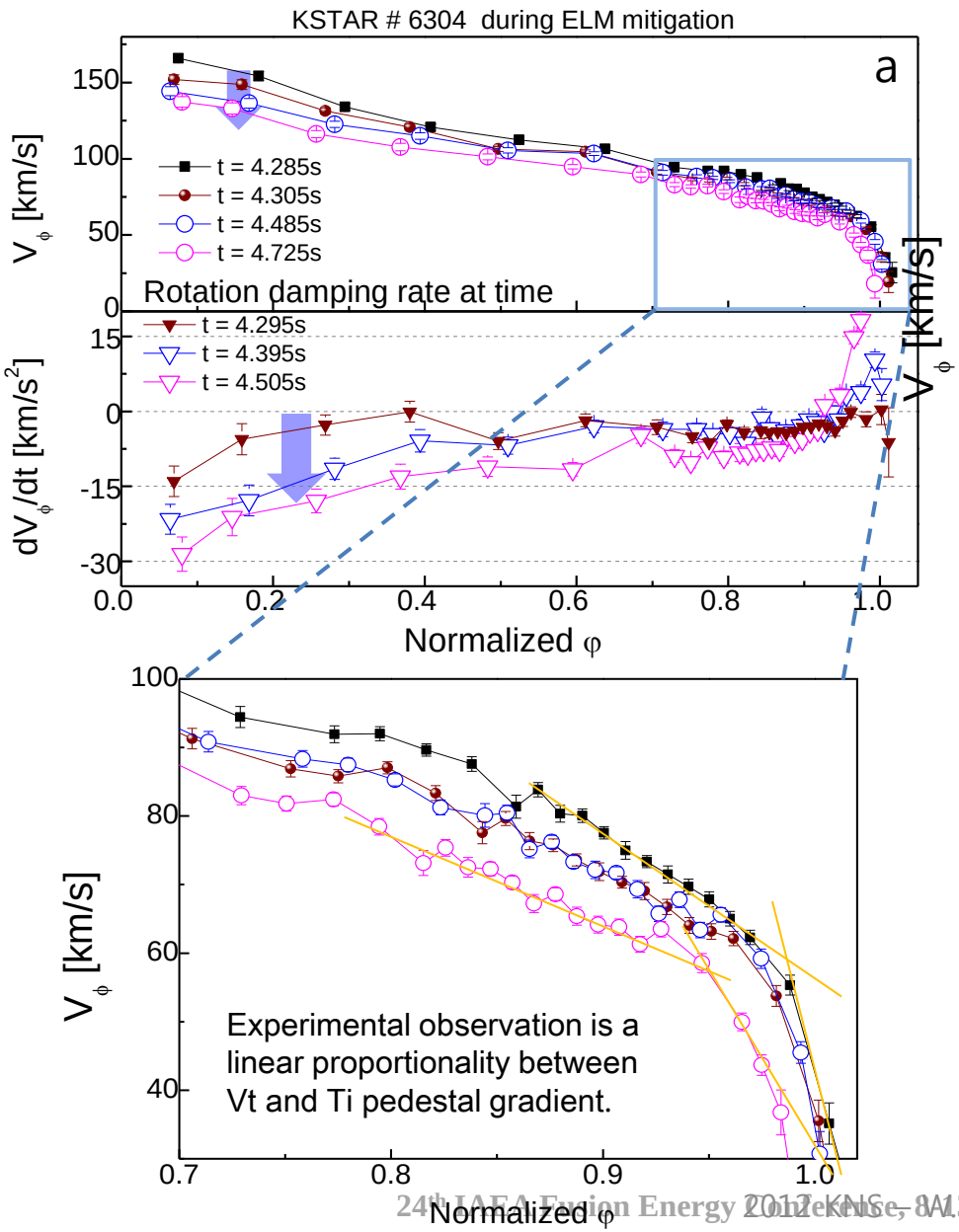


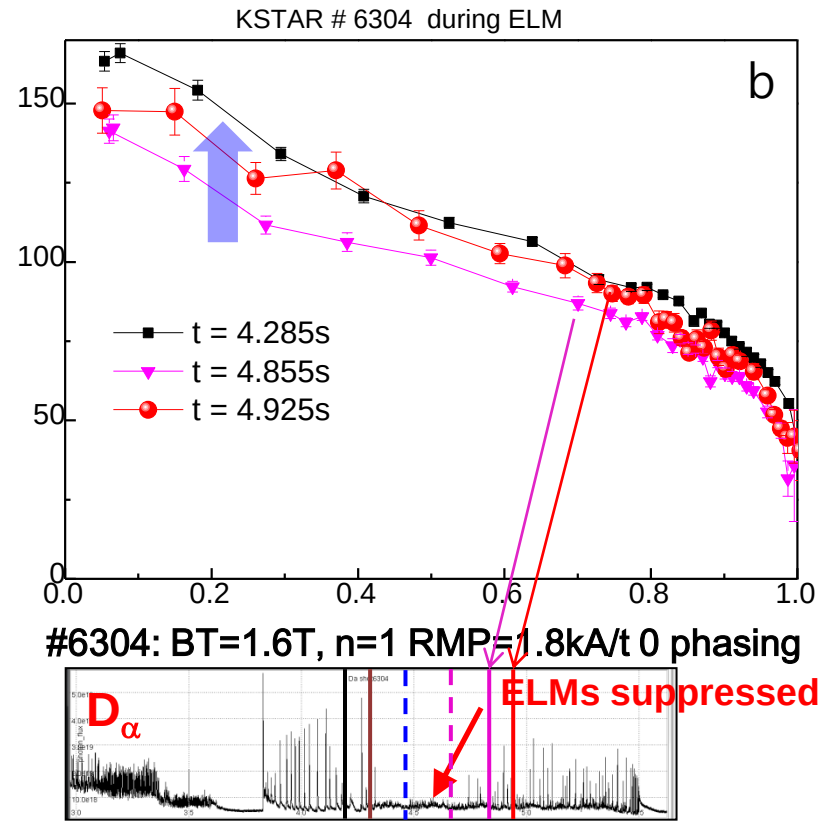
The fluctuation in core T_i is correlated with sawtooth from ECE. Core T_i and V_ϕ have no drop while others decrease after back transition. Core confinement time is better than edge (← delayed sawtooth burst in the region).

Edge V_ϕ drops rapidly compared to the edge T_i during back transition.

4. Profile Evolution during ELM cycle

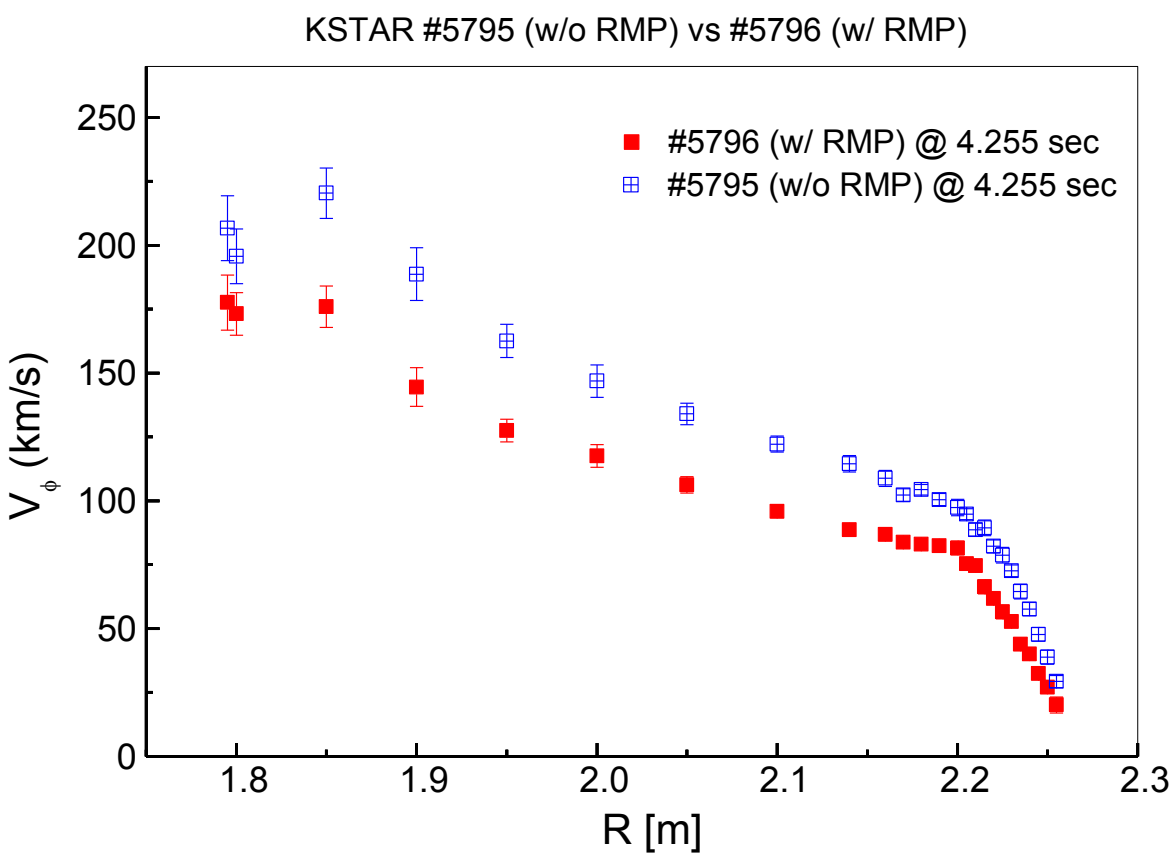
V_ϕ Evolution during ELM Mitigation by RMP





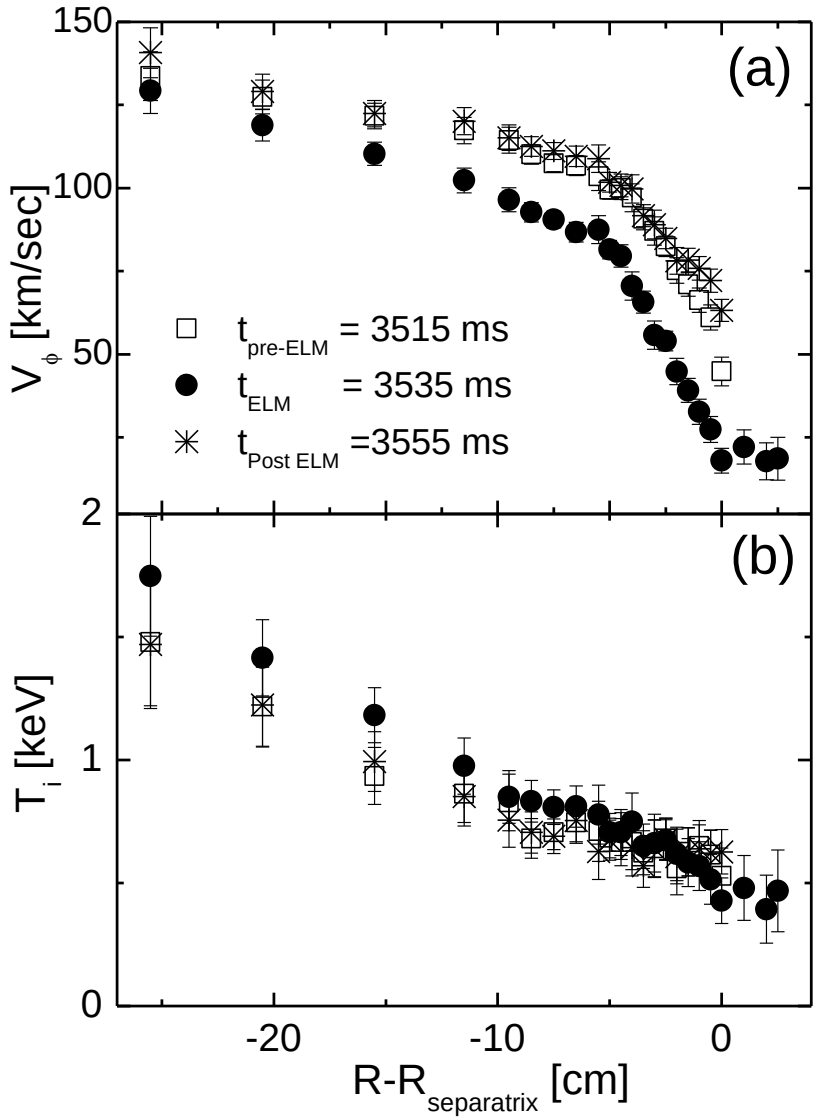
- We obtained an ELM suppressed state by applying n=1 RMP with the coil current Ic=1.8kA/t and 0-phasing configuration. The pedestal top value of V_ϕ drops during ELM suppression. The rotation pedestal width expands during the ELM suppression.
- V_ϕ decreases during ELM suppression but recovers its pre-suppression value once ELMs reappear.

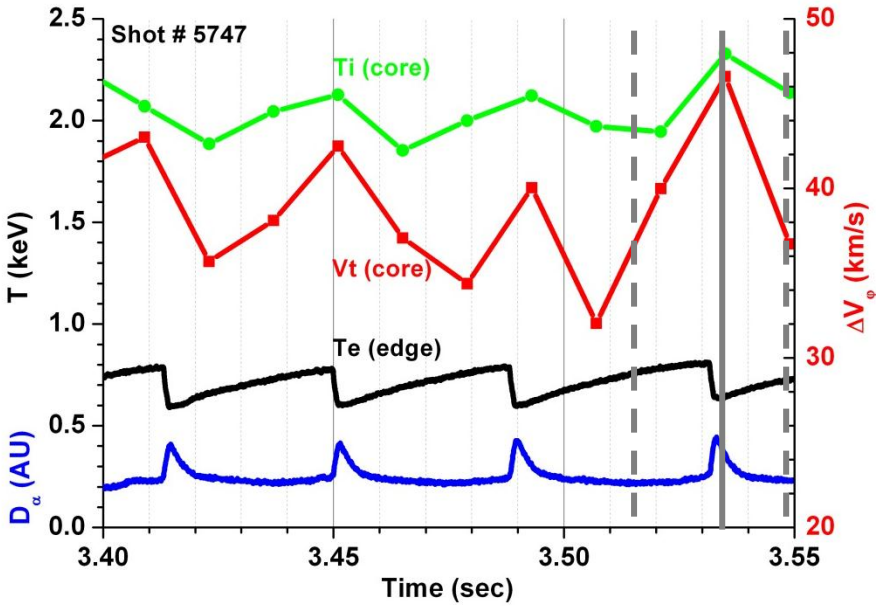
T_i and V_ϕ Profiles with No Mitigation (n=2 RMPs)



- KSTAR RMP system can apply n=1,2 RMPs with various parity.
- For no ELM mitigation, both Ti and V_ϕ decrease with n=2 RMPs.
- There is slight change of toroidal rotation at pedestal top.

Contrast of Rotation Pedestal Changes during ELM

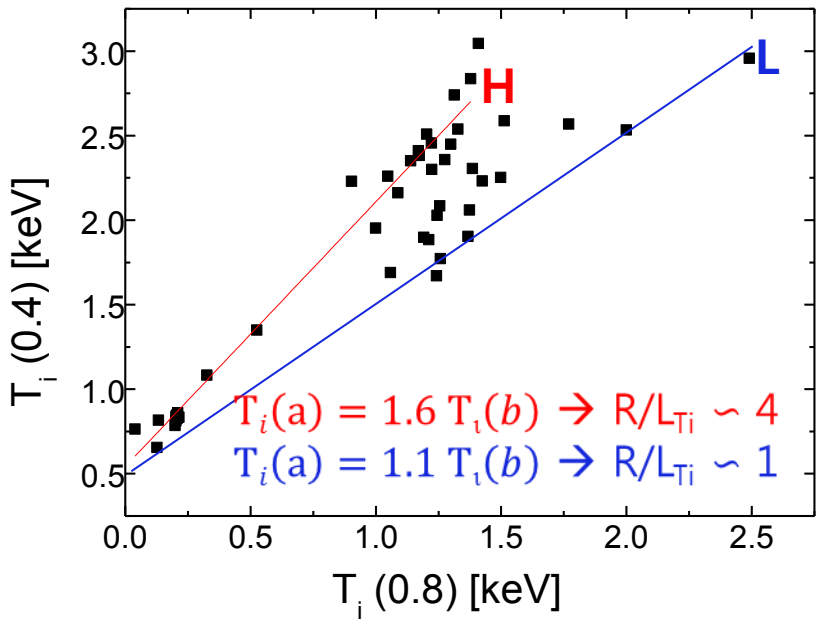


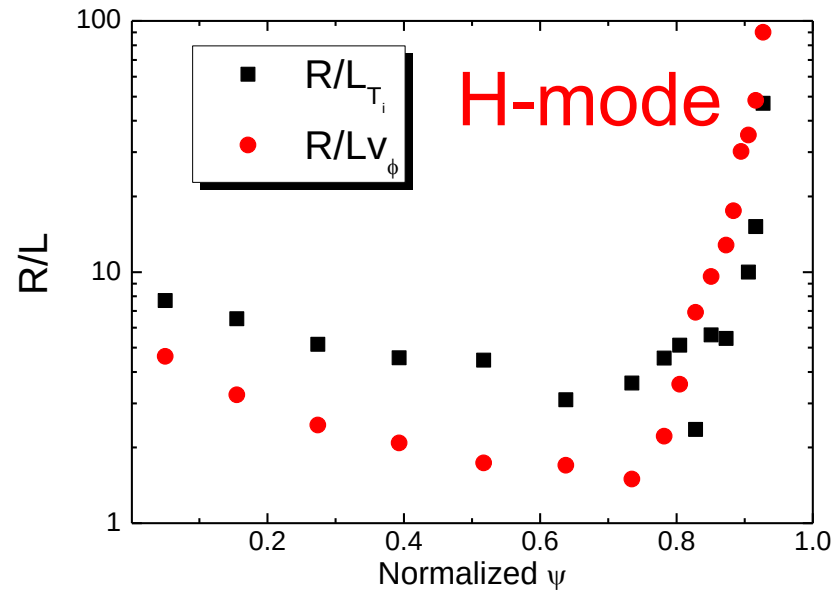


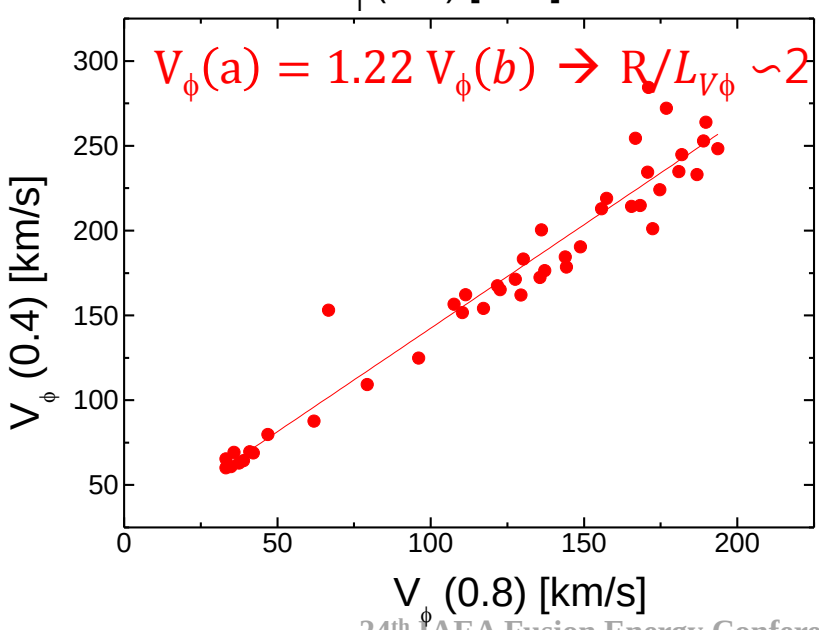
- The top of V_ϕ^{ped} drops during an ELM, as compared to pre-ELM and post-ELM.
- The T_i^{ped} top is slightly smaller during ELM than in pre-ELM and post-ELM.

5. Transport Analysis

Profile Structure During L→H Transition

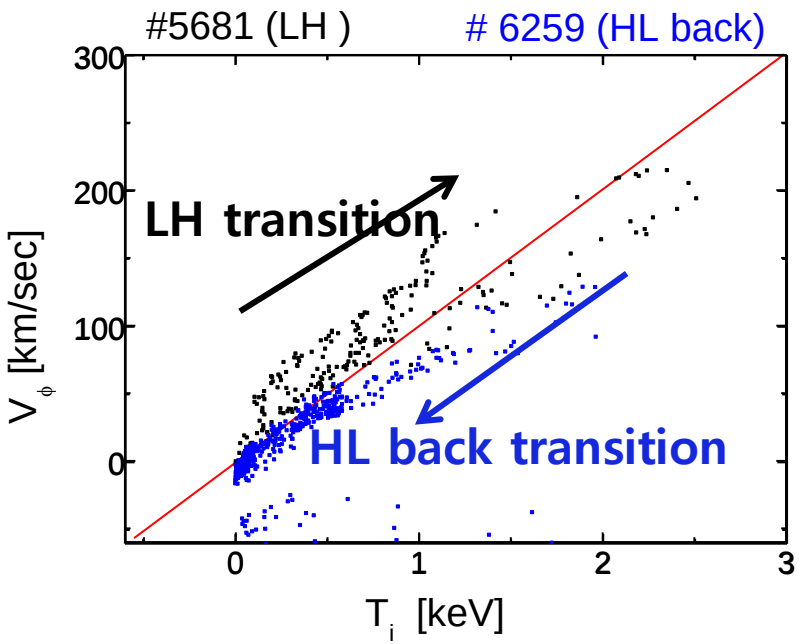


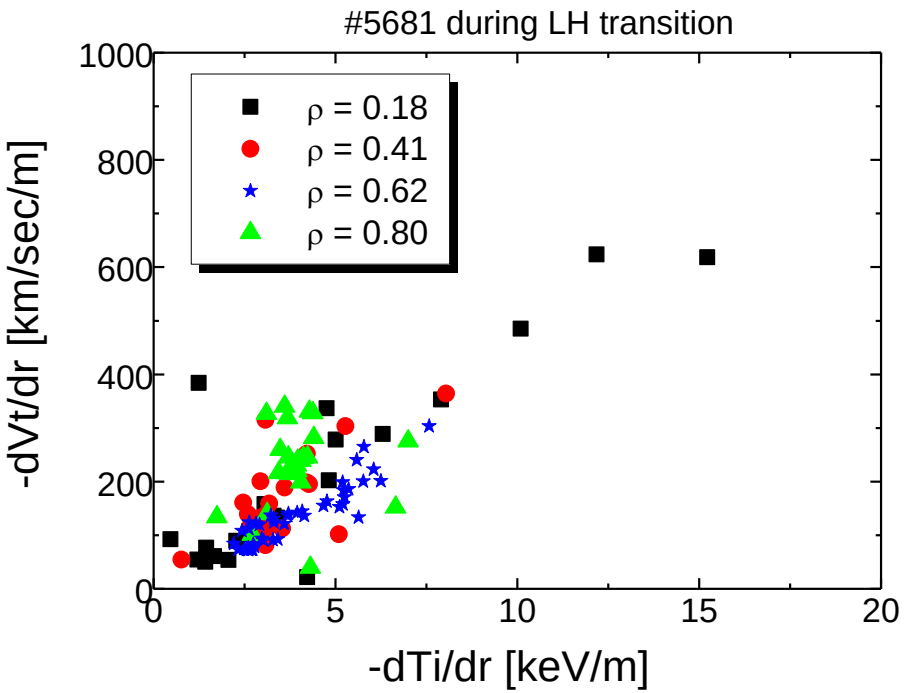




- T_i plot between ρ=0.4 and 0.8 exhibits two slopes during L→H transition.
  - ✓ $R/L_{Ti} \sim 1$ in early time (close to L-mode)
  - ✓ $R/L_{Ti} \sim 4$ in later time (close to H-mode)
- V_ϕ plot between ρ=0.4 and 0.8 exhibits only one slope during L→H transition: $R/L_{V_\phi} \sim 2$

Core Rotation and Ti in L→H and H→L back Transition

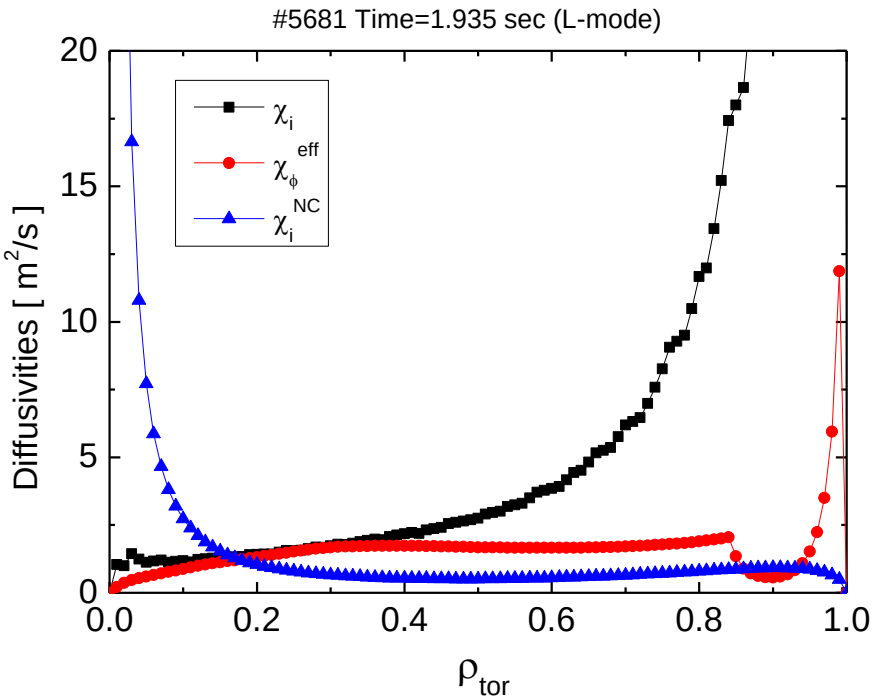


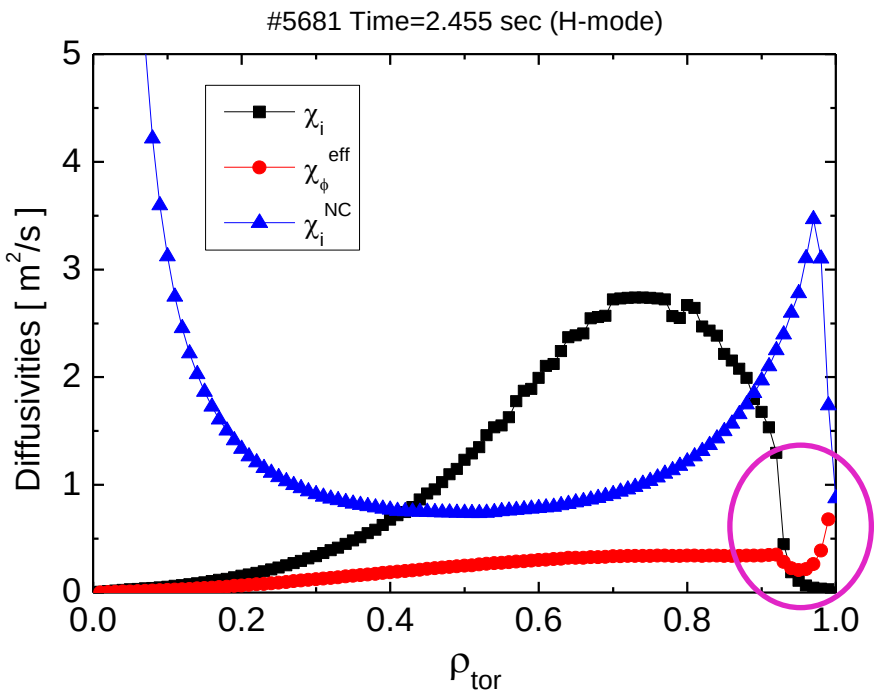


- V_ϕ during L→H transition(black) is higher than during HL back transition(blue) at the same ion temperature.

- Core ▽Vϕ and ▽Ti are also correlated across L→H transition.

Preliminary Transport Analysis





- After transition $\chi_i < \chi_i^{neo} \rightarrow \chi_i < \chi_i^{neo}$ near pedestal
- In core $\chi_\phi^{eff}/\chi_i \sim 1$. Toward the edge, $\chi_\phi^{eff}/\chi_i < 1$

  ➔ evidence of intrinsic torque?
- $\chi_\phi^{eff}/\chi_i \sim 1$ in H-mode pedestal

  ➔ origin of residual momentum transport?
- $H_{eff} \sim 1.43$

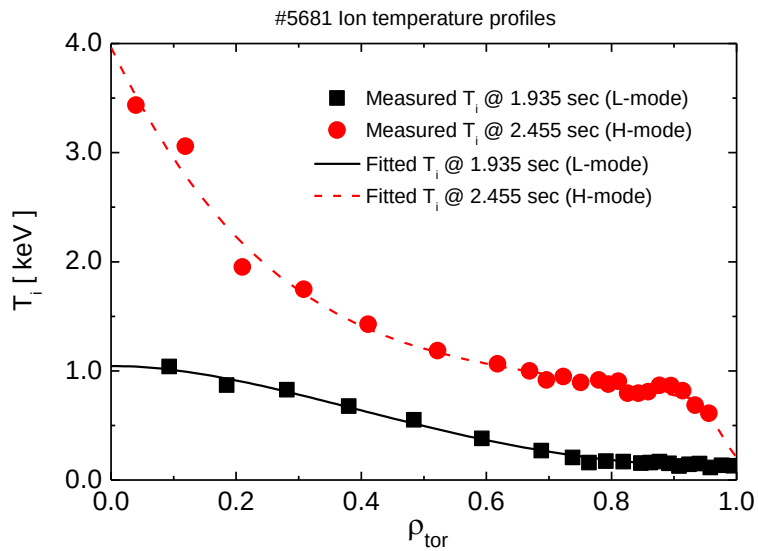
We have assumed

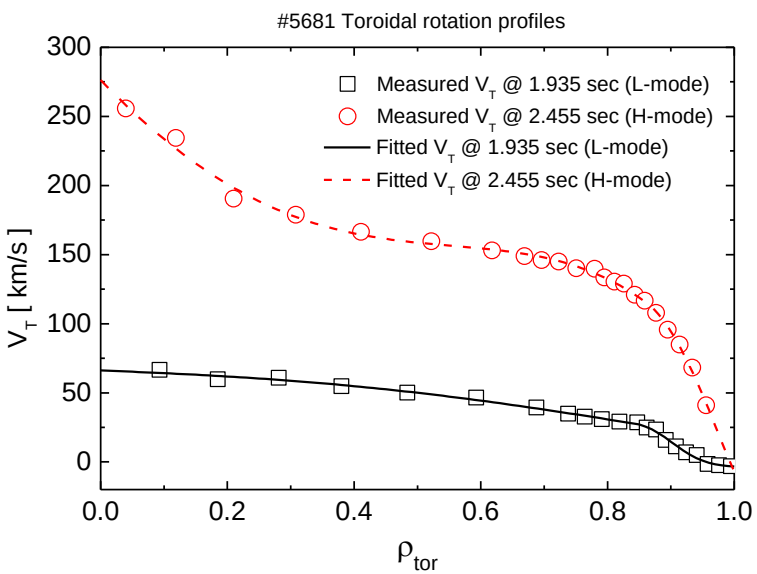
✓ $T_i = T_e$

✓ Synthesized density profile (constrained by line averaged density)

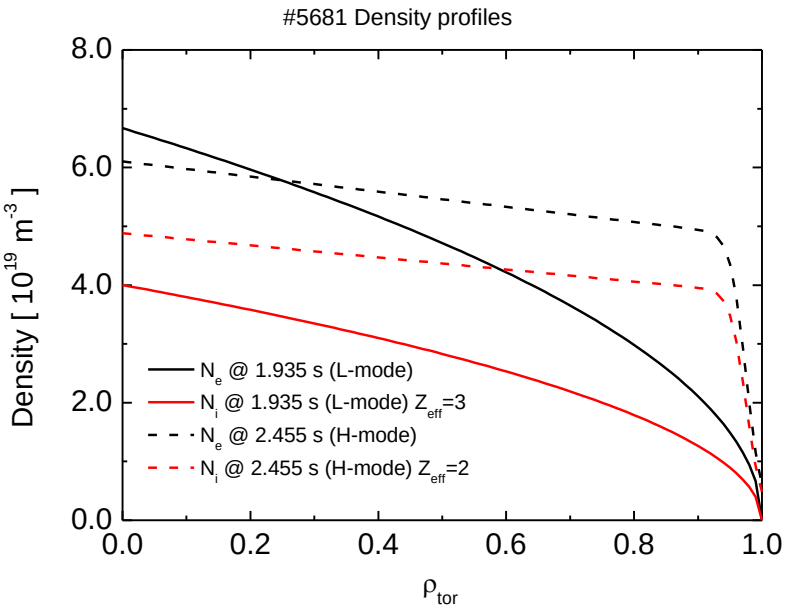
✓ Only diffusive form of heat and momentum flux

Input Profile for Transport Analysis





Input Profiles for transport analysis



Summary

- We studied the structure and evolution of T_i and V_ϕ profiles in co-NBI heated plasmas on KSTAR using CES (Δ R= 5mm, Δ t=10 msec).
  - in H-mode, both T_i and V_ϕ show clear pedestal structure.
  - in L-mode, only V_ϕ shows pedestal structure.
- In H-mode plasmas, we observe $\Delta_\phi^{ped} > \Delta_i^{ped} \rightarrow$ contrary to conventional wisdom $\Delta_i^{ped} > \Delta_\phi^{ped}$.
- During L→H transition and ELM, V_ϕ responds faster and more strongly than Ti does.
- During L→H and H→L transitions,
  - linear proportionality between ∇T_i and ∇V_ϕ appears ➔ likely single transport process controls both channels
  - τ vs. ∇V_ϕ bifurcation curve reconstructed.
  - hysteresis appears for both T_i and V_ϕ
  - hint of weak relative hysteresis between ∇T_i and ∇V_ϕ
- V_ϕ pedestal top value drops and Δ_ϕ^{ped} increases during ELM suppression by RMP. V_ϕ pedestal structure is recovered once ELM reappears.

Future Plan

- Measurement of pedestal density during L→H and H→L transition.
- Fluctuation measurement during the transitions using BES.
- More detailed transport analysis:
  - $\pi = -\chi_\phi(\nabla V_\phi - \pi_{red}/\chi_\phi)$ Fit time evolution to χ_ϕ, π_{red}
  - Intrinsic torque evolution during L→H and H→L transitions.
  - Analyze momentum transport bifurcation and comparison with ion heat transport(i.e. S-curve emphasis).

- Investigation of residual momentum transport in pedestal:
  - Comprehensive analysis of pedestal micro-stability using GS2.
  - Role of strong pedestal ∇V_ϕ ➔ parallel shear flow instability?

- Poloidal CES system for the study of V_θ and E_r during transitions.

Thank You for Your Attention