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

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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 $V_\phi$ (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 $V_\phi$ 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.
Ti 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. Δ_{i ped} > Δ_{φ ped}). However, V_φ pedestal is broader than T_i (i.e. Δ_{φ ped} > Δ_{i ped}) in KSTAR.
2. Profile Evolution through $L \rightarrow H$ Transition
Detailed profiles of $V_\phi$ and $T_i$ have been obtained during the $L\rightarrow H$ transition and during ELMs. Time resolution is 10 msec.

During the $L\rightarrow H$ transition, $V_\phi$ pedestal formation leads $T_i$ pedestal formation, and builds inward from the separatrix.
Evolution of Pedestal Top Through L→H Transition

- $V_\phi$ pedestal formation leads $T_i$ formation i.e. $V_\phi$ 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 $V_\phi$ 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 $V_\phi$ also responds faster and more strongly to the ELM than $T_i$ does.
• $V_\phi(0)$ exhibits “Rice Scaling” trend, though with NBI (?!) → see next
• $V_\phi^{ped}$ (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:

\[
\partial_t \overline{V}_\phi + \frac{\overline{V}_\phi}{\tau_\phi} = T_b + T_{intr}
\]

\[
T_{intr} \cong -\partial_r \langle \bar{V}_r \bar{V}_\phi \rangle_{resid} \cong -\partial_r \left( \frac{\chi_\phi V_{th}}{L_{sym}} \right) \cong \frac{\chi_\phi V_{th}}{L_{ped} L_{sym}}
\]

- Key point:
  - At transition 2 effects enter:
    ① Enhanced confinement → \( \tau_\phi \) increases
    ② Pedestal intrinsic torque enters → \( \tau_{intr} \) rises

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

\[
\tau_\phi^{-1} \bigg|_L \sim \frac{\chi_\phi}{a^2}, \quad \tau_\phi^{-1} \bigg|_H \sim \frac{\chi_\phi}{a^2} F \left( \frac{V'_{E}}{\omega_0} \right)
\]

An Example

\[
F \left( \frac{V'_{E}}{\omega_0} \right) \sim \frac{1}{1 + V'_{E}^2/\omega_0^2}
\]
Stored Energy and Rotation During L→H Transition

\[ \Delta \bar{V}_\phi \cong \tau^L_\phi T_b \left( \frac{V'_E^2}{\omega_0^2} \right) + \tau^L_\phi \left( \frac{V_{thi} \chi^L_\phi}{L_{ped} L_{sym}} \right) \]

N.B. \[ \frac{V_{thi} \chi^L_\phi}{L_{ped} L_{sym}} \sim \frac{V_{thi} Q L_{Ti}}{T_i L^2_{ped}} \]

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 \( \sim 1/L^2_{ped} \)

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

• Common length scale dependence and Q \( \leftrightarrow T_b \) 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 $\nabla T_i$ and $\nabla V_\phi$

- 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 $\nabla V_\phi$ and $\nabla T_i$ 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. $\nabla V_\phi$, $\nabla T_i$ — directly related to the driving fluxes!) is more fundamental than the correlation in the quantities.
• Bifurcation studies reconstruct a torque($\tau$) vs $\nabla V_\phi$ S-curve from CES data for the L→H transition.
• Related $Q_i$ vs $\nabla T_i$ 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 $V_\phi$ and $T_i$ for L→H and H→L back transition.
- Both pedestal $V_\phi$ 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 $V_\phi$ and $T_i$ for H→L back transition both with and without RMP. Pedestal $V_\phi$ 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 $V_\phi$ and $T_i$ show similar correlation both with and without RMP.
- Edge $V_\phi$ and $T_i$ show different trends with and without RMP.
  - With RMP, $V_\phi$ damping enters during H→L back transition.
- With RMP, $V_\phi$ 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 $V_\phi$ have no drop while others decrease after back transition. Core confinement time is better than edge (← delayed sawtooth burst in the region). 

Edge $V_\phi$ drops rapidly compared to the edge $T_i$ during back transition.
4. Profile Evolution during ELM cycle
$V_\phi$ Evolution during ELM Mitigation by RMP

KSTAR # 6304 during ELM mitigation

- Rotation damping rate at time
- Experimental observation is a linear proportionality between $V_{t}$ and $T_i$ pedestal gradient.

KSTAR # 6304 during ELM

- ELMs suppressed
- We obtained an ELM suppressed state by applying $n=1$ RMP with the coil current $I_c=1.8\text{kA/t}$ and 0-phasing configuration. The pedestal top value of $V_\phi$ drops during ELM suppression. The rotation pedestal width expands during the ELM suppression.
- $V_\phi$ decreases during ELM suppression but recovers its pre-suppression value once ELMs reappear.
• KSTAR RMP system can apply n=1,2 RMPs with various parity.
• For no ELM mitigation, both Ti and Vφ 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 $V_{\phi}^{ped}$ 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 $\rho=0.4$ and $0.8$ exhibits two slopes during L→H transition.
  - $R/L_{T_i} \sim 1$ in early time (close to L-mode)
  - $R/L_{T_i} \sim 4$ in later time (close to H-mode)

- $V_\phi$ plot between $\rho=0.4$ and $0.8$ exhibits only one slope during L→H transition: $R/L_{V_\phi} \sim 2$

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\[ T_i(a) = 1.6 \, T_i(b) \Rightarrow R/L_{T_i} \sim 4 \]
\[ T_i(a) = 1.1 \, T_i(b) \Rightarrow R/L_{T_i} \sim 1 \]

\[ V_\phi(a) = 1.22 \, V_\phi(b) \Rightarrow R/L_{V_\phi} \sim 2 \]
Core Rotation and Ti in L→H and H→L back Transition

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

- Core $\nabla V_\phi$ and $\nabla Ti$ are also correlated across L→H transition.
We have assumed

- $T_i = T_e$
- Synthesized density profile (constrained by line averaged density)
- Only diffusive form of heat and momentum flux

Preliminary Transport Analysis

- After transition $\chi_i < \chi_{i}^{\text{neo}} \rightarrow \chi_i < \chi_{i}^{\text{neo}}$ near pedestal
- In core $\chi_{\phi}^{\text{eff}} / \chi_i \sim 1$. Toward the edge, $\chi_{\phi}^{\text{eff}} / \chi_i < 1$
  - evidence of intrinsic torque?
- $\chi_{\phi}^{\text{eff}} / \chi_i \sim 1$ in H-mode pedestal
  - origin of residual momentum transport?
- $H_{\text{eff}} \sim 1.43$
Input Profile for Transport Analysis

#5681 Ion temperature profiles

- Measured $T_i$ @ 1.935 sec (L-mode)
- Measured $T_i$ @ 2.455 sec (H-mode)
- Fitted $T_i$ @ 1.935 sec (L-mode)
- Fitted $T_i$ @ 2.455 sec (H-mode)

#5681 Toroidal rotation profiles

- Measured $V_T$ @ 1.935 sec (L-mode)
- Measured $V_T$ @ 2.455 sec (H-mode)
- Fitted $V_T$ @ 1.935 sec (L-mode)
- Fitted $V_T$ @ 2.455 sec (H-mode)

#5681 Density profiles

- $N_e$ @ 1.935 s (L-mode)
- $N_e$ @ 1.935 s (L-mode) $Z_{\text{eff}}=3$
- $N_e$ @ 2.455 s (H-mode)
- $N_e$ @ 2.455 s (H-mode) $Z_{\text{eff}}=2$

Input Profiles for transport analysis
Summary

• We studied the structure and evolution of $T_i$ and $V_\phi$ profiles in co-NBI heated plasmas on KSTAR using CES ($\Delta R=5\text{mm}$, $\Delta t=10\text{msec}$).
  – in H-mode, both $T_i$ and $V_\phi$ show clear pedestal structure.
  – in L-mode, only $V_\phi$ 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, $V_\phi$ responds faster and more strongly than $T_i$ does.

• During L→H and H→L transitions,
  – linear proportionality between $\nabla T_i$ and $\nabla V_\phi$ appears $\Rightarrow$ likely single transport process controls both channels
  – $\tau$ vs. $\nabla V_\phi$ bifurcation curve reconstructed.
  – hysteresis appears for both $T_i$ and $V_\phi$
  – hint of weak relative hysteresis between $\nabla T_i$ and $\nabla V_\phi$

• $V_\phi$ pedestal top value drops and $\Delta_\phi^{ped}$ increases during ELM suppression by RMP. $V_\phi$ 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 $\chi_\phi$, $\pi_{red}$
  - 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:
  - Role of strong pedestal $\nabla V_\phi \Rightarrow$ parallel shear flow instability?

- Poloidal CES system for the study of $V_\theta$ and $E_r$ during transitions.
Thank You for Your Attention