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Optimizing edge confinement and stability via adaptive ELM control using RMPs

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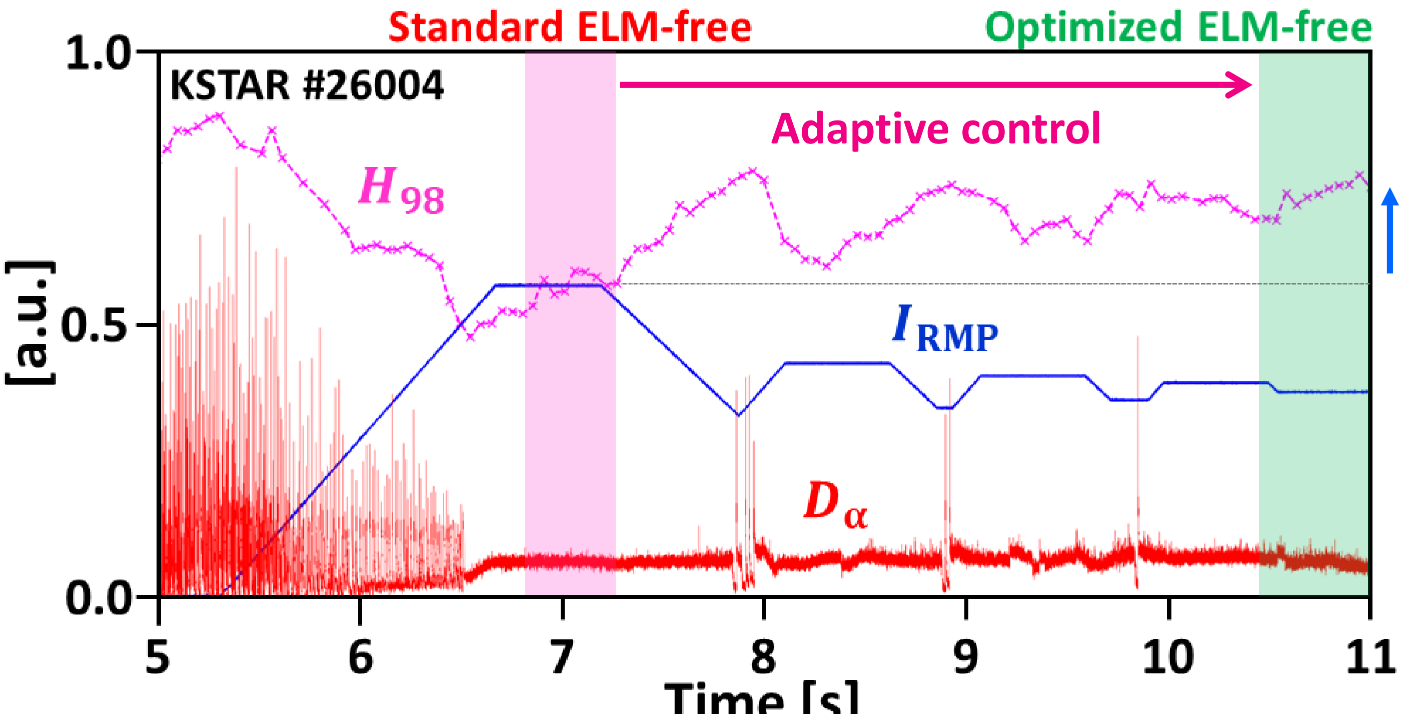
RMPs are promising method to stabilize the ELM crash, however there is remaining challenges for its application on ITER or future devices

- **Challenges in ELM control via RMP**
  - ✓ Less sustainability by small window.
  - ✓ Loss of plasma confinement.

- **Real-time pedestal optimization with ELM control**



[Optimized ELM-free via adaptive control]

✓ RT adaptive ELM control.
- Keep ELM-free.
- Recovers confinement (>60%).

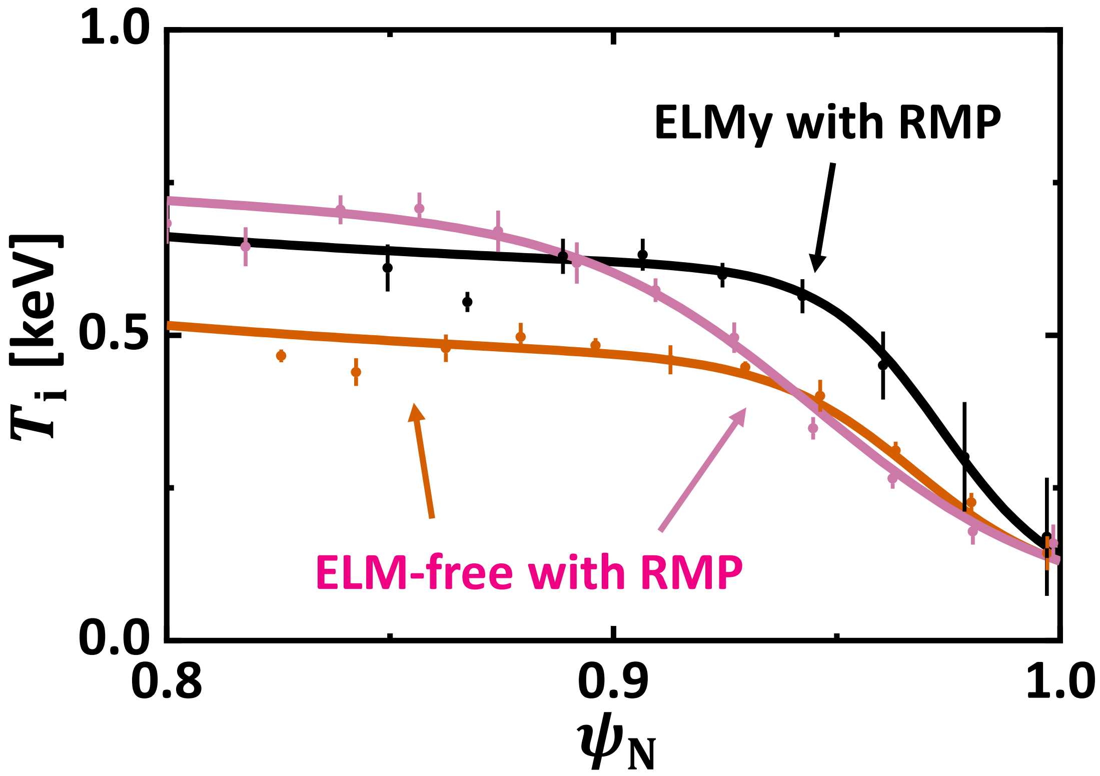
➡ **Optimized ELM-free state**
One of solutions for existing challenges.

Ion pedestal widening is key of effective pedestal optimization using adaptive ELM control

- **Key of successful pedestal optimization**
  - ✓ **Ion pedestal widening**
    - **In ELM-suppressed state.**
  - ✓ **Contribution to adaptive control**
    - **Stronger confinement recovery (>50%)**
    - **Faster control convergence.**

➡ **This talk introduces…**

- Principle of adaptive control.
- Role of widened ion-pedestal.
- Origin of pedestal widening.



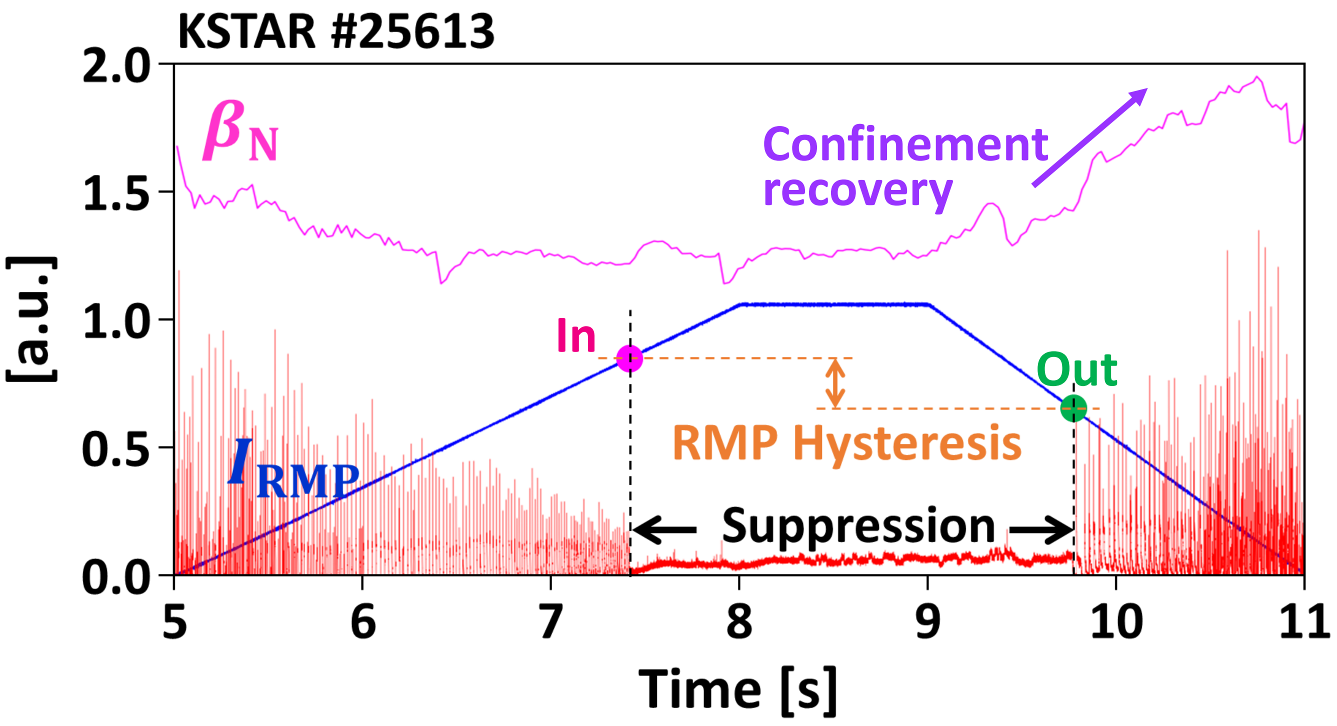
[Ion pedestal widening in ELM-free state]

Contents

Adaptive ELM control is effective approach to achieve and sustain steady-state ELM-free high confinement plasma

- **RMP-hysteresis on confinement recovery**
  - ✓ Hysteresis in RMP-ELM suppression
    - $I_{\mathrm{RMP,IN}} \geq I_{\mathrm{RMP,OUT}}$.
    - Enables confinement recovery.
      → By lowering I_{RMP} upto $I_{\mathrm{RMP,OUT}}$.

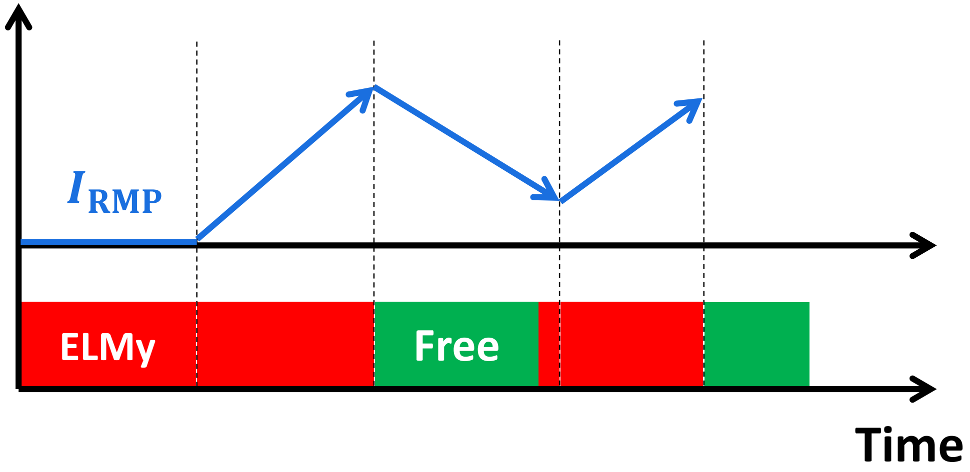
- **Real-time (RT) RMP control**
  - ✓ I_{RMP} for edge optimization
    - Sufficient to sustain suppression.
    - Minimal to maximize confinement.
      → By real-time adaptive control.



[RMP hysteresis at KSTAR, #25613]

Adaptive ELM control relies on simple concept, but its successful utilization is not trivial because of system discontinuity ($I_{\mathrm{RMP,IN}} \neq I_{\mathrm{RMP,OUT}}$)

- **Adaptive ELM control using RMPs**
  - ✓ I_{RMP} control with ELM detection [R. Shousha, APS-DPP 21]
    - ELMy → I_{RMP} ↑.
    - ELM-free → I_{RMP} ↓.

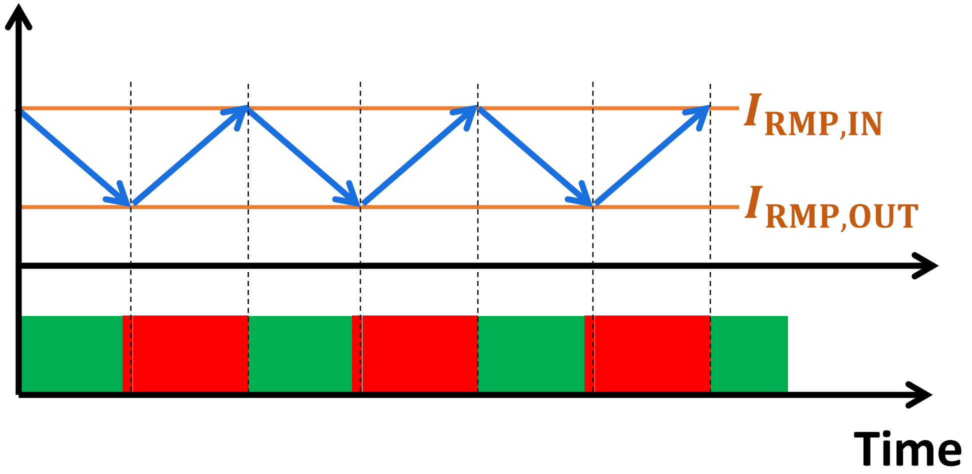


[Schematic of adaptive ELM control]

- **Convergence problem with bifurcation**
  - ✓ Discontinuous transition of system.
    - $I_{\mathrm{RMP,IN}} \neq I_{\mathrm{RMP,OUT}}$.
    - Oscillatory behavior in control.
    - Poor convergence.

    → Obstacles for fast convergence.

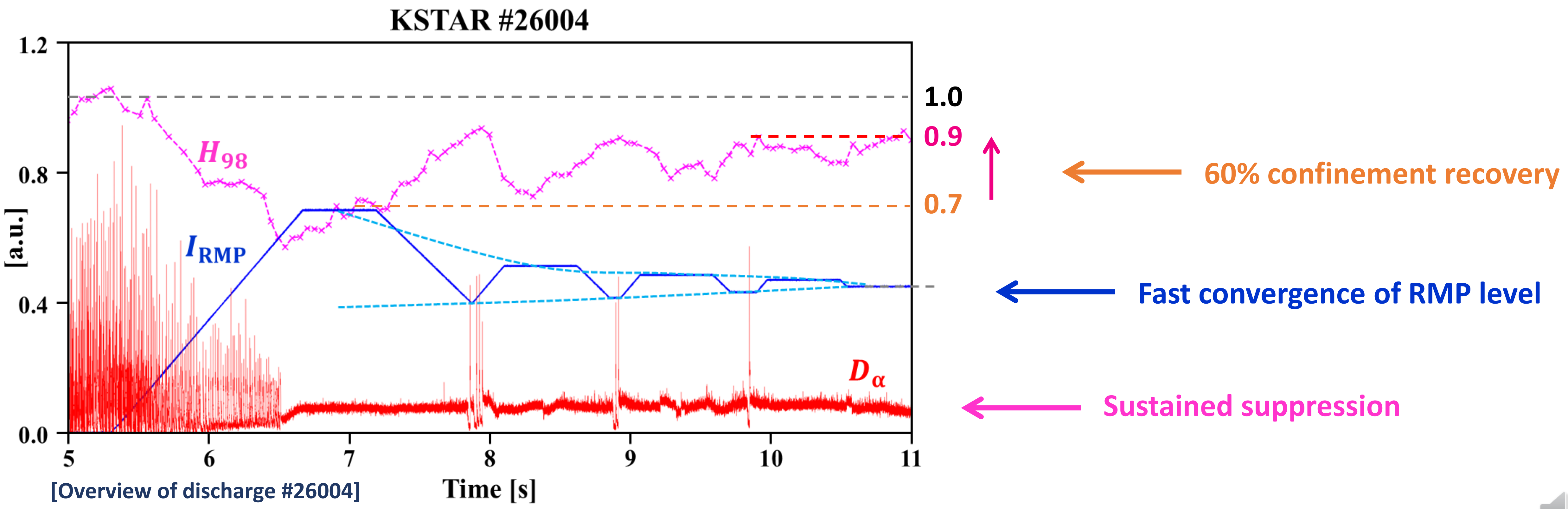
However, adaptive control is successful by resolving this issue



[Schematic of adaptive ELM control]

Adaptive ELM control successfully optimizes the RMP level, maximizing the confinement recovery while maintaining ELM suppression

- **ELM suppression in KSTAR with adaptive ELM control**
  - ✓ Recovered initial H_{98} loss up to 60% ($G = H_{98}\beta_N/q_{95}^2$, 45%).
  - ✓ Fast convergence within 4 iterations (~5 s).
  - ✓ Well sustained ELM suppression.



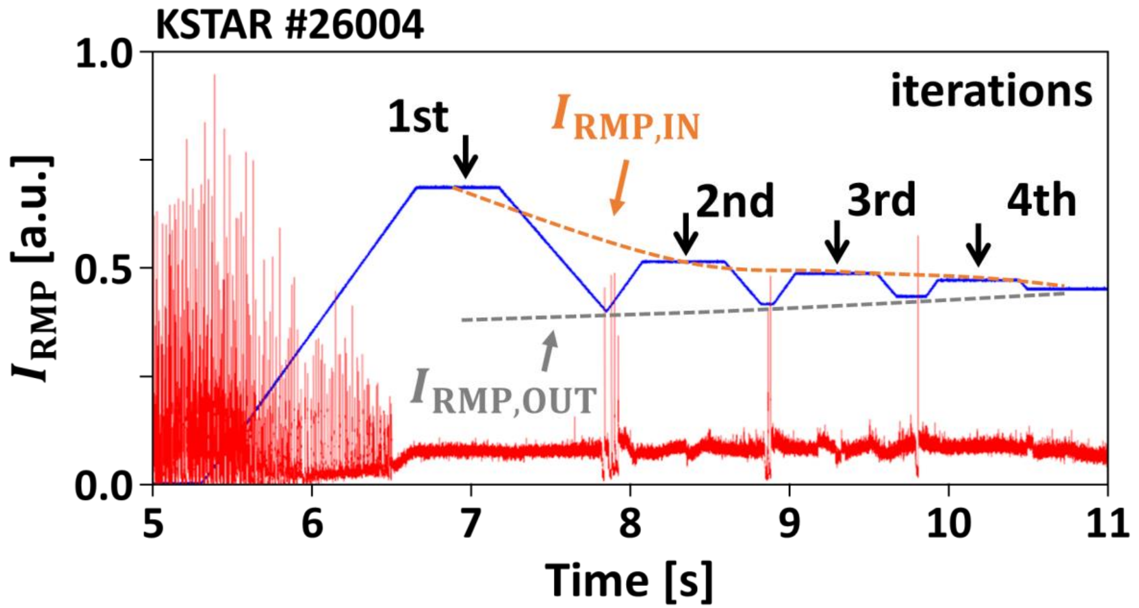
[Overview of discharge #26004]

Successful control convergence is due to weakened discontinuity of RMP-hysteresis: Easier re-access to the ELM suppression

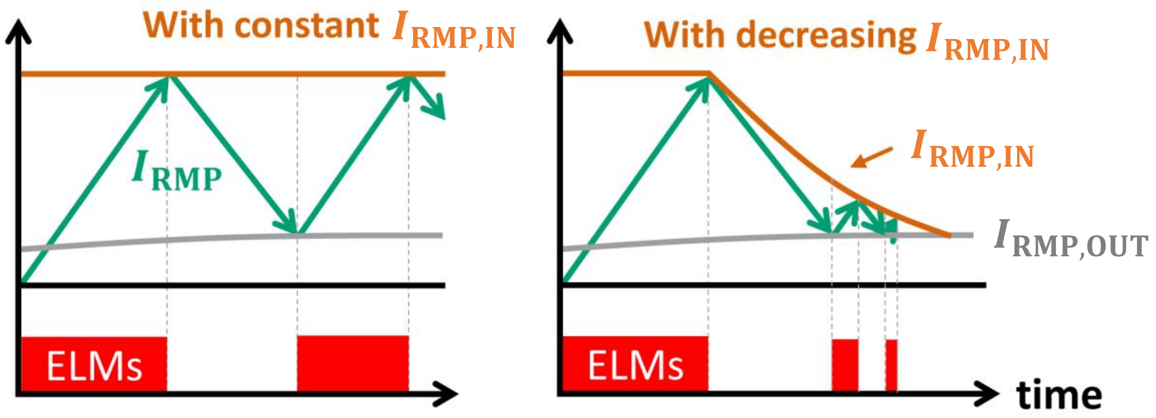
- **Changes in $I_{\mathrm{RMP,IN/OUT}}$ during control**
  - ✓ $I_{\mathrm{RMP,IN}}$: $4.6 \rightarrow 3.5$ kA **(dominant).**
  - ✓ $I_{\mathrm{RMP,OUT}}$: $3.3 \rightarrow 3.5$ kA.
  - ✓ Discontinuity $|I_{\mathrm{RMP,IN}} - I_{\mathrm{RMP,OUT}}| \downarrow$.

- **Effect of decreasing $I_{\mathrm{RMP,IN}}$**
  - ✓ Easier re-suppression.
  - ✓ Fast convergence and short ELMy period.

➡ **Focusing on profile dynamics in 1st iteration.**



[Overview of discharge #26004]

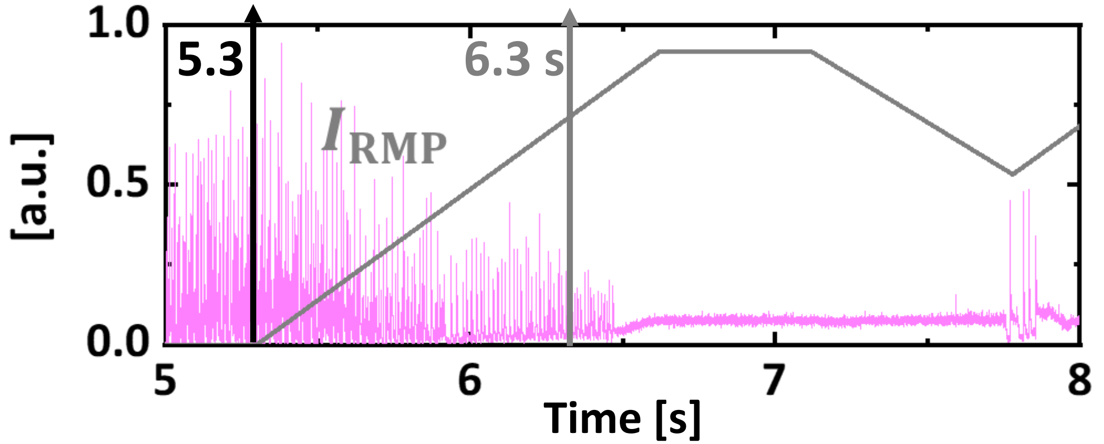


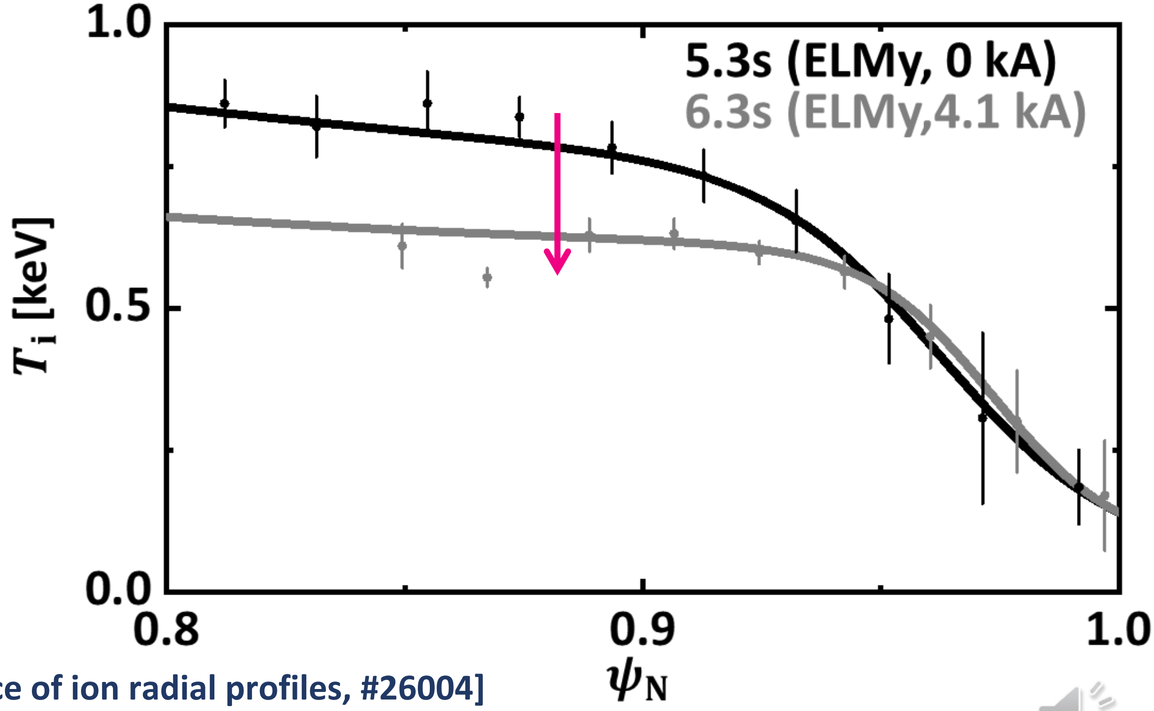
[Effect of decreasing $I_{\mathrm{RMP,IN}}$ on control convergence]

Contents

During ELM suppression periods, ion pedestal shows wider structure than ELMy phase.

- **Widening of ion pedestal**
  - ✓ Ion pedestal trace.
    - 5.3 → 6.3 → : ELMy, I_{RMP} ↑.
      - Entering ELM-free with decreasing height.

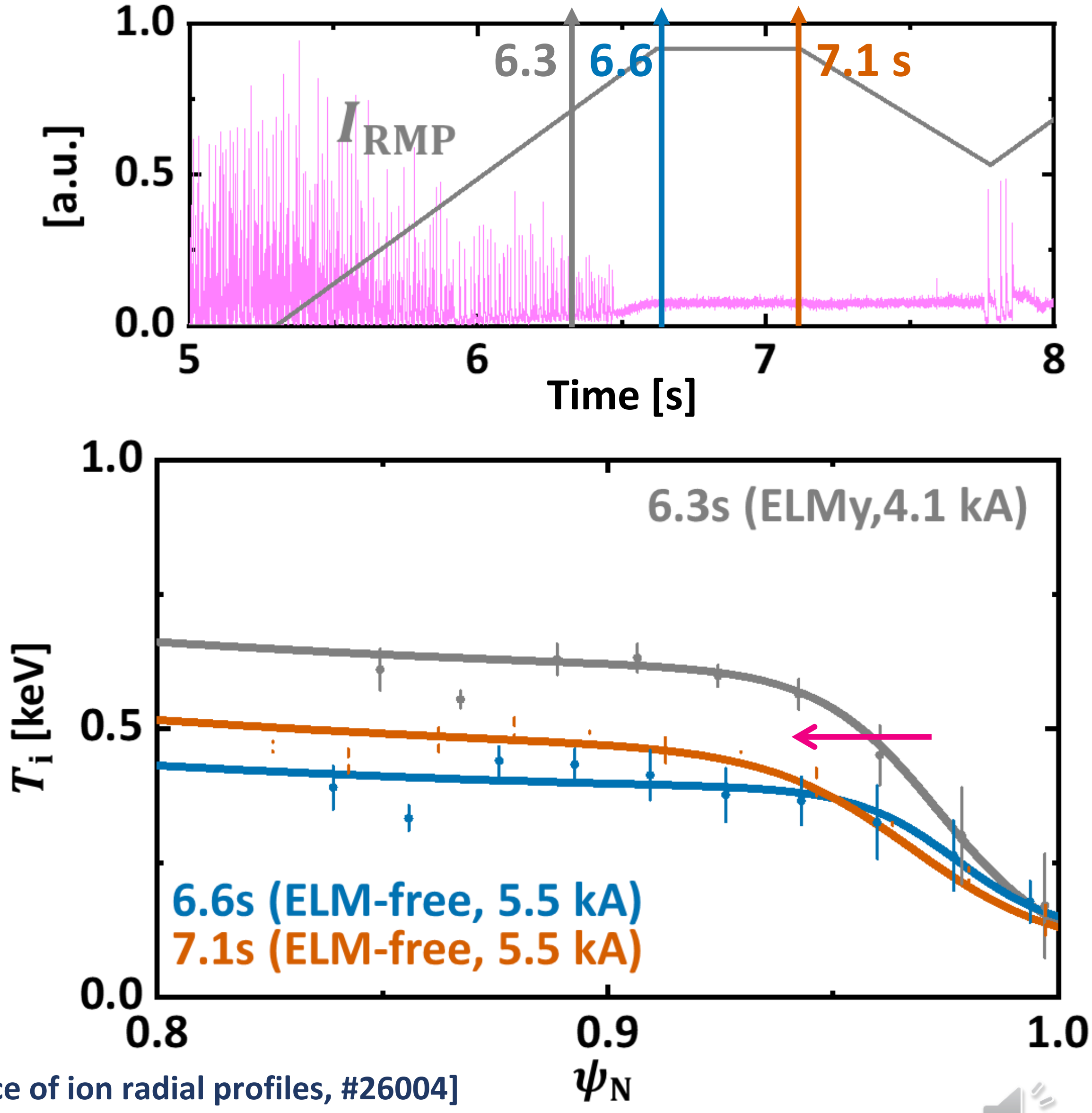




[Time trace of ion radial profiles, #26004]

During ELM suppression periods, ion pedestal shows wider structure than ELMy phase.

- **Widening of ion pedestal**
  - ✓ **<u>Ion pedestal</u> trace.**
    - **5.3 → 6.3 → : ELMy, I_{RMP} ↑.**
      - Entering ELM-free with decreasing height.
    - **→ 6.6 → 7.1s : ELM-free**
      - Saturation with increasing width.
      (Decreased gradient)

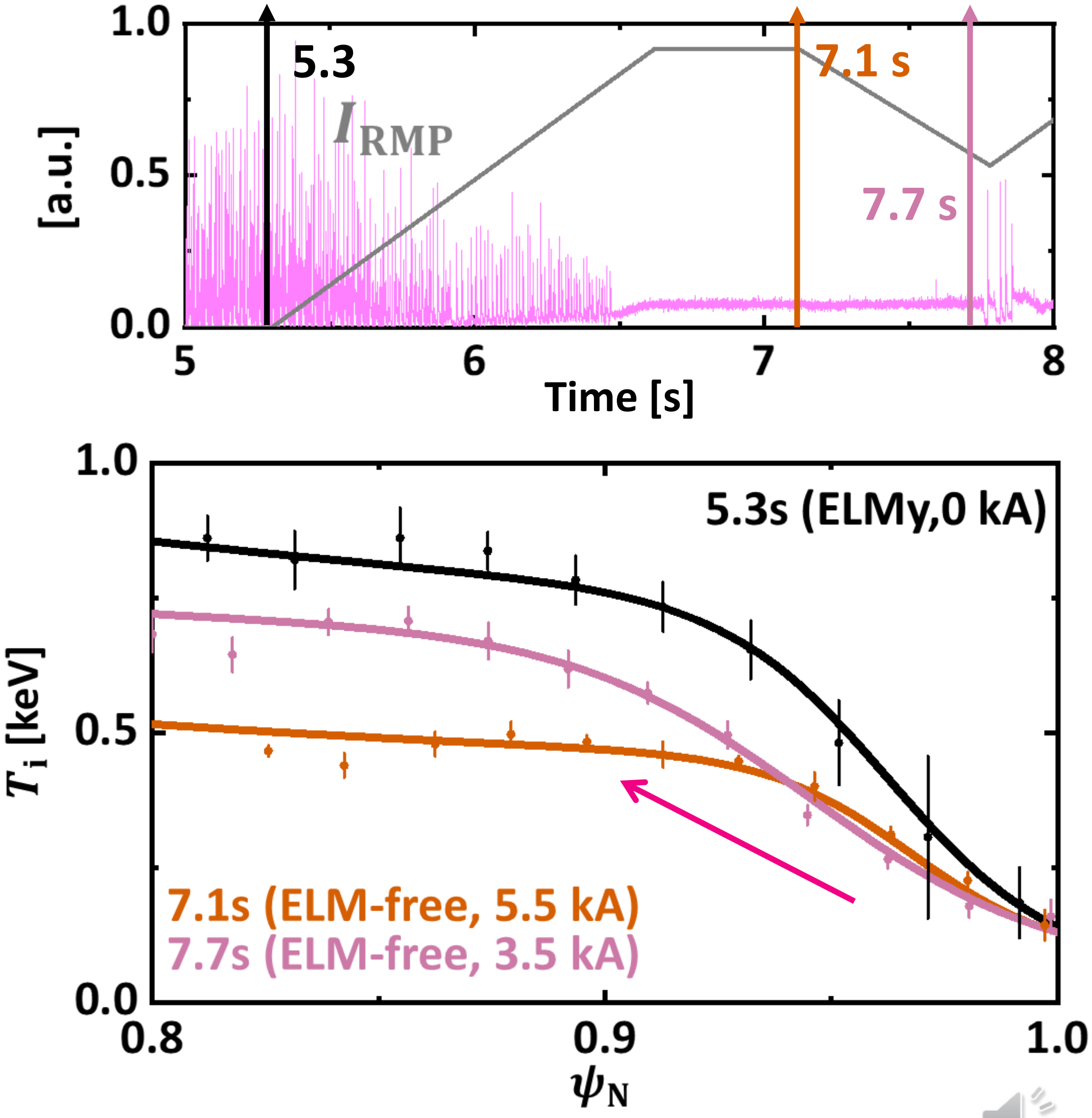


[Time trace of ion radial profiles, #26004]

During ELM suppression periods, ion pedestal shows wider structure than ELMy phase.

- **Widening of ion pedestal**
  - ✓ **Ion pedestal trace.**
    - **5.3 → 6.3 → : ELMy, I_{RMP} ↑.**
      - Entering ELM-free with decreasing height.
    - **→ 6.6 → 7.1s : ELM-free**
      - Saturation with increasing width.
      (Decreased gradient)
    - **→ 7.1s → 7.7 s: ELM-free, I_{RMP} ↓.**
      - Increasing pedestal height/width.
      (Same gradient)

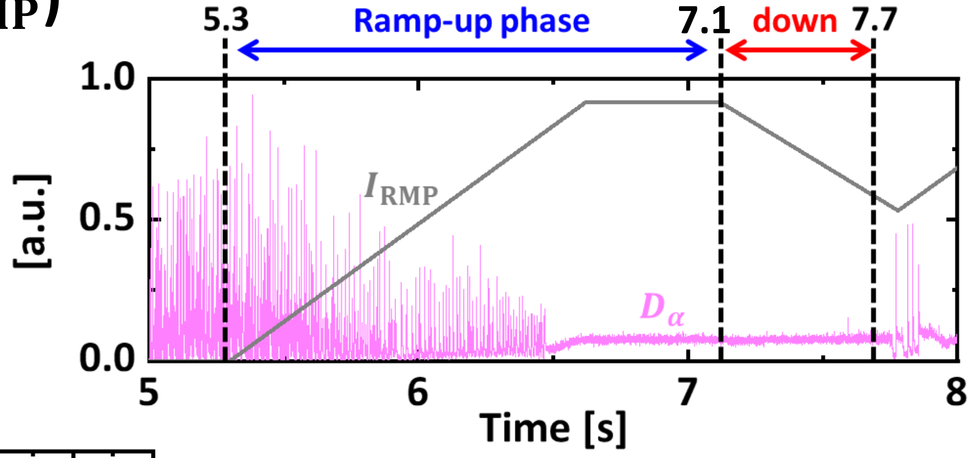
➡ **Wider Ion pedestal during ELM-free state.**

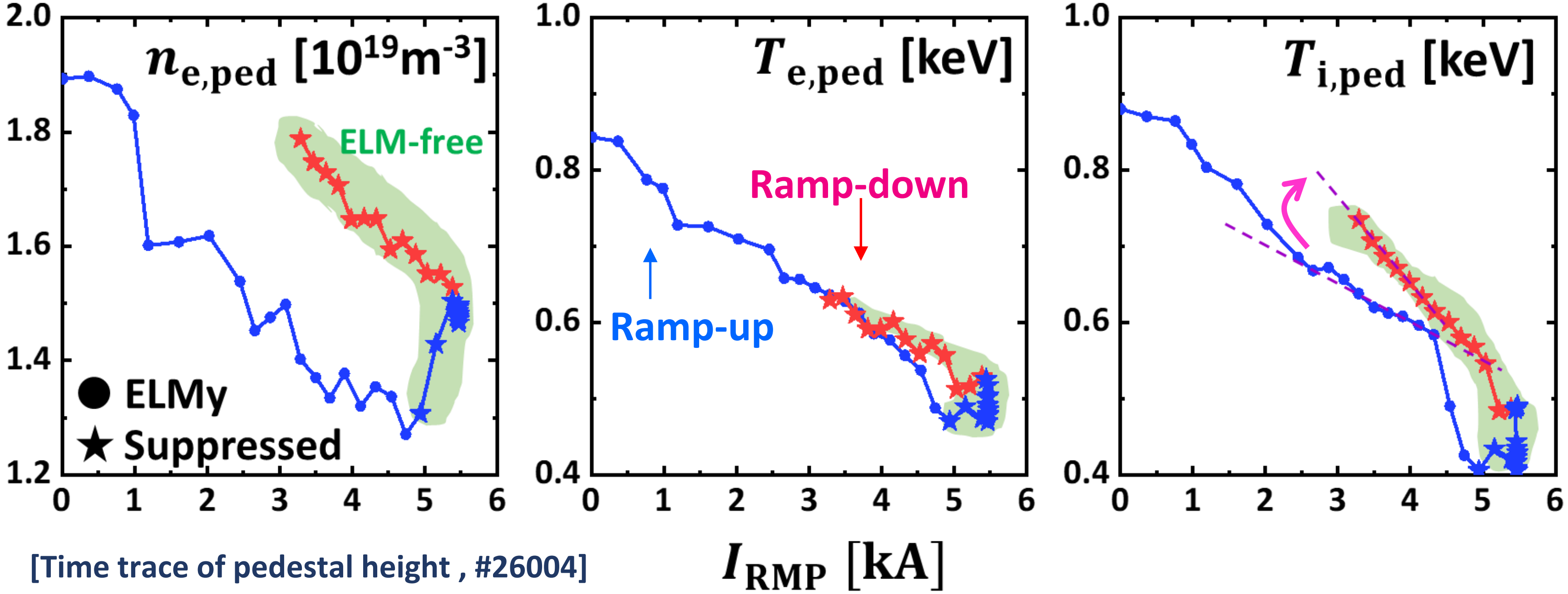


During ramp-down (ELM-free) periods, ion pedestal height shows larger variation to RMP strength than ramp-up (ELMy) phase.

✓ Variation of pedestal height to RMP ($h' = -\partial h / \partial I_{\mathrm{RMP}}$)

Channel (h')	Ramp-up	Ramp-down	Comparison
$n_{\mathrm{e,ped}}$	$\sim 10^{15}/\mathrm{m^3A}$	$\sim 10^{15}/\mathrm{m^3A}$	Similar
$T_{\mathrm{e,ped}}$	$0.06\ \mathrm{eV/A}$	$0.06\ \mathrm{eV/A}$	Similar
$T_{\mathrm{i,ped}}$	$0.06\ \mathrm{eV/A}$	$0.09\ \mathrm{eV/A}$	50% ↑





[Time trace of pedestal height , #26004]

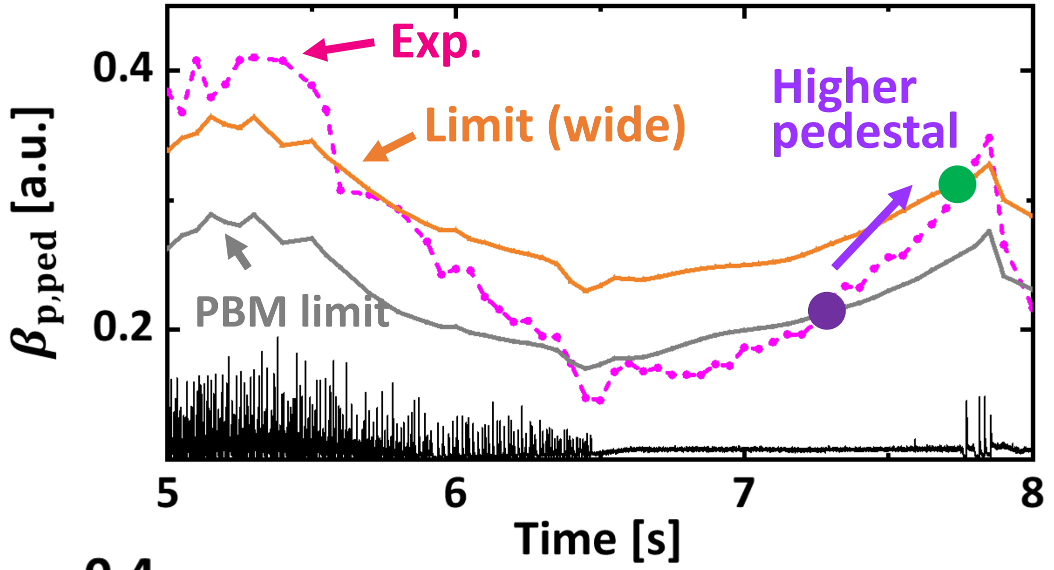
➡ Boosted $T'_{\mathrm{i,ped}}$ during ELM-free state.

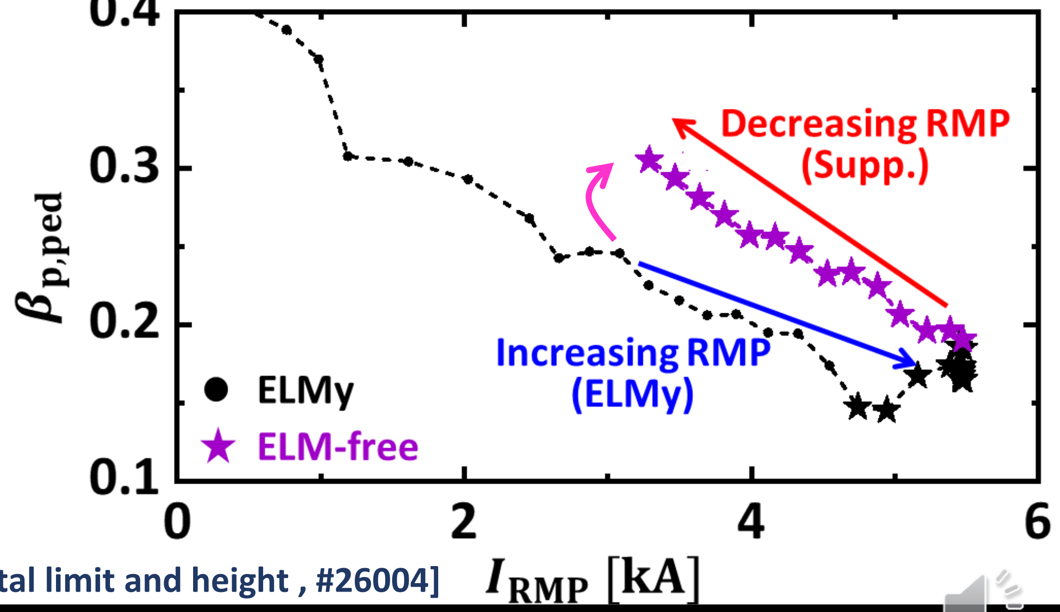
- May be explained by <u>wider ion pedestal</u> [Q. Hu PRL 2020].

Changed ion pedestal behavior in suppression periods lead plasma to the new state during RMP ramp down, affecting pedestal recovery

- **Pedestal recovery during ramp-down**
  - ✓ Increased limit (Pedestal height: $\beta_{\mathrm{p,ped}}$)
    - $\beta_{\mathrm{p,ped}}$ < 70 % PBM limit: ELM free.
    - Wider ion pedestal → Enhanced limit [T. Osborne 09].
    - Higher pedestal with ELM-free.
  - ✓ Faster recovery with $I_{\mathrm{RMP}} \downarrow$
    - Larger $T'_{\mathrm{i,ped}}$ and $\beta'_{\mathrm{p,ped}}$ in ELM-free.
    - Higher pedestal than ELMy for "same" RMP.

➡ **Enhanced pedestal recovery during ELM-free state by wider pedestal.**





[Trace of pedestal limit and height , #26004]

Contents

- **Adaptive ELM control using RMPs** → Successful control convergence due to decreasing $I_{\mathrm{RMP,IN}}$.
- **Widened ion pedestal and increased pedestal response** → Enhanced pedestal recovery.
- **Enhanced confinement recovery and field amplification**
- **Origin of widened ion pedestal**
- **Conclusion**

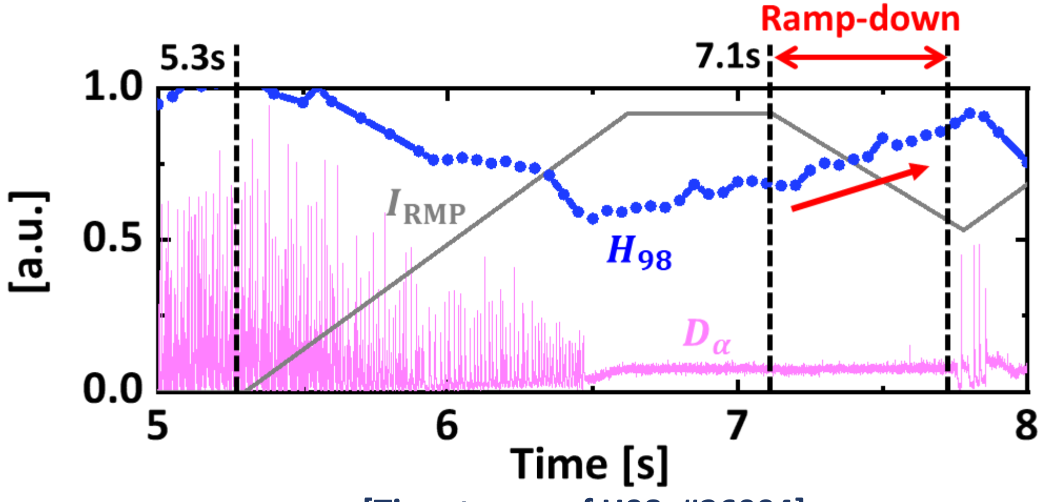
Enhanced pedestal recovery results in net confinement recovery more than just returning to previous ELMy state by lowering RMP

- **Confinement recovery by RMP ramp-down**
  - ✓ Confinement (H_{98}) recovery by pedestal ↑
    - Enhanced ion recovery as main contributor.

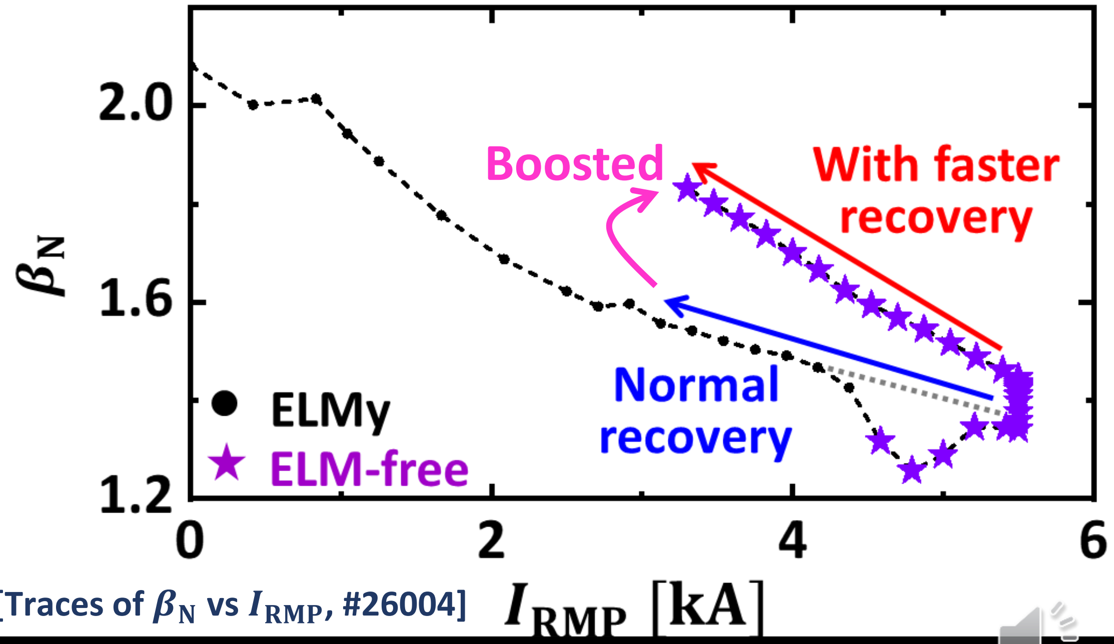
$n_{e,ped}$	$T_{e,ped}$	$T_{i,ped}$
20%	13%	67%

  - ✓ Benefit from enhanced pedestal recovery
    - Improved β_N path in ELM-free state.
    - Higher confinement by smaller I_{RMP} ↓.
      - Higher: Increased $\beta_{p,ped}$ limit
      - Smaller: Faster pedestal recovery

➡ Boosted confinement recovery (>50%).



[Time traces of H98, #26004]

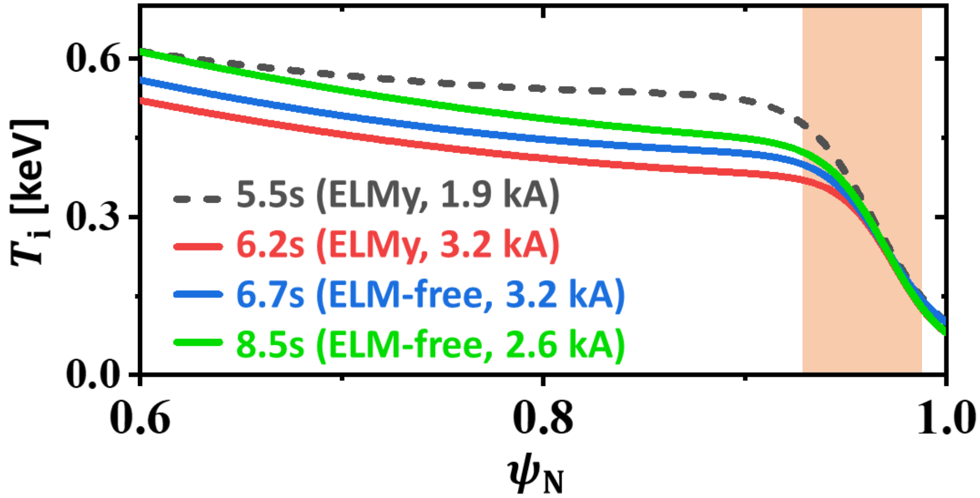


[Traces of β_N vs I_{RMP}, #26004]

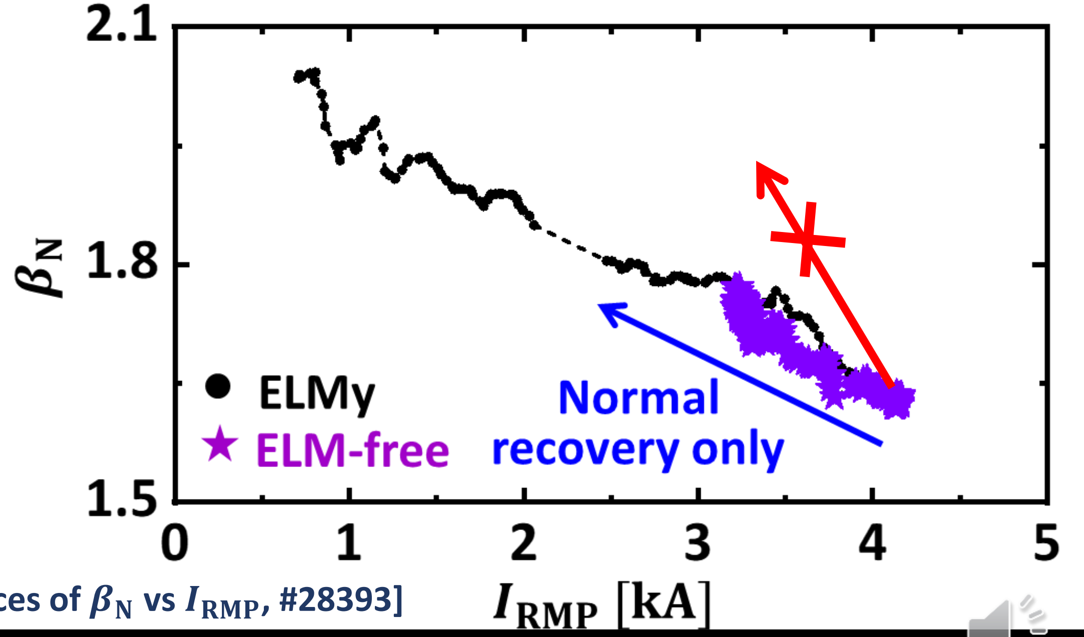
Shot comparison clearly shows that "boosted" confinement recovery is outcome of widened ion pedestal

- **Recovery without pedestal broadening**
  - ✓ Without wider ion-pedestal
    - If no ion-pedestal widening
      → No favorable state during ELM-free.
  - ✓ Reduced confinement recovery
    - No boosted or bonus recovery.

➡ Boosted recovery by widened ion pedestal.



[Time traces of ion pedestal, #28393]

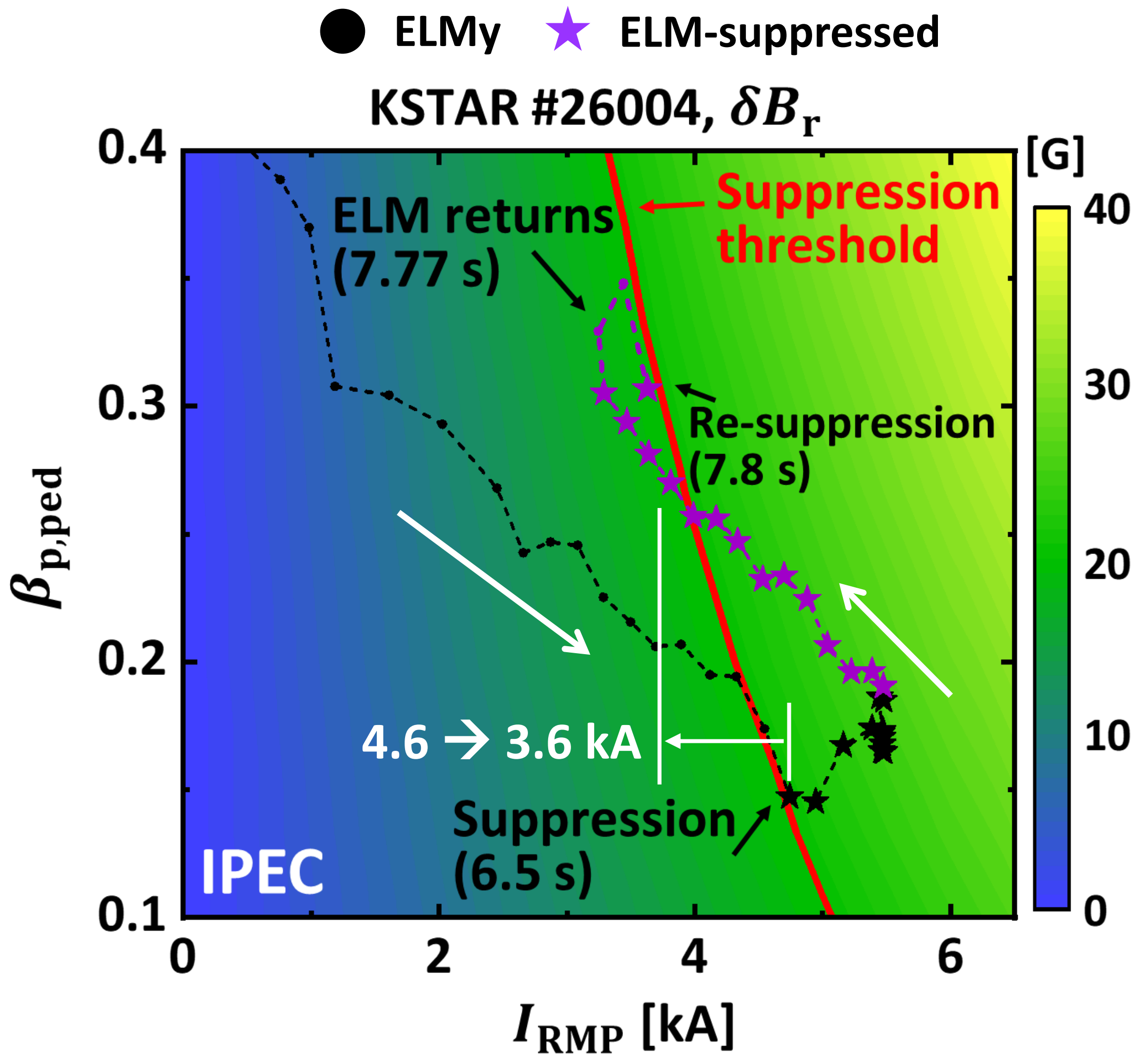


[Traces of β_N vs I_{RMP}, #28393]

Enhanced pedestal recovery amplifies the RMP response, resulting in easier ELM suppression re-entrance with smaller RMP current

- **Decreased $I_{\mathrm{RMP,IN}}$ for ELM suppression**
  - ✓ Suppression entry at field threshold ($\delta B_{\mathrm{r,th}}$)
    - Perturbed field (δB_{r}) by I_{RMP}.
    - Suppression for $\delta B_{\mathrm{r}} \geq \delta B_{\mathrm{r,th}}$ [J.-K.Park 18].
    - $\delta B_{\mathrm{r,th}} \approx 20$ G in experiment → Red line.
  - ✓ Amplified δB_{r} by $\beta_{\mathrm{p,ped}}$
    - Same δB_{r} with smaller I_{RMP}.
    - Larger $\beta_{\mathrm{p,ped}}$ at re-suppression.
    - $I_{\mathrm{RMP,IN}}$: 4.6 → 3.6 kA.

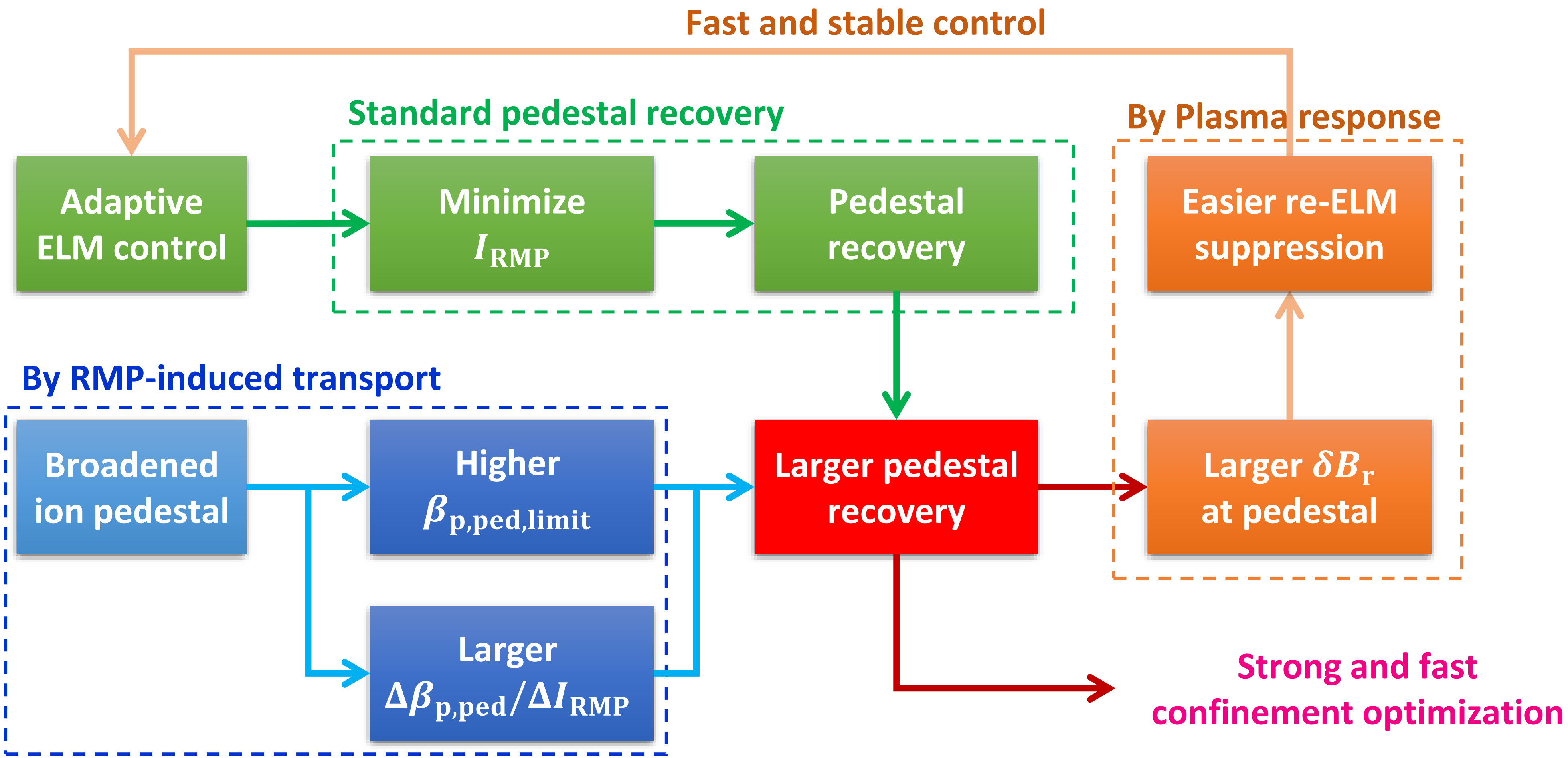
➡ $I_{\mathrm{RMP,IN}} \downarrow$ by wider ion pedestal.



[Time traces of pedestal, #26004]

Overall, widened ion pedestal facilitate the adaptive ELM control method by boosting the confinement hysteresis and reducing the system discontinuity

- **Overall effect of ion pedestal broadening on adaptive ELM control**



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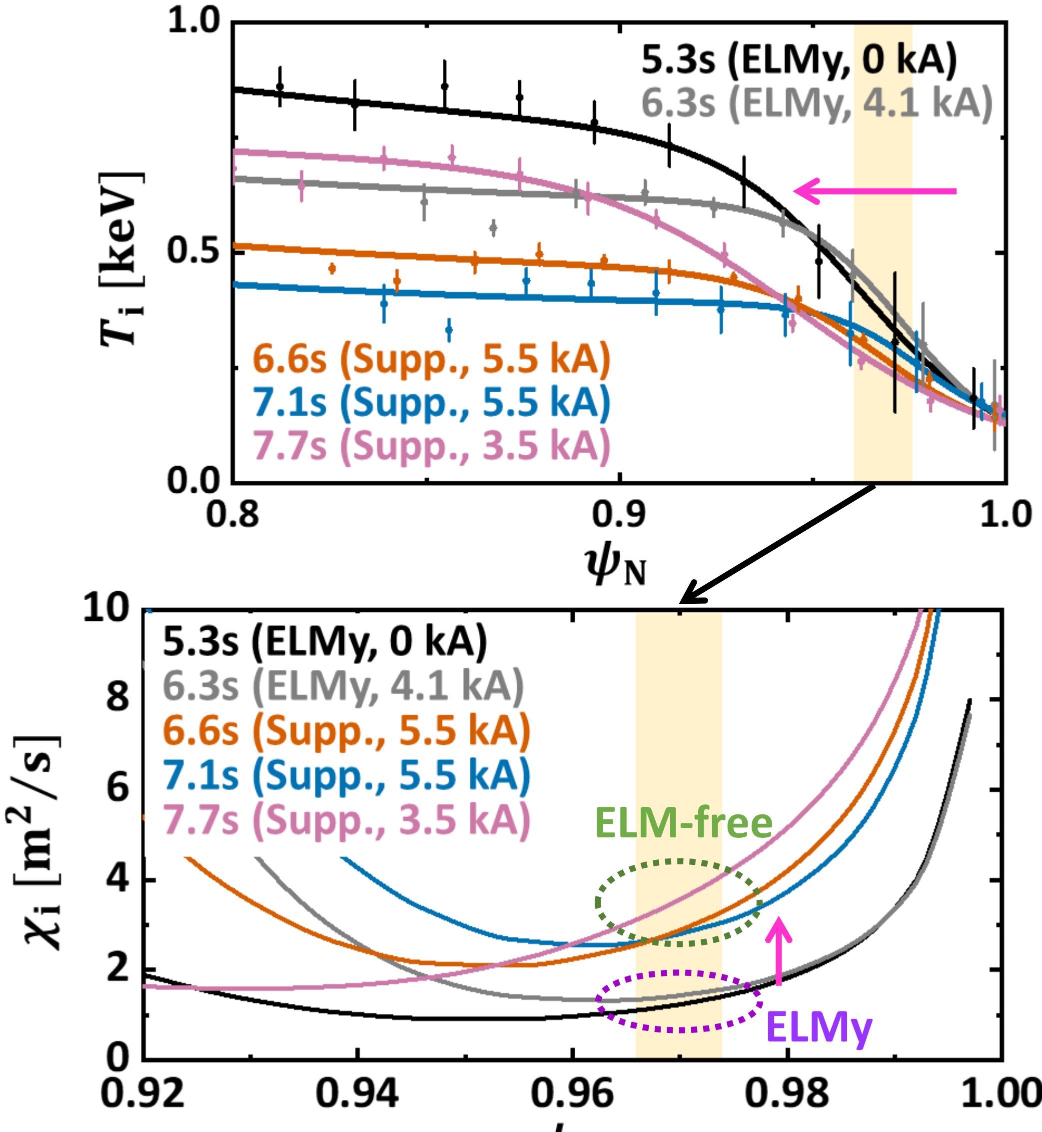
- **Widened ion pedestal and increased pedestal response** → **Enhanced pedestal recovery.**
- **Enhanced confinement recovery and field amplification** → **Decreases $I_{\mathrm{RMP,IN}}$.**
- **Origin of widened ion pedestal**
- **Conclusion**

Interpretive analysis suggests that ion pedestal broadening can be an outcome of increased heat transport during ELM suppression phase

- **Origin of widened ion pedestal**
  - ✓ RMP-induced transport in ELM-suppression
    - ELMy : No effective change.
    - ELM-free (>6.6s): Increased χ_i at pedestal.

      → Decreased pedestal gradient and broadening.
  - ✓ Distinguished properties of RMP-induced transport
    - Occurrence at ELM-free state.
    - No proportionality on I_{RMP} during ELM-free.

      → Sustained pedestal gradient with I_{RMP} ↓.

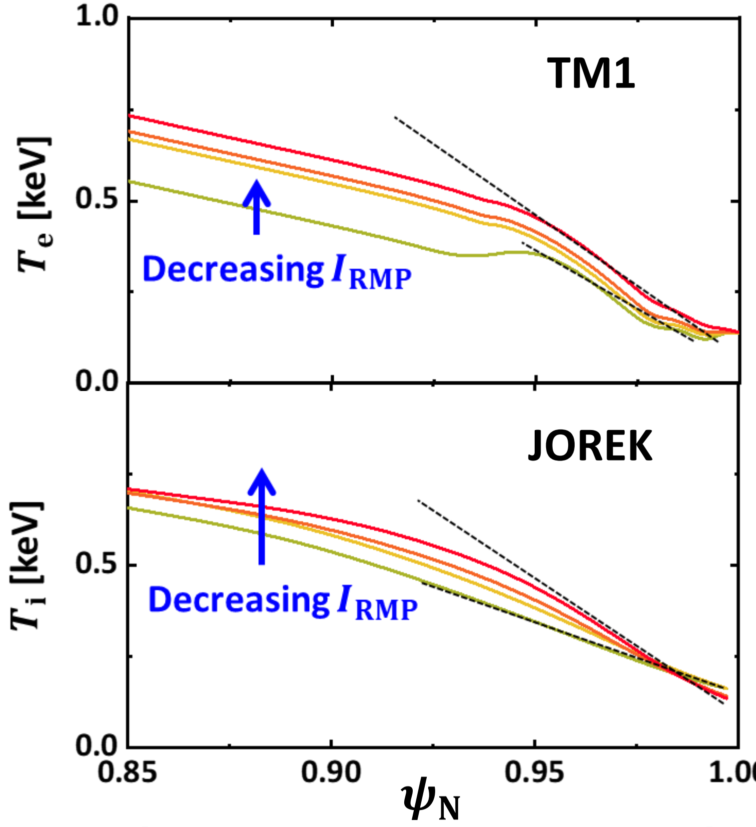


[Time traces of ion profile and diffusivity]

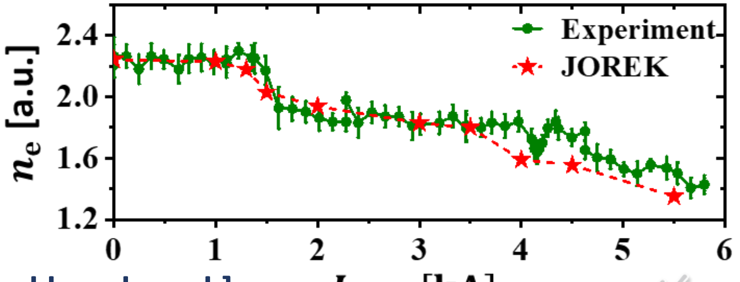
Preliminary nonlinear MHD simulation on RMP response shows that classical transport may have difficulty in explaining insensitivity of χ_i on I_{RMP}

- **Nonlinear MHD simulation with decreasing I_{RMP}**
  - ✓ **TM1 simulation** [Q. Yu 2012, Q. Hu 2020]
    - T_e & n_e + island physics.
    - $T_{e,ped}$ ↑ and no width extension by I_{RMP} ↓.
      → So, not by T_e widening via thermal coupling.
  - ✓ **JOREK simulation** [G. Huijsmans 2009]
    - $T_{i,e}$ & n_e + NTV, island/kink physics.
    - Recently, reasonable validation [S. K. Kim submitted].
    - $T_{i,ped}$ and $\nabla T_{i,ped}$ ↑ by I_{RMP} ↓.
      → Further analysis is ongoing.

➡ Additional transport mechanism may be required to explain pedestal gradient behavior.



[Numerically prediction on T profiles]



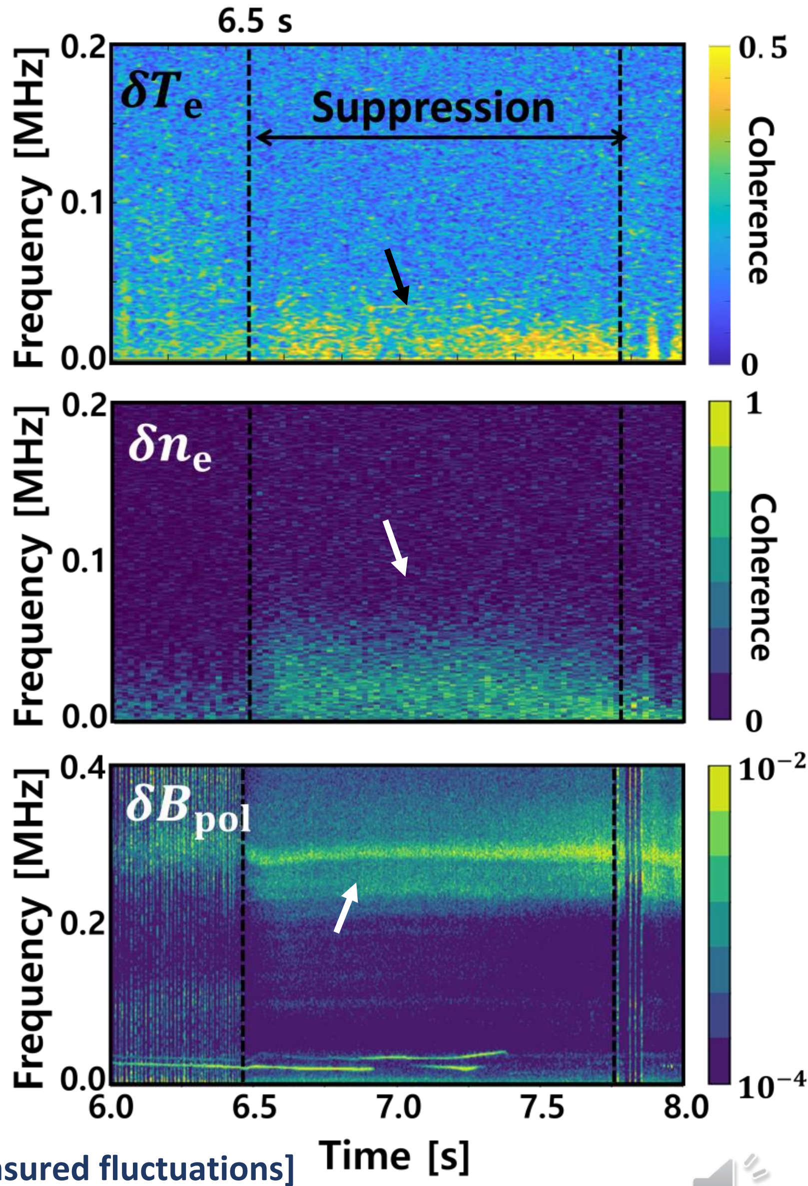
[Recent numerical benchmark]

Immediate occurrence of edge turbulence is observed after entering ELM suppression

- **Occurrence of fluctuations**
  - ✓ **Measured fluctuation**
    - **Immediate occurrence at ELM-free.**
    - **ECEI (δT_e), BES (δn_e), Mirnov (δB_{pol}) and CSS.**

- **Properties of edge turbulence**
  - ✓ **Frequency range**
    - **δT_e and δn_e : 30-80 kHz (longer, $k\rho_s < 1$).**
    - **δB_{pol} and CSS: 200-400 kHz (shorter, $k\rho_s > 1$).**

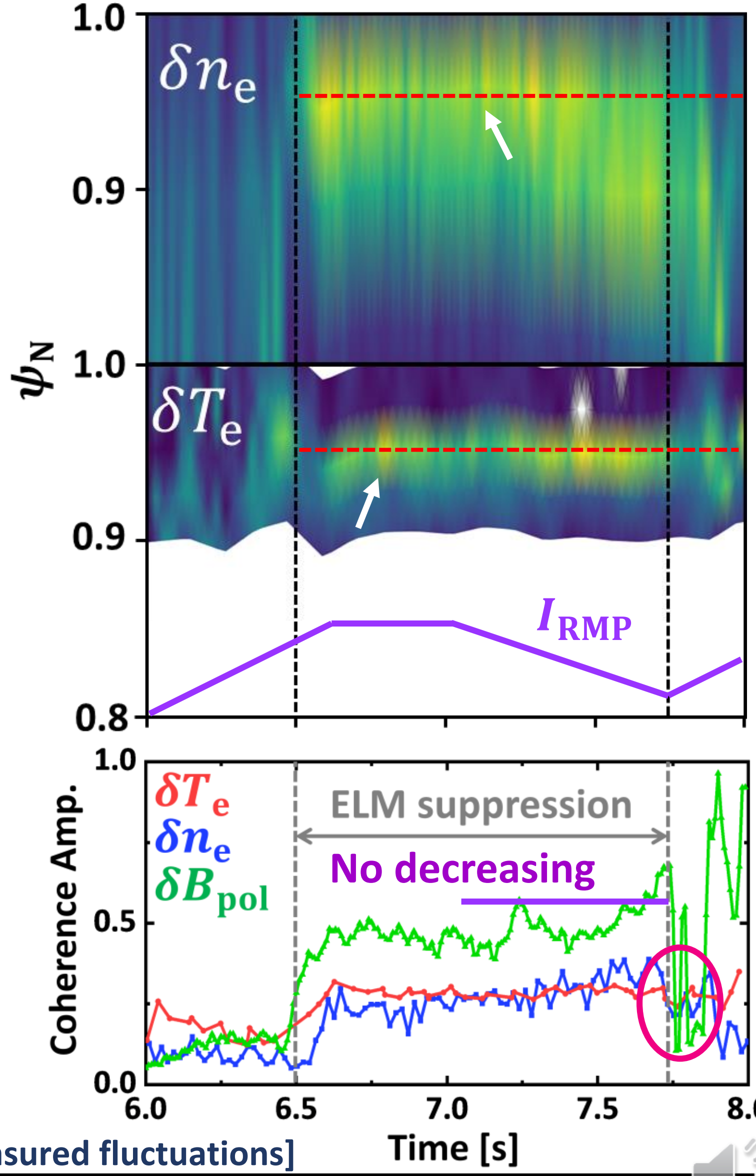
    → More than one different fluctuations.



[Time traces of measured fluctuations]

Edge localized fluctuation exhibits similar trends with ion diffusivity, suggesting the ion-scale turbulence as a main contributor to pedestal widening

- **Properties of edge turbulence**
  - ✓ Radial range
    - δT_e and δn_e : $\psi_N > 0.9$.
- **Correlation of edge turbulence with I_{RMP}**
  - ✓ No reduction by $I_{RMP} \downarrow$.
    - Same for ion diffusivity.
      → Suggesting it as a main contributor.
  - ✓ Rapidly decreasing with losing suppression (at 7.8s) .
    - Immediate RMP ramp for maintain favorable wide pedestal.
      → RT-Adaptive control is key.

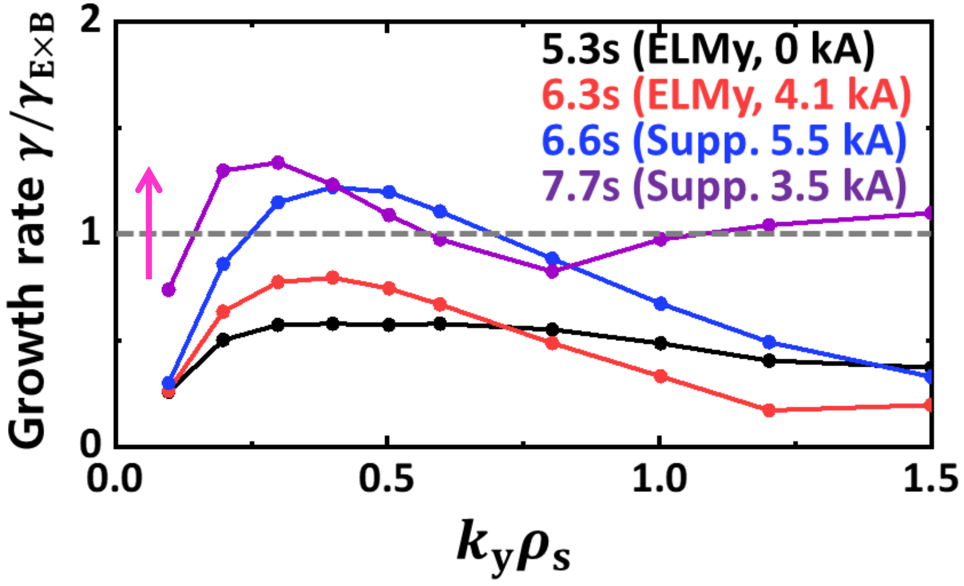


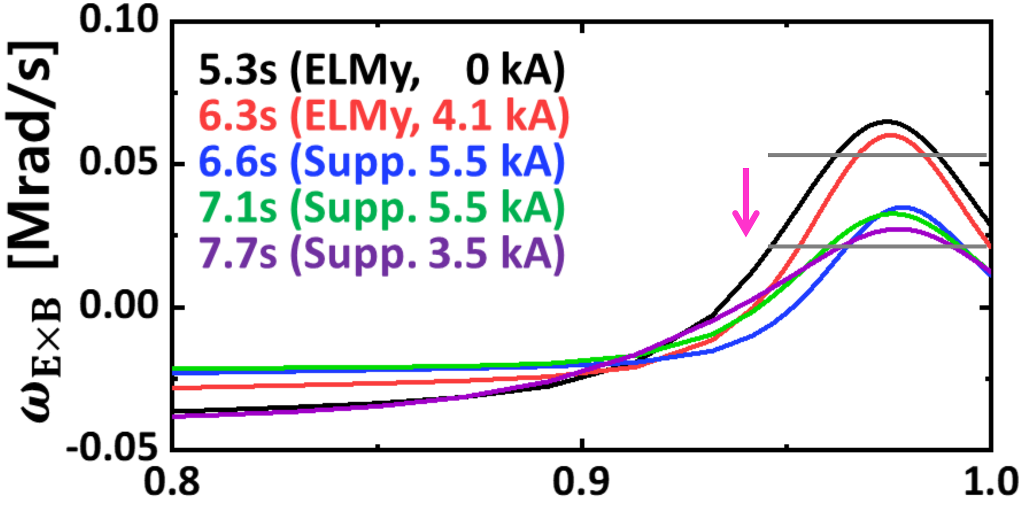
[Time traces of measured fluctuations]

Linear gyro-kinetic simulation suggests the occurrence of turbulence but detailed numerical analysis is needed for complete explanation.

- **Linear CGYRO calculation** (ψ_N~0.96) [J. Candy 16]
  - ✓ Onset ($\gamma/\gamma_{E\times B}$>1) at ELM free (> 6.6s).
    - Mainly due to reduced $\gamma_{E\times B}$.
    - ITG/TEM branch.
      → Closer to electron channel fluctuation.

- **Limitation of the linear results**
  - ✓ Inconsistency in electron heat fluxes.
    - No evidence for widening of electron pedestal.
  - ✓ Importance of nonlinear study w/ RMPs.
    - Interactions with kink/island [R. Hager 20].
    - Non-local effect [S. Taimourzade 19].

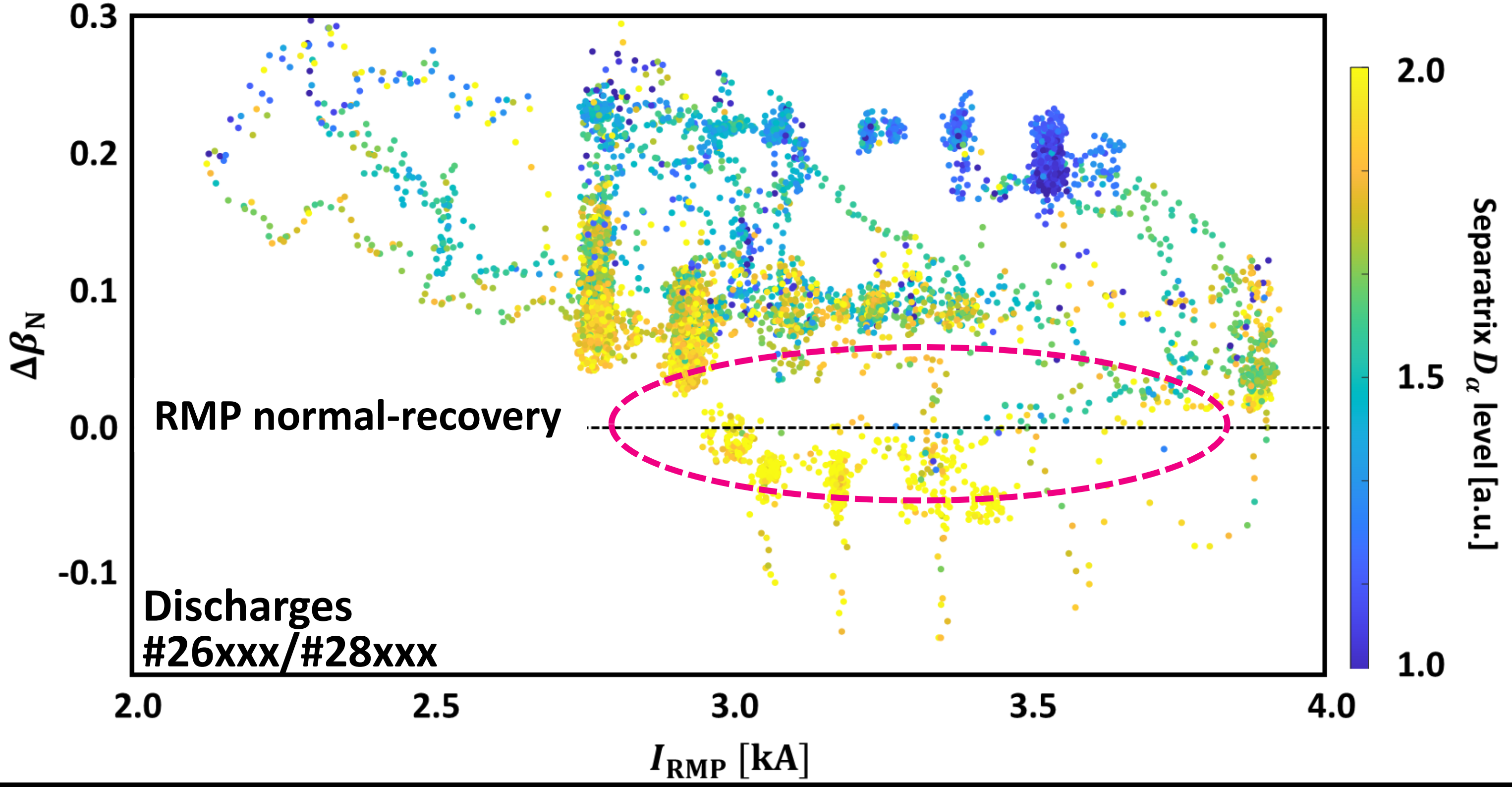


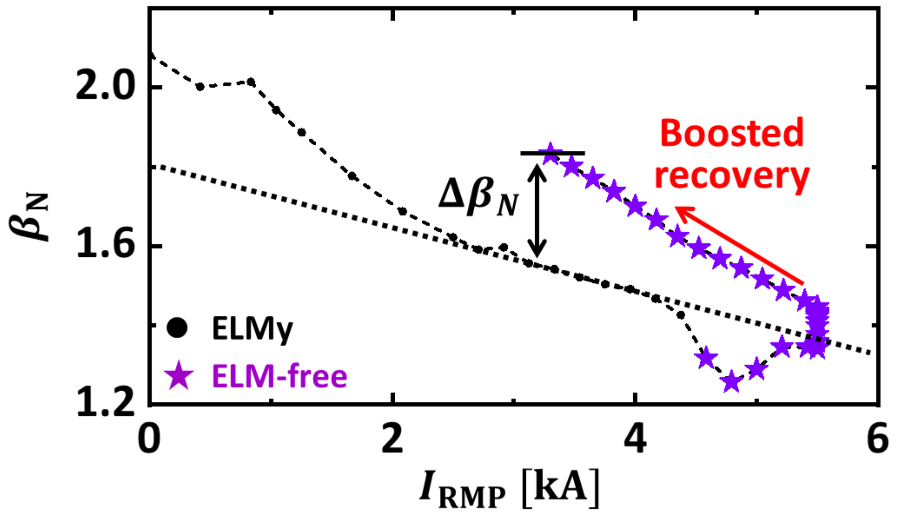


[Growth rate and ExB shearing rate, CGYRO]

FY20-21 database suggest that the favorable effect of turbulence can vary depending on edge conditions.

- **Edge gas level and boosted recovery**
  - ✓ Weakening $\Delta\beta_N$ with separatrix D_α level.
    → Turbulence may be reduced with edge density, collisionality.
  - ✓ No clear dependency with density pedestal height (n_{ped}).





➡ Favorable edge conditions for these effect has to be investigated for the projection to future devices.

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- **Enhanced confinement recovery and field amplification** → **Decreases $I_{\mathrm{RMP,IN}}$.**
- **Origin of widened ion pedestal** → **Highly correlates to ion-scale turbulence.**
- **Conclusion**

Adaptive ELM control paves new strategy to optimize the pedestal via 3D field, revealing new physics of edge-turbulence and its favorable aspects.

- **Successful demonstration of adaptive ELM control in KSTAR**
  - ✓ ELM-free state with optimized confinement.
- **Widened ion pedestal plays key role in control optimization.**
  - ✓ Boosted recovery and good convergence.
- **RMP-induced ion-scale turbulence highly correlates to ion pedestal**
  - ✓ Similar trend in fluctuation and numerical prediction.
- **Adaptive scheme is an effective way to utilize its favorable effect**
  - ✓ Immediate RMP ramp to sustain the turbulence and wide pedestal.
    - Adaptive ELM control is an effective way to utilize RMP-induced turbulence.

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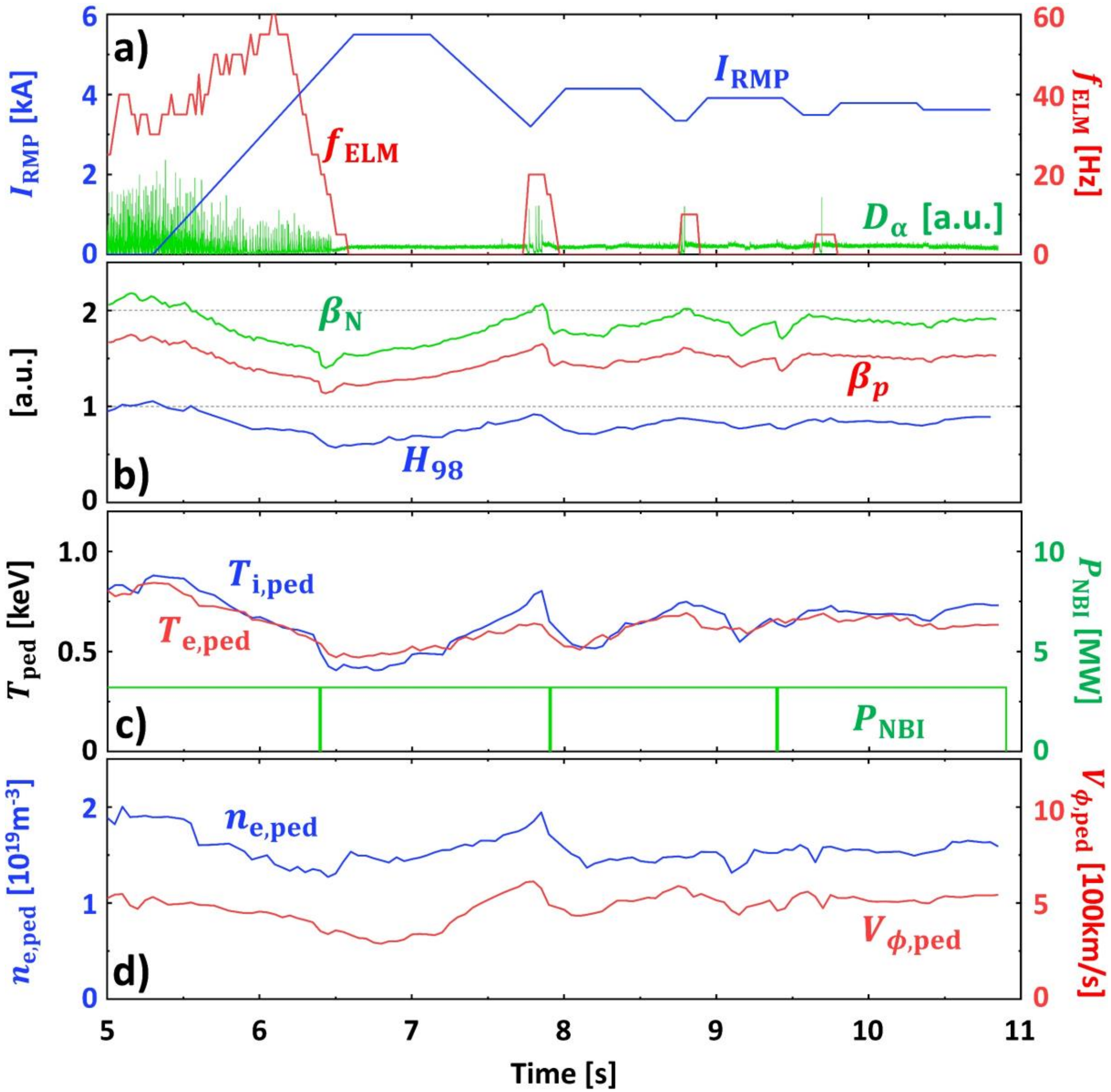
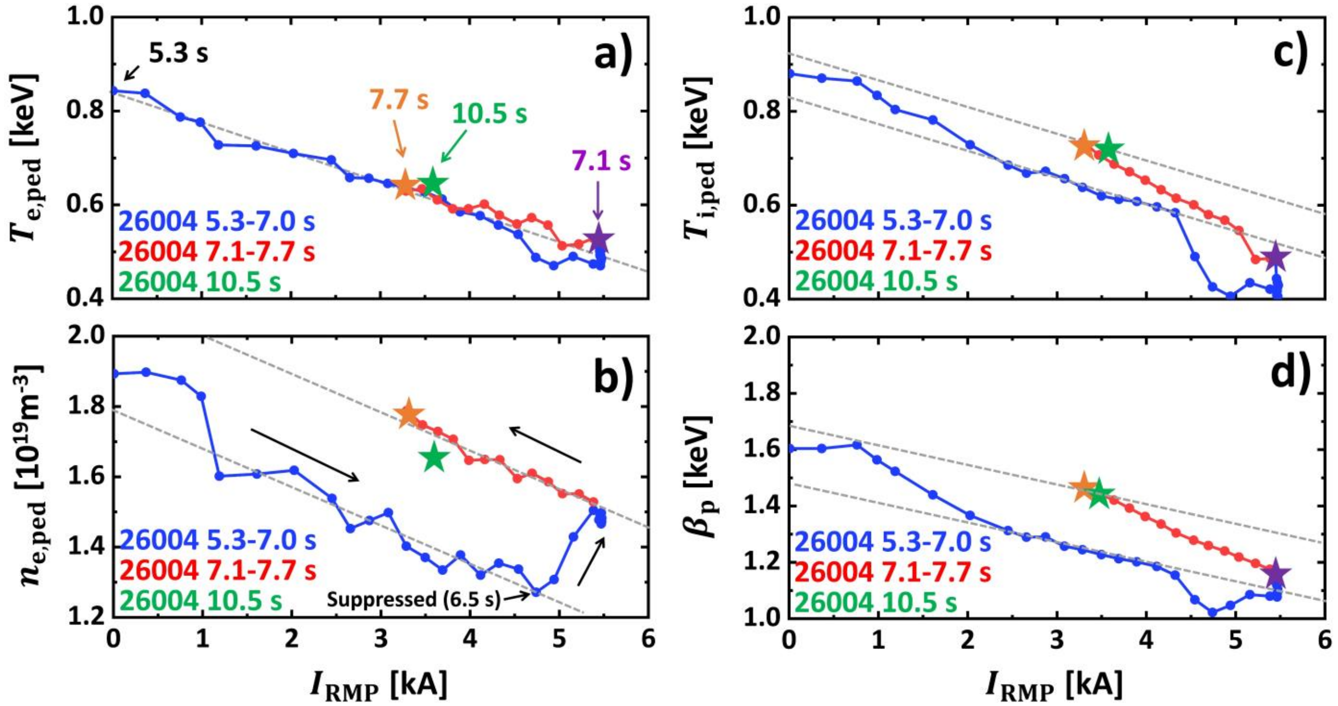
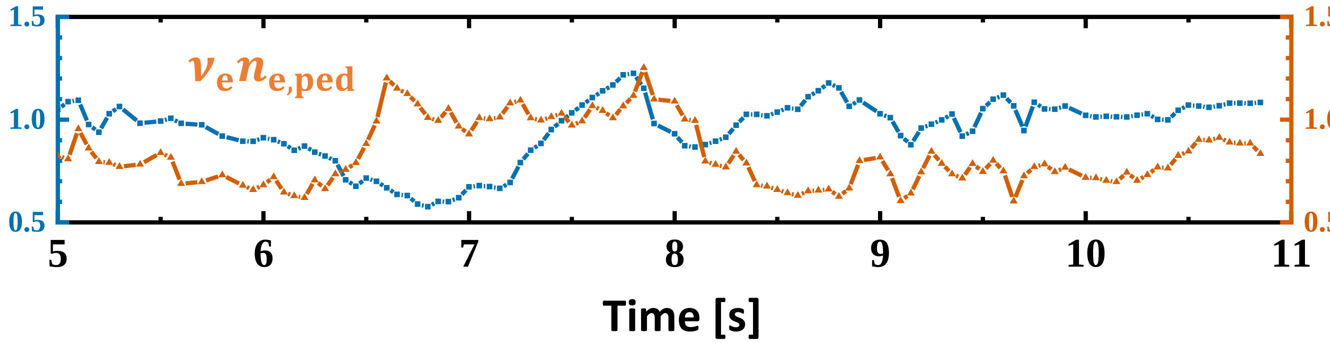
Backup – Time traces







Backup - Broadening ion pedestal can result in larger response of $T_{\mathrm{i,ped}}$ to I_{RMP}

- **Pedestal degradation by island flattening**
  - ✓ Island flattening
    - Profile flattening by (m, n) island at $q = m/n$.
    - Degradation of pedestal height → $\Delta T_{\mathrm{ped,m/n}} = \nabla T_{\mathrm{ped}} W_{\mathrm{m/n}}$
    - Island width $W_{\mathrm{m/n}}$ and pedestal gradient ∇T_{ped}.
  - ✓ Net pedestal degradation
    - Accumulation of $\Delta T_{\mathrm{ped,m/n}}$ by island in pedestal region.
    - q value at pedestal top, q_{ped}.
    - Lower bound of islands $m \geq nq_{\mathrm{ped}}$.

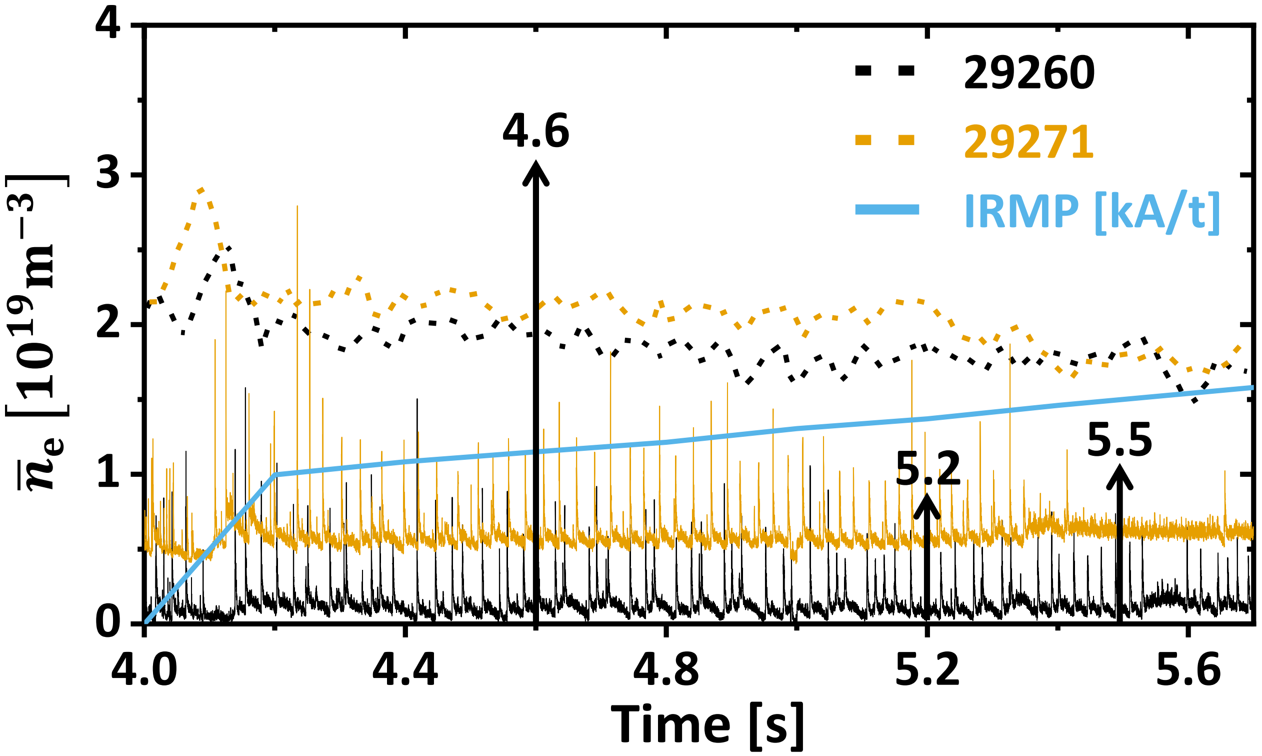
$$\Delta T_{\mathrm{ped,n}} = \sum_{m \geq q_{\mathrm{ped}}} \Delta T_{\mathrm{ped,m/n}} = \sum_{m \geq q_{\mathrm{ped}}} \nabla T_{\mathrm{ped}} W_{\mathrm{m/n}}$$

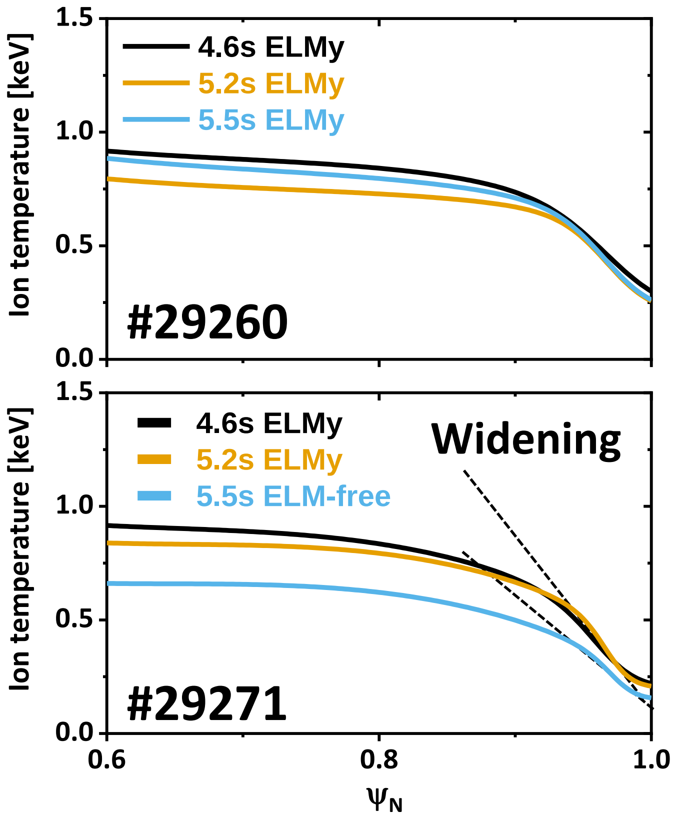
  - ✓ Response of T_{ped} to I_{RMP}
    - Increases with larger ∇T_{ped} and smaller q_{ped}.
    - Wider pedestal width → Smaller q_{ped}
      → Larger $\Delta T_{\mathrm{ped}}/\Delta I_{\mathrm{RMP}}$

$$\frac{\Delta T_{\mathrm{ped,n}}}{\Delta I_{\mathrm{RMP}}} \approx \nabla T_{\mathrm{ped}} \sum_{m \geq q_{\mathrm{ped}}} \frac{\Delta W_{\frac{\mathrm{m}}{\mathrm{n}}}}{\Delta I_{\mathrm{RMP}}}$$

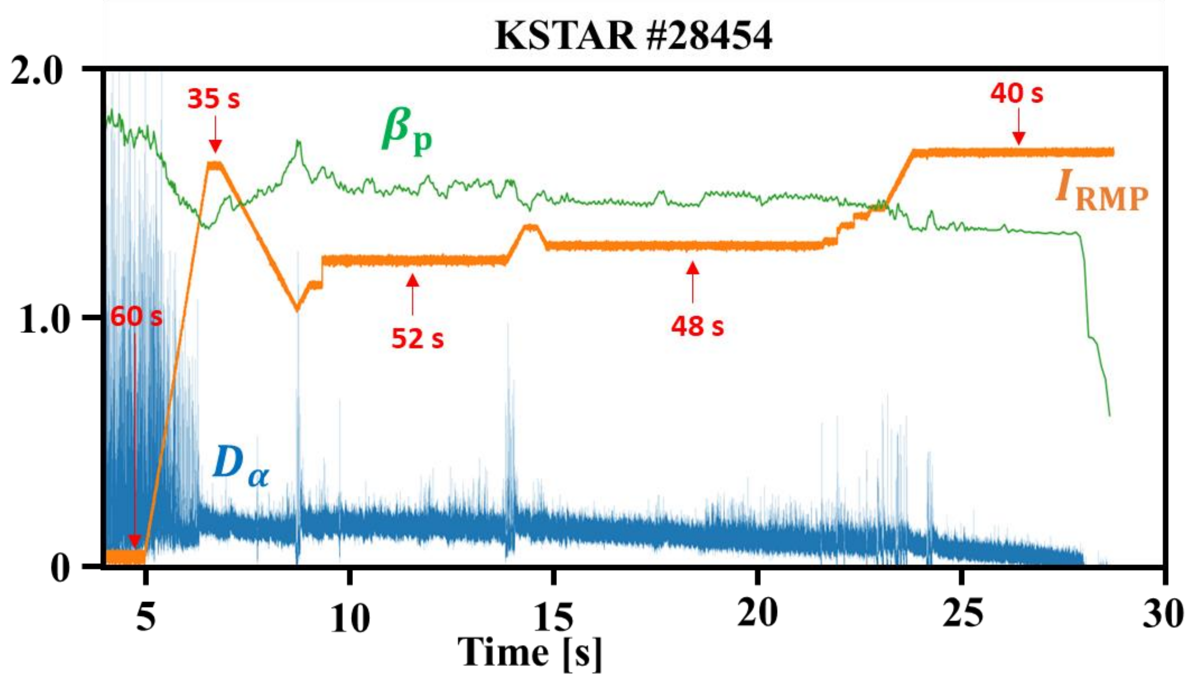
Backup – ELM entrance and ion pedestal broadening is supported by case comparison

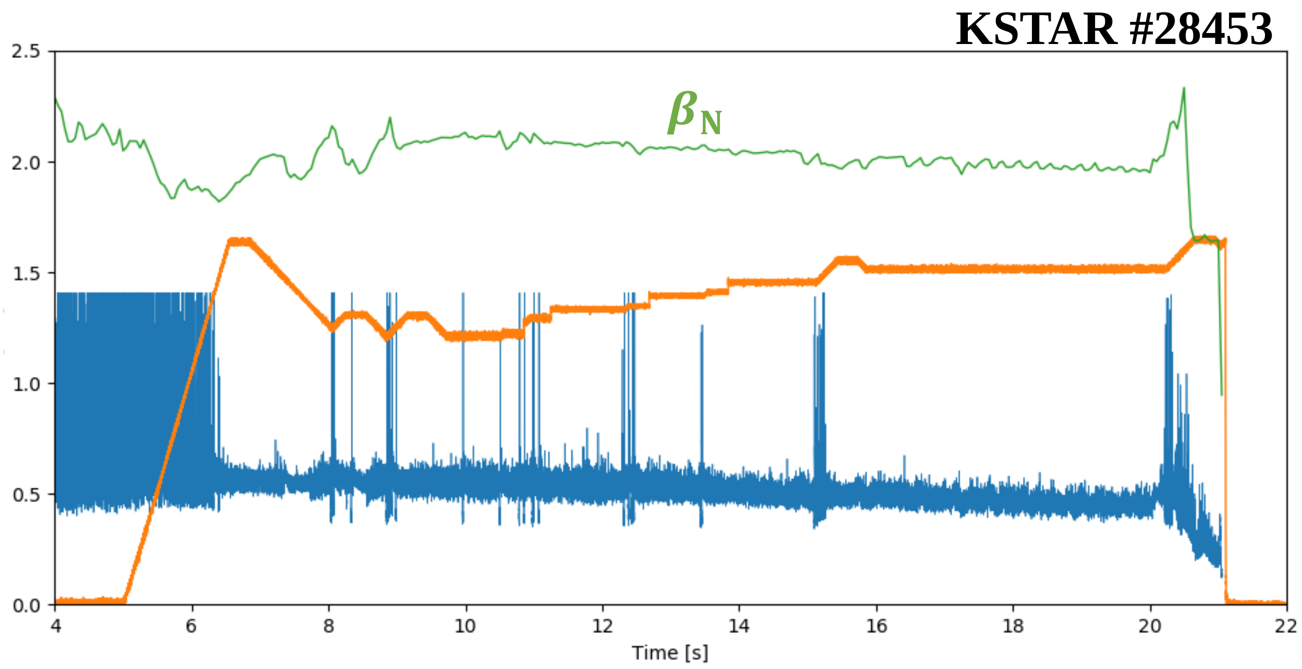
- **ELMy vs ELM-free**
  - ✓ Similar discharge with RMP-ramp (same heating, BT).
  - ✓ No suppression due to unfavorable condition for Supp. window.
  - ✓ #29260 (no Supp.) vs #29271 (Supp. at 5.3 s)



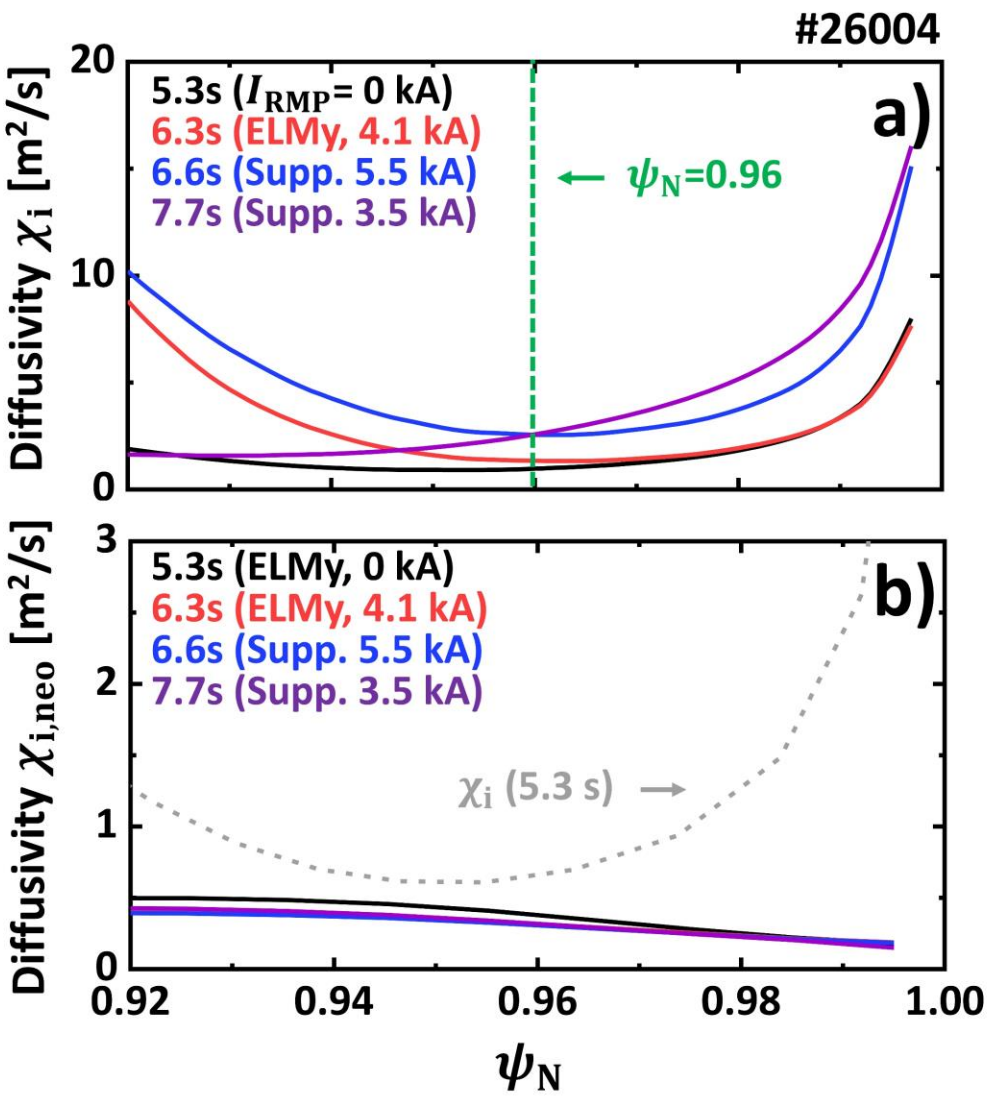


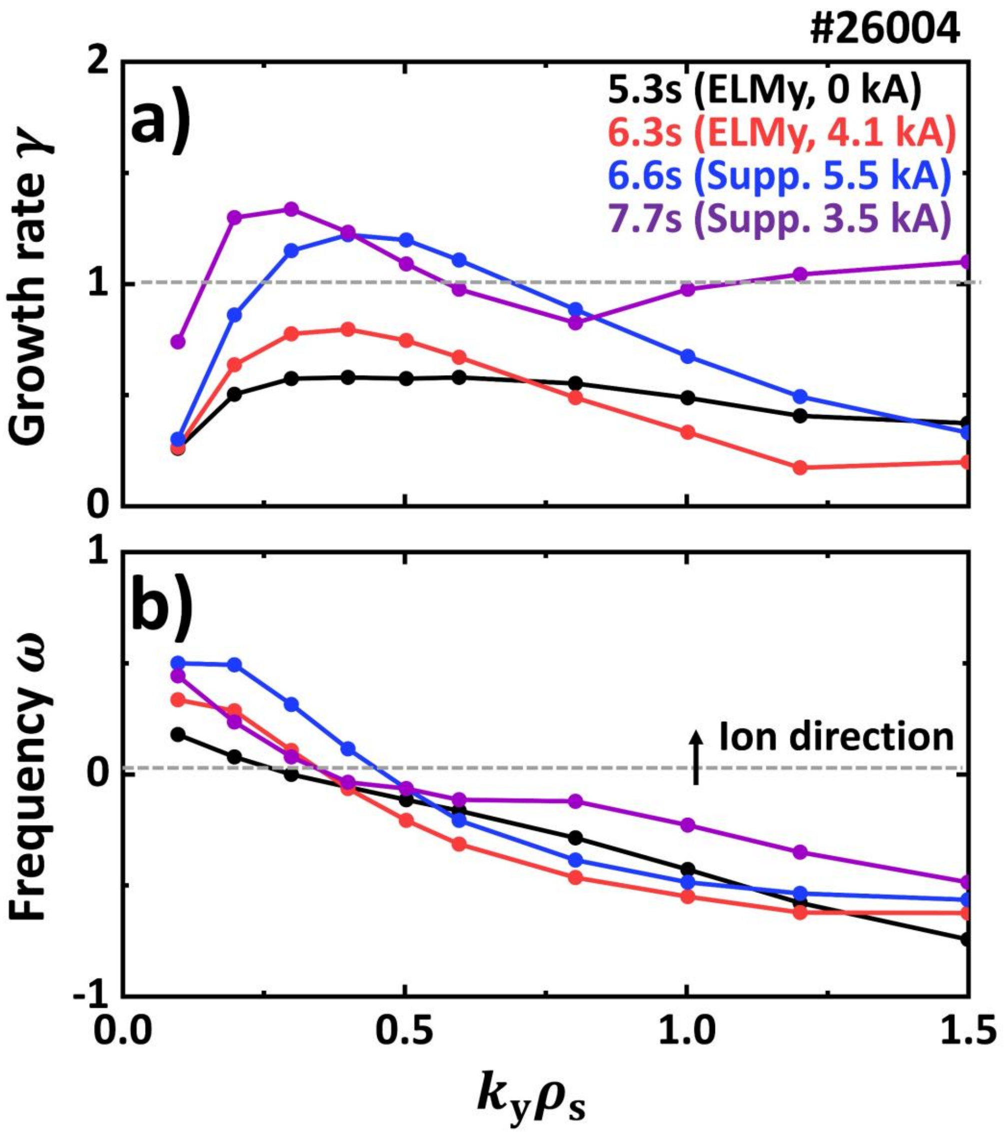
Backup – Other adaptive ELM controls



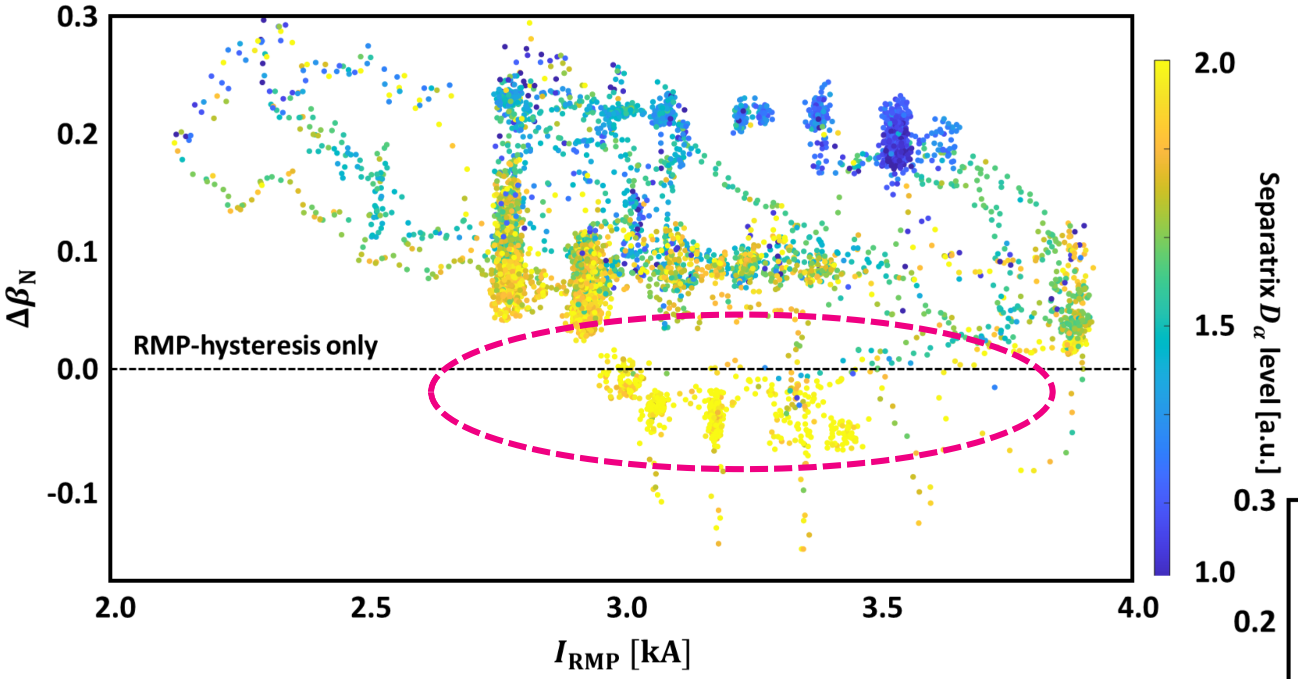


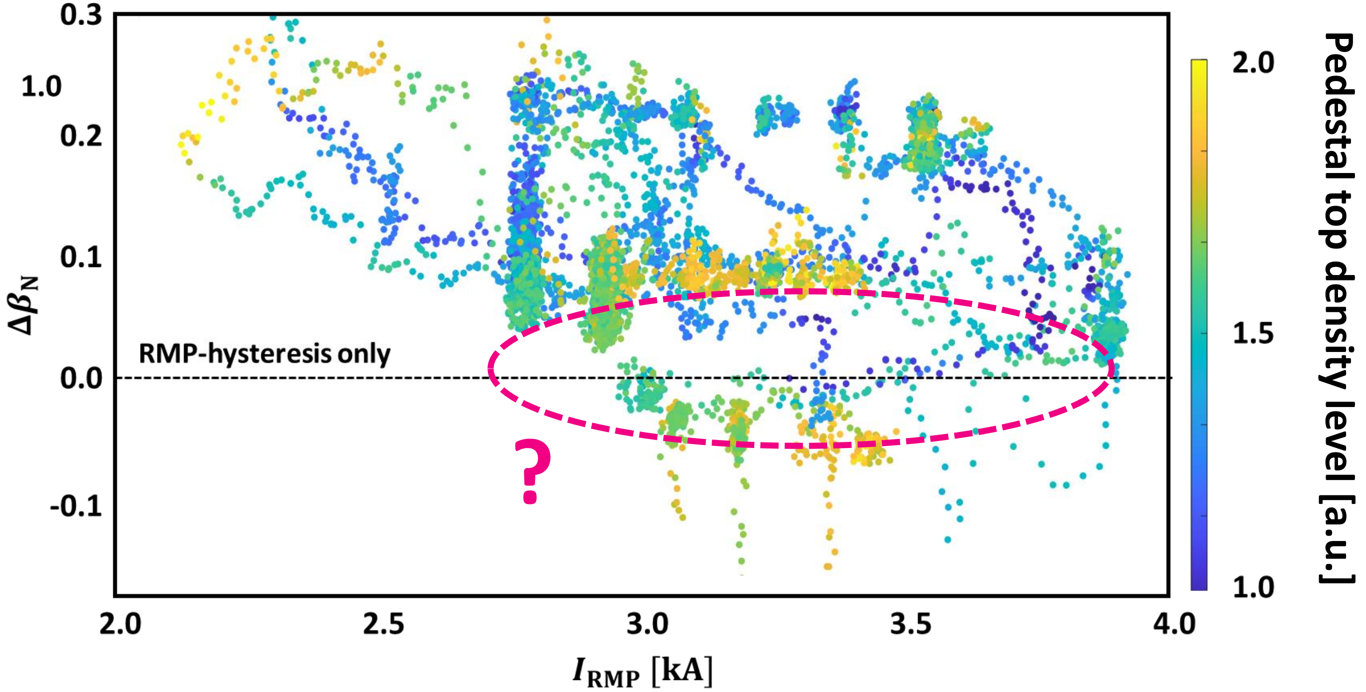
Backup – Heat diffusivities and CGYRO real frequencies





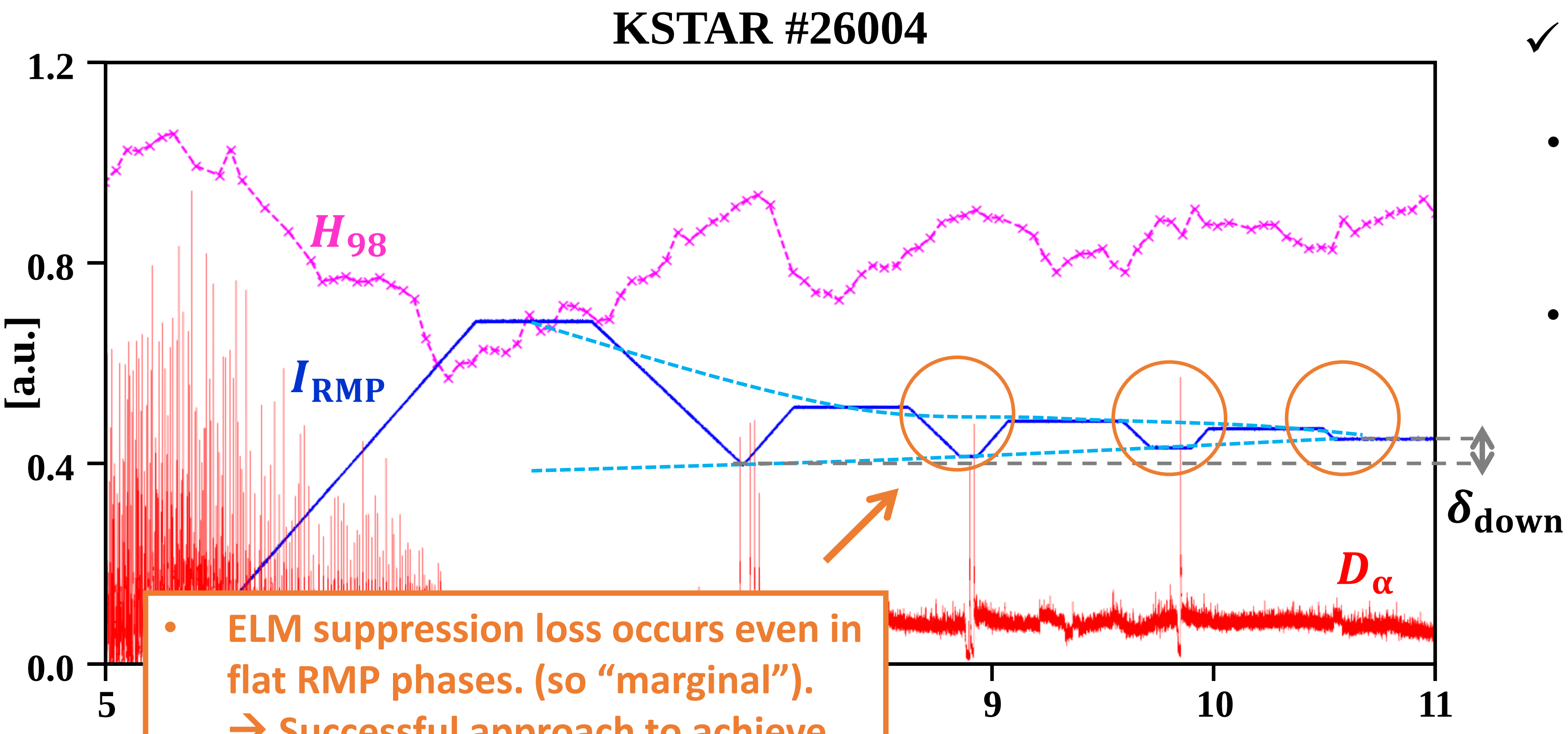
Backup – Boosted confinement recovery vs pedestal density / separatrix Da





Backup - Decreased oscillatory RMP control: Lower bound

- **Decreased oscillatory amplitude during ELM control**



- ELM suppression loss occurs even in flat RMP phases. (so "marginal"). → Successful approach to achieve **marginal RMP level for suppression.**

✓ δ_{down} **by ELM controller scheme.**

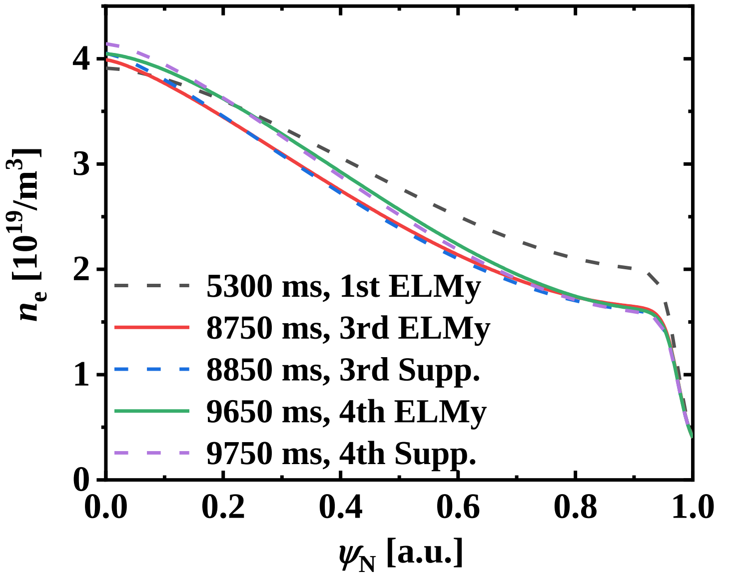
- Controller limits the lower I_{RMP} limit I_{limit} as the level where previous suppression loss occurs (I_{loss}).
- There is ~40ms delay in detecting suppression loss, further decrease of I_{RMP} by 0.06kA/turn after suppression loss. So,

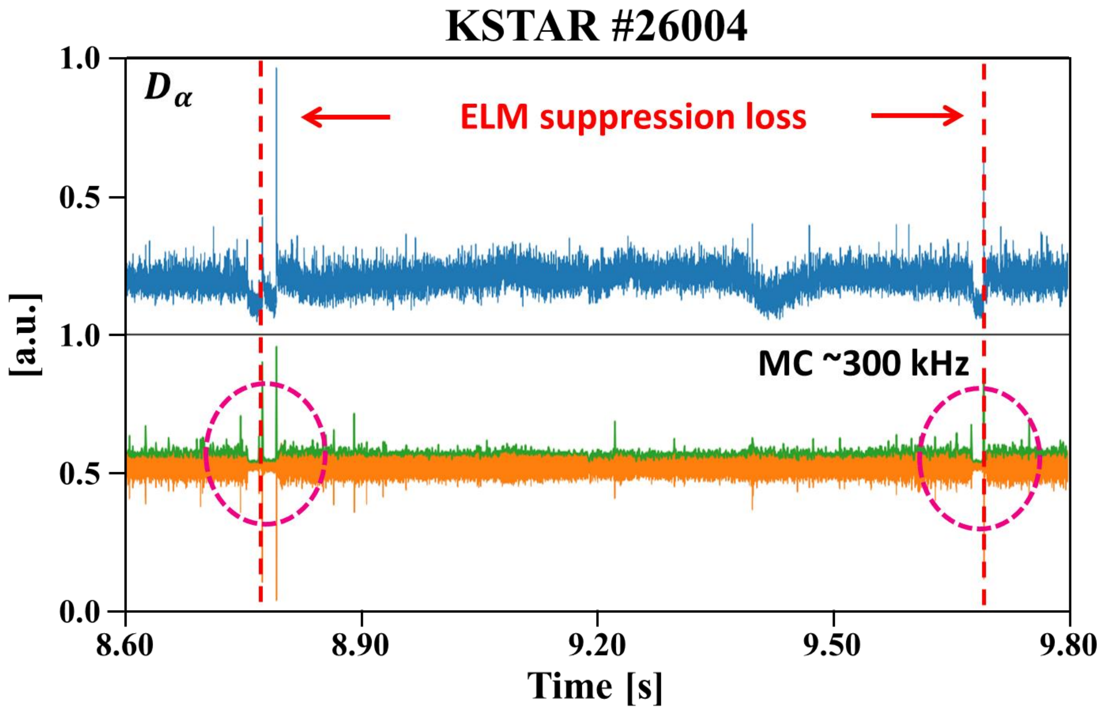
$$I_{limit} \approx I_{loss} + 0.07$$

$$\therefore \delta_{down} \approx 0.07 \times 3 \approx 0.2$$

Backup - Disappearance of bifurcative of pedestal change

- **Marginally suppressed ELM without bifurcative change**
  - ✓ Suppression loss and re-entering without bifurcative pedestal behavior.
  - ✓ No considerable change in pedestal. → Possibly, no island physics.
  - ✓ They are “very” stabilized in terms of linear PBM theory.
  - ✓ Decreased ~300kHz fluctuation before suppression losses.



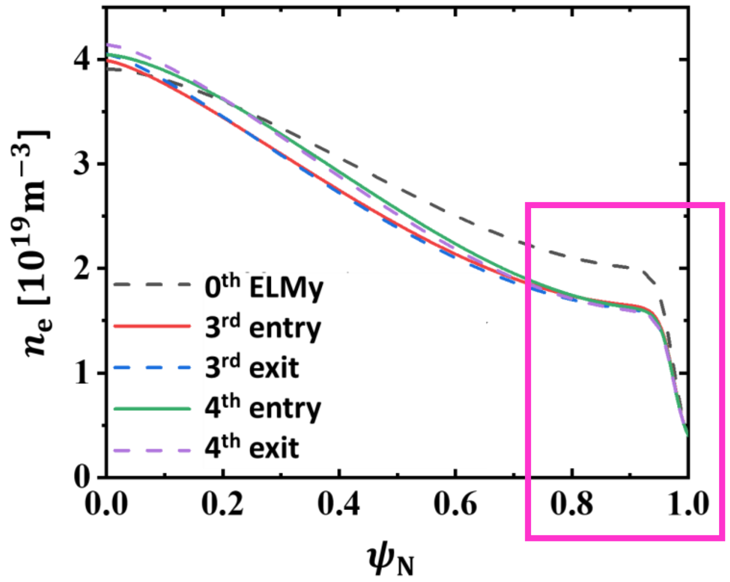


← This mode may contribute to ELM suppression by a mechanism other than a change in mean profile.

Suggest additional contributor for ELM-free.

Multiple entry to ELM suppression reveals the possibility of additional mechanism for ELM suppression other than profile effect

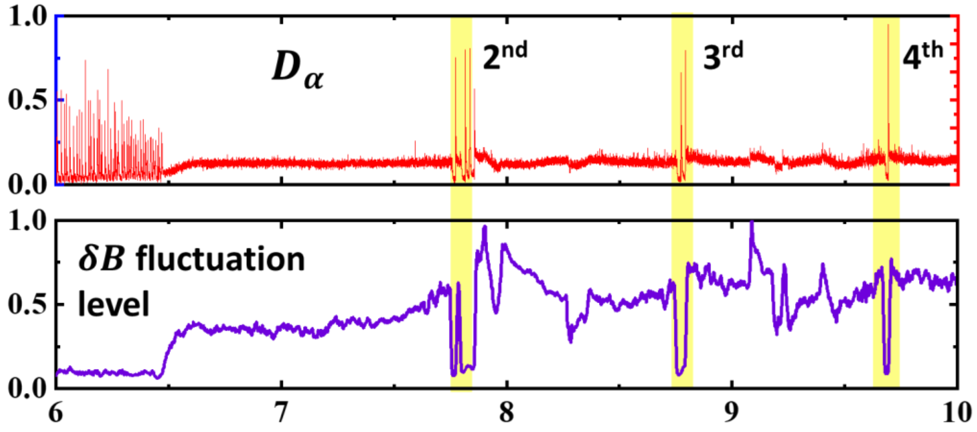
- **ELM suppression re-entry without changes in pedestal**
  - ✓ **Transition between ELMy and ELM-free state.**
    - **No considerable change in pedestal at 3rd and 4th ELM suppression entry and exit.**
      → Additional suppression mechanism other than profile effect.



[Time traces of pedestal, #26004]

- **Correlation between turbulence and ELM-free state.**
  - ✓ **Returning ELMs with turbulence disappearances.**
    - **Strong correlation with δB fluctuation.**
    - **Measured at both LFS and HFS.**

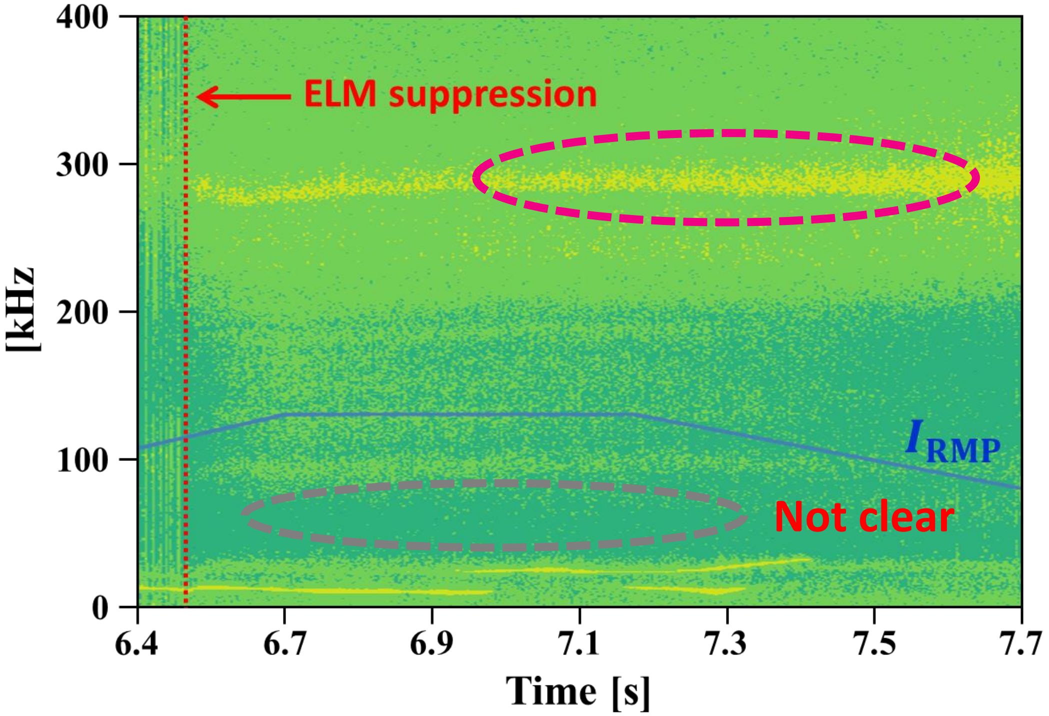
→ Possible direct contributions of edge turbulence on the ELM suppression.

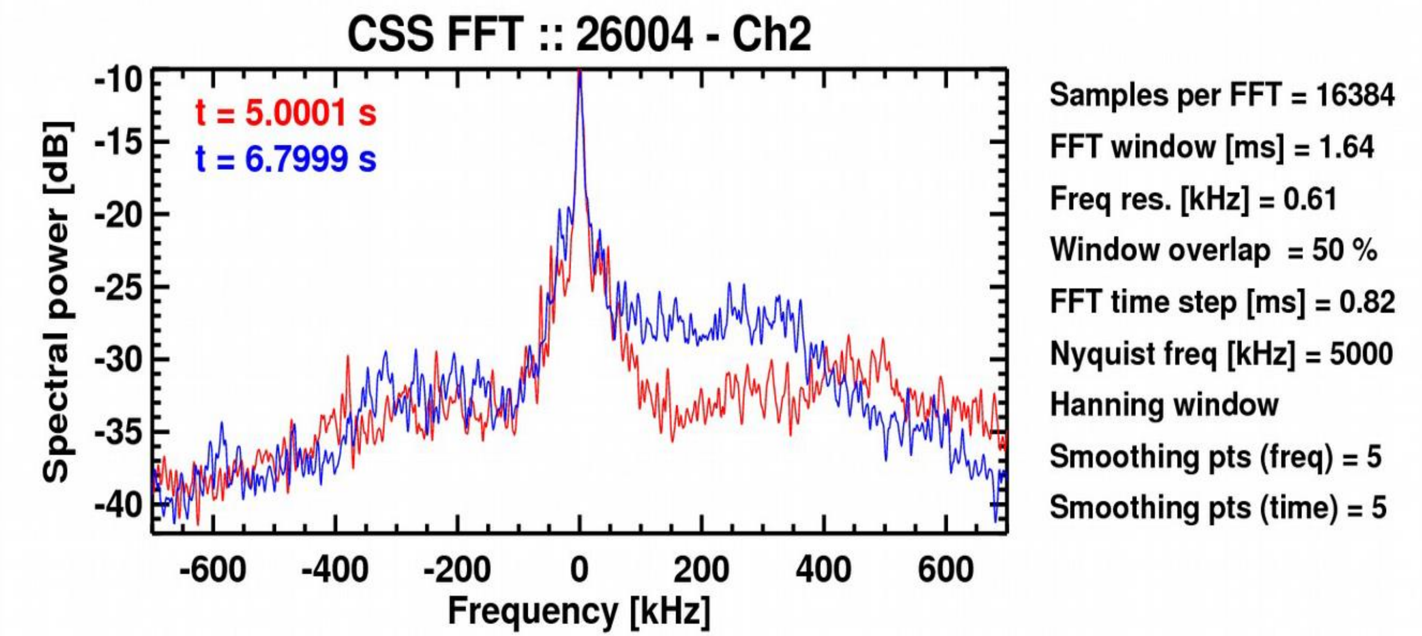


[Time traces of fluctuation level, #26004]

Backup – CSS signal

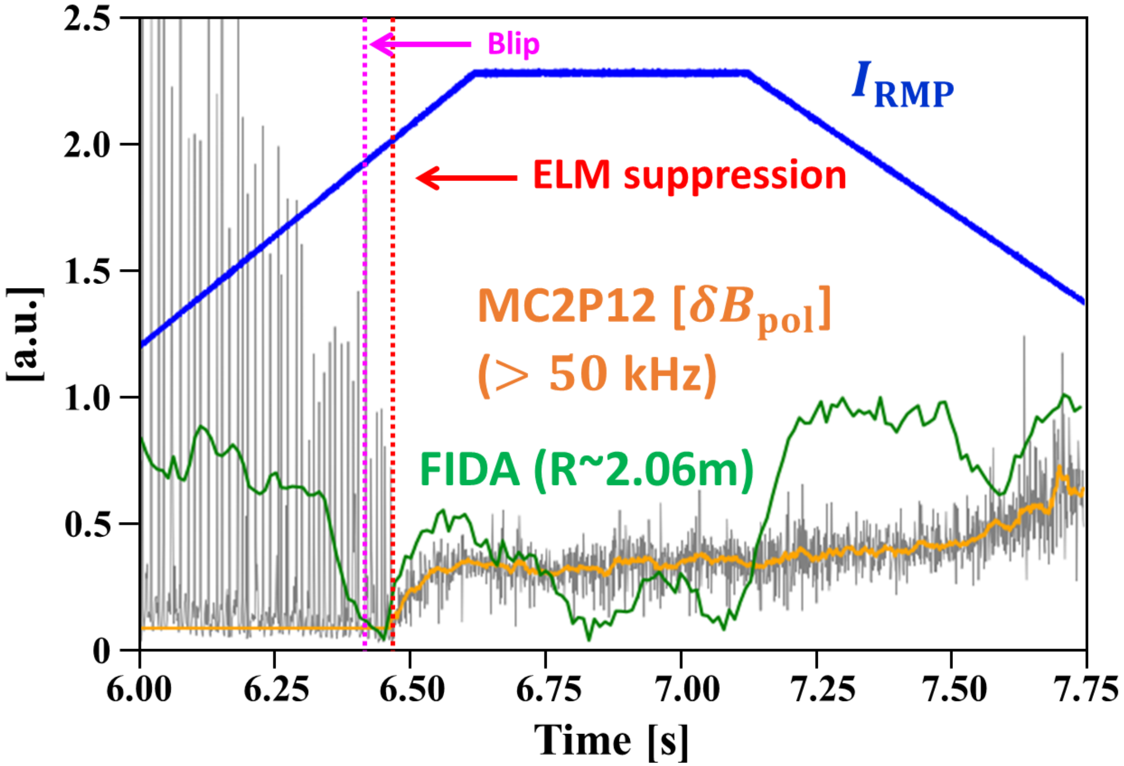
- **CSS signal (kp~18/cm)**
  - ✓ **Similar frequency to MC signal**





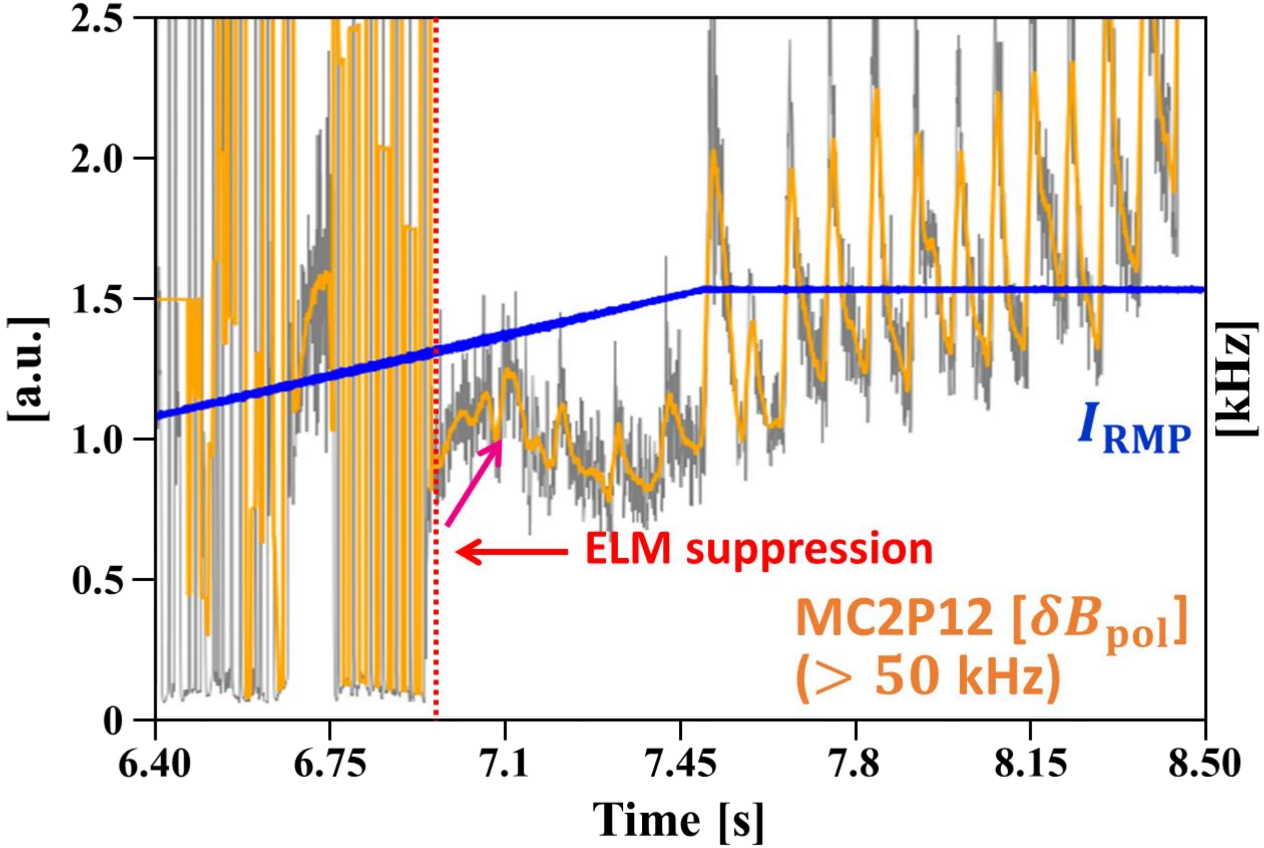
Backup – Mironov signal and FIDA

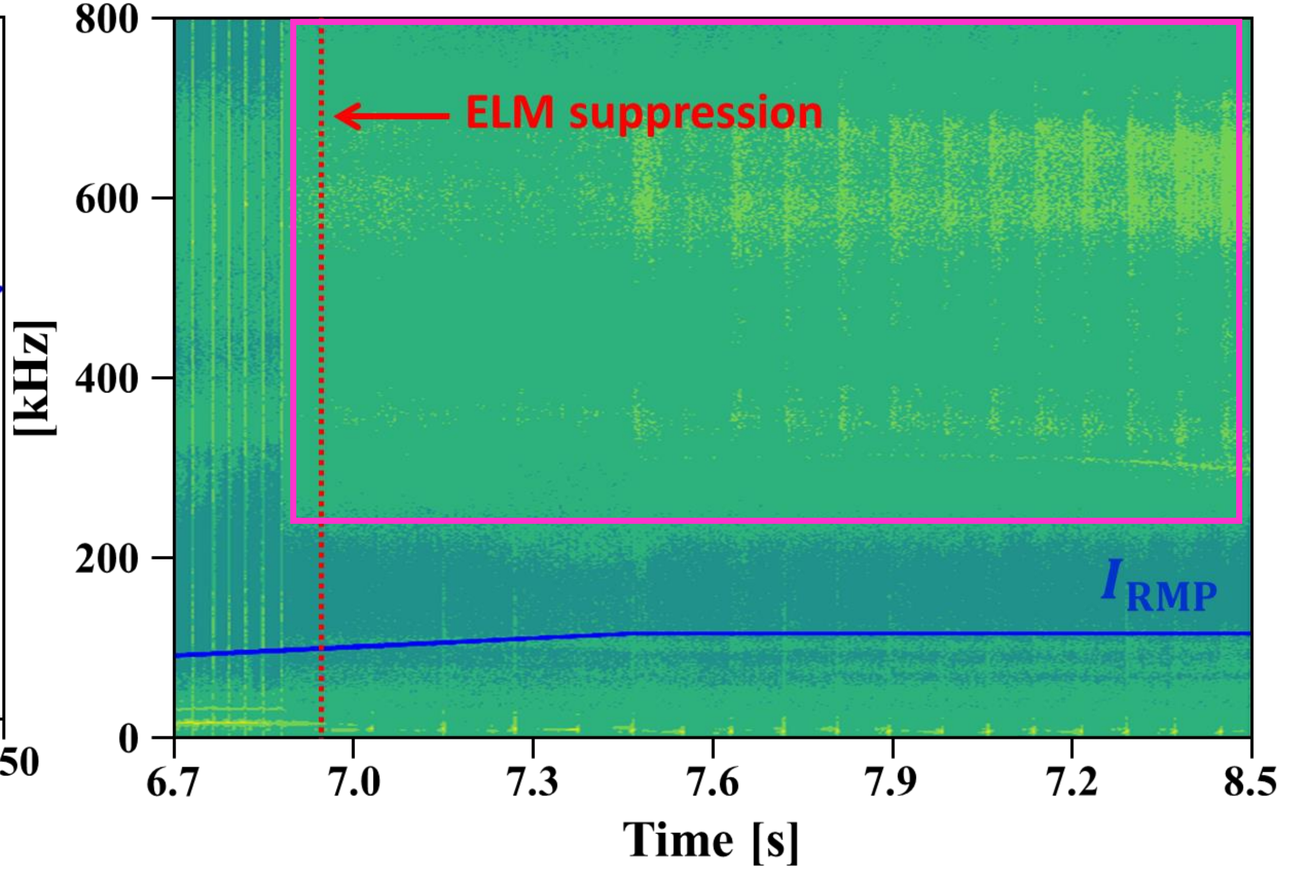
- **Increased edge turbulence after RMP-ELM suppression**
  - ✓ Mironov signal: Possibly, strong EM fluctuation. (~300kHz)
  - ✓ Small correlation between spectral power and fast ion density.
    → Less likely to be core Alfven-eigen mode.



Backup - Mironov signal (for n=2 case)

- **MC2P12 signal**
  - ✓ **Broad signal occurs at 70-400 kHz range.**

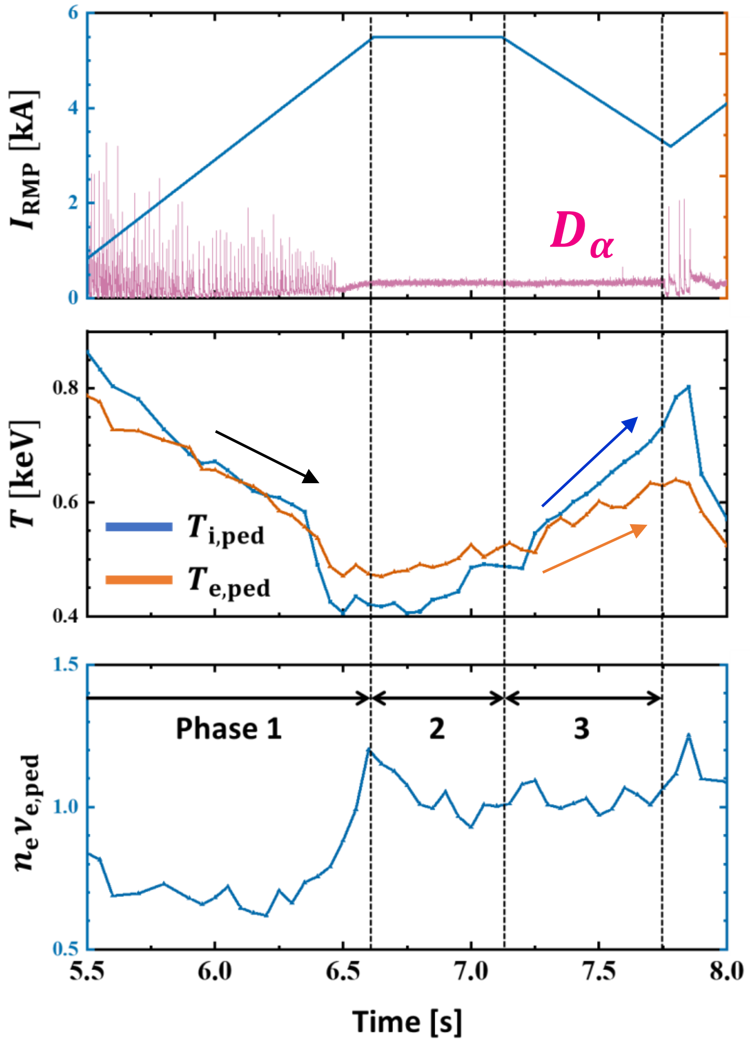




Backup - Time traces of pedestal height suggest that additional transport has been introduced to the ion channel, changing the response of $T_{\mathrm{i,ped}}$ to I_{RMP}

- **Before ELM suppression (phase 1)**
  - ✓ Decrease in both T_{i} and T_{e} pedestal height
    - Similar behavior of $T_{\mathrm{i,ped}}$ and $T_{\mathrm{e,ped}}$.
    - Decreasing pedestal height with $\Delta T_{\mathrm{ped}}/\Delta I_{\mathrm{RMP}} \sim -0.063\ \mathrm{eV/A}$.

- **Recovery phase (phase 3)**
  - ✓ Decoupled $T_{\mathrm{i,ped}}$ and $T_{\mathrm{e,ped}}$ pedestal height
    - Similar behavior of $T_{\mathrm{e,ped}}$ with phase 1 ($\sim 0.058\ \mathrm{eV/A}$).
    - ~50% larger response of $T_{\mathrm{i,ped}}$ ($\sim 0.092\ \mathrm{eV/A}$).
  - ✓ Increased $\Delta T_{\mathrm{i,ped}}/\Delta I_{\mathrm{RMP}}$
    - Not a result from change in thermal coupling between ion and electron ($\propto n_{\mathrm{e}}\nu_{\mathrm{e,ped}}$) [L.Cui 17].
    - Indicating additional transport "mainly" on ion pedestal.



[Time trace of pedestal height, #26004]

Backup - Comparison of pedestal profiles in each phase suggests the effect of edge turbulence on the ion-pedestal: Pedestal broadening

- **Comparison of phases**

	Phase 1	Phase 2	Phase 3
I_{RMP}	Increased	-	Decreased
Fluctuation level	↕ -	Increased	↕ -
$T_{\mathrm{i,ped}}$	Decreased	↕ -	Increased
$\nabla T_{\mathrm{i,ped}}$	-	Decreased	-

→ $\nabla T_{\mathrm{i,ped}}$: Mainly by turbulence (turbulence transport)

→ $T_{\mathrm{i,ped}}$: Mainly by I_{RMP} (collisional transport?)

- **Effect of edge turbulence on ion-pedestal**
  - ✓ Widened pedestal width & decreased $\nabla T_{\mathrm{i,ped}}$.
  - ✓ Increased $|\Delta T_{\mathrm{i,ped}}/\Delta I_{\mathrm{RMP}}|$.
    - If $\Delta T_{\mathrm{i,ped}}/\Delta I_{\mathrm{RMP}}$ by collisional transport [Q. Hu 20]. → Can be increased with pedestal width.
  - ✓ Weak effect on electron pedestal width.
    - Not clear due to limits in spatial resolution. → But statistically no large variation.