Mechanical and Aerospace Engineering

NSTX-U, MFS meeting

PPPL

Optimizing edge confinement and stability via adaptive ELM control using RMPs

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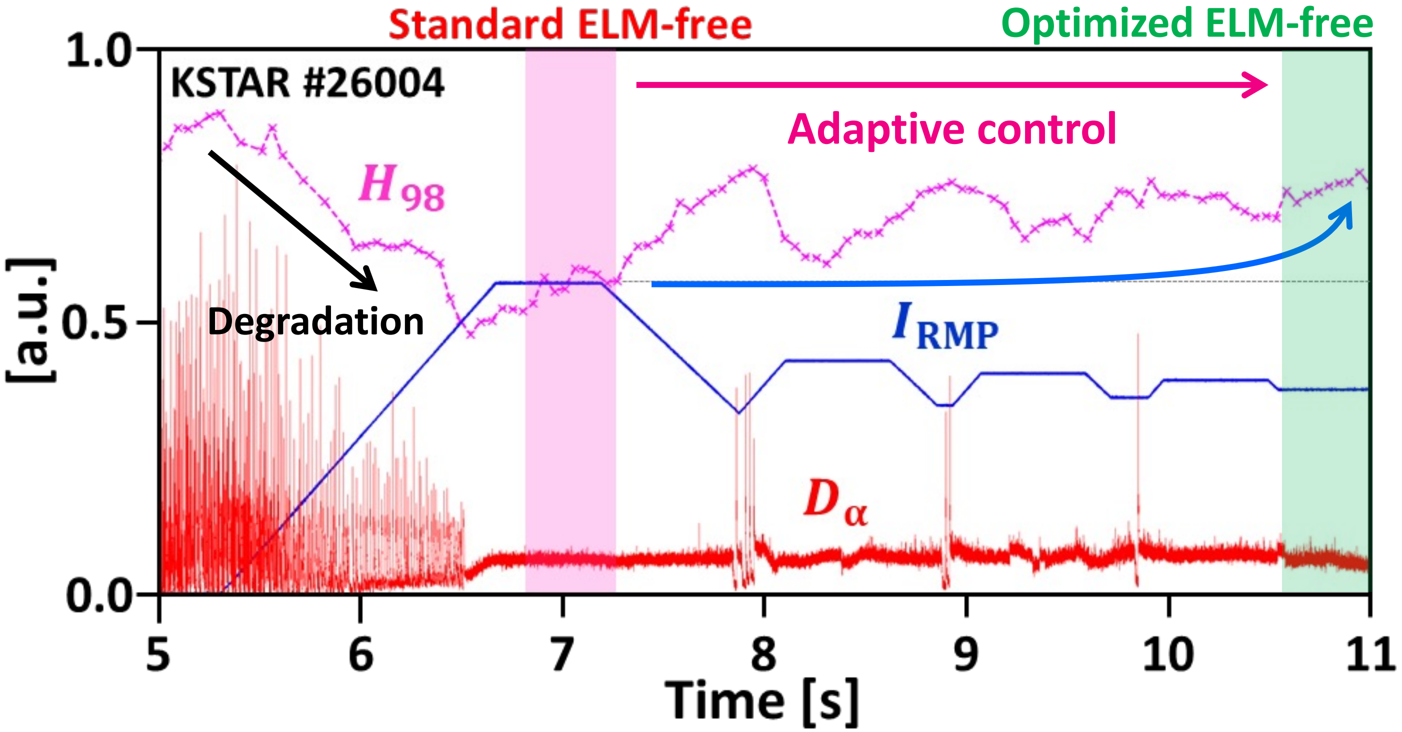
RMPs are promising method to stabilize the ELM crash, however there is remaining challenges for its application on ITER or future devices

- **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%).

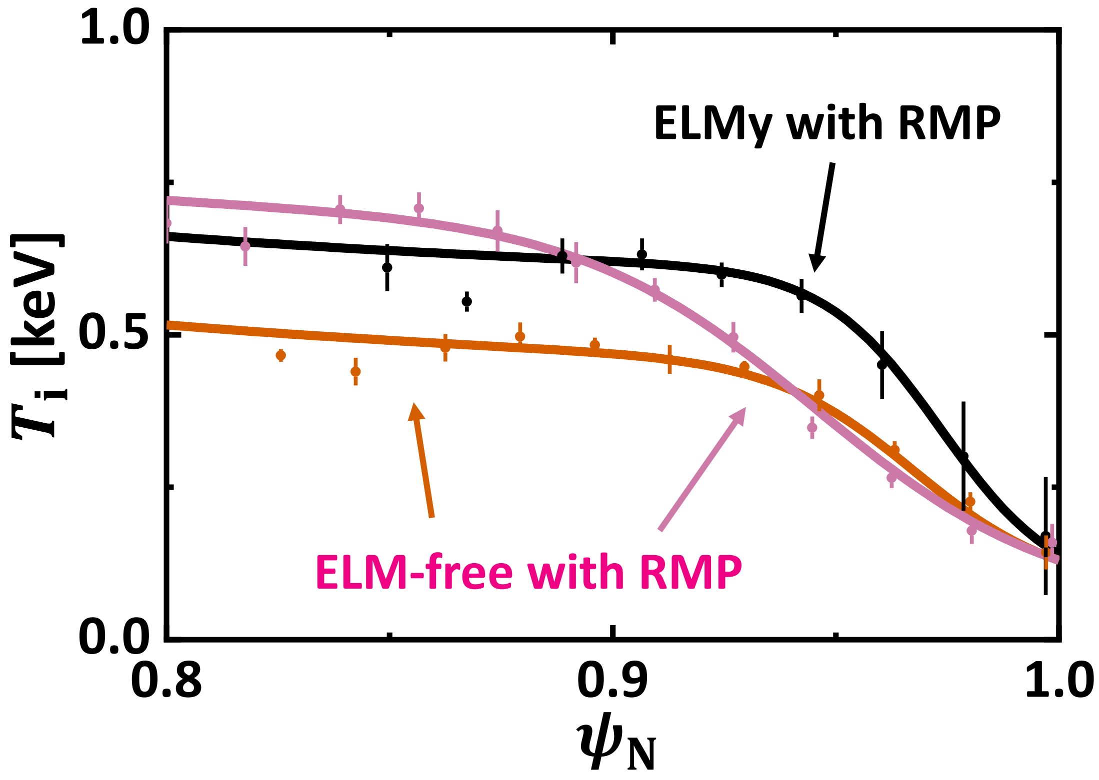
➡ Optimized ELM-free state

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.



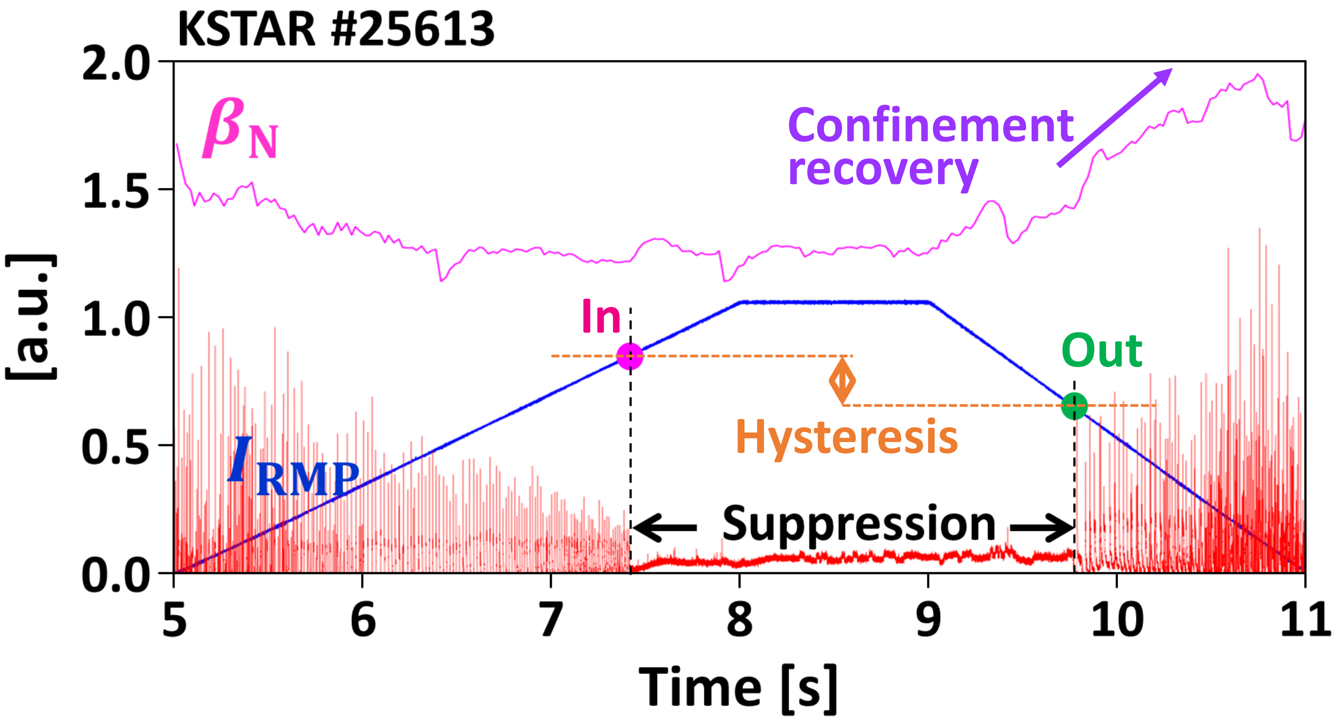
[Ion pedestal widening in ELM-free state]

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.

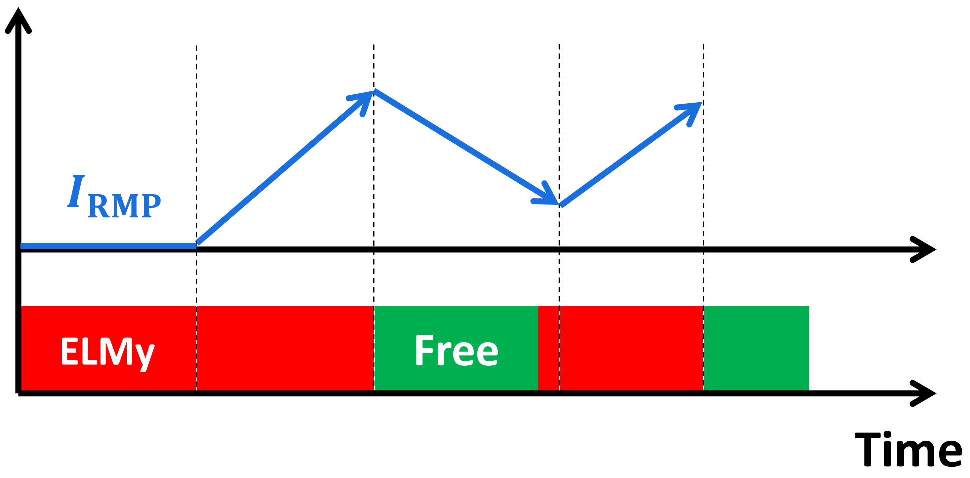


[RMP hysteresis at KSTAR, #25613]

Adaptive ELM control relies on simple concept, initiated from DIII-D and further demonstrated in KSTAR

- **Adaptive ELM control using RMPs**
  - ✓ I_{RMP} control with ELM detection [R. Shousha, APS-DPP 21]
    - ELMy → I_{RMP} ↑.
    - ELM-free → I_{RMP} ↓.
  - ✓ Previous real-time ELM control
    - Initiated from DIII-D [F. Laggner, NF 20].
    - Preliminary trial with prescribed control boundary.
    - Effective confinement recovery.

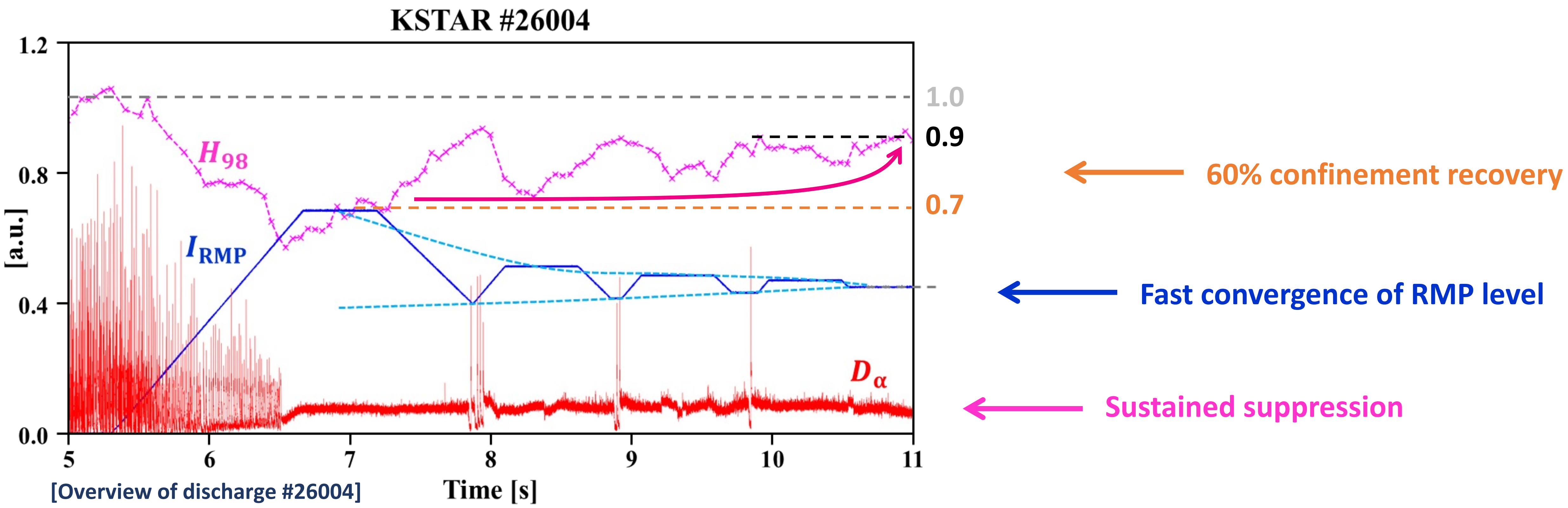
Further demonstration in KSTAR with more adaptive scheme



[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.**



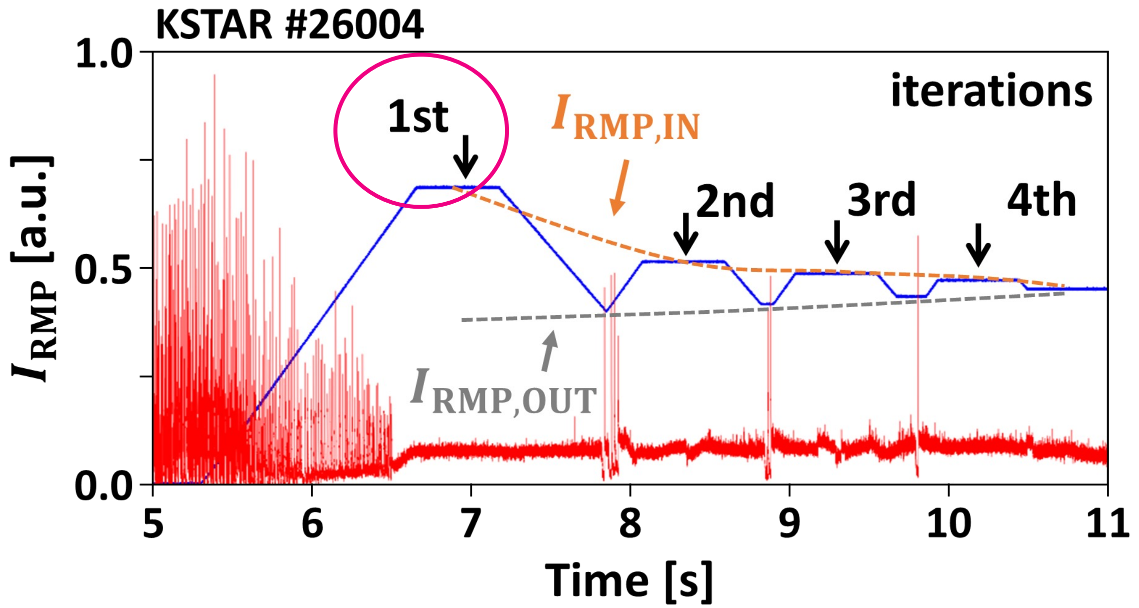
[Overview of discharge #26004]

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

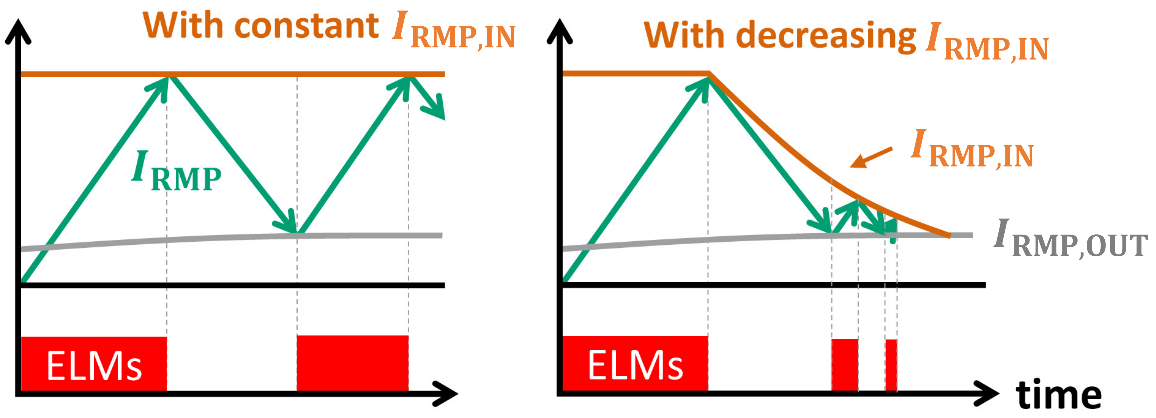
- **Changes in $I_{\mathrm{RMP,IN/OUT}}$ during control**
  - ✓ $I_{\mathrm{RMP,IN}}$: $4.6 \rightarrow 3.5$ kA (dominant).
  - ✓ $I_{\mathrm{RMP,OUT}}$: $3.3 \rightarrow 3.5$ kA.
  - ✓ Discontinuity $|I_{\mathrm{RMP,IN}} - I_{\mathrm{RMP,OUT}}| \downarrow$.

- **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]



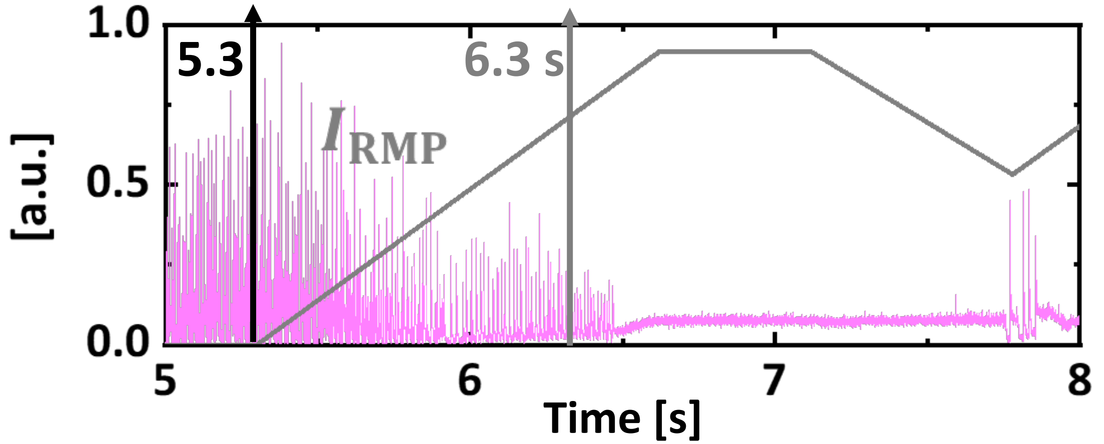
[Effect of decreasing $I_{\mathrm{RMP,IN}}$ on control convergence]

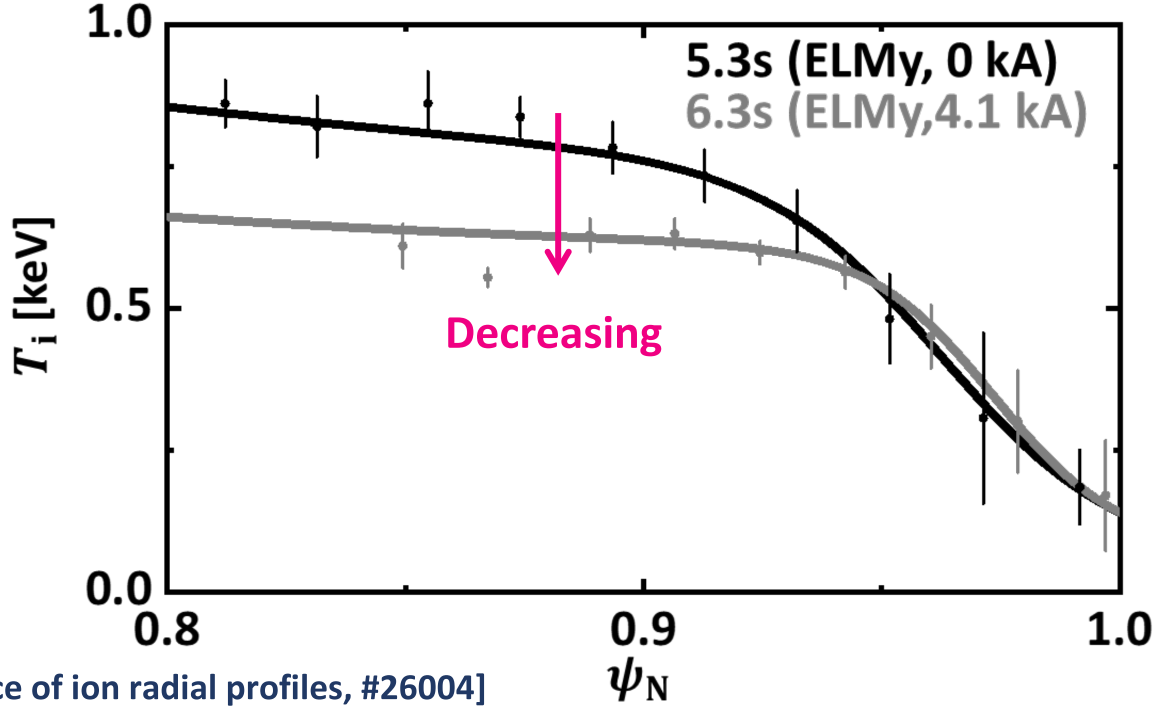
Contents

- **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 and field amplification
- Origin of widened ion pedestal
- Pedestal widening in other device
- Conclusion

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} ↑.**
      - Decreasing height.

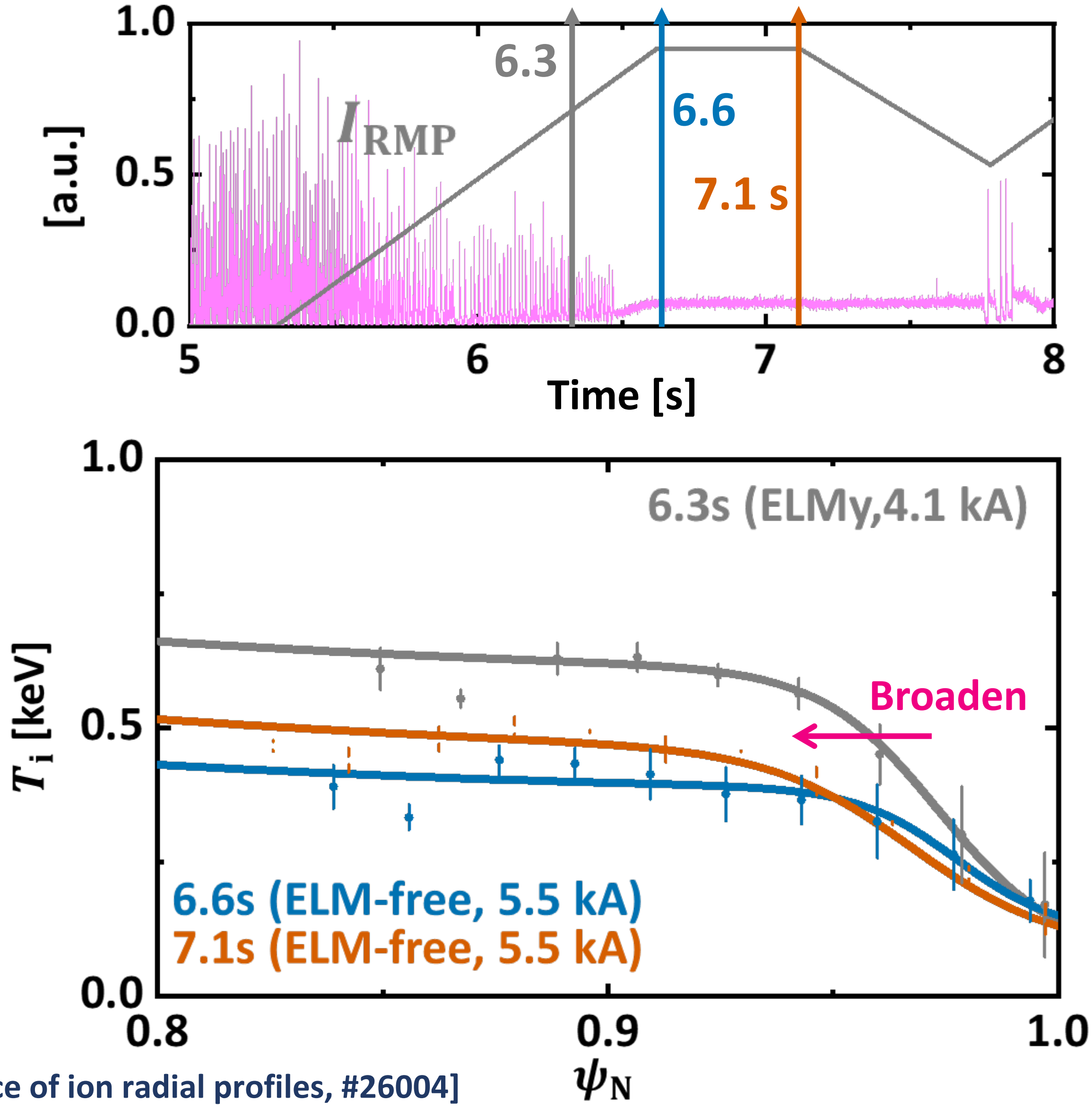




[Time trace of ion radial profiles, #26004]

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

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

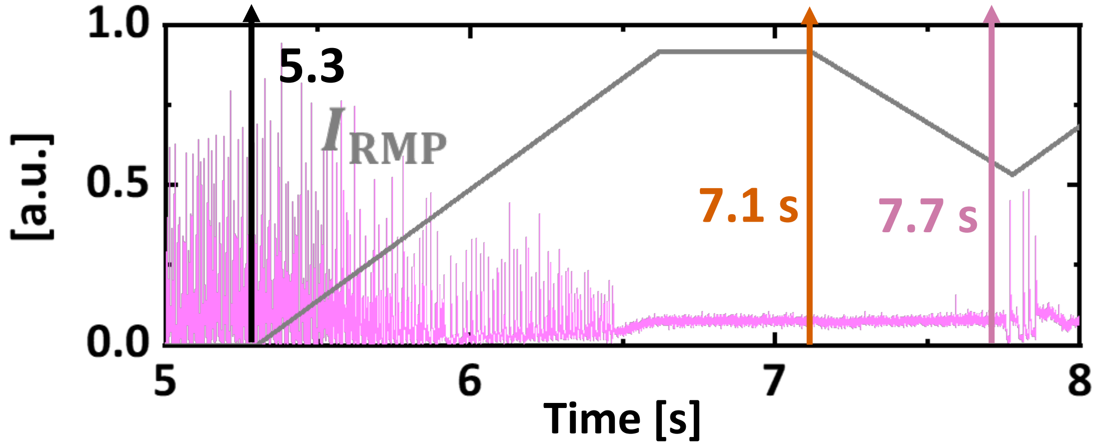


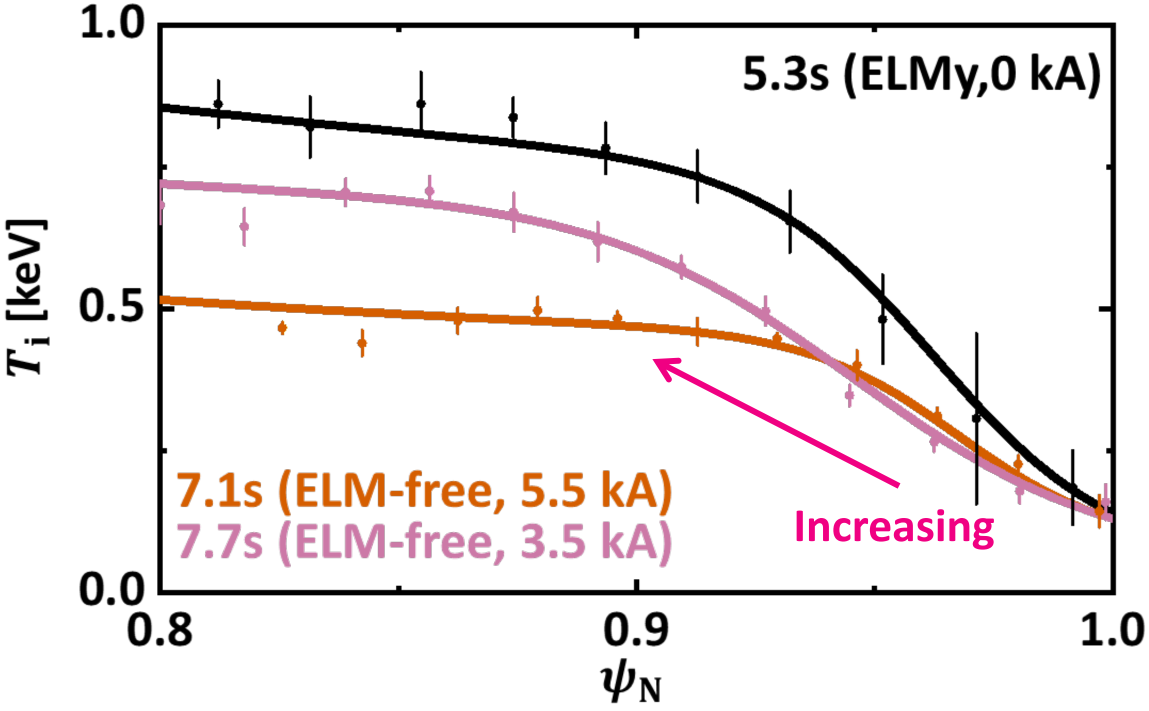
[Time trace of ion radial profiles, #26004]

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

- **Widening of ion pedestal**
  - ✓ <u>Ion pedestal</u> trace.
    - 5.3 → 6.3 → : ELMy, I_{RMP} ↑.
      - 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.

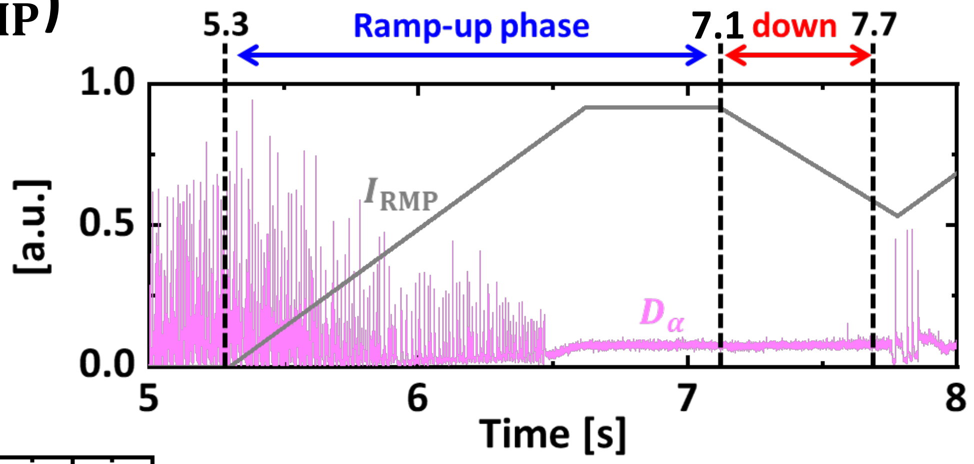


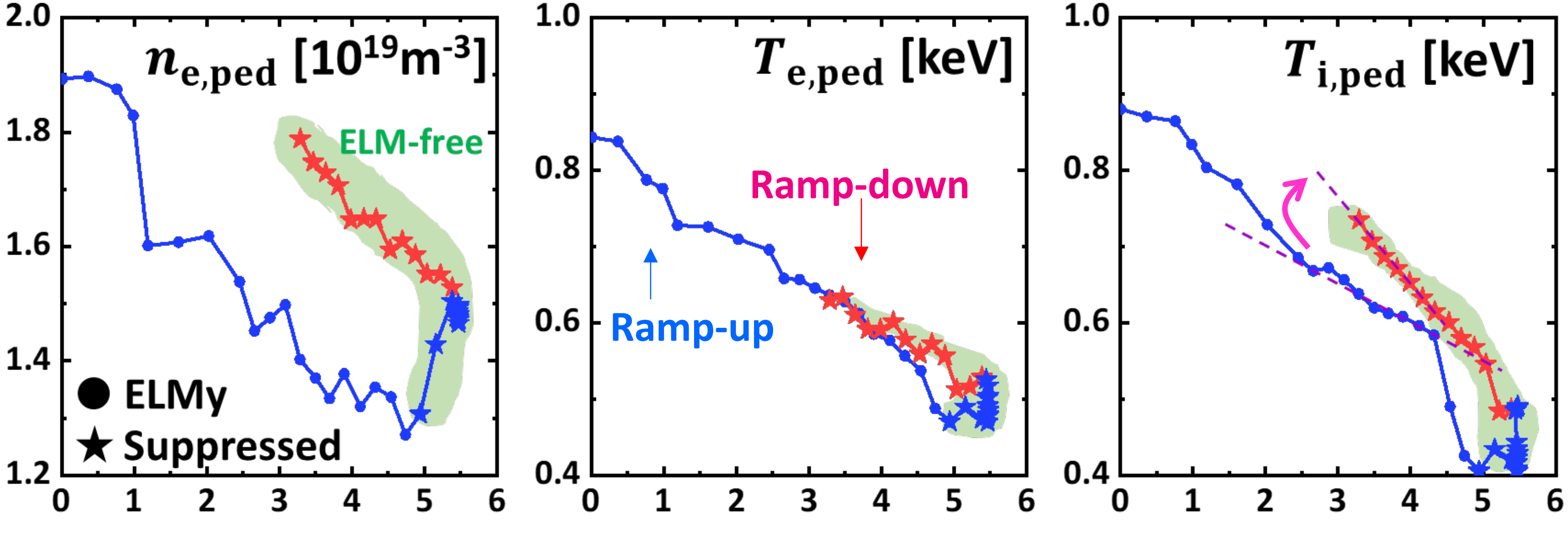


During ramp-down (ELM-free) periods, ion pedestal height shows larger variation to RMP strength than ramp-up (ELMy) phase.

✓ 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]

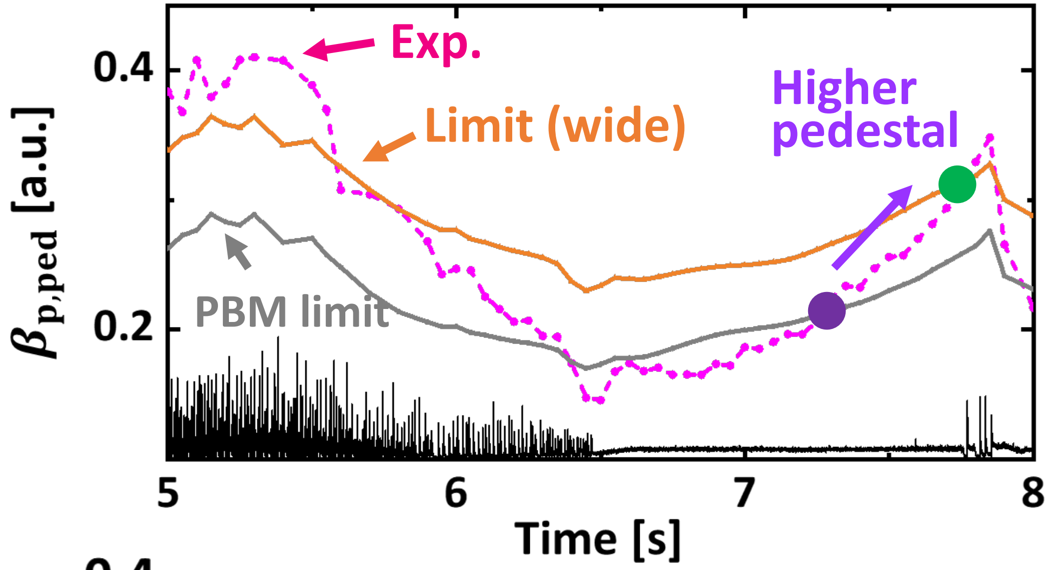
Boosted $T'_{\mathrm{i,ped}}$ during ELM-free state.

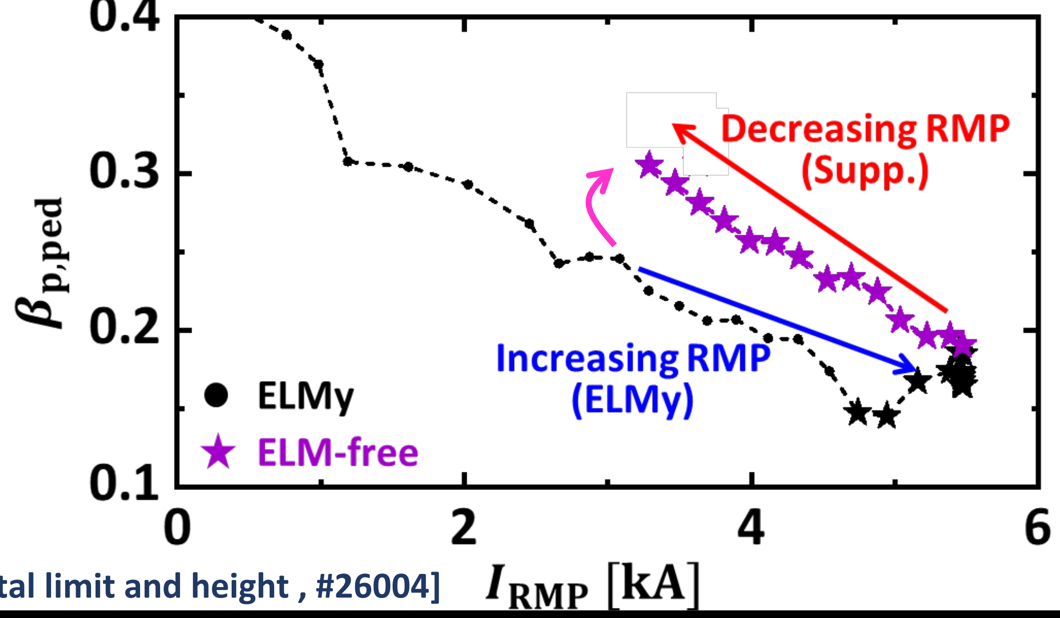
- May be explained by wider ion pedestal [Q. Hu PRL 2020].

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]

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- **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**
- **Pedestal widening in other device**
- **Conclusion**

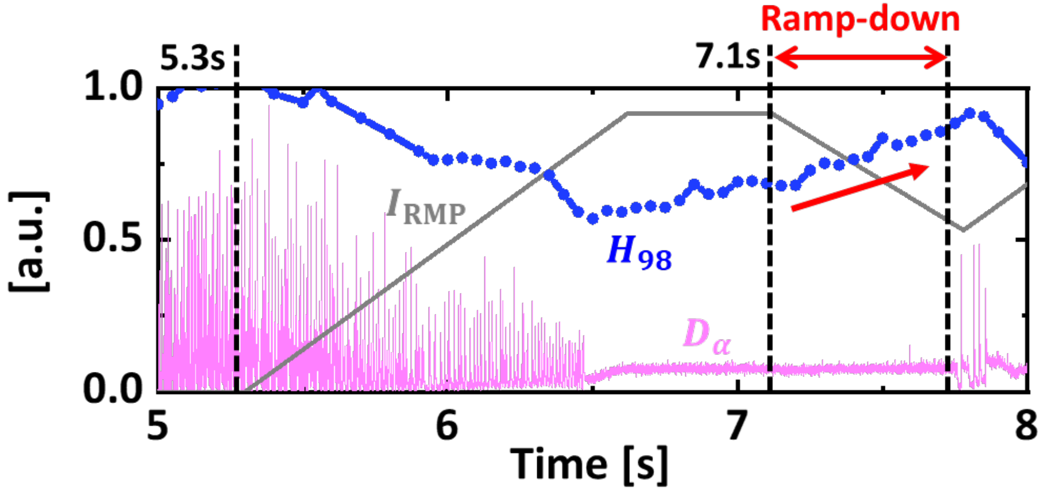
Enhanced pedestal recovery results in net confinement recovery more than just returning to previous ELMy state by lowering RMP

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

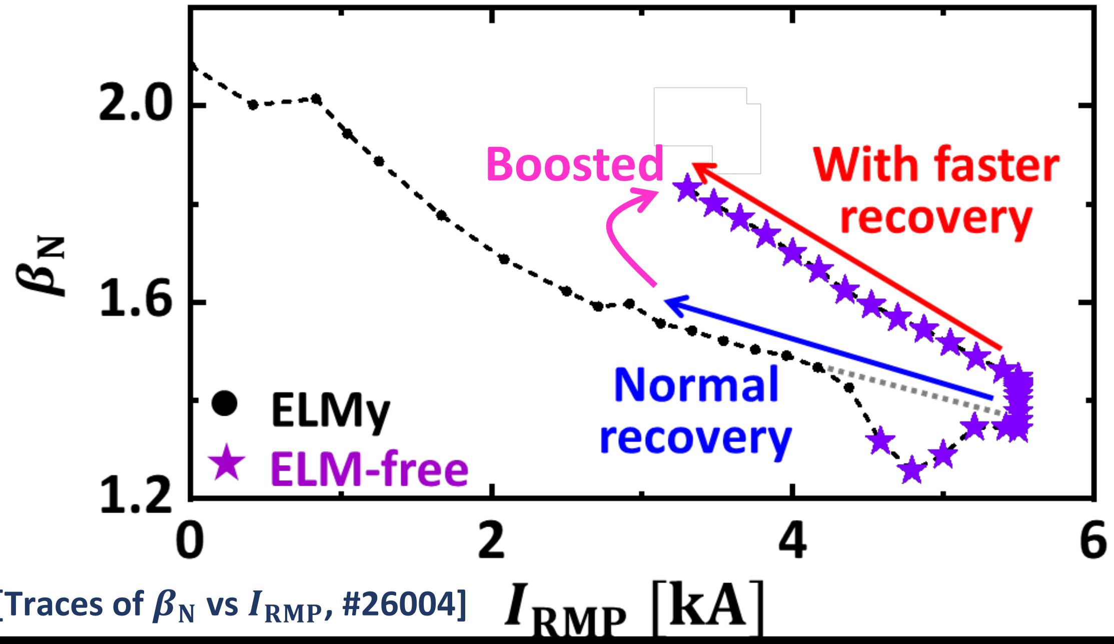
$n_{e,ped}$	$T_{e,ped}$	$T_{i,ped}$
20%	13%	67%

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

➡ Boosted confinement recovery (>50%).



[Time traces of H98, #26004]

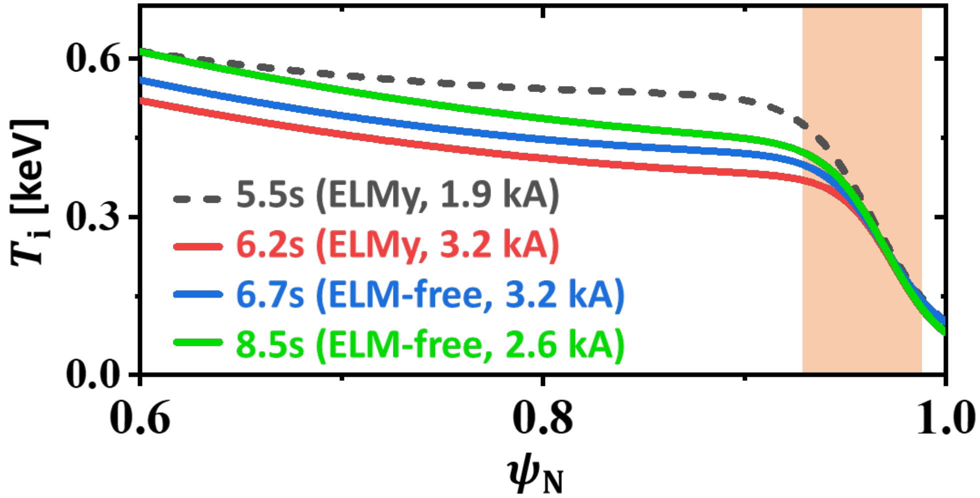


[Traces of β_N vs I_{RMP}, #26004]

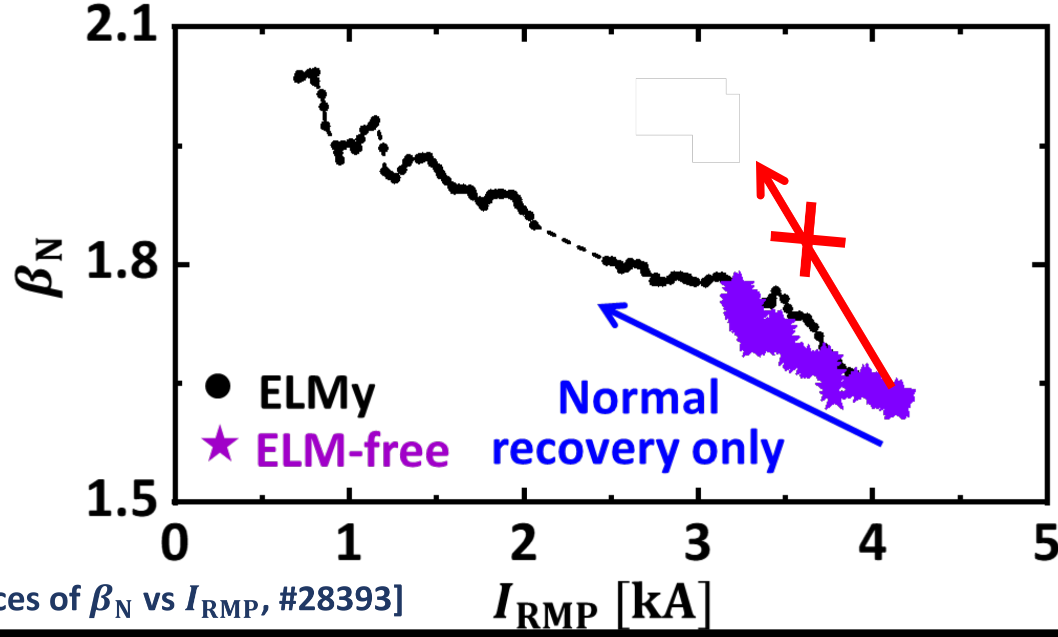
Shot comparison clearly shows that "boosted" confinement recovery is outcome of widened ion pedestal

- **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]

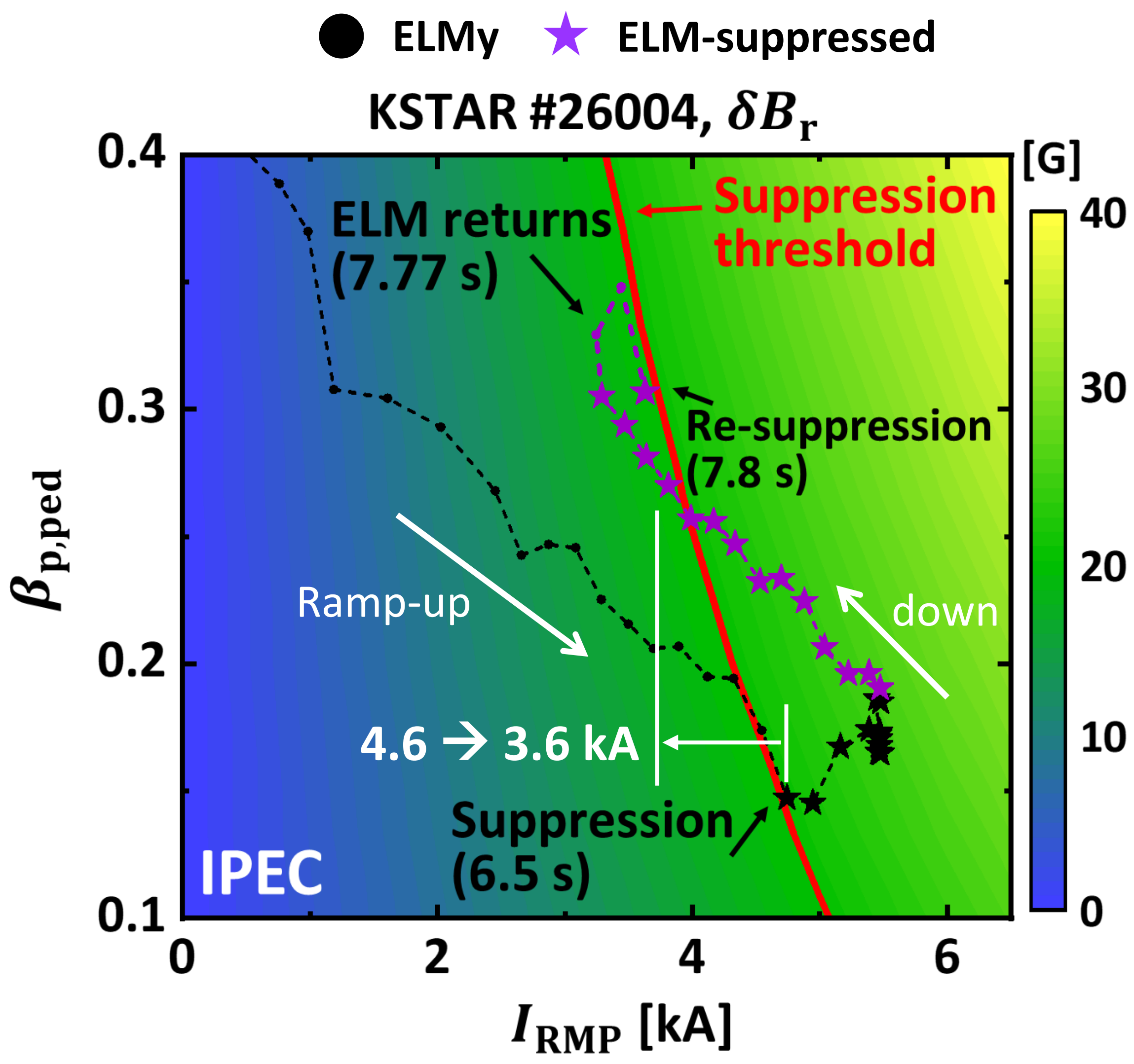


[Traces of β_N vs I_{RMP}, #28393]

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 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.

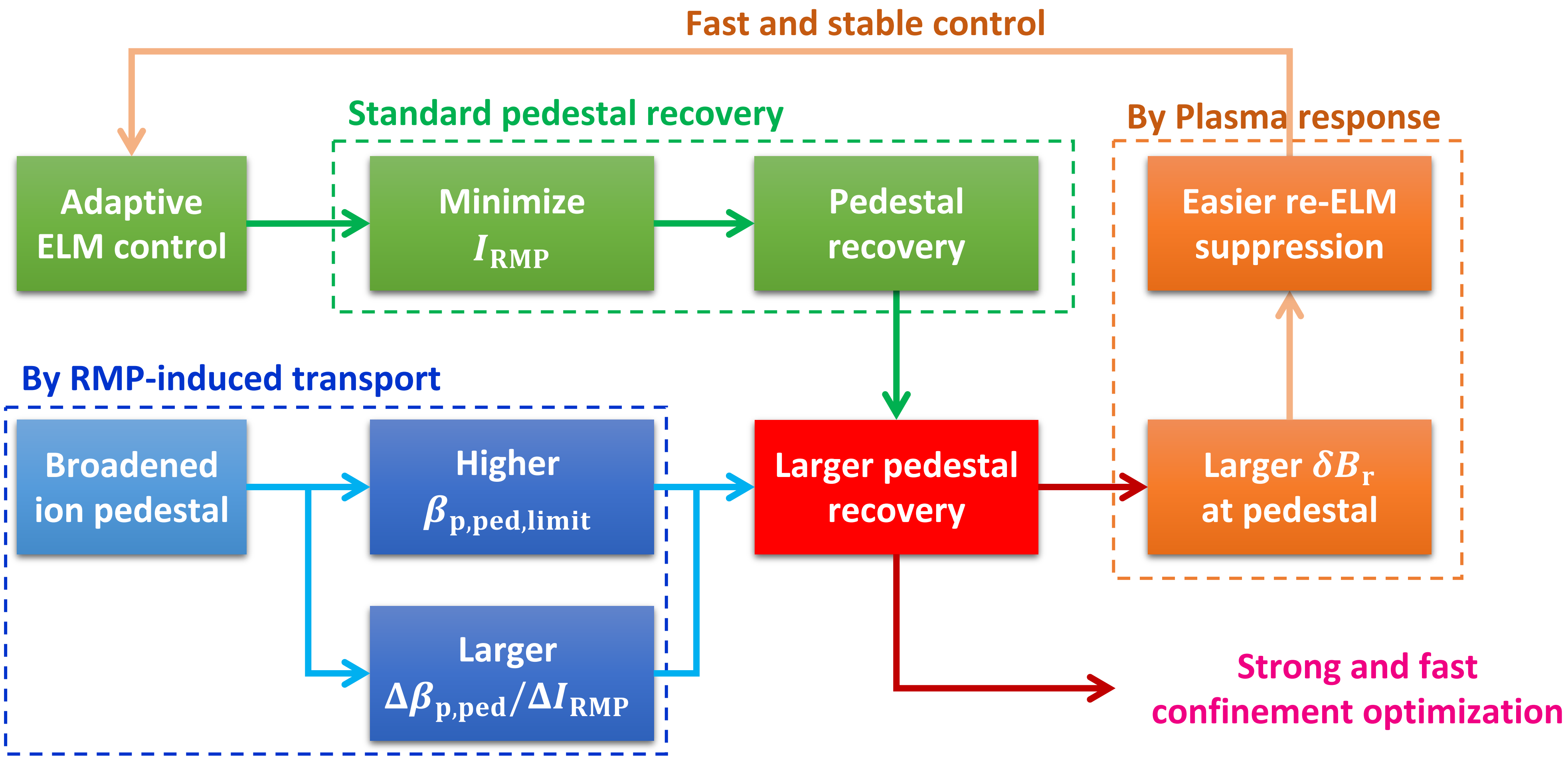
➡ $I_{\mathrm{RMP,IN}}\downarrow$ by wider ion pedestal.



[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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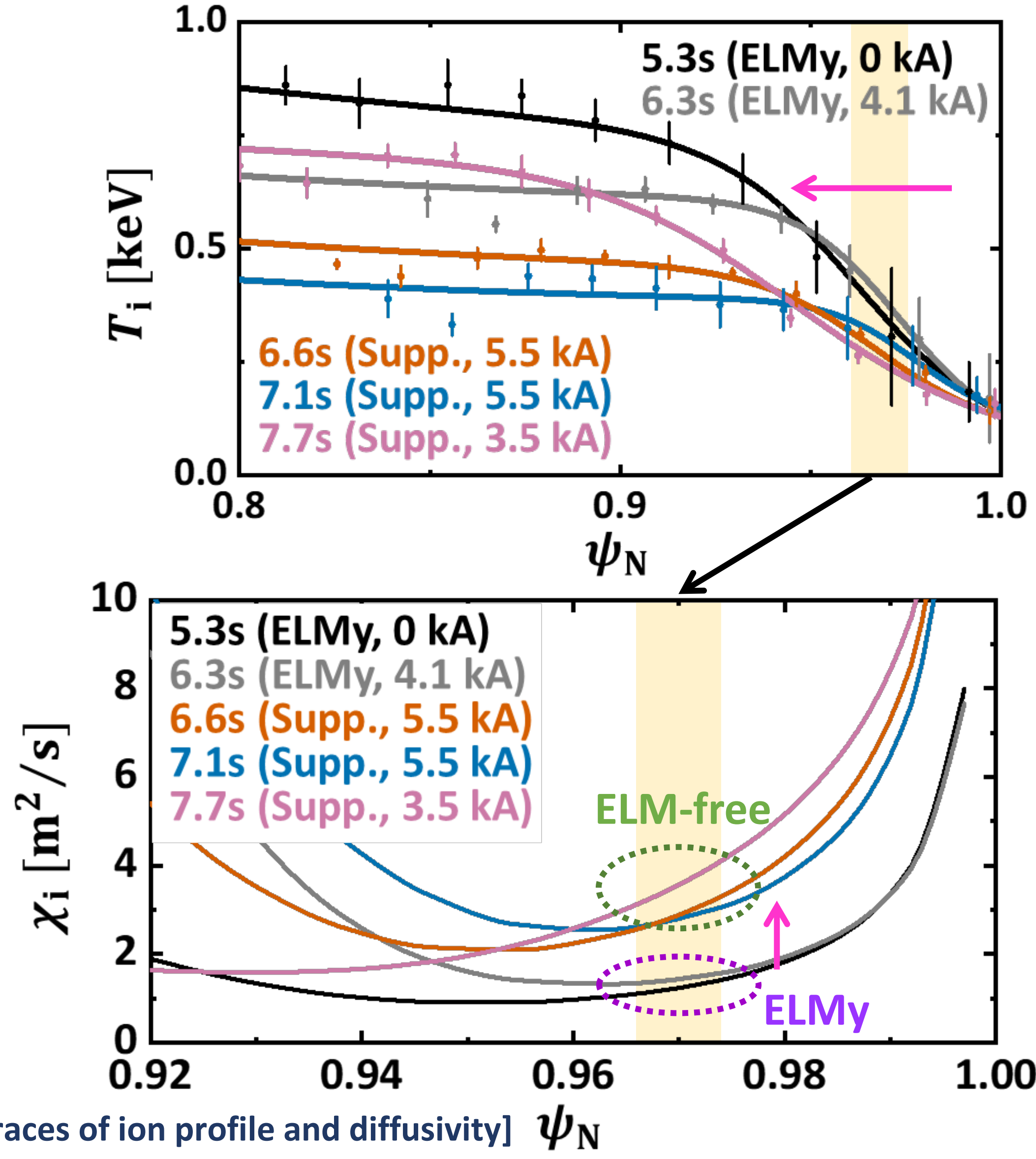
- **Enhanced confinement recovery and field amplification** → **Decreases $I_{\mathrm{RMP,IN}}$.**
- **Origin of widened ion pedestal**
- **Pedestal widening in other device**
- **Conclusion**

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.**
    - **<u>No proportionality</u> on I_{RMP} during ELM-free.**
      → Sustained pedestal gradient with I_{RMP} ↓.

➡ **Additional transport mechanism may be required to explain pedestal gradient behavior. (in addition to classical transport)**



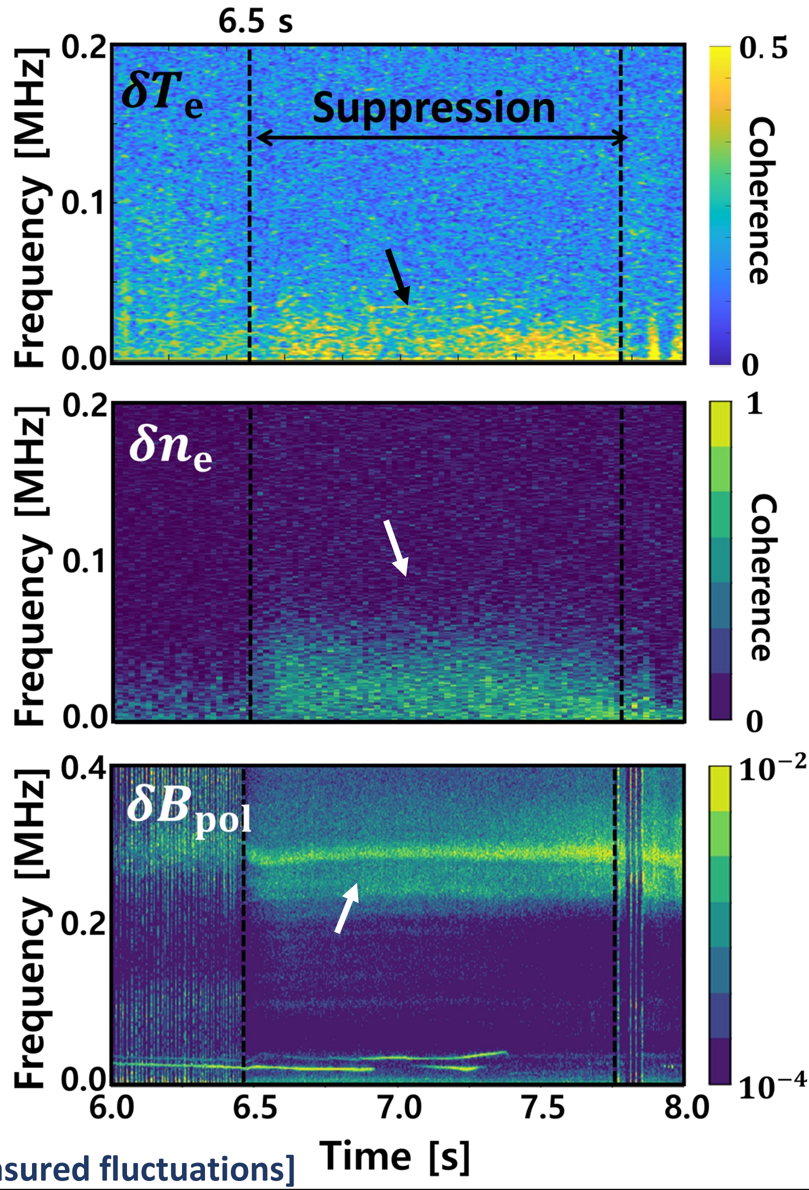
[Time traces of ion profile and diffusivity]

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, $k\rho_s < 0.3$).
    - δB_{pol} and CSS: 200-400 kHz (shorter, $k\rho_s > 1$).

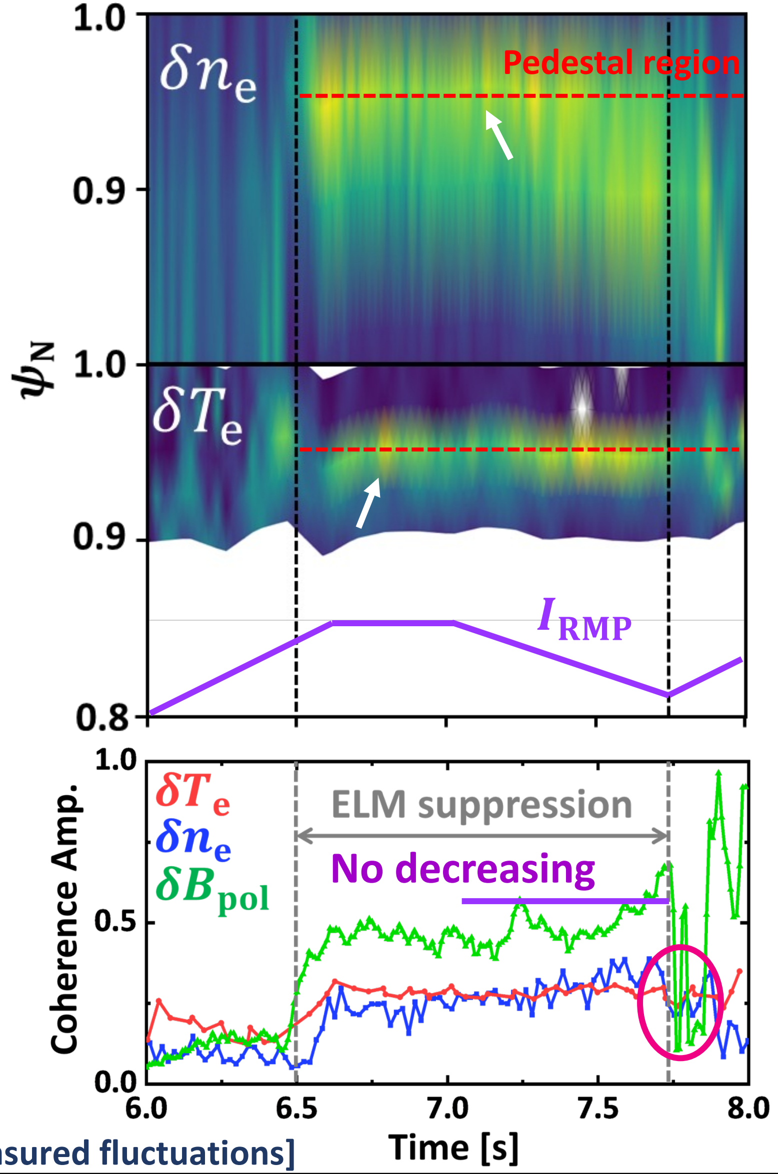
      → More than one different fluctuations.



[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 maintaining favorable wide pedestal. → RT-Adaptive control is effective.



[Time traces of measured fluctuations]

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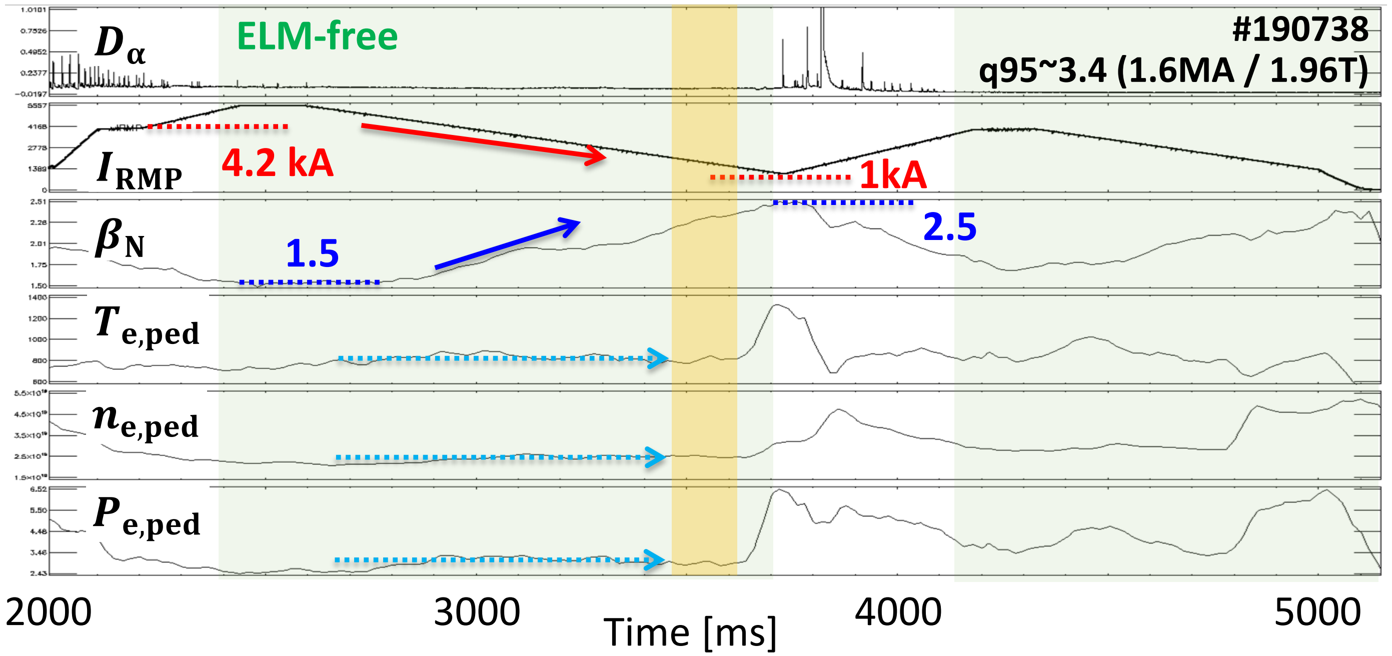
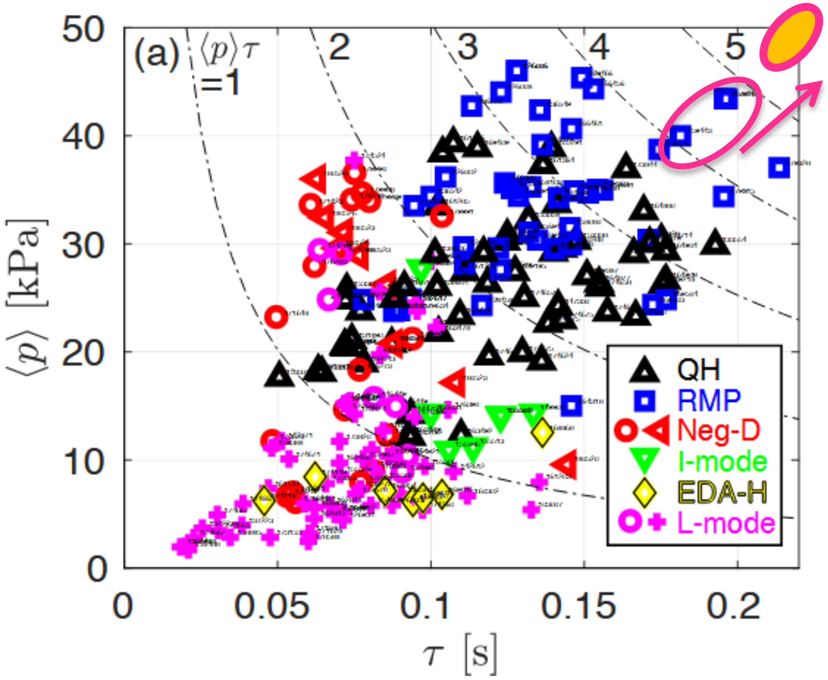
- **Widened ion pedestal and increased pedestal response** → **Enhanced pedestal recovery.**
- **Enhanced confinement recovery and field amplification** → **Decreases $I_{\mathrm{RMP,IN}}$.**
- **Origin of widened ion pedestal** → **Possibly, turbulence.**
- **Pedestal widening in other device**
- **Conclusion**

New adaptive ELM control in DII-D exhibits long ELM-free state with very low RMP strength, beating the previous 3D control record

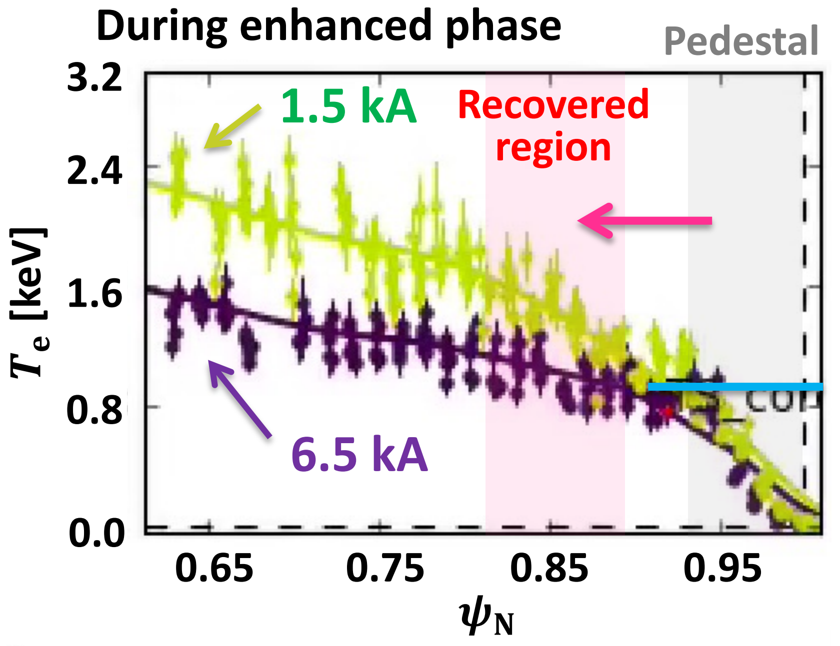
- **Confinement recovery with new adaptive control**
  - ✓ **<u>Feedback</u> lower I_{RMP} boundary**
    - **Achieving high confinement exceeding the previous control record.**
  - ✓ **Enhanced recovery**
    - **Significant β_N recovery I_{RMP} ↓.**

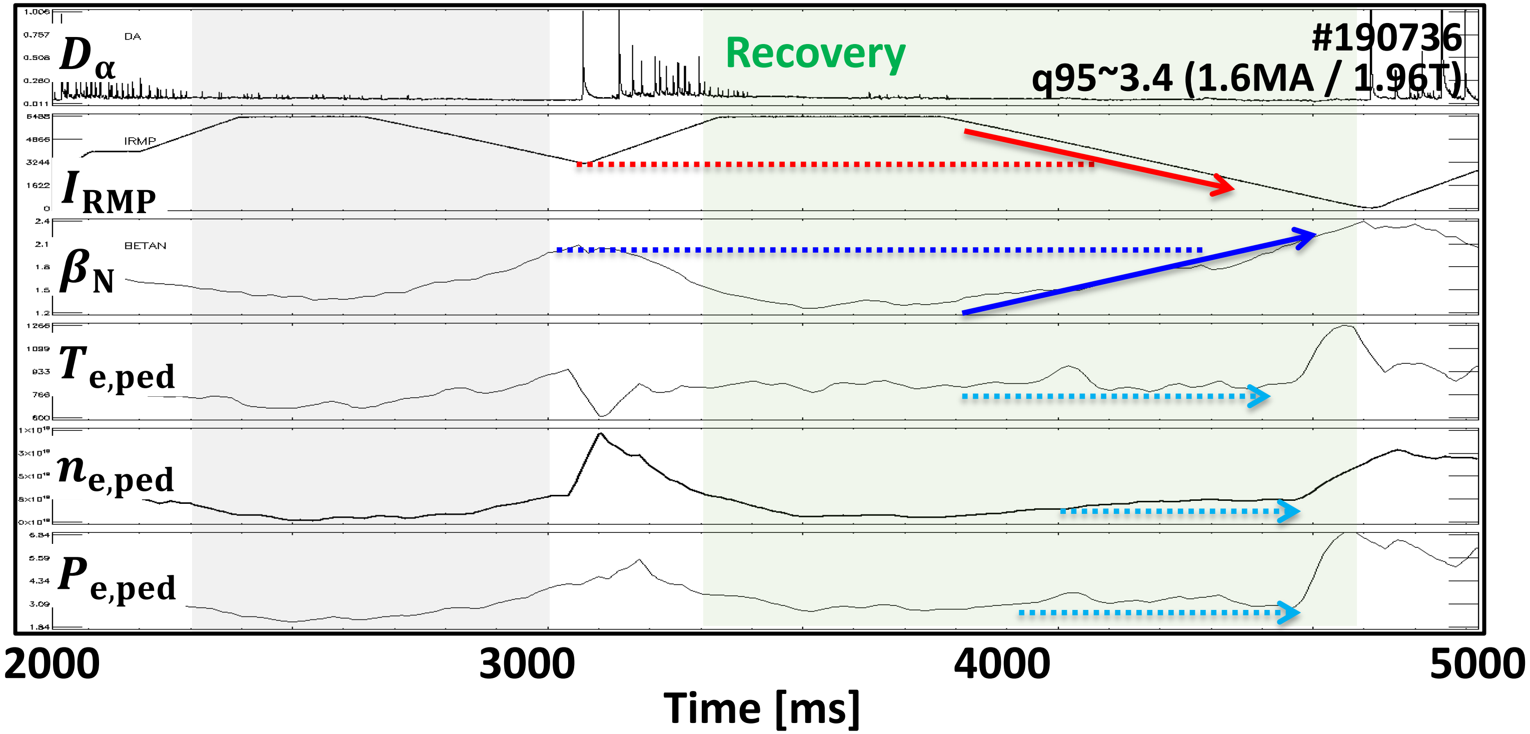


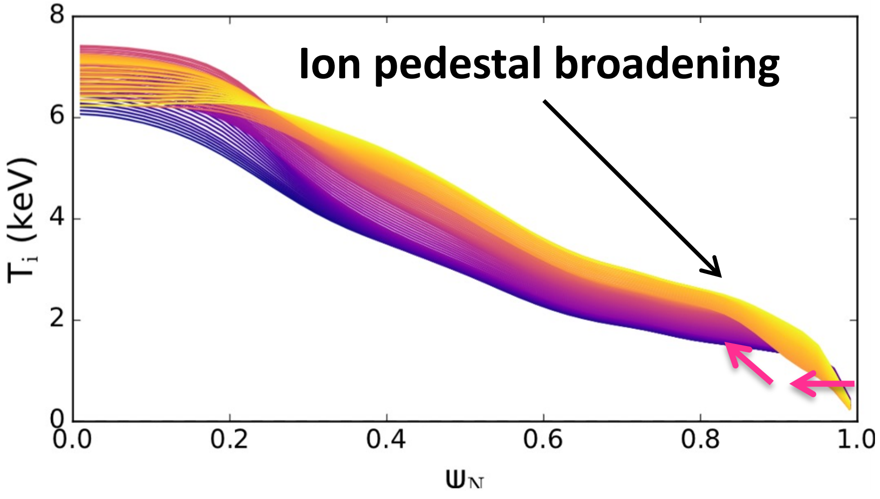


Profile shows that adaptive control and enhanced confinement recovery followed by wider pedestal

- **Enhanced confinement recovery**
  - ✓ Pedestal broadening
    - Strong in ion and weaker in electron pedestal.
      - More stable pedestal and higher confinement.







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- **Origin of widened ion pedestal** → **Possibly, turbulence.**
- **Pedestal widening in other device** → **Seems consistent.**
- **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 better convergence.**
- **RMP-induced ion-scale turbulence highly correlates to ion pedestal**
  - ✓ **Similar trend in fluctuation and ion transport.**
- **Adaptive scheme is an effective way to utilize its favorable effect**
  - ✓ **Immediate RMP ramp to sustain the turbulence and wide pedestal.**

[More details in S.K.Kim et al., NF 62, 026043 / R. Shousha et al., POP 29, 032514]

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