NFRI 국가핵융합연구소 National Fusion Research Institute

Successful ELM Suppressions in a Wide Range of q_{95} Using Low n RMPs in KSTAR and its Understanding as a Secondary Effect of RMP

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OUTLINE

1. A brief summary of ELM-RMP experiments in KSTAR

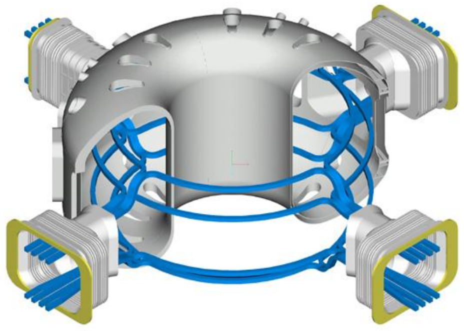
- Complete ELM-suppressions by using low n (=1 or 2) RMP fields in a wide range of q_{95}

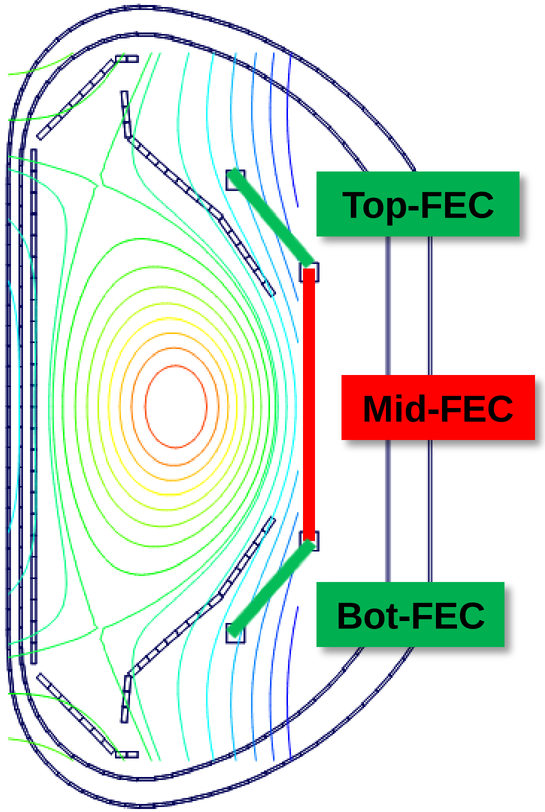
2. Understanding of ELM-suppression physics mechanism

- Observation as a secondary effect of RMP
- A distinctive transport bifurcation as a key
- ELM-suppression as a new state of H-mode

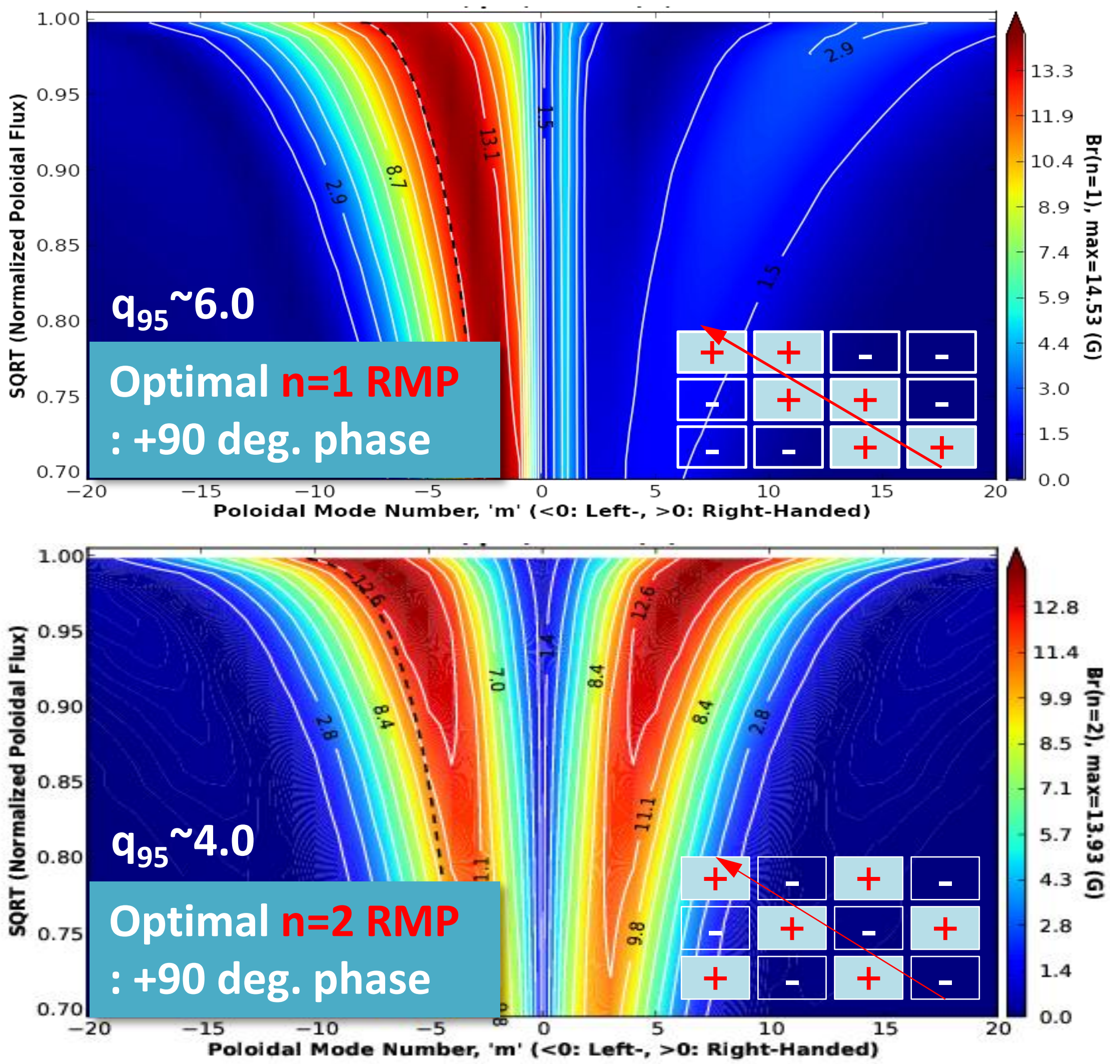
3. Summary and discussion

Optimal RMP fields by three rows of FEC coils

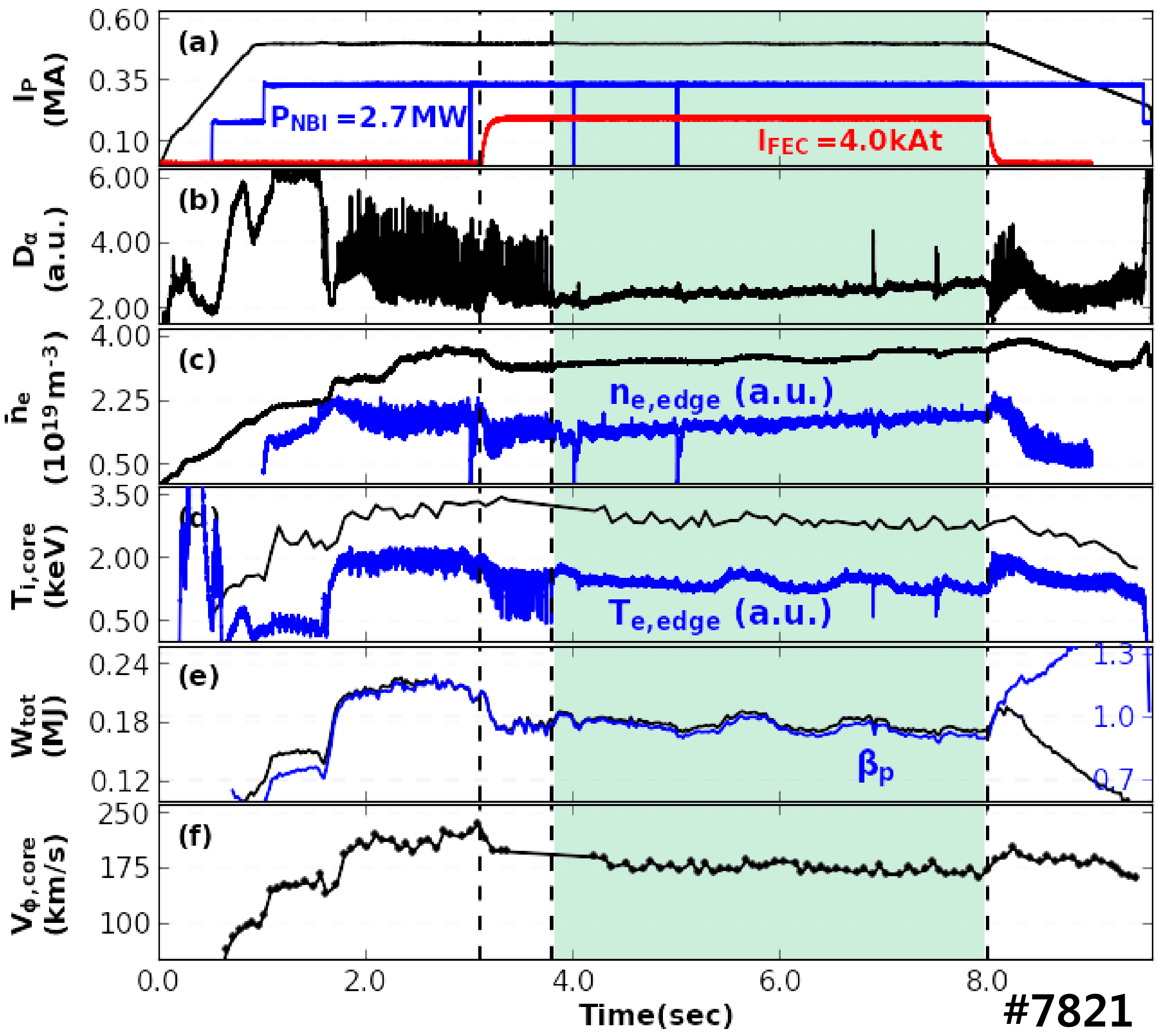




FEC coils used for RMP = 3 (poloidal) x 4 (toroidal)



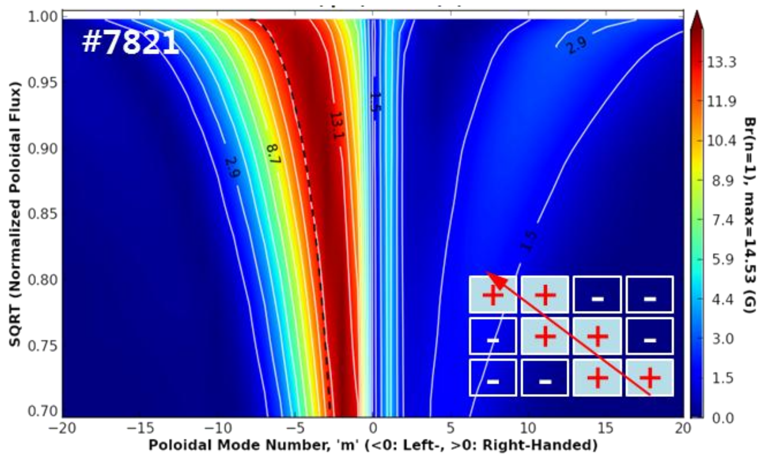
A long (>4.0sec) ELM-suppression achieved by using n=1 RMP (High q_{95})



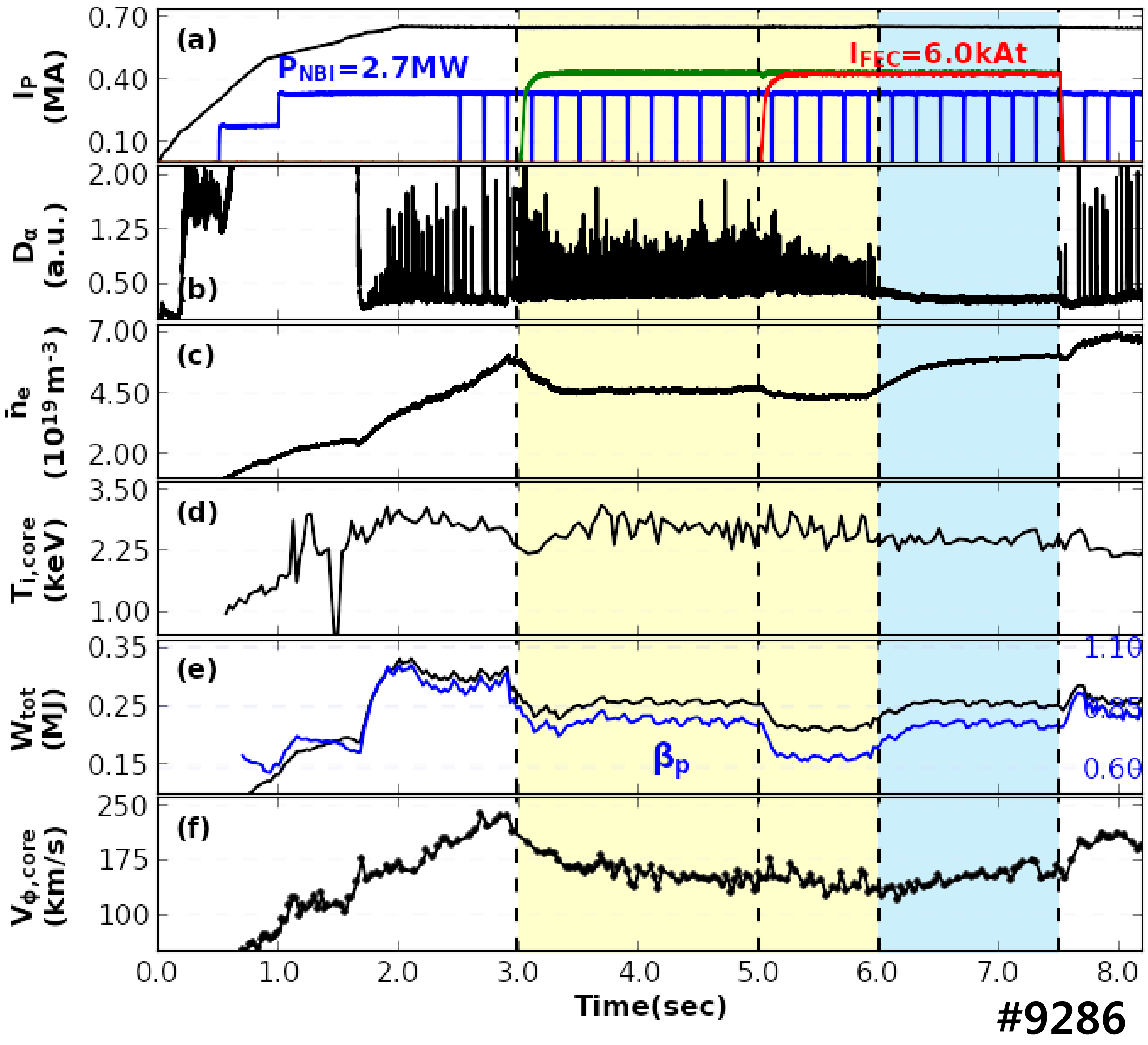
- **Optimal q_{95} range=5.2~6.3**
- **Long suppression (t>4.0sec)**

- **Up to ~15% confinement degradations: n_e, W_{tot}, β_p etc**

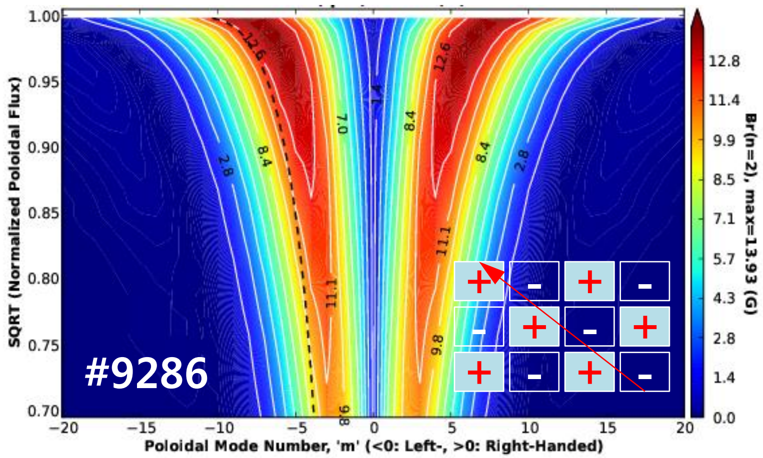
- **Global decrease of V_ϕ**



In a low q_{95}, ELM-suppression achieved by using n=2 RMPs in a similar way



- **Optimal q_{95} range=3.7~4.1**
- **Up to ~28% confinement degradations: n_e, W_{tot}, β_p etc**
- **Take a look at the change of confinements when ELMs suppressed**



Generic features of RMP-driven ELM-suppressed H-mode discharges in KSTAR

Universal to most of devices

- ELMs can be mitigated or suppressed by properly configuring RMP fields
- ELM changes are dominantly relying on the resonant plasma responses
- Usually some amounts of confinement degradations are accompanied, such as on $\langle n_e \rangle$, W_{tot}, β_p etc

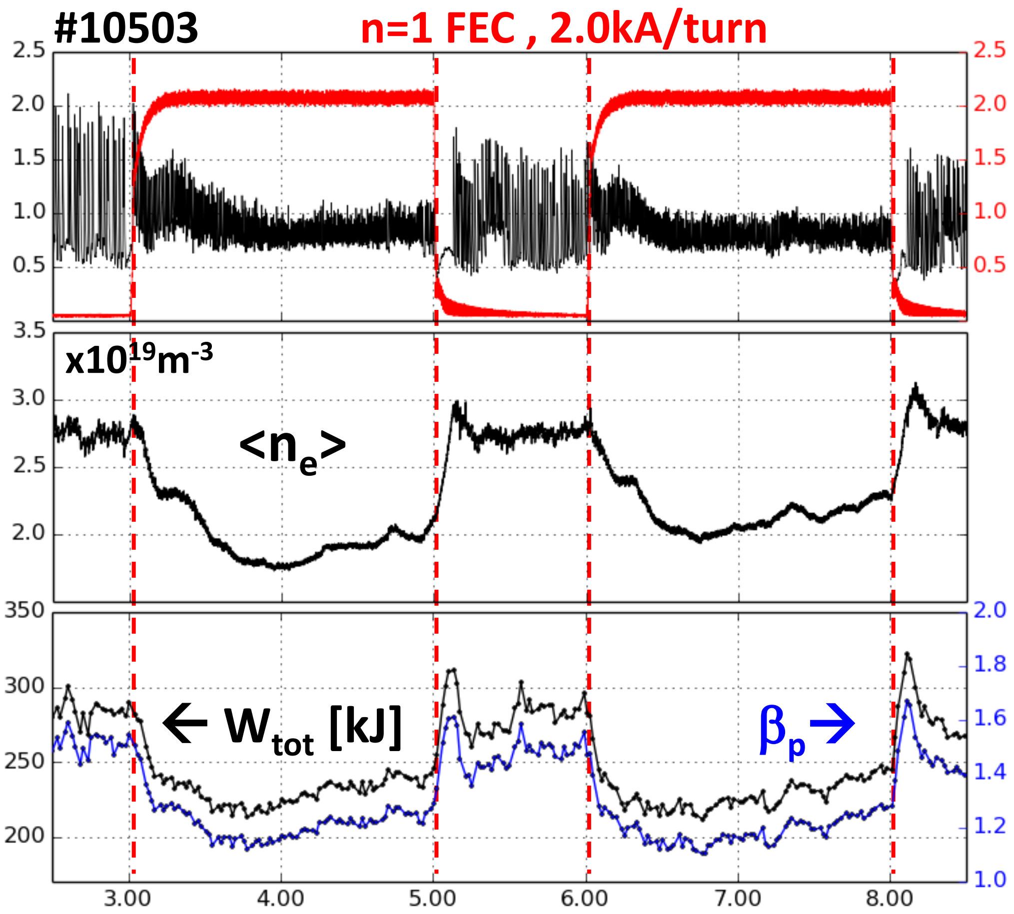
Unique in KSTAR

- Interestingly, the change of confinement is depending on not only the applied field strength but also the ELM state
- Several distinctive phenomena associated with ELM-suppression observed such as saturated evolutions of $T_{e,edge}$ and D_α, broad-band increase of dB_θ/dt, increased spikes on I_{sat}, and so on

ELM-suppression appears as a delayed or secondary effect of RMP

- Note that most of other plasma responses such as density pump-out, rotation changes, and ELM-mitigation, are observed as a prompt response

Most of plasma responses, including ELM-mitigation, appear promptly after RMP fields on

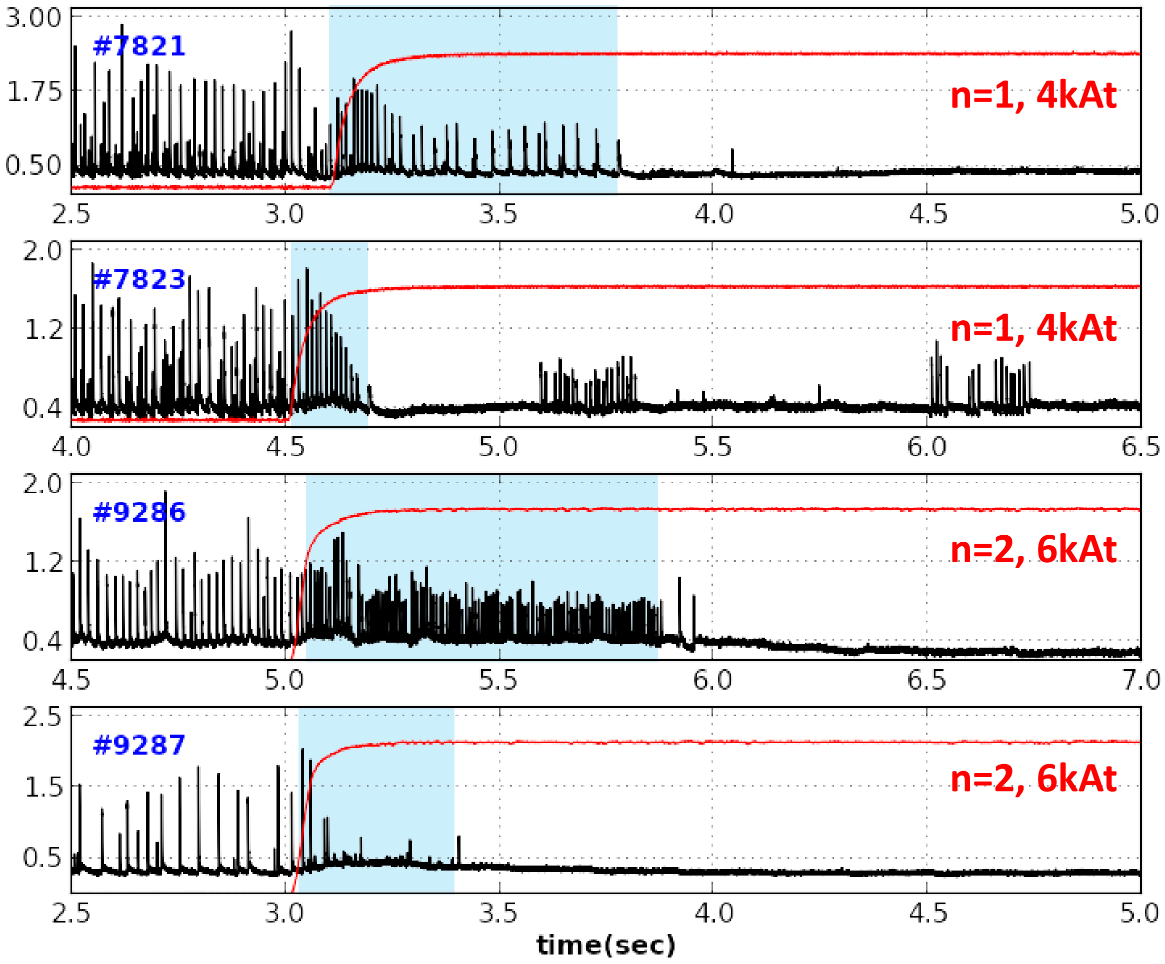


Most of plasma responses appear quickly (promptly) after RMP applied

- Density pump-out
- Stored energy drop
- Rotation damping
- ELM-mitigation
- …

ELM-mitigation is also one of prompt responses

However, ELM-suppression seems to be a delayed response (or a secondary response)



- **Various time-delays were found prior to ELM-suppression**
  - **Varied from 0.1 to >1.0sec**

- **Typical field penetration or transport time-scales are shorter than these**

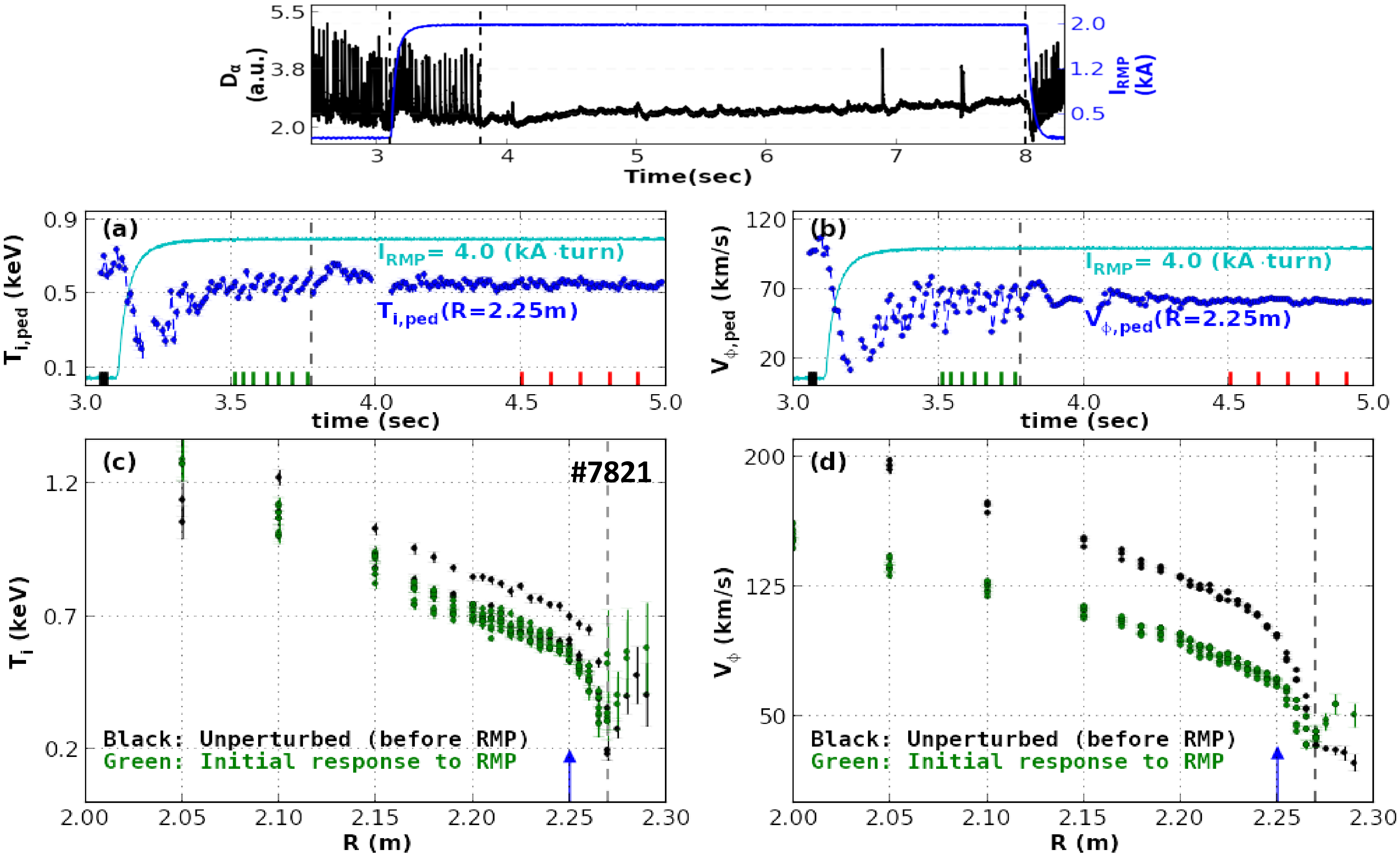
- **This time delay, prior to ELM-suppression, might be universal**
  - **Similar time-delays found in DIII-D plasmas as well**

What makes the long time delay before the transition to ELM-suppression phase ?

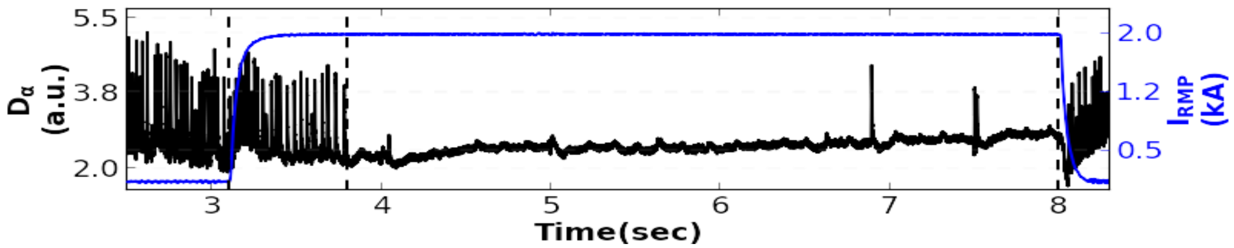
- **Is there something slowly varying quantities?**
- **Is the edge profile change able to explain it ?**

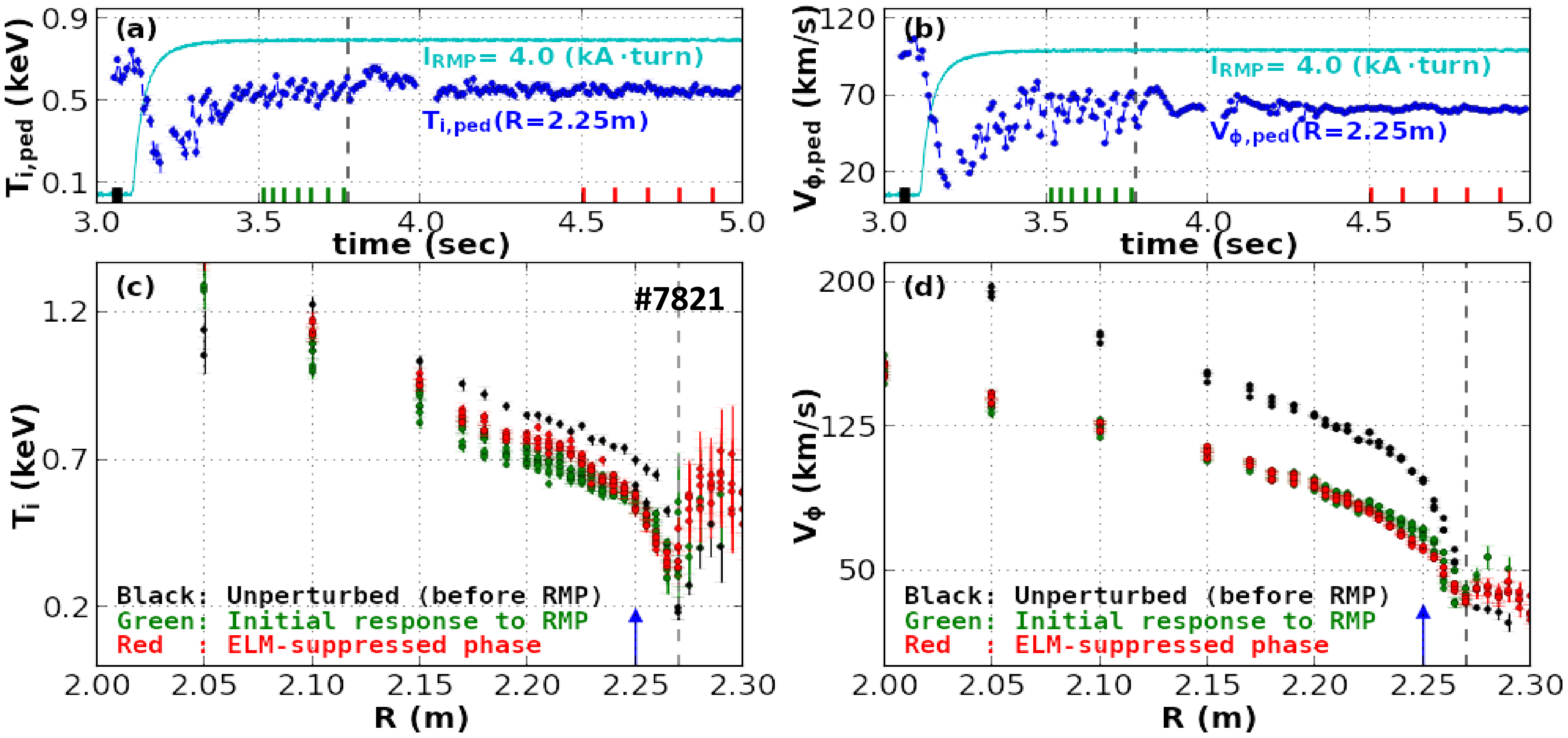
➔ Looks not clear and not sufficient to explain it

Dominant changes of edge profiles appeared shortly in the initial phase and then settled down quickly



Another small changes on edge profiles were followed once the ELM state changed (suppressed)





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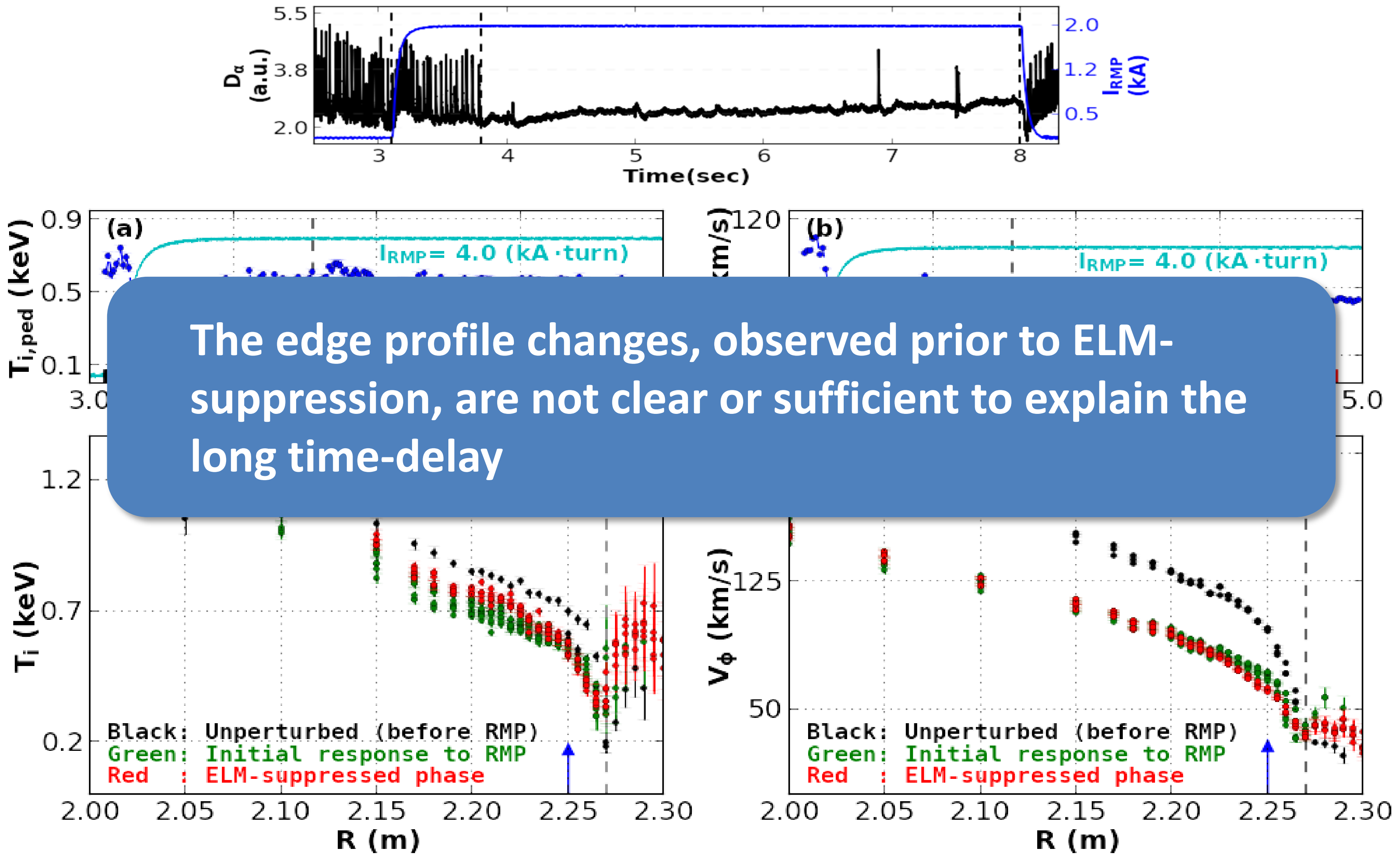
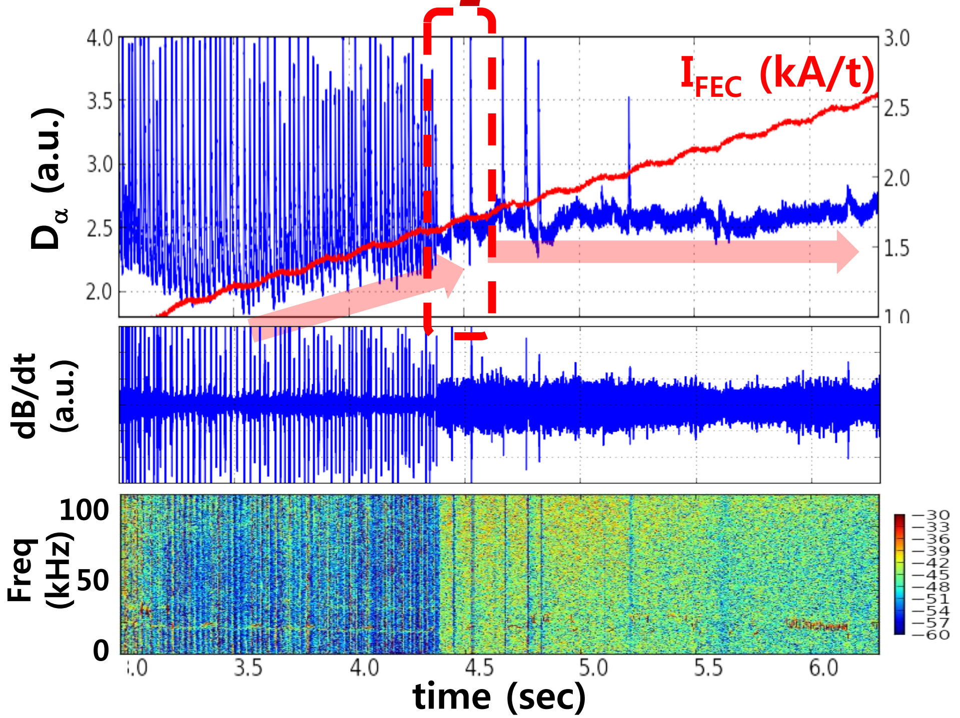


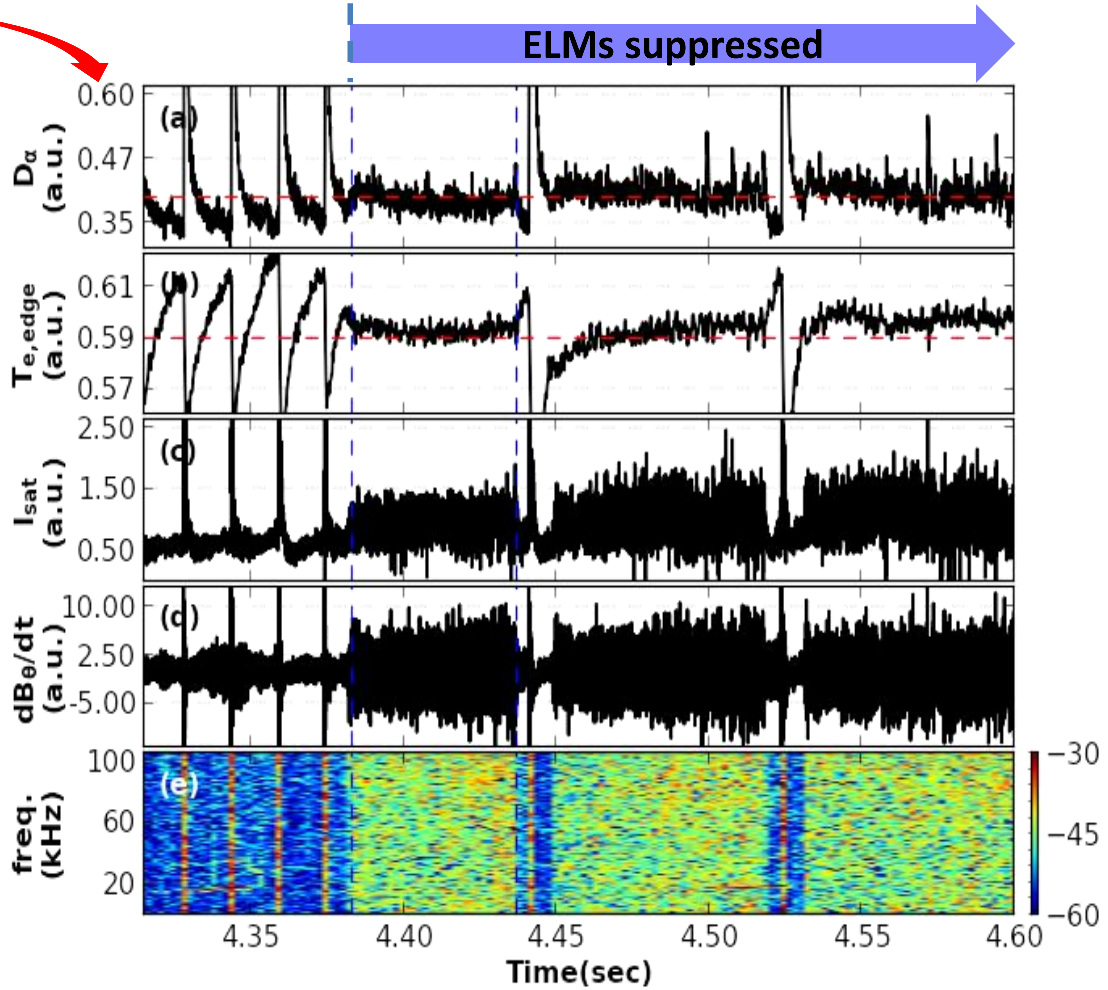
The edge profile changes, observed prior to ELM-suppression, are not clear or sufficient to explain the long time-delay

Then, what happened prior to ELM suppression ?
Is there something abruptly occurred ?

→ Yes, we found several distinctive phenomena directly associated with ELM-suppression

Several apparent and abrupt changes were found associated with the ELM state change (i.e. suppression)



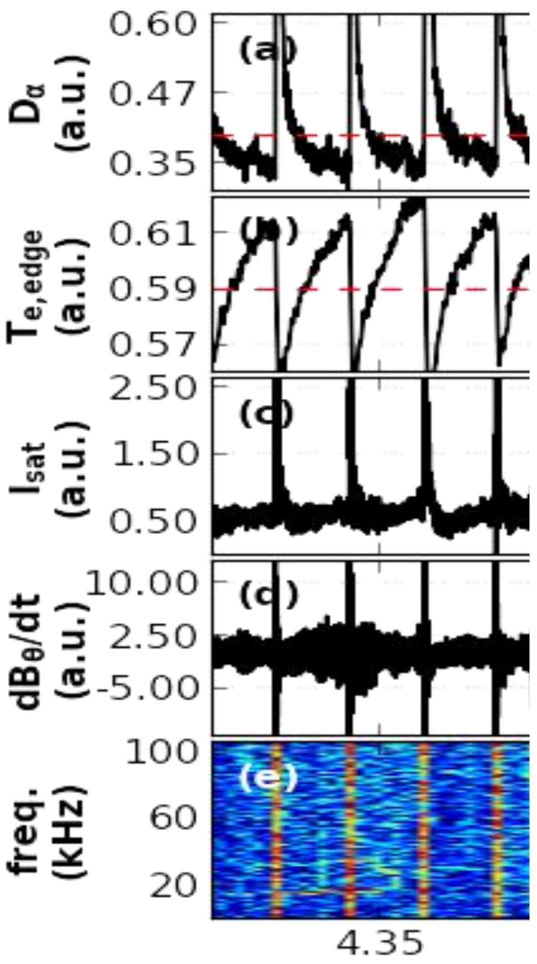


* Y.M. Jeon, et al., submitted to PRL 2013

- Base-level of $D_\alpha \propto I_{FEC}$ (particle pump-out)
- Then, it was saturated as ELMs suppressed

- Apparent, abrupt changes found in various parameters

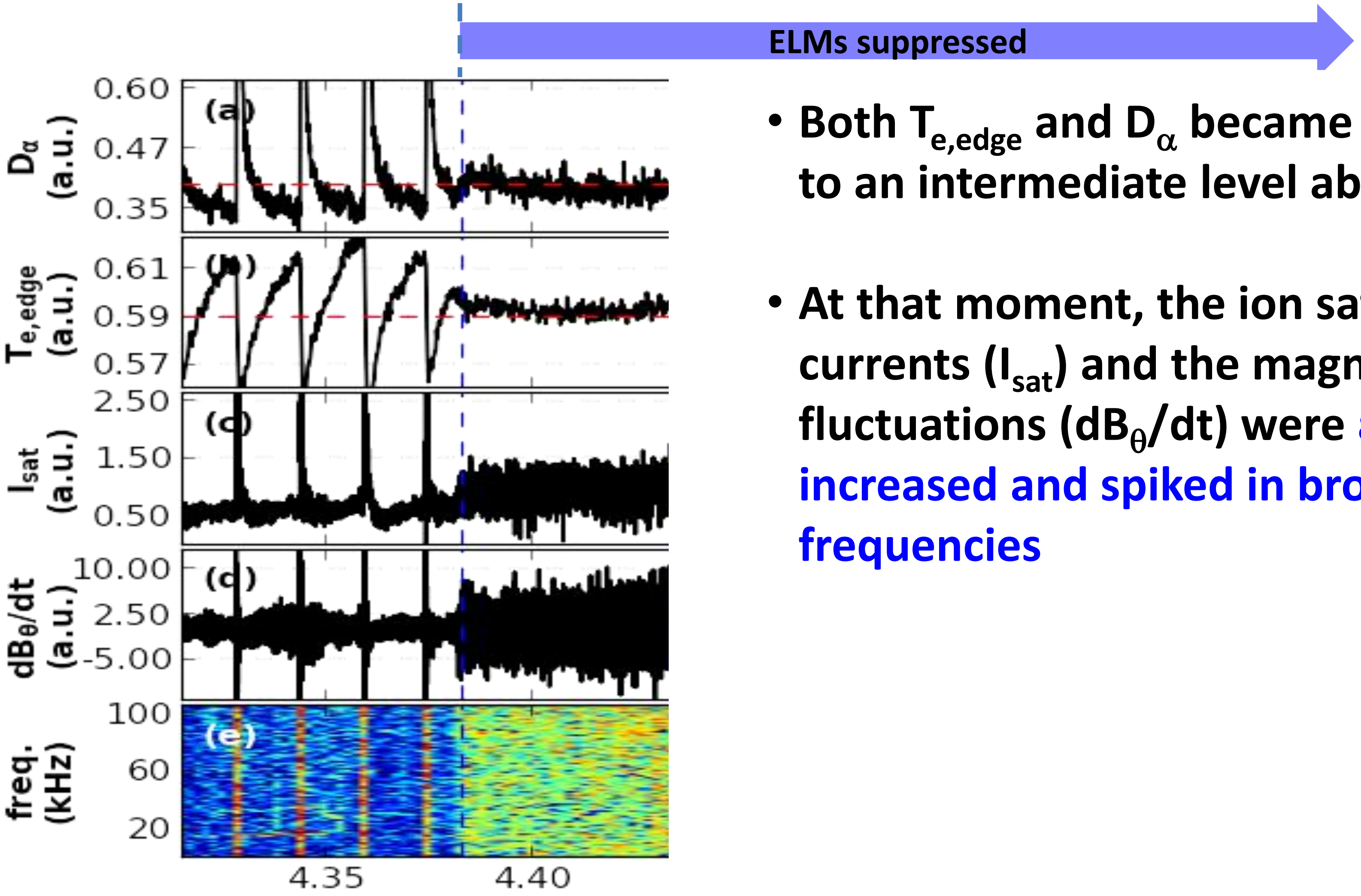
Typical ELM phenomena shows a periodic, sawteeth-like patterns



- Sawteeh-like $T_{e,edge}$ evolution
- In every ELM crashes, other quantities were spiked

- Note that the magnetic fluctuations usually become quiescent in-between ELM crashes

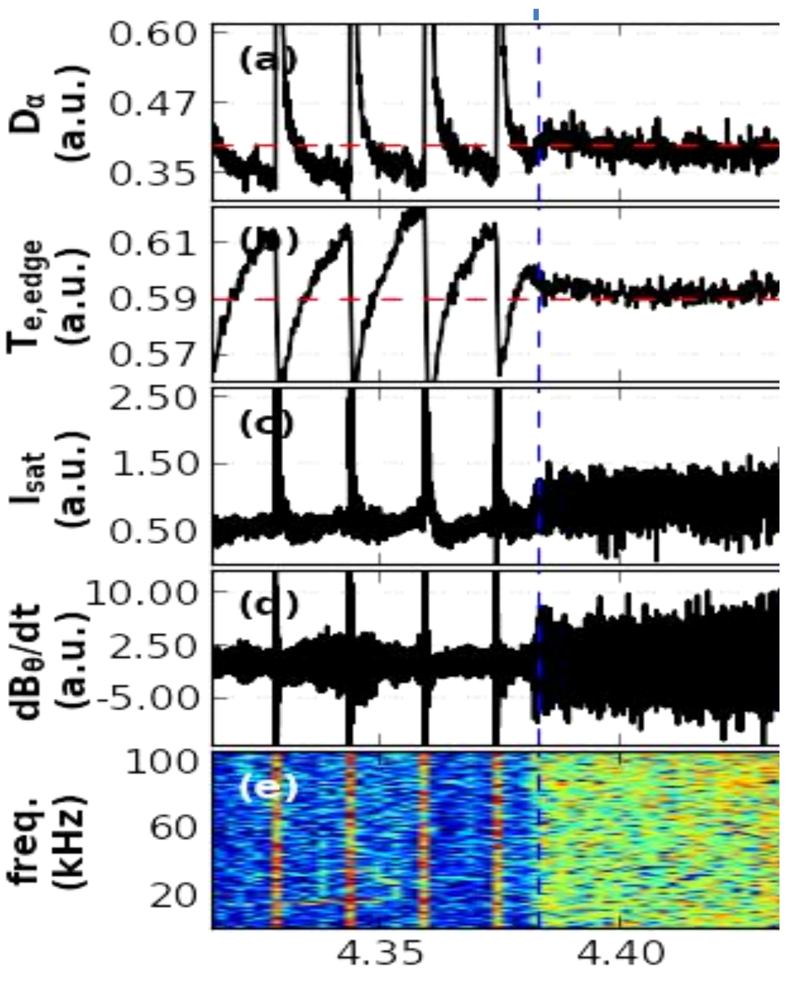
Unusual saturated evolutions appeared in the transition to the ELM-suppressed state

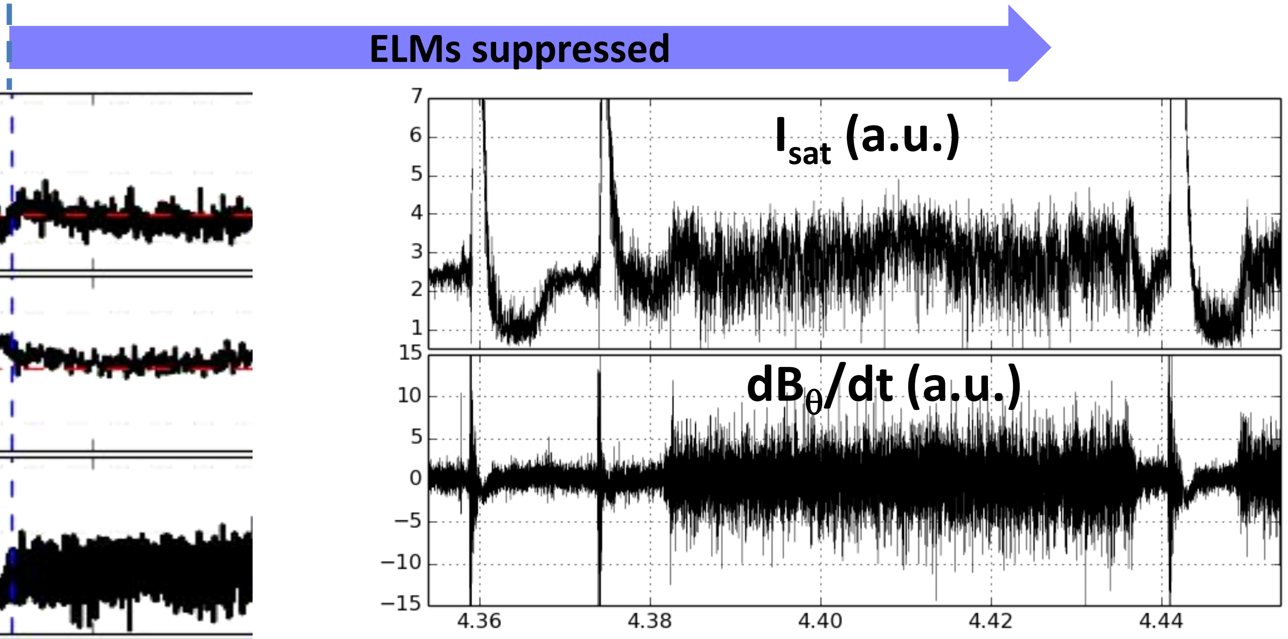


- Both $T_{e,edge}$ and D_α became saturated to an intermediate level abruptly

- At that moment, the ion saturation currents (I_{sat}) and the magnetic fluctuations (dB_θ/dt) were abruptly increased and spiked in broad-band frequencies

Unusual saturated evolutions appeared in the transition to the ELM-suppressed state

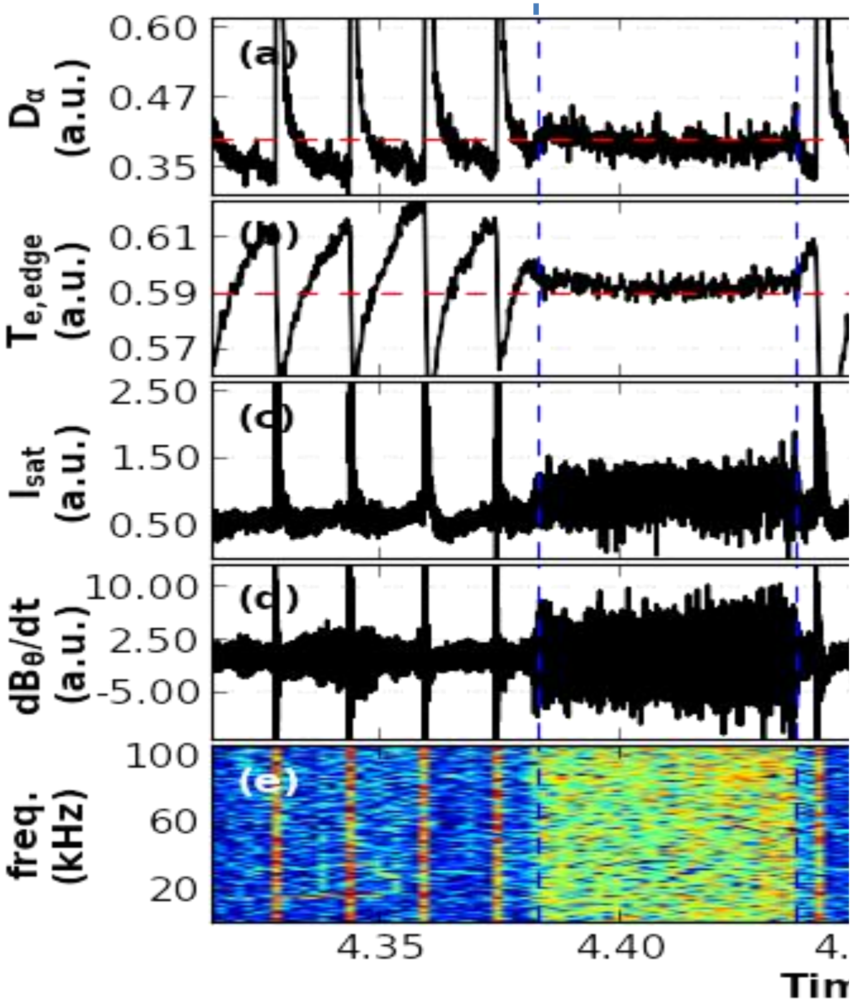




- A careful look of I_{sat} and dB $_{\theta}$/ dt by considering other saturated evolutions suggests that a persistent, rapidly repeating bursty event is activated in the edge region at the moment thus resulting in the saturation of $T_{e,edge}$ and D_{α}.

Occasionally original evolutions resumed when the saturated (or bursty edge) condition was broken

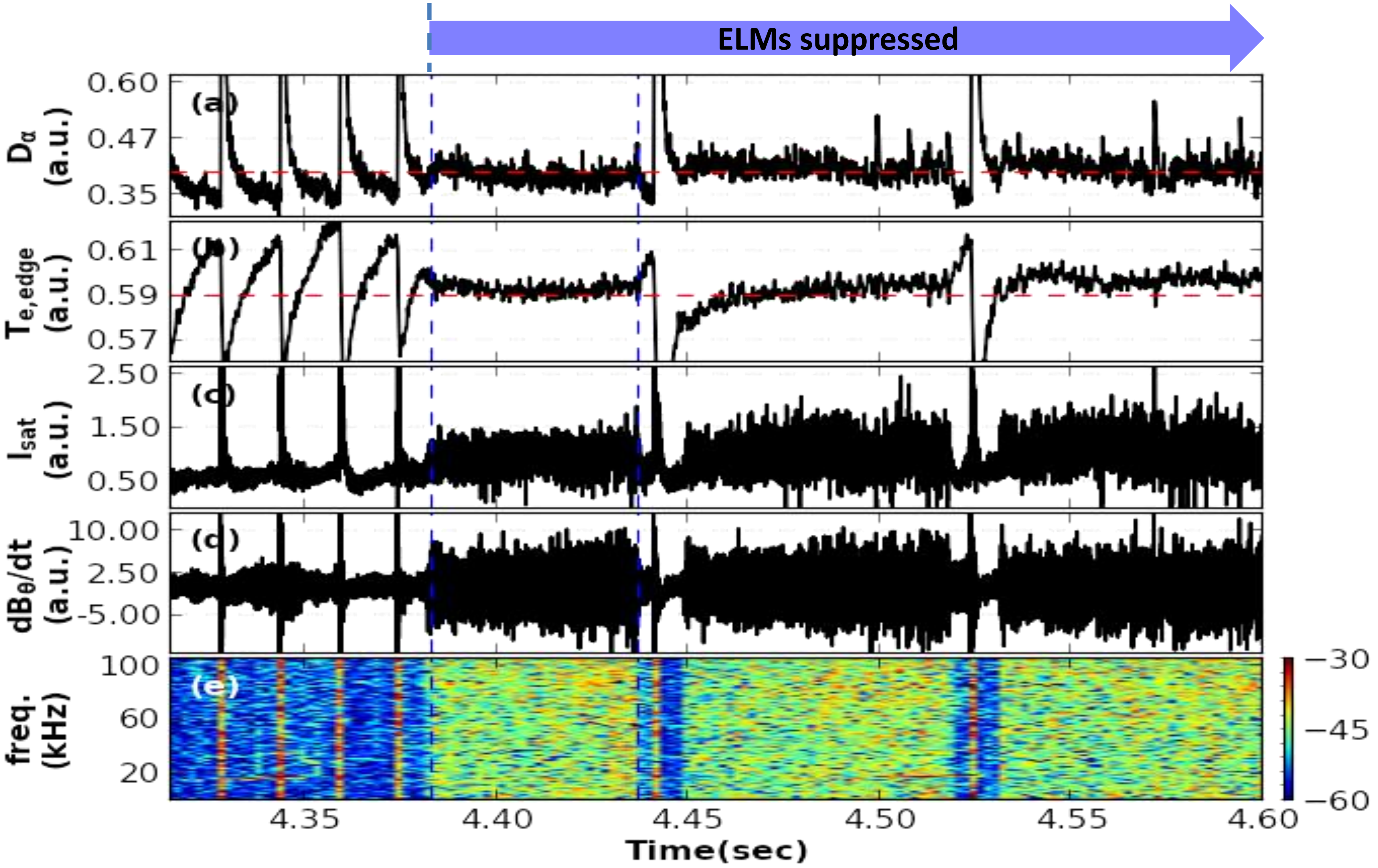
ELMs suppressed



- When the original evolutions resumed,
  - $T_{e,edge}$ starts to increase
  - D_α starts to decrease
  - The spikes on I_{sat} and the fluctuation on dB_θ/dt are cleaned up

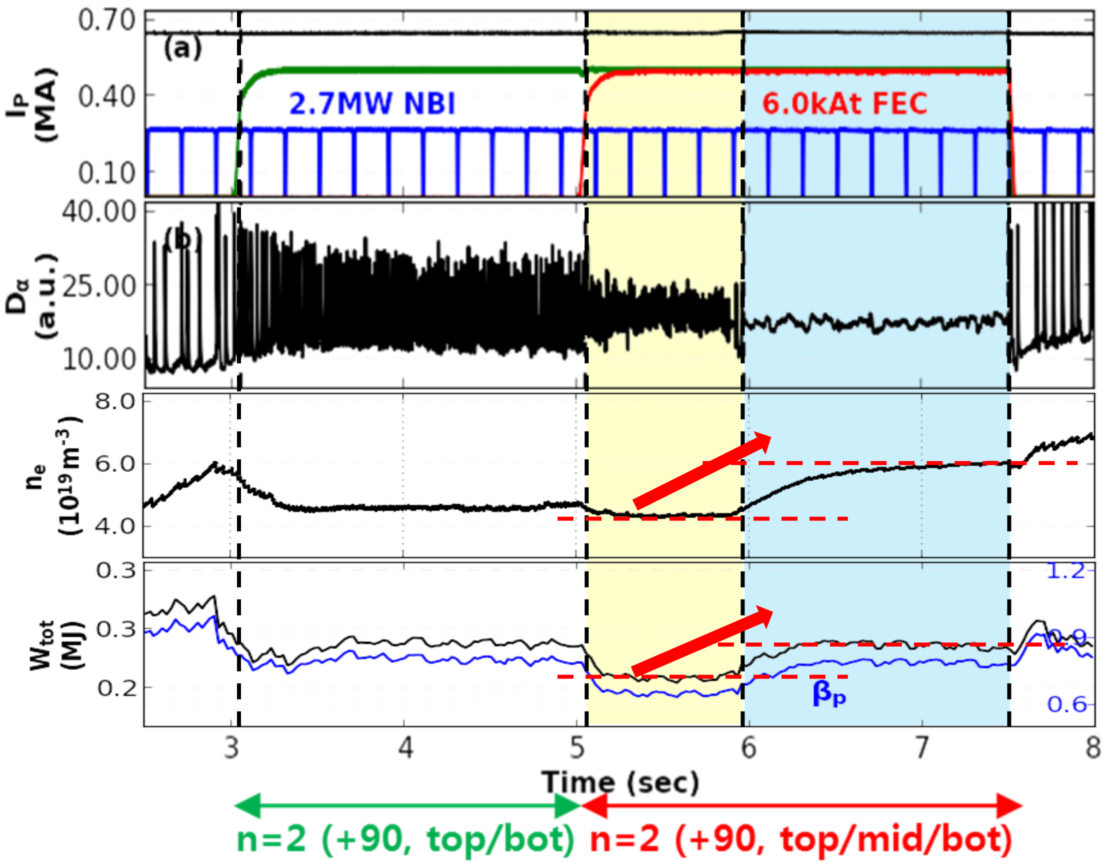
  - Then, finally reaching to the stability limit, resulting in an ELM crash

ELM-suppression can be thought as a stably sustained, bursty edge state



The altered edge transport (bursty edge) leads an unexpected change on global confinements

A distinctive nature of RMP-driven ELM-suppressed KSTAR plasmas



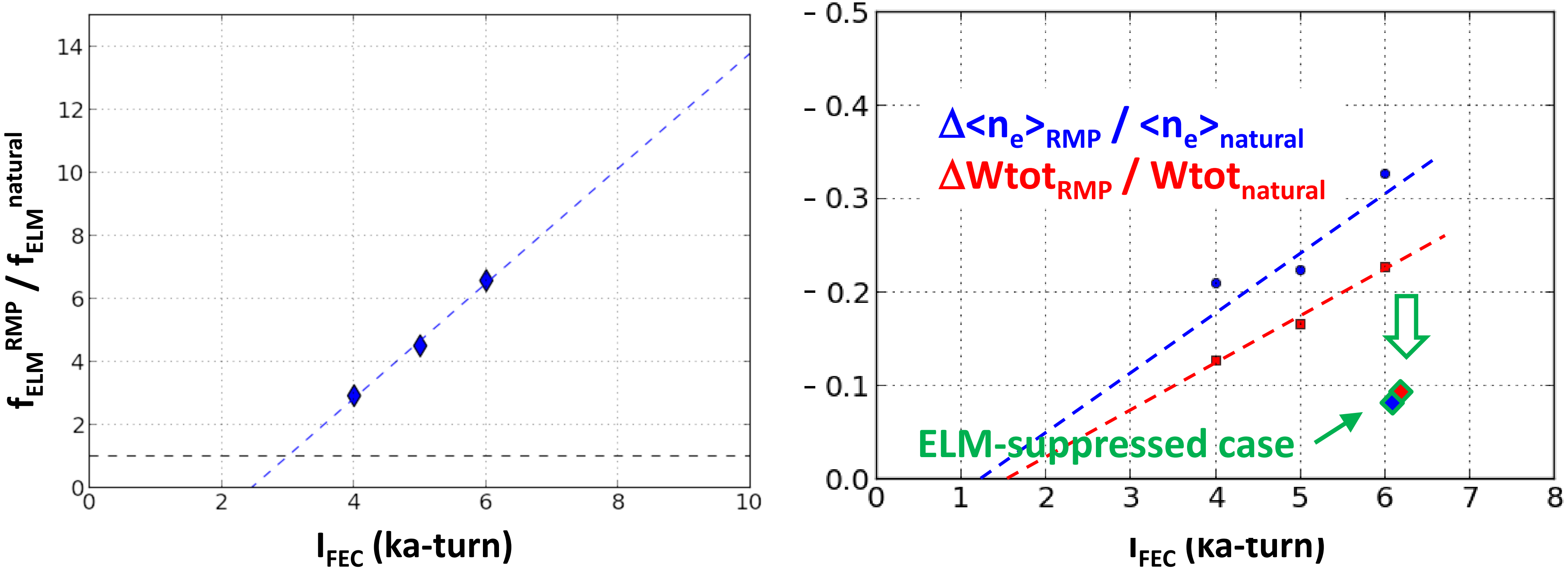
RMP field strength: "n=2 green" < "n=2 red"

- In ELM-mitigated phases (3.0~6.0sec), the confinement degradation is proportional to the strength of RMP field (similar to other devices)
- However, once ELMs are suppressed (6.0~7.5sec), the confinements are improved in both particle and energy
- Note that two distinctive phases (yellow vs blue boxes) of ELMs exist in a steady state under same RMP fields

➔ Indicating a certain mode transition or transport bifurcation

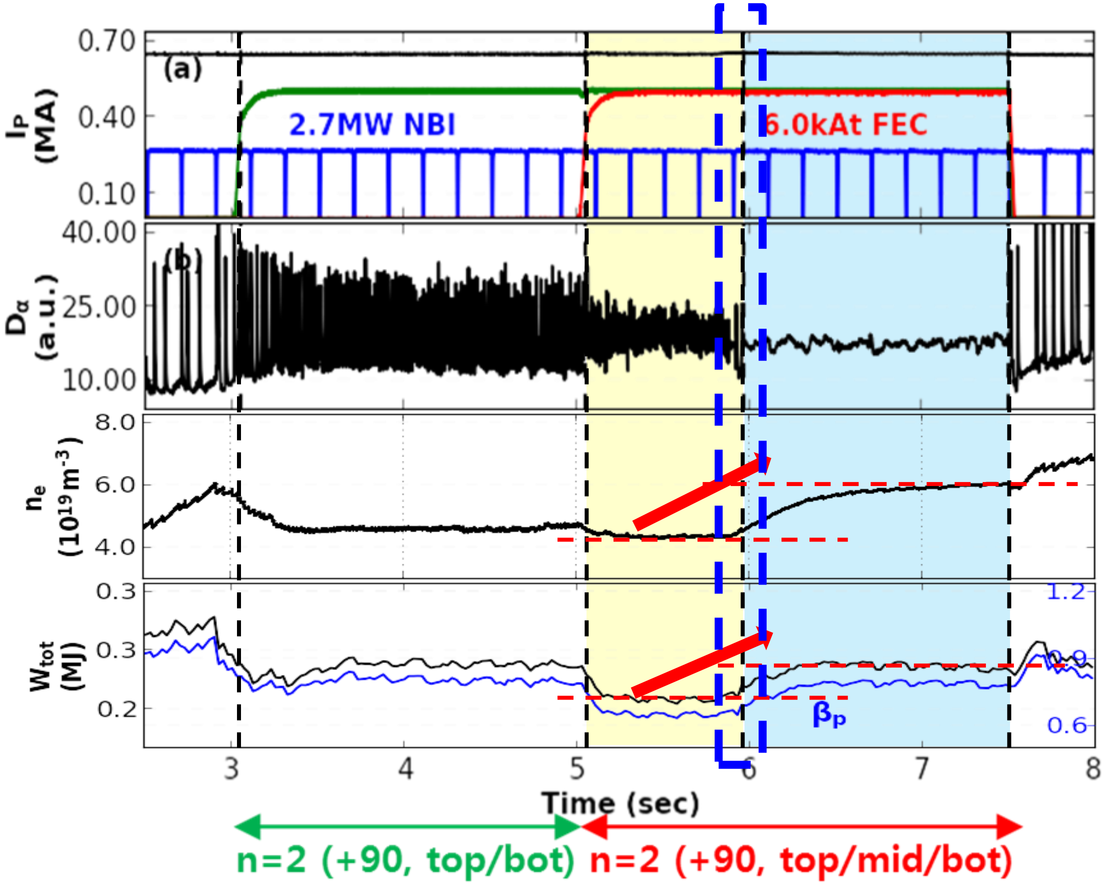
Changes of global quantities are related to the ELM state as well as applied field strength

*** When ELMs were mitigated by n=2 RMPs**



- In cases of ELM-suppression, it didn't follow the tendency any more
- i.e. ELM-suppression can give less reductions of global confinement than ELM-mitigation

A distinctive nature of RMP-driven ELM-suppressed KSTAR plasmas



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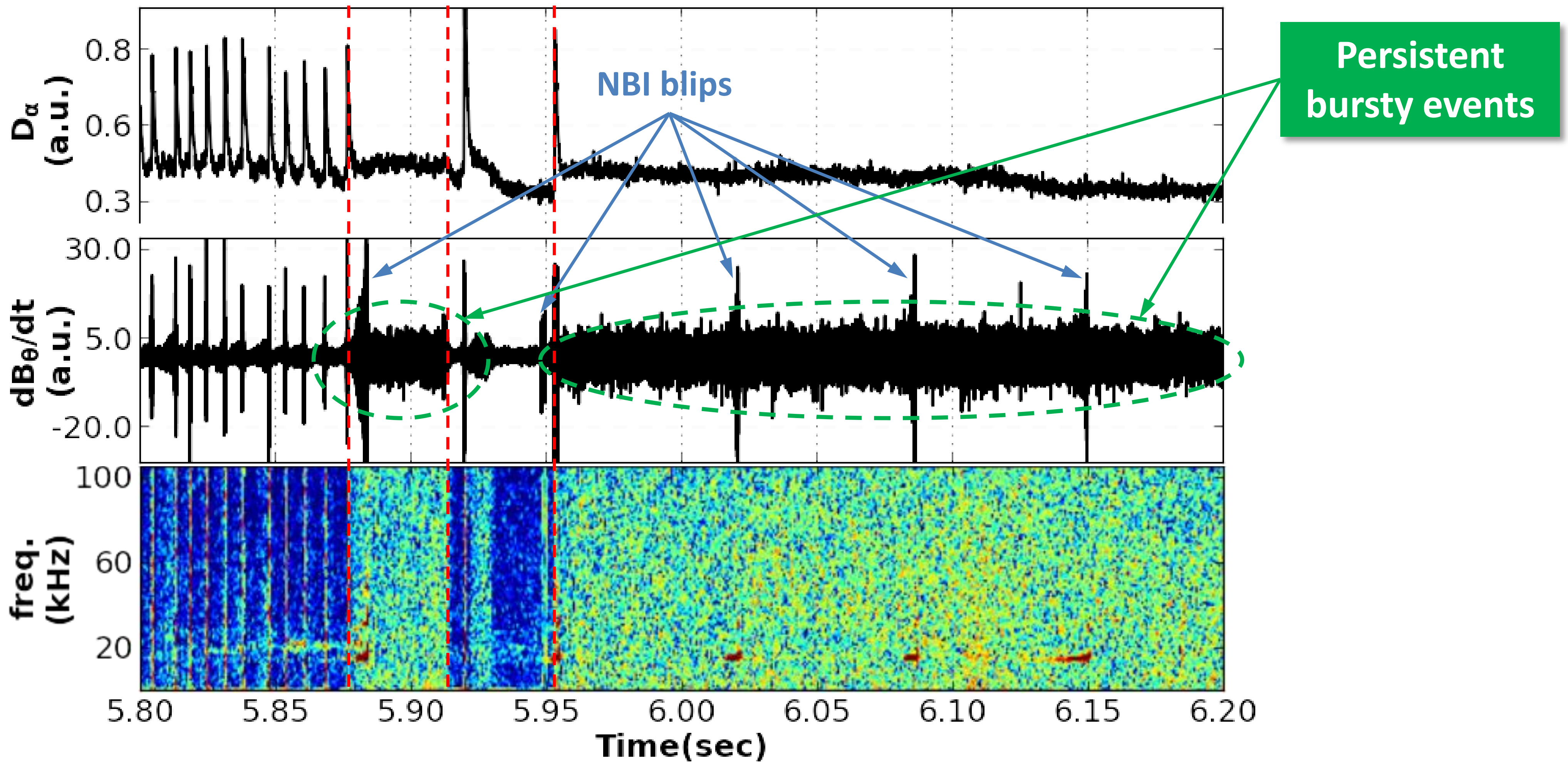
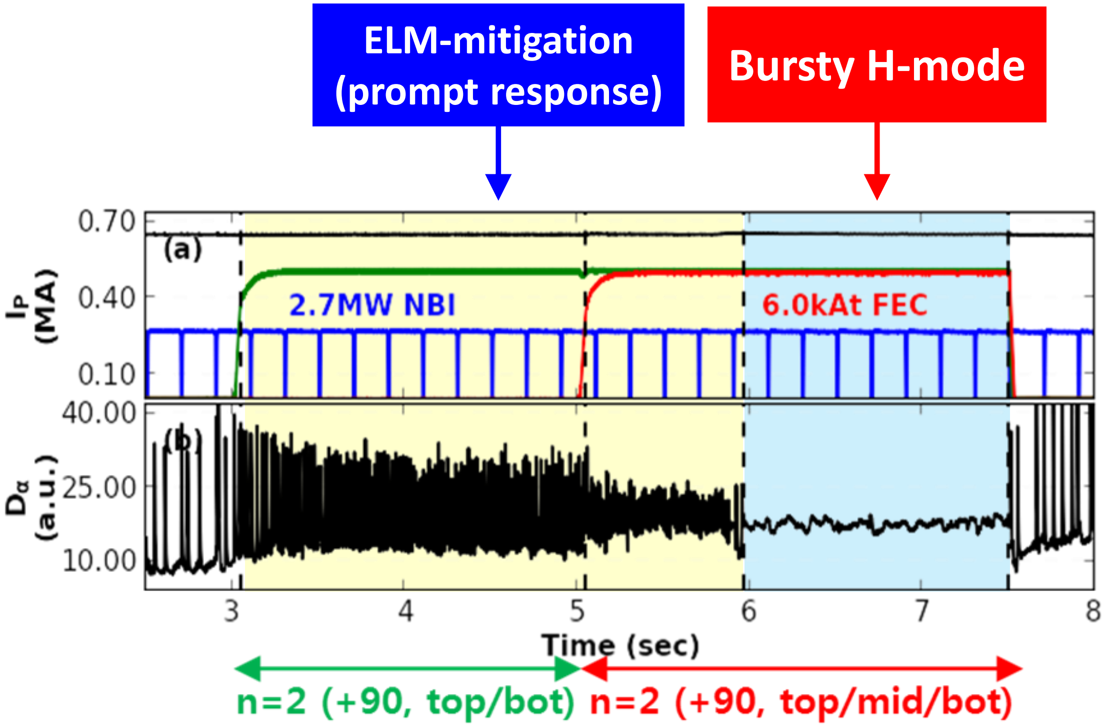
➔ Indicating a certain mode transition or transport bifurcation

The persistent bursty event may play a key role on the change of confinement as well as the change of ELM state



ELM-suppressed H-mode can be considered as a new state of H-mode ('Bursty H-mode')



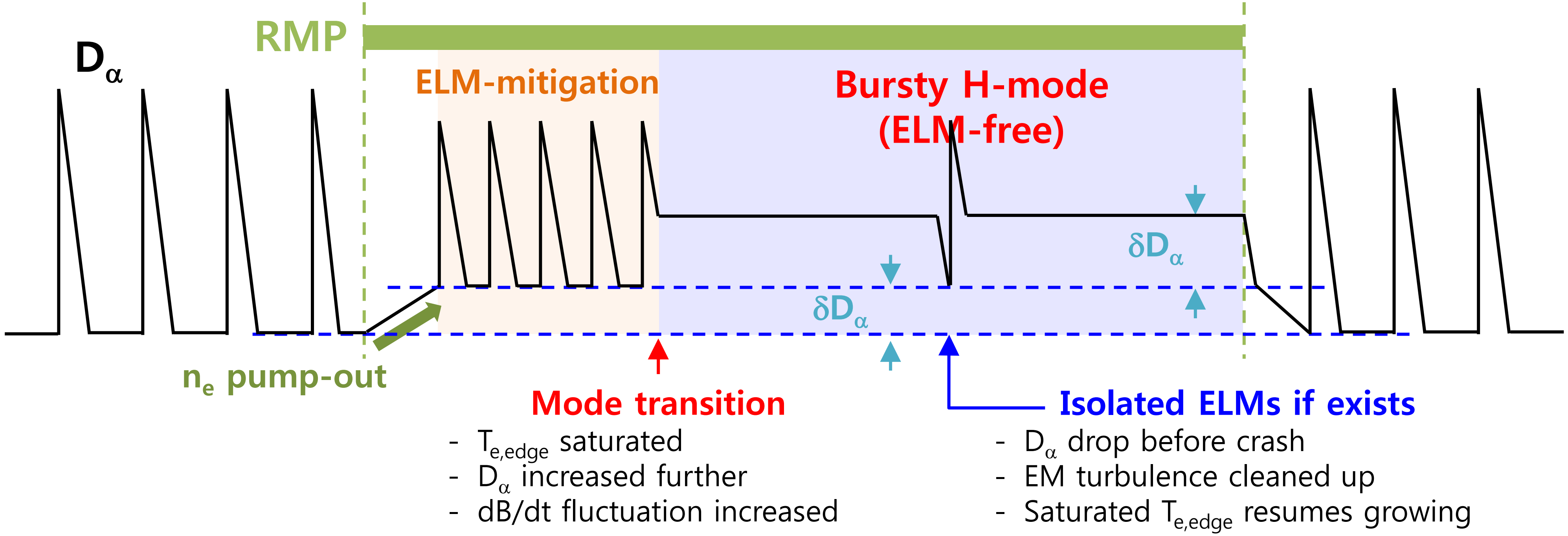
(1) Both ELM-mitigated and –suppressed phases can be existed steadily under same RMP fields

(2) ELM suppression appears as a delayed or secondary effect of RMP

(3) A certain edge transport bifurcation (via persistent, bursty event) seems to be responsible for the change of ELM state

(4) Confinement enhancements from both particle and energy are followed by the transport change

Schematic summary of ELM-free Bursty H-mode

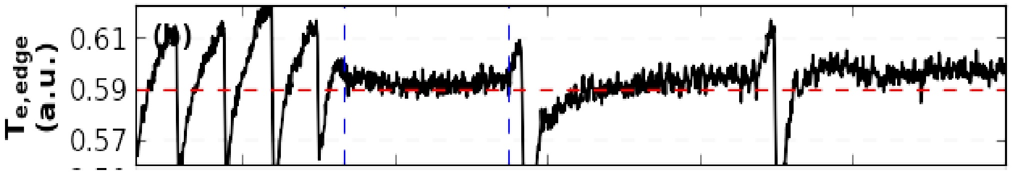


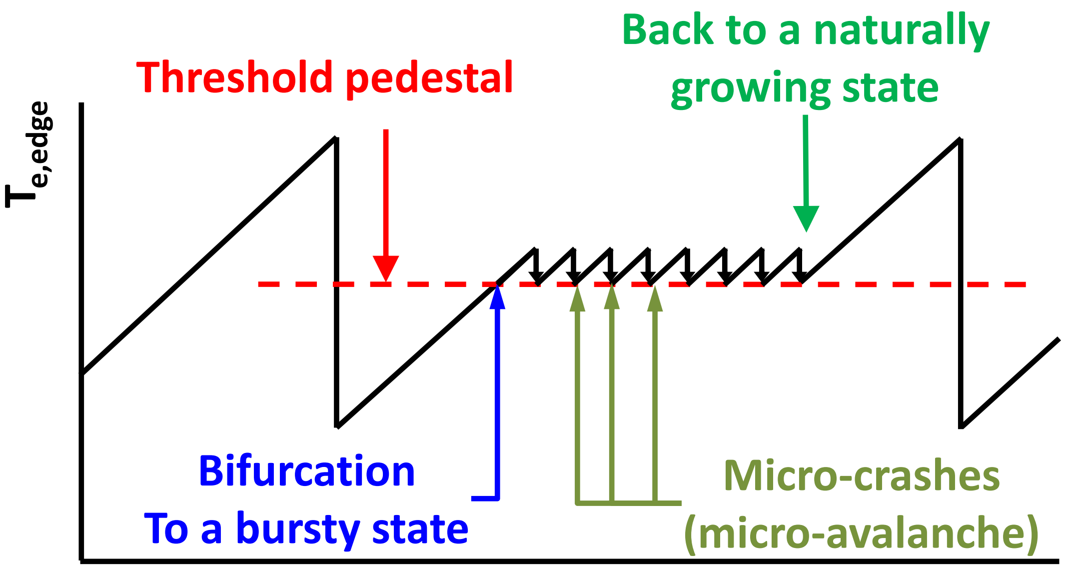
RMP makes primary changes on edge plasmas
- **Edge stochastized**
- **n_e pump-out (D_α increased)**
- **Edge T_i, T_e, and V_ϕ decreased**

➡

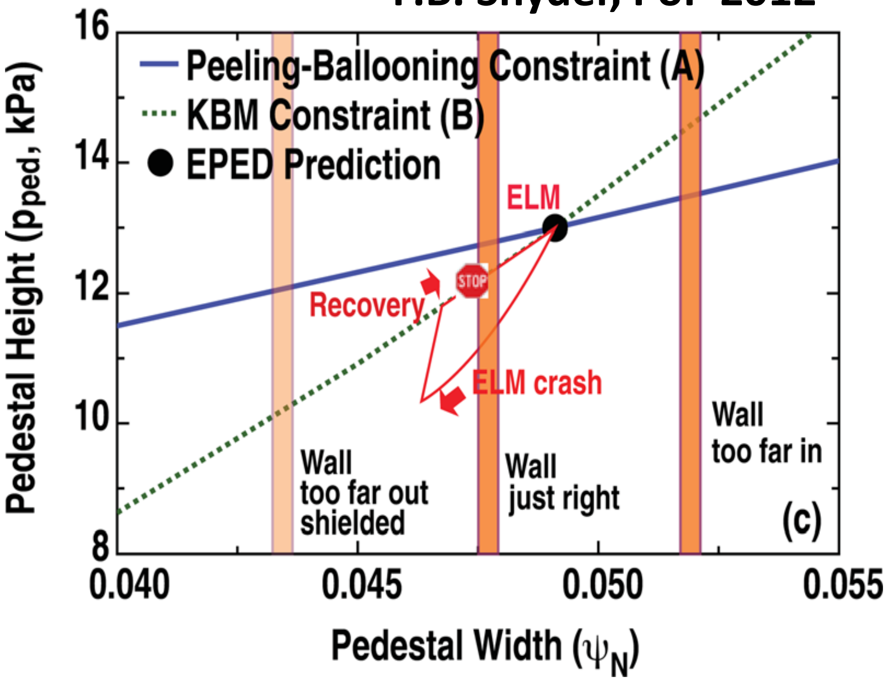
Abrupt appearance of persistent bursty event
- **D_α increased further**
- **$T_{e,edge}$ saturated**
- **ELMs suppressed**
- **Confinement enhanced**

Blocking pedestal penetration (saturated $T_{e,edge}$) can be understood





* P.B. Snyder, PoP 2012



Persistent micro-crashes lead micro-avalanche. Thus it does not grow any more

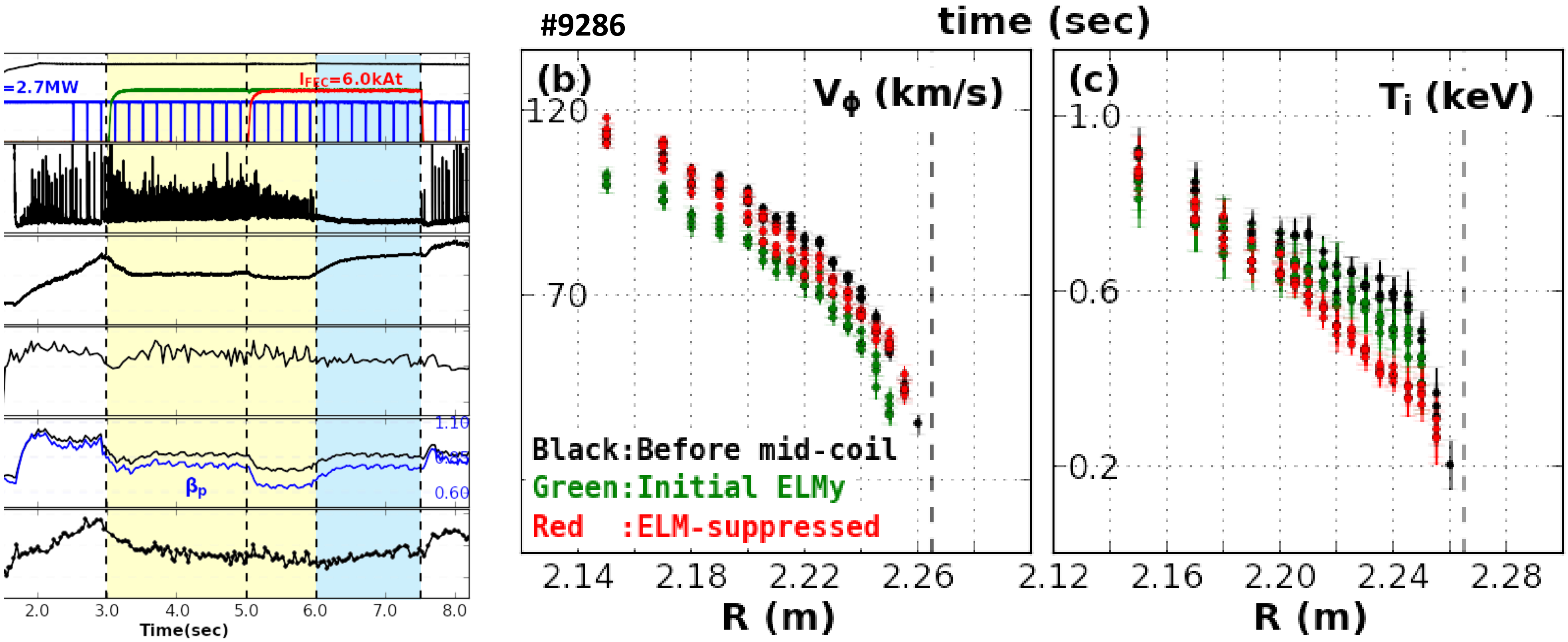
Summary and discussion

1. **ELM-suppression was successfully demonstrated in a wide range of q_{95} in KSTAR by utilizing low n RMPs**
   - n=1 RMP used for high q_{95} and n=2 for low q_{95}
   - Various interesting phenomena observed commonly without any clear dependency on the toroidal mode of RMP fields

2. **ELM suppression was observed and understood as a delayed, secondary effect of RMP**
   - ELM suppression is clearly distinguished from ELM-mitigation, by a long time delay prior to ELM-suppression
   - Various abrupt phenomena (persistent, rapidly bursty event) that led saturated evolution of edge quantities might play a key role on ELM-suppression
   - The altered edge transport led an (unexpected) improvement of confinement

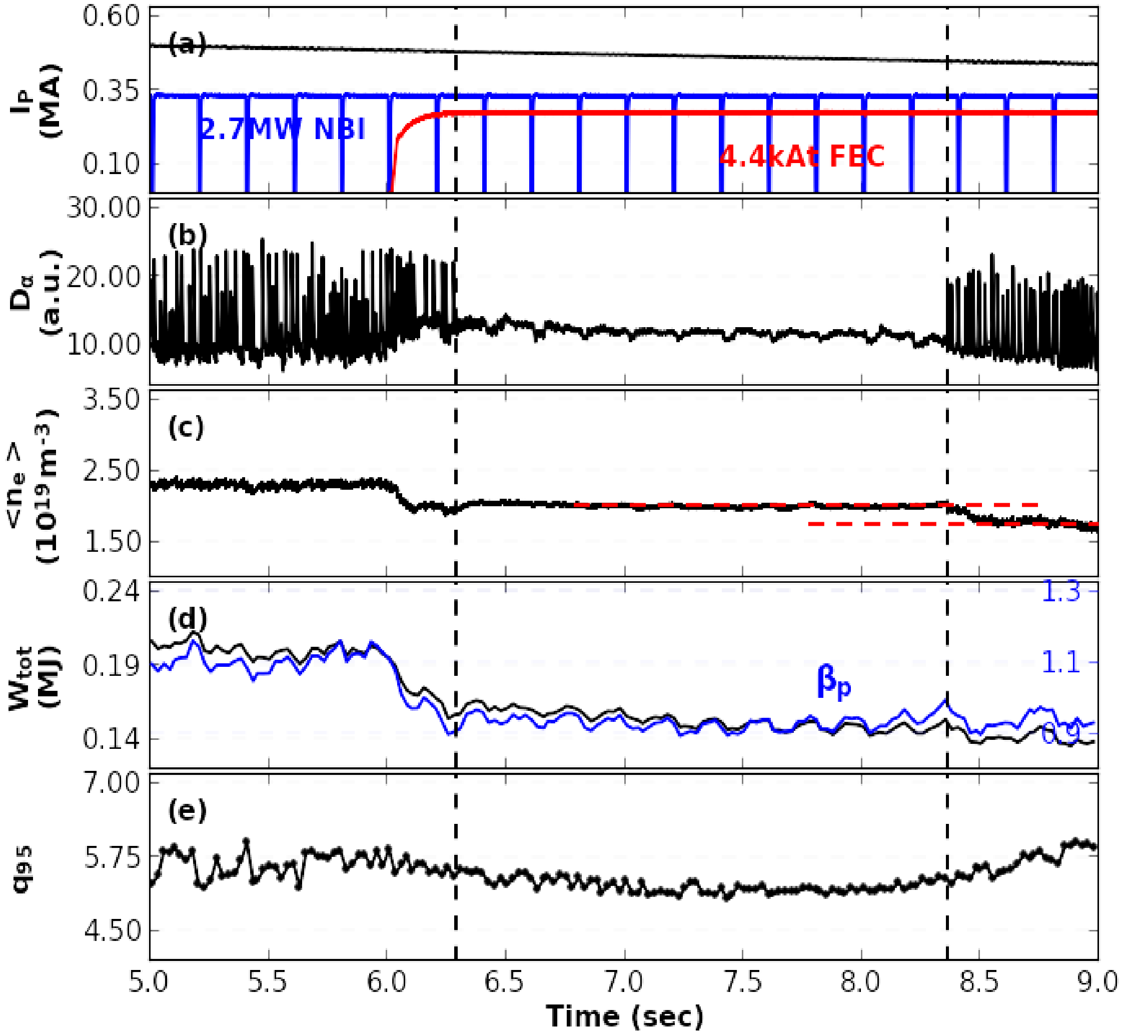
3. **ELM-suppression would be worth being considered as a new state of H-mode ('bursty H-mode')**

Edge profiles depending on ELM state: n=2 RMP



An apparent change of edge Ti → A clear change on pedestal penetration ?
Does it show an increase of edge V_ϕ similar as that in DIII-D ??

A distinctive nature of RMP-driven ELM-suppressed KSTAR plasmas (n=1 RMP)



*** n=1 RMP**

#8969: I_p=0.47MA B_T=1.8T

→ **ELM-suppressed by 4.4kAt RMP**

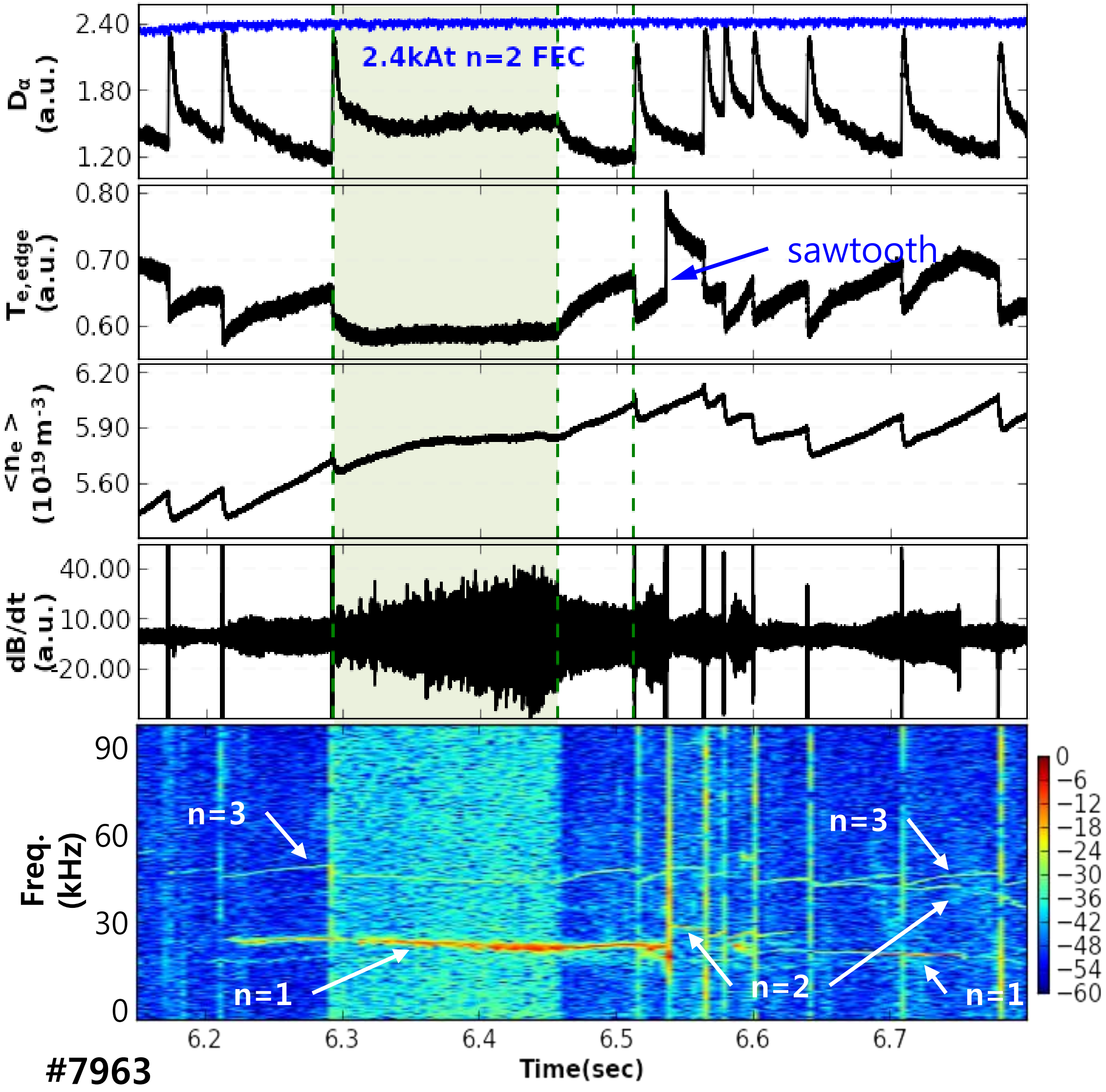
→ **q_{95}=5.2~5.5**

- **Under RMP fields, weaker density pump-out in ELM-suppressed** phase than ELMy phase
- **Similar change on stored energy (and β)**

➔ **Better confinement in ELM-suppressed phase**

- **Changes of W_{tot}(or β_p) are relatively weak and small**

The persistent bursty event occurred in the plasma edge : EM fluctuations come from the plasma edge



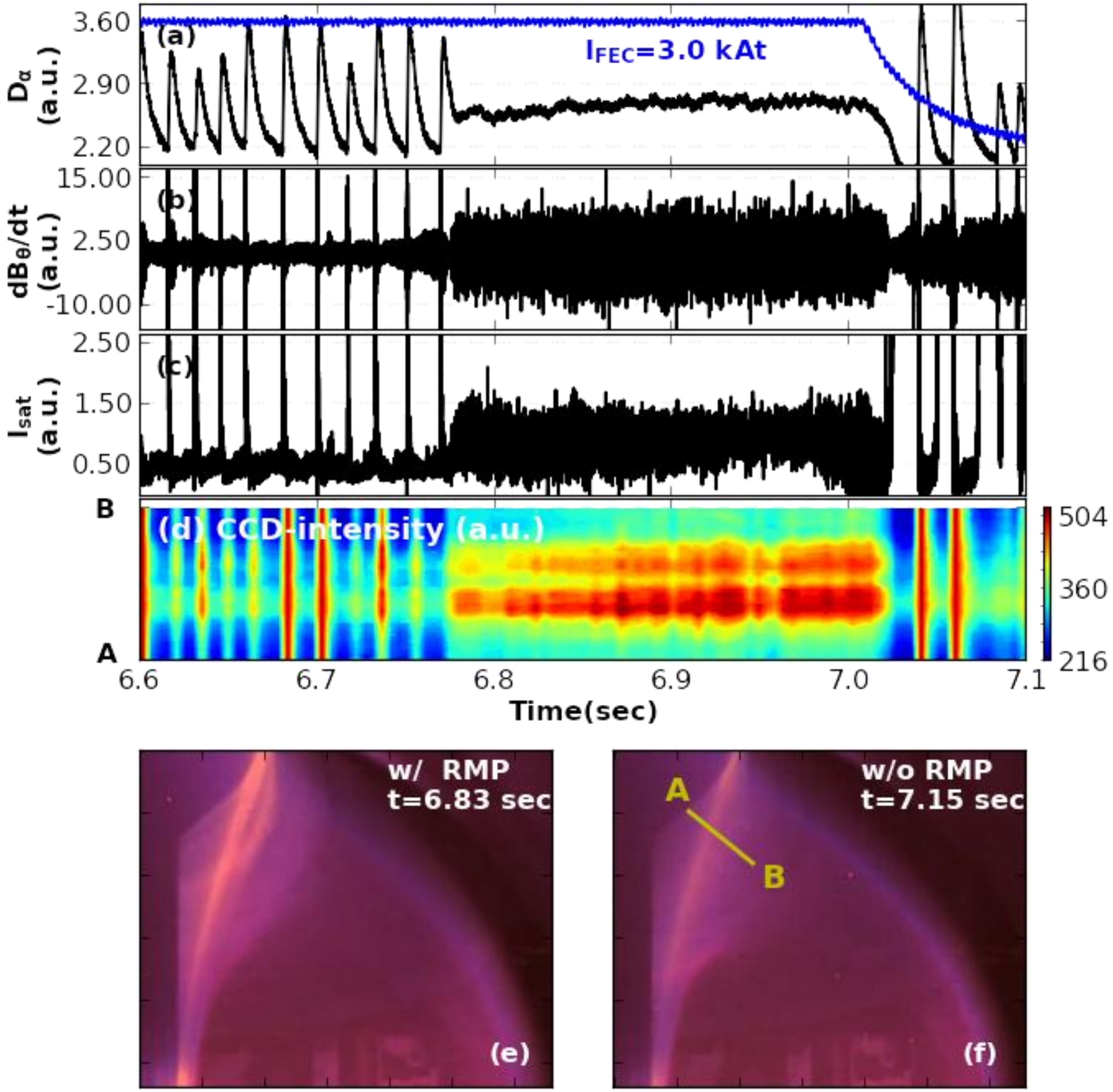
Short ELM-suppression under n=2 RMP of 2.4kAt

- **Ip=0.75kA, BT=1.65T → q_{95}~4.0**
- **More prone to various MHD activity due to lower q_{95} and higher β**

A 25kHz core (internal kink) MHD activity was not affected by the overlapped uniform broadband EM fluctuations

➔EM fluctuation (persistent bursty event) was originated from the plasma edge

The persistent bursty event occurred in the plasma edge : Increased D_α emission near the plasma boundary



- Emission from CCD ∝ D_α
- No clear change on topology at the transition
- Only emission intensity was increased strongly

➔The persistent bursting event in the plasma edge leads increased neutral recycling near the plasma boundary, thus increasing D_α emission