NFRI 국가핵융합연구소 National Fusion Research Institute

Reliable RMP-ELM Suppression for High-Beta Long Pulse Operation in KSTAR

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Background and issues

- In 2016~2017, low-n RMP-ELM suppression has been substantially improved in KSTAR

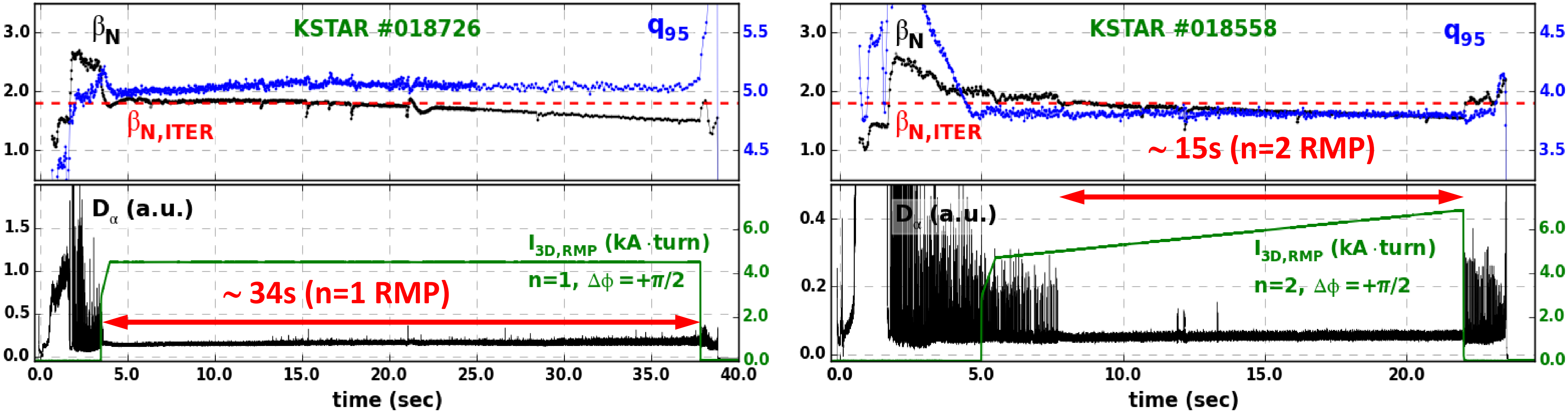
- What was the key element? and how we understand it?
  - → Plasma shape effect on RMP coupling
  - → Anything else? : density, rotation, etc

- Applicable to high beta, long pulse operation?
  - → Challenging to high beta plasmas

Substantial improvement of low-n RMP-ELM suppression achieved in 2016~2017 KSTAR

More stable and robust, even universal ELM-suppressions enabled

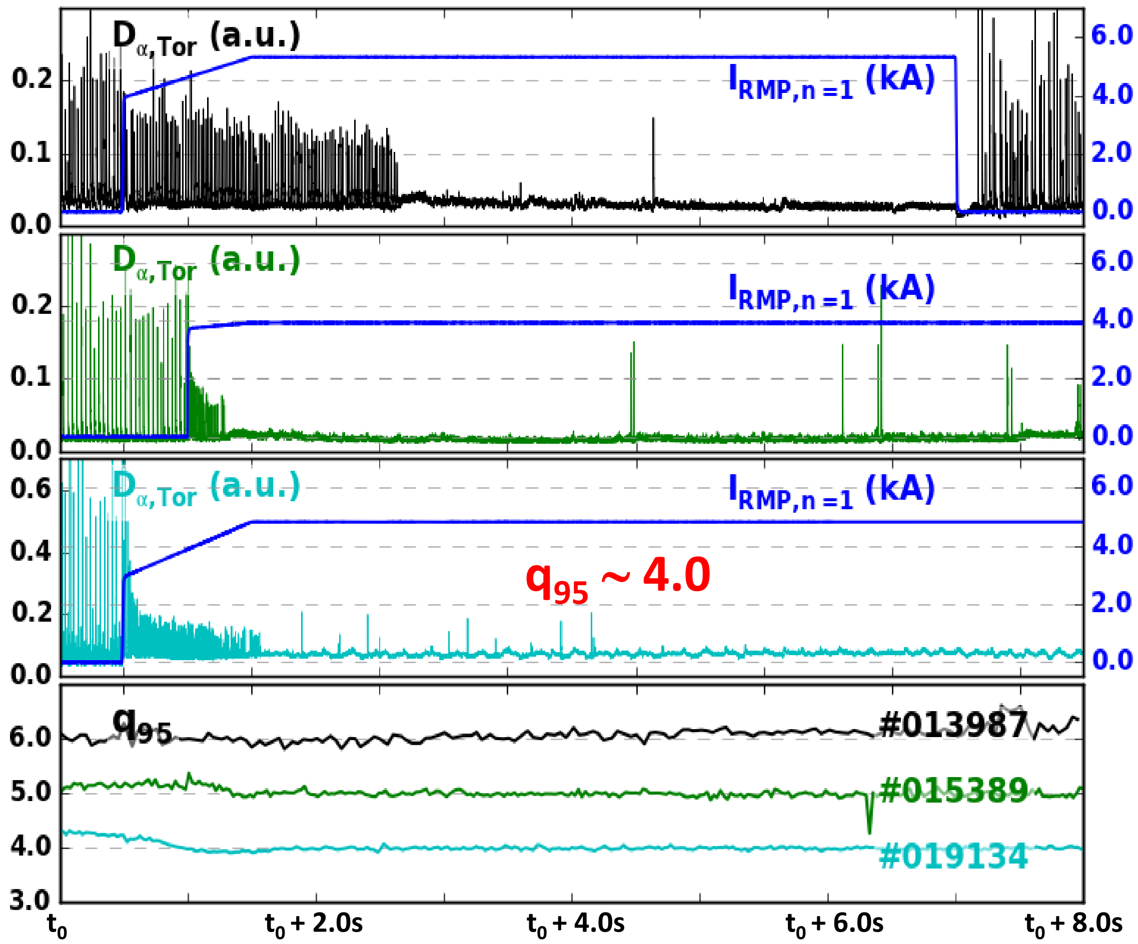
Record-long ELM-suppressions achieved for both n=1 & n=2 RMPs



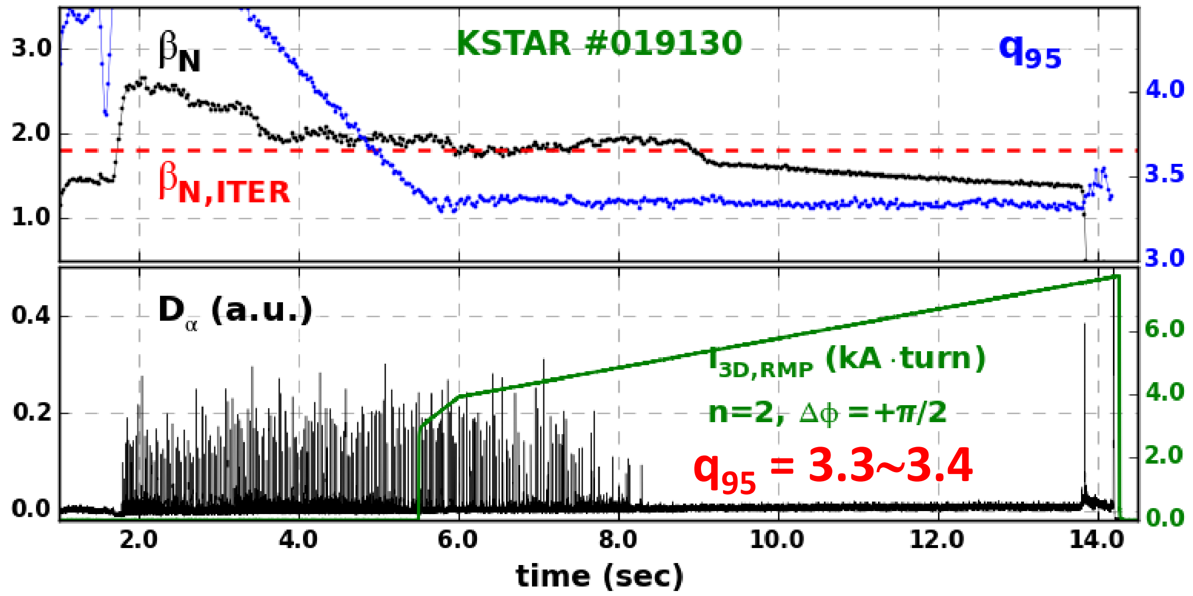
- ELM suppressions achieved for both n=1 and n=2 RMPs with same conditions (universality)
- Much long pulse ELM-suppressions enabled : ~10s in 2016 → ~34s in 2017 (stable/robust)

New operation regimes for ELM-crash suppression discovered

Lowest q_{95} ELM-suppression by n=1 RMP



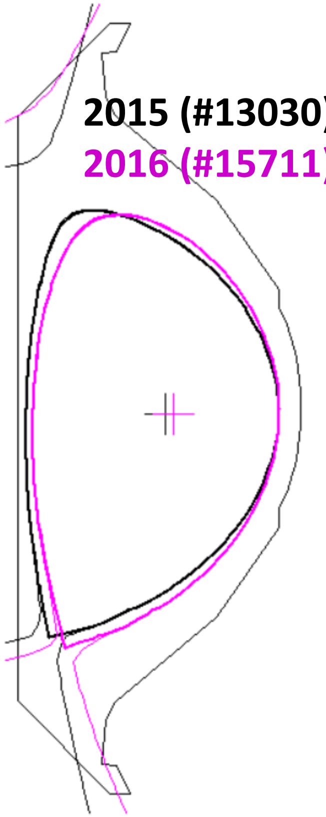
Lowest q_{95} ELM-suppression by n=2 RMP



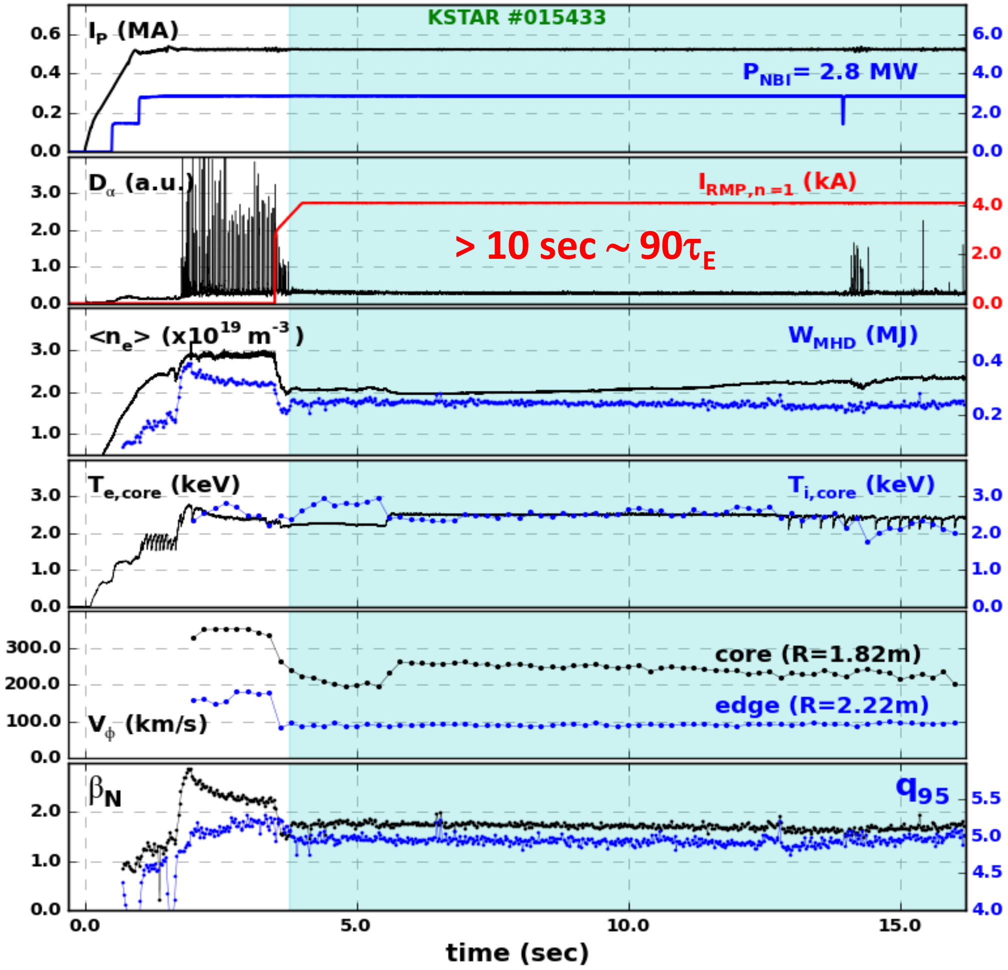
A small change of plasma shape was a key

Substantial improvements of RMP-ELM suppression achieved in 2016 by a small change of plasma shape

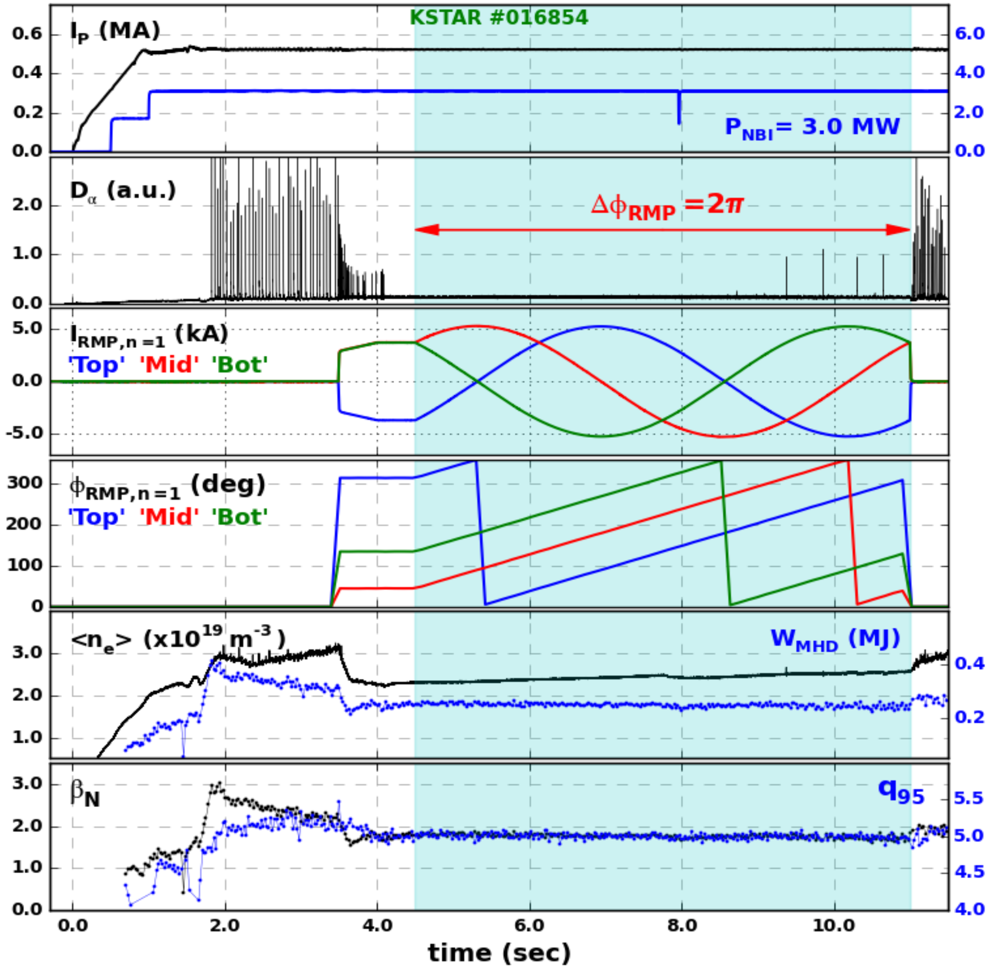
* Y.M. Jeon, et al., IAEA-FEC (2016)



Triangularity reduced

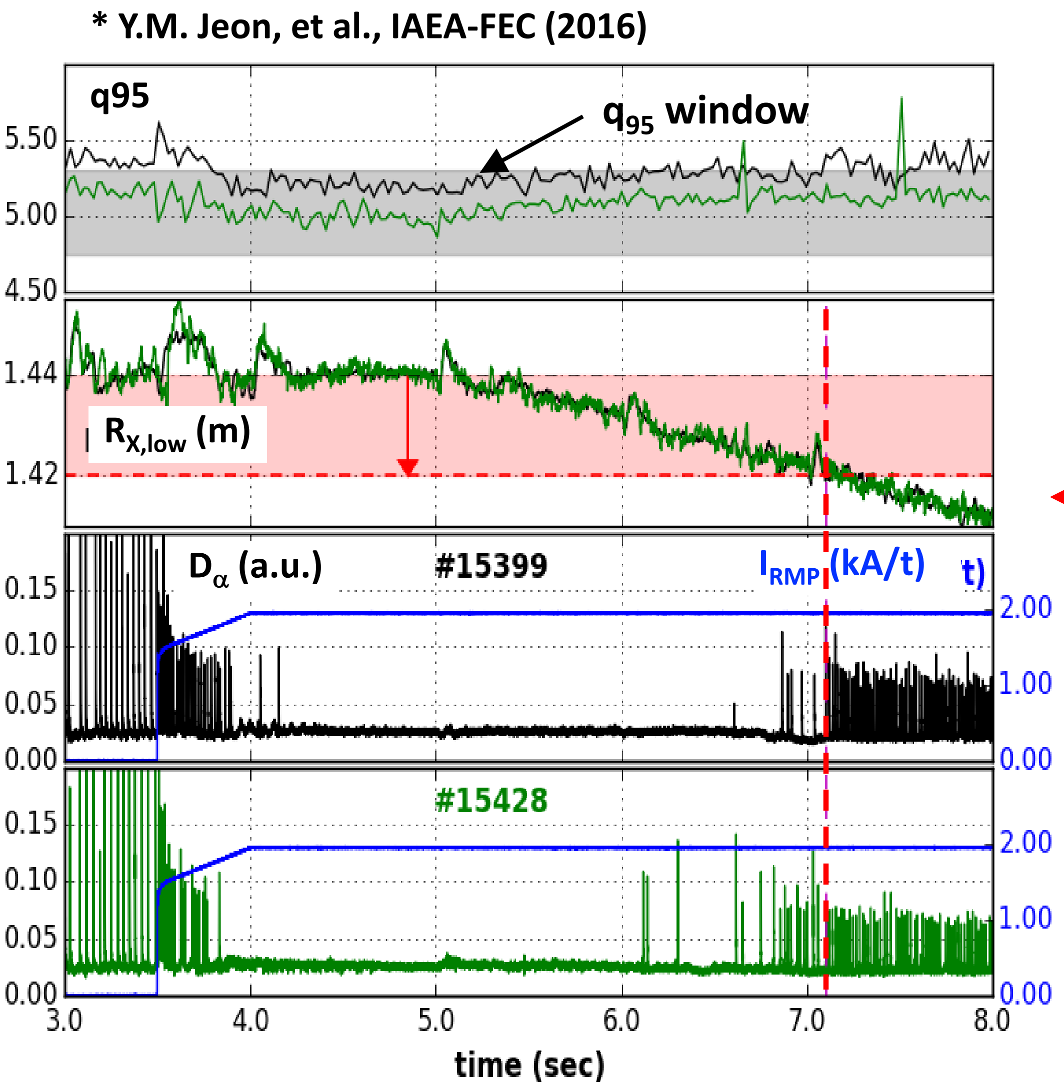


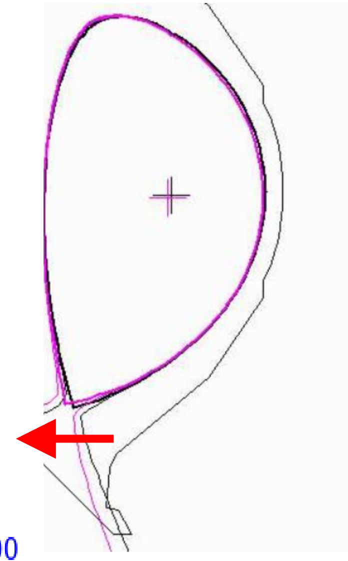
Long ELM-suppression (2016)
by n=1, $\Delta\phi$ = +90° RMP at $q_{95} \sim 5.0$



First demonstration of ELM-suppression under full rotation of n=1 RMP

ELM suppression was sensitive to a small change of plasma shape, particularly triangularity





- Decreasing $R_{X,low}$ (δ_{low} ↑)
  - ELM : suppressed → mitigated

- $R_{X,low}$=1.42m played as a lower bound for ELM suppression in 2016

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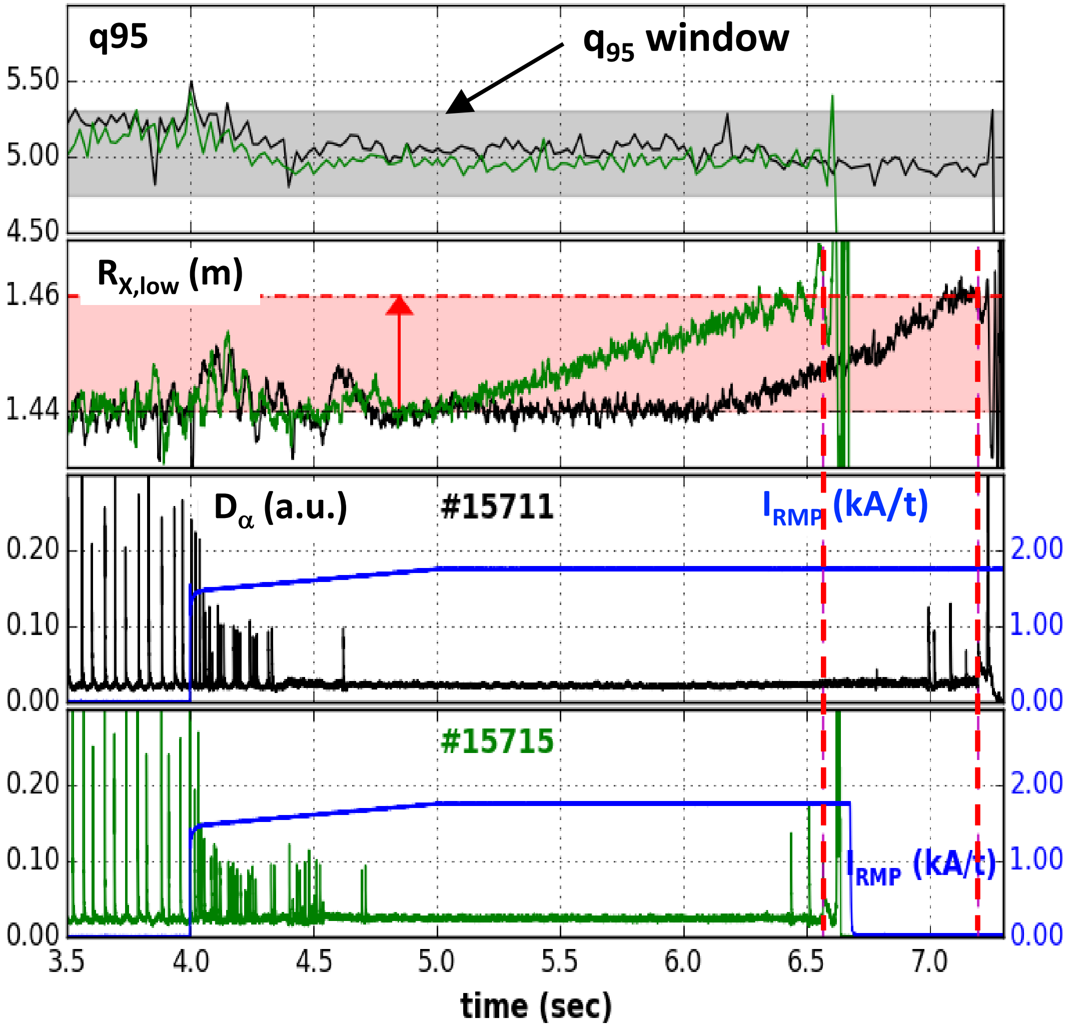
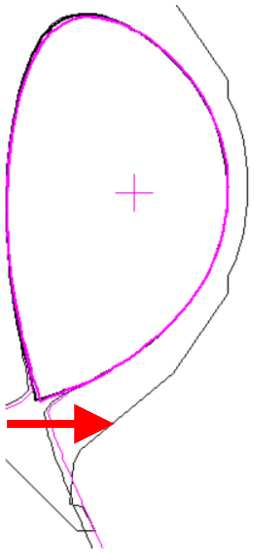


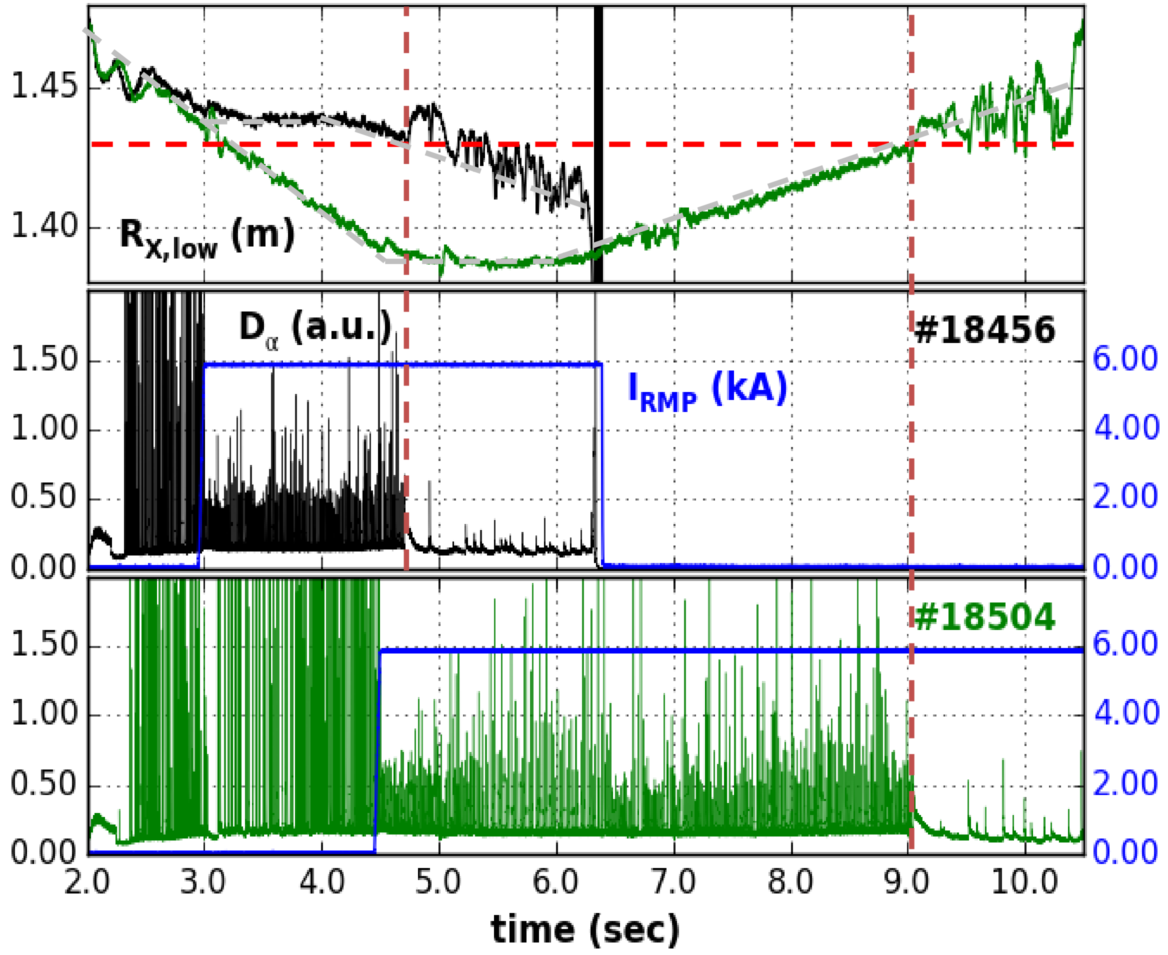


- Increasing $R_{X,low}$ (δ_{low} ↓)
  - Plasma locking occurred
  - → Core plasma response dominant
- $R_{X,low}$=1.46m played as a upper bound for ELM suppression in 2016

A narrow shape window, similar to q_{95} window, obtained
- $1.42 \leq R_{X,low} \leq 1.46$m ($\Delta R_{X,low} \sim 4.0$cm)
- $0.70 \leq \delta_{low} \leq 0.78$ ($\Delta\delta_{low} \sim 0.08$)

Unusual singular shape response observed in plasma locking response with q_{95} dependence

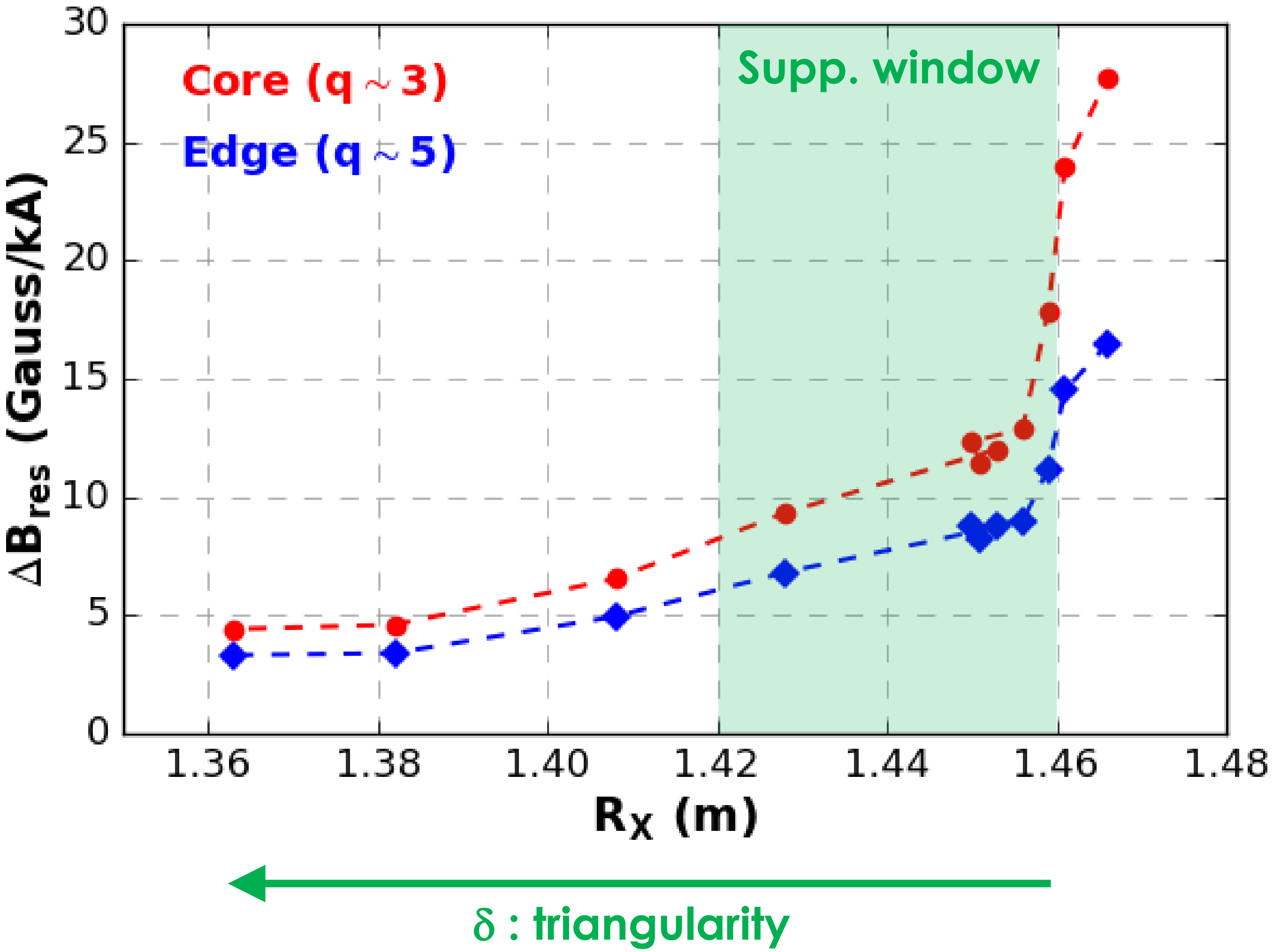
$R_{X,low}$ scan under n=1 RMP at q_{95}~ 6.0



- Always locked, no matter how $R_{X,Low}$ approaches to ~1.43m
  - → $R_{X,Low}$ ~1.43m is a singular point for q_{95} ~ 6.0
- For q_{95} ~ 5.0, it seems the singular $R_{X,Lower}$ is ~ 1.46m

➔ The origin of upper bound in R_X window

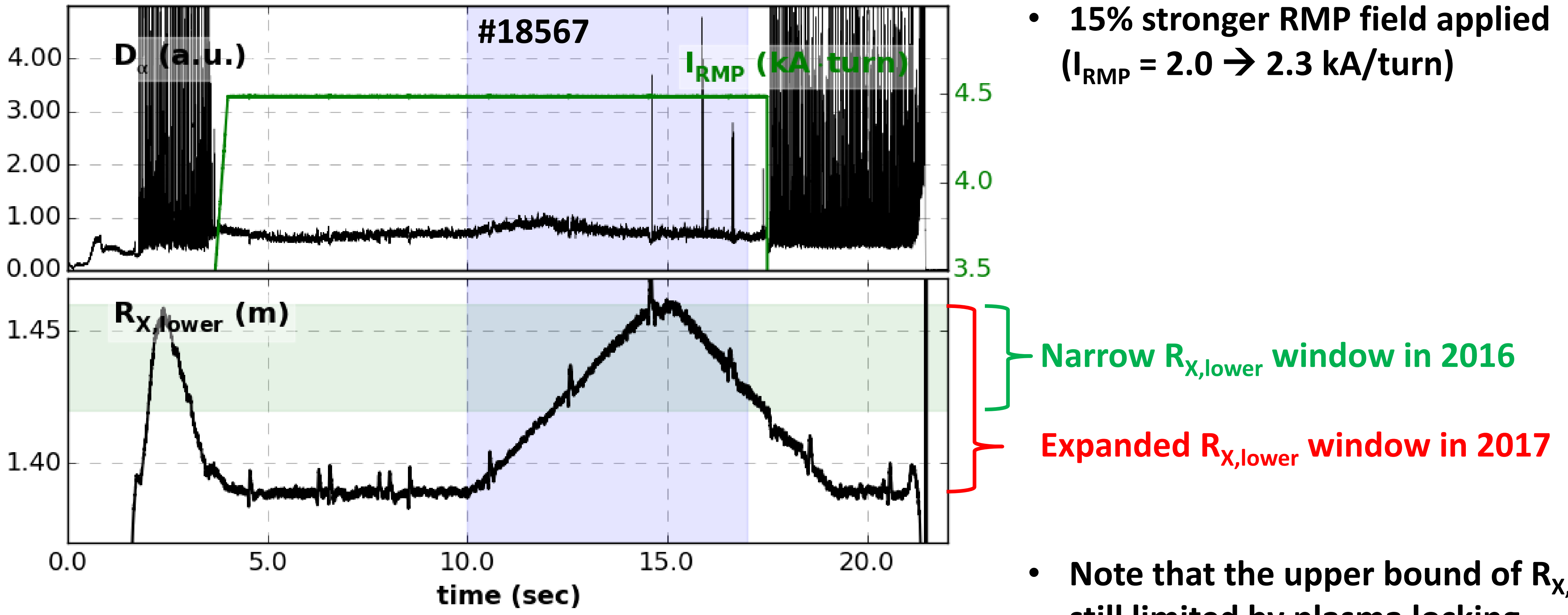
Linear ideal MHD modeling analysis (IPEC) could capture a part of nature, associated with shape effect



- Based on mag. EFIT (i.e. no pedestal)
- Improved coupling as δ reduces
  → May explain why ELMs re-appeared when δ increased
- Fields amplified when R_X approached to a certain value (~1.46m)
- Well in line with experimental observation

➔ Suggesting that ELM re-appearance when R_X reduced might be due to reduction of resonant fields

Stronger RMP fields were able to expand the lower bound of R_X window, as expected

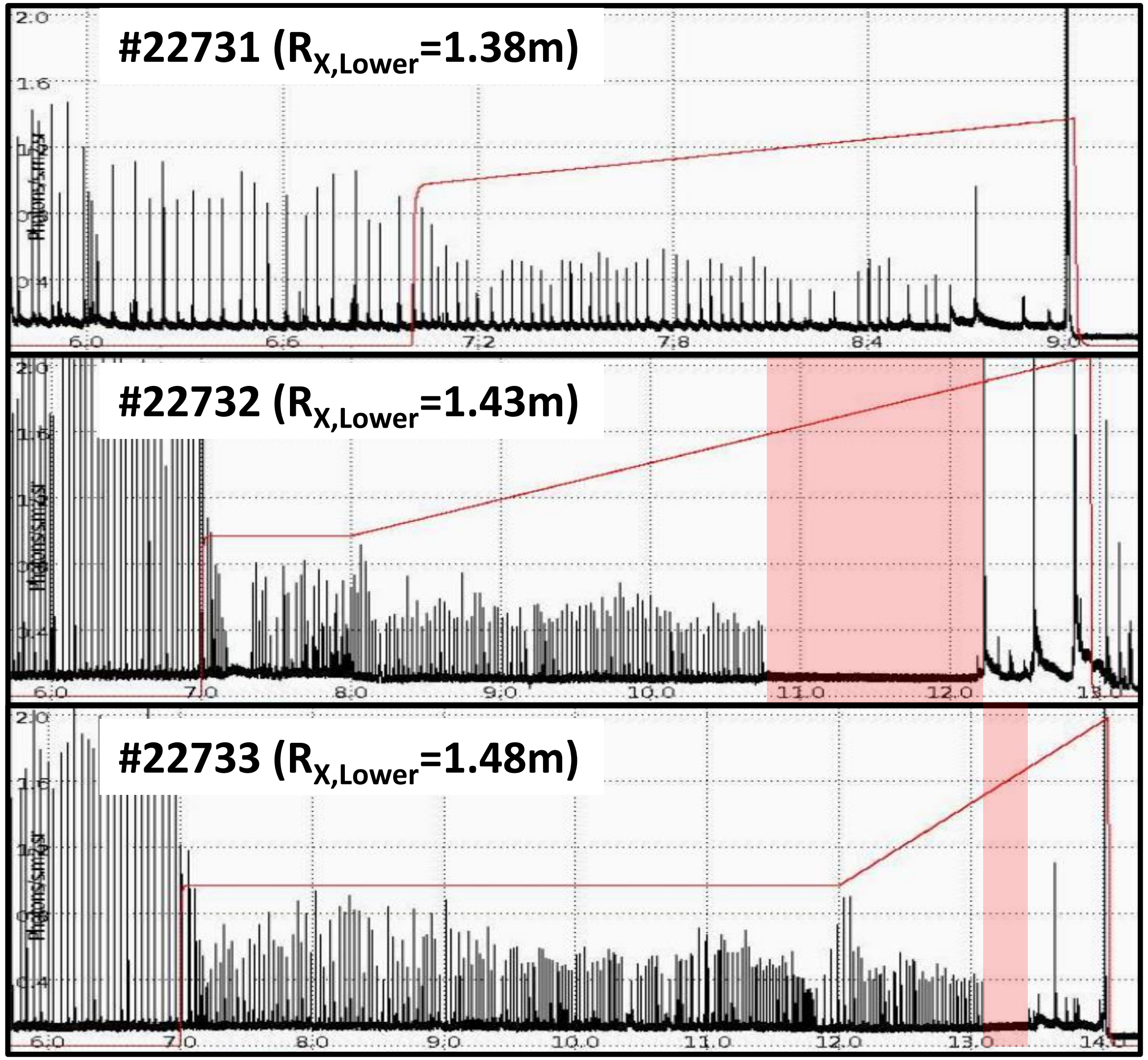


ELM-suppression maintained for wider range of $R_{X,lower}$

- 15% stronger RMP field applied (I_{RMP} = 2.0 → 2.3 kA/turn)
- Note that the upper bound of $R_{X,lower}$ was still limited by plasma locking
- All valuable results in 2017 were obtained with R_X=1.38m plasma shape

Plasma density and rotation are also important as much as plasma shape

Plasma shaping alone is not enough to ensure the success of ELM-suppression



- **All under same condition except $R_{X,Lower}$**
  - **NB1-A/C = 100/70keV=2.8MW**
  - **β_N~2.1, β_P~1.65**

- No ELM-suppression
- Locked at I_{RMP}=1.3kA/t

➔ Quite low locking threshold. Why?

- ELM-suppressed
- I_{RMP}=1.61~1.94kA/t

➔ ΔI_{RMP} ~0.33kA/t

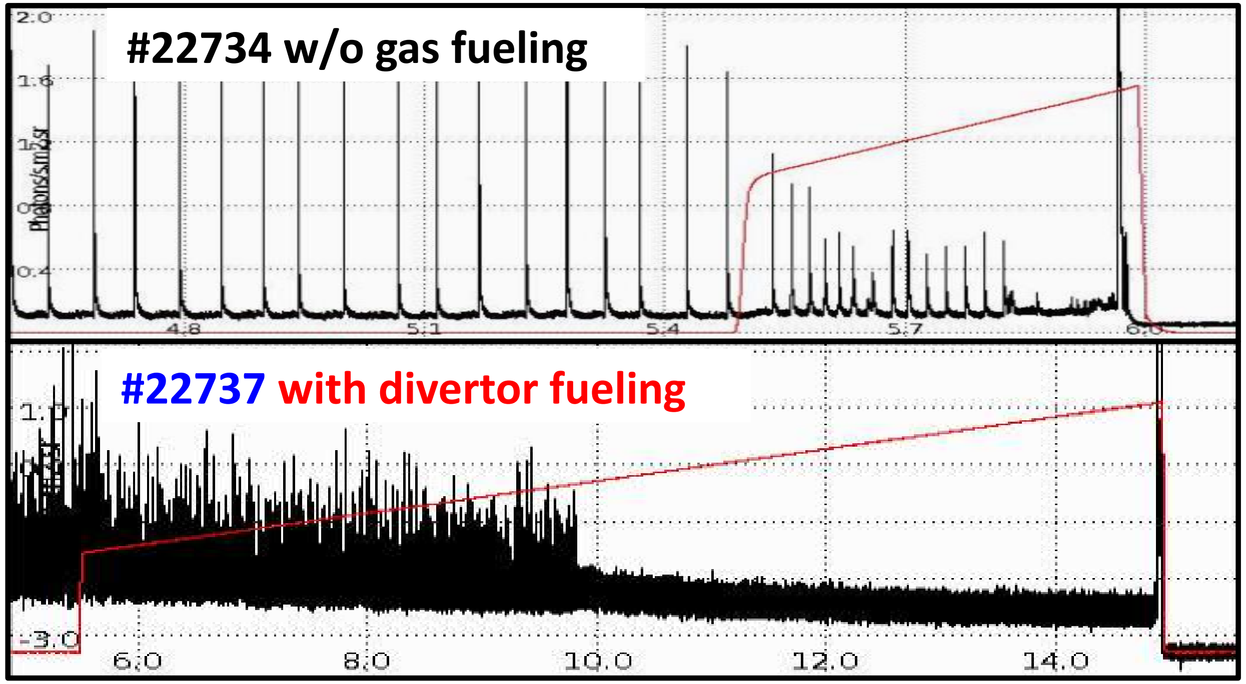
- ELM-suppressed
- I_{RMP}=1.54~1.82kA/t

➔ ΔI_{RMP} ~0.28kA/t

Nominal ELM-sup. window

Additional fueling is an effective way to expand the operation window by increasing locking threshold

- **All under same condition except $R_{X,Lower}$**
  - NB1-A/B = 100/90keV=3.4MW
  - β_N~2.3, β_P~1.80



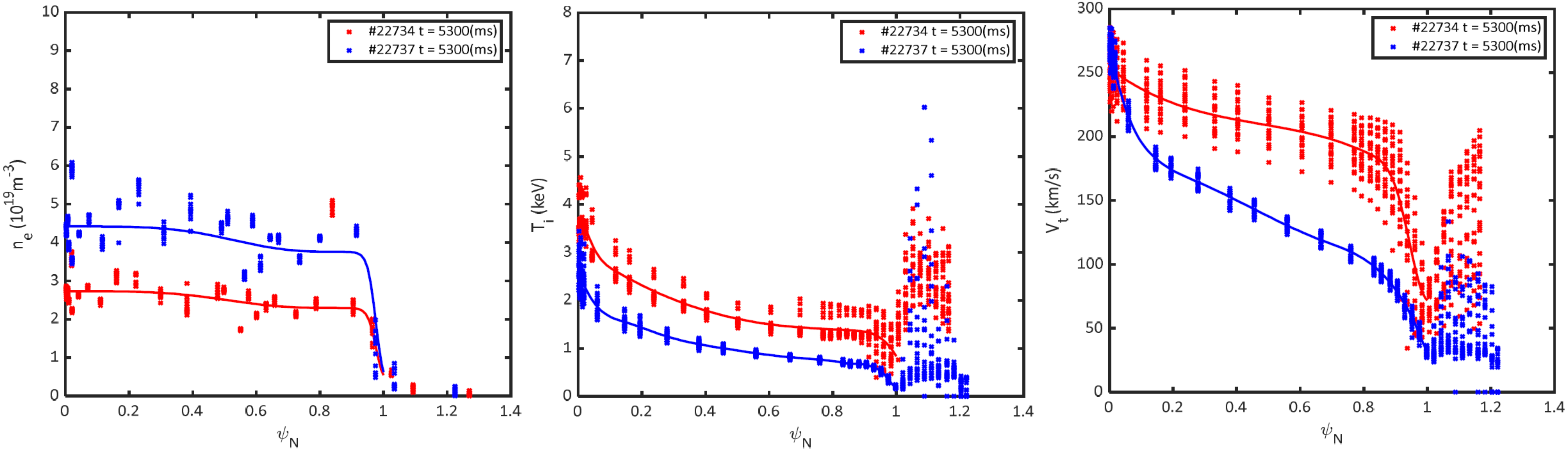
- No ELM-suppression
- Locked at I_{RMP}=1.5kA/t

➔ Low locking threshold

- ELM-suppressed
- I_{RMP}=1.63~2.43kA/t

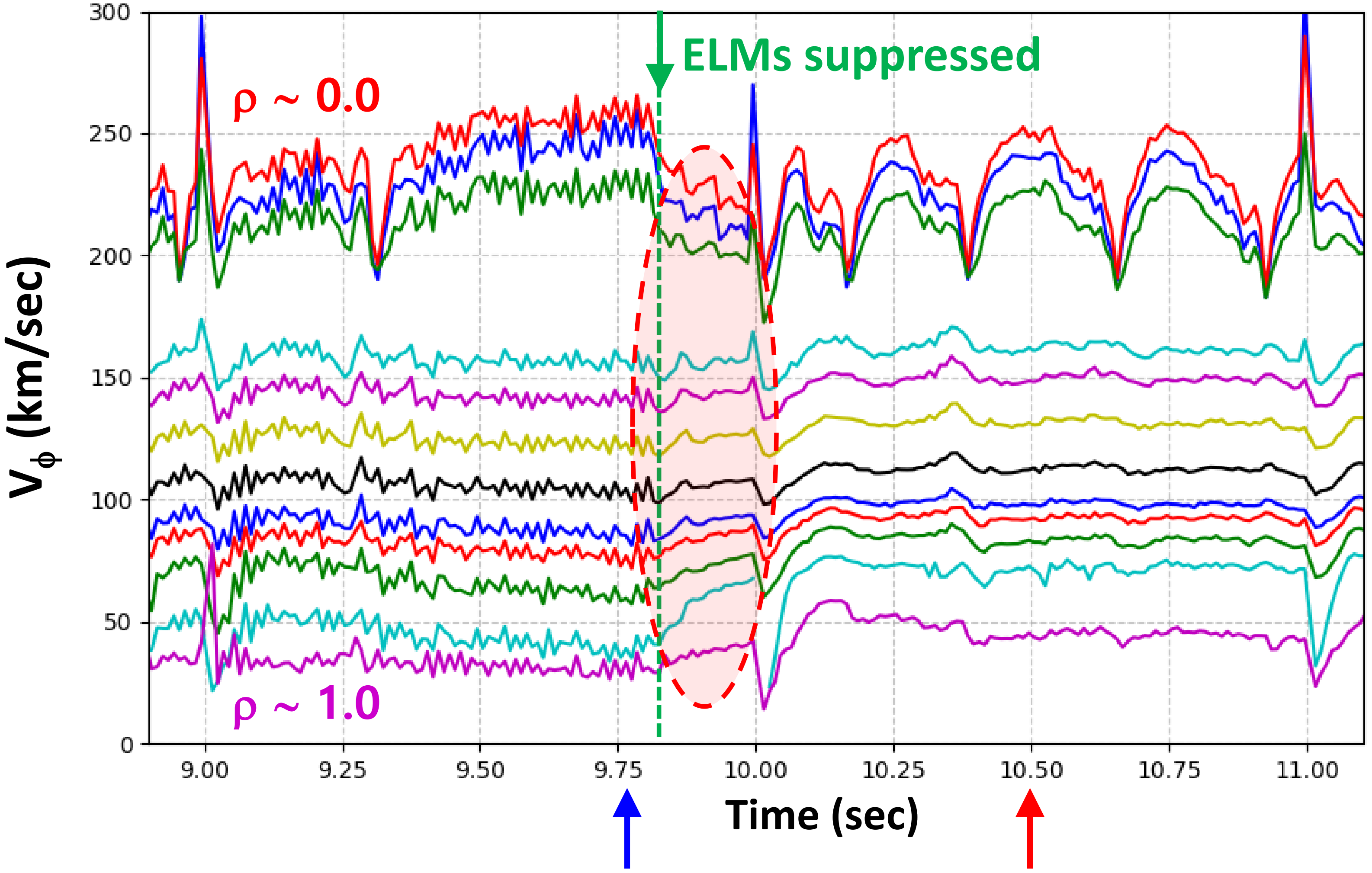
➔ ΔI_{RMP} ~0.80kA/t

Additional fueling is an effective way to expand the operation window by increasing locking threshold



- **Increased density is clearly helpful to increase locking threshold**
- **Also, the difference in rotation profile is important**
  - **flat vs peaked profile**
  - **pedestal gradient**

#022737: Edge rotation increases when ELMs suppressed



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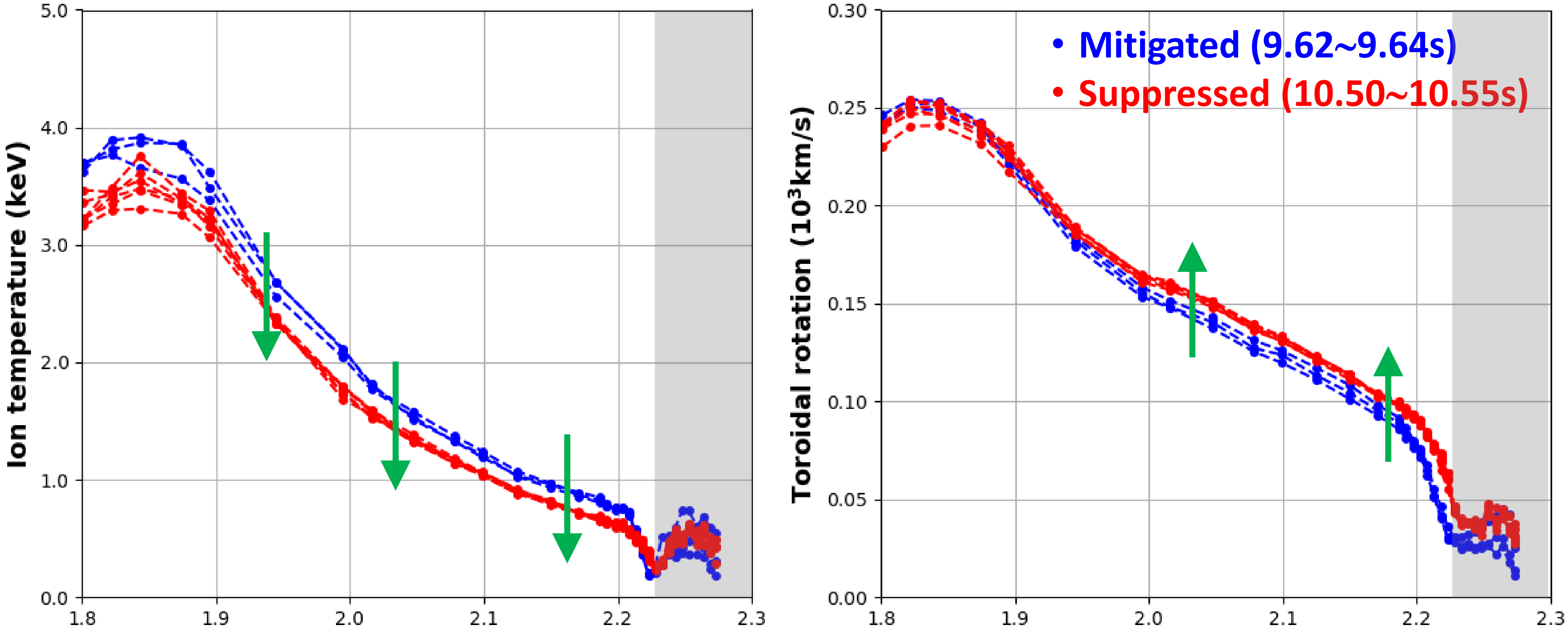

- **Note that rotation increase appeared rather globally (not edge localized)**

Low-n RMP-ELM suppression is challenging for high beta

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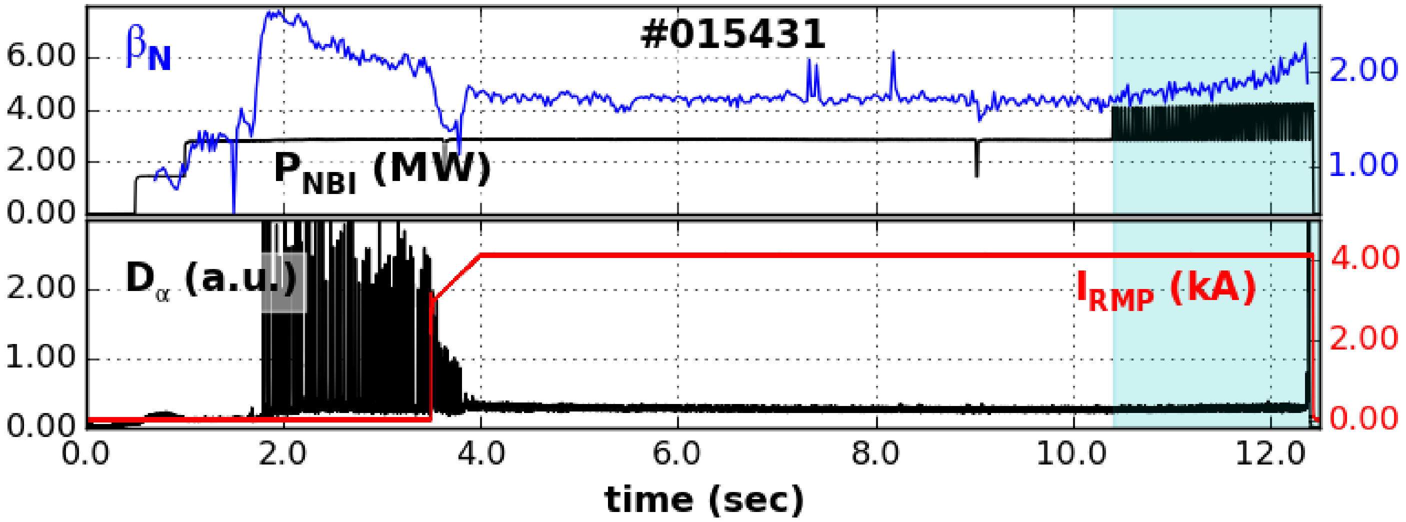

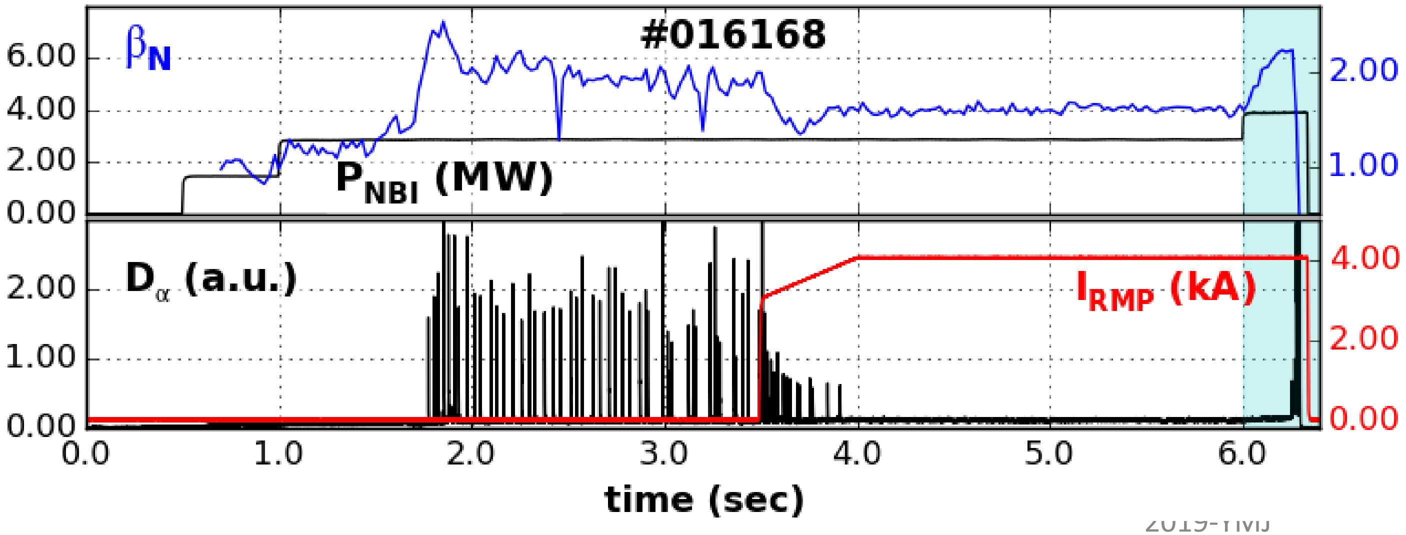

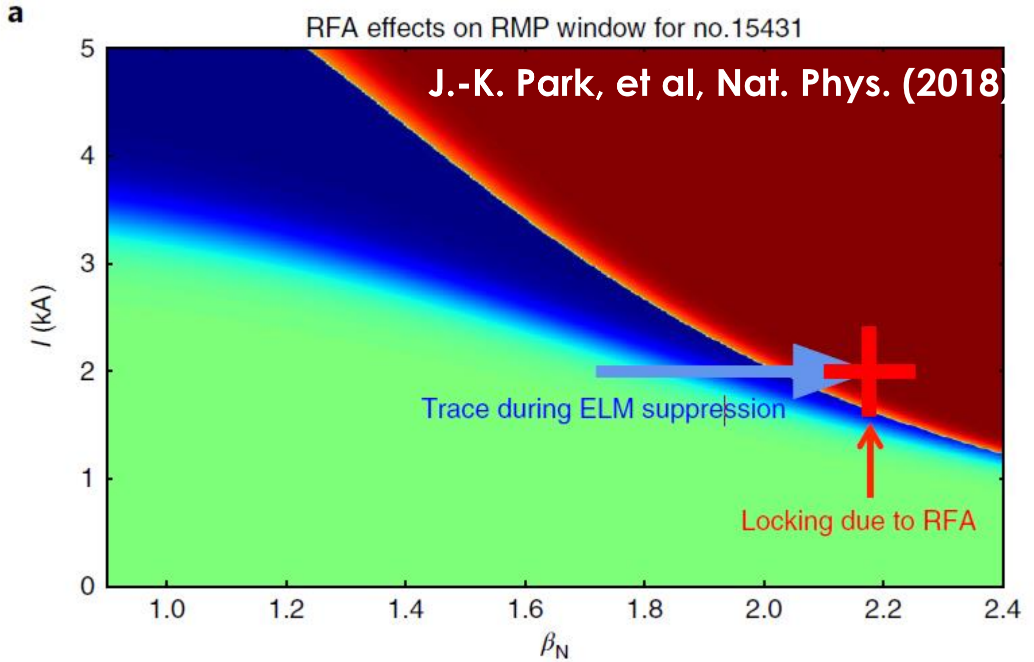

Possible to expand the suppression window in high beta plasma?

Concise summary and discussion

- Recently, low-n RMP-ELM suppression has been substantially improved in KSTAR, particularly taking into account the plasma shape dependence.

- Various experimental observations suggest that the plasma locking is the main obstacle for reliable ELM-suppression by low-n RMP

- Theory/modeling support is highly required in KSTAR for further physics understanding such as TM1, MARS, etc in collaboration with PPPL.