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Feedback Adaptive RMP ELM Control on DIII-D and KSTAR

Towards robust, performance optimized long pulse ELM suppression

Ricardo Shousha

Co-authors: S.K. KIM, K.G. ERICKSON, J.-K. PARK, S.M. YANG, A.O. NELSON, N.C. LOGAN, Q.M. HU, M.W. KIM, G. SHIN, S.-H. HAHN, C. PAZ-SOLDAN, R. WILCOX, A. BATTEY, W.H. KO, G.Y. PARK, Y.M. JEON, J. ABBATE, A. ROTHSTEIN and E. KOLEMEN

DIII-D NATIONAL FUSION FACILITY

Department of Mechanical and Aerospace Engineering
Princeton University

KSTAR

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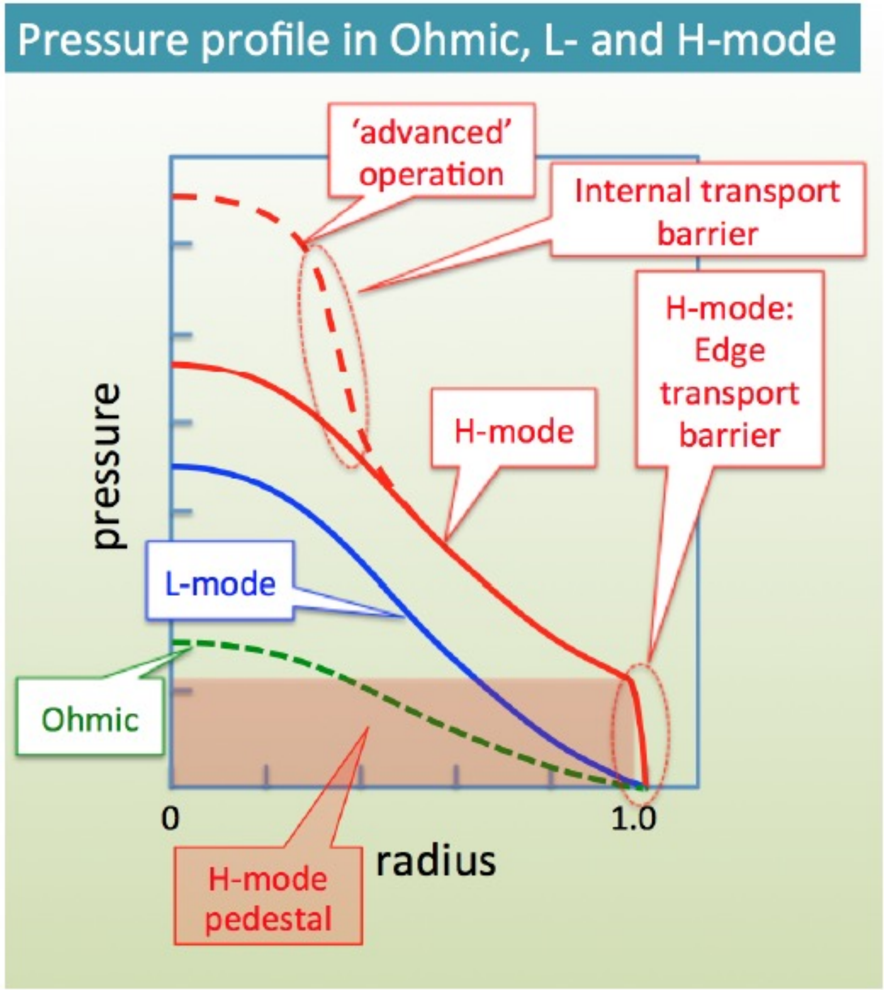
KSTAR

H-mode is promising for fusion because of increased performance. However, at the expense of instabilities

- By "default" plasma in L-mode
- When sufficient external heating applied, plasma enters H-mode
  - Elevated core pressure enabled by edge transport barrier
  - Steep edge gradient can destabilize Edge Localized Modes (ELM)
  - ELMs are quasi-periodic expulsions of particle and heat to vessel wall

Do we need to deal with this…?



N.C. Lopes Cardozo FOTBOAE lecture notes TU/e 2015

In Fusion-scale devices (ITER), the ELM transients are likely to exceed material limits and need to be dealt with

- Thermal cycling
  - Tungsten cracking
  - Brittle

- Tungsten erosion (physical sputtering)
  - Migration
    - Redeposition
      - Tritium retention
      - Unwanted conduction

➢ Lots of problems that don't scale well.

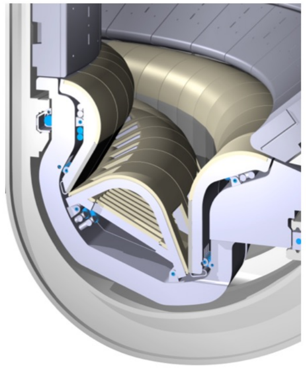
➢ ELMs need to be controlled or avoided

HWR

Re-entry vehicle

Ariane 5/Vulcain 2

Rolls Royce Trent 900



ITER steady-state

ITER transients

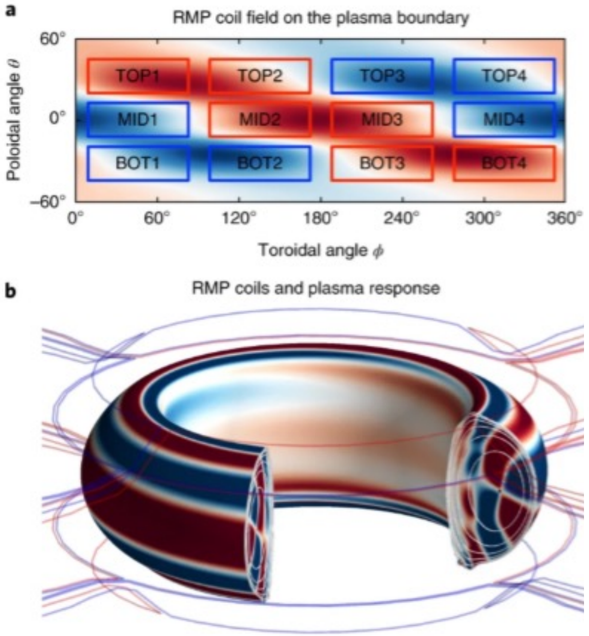
T.W. Morgan PFC lecture TU/e 2015

ELMs can be suppressed using specific 3D magnetic perturbations, but feedback needed to regain performance

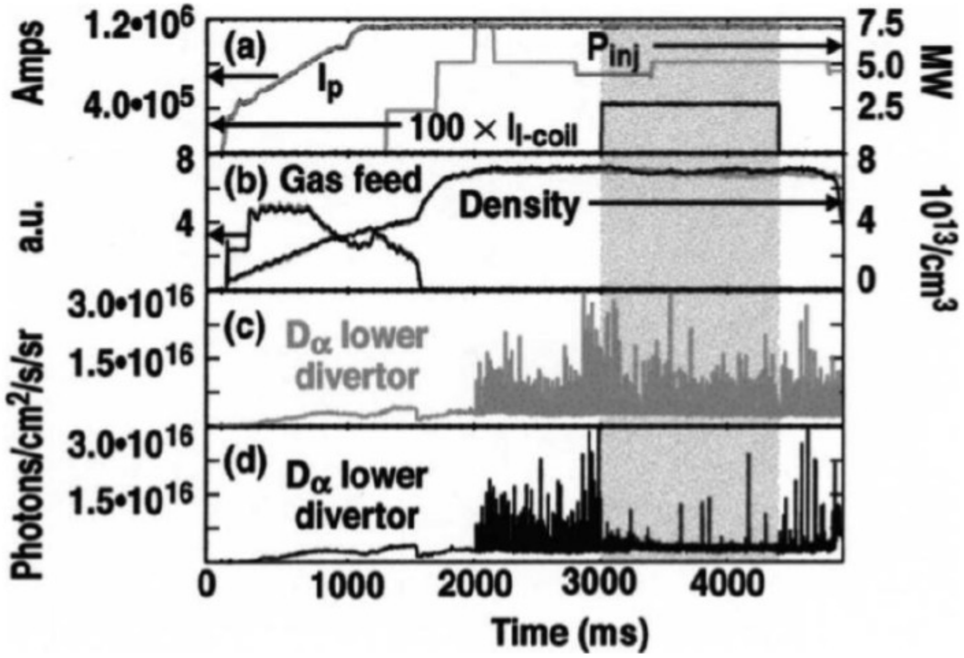
- ELM suppression through application 3D Resonant Magnetic Perturbation (RMP) discovered by late Todd Evans (2004)

However, there are challenges:

- "ELM-suppression window" required
  - RMP amplitude for ELM suppression unknown a-priori
  - Evolves with plasma
- **RMP reduces plasma performance (confinement)**



J.K. Park et al , Nature Physics 2018



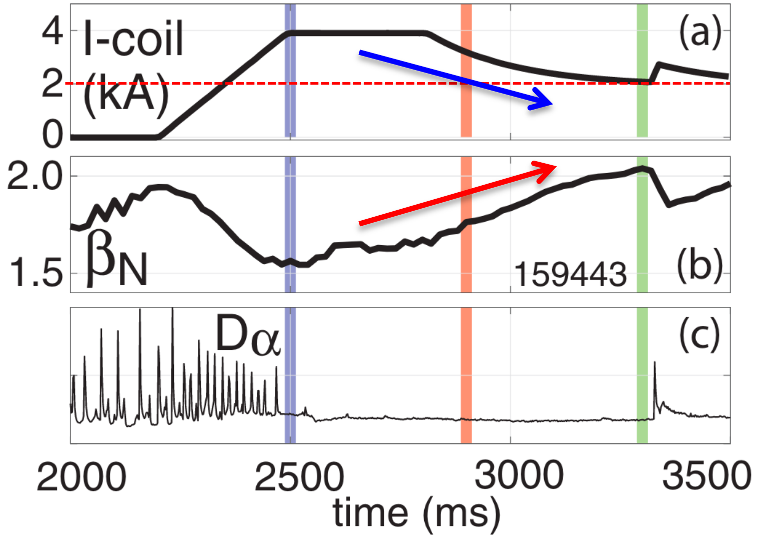
T.E. Evans et al, PRL 2004

➢ **Feedback Adaptive RMP ELM Controller** could provide solutions:
  - ➢ Use RT-ELM detector to monitor ELM activity
  - ➢ Use ELM detection to inform RMP spectrum to 3D coils to achieve suppression
  - ➢ Once suppression is achieved, optimize plasma performance by reducing RMP, exploiting hysteresis effect

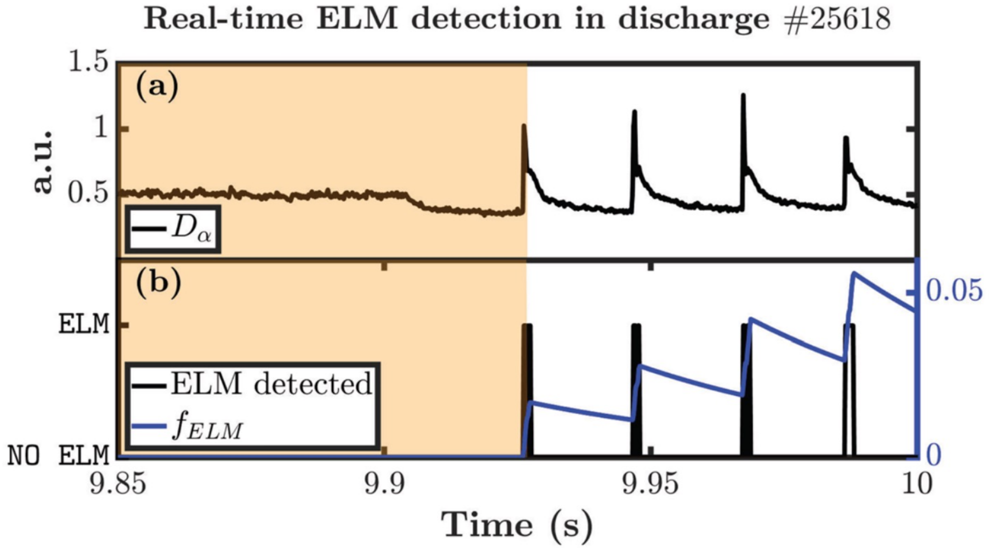
Main Idea: Let controller try to reduce applied RMP amplitude while sustaining ELM suppression, to maximize performance

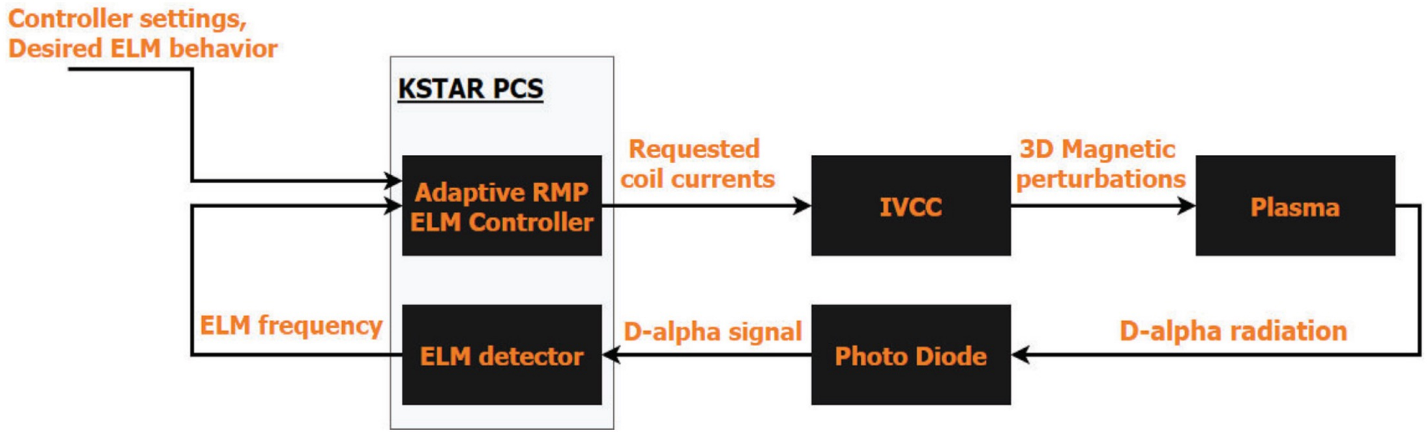
Hysteresis explained:

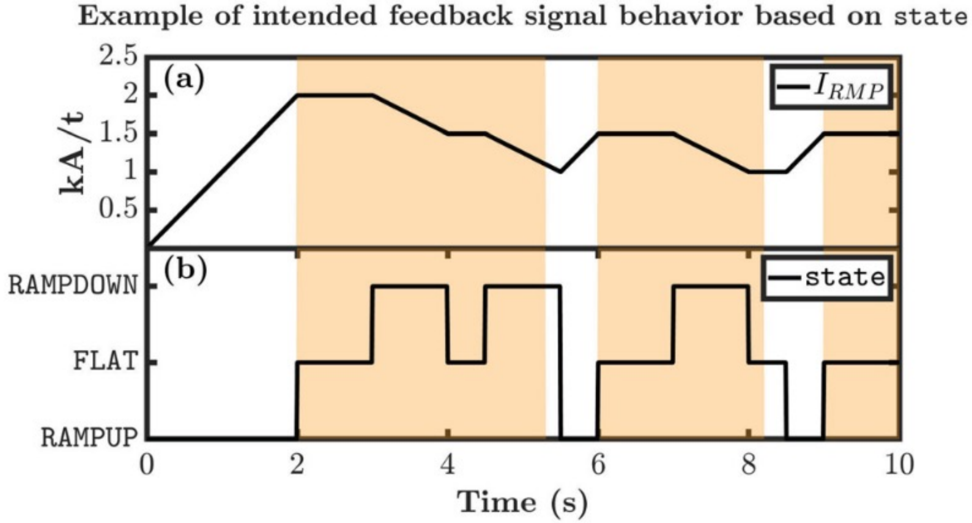
- Less RMP amplitude required to <u>sustain</u> ELM suppression, than to access it



[RT-RMP control at DIII-D (F. Laggner, NF20)]







Controller recovers 60% of confinement degradation using amplitude feedback and adaptive lower bound on KSTAR

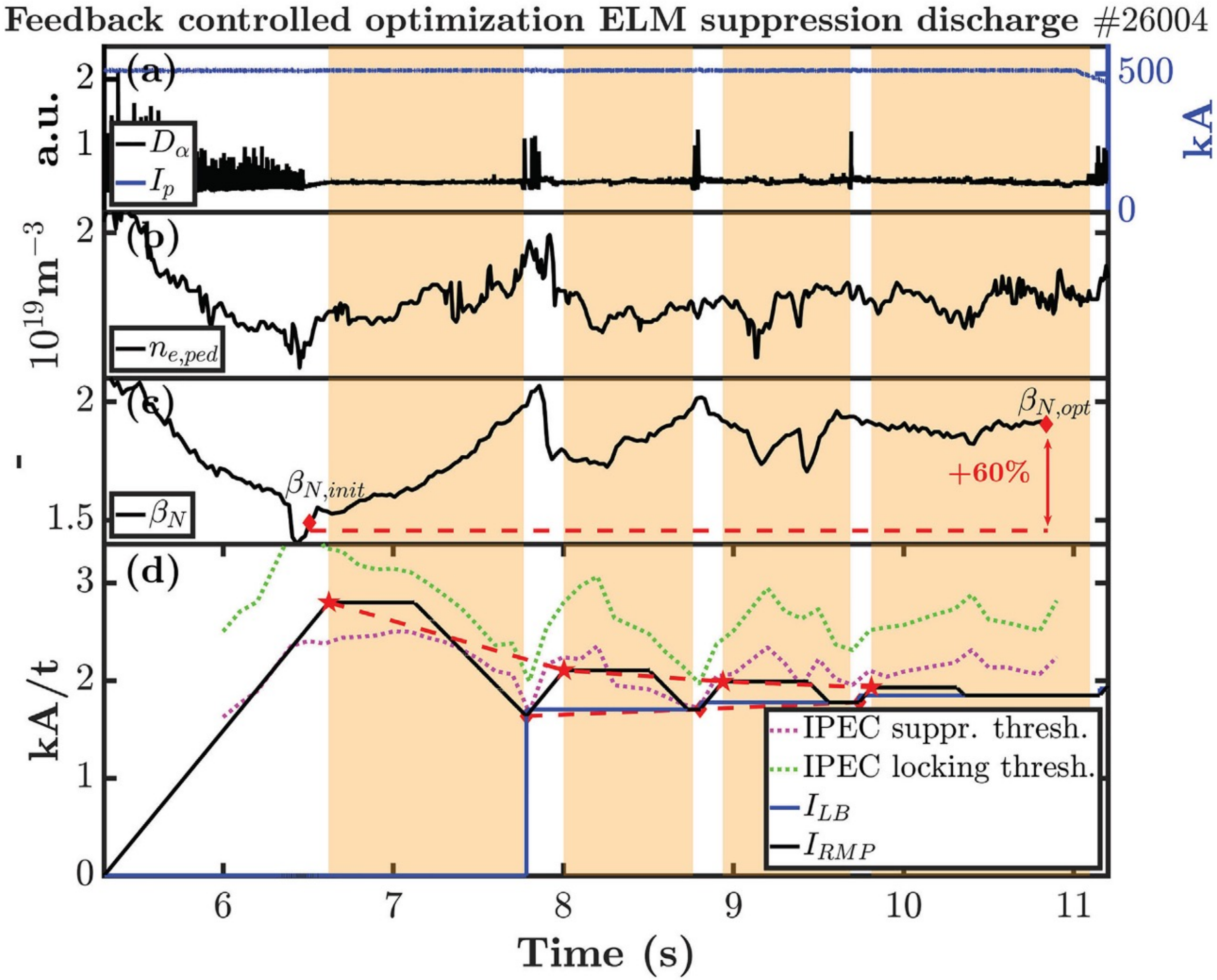
Adaptive Lower bound:

- Controller stores RMP amplitude in case of loss of suppression
- Controller tries to regain suppression
- Controller does NOT allow RMP amplitude below adaptive lower bound

Observations:

- Discharge mostly ELM suppressed by feedback
- Feedback allows to stay well below locking threshold, and mostly just above suppression threshold

- Inherently needs to LOSE ELM suppression AT LEAST *ONCE* to optimize → Not desired!



Challenge I: Need to avoid initial ELMs after LH-transition

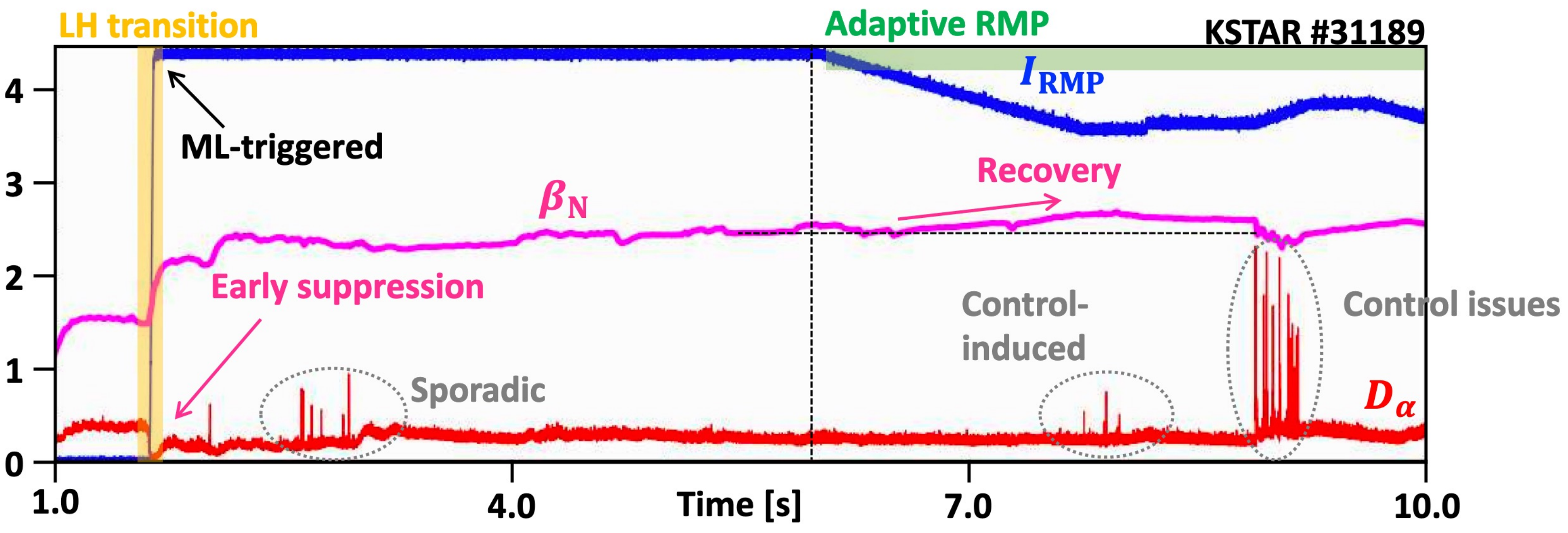
Controller recovers 60% of confinement degradation using amplitude feedback and adaptive lower bound on KSTAR

Challenge:

- RMP hinders LH-transition, but any and all ELMs after transition should be avoided

Solution:

- Use ML LH-transition detector [Shin, Ko, Kim] to trigger initial feed-forward RMP before handing off to feedback performance optimization



✓ Feedback Initialization allows smooth takeover of FF by controller

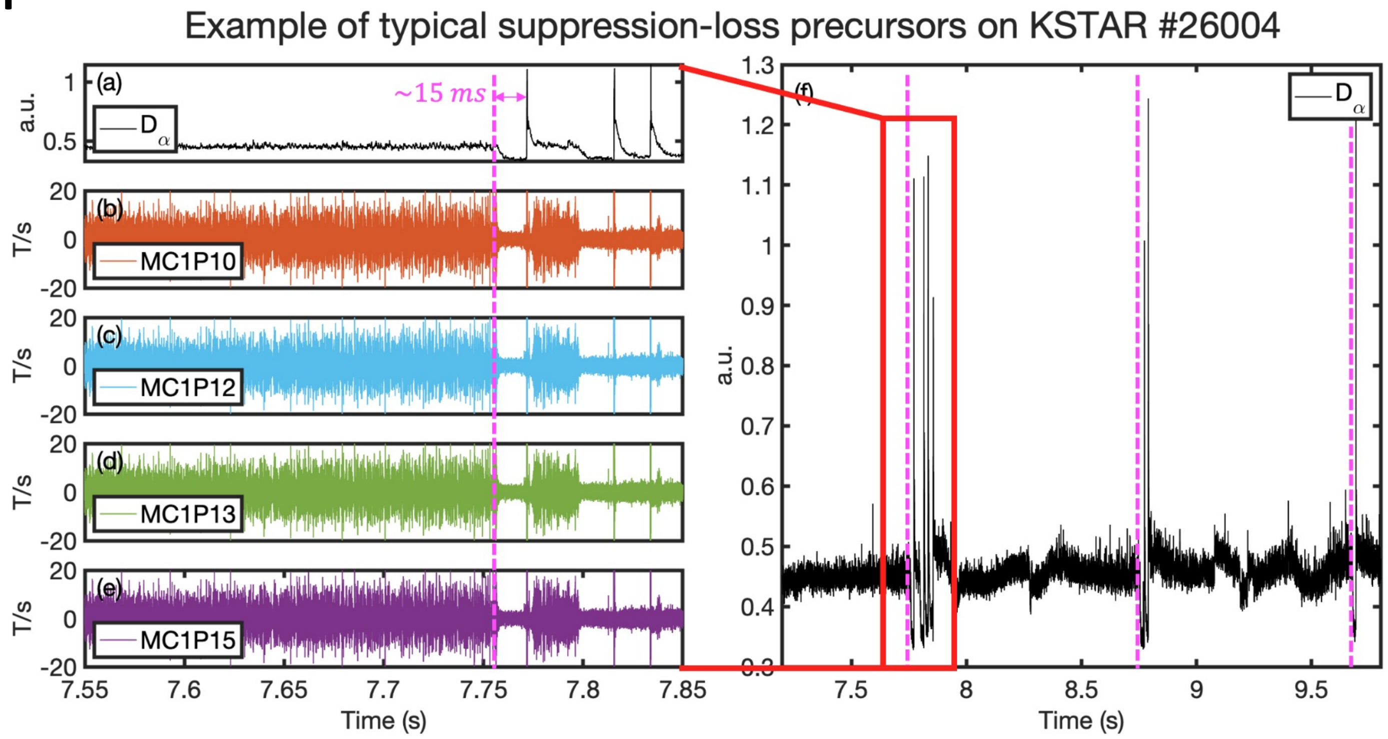
✓ Early ramp at detected LH-transition promising method for eliminating initial ELMs in H-mode

Challenge II: Need to detect ELMs BEFORE they happen and take action

Precursor patterns prior to loss of ELM suppression visible on D-a and Mirnov signals on KSTAR

Diagnostics that show precursors to loss of ELM suppression:

1) The D_α signal characteristics:
   - ***Rapid sustained dip before ELM***
2) The Mirnov probe signal characteristics:
   - ***Rapid sustained reduction in standard deviation before ELM***



Time scales that need to be considered (and can be device specific, here just rough est.):

- pedestal confinement time (τ_{ELM} ~10-50ms)

- The instability itself is very fast (~1ms) so no use to detect
- Precursor needs to be detected at least ~10ms before the ELM on KSTAR

Precursor detector avoids false positives by integration with ELM detector

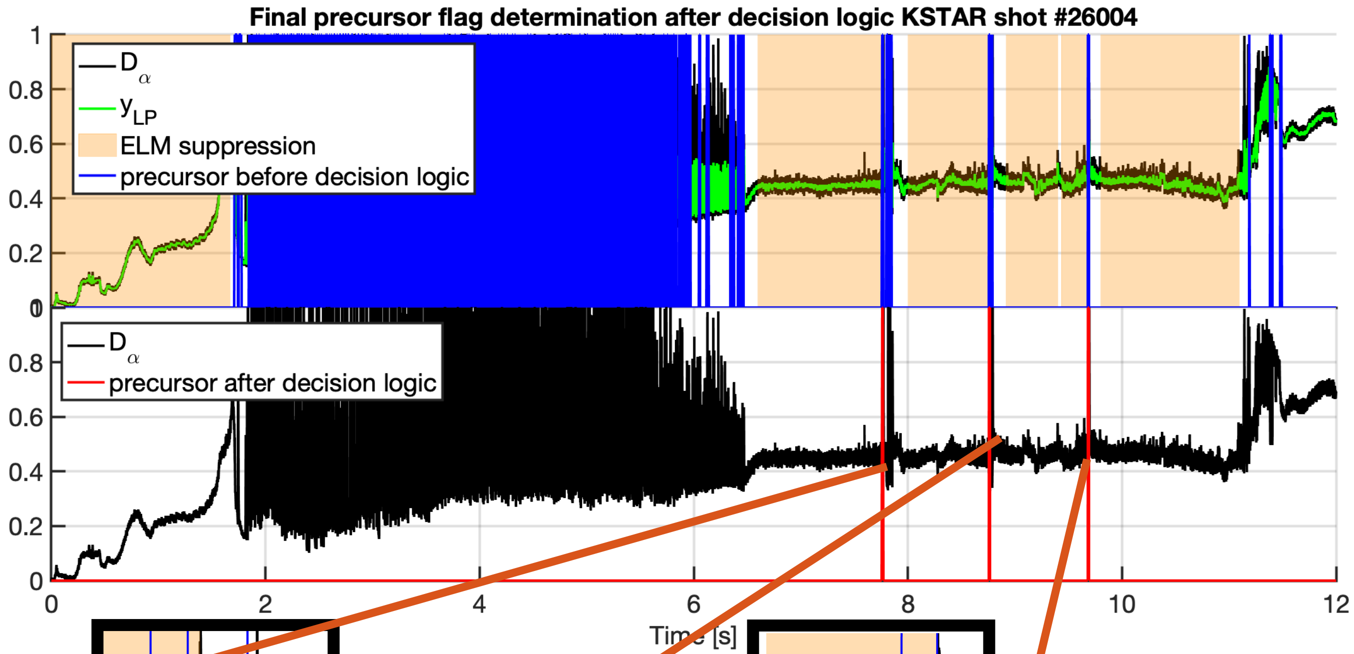
“raw” precursor detector output

+

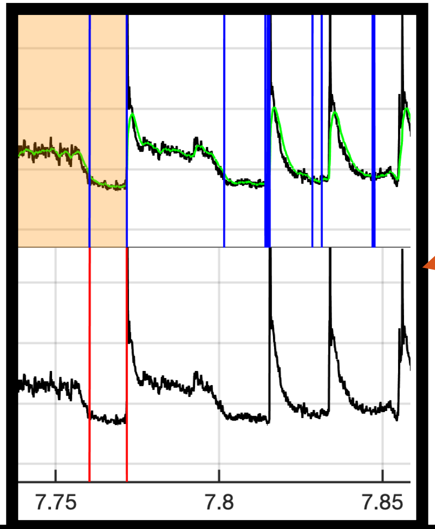
ELM detector output

=

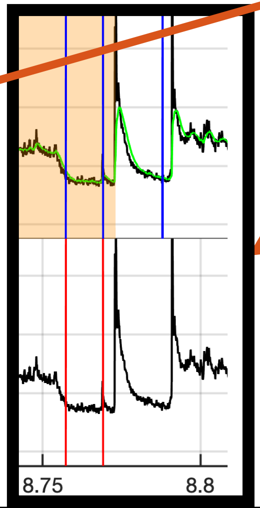
Actual precursor output



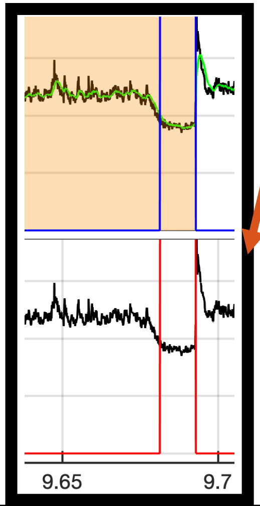
>12ms



>15ms



>11ms



RT-precursor detection + *jump scheme* can avoid imminent ELMs, but more optimization is needed to increase reliability

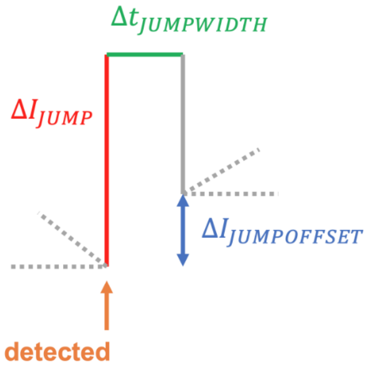
Challenge:

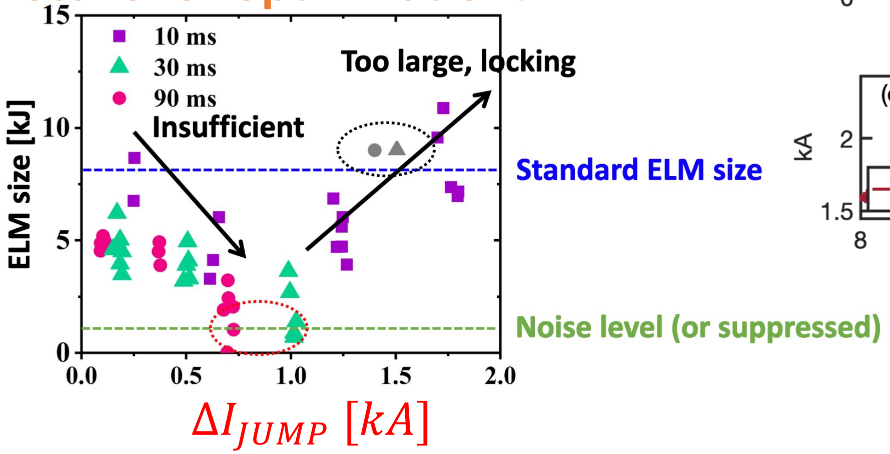
Can we avoid an imminent ELM after detecting a precursor?

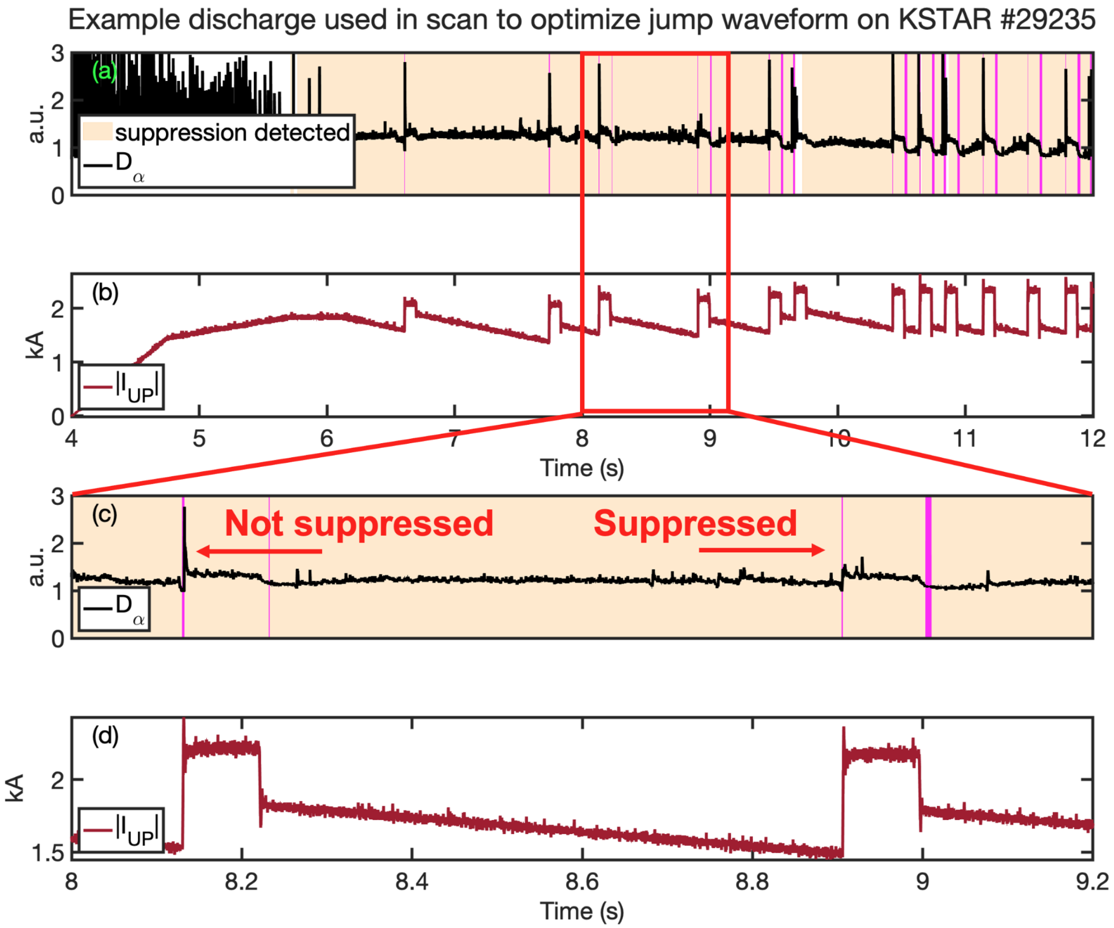
Solution:

1) Precursor detector detects precursor
2) If Jump-scheme active, controller jumps up by amount ΔI_{JUMP}
3) Controller holds RMP at elevated level for $\Delta t_{JUMPWIDTH}$
4) After $\Delta t_{JUMPWIDTH}$ has elapsed, controller goes back to previous level, modified by offset $\Delta I_{JUMPOFFSET}$

→**Result: sometimes. Need scans for optimization.**







RT-precursor detection + *active probing scheme* <u>can</u> reduce lower bound in long pulse, but more optimization needed for reliability

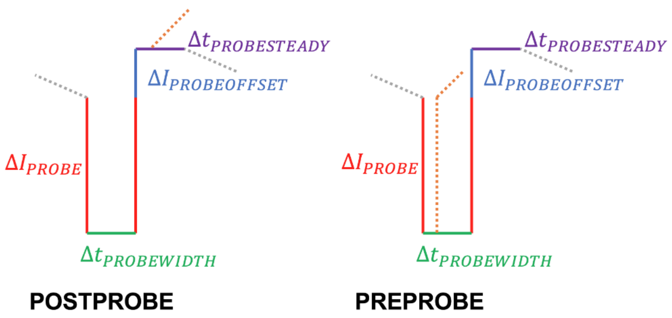
Challenge:

Lower bound evolves with plasma in long pulse. Can marginal stability be probed to adjust lower bound?

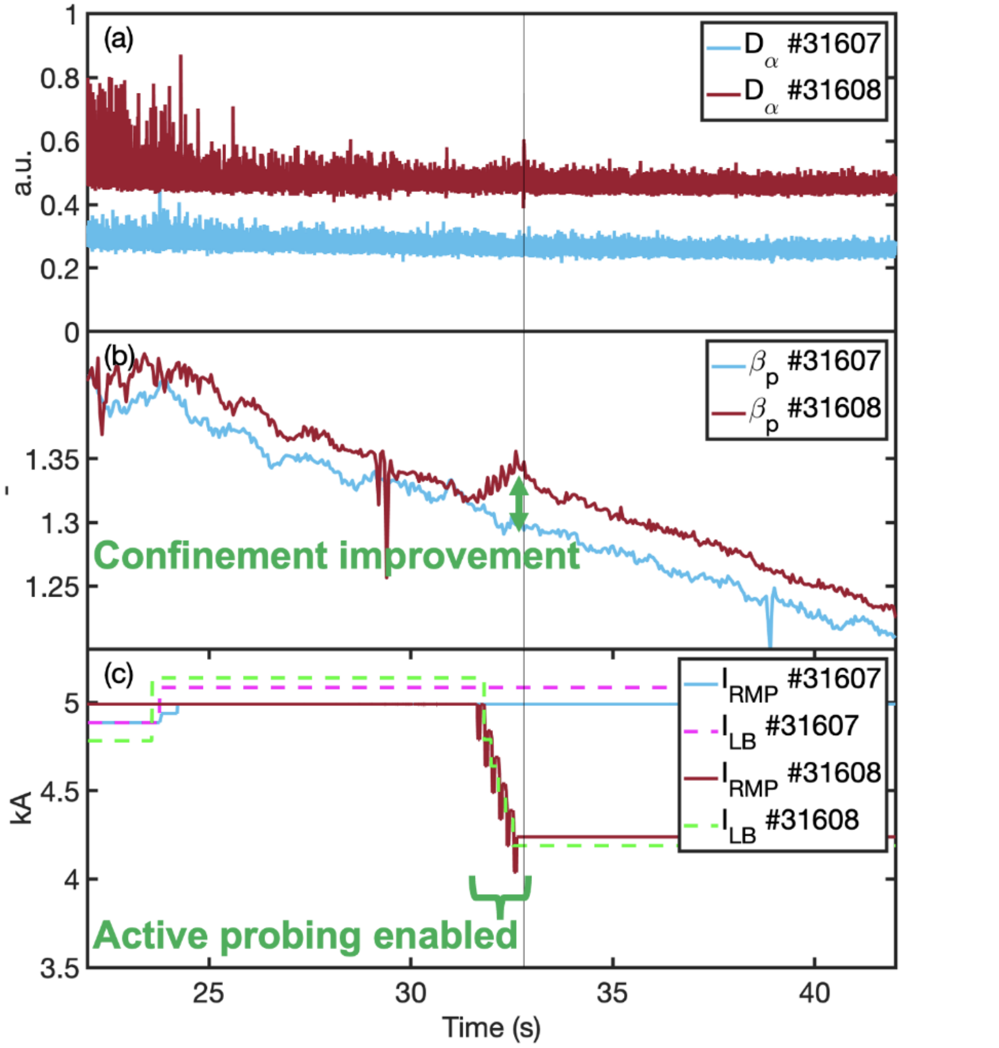
Solution:

1) Lower bound is activated and preventing RMP from decreasing
2) Once probing activated, controller applies downward pulse (customizable)
   1) If PREPROBE, controller starts checking for precursors DURING pulse and exit immediately at time of event
   2) If POSTPROBE, controller starts checking for precursors AFTER downward pulse (to study transients)

→Result: Effective at reducing lower bound, but not able to prevent all ELMs that follow precursor yet



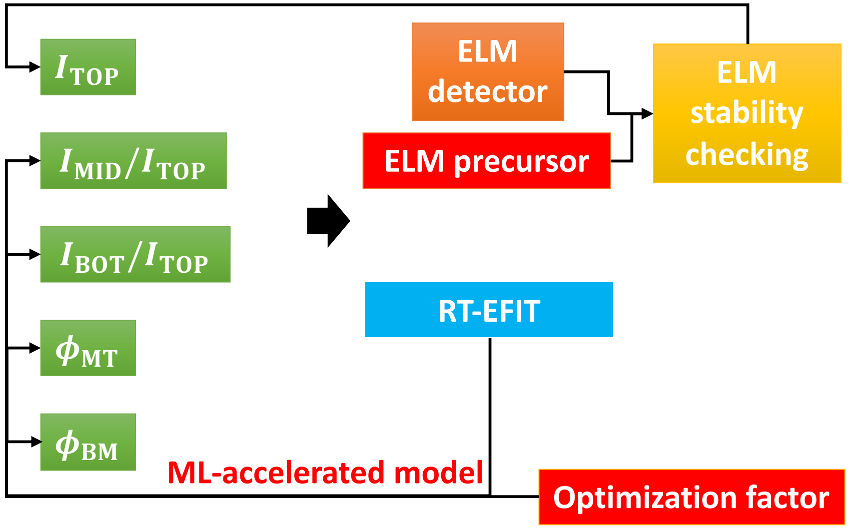
Confinement improvement by active probing scheme in long pulse #31607 vs. #31608



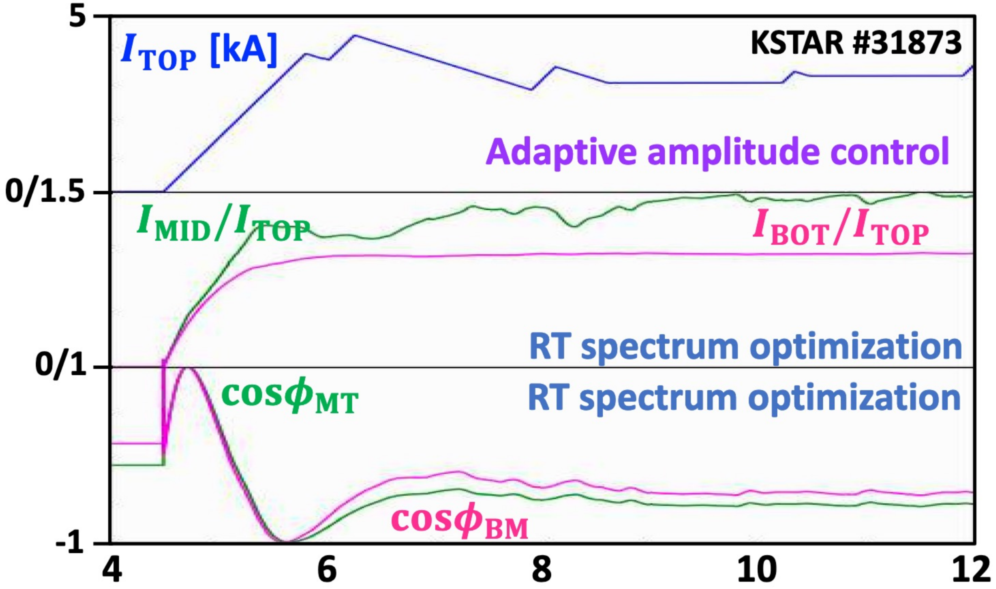
Challenge III: Need to implement more "brains" in controller

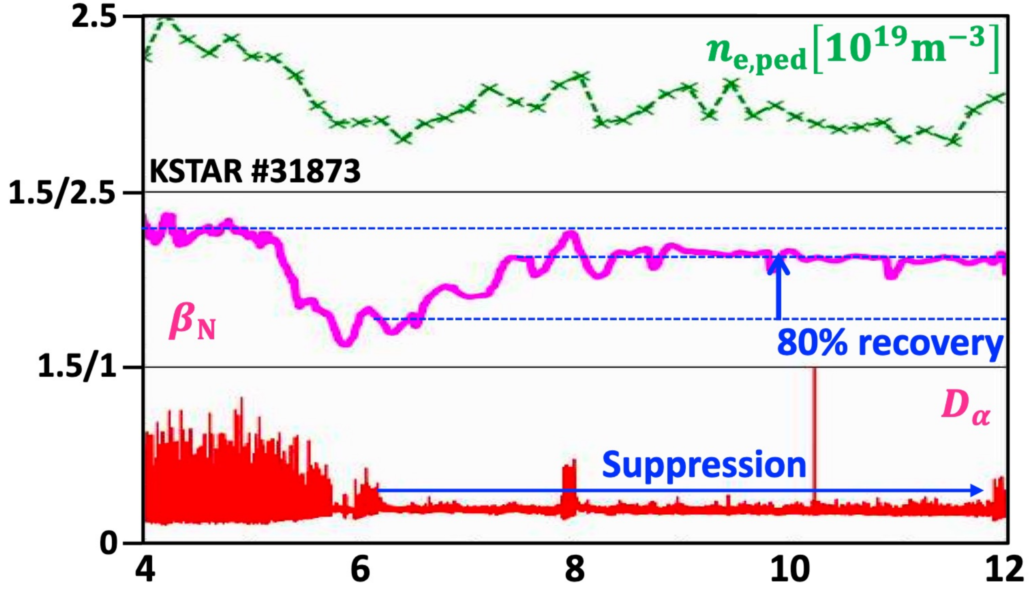
Real-time full 3D feedback control using ML surrogate model demonstrated safer ELM suppression and higher confinement

- Full 3D feedback control:
  - Re-use Amplitude feedback mode
  - Amplitude ratios, phasings given by ML model
  - ML IPEC surrogate enables RT spectrum optimization (ERMP) in addition to existing amplitude recovery



✓ **Safe ELM-free access and 80% confinement recovery**





Selected Control Achievements

When combining all LPT efforts in long pulse attempt, we achieve considerable ELM suppression and show potential for optimized LP

Idea:

1) Use Feedback Adaptive RMP ELM Controller in I_UP RATIO amplitude feedback
2) Use ERMP optimal amplitude ratios computed by S.M. Yang
3) Use ML trigger developed by [Shin, Ko, Kim]
4) Use scenario development by LPT team under leadership J.-K. Park

2022 (1):

✓ **Record length Feedback ELM suppressed discharge**

However:

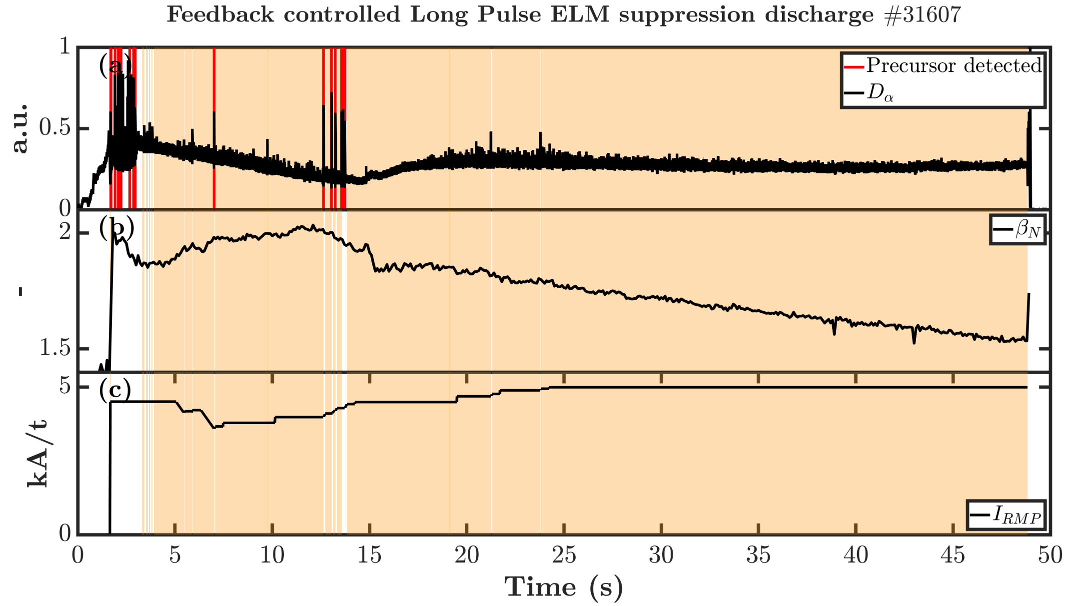
- Sporadic ELMs in early phase made controller set LB high
- Probing not turned on so no LB reduction possible
- Confinement could not be optimized due to absence probing

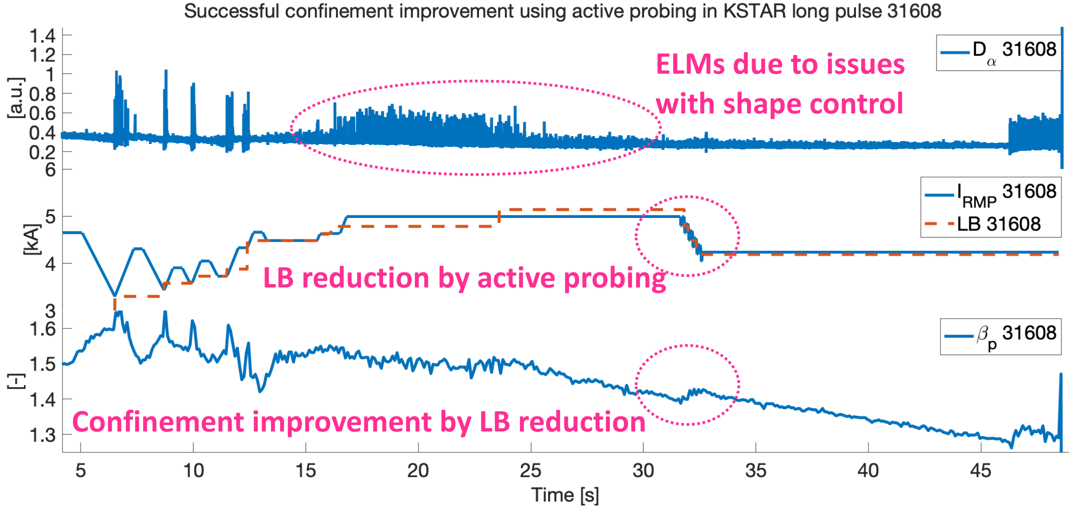
2022 (2):

✓ **Active probing successfully used to reduce LB**

However:

- Due to some shape control issues causing ELMs in early phase, not perfect trophy shot yet





Thank You