Mechanical and Aerospace Engineering

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Feedback Adaptive RMP ELM Control:

ELM suppressed high performance fusion scenarios achieved with Feedback Adaptive RMP ELM Control

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We must control ITER-scale ELM transients to stay within material limits.

ITER ELM:

- Thermal cycling
  - Tungsten cracking
  - Brittle

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

➢ Lots of problems that don't scale well.

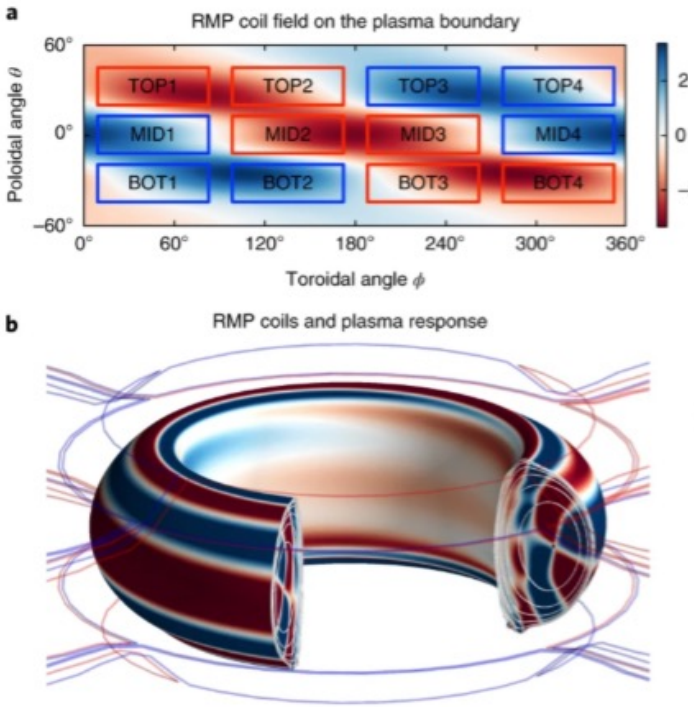
➢ ELMs need to be <u>controlled</u> or avoided

<u>Transients in current devices</u> vs. **<u>Transients in ITER-scale devices</u>**

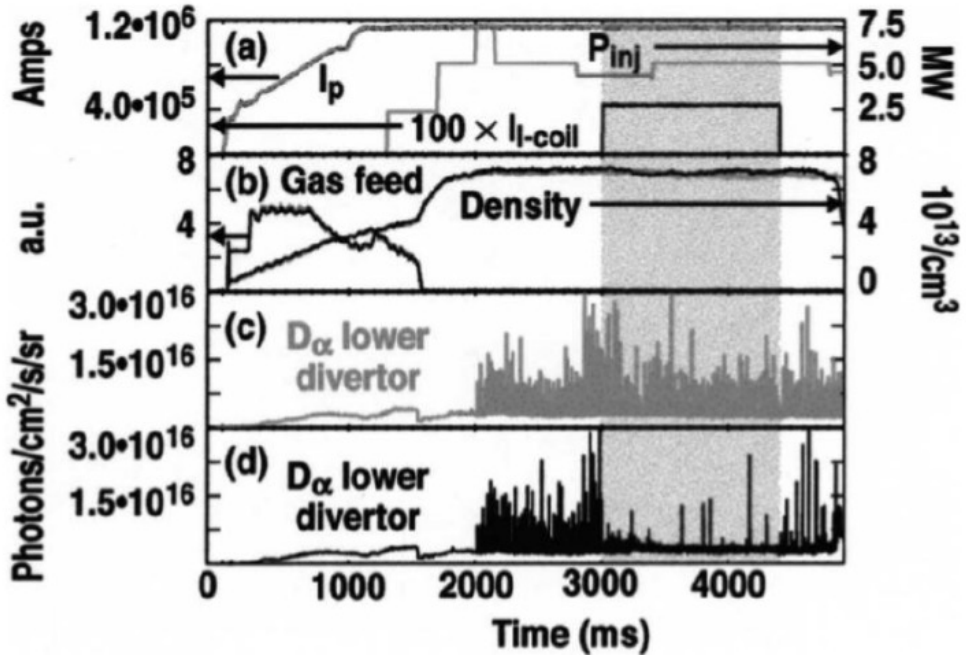
Why Control?

Feedforward RMP Experiments have shown promise, but issues remain. Need feedback to address plasma evolution and performance

- Resonant Magnetic Perturbations (RMPs) have demonstrated robust ELM suppression on many devices
- RMP suppression degrades performance and limits operating space within sensitive "access conditions"
- Feedback control of RMPs can adapt to evolving access conditions and recover performance by utilizing hysteresis effect



J.K. Park et al , Nature Physics 2018



T.E. Evans et al, PRL 2004

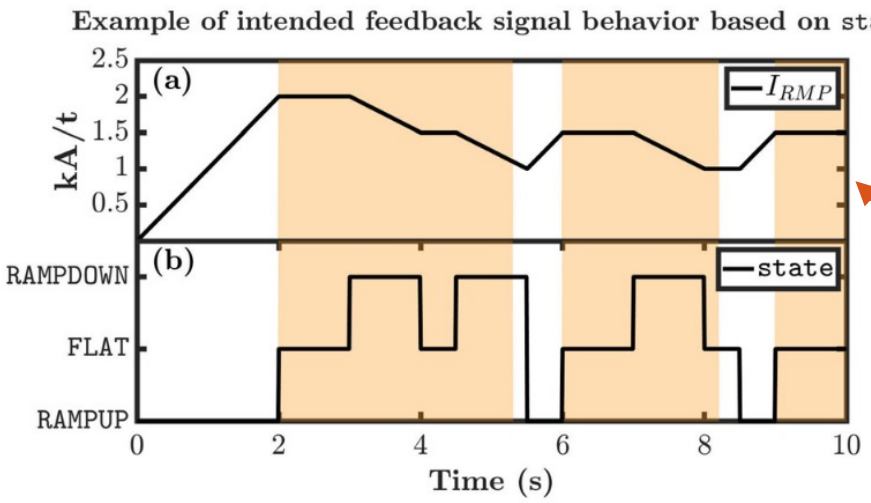
Hysteresis: less RMP required to sustain suppression than is needed to enter it

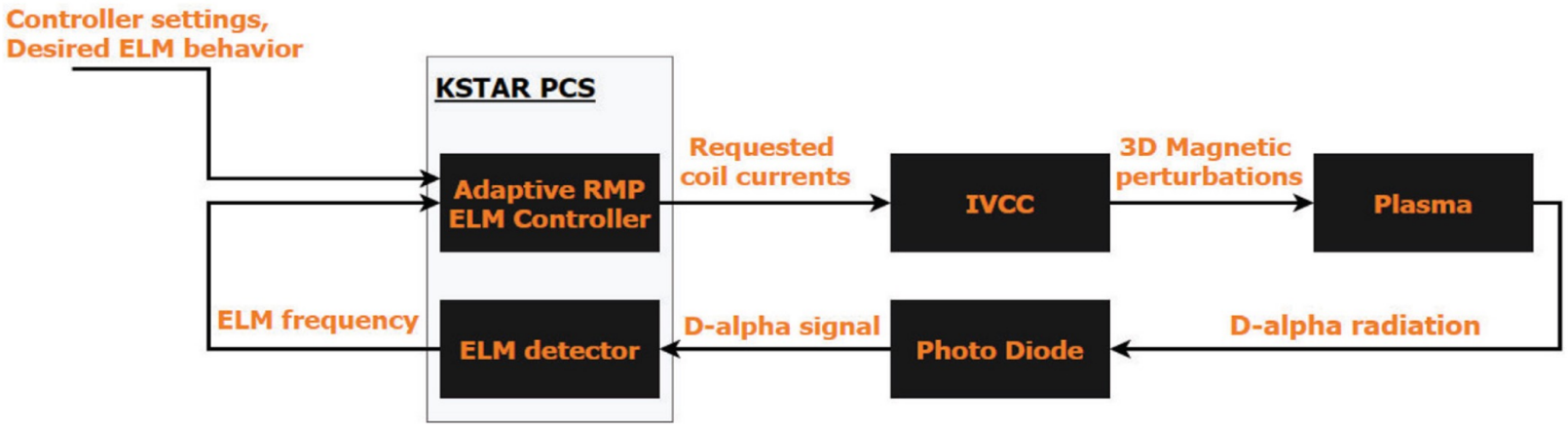
- **Allows longer more higher performance shots without ELMs. And does it automatically.**

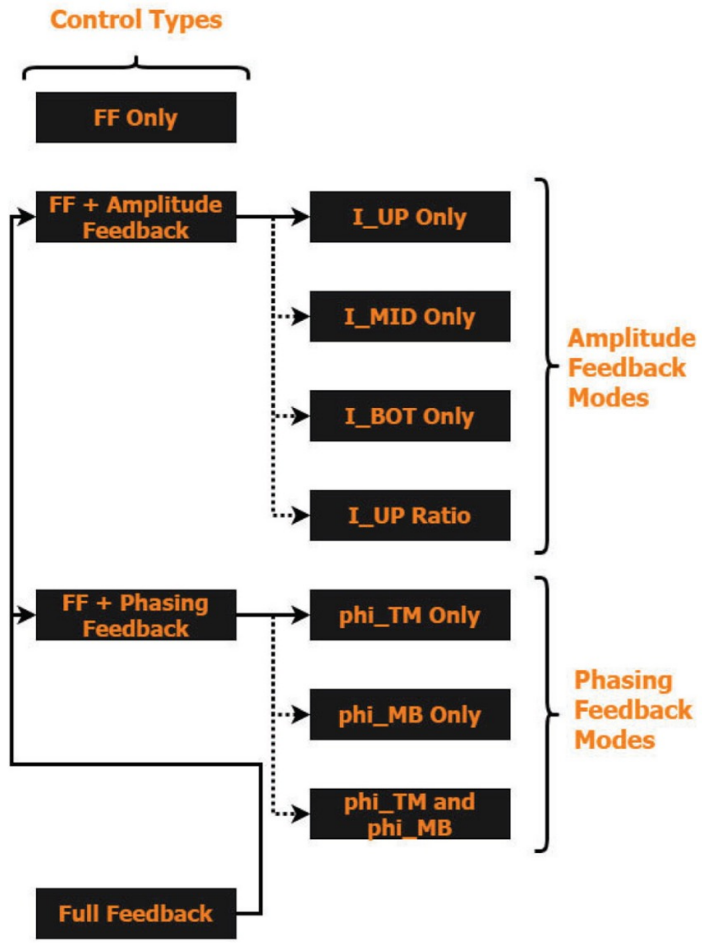
Controller based on Finite State Machine design, modular and generic for maximum portability

- No reliable RT-model to predict minimum required RMP amplitude and phasing
- Need to adjust RMP based on measurements
- RMP request dynamics should be constrained (avoid locking, avoid RMP to zero when suppressed)

→ FSM allows this!





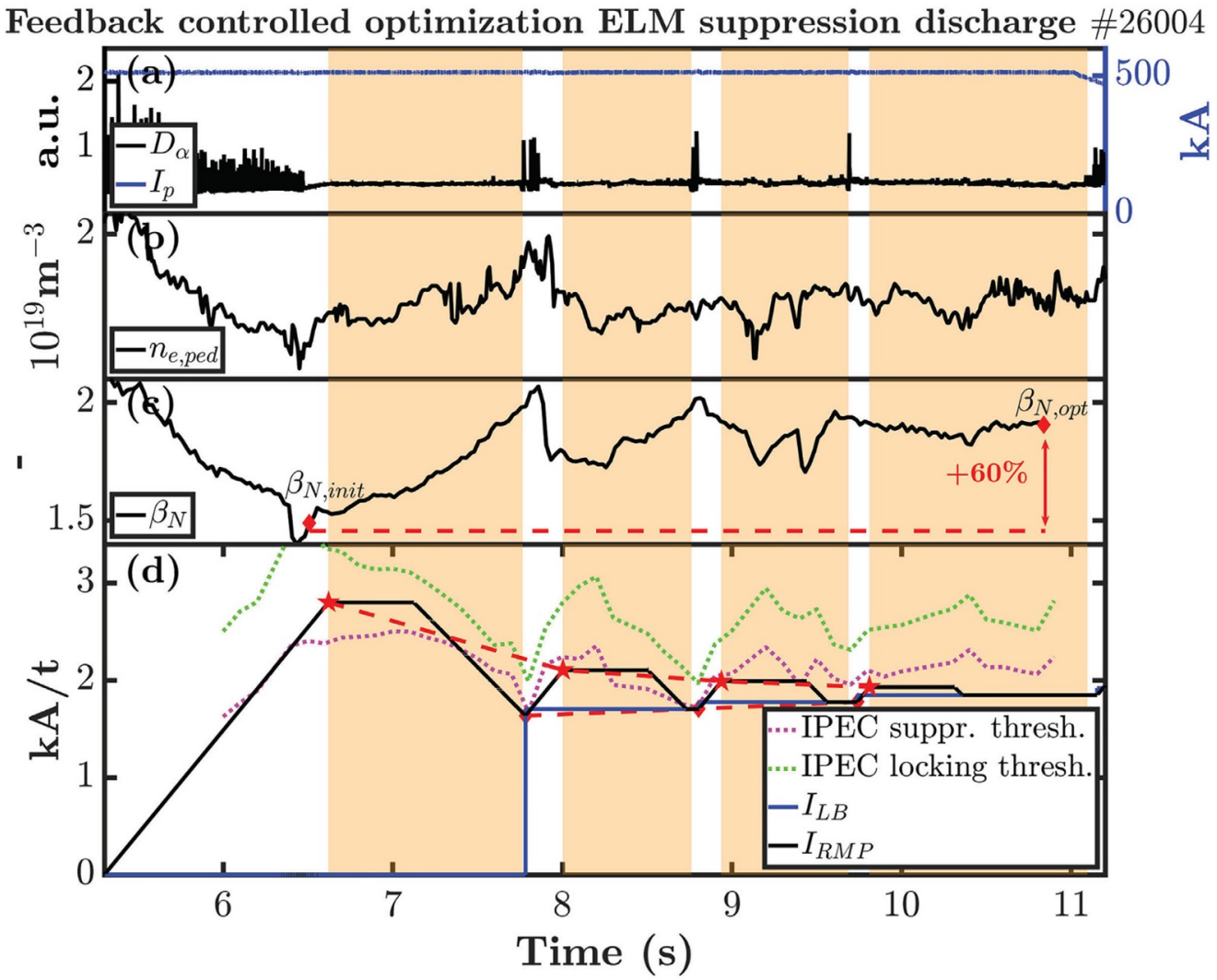


Feedback Adaptive RMP ELM Controller optimized confinement in feedback while maintaining ELM suppression for majority of time

Results obtained with controller at KSTAR

Adaptive lower bound successful:

- ✓ Decreased hysteresis margin observed again: 0.9→0.37→0.2→0.1→0 kA/t
- ✓ Converged RMP level after 10.5s with minimized performance degradation
- ✓ Degradation of beta by RMP restored by >60%



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

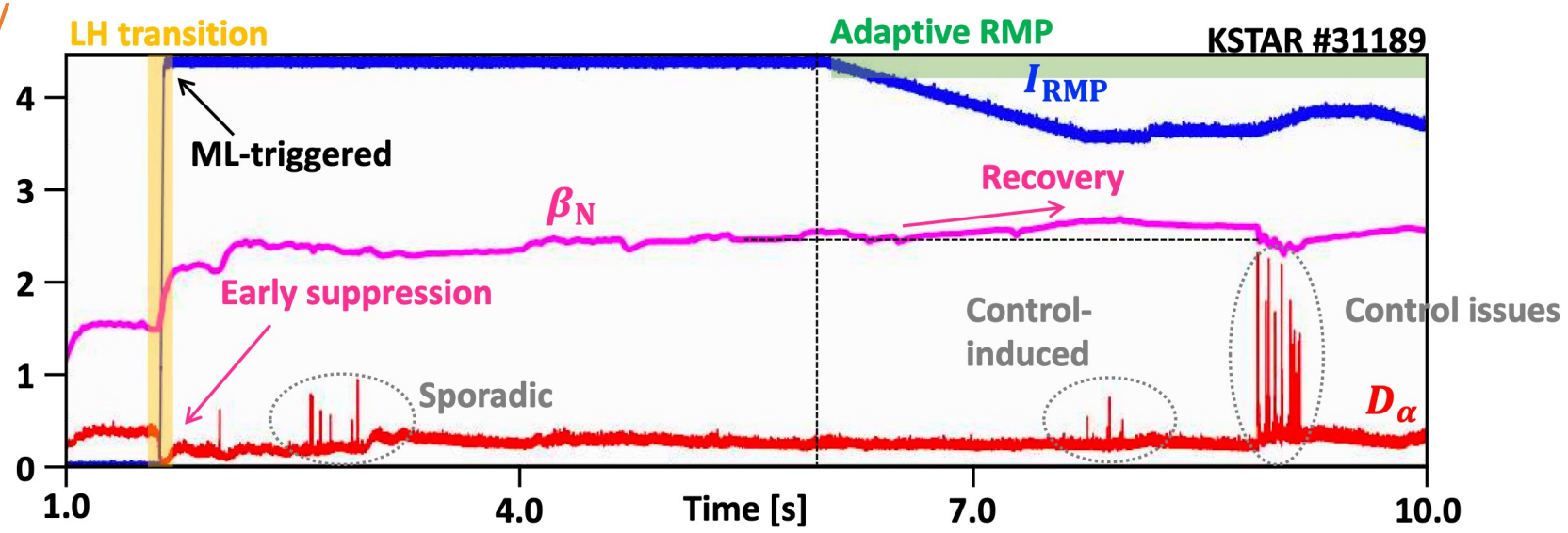
Feedback Init and ML trigger integration enable first ELM avoidance and accommodate smooth FF-FB transitions

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

D-alpha and Mirnov signals on KSTAR exhibit precursor patterns prior to loss of ELM suppression and could be used in RT detection

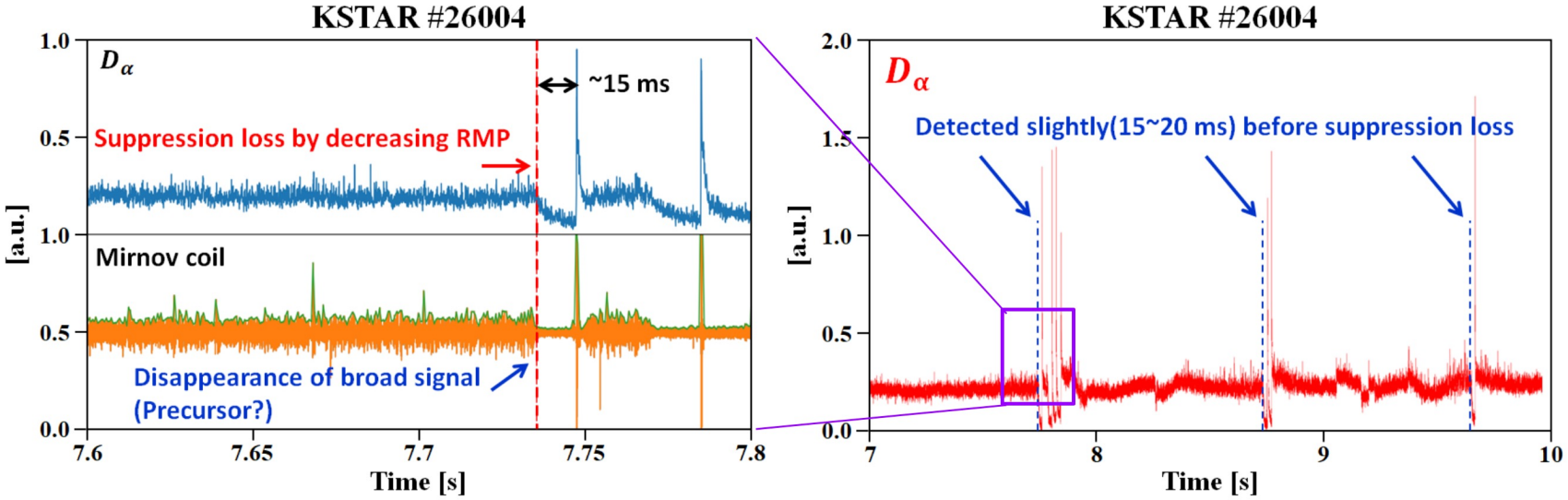
Diagnostics that show precursors to loss of ELM suppression:

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***

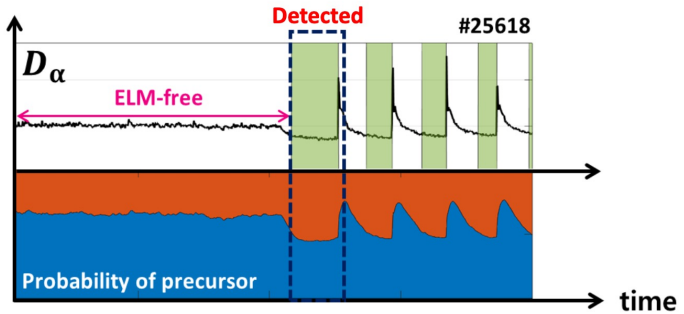
Time scales that need to be considered (and can be device specific, here just rough est.):

- pedestal confinement time (τ_{ELM} ~10-50ms)
- PCS commands (~50-250 μs)
- Power supply control / ramp rate
- Recovery of suppression (~3ms)

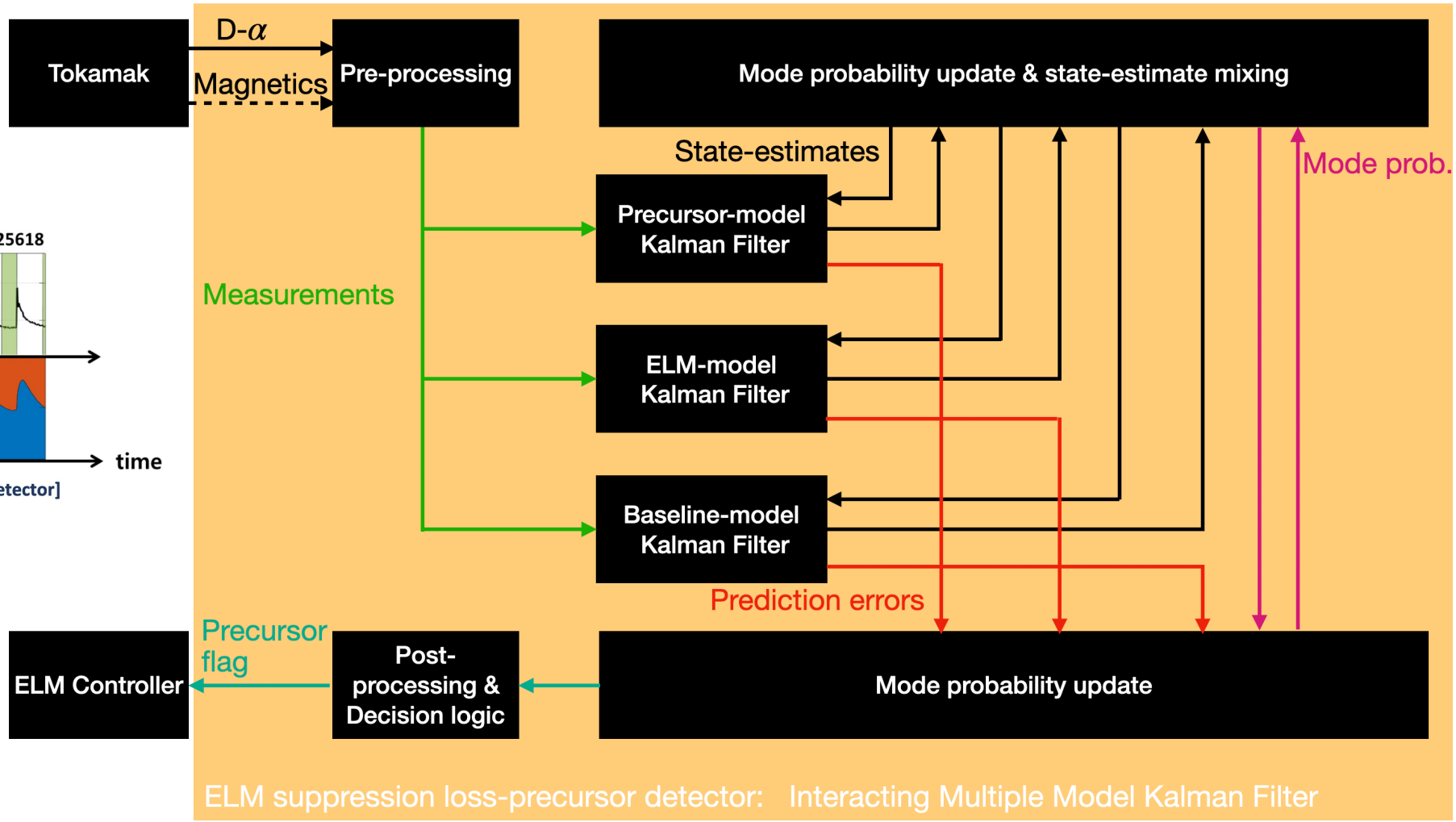
- So we can recover an island in ~5-10ms < 10-50ms evolution from suppressed to ELMing state
- The instability itself is very fast (~1ms) so no use to detect the early phase of the ELM itself
- Precursor needs to be detected at least ~10ms before the ELM on KSTAR



Schematic representation of RT-precursor detector shows how the measurements are propagated to determine the most probable model



[Kalman filter+ RT-ELM precursor detector]



When combined with the ELM detection system, the precursor detector only labels the first ELM that marks the end of ELM suppression

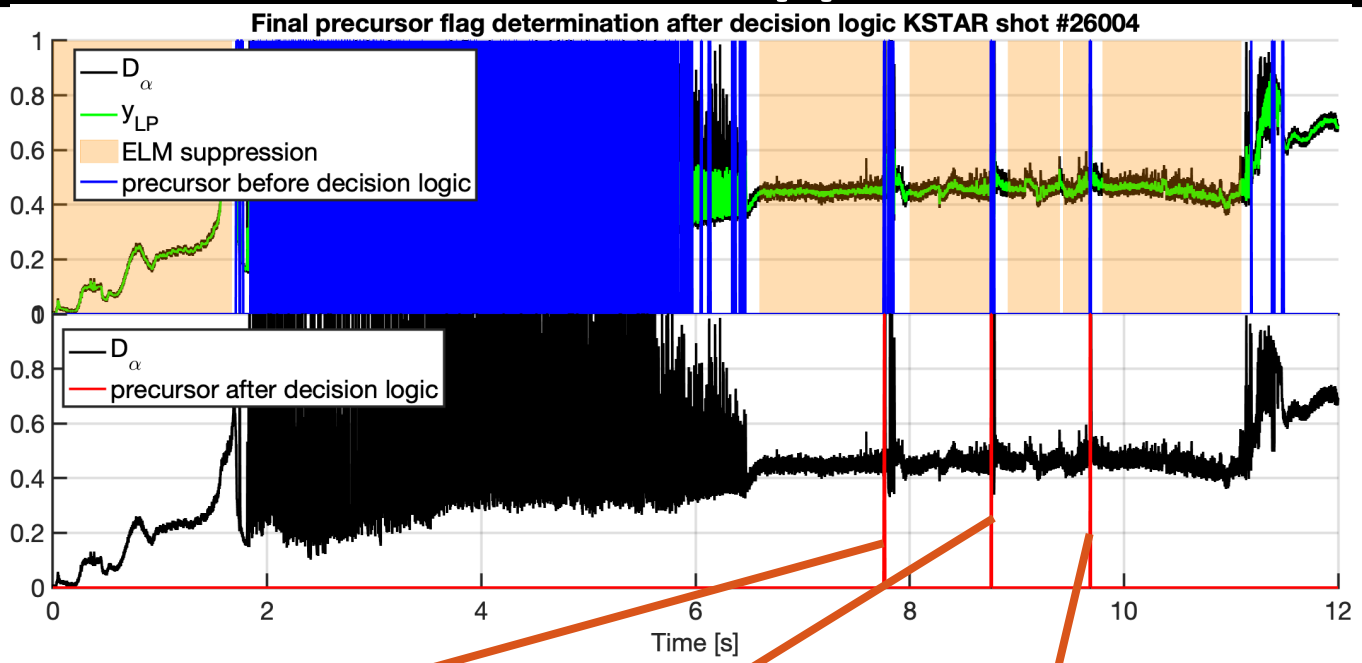
"raw" precursor detector output

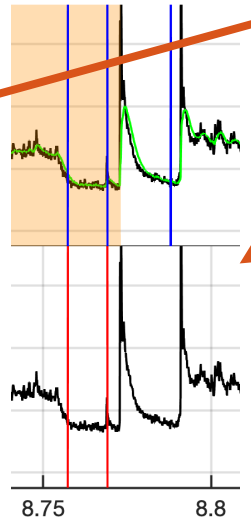
+

ELM detector output

=

Actual precursor output





RT-precursor detection + Jump-scheme can avoid imminent ELMs, but more optimization is needed for reliability

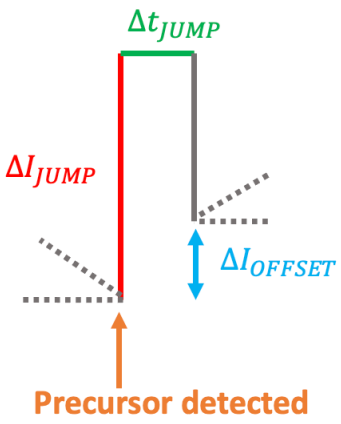
Challenge:

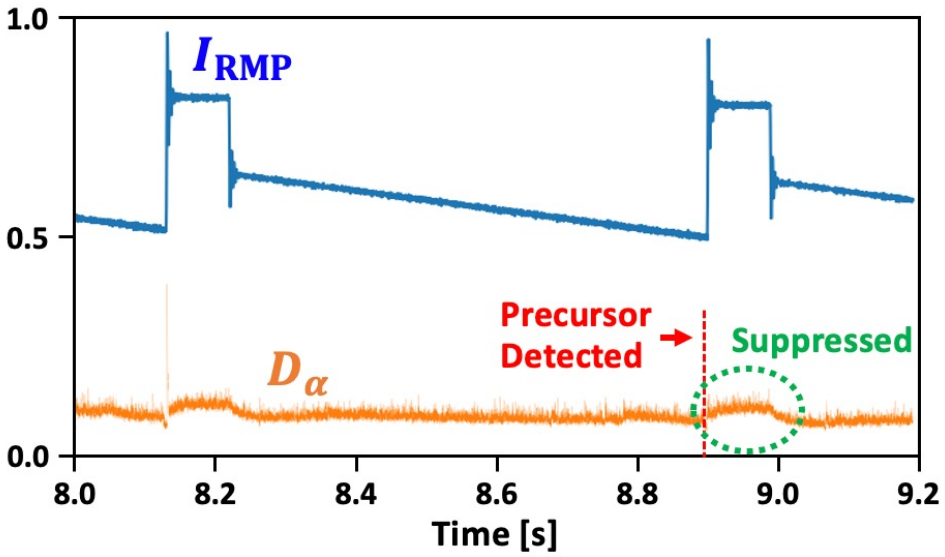
Can we avoid an imminent ELM after detecting a precursor?

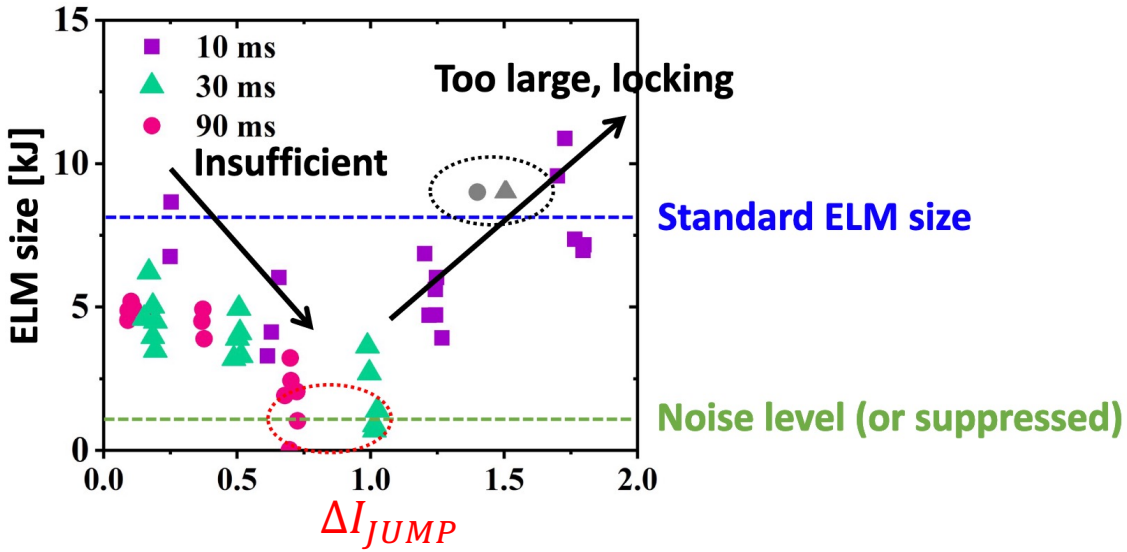
Solution:

1) Precursor detector detects precursor to loss of ELM suppression
2) If Jump-scheme active, controller jumps up by amount ΔI_{JUMP} (PCS configurable target)
3) Controller holds RMP at elevated level for Δt_{JUMP} (PCS configurable target)
4) After Δt_{JUMP} has elapsed, controller goes back to previous level, changed by offset ΔI_{OFFSET} (PCS configurable target)

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







RT precursor detection + Active probing scheme can reduce lower bound in long pulse, but more optimization needed for reliability

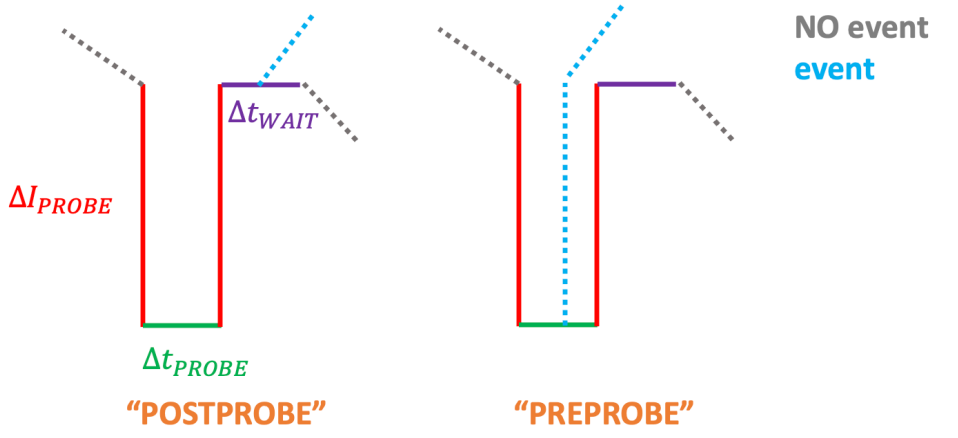
Challenge:

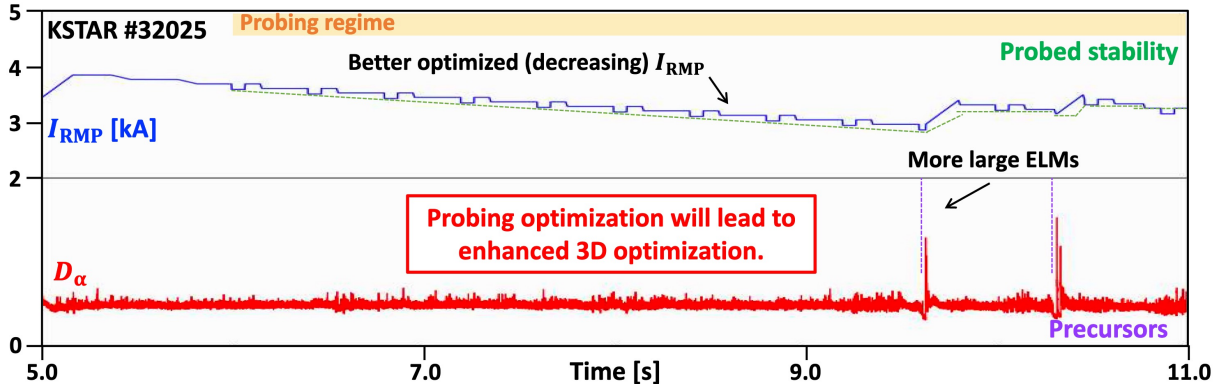
Lower bound evolves with plasma in long pulse. Can marginal stability be probed to adjust lower bound?

Solution:

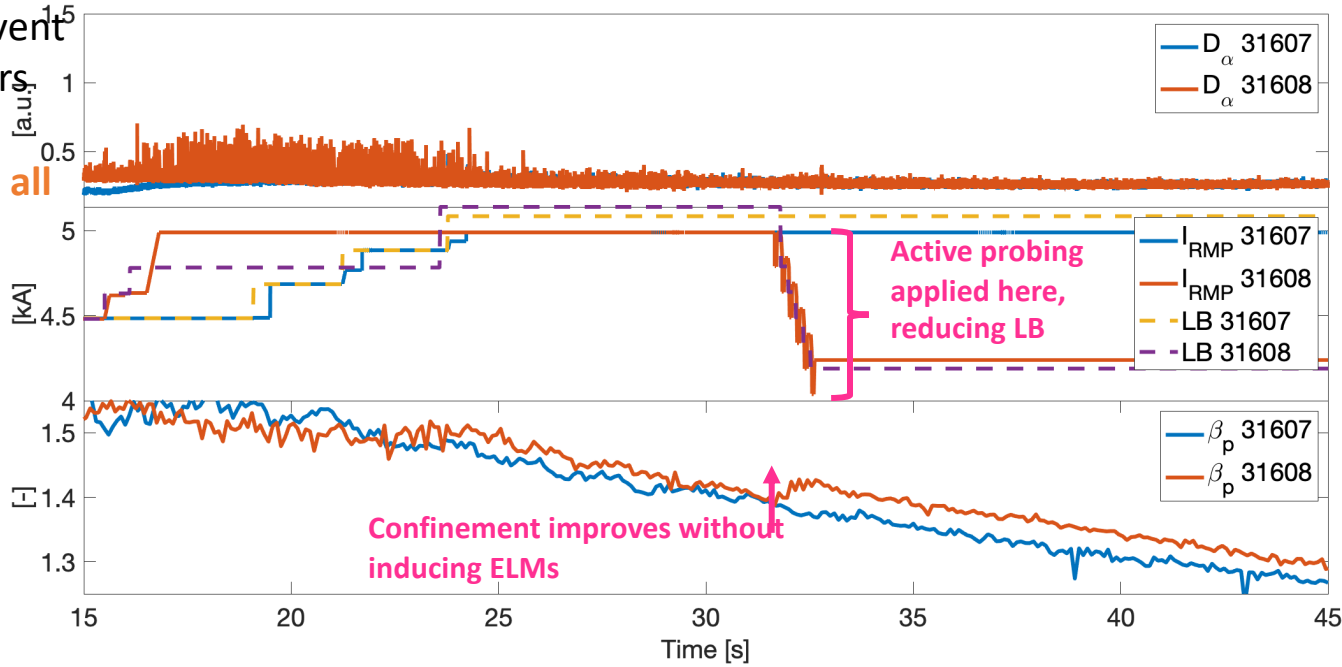
1) Lower bound is activated and preventing RMP from decreasing
2) Once probing activated, controller applies downward pulse (customizable)
   1) If PREPROBE mode, controller starts checking for precursors DURING downward pulse and exit immediately at time of event
   2) If POSTPROBE mode, controller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





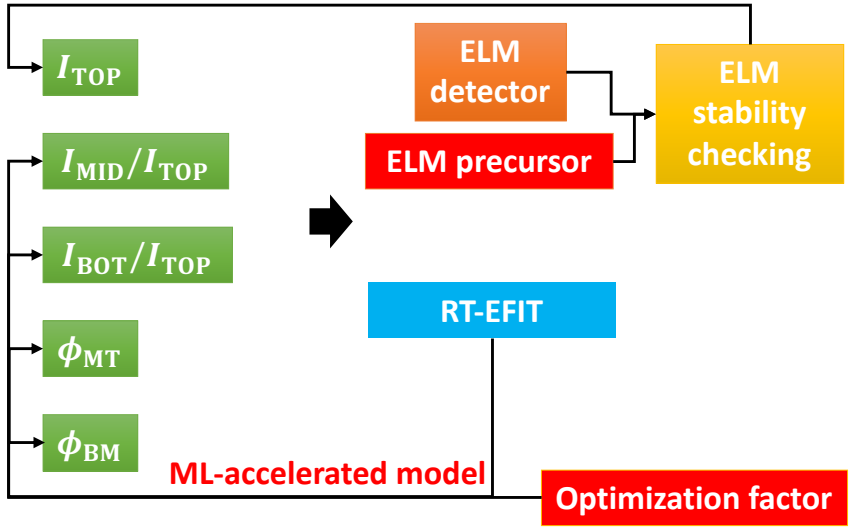
Successful confinement improvement using active probing in KSTAR long pulse 31607 vs 31608

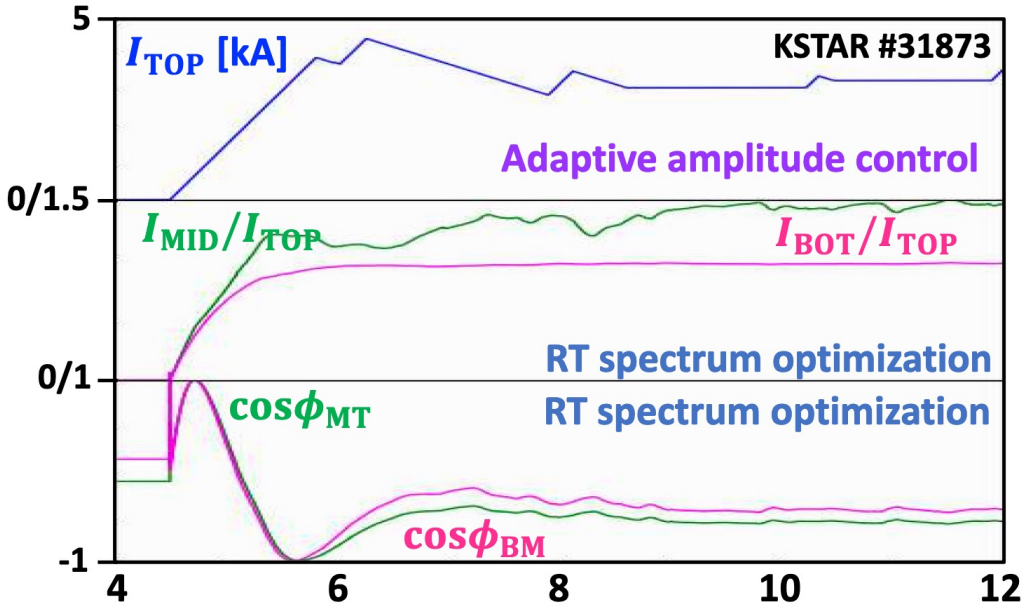


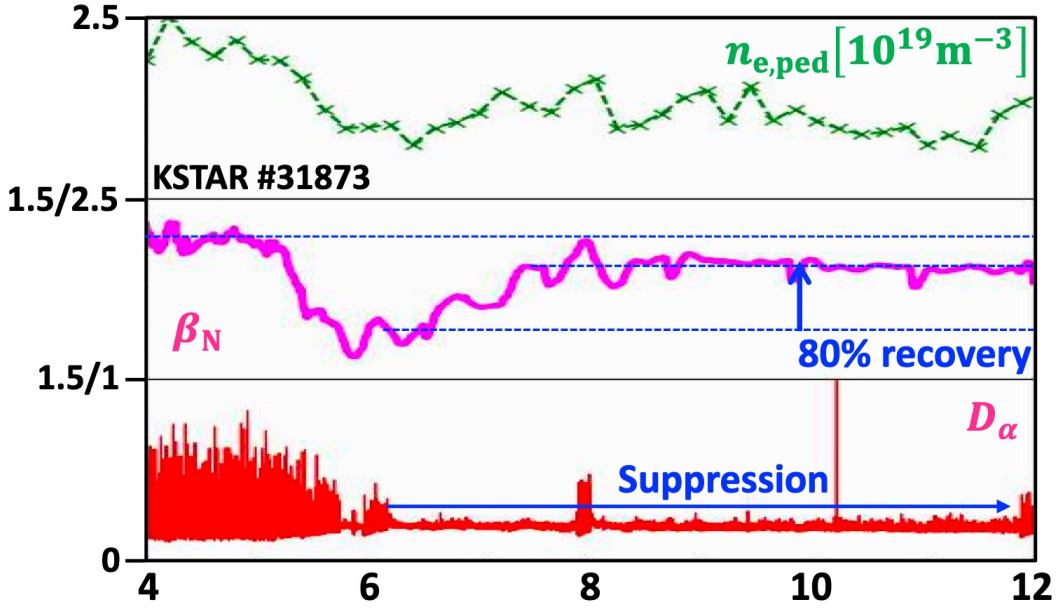
Challenge III: Need to implement more “brains” in controller

Real-time full 3D feedback control is successfully demonstrated: Safer ELM suppression and higher-confinement

- **Full 3D feedback control**
  - ✓ **Optimized 3D configuration using plasma response**
    - **Spectrum (ERMP) + Amplitude (Recovery) .**
  - ✓ **Safe ELM-free access and 80% confinement recovery**
    - **ML will be improved to cover more various plasma states:**
      Compatible with tungsten divertor.



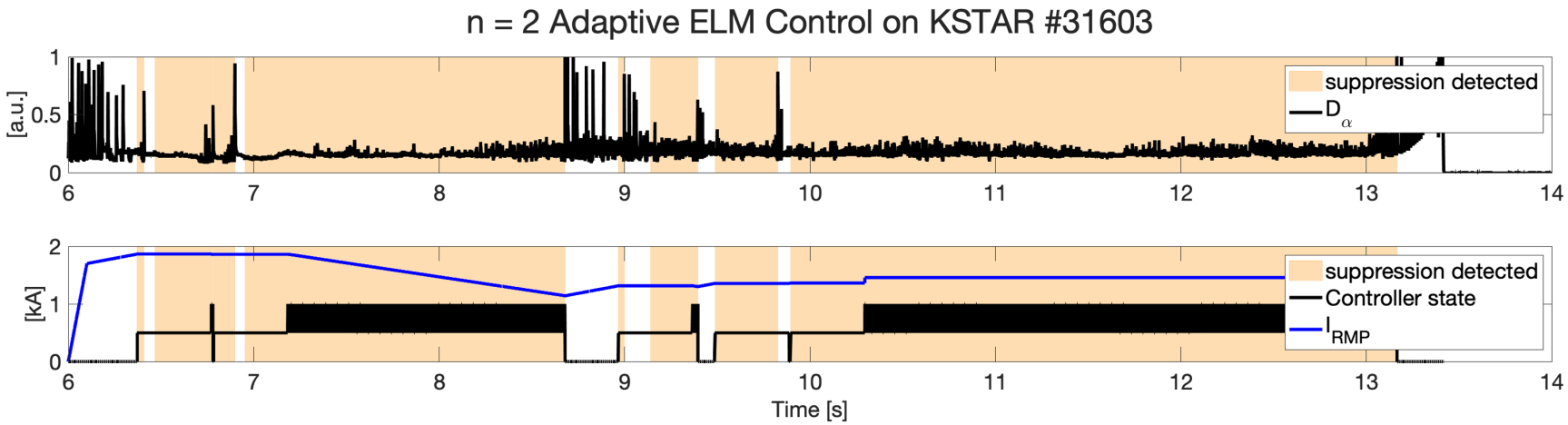


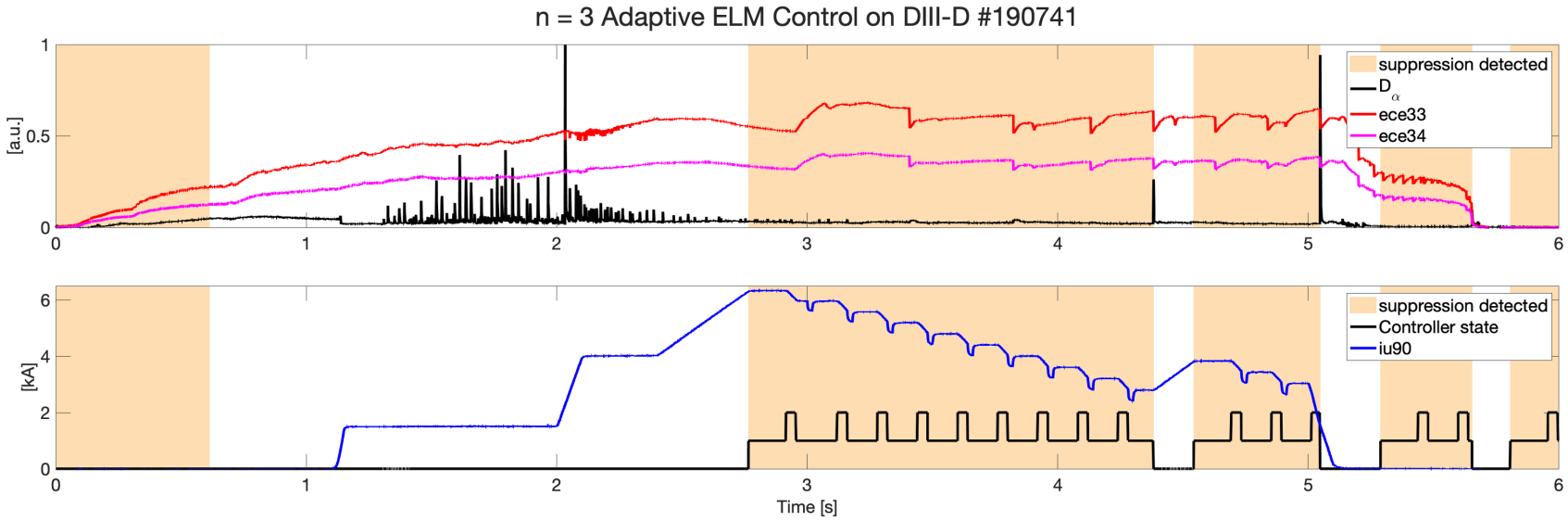


Challenge IV: Need to implement multi-n multi-device capabilities

Controller extended to n=2 capability on KSTAR and n=3 on DIII-D in preparation for ITER.

- Successful extension to using:
  - n=2 on KSTAR
  - n=3 on DIII-D
- Suppression at higher 'n' feasible, usually lower confinement recovery.
- Controller optimizes confinement until sawtooth induced spikes on D-a
- Sawteeth negatively affect ELM detection. Need to be addressed.





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 Dr. S.M. Yang
3) Use ML trigger developed by Dr. Giwook Shin
4) Use scenario development by LPT team under leadership J.-K. Park

2022 (1):

✓ **Record length Feedback ELM suppressed discharge**

However:

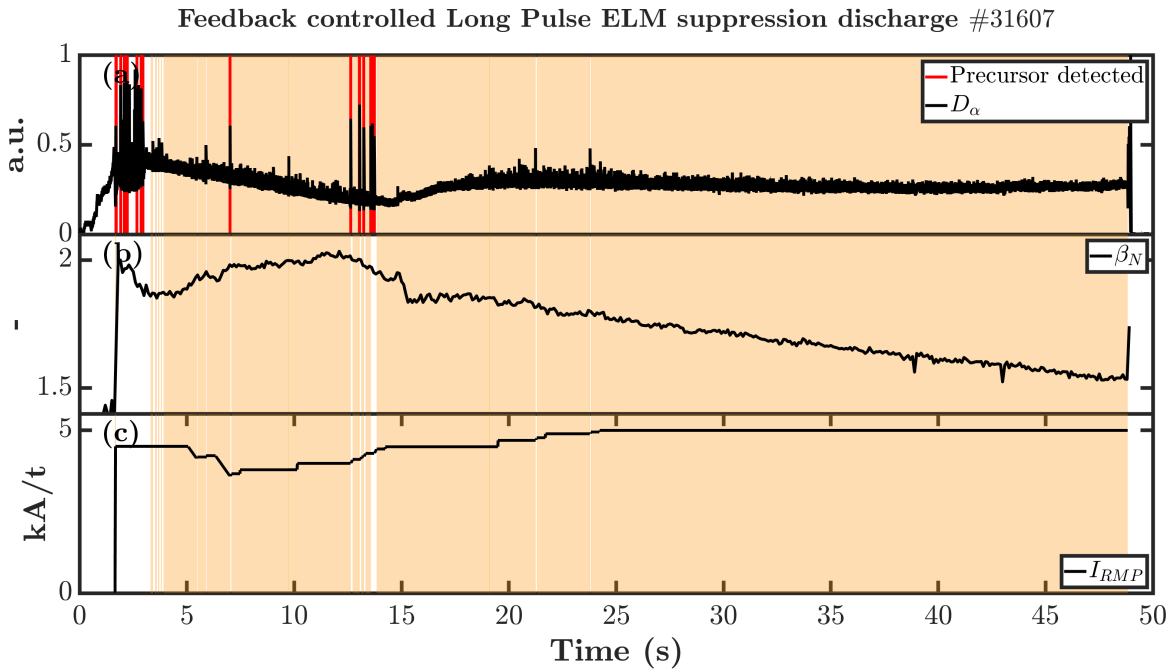
- Sporadic ELMs in early phase made controller set LB high
- Probing not turned on so no LB reduction possible
- Confinement could not be optimized due to absence probing

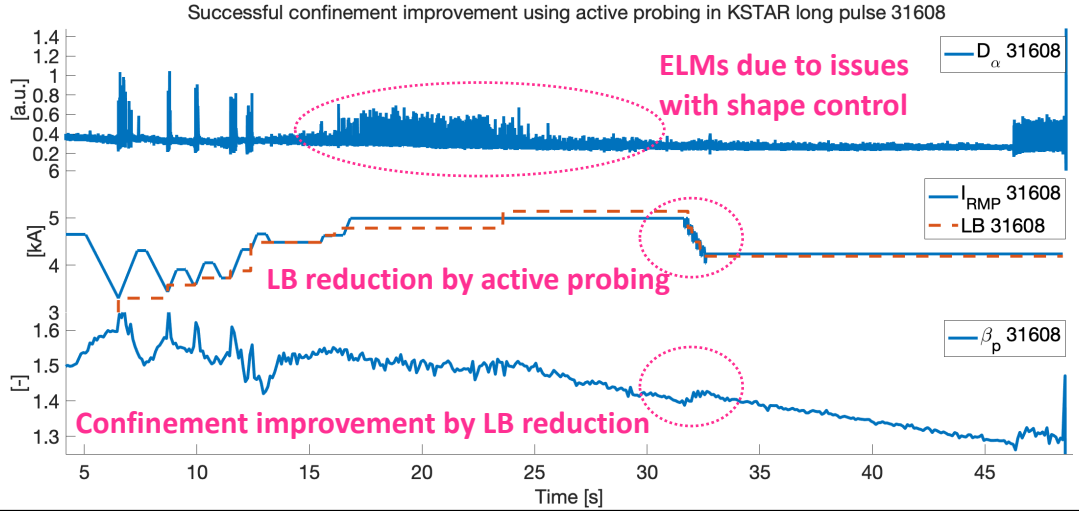
2022 (2):

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

However:

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





Conclusions and future work

Feedback Adaptive RMP ELM Controller

Generality, flexibility and robustness:

- ✓ Has demonstrated cross-device applicability (KSTAR,DIII-D)
- ✓ Has demonstrated multi-n actuation capability: n=1,n=2,n=3
- ✓ Can be used for:
  - ✓ Amplitude feedback, phasing feedback , full 3D control feedback (IPEC ML)

Toward complete ELM-free operation:

- ✓ Has RT-precursor detection that works well on KSTAR
  - ✓ Allows Jump-scheme to avoid ELMs (needs optimization)
  - ✓ Allows Active-probing scheme to find marginal stability (needs optimization)
    - ✓ Successful adjustment RMP lower bound in long pulse with evolving plasma
- ✓ Triggered early ramp-up scheme with feedback init successful at eliminating initial ELMs

Future work and other improvements needed:

- ML based precursor detection approach for DIII-D and KSTAR
- Improved ELM detector (dealing with sawteeth)
- Parameter control on long pulse (Shape,q95, density)
- Integration with detachment control
- Optimized probing and jumping scheme parameters

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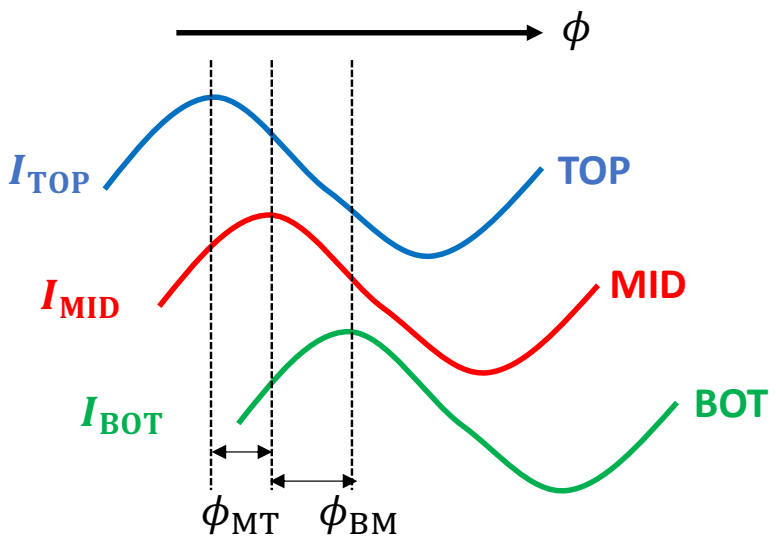
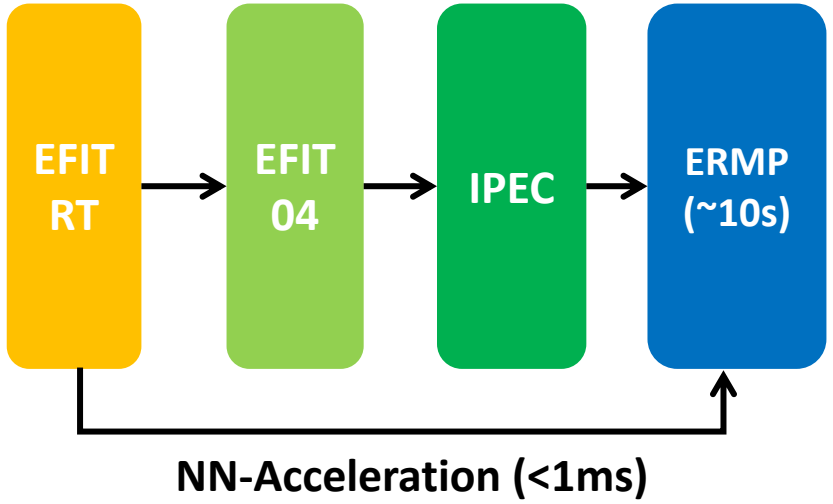
The real-time phasing control can lead to the safer ELM suppression entrance and edge localization RMP

- **Real-time 3D field optimization**
  - ✓ **Edge-localized RMP (ERMP, S. Yang NF20)**
    - IPEC based.
    - Wider window/Higher confinement.
    - Parameters: $I_{\mathrm{TOP,MID,BOT}}$ and $\phi_{\mathrm{MT/BM}}$.
    - Not fast enough for real-time use (~10s).
  - ✓ **NN-acceleration for RT-control (developed by S.K. Kim)**
    - NN-trained ERMP dataset (using Keras).
    - Real-time ERMP with rtEFIT (<1ms).



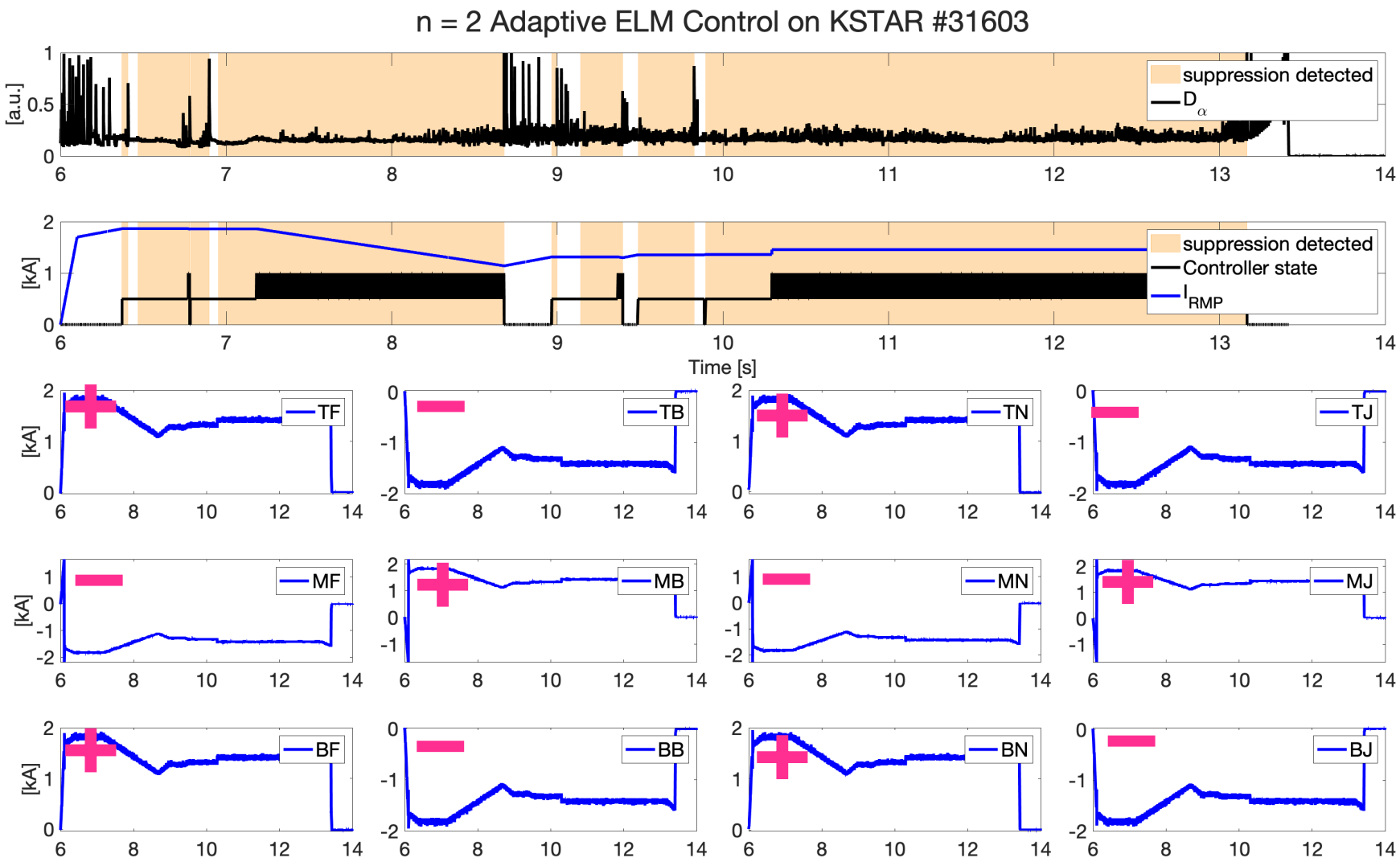


Promising initial results, but need to develop additional capabilities to avoid remaining ELMs and optimize control further for long pulse and ITER

- Inherent to design, need to **LOSE** ELM suppression at least once to optimize it
  - Need to avoid early H-mode ELMs. → Control activation triggered at LH transition by detector
  - Need to detect imminent ELMs. → RT ELM suppression-loss precursor detector
  - Need to try and avoid imminent ELMs. → Jump Scheme
- Feedback lower bound can only increase over time, regardless of plasma evolution long pulse
  - Need to be able to probe marginal stability level → Active Probing Scheme
- Full 3D feedback (with phasing) benefits from more informed feedback mechanism than FSM
  - Need to add more "brains" to controller → RT ML IPEC surrogate model
- Strive for device independent, flexible and robust controller
  - Need to test cross-device applicability. → FARMPEC ported to DIII-D
  - Need to test multi-n capability → n=2 on KSTAR, n=3 on DIII-D

Controller extended to n=2 capability on KSTAR (and n=3 on DIII-D) in preparation for ITER. Here n = 2 on KSTAR as an example:

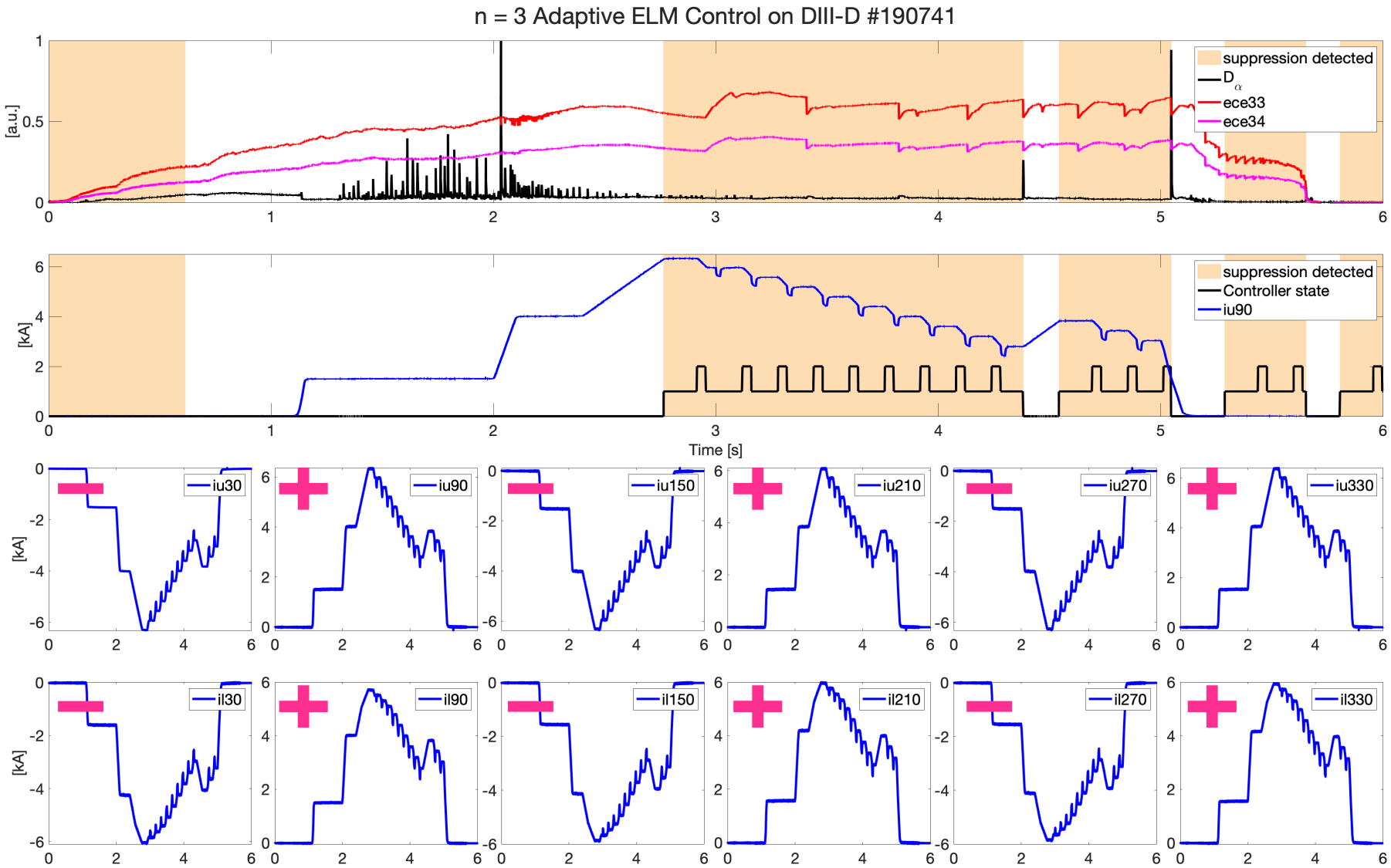
- Successful extension to using:
  - n=2 on KSTAR
- Suppression at higher ‘n’ feasible, usually lower confinement recovery.



Controller extended to n=2 capability on KSTAR (and n=3 on DIII-D) in preparation for ITER. Here n = 3 on DIII-D as an example:

- n = 3 extension in DIII-D application successful
- Controller optimizes confinement until sawtooth induced spikes on D-a

- Sawteeth negatively affect ELM detection. Need to be addressed.



Controller extended to n=2 capability on KSTAR (and n=3 on DIII-D) in preparation for ITER