Proximity-to-Instability Control and Cross-Machine VDE Stability Metrics on DIII-D and KSTAR

Jayson Barr[1]

with D.A. Humphreys[1], N.W. Eidietis[1], E. Olofsson[1], D. Orozco[1], B. Sammuli[1], H. Anand[1], Z.A. Xing[1], S.-H. Hahn[2], F. Turco[3], C. Rea[4], M. Boyer[5], D. Mueller[5]

[1] *General Atomics*
[2] *Korea Institute of Fusion Energy*
[3] *Columbia University*
[4] *MIT Plasma Science & Fusion Center*
[5] *Princeton Plasma Physics Lab*

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July 19th-22nd, 2022

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KSTAR

KFE KOREA INSTITUTE OF FUSION ENERGY

GENERAL ATOMICS

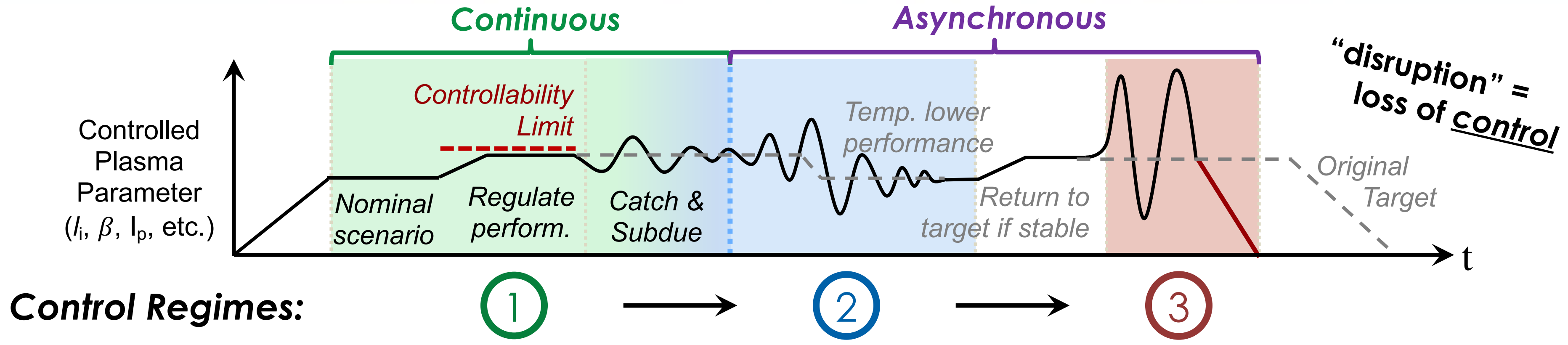
Outline

- **Proximity-to-Instability Control ("Proximity Control") for robust stability**

- **Applications in experiment on DIII-D:**
  - Vertical Displacement Events (VDEs)
    → *Additional VDE stability metric assessment on* ***KSTAR***
  - Unintended H-L back-transitions
  - Tearing Modes
  - ML informed stable operating space

- **Future Work & Conclusions**

Comprehensive disruption prevention must cover the full range of control regimes



1. Continuous Prevention

- Stable scenarios
- Regulate stability vs performance
- ***Should prevent majority of disruptions, but possibly the least developed!***

2. Asynchronous Avoidance

3. Emergency Response

J. Barr/IAEA Tech. Mtg. on Disr. & Mit./July 19th-22nd, 2022

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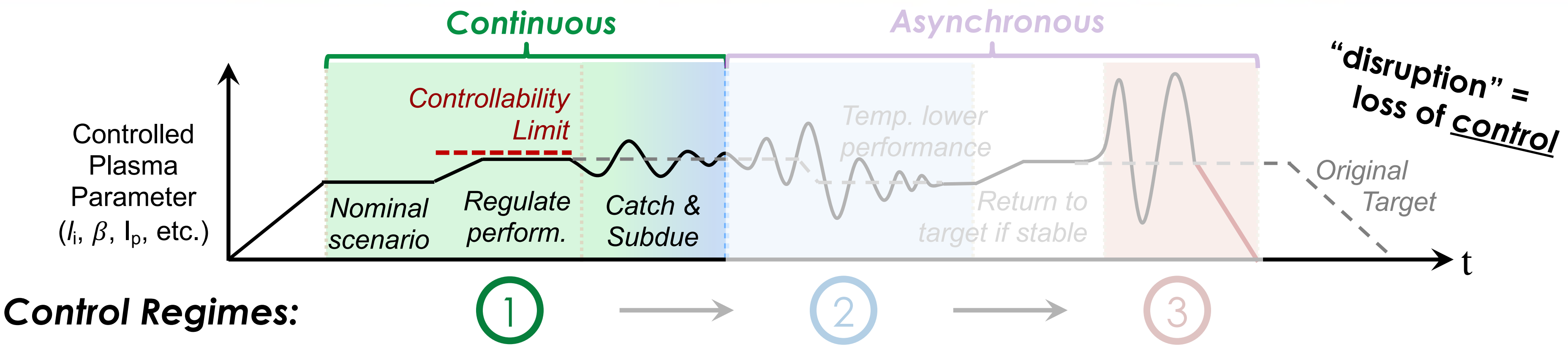

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Proximity Controller

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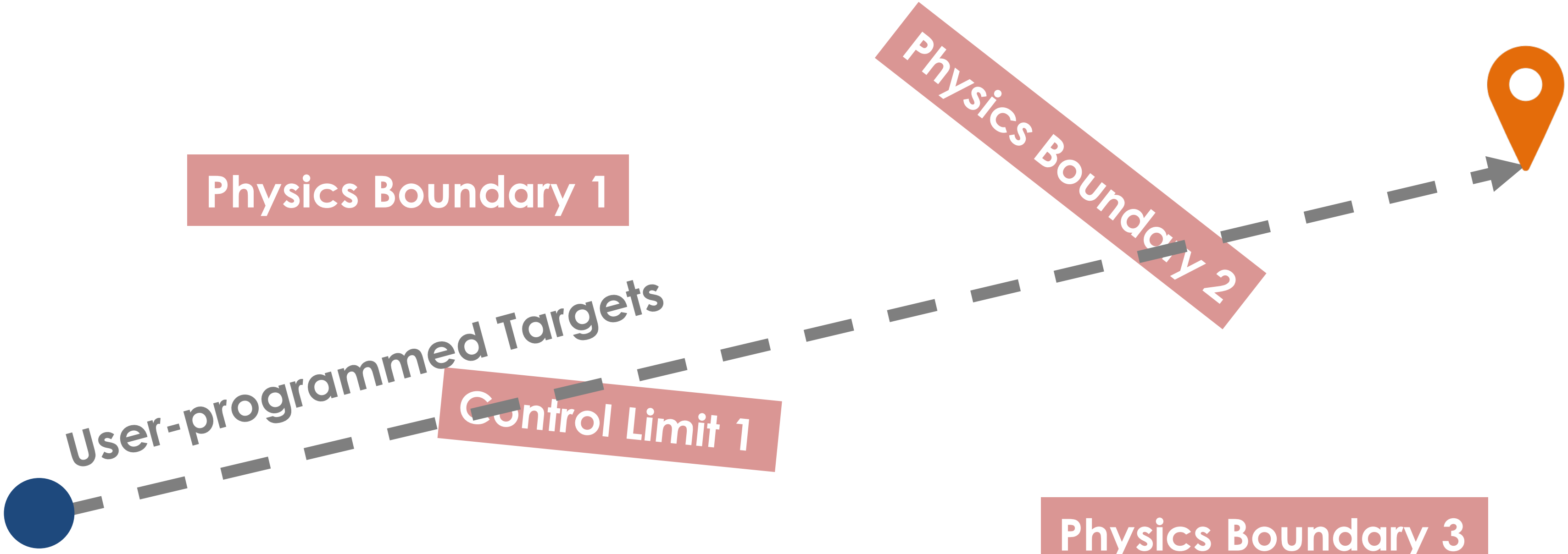
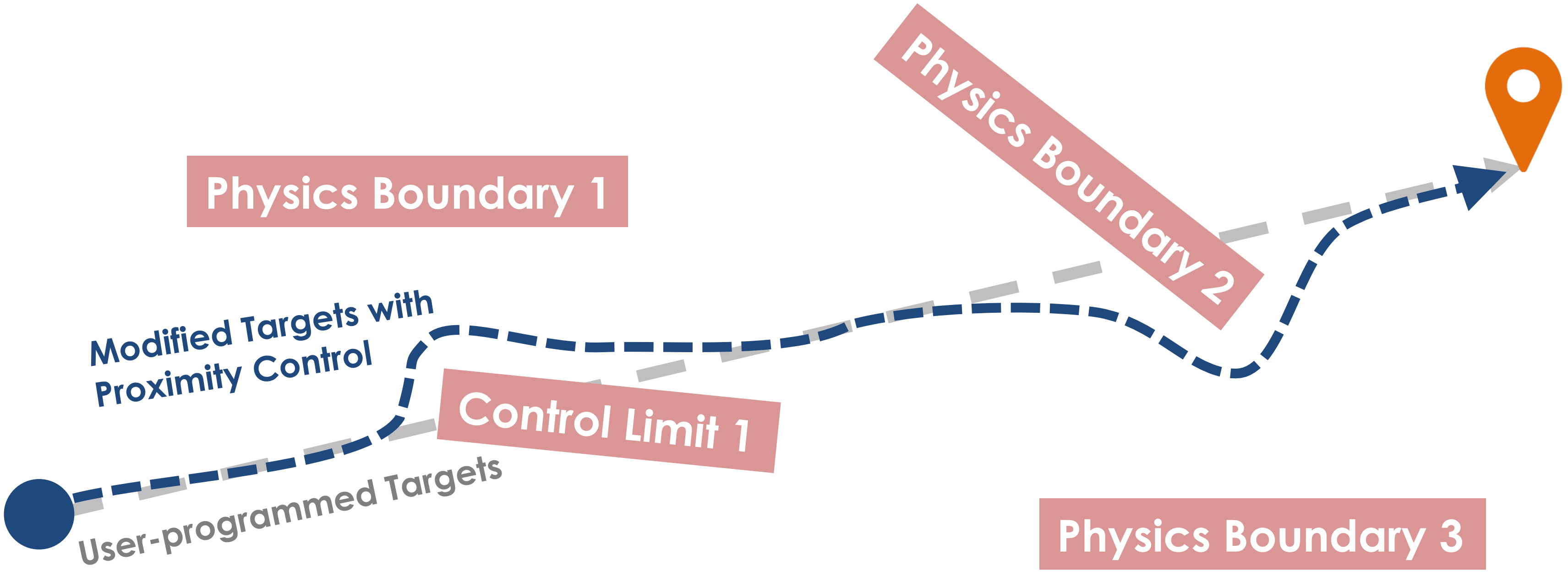
Proximity Control for robust stability



- ***Proximity control:*** *continuous monitoring and adjustment of targets away from stability/control limits*

Proximity Control for robust stability



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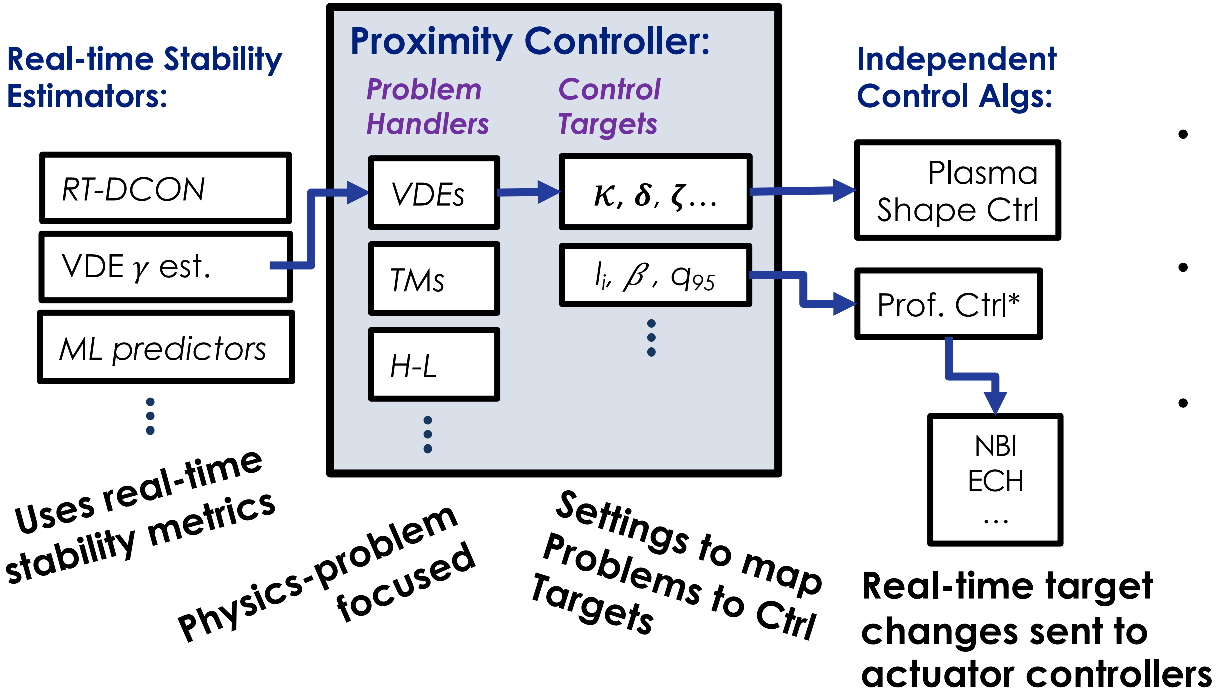
Proximity-to-instability control architecture maps real-time stability metrics to modified scenario targets

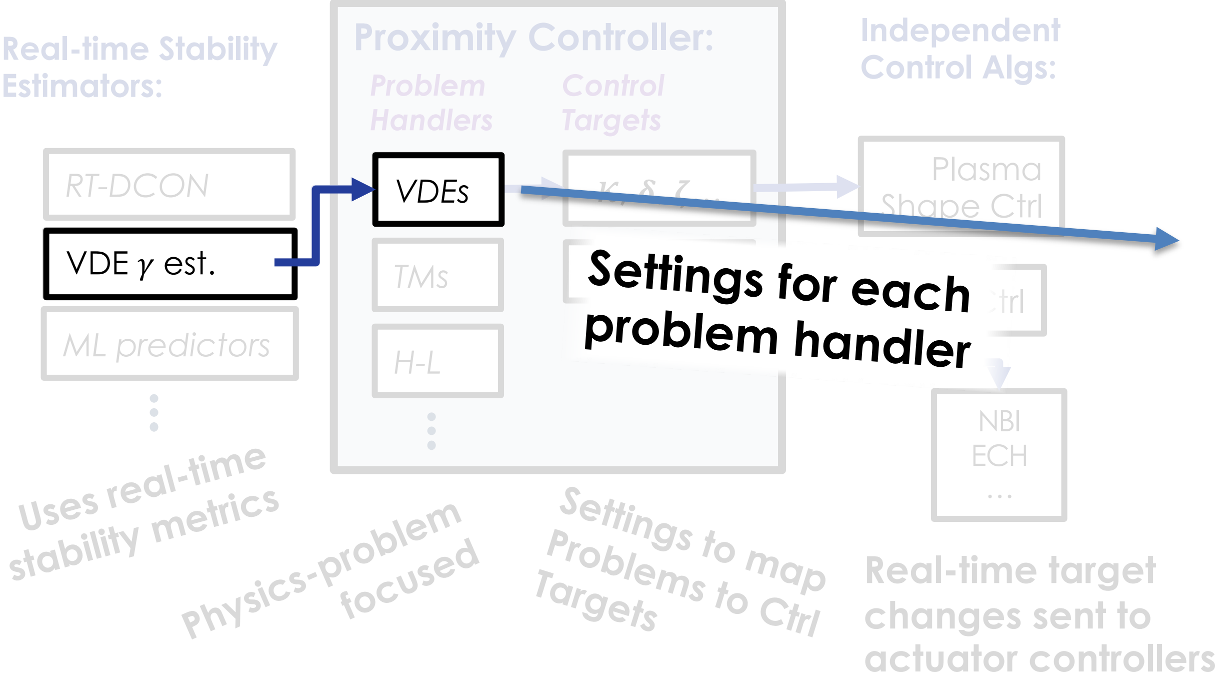


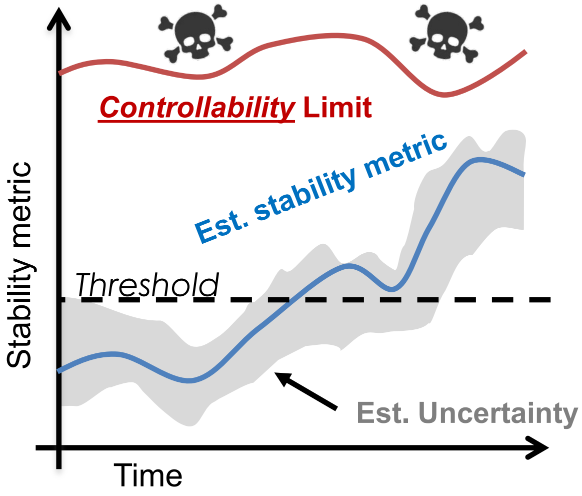
- **Integrates available real-time stability tools**
- **Maps metrics to problem-specific handlers**
- **Modifications control targets in real-time**

J.L. Barr *et al.* NF 2021

*W. Wehner *et al.* FED 2017

Proximity-to-instability control architecture maps real-time stability metrics to modified scenario targets



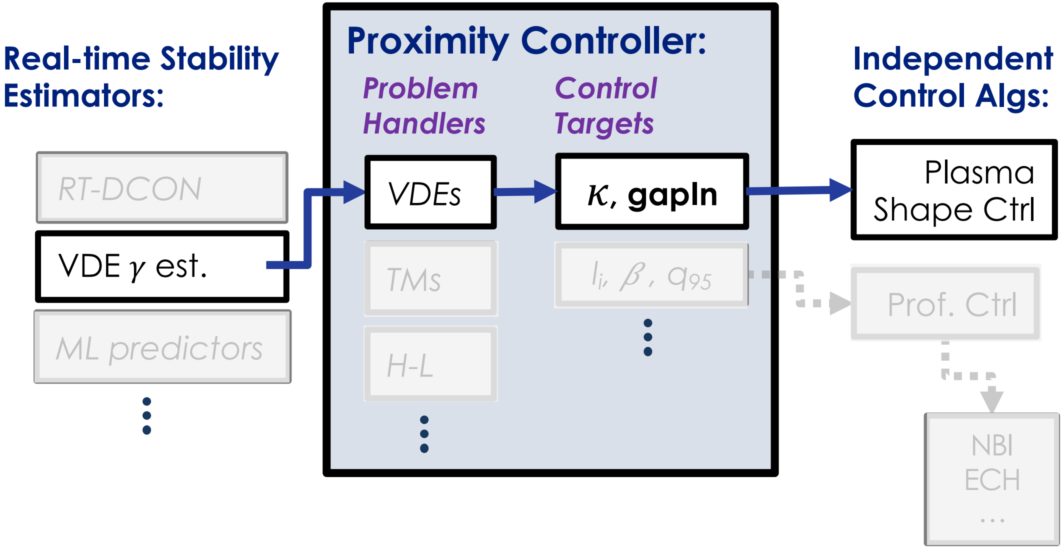


- **Thresholds for intervention**
- **Problem-focused**
- **Target changes combined, update in real-time**

J.L. Barr *et al.* NF 2021

Robust VDE prevention with Proximity Control

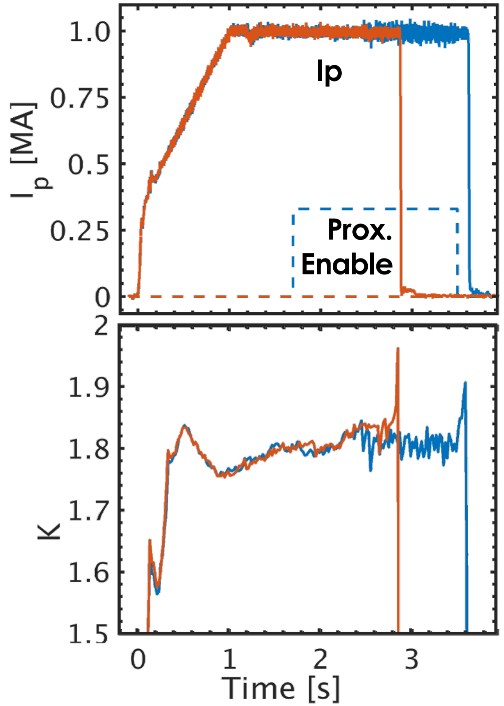
- **Implemented, tuned, tested for robust VDE prevention**
- **Real-time VDE-γ estimator:**
  - Linear, rigid motion [1-2]
  - RT implementation of offline TokSys analysis
- **Actuators:**
  - Elongation
  - Inner-gap between LCFS and HFS wall

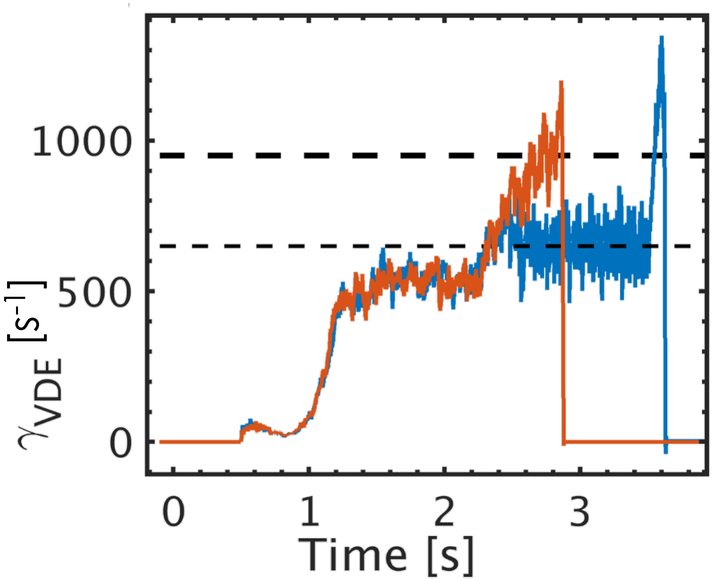


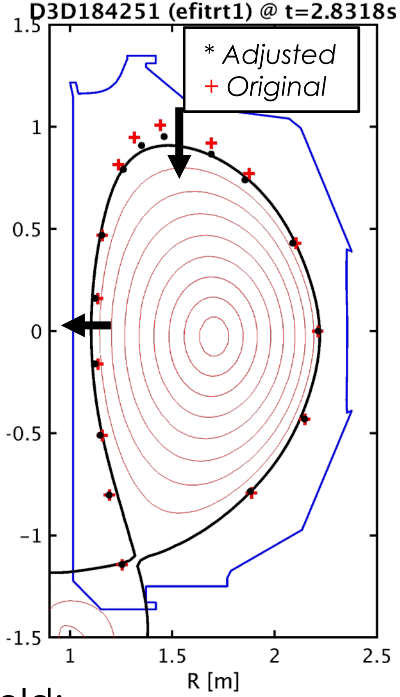
[1] E. Olofsson 2022 PPCF
[2] B. Sammuli 2021 FED

Updated Proximity controller with new full RT γ calc successfully prevented VDEs, regulating only near γ-limit

- **VDE reliably prevented until Proximity Controller intentionally disabled**



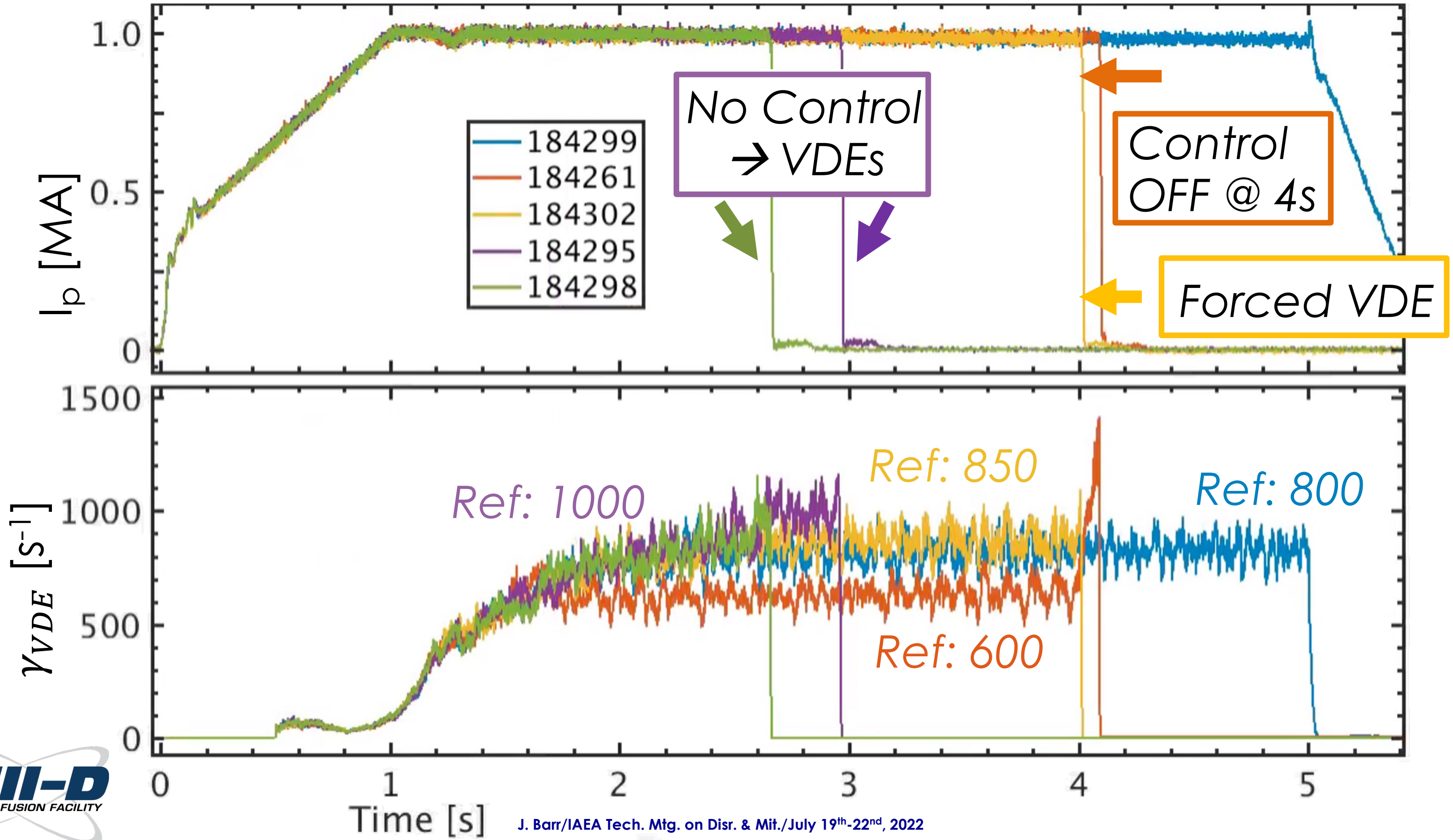




Red:
No Prox. Ctrl
Pre-shot K-target ramp to VDE

Blue:
Prox. Ctrl on from 1.75-3.5s
Prox. control when γ>threshold: reduces K, gap-in

Robust protection with VDE-γ up to 850 rad/s



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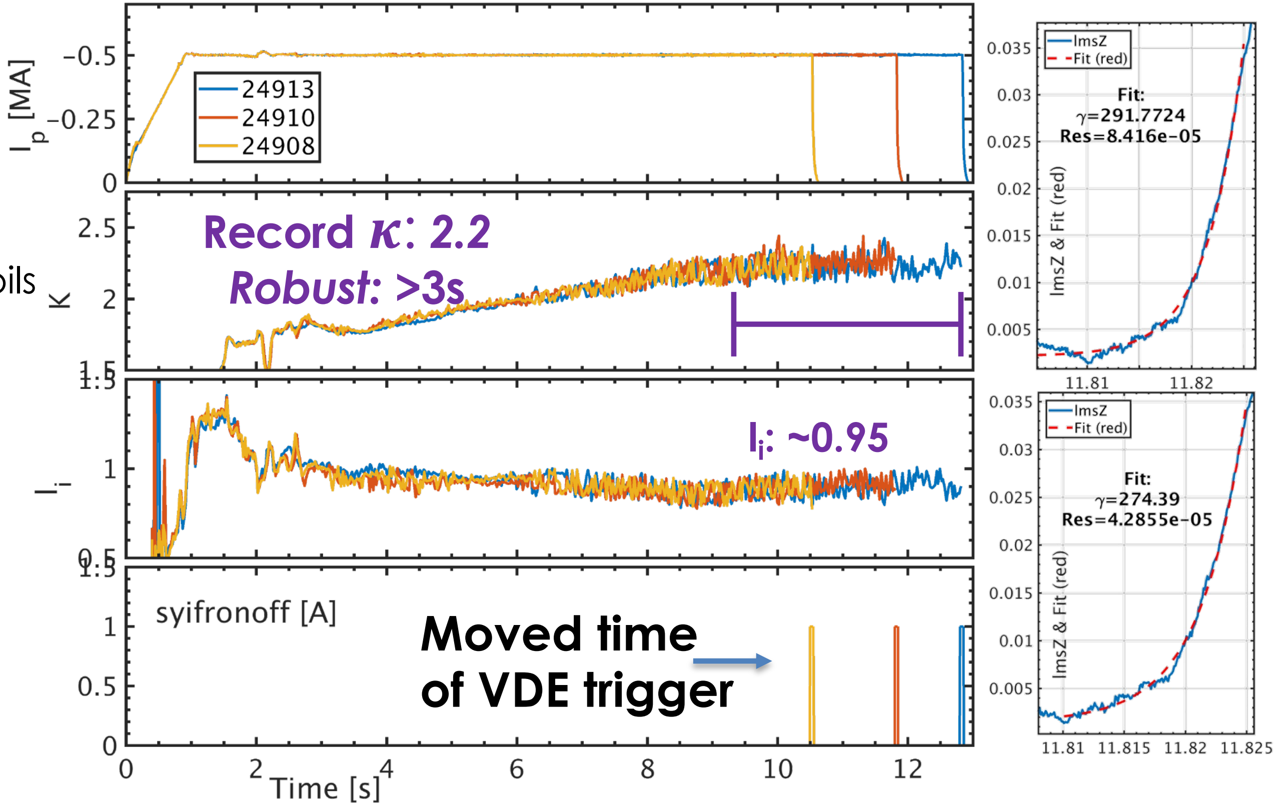
KSTAR has achieved elongation (κ) as high as 2.2+ in recent campaigns

- **Significant VS control dev. [1-2] has led to robust ops at K=2.2**
  - Decoupled fast-Z control w/internal Cu coils

    [1] D. Mueller et al. FED *2019*
    [2] S.-H. Hahn et al. FED *2020*

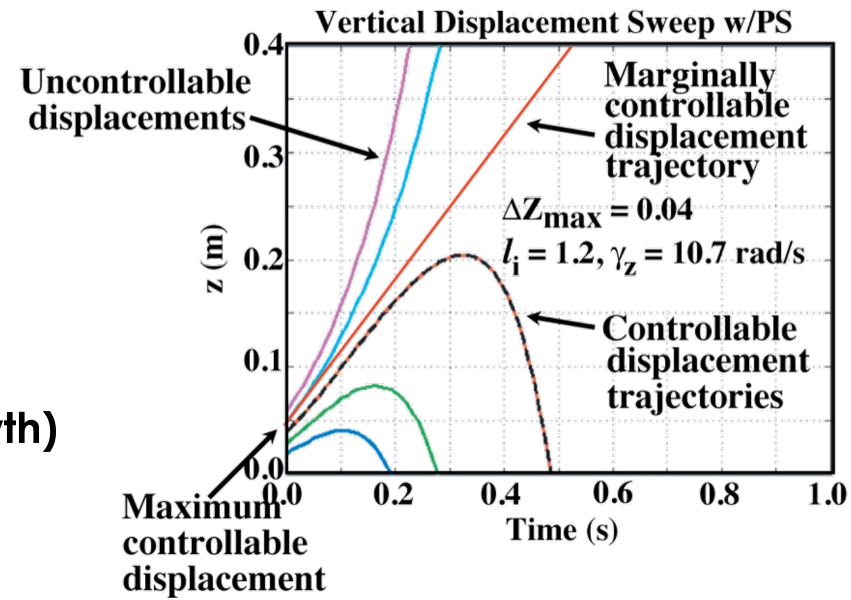
- **K=2.2 held for >3s**
  - γ=250-300 s^{-1} verified with triggered VDEs



dZ_{max} provides a fundamental VDE stability metric

- **Variety of potential stability metrics exist for VDEs (K, γ_{VDE}, m_s, dZ-max…)**
- dZ_{max}**: the max ΔZ beyond which the VS control cannot recover**
- dZ_{max}/a **and** $dZ_{max}/\langle Z\rangle_{noise}$ **used to compare cross-machine VS control capability**
- **Measured via "release-and-catch": short windows disabling VS control (→VDE growth)**
  - Compared on multiple devices [1]
  - More recent assessment in S-C devices

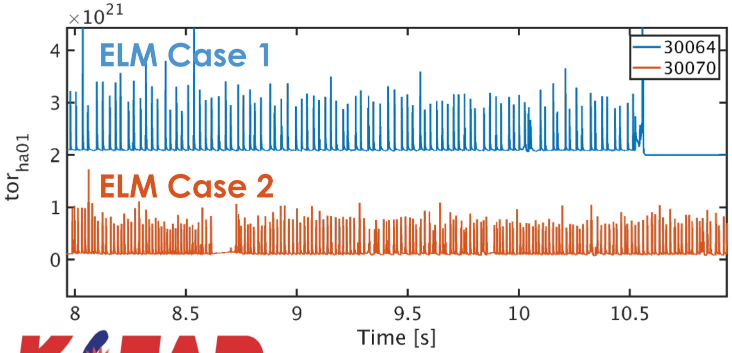
Example of Analysis and Gedanken Experiment to Calculate ΔZ_{max}



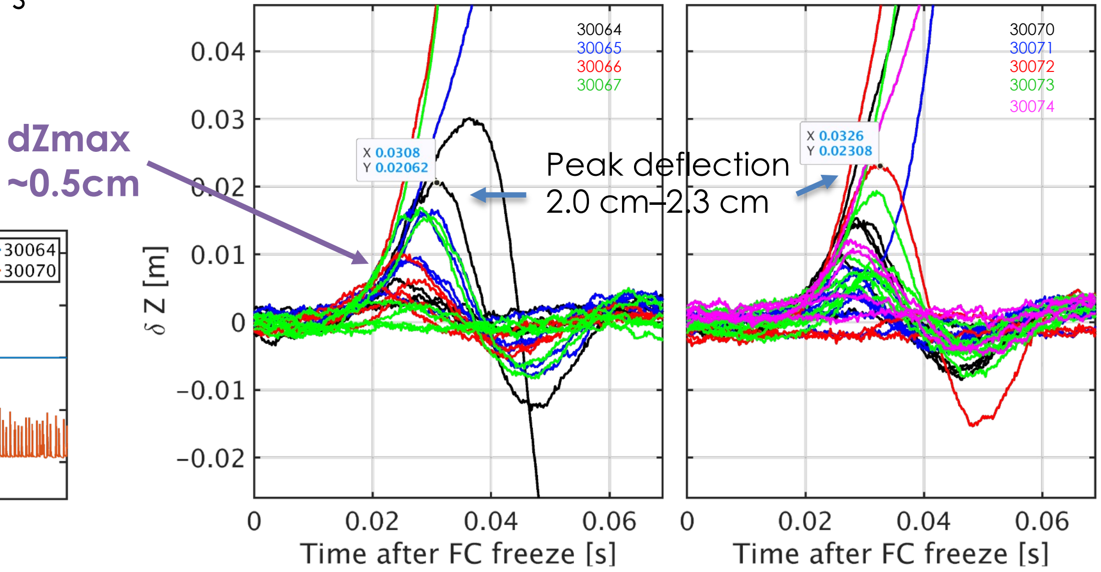
[1] Humphreys, D.A., et al., Nucl. Fusion *2009*

dZmax diagnosed in high-*K* KSTAR discharges under varied ELMing conditions

- **dZmax on KSTAR measured for high *K*=2.2 cases: ~0.5cm**
  - "Release-and-catch" method: coil currents frozen for short periods of time to drift
  - *K*=2.2 β_p=1.75 $l_i(1)$=0.8 γ_{VDE}~300 s^{-1} at 2 ELM frequencies
  - Previous studies [1] diagnosed dZmax of 2.5cm at K=1.75 γ_{VDE}~110 s^{-1}
- **dZ_{max}/a ~ 1% @ K=2.2**
- **dZ_{max}/a ~ 5% @ K=1.75**



ELM Case 1   ELM Case 2



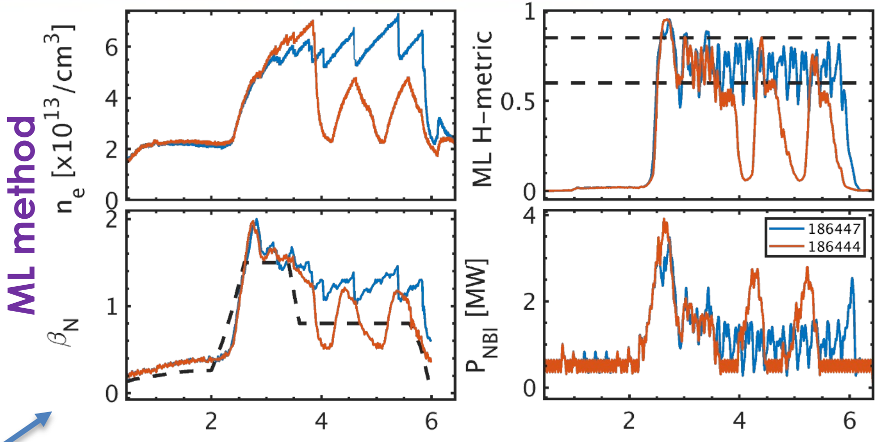
S.-H. Hahn *et al* IAEA FEC 2016

Unintended H-L Back Transition Prevention Techniques Demonstrated with DIII-D Proximity Controller

- **Unintended H-L back-transitions lead to large control transients**

- **Proximity Control applied for RT prevention**
  - **Control response used:** adjustment of NBI control's *minimum* input power in real-time

- **2 warning systems / monitors implemented:**
  - **ML model [1]:** predicts H/L mode in next 1ms, based on 20ms history in major EFIT param, P_{in}
  - **Power bal. metric:** enforces minimum P_{in}-P_{rad}



- **Both successfully demonstrated:**
  - Test case: user-programmed drop in β target → P_{NBI} reduction → H-L

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[1] D. Orozco *et al IEEE Transactions,* submitted, in review

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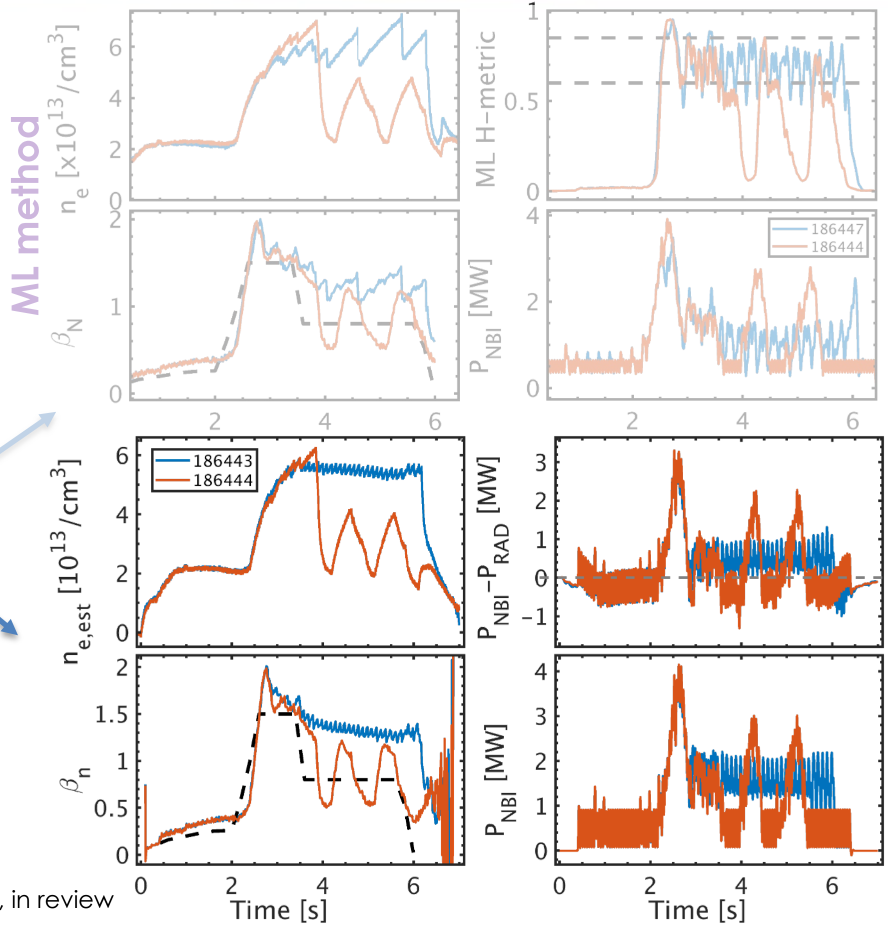

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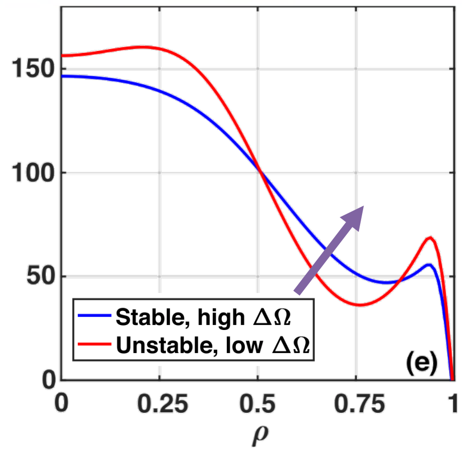
Tearing Mode stability a critical need for robust disruption prevention

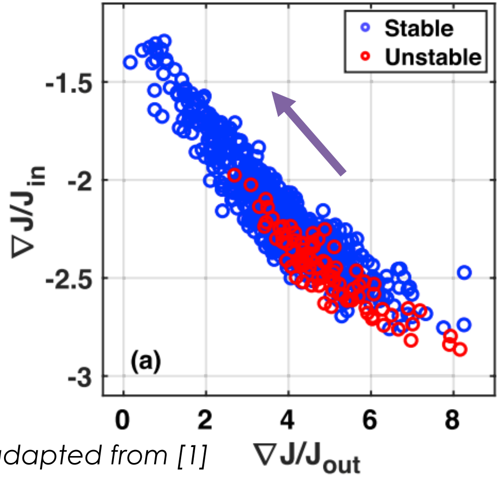
- **J‖ gradient "well" identified as indicator of disruptive TM stability in the IBS [1]**
  - Steeper gradients near q=2 surface permits TM generation in the IBS
  - Plasma shape a potential actuator
  - MSE EFIT analysis from Turco [1]

  [1] F. Turco *et al* 2018 *Nucl. Fusion* **58** 106043

- **Fast, real-time calculation of $J_{||}$ profile via "Sobol" method, RT-EFITs with MSE**
  - EFIT settings to resolve J-well based on [1]

- **Potential for Proximity Control provided sufficient controllability of $J_{||}$ modification**





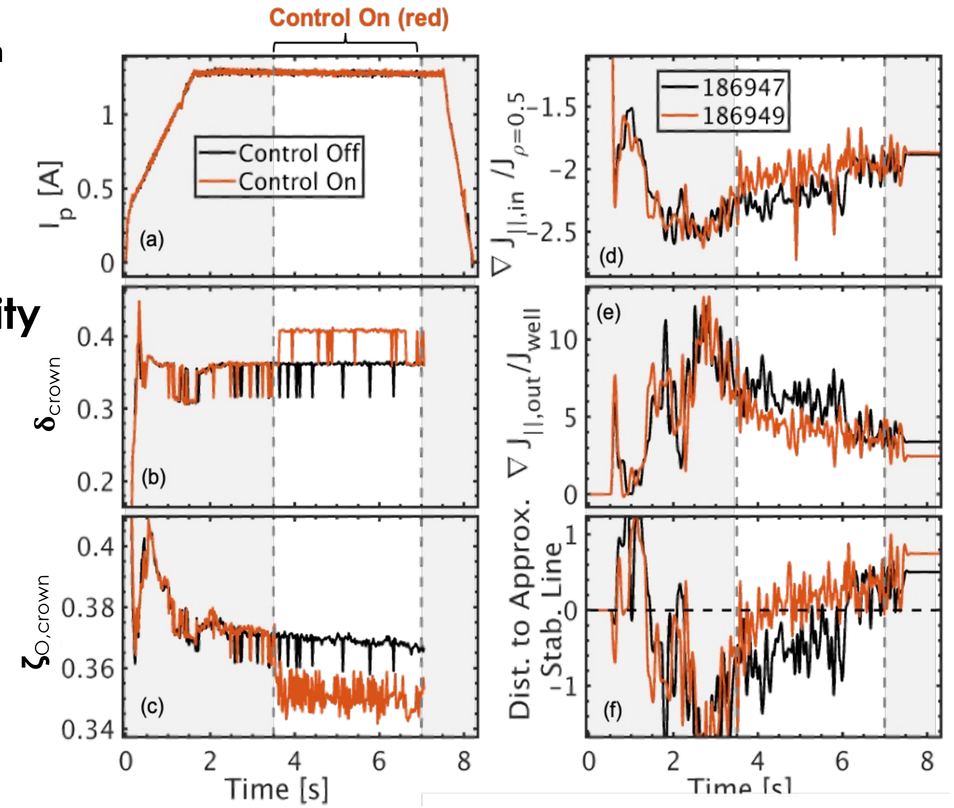
Figs. adapted from [1]

Regulating gradients in $J_{||}$ with shaping modifications being evaluated for reinforcing TM stability in DIII-D

- **$J_{||}$-well depth found to respond to δ_{crown} (tri.), and $\zeta_{O,crown}$ (sqr.-ness)**
  - Shape mods of $+\Delta\delta_{crown}$ & $-\Delta\zeta_{O,crown}$ were found to reduce gradients

- **Proximity control: limited $J_{||}$ controllability with RT shape mods in high-torque IBS**
  - Future experiments: test application for TM prevention in low-torque

- **Variety of additional tools recently connected to the Proximity Control algorithm (RT-DCON[1-2], AMS[3])**
  - Awaiting experiments & further dev.



* **Crown:** side opposite X-pt in SN

[1] R. Conlin et al 2020 APS DPP
[2] A. Glasser et al 2020 PoP
[3] J M Hanson et al 2012 NF

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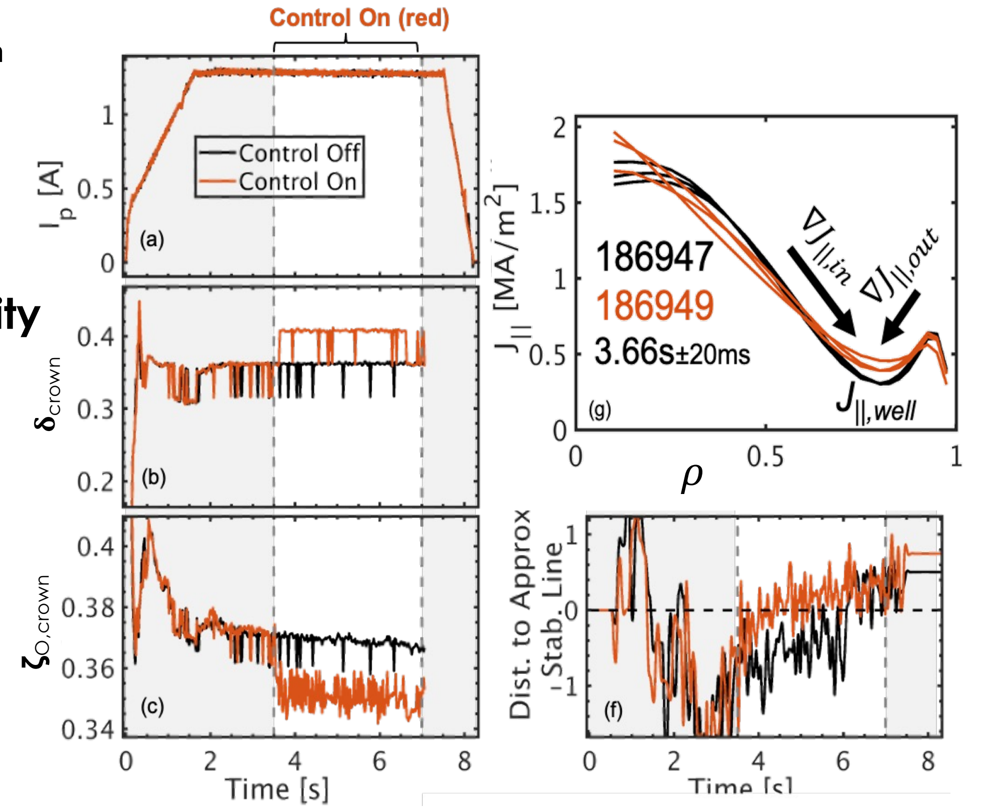

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Interpretable ML recently integrated into proximity controller for experiments in 2022-2023

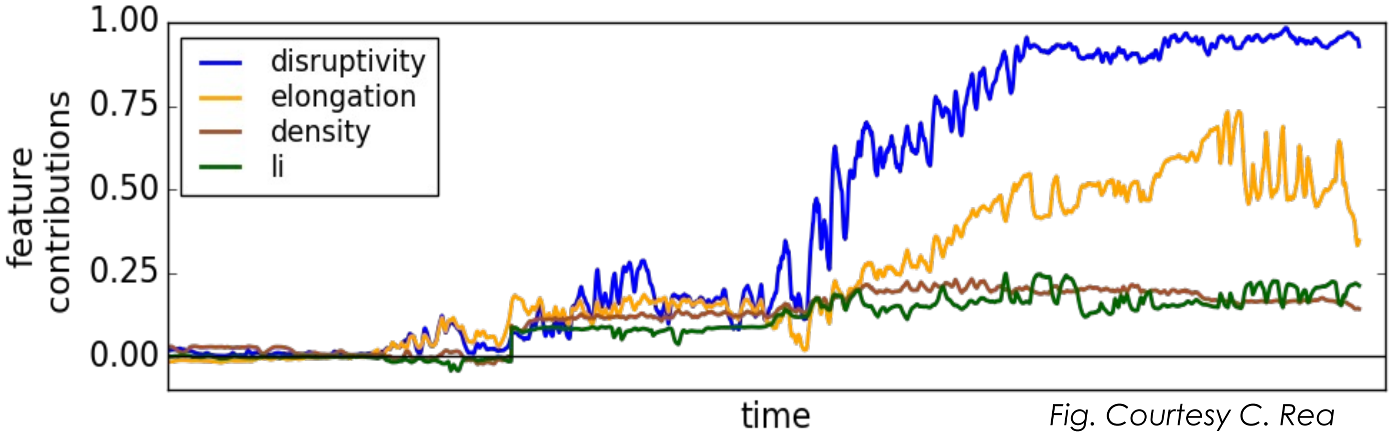

Fig. Courtesy C. Rea

- **Control paradigm with interpretable ML:**
  - Monitoring prox. to edge of stable operating space

- **DPRF: Disruption Prevention via Random Forests [1]**

  [1] C. Rea Nucl. Fusion 2019

- **Many contribution factors (f_c) map (mostly) to control targets**

Conclusions: *DIII-D & KSTAR are developing, testing, and qualifying control tools for comprehensive disruption avoidance*

- **Proximity-to-Instability control architecture implemented for real-time scenario modification to maintain *robust* stability on DIII-D**

- **A variety of problem-specific handlers already under testing, more on the way**
  - **VDEs:** robust prevention with regulation of VDE-γ near device limits
  - **Unintended H-L back-transitions:** minimum heating based on ML and power-balance
  - **TMs:** multiple methods under current, active development (JII, rt-DCON, AMS…)
  - **General maintenance of safe operating spaces:** ML with the DPRF

- **Evaluating, qualifying stability metrics and proposed control response suitability for real-time proximity control application as we go**
  - Including cross-device stability metrics
  - Extension to KSTAR on the way

Acknowledgement & Disclaimer

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