Development and Experimental Qualification of Novel Disruption Prevention Techniques on DIII-D

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GENERAL ATOMICS

Abstract

Novel disruption prevention solutions spanning a range of control regimes are being developed and tested on DIII-D to enable ITER success. First, a new control algorithm has been developed and tested for regulating nearness to stability limits and maintaining safety-margins in real-time. Its first application has been for reliable prevention of vertical displacement events (VDEs) by adjusting plasma elongation (κ) and the inner-gap between the plasma and inner-wall in response to real-time open-loop VDE growth rate (γ) estimators. VDEs were robustly prevented up to average open-loop growth rates of 800 rad/s with initial tunings, with only applying shape modification when near safety limits. Second, the disruption risk during fast, emergency shutdown after large tearing and locked modes can be significantly improved by transitioning to a limited topology during shutdown. More than 50% of emergency limited shutdowns after locked modes reach a final normalized current $I_N < 0.3$ before terminating, scaling to the 3 MA ITER requirement. This is in contrast to diverted shutdowns, the majority of which disrupt at $I_N > 0.8$. Despite improvements, these results highlight the critical importance of early prevention. Third, a novel emergency shut down method has been developed which excites MHD instabilities to form a warm, helical core post-thermal quench. The current quench extends to ~100ms and avoids VDEs and runaway electron generation. Novel real-time machine learning disruption prediction has been integrated into the DIII-D plasma control system (PCS) and proximity control architecture, and a multi-mode MHD spectroscopy technique has been developed which is real-time compatible. Results presented here were enabled by a focused effort, the Disruption Free Protocol, in DIII-D's 2019-20 campaign to complement disruption prevention experiments with a large piggy-back program. In addition to testing novel techniques, it is estimated to have directly prevented >45 disruptions in piggyback operations.

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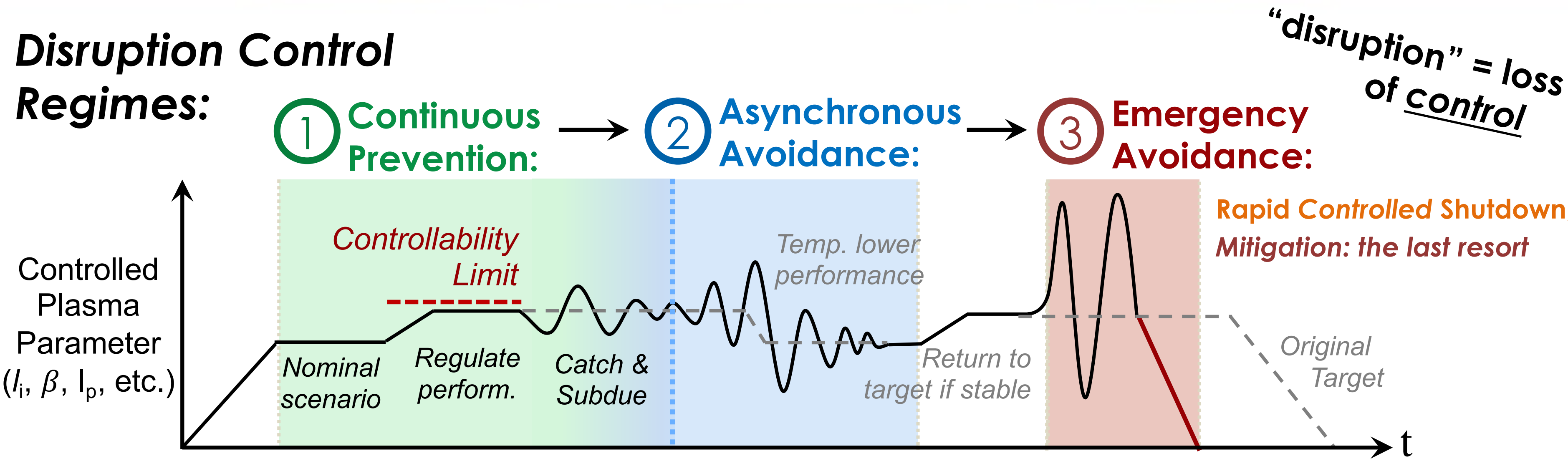
Comprehensive disruption prevention must cover the full range of control regimes



(1) Should catch 99%+ of disruptions!

The Disruption Free Protocol:

- ***To qualify ITER-scalable, comprehensive disruption control in routine operations***
- ***Large-scale piggybacks to complement experiments:***

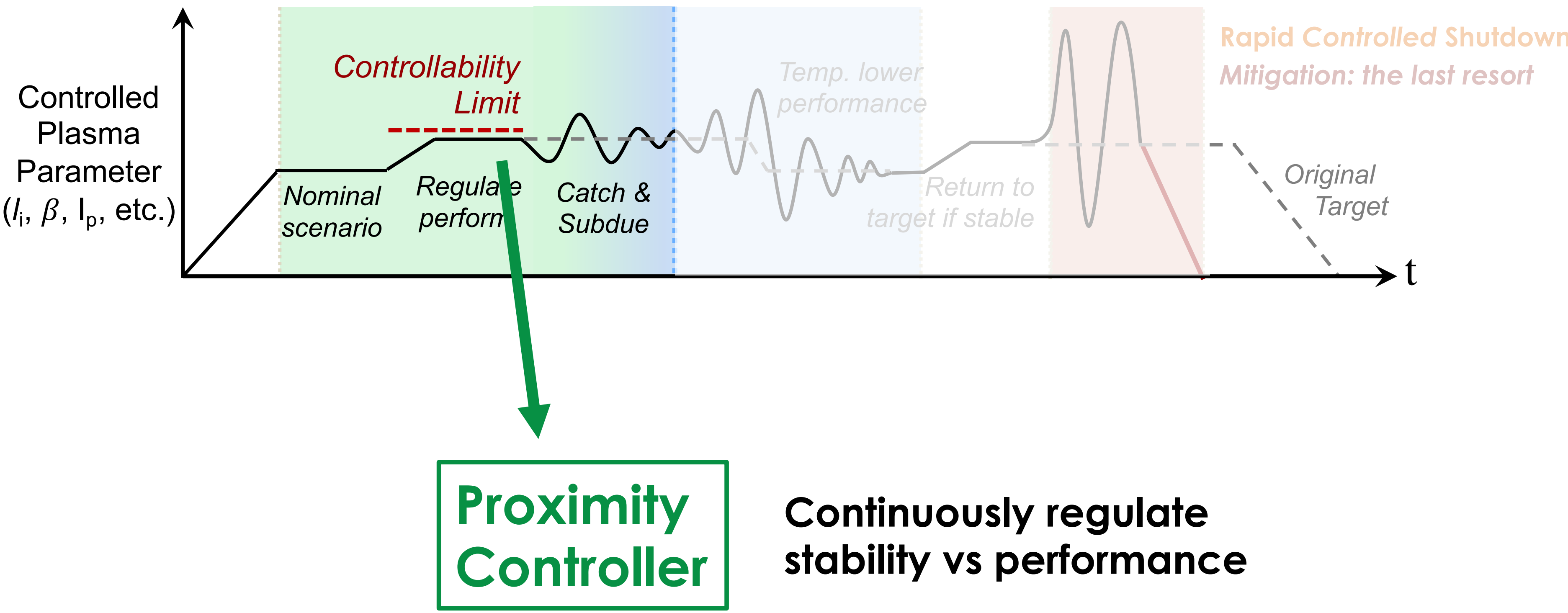
  >40% run days in '19

Comprehensive disruption prevention must cover the full range of control regimes

“disruption” = loss of control

Disruption Control Regimes:

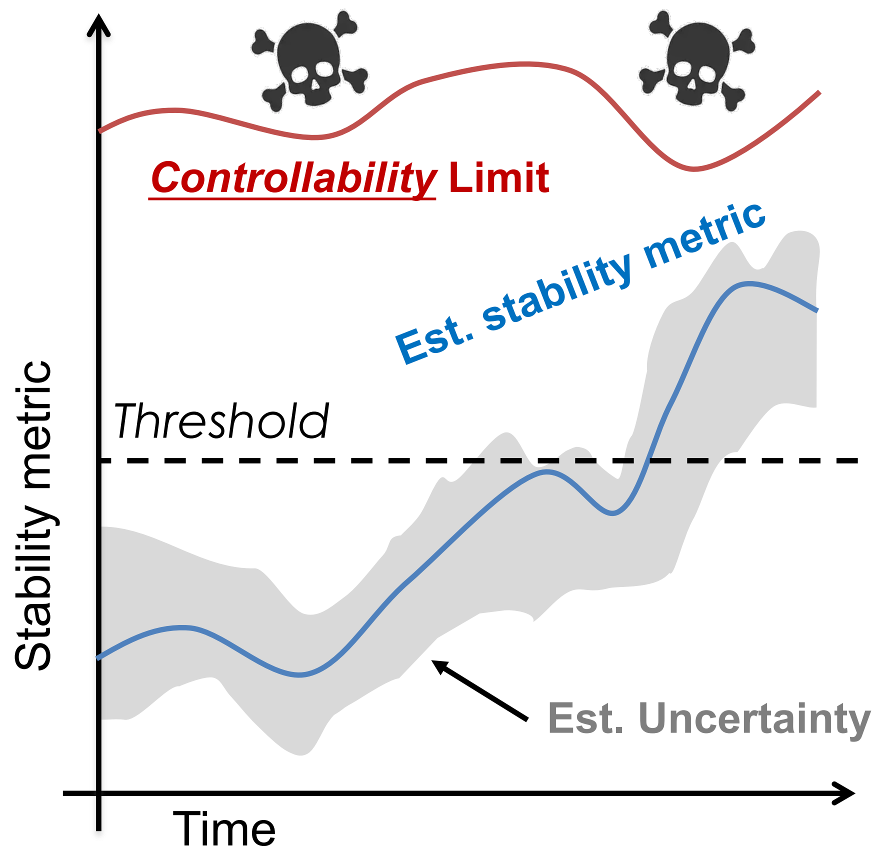
1 **Continuous Prevention:** → 2 **Asynchronous Avoidance:** → 3 **Emergency Avoidance:**



Continuously regulate stability vs performance

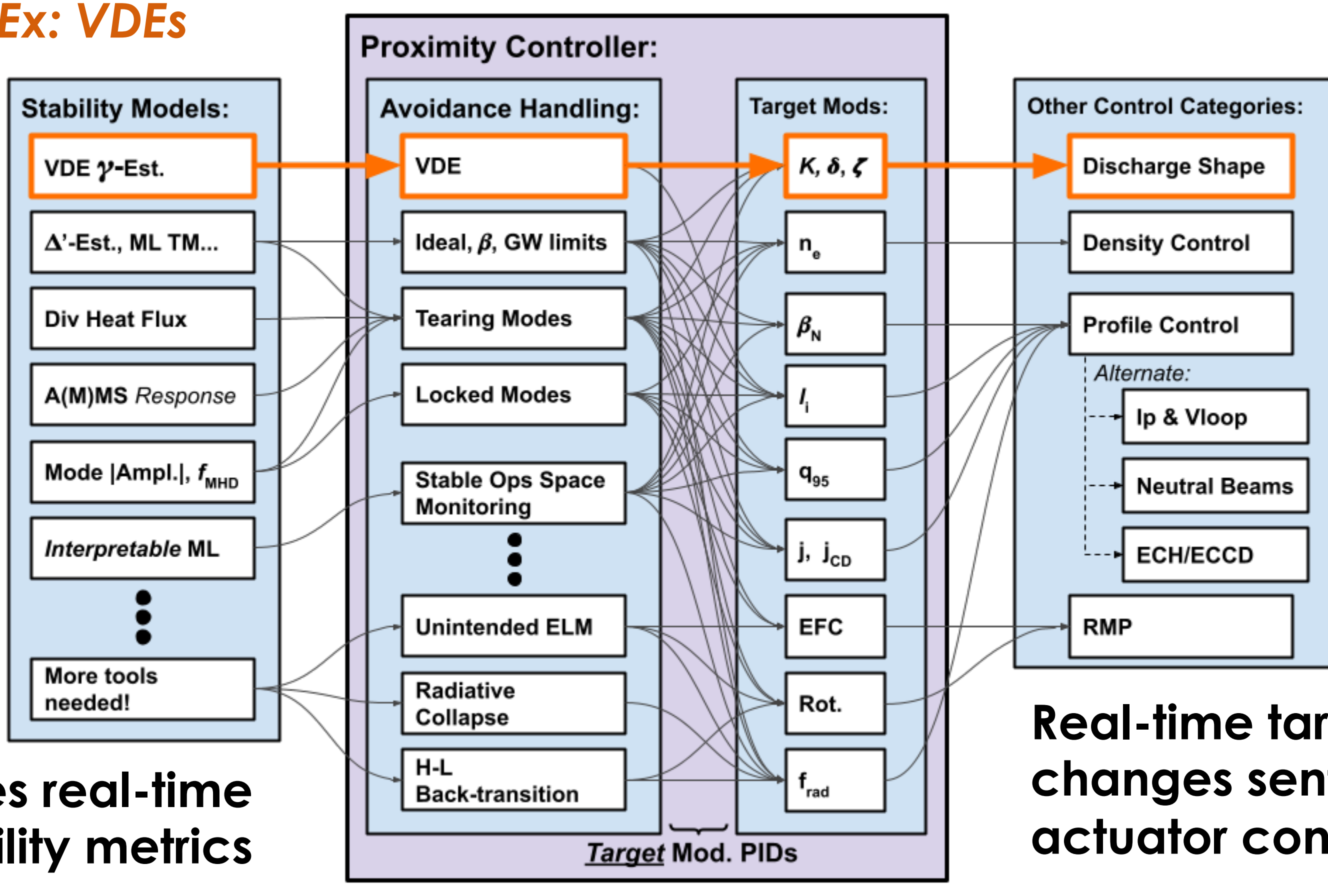
A new proximity-to-instability control architecture has been developed for DIII-D in FY 2020

- **Threshold instability value for applying action**
  - Allows setting margin of stability
- **Generalized architecture maps stability metrics to target changes**
  - Tunable PIDs, gains
  - Control error from metric over threshold
- **Output target mods combined, weighted by problem importance**



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

Ex: VDEs



Uses real-time stability metrics

Real-time target changes sent to actuator controllers

Physics-problem focused

Settings map metrics to scenario targets

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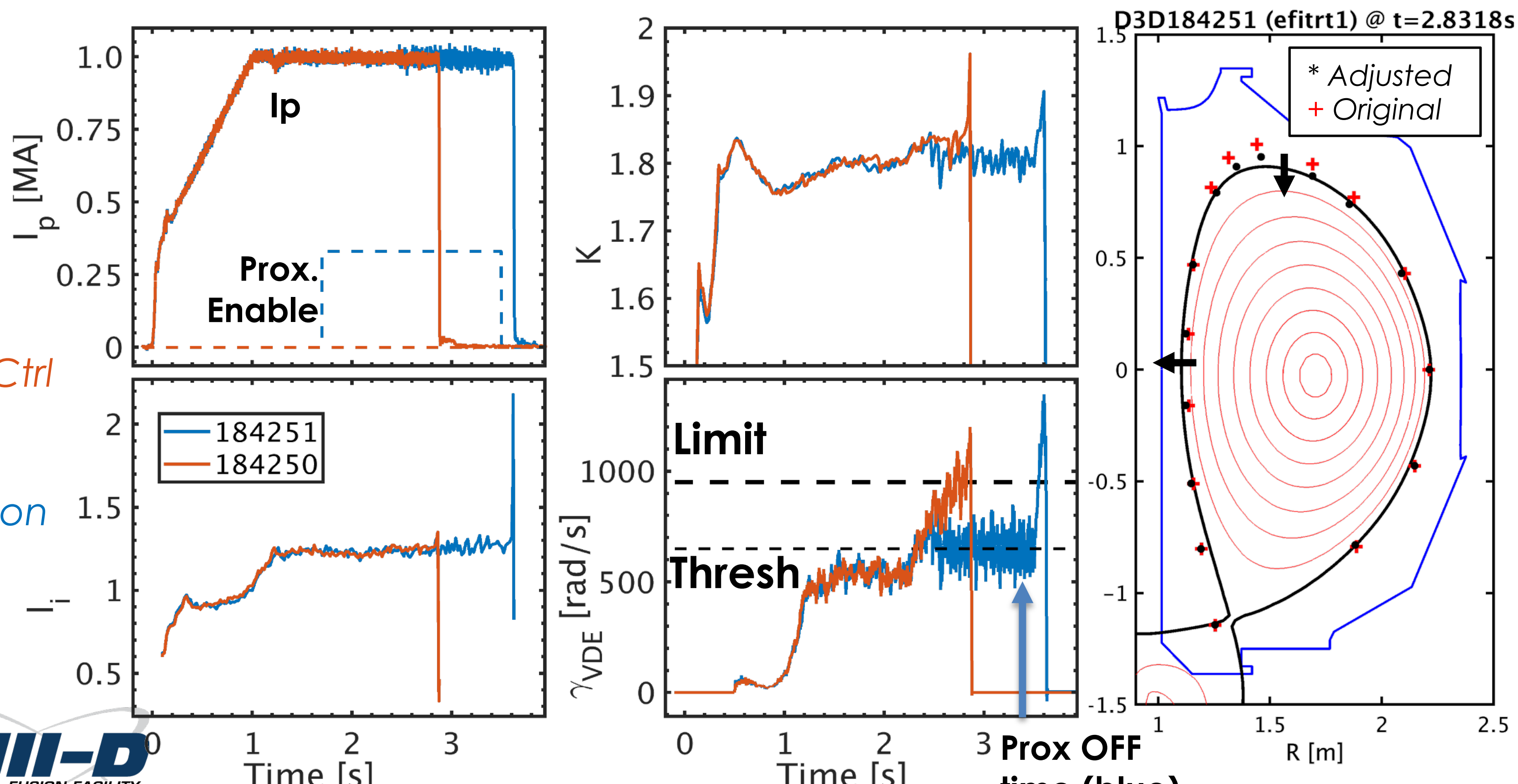
Proximity controller applied for robust VDE prevention using real-time VDE-γ estimator for shape target feedback

- **VDE reliably prevented until Proximity Controller disabled**
  - Example: (red) pre-shot K-target ramp to induce VDE
    (blue) Prox. control when $\boldsymbol{\gamma}$>threshold: reduces K, inner-gap

- **Real-time VDE-γ estimators:** rigid motion, or ML-based models

Red:
No Prox Ctrl

Blue:
Prox Ctrl on 1.75-3.5s



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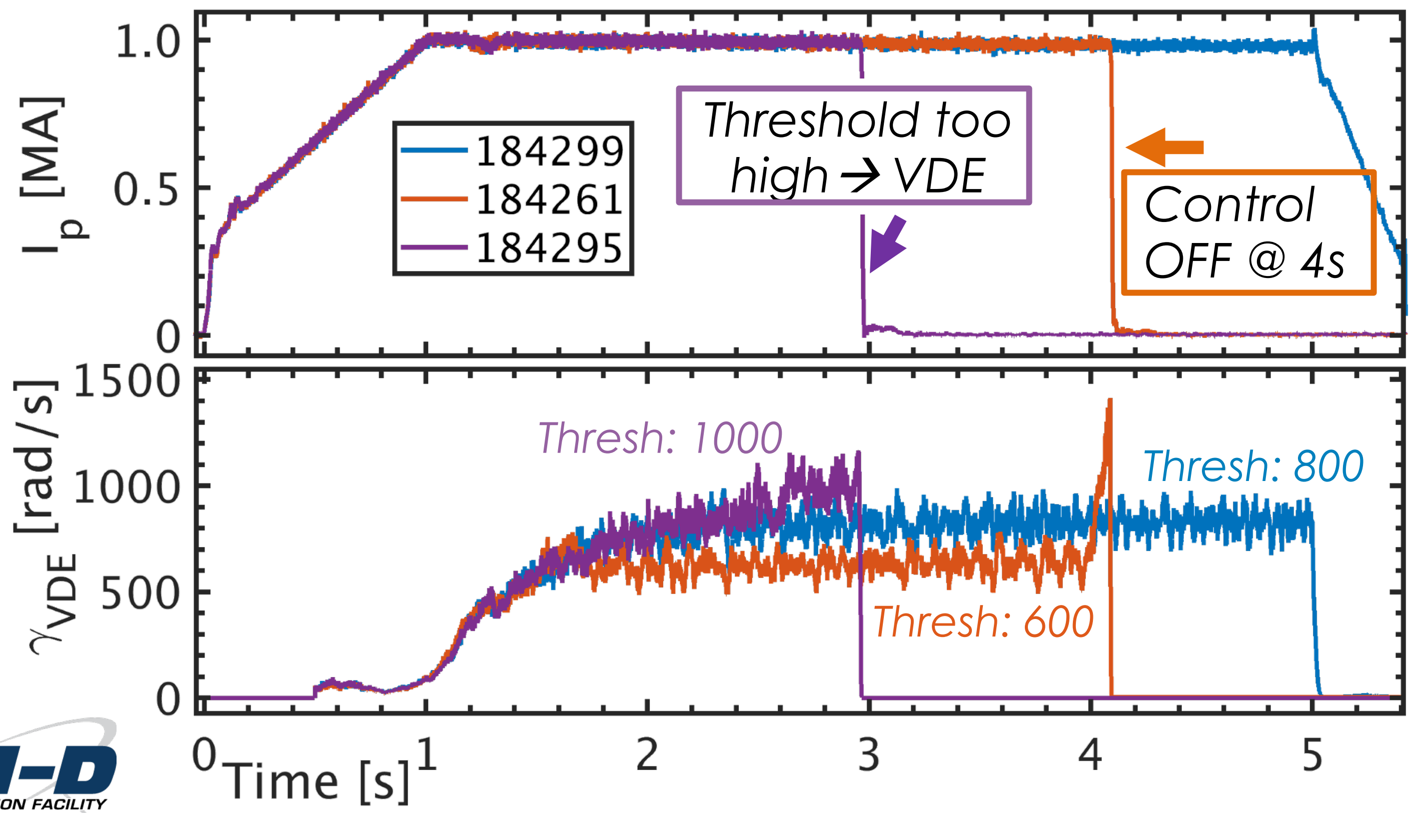
Robust control is a requirement for safe operations near stability limits

- Operational limits are limited by *physics* & *control*
- Robustly controllable VDE growth-rates assessed in recent experiments
- Robust control at γ ~800-850 /s for >= 3s



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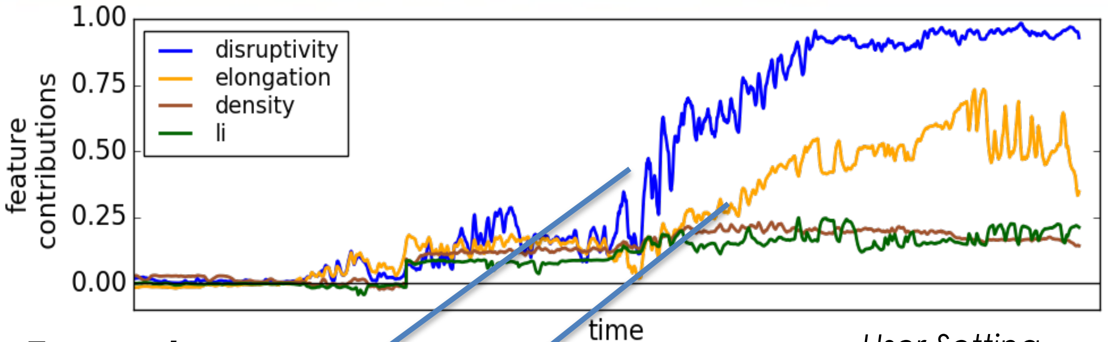
Future integration with include Interpretable ML, MHD Spectroscopy planned for experiments in 2021

- **Integrating with Interpretable ML**
  - *DPRF: Disruption Prevention via Random Forests* [1]
  - Contribution factors (f_c) map to controllable params
  - *Scale by overall disruptivity*



Example:

User Setting

$$\Delta\kappa = PID\left[f_{danger} * f_{\kappa-contrib} * sign\left(\frac{d\kappa}{dt}\right)\left(\frac{\Delta\kappa_{target}}{\Delta f_{\kappa-contrib}}\right)\right]$$

- **Active Multi-Mode Spectroscopy Demonstrated Offline [2-3]**
  - Continuous monitoring of closest-to-unstable modes
  - Real-time version ready for upcoming experiments

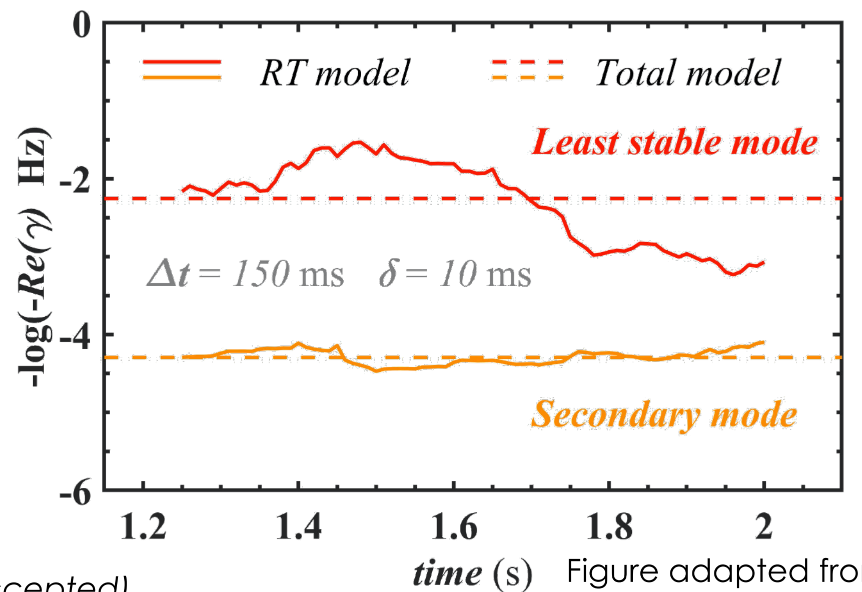
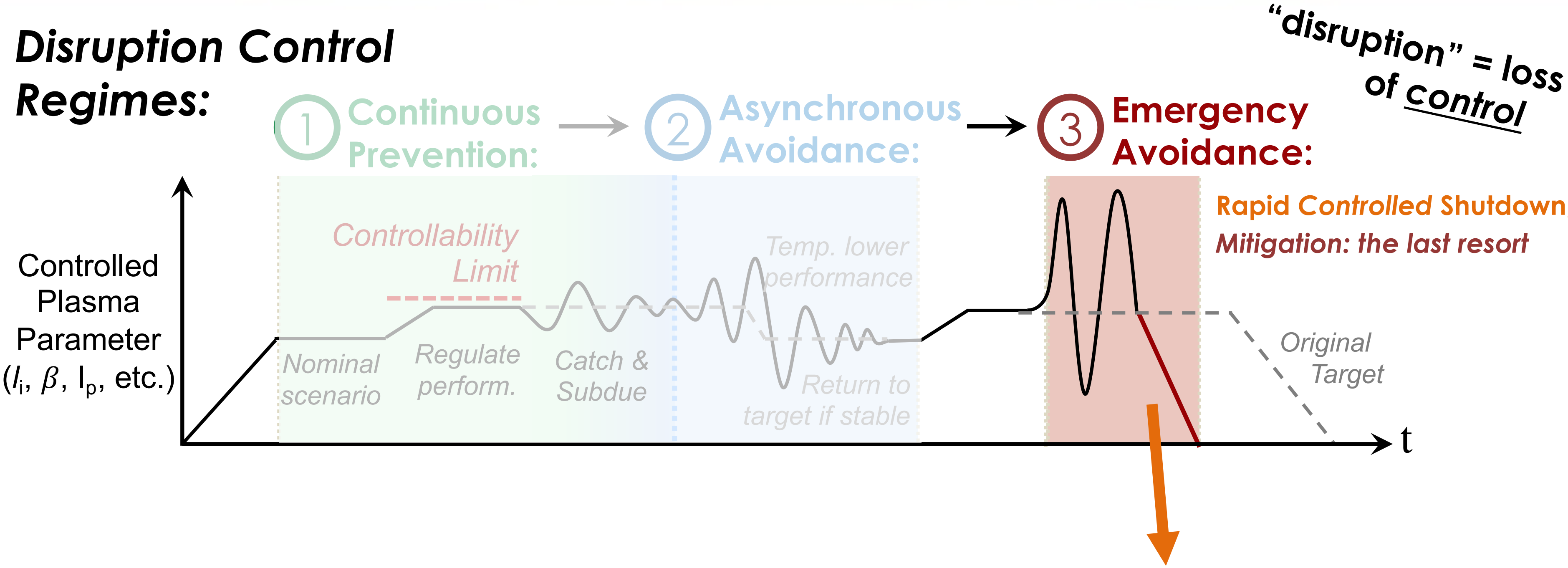


Figure adapted from T. Liu NF [2]

[1] C. Rea et al 2020 IAEA FEC
[2] T. Liu *et al* 2021 *Nucl. Fusion (accepted)*
[3] Z.R. Wang *et al* 2019 *Nucl. Fusion* **59** 024001

Comprehensive disruption prevention must cover the full range of control regimes

Disruption Control Regimes:



Rapid Controlled Shutdown

2^{nd}-to-last resort before mitigation

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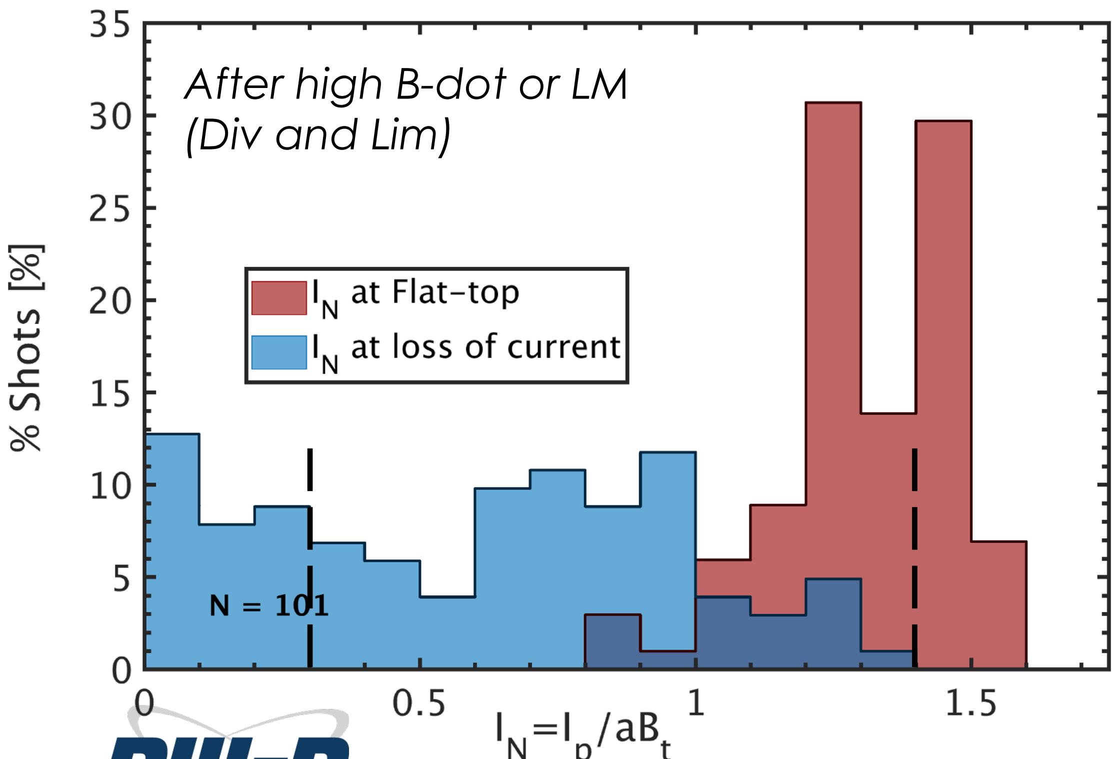
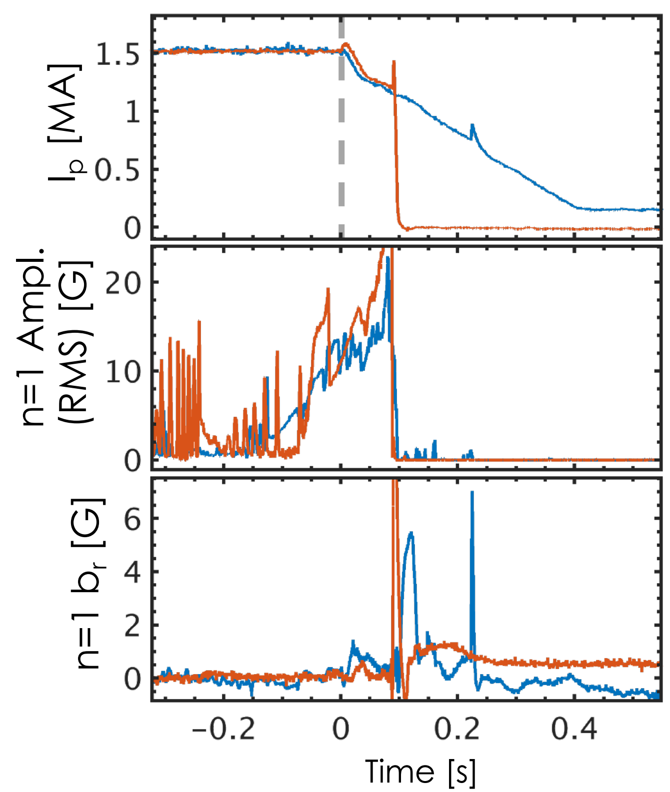
Qualifying fast, emergency shutdown after large n=1 tearing, locked modes for effectiveness on DIII-D

- **Applied shutdown survey recipe[1]:**
  - $dI_p/dt \sim 2\text{–}3$ MA/s , sustained P_{NBI}~2-3MW

- **Metric of success is *lower final* I_N** *($W_m \sim I_p^2 \sim I_N^2$)*

Example emergency shutdown:





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[1] J.L. Barr *et al.* IAEA FEC 2018

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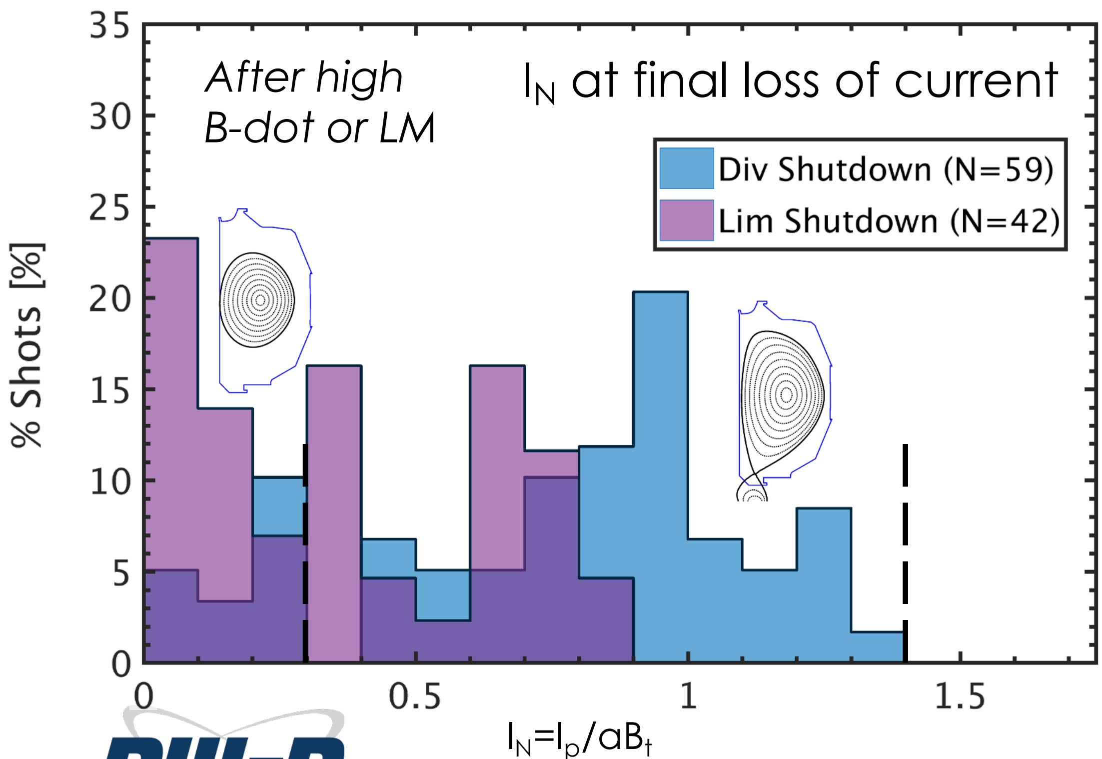

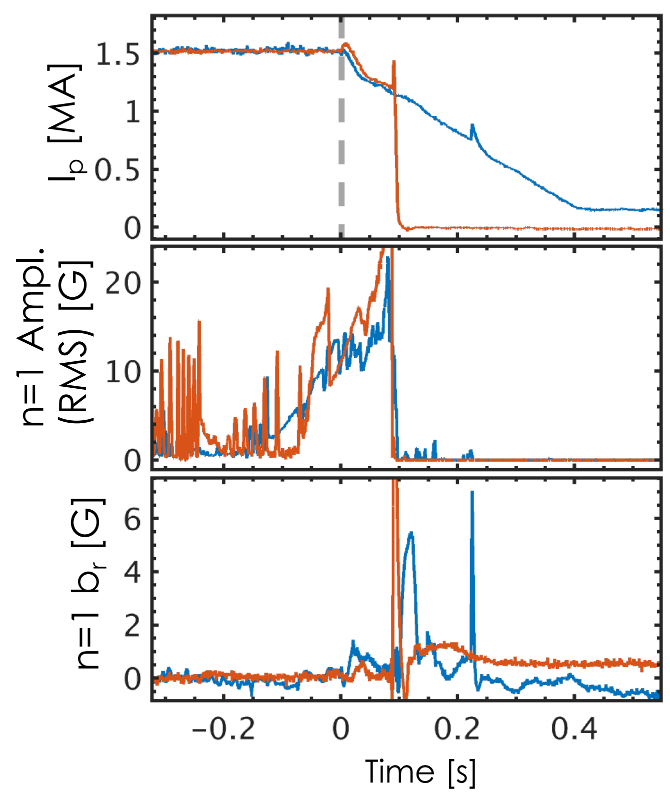

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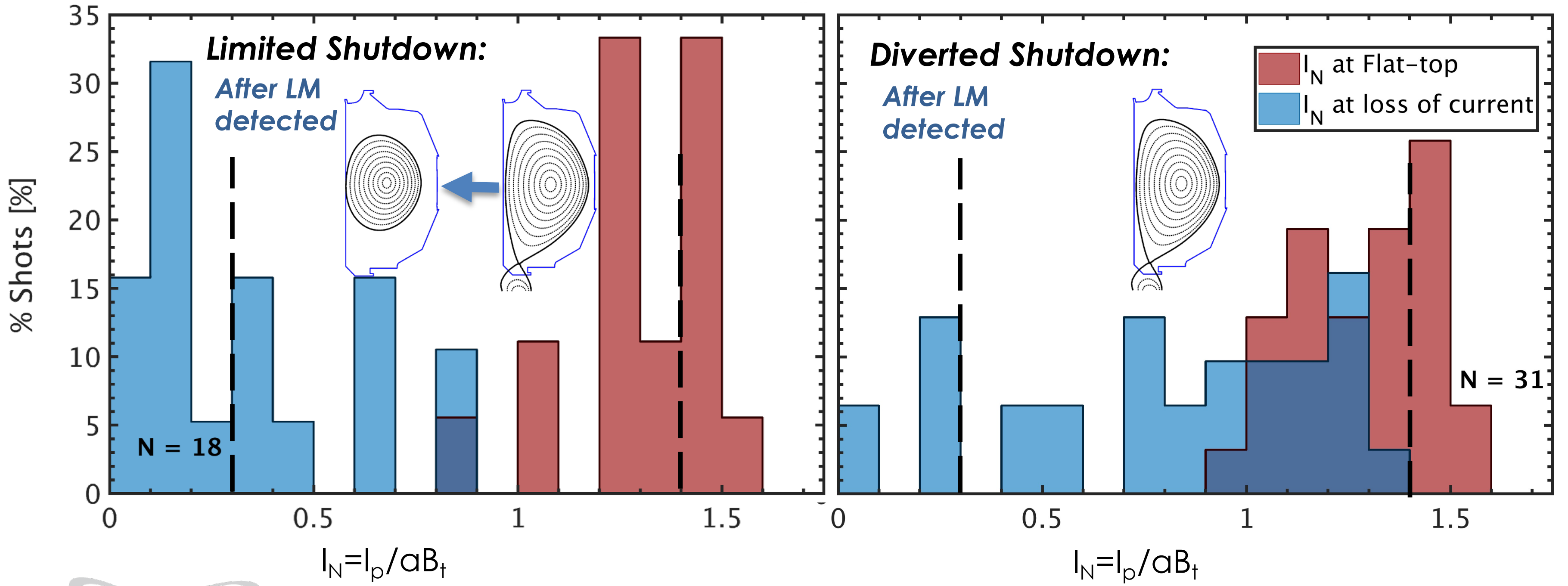
Transitioning to limited topology for emergency shutdown *dramatically* reduces LM disruption risk on DIII-D

- **After LM is detected, shape modification immediately applied**
- **Despite common use and improvements, ITER will likely require multiple prevention tools to improve these rates**

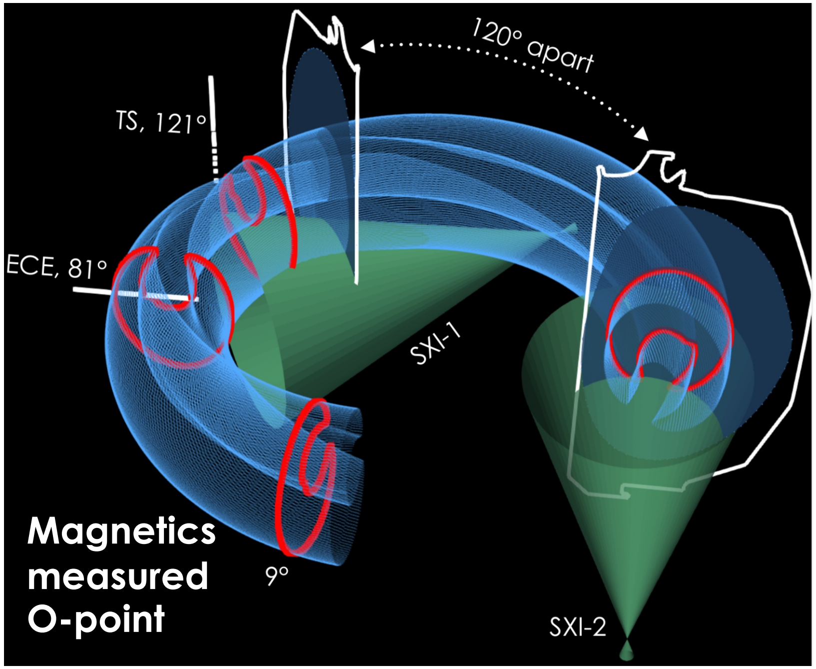
Focus on LM trips:

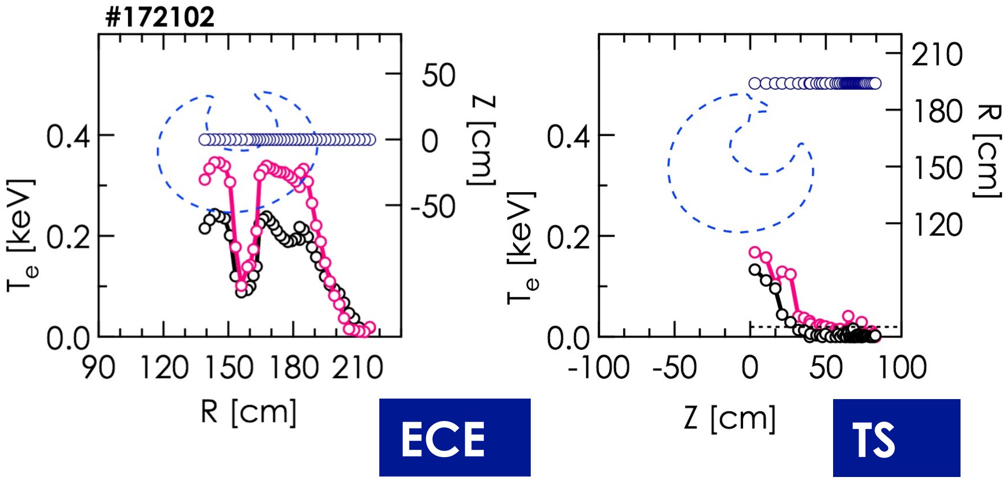


J. Barr/ITER FEC 2020/May 14th, 2021 [1] J.L. Barr *et al.* IAEA FEC 2018

Warm, helical plasma core generation is a promising technique for emergency shutdown / alternate mitigation

- **Novel emergency shutdown technique for long current quench durations**
  - DIII-D high-Ip discharges (~1.7MA+)
  - Improves confinement after thermal quench
- **Helical structure induced after thermal quench with large applied 3-D fields**
  - Reconstructed with dual Soft X-ray Imaging
  - Consistent with ECE, TS
- **Can modify current quench alongside Ne injection**
  - Can extend current quench to ~100ms





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[1] X.D. Du *et al* 2019 *Nucl. Fusion* **59** 094002

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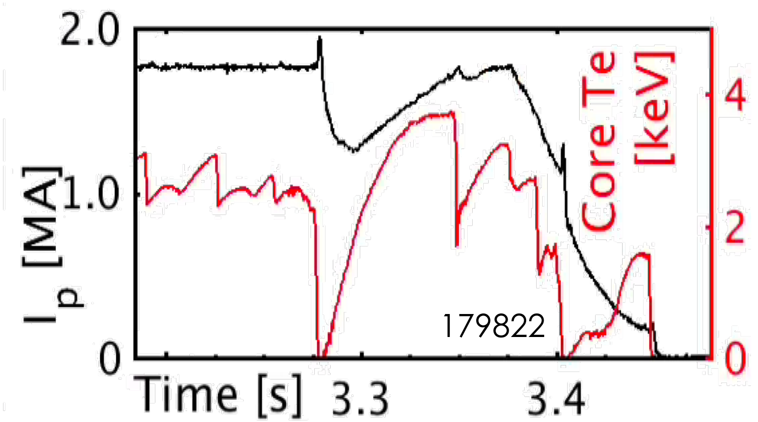

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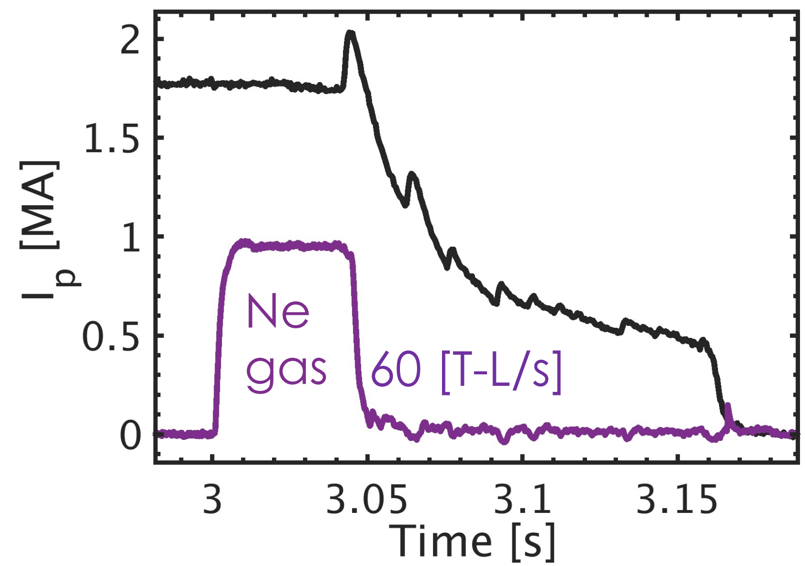

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Conclusions: *DIII-D is developing, testing, and qualifying control tools for comprehensive disruption avoidance*

- **DIII-D Disruption Free Protocol: initiative for qualifying comprehensive disruption prevention tools**
  - Large-scale piggyback to support dedicated experiments
- **Novel Proximity-to-Instability controller implemented for real-time scenario mod's to maintain stability, applied for robust VDE prevention**
  - Operates continuously, handles multiple physics problems in parallel
- **The effectiveness of emergency shutdown for disruption prevention is being rigorously quantified**
  - Changing to a limited shutdown dramatically reduces the disruption risk in emergency shutdowns, but further improvement needed!
- **Novel technique generates warm, helical core after thermal quench to significantly slow current quench**
- **Next steps:**
  - Disruption Free Protocol continuing now, more tools under testing!
  - Expansion of proximity controller: focus on tools for TM prevention