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

Jayson Barr[1]

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[2] Princeton Plasma Physics Lab
[3] Dalian University of Technology
[4] MIT

And the DIII-D team

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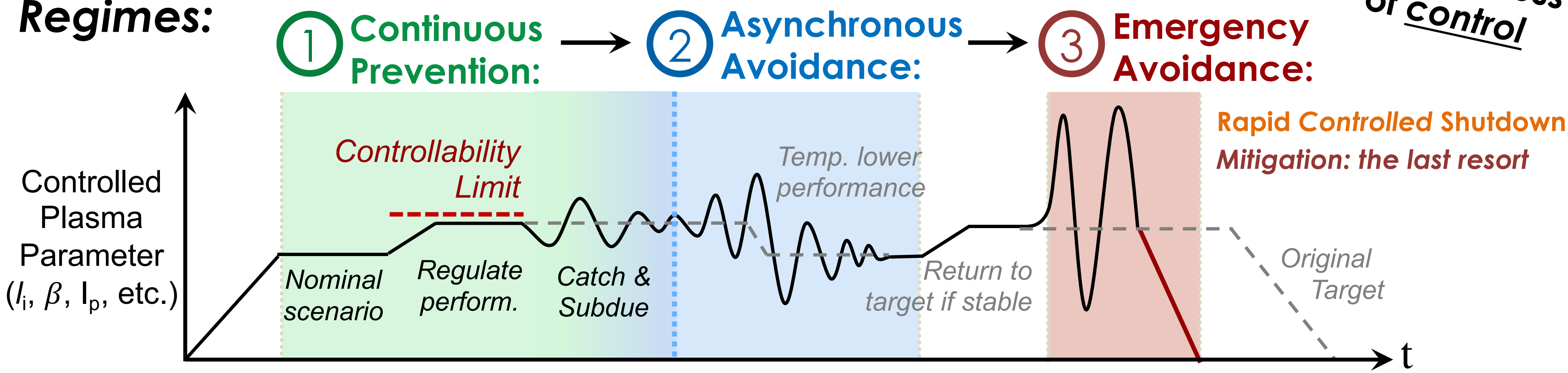
GENERAL ATOMICS

Comprehensive disruption prevention must cover the full range of control regimes

“disruption” = loss of control

Disruption 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

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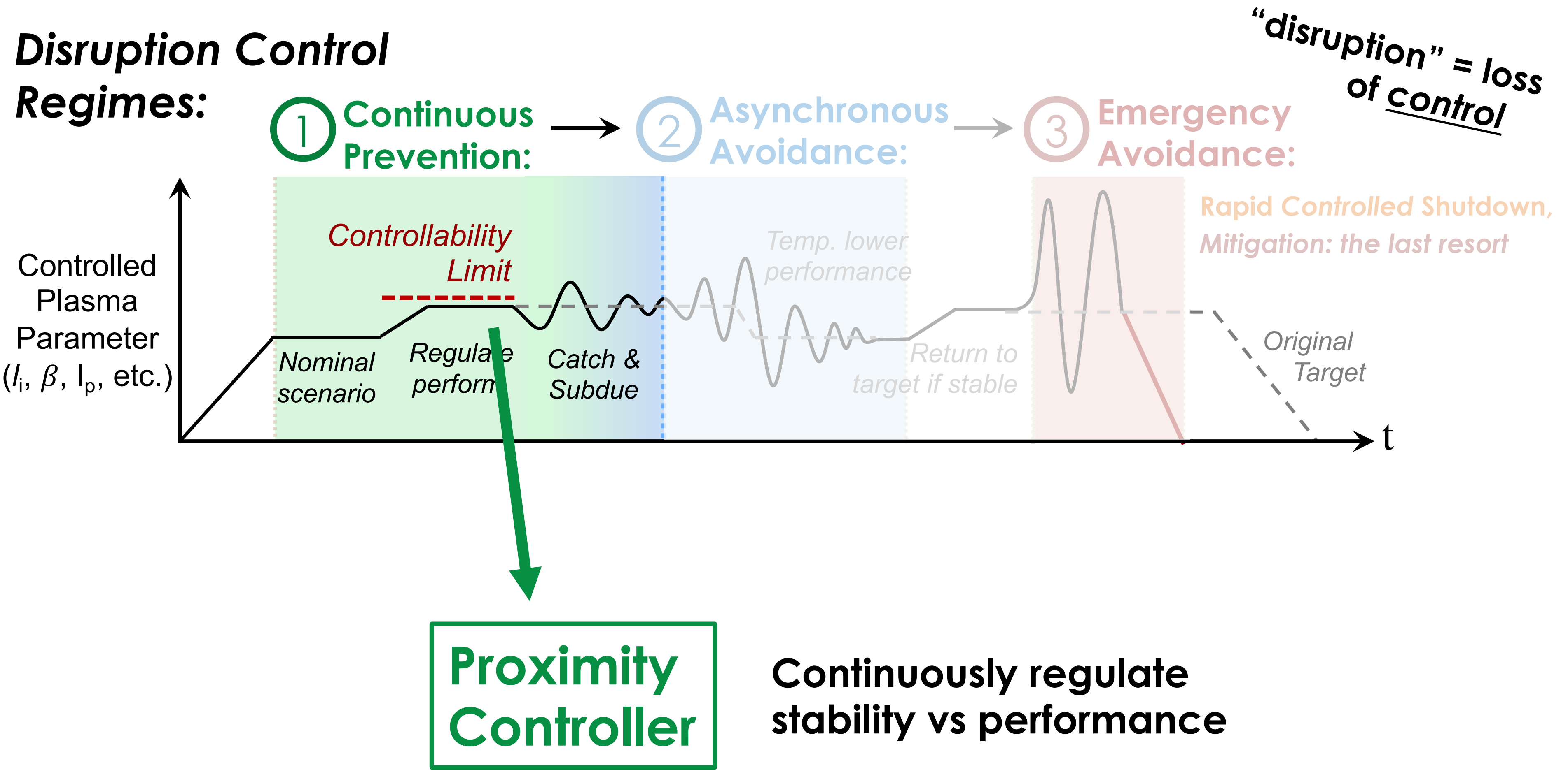
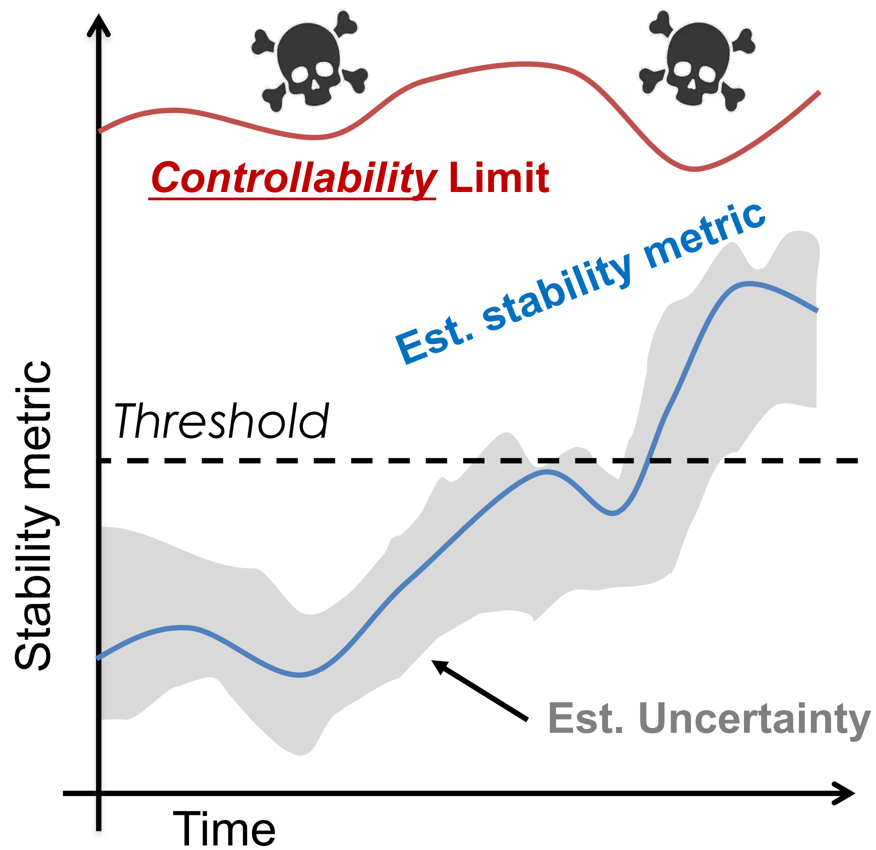


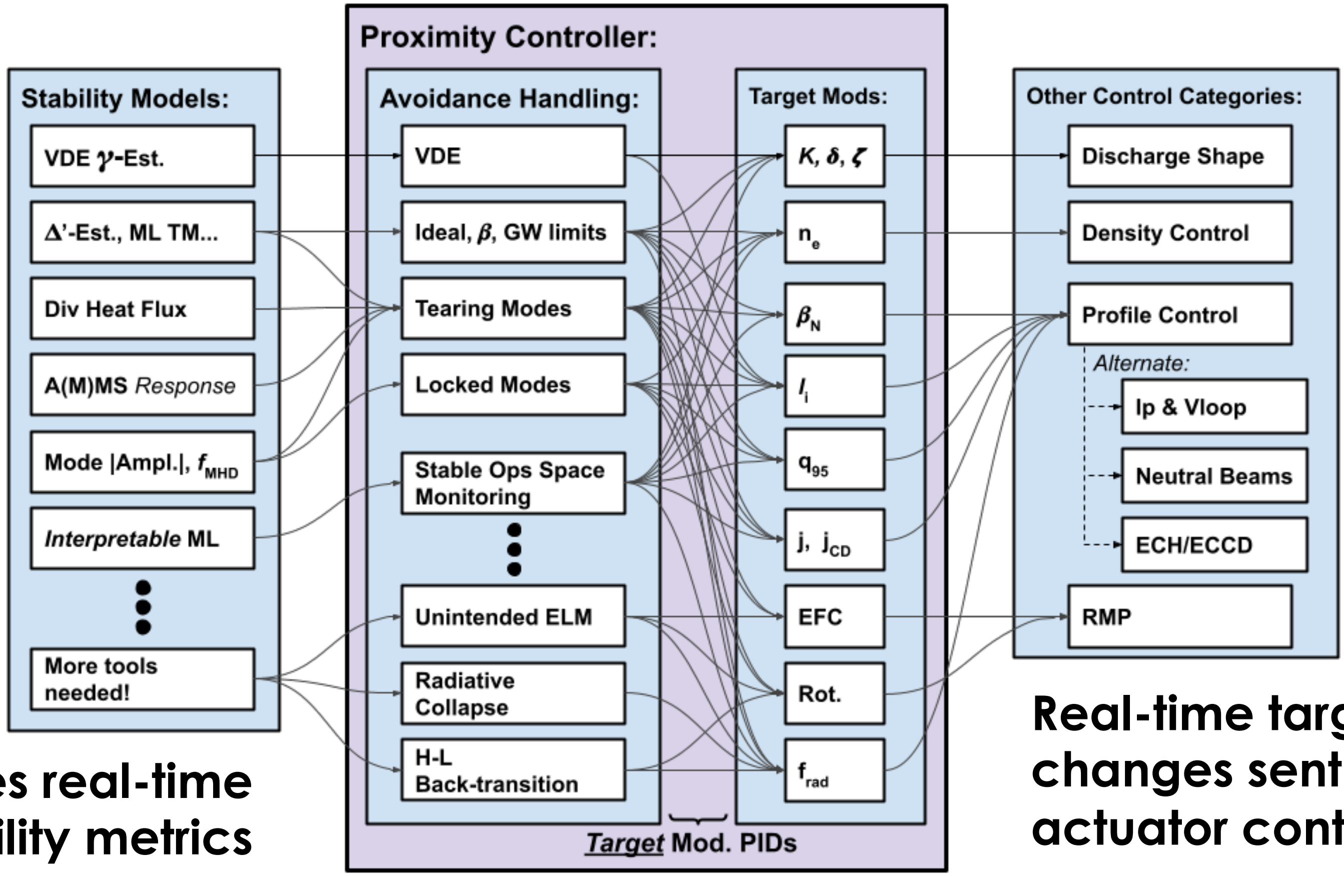
Continuously regulate stability vs performance

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 requested changes in plasma targets**
  - Shape, Ip, β…
  - Tunable PIDs, gains
- **Output target mods combined, weighted by problem importance**



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



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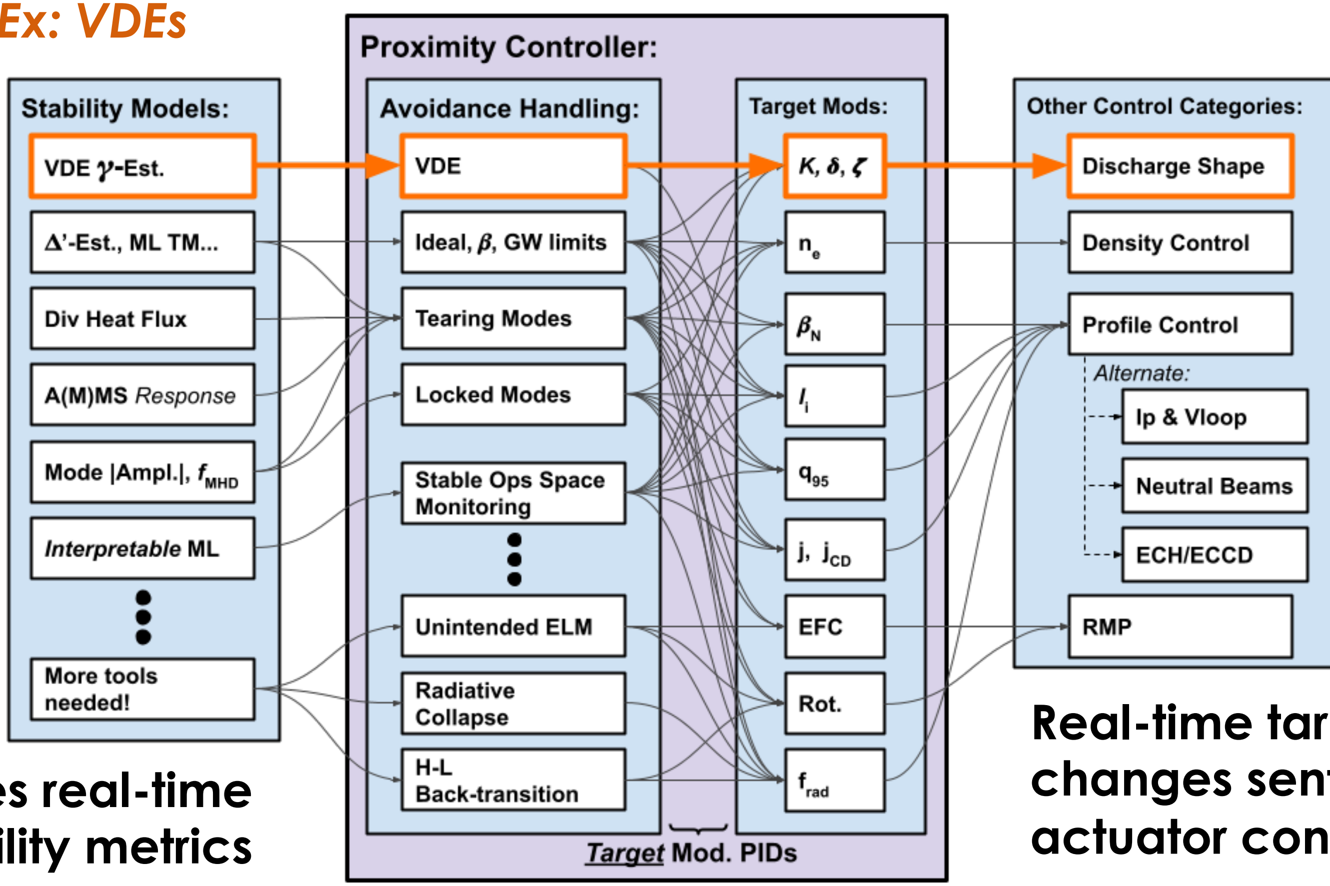
Proximity-to-instability control architecture maps real-time stability metrics to modified scenario targets

Ex: VDEs



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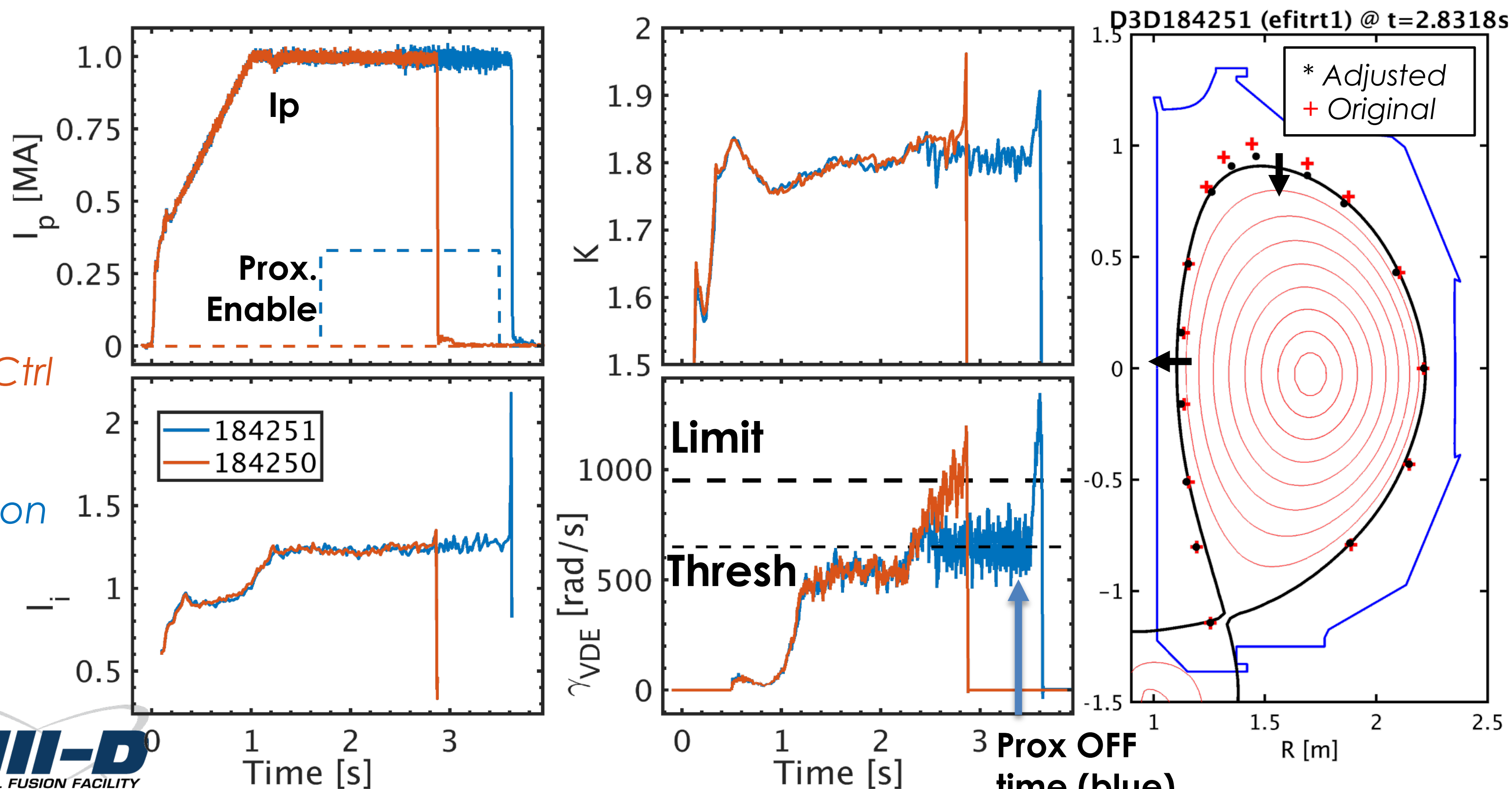
Proximity controller applied for robust VDE prevention using real-time VDE-γ estimator for shape target feedback

- **VDE reliably prevented until Proximity Controller disabled**
  - Example: pre-shot K-target ramp to induce VDE

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

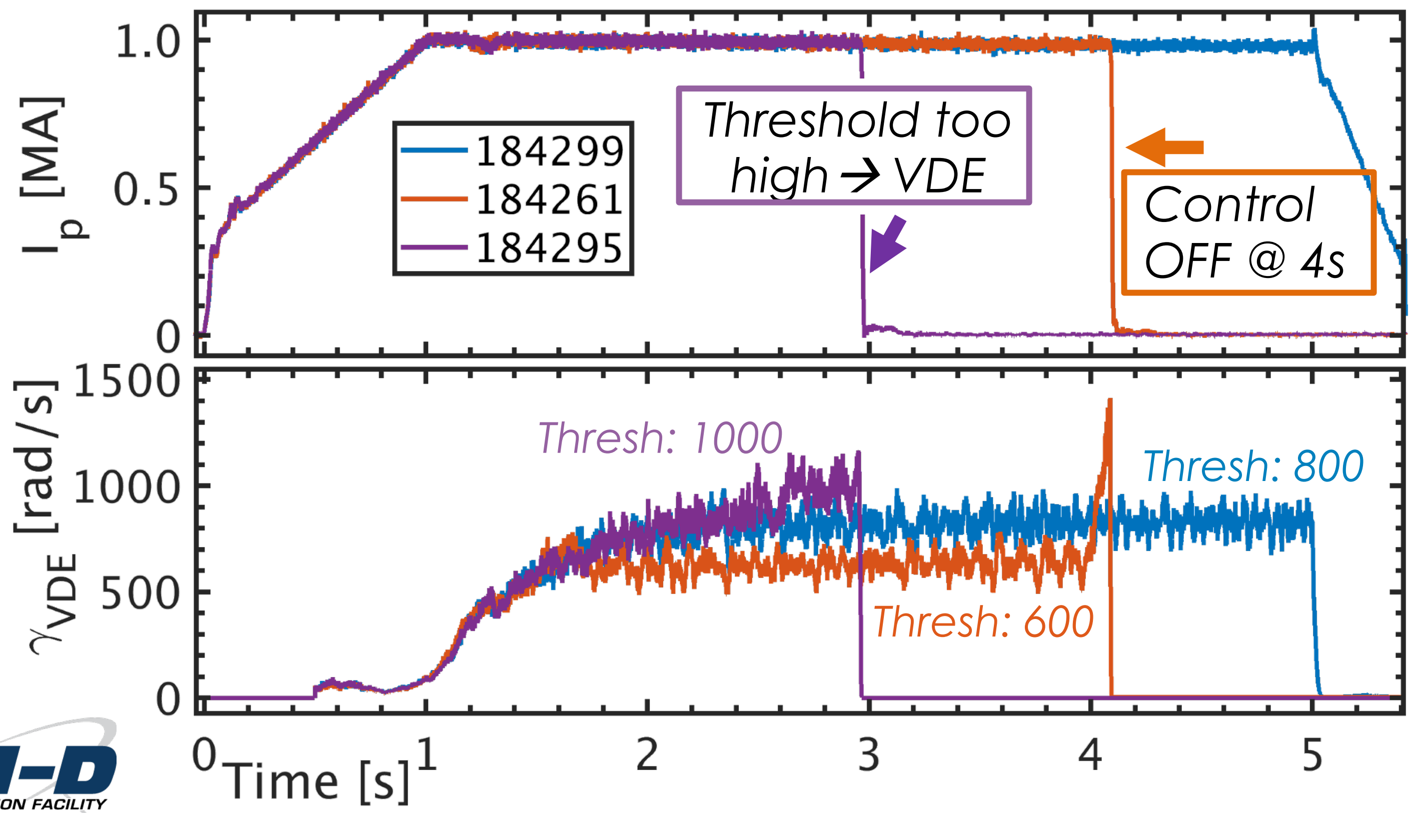
Red:
No Prox Ctrl

Blue:
Prox Ctrl on 1.75-3.5s



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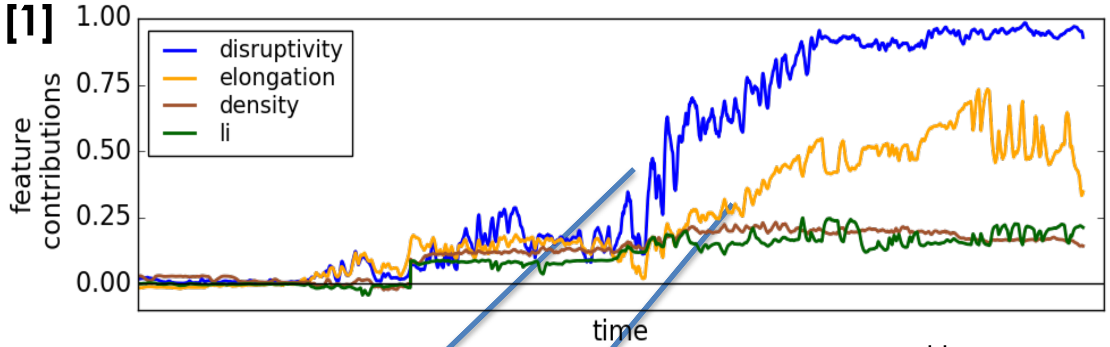
Future integration with include Interpretable ML, MHD Spectroscopy planned for experiments in 2021

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



Example:

User Setting

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

[1] C. Rea et al 2020 IAEA FEC
[2] T. Liu *et al* 2021 *Nucl. Fusion (accepted)*
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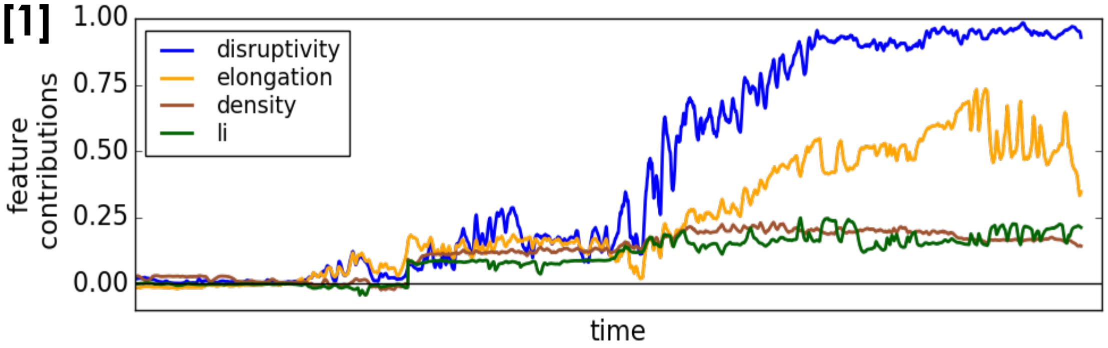

- **Active Multi-Mode Spectroscopy Demonstrated Offline [2-3]**
  - Continuous monitoring of closest-to-unstable modes
  - Real-time version ready for upcoming experiments

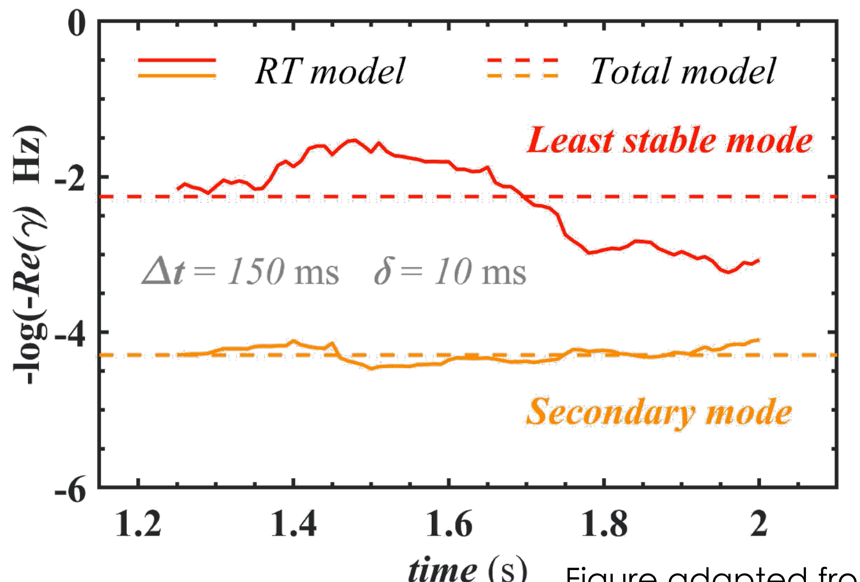

Figure adapted from T. Liu NF [2]

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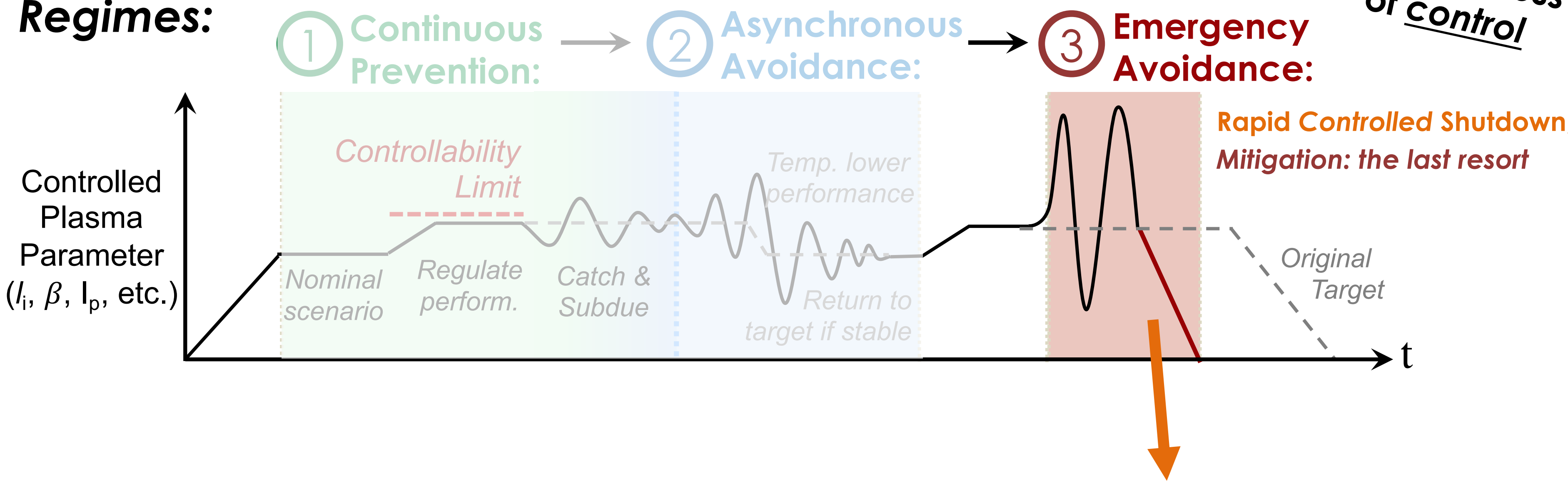

Rapid Controlled Shutdown

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

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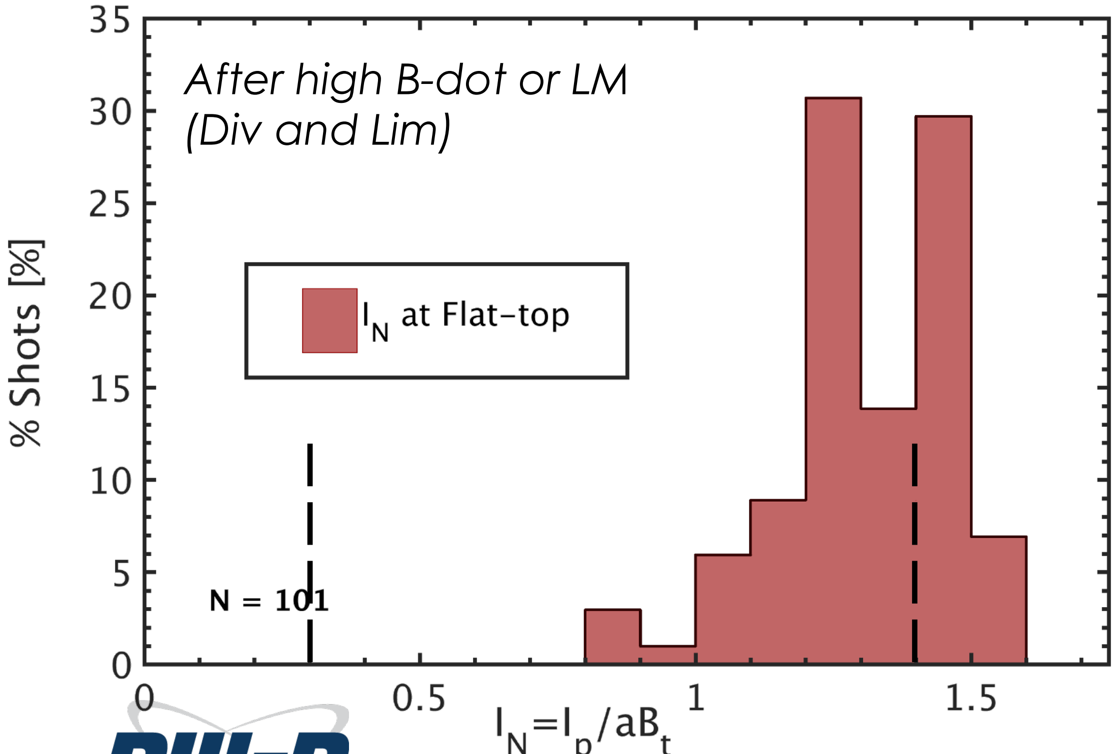
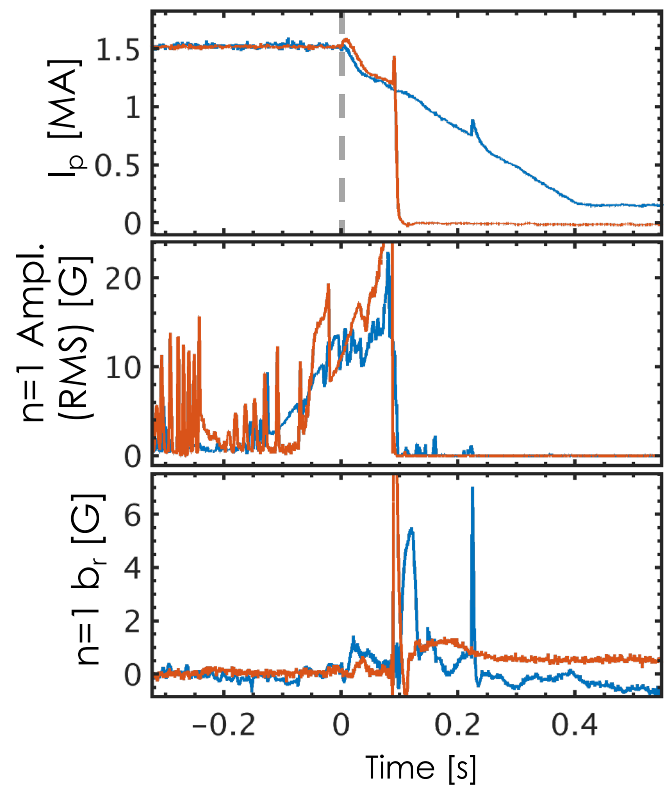
Qualifying fast, emergency shutdown after large n=1 tearing, locked modes for effectiveness on DIII-D

- **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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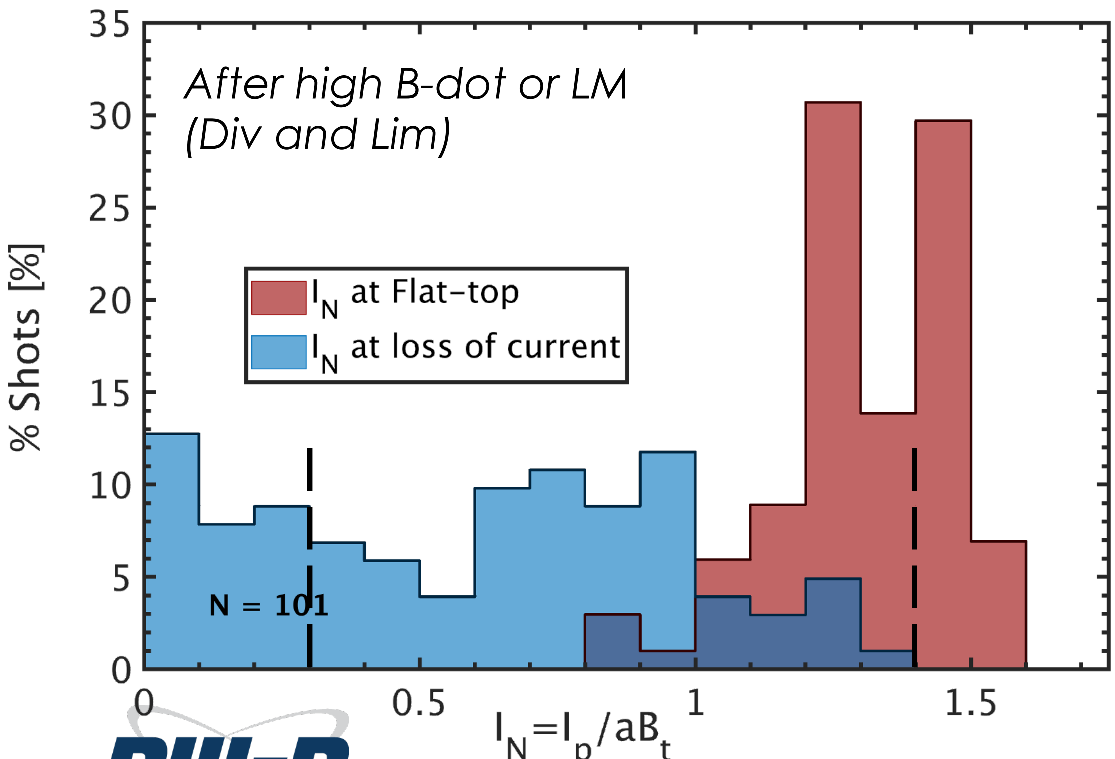

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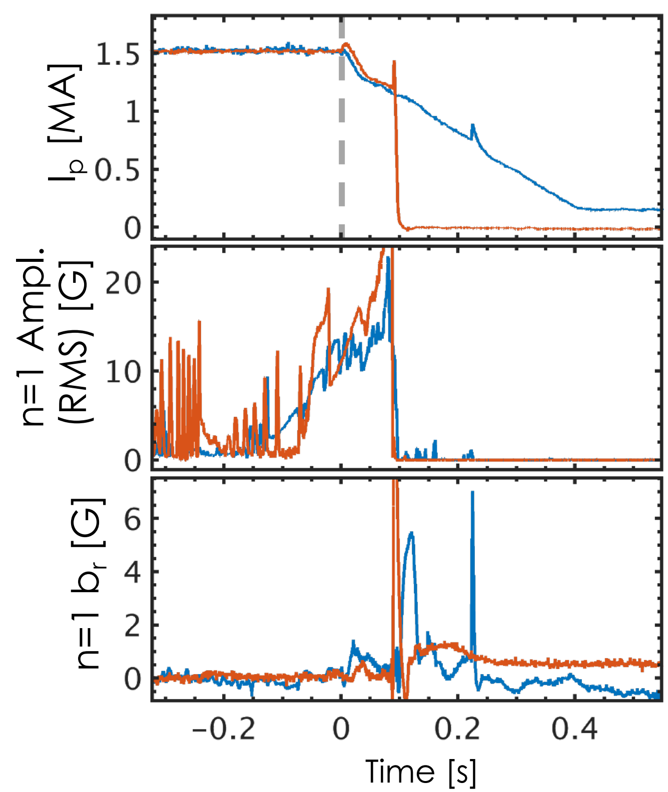

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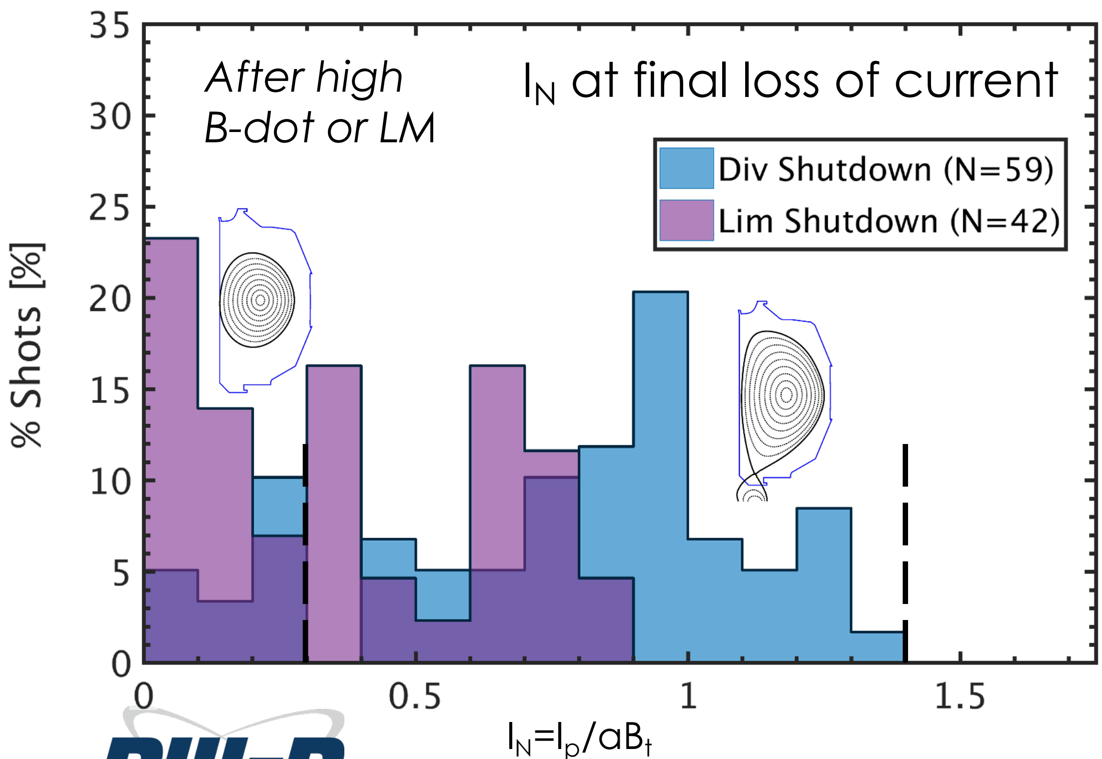

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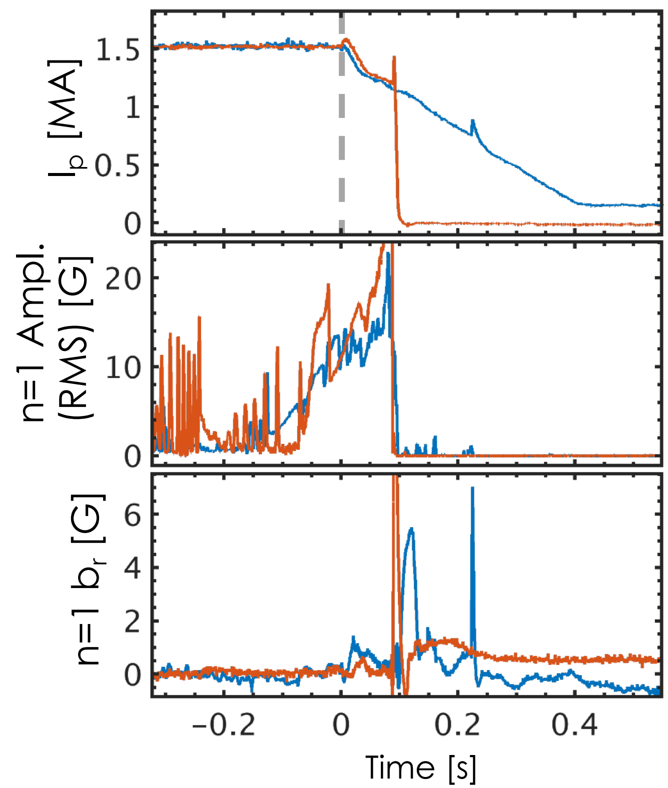

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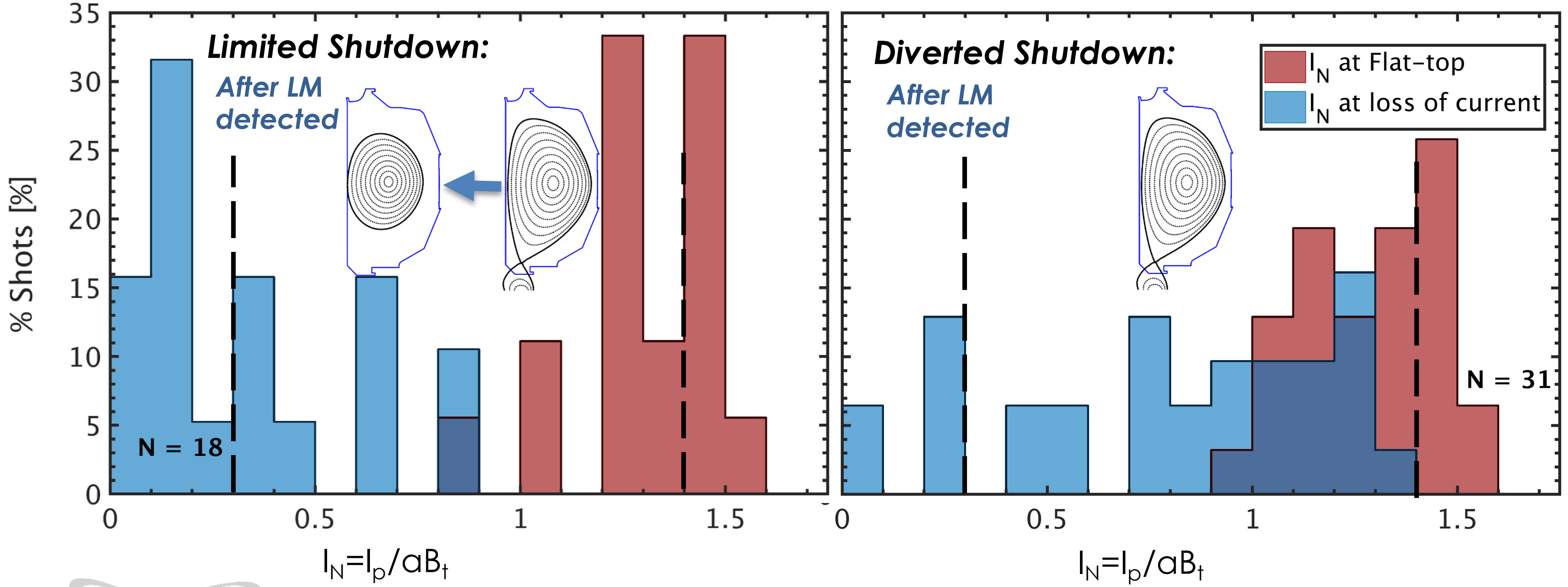
Transitioning to limited topology for emergency shutdown *dramatically* reduces LM disruption risk on DIII-D

- **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:



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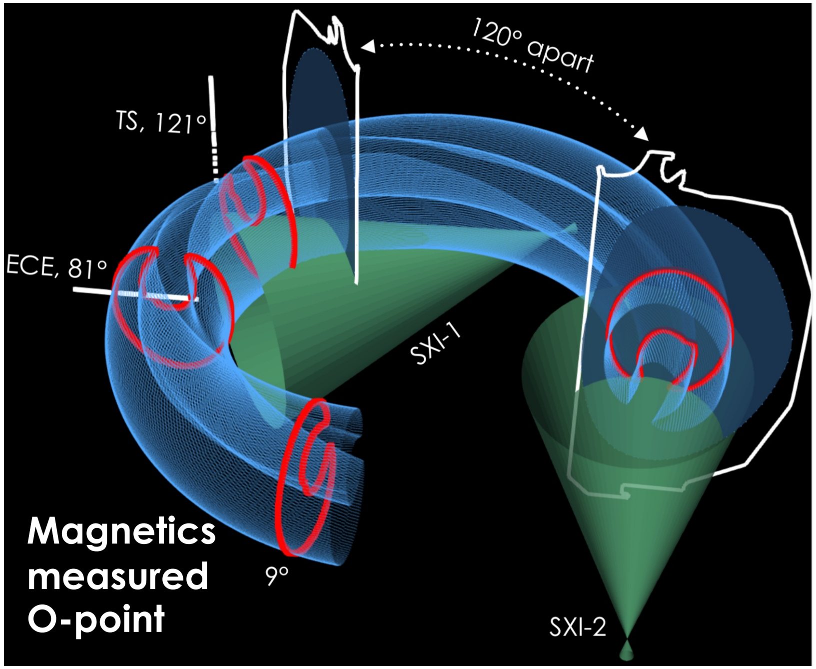
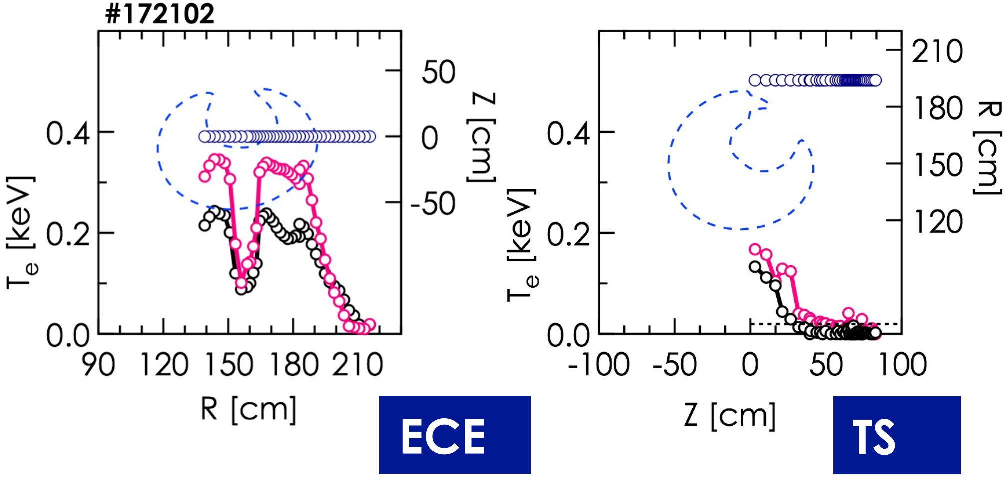
Warm, helical plasma core generation is a promising technique for emergency shutdown / alternate mitigation

- **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 MGI mitigation**
  - Can extend current quench to ~100ms





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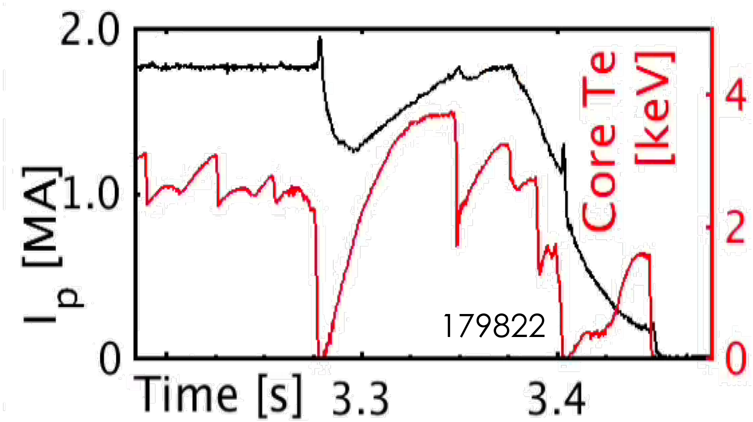

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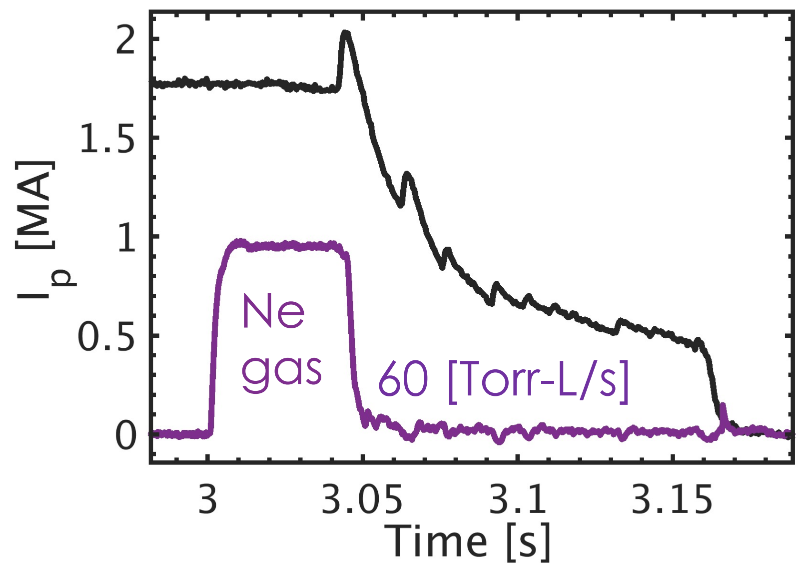

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Conclusions: *DIII-D is developing, testing, and qualifying control tools for comprehensive disruption avoidance*

- **DIII-D Disruption Free Protocol: initiative for qualifying comprehensive disruption prevention tools**

- **Novel Proximity-to-Instability controller implemented for real-time scenario mod's to maintain stability, applied for robust VDE prevention**

- **The effectiveness of emergency shutdown for disruption prevention is being rigorously quantified**

- **Novel technique generates warm, helical core after thermal quench to significantly slow current quench**