Control Solutions Supporting Disruption Free Operation on DIII-D and EAST

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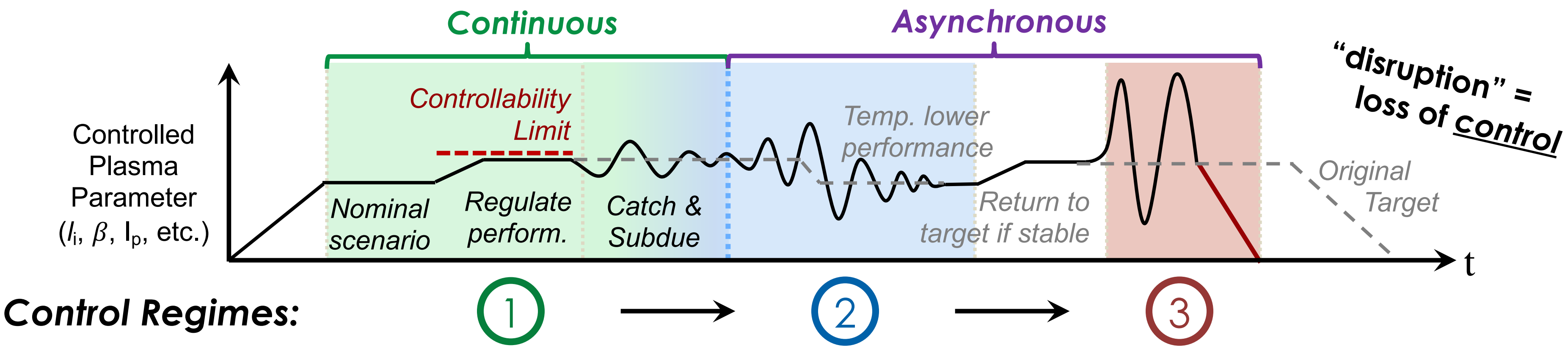
ASIPP GENERAL ATOMICS

Comprehensive disruption prevention must cover the full range of control regimes



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- Perturbative mode response, state-change
- Temporarily de-rate scenario, then return
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3. Emergency Avoidance:

Rapid Controlled shutdown:

- Large piggyback study on DIII-D
- **< 0.09% of disruptions!**

Mitigation should be the last resort:

- Has side-effects
- **< 0.01% of disruptions!**

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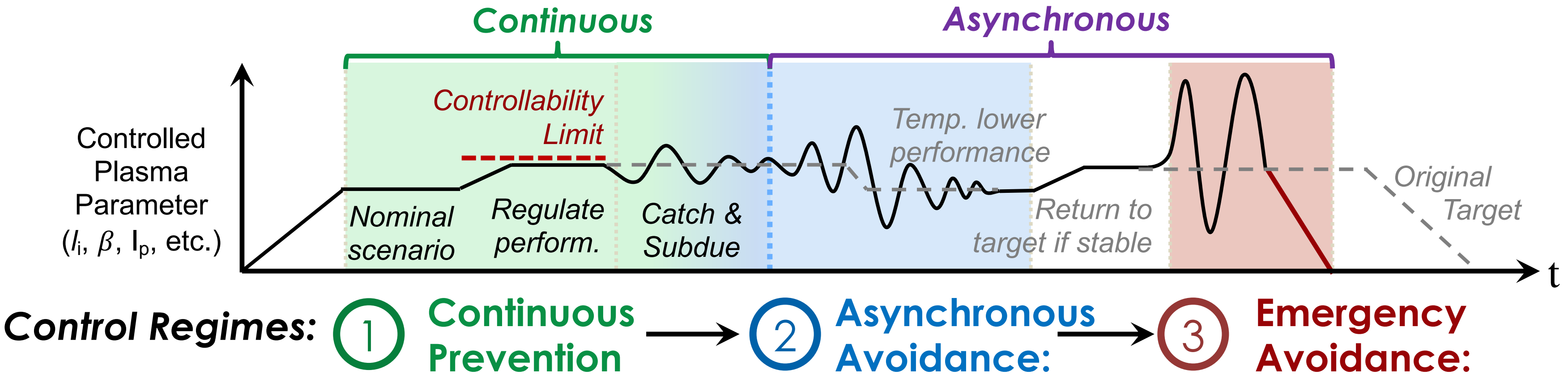
Disruption Free Protocol: Large-scale piggyback in addition to dedicated XPs to confidently qualify disruption solutions



The Disruption Free Protocol:

- ***To qualify ITER-scalable, comprehensive disruption control in routine operations***
- ***Large-scale piggyback:*** *43% days in '19*

Dedicated XPs: *Detailed physics understanding*

Control Tests: *Develop, test, & demonstrate*

Large-scale Piggyback: *Explore, qualify, & integrate*

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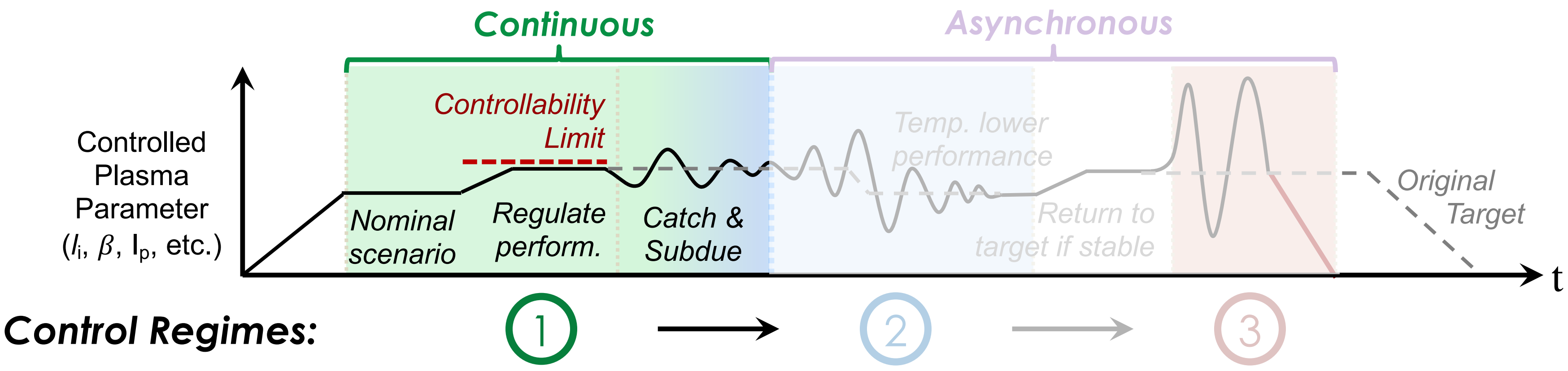

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Proximity Controller

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

Stability estimators:

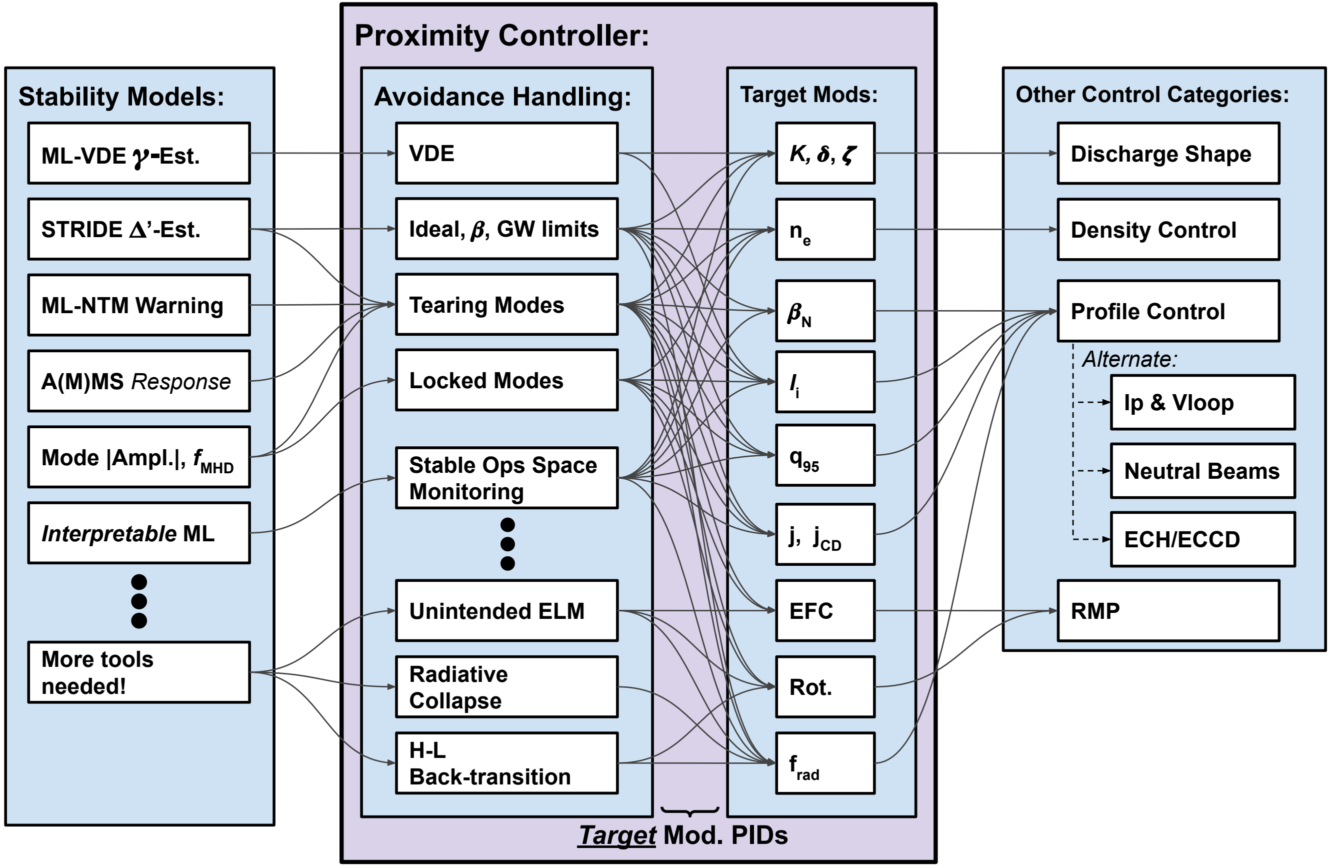
- Stability ***metrics*** &
- Stability ***limits***
- **Error bars!**

Target modification:

- ***Problem focused***
- Maps stability to plasma target mod's

Integration:

- **D3D PCS Architecture:**
  - Integrate with actuator algorithms
- **Future (missing) piece:** *actuator authority*



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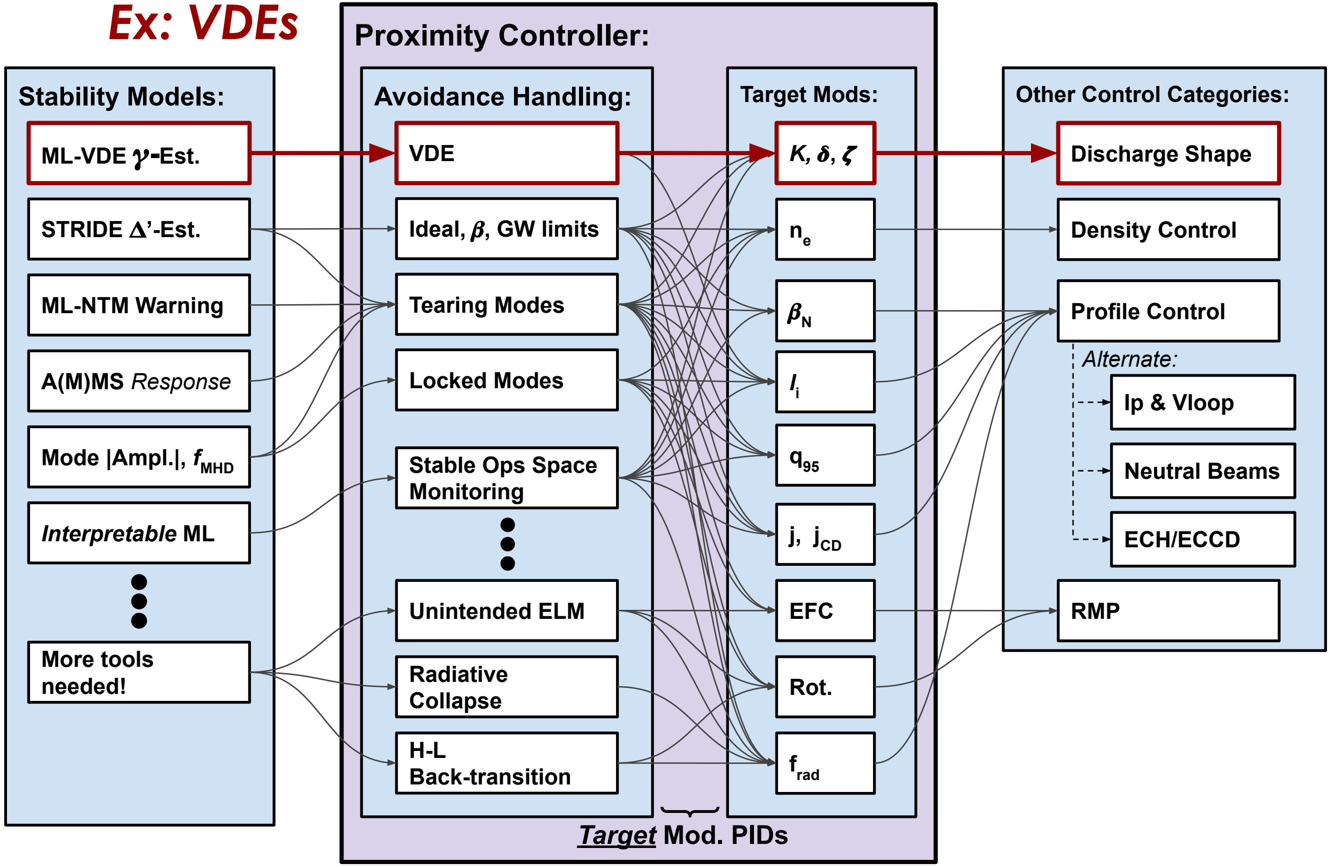
Ex: VDEs



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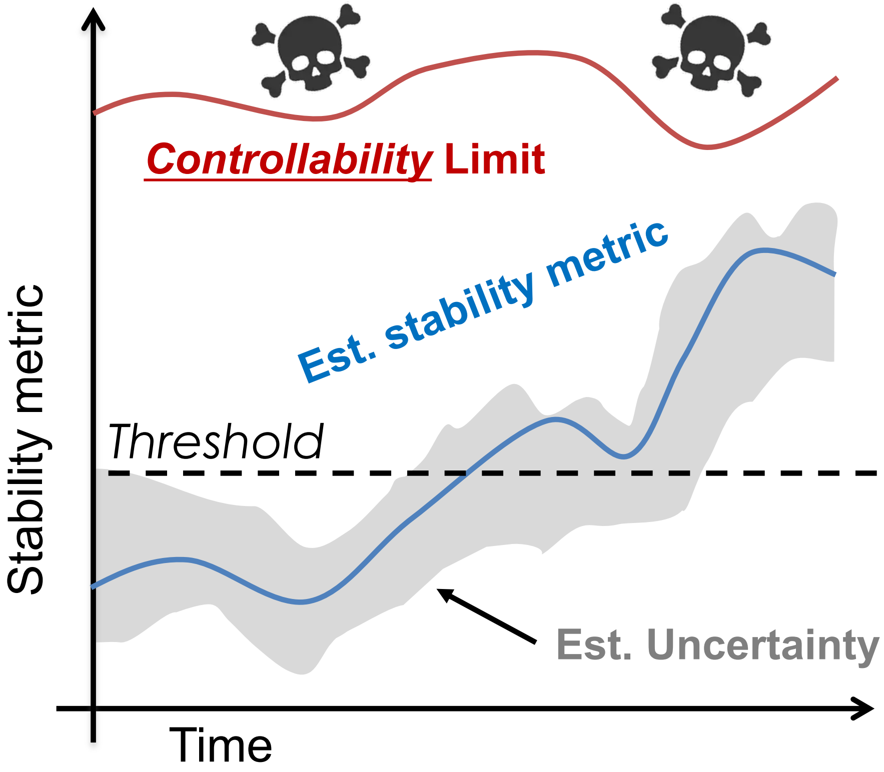
Handling safety margins and implementing responses

- **Generalized architecture**
  - Choice of input stability models (VDE Ex: estimated γ, l_i, or *K)*
  - Tunable PIDs, matrices map stability "errors" to target modifications
- **Thresholds for action**
  - Action taken above threshold margin of stability, acceptable uncertainty
  - Target mods relative to nearness to stability limit. ***Ex:*** *(metric-ref)/(lim-ref)*
  - ***Future:*** "Hazard function" analysis
- **Output target mods combined, weighted by problem importance**
  - ***Future:*** implement true actuator sharing / authority and supervisory control



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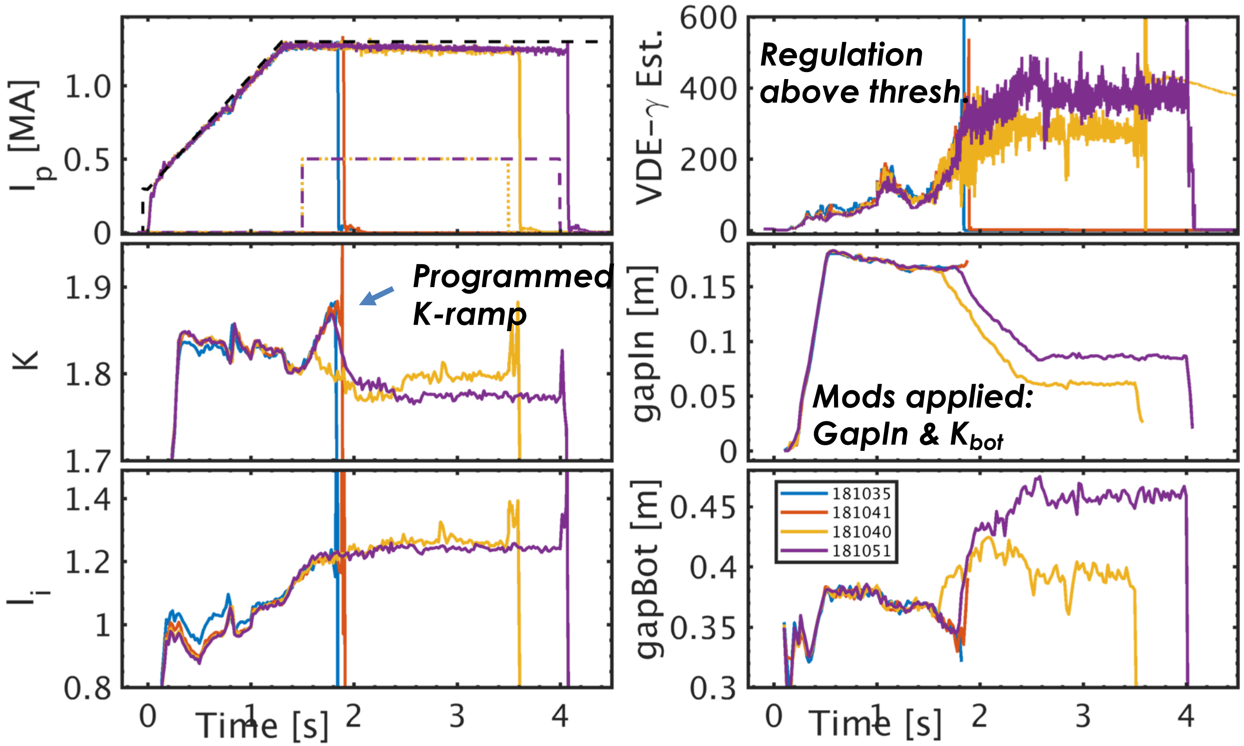
Proximity controller applied for robust VDE prevention using novel NN-based VDE-γ estimator for shape target feedback

- **Novel NN-based VDE-γ estimator**
- **K ramped to induce VDE**
  - Disrupt @ t=1.9s
  - (red, blue)
- ***With* Proximity Control:**
  - γ held at safe levels
  - Controlled via gapIn, *K*



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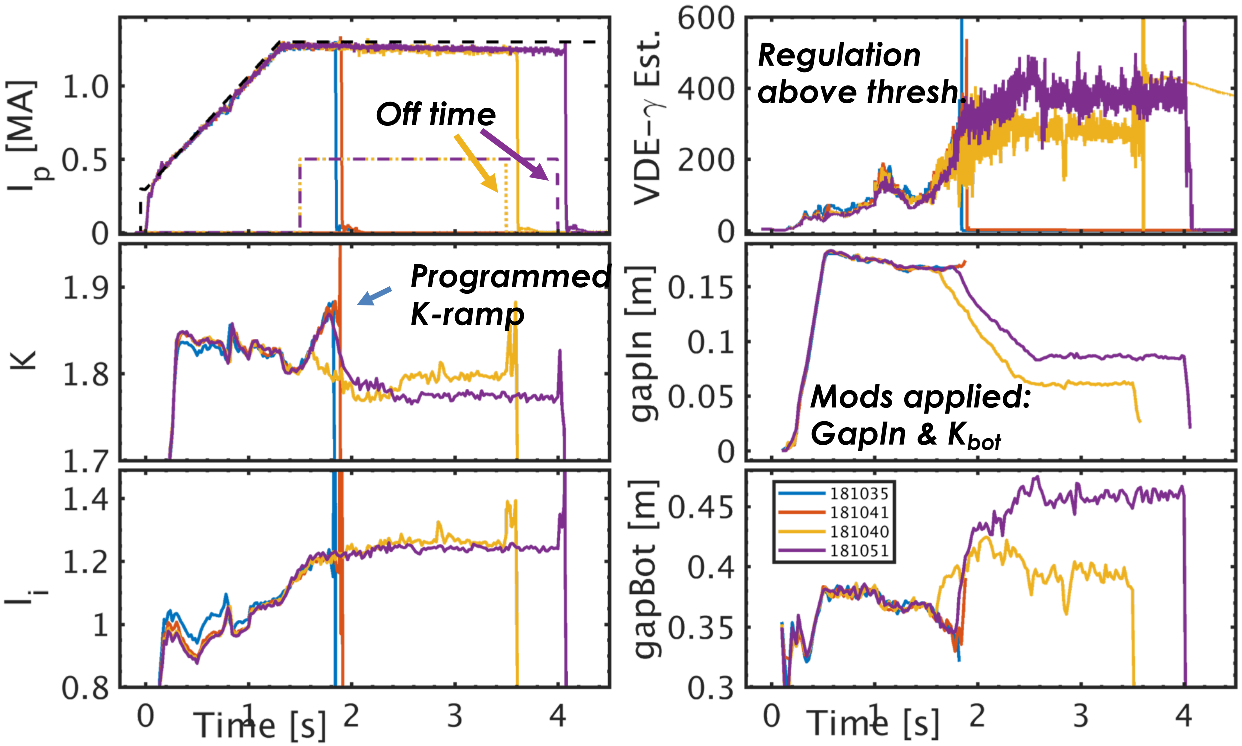
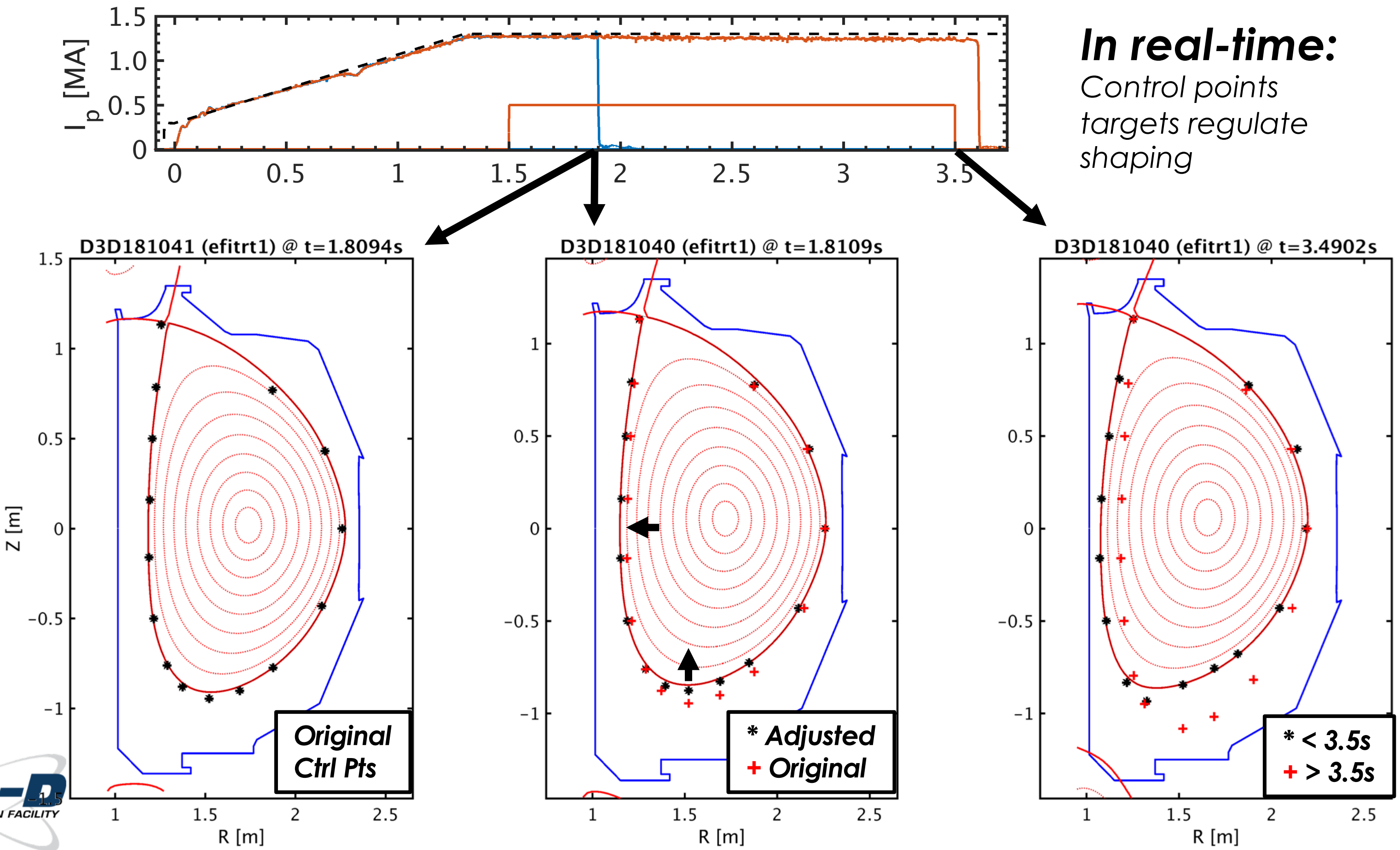
- **VDEs prevented until proximity controller *disabled***



Shaping targets adjusted in real-time to ensure stability



In real-time:

Control points targets regulate shaping

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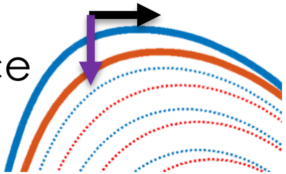
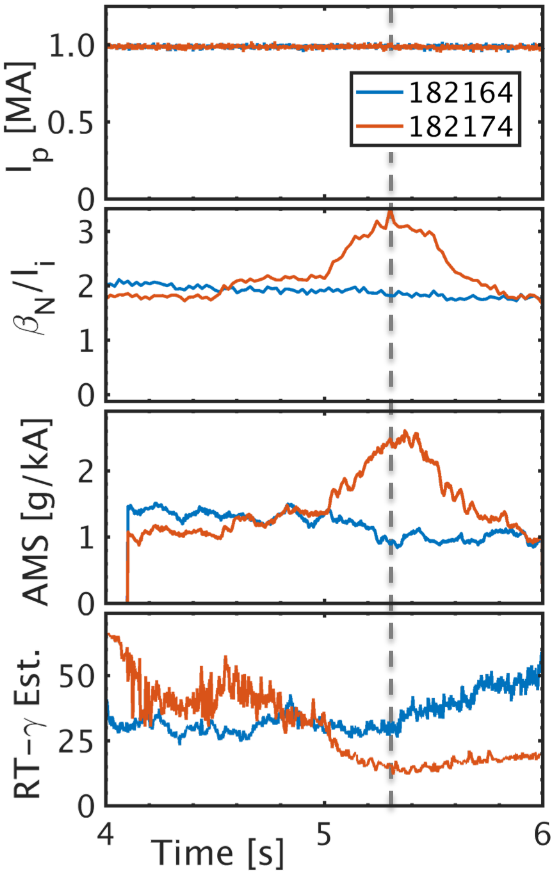
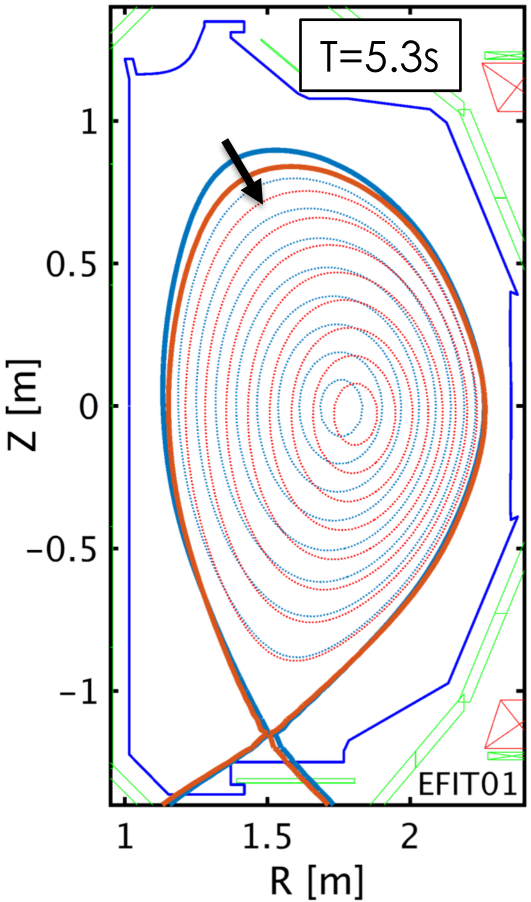
Multiple stability metrics are controlled in parallel, demonstrated with Active MHD Spectroscopy

- **Active MHD Spectroscopy (AMS) newly incorporated**
  - ***1st test:*** added NBI to increase β_N/l_i → amplify plasma response
  - Controller to reduce triangularity w/AMS
  - ***Future:*** attempt TM onset prevention?
- **Proximity Controller applied VDE protection in ||**
  - ***AMS:*** reduce top triangularity
  - ***VDE-γ:*** reduce elongation







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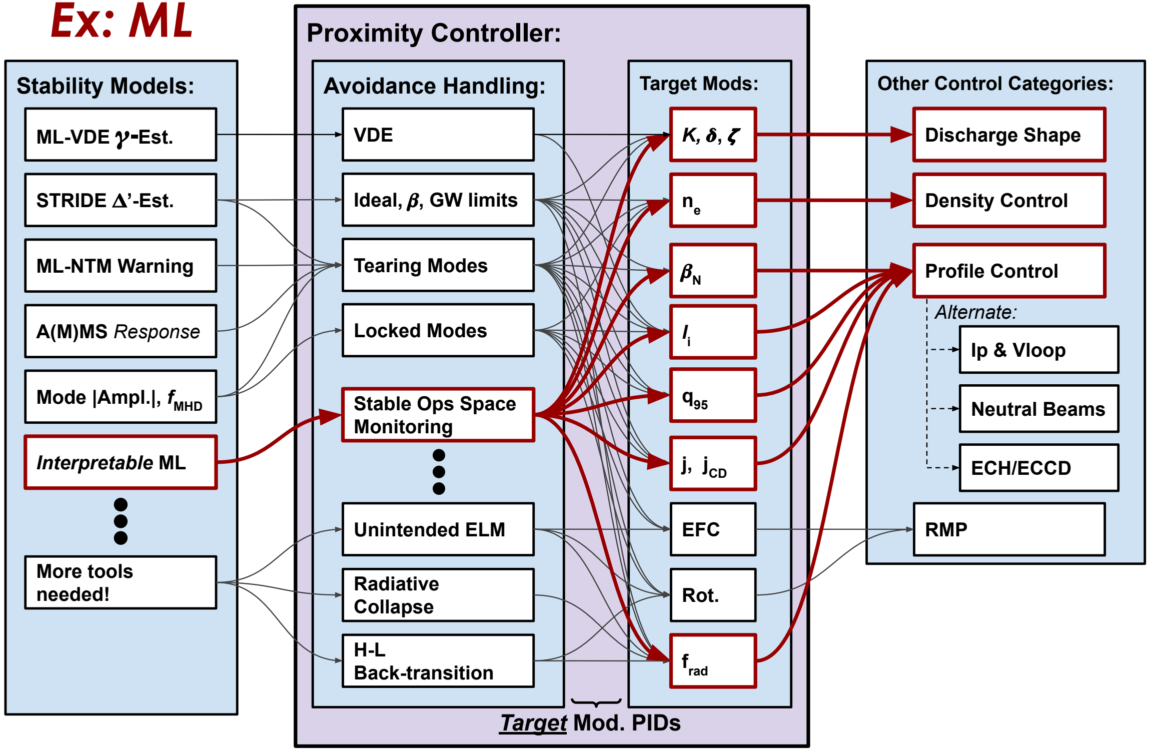
Interpretable ML currently being integrated into proximity controller for experiments in 2020

- **Control paradigm with interpretable ML:**
  - Monitoring prox. to edge of stable operating space
- **DPRF: Disruption Prevention via Random Forests**

  C. Rea Nucl. Fusion 2019
- **Contr. factors (f_c) should map to controllable params**
- **Responses scaled by:**
  - ***Overall risk*** (& *thresholds!*)
  - ***Contribution***-specific factor
- ***Direction (sign) of response:***
  - Just mod unstable targets? *Reinforce stable ones too?*

Ex: ML



Example:

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

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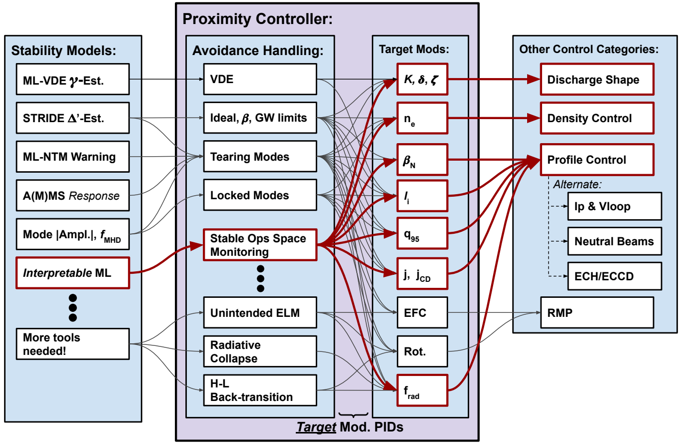

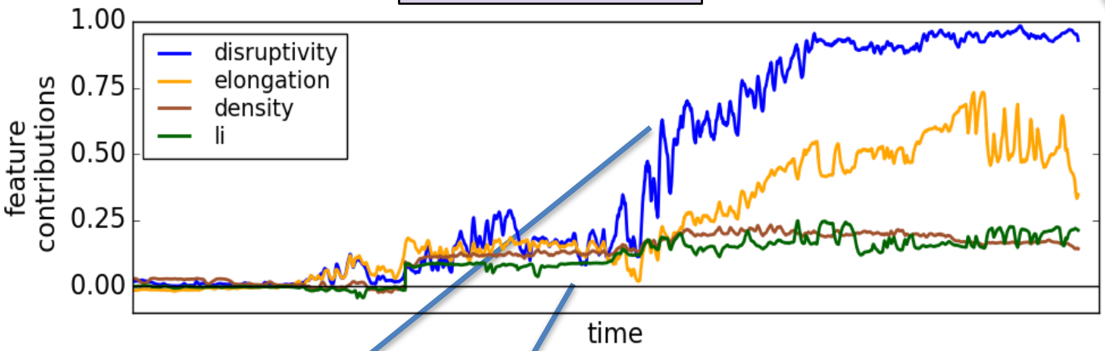

User Setting

Example:

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

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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 on EAST in recent experiments**
  - Variations in shaping and li to scan γ, RT estimated
- **Robust control at γ ~550 /s for >= 2s**
  - RT-γ accuracy confirmed with triggered VDEs: < 20% err.
- **Future experiments:**
  - Assess of max dZ displacements tolerable
  - Scaling with noise, ELMs
  - Porting prox. Ctrl. to EAST

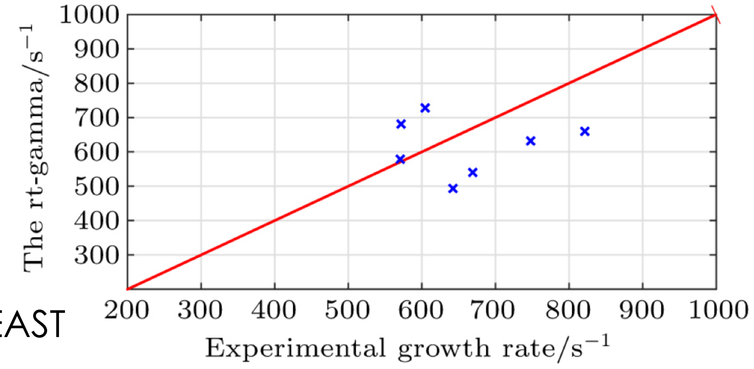
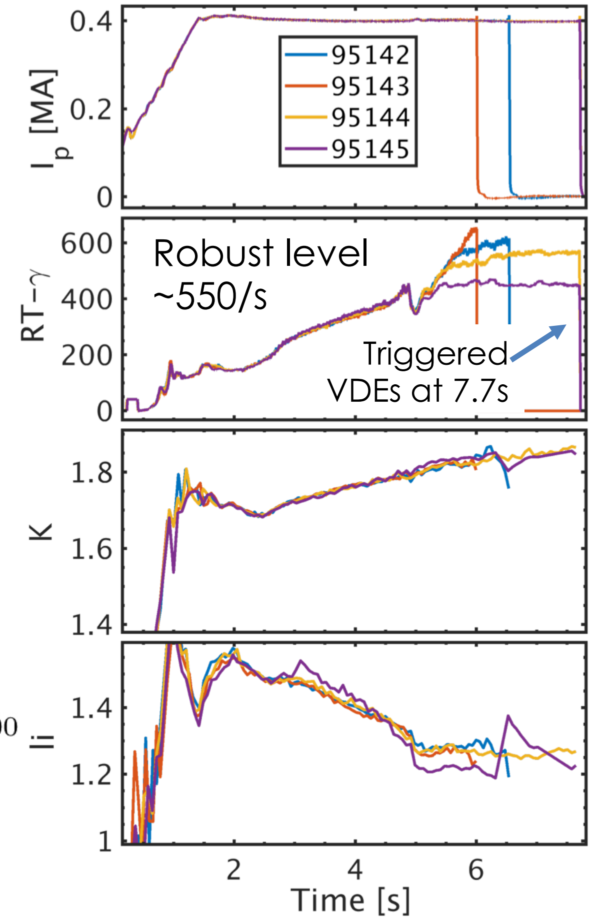


Fig 5: N.-N. Bao *et al* 2020 *Chinese Phys. B* **29** 065204



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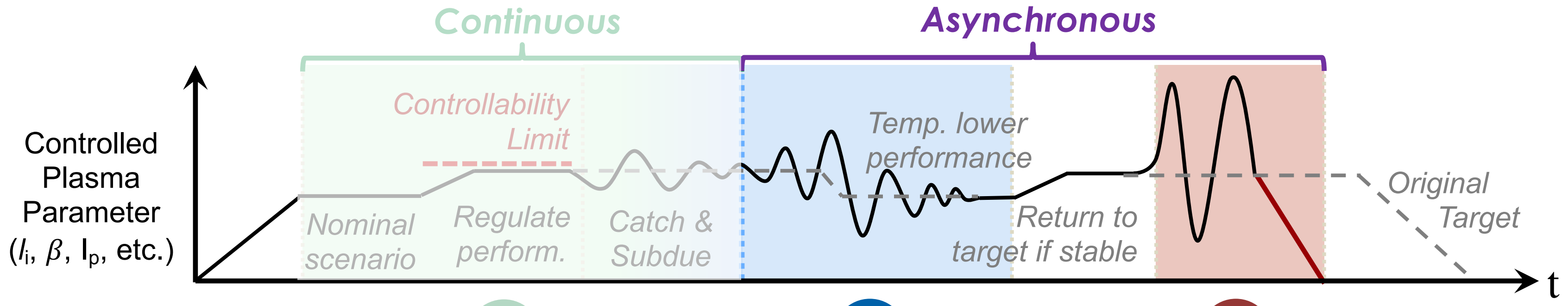
ASIPP

Comprehensive disruption prevention must cover the full range of control regimes



Control Regimes: 1 → 2 → 3

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- ***Should ... preven... disrupt...***

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Off Normal & Fault Response

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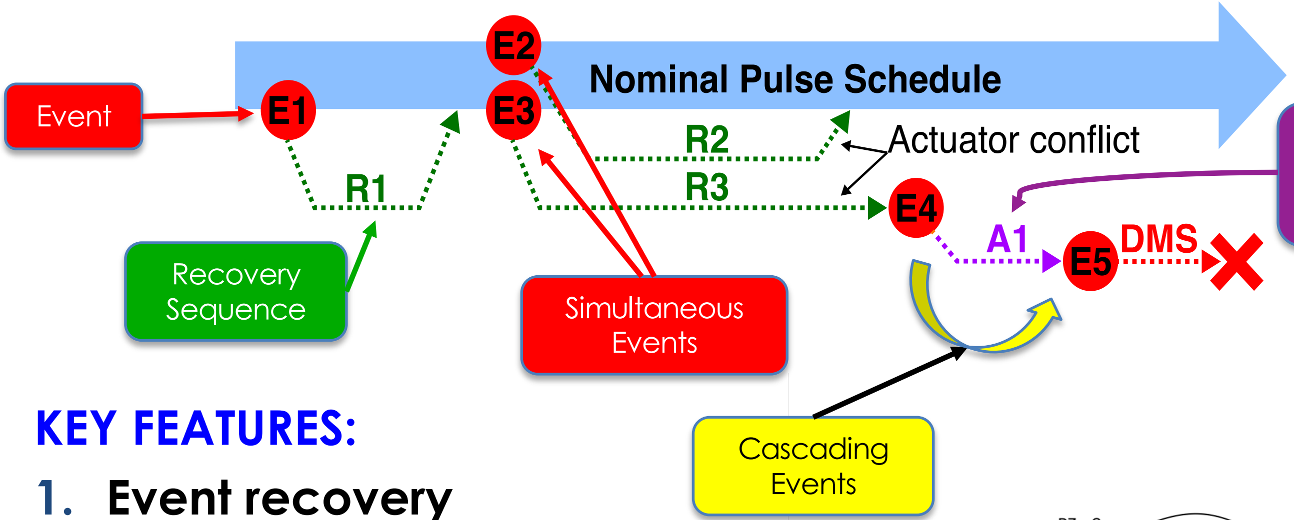
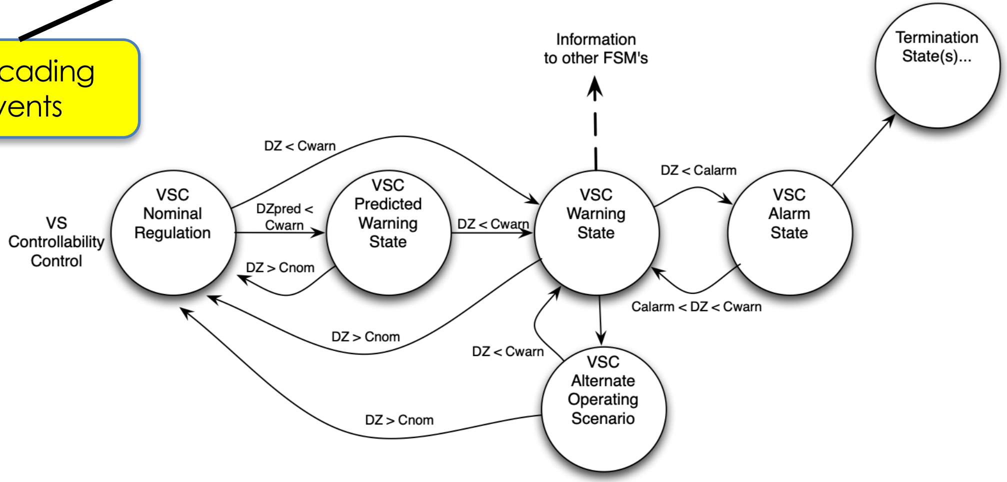
DIII-D Off Normal & Fault Response Algorithm: a State-Machine for Asynchronous Disruption and Device Protection



KEY FEATURES:

1. Event recovery
2. Simultaneous events
3. Actuator prioritization
4. Sequential responses to cascading events



N.W. Eidietis 2018 *Nucl. Fusion*

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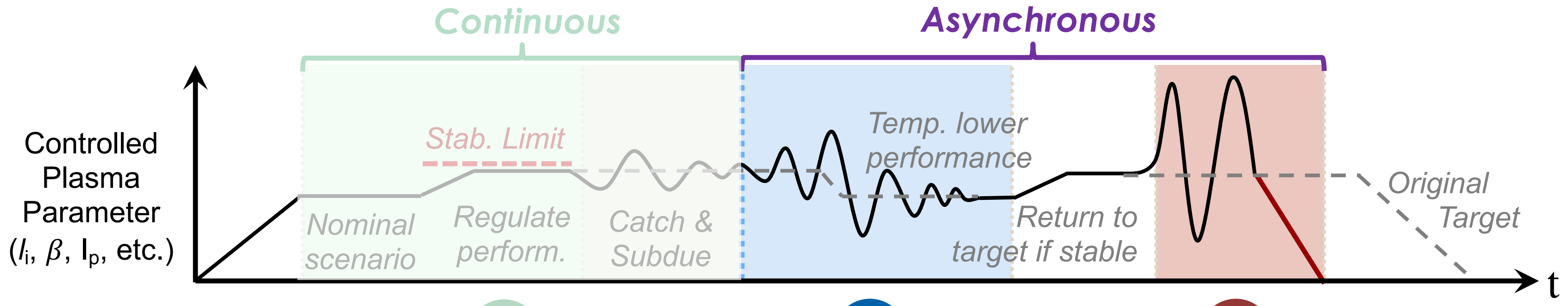

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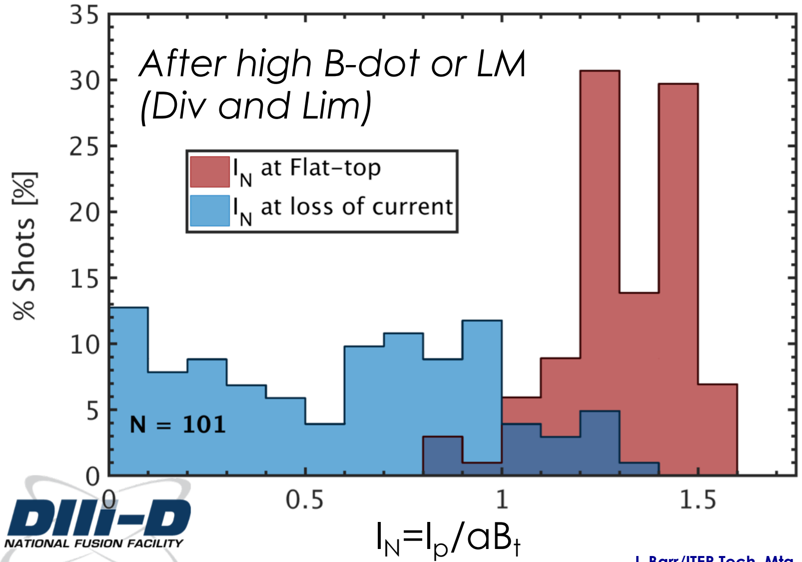
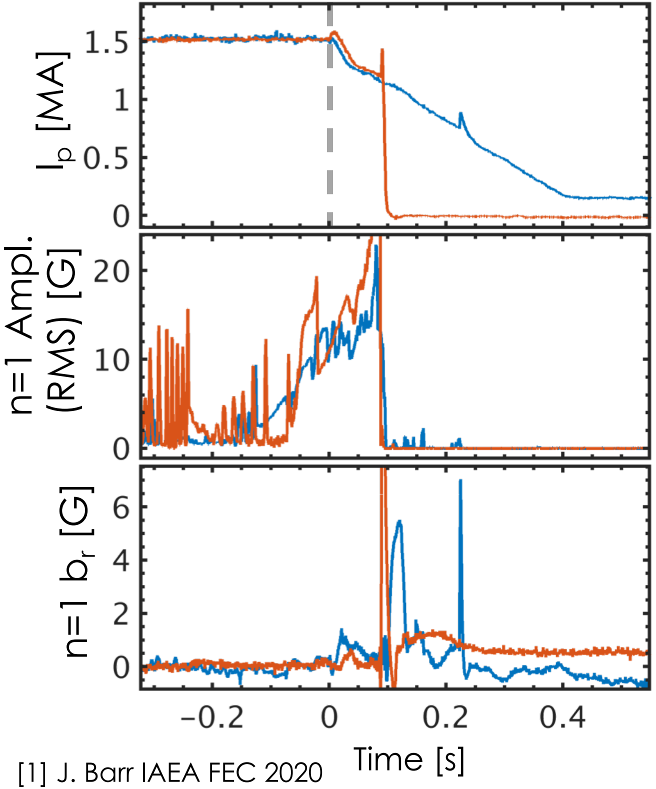
Qualifying fast, emergency shutdown after large n=1 tearing, locked modes for effectiveness on DIII-D

- **Focused application to *Emergency Shutdowns (SN)***
  - After detect large n=1 tearing, locked mode
- **Applied shutdown survey recipe[1]:**
  - $\mathrm{dI_p/dt} \sim 2\text{–}3\ \mathrm{MA/s}$, 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. Barr IAEA FEC 2020

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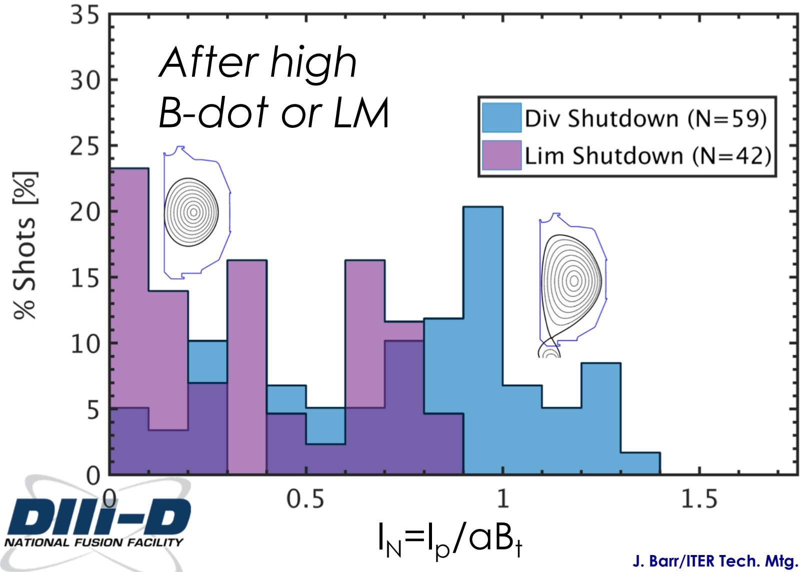

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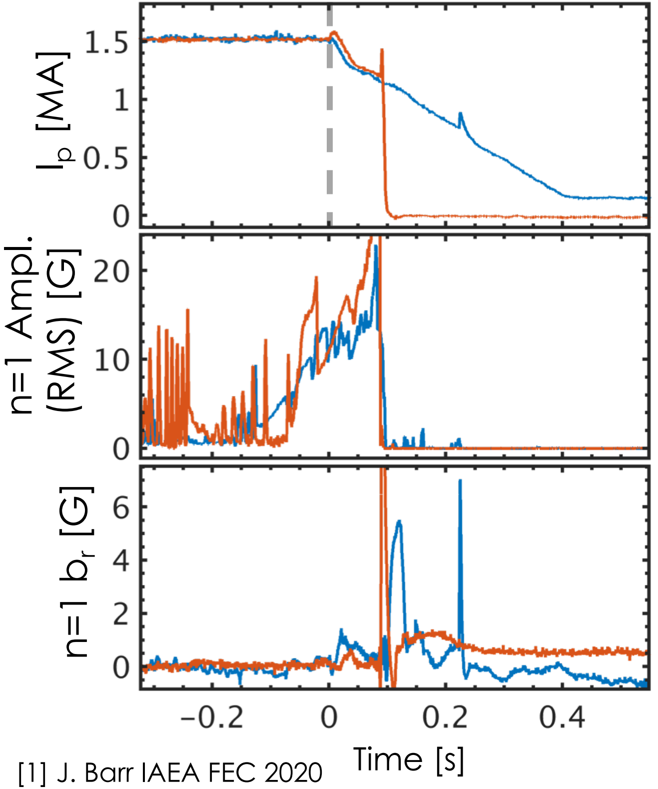

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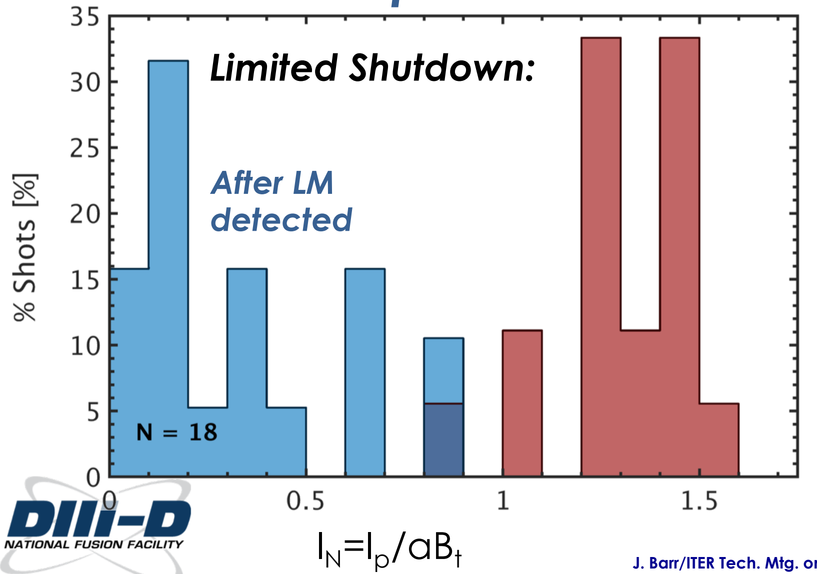
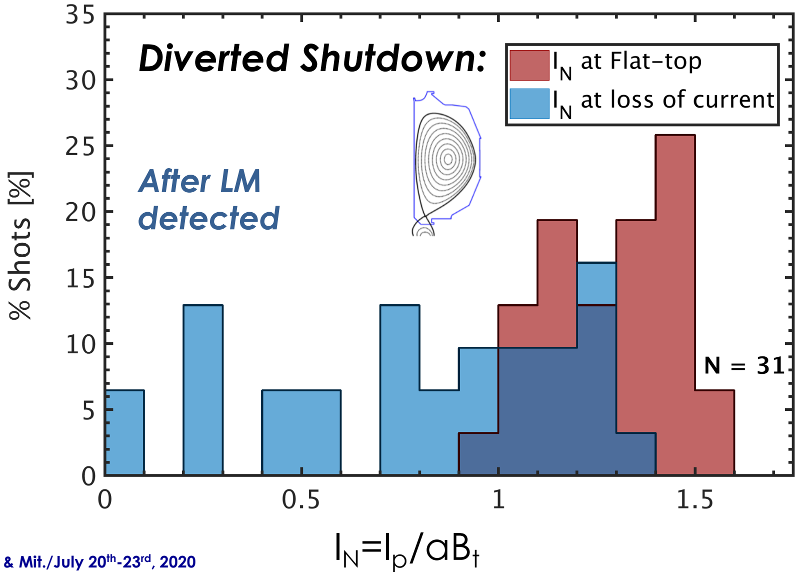
[1] J. Barr IAEA FEC 2020

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

- **After LM is detected, shape modification immediately applied:**
  - **Continuing diverted *(SN)*:** 19% reach $I_N < 0.3$ (ITER req.), 26% $I_N<0.5$
  - **Transitioning to limited (*from SN*):** 53% reach $I_N < 0.3$ (ITER req.), 74% $I_N< 0.5$
- **Despite common use and improvements, ITER *must achieve better***
  - *Synergy with multiple prevention tools likely required: ECH, RMP spin-up strategies (many)*

Focus on LM disruptions:



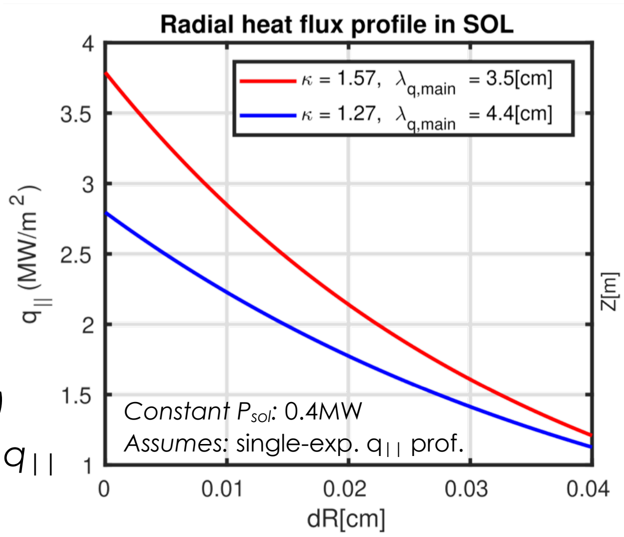


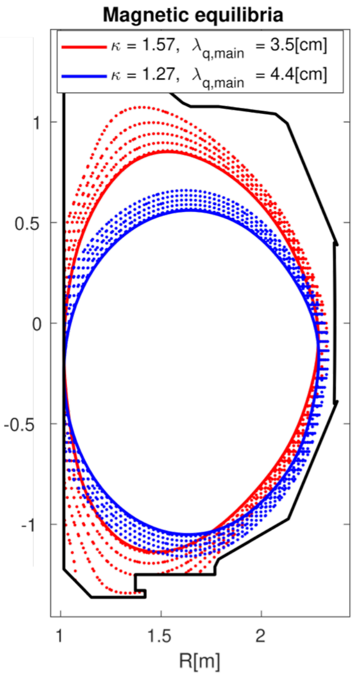
Methods for heat flux control during limited shutdown under investigation, including shape modification

- **Tile heat-fluxes limit the acceptable I_p, W_{mhd}, … when plasma can limit**
  - Current ITER plan: stay diverted when Ip > 3 MA
  - Emergency lim. shutdown is a common tool, advantage of reduced disruptivity
- **Dropping elongation while limited can reduce heat-flux on inner wall:**
  - Reducing K increases λ_q *(Horacek[1]):*

$$\lambda_q = 10\ \left({}^{P_{SOL}}/_{V}\right)^{-0.38}\ \left({}^{a}/_{R_0\kappa}\right)^{1.3}$$

  - Can reduce heat flux (incl. touch-pt)
  - SMITER[2,3] modeling: lim. discharge w/K change for 1st investigation *(H. Anand)*
    - *Const. P_{sol}=0.4MW, assumes single-exp $q_{||}$*
- **Shutdown (already) requires κ drop for VDE stability (l_i rising)**
- **Further improvement with impurity fueling[3]?**





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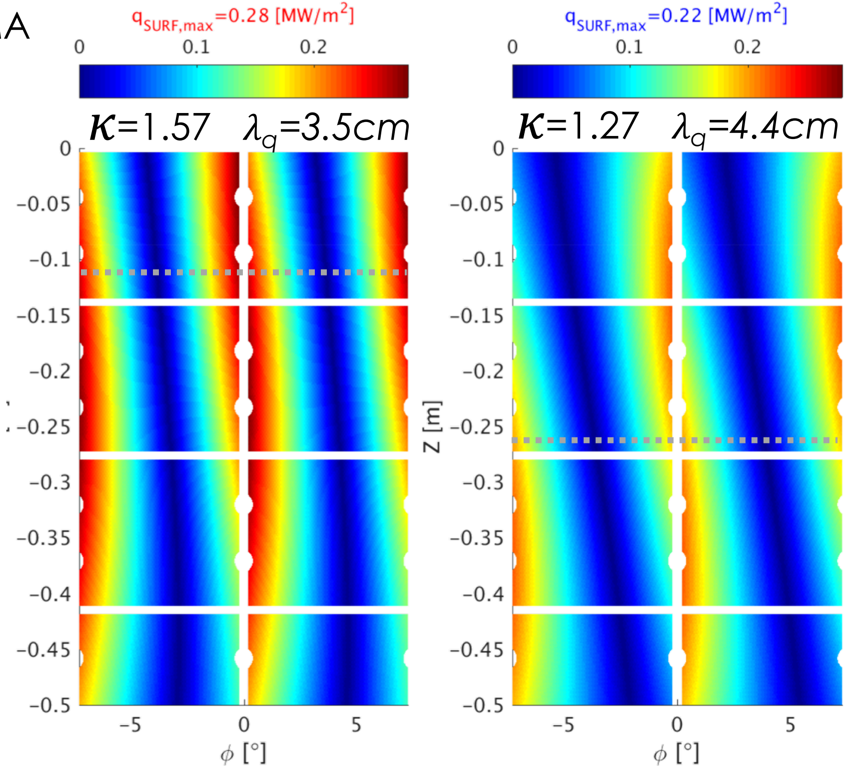

*All pictured area is wetted (no shadowing)

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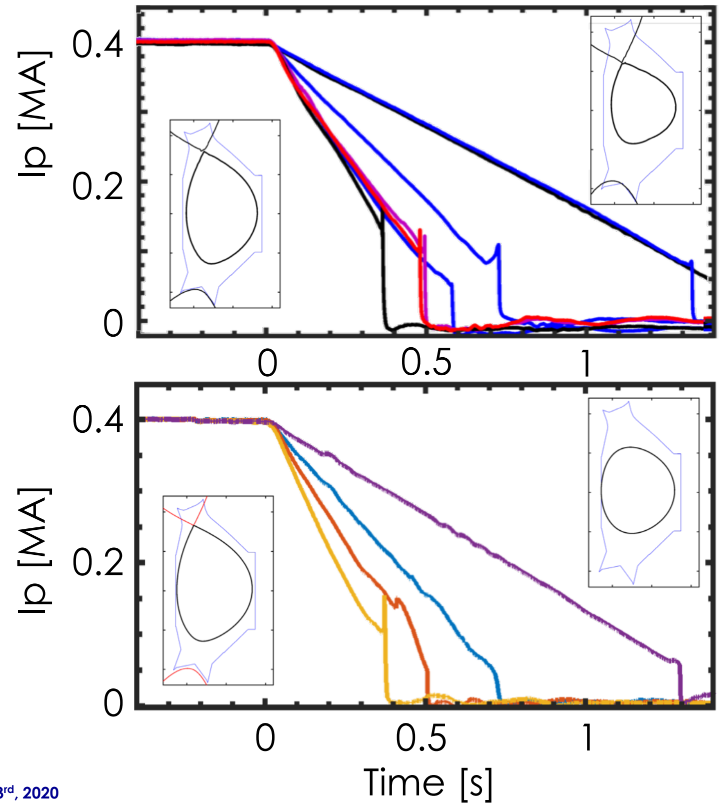
EAST record-fast shutdown developed for general and emergency use

- **Fast, diverted & limited shutdown scenarios developed for EAST**
- **Started from DIII-D shutdown study recipe: *faster dI_p/dt, sustained P_{LH}***
- **New limited scenario developed**
  - Feed-forward currents always a challenge with long-pulse
  - → Importance of RT-FF or MPCs
- **0.7 MA/s achieved safely:**
  - Scales to 0.1 MA/s speeds on ITER

Safe shutdown up to 0.7 MA/s on EAST



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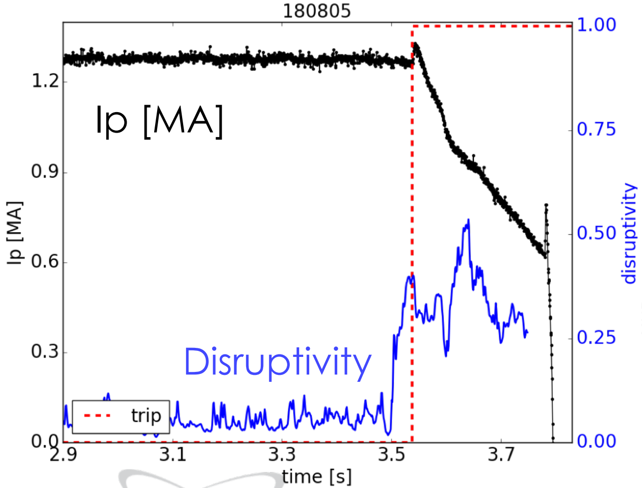
ASIPP

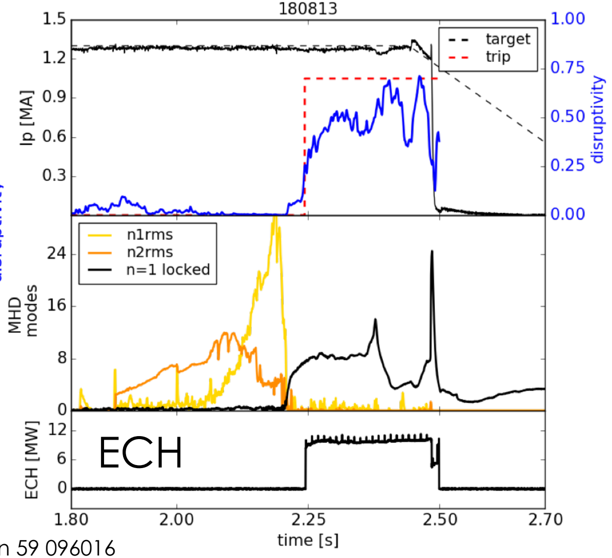
Machine Learning integrated with DIII-D Fault Response control for real-time trigger for disruption prevention

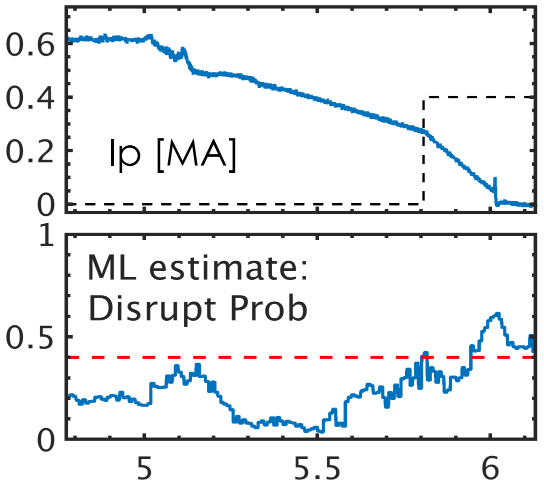
- **A variety of ML disruption predictors are integrated with the DIII-D Off Normal & Fault Response System, and participate in the Disruption Free Protocol**

- **Disruption Prediction via Random Forests (DPRF) interpretable ML (*C. Rea**)**
  - Triggered early (attempted) shutdown, ECH, MGI…
  - Included real-time contribution factors

- **ML disruptivity with decision trees (*Y. Fu**)**
  - Triggered modified (faster) shutdown programming







C. Rea et al 2020 IAEA FEC
C. Rea et al 2019 Nucl. Fusion 59 096016

Y. Fu, et al. Physics of Plasmas **27**, 022501 (2020)

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

- **DIII-D Disruption Free Protocol: qualify disruption prevention tools in time for ITER**
- **Off Normal & Fault Response and Proximity-to-instability controllers designed to prevent disruptions over handle wide range of control regimes**
  - Porting to EAST in progress
- **Novel "Proximity-to-Instability" control architecture implemented for real-time scenario modification to maintain stability, applied for robust VDE prevention**
  - Operates continuous and handles multiple physics problems in parallel
- **The effectiveness of emergency shutdown for disruption prevention is being rigorously quantified on DIII-D and EAST**
  - Changing to a limited shutdown dramatically reduces the disruption risk in emergency shutdowns.
- **DFP 2020 experimental priorities:** *rigorous qualification of…*
  - Wide application of proximity control for: ***tearing, locked mode*** prevention (STRIDE, ML, AMS…
  - Focused qualification (of the many) ***tearing, locked mode*** response techniques