Operating Without Disruptions in ITER and Beyond

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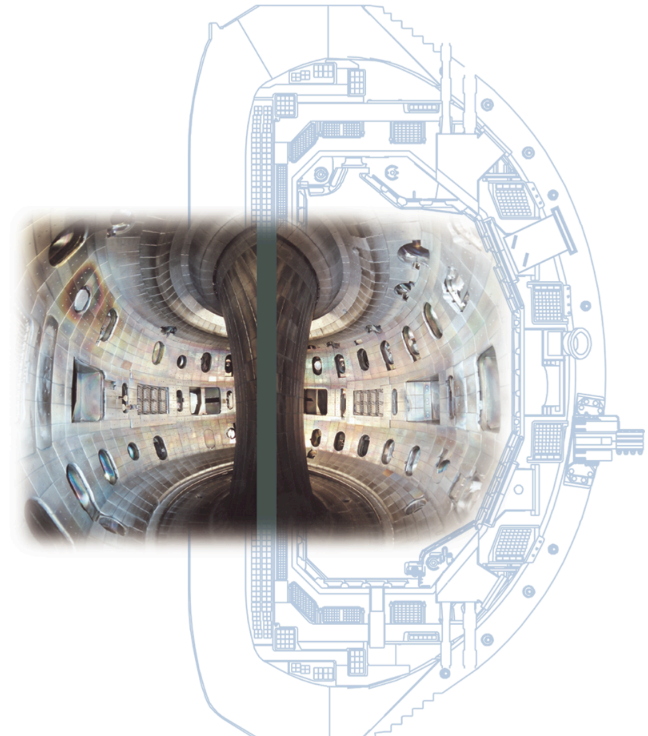
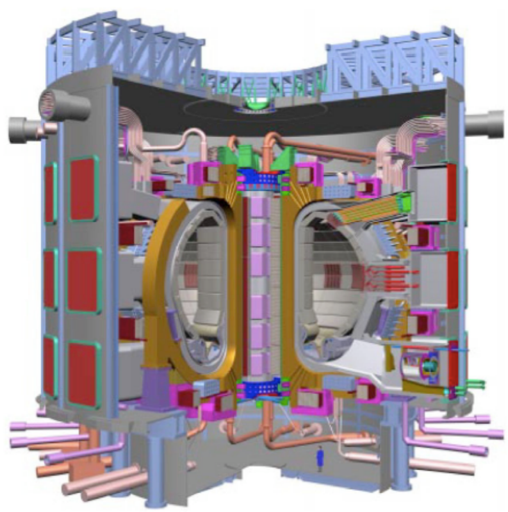




BPO Seminar
17 October 2018

Outline

- Motivation: Disruptions need to be largely prevented in ITER, and ABSOLUTELY prevented in power reactors… Attention to research, design, and optimization for control solutions will maximize effectiveness in preventing disruption

- The keys to disruption prevention: (ITER) PCS & control algorithms

- Control of proximity to controllability boundaries

- Exception Handling

- Forecasting and usefulness metrics for predictors

- Research Implications and Conclusions

Caveats

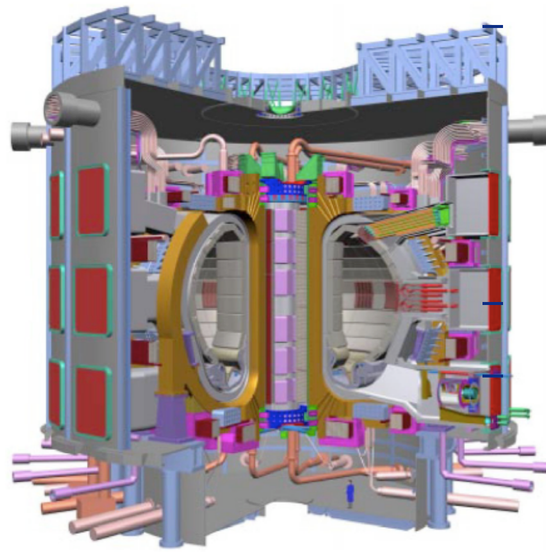
- The following are personal thoughts on ITER, general tokamak control, and prediction of high-risk states, and disruption prevention

- These perspectives and suggestions are not necessarily those of the IO or the ITER PCS design group (but they should be…)

- However, technical figures here have generally been taken from previously-shown and approved presentations from various sources…

Success of ITER Requires Sufficiently Low Disruption Rate

- Mid-pulse disruptions eliminate planned discharge time following disruption, reducing physics productivity



> 80% availability (during operation periods)

Design target:

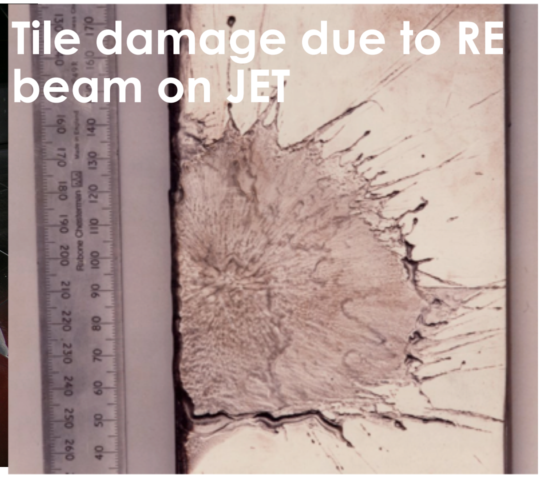
<10% disruptivity

- Disruptions may require long recovery time, reducing overall shot frequency

- Disruption heat fluxes can reduce component lifetime (e.g. divertor target ablation)

- Damage to in-vessel components can require shutdown for repair

Tile broken by disruption forces in DIII-D

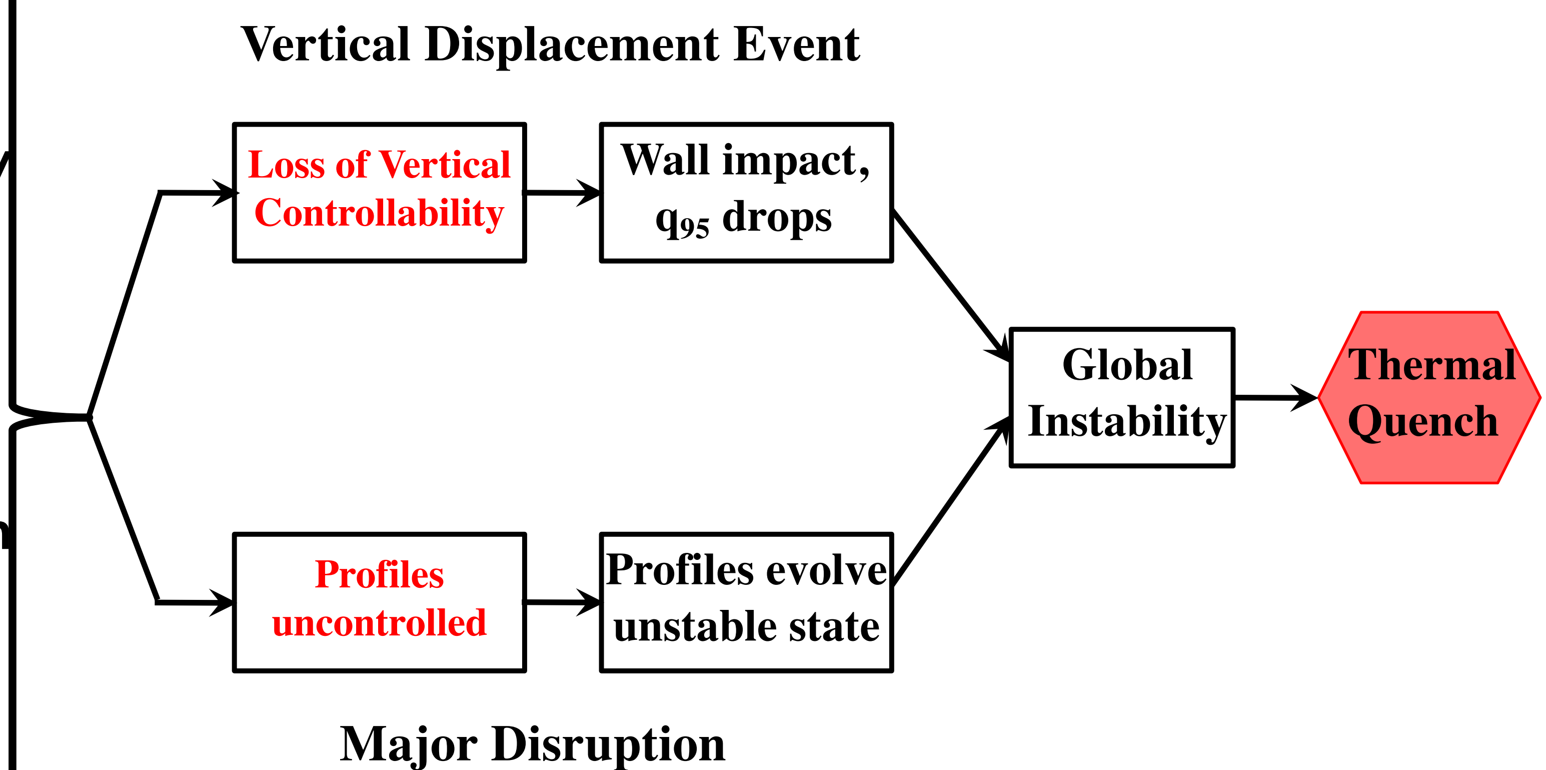


Tile damage due to RE beam on JET

Disruptions Are a Control Problem: Result of Insufficient Controllability of Operating Regime and System Faults

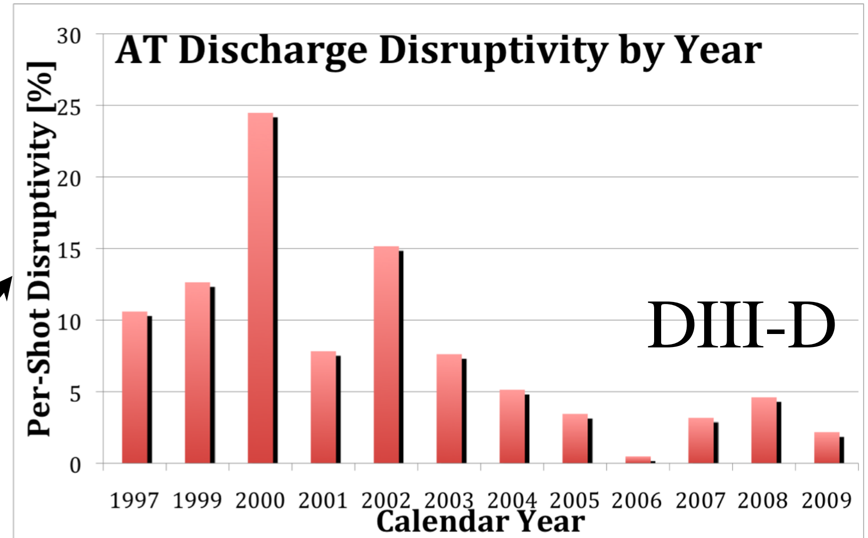
Primary Causes of Control Loss

- Insufficient control capability for operating regime
- Design choice
- Hardware/system failure
- Human error
- Human intention



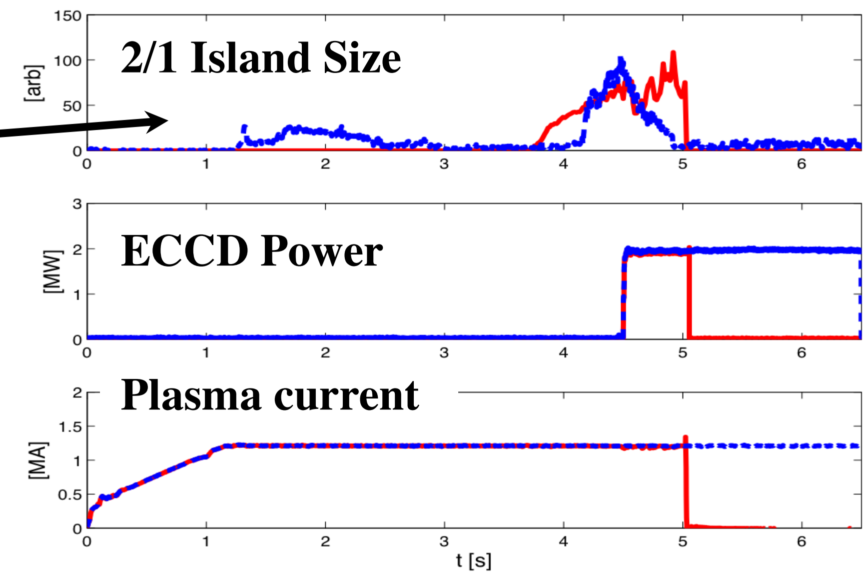
Improved Control Leads to Reduced Disruption Rate

- **JET disruptivity analysis [deVries, 2009]:**
  - "…lower disruption rates [over time]… primarily due to improvement in technical ability to operate JET"



- **DIII-D Steady-State Scenario disruption rate analysis 1997-2009:**
  - Experience, improved control reduces per-shot disruptivity from ~10-15% to <3%

- **ECCD at rational surface controls NTM:**
  - Replaces missing bootstrap current
  - Prevents disruption



- **Improved vertical control prevents VDE:**
  - Routinely robust in operating devices
  - High confidence extrapolation to ITER design

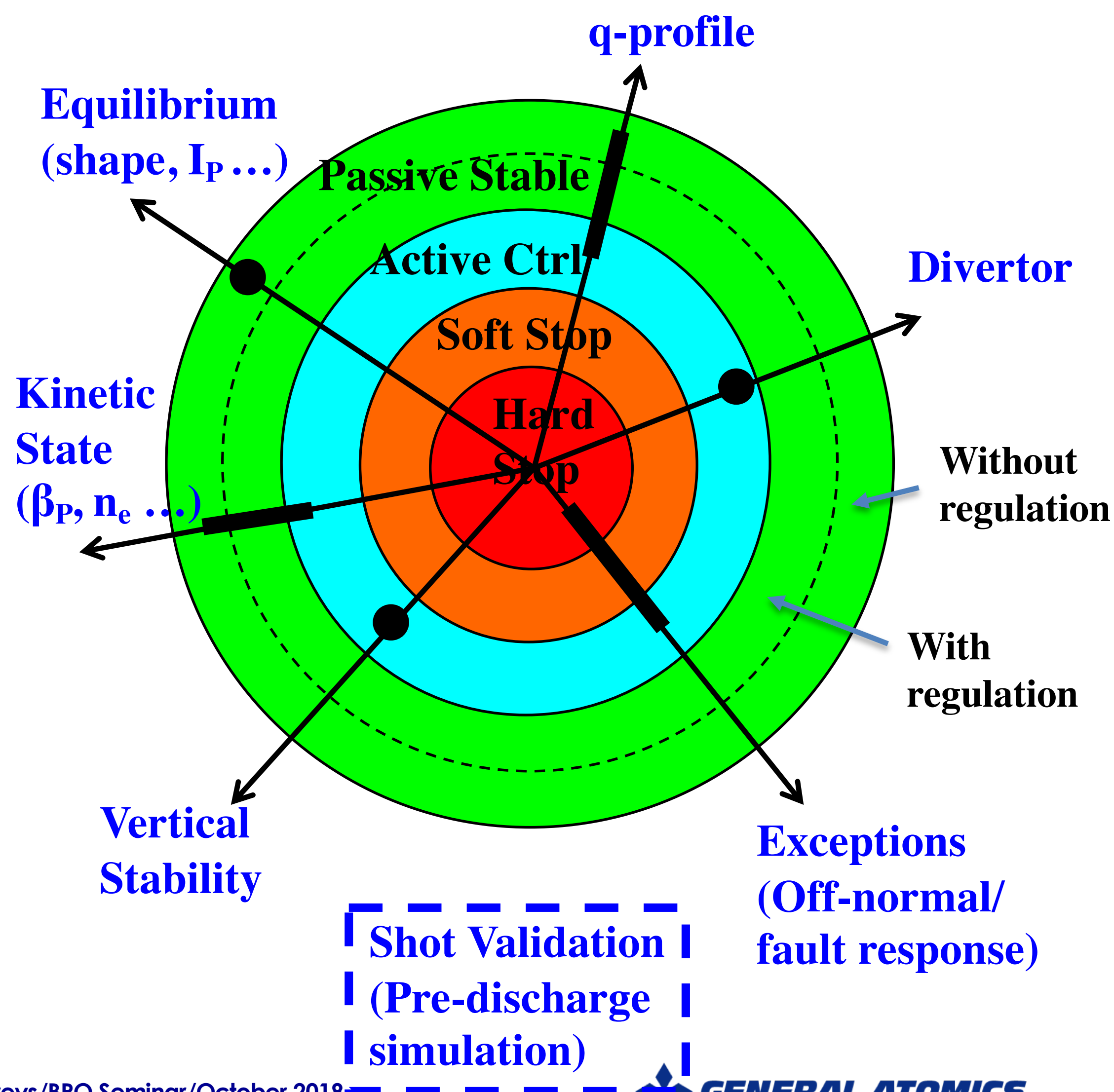
A Complete Control Solution is the Necessary and Sufficient Condition for Disruption-free Operation

- **Control of tokamak plasmas involves many different (somewhat) discrete control goals**

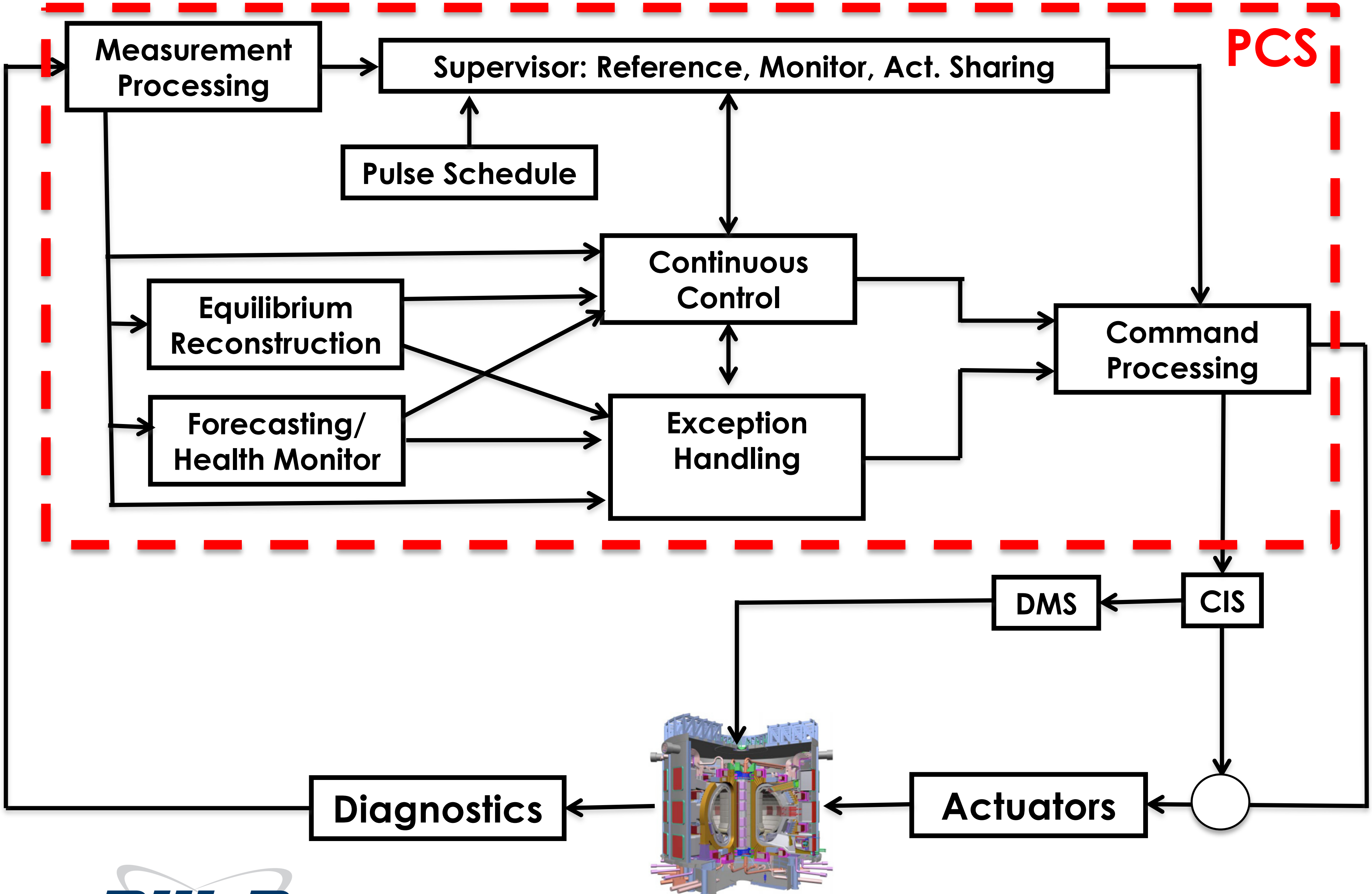
- **Different types of control fall into different Control Operating Regimes:**
  - Open-loop Passive Stable
  - Closed-loop Passive Stable
  - Actively Stabilized
  - Asynchronous Control

- **ITER has formalized approaches to off-normal/fault responses:**
  - Pre-discharge validation
  - Supervisory Monitoring
  - Exception Handling

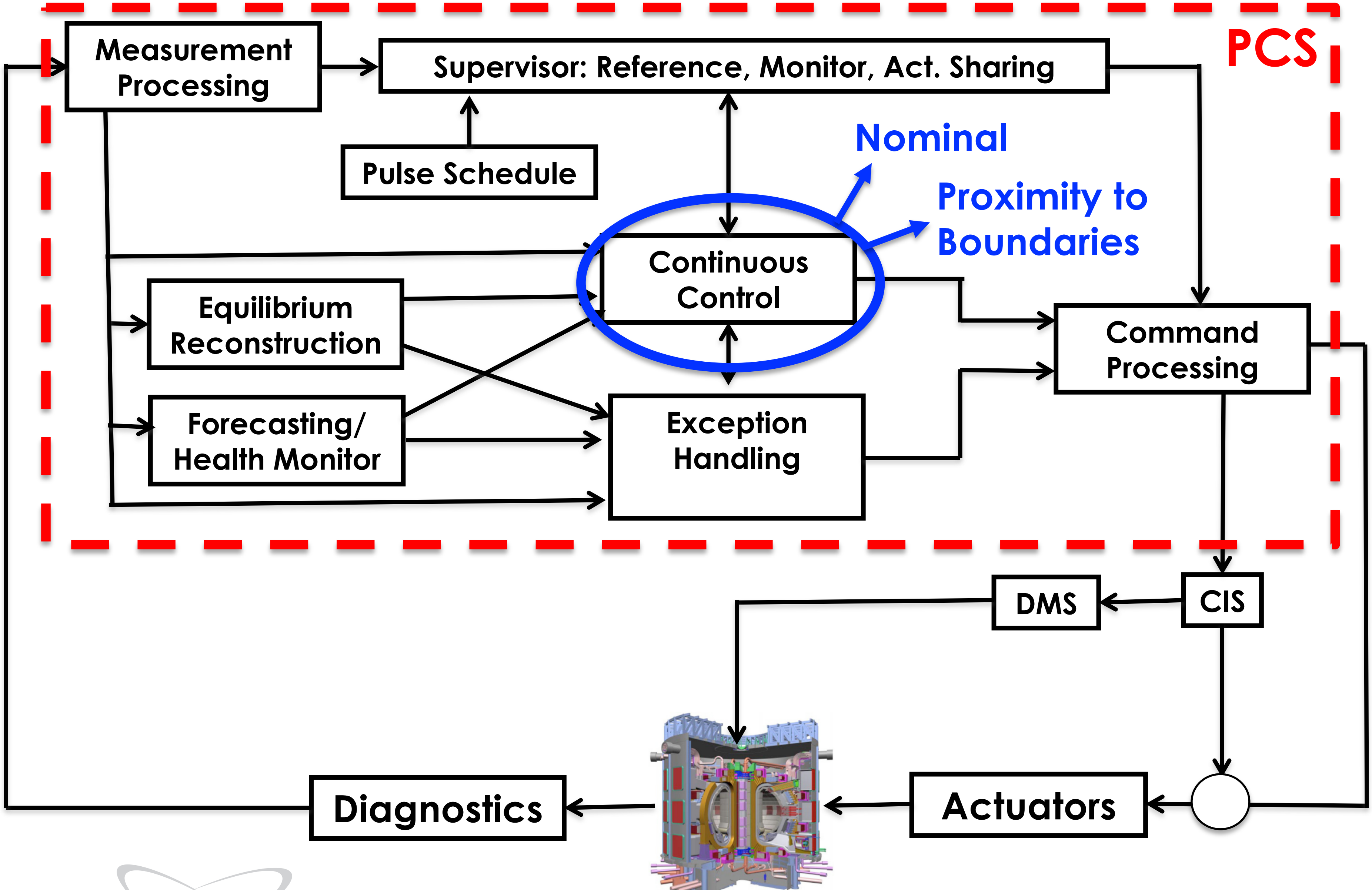
Control Operating Regime Map



ITER Plasma Control System Elements Address Requirements of Performance, Robustness, Low Disruptivity

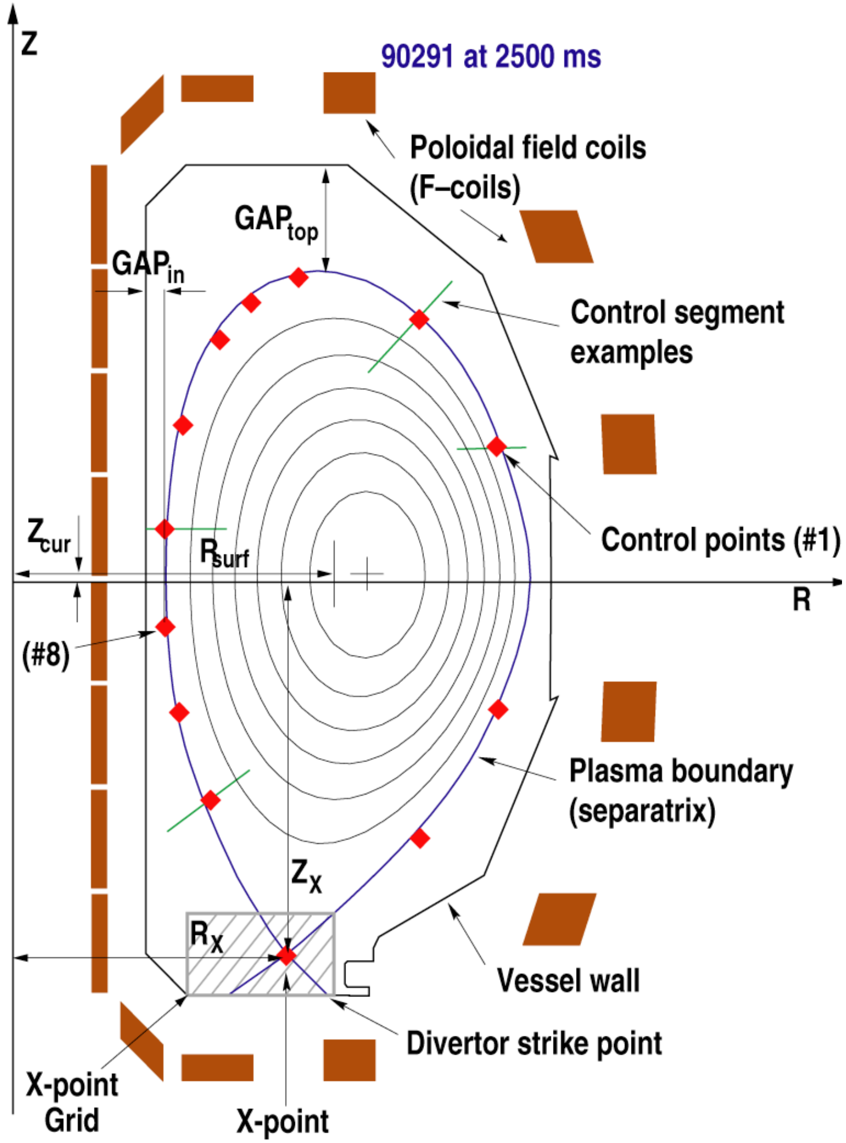


Focus on Role of Continuous Control in ITER Disruption Prevention…



Nominal Continuous Control Acts (Continuously) to Produce the Desired Scenario Robustly

- **Equilibrium/Boundary Control**
- **Vertical stabilization**
- **Divertor detachment**
- **Profile control**
- **Tearing mode stabilization**
- **Generally, continuous algorithms are designed to be robust to expected noise/disturbances/ uncertainties without changing gains…**



Most Continuous Control Algorithms Will Have Two Parallel Functions: Nominal and Controllability Proximity Regulation

Use these controls…

- Equilibrium/Boundary Control
- Vertical stabilization

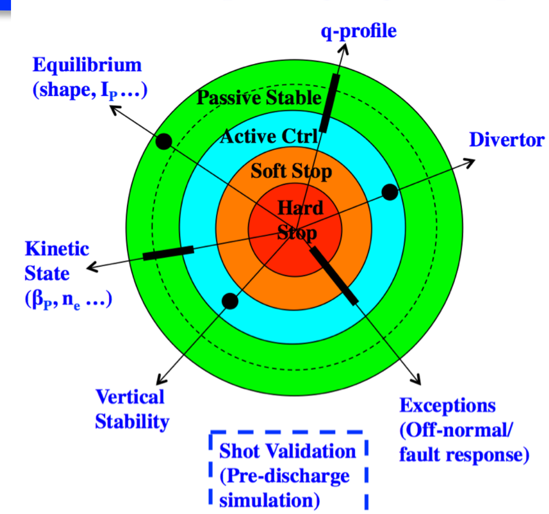
- Divertor detachment

- Profile control
- Tearing mode stabilization

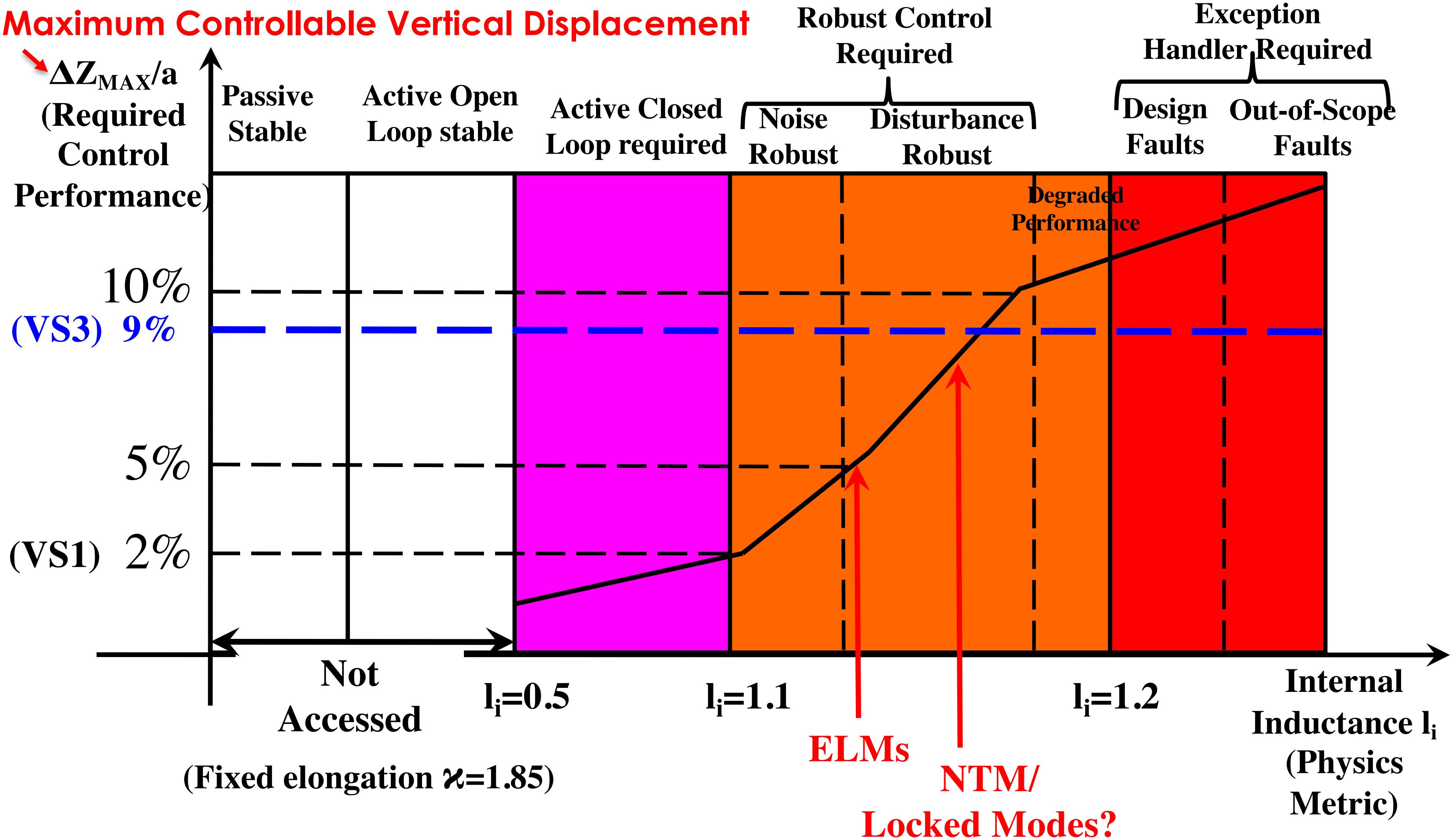
…to regulate this (different control goal):

- Proximity to vertical controllability boundary
- Proximity to MARFE/radiative collapse boundary
- Proximity to Tearing mode boundary

Control Operating Regime Map



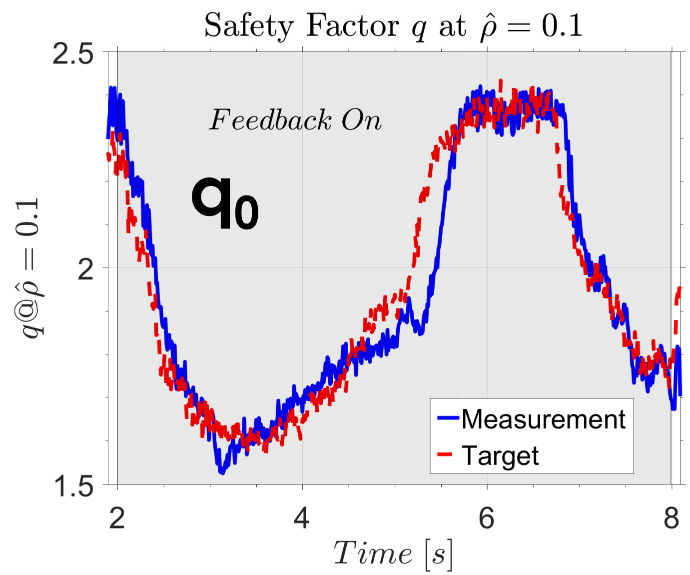
Control Operating Space for ΔZ_{MAX} Performance in ITER Shows VS3 Coils Provide Robustness to Disturbances

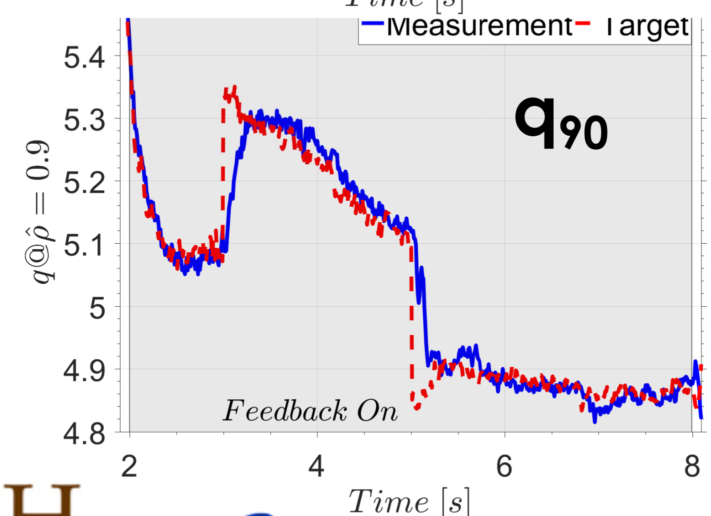


Active Profile Control Can Achieve Accurate, Reproducible Targets to Sustain Desired Scenarios

- **Model-based profile controllers used routinely on DIII-D:**
  - Lehigh model-based q-profile controller
  - NBI, ECH/ECCD, ne, Ip as actuators
  - Optimized access to target profiles early in discharge, accurate reproducibility
  - Focus in DIII-D has been steady state high performance plasmas

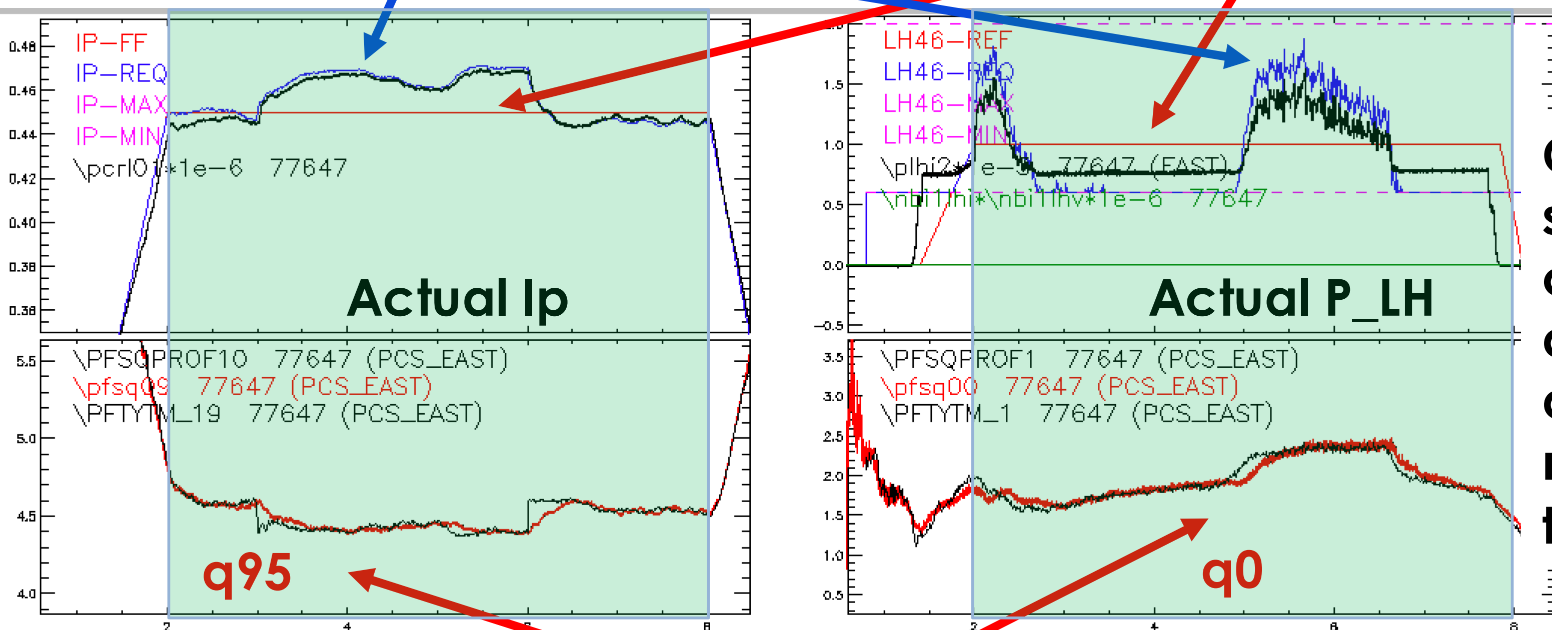
- **First q-profile closed-loop control in EAST 2018:**
  - Model-based q-profile control design follows same process as DIII-D designs
  - LH, NBI, Ip as actuators
  - Successful target tracking and disturbance rejection demonstrated





q-Profile Control Demonstrated by Reproducing Previous Shot Trajectories Through Feedback

FF+FB Control **FF-only Control**



Control produces same actuator commands when driven only by algorithm to match q-profile trajectory

Feedback ON Feedback ON

Both q0 and q95 are Tracked by FF+FB Control (Actual (red) vs Target (black))

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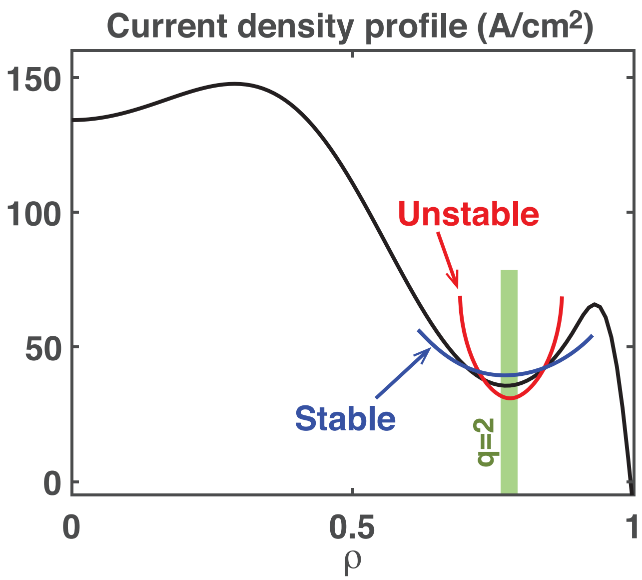
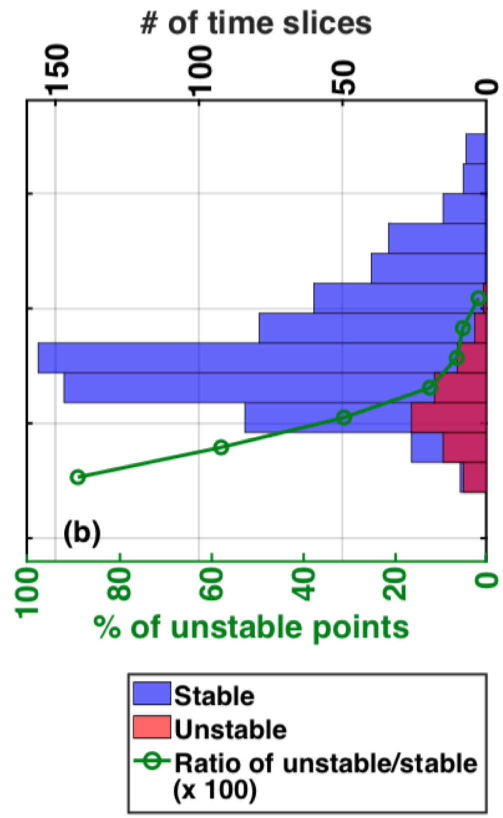
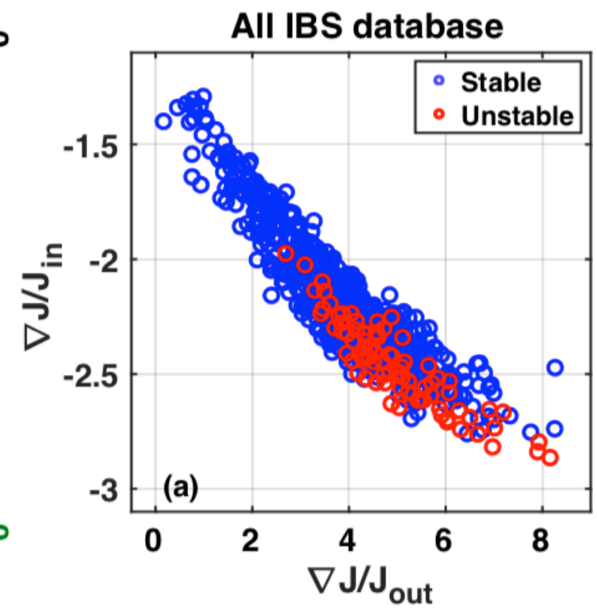
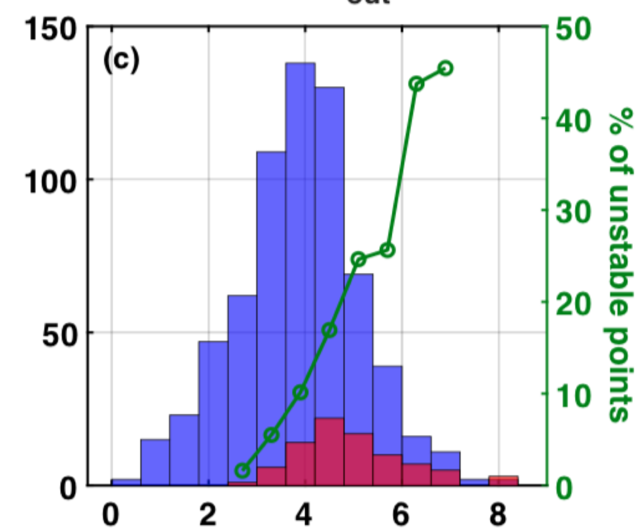
Progress Made in Identifying Profile Metrics for Tearing Stability May Enable Disruption-Free IBS

- **Unstable points have steeper "current well" around the q=2 surface**









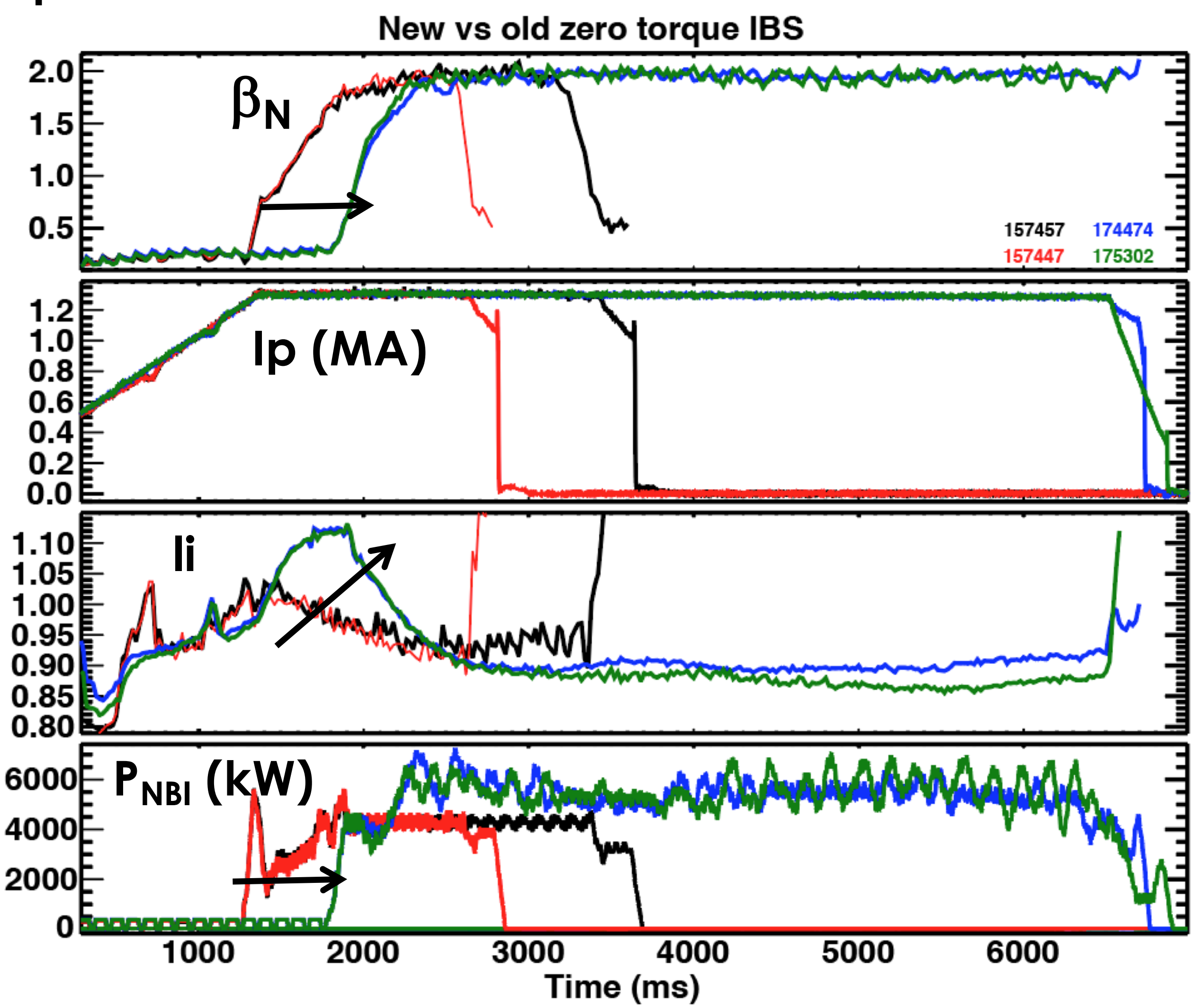
- **∇J at q=2 is ~0 → not usual intuition from cylindrical theory**

- **Regulation of key profile characteristic(s) may provide margin from TM disruptivity: disruption prevention…**

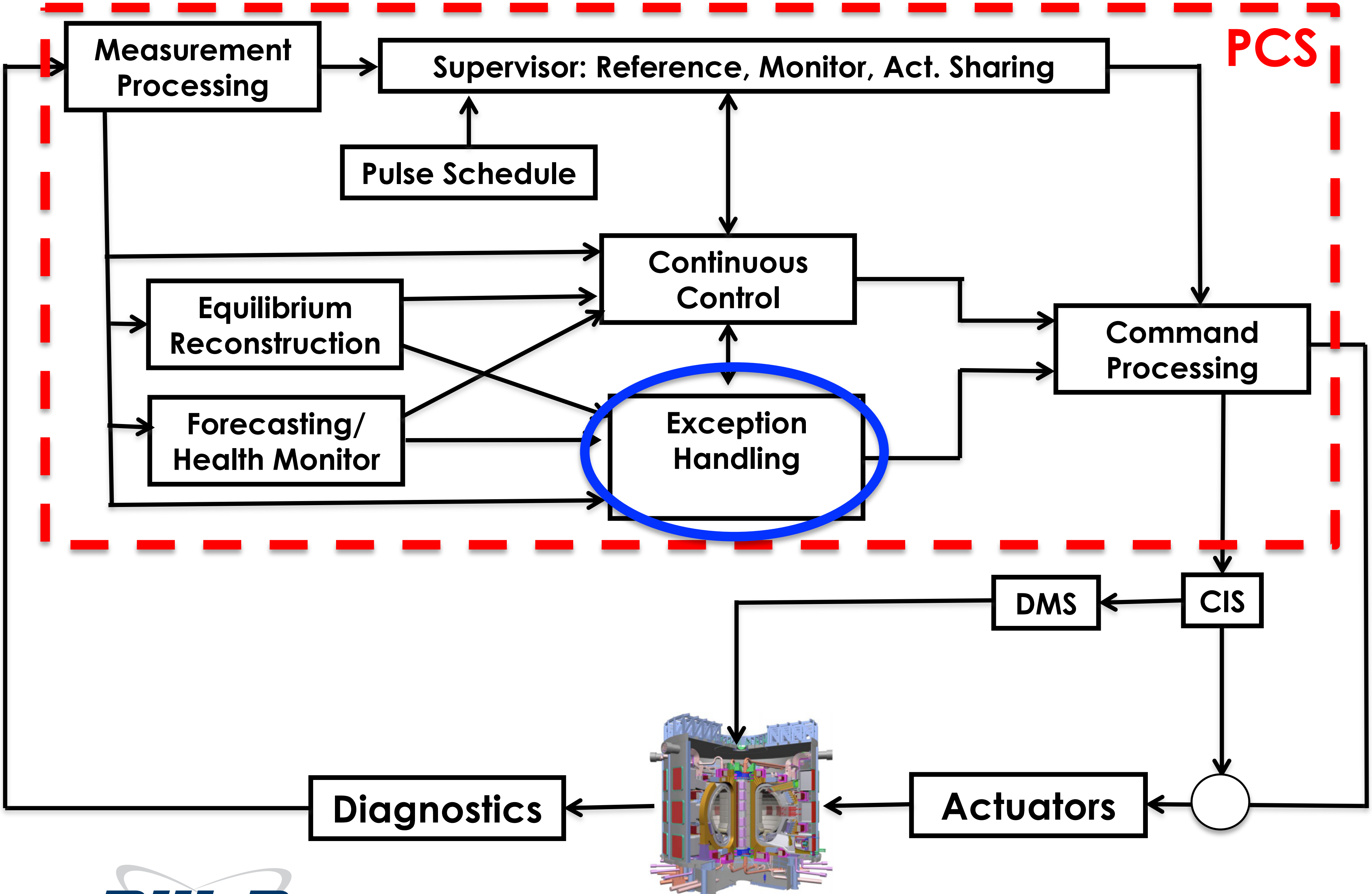
Database study indicates that the early current evolution is crucial for stability → created new β_N ramp up recipe

Applied to design the 2017 experiments:

- Delay heating power by ~400 ms
- H-mode transition <u>after</u> Ip flattops
- li increases then flattops
- J has time to diffuse to the core



Focus Now on Asynchronous Control = Exception Handling in ITER…

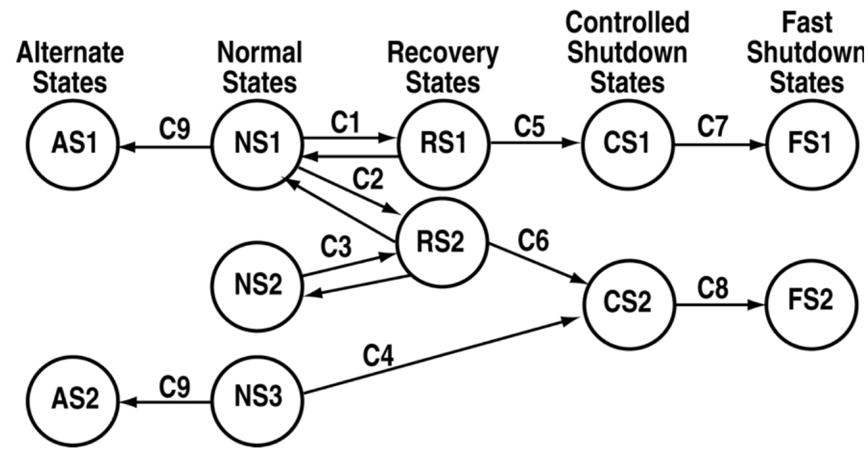


Accomplishment of ITER Control Requires a Sophisticated Exception Handling System

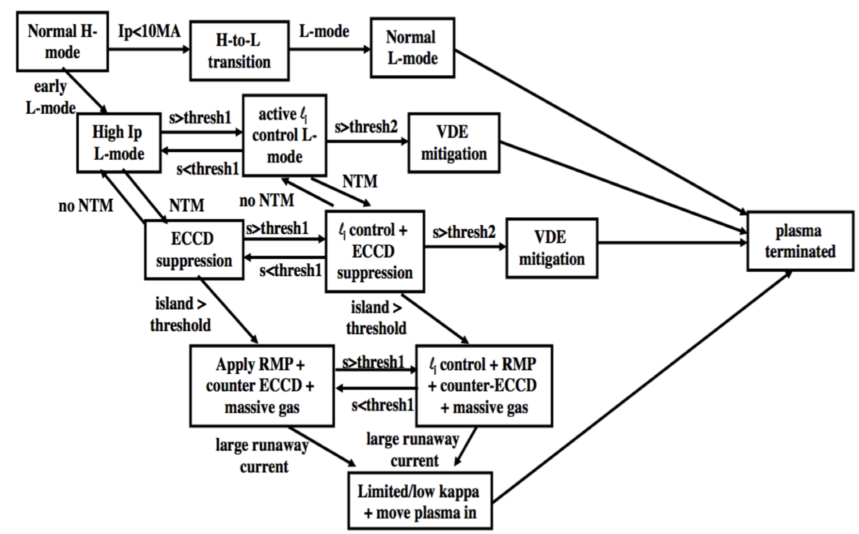
- **Exceptions:**
  - Off-normal event requiring a change in control
  - Prediction by forecasting system
  - Direct detection of exception

- **Exception handling policy includes:**
  - Relevant plasma/system context (e.g. stored energy, saturation state of actuators)
  - Specific signals to be predicted or detected
  - Control modification response to exception: command waveforms, algorithm characteristics…

Exception Handling Will Use a Finite State Machine Architecture

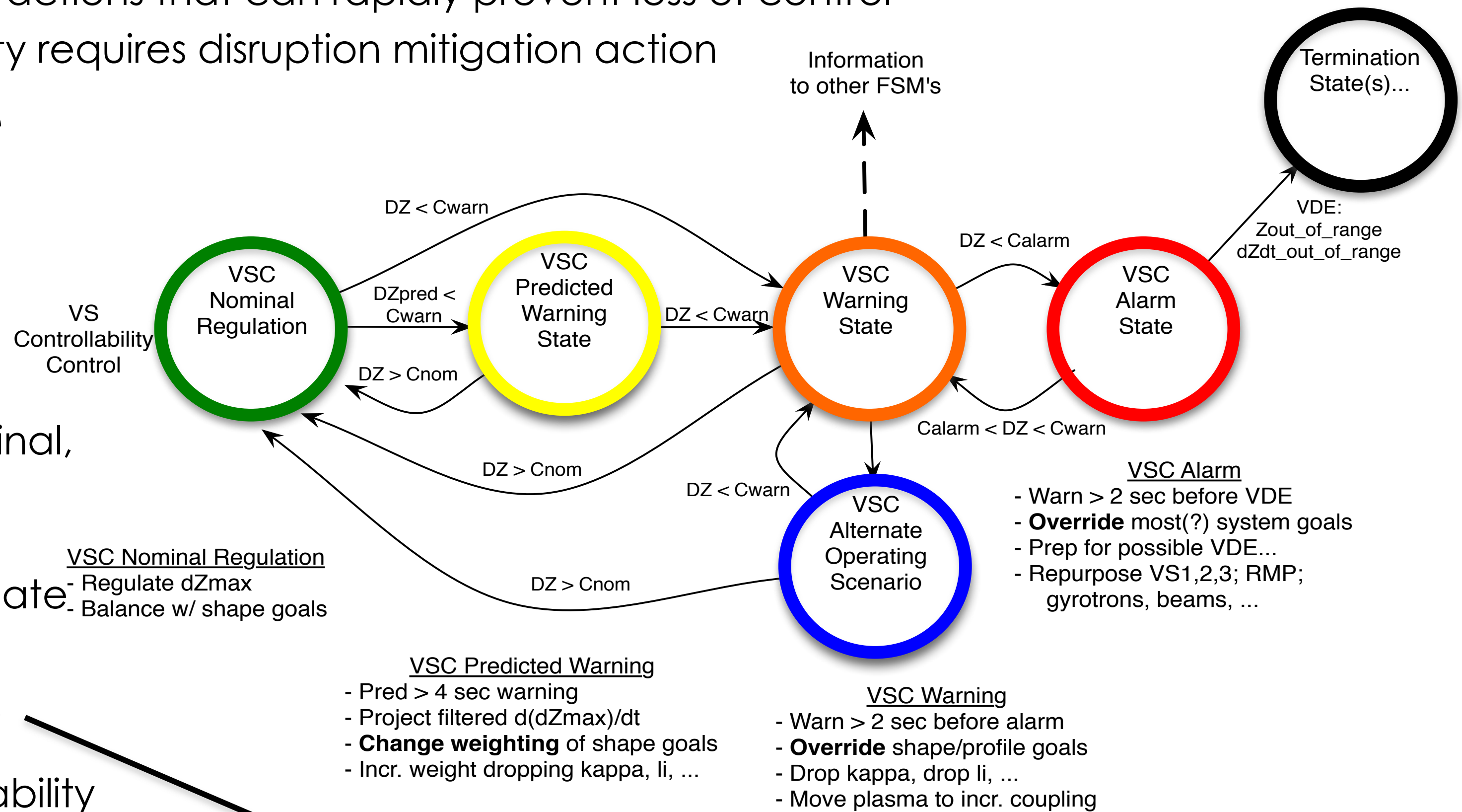


Research is Required to Prevent Explosion in Complexity



Vertical Controllability Exception Handling Exemplifies Broad Class of Finite State Machine Approaches

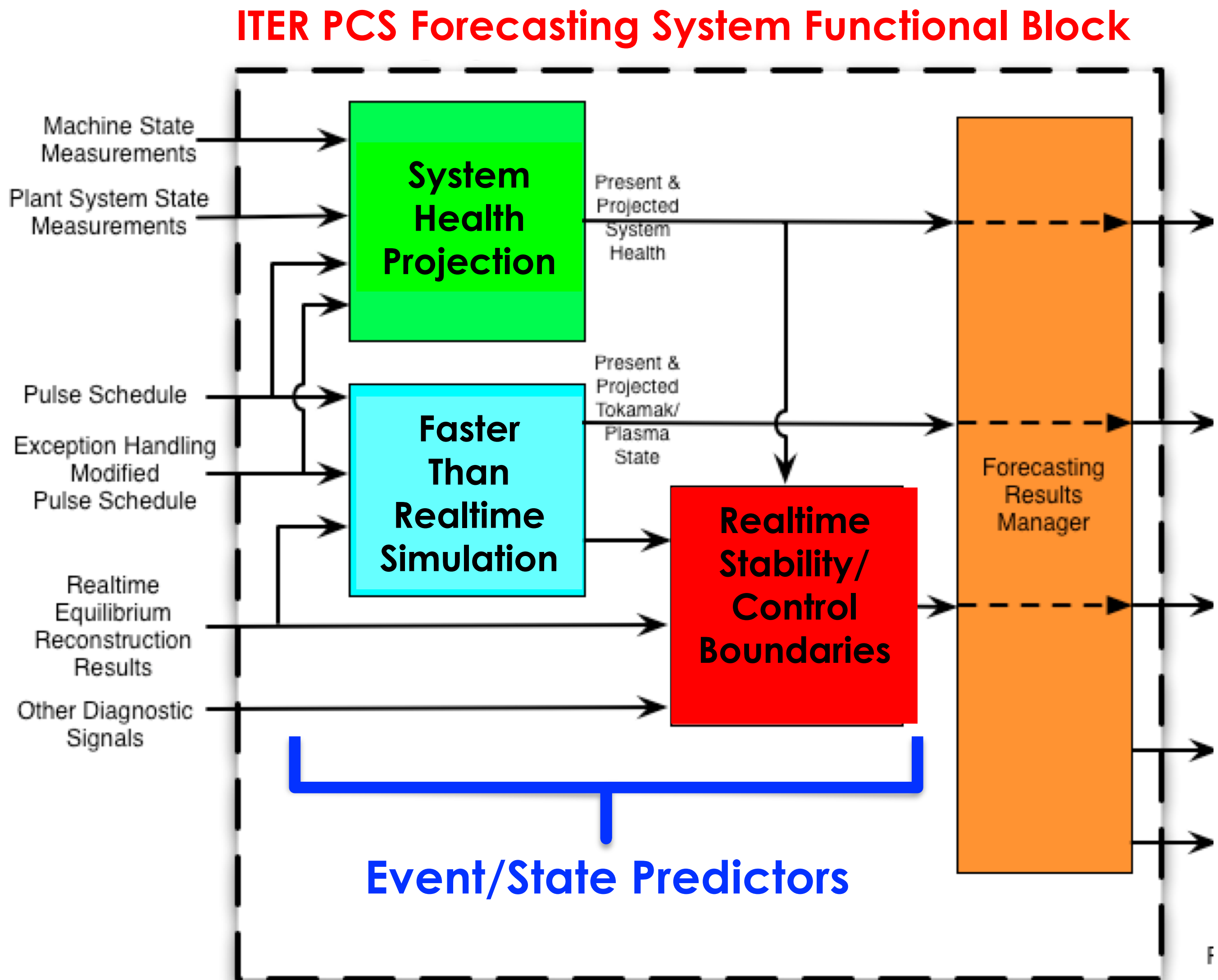
- **Vertical control exception aspects common to many instabilities:**
  - Accurate metric to quantify proximity to boundary
  - Equilibrium, profile actions that can rapidly prevent loss of control
  - Growth of instability requires disruption mitigation action
- **Finite State Machine Exception Handling architecture:**
  - Enables tracking gradual loss of controllability
  - Responses to nominal, warning, alarm, or termination states
  - Recovery or alternate scenario actions
  - Stability margin m_S proxy for more accurate controllability metrics



$$m_S \approx \left[\frac{1.47}{(\kappa-1.13)}\frac{\left(1+e^{-2\ell_i+1}\right)}{2}-1\right]\left\{1+0.60\left(\beta_P-0.1\right)\right\}$$

- **Finite State Machine Exception Handling operational in DIII-D PCS**

ITER Exception Handling System Requires a Powerful Forecasting Capability for Sufficient Look-Ahead



- **Forecasting Outputs:**
  - **Controllability thresholds to inform Exception Handling response**
  - **Quantified Risk of disruptive state to trigger Disruption Mitigation System**

What Roles Must Predictors/Detectors (of anything) Play in ITER Operation? How Are They Used?

- **Predict future STATE (plasma or plant system) under present control trajectory**
- **Predict future STABILITY or CONTROLLABILITY (boundary proximities)**
- **Enable control to REGULATE the STATE (e.g. Model Predictive Control)**
- **Enable control to REGULATE PROXIMITY to controllability boundaries**
- **Predict specific exceptions and faults for EXCEPTION HANDLING**
- **Provide specific basis for TRIGGER OF EMERGENCY RESPONSES**
  - Shutdowns: rapid controlled, emergency "uncontrolled"
  - Mitigation action (view as a part of shutdown, but critical action)

What Roles Must Predictors/Detectors (of anything) Play in ITER Operation? How Are They Used?

- Predict future STATE (plasma or plant system) under present control trajectory

Predictors Must Support and Enable Control Actions:

- Continuous Control
- Control of Proximities to Boundaries
- Exception Handling
- Alarms/Emergency Response

- Predict specific exceptions and faults for EXCEPTION HANDLING
- Provide specific basis for TRIGGER OF EMERGENCY RESPONSES
  - Shutdowns: rapid controlled, emergency "uncontrolled"
  - Mitigation action (view as a part of shutdown, but critical action)

Exception Handling and Control is Possible Only If Predictors Are Designed to Provide Information in Actionable Form

"Disruption" Predictor Requirement Metrics

1. **Must predict SPECIFIC pre-disruptive phenomena to enable control:**
   - VDE, radiation limit, n≠0 MHD stability/controllability, TM-stability profile state, etc…
   - For PREDICTOR, identify proximity NOT actual mode growth (= detect)
   - Disruptions aren't a thing to predict!!!! They're the end result of many different risky phenomena which must THEMSELVES be predicted individually…

2. **Must provide a CONTINUOUS variable that quantifies proximity (& can GENERATE triggers):**
   - Vertical Controllability metric: e.g. $\Delta Z max$
   - Tearing mode stability metric: Turco J-well depth

3. **Must be REAL-TIME CALCULABLE (control is real-time by definition…)**

4. **Must be linked to SPECIFIC CONTROL ACTIONS and provide SUFFICIENT LEAD TIME**

5. **Must be EXTRAPOLABLE to new device (ITER) control solution prior to operation:**
   - ITER control requirement: must validate shot prior to execution…
   - COULD allow iterative improvement over time…

Approaches to Predictors and Detectors of Disruption Risk Exceptions

- **Monitor physics parameters :**
  - Identify approach to boundary
  - Detect crossing of boundary
- **Monitor system fault parameters:**
  - Reflect approaching fault
  - Detect fault underway
- **Must determine good heuristic exception definitions:**
  - Choice is critical to effective action: should reflect RISK
  - MUST BE VERY CAREFUL TO DISCRIMINATE BETWEEN PREDICTION AND DETECTION!!!

Phenomenon	Parameter/ diagnostic	Criterion
Radiation collapse	bolometer array(s)	total radiated power / total input power > tbd
Impurity accumulation	bolometer array(s), SXR	ratio central/edge radiation > tbd
Large rotating modes	fast poloidal coils + magnetics for equilibrium	B_θ > to be defined
Peaked current	magnetics for equilibrium	li > tbd
LM	saddle coils + magnetics for equilibrium	Br > function of (Ip, li, q_{95})
Resistive plasma	loop voltage	U_{loop} > tbd
Thermal energy	thermal energy or beta poloidal	E_{th} or β_θ < tbd
Beta limit	βN	β_N > tbd
Density limit	interferometer	n_e ~ Greenwald limit
Poor thermal confinement	equilibrium and others → energy confinement time	τ_E < tbd
Low q_{95}	equilibrium	q_{95} ~ 2

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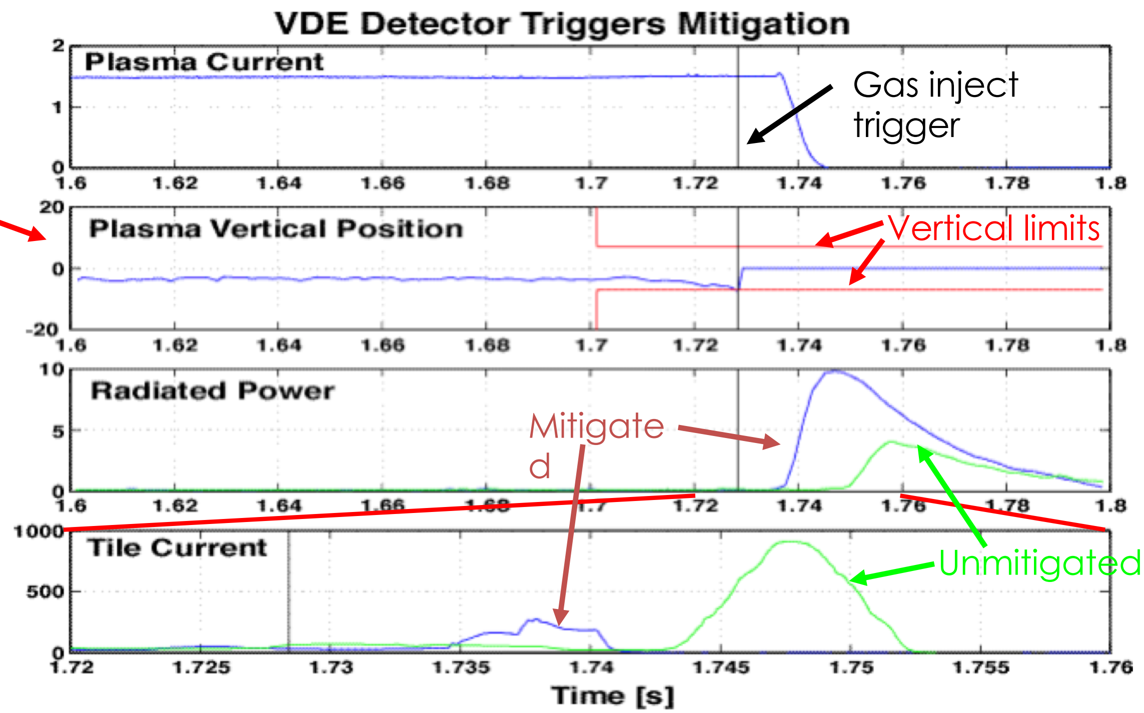
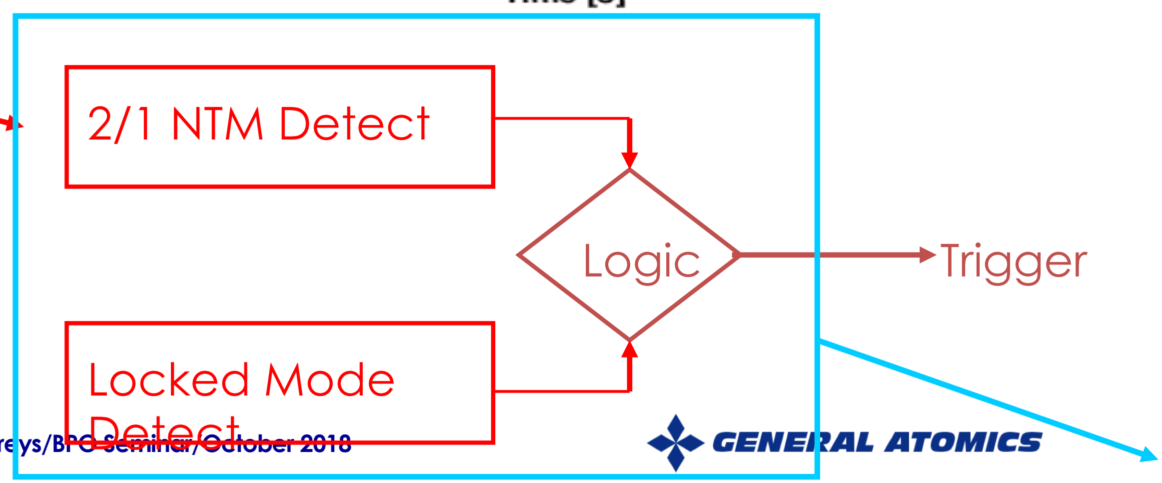
Physics-Based Disruption Detection and Mitigation with the DIII-D Plasma Control System (2002)

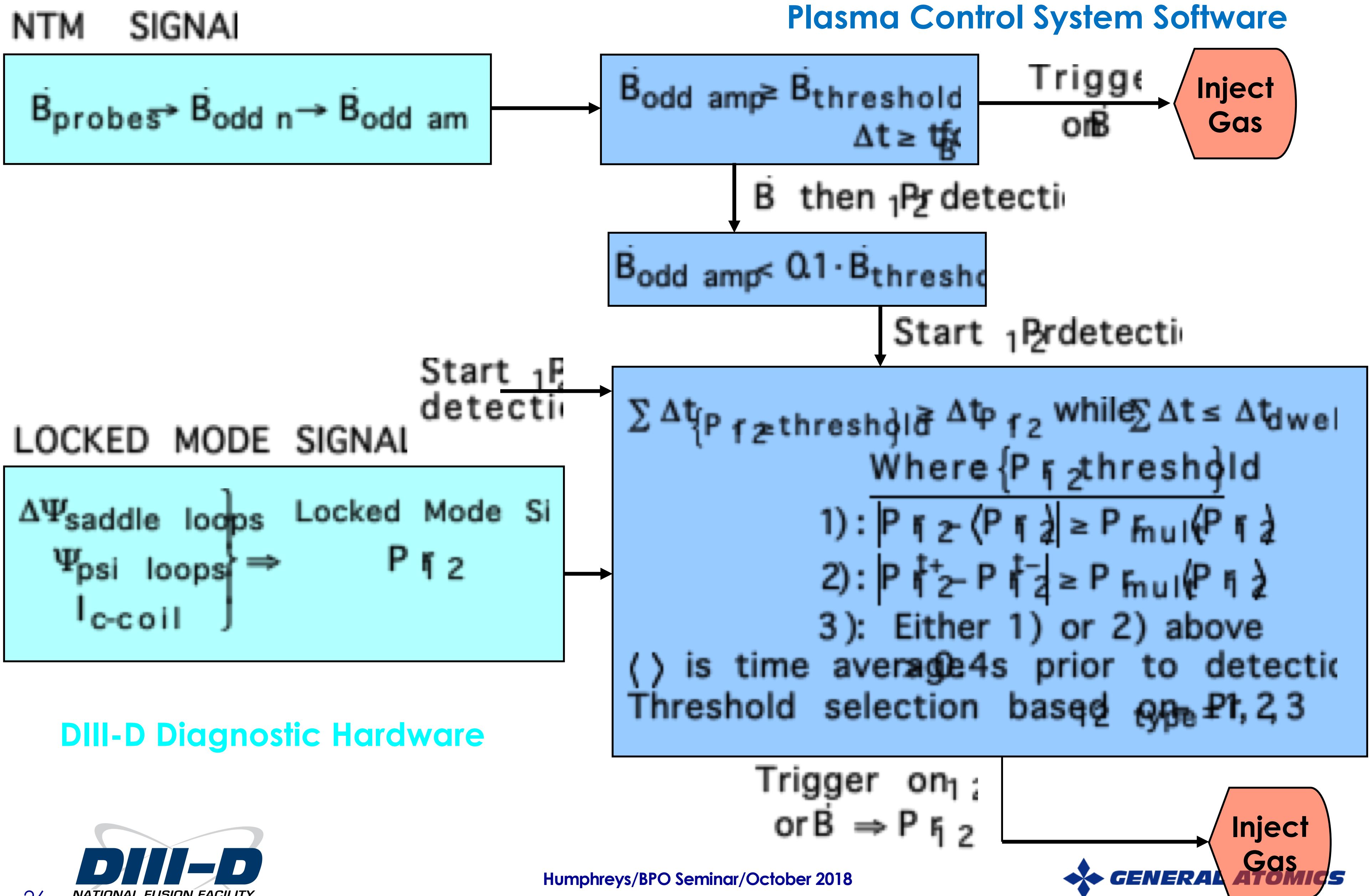
Humphreys, EPS 2002

- **VDE detector:**
  - Detects plasma vertical position past threshold
  - Triggers gas injection system to mitigate
  - Trigger→quench ~5ms
- **Radiated power limit detector/predictor:**
  - Detects plasma radiated power fraction exceeding threshold
- **2/1-Locked mode detector:**
  - Detects presence of 2/1 NTM and growth of locked mode with disruptive dynamics





2/1 NTM and Locked Mode Detector Logic in DIII-D Plasma Control System (2002)



Applying Metrics to Black-Grey-White Box Models: Linear System ID, RNN's, CNN's, Branching Tree/Random Forest…

- **Train for continuous variable? Yes…**
  - DIII-D NN example identifies proxy β
  - Continuous evolution, proximity…
- **Specific phenomenon? Maybe…**
  - Beta-limit major disruptions
- **Control action? Maybe…**
  - Reduce heating…
- **Extrapolable? Not in this form…**
  - Inputs = many raw magnetic signals
  - EXTREMELY black box…
  - BUT: provides existence proof!!!

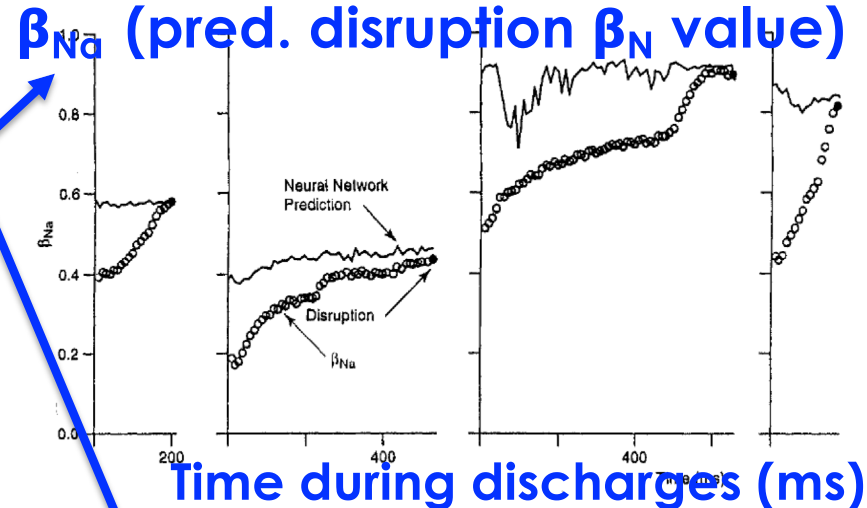


FIG. 6. Results of the neural network test on the data not included in the training set. As in Fig. 5, the actual β_{Na} and the network prediction are plotted.

Wroblewski, Leuer et al, NF 1997

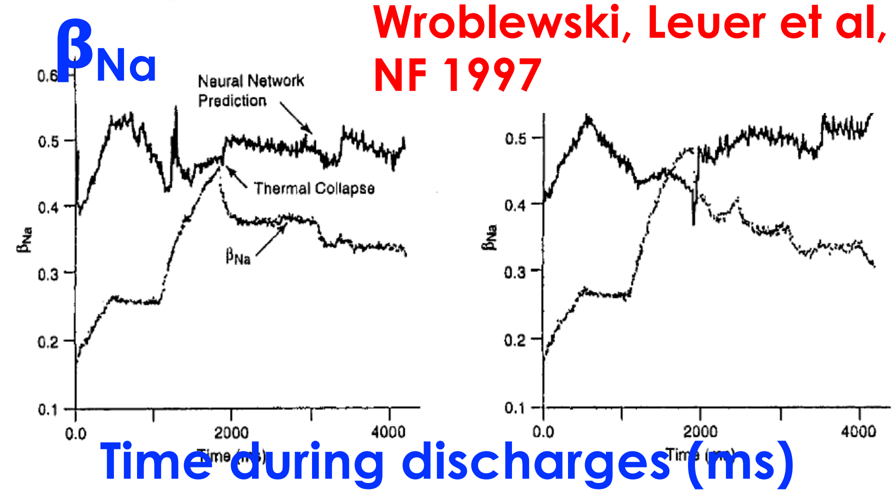


FIG. 7. Disruption alarm neural network prediction of a thermal collapse in two non-disruptive discharges. As in Figs 5 and 6, the actual β_{Na} and the network prediction, A, are plotted. $\beta_{Na} > A$ indicates that the discharge should disrupt.

Thoughts on General Data-derived Models…

- **Data-trained systems: Good/Bad…**
  - Need data… Can we train with simulated data? Evolve with ITER?
  - Advantages: can bridge lack of understanding in physics!!! Provide existence proofs…
  - Disadvantage: poor tools for provability, reliability, robustness…

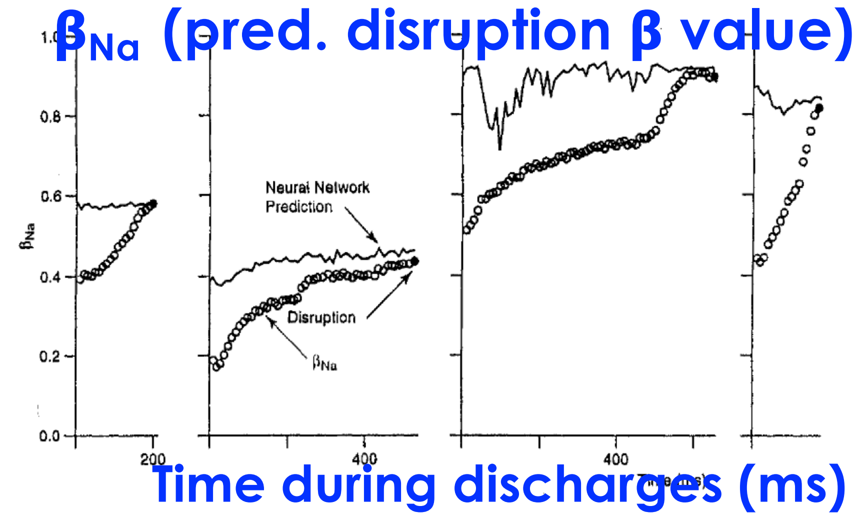


FIG. 6. Results of the neural network test on the data not included in the training set. As in Fig. 5, the actual β_{Na} and the network prediction are plotted.

- **Realtime Control action? Very likely**
  - Famously: self-driving cars…
  - Mix of data mining and deterministic control already well-established…

Wroblewski, Leuer, et al, NF 1997

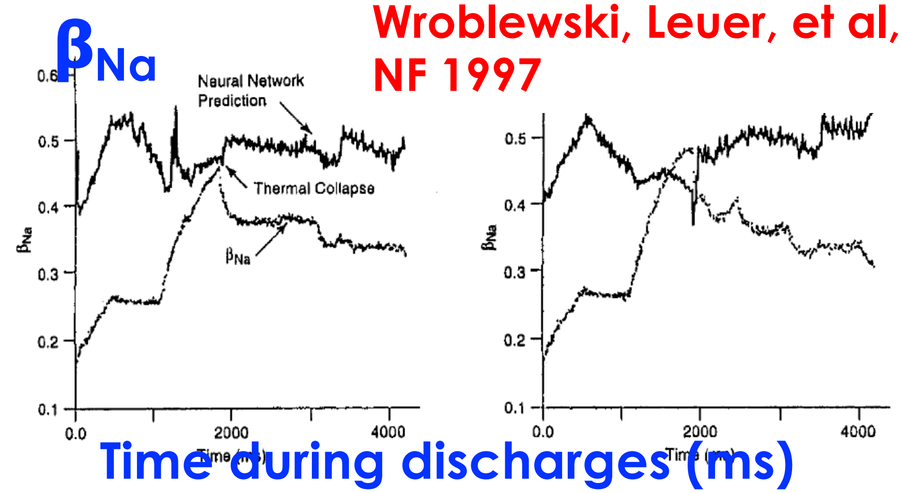


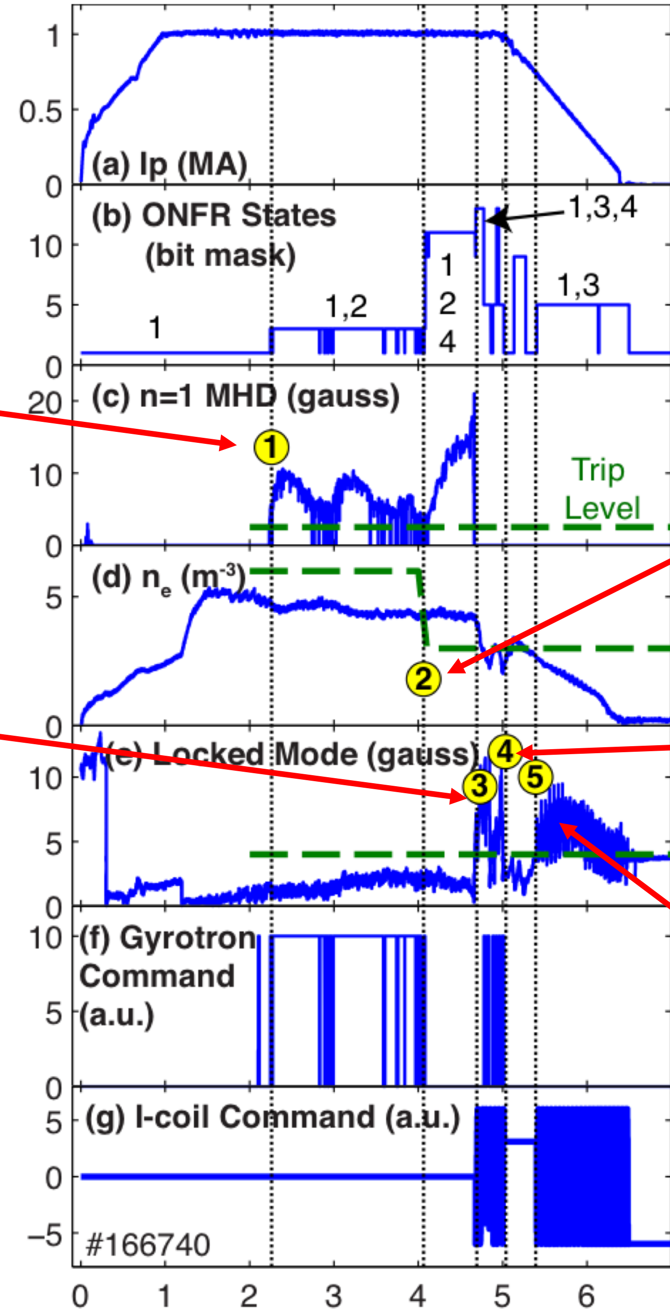
FIG. 7. Disruption alarm neural network prediction of a thermal collapse in two non-disruptive discharges. As in Figs 5 and 6, the actual β_{Na} and the network prediction, A, are plotted. $\beta_{Na} > A$ indicates that the discharge should disrupt.

- **Extrapolable? Maybe…**
  - Active area of research now… and important to pursue to find answers

Shutdowns May Benefit from Complex Control Before Final Termination Trigger – IF SUFFICIENT PREDICTOR LEAD TIME…

(1) NTM Detected
→ECCD suppression

(3) Locked mode detected→3D entrainment + synchronous ECCD



(2) High Density trip disables ECCD temporarily, NTM grows

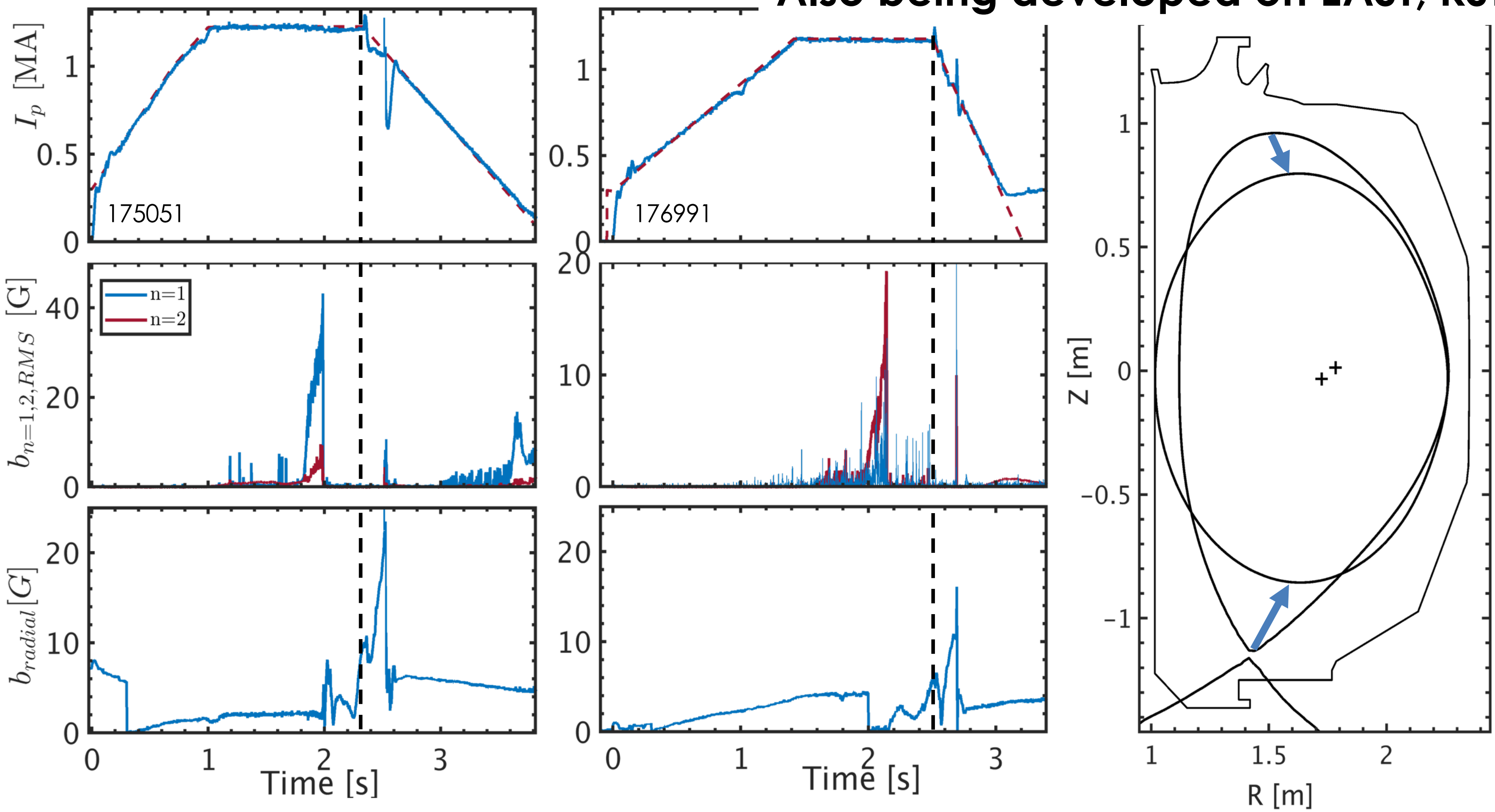
(4) Temporary locked mode recovery

(5) Successful handling of new locked mode through safe rampdown

Shutdowns in Which the Plasma is Allowed to Limit May Provide Significant Ability to Control RE Channel

…But requires long lead-time > 20 s to accomplish in ITER…

DIII-D IWL Fast-rampdown experiments
Also being developed on EAST, KSTAR…



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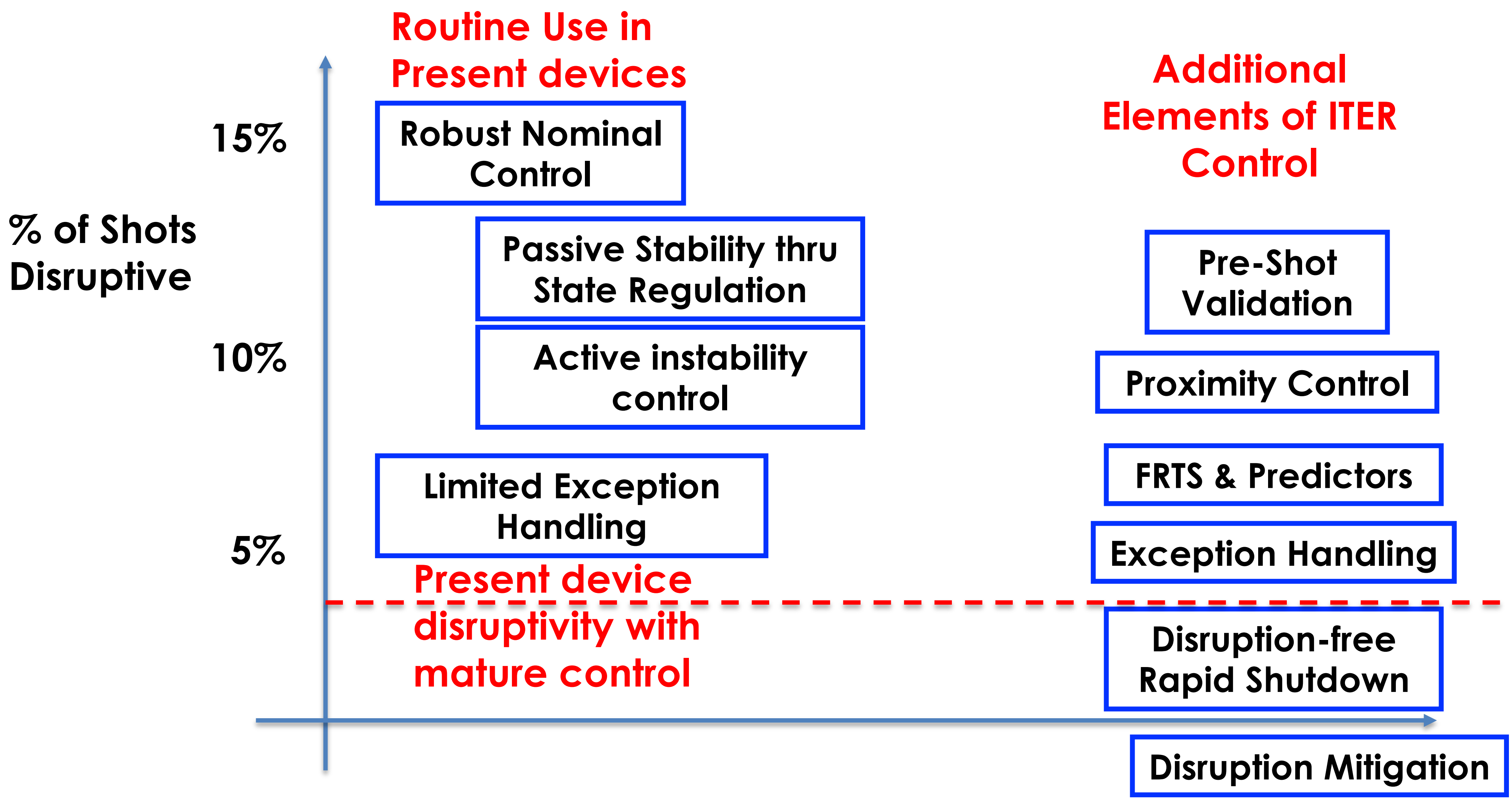
ITER Disruption Prevention Strategy Employs Layers of Control to Successively Reduce Disruptivity



Research Implications and Observations (1)

- **Great progress has been made in disruption management (e.g. predictors, DMS triggers), but including the rest of the disruption-preventing control problem is increasingly important now:**
  - Essential in order to minimize disruptivity
  - Possibly a key part of an effective rapid shutdown solution

- **Many realtime algorithm solutions still urgently needed:**
  - Controllability boundary calculation + regulation of proximity
  - Accurate realtime kinetic equilibria + stability calculation
  - Effective and accurate Faster Than Real-time Simulation (FRTS)
  - Predictors specific to exceptions leading to disruptions
  - Provable DMS triggers that make use of quantified risk assessment

- **Application of the Predictor Metrics can improve effectiveness:**
  - Primary goal is to maximize usefulness in CONTROL application & action

Research Implications and Observations (2)

- **Research guided by control requirements can focus and sharpen effectiveness of true disruption prevention solutions:**
  - Physics and experimental development of the full control problem
  - Integration with Exception Handling scenarios that must be implemented with PROVABLE effectiveness
  - Mathematics solutions for high robustness, high confidence EVEN WITH GAPS IN PHYSICS KNOWLEDGE

- **Experimental studies on DMS approaches:**
  - Complex operational sequence will be optimized by addressing control integration at all stages of research
  - DMS effectiveness may be enhanced by control action before and/or after triggering…
  - IF we expect a 12 MA RE beam under DMS triggering with some likelihood, what are tradeoffs in preparatory/post-DMS control action?

Summary and Conclusions

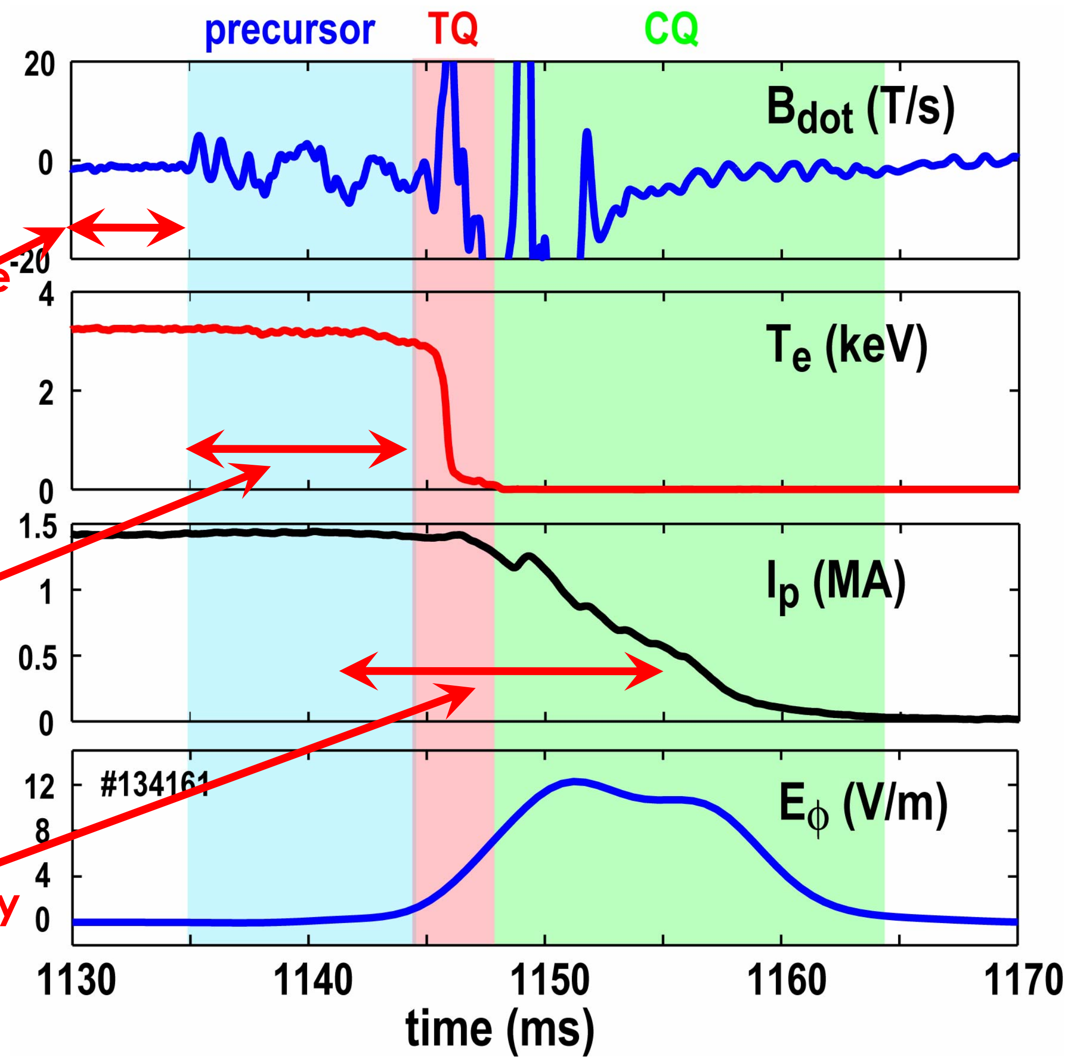
- **Disruptions are the result of insufficient control capability:**
  - Consequence of design and operational choices
  - Hardware/system faults + human error or human intention
- **Focused efforts on robust control hold the promise of reducing ITER disruptivity to well below present design requirements**
  - Requires prioritizing specific research to enable disruption-preventing control
  - Identify controllability boundaries, apply metrics to predictor research, support mathematics advances for quantified-confidence
  - Control mathematics can play strong role in managing gaps in physics knowledge
- **Recent control physics advances illustrate the approach and the promise:**
  - Profile control to regulate target and performance
  - Candidate for profile metric reflecting tearing stability
  - Effective exception handling and rapid shutdown algorithms

Random Old Slides

Response to Disruption May Require Significant Magnetic Control Action

- Adapt to initial faults:
  - Loss of power supply (e.g. proximity to current limits)
  - Loss of discrete diagnostics (e.g. magnetic probe)
  - Change of reconstruction algorithm, use of actuators
- Adapt to Change of Operating Regime:
  - H-L transition or NTM/locked mode change plasma dynamics
  - Change of control algorithms
- Respond to impending or occurring disruption:
  - Control of post-thermal quench runaway current

DIII-D Disruption time sequence



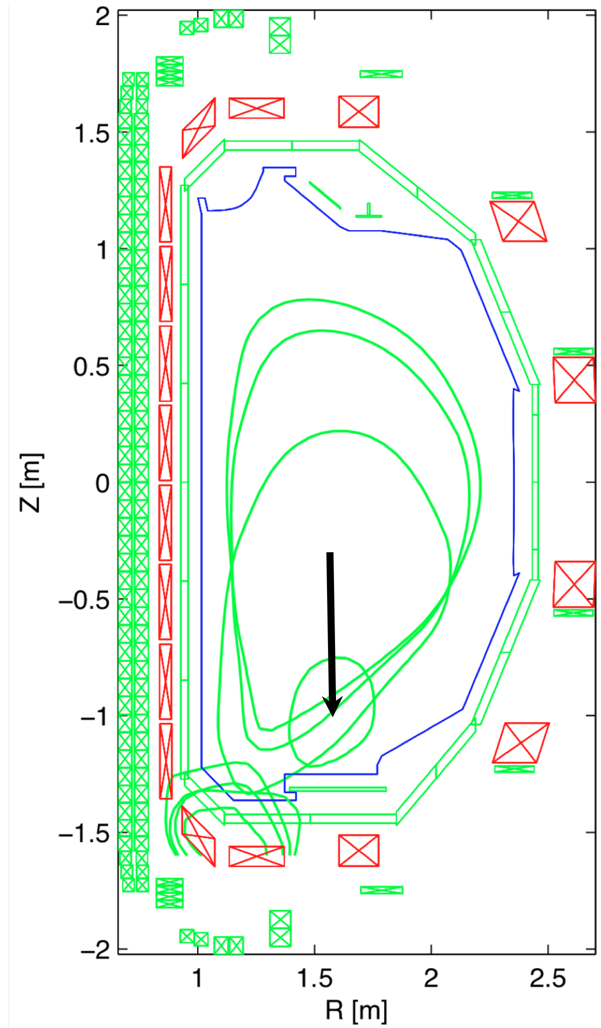
Disruptions Are Plasma-Terminating Events That Result from Uncontrolled Instability Growth

- **Examples of instabilities that can grow and cause disruption:**
  - Vertical instability
  - Tearing mode

- **Vertical Displacement Event (VDE): loss of vertical control leads to global MHD instability and thermal quench**

- **Major Disruption: absence of profile control allows unstable profiles to evolve, triggering global MHD instability and thermal quench**

Intentional VDE in DIII-D



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GENERAL ATOMICS

Integrated Control Research is Required In Order to Operate ITER Robustly Without Disruptions

- **Identify robust operating scenarios:**
  - Passively stable
  - Actively controllable
  - Demonstration on operating machines

- **Develop robust controllability for scenarios:**
  - Validated models of instabilities, actuators, plasma
  - Quantified controllability with noise, disturbances
  - Real-time monitoring of controllability boundaries

- **Develop provable algorithms to avoid or recover from impending fault trajectories:**
  - Prediction with Faster Than Real-Time simulation
  - Algorithms for off-normal responses
  - Soft Shutdown if required
  - Hard Shutdown (mitigated disruption effects) as rare last resort

Preventing Disruptions Requires Effective Off-Normal and Fault Response (ONFR) Supervisory Function

- **Unified Finite State Machine system handles**
  - Off-normal plasma events
  - Hardware faults

➔ **Provides logic to switch to Recovery, Alternate State, or Shutdown**

- **Supports:**
  - multiple parallel states
  - cascading faults
  - actuator prioritization to negotiate conflicting actuator needs