Design of the ITER Plasma Control System for Disruption Prevention and Mitigation

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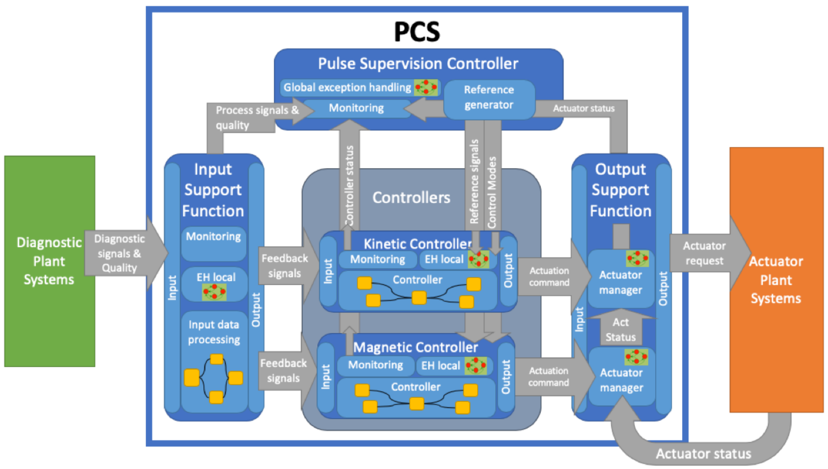

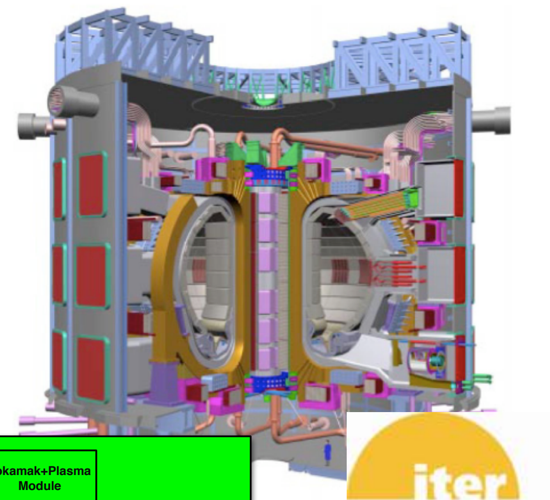

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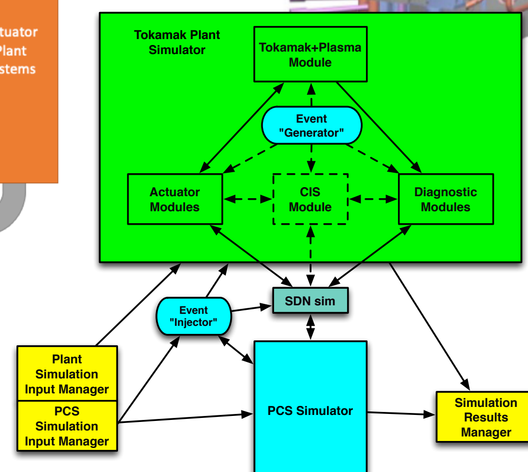


1st IAEA Technical Meeting on Disruptions, etc…
ITER HQ (Remote)
St. Paul lez Durance, France

Outline

- Overview of disruption management issues
- The ITER PCS & its role in disruption prevention/mitigation
- Control of proximity to controllability boundaries
- Exception Handling
- Forecasting and usefulness metrics for predictors
- The DMS and the specification of mitigation scenarios
- Research Implications and Conclusions

Disclaimer and Caveats

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

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

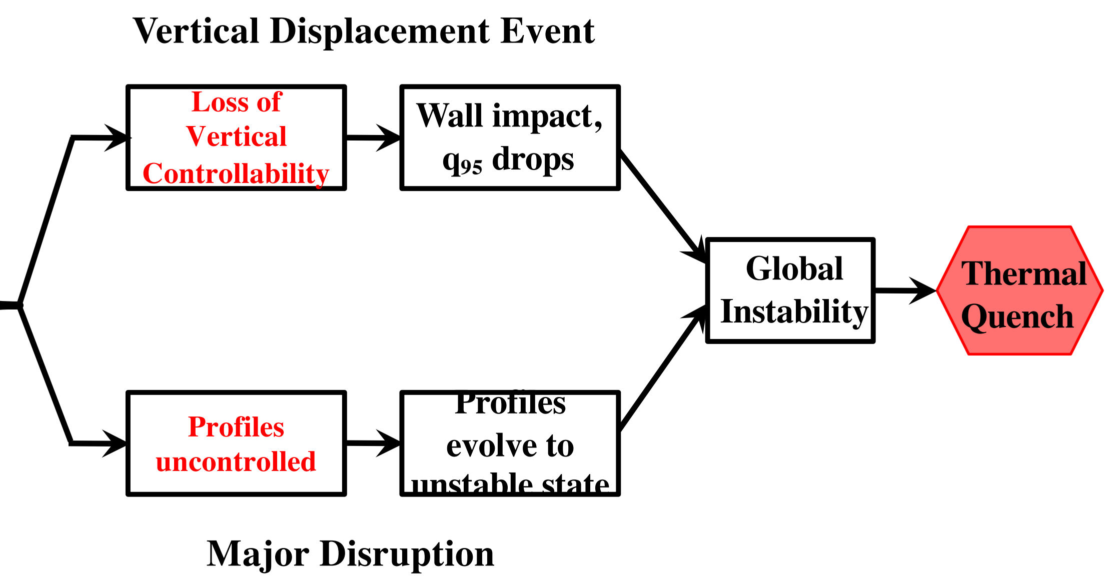
- However, technical figures here have generally been taken from previously-shown and approved presentations from various sources…

Disruption Prevention, Avoidance, and Mitigation

Disruptions Are a Control and Operations Problem: Result of Insufficient Control of Operating Regime, System Faults, and Operational Errors

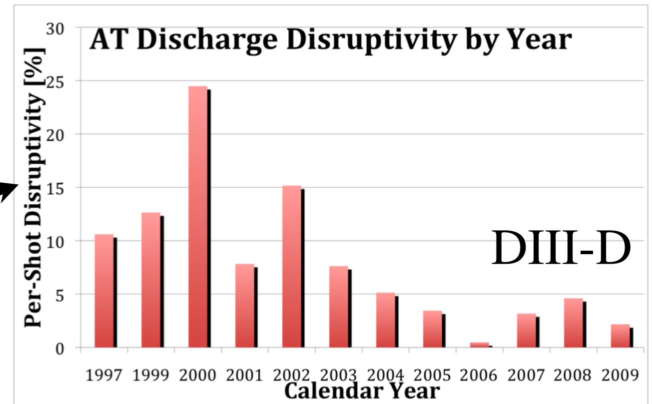
Primary Causes of Disruption

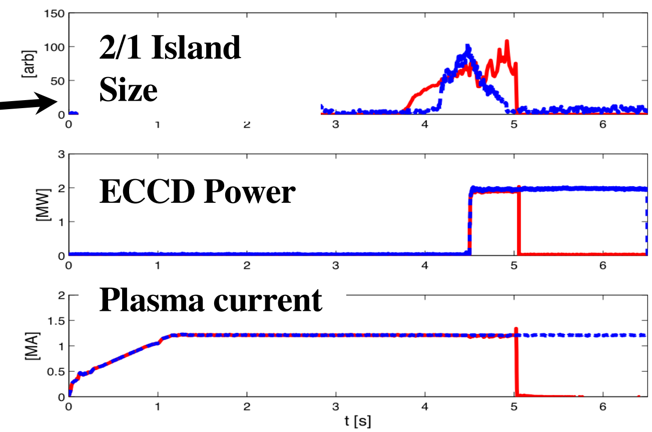
- Insufficient control capability for operating regime + off-normal events
- Hardware/system failure
- Human error
- (Design choice)
- (Human intention)



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% reduced to **<1-2%**
- **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

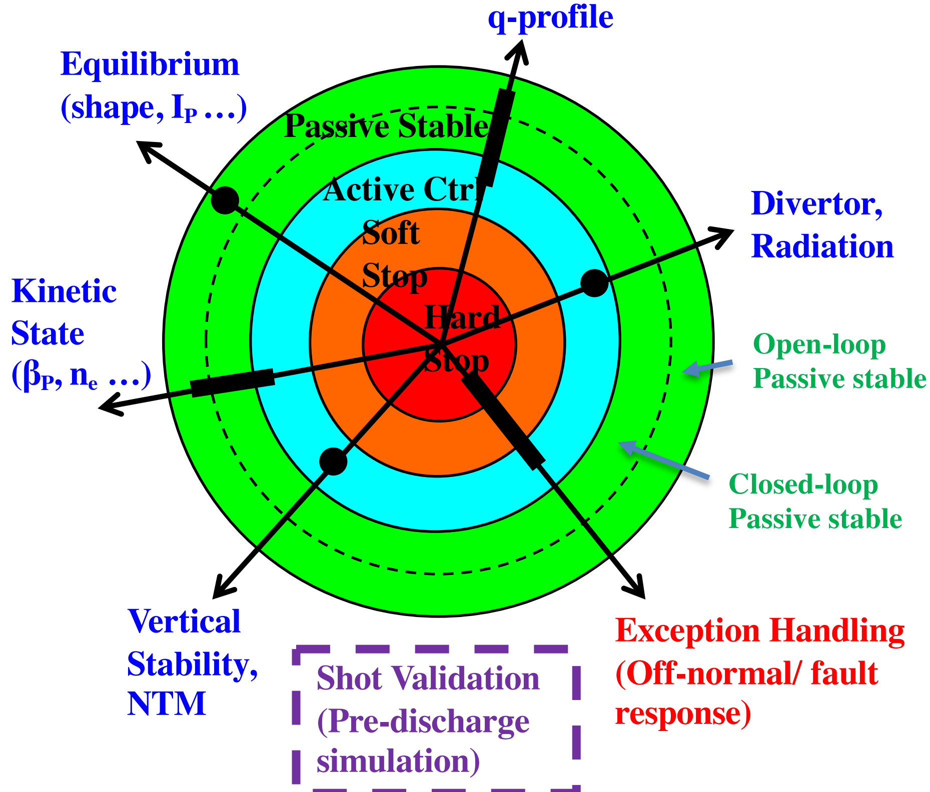




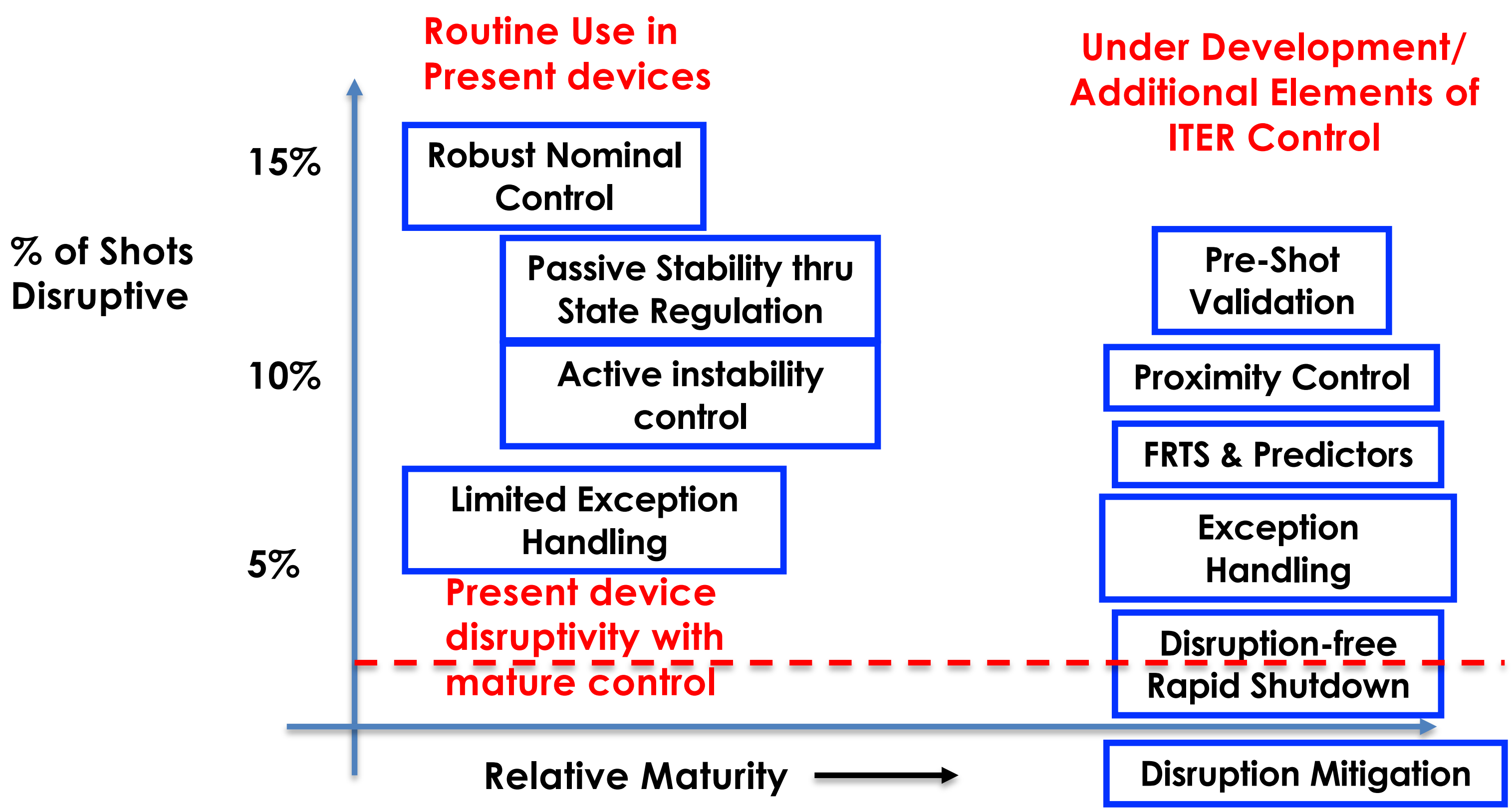
A Complete Control Solution is the Necessary and Sufficient Condition for Disruption-free Operation

- **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 shot validation**
  - Exception Handling

Control Operating Regime Map



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



The ITER PCS and its Role in Disruption Management

ITER PCS Functional Elements Implement the Layered Approach to Disruption Prevention and Avoidance

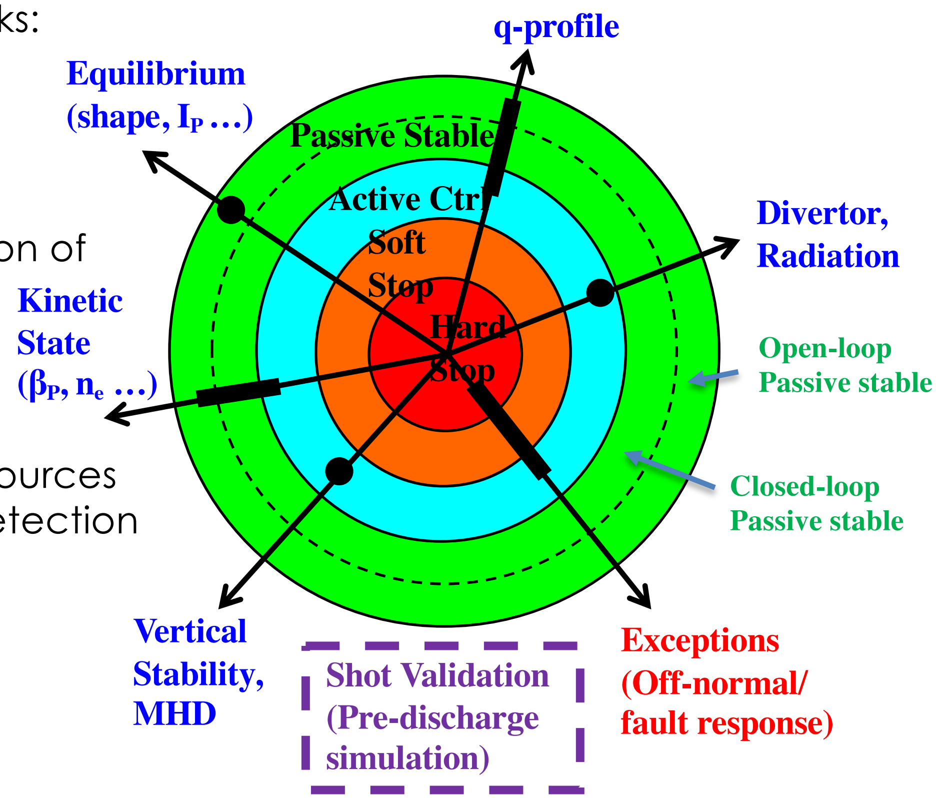
- **Minimize disruptivity in CONTINUOUS control:**
  - **Control algorithms robust** to noise/disturbances
  - Standardized, validated algorithm building blocks: **compact controllers**

- **Active, CONTINUOUS disruption PREVENTION:**
  - **Control of proximity** to controllability boundaries
  - Realtime **forecasting** of trajectories and prediction of risk to prevent approach to boundaries

- **ASYNCHRONOUS AVOIDANCE of disruptive states:**
  - High-level **Supervisory** monitoring and action
  - **Actuator Management** to coordinate limited resources
  - Off-normal event and system fault prediction/detection
  - Effective **Exception Handling** responses

- **Mitigate HUMAN ERROR:**
  - **Shot validation**: simulate expected control and exception handling performance

Control Operating Regime Map



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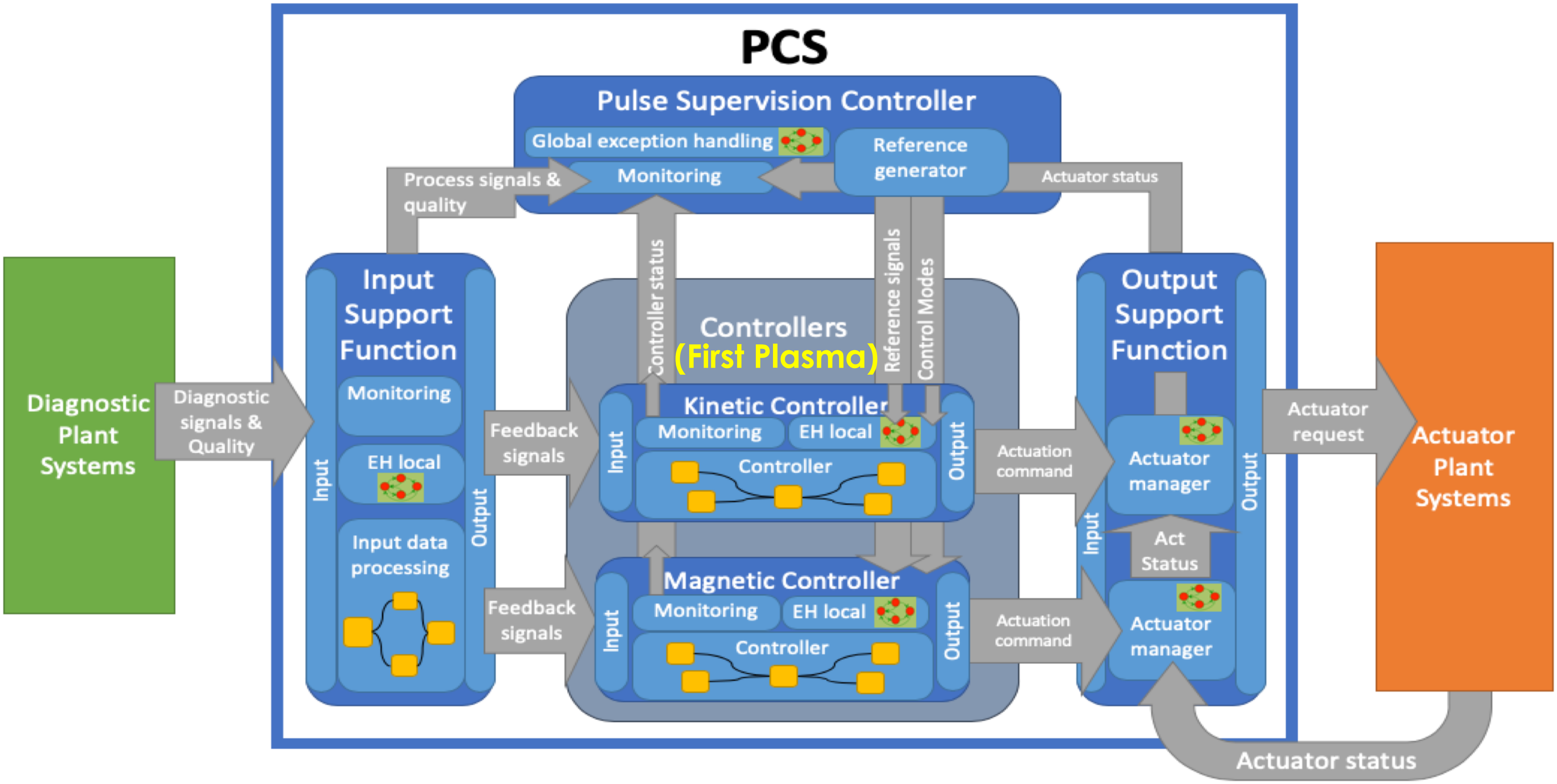
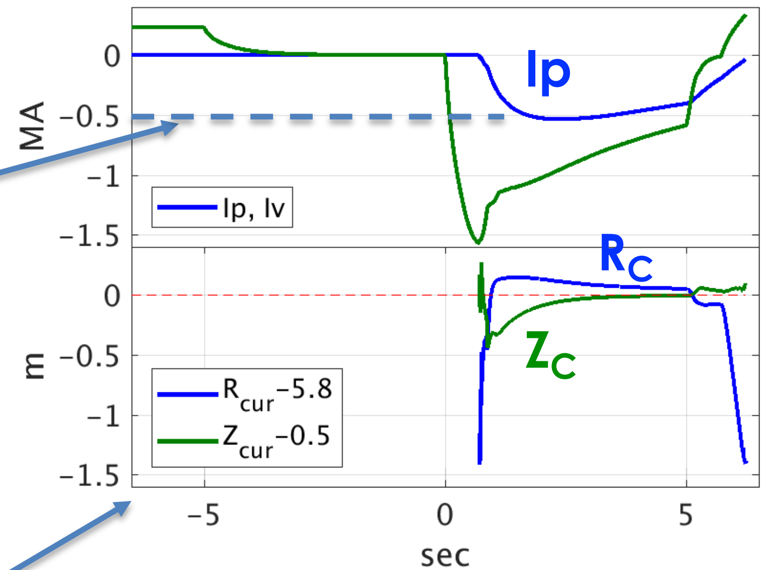
GENERAL ATOMICS

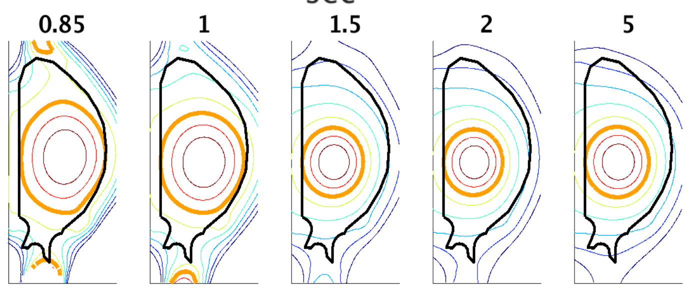
ITER PCS Architecture Enables All Control Functions and Provides Flexible, Scalable Framework for Subsequent Research Phases



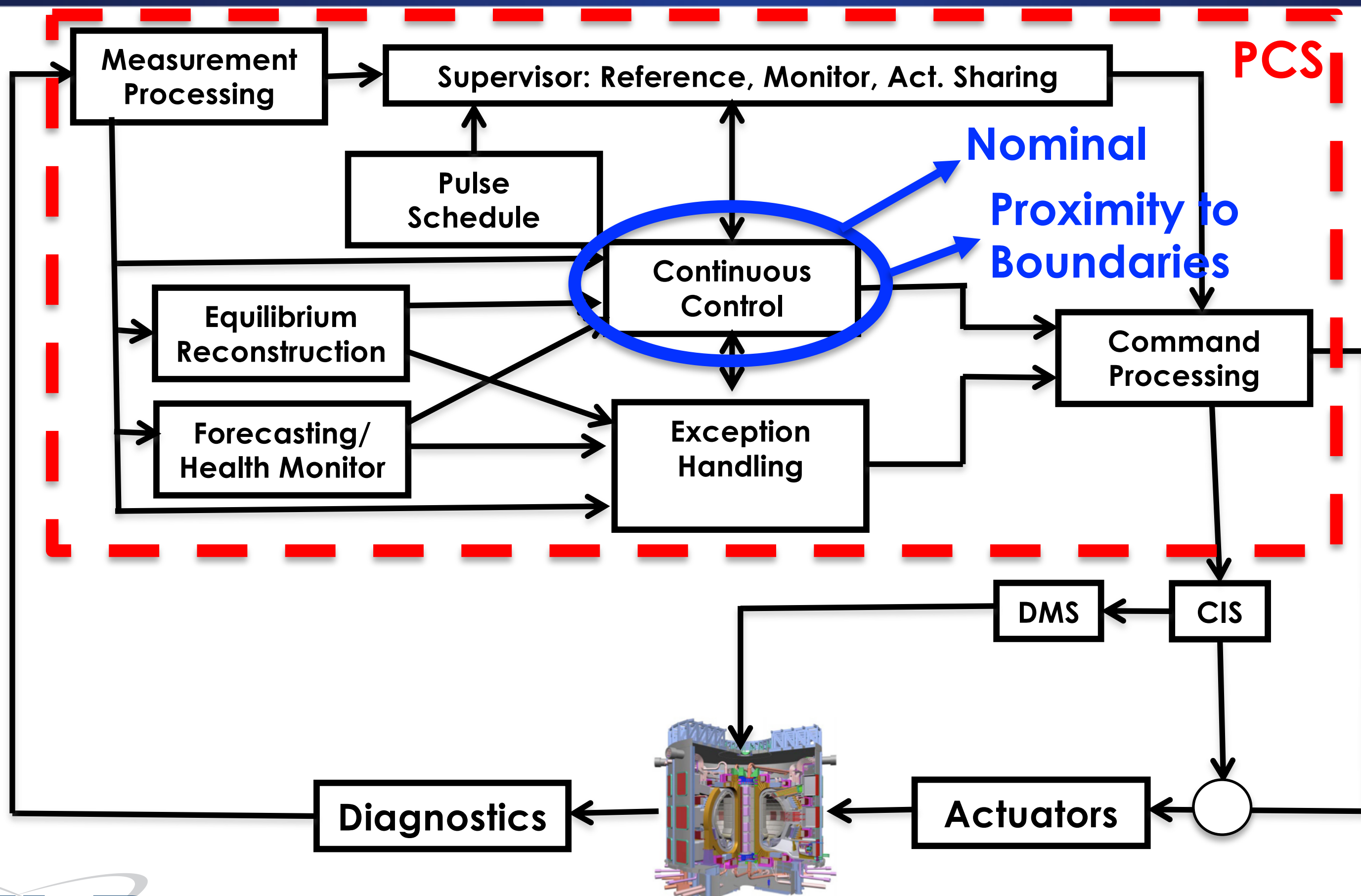
ITER First Plasma Requires Very Limited Disruption Management

- **0.1 s < pulse length < few seconds**
- **0.1 < Ip < 1.0 MA**
  - Algorithms/EH hold < 0.5 MA
- **Ohmic heating only**
  - ECH < ~6 MW for pre-ionization/ burnthrough assist
  - Exception handling in PCS + CIS
- **Limited in-vessel components and protection, limited diagnostics:**
  - Basic position control with SC PF's
  - No in-vessel VS3 coil
  - Exception handling for RE, etc…





ITER PCS Design Elements Provide Performance, Robustness, Low Disruptivity Beyond First Plasma: Continuous Control for Disruption Prevention



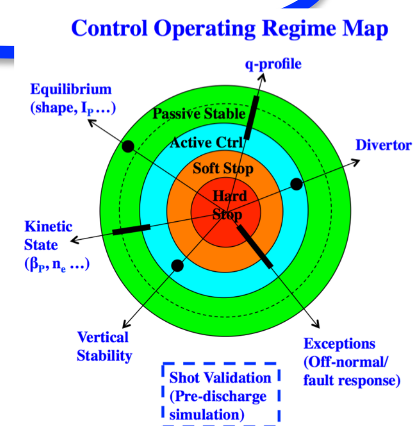
Most Continuous Control Algorithms Will Have Two Parallel Functions: Nominal and Controllability Proximity Regulation

Use these controls…

- Equilibrium/Boundary Control
- Vertical stabilization
- Divertor detachment
- Profile control
- Tearing mode stabilization

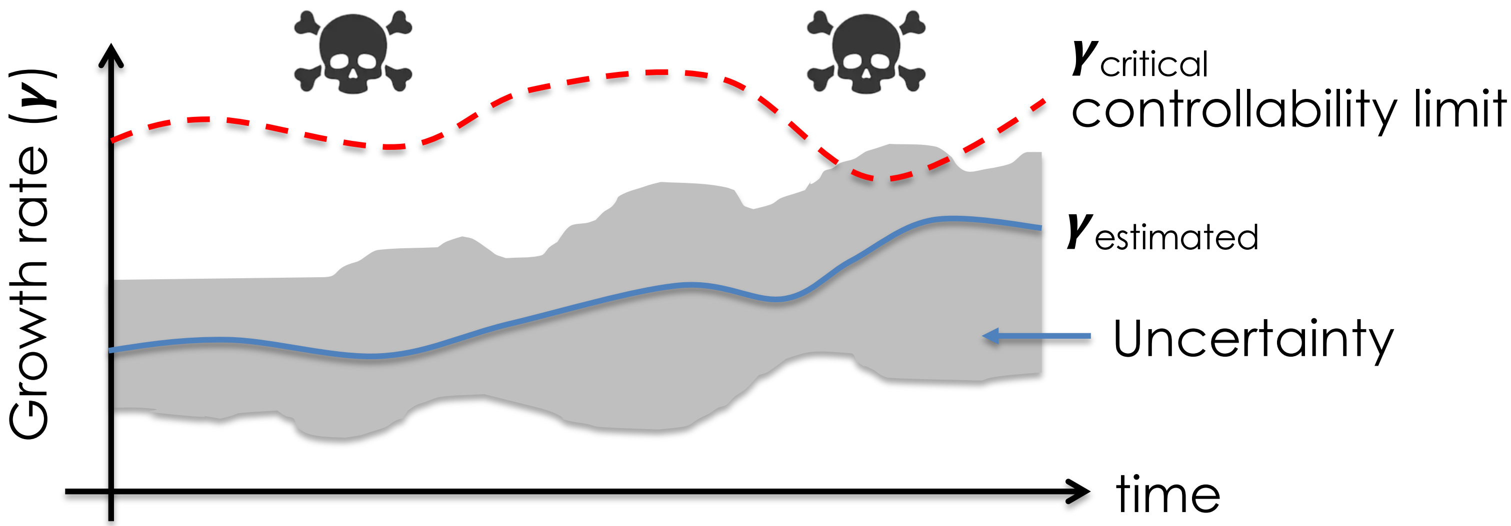
…to ALSO regulate these (different control goals):

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



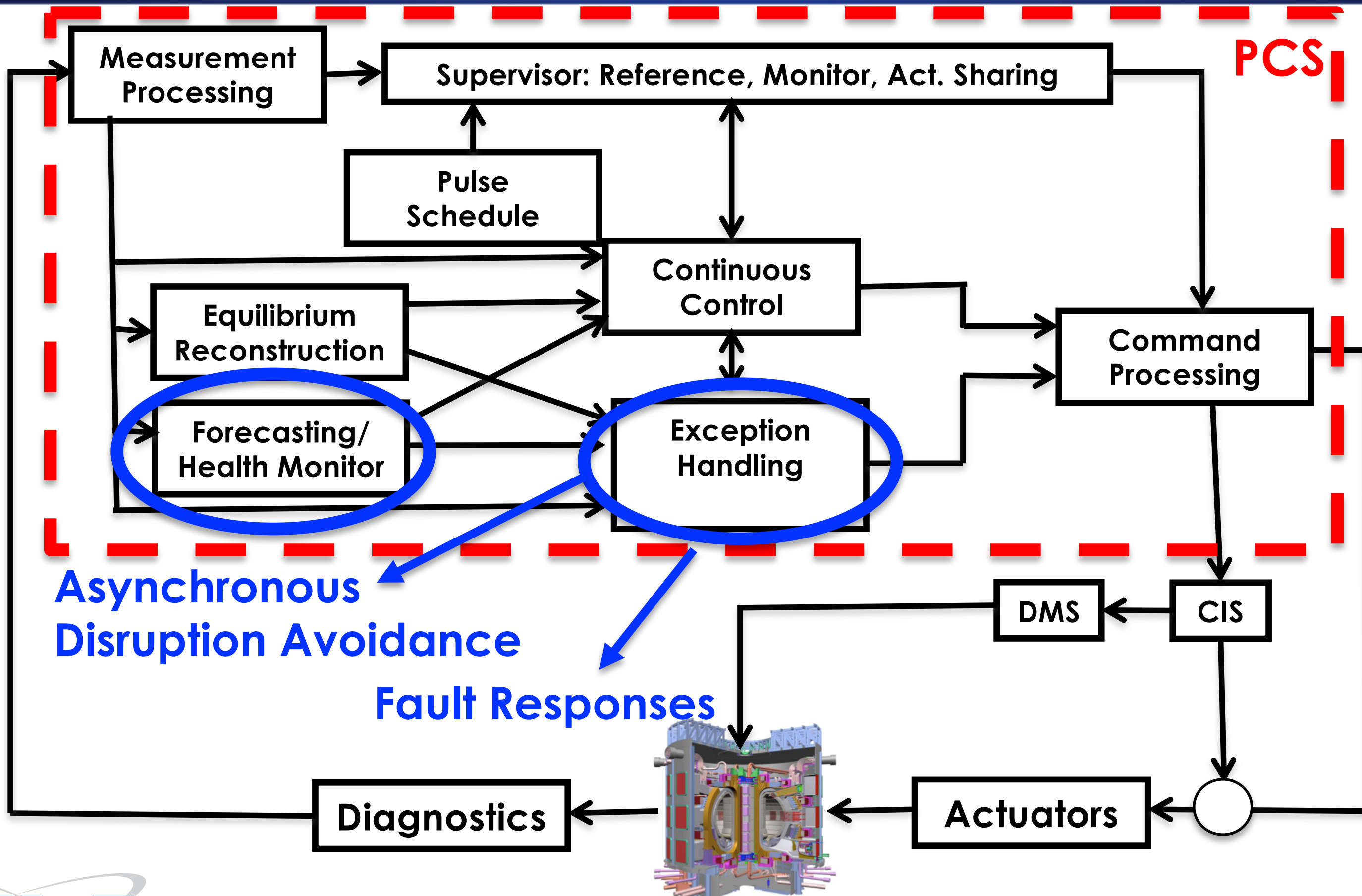
Continuous Regulation of Proximity to Controllability Limits is Key to Disruption Prevention: Safe Vertical Controllability → Prevents VDE's

- **Separate proximity control loop augments equilibrium/shape control**
- **Compensates for disturbances to internal inductance, elongation**
- **General proximity control scheme applicable to many controllability boundaries:**
  - Weak control action when far from limit, stronger as approach limit…



See talk by J. Barr, this meeting

ITER PCS Design Elements Provide Performance, Robustness, Low Disruptivity Beyond First Plasma: Asynchronous Control for Disruption Avoidance



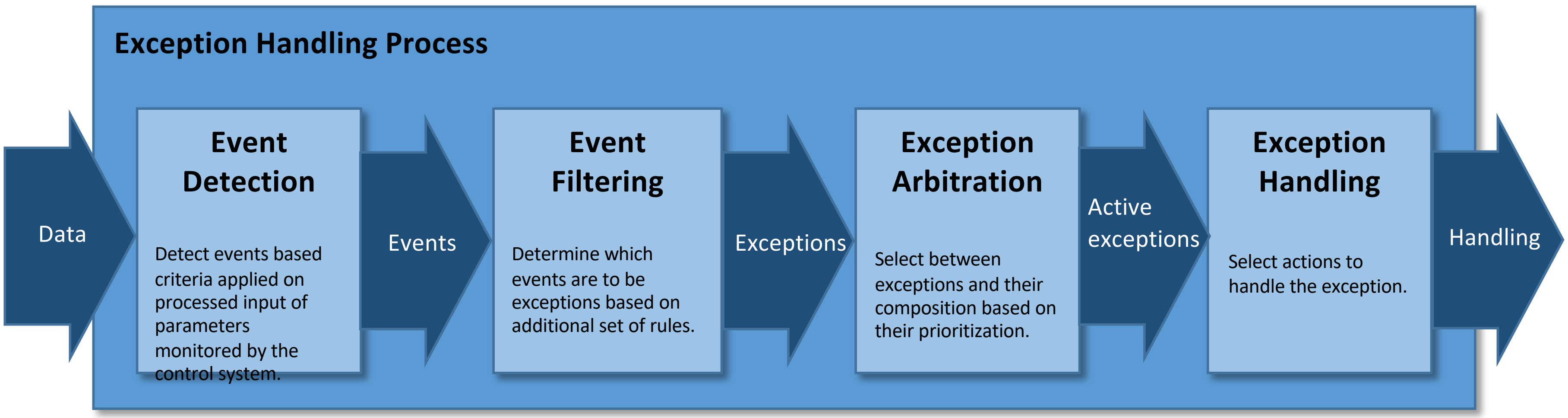
What is exception handling?

- General definition from the ITER PCS glossary[1] (i.e. event versus exception)
  - An **event** is an extraordinary occurrence or a phenomenon that might be relevant for control. An event is *not* an exception but can be considered a *potential* exception.
  - An **exception** is an event requiring a change in the method of control.
- An event becomes an exception when its relevance is validated, i.e. if it is decided that the extraordinary occurrence (the event) requires a change in the control method.
- An exception is the adaption of the control system either at local level, with a change in the behavior of an individual PCS function, or a global coordinated action among different PCS functions
- Exception handling will change the control method, i.e. change control scheme, reference waveforms, controller gains, diagnostic input, use of actuators, but nominal control will remain in charge. Hence, nominal control requirements remain applicable through-out the exception handling process.

[1] PCS glossary: IDM_D_3TDY3S

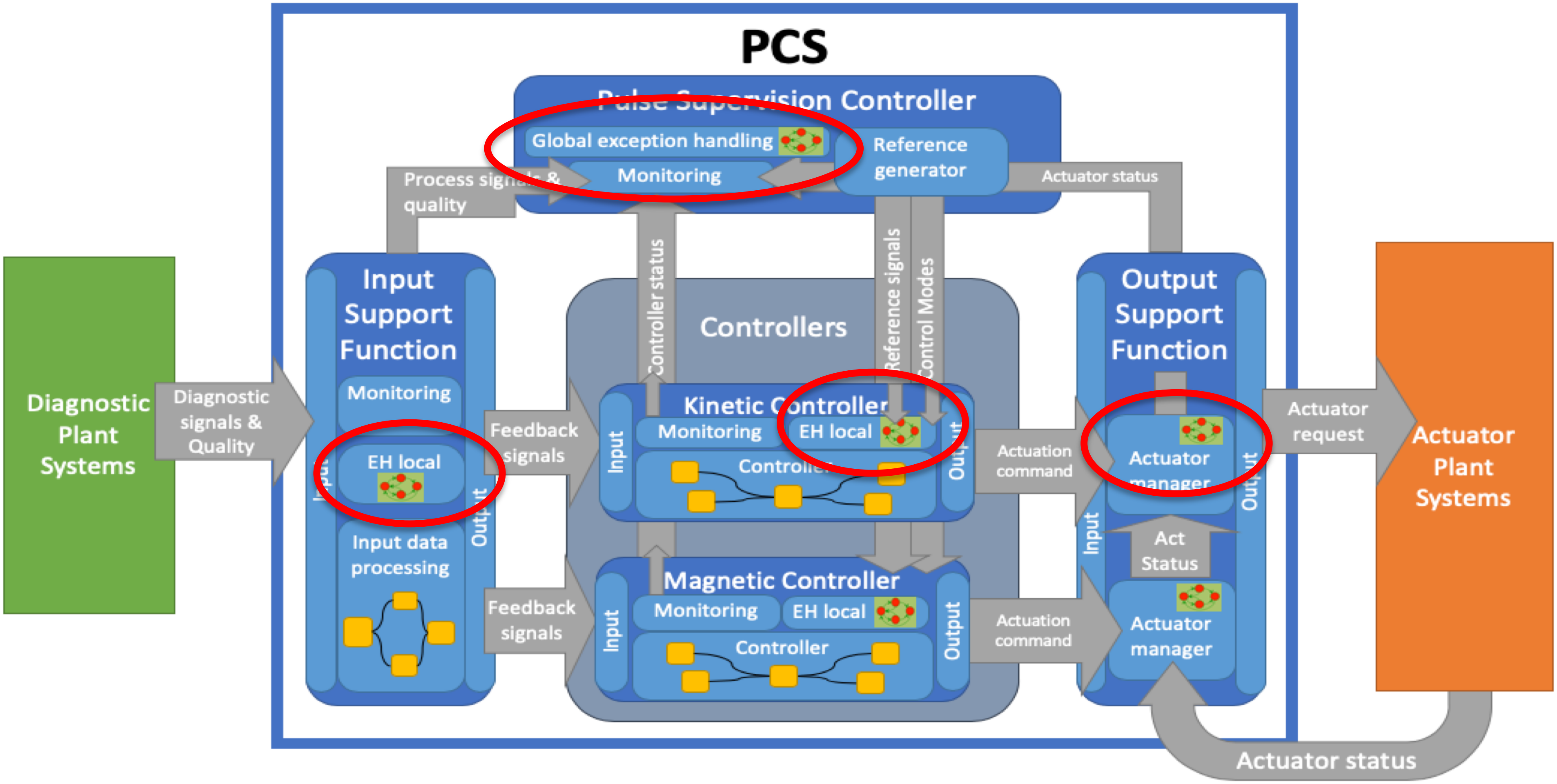
Exception handling architecture: components

- Decomposition of exception handling derived from use cases [1][2]
  - Event detection - Detect an event to which one may need to react.
  - Filtering – Determine whether the event requires a change of control under the current context.
  - Arbitration - Prioritize in the case of concurrent events.
  - Handling – Determine the most appropriate (set of) action(s).



[1] Exception handling use cases: IDM_D_YRJ5KM
[2] Exception Handling architecture: IDM_D_YSW2GV

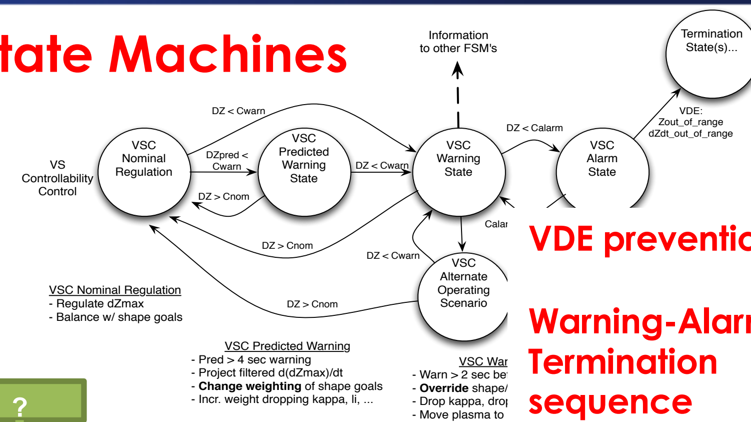
Exception Handling is Performed Globally at the Supervisor Level and Locally at Support Function and Controller Level



ITER PCS Will Support Several Decision Architectures for Exception Handling and Asynchronous Disruption Avoidance

- **Finite State Machines**
  - States, Transition Logic, and Responses
- **Behavior Trees**
  - Tree branching on conditionals, Responses
- **IF-THEN-ELSE conditional logic**

Finite State Machines



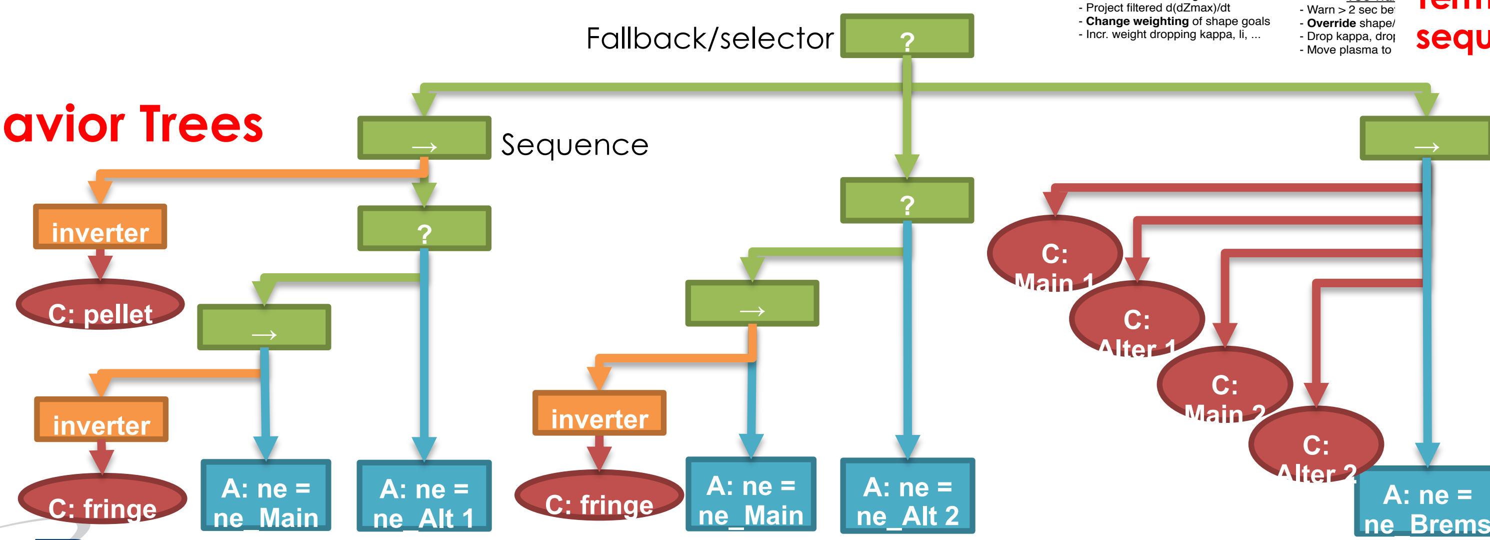
VDE prevention:

Warning-Alarm-Termination sequence

Behavior Trees

ASDEX-UG:

Select ne source based on plasma state and signal quality



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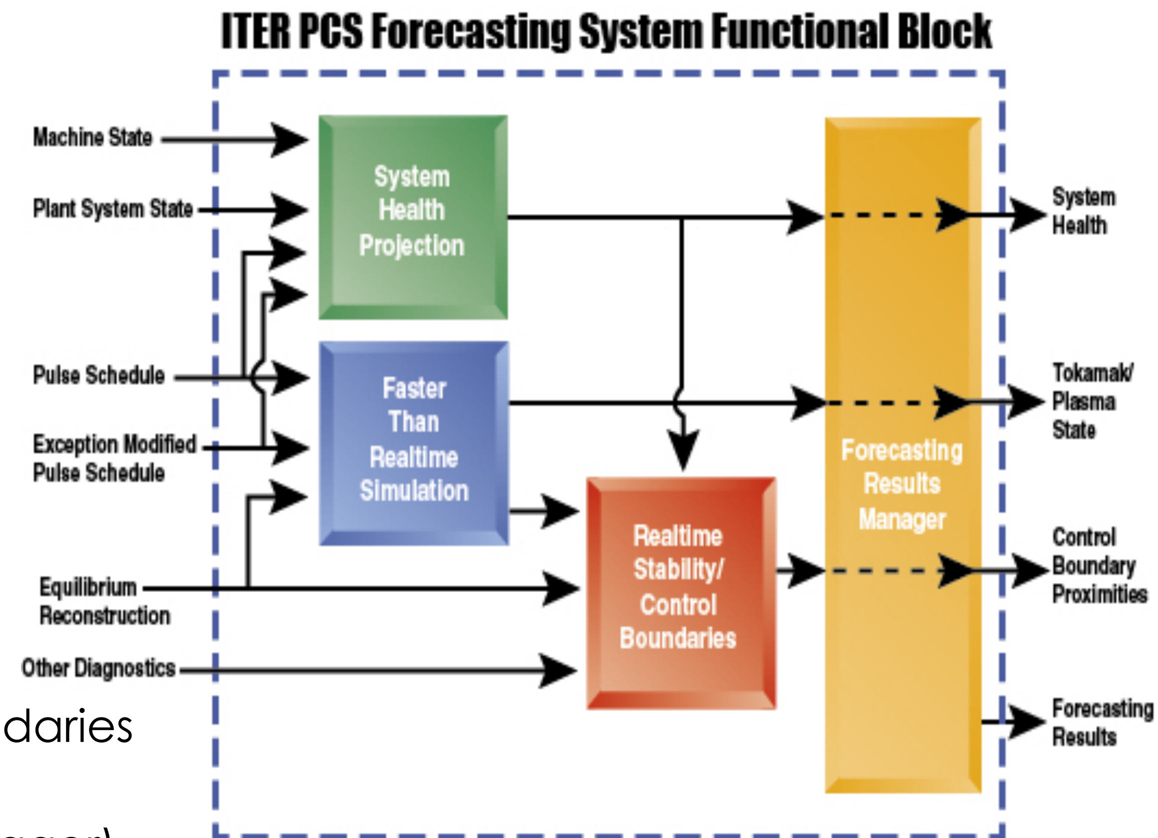
GENERAL ATOMICS

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

- **System Health Projection:**
  - Monitors present health state
  - PROJECTS to future health
- **Faster-than-Realtime-Simulation:**
  - Projection of system evolution
- **Realtime Stability/Controllability:**
  - Identify boundaries
- **Key integrated results:**
  - Proximity to controllability boundaries
  - Quantified risks: pre-disruptive events, disruptive state (DMS trigger)



Several Kinds of Predictors are Needed for Disruption Management

- **Predict future STATE (plasma or plant system) under present control trajectory**
  - Faster-than-Real-Time-Simulation forecasting
- **Predict future STABILITY or CONTROLLABILITY (boundary proximities)**
  - Real-time stability/controllability projection (applied to FRTS results)
- **Predict specific exceptions and faults for EXCEPTION HANDLING**
  - System health projection (monitoring quality signals, infer from realtime data analysis)
- **Provide specific basis for TRIGGER OF EMERGENCY RESPONSES**
  - Shutdowns: rapid controlled, emergency "uncontrolled"
  - Mitigation action preparatory to shutdown
  - Define DMS scenario
  - Fire DMS

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

1. **Must predict SPECIFIC pre-disruptive phenomena to enable control action:**
   - VDE, radiation limit, n≠0 MHD stability/controllability, TM-stability profile state, system fault, etc…
   - "Disruptions" aren't a single thing to predict!!!! They're the end result of many different risky phenomena which should THEMSELVES be predicted individually… (possible exception is a final "Disruption Alarm")

2. **Must provide a CONTINUOUS variable that quantifies proximity (& can GENERATE triggers):**
   - Vertical Controllability metric: e.g. ΔZmax; Tearing mode stability metric: Turco J-well depth
   - Formal "Hazard" probability, quantified risk metric

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

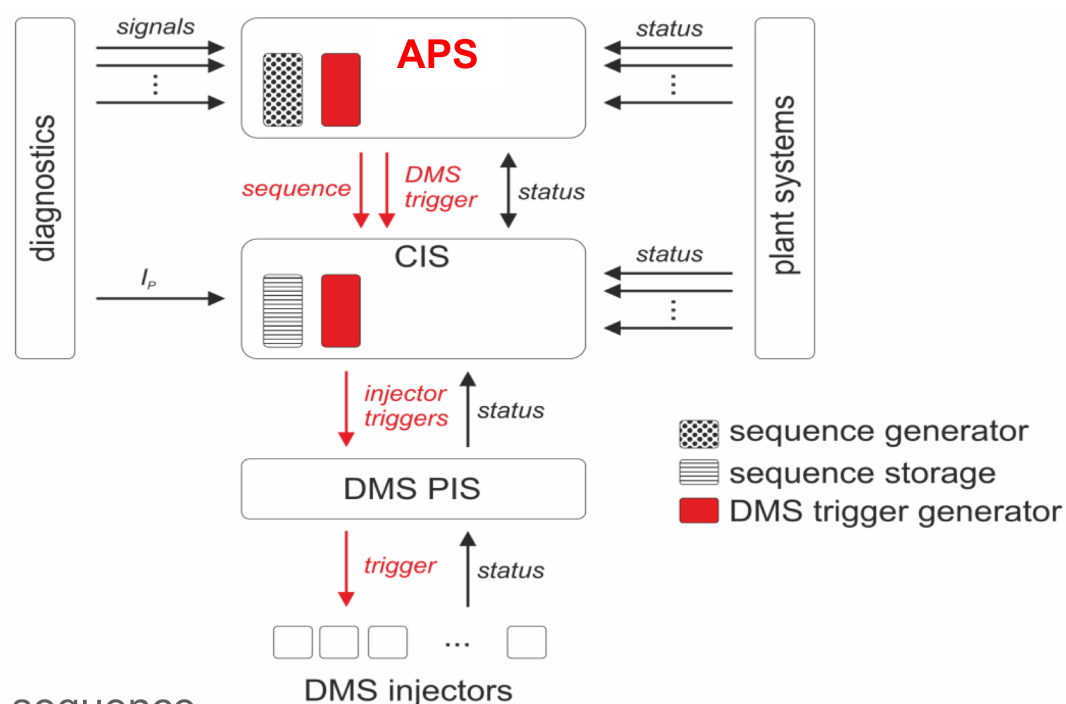
4. **Must be linked to SPECIFIC CONTROL ACTIONS and provide SUFFICIENT LEAD TIME**
   - Predictor interpretability: must provide information on source of prediction and implied control action

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…

Disruption Mitigation Function – Role of PCS/APS/CIS/DMS

NOTE: this scheme is in flux… will likely be realigned with full Investment Protection scheme now under development…

APS = Advanced Protection System



Responsibilities

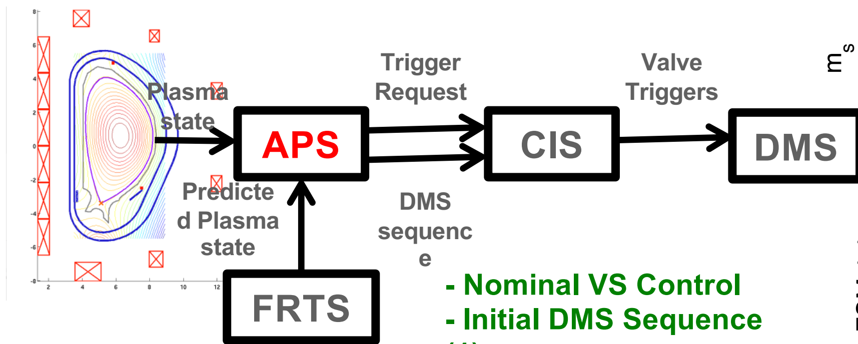
APS: DMS trigger, calculate sequence

CIS: execute sequence, DMS trigger on plant fault or other safety interlock

DMS: injector status, activate injectors, pre-pulse configuration (via CODAC)

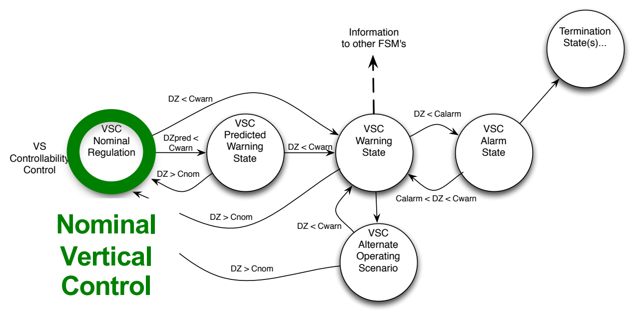
ITER_D_T97WNG

DMS Triggering Sequence Illustration



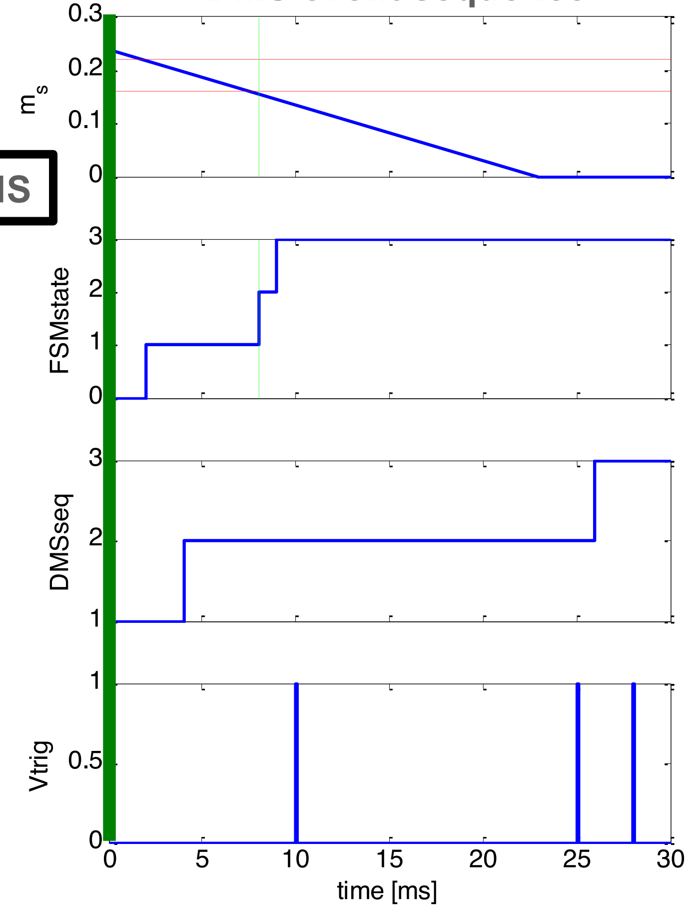
- Nominal VS Control
- Initial DMS Sequence (1)

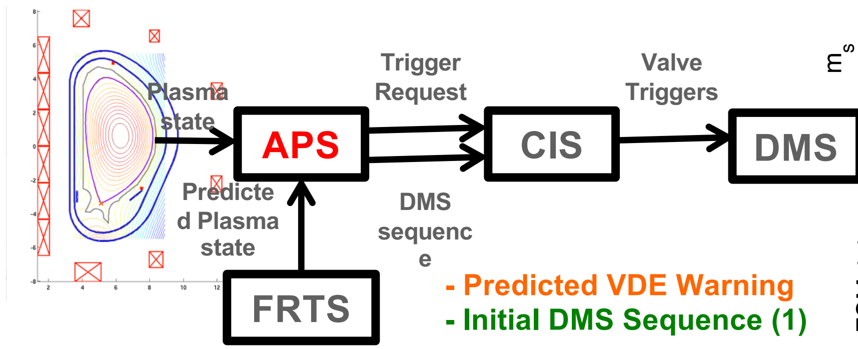
Sequence Idx	# TLM	Delay < TLM [ms]	# REM	Delay < REM [ms]
1	5	0	5	20
2	3	0	5	15
3	3	0	3+2 (repl)	15+18



Nominal Vertical Control

DMS event sequence





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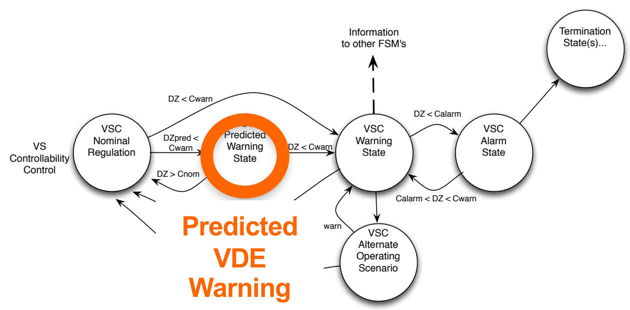
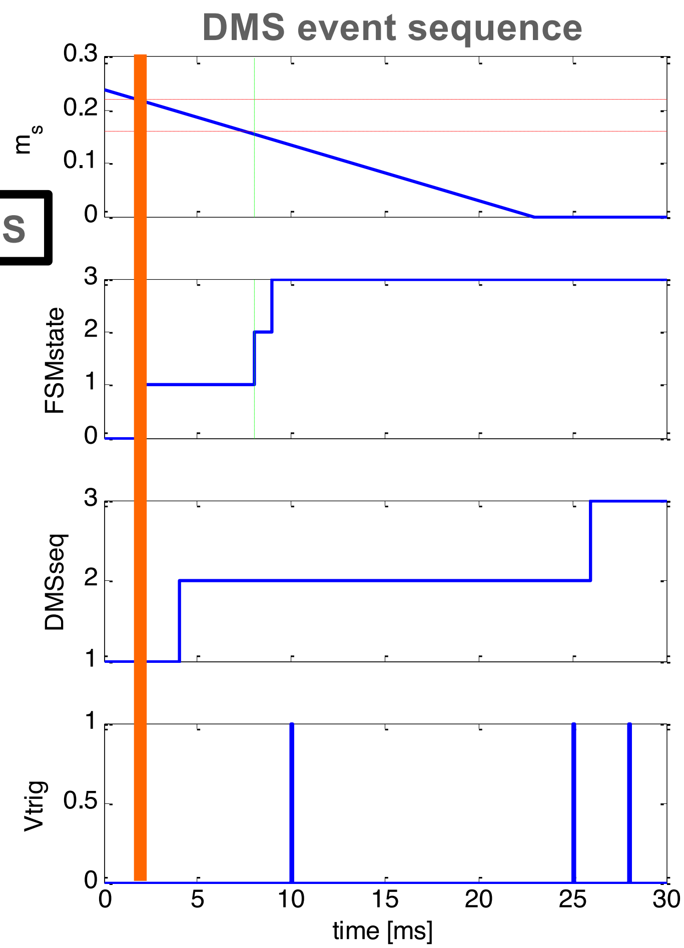
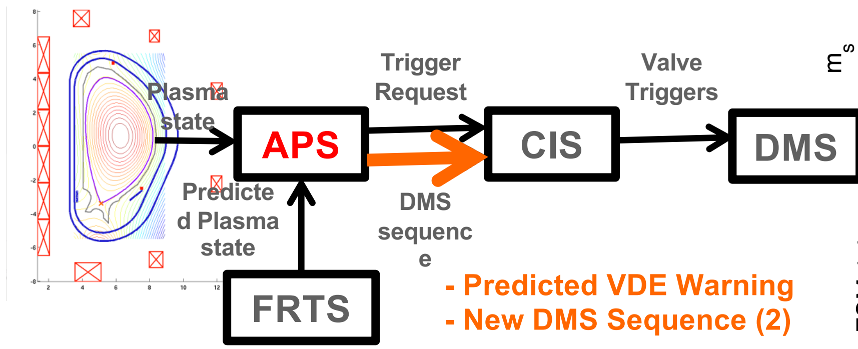




DMS Triggering Sequence Illustration



- Predicted VDE Warning
- New DMS Sequence (2)

Sequence Idx	# TLM	Delay < TLM [ms]	# REM	Delay < REM [ms]
1	5	0	5	20
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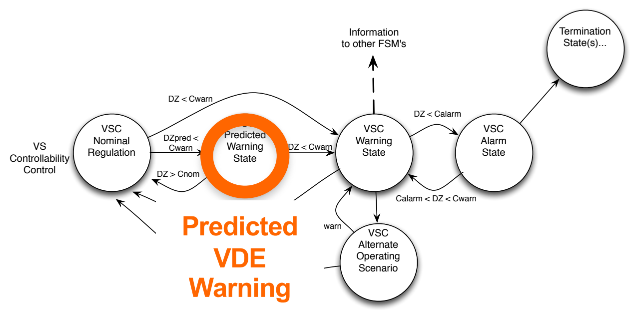

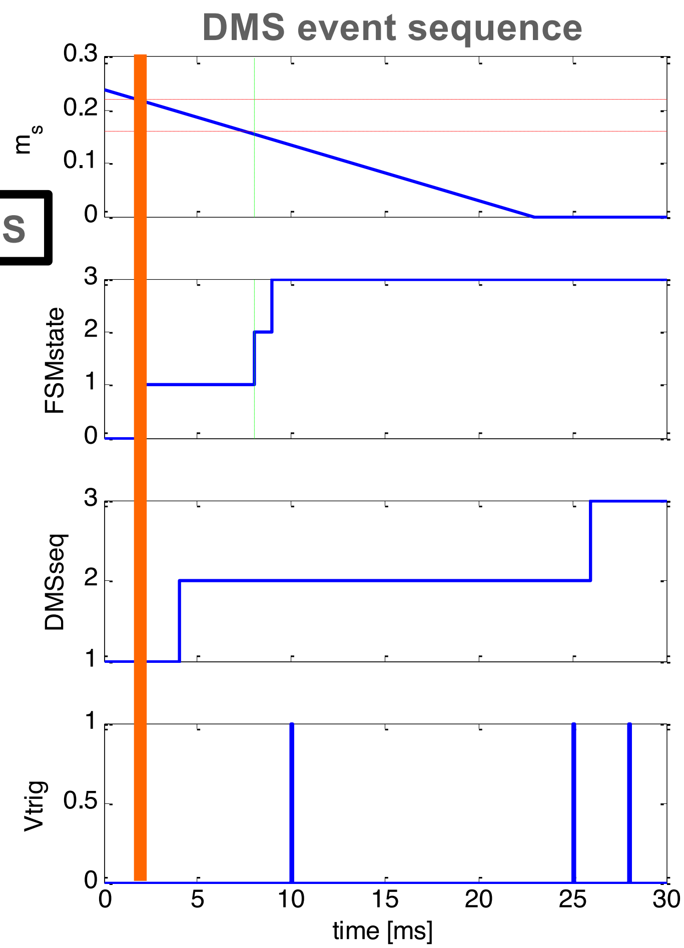

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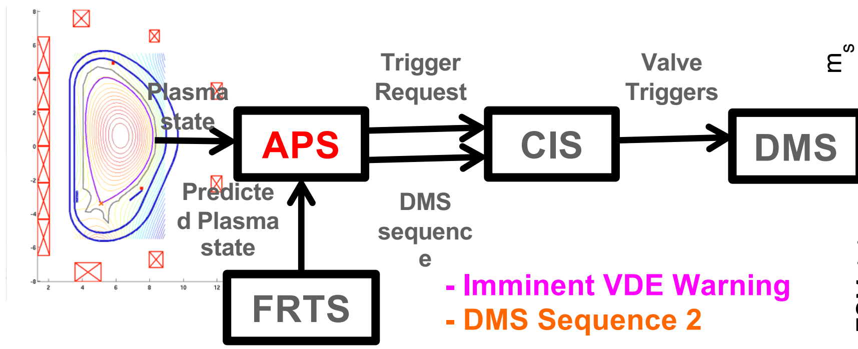

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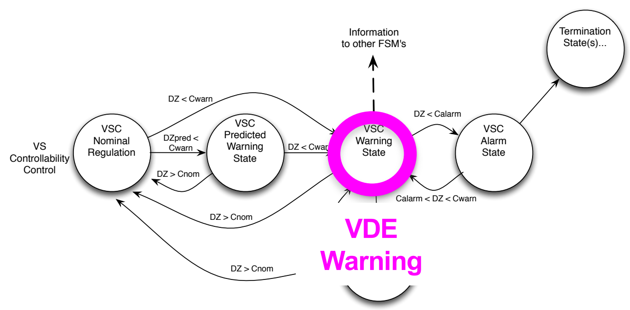

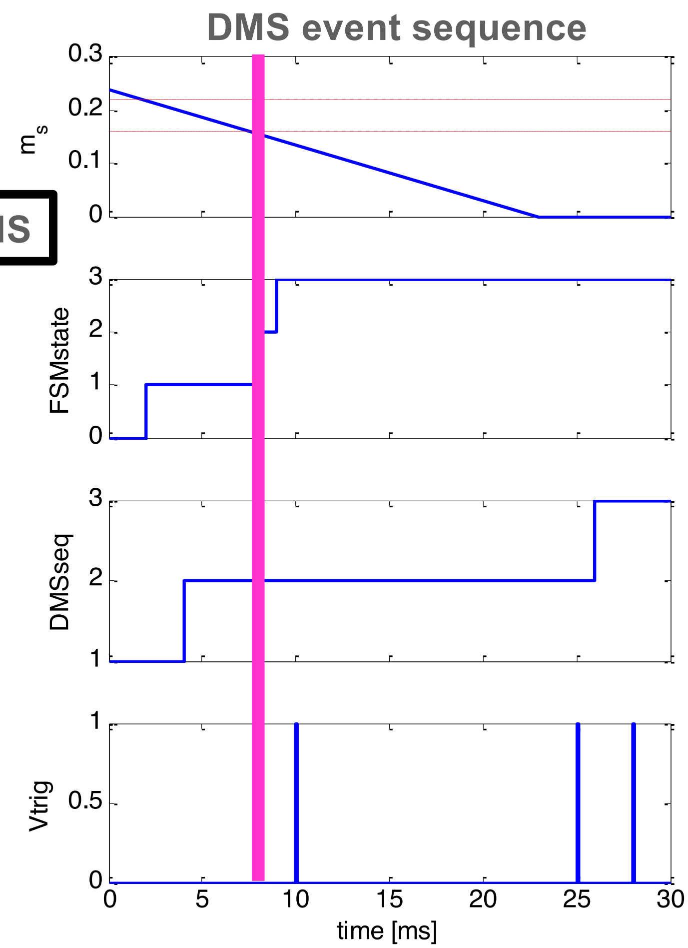

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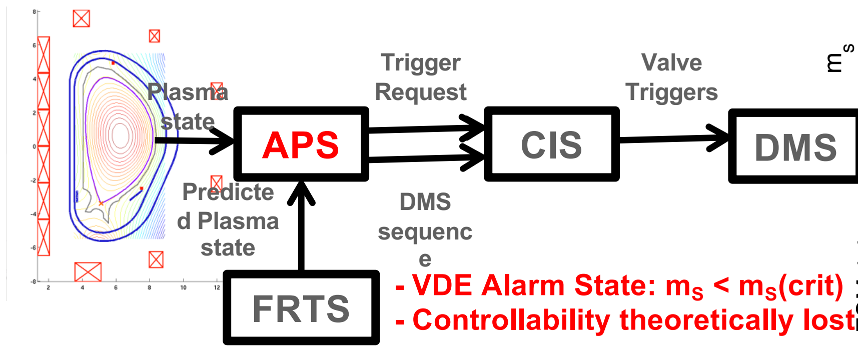

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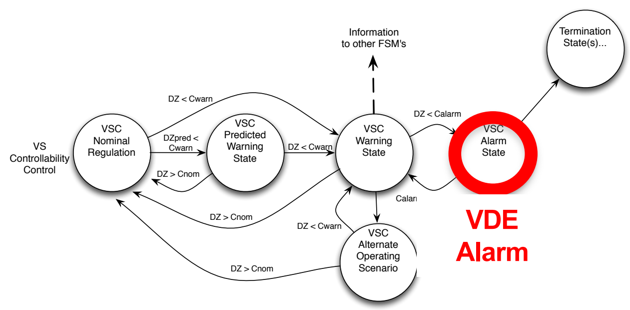

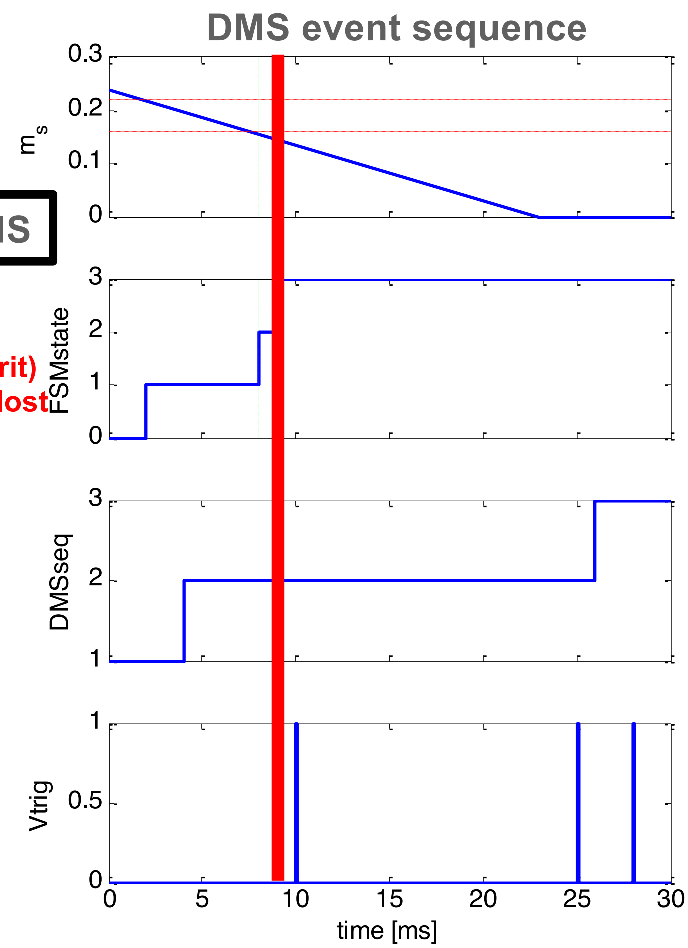

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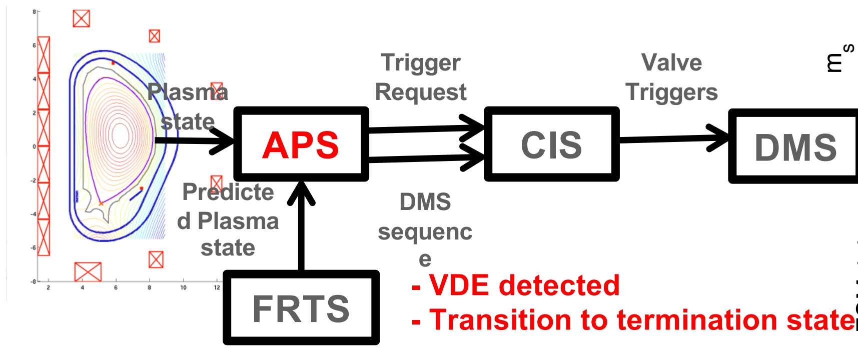

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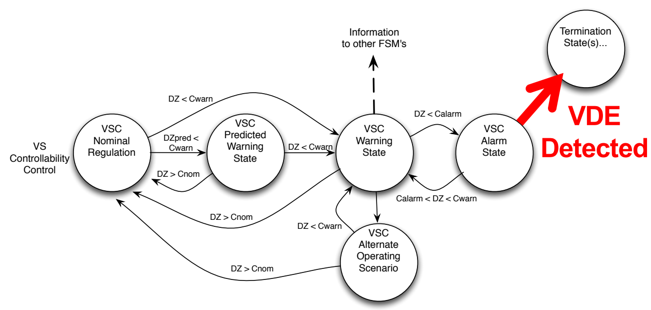

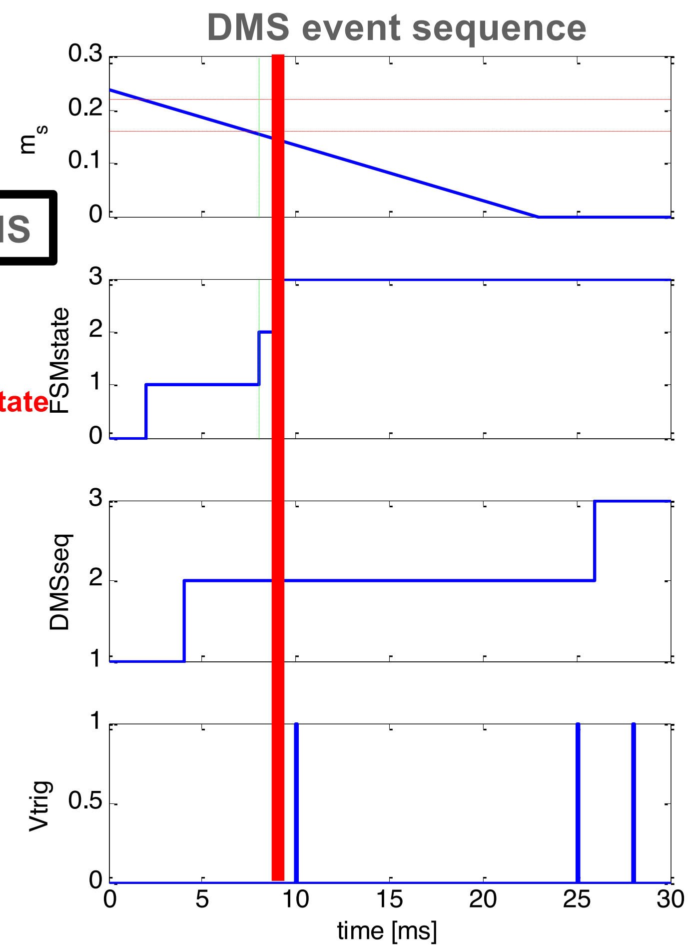

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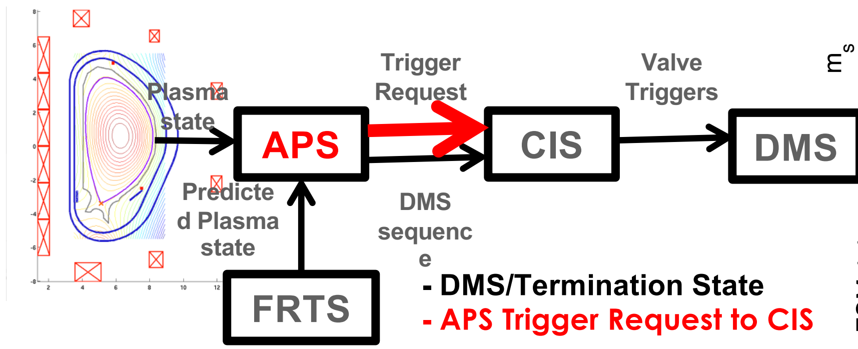

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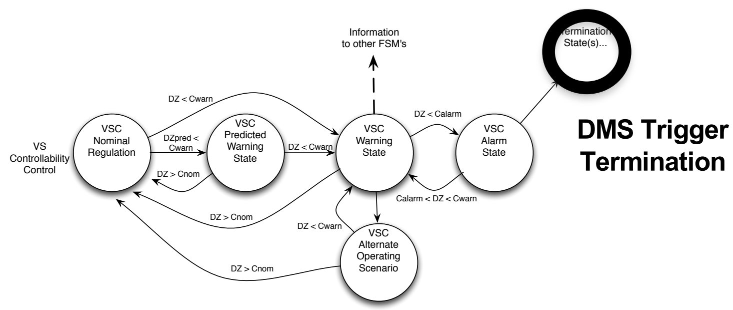

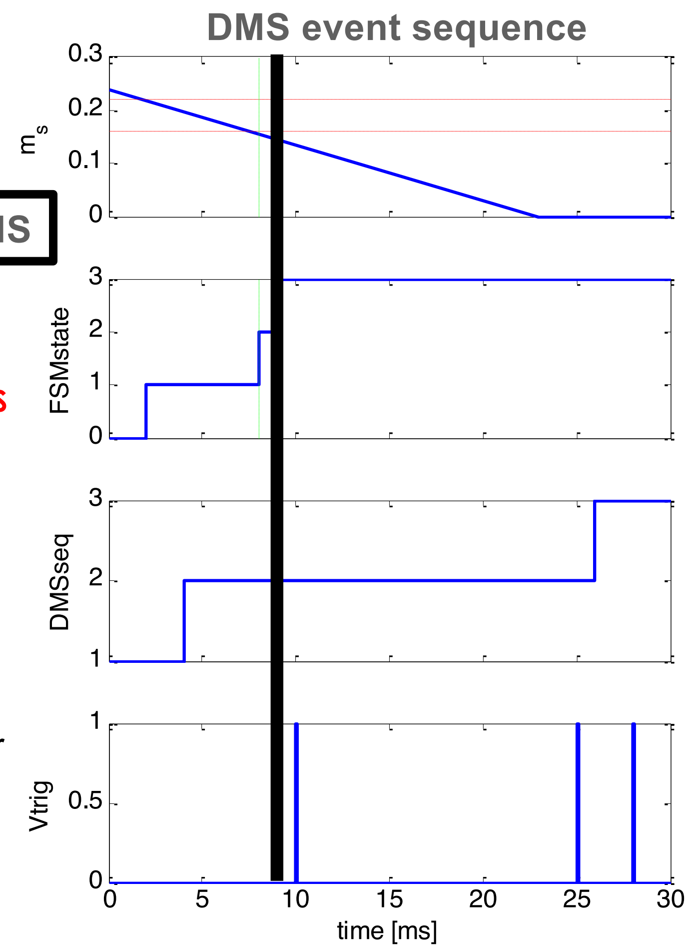

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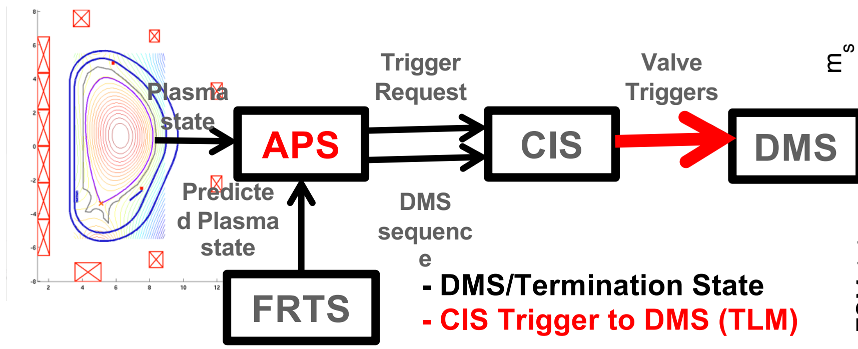

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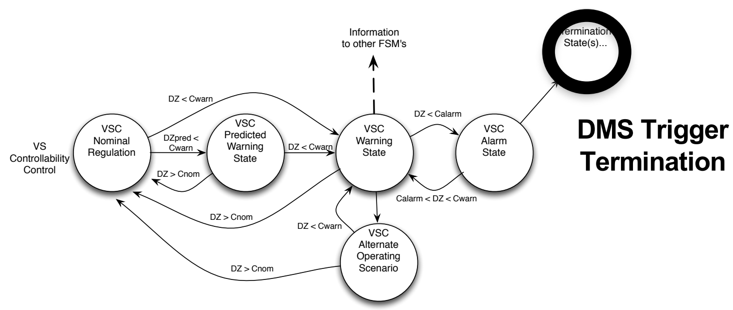

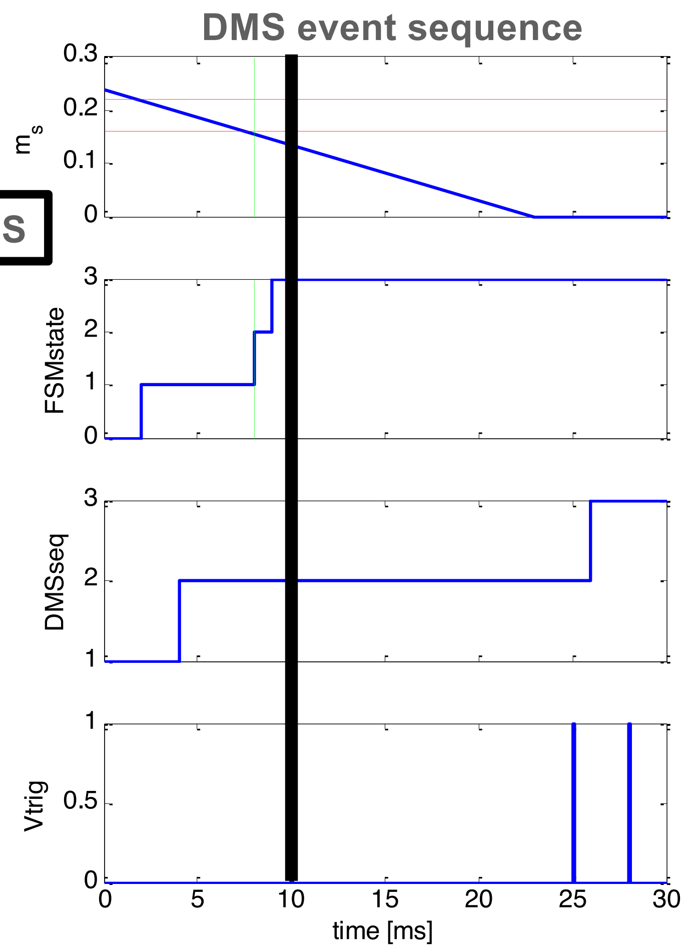

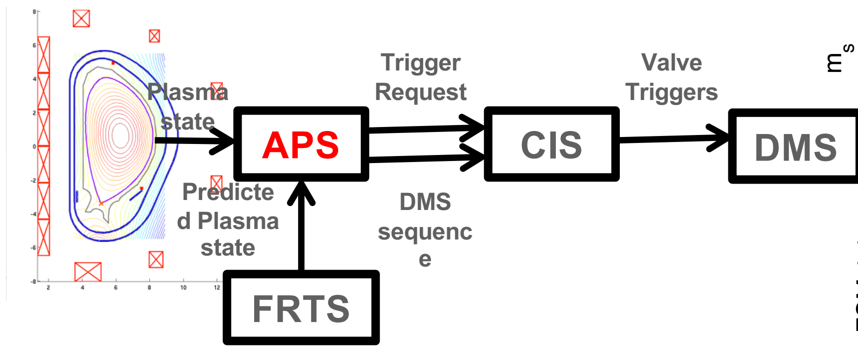

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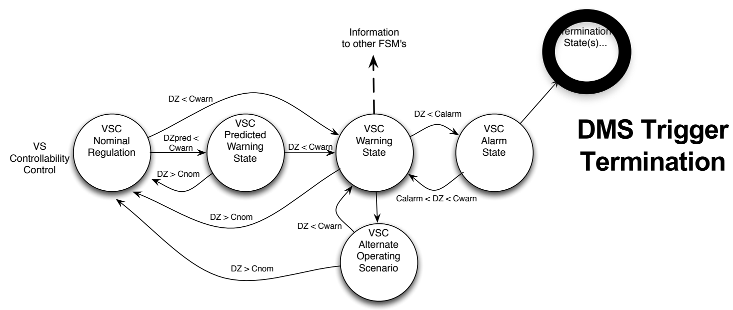
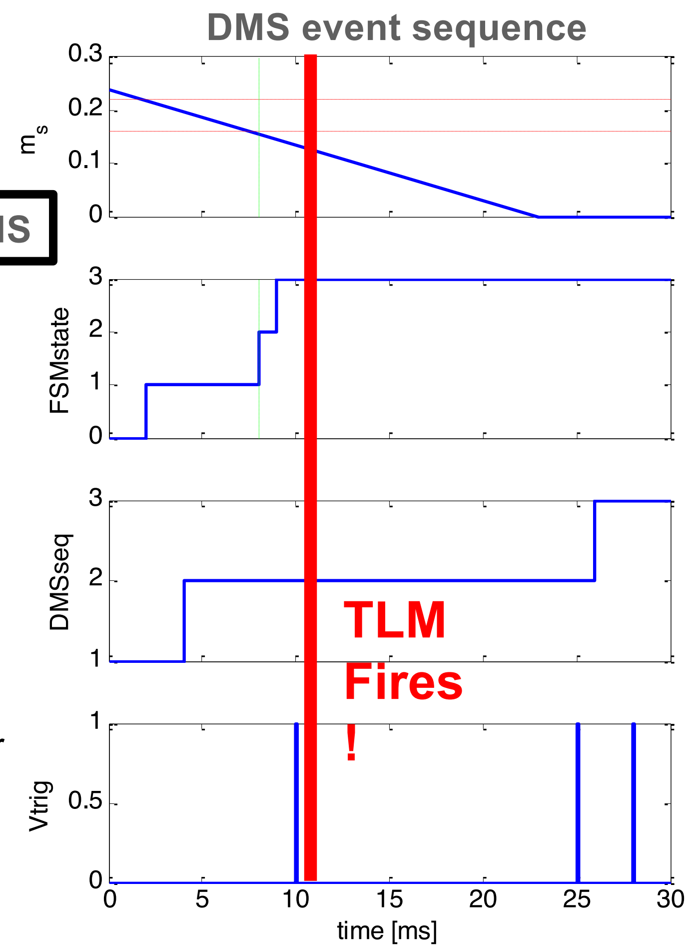
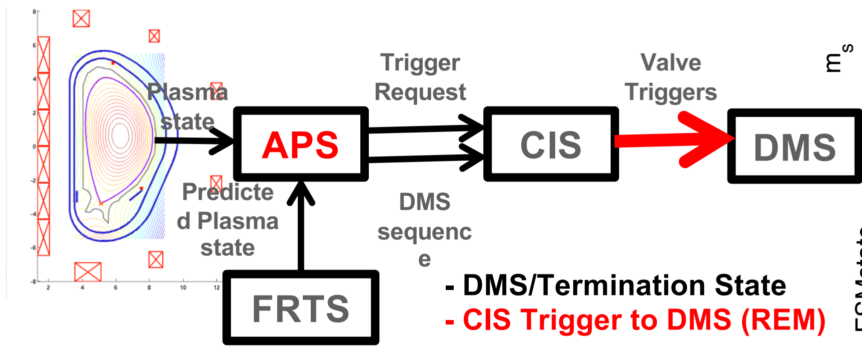




DMS Triggering Sequence Illustration



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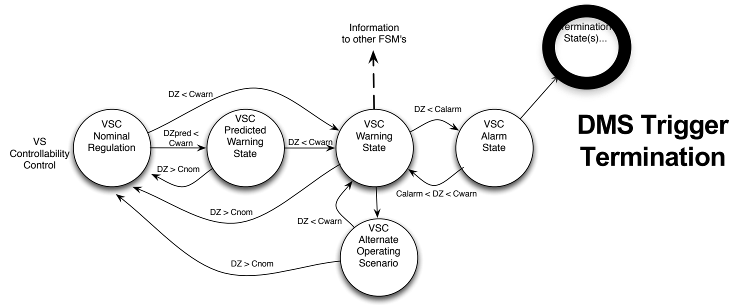

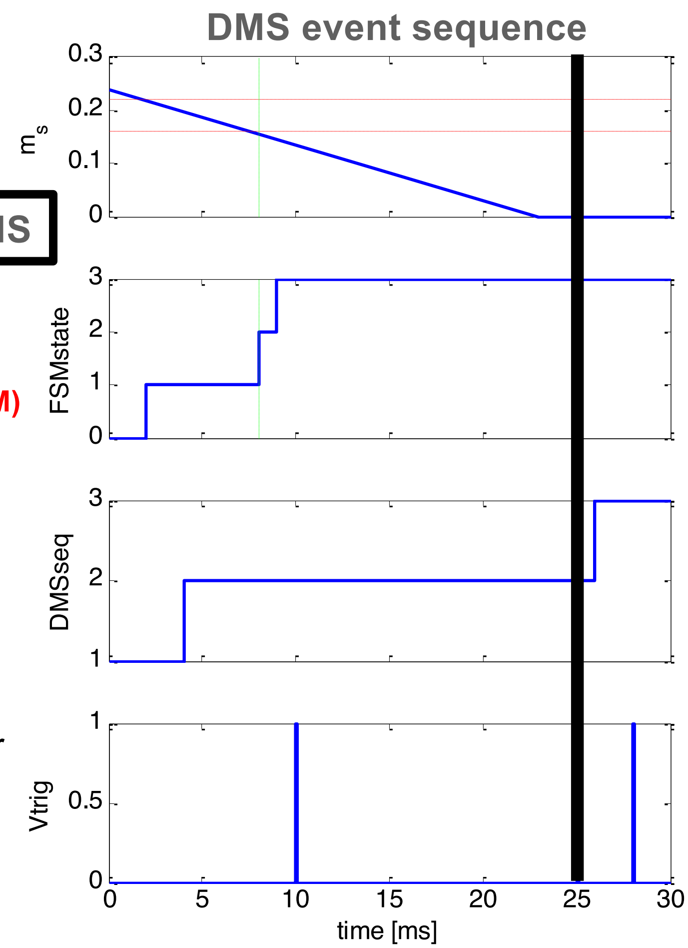

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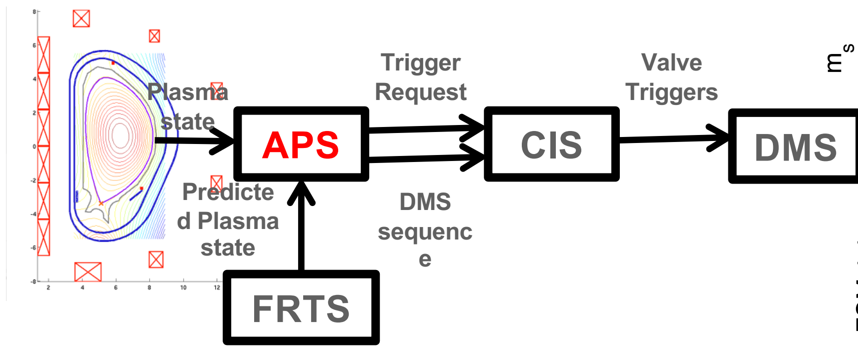

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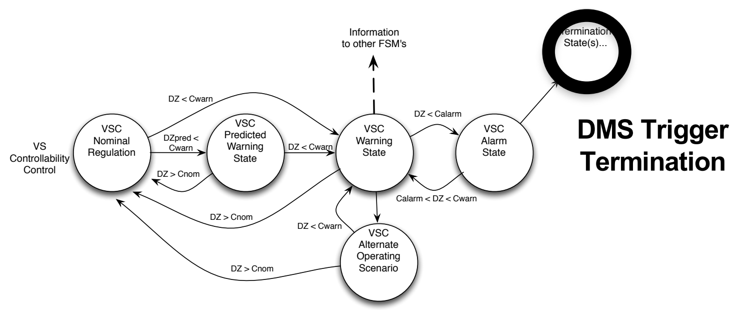

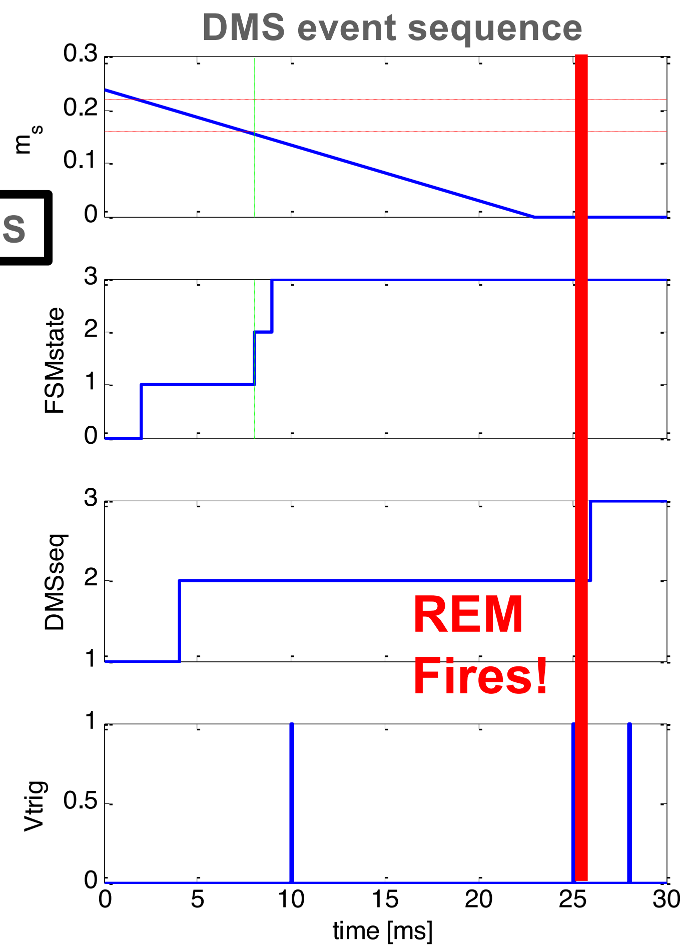

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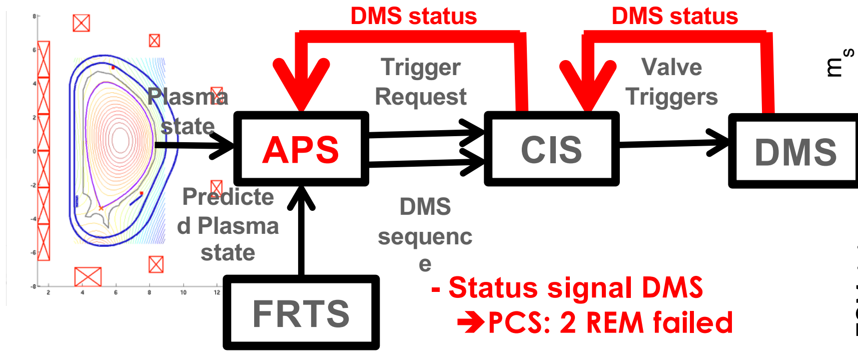

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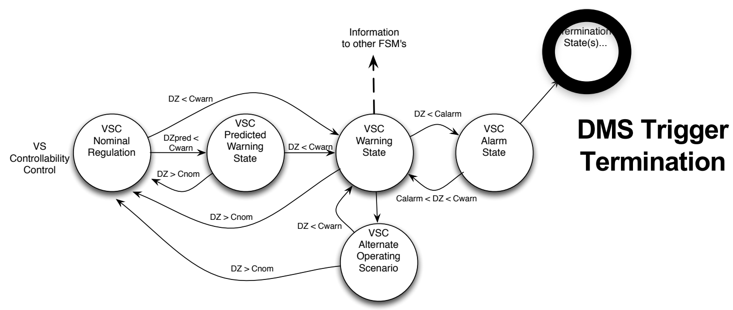

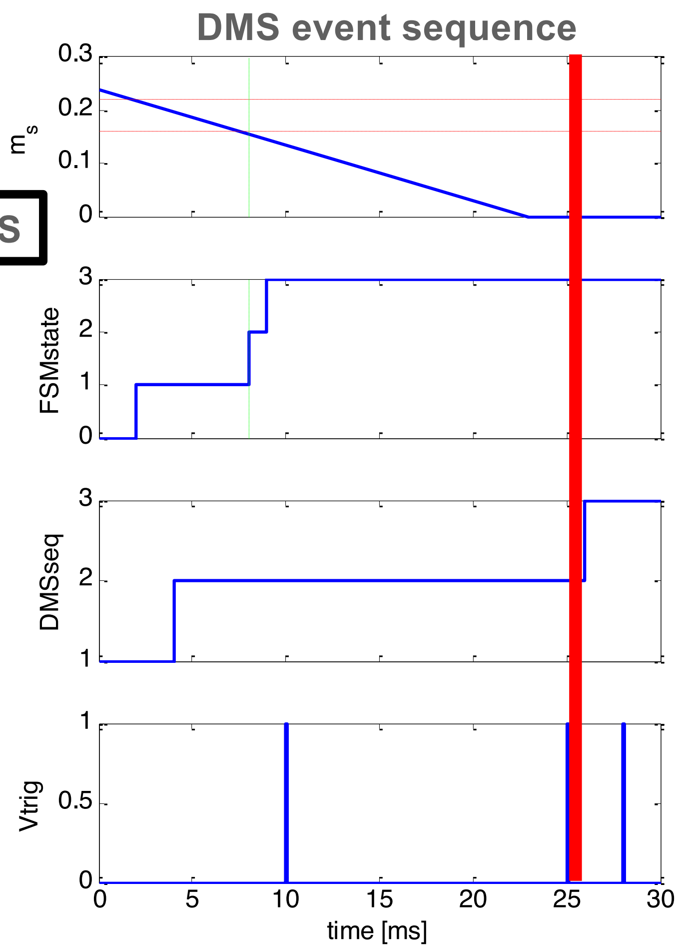

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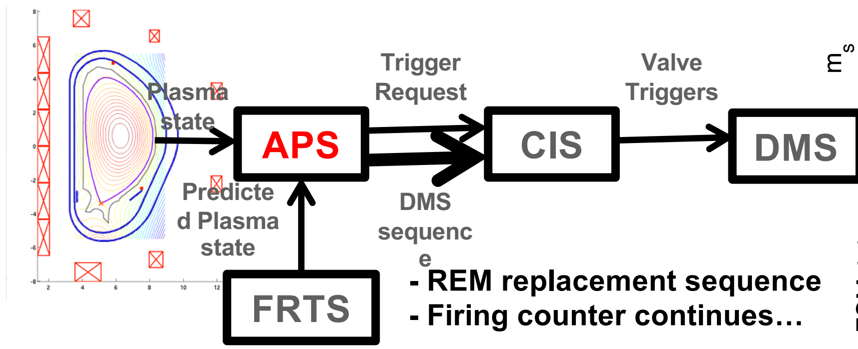

- REM replacement sequence
- Firing counter continues…

Sequence Idx	# TLM	Delay < TLM [ms]	# REM	Delay < REM [ms]
1	5	0	5	20
2	3	0	5	15
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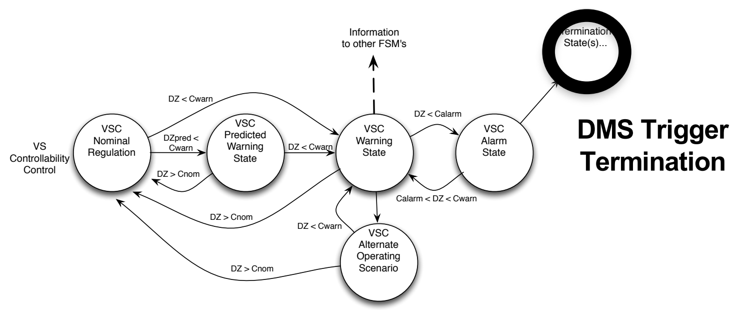

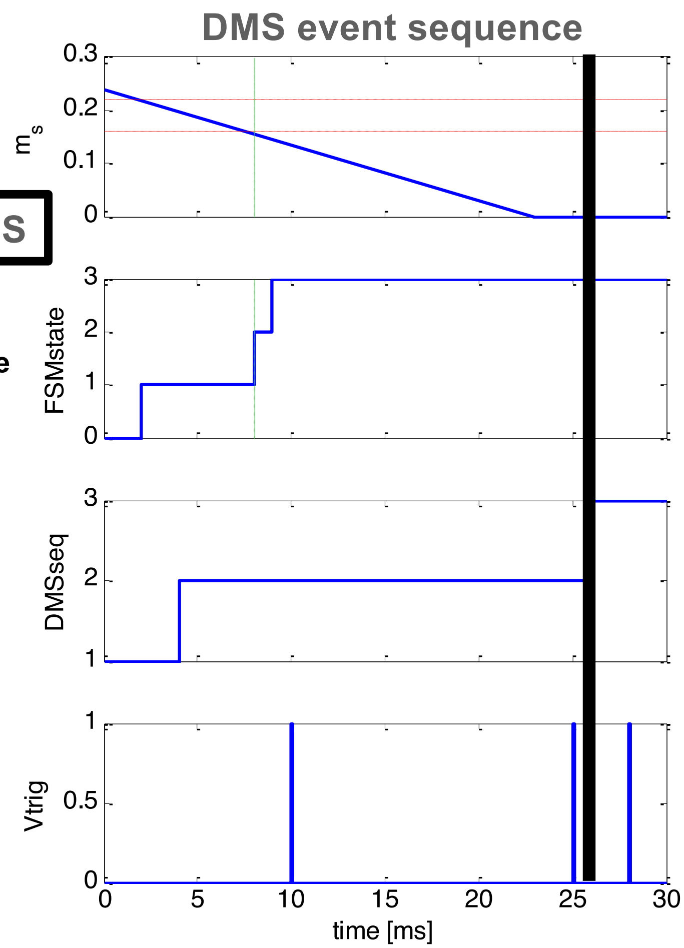

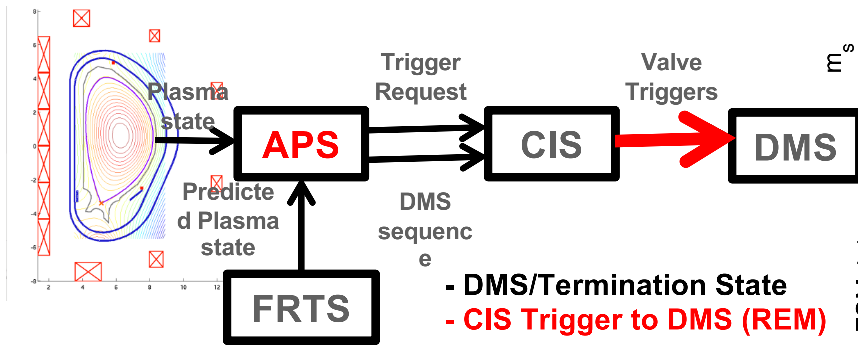

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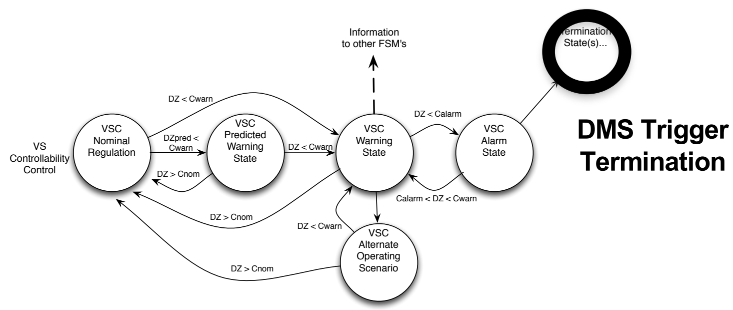
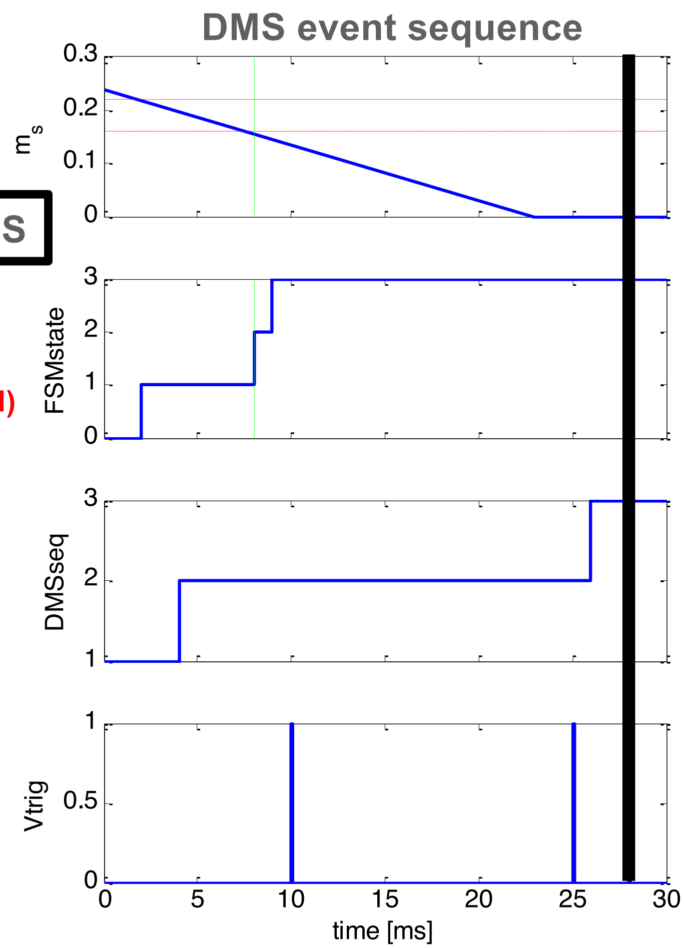
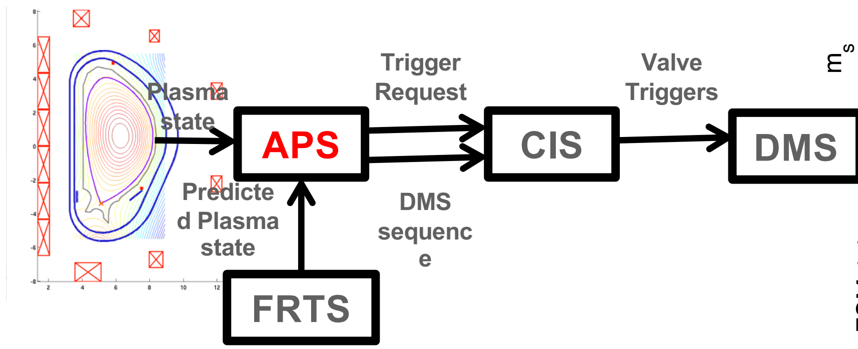




DMS Triggering Sequence Illustration



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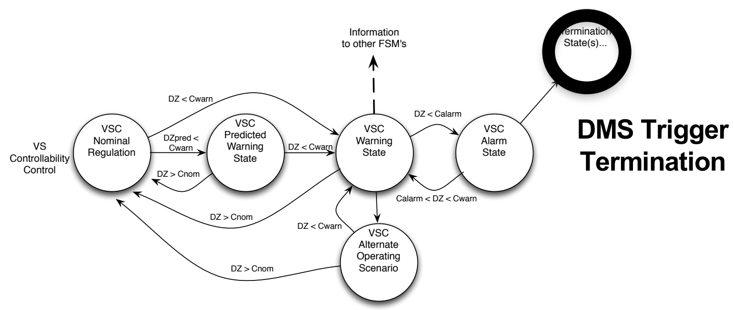

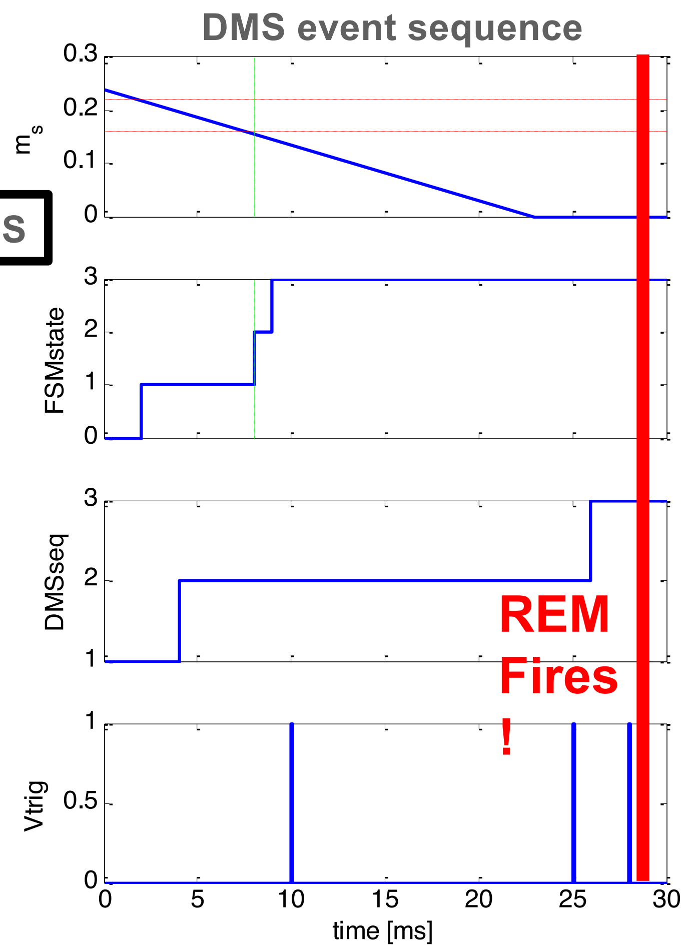

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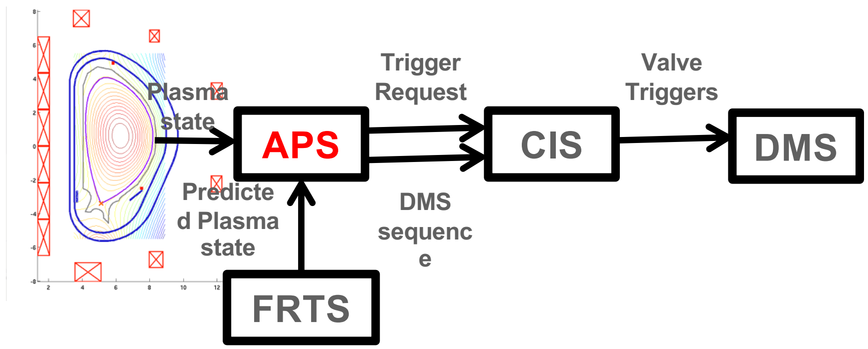

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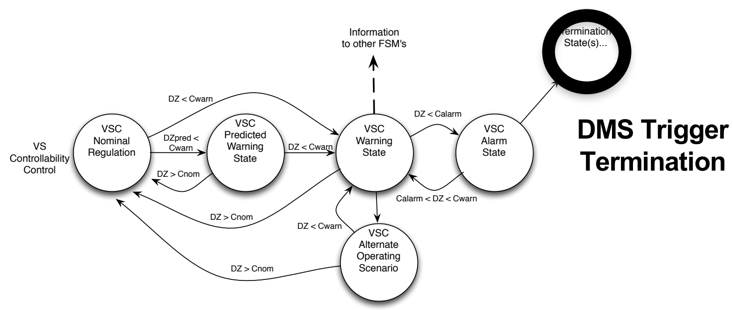
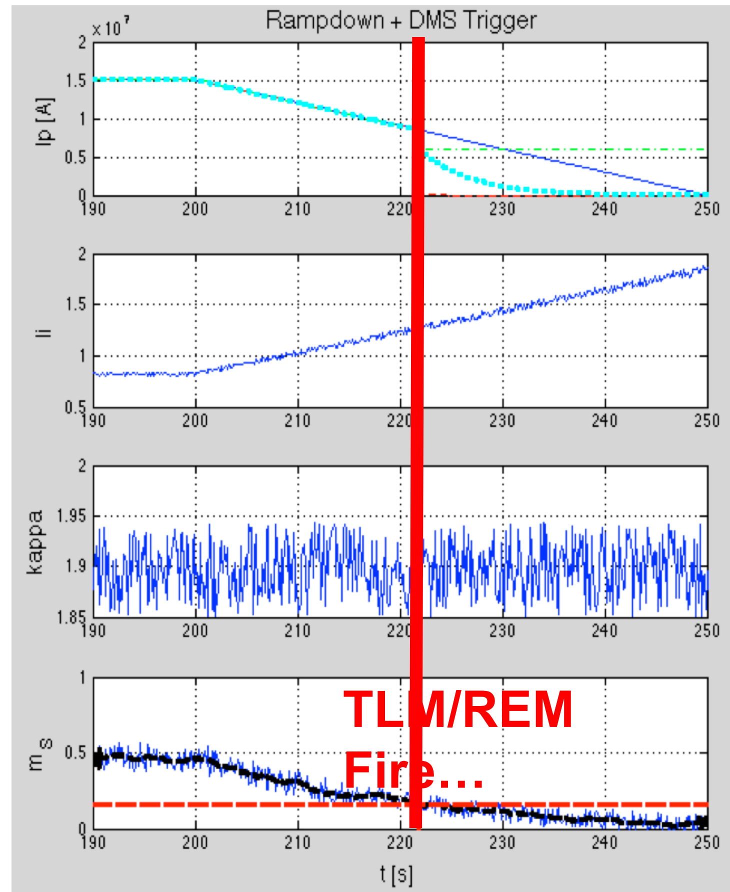
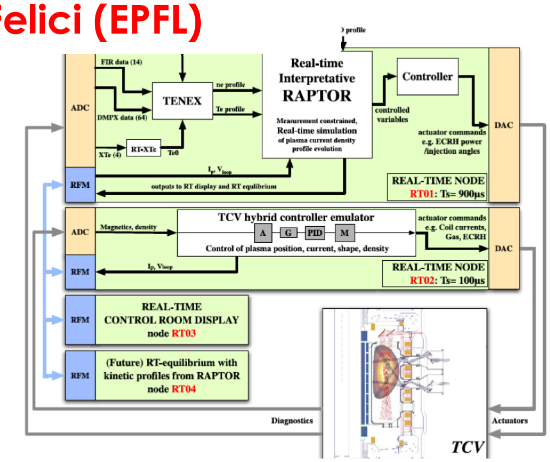




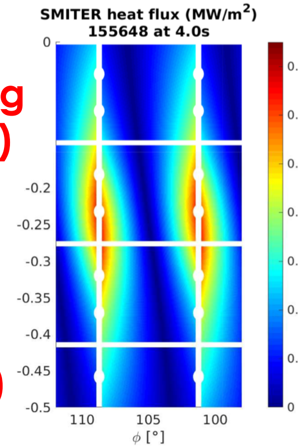
Developing the Remaining ITER PCS Solutions

Candidate Approaches Are Under Development at Many Devices to Qualify Needed Solutions for ITER in PFPO1-2 and Beyond

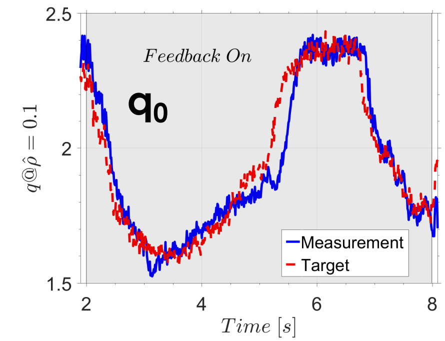
RAPTOR FRTS – Felici (EPFL)



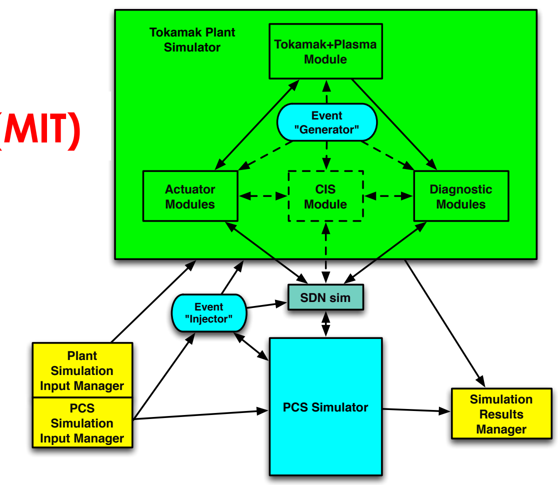
RT Wall monitoring – IO&Anand (GA)



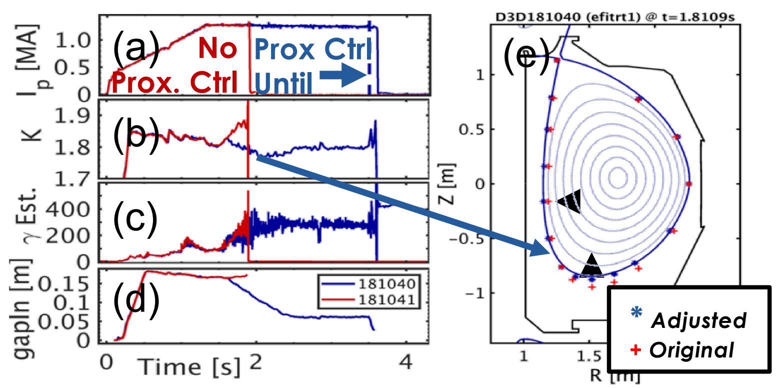
q-profile control- Schuster (LU)



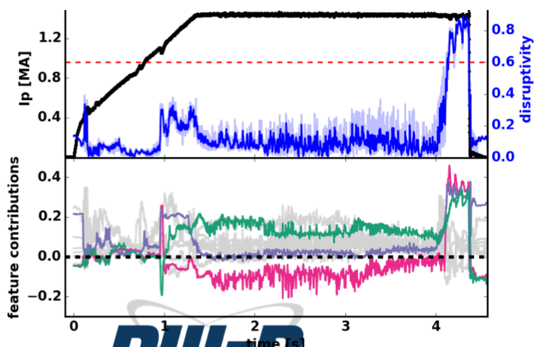
Shot Validation– PCSSP (IO)



VDE proximity control– Barr (GA)



Interpretable predictors– Rea (MIT)



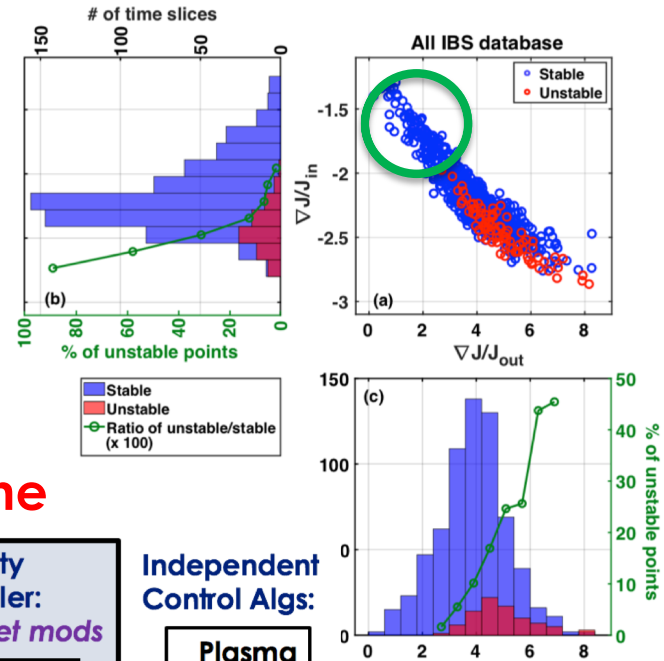
New ITPA IOS-MDC Topical Groups Joint Activity on "Control for Disruption-Free Operation"

- **Multi-machine/lab effort driven by Joe Snipes to coordinate IOS and MDC toward control for disruption-free ops**

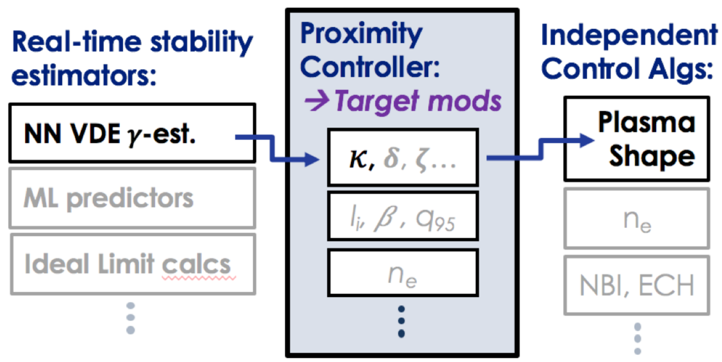
- **Long-term Goals:**
  - Study scenarios with low disruptivity
  - Improve understanding of events leading to disruptive states
  - Determine and qualify methods of control for disruption-free operation

- **Near-term Goals:**
  - Initial focus on proximity control for continuous disruption prevention…

Turco NTM Jwell Metric



Proximity Control Scheme



Summary and Conclusions

- **The ITER PCS plays a central role in preventing and managing ITER disruptions**

- **Key PCS functions for disruption management include:**
  - Shot validation through control simulation verification: mitigate human error
  - Robust control algorithms: tolerate expected noise/disturbances
  - Proximity control: prevent approach to disruptive states, continuously minimize risk
  - Effective Exception Handling: respond to system faults to avoid disruptive states
  - FRTS Forecasting and effective predictors: avoid potential disruptive states
  - DMS triggering (maybe) and effective mitigation scenarios: mitigate effects

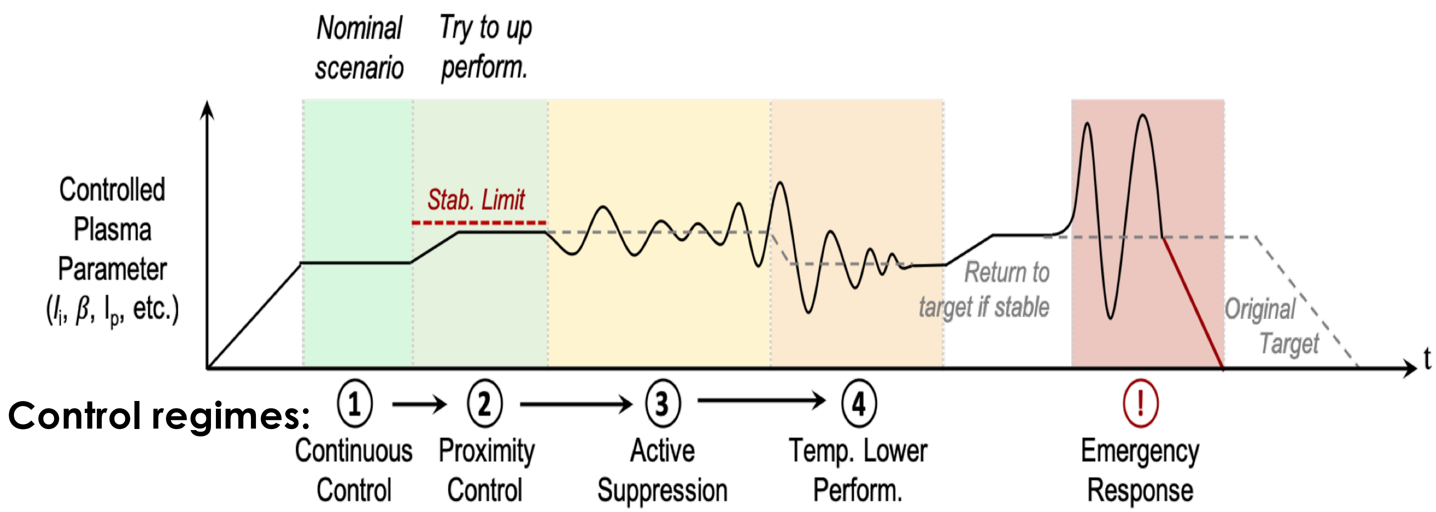
- **Novel elements needed for ITER PCS are now subject of active research:**
  - Proximity control, controllability assessment/prediction, disruptivity risk assessment
  - ITPA Joint Activity between IOS and MDC TG's: disruption-free operation

Additional Slide Material

Control Solutions Act at Every Stage in Operating Space to Prevent or Avoid (in case of fault) Disruptions

Solution must be:
A *fully qualified suite* of *ITER/reactor -scalable* disruption prevention & avoidance control tools for *routine operation with quantifiable, high confidence reliability*

This is the domain of control mathematics informed by physics



DIII-D NATIONAL FUSION FACILITY

ITER Plasma Control System Architecture and Functions Must Satisfy Many Functional Requirements with Scalability to Future Needs